Analysis of the diffractively produced $\pi^-\pi^-\pi^+$ Final State at COMPASS

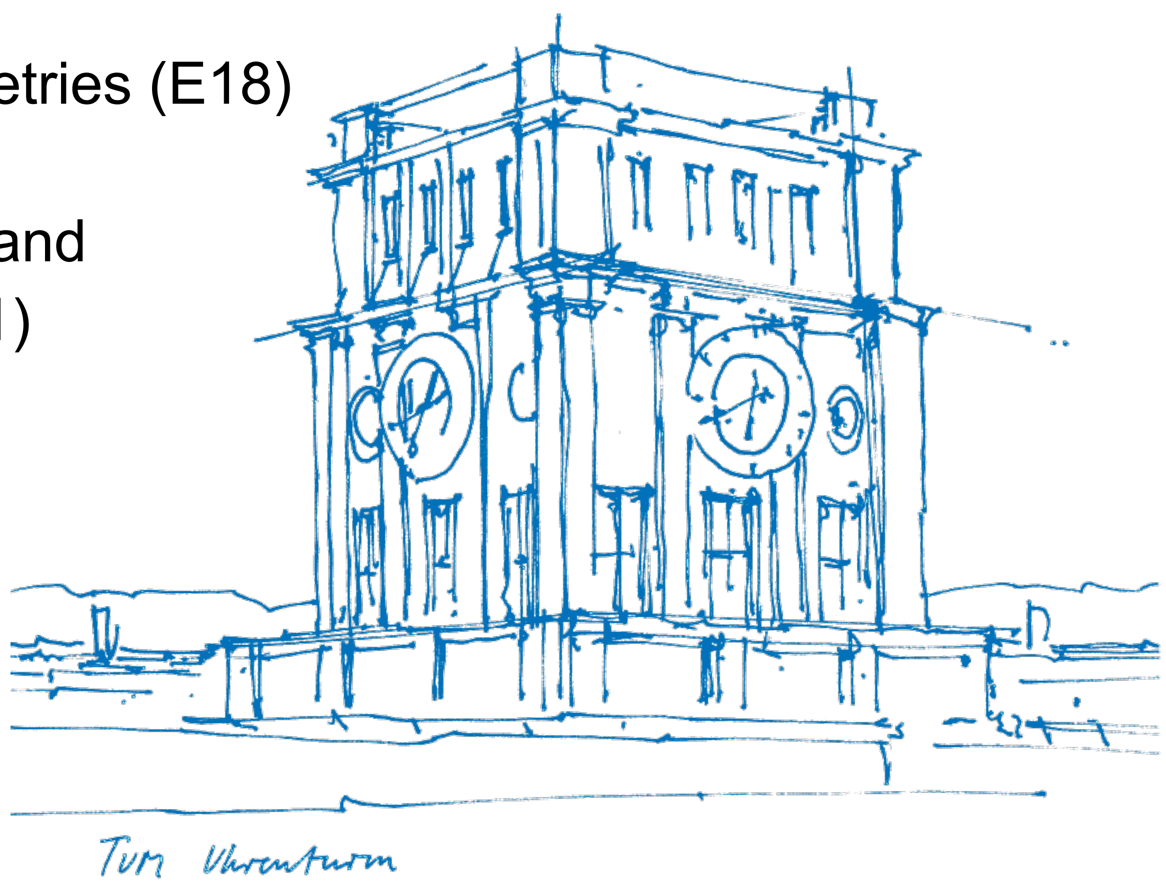
A Surprising π-like Signal

Florian Markus Kaspar
for the COMPASS Collaboration

Technische Universität München
Fakultät für Physik
Institute for Hadronic Structure and Fundamental Symmetries (E18)

19th International Conference on Hadron Spectroscopy and Structure in memoriam Simon Eidelman (HADRON 2021)

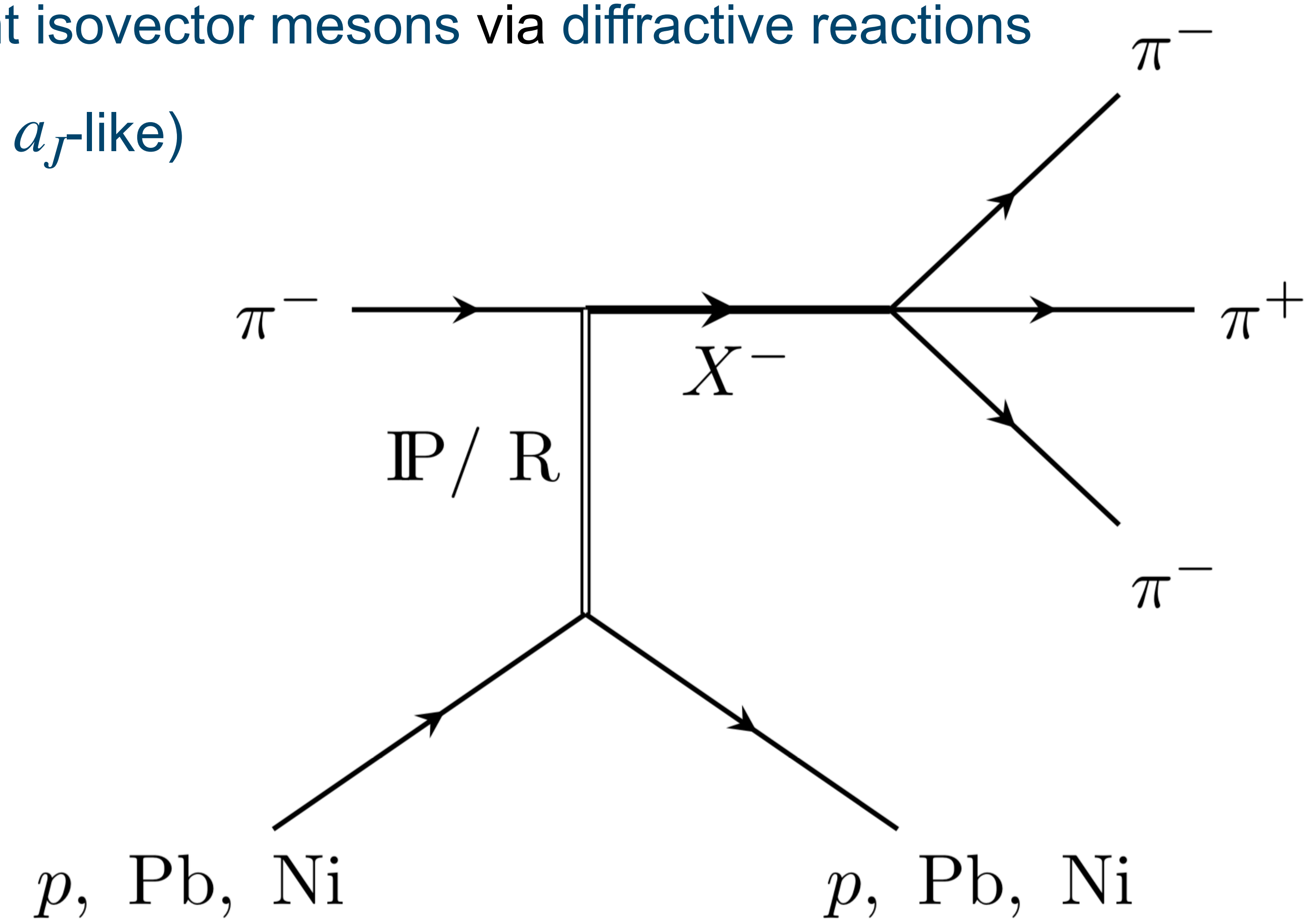
28th July 2021 9:50 (CDMX)



Light-Meson Resonances at COMPASS

Light-Meson Resonances at COMPASS

- π^- beam $190\ \mathrm{GeV/c} \rightarrow$ production of light isovector mesons via diffractive reactions
- beam excited to resonance X^- (π_J-like and a_J-like)
- X^- decays into $\pi^-\pi^-\pi^+$ final-state
- target stays intact



Analyzed Targets at COMPASS:

- (light) proton target (in the form of $l\mathrm{H}_2$)
- (heavy) solid state targets lead (Pb) and Nickel (Ni)

Details on the resonance production in: COMPASS Collaboration, Phys. Rev. D 95 (2017) 032004, arXiv:1509.00992 [hep-ex].

Event Selection

updated $l\mathrm{H}_2$ analysis:

- more data + improved event selection

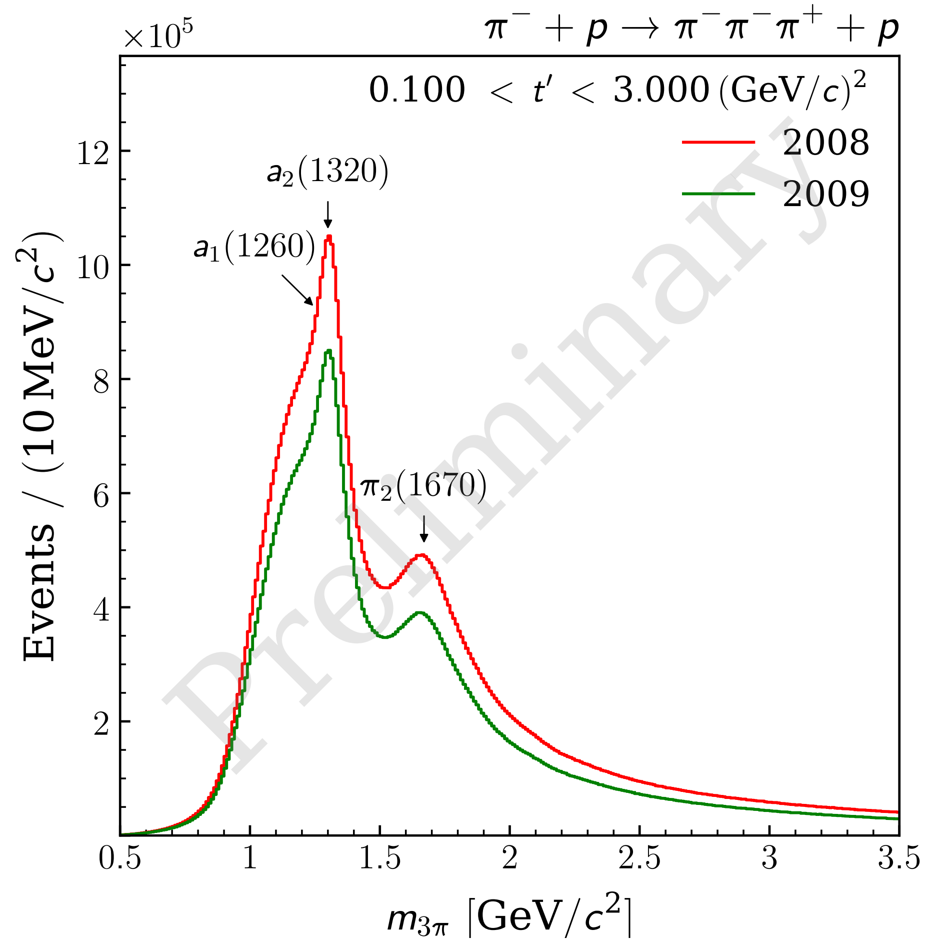
  more than 115 million exclusive $\pi^-\pi^-\pi^+$ events

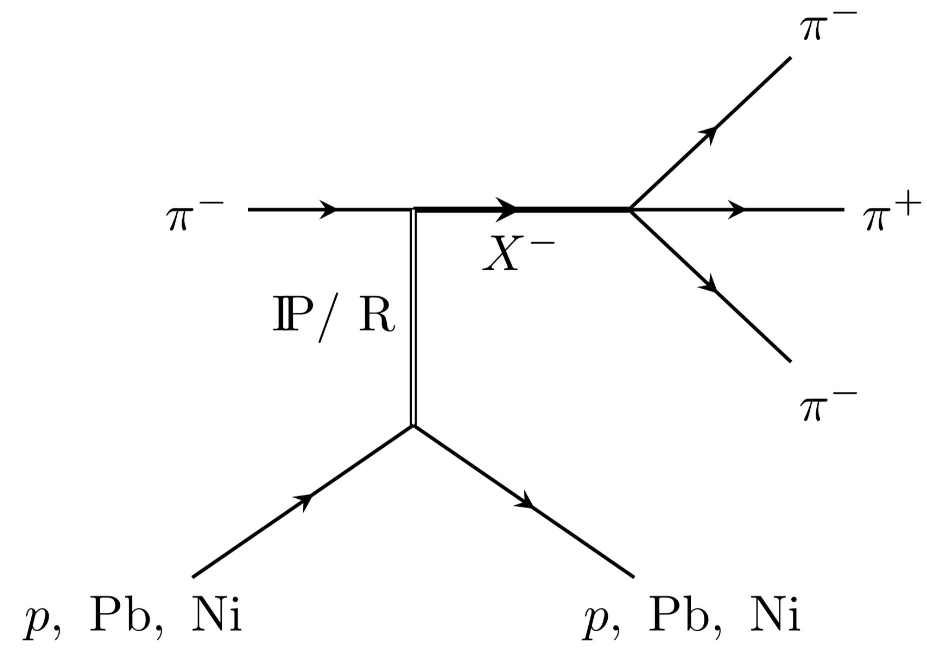
- (for this talk) kinematic range:
  - $0.5 < m_{3\pi} < 2.5\,\mathrm{GeV}/c^2$
  - $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$

Heavy targets (Pb and Ni):

- 13.5 million events for Pb target
- 12 million for Ni target
- different t' range: $0.0 < t' < 1.5\,(\mathrm{GeV}/c)^2$

$\rightarrow l\mathrm{H}_2$ + heavy targets: large kinematic range





Details on the previous $l\mathrm{H}_2$ analysis: COMPASS Collaboration, Phys. Rev. D 95 (2017) 032004, arXiv:1509.00992 [hep-ex].

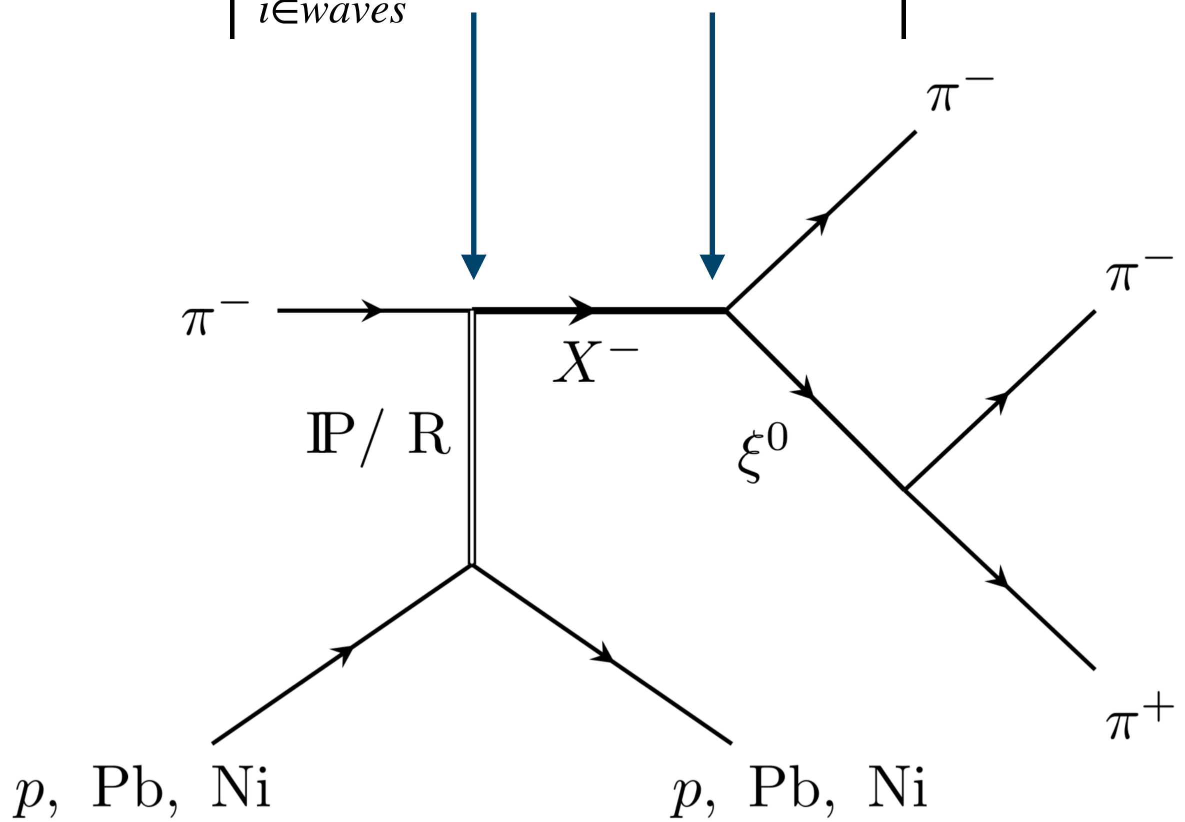
Partial-Wave Decomposition: Method

Partial-Wave Decomposition: Method

Model the full measured distribution:

- event described by 5-dim. kinematic variable τ
- factorization + isobar model
- sum over X^- quantum numbers and decays (wave) $i = (I^G, J^{PC}, M, \xi_0, L)$:
  88 wave model (as published)
- build fit model

$$I(\tau; m_{3pi}, t') = \left| \sum_{i \in waves} T_i(m_{3\pi}, t')\, \psi_i(\tau; m_{3\pi}) \right|^2 + \left| T_{flat} \right|^2$$



Isobars ξ_0:

- $\sigma(500)$
- $\rho(770)$
- $f_0(980)$
- $f_2(1270)$
- $f_0(1500)$
- $\rho_3(1690)$

Details of the Partial-Wave Decomposition in: COMPASS Collaboration, Phys. Rev. D 95 (2017) 032004, arXiv:1509.00992 [hep-ex].

Partial-Wave Decomposition: Method

$$I(\tau; m_{3pi}, t') = \left| \sum_{i \in waves} T_i(m_{3\pi}, t')\, \psi_i(\tau; m_{3\pi}) \right|^2 + \left| T_{flat} \right|^2$$

$$i = (I^G, J^{PC}, M, \xi_0, L)$$

$T_i \;\rightarrow\; X^-$ resonance information

- 2D-binning in $m_{3\pi}$ and $t' \rightarrow T_i(m_{3\pi}, t')$
- fit in every bin:
  - intensities $|T_i|^2$
  - relative phases $\arg(T_i T_j^*)$

→ non-parametric / “model independent” extraction

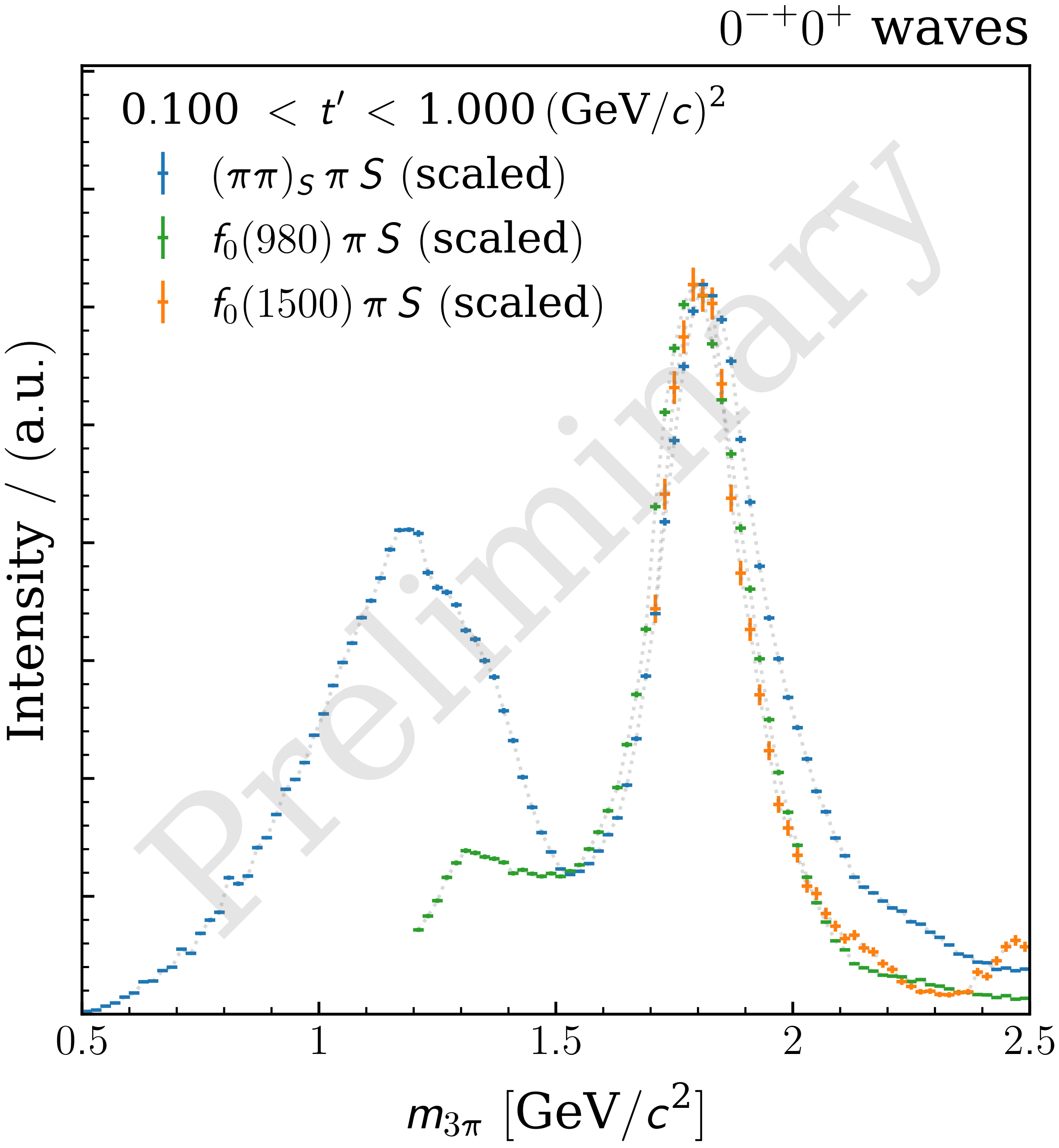
Partial-Wave Decomposition: Results

Partial-Wave Decomposition: 0^{-+} waves

Here $l\mathrm{H}_2$ data: π-like objects

- signal of the $\pi(1800)$ resonance decaying into scalar isobars
- scaled to $\pi(1800)$ intensity peak
- excellent agreement in $\pi(1800)$ peak

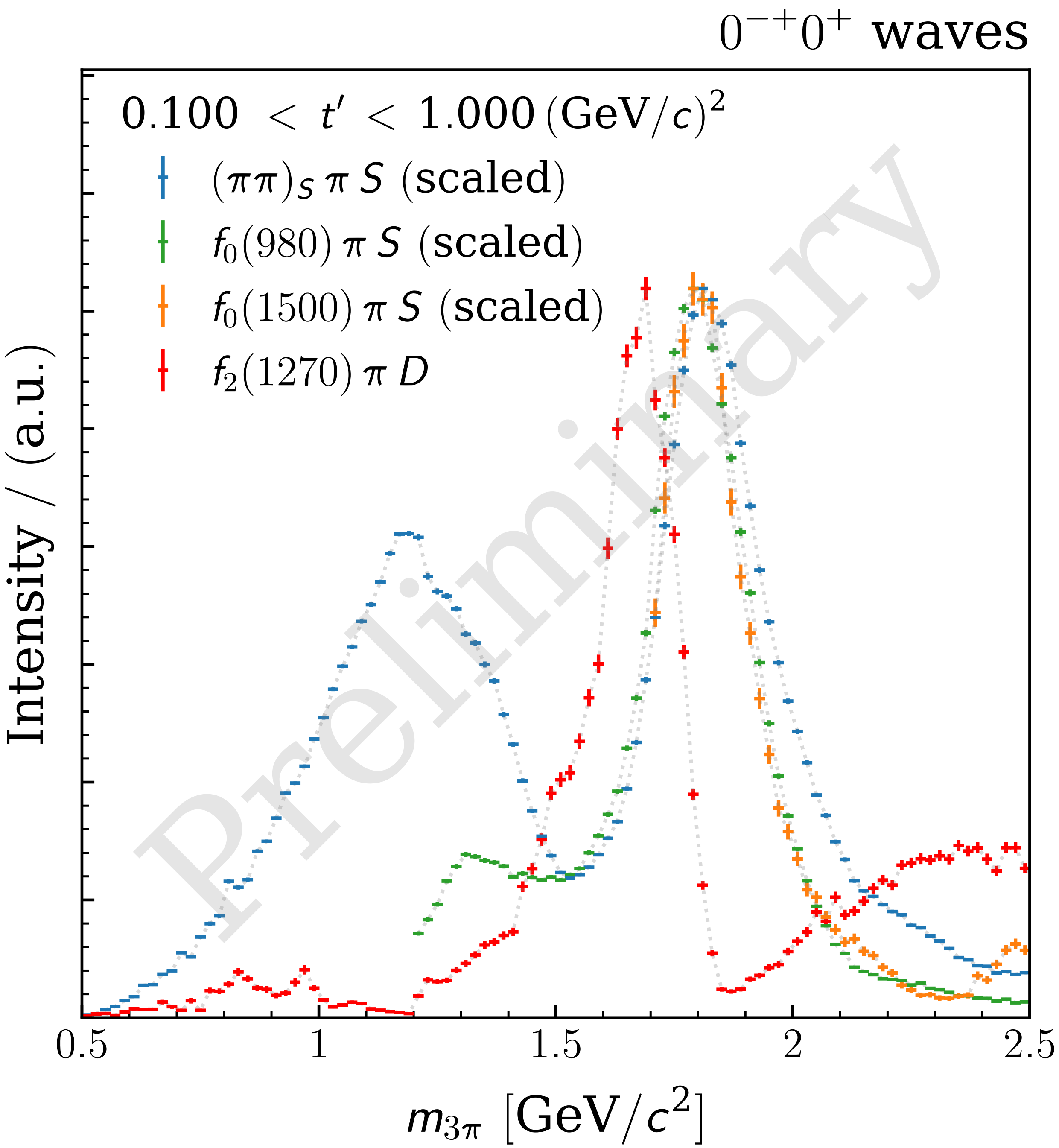
→ what about decays into other isobars?



Partial-Wave Decomposition: 0^{-+} waves

Here $l\mathrm{H}_2$ data:

- narrow signal in $0^{-+}0^{+} f_2(1270)\,\pi\, D$ wave but at lower mass



Partial-Wave Decomposition: 0^{-+} waves

Here $l\mathrm{H}_2$ data:

- narrow signal in $0^{-+}0^{+} f_2(1270)\,\pi\,D$ wave but at lower mass
- seen by the VES experiment [1] →
  26 wave model
  Be target at low $t' < 0.06\,(\mathrm{GeV}/c)^2$

$0^{-+}0^{+} f_2(1270)\,\pi\,D$

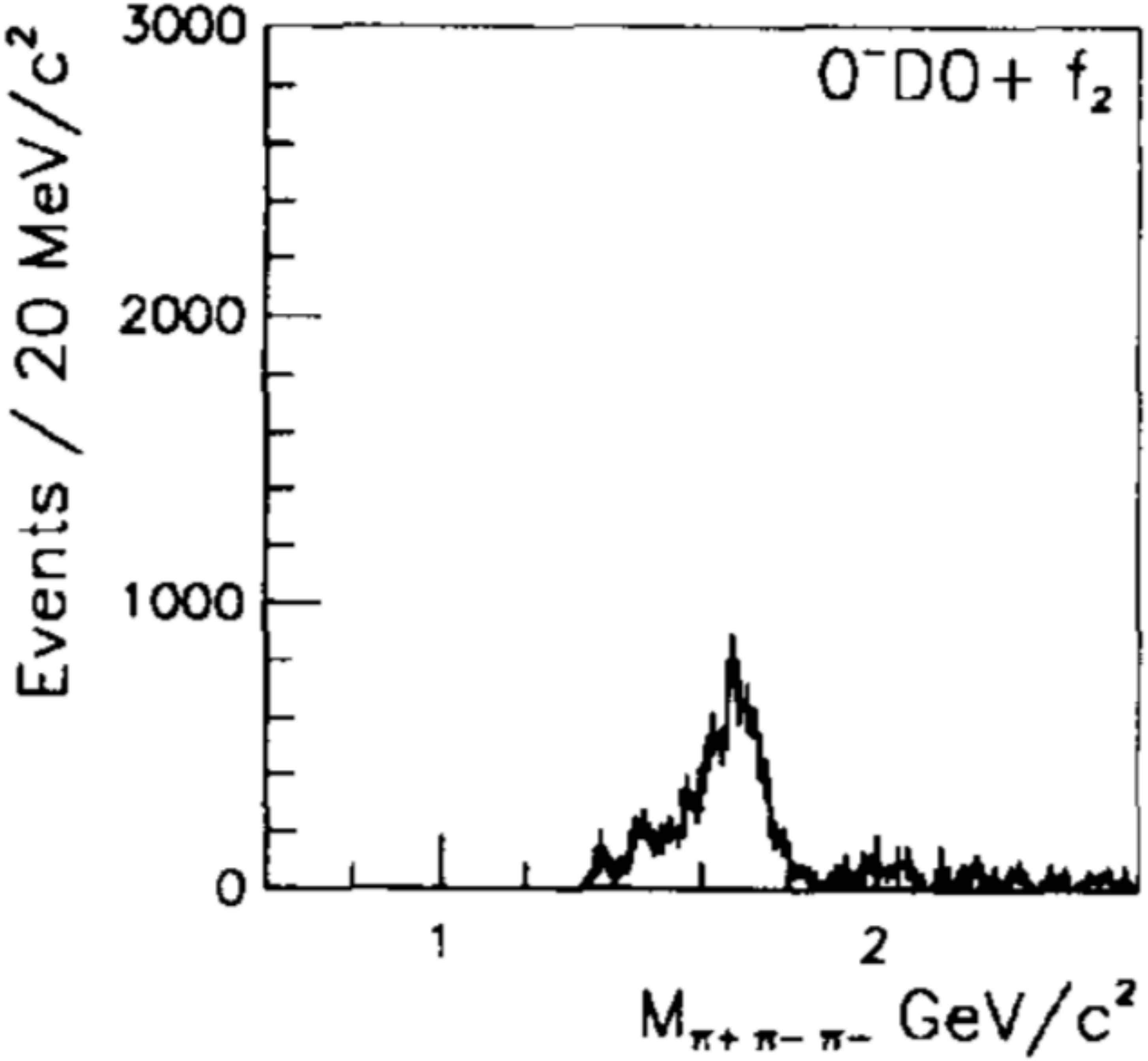


Figure 4 (d) of [1]

[1] VES Collaboration, D.V Amelin et al., Physics Letters B, Volume 356, Issue 4, 1995, Pages 595-600

Partial-Wave Decomposition: 0^{-+} waves

Here $l\mathrm{H}_2$ data:

- narrow signal in $0^{-+}0^{+} f_2(1270)\,\pi\,D$

  wave but at lower mass

- seen by the VES experiment [1] →

  26 wave model

  Be target at low $t' < 0.06\,(\mathrm{GeV}/c)^2$

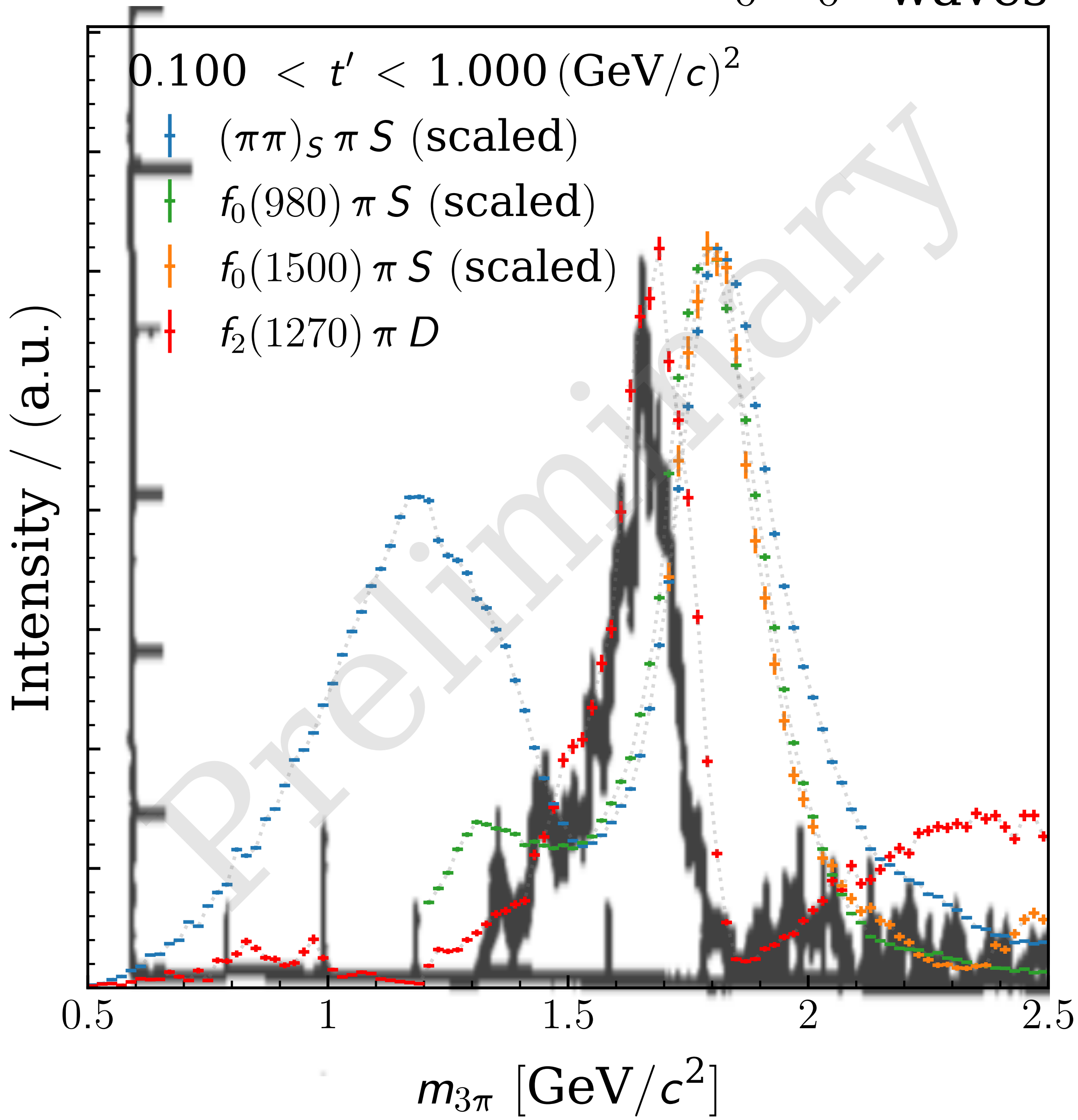
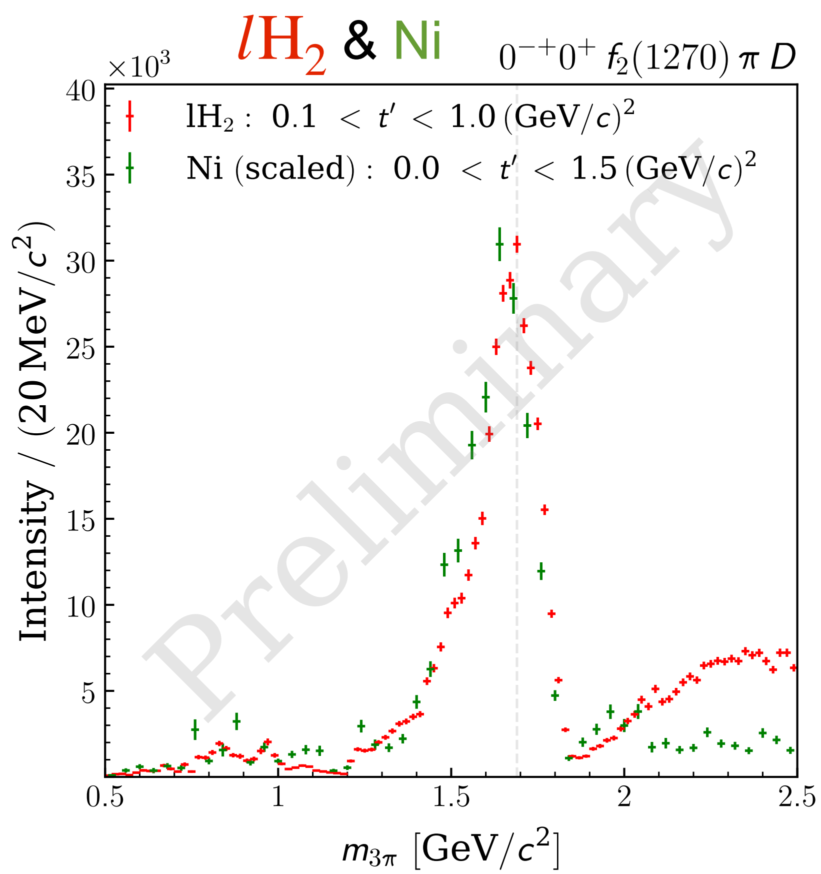


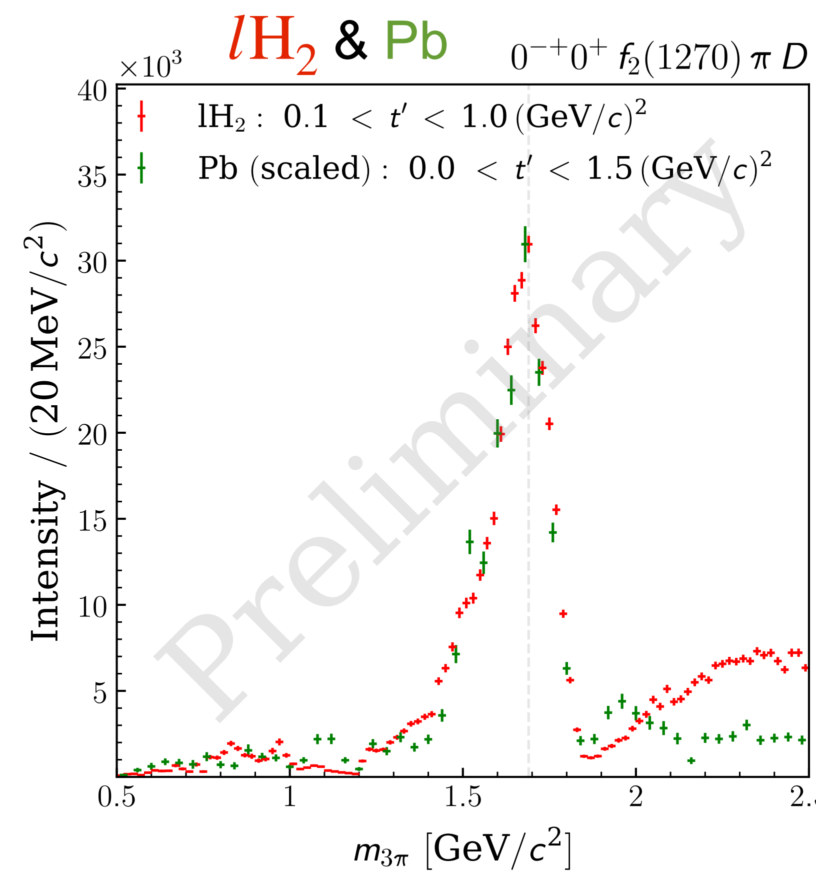
Figure 4 (d) of [1] (scaled)

[1] VES Collaboration, D.V Amelin et al., Physics Letters B, Volume 356, Issue 4, 1995, Pages 595-600

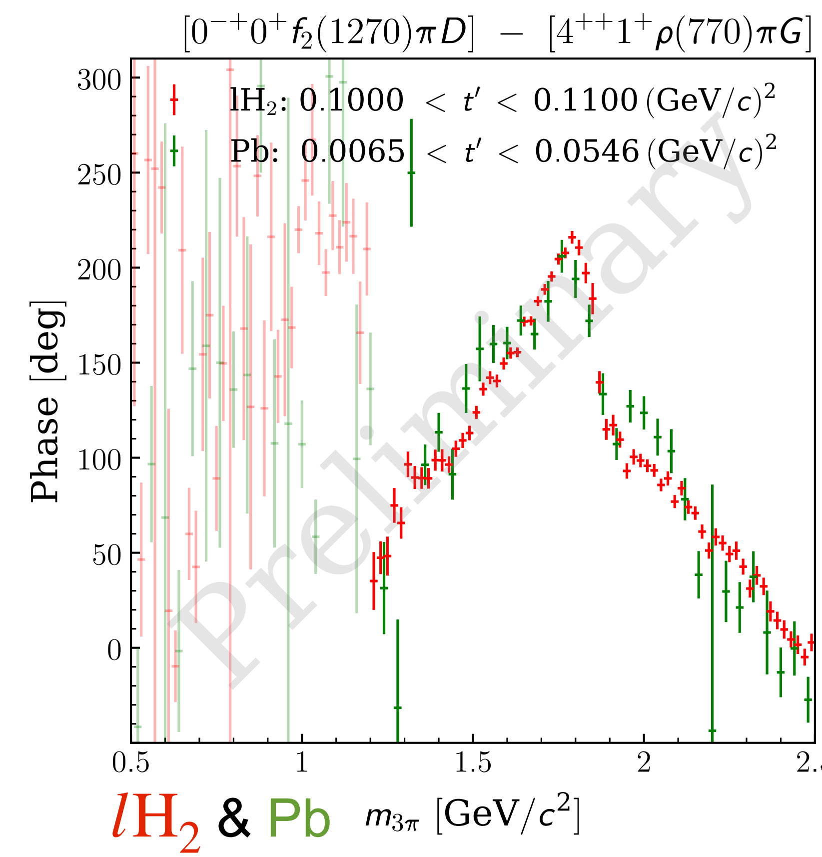
Partial-Wave Decomposition: Comparison

Comparison of
liquid hydrogen ($l\mathrm{H}_2$)
heavy target (Ni & Pb)





- intensity peak at the same position
- rapid phase motion!
- for liquid-hydrogen data: shoulder above $1.8\,\mathrm{GeV}/c^2$
  → most likely non-resonant:
  - strong t' dependence of shoulder
  - wave-set dependence



Resonance-Model Fit

Resonance-Model Fit: 7 selected waves

Fit selected waves:

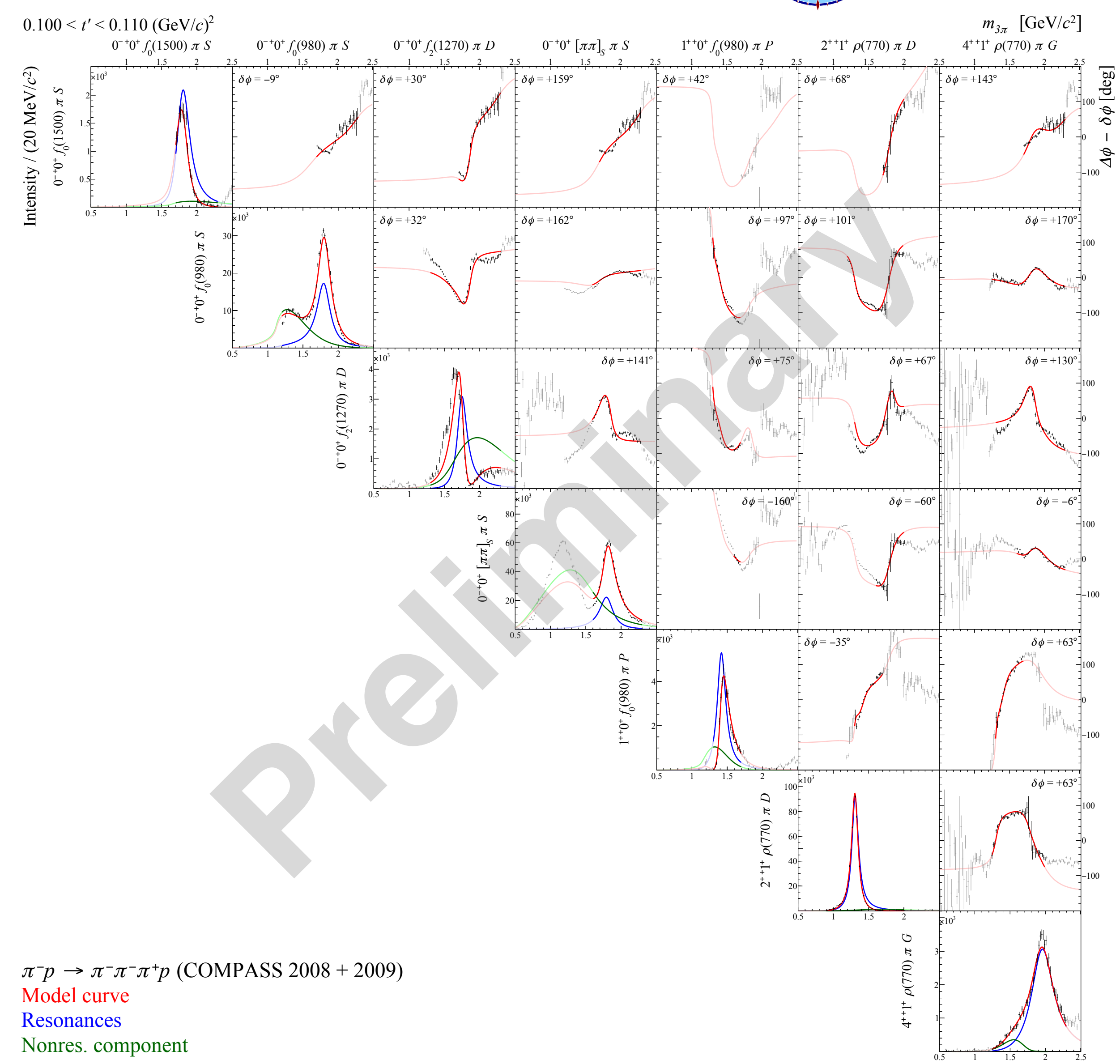
- Breit-Wigner + nonresonant component
- seven waves
- fit intensities and phases simultaneously

Model:

- four 0^{-+} waves:
  - $0^{-+}0^{+}\,[\pi\pi]_S\,\pi\,S$
  - $0^{-+}0^{+}\,f_0(980)\,\pi\,S$
  - $0^{-+}0^{+}\,f_0(1500)\,\pi\,S$
  - $0^{-+}0^{+}\,f_2(1270)\,\pi\,D$: different models

  (first three waves bracketed: $\pi(1800)$)

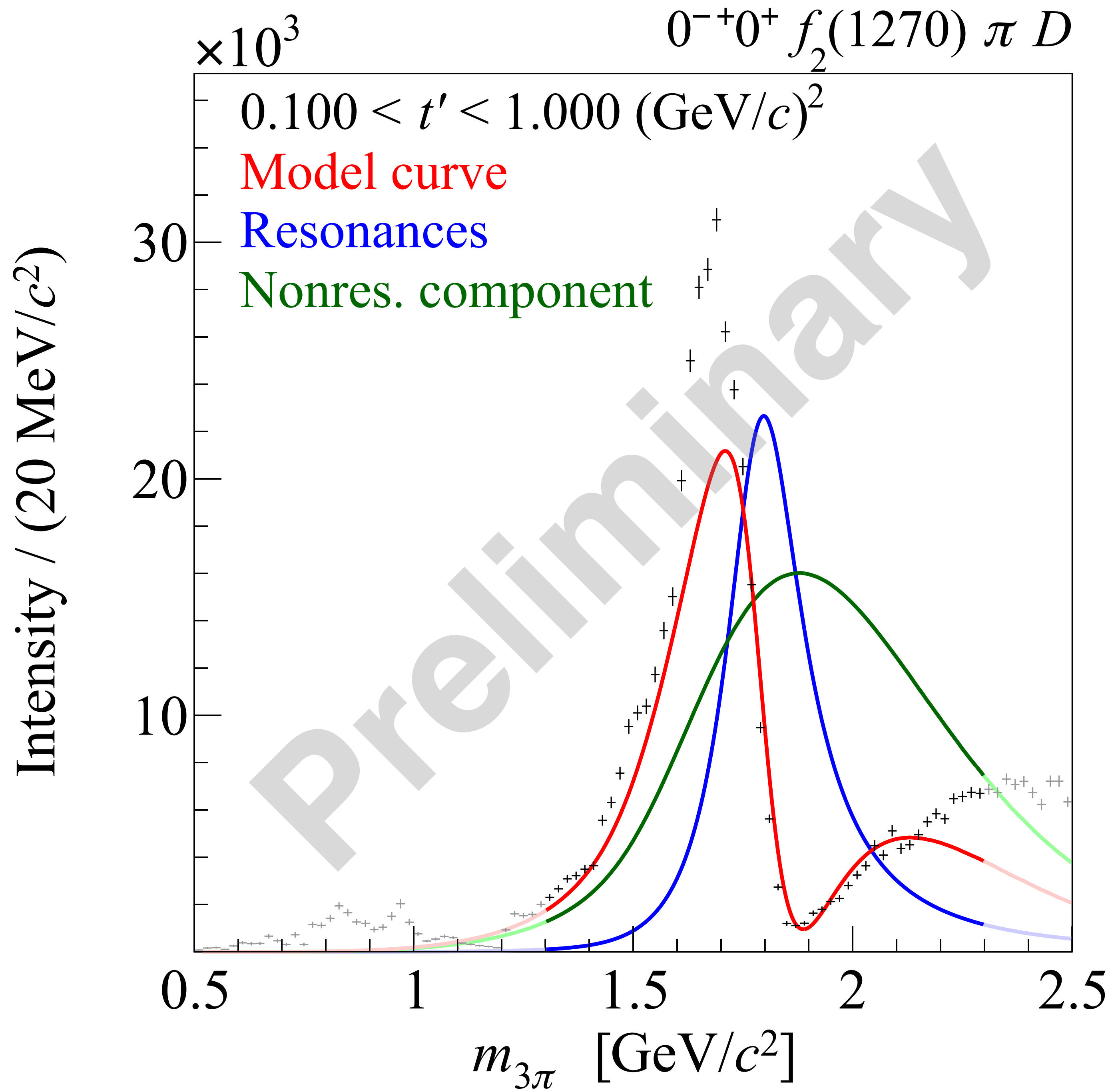
- three additional waves to interfere against:
  - $1^{++}0^{+}\,f_0(980)\,\pi\,P$: $a_1(1420)$
  - $2^{++}1^{+}\,\rho(770)\,\pi\,D$: $a_2(1320)$
  - $4^{++}1^{+}\,\rho(770)\,\pi\,G$: $a_4(1970)$



Details of resonance-model fit in: COMPASS Collaboration, Phys. Rev. D 98 (2018) 092003, arXiv:1802.05913 [hep-ex].

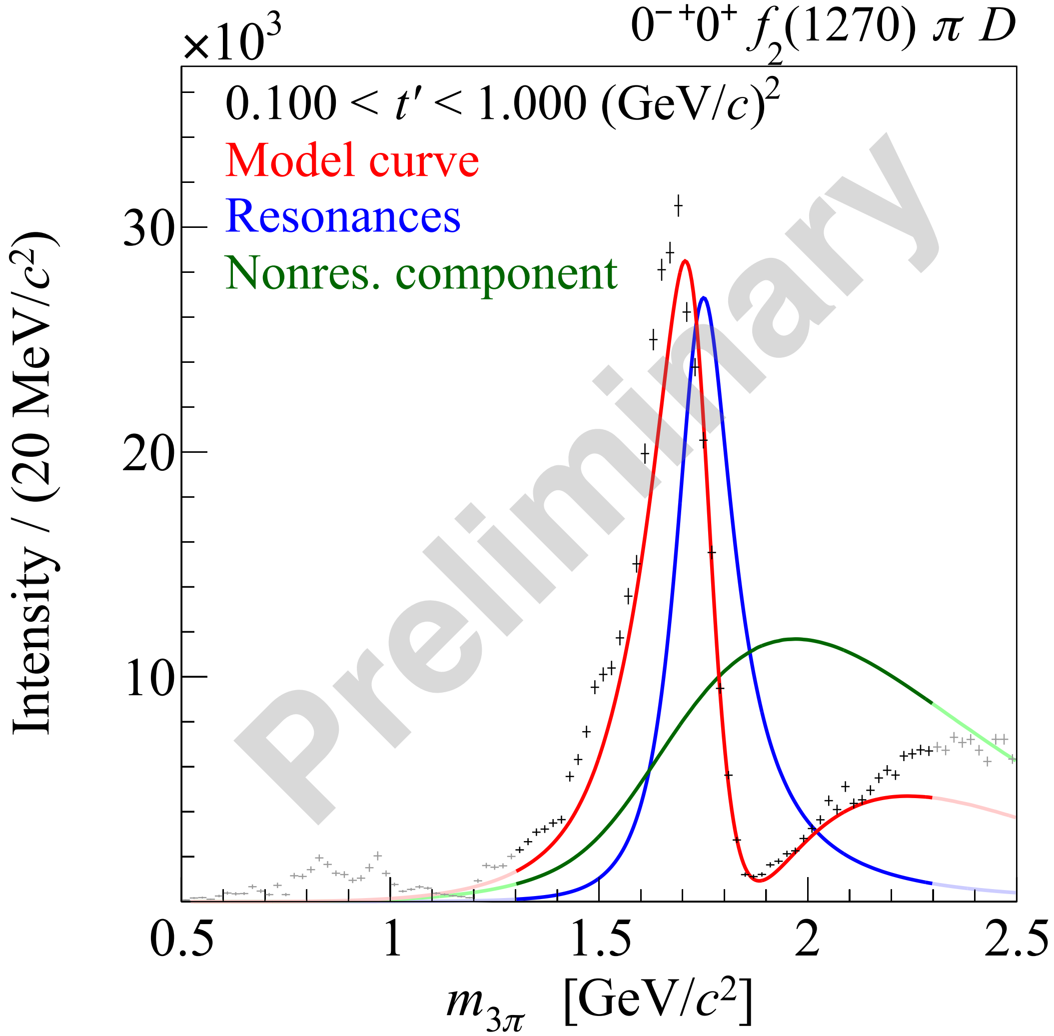
Resonance-Model Fit: $l\mathrm{H}_2$ data

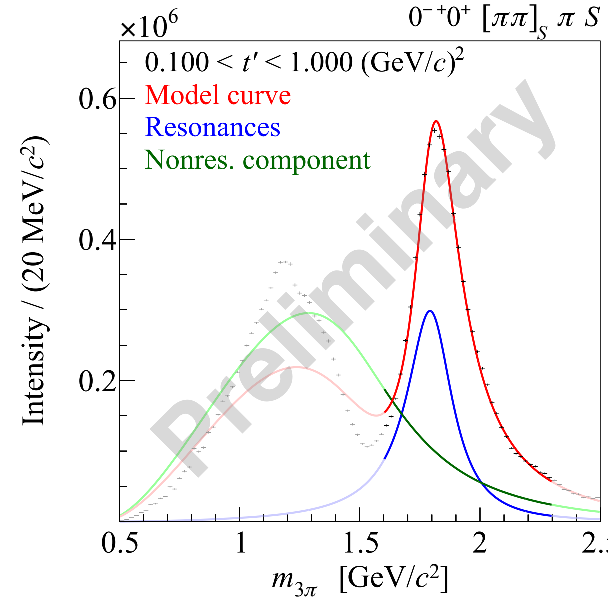
$0^{-+}0^{+} f_2(1270)\,\pi\,D$: $\pi(1800)$ + nonresonant component:

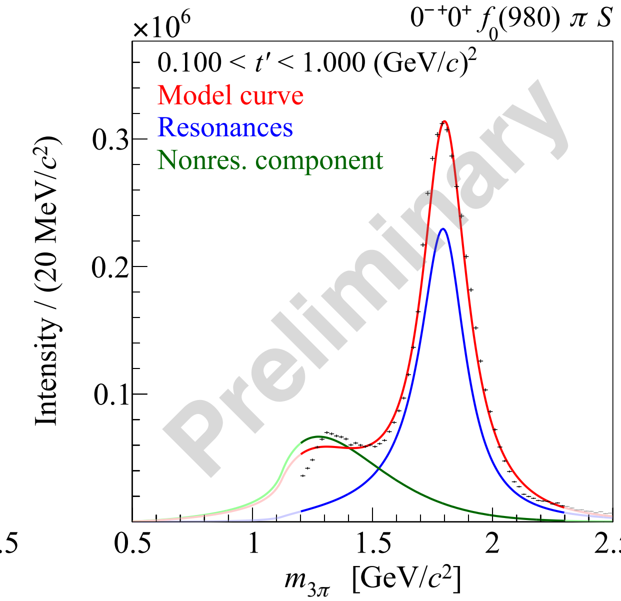


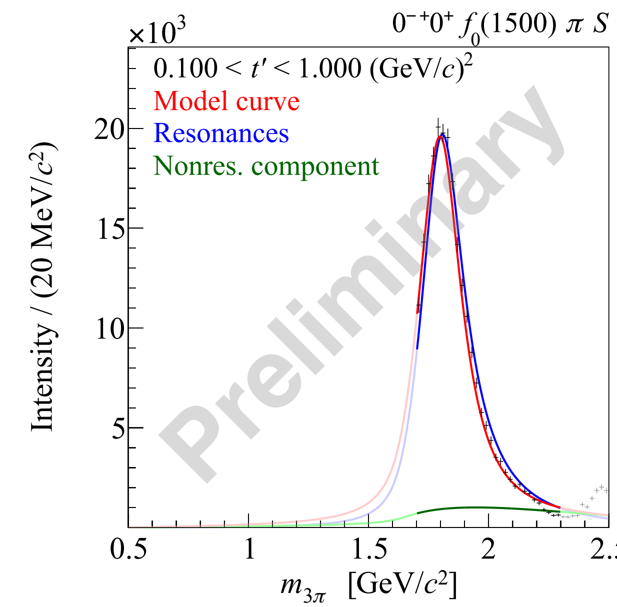
fails to described intensity peak → try separate "$\pi(1700)$"

Resonance-Model Fit: $l\mathrm{H}_2$ data









"$\pi(1700)$":

$m_0 = 1740\,\mathrm{MeV}/c^2, \Gamma_0 = 171\,\mathrm{MeV}/c^2$

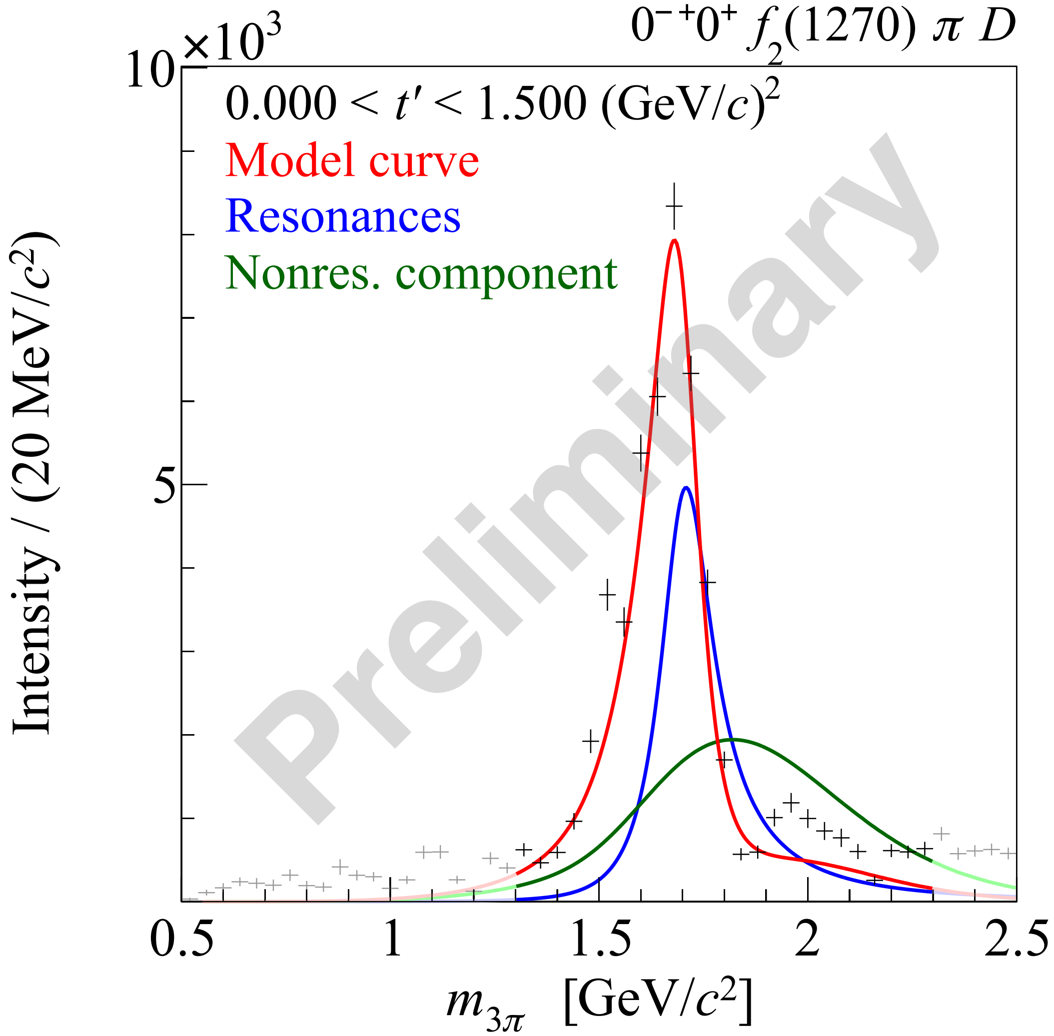
$\Delta m_0 = 55\,\mathrm{MeV}/c^2$ and $\Delta\Gamma_0 = 59\,\mathrm{MeV}/c^2$

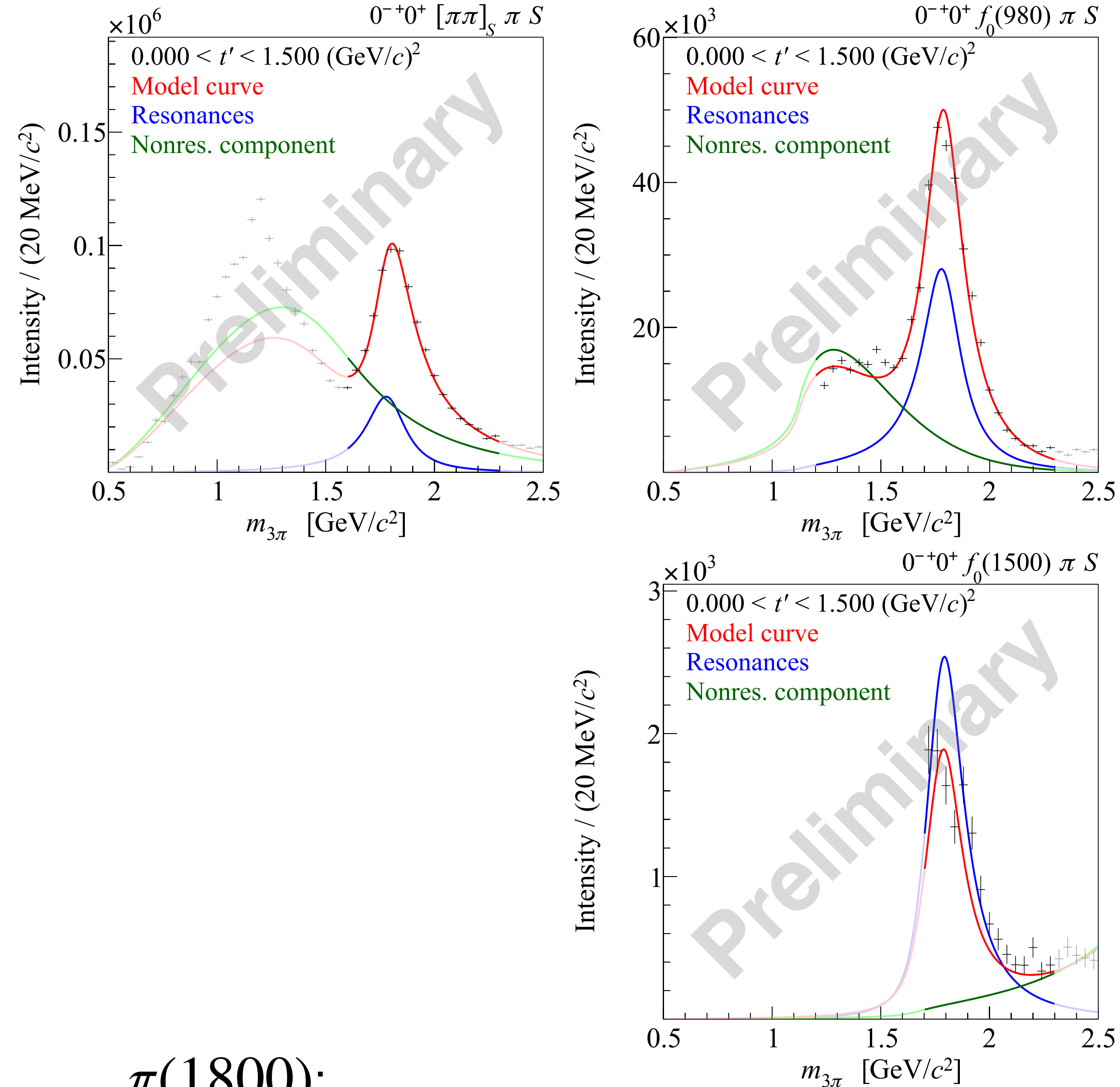
$\pi(1800)$:

$m_0 = 1795\,\mathrm{MeV}/c^2, \Gamma_0 = 230\,\mathrm{MeV}/c^2$

- excellent description

Resonance-Model Fit: Lead (Pb) data





"$\pi(1700)$":
$m_0 = 1698\,\mathrm{MeV}/c^2, \Gamma_0 = 157\,\mathrm{MeV}/c^2$

$\Delta m_0 = 83\,\mathrm{MeV}/c^2$ and $\Delta\Gamma_0 = 64\,\mathrm{MeV}/c^2$

$\pi(1800)$:
$m_0 = 1781\,\mathrm{MeV}/c^2, \Gamma_0 = 221\,\mathrm{MeV}/c^2$

- excellent description

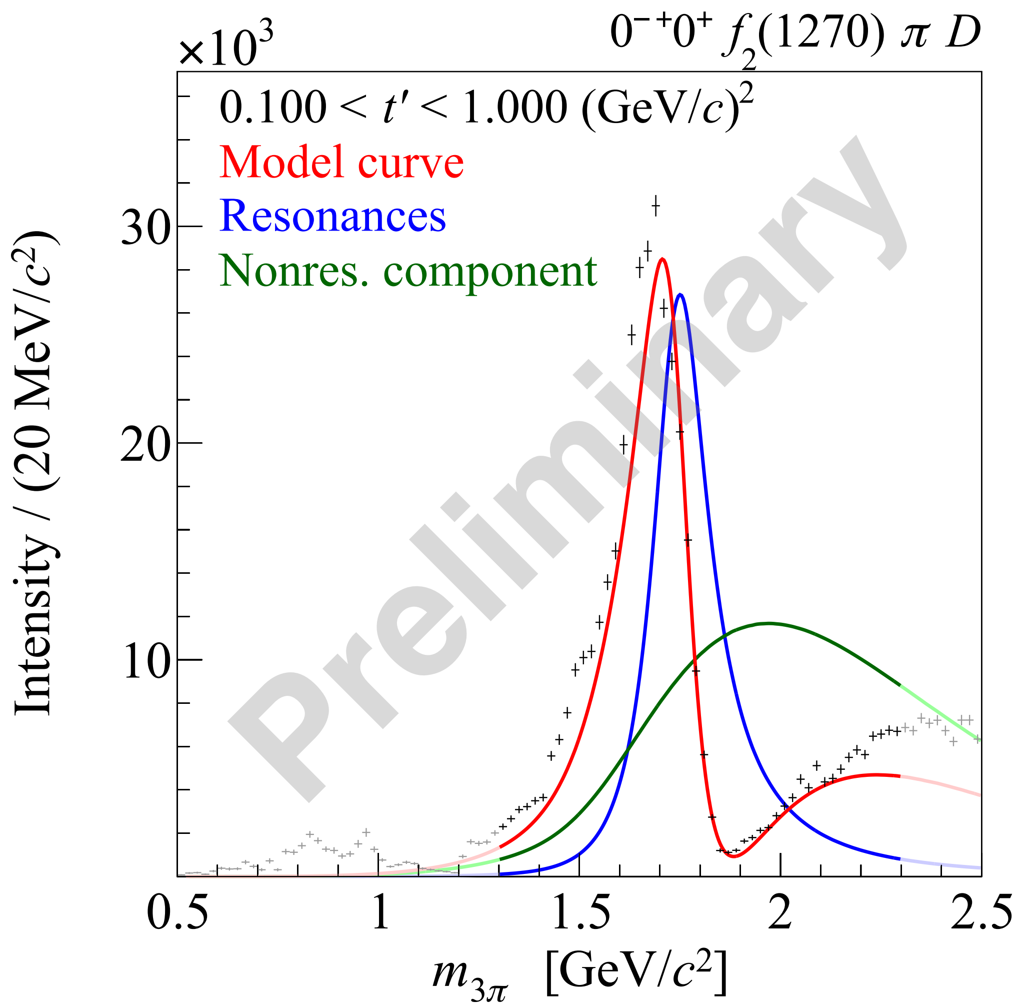
→ consistent picture for both data sets:

separation in lighter "$\pi(1700)$" and heavier $\pi(1800)$ preferred

Possible Interpretations

Possible Interpretations: Shifted $\pi(1800)$

$\pi(1800)$ peak shifted by interference with more complicated nonresonant component (?)



We tried:

- studies of partial-wave model (we go beyond the 88-wave model: up to $\mathcal{O}(700)$ waves)
  → peak stable, high-mass shoulder changes
- studies of models for coherent non-resonant background: Deck, Central Production
- more complicated resonance-models: e.g. two Breit-Wigners
  → one resonance used as effective background

Possible Interpretations: Resonance?

Close and Page: How to distinguish hybrids from radial quarkonia [1]

→ hybrid $\pi_{\mathrm{H}}(1800)$ + additional quark-model state at lower mass?

- theory prediction for $\pi_{\mathrm{H}}(1800)$ decay: $f_2\,\pi\,D$ and $\omega\rho$ decays suppressed
- VES
  - $\pi^-\mathrm{Be} \to \pi^+\pi^-\pi^-\mathrm{Be}$ [2] → $f_2\,\pi\,D$ signal like we see it
  - $\pi^-\mathrm{Be} \to \omega\pi^-\pi^0\mathrm{Be}$ [3] → $\omega\rho$ signal: $m_0 = 1737\,\mathrm{MeV}/c^2,\ \Gamma_0 = 259\,\mathrm{MeV}/c^2$

    → speculate about π_{H} and $q\bar{q}$-state
- $\omega\rho$ also accessible at COMPASS (upcoming analysis)
- Maybe further insights from lattice QCD?
  e.g. like prediction of $\pi_1(1600)$ decay modes by the Hadron Spectrum Collaboration [4]

[1] Close, Frank E. and Page, Philip R., Phys.Rev.D 56 (1997) 1584-158
[2] VES Collaboration: D.V Amelin et al., Physics Letters B, Volume 356, Issue 4, 1995, Pages 595-600
[3] VES Collaboration arXiv:hep-ex/9810013v1, 6 Oct 1998
[4] A.Woss et al., PRD 103, 054502 (2021)

Thank you for your attention!

Questions?

Acknowledgements

Acknowledgements

I would like to thank:

The HADRON 2021 LOC

My colleagues:

Sergei Gerassimov, Boris Grube, Stefan Wallner, Dima Ryabchikov, Andrei Maltsev,

Stephan Paul and the COMPASS hadron analysis group

Additional Material for Discussion

Partial-Wave Decomposition: Method

From the intensity of an event we can get it's detection probability (for a specific set of parameters):

$$P(\tau^j; m^j_{3pi}, t'^j) = \frac{I(\tau^j; m^j_{3pi}, t'^j)}{\int_\Omega I(\tau; m_{3pi}, t')\mathrm{d\ LIPS}(\tau)}$$

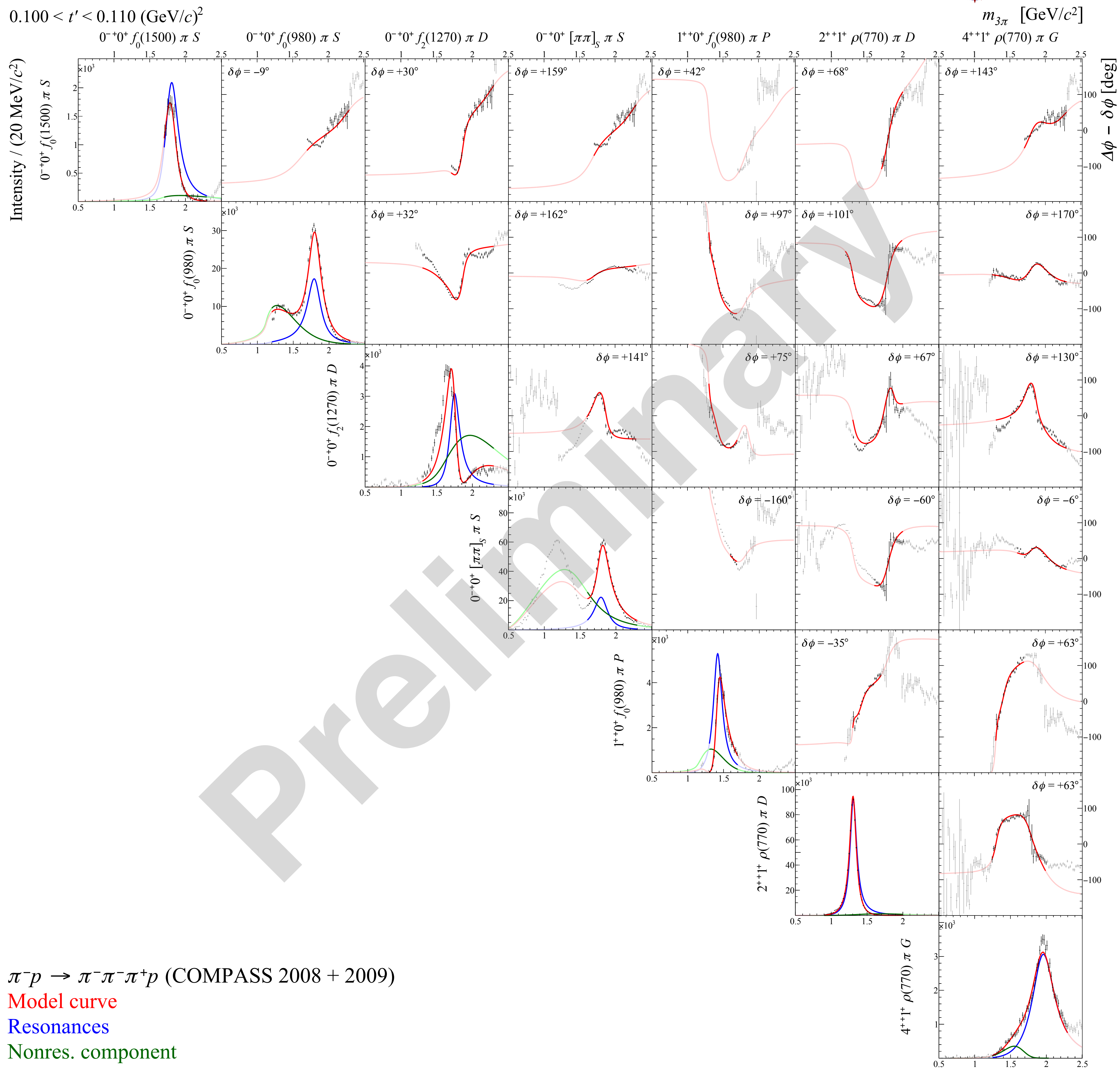
The product of the individual probabilities over all events times the Poisson distribution of the number of events (it's also random!) results in extended likelihood Ansatz:

$$\mathscr{L} = \frac{\bar{n}}{n!} e^{-\bar{n}} \prod_j^n P(\tau^j; m^j_{3pi}, t'^j)$$

For numerical stability: take the logarithm $\mathscr{L} \rightarrow \log(\mathscr{L})$

$\rightarrow$ maximize $\log(\mathscr{L}) \rightarrow n$ transition amplitudes per bin $(T_0, T_1, \ldots, T_i, \ldots, T_n)^T = \overrightarrow{T} \in \mathbb{C}^n$

Resonance Model Fit: $l\mathrm{H}_2$ data



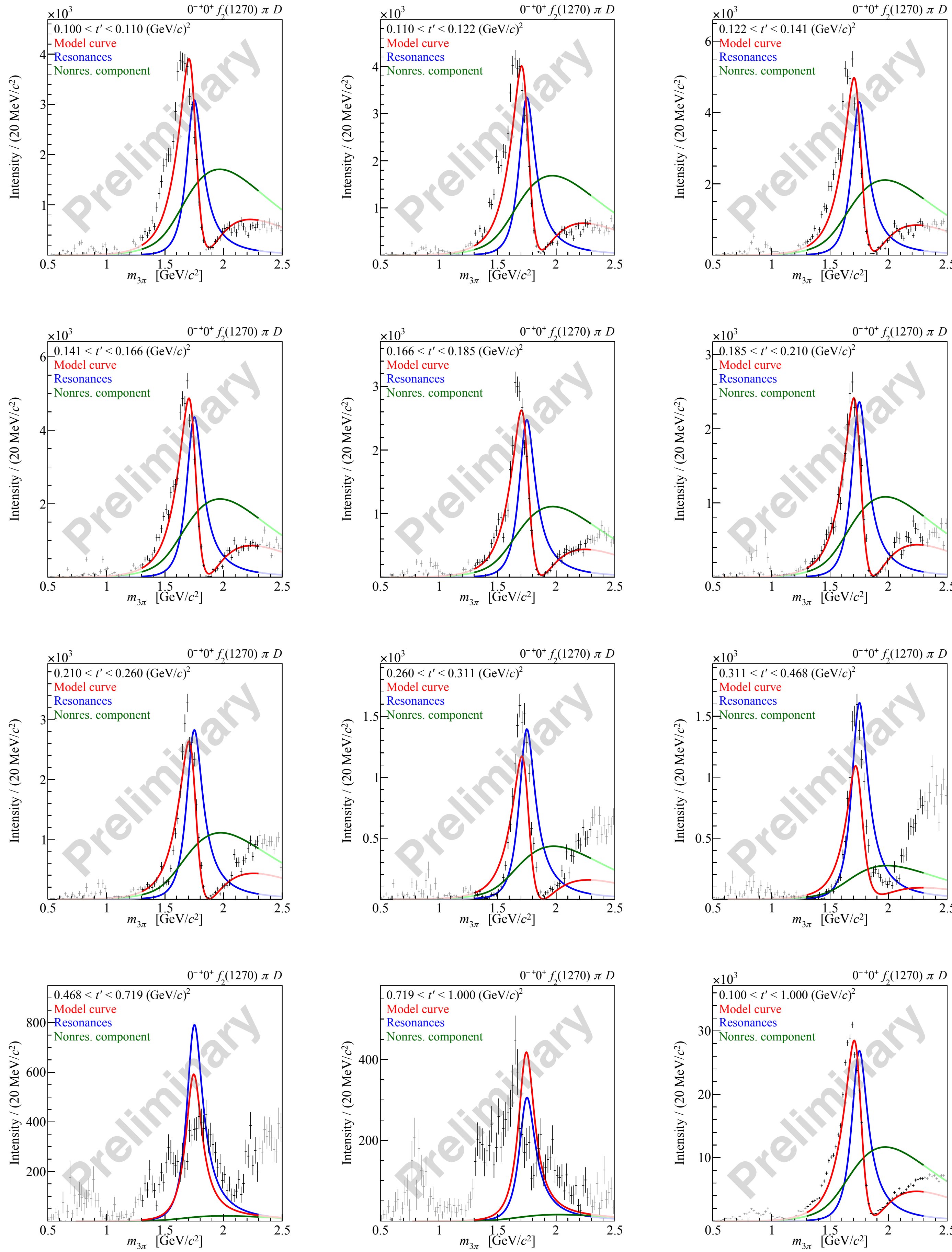
$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008 + 2009)

Model curve

Resonances

Nonres. component

Resonance Model Fit: $l\mathrm{H}_2$ data

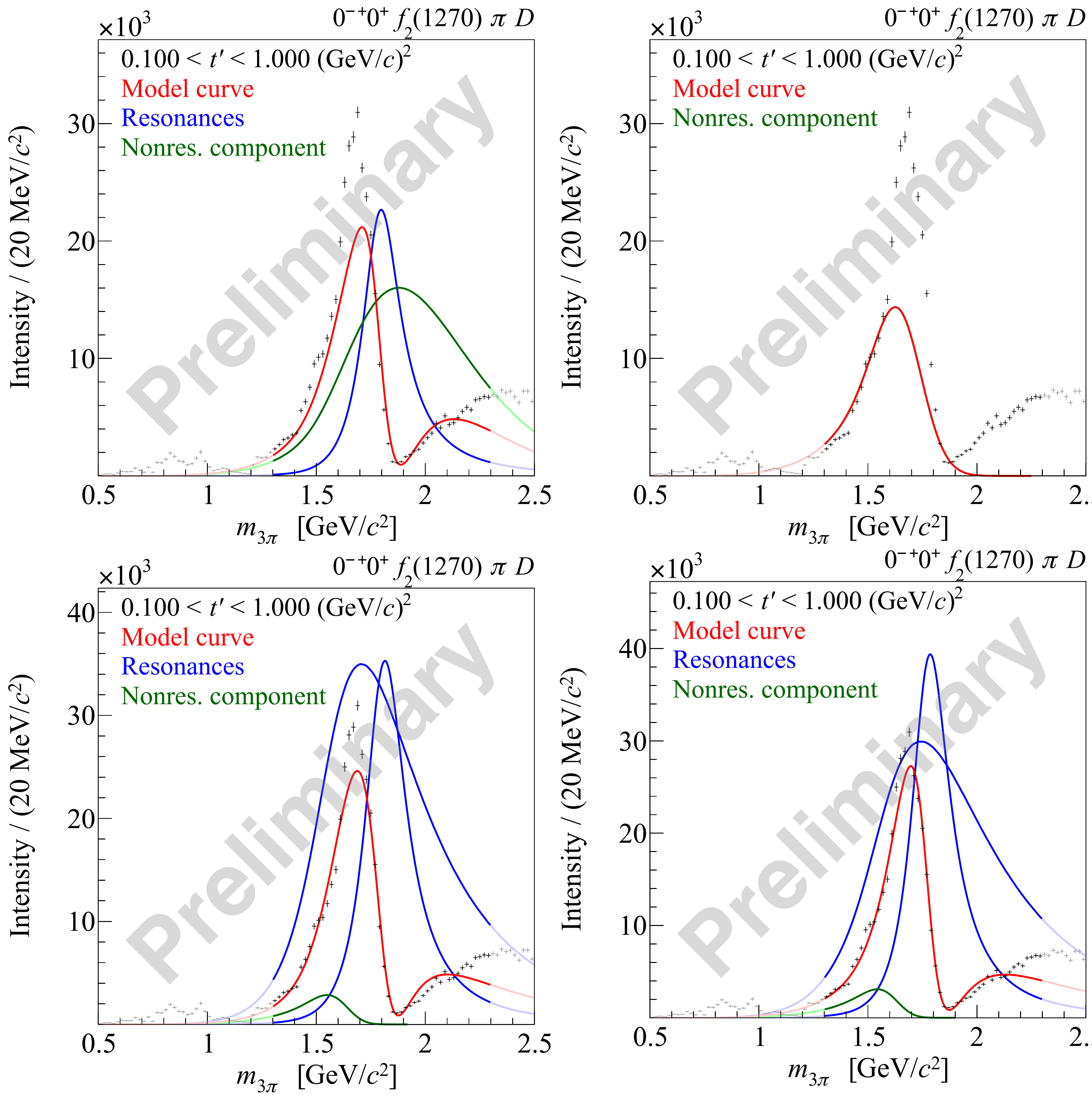


Resonance Model Fit: $l\mathrm{H}_2$ Systematics

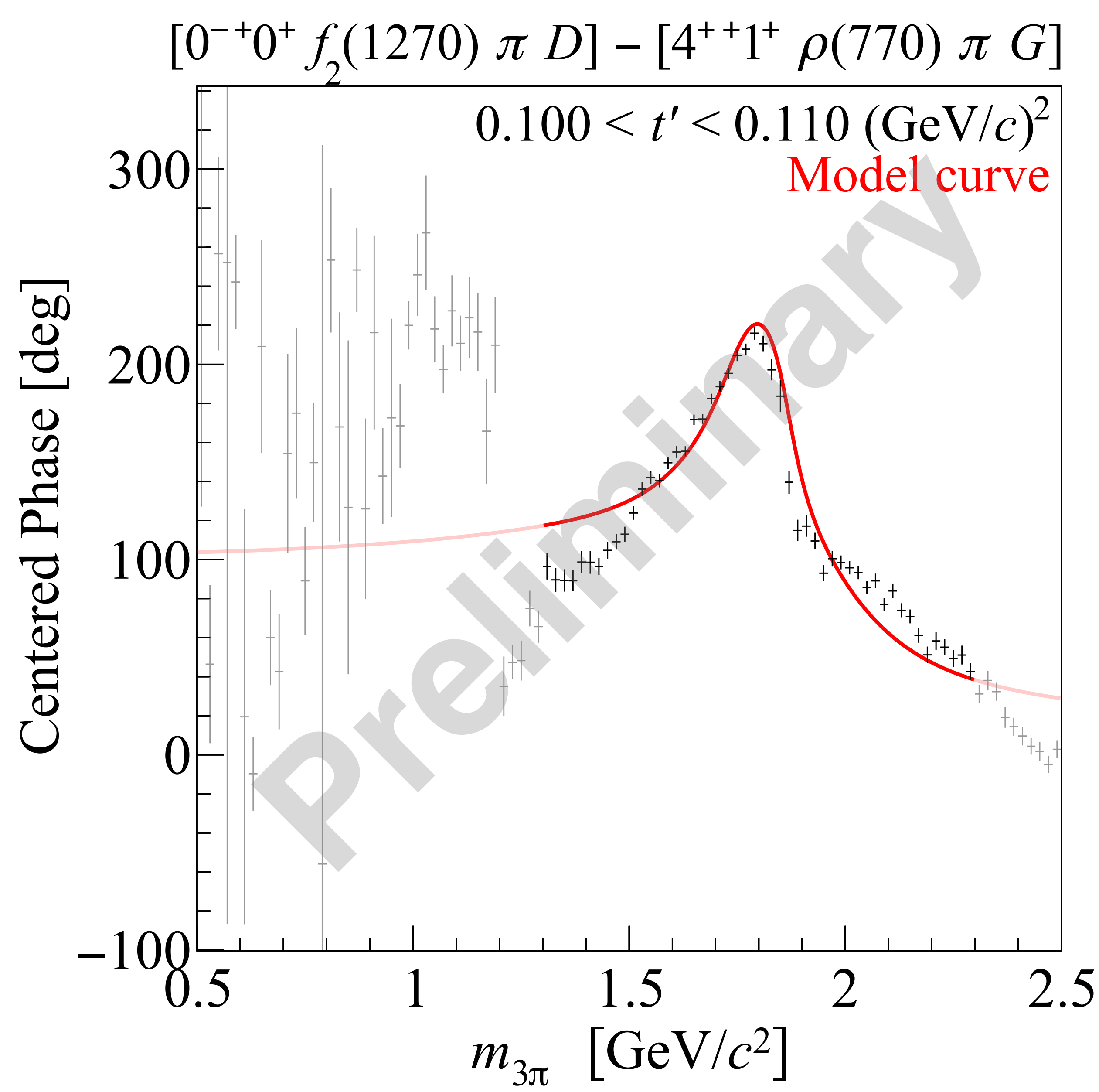
Systematic Studies:

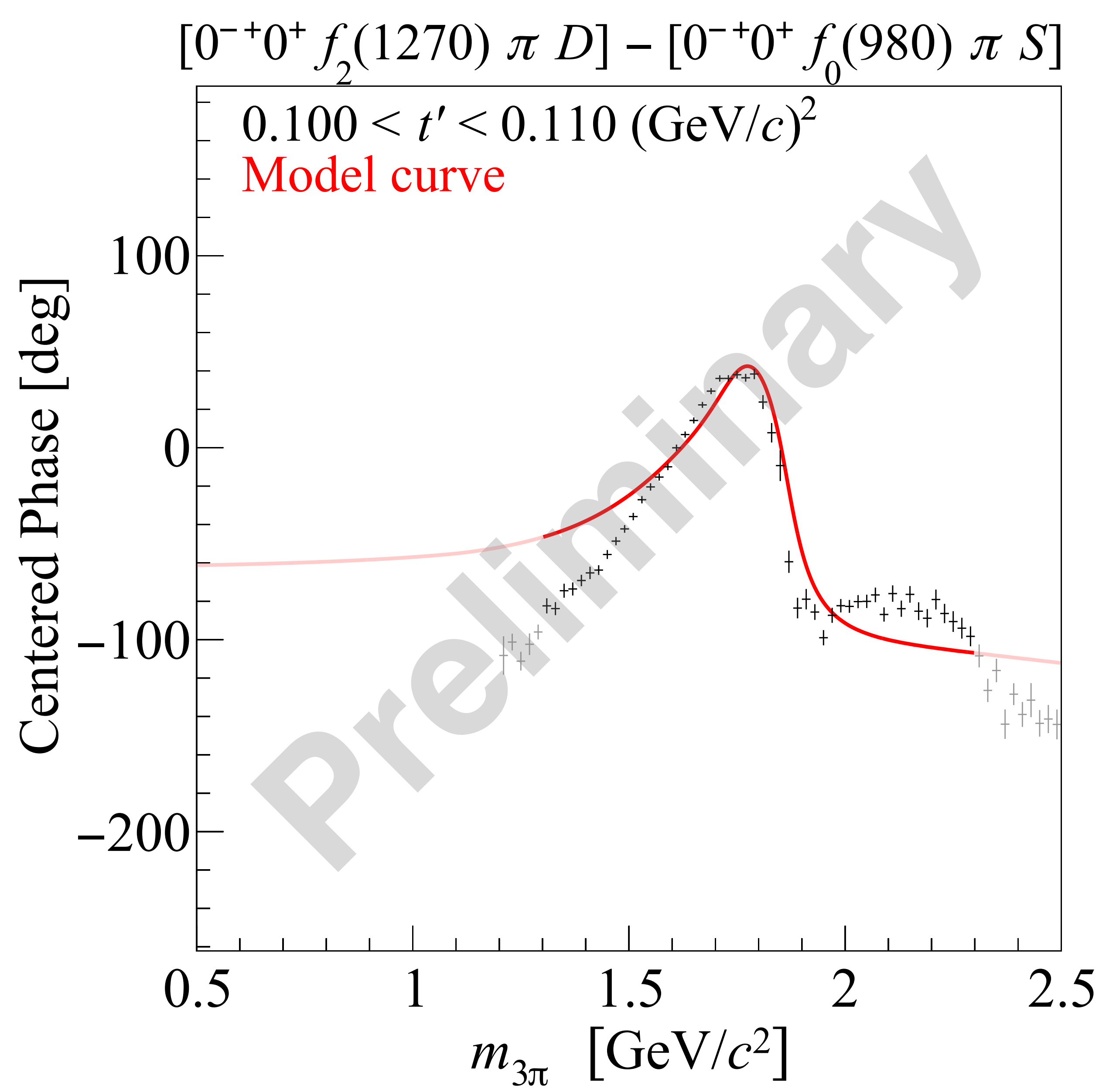
- top left: fit only $\pi(1800)$
  - intensity not well described
- top right: fit only nonresonant:
  - no able to capture the signal at all
- bottom two resonances:
  - left: “$\pi(1700)$” + $\pi(1800)$
  - right: two free resonances
  - one resonance used as background

    → unphysical addition of BW



Resonance Model Fit: $l\mathrm{H}_2$ data



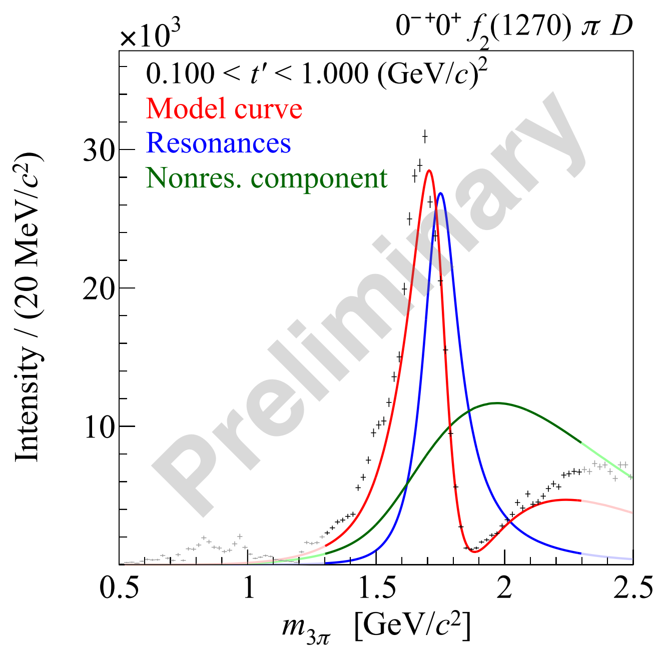


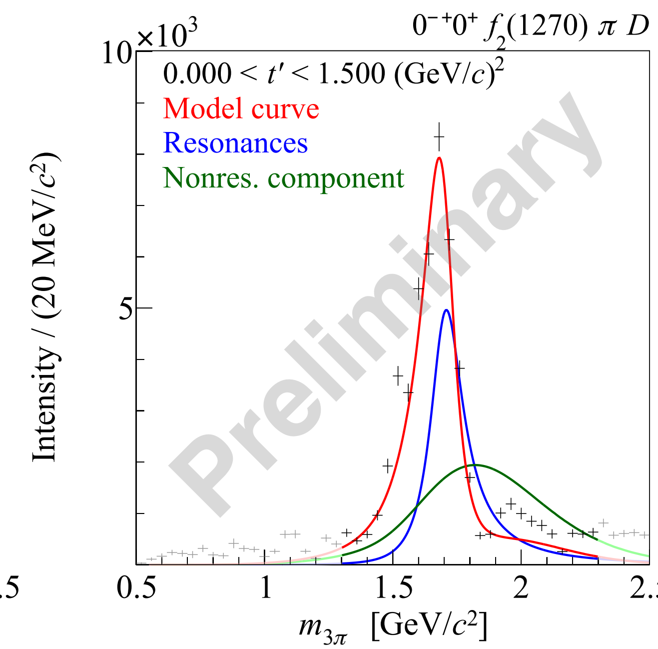
Resonance Model Fit

Both $l\mathrm{H}_2$ and Pb data show a separation of the additional free "$\pi(1700)$" component

Resonance	Mass [MeV/c^2]	Width [MeV/c^2]	Published Mass [MeV/c^2]	Published Width [MeV/c^2]
$\pi(1700)$	1740	171	—	—
$\pi(1800)$	1795	230	1804^{+6}_{-9}	220^{+8}_{-11}
$a_1(1420)$	1414	149	1411^{+4}_{-5}	161^{+11}_{-14}
$a_2(1320)$	1316	115	$1314.5^{+4.0}_{-3.3}$	$106.6^{+3.4}_{-7.0}$
$a_4(1970)$	1939	395	1935^{+11}_{-13}	333^{+16}_{-21}

Resonance	Mass [MeV/c^2]	Width [MeV/c^2]
$\pi(1700)$	1698	157
$\pi(1800)$	1781	221
$a_1(1420)$	1414	166
$a_2(1320)$	1318	102
$a_4(1970)$	1988	322





Pb data stronger separation: different (maybe smaller?) background (t' range)

Published results in: M. Aghasyan et al., [COMPASS Collaboration], "Light isovector resonances in $\pi^- p \to \pi^-\pi^-\pi^+ p$ at 190 GeV/c," Phys. Rev. D 98 (2018) 092003, arXiv:1802.05913 [hep-ex].