Exotic Meson Spectroscopy at COMPASS

Bernhard Ketzer

Rheinische Friedrich-Wilhelms-Universität Bonn

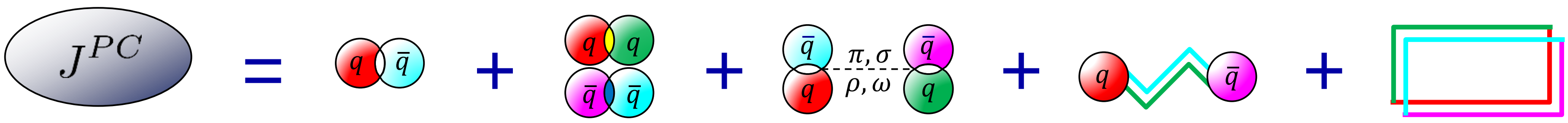
on behalf of the COMPASS Collaboration

International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy (PWA11 / ATHOS6)

Rio de Janeiro

2 September 2019

Exotic States



$(q\bar{q})_0$ $(qq)_8(\bar{q}\bar{q})_8$ $(q\bar{q})_0(q\bar{q})_0$ $(q\bar{q})_8 g$ $(gg)_0$

Tetraquark Molecule Hybrid Glueball

+ …

Where are they?

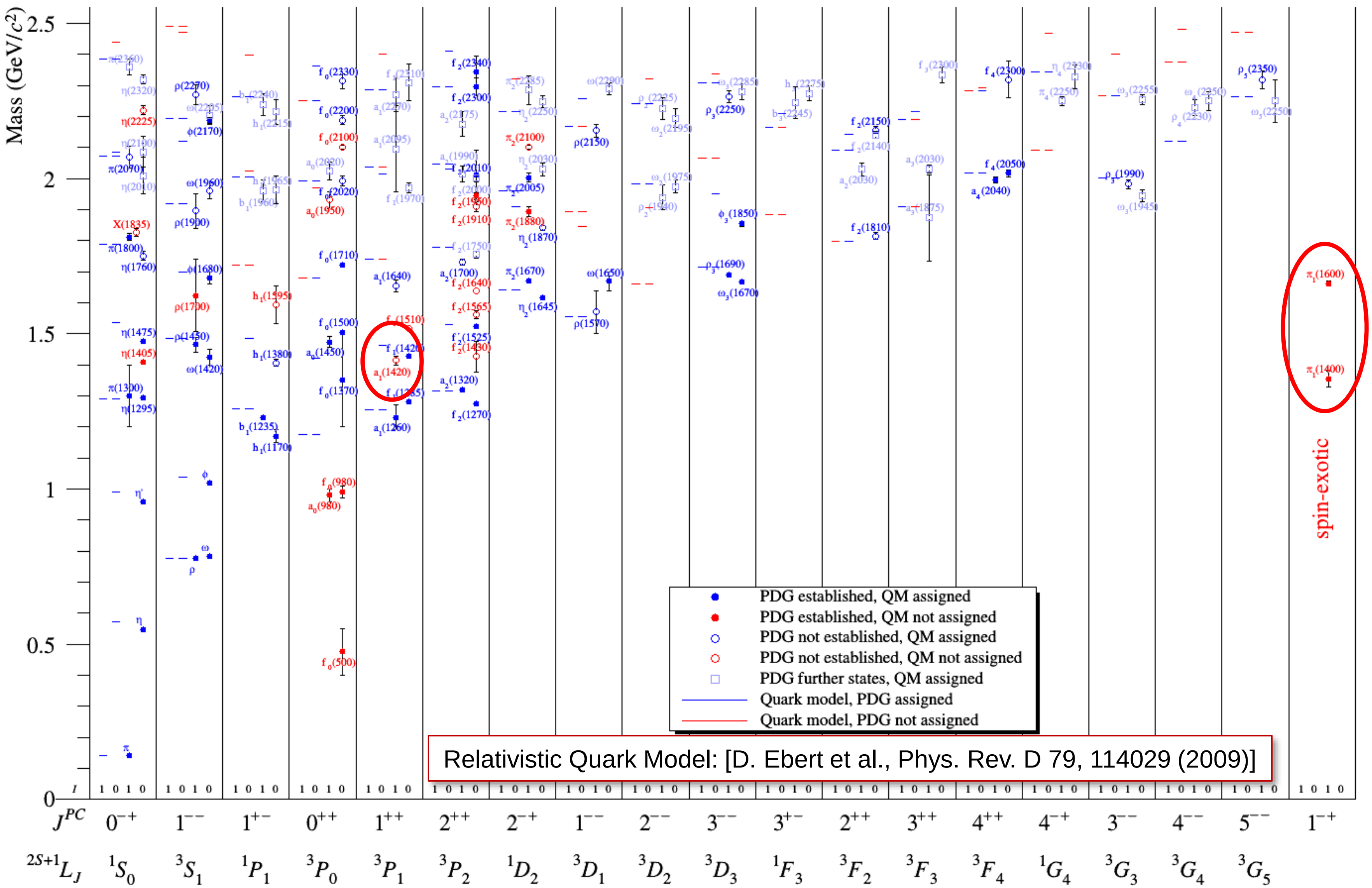
How to identify them?

- Spin-exotic: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$
- Supernumerary states
- Flavor-exotic: $|Q|, |I_3|, |S|, |C| \geq 2$
- Comparison with models, lattice

Need:

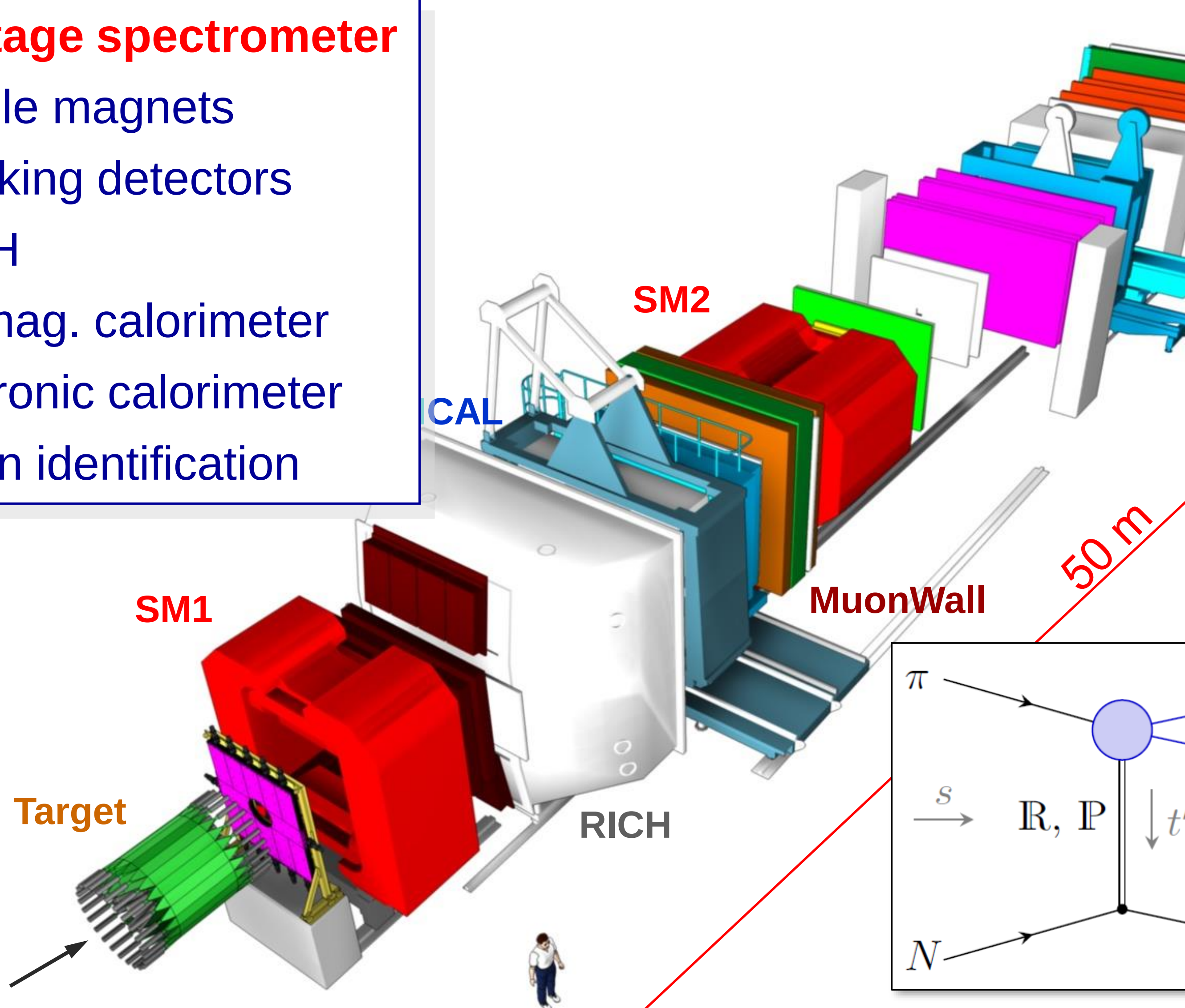
- Large data sets with small statistical uncertainties
- Complementary experiments
  - production mechanisms
  - final states
- Advanced analysis methods
  - reaction models
  - theoretical constraints

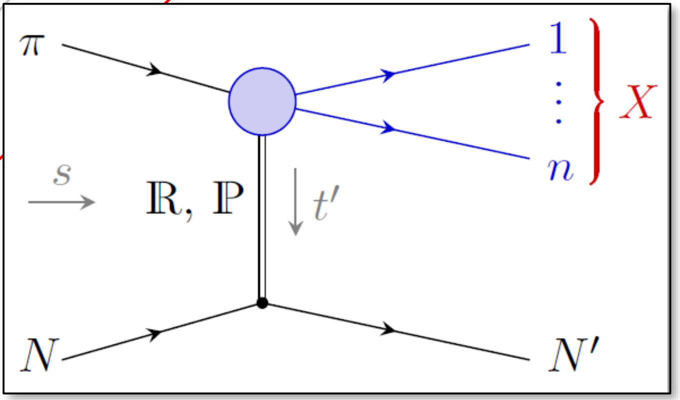
Light Meson Spectrum



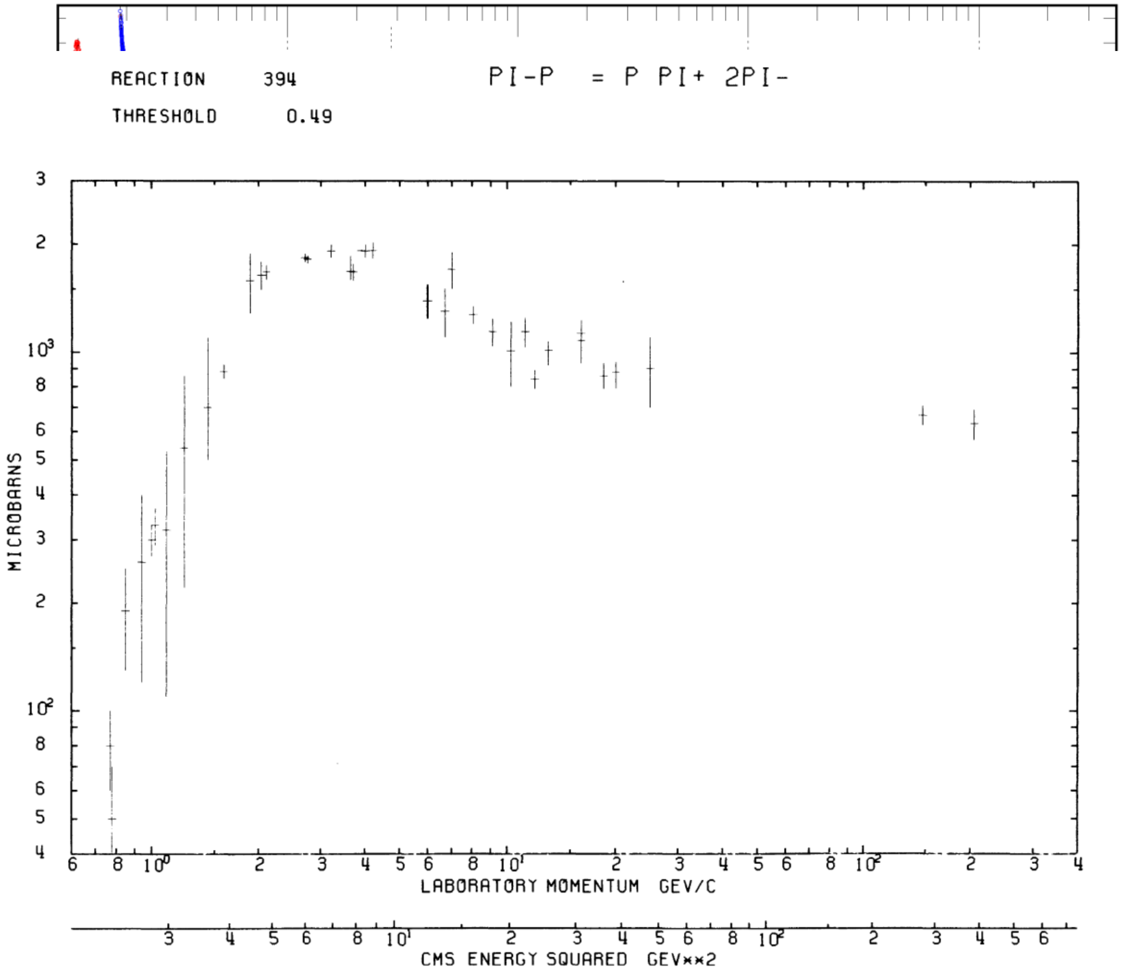
The COMPASS Experiment

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)]



Plots from [V. Flaminio et al., CERN-HERA 83-01, 1983]

COMPASS (190 GeV):

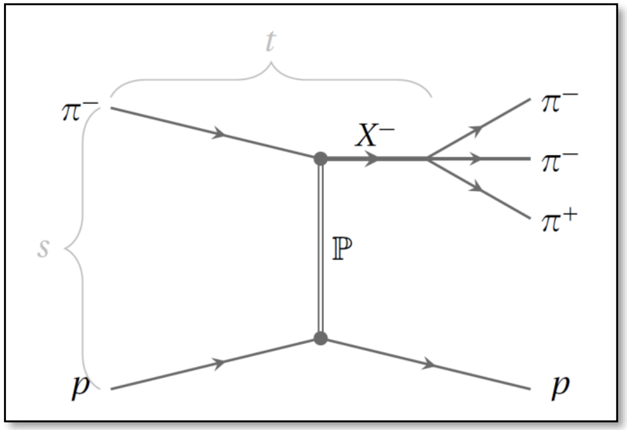
$\sqrt{s} = 18.9$ GeV

Total $\pi^- p$: 24 mb [Carroll 1979]

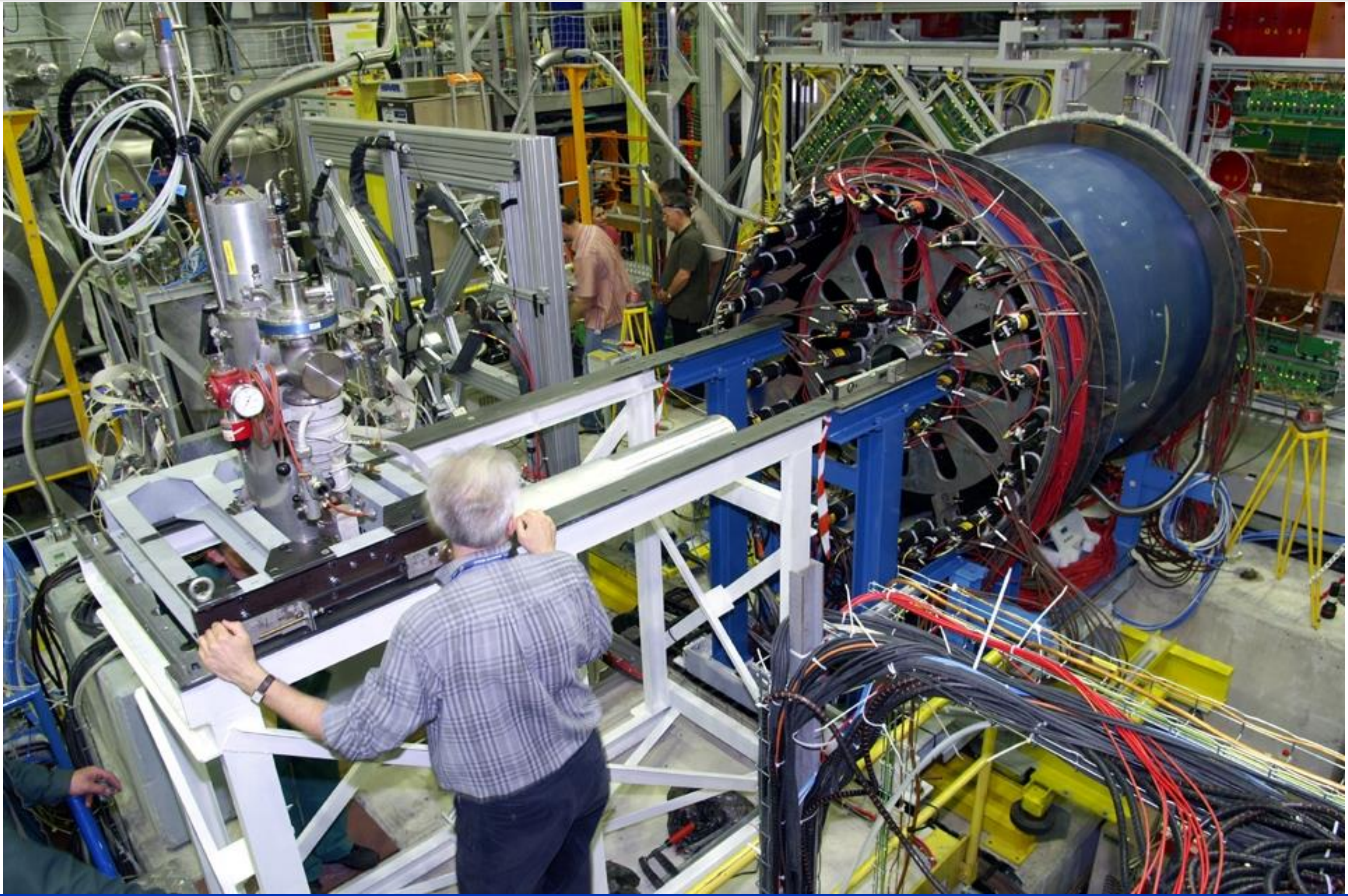
Elastic $\pi^- p$: 3 mb [Schiz 1981]

Single π diffraction (205 GeV):
1.9 ± 0.2 mb [Winkelmann 1974]

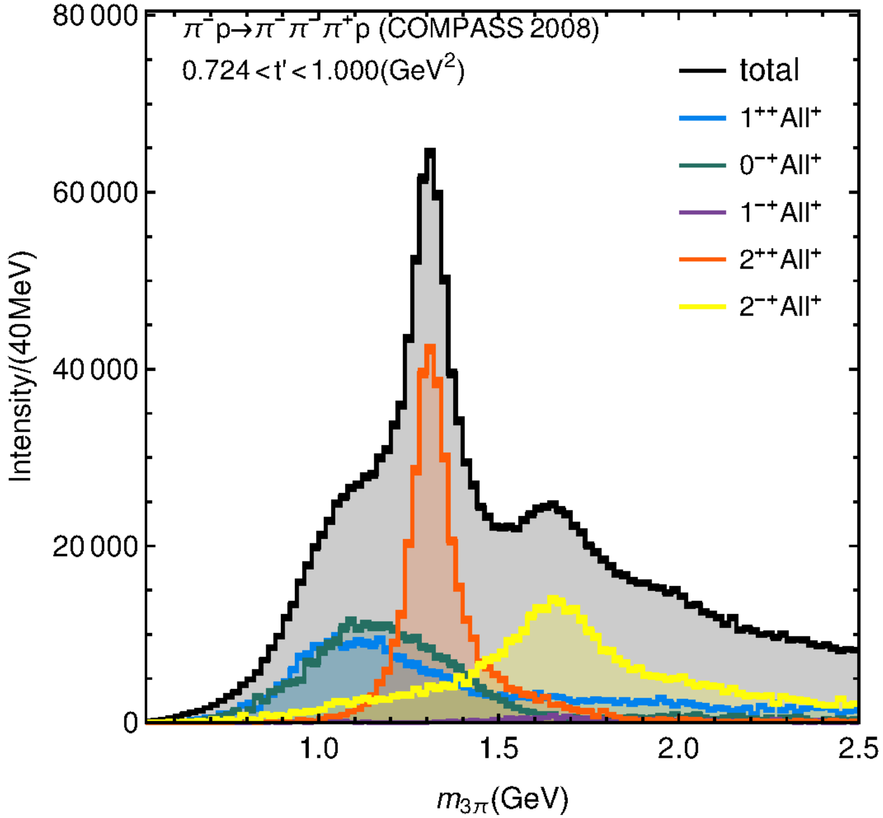
π diffr. into $\pi^-\pi^-\pi^+$:
$416 \pm 50\ \mu$b [Bingham 1974]



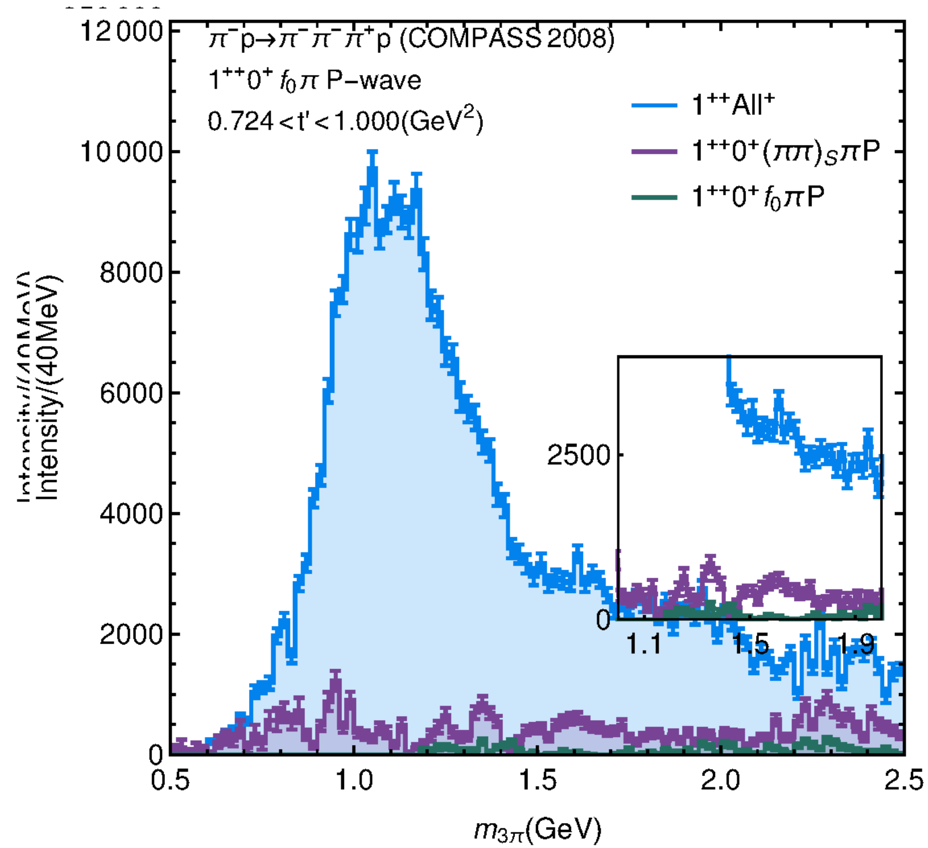
The COMPASS Experiment



Total intensity



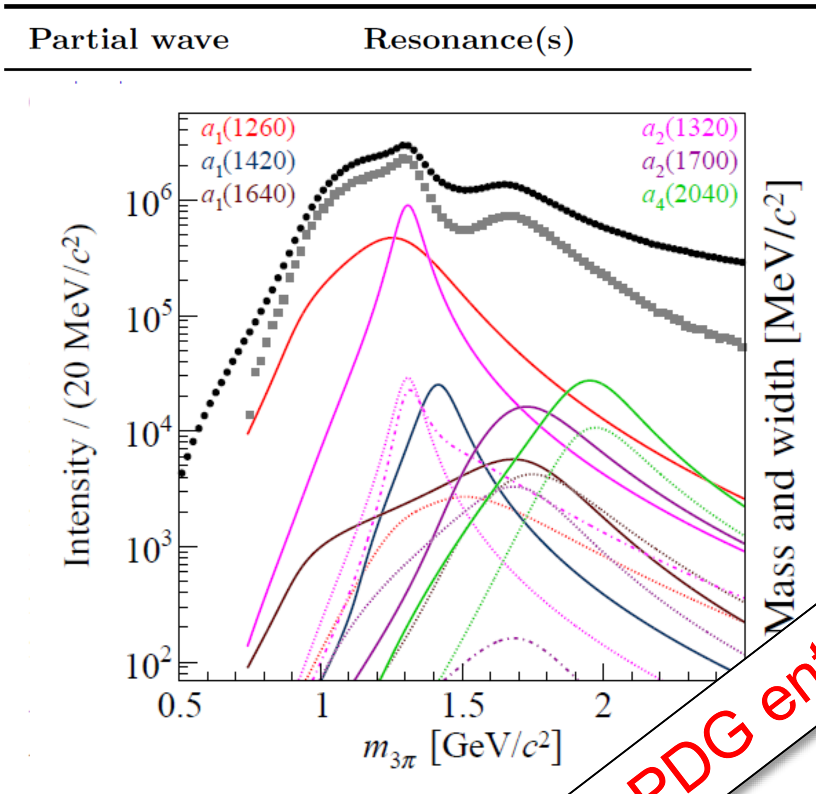
1^{++} Waves

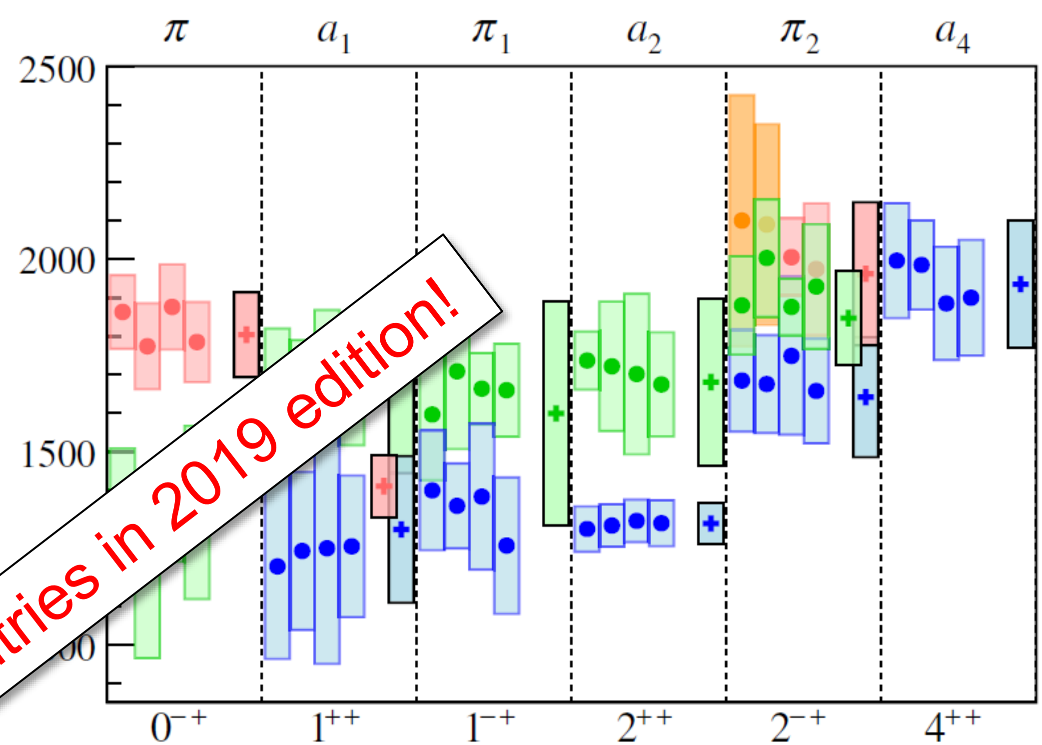


- Largest wave-set to date: 88 waves
- Independent fits in 100 bins (20 MeV) of $m_{3\pi}$ and 11 bins of t'

[COMPASS, C. Adolph et al., PRD 95, 032004 (2017)]

Model Fit





11 new PDG entries in 2019 edition!

Breit-Wigner model

- 14 waves, 11 resonances
- simultaneous over all t‘ slices

[COMPASS, M. Aghasyan et al., PRD 98, 092003 (2018)]

- previous measurements

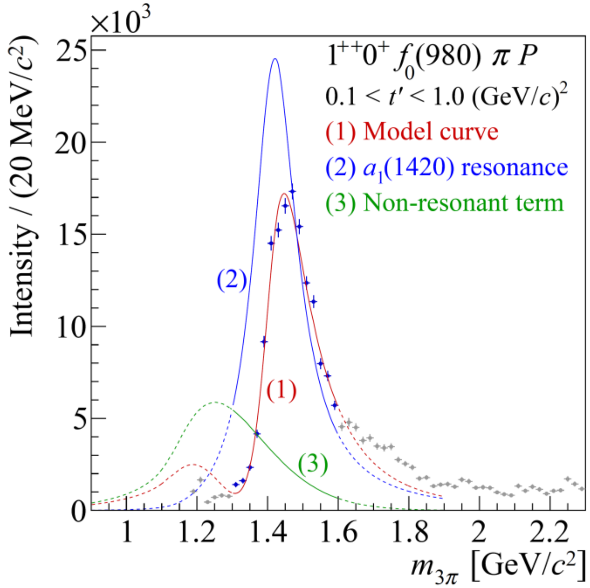
\+ new COMPASS results

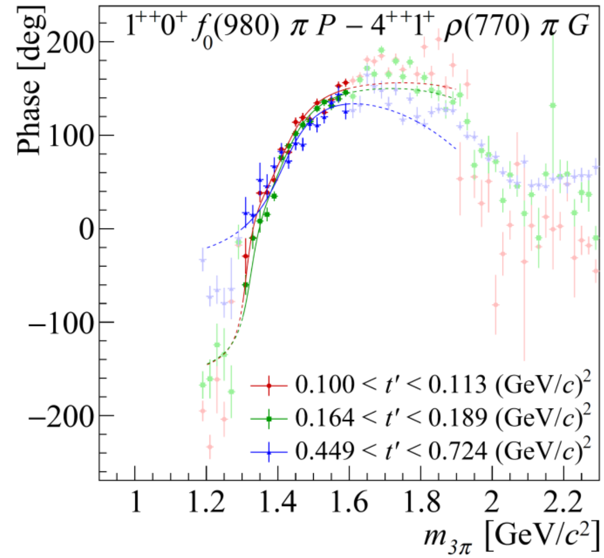
□ decay width

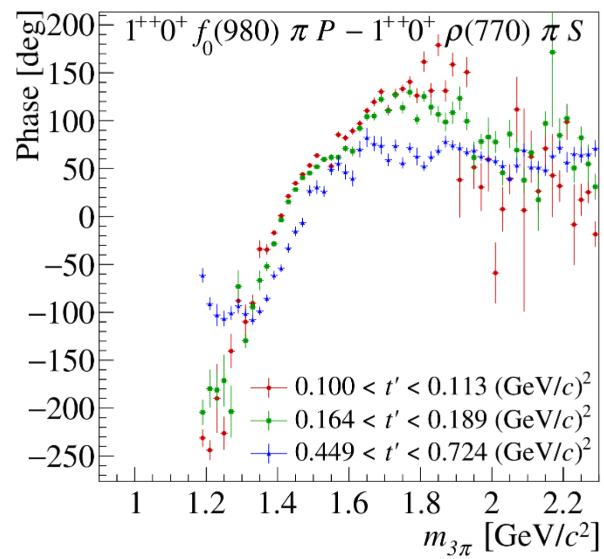
colors: different excitations

New $a_1(1420)$

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







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

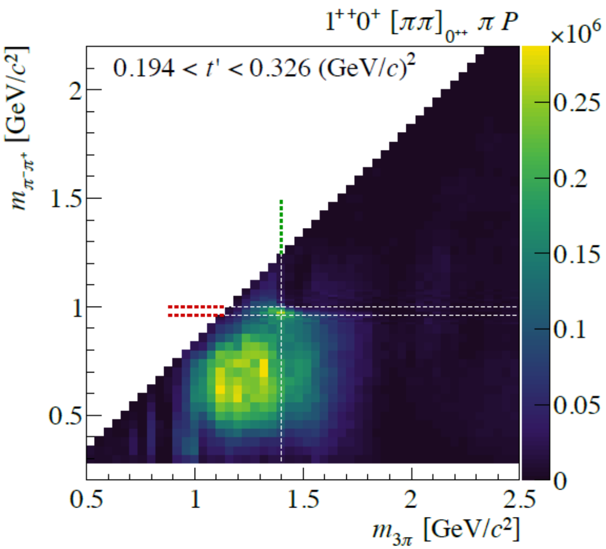
  $M_0 = 1414^{+15}_{-13}$ MeV/c

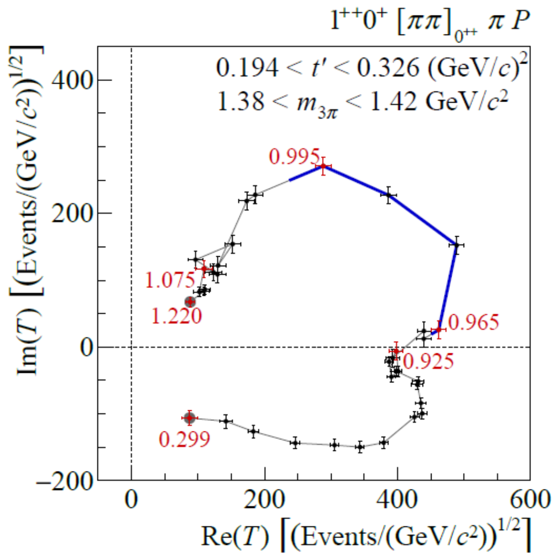
  $\Gamma_0 = 153^{+8}_{-23}$ MeV/c
- Not an artefact of analysis (↗ freed isobar fit)

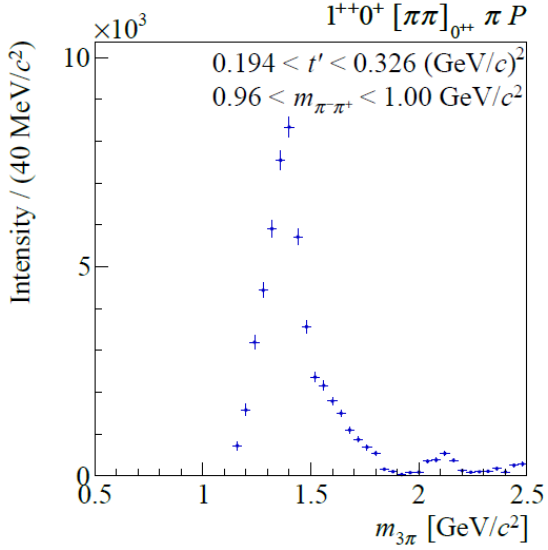
[C. Adolph et al., COMPASS, PRL 115, 082001 (2015)]

New $a_1(1420)$

[C. Adolph, et al. (COMPASS Collaboration), PRD 95 (2017) 032004]
[F. Krinner et al., PRD 97 (2018) 114008]







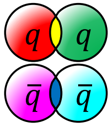
F. Krinner, Thu 9:00

Freed isobar analysis (model-independent isobar amplitude)

- Replace fixed parameterization of 2-body amplitude $J_{\mathrm{iso}}^{PC} = 0^{++}$ by set of free (complex) parameters in 2-body mass bins
- No separation into several isobars
- Amplitude for $[\pi\pi]_{0^{++}}$ isobars determined from data for three $J_{3\pi}^{PC} = 0^{-+},\ 1^{++},\ 2^{-+}$, now also extended to $[\pi\pi]_{1^{--}}$ and $[\pi\pi]_{2^{++}}$

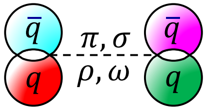
Interpretations

- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]



$(qq)_8(\bar{q}\bar{q})_8$

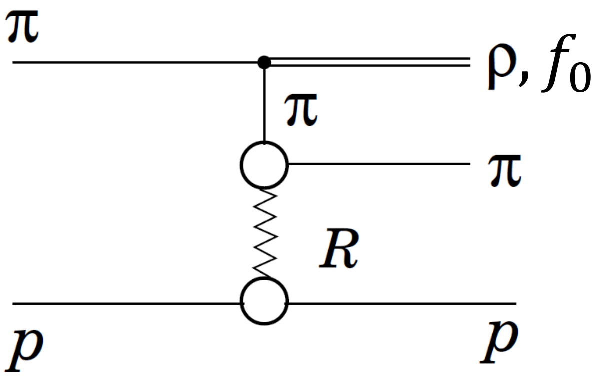
- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]
- $K^*\overline{K}$ molecule [T. Gutsche et al. (2017)]



$$(q\bar{q})_0(q\bar{q})_0$$

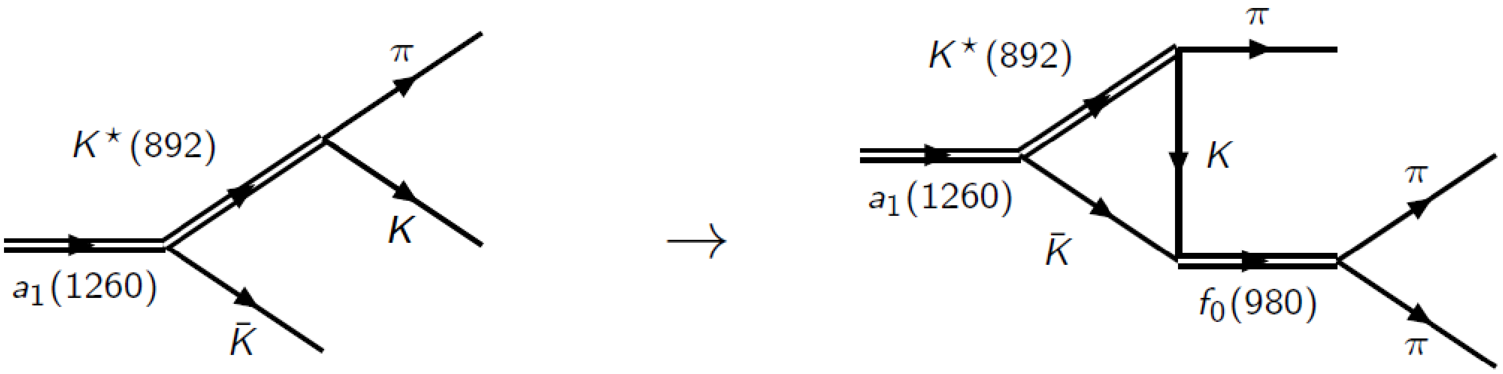
Interpretations

- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]
- $K^*\bar{K}$ molecule [T. Gutsche et al. (2017)]
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al. (2015)]



Interpretations

- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]
- $K^*\overline{K}$ molecule [T. Gutsche et al. (2017)]
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al. (2015)]
- Triangle singularity [M. Mikhasenko et al., PRD 91, 094015 (2015), F. Aceti, PRD 94, 096015 (2016)]

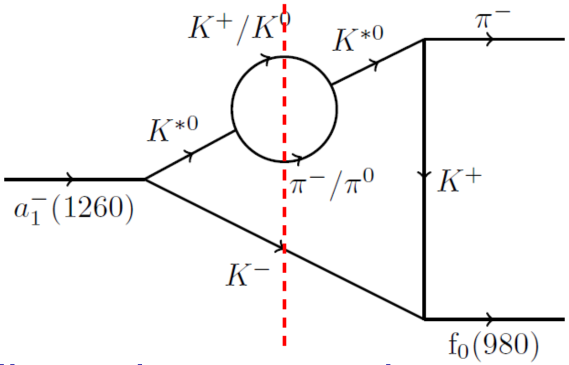


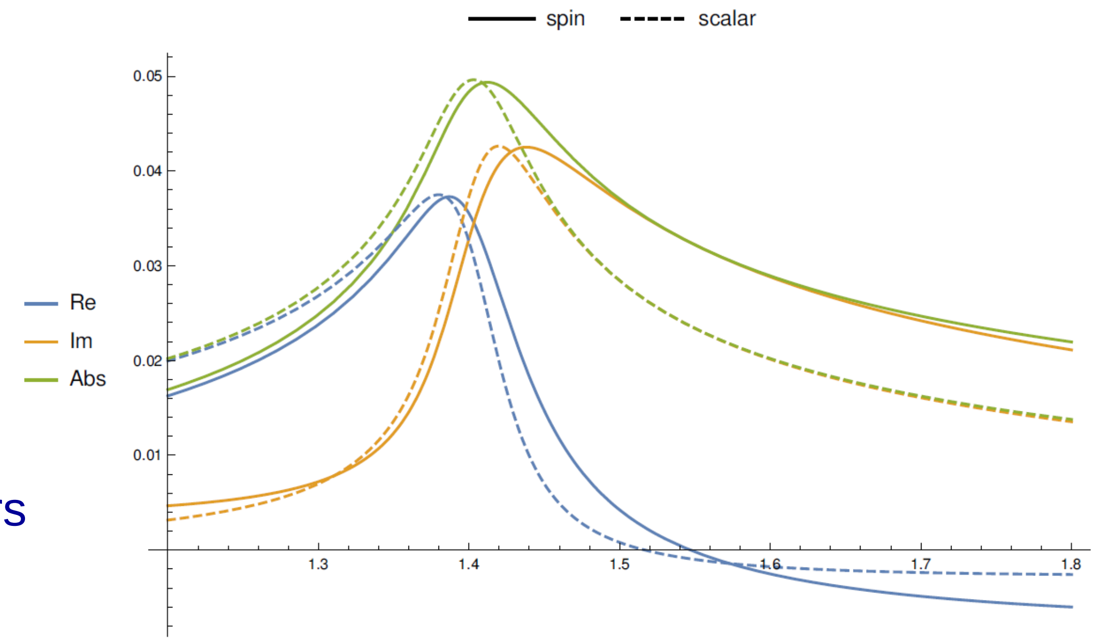
  - Decay of $a_1(1260) \to K^*\overline{K}$ above threshold
  - Final-state rescattering of $K\overline{K}$ to $f_0(980)$

    ⇨ logarithmic singularity of amplitude if particles close to mass shell

Triangle Amplitude

Scalar case:

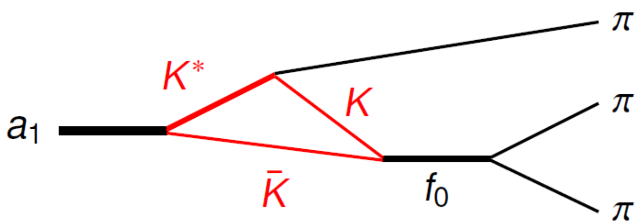


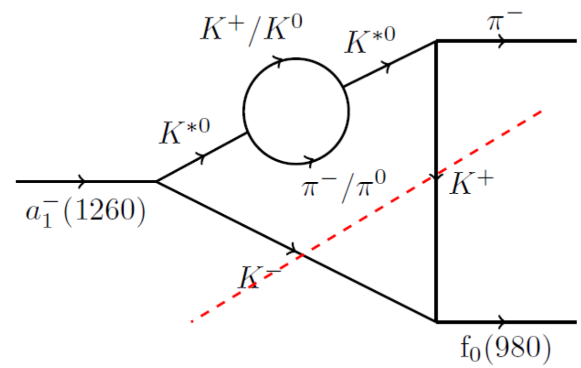


- dispersive approach
- all particles treated as scalars
- finite width of K* included

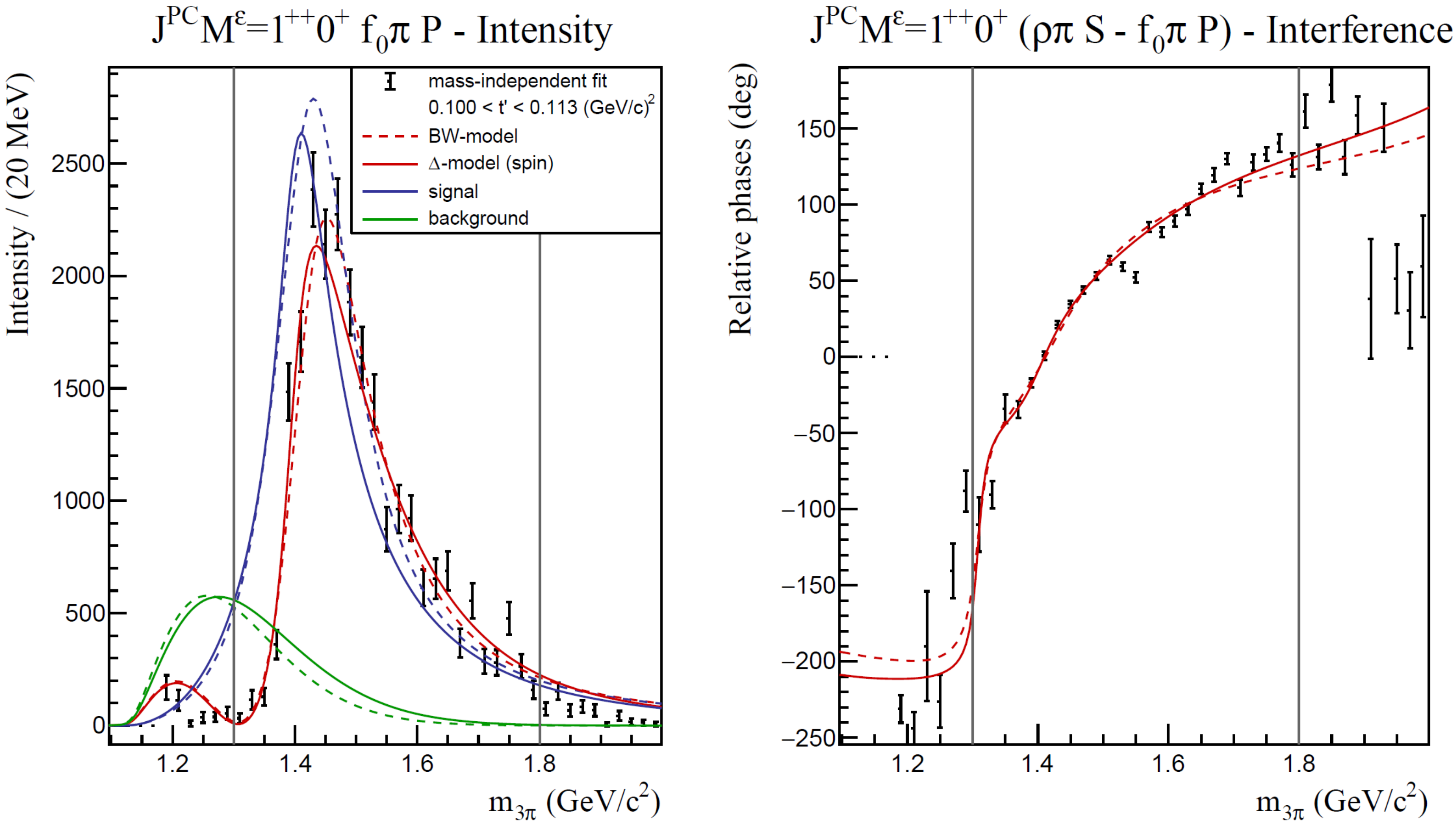
Take into account spins:

- partial-wave projection method





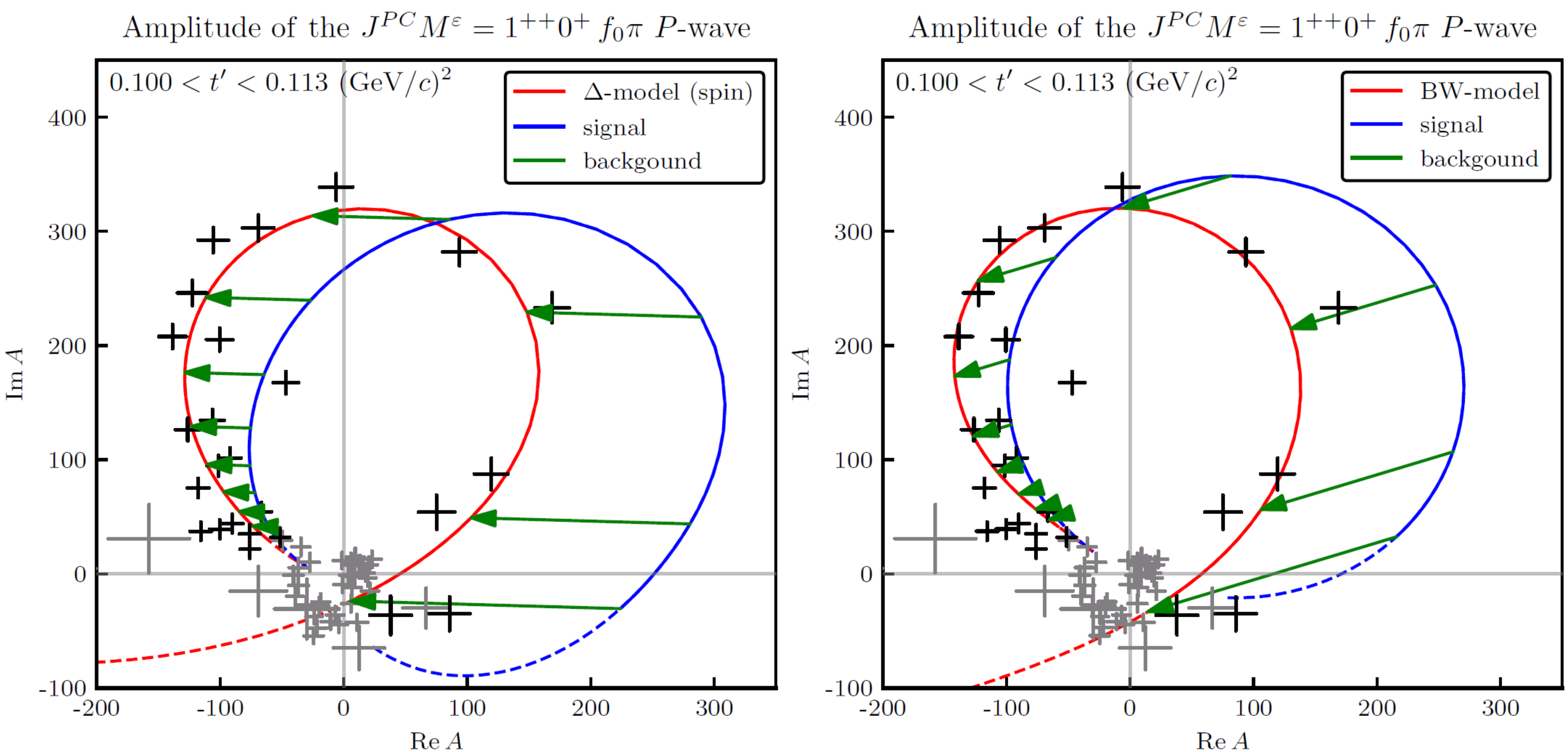
Comparison TS - BW



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

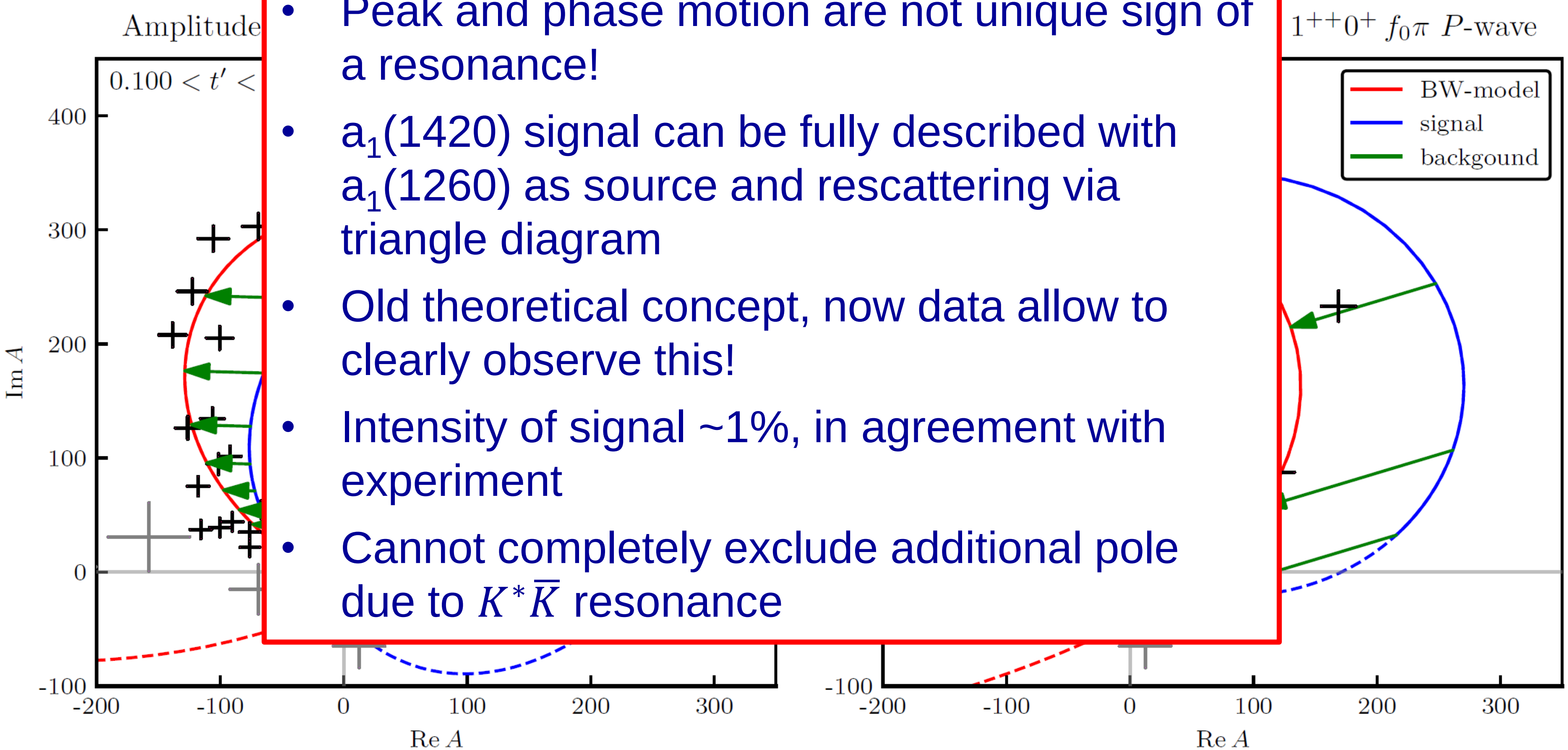
Comparison TS - BW

- Phase motion of pure triangle diagram is only ~ 90°
- Observed phase motion close to 180° produced by shift due to background



Comparison TS - BW

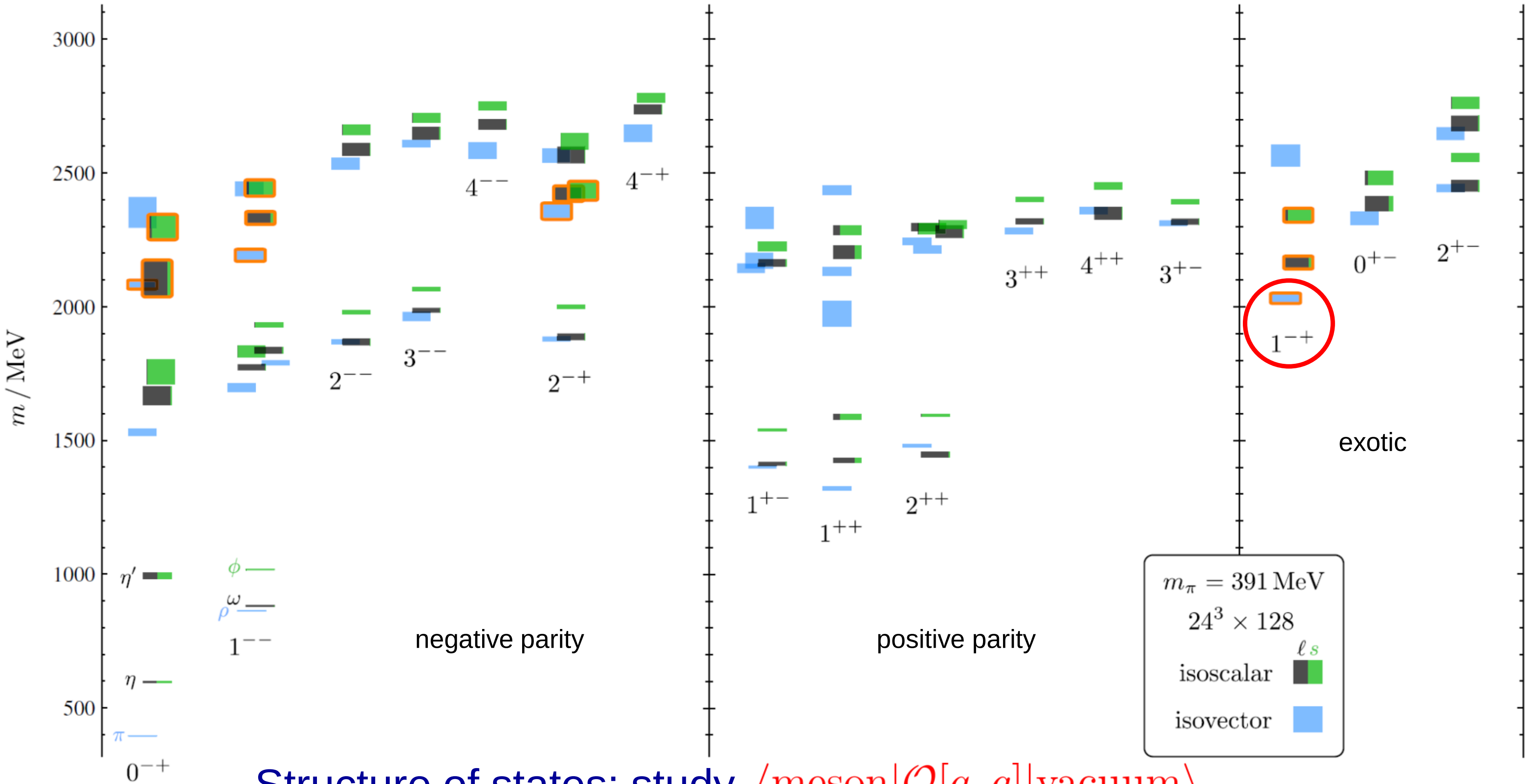
- Phase motion of pure triangle diagram is only ~ 90°
- Observe … to background



Summary for $a_1(1420)$

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

Hybrids: Lattice QCD

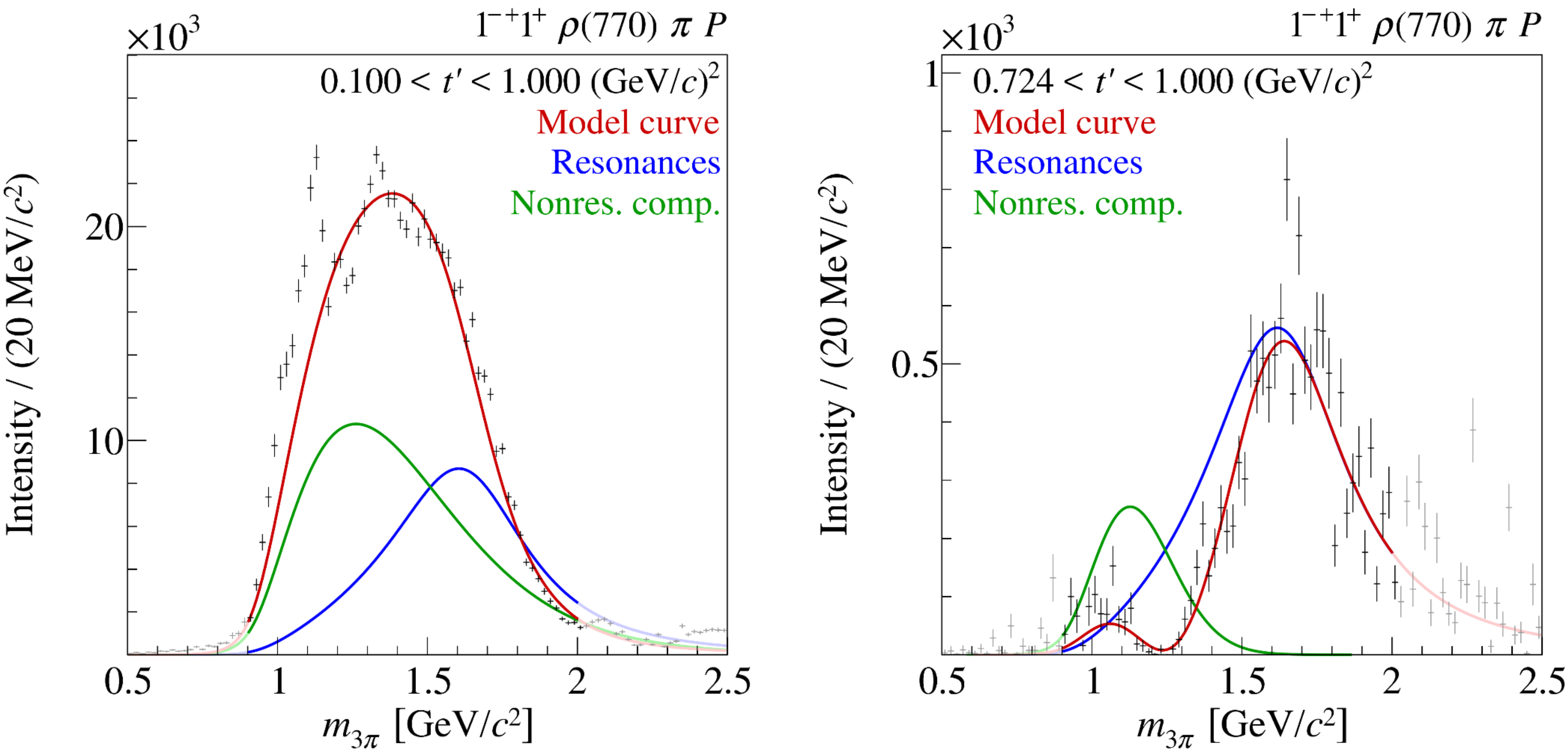


Structure of states: study $\langle \text{meson} | \mathcal{O}[q,g] | \text{vacuum} \rangle$

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

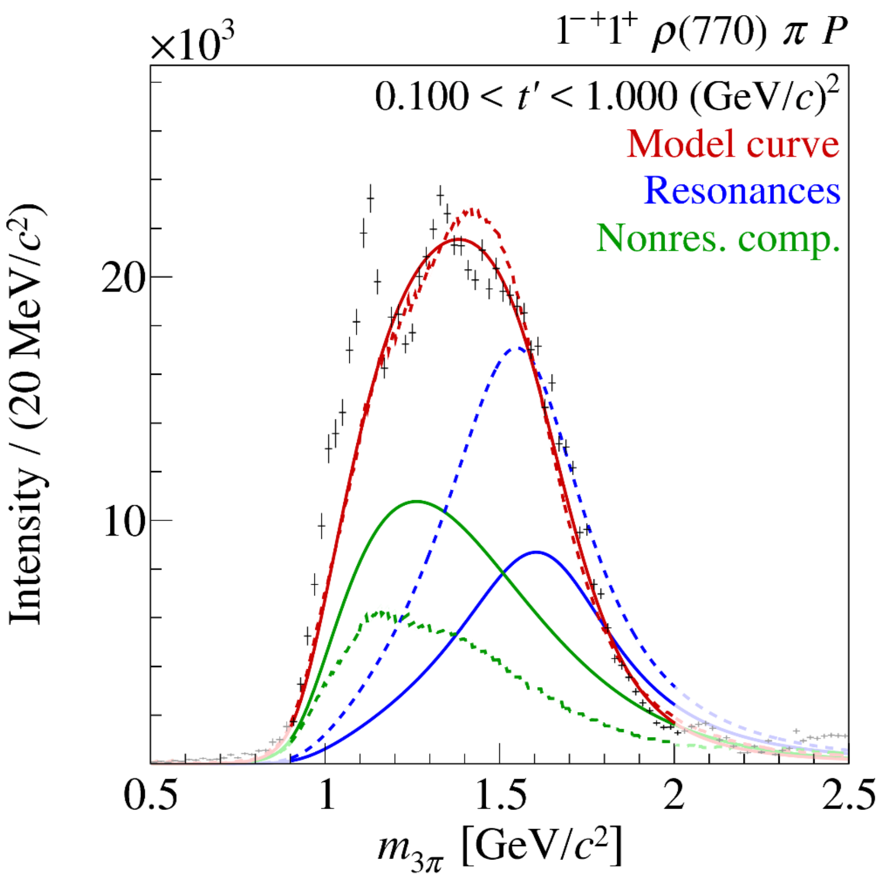
[J. Dudek et al., Hadron Spectrum Collaboration, Phys. Rev. D 88, 094505 (2013)]

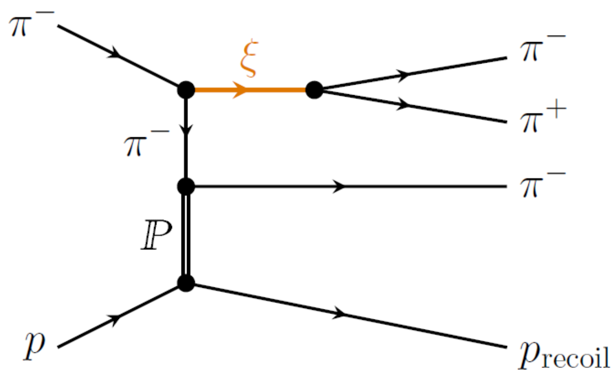
1^{-+} Partial Wave



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

[M. Aghasyan et al. (COMPASS), Phys. Rev. D 98, 092003 (2018)]





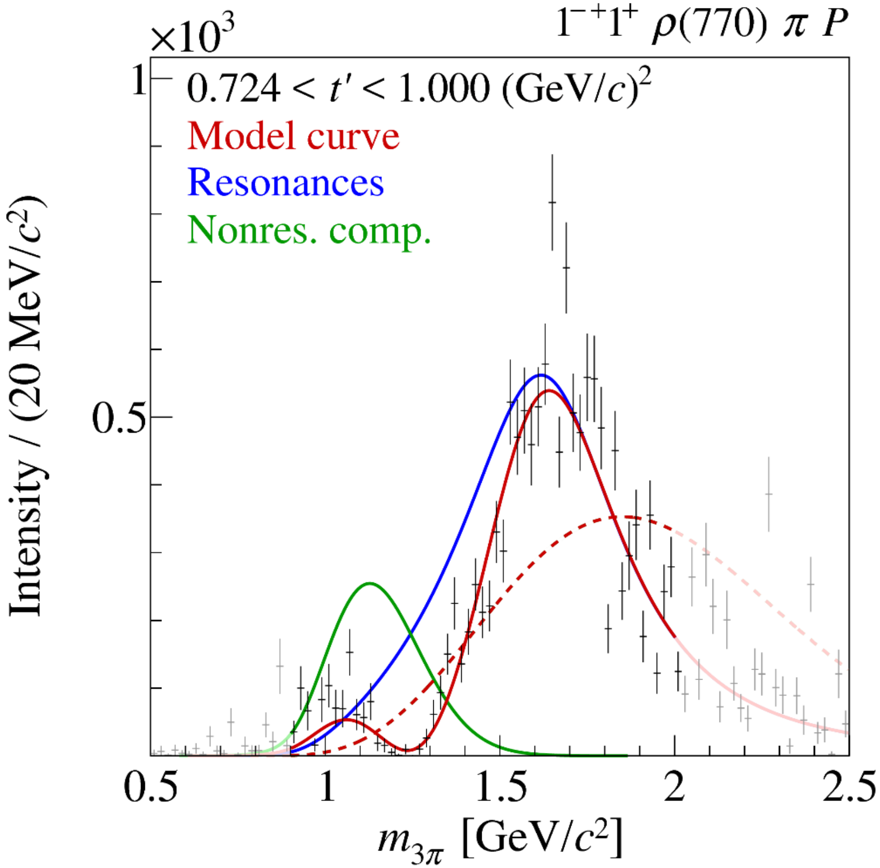
- Background shape in agreement with Deck-model studies
- Resonance parameters for $\pi_1(1600)$

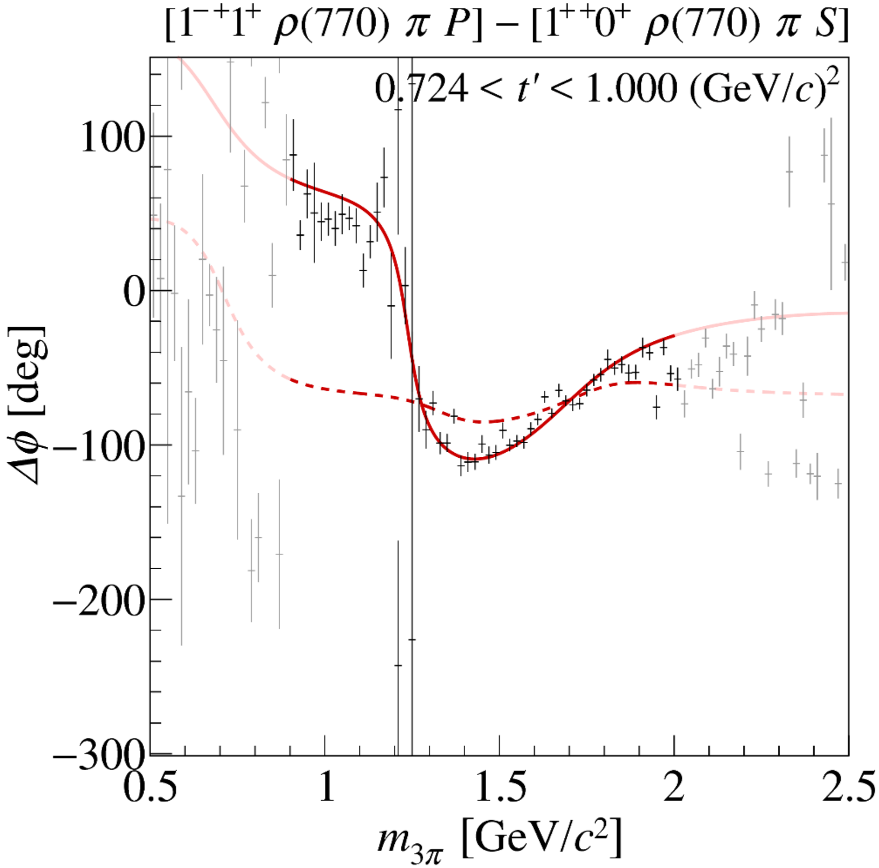
$$M_0 = 1600^{+110}_{-60}\ \text{MeV}/c^2$$

$$\Gamma_0 = 580^{+100}_{-230}\ \text{MeV}/c^2$$

- Bad description of data without resonance component

[M. Aghasyan et al. (COMPASS), Phys. Rev. D 98, 092003 (2018)]



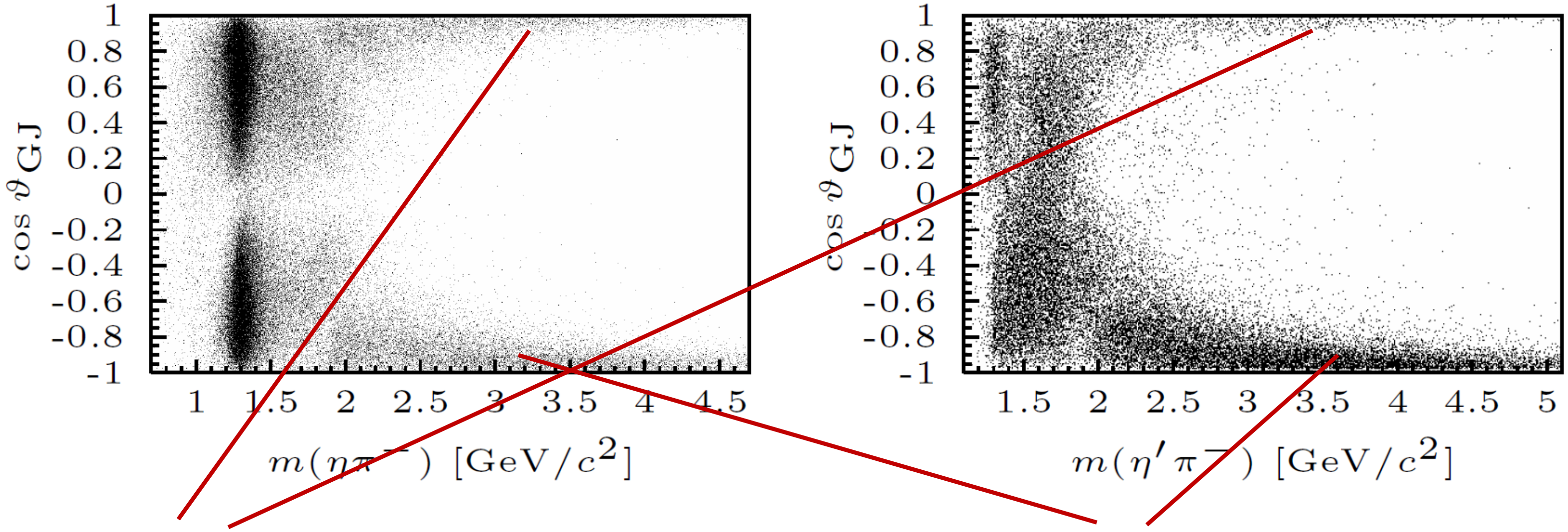


Bad description of data without resonance component

⇨ $\pi_1(1600)$ needed to describe data

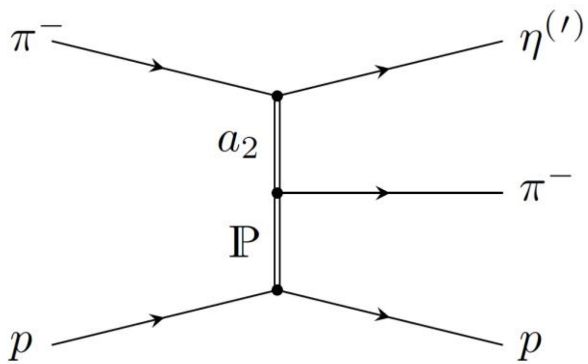
[M. Aghasyan et al. (COMPASS), Phys. Rev. D 98, 092003 (2018)]

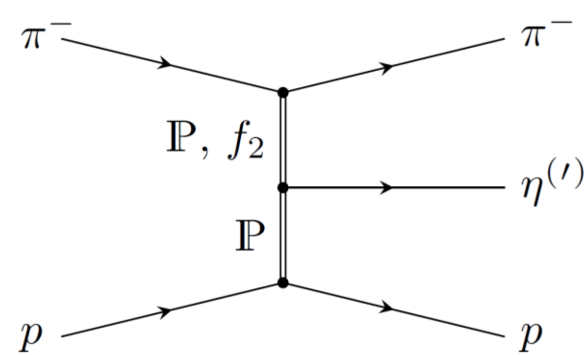
$\eta\pi^-$ / $\eta'\pi^-$ Final States



Forward $\eta^{(\prime)}$

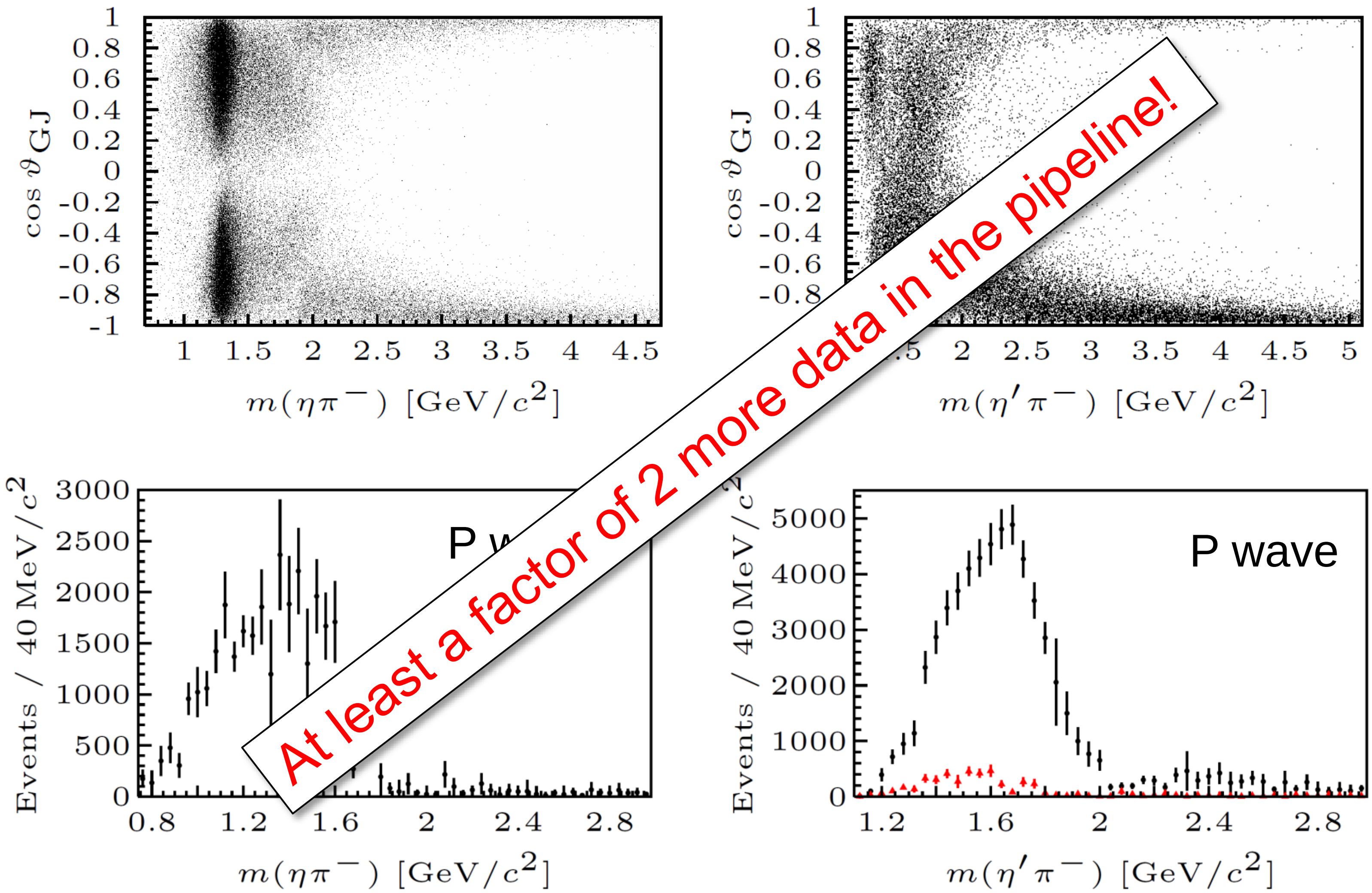
Backward $\eta^{(\prime)}$





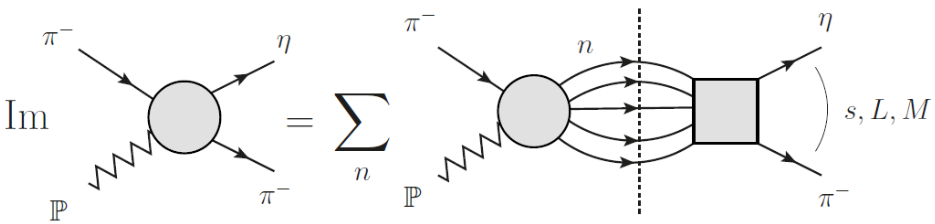
[C. Adolph (COMPASS), Phys. Lett. B 740, 303 (2015)]

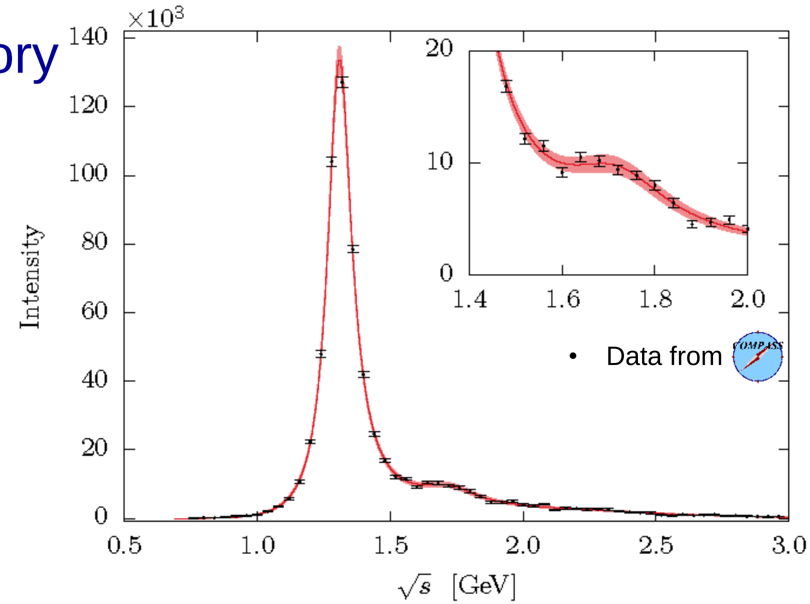
$\eta\pi^-$ / $\eta'\pi^-$ Final States

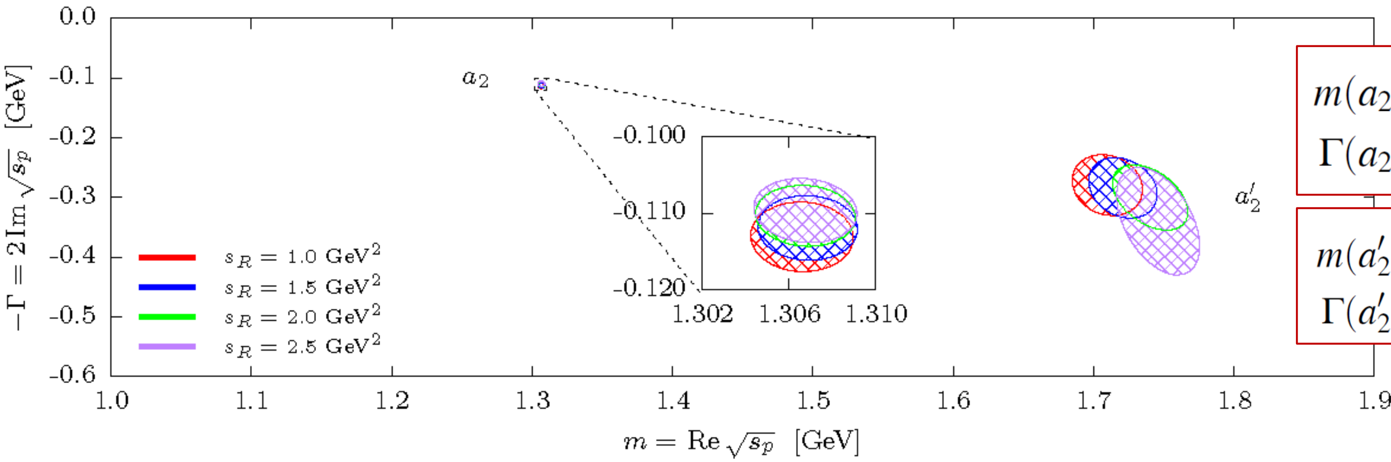


[C. Adolph (COMPASS), Phys. Lett. B 740, 303 (2015)]

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





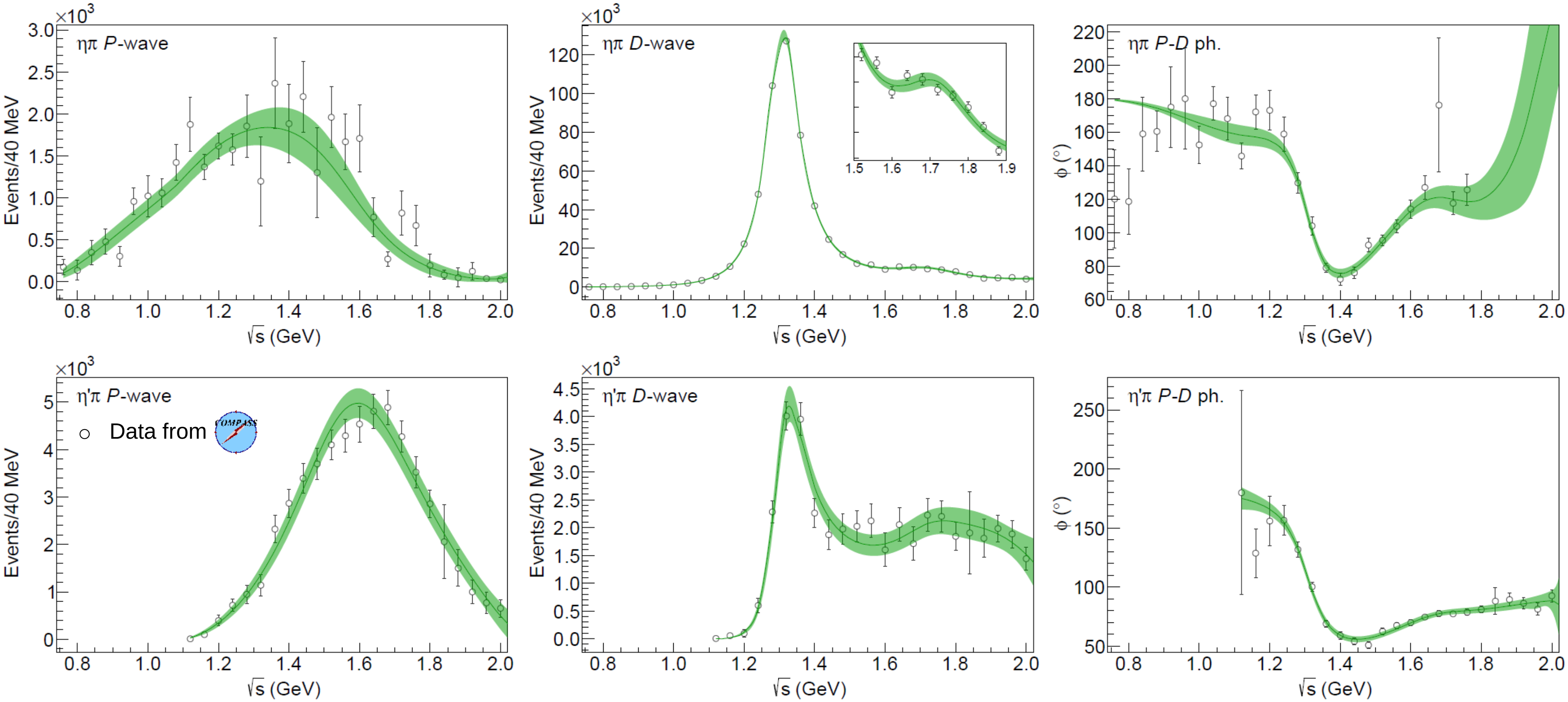


$$m(a_2) = (1307 \pm 1 \pm 6)\ \mathrm{MeV},$$
$$\Gamma(a_2) = (112 \pm 1 \pm 8)\ \mathrm{MeV},$$

$$m(a_2') = (1720 \pm 10 \pm 60)\ \mathrm{MeV},$$
$$\Gamma(a_2') = (280 \pm 10 \pm 70)\ \mathrm{MeV},$$

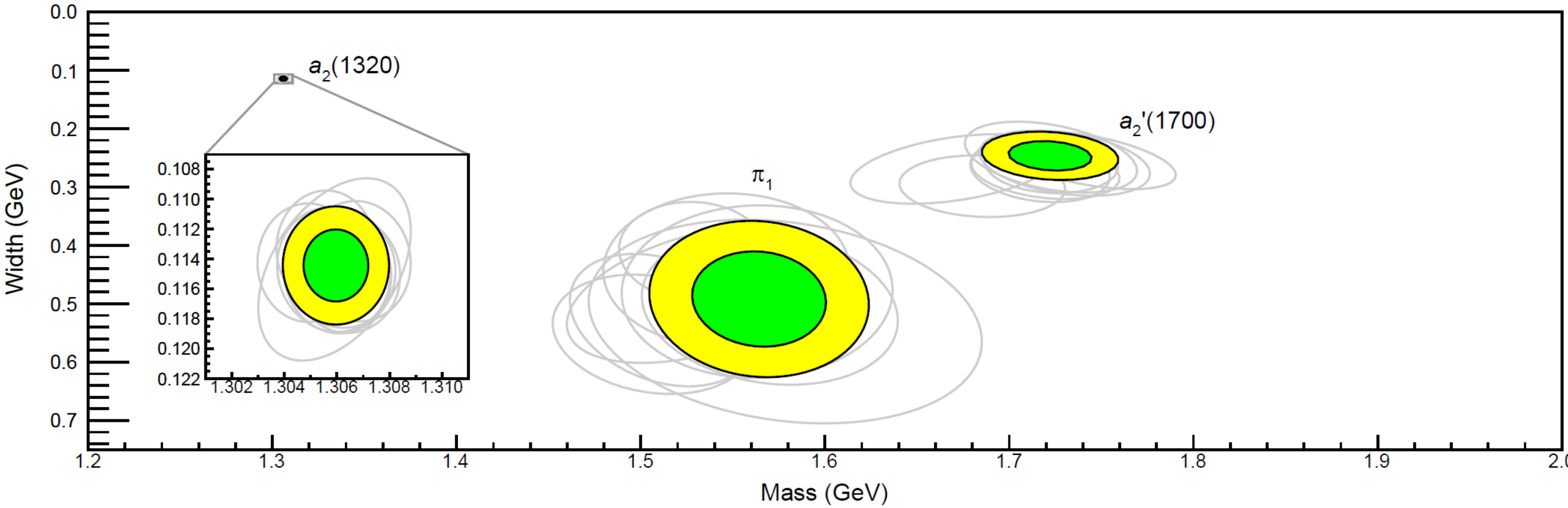
[A. Jackura et al. (JPAC, COMPASS), Phys. Lett. B 779, 464 (2018)]

ηπ–η′π Coupled Channels



[A. Rodas et al. (JPAC), Phys. Rev. Lett. 122, 042002 (2019)]

ηπ–η′π Coupled Channels



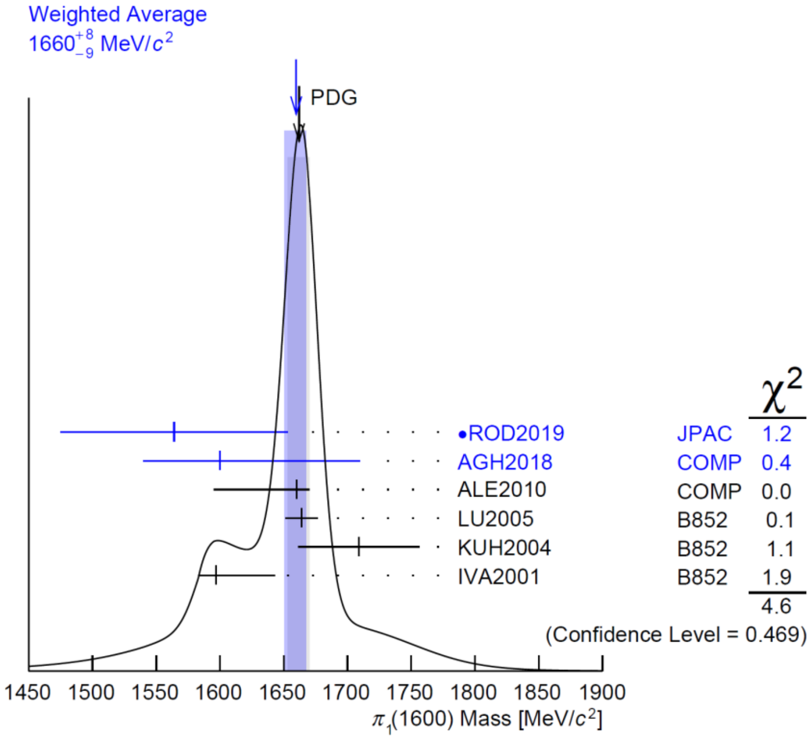
- only a single pole needed to describe both ηπ and η′π peaks
- consistent with π_1(1600)

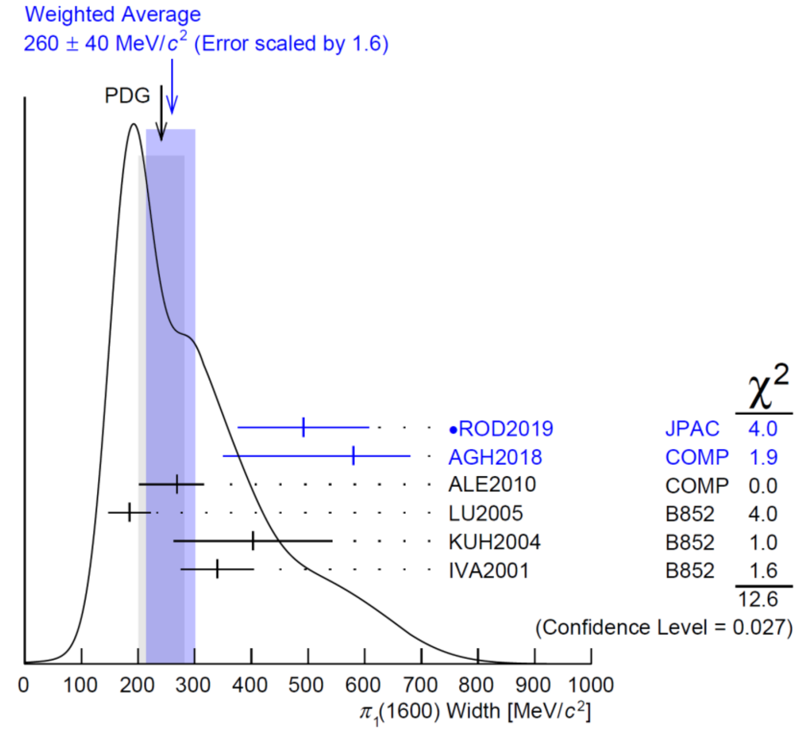
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

[A. Rodas et al. (JPAC), Phys. Rev. Lett. 122, 042002 (2019)]

Summary for π_1

- Resonant nature of signal in $J^{PC} = 1^{-+}$ established from COMPASS 3π data
- Coupled-channel analysis for $\eta\pi$ and $\eta'\pi$ using a unitary model only requires one single pole to describe P-wave peaks at 1.4 and 1.6 GeV
- Fit allows to extract pole position of lightest hybrid meson for first time





Conclusions

- Hadron spectroscopy is entering precision era
- Extremely large data samples with π and μ beams from COMPASS
- Very small statistical uncertainties for dominating resonances
  - ⇨ systematic model uncertainties dominate
  - ⇨ multi-dimensional PWA in bins of m_X and t'
- 14 new PDG entries (Jan. 2019) based on COMPASS data (3 w/ JPAC)
- Small signals and effects can be studied for the first time
- Spin-exotic $\pi_1(1600)$: (re-) observed by COMPASS
  - ⇨ resonant nature established
  - ⇨ one single pole sufficient to describe peaks at 1.4 and 1.6 GeV
- New axial vector signal observed in $a_1(1420) \rightarrow f_0(980)\pi$
  - ⇨ has all features of a genuine resonance
  - ⇨ data can be described by triangle singularity

Outlook

- Strongly coupled QCD still far from being understood
- Identify (exotic) multiplets and measure decay patterns
- Need large data samples for
  - complementary production mechanisms
  - different final states
- Advanced analysis methods
  - simple BW fits may be misleading
  - reaction models satisfying principles of S-matrix theory
- Advances in Lattice QCD (multi-particle scattering states)
- A new QCD facility is proposed at the M2 beamline of CERN SPS from 2022 onwards

COMPASS++ / AMBER

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN

Letter of Intent (Draft 2.0)

A New QCD facility at the M2 beam line of the CERN SPS

October 17, 2018

Proton radius measurement using muon-proton elastic scattering
Hard exclusive reactions using a muon beam and a transversely polarised target
Drell-Yan and charmonium production
Measurement of antiproton production cross sections for Dark Matter Search
Spectroscopy with low-energy antiprotons
Spectroscopy of kaons
Study of the gluon distribution in the kaon via prompt-photon production
Low-energy tests of QCD using Primakoff reactions
Production of vector mesons and excited kaons off nuclei

https://arxiv.org/abs/1808.00848

COMPASS++ / AMBER

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent (Draft 2.0)

A New QCD facility at the M2 beam line of the CERN SPS

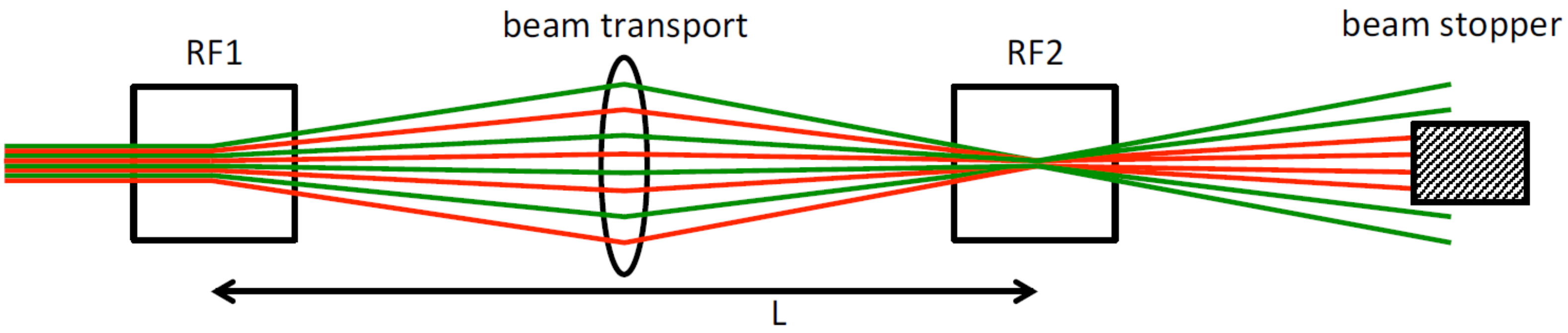
October 17, 2018

Proton radius measurement using muon-proton elastic scattering
Hard exclusive reactions using a muon beam and a transversely polarised target
Drell-Yan and charmonium production
Measurement of antiproton production cross sections for Dark Matter Search
Spectroscopy with low-energy antiprotons
Spectroscopy of kaons
Study of the gluon distribution in the kaon via prompt-photon production
Low-energy tests of QCD using Primakoff reactions
Production of vector mesons and excited kaons off nuclei

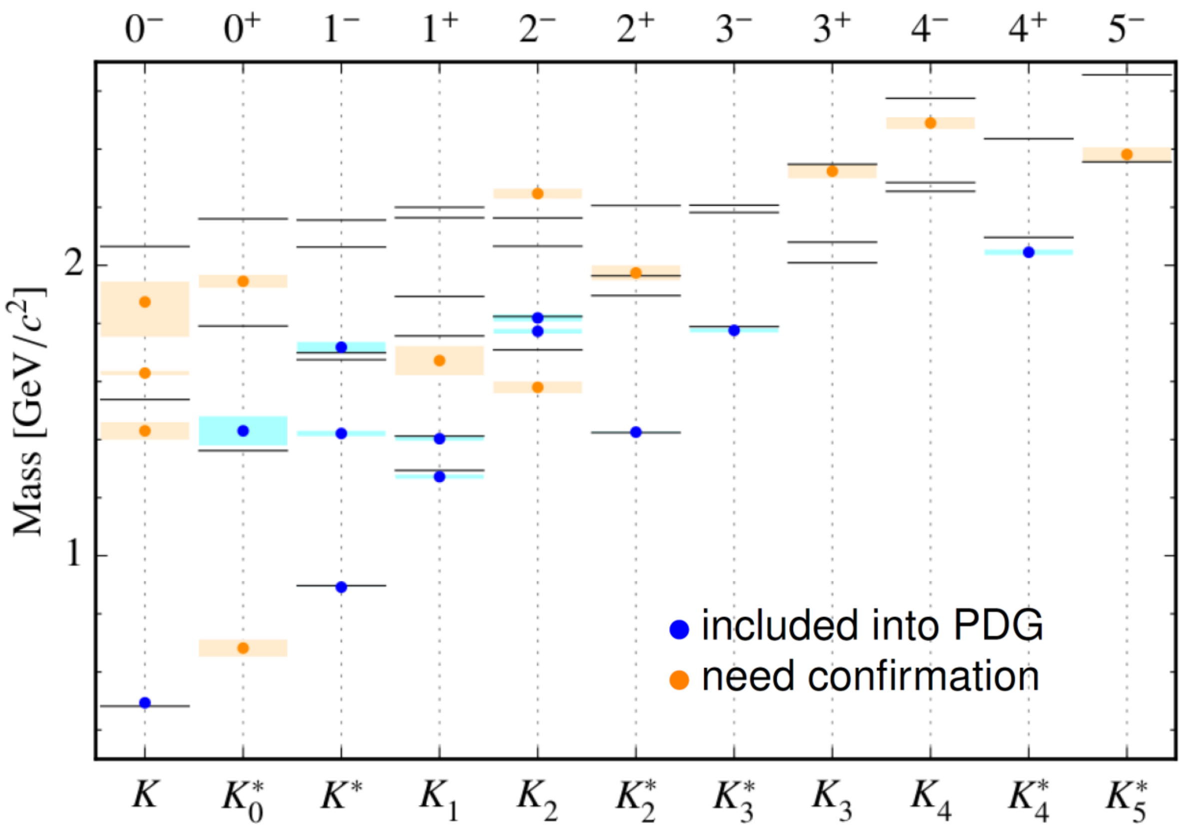
https://arxiv.org/abs/1808.00848

New Beam: RF Separation

Reminder: Panofsky-Schnell-System with two cavities (CERN 68-29)



- Particle species: same momenta but different velocities
- Time-dependent transverse kick by RF cavities in dipole mode
- RF1 kick compensated or amplified by RF2
- Selection of particle species by selection of phase difference
  $\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$
- For large momenta: $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2\mathbf{p}^2$



- 25 kaon states listed by PDG ($M < 3.1$ GeV), 13 of those need confirmation
- many predicted quark-model states still missing
- some hints for supernumerary states

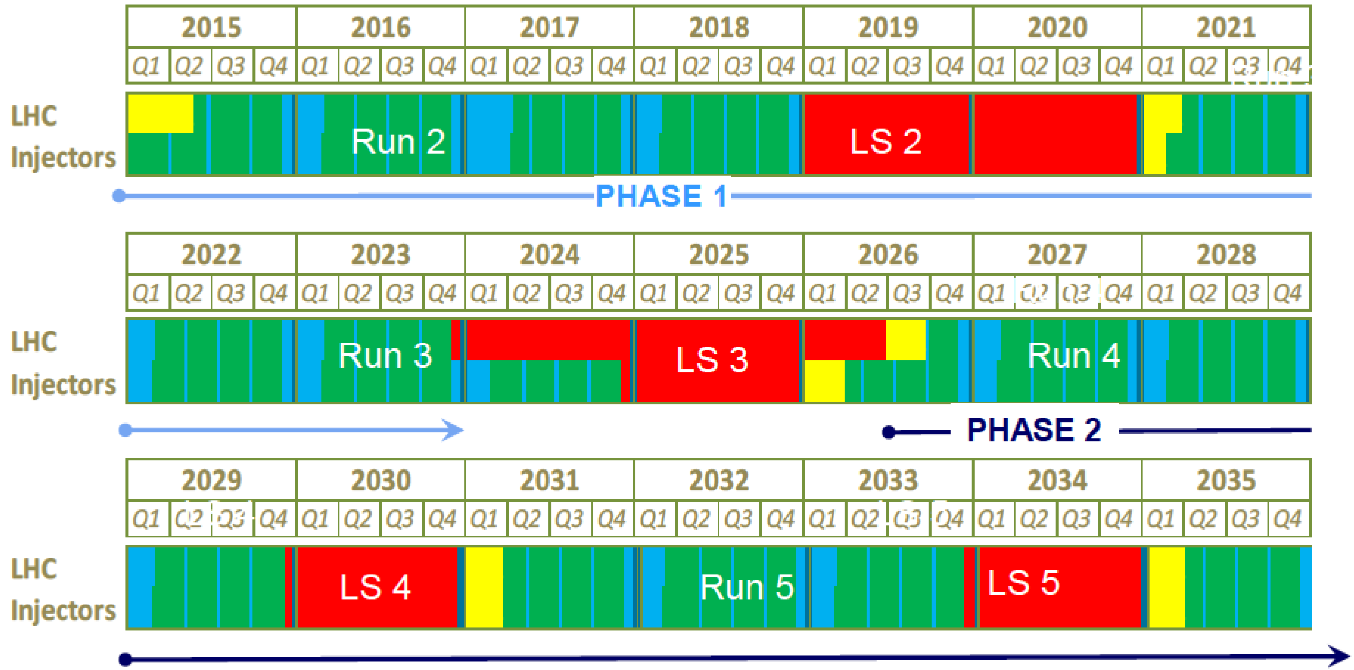
S. Wallner, Fri 9:30

Timelines

LHC roadmap: according to MTP 2016-2020 V1

LS2	starting in 2019	=> 24 months + 3 months BC
LS3	LHC: starting in 2024	=> 30 months + 3 months BC
	Injectors: in 2025	=> 13 months + 3 months BC

Physics
Shutdown
Beam commissioning
Technical stop



- conventional-beams program: 2022-2024
- RF-separated beams: from 2026 on

Spare Slides

Freed Isobar Analysis

Conventional PWA

- requires fixed isobar parameterizations
- wrong isobar shape might influence results

Novel method: freed-isobar PWA

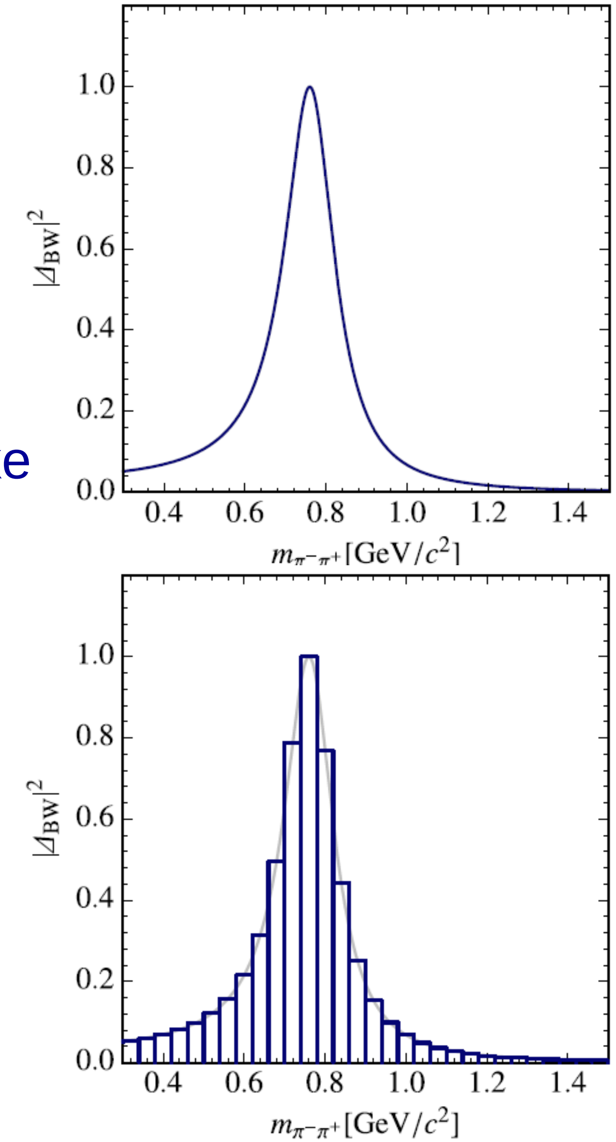
[F. Krinner et al., PRD 97 (2018) 114008]

- replace fixed isobar parameterizations by step-like functions, i.e. a set of free (complex) parameters in 2-body mass bins with δm=40 MeV (10 MeV around 980 MeV)
- Combined phase information: $\phi_{tot} = \phi_{prod} + \phi_{decay}$

⇨ Determine dynamics of isobars from data

⇨ Obtain model-independent isobar amplitude

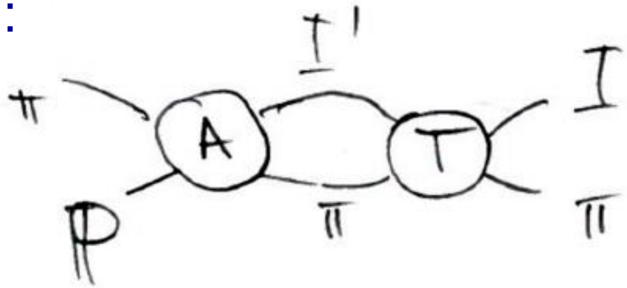
⇨ Study rescattering effects (C. Hanhart et al.)



Unitarity constraints for production and interaction:

$$\Delta_s \hat{a}(s) = 2i\,\rho(s)\,\hat{t}^*(s)\,\hat{a}(s), \qquad (1)$$

$$\Delta_s \hat{t}(s) = 2i\,\rho(s)\,|\hat{t}(s)|^2, \qquad (2)$$



With $\hat{t}(s) = N(s)/D(s)$

(2) becomes $\Delta_s D(s) = -2i\rho(s)N(s)$

with general solution $D(s) = D_0(s) - \frac{1}{\pi}\int_{s_{th}}^{\infty} ds' \frac{\rho(s')N(s')}{s'-s}.$

Parameterize $D(s)$ with CDD poles $D_0(s) = c_0 - c_1 s - \frac{c_2}{c_3 - s},$

LHC of $N(s)$ modeled with a higher-order pole

$$\rho(s)N(s) = g\lambda^{\frac{5}{2}}(s, m_\eta^2, \mathrm{m}_\pi^2)/(s+s_R)^7$$

Formalism

General solution for $\hat{a}(s)$ for a given $D(s)$ and $N(s)$

$$\hat{a}(s) = b(s) + \frac{1}{\pi D(s)} \int_{s_{th}}^{\infty} ds' \rho(s') \frac{N(s')b(s')}{s' - s} \equiv \frac{n(s)}{D(s)},$$

Parameterization of $n(s)$

$$n(s) = \frac{1}{c_3 - s} \sum_j^{n_p} a_j T_j(\omega(s)).$$