Light Exotic Meson Candidates in COMPASS

Bernhard Ketzer

Rheinische Friedrich-Wilhelms-Universität Bonn

for the COMPASS Collaboration

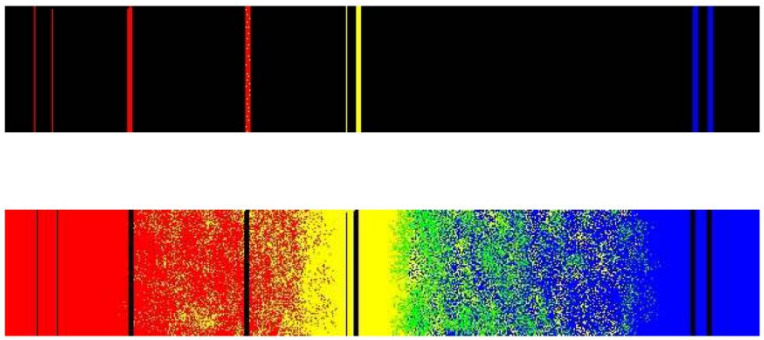
Bundesministerium
für Bildung
und Forschung

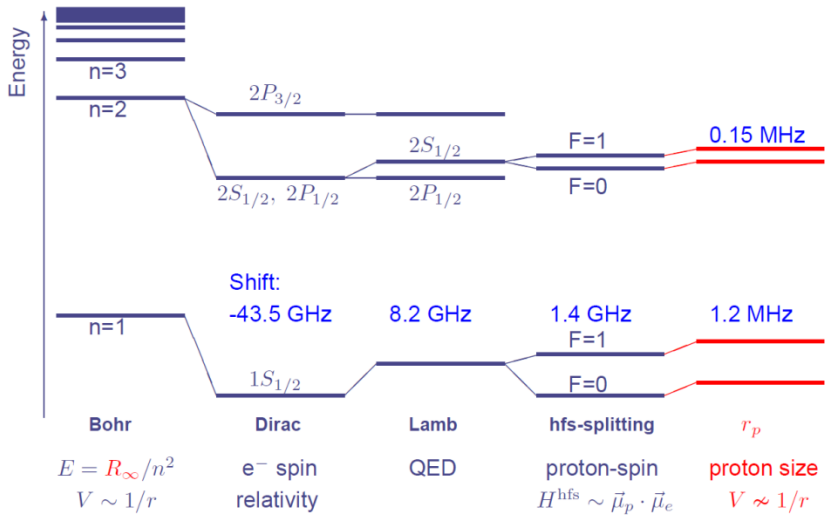
HADRON 2017

29 September 2017

Why Hadron Spectroscopy?

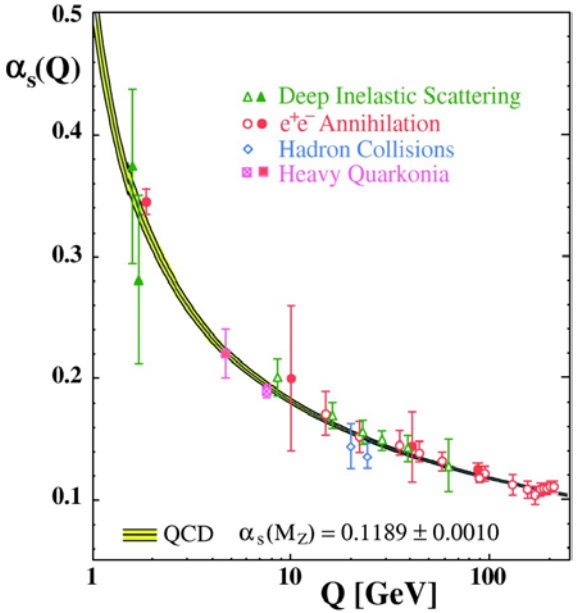
Remember the hydrogen atom…





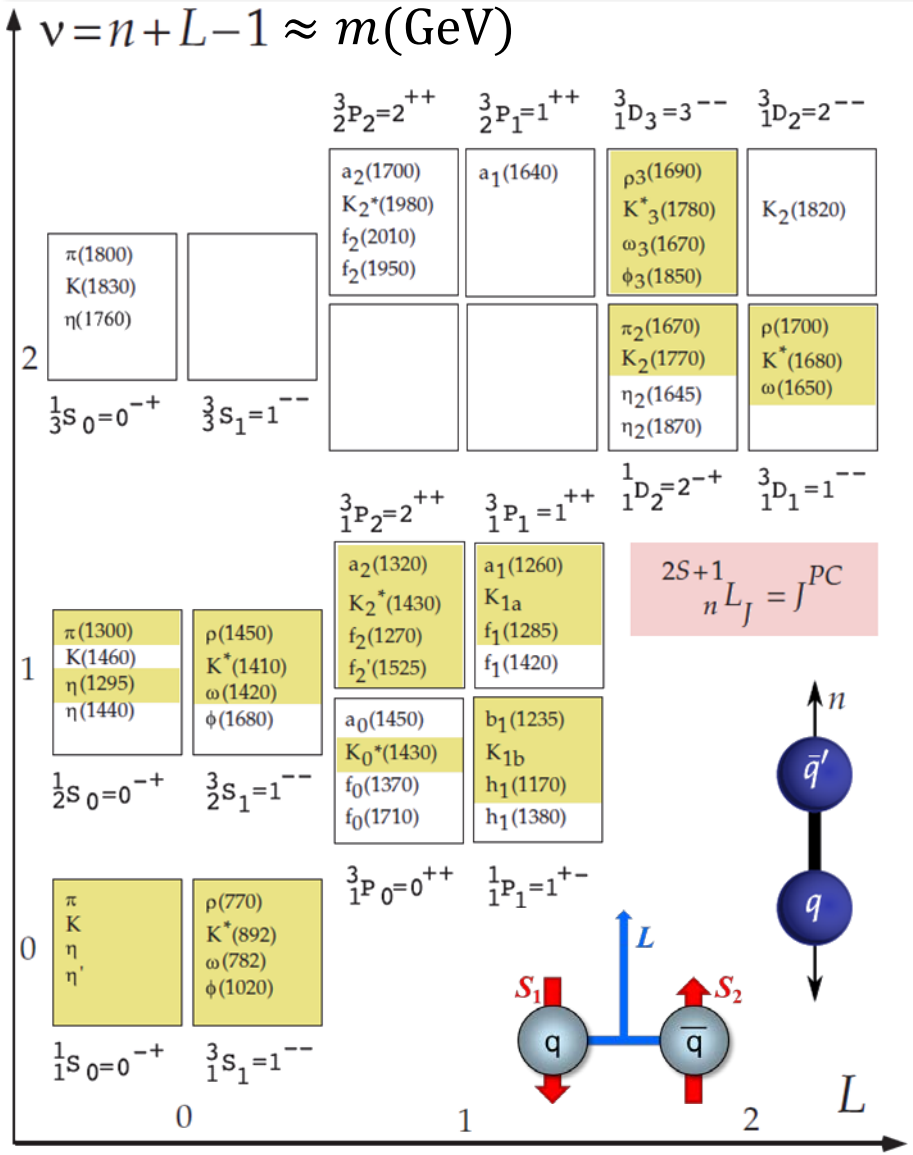
Similarly: study QCD through the excitation spectrum of strong interaction

- Strongly coupled theory
- Models, effective theories, L-QCD
- Which are the correct degrees of freedom?
- What are the effective forces?



[S. Bethke, Progr. Part. Nucl. Phys. 58, 351 (2007)]

Light Meson Spectrum



Quark model:

- $SU(3)_{flavor}$:

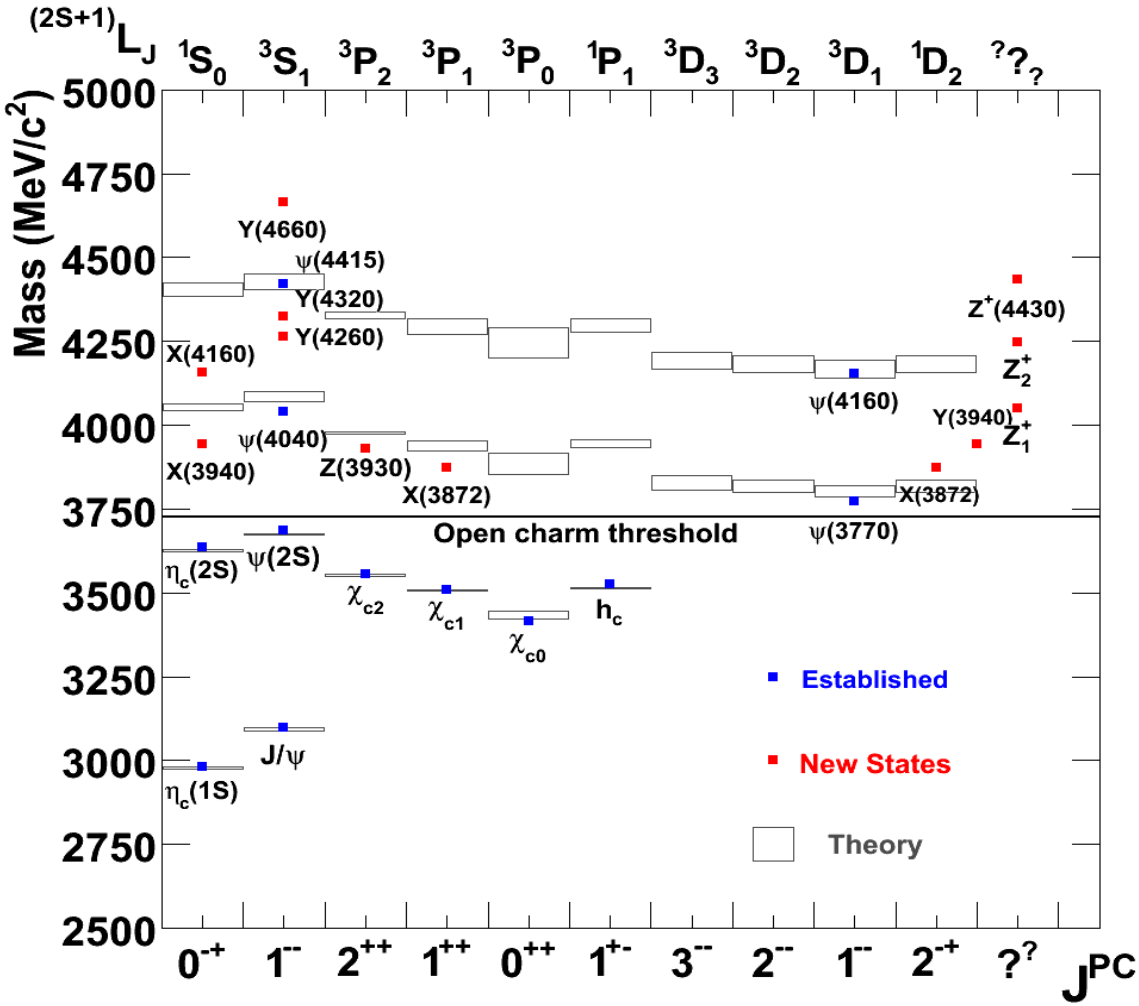
$$q \otimes \bar{q}' = 3 \otimes \bar{3} = 8 \oplus 1$$

- color singlets

- Ground state 0^{-+}, 1^{--} nonets ok
- Many predicted radial and orbital excitations missing / unclear

[Amsler et al., Phys. Rept. 389, 61 (2004)]

Charmonium Spectrum



[V. Santoro, Hadron 2015]

Quark model:

- $SU(3)_{flavor}$:

$$q \otimes \overline{q}' = 3 \otimes \overline{3} = 8 \oplus 1$$

- color singlets

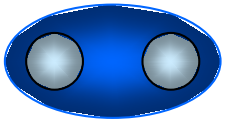
- Many new (narrow) states discovered in recent years
- Assignment not clear
- Some definitively not charmonium-like

[N. Brambilla et al., EPJ C 71, 1534 (2011)]

Beyond the Quark Model

How to identify them?

- Spin-exotic
- Supernumerary states
- Charged QQbar, doubly charged QQ
- Comparison with models, lattice



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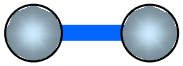


$(q\bar{q})_0$

+

$(q\bar{q})(q\bar{q})$

+ Molecule / 4 quarks

$(q\bar{q})_8\, g$

+ Hybrids

gg

Glueballs

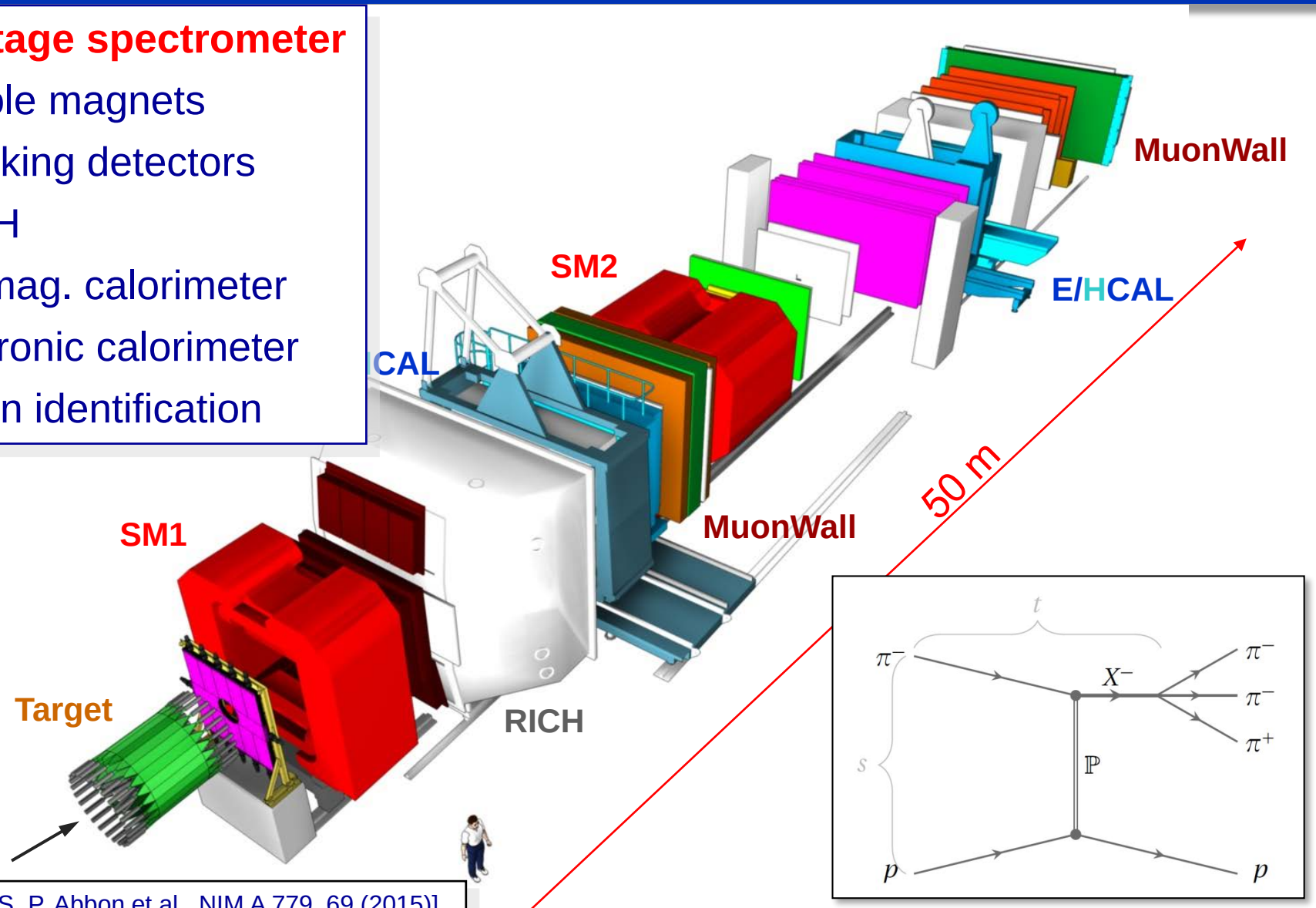
+ ...

The COMPASS Experiment

The COMPASS Experiment

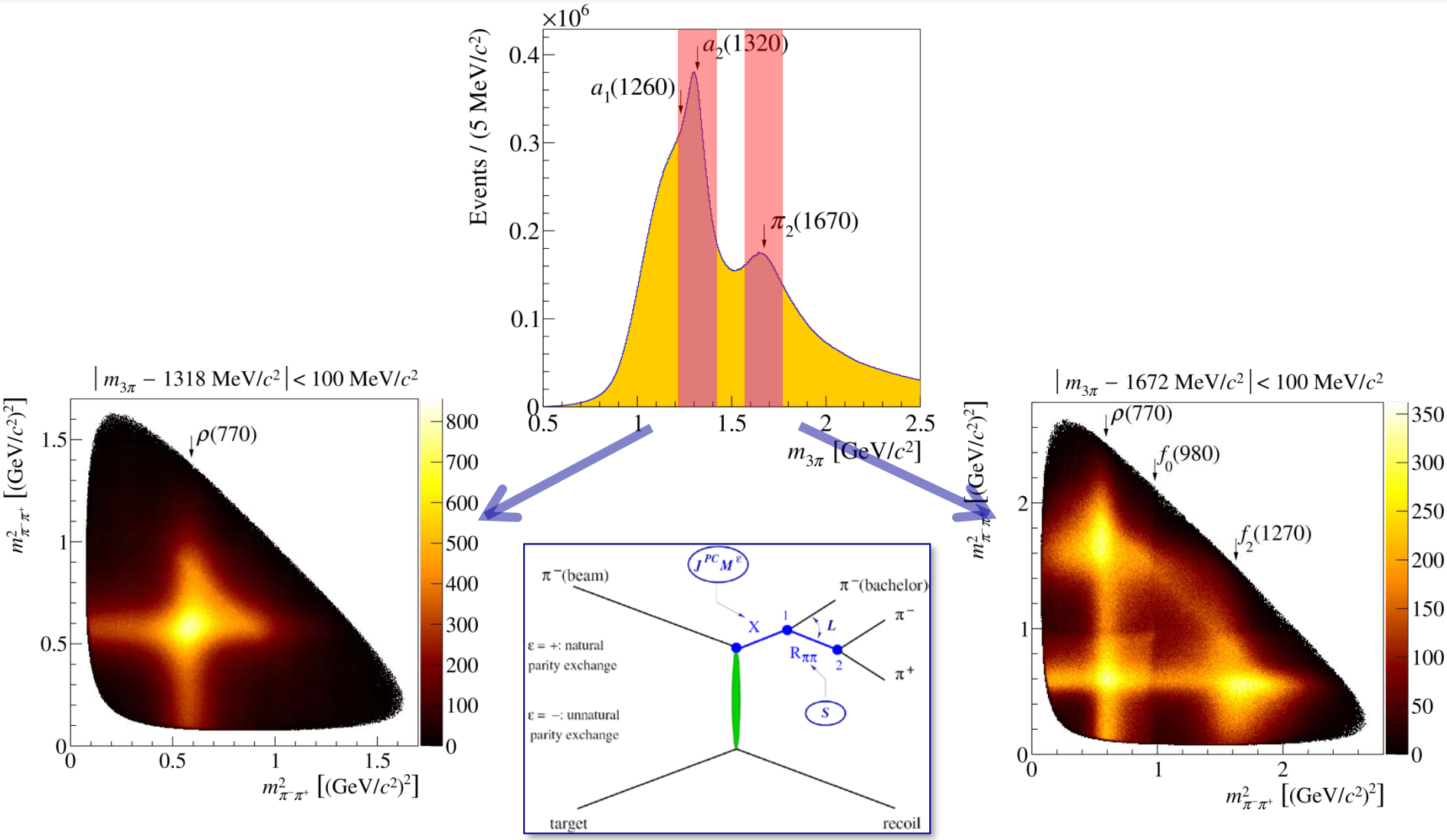
Two-stage spectrometer

- Dipole magnets
- Tracking detectors
- RICH
- El.-mag. calorimeter
- Hadronic calorimeter
- Muon identification



[COMPASS, P. Abbon et al., NIM A 779, 69 (2015)]

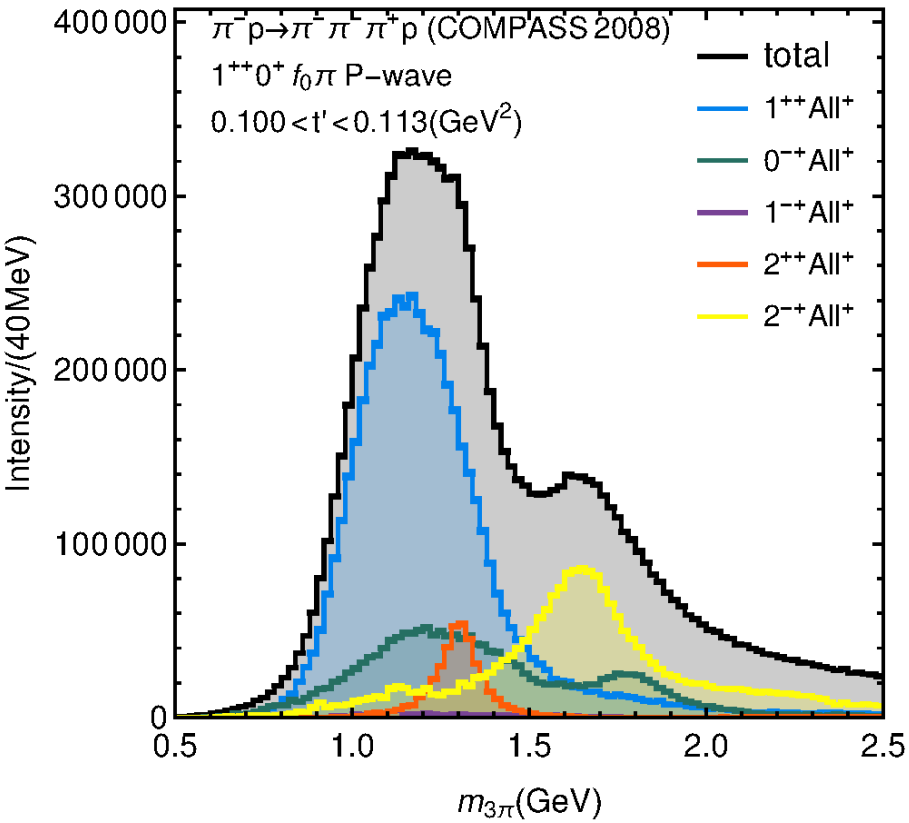
3π Final State



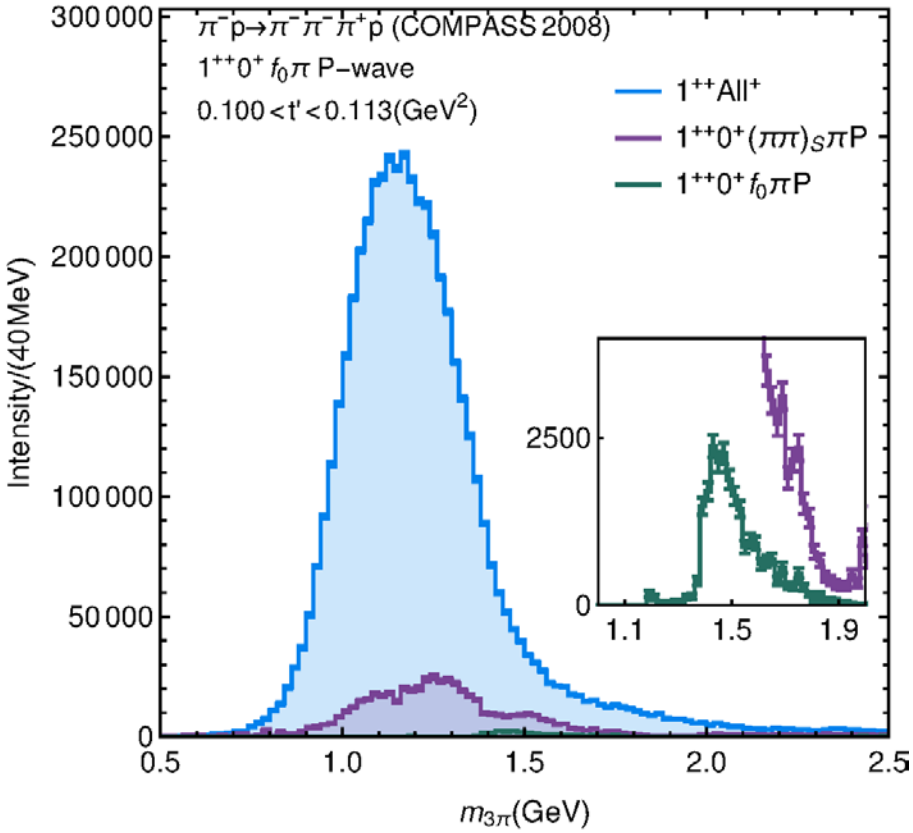
[C. Adolph et al., Phys. Rev. D 95, 032004 (2017)]

Partial-Wave Analysis

Total intensity



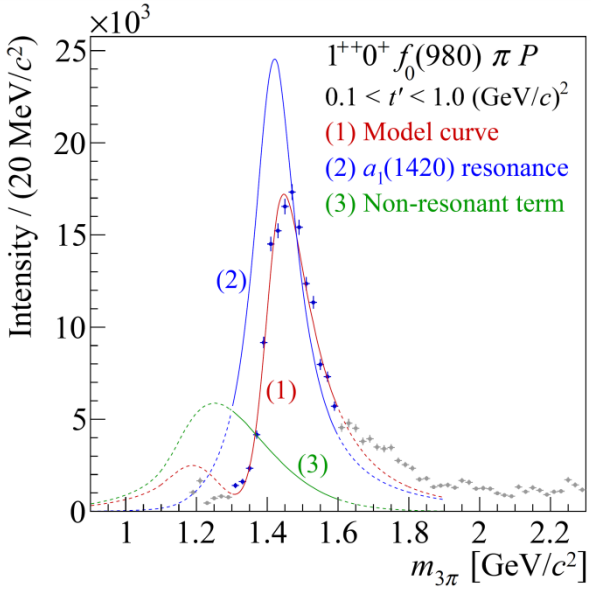
1^{++} Waves

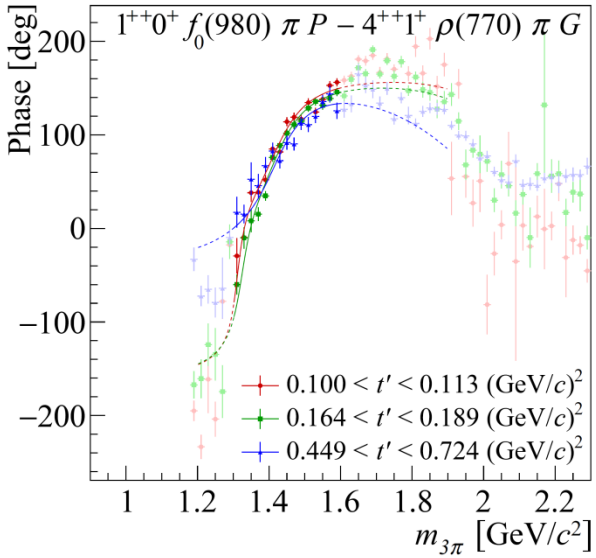


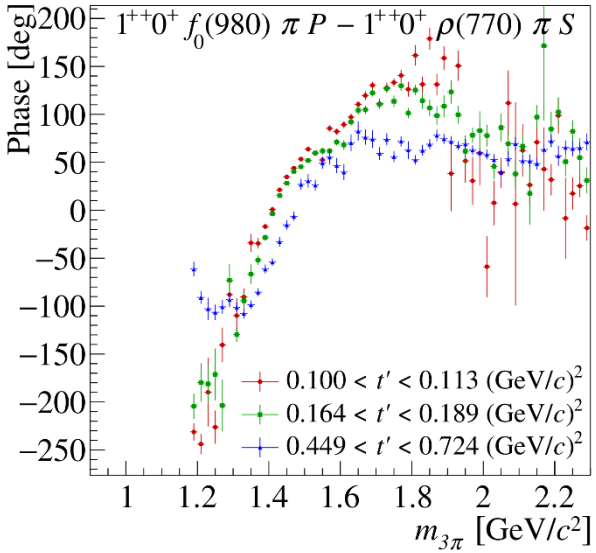
- Largest wave-set to date: 88 waves
- Independent fits in 100 bins (20 MeV) of $m_{3\pi}$ and 11 bins of t'

New $a_1(1420)$

$$\pi^- + p \rightarrow 3\pi + p$$







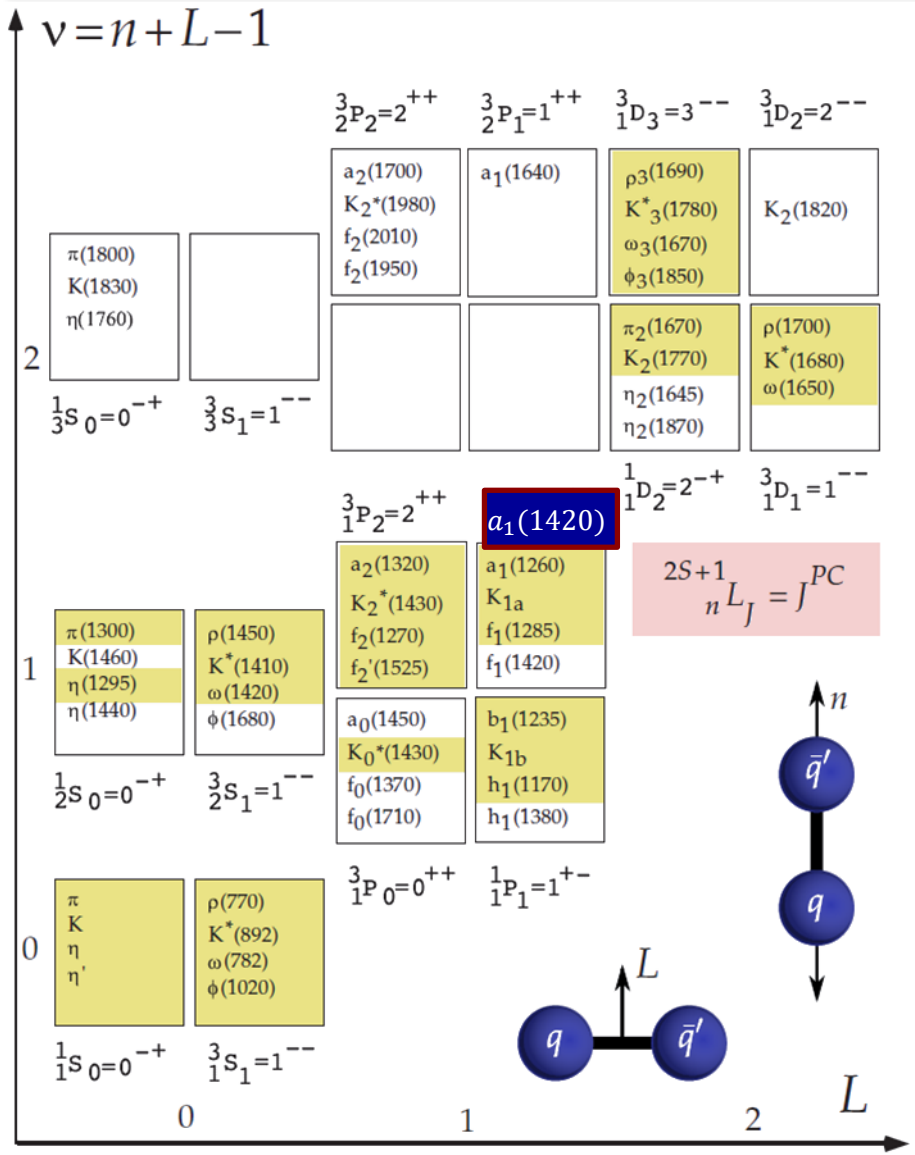
- Data described well by Breit-Wigner and non-resonant background
- Parameters for BW:

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

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

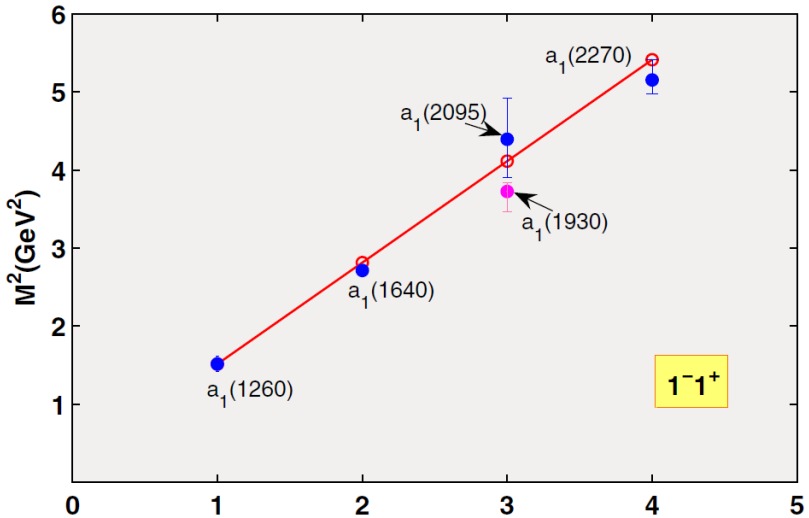
[C. Adolph et al., COMPASS, PRL 115, 082001 (2015)]

New $a_1(1420)$



Issues to be clarified:

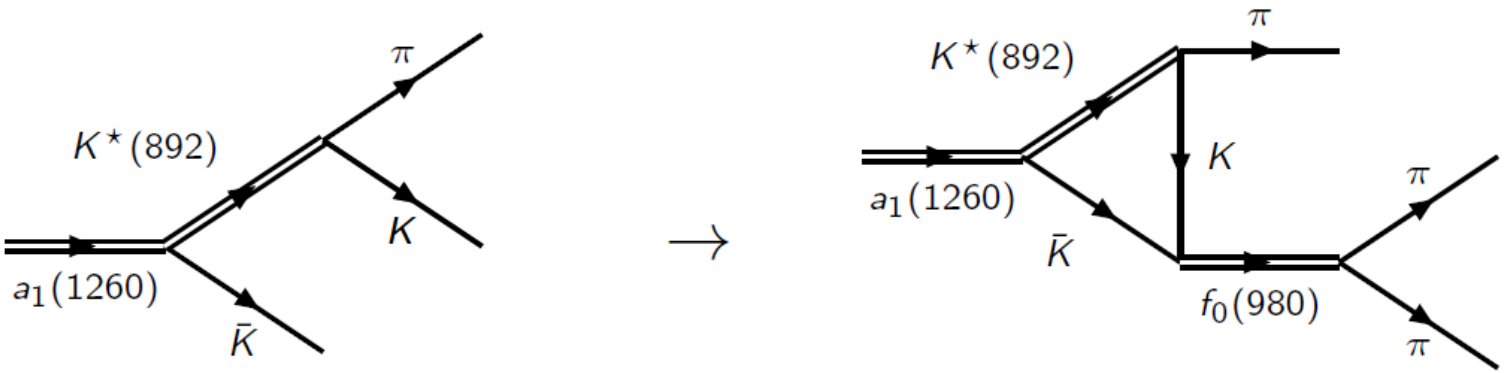
- Does not fit to radial excitation trajectory
- Too close to $a_1(1260)$
- Width narrower than ground state
- Mass very close to $K^*(892)\bar{K}$ threshold $\approx 1.38\ \mathrm{GeV}/c^2$



[Chen et al., PRD 91, 074025 (2015)]

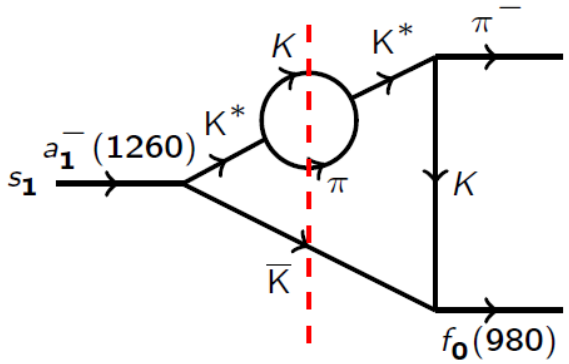
Interpretations

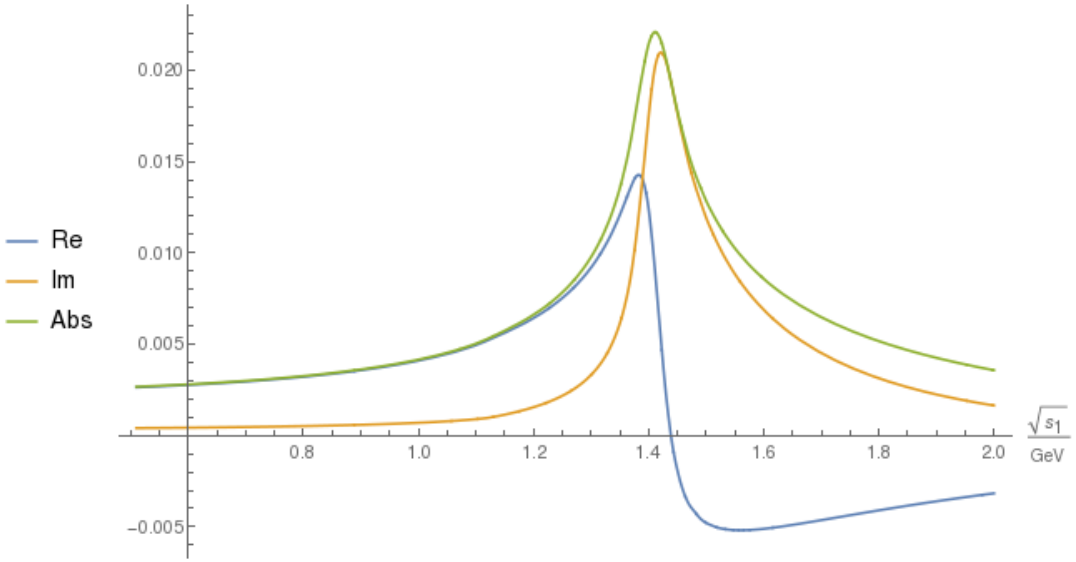
- 4-quark state candidate [Z.-G. Wang, arXiv:1401.1134], [H.-X.Chen, PRD 91, 094022 (2015)]
- $K^*\bar{K}$ molecule (similar to X(3872) interpretation)
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al., PRL 114, 192001 (2015)]
- Triangle singularity [M. Mikhasenko, BK, A.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



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

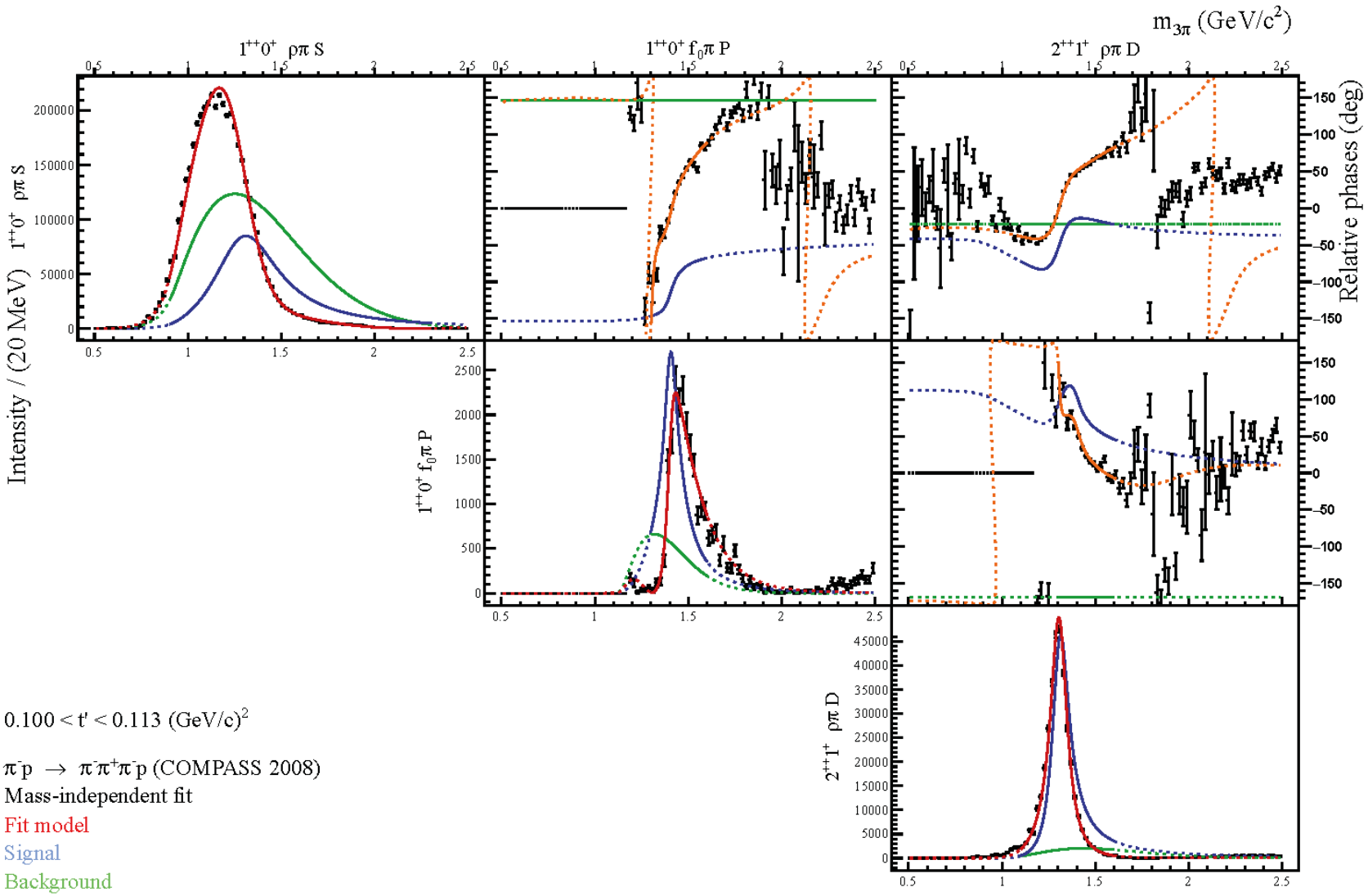
Triangle Amplitude





- Similar shape as Breit-Wigner
- No free parameters
- Intensity estimated to be ~1% of $a_1(1260)$
- Confirmed by [Acet et al., Phys.Rev. D94, 096015 (2016)]

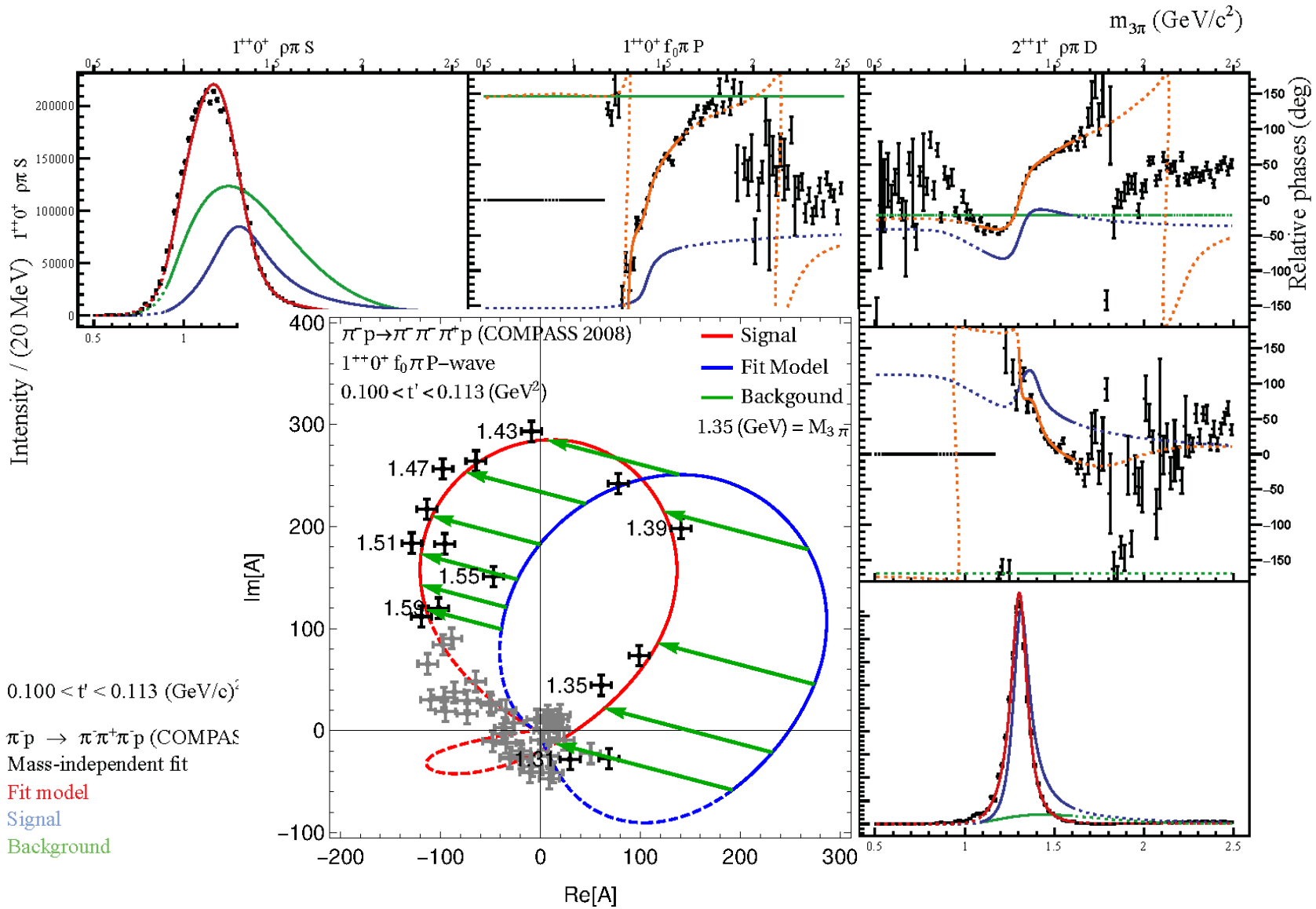
Fit of Triangle Amplitude



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

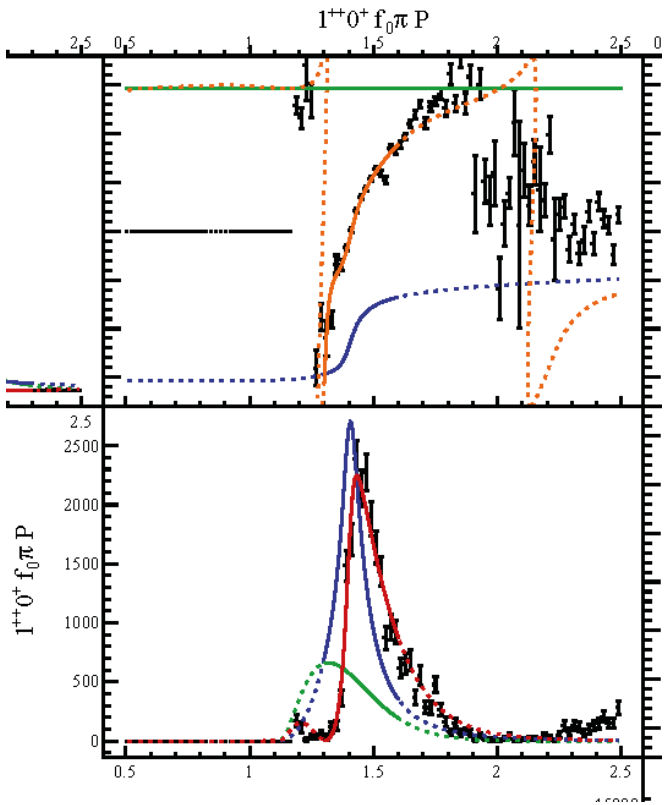
$\pi^- p \rightarrow \pi^-\pi^+\pi^- p$ (COMPASS 2008)
Mass-independent fit
Fit model
Signal
Background

Fit of Triangle Amplitude

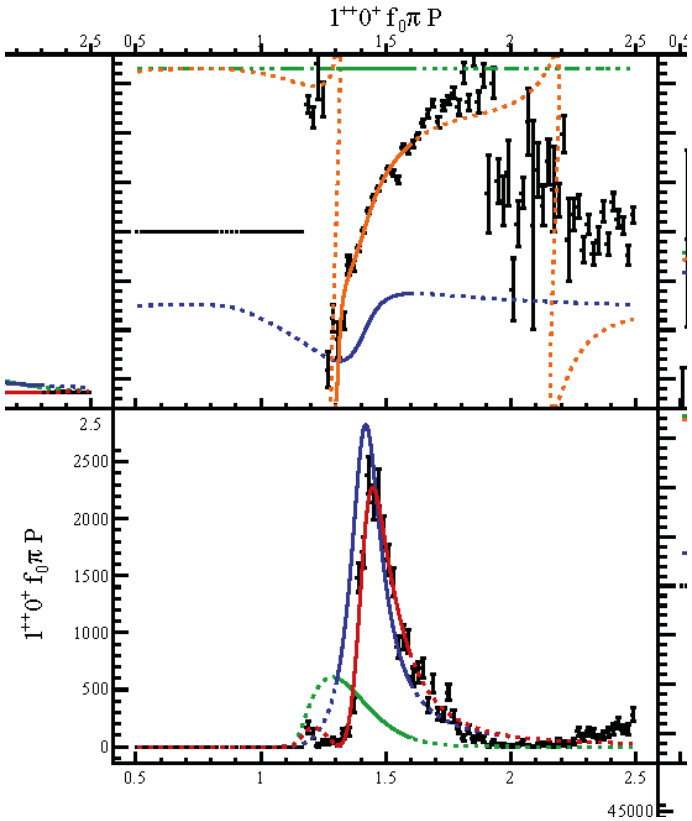


Comparison TA - BW

Triangle Amplitude



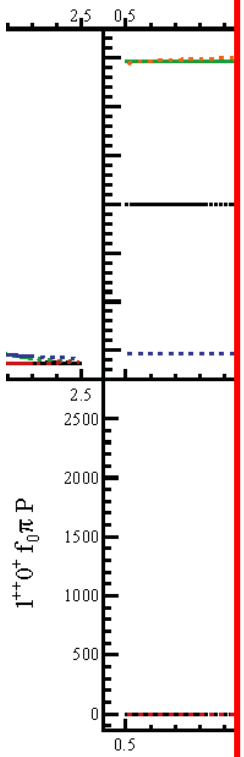
Breit-Wigner



- Equal χ^2_{red} for both fits
- No new free parameters for $a_1(1420)$ signal by triangle mechanism

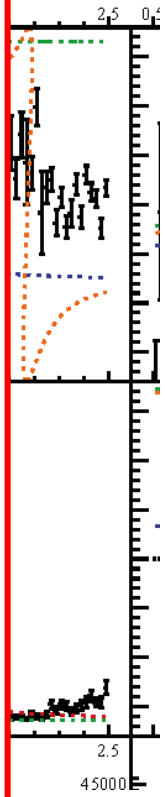
Comparison TA - BW

Triangle Amplitude **Breit-Wigner**



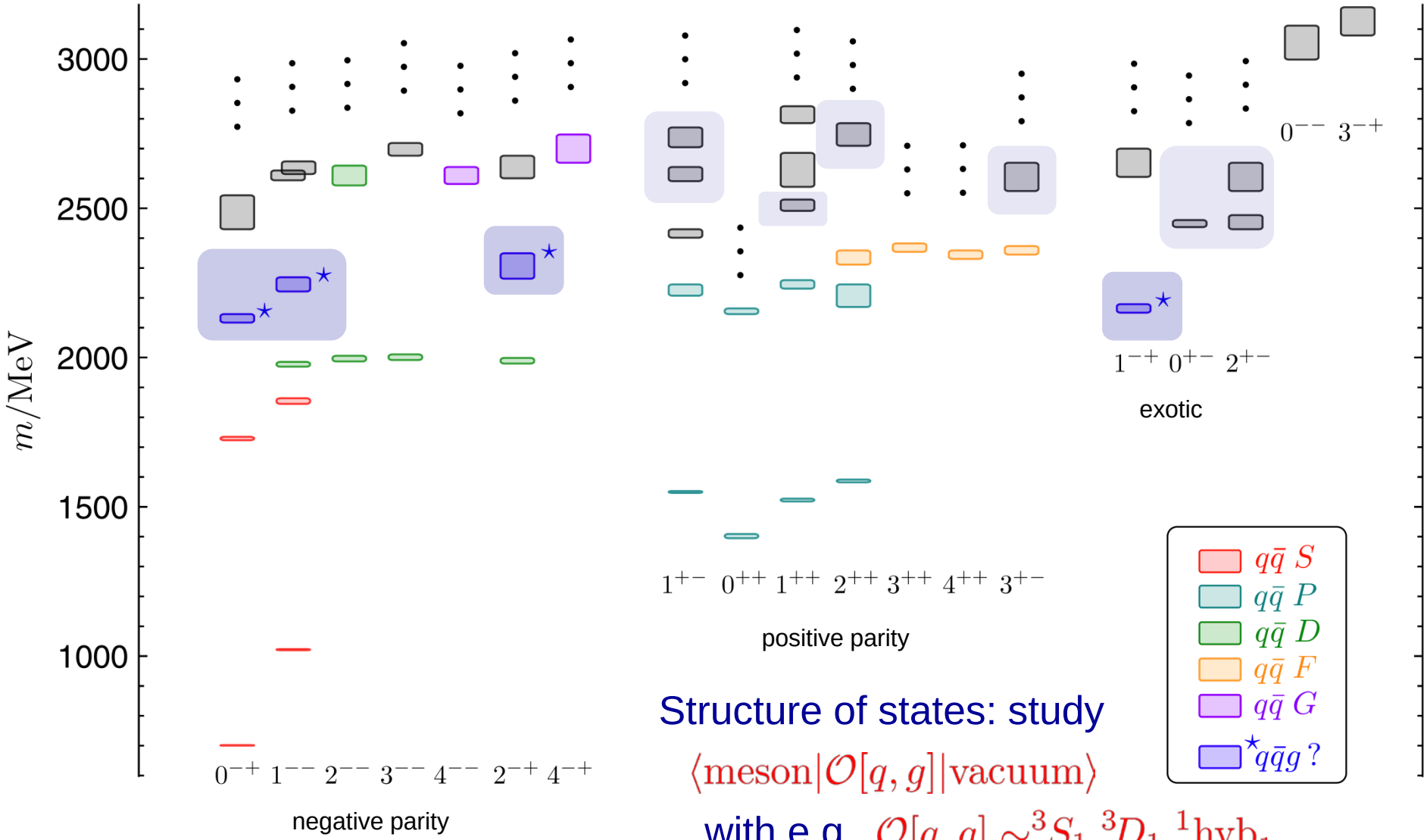
Summary for $a_1(1420)$

- Peak and phase motion are not unique sign of a resonance!
- $a_1(1420)$ signal can be described solely with $a_1(1260)$ as source and rescattering via triangle diagram
- Old theoretical concept, now data allow to clearly observe this for the first time!
- Intensity of signal ~1%, in agreement with experiment
- Cannot completely exclude additional pole due to $K^*\overline{K}$ resonance



- Equal χ^2_{red} for both fits
- No new free parameters for $a_1(1420)$ signal by triangle mechanism

Hybrids: Lattice QCD



Structure of states: study

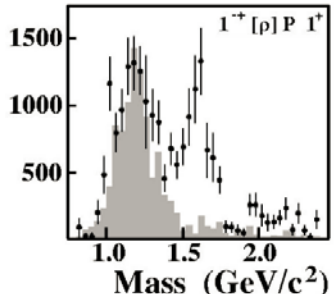
$\langle \mathrm{meson} | \mathcal{O}[q,g] | \mathrm{vacuum} \rangle$

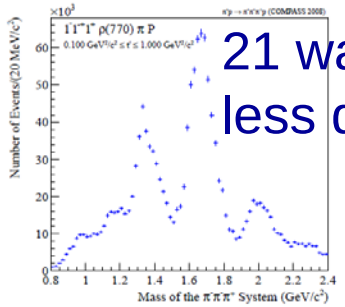
with e.g. $\mathcal{O}[q,g] \sim {}^3S_1, {}^3D_1, {}^1\mathrm{hyb}_1$

[J. Dudek, Phys. Rev. D 84, 074023 (2011)]

[J. Dudek et al., Hadron Spectrum Collaboration, Phys. Rev. D 82, 034508 (2010)]

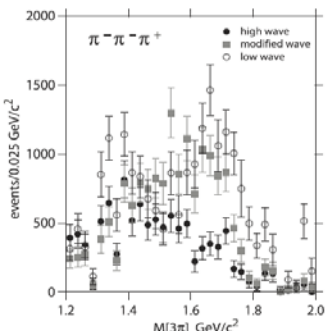
1^{-+} Partial Wave

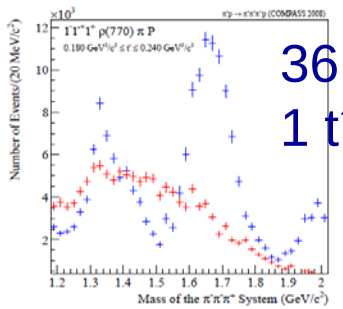




21 waves
less data

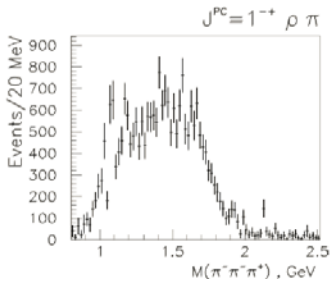
[BNL E852, Adams et al., Phys. Rev. Lett. 81, 5760 (1998)]

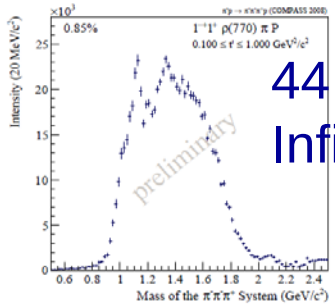




36 waves
1 t´bin

[BNL E852, Dzierba et al., Phys. Rev. D 73, 072001 (2006)]

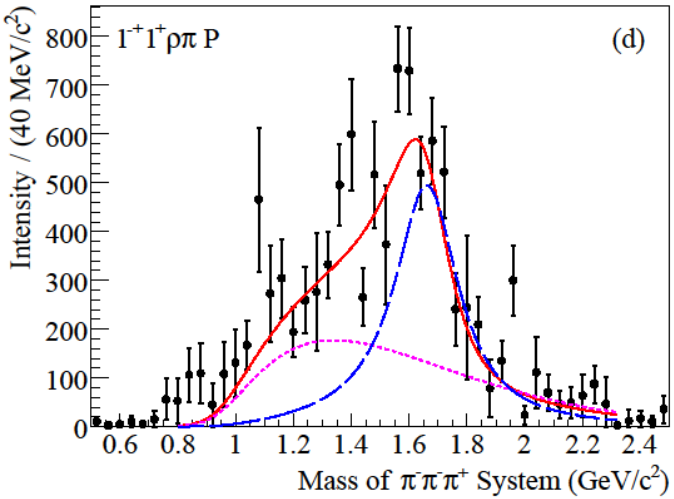




44 waves
Infinite rank

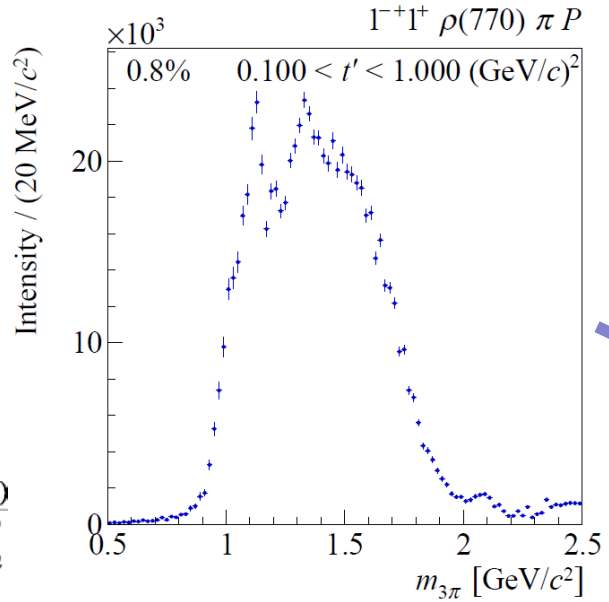
[VES, Zaitsev, Nucl.Phys. 830 A675, 155C (2000)]

- Previous analyses seemingly inconsistent
- COMPASS: 10 × more data
- Results can be reproduced using (limited) wave sets and *t´* ranges
- 1st (re-)observation in p Pb in COMPASS



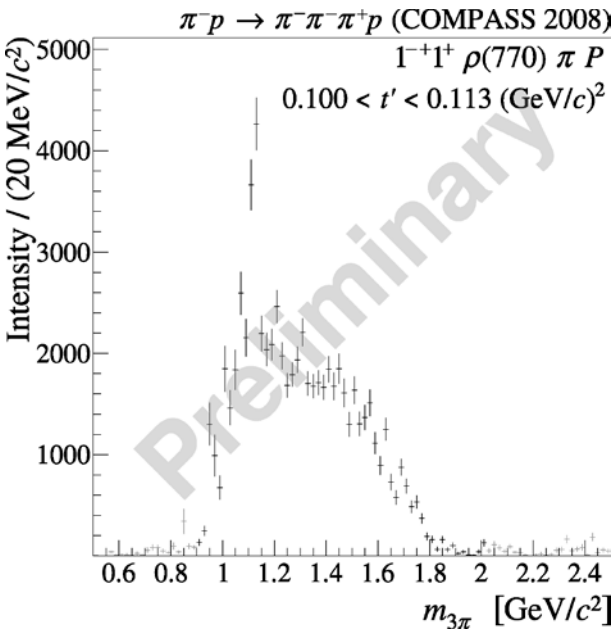
[Alekseev et al., Phys. Rev. Lett. 104, 241803 (2010)]

1^{-+} Partial Wave

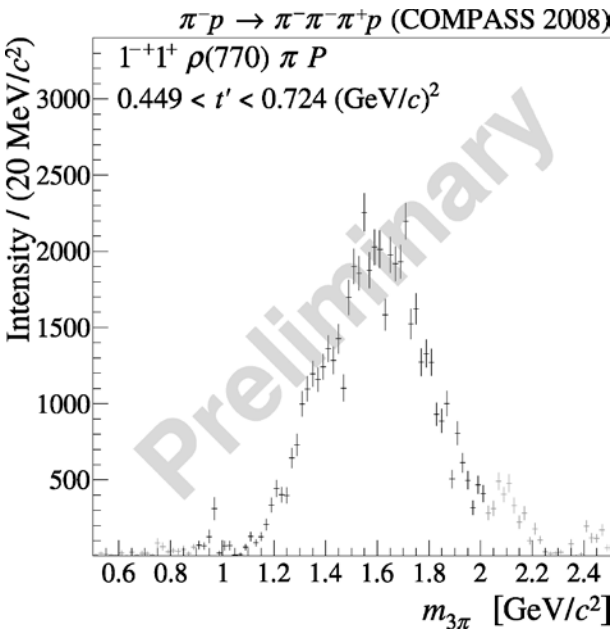


low t'

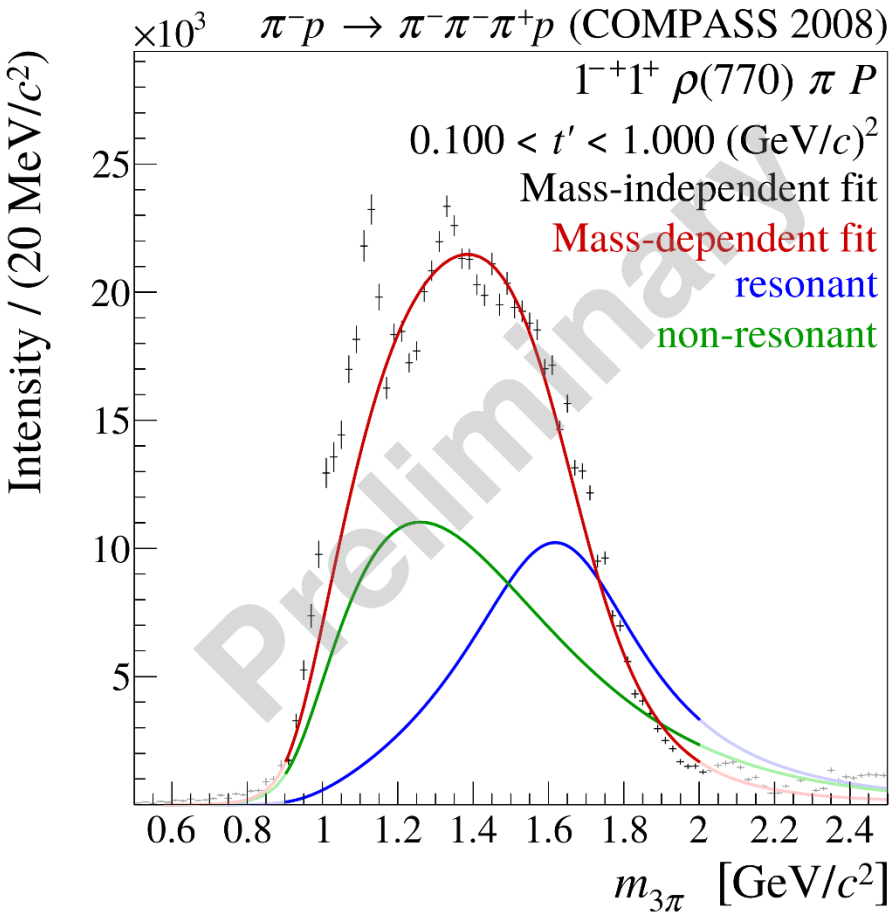
high t'

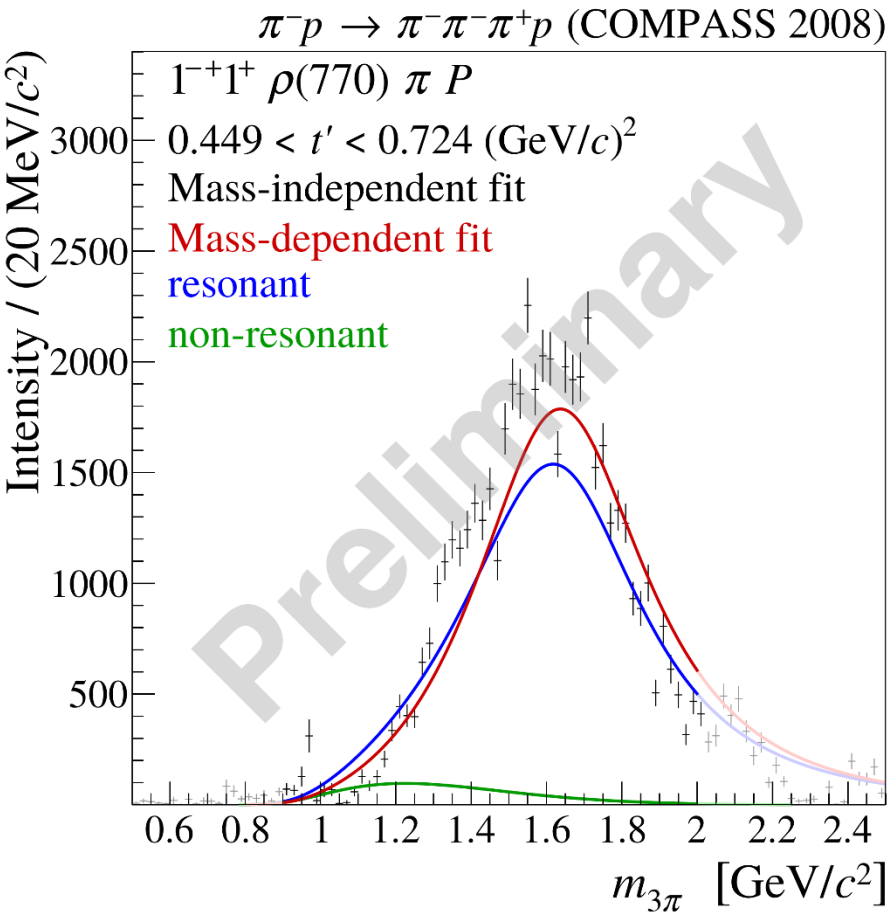


- Broad intensity distribution
- Strong evolution with t'



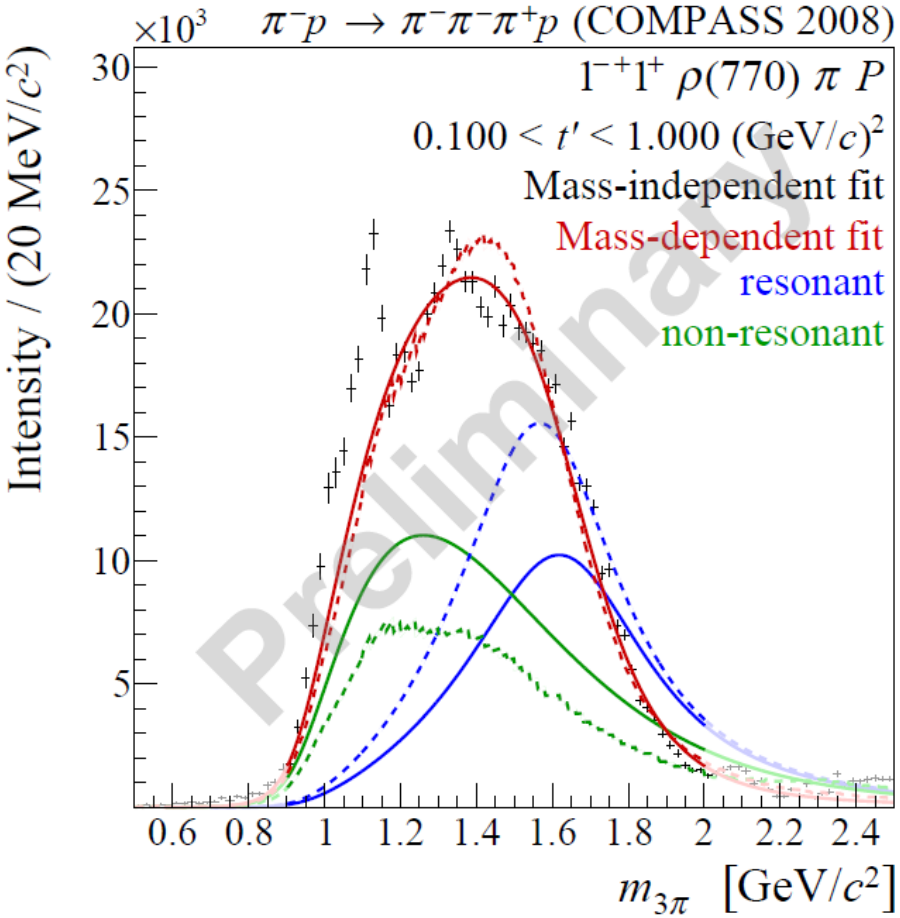
1^{-+} Partial Wave

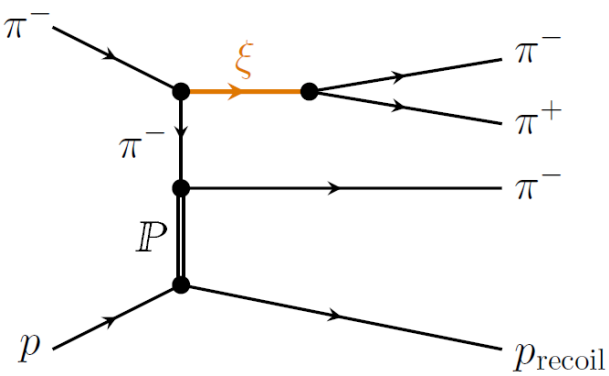




- Resonance-model fit to spin-density matrix: 14 waves
- Exploit t' dependence to separate resonant and non-resonant contributions

1^{-+} Partial Wave



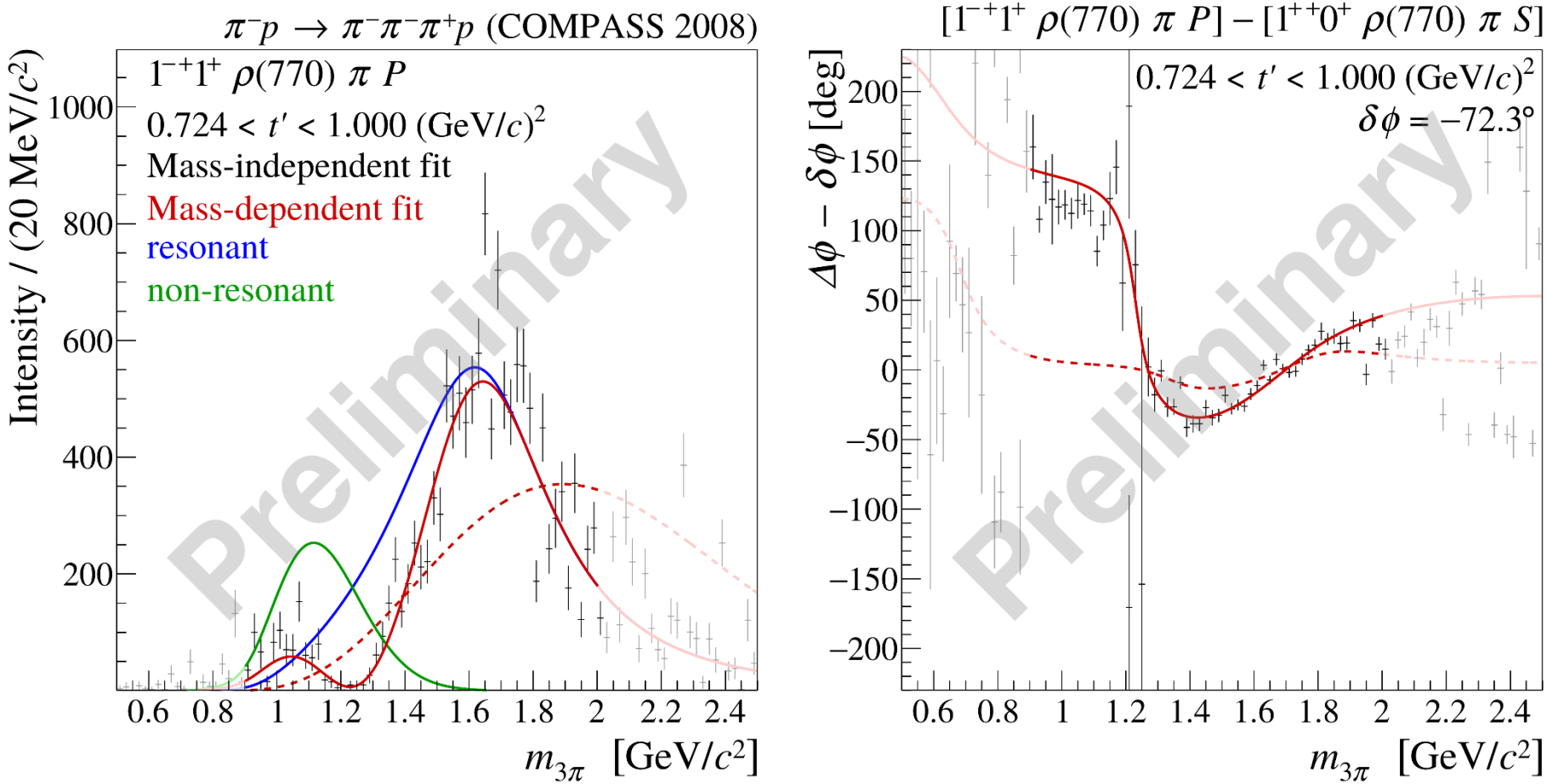


- Background shape in agreement with Deck-model studies
- Resonance parameters for $\pi_1(1600)$

$$M_0 = 1600^{+100}_{-50}\ \mathrm{MeV}/c^2$$

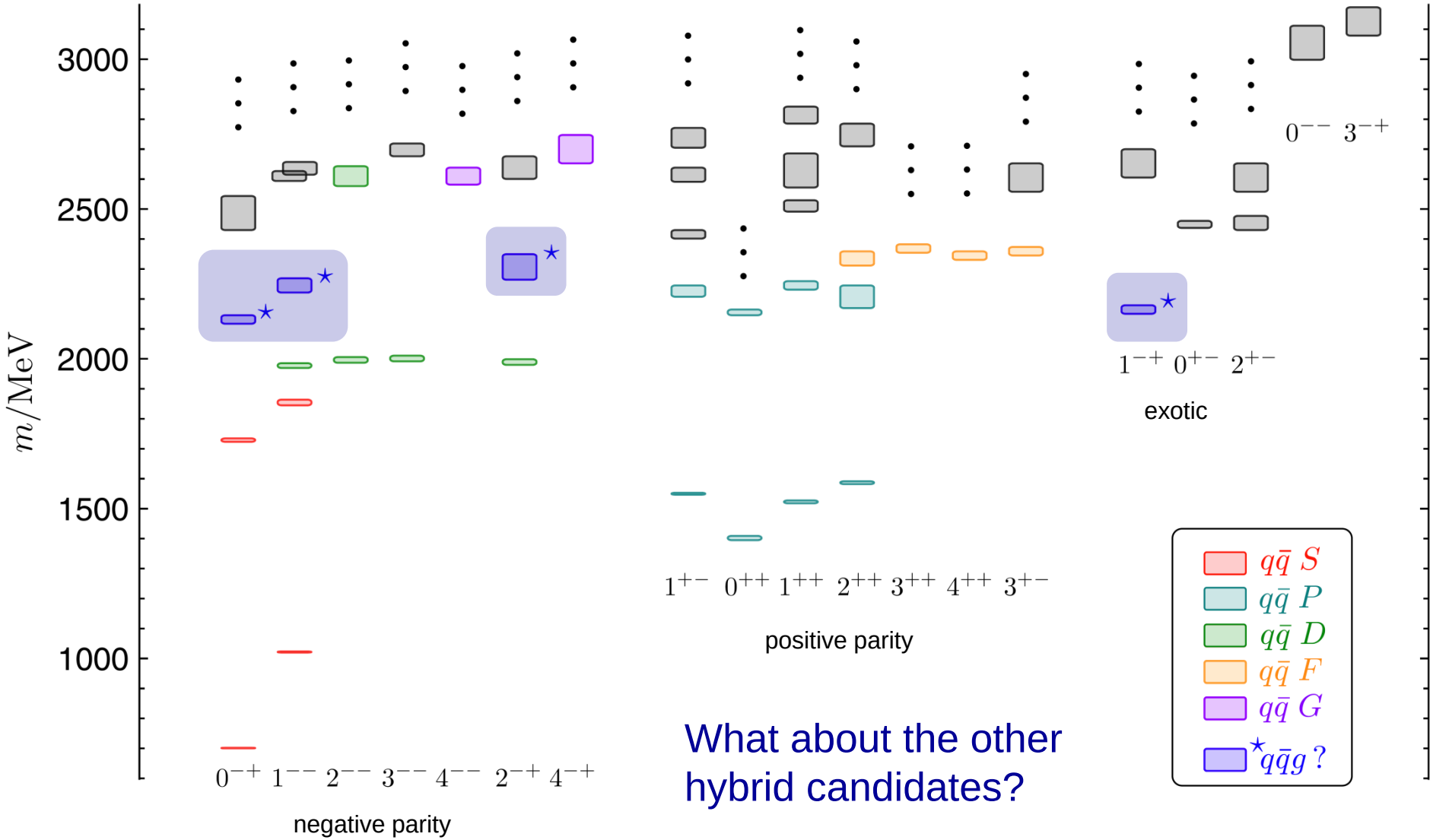
$$\Gamma_0 = 610^{+70}_{-240}\ \mathrm{MeV}/c^2$$

1^{-+} Partial Wave



Bad description of data without resonance component

Lattice QCD

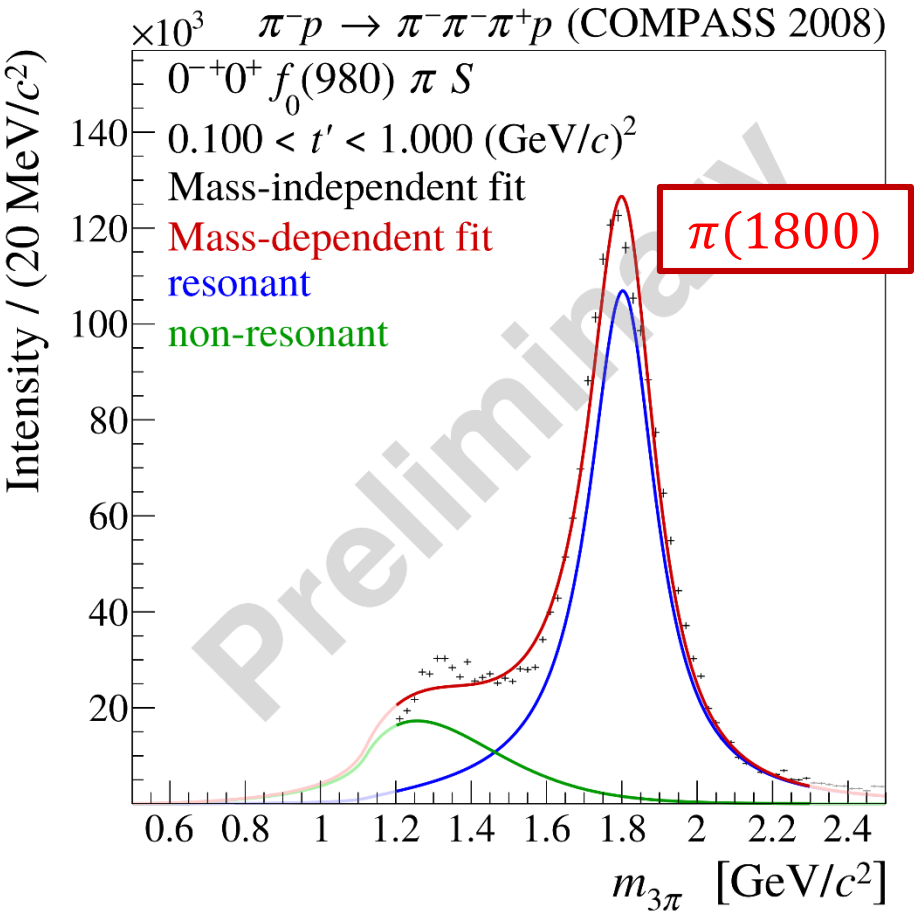


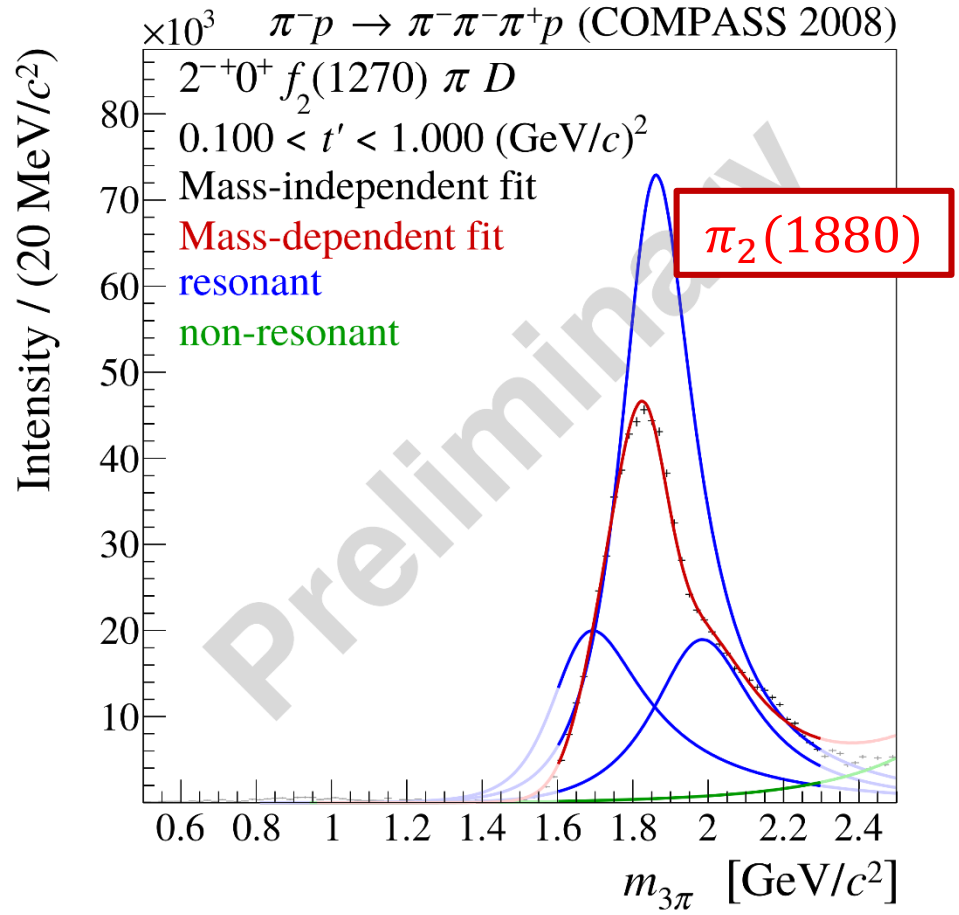
What about the other hybrid candidates?

[J. Dudek, Phys. Rev. D 84, 074023 (2011)]

[J. Dudek et al., Hadron Spectrum Collaboration, Phys. Rev. D 82, 034508 (2010)]

Other Hybrid Candidates





$M_0 = 1802^{+8.0}_{-3.5}\ \mathrm{MeV}/c^2$

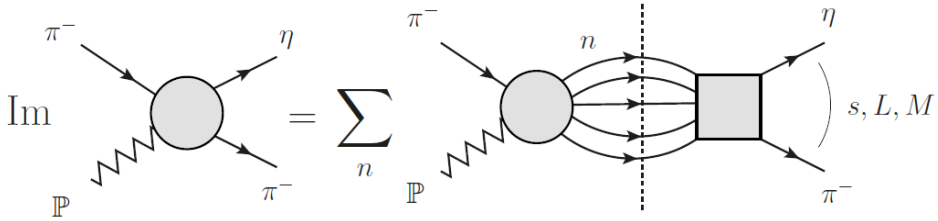
$\Gamma_0 = 218^{+11}_{-6}\ \mathrm{MeV}/c^2$

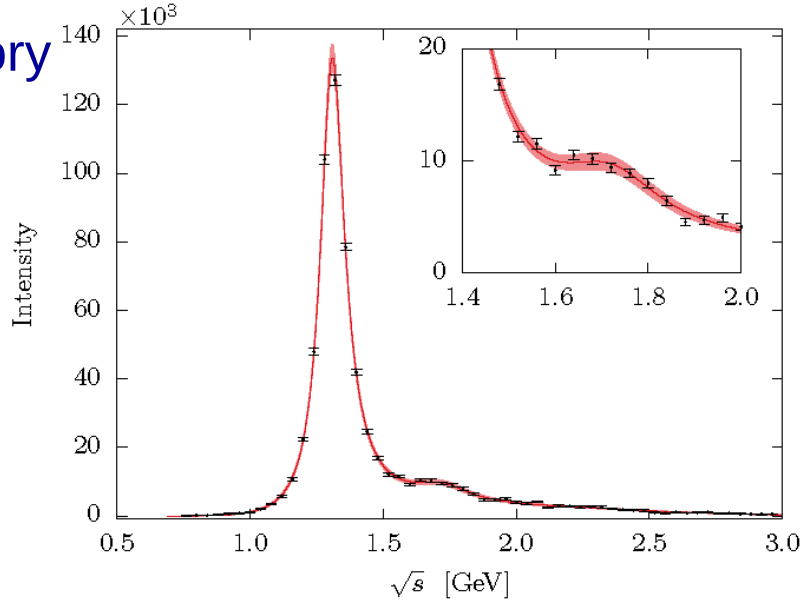
$M_0 = 1847^{+14}_{-6}\ \mathrm{MeV}/c^2$

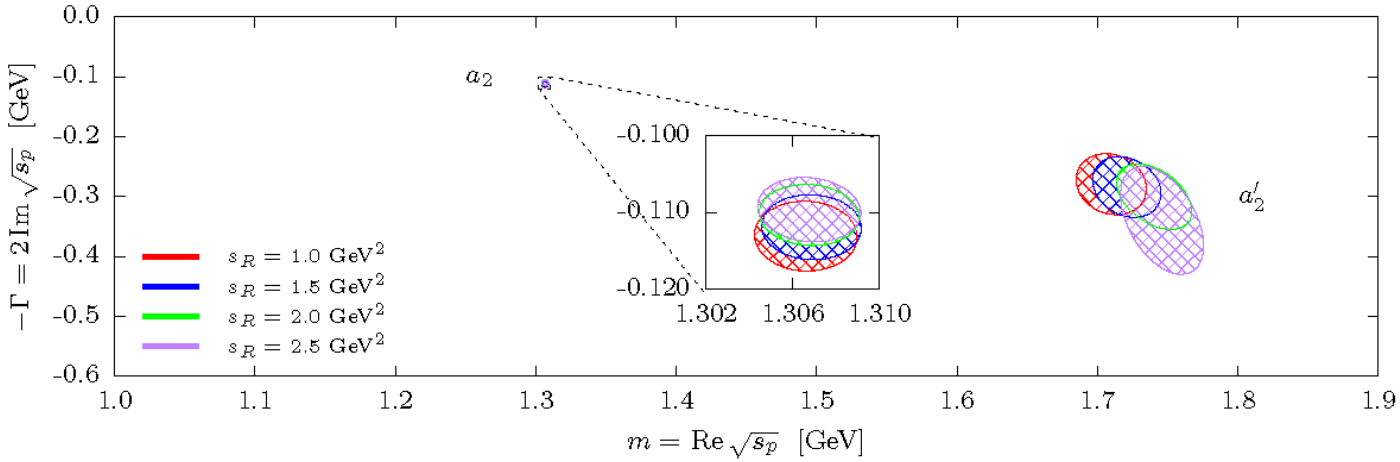
$\Gamma_0 = 247^{+41}_{-18}\ \mathrm{MeV}/c^2$

Extraction of Poles

- Analytical model based on S-matrix theory
- Test case: $\eta\pi$ D-wave
- Unitarity: $\mathrm{Im}\,\hat{a}(s) = \rho(s)\hat{f}^*(s)\hat{a}(s)$



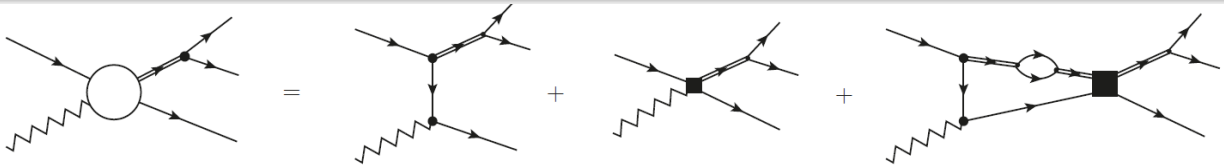


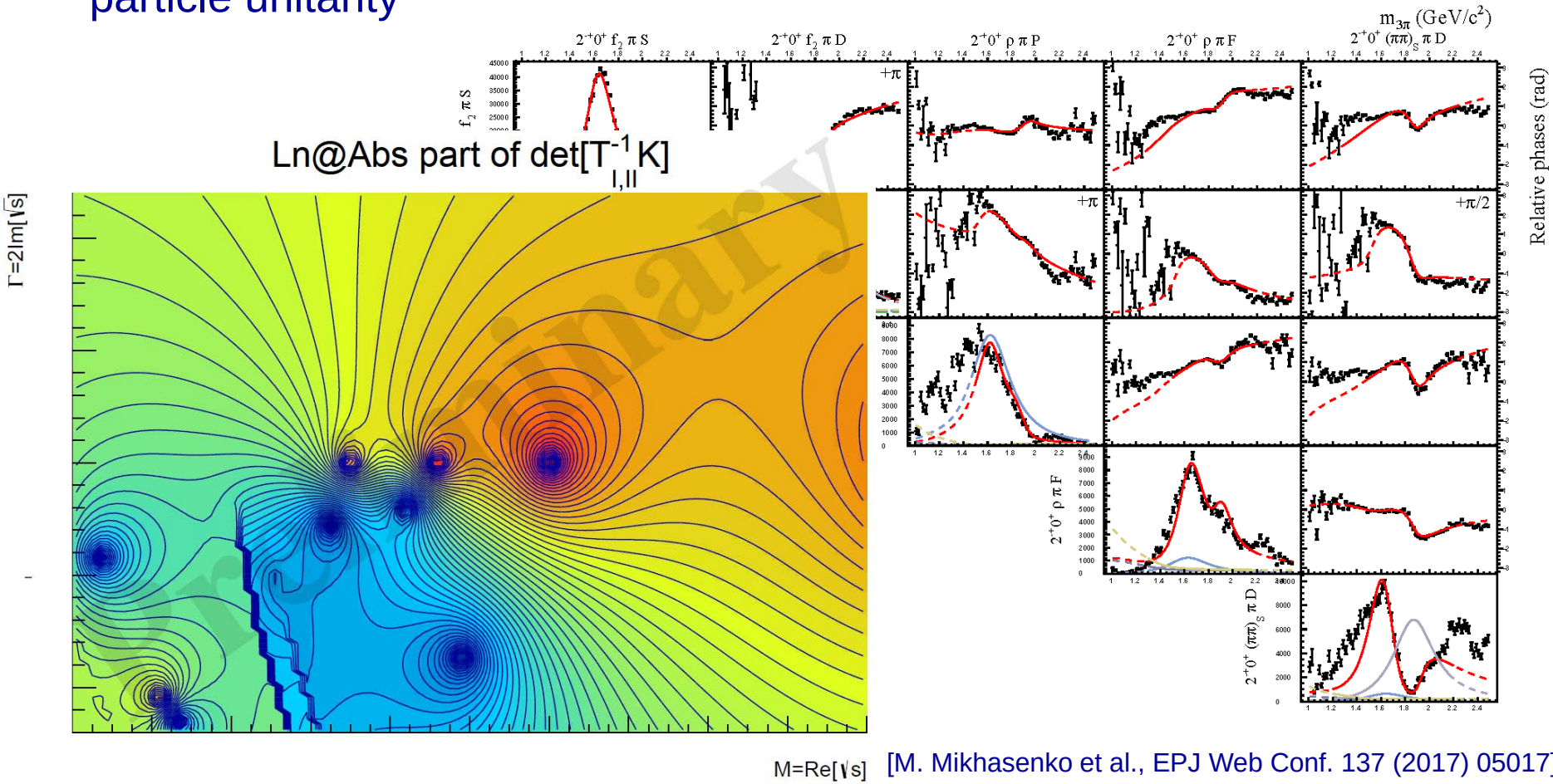


[JPAC, COMPASS, arXiv: 1707.02848]

Extraction of Poles

- 3π system: 2^{-+} wave
- Use quasi two-particle unitarity





[M. Mikhasenko et al., EPJ Web Conf. 137 (2017) 05017]

Conclusions

- Hadron spectroscopy is entering precision era
- Statistical uncertainties very small, systematic model uncertainties dominate
- Spin-exotic $\pi_1(1600)$: (re-) observed by COMPASS
- Large 3π data sample of COMPASS ⇨ PWA in bins of m_X and t'
  - ⇨ Strong non-resonant contributions to $\rho\pi$, $\eta'\pi$
  - ⇨ Can be well described by Deck effect
  - ⇨ Resonant part dominates at high t'
- New axial vector signal observed in $a_1(1420) \to f_0(980)\pi$
  - Has all features of a genuine resonance
  - Data can be described by triangle singularity

- Develop models satisfying principles of S-matrix theory
- $a_1(1420)$: look for it in τ decays, $K\bar{K}\pi$ final state
- Hybrids: identify (exotic) multiplets and measure decay patterns