Diffractively Produced 3-Pion States at COMPASS

Bernhard Ketzer

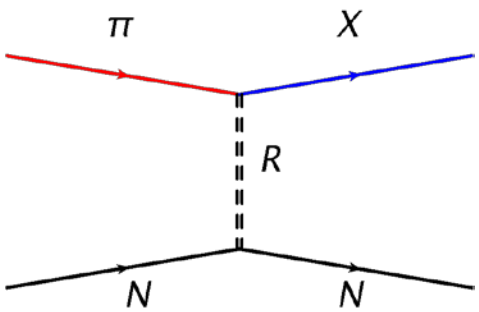
Rheinische Friedrich-Wilhelms-Universität Bonn

XVI International Conference on Hadron Spectroscopy

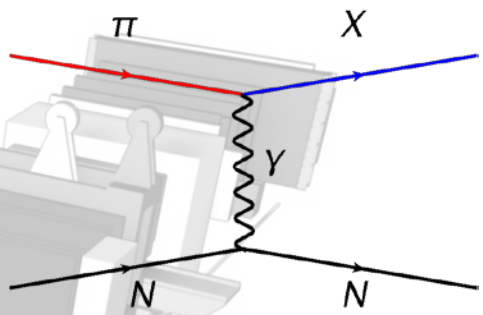
Newport News, USA

17 September 2015

The COMPASS Experiment



B. Grube, Plenary talk, Sep 16, 12:20



Diffractive dissociation

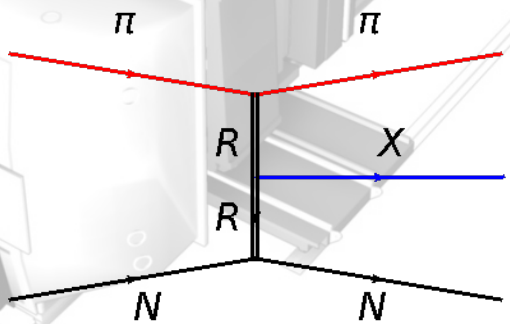
- Isovector states: π_J, a_J
- Hybrids, exotics
- Scalar states

⇨ F. Krinner, 1E2, Sep 17, 08:55

Photoproduction

- Polarizabilities: π
- Spectroscopy

⇨ M. Krämer, 6C4, Sep 17, 11:45



Central production:

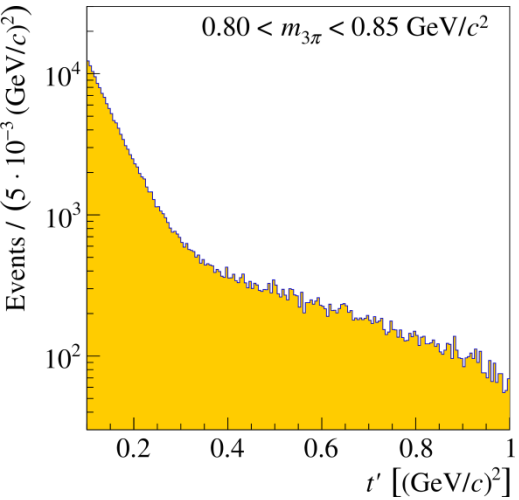
- Scalar states
- Glueballs

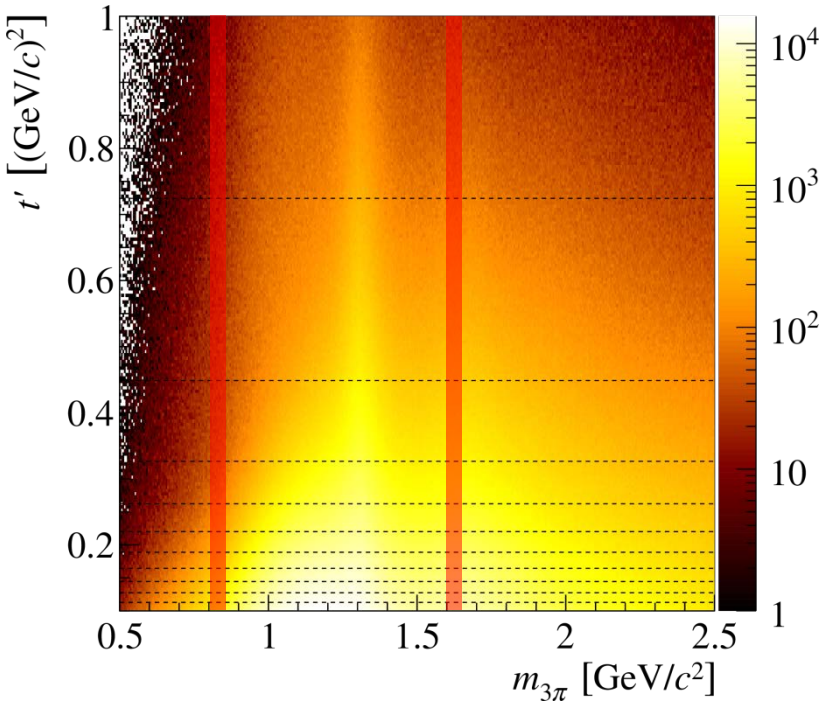
⇨ A. Austregesilo, 1E1, Sep 17, 08:30

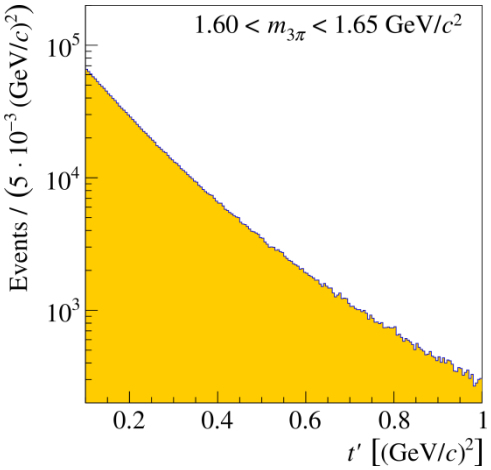
Plan of the Talk

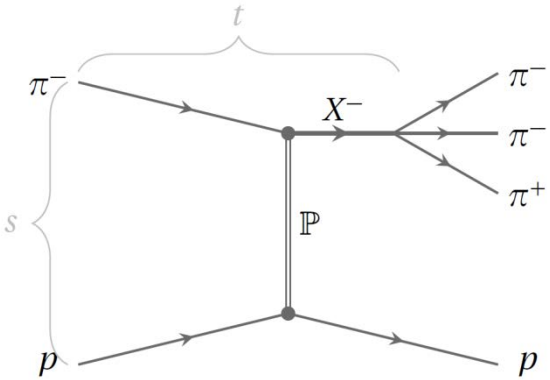
- Introduction: diffractive production and PWA at COMPASS
- Challenges for the analysis
  - axial-vector states
  - spin-exotics
- New approaches
  - fit in bins of mass and squared 4-momentum transfer
  - Deck-like non-resonant production
  - include amplitudes for dynamic processes, e.g. triangle diagram
  - use analytic amplitudes which satisfy unitarity
- Conclusions and Outlook

3π Final State - Kinematics



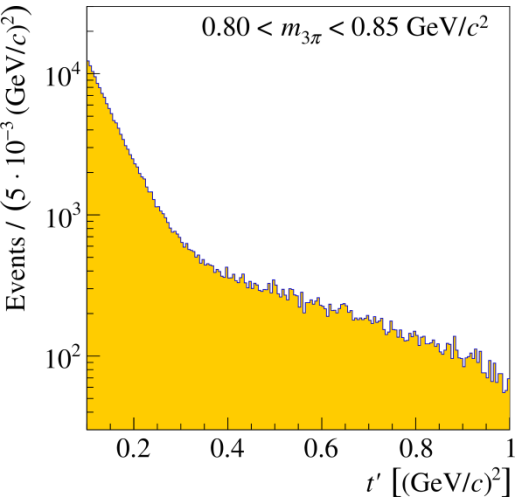


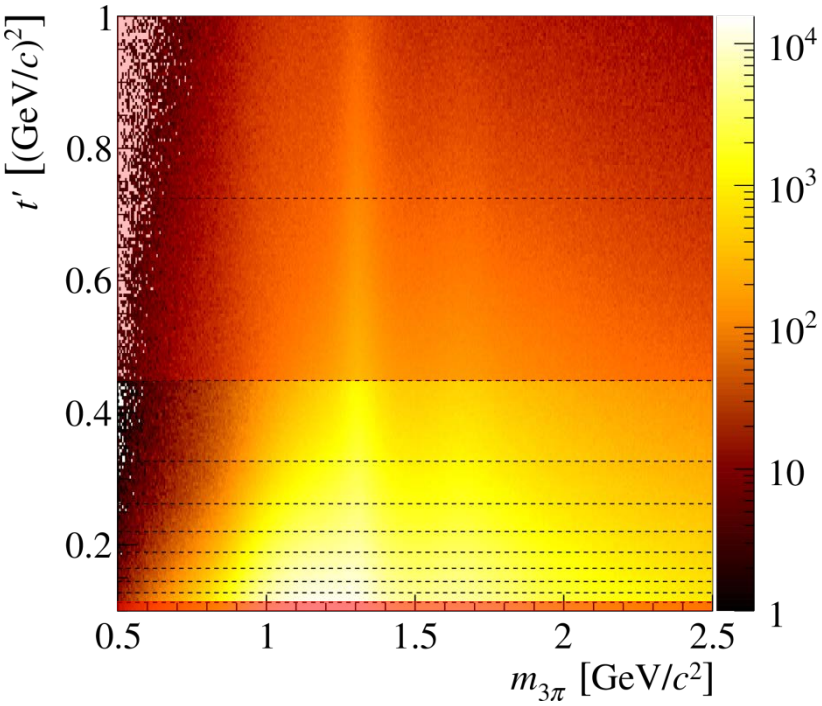


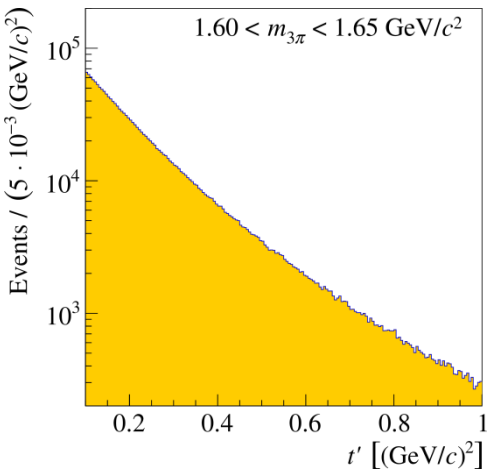


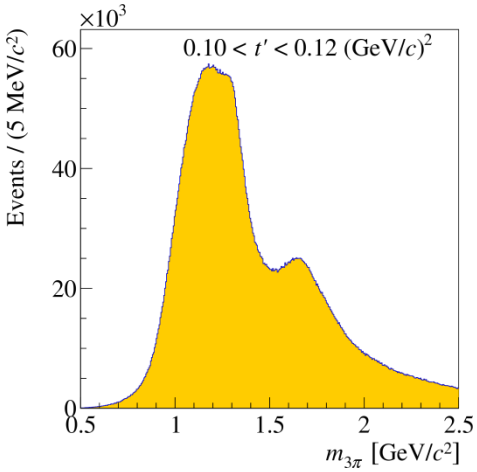
[C. Adolph et al., arXiv1509.00992]

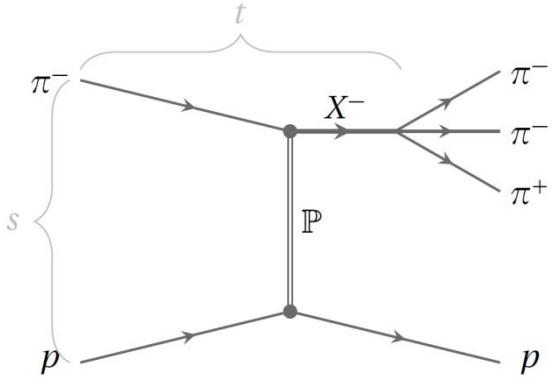
3π Final State - Kinematics

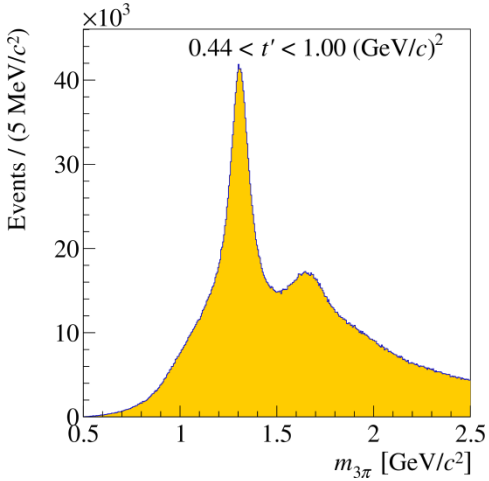












[C. Adolph et al., arXiv1509.00992]

Partial Wave Analysis

1. **PWA** of angular distributions in **mass bins** and **t' bins**: 100 × 11 bins

$$I(\tau) = \left| \sum_{\xi} T_{\xi} A_{\xi}(\tau) \right|^2$$

- T_{ξ} = production amplitude for state with $\chi = I^G(J^{PC})M$ decaying to ζ
- $A_{\xi}(\tau)$ = decay amplitude (calculable without free parameters)
- Result: spin-density matrix $\rho_{\xi\xi'} = T_{\xi} T^*_{\xi'}$

Assumptions:

- Production and decay of a state factorize
- Decay into multi-particle final state can be described by a sequence of 2-body decays

Isobars used in present analyses:

$$[\pi\pi]_S, \rho(770), f_0(980), f_2(1270), f_0(1500), \rho_3(1690)$$

Partial Wave Analysis

2. χ^2-Fit of mass- and t-dependence of spin-density matrix

- Determine resonance parameters
- Only subset of spin-density matrix is considered for computational reasons
- Production amplitude for wave ξ: k components

  $T_\xi = \sum_k C_{\xi k}(t')\, D_k(m_{3\pi}, t'; \theta_k)$

  – resonant terms: $$D_k\left(m_{3\pi}; M_0, \Gamma_0\right) = \frac{M_0 \Gamma(m_{3\pi})}{M_0^2 - m_{3\pi}^2 - i M_0 \Gamma(m_{3\pi})}$$

  – non-resonant terms:

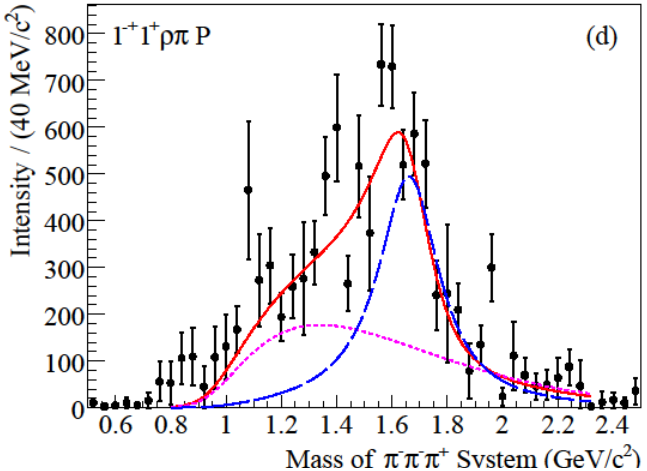
  $$D_k\left(m_{3\pi}, t'; c_i\right) = \left[\frac{m_{3\pi} - m_{\mathrm{thr}}}{m_{\mathrm{thr}}}\right]^{c_0} e^{-\left(c_1 + c_2 t' + c_3 t'^2\right) q^2}$$

  – fit parameters: complex couplings $C_{\xi k}(t')$, parameters of dynamic functions θ_k

The $\pi_1(1600)$

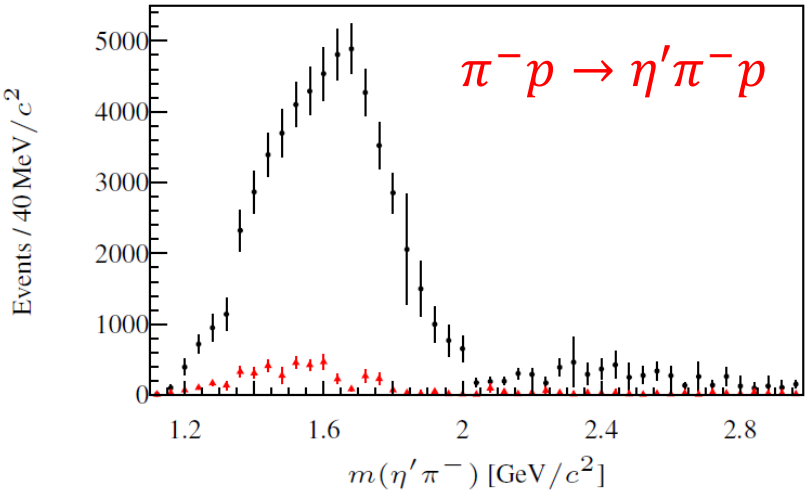
$1^{-+}1^{+}$ ρπ P – Wave

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



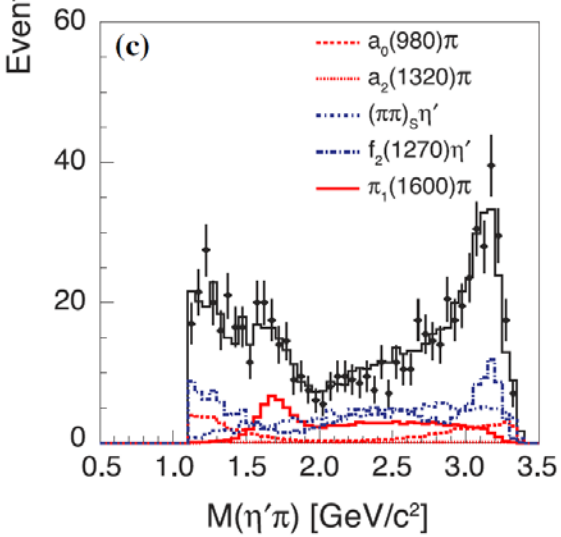
- Resonance-like signal observed
- Large contribution of non-resonant background
- Need to understand origin for a reliable fit of spin-density matrix of high-statistics H_2 data

[Alekseev et al., Phys. Rev. Lett. 104, 241803 (2010)]



[C. Adolph et al., PLB 740, 303 (2015)]

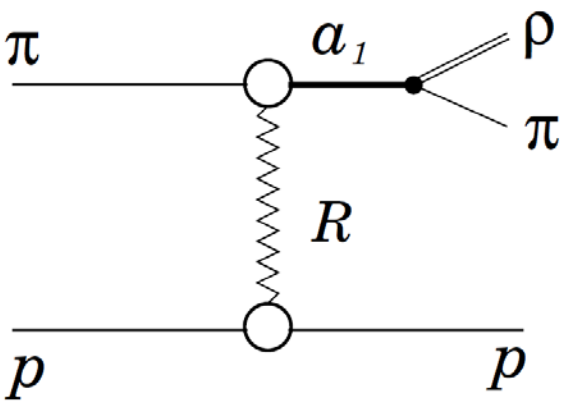
$\chi_{c1} \rightarrow \eta'\pi^-\pi^+$



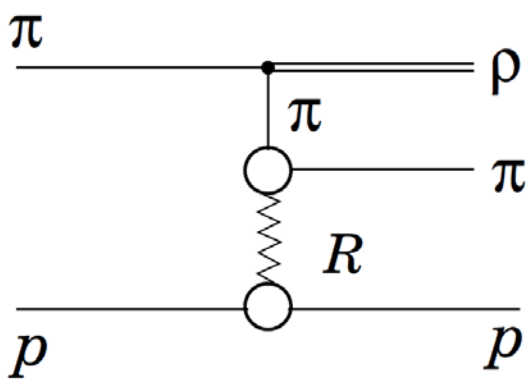
[G.S. Adams et al., Phys. Rev. D **84**,112009 (2011)]

Deck Effect

Resonant production



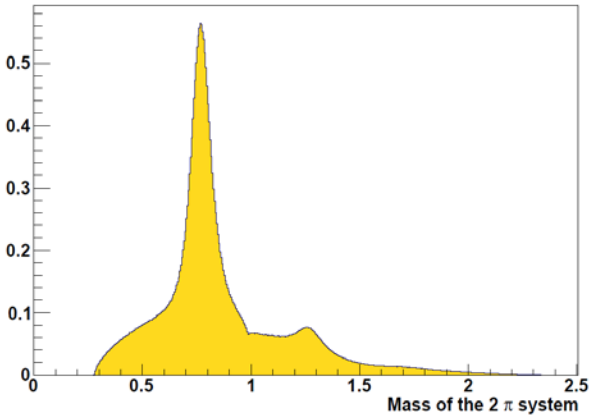
Non-resonant production



- Generate pure Deck-like events

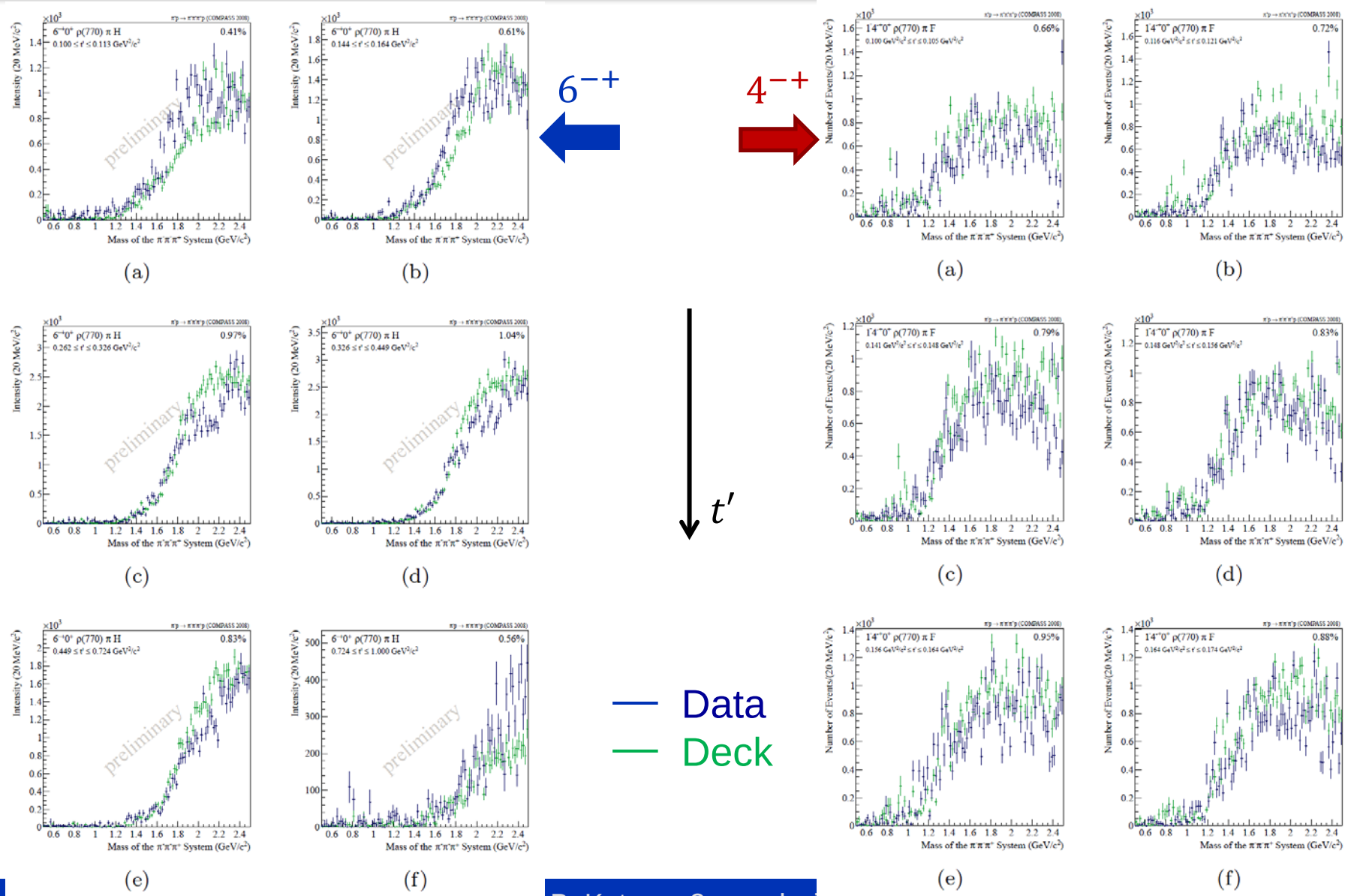
$$\psi(M_{\pi\pi}, t_\pi, t) = \frac{A_{\pi\pi}(M_{\pi\pi}, t_\pi) A_{\pi p}(s_{\pi p}, t)}{m_\pi^2 - t_\pi}$$

[G. Ascoli et al., Phys. Rev. D 8, 3894 (1973)]

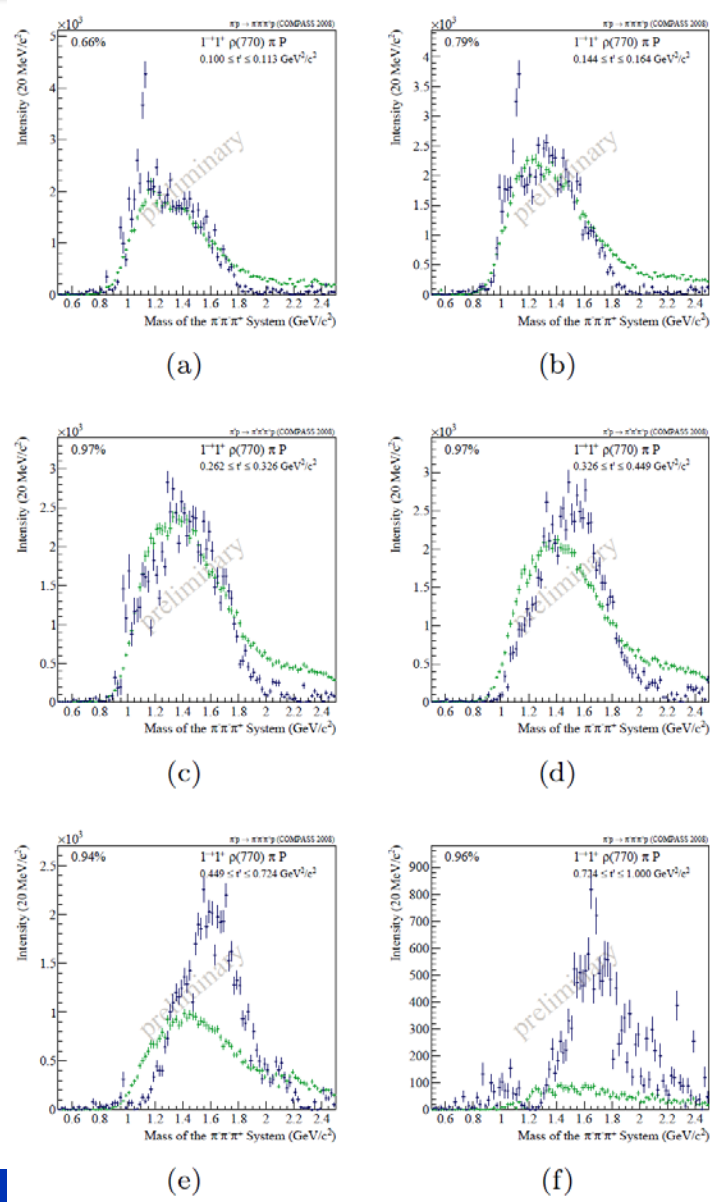


- Pass through Monte Carlo & PWA
- Normalize intensity to data for each wave and sum over t'
- Benchmark on waves w/o resonances, test on exotic wave

Data vs Deck



Data vs Deck



1^{-+}

t'

Data

Deck

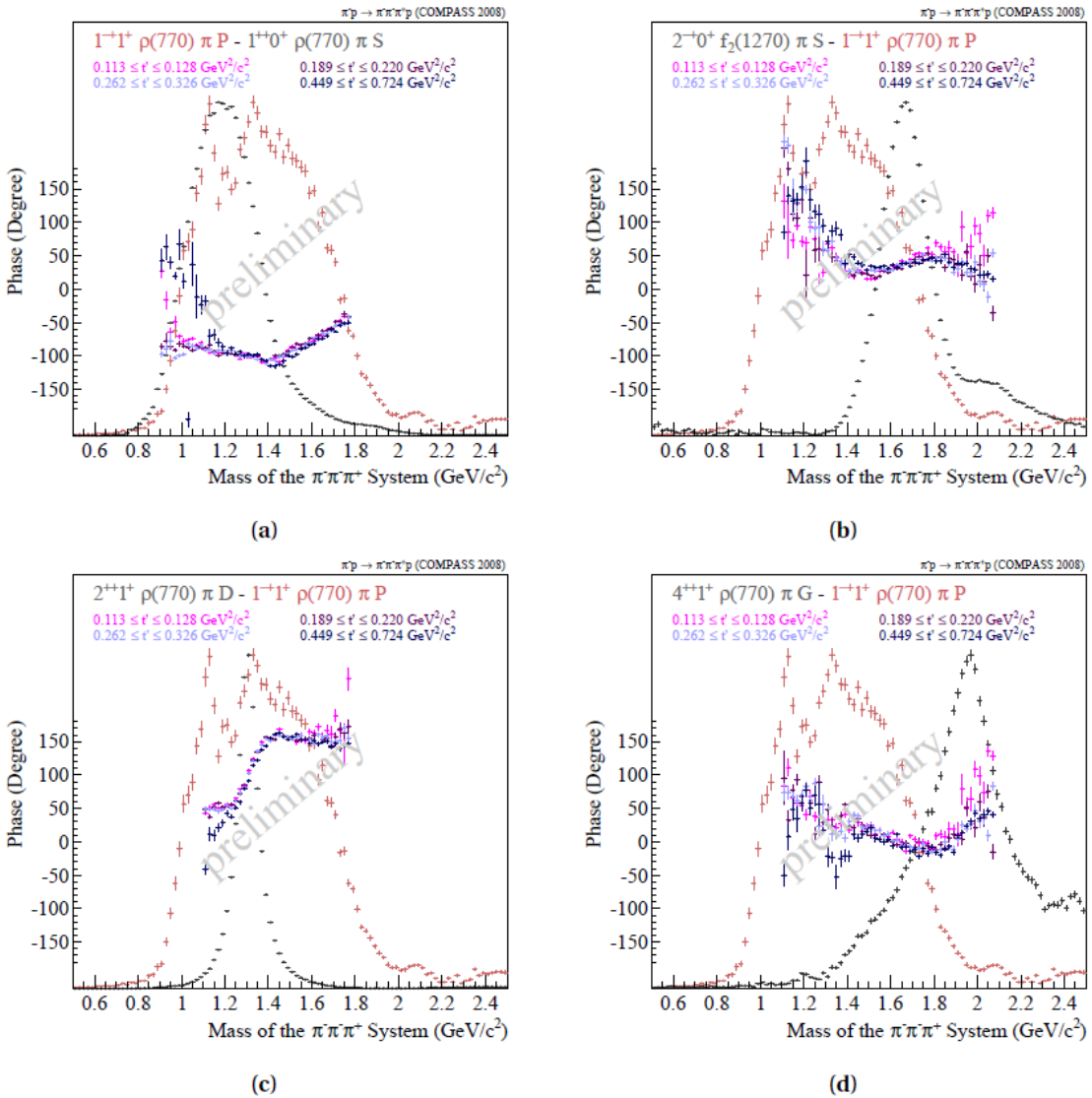
Low values of t':

- Mostly non-resonant production
- Good description by Deck model

High values of t':

- Deck background disappears
- Resonant component increasing
- Dominates highest t' - bin

Phase of 1^{-+} Wave



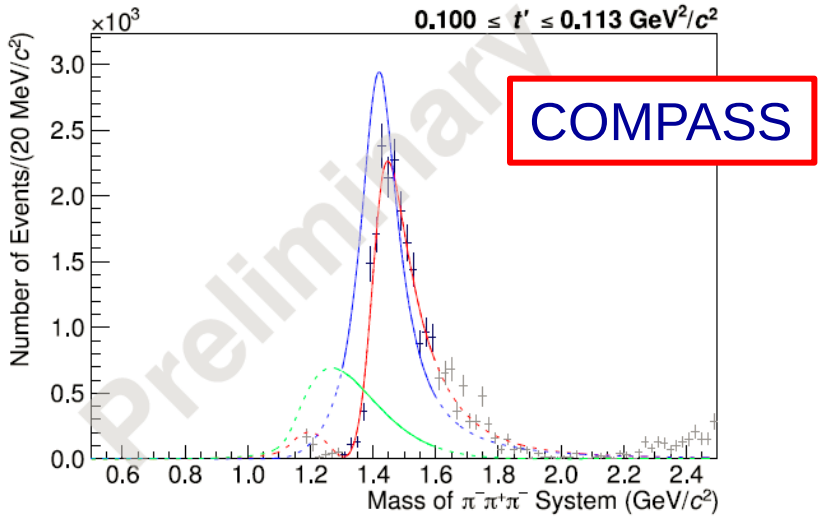
- Clear phase variation
- Phase motion about 60°
- Independent of t'

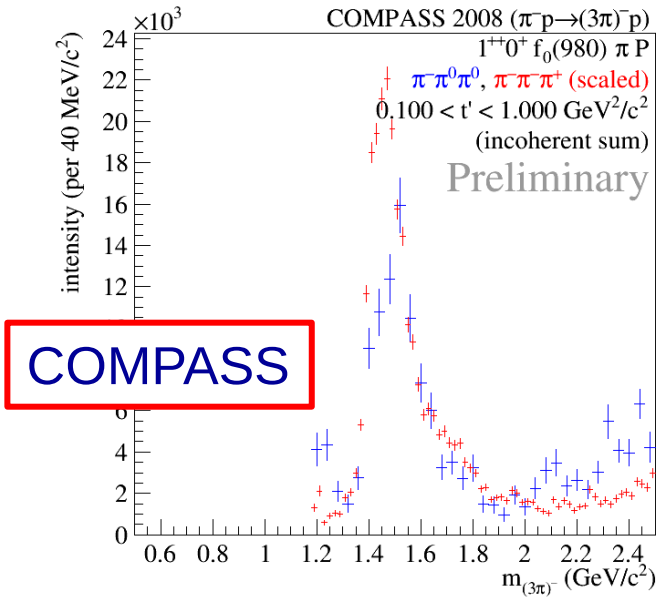
⇨ Bgr model qualitatively ok

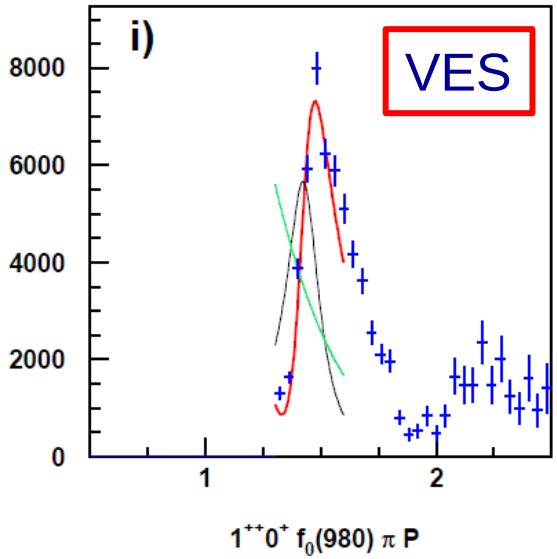
⇨ need to include non-isobaric waves in mass-independent fit

The $a_1(1420)$

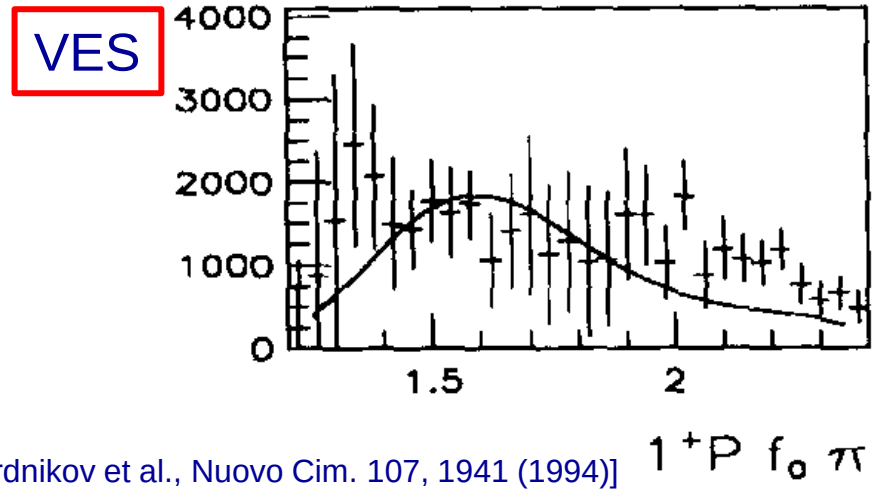
New a_1 – $1^{++}0^+$ $f_0(980)\pi$ P





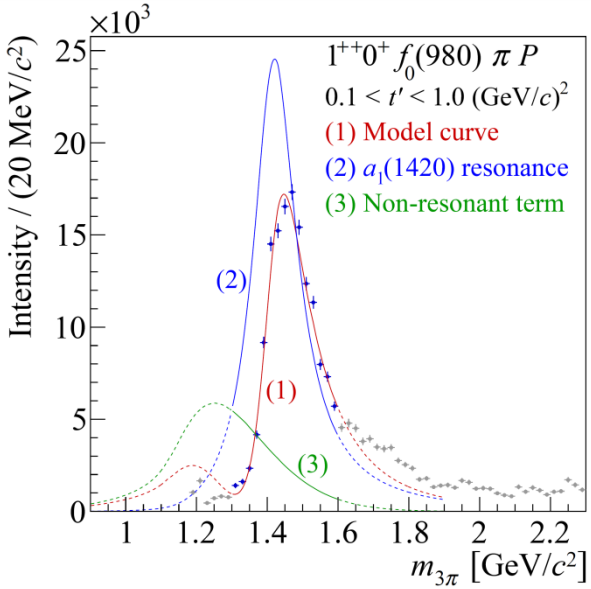


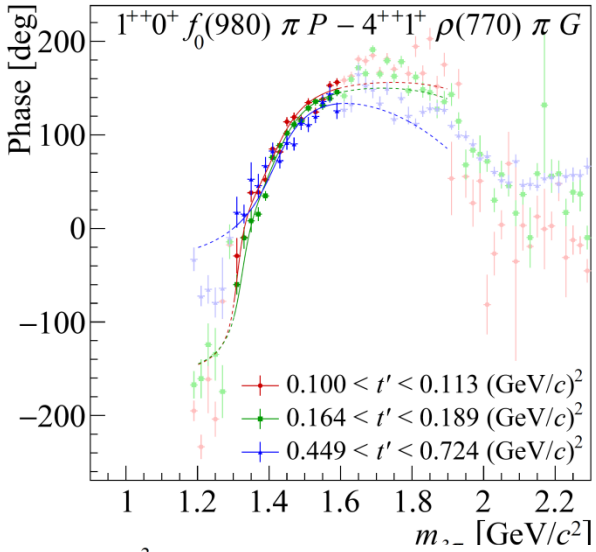
[Yu. Khokhlov, PoS Hadron 088 (2014)]

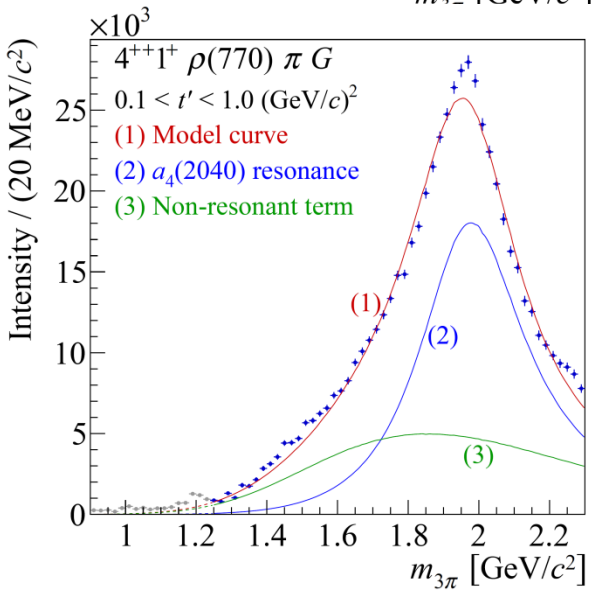


[E.B. Berdnikov et al., Nuovo Cim. 107, 1941 (1994)]

New a_1 – $1^{++}0^+$ $f_0(980)\pi$ P







- Data described well by Breit-Wigner and non-resonant background
- Parameters for BW:

$$M_0 = 1414^{+15}_{-13}\ \mathrm{MeV/c}$$

$$\Gamma_0 = 153^{+8}_{-23}\ \mathrm{MeV}/c$$

[C. Adolph et al., COMPASS, PRL 115, 082001 (2015)]

$(\pi\pi)_S$ Wave

Systematic study:

- New $a_1(1420)$ couples exclusively to $f_0(980)$
- Influence of isobar parameterization? Ambiguities? Artefact?

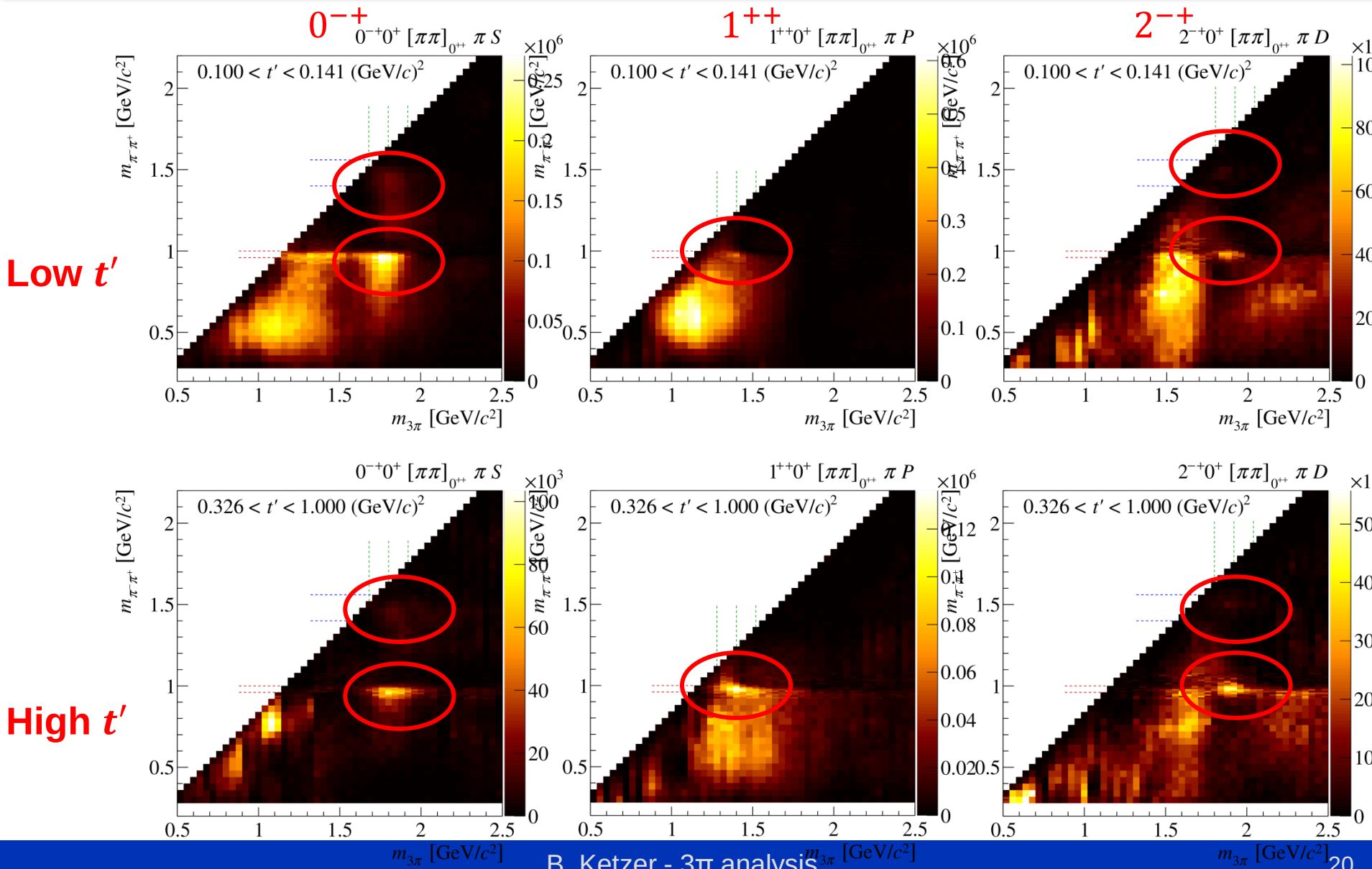
Goal:

- Determine dynamics of isobars with $J^{PC}_{\text{iso}} = 0^{++}$ from data
- Obtain model-independent isobar amplitude

Method:

- Replace fixed parameterization of $J^{PC}_{\text{iso}} = 0^{++}$ 2-body amplitude (e.g. AMP for $(\pi\pi)_S$ wave or Flatté/BW for $f_0(980)/f_0(1500)$) by set of free (complex) parameters in 2-body mass bins with δm=40 MeV (10 MeV around 980 MeV)
- No separation into several $J^{PC}_{\text{iso}} = 0^{++}$ isobars
- Amplitude for $J^{PC}_{\text{iso}} = 0^{++}$ isobars determined from data for three $J^{PC}_{3\pi} = 0^{-+}, 1^{++}, 2^{-+}$
- Combined phase information: $\phi_{tot} = \phi_{prod} + \phi_{decay}$

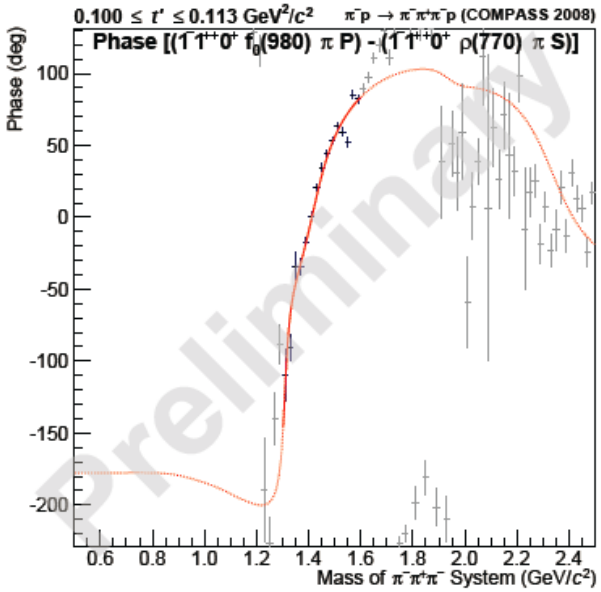
Correlation $m_{3\pi}$ vs $m_{2\pi}$



Is the $a_1(1420)$ a resonance?

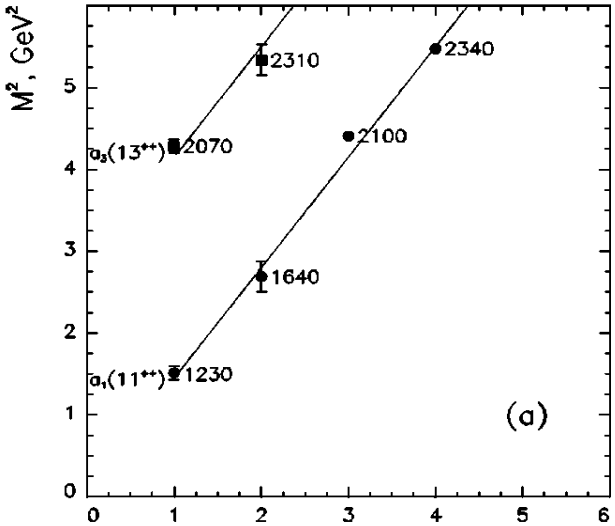
Maybe, because it has all features of a resonance:

- narrow peak in intensity
- sharp phase motion
- well described by Breit-Wigner + Bgr



Issues to be clarified:

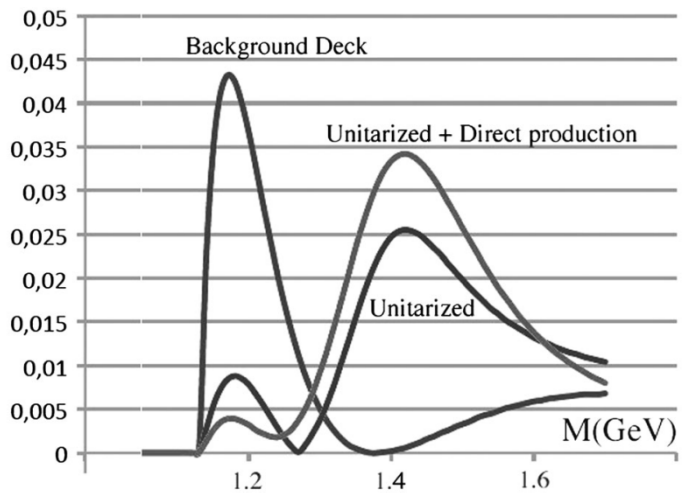
- too close in mass to $a_1(1260)$
- fits neither to radial excitation trajectory nor to angular momentum trajectory
- width narrower than ground state
- strange coincidence of mass to $K^*(892)\bar{K}$ threshold $\approx 1.38\ \mathrm{GeV}/c^2$

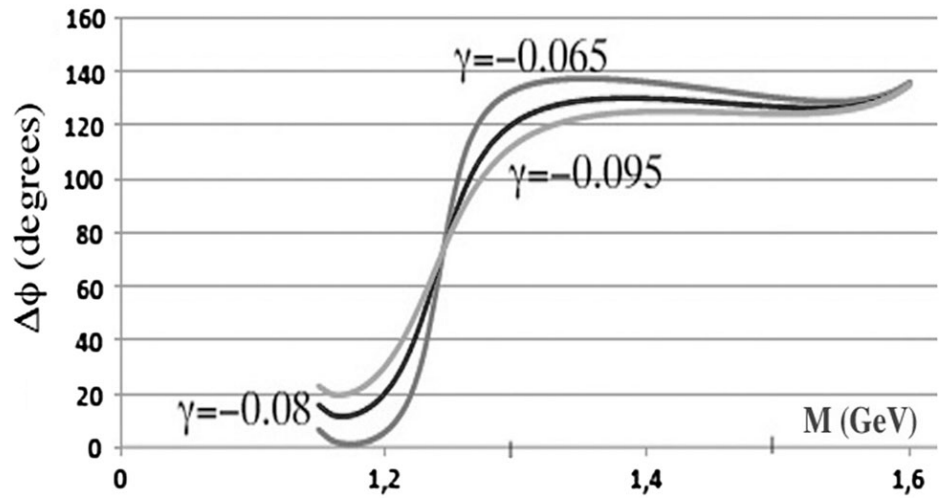


[A.V. Anisovich et al., PRD 62, 051502 (2000)]

Interpretations

- 4-quark state candidate [Z.-G. Wang, arXiv:1401.1134, H.-X.Chen, PRD 91, 094022 (2015)]
- K^*K molecule (similar to X(3872) interpretation)
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al., PRL 114, 192001 (2015)]





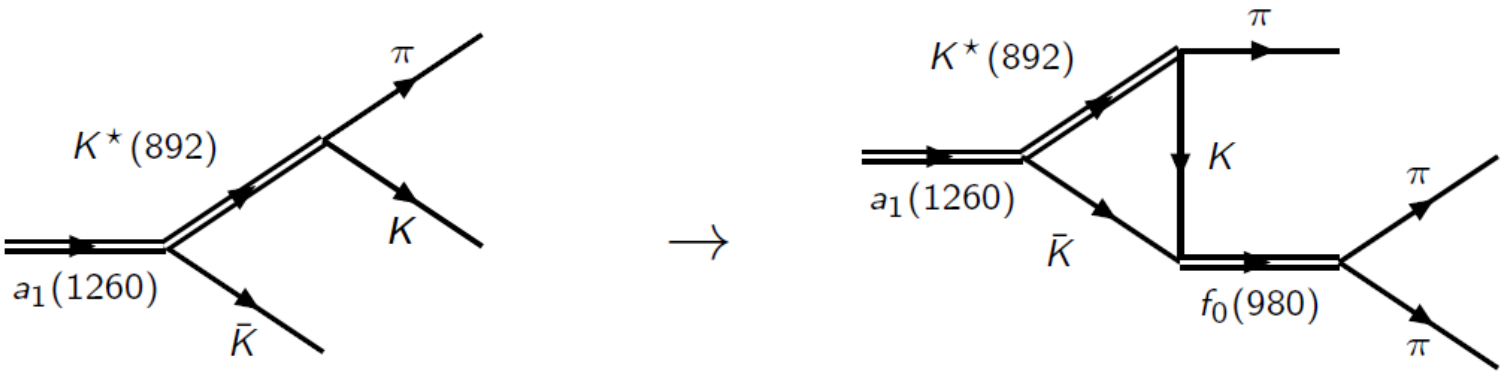
⇨ $a_1(1260)$ splits into two peaks

⇨ phase motion 120°, but too low in mass

⇨ could be modified by including $K\overline{K}^*$ channel?

Interpretations

- 4-quark state candidate [Z.-G. Wang, arXiv:1401.1134], [H.-X.Chen, PRD 91, 094022 (2015)]
- K^*K molecule (similar to X(3872) interpretation)
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al., PRL 114, 192001 (2015)]
- Triangle singularity [M. Mikhasenko, BK, A. Sarantsev, PRD 91, 094015 (2015)]



  - Decay of $a_1(1260) \rightarrow K^*\overline{K}$ above threshold
  - Final state rescattering of $K\overline{K}$ to $f_0(980)$
    - ⇨ logarithmic singularity of amplitude if particles close to mass shell

Calculation of Amplitude

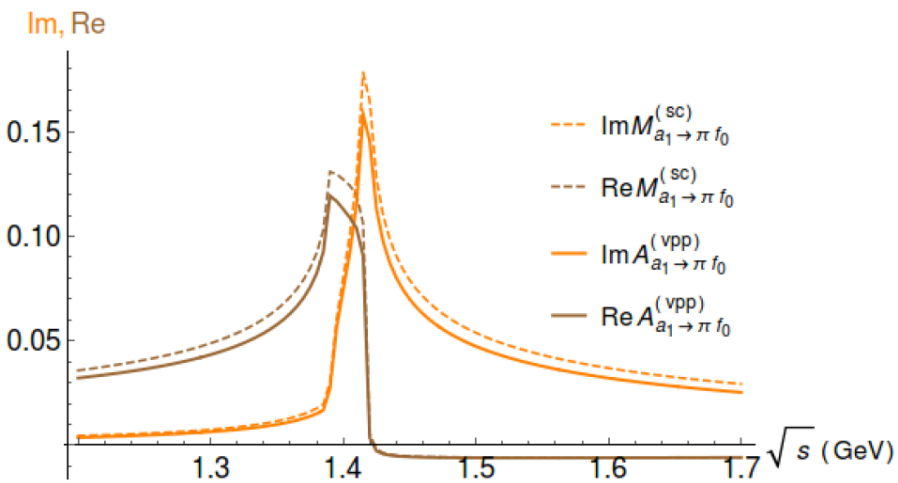
Feynman rules for hadronic processes:

- Scalar case

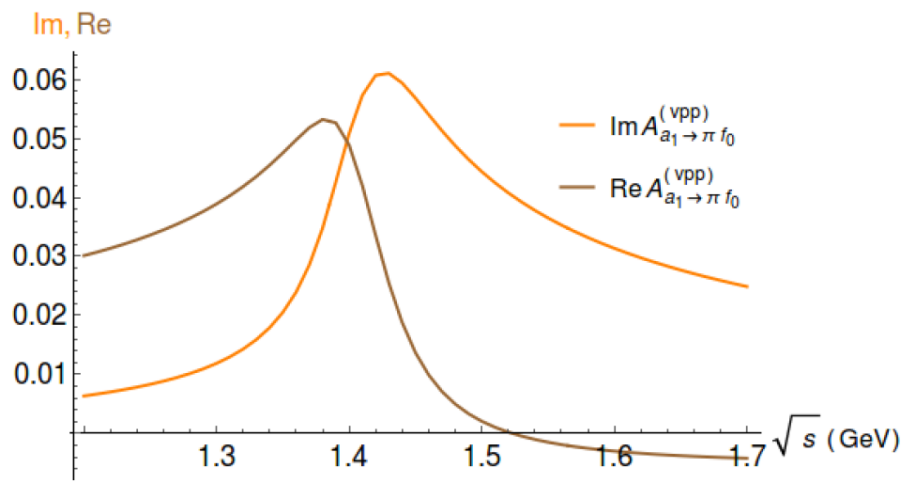
$$\mathbb{M}^{(\mathrm{sc})}_{a_1\to f_0\pi} = g^3 \int \frac{\mathrm{d}^4 k_1}{(2\pi)^4 i} \frac{1}{(m_1^2 - k_1^2 - i\epsilon)(m_2^2 - (p_0 - k_1)^2 - i\epsilon)(m_3^2 - (k_1 - p_1)^2 - i\epsilon)}$$

- VPP case: numerator carries spin structure

Scalar vs VPP



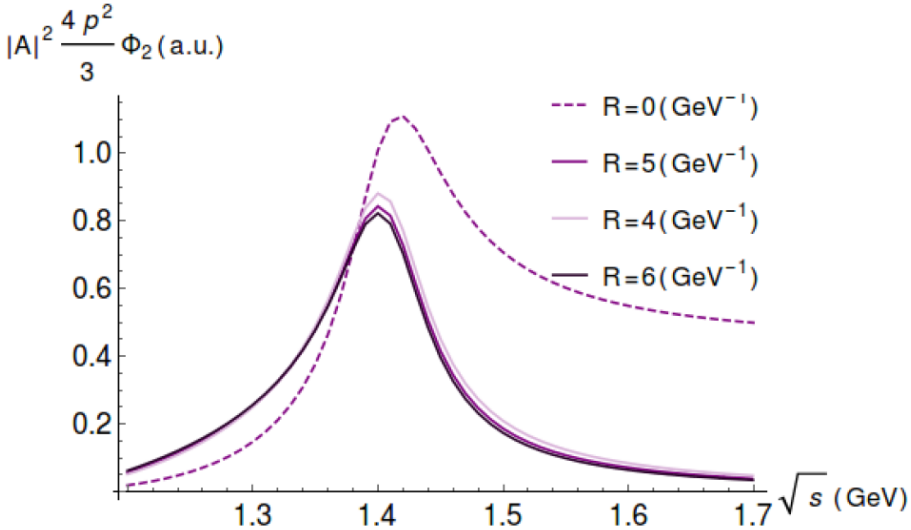
+ finite width of K^*

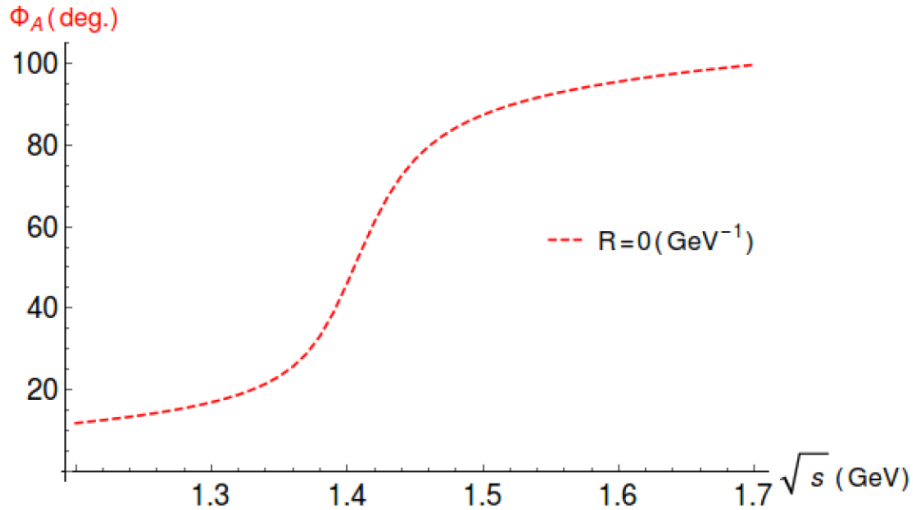


Corrections to Vertices

- Finite width of K^*
- Suppression of P-wave tail due to $K^* \to K\pi$ decay
  - Blatt-Weisskopf barrier factors
  - Exponential correction factors for finite meson-size
  - Introduce left-hand singularity in the amplitude

$$F(k_1) = \frac{M^2 - m_{K^\star}^2}{M^2 - k_1^2}, \quad M^2 = (m_\pi + m_K)^2 - \frac{4}{R^2}$$

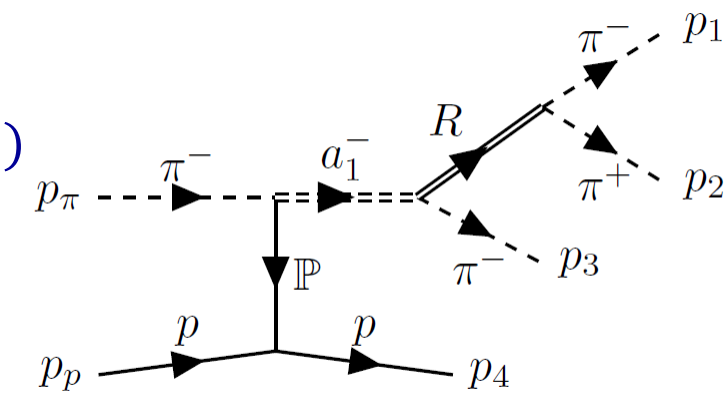


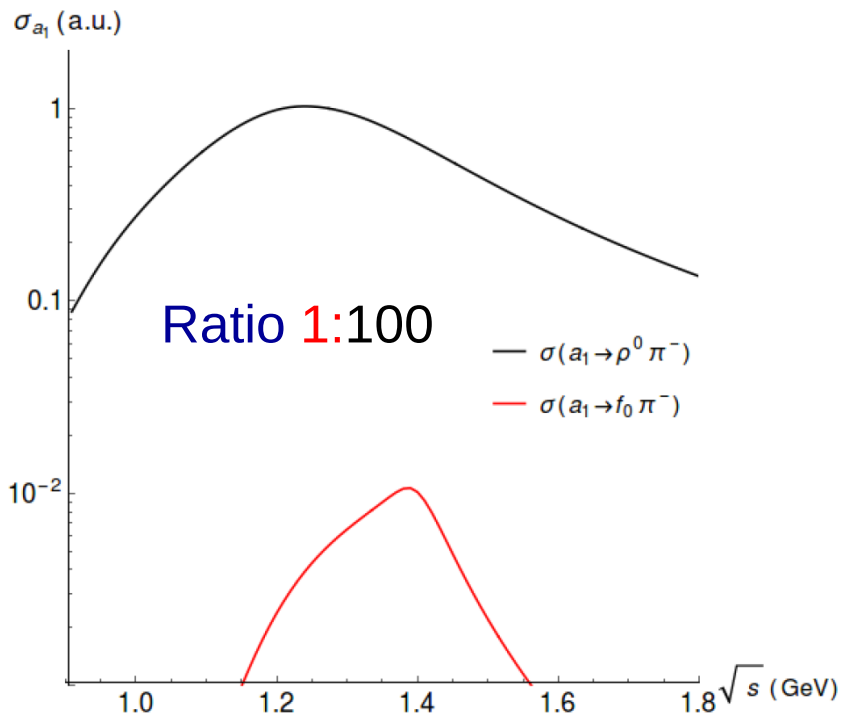


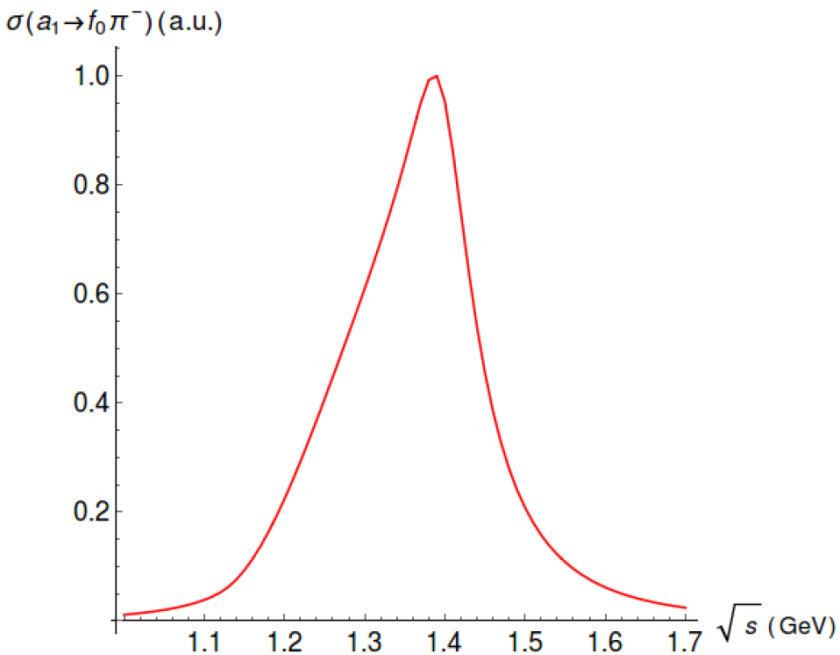
Cross Section Ratio

Consider full process:

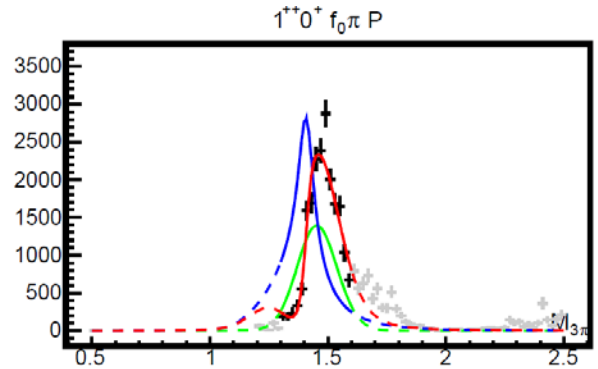
- Diffractive production of resonant $a_1(1260)$
- Direct decay to $\rho\pi$
- Decay to $f_0\pi$ only via triangle diagram

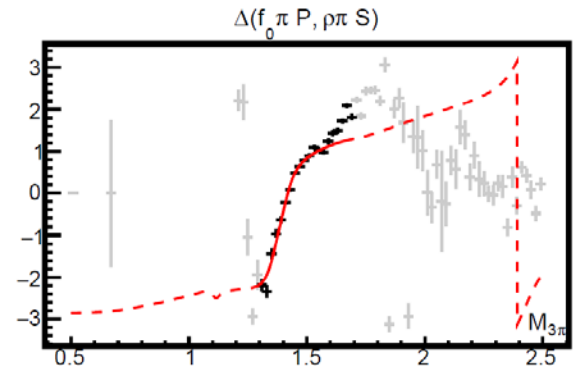


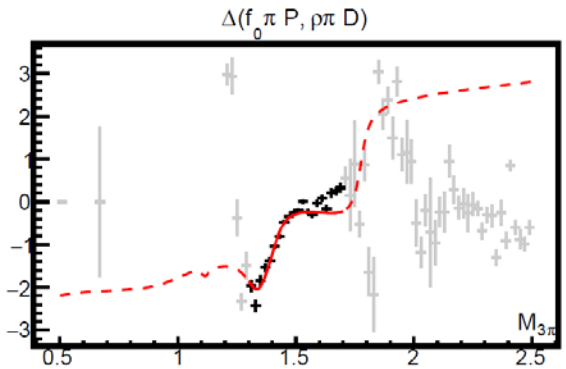




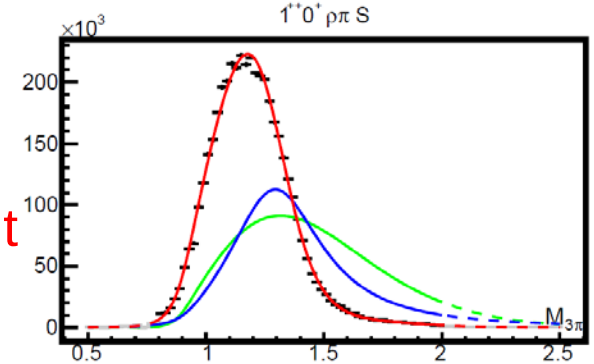
Fit to Data

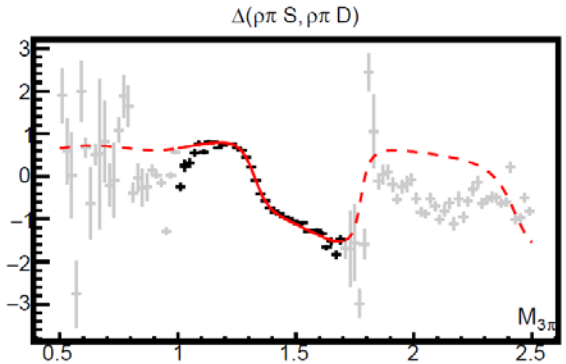




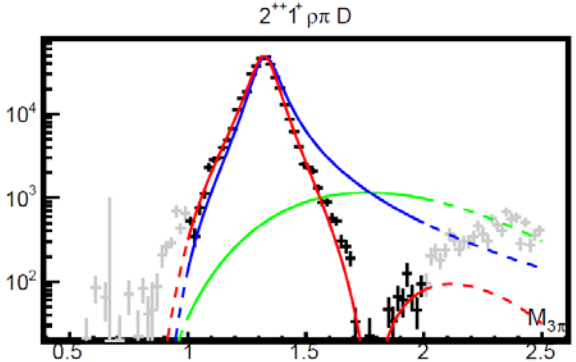


- Preliminary!
- No fit in t' bins yet
- Not a COMPASS result

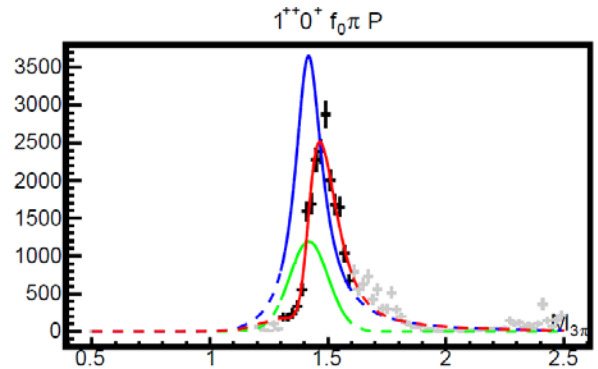


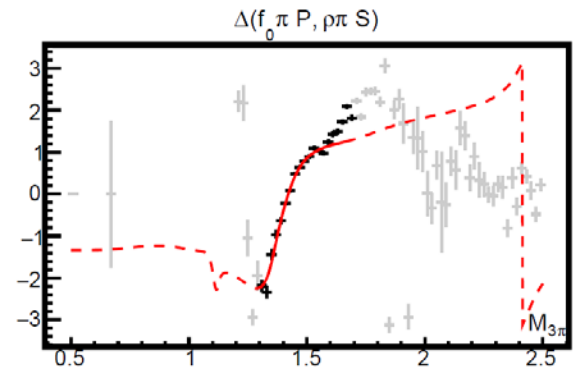


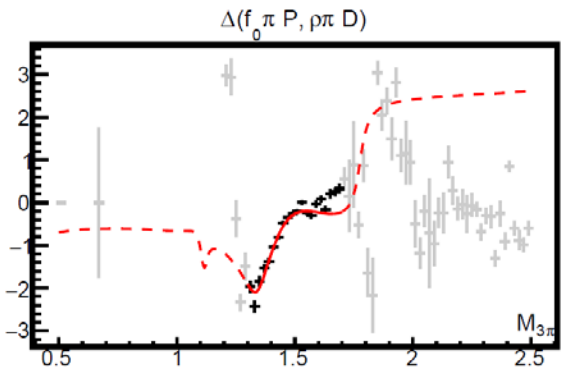
- Use published spin density matrix for 3 waves (1 t' bin)
- compare fit with BW and triangle amplitude in 1^{++} $f_0\pi$ P wave

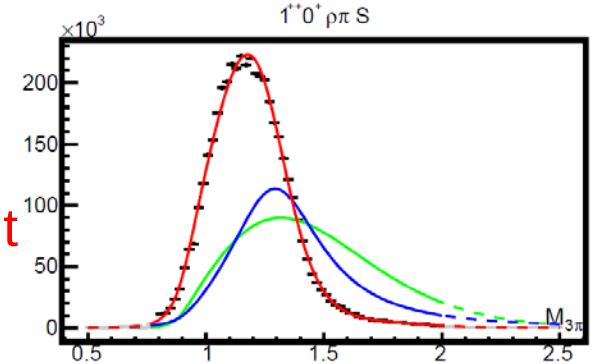


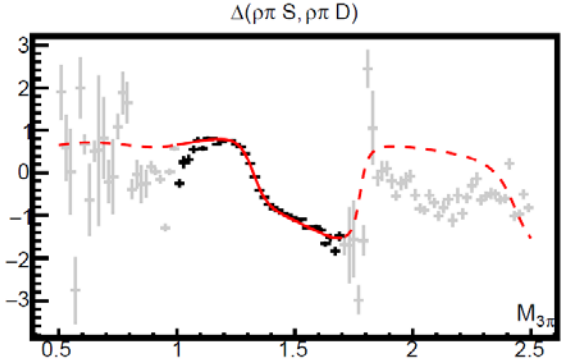
Fit to Data



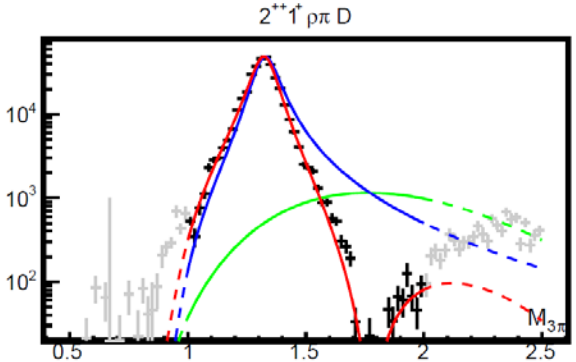








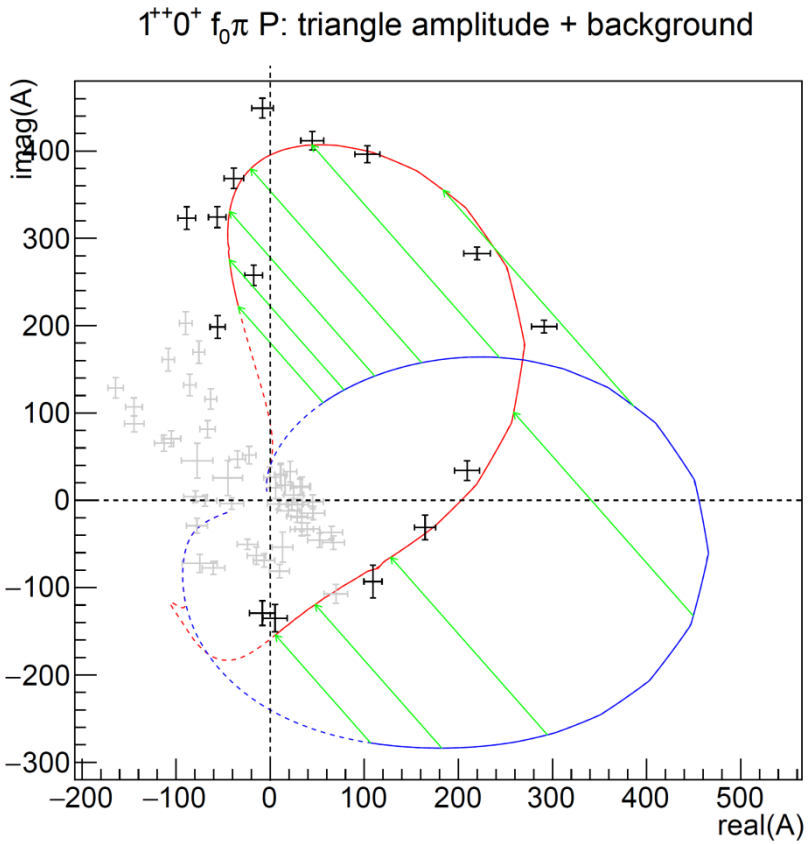
- Preliminary!
- No fit in t' bins yet
- Not a COMPASS result

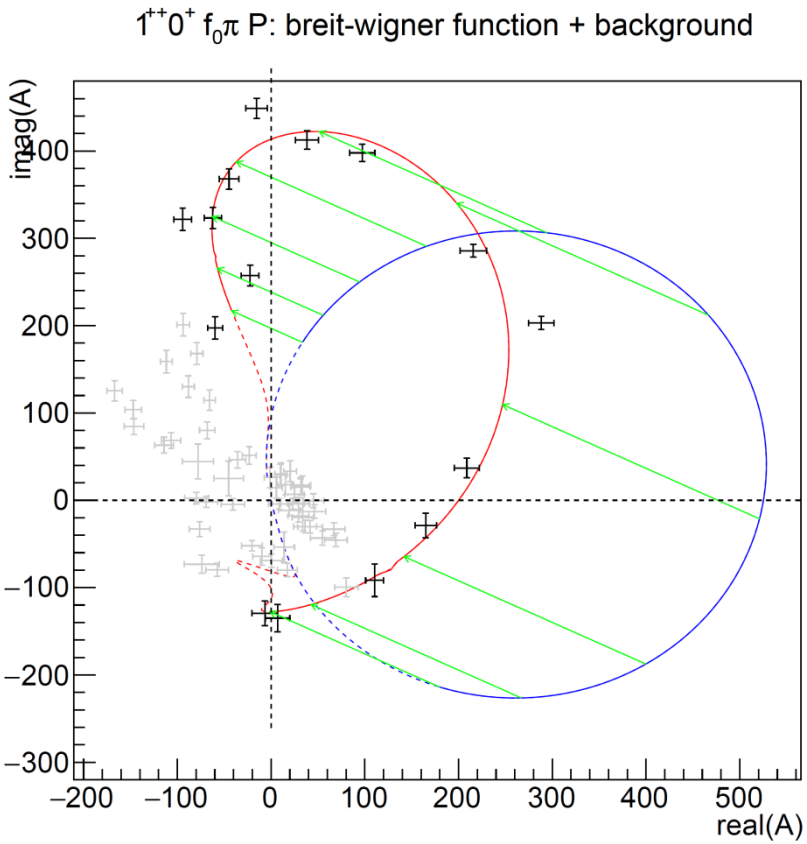


- Use published spin density matrix for 3 waves (1 t' bin)
- compare fit with BW and triangle amplitude in 1^{++} $f_0\pi$ P wave

Phase

- Phase motion of pure triangle diagram is only ~ 90°
- How can a Deck-like background produce a phase motion close to 180° ?





New Fit Model for 3π Data

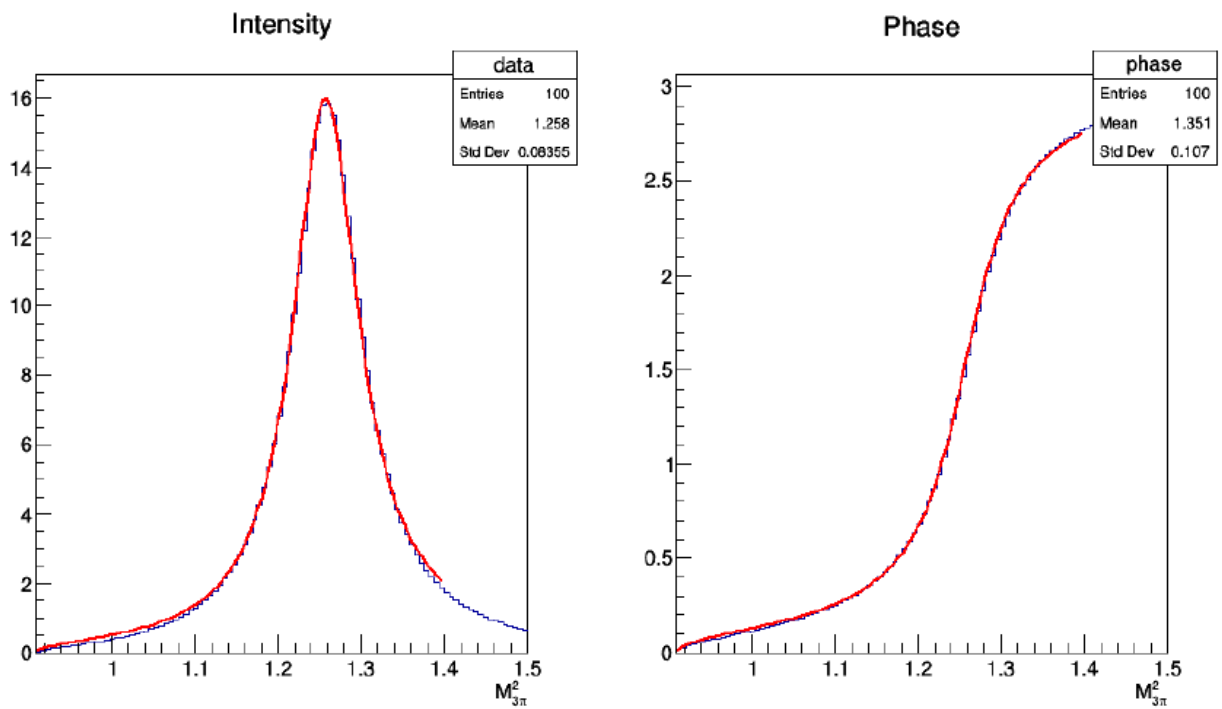
- Work in collaboration with Indiana-JLAB JPAC (A. Szczepaniak, A. Jackura, M. Mikhasenko)
- **Goal:** Improve mass-dependent analysis of diffractive data by constructing general amplitude which satisfies
  - unitarity and analyticity
  - reduces model dependence (shape of background, resonances)
  - allows to extract pole positions in complex energy plane

Method:

- construct amplitude T satisfying unitarity $T^+ - T^- = i\rho T^+ T^-$ and Hermitian analyticity $T^- = {T^+}^*$
- Ansatz: $T(s) = N/D$, with RHC given by D and LHC given by N
- model $N(s)$ as polynomial in conformal variable ω
- determine $D(s)$ from dispersion relation
- full amplitude is $A(s) = \alpha(s)\, T(s)$, where $\alpha(s)$ is constructed similarly to N

Test of method on simple BW

- Generate data BW amplitude with $m_0 = 1.26\ \mathrm{GeV},\ \Gamma_0 = 0.1\ \mathrm{GeV}$
- Fit with general unitary amplitude model
- Extract poles (= zeros of D) ⇨ $m = 1.256\ \mathrm{GeV},\ \Gamma = 0.097\ \mathrm{GeV}$



⇨ Work on 1^{++} and 2^{-+} waves ongoing

Conclusions

- COMPASS: world's largest data set on 3π final state
  - ⇨ small signals detectable with sufficient significance for the first time
  - ⇨ statistical uncertainties very small, systematic model uncertainties become dominant
- 2D-PWA in bins of m_X and t' helps to separate resonance production and background processes
- Freed-isobar technique instead of fixed parameterization for $[\pi\pi]_S$ wave
- Background model qualitatively validated by projection of Deck events onto partial-wave set
- Fit of triangle amplitude to $a_1(1420)$ describes data equally well when background is added

Outlook

Ongoing work:

- Extend freed-isobar technique to other isobars
- Include non-isobaric amplitudes in mass-independent fit, avoid double counting (in coll. with JPAC, e.g. V. Mathieu for $\eta\pi, \eta'\pi$)
- Fit triangle amplitude to all t' bins
- First attempts to extract pole positions from amplitudes which satisfy unitarity and analyticity (in coll. with JPAC)