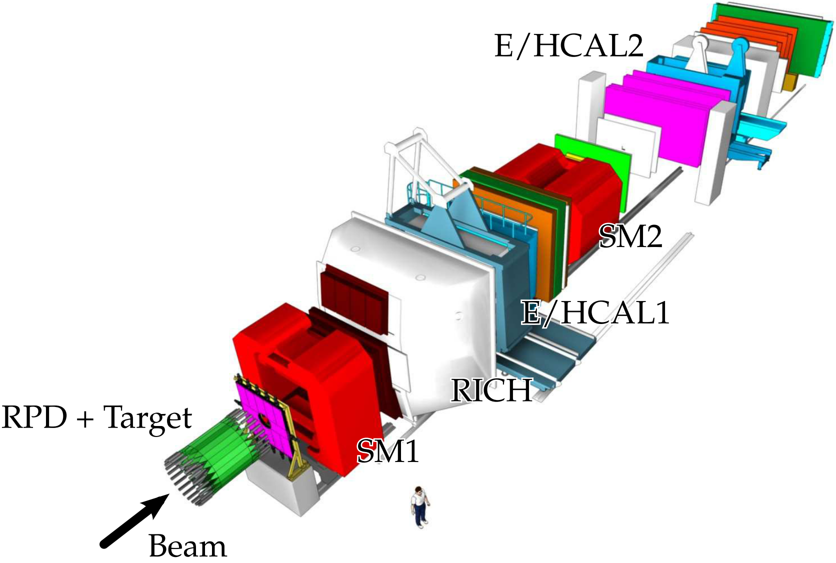
The 2π subsystem in diffractively produced $\pi^-\pi^+\pi^-$ at COMPASS

Fabian Krinner
for the COMPASS collaboration

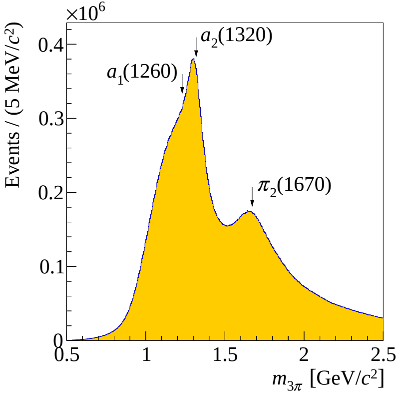
Physik-Department E18
Technische Universität München

Hadron 2015
Newport News, VA, USA

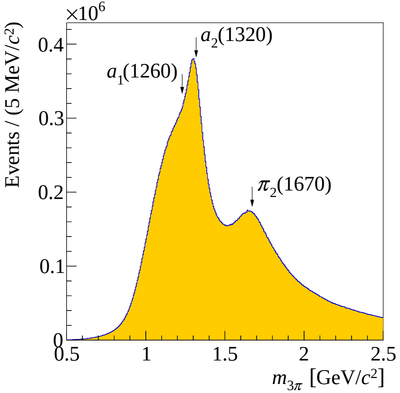


E/HCAL2
SM2
E/HCAL1
RICH
RPD + Target
SM1
Beam

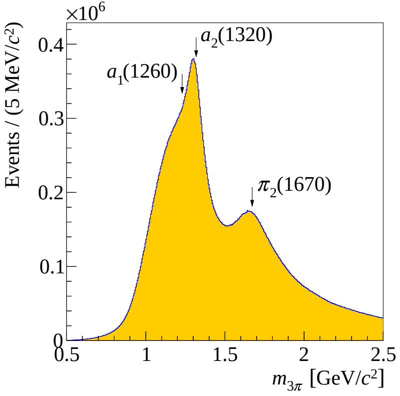
- COMPASS: World's largest data-set up to now for $\pi^- p \to \pi^-\pi^+\pi^- p$



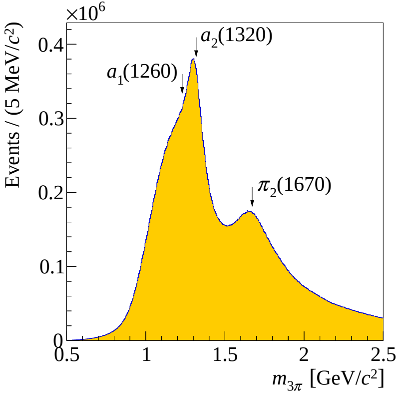
- COMPASS: World's largest data-set up to now for $\pi^- p \to \pi^- \pi^+ \pi^- p$
- Results of "conventional" PWA shown by Boris Grube yesterday



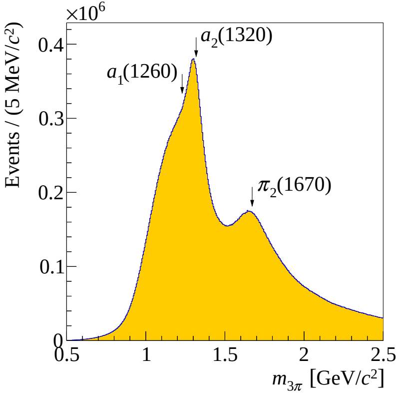
- COMPASS: World's largest data-set up to now for $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$
- Results of "conventional" PWA shown by Boris Grube yesterday
- Detailed PWA with 88 partial waves



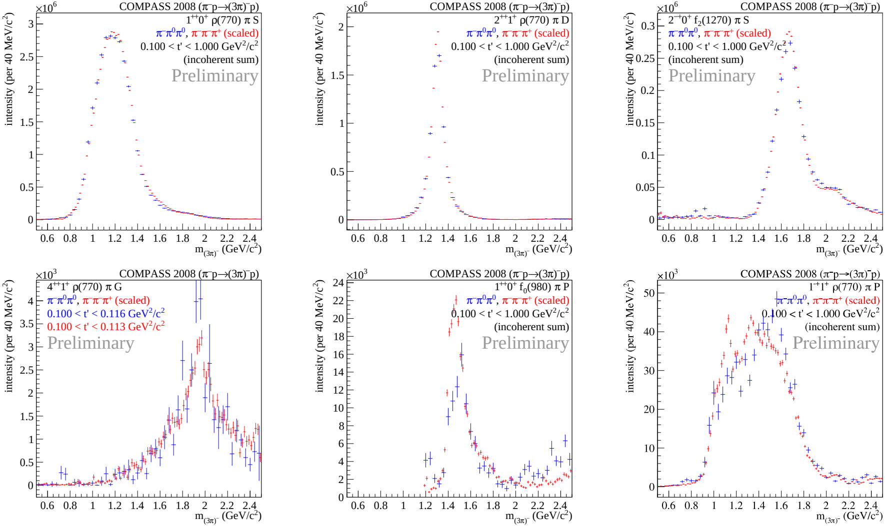
- COMPASS: World's largest data-set up to now for $\pi^- p \to \pi^-\pi^+\pi^- p$
- Results of "conventional" PWA shown by Boris Grube yesterday
- Detailed PWA with 88 partial waves
  - Reliable extraction of waves contributing less than 1% to the intensity

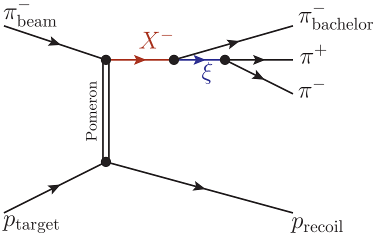


- COMPASS: World's largest data-set up to now for $\pi^- p \to \pi^-\pi^+\pi^- p$
- Results of "conventional" PWA shown by Boris Grube yesterday
- Detailed PWA with 88 partial waves
    - Reliable extraction of waves contributing less than 1% to the intensity
- Good agreement with $\pi^- p \to \pi^-\pi^0\pi^0 p$



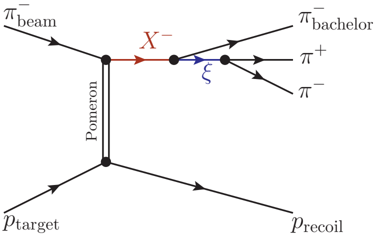
3π spectroscopy at COMPASS
Overview over results



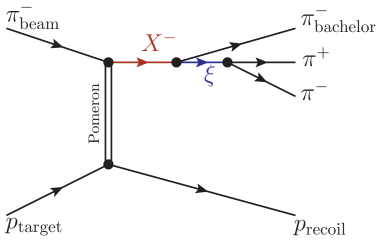


π^-_{beam}
X^-
π^-_{bachelor}
π^+
ξ
π^-
Pomeron
p_{target}
p_{recoil}

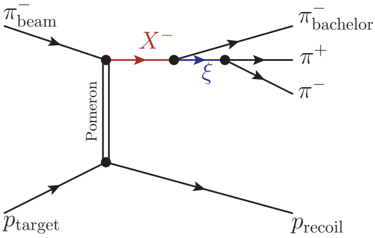
- The intermediate state X^- undergoes subsequent two-particle decays



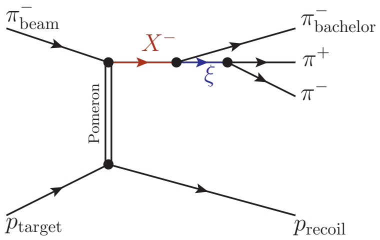
- The intermediate state X^- undergoes subsequent two-particle decays
- Narrow bins in $m_{3\pi} \rightarrow$ no assumptions on X^-



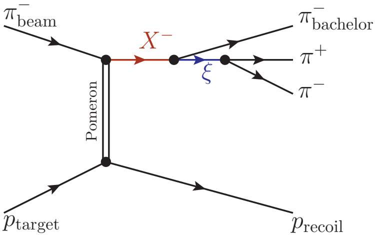
- The intermediate state X^- undergoes subsequent two-particle decays
- Narrow bins in $m_{3\pi} \to$ no assumptions on X^-
- Fixed amplitudes of the *isobars* ξ



- The intermediate state X^- undergoes subsequent two-particle decays
- Narrow bins in $m_{3\pi} \rightarrow$ no assumptions on X^-
- Fixed amplitudes of the *isobars* ξ
- Direct fit of resonance parameters of the isobars computationally very expensive

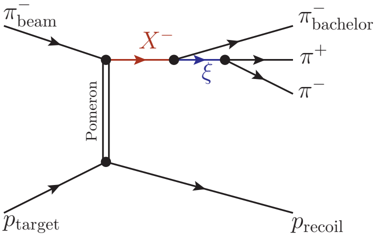


- The intermediate state X^- undergoes subsequent two-particle decays
- Narrow bins in $m_{3\pi} \rightarrow$ no assumptions on X^-
- Fixed amplitudes of the *isobars* ξ
- Direct fit of resonance parameters of the isobars computationally very expensive



How good is the isobar model?

- The intermediate state X^- undergoes subsequent two-particle decays
- Narrow bins in $m_{3\pi} \to$ no assumptions on X^-
- Fixed amplitudes of the *isobars* ξ
- Direct fit of resonance parameters of the isobars computationally very expensive

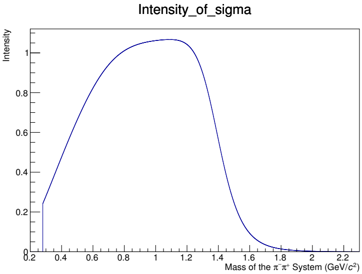


How good is the isobar model?

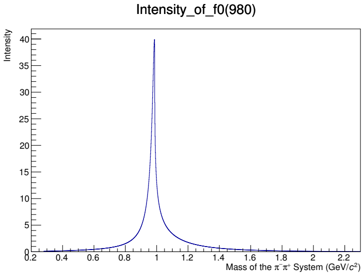
How good are the parametrizations used?

- Isobar amplitudes in conventional PWA for different J^{PC}:

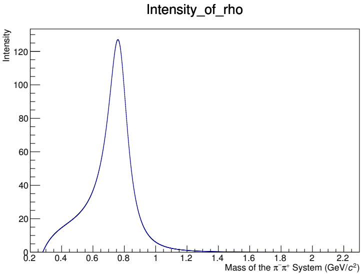
- Isobar amplitudes in conventional PWA for different J^{PC}:
  - 0^{++}: $f_0(500)$(or σ, $[\pi\pi]_S$)



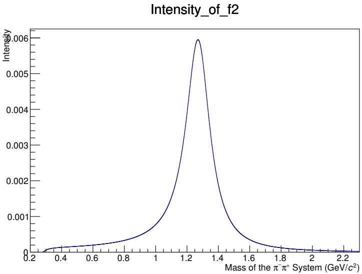
- Isobar amplitudes in conventional PWA for different J^{PC}:
  - 0^{++}: $f_0(500)$(or σ, $[\pi\pi]_S$)
  - 0^{++}: $f_0(980)$



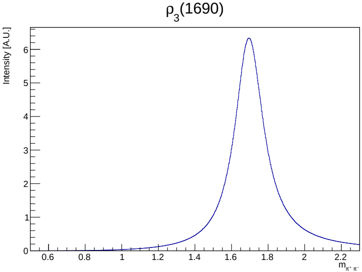
- Isobar amplitudes in conventional PWA for different J^{PC}:
  - 0^{++}: $f_0(500)$(or σ, $[\pi\pi]_S$)
  - 0^{++}: $f_0(980)$
  - 1^{--}: $\rho(770)$



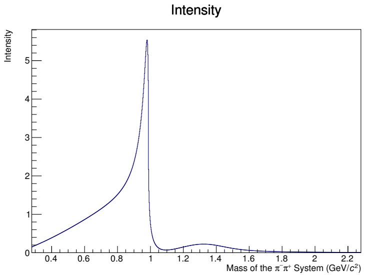
- Isobar amplitudes in conventional PWA for different J^{PC}:
  - 0^{++}: $f_0(500)$(or σ, $[\pi\pi]_S$)
  - 0^{++}: $f_0(980)$
  - 1^{--}: $\rho(770)$
  - 2^{++}: $f_2(1270)$



- Isobar amplitudes in conventional PWA for different J^{PC}:
  - 0^{++}: $f_0(500)$(or σ, $[\pi\pi]_S$)
  - 0^{++}: $f_0(980)$
  - 1^{--}: $\rho(770)$
  - 2^{++}: $f_2(1270)$
  - 3^{--}: $\rho_3(1690)$

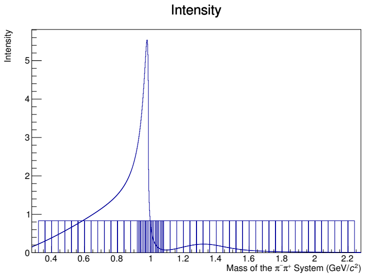


- Isobar amplitudes in conventional PWA for different J^{PC}:
  - 0^{++}: $f_0(500)$(or σ, $[\pi\pi]_S$)
  - 0^{++}: $f_0(980)$
  - 1^{--}: $\rho(770)$
  - 2^{++}: $f_2(1270)$
  - 3^{--}: $\rho_3(1690)$



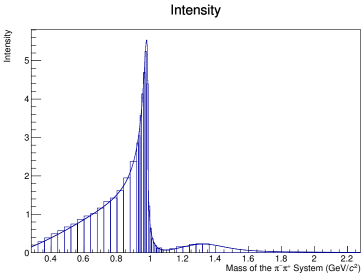
Example: Shape of 0^{++} resulting from interference of $f_0(500)$ and $f_0(980)$

- Isobar amplitudes in conventional PWA for different J^{PC}:
  - 0^{++}: $f_0(500)$(or σ, $[\pi\pi]_S$)
  - 0^{++}: $f_0(980)$
  - 1^{--}: $\rho(770)$
  - 2^{++}: $f_2(1270)$
  - 3^{--}: $\rho_3(1690)$
- Fit of isobar resonance parameters not practical $\rightarrow$ "binned isobars"



Example: Shape of 0^{++} resulting from interference of $f_0(500)$ and $f_0(980)$

- Isobar amplitudes in conventional PWA for different J^{PC}:
  - 0^{++}: $f_0(500)$(or σ, $[\pi\pi]_S$)
  - 0^{++}: $f_0(980)$
  - 1^{--}: $\rho(770)$
  - 2^{++}: $f_2(1270)$
  - 3^{--}: $\rho_3(1690)$
- Fit of isobar resonance parameters not practical $\rightarrow$ “binned isobars”
- Extract binned amplitudes



Example: Shape of 0^{++} resulting from interference of $f_0(500)$ and $f_0(980)$

- Total intensity in conventional PWA

$$\mathcal{I}(m_{3\pi}, m_{\pi^+\pi^-}, \tau) = \left| \sum_{i}^{\text{waves}} T_i(m_{3\pi}) \psi_i(\tau) \Delta_i(m_{\pi^+\pi^-}) \right|^2$$

Production amplitudes $T_i(m_{3\pi})$, angular distributions $\psi(\tau)$ and isobar amplitudes $\Delta_i(m_{\pi^+\pi^-})$ (e.g. Breit-Wigner)

- Total intensity in conventional PWA

$$\mathcal{I}(m_{3\pi}, m_{\pi^+\pi^-}, \tau) = \left| \sum_i^{\text{waves}} T_i(m_{3\pi}) \psi_i(\tau) \Delta_i(m_{\pi^+\pi^-}) \right|^2$$

Production amplitudes $T_i(m_{3\pi})$, angular distributions $\psi(\tau)$ and isobar amplitudes $\Delta_i(m_{\pi^+\pi^-})$ (e.g. Breit-Wigner)

- Replace fixed isobar amplitudes by bins:

$$\Delta_i(m_{\pi^+\pi^-}) \to \sum_{\text{bins}} \Delta_i^{\text{bin}}(m_{\pi^+\pi^-}) = [\pi\pi]_{J^{PC}}$$

$$\Delta_i^{\text{bin}}(m_{\pi^+\pi^-}) = \begin{cases} 1, & \text{if } m_{\pi^+\pi^-} \text{ in corresponding bin.} \\ 0, & \text{otherwise.} \end{cases}$$

- Total intensity in conventional PWA

$$\mathcal{I}(m_{3\pi}, m_{\pi^+\pi^-}, \tau) = \left| \sum_{i}^{\text{waves}} T_i(m_{3\pi}) \psi_i(\tau) \Delta_i(m_{\pi^+\pi^-}) \right|^2$$

Production amplitudes $T_i(m_{3\pi})$, angular distributions $\psi(\tau)$ and isobar amplitudes $\Delta_i(m_{\pi^+\pi^-})$ (e.g. Breit-Wigner)

- Replace fixed isobar amplitudes by bins:

$$\Delta_i(m_{\pi^+\pi^-}) \to \sum_{\text{bins}} \Delta_i^{\text{bin}}(m_{\pi^+\pi^-}) = [\pi\pi]_{J^{PC}}$$

$$\Delta_i^{\text{bin}}(m_{\pi^+\pi^-}) = \begin{cases} 1, & \text{if } m_{\pi^+\pi^-} \text{ in corresponding bin.} \\ 0, & \text{otherwise.} \end{cases}$$

- Step-like functions behave like independent Partial Waves:

$$\mathcal{I} = \left| \sum_{i}^{\text{waves}} \sum_{\text{bin}}^{\text{bins}} T_i^{\text{bin}}(m_{3\pi}) \psi_i(\tau) \Delta_i^{\text{bin}}(m_{\pi^+\pi^-}) \right|^2$$

Two dimensional results

- Conventional analysis: Binned in $m_{3\pi}$: $T(m_{3\pi})$
- Now: Two-dimensional binning: $T(m_{3\pi}, m_{\pi^+\pi^-})$
- $\rightarrow$ Two-dimensional picture
- Here: Three waves with freed isobars:
  - $0^{-+}0^{+}[\pi\pi]_{0^{++}}\,\pi S$
  - $1^{++}0^{+}[\pi\pi]_{0^{++}}\,\pi P$
  - $2^{-+}0^{+}[\pi\pi]_{0^{++}}\,\pi D$
- All other waves still with fixed isobar amplitudes
- In principle also possible for 1^{--}, 2^{++}, ... isobars

Two-dimensional intensities for waves with freed isobars

MASS OF THE $\pi^-\pi^+$ SYSTEM

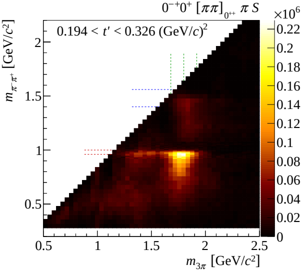
MASS OF THE $\pi^-\pi^+\pi^-$ SYSTEM

These plots should not be mistaken as Dalitz plots

Two-dimensional intensities for waves with freed isobars

MASS OF THE $\pi^-\pi^+$ SYSTEM

$0^{-+}0^{+}[\pi\pi]_{0^{++}}\ \pi\ S$



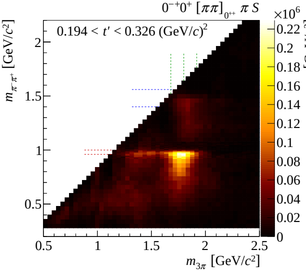
MASS OF THE $\pi^-\pi^+\pi^-$ SYSTEM

These plots should not be mistaken as Dalitz plots

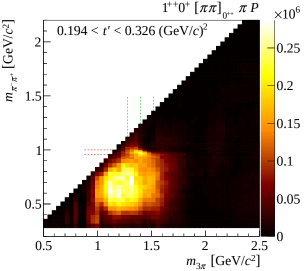
Two-dimensional intensities for waves with freed isobars

MASS OF THE $\pi^-\pi^+$ SYSTEM

$0^{-+}0^+[\pi\pi]_{0^{++}}\ \pi\ S$



$1^{++}0^+[\pi\pi]_{0^{++}}\ \pi\ P$



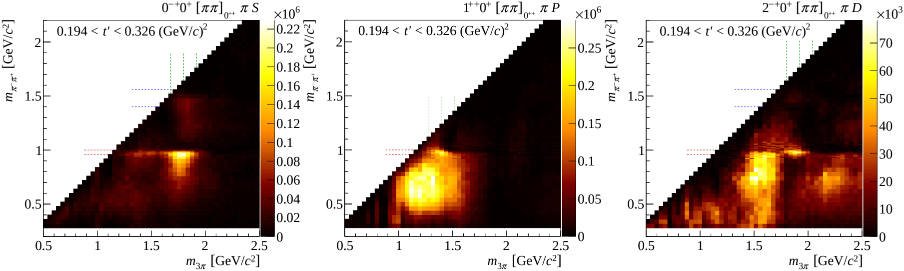
MASS OF THE $\pi^-\pi^+\pi^-$ SYSTEM

These plots should not be mistaken as Dalitz plots

Two-dimensional intensities for waves with freed isobars

MASS OF THE $\pi^-\pi^+$ SYSTEM

$0^{-+}0^+[\pi\pi]_{0^{++}}\ \pi\ S$ $1^{++}0^+[\pi\pi]_{0^{++}}\ \pi\ P$ $2^{-+}0^+[\pi\pi]_{0^{++}}\ \pi\ D$

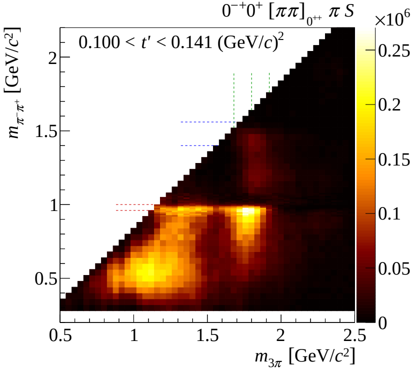


MASS OF THE $\pi^-\pi^+\pi^-$ SYSTEM

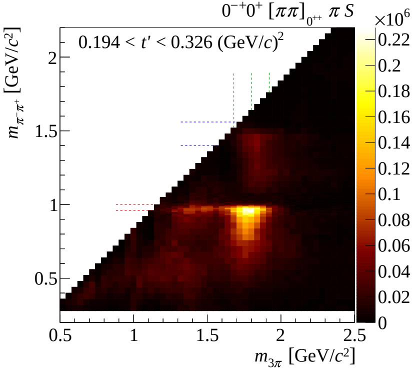
These plots should not be mistaken as Dalitz plots

Different regions of the four-momentum transfer t'

$0.10 < t' < 0.14\,(\mathrm{GeV}/c)^2$
$0^{-+}0^{+}[\pi\pi]_{0^{++}}\,\pi S$



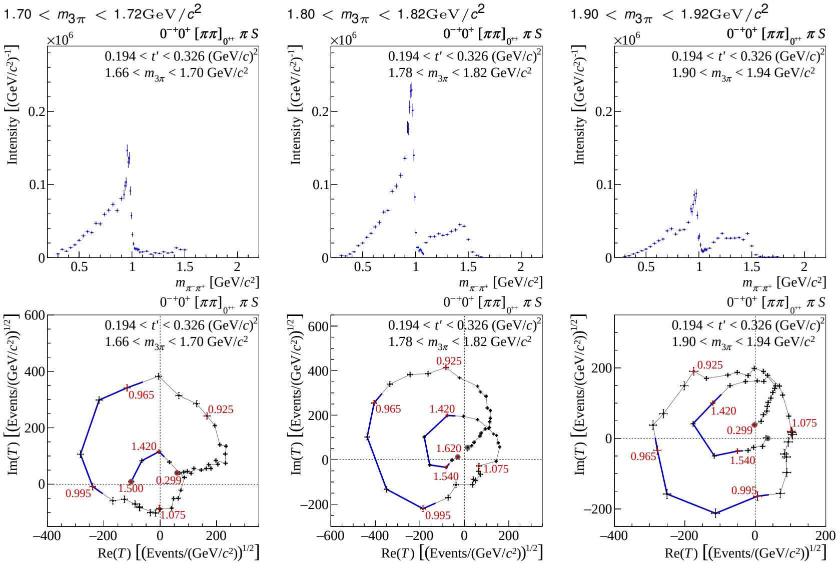
$0.19 < t' < 0.32\,(\mathrm{GeV}/c)^2$
$0^{-+}0^{+}[\pi\pi]_{0^{++}}\,\pi S$



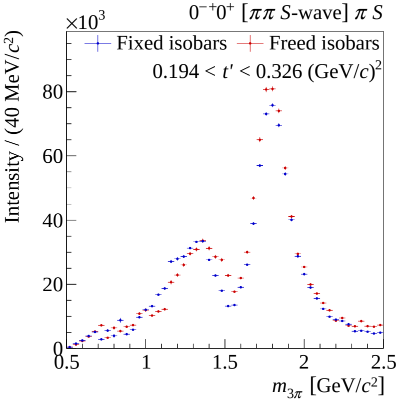
$0^{-+}0^{+}[\pi\pi]_{0^{++}}\,\pi S$

Slices at constant $m_{3\pi}$

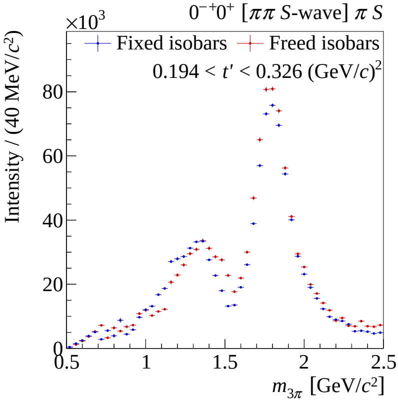
High $0.19 < t' < 0.32 (\mathrm{GeV}/c)^2$



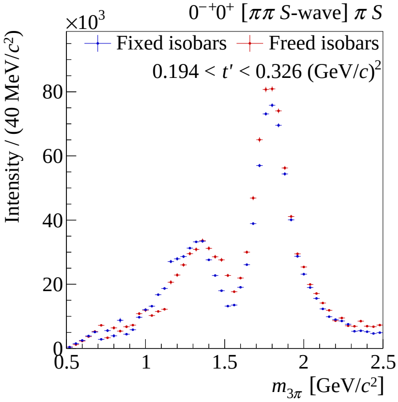
- Sum up all bins in $m_{\pi^+\pi^-}$



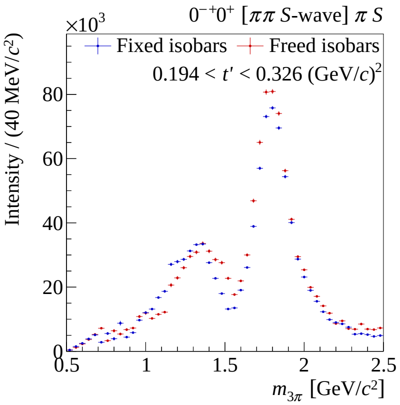
- Sum up all bins in $m_{\pi^+\pi^-}$
- Compare with sum of conventional $0^{-+}f_0$ and $0^{-+}\sigma$ waves



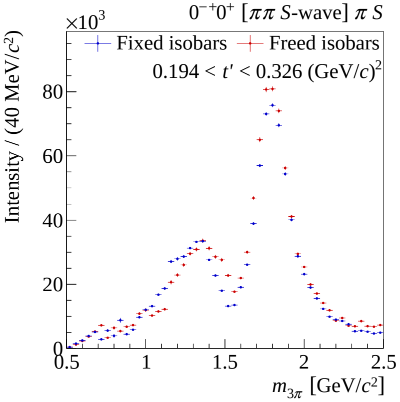
- Sum up all bins in $m_{\pi^+\pi^-}$
- Compare with sum of conventional $0^{-+}f_0$ and $0^{-+}\sigma$ waves
- Compatible shapes



- Sum up all bins in $m_{\pi^+\pi^-}$
- Compare with sum of conventional $0^{-+}f_0$ and $0^{-+}\sigma$ waves
- Compatible shapes
- $\pi(1800)$ peak visible

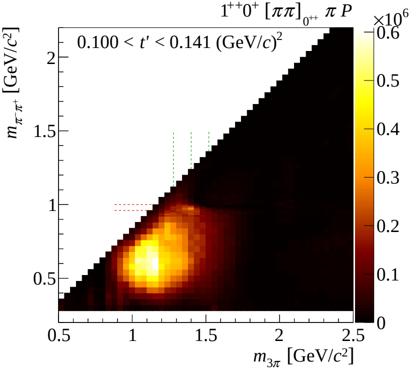


- Sum up all bins in $m_{\pi^+\pi^-}$
- Compare with sum of conventional $0^{-+}f_0$ and $0^{-+}\sigma$ waves
- Compatible shapes
- $\pi(1800)$ peak visible
- Novel method reproduces shape in $m_{3\pi}$

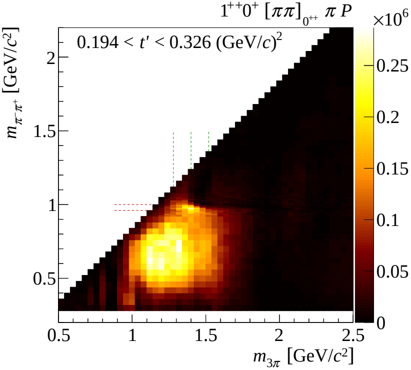


Different regions of the four-momentum transfer t'

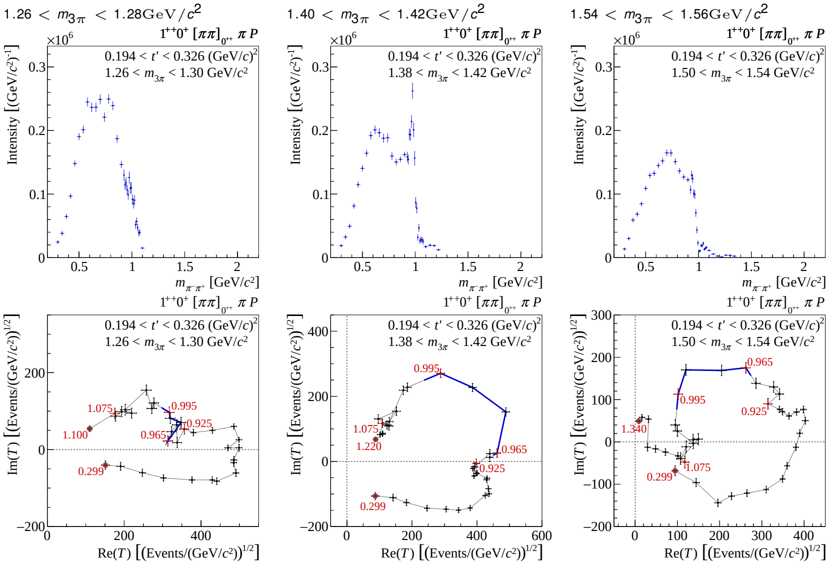
$0.10 < t' < 0.14\,(\mathrm{GeV}/c)^2$
$1^{++}0^{+}[\pi\pi]_{0^{++}}\,\pi P$



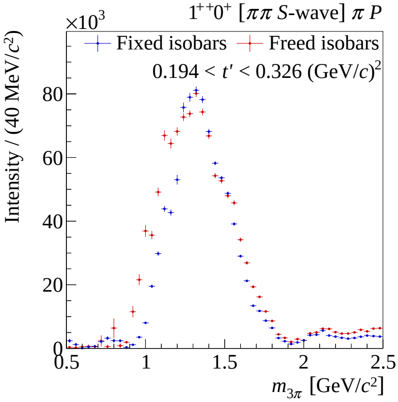
$0.19 < t' < 0.32\,(\mathrm{GeV}/c)^2$
$1^{++}0^{+}[\pi\pi]_{0^{++}}\,\pi P$



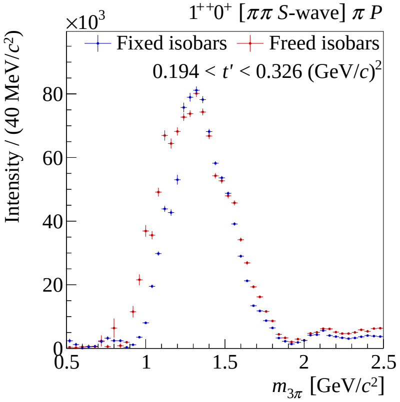
High $t' = 0.19 - 0.32 (\mathrm{GeV}/c)^2$



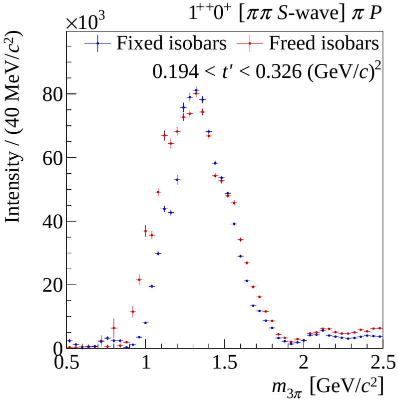
- Sum all bins in $m_{\pi^+\pi^-}$



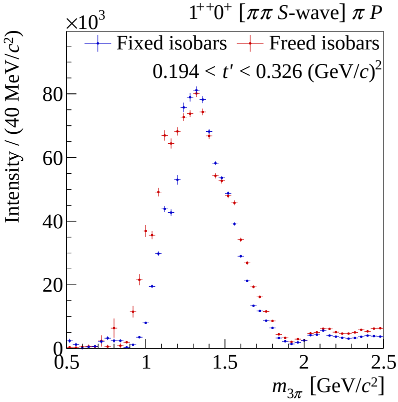
- Sum all bins in $m_{\pi^+\pi^-}$
- Compare with sum of corresponding waves in conventional PWA



- Sum all bins in $m_{\pi^+\pi^-}$
- Compare with sum of corresponding waves in conventional PWA
- Shapes are compatible

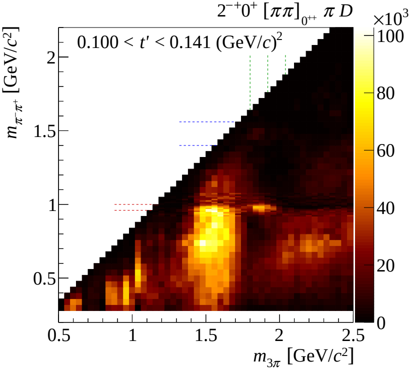


- Sum all bins in $m_{\pi^+\pi^-}$
- Compare with sum of corresponding waves in conventional PWA
- Shapes are compatible
- New resonance, $a_1(1420)$, visible as peak

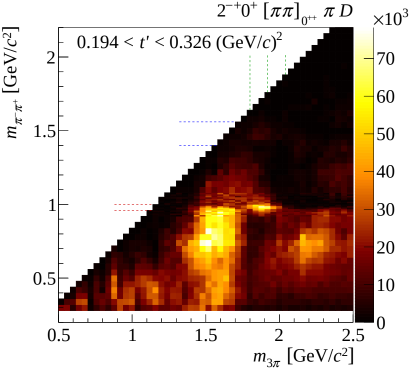


Different regions of the four-momentum transfer t'

$0.10 < t' < 0.14\,(\mathrm{GeV}/c)^2$
$2^{-+}0^+[\pi\pi]_{0^{++}}\,\pi D$

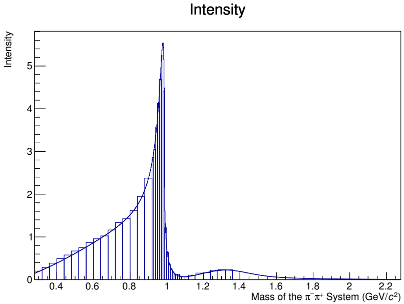


$0.19 < t' < 0.32\,(\mathrm{GeV}/c)^2$
$2^{-+}0^+[\pi\pi]_{0^{++}}\,\pi D$

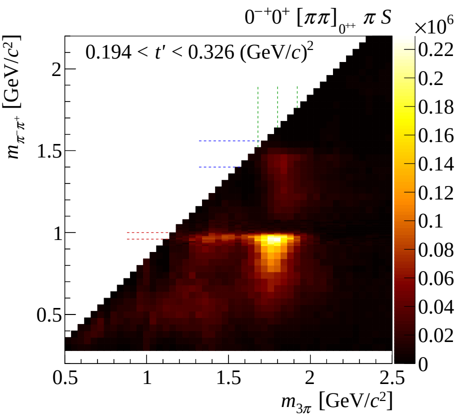


Origin of broad structures not clear at the moment
(Shadows of fixed-shape waves?)

- Isobar amplitudes are replaced by sets of step-like functions $[\pi\pi]_{J^{PC}}$
- Novel method allows to extract the amplitudes of isobars

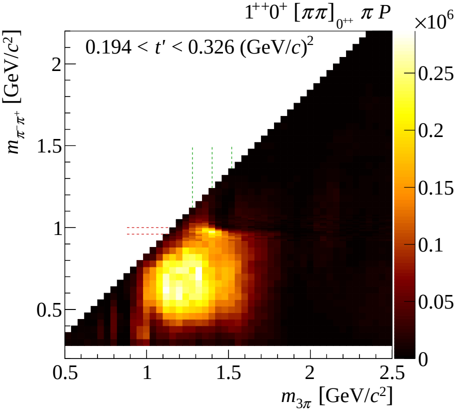


- Isobar amplitudes are replaced by sets of step-like functions $[\pi\pi]_{J^{PC}}$
- Novel method allows to extract the amplitudes of isobars
- Study resonance production in three dimensions: $m_{3\pi}$, $m_{\pi^+\pi^-}$ and t'



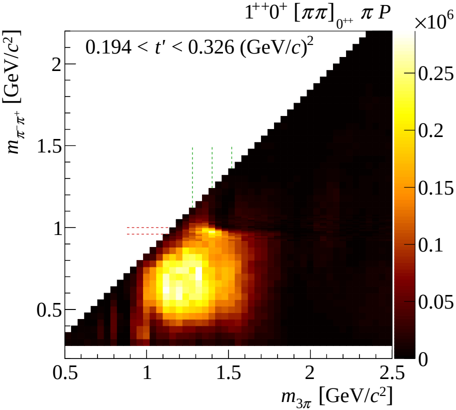
Conclusions

- Isobar amplitudes are replaced by sets of step-like functions $[\pi\pi]_{J^{PC}}$
- Novel method allows to extract the amplitudes of isobars
- Study resonance production in three dimensions: $m_{3\pi}$, $m_{\pi^+\pi^-}$ and t'
- Known waves and decay modes reproduced, especially the new $a_1(1420) \to f_0(980)\pi^-$



Conclusions

- Isobar amplitudes are replaced by sets of step-like functions $[\pi\pi]_{J^{PC}}$
- Novel method allows to extract the amplitudes of isobars
- Study resonance production in three dimensions: $m_{3\pi}$, $m_{\pi^+\pi^-}$ and t'
- Known waves and decay modes reproduced, especially the new $a_1(1420) \to f_0(980)\pi^-$
- t' dependent, broad structures at small $m_{3\pi}$, $m_{\pi^+\pi^-}$
  $\to$ Possible non-resonant processes



Outlook

- Reduce effects from imperfect parameterizations in other waves

  $\rightarrow$ Free isobar-amplitudes for all large waves

Outlook

- Reduce effects from imperfect parameterizations in other waves

  $\rightarrow$ Free isobar-amplitudes for all large waves

- Goal at the moment: Free 11 waves

$0^{-+}\,0^{+}\,f_0(980)\pi\,S$

$0^{-+}\,0^{+}\,\rho(770)\pi\,P$

$1^{++}\,0^{+}\,f_0(980)\pi\,P$

$1^{++}\,0^{+}\,\rho(770)\pi\,S$

$1^{++}\,1^{+}\,\rho(770)\pi\,S$

$2^{-+}\,0^{+}\,f_0(980)\pi\,D$

$2^{-+}\,0^{+}\,\rho(770)\pi\,P$

$2^{-+}\,0^{+}\,\rho(770)\pi\,F$

$2^{-+}\,0^{+}\,\rho(770)\pi\,P$

$2^{-+}\,1^{+}\,f_2(1270)\pi\,S$

$2^{++}\,1^{+}\,\rho(770)\pi\,S$

Outlook

- Reduce effects from imperfect parameterizations in other waves

  $\rightarrow$ Free isobar-amplitudes for all large waves

- Goal at the moment: Free 11 waves
  - 75% of the total intensity
  - All waves above 1% of the intensity

$0^{-+}\,0^{+}\,f_0(980)\pi S$

$0^{-+}\,0^{+}\,\rho(770)\pi P$

$1^{++}\,0^{+}\,f_0(980)\pi P$

$1^{++}\,0^{+}\,\rho(770)\pi S$

$1^{++}\,1^{+}\,\rho(770)\pi S$

$2^{-+}\,0^{+}\,f_0(980)\pi D$

$2^{-+}\,0^{+}\,\rho(770)\pi P$

$2^{-+}\,0^{+}\,\rho(770)\pi F$

$2^{-+}\,0^{+}\,\rho(770)\pi P$

$2^{-+}\,1^{+}\,f_2(1270)\pi S$

$2^{++}\,1^{+}\,\rho(770)\pi S$

Outlook

- Reduce effects from imperfect parameterizations in other waves

  $\rightarrow$ Free isobar-amplitudes for all large waves

- Goal at the moment: Free 11 waves
  - 75% of the total intensity
  - All waves above 1% of the intensity
- Some challenges:
  - Freeing isobars heavily increases the number of parameters
  - Some problems with non-orthogonality of Partial Waves

$0^{-+}\,0^{+} f_0(980)\pi S$

$0^{-+}\,0^{+} \rho(770)\pi P$

$1^{++}\,0^{+} f_0(980)\pi P$

$1^{++}\,0^{+} \rho(770)\pi S$

$1^{++}\,1^{+} \rho(770)\pi S$

$2^{-+}\,0^{+} f_0(980)\pi D$

$2^{-+}\,0^{+} \rho(770)\pi P$

$2^{-+}\,0^{+} \rho(770)\pi F$

$2^{-+}\,0^{+} \rho(770)\pi P$

$2^{-+}\,1^{+} f_2(1270)\pi S$

$2^{++}\,1^{+} \rho(770)\pi S$