Exotic Meson Candidates from COMPASS

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Rheinische Friedrich-Wilhelms-Universität Bonn

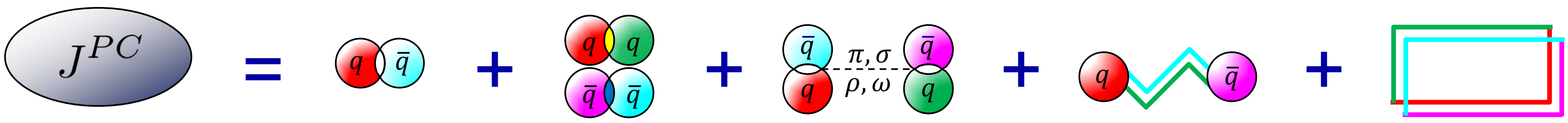
on behalf of the COMPASS Collaboration

International Workshop on e+e- collisions from Phi to Psi

Novosibirsk

27 February 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?

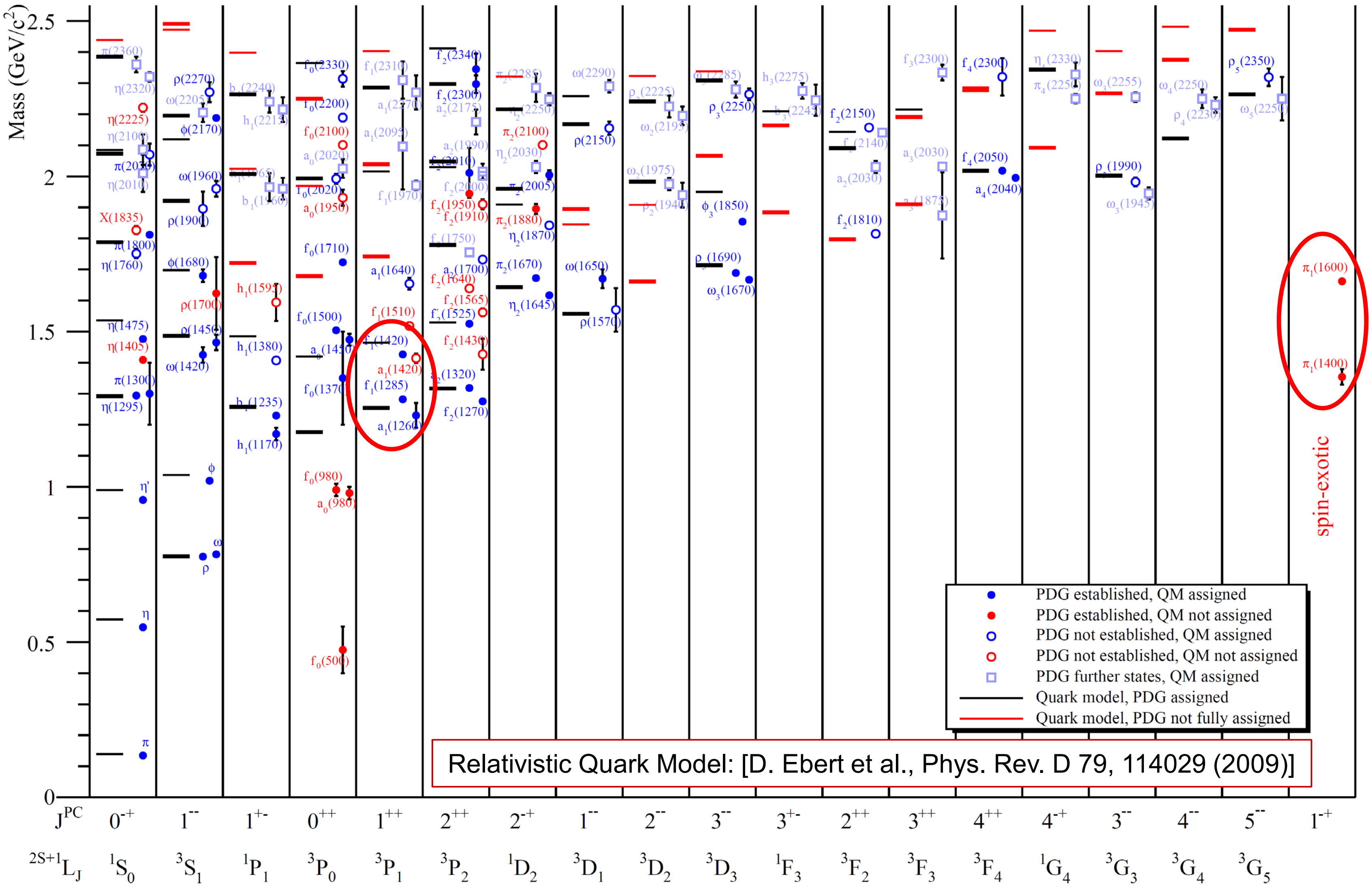
How to identify them?

- 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

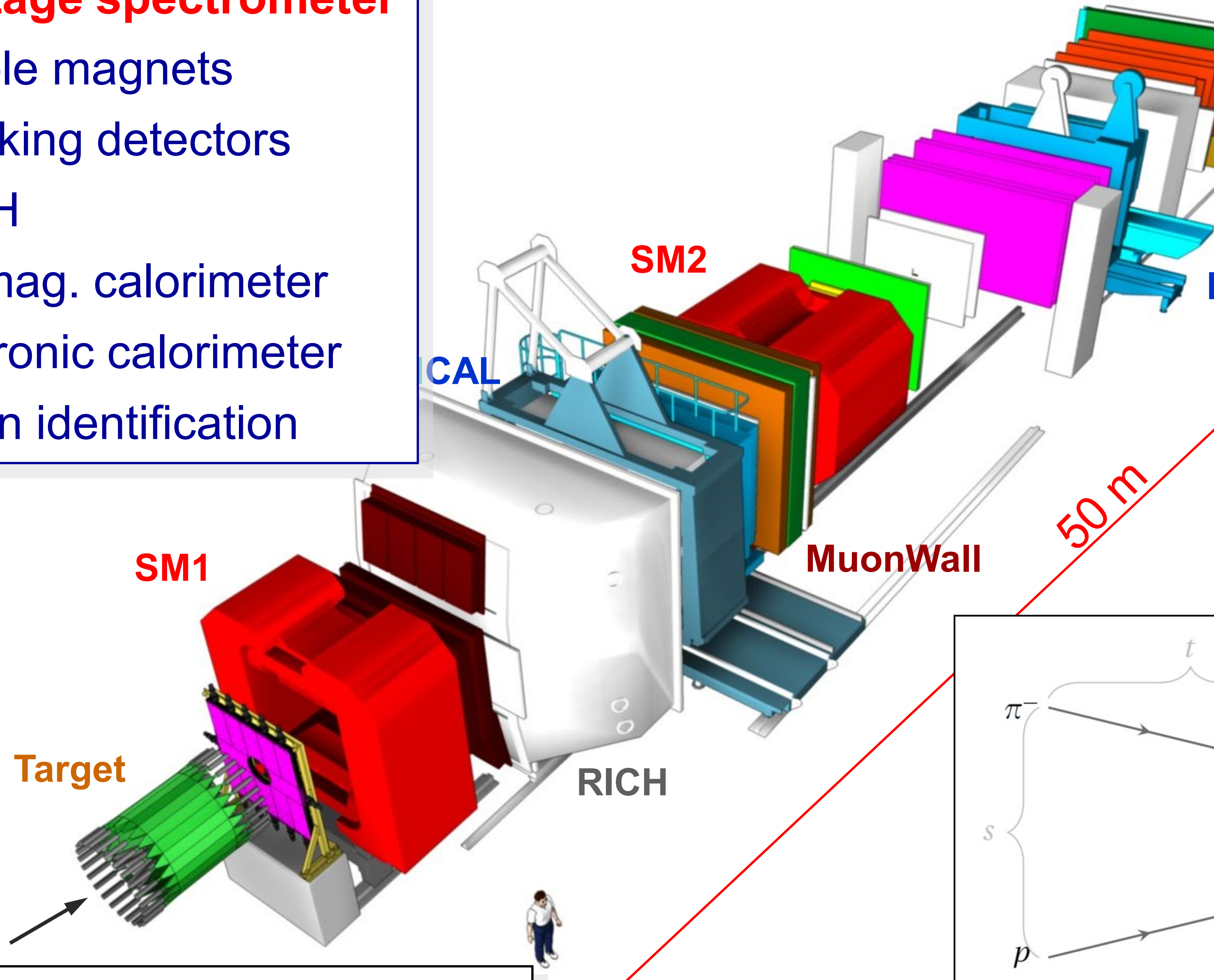
Light Meson Spectrum

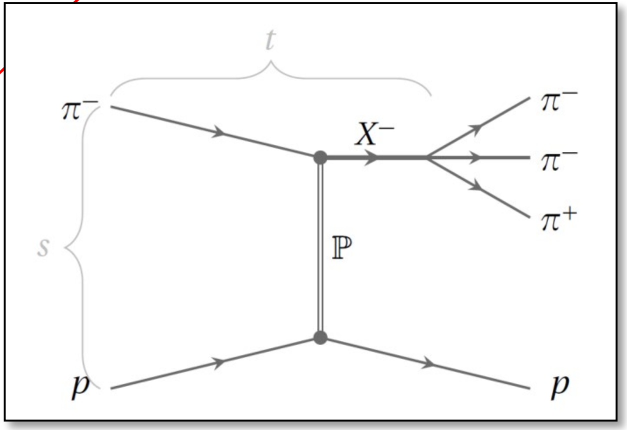


The COMPASS Experiment

Two-stage spectrometer

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

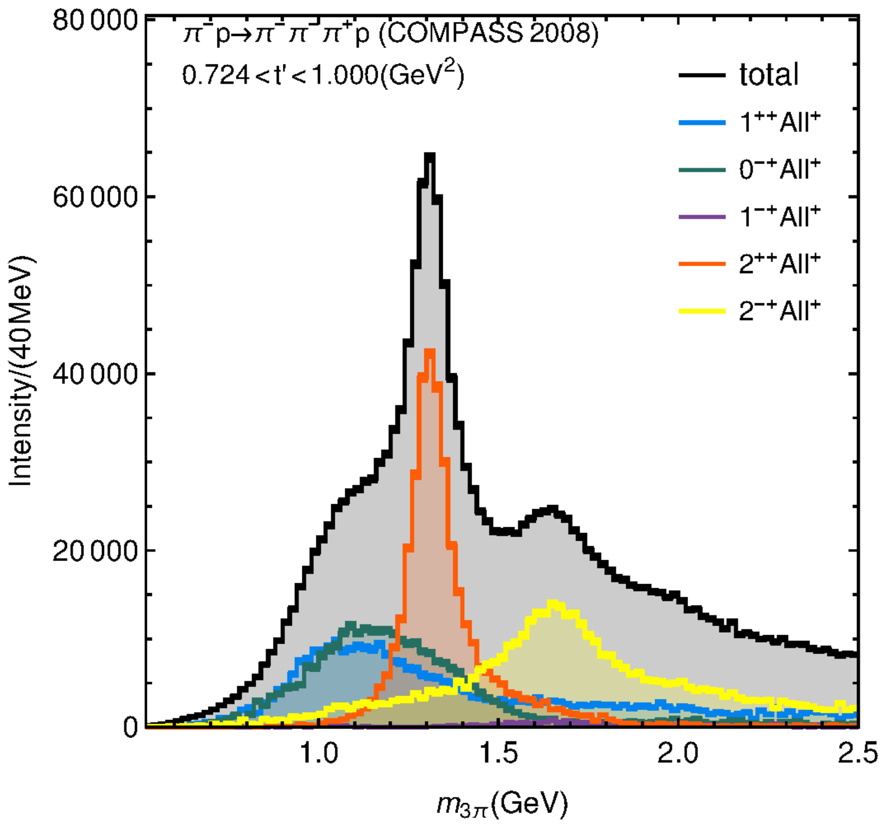




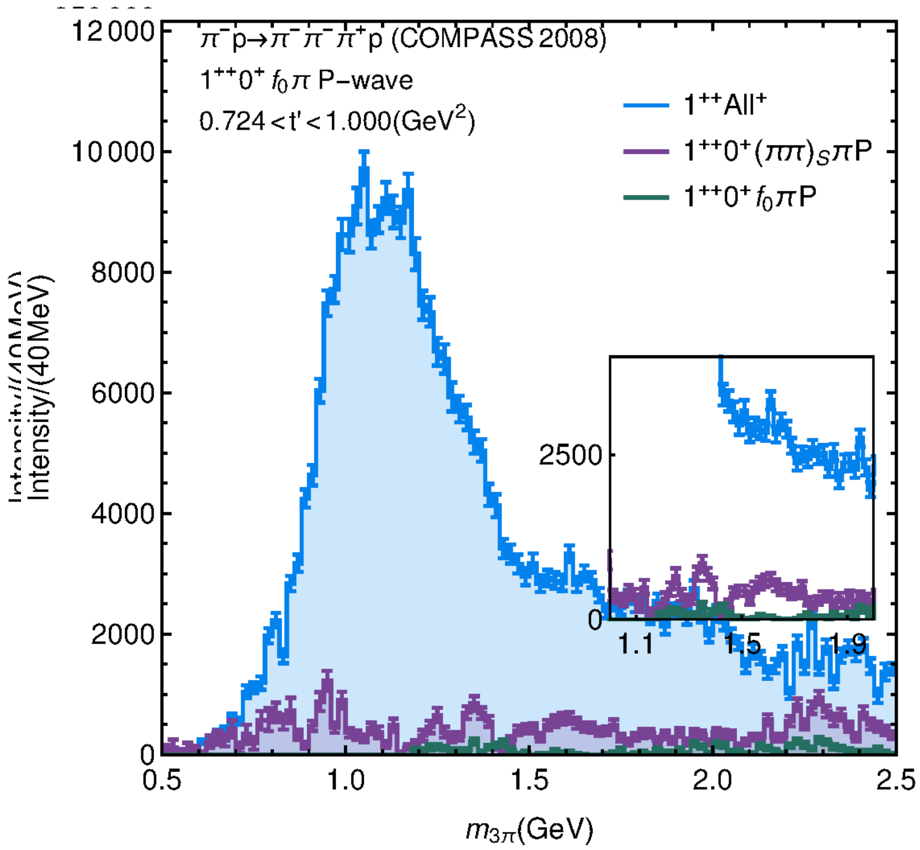
[COMPASS, P. Abbon et al., NIM A 779, 69 (2015)]

Partial-Wave Analysis

Total intensity



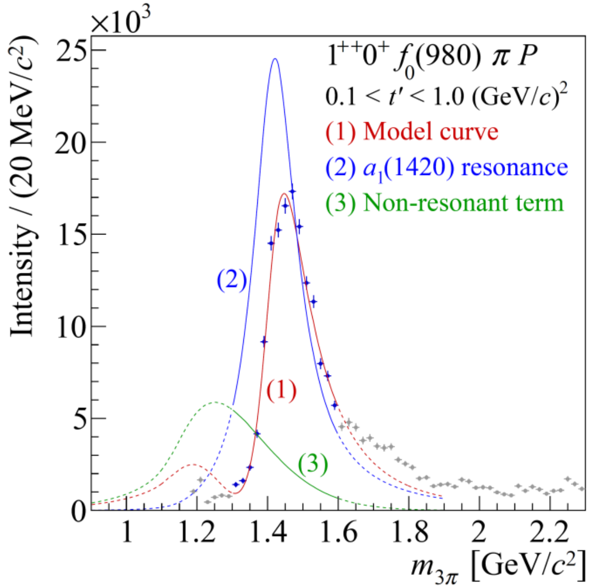
1^{++} Waves

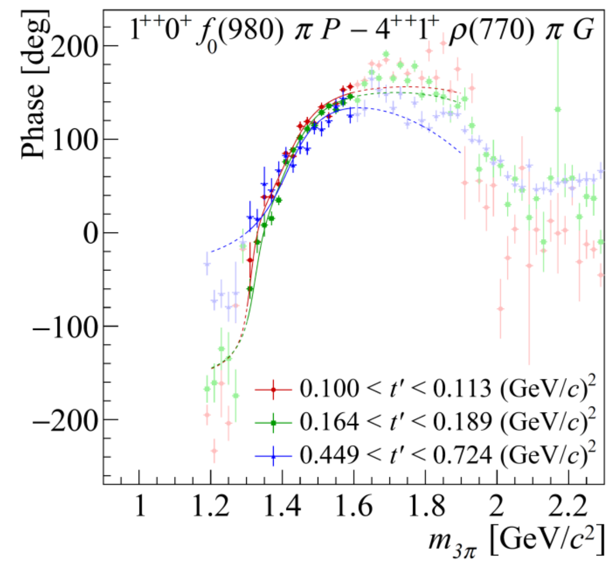


- Largest wave-set to date: 88 waves
- Independent fits in 100 bins (20 MeV) of $m_{3\pi}$ and 11 bins of t'

New $a_1(1420)$

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



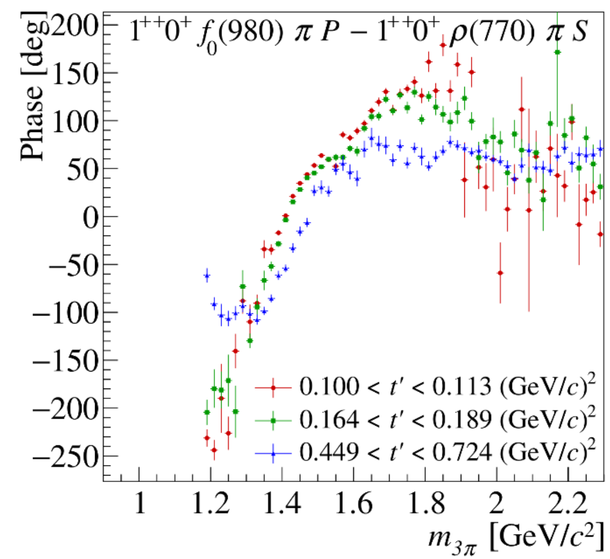


- Data described well by Breit-Wigner and non-resonant background
- Parameters for BW:

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

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

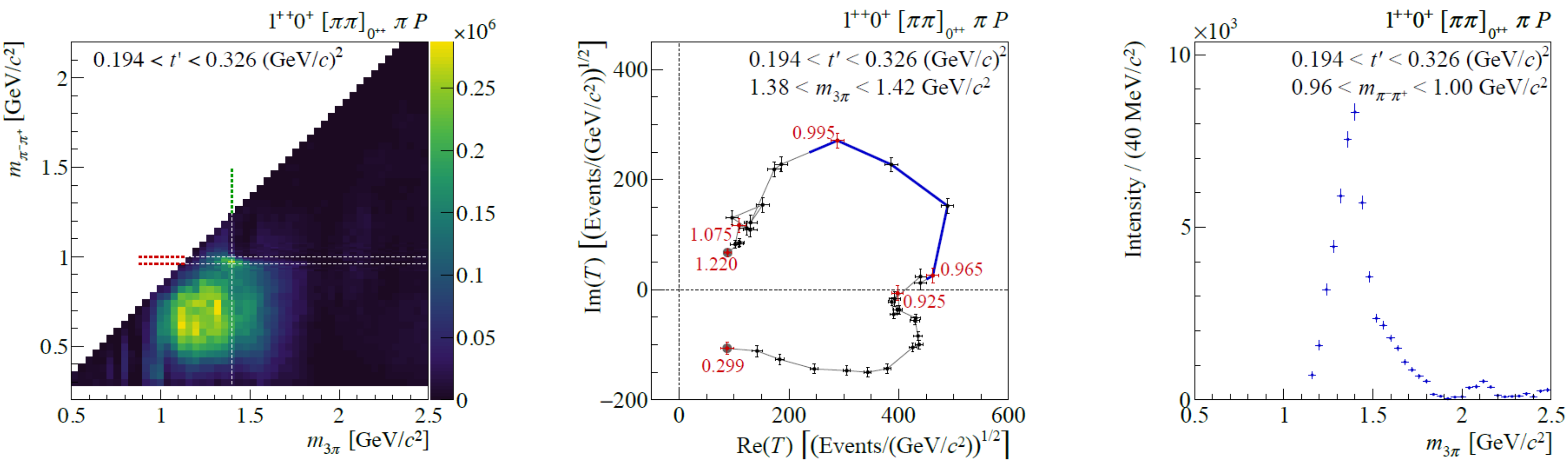
- Not an artefact of analysis (↗ freed isobar fit)



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

New $a_1(1420)$

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

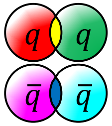


Freed isobar analysis (model-independent isobar amplitude):

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

Interpretations

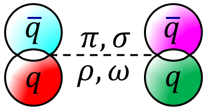
- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]



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

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)]



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

Interpretations

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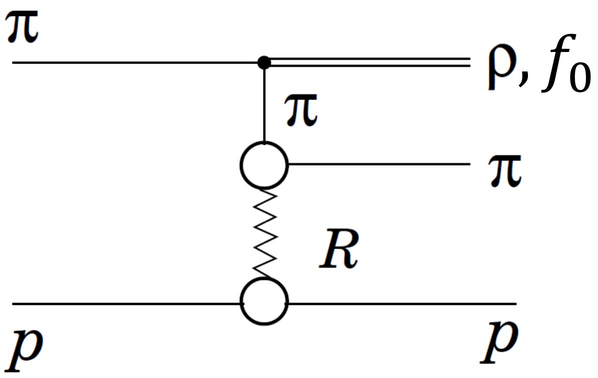
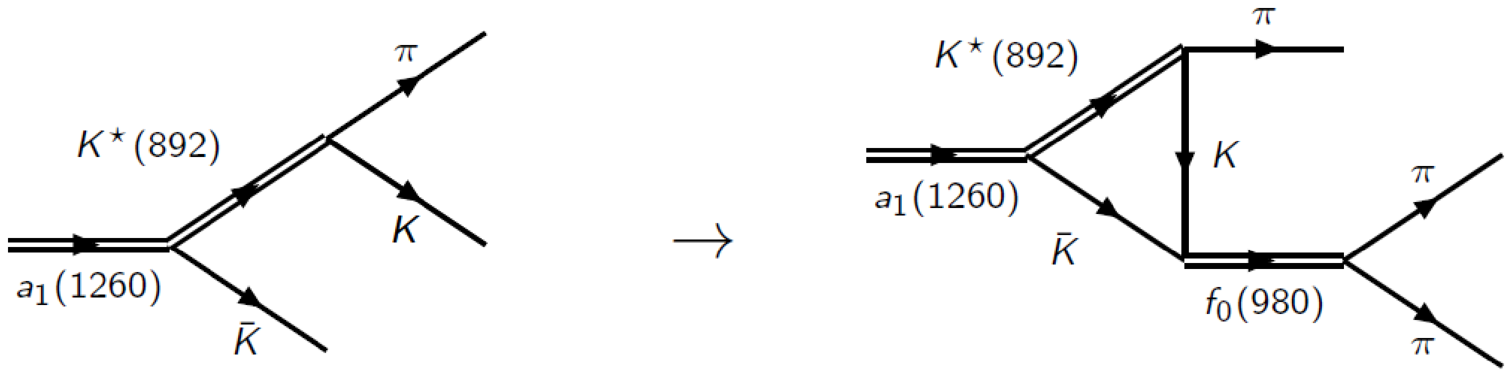
- $K^*\overline{K}$ molecule [T. Gutsche et al. (2017)]
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al. (2015)]



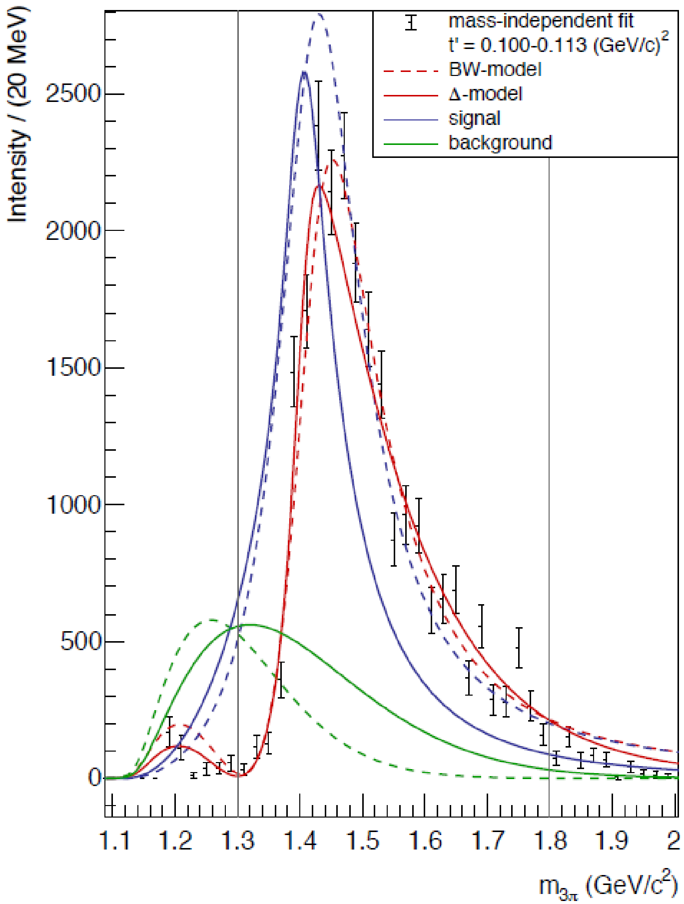
Interpretations

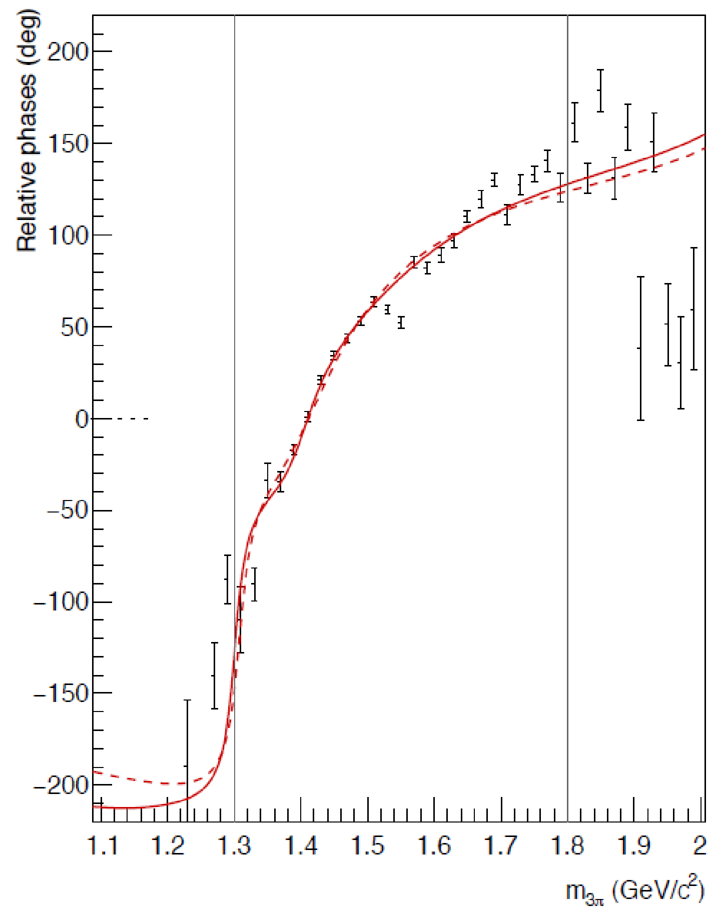
- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]
- $K^*\overline{K}$ molecule [T. Gutsche et al. (2017)]
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al. (2015)]
- Triangle singularity [M. Mikhasenko et al., PRD 91, 094015 (2015),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

Comparison TS - BW

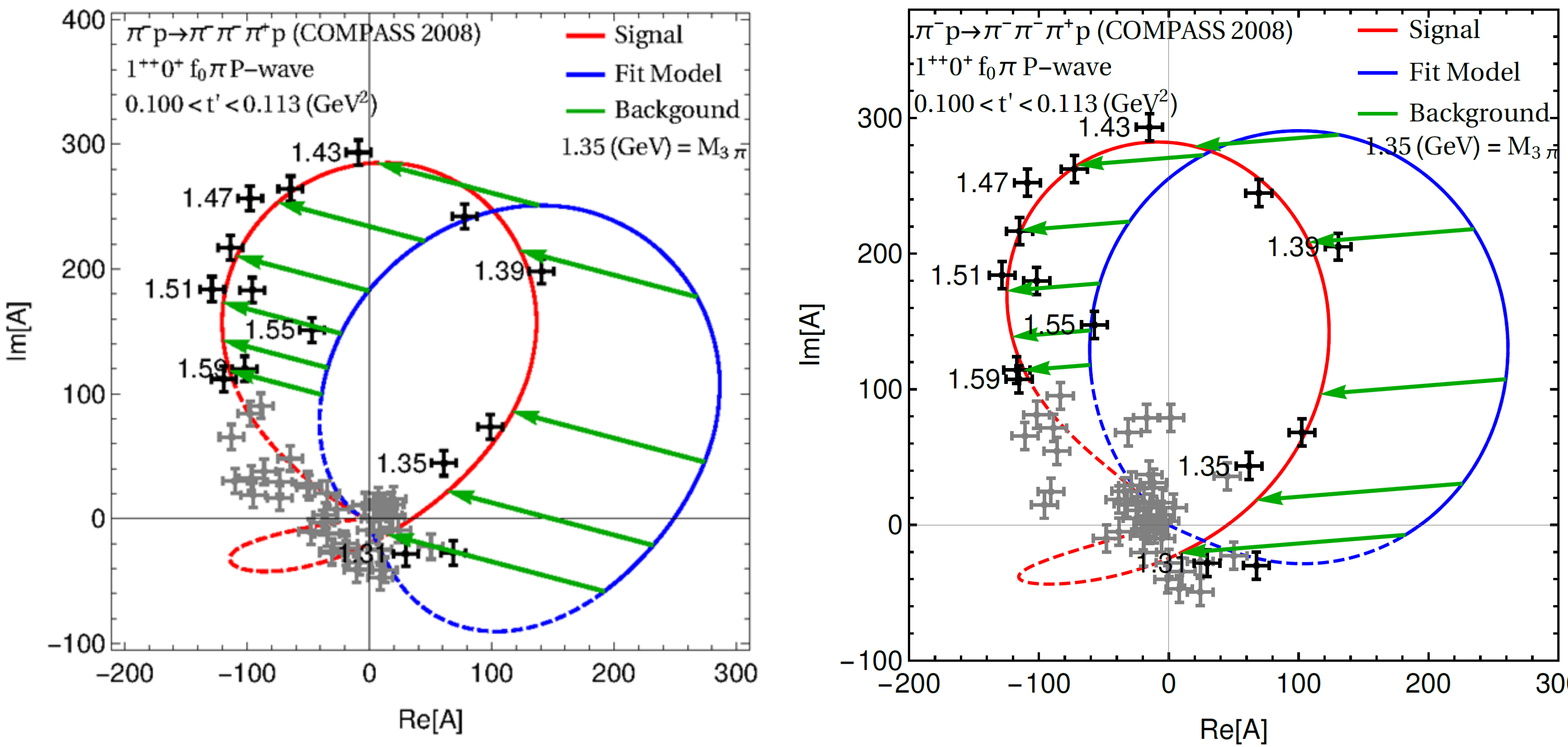




- Similar χ^2_{red} for both fits (slightly better for triangle)
- No new free parameters for $a_1(1420)$ signal by triangle mechanism

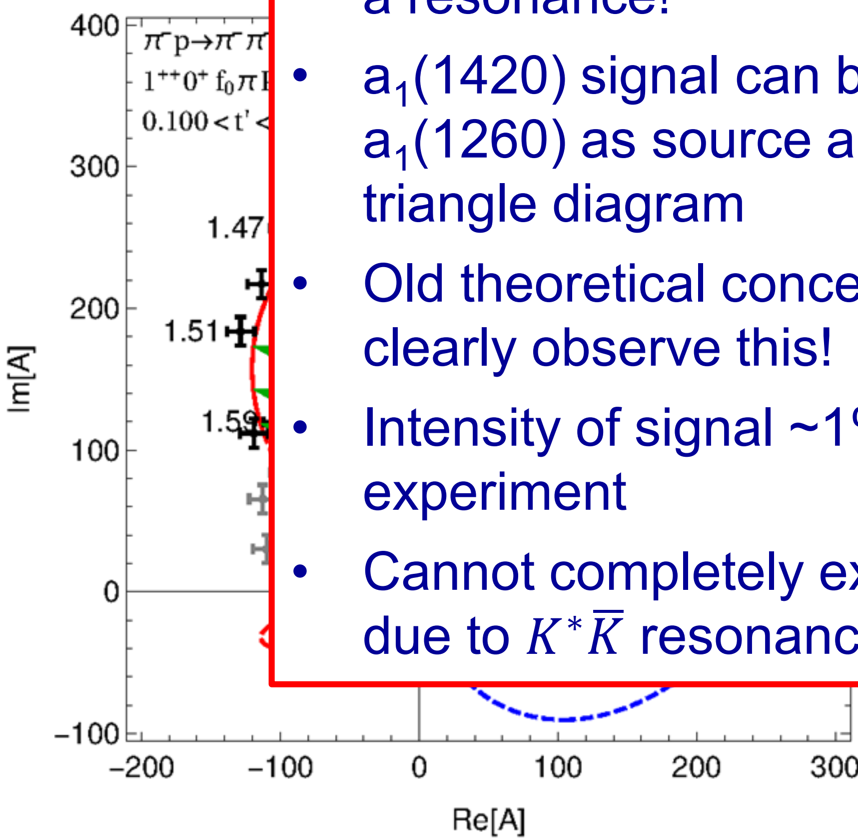
Comparison TS - BW

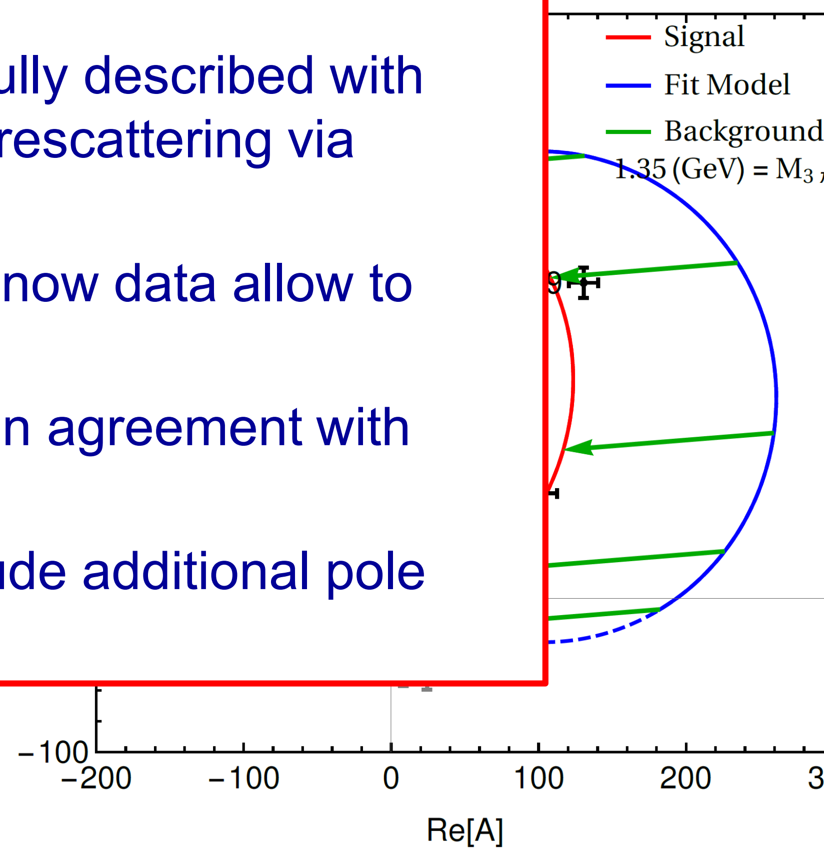
- Phase motion of pure triangle diagram is only ~ 90°
- Observed phase motion close to 180° produced by shift due to background



Comparison TS - BW

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

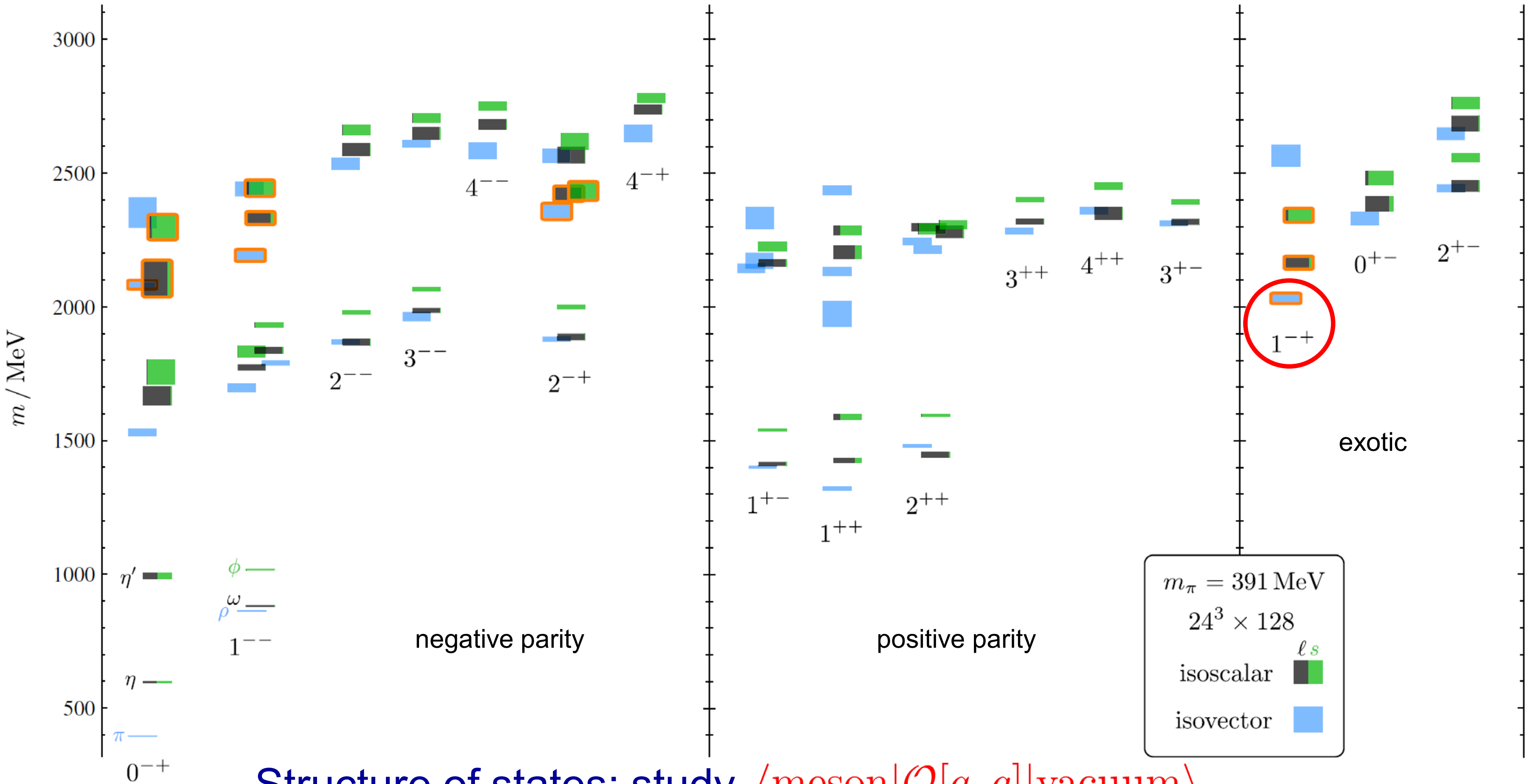




Summary for $a_1(1420)$

- 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

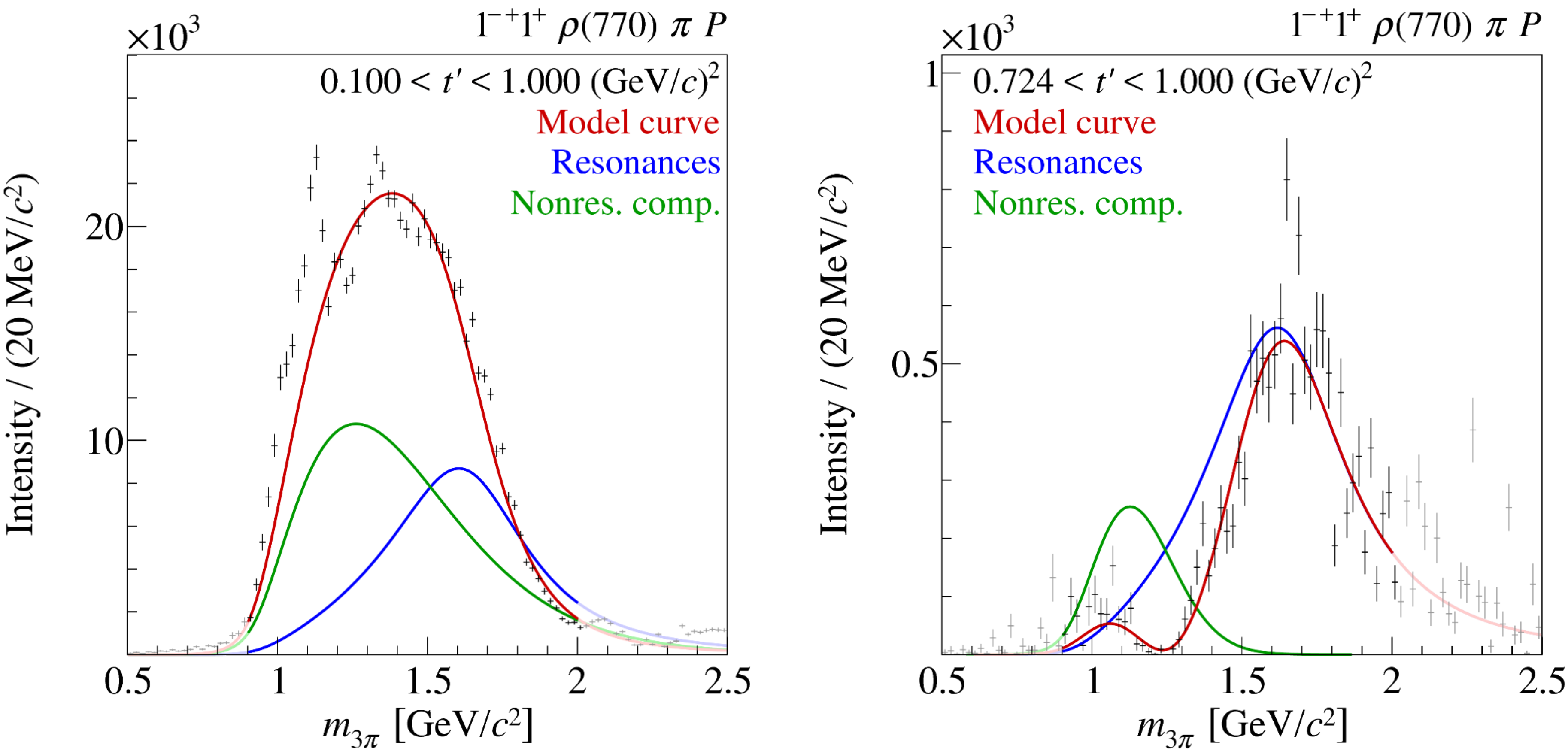


Structure of states: study $\langle \text{meson} | \mathcal{O}[q,g] | \text{vacuum} \rangle$

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)]

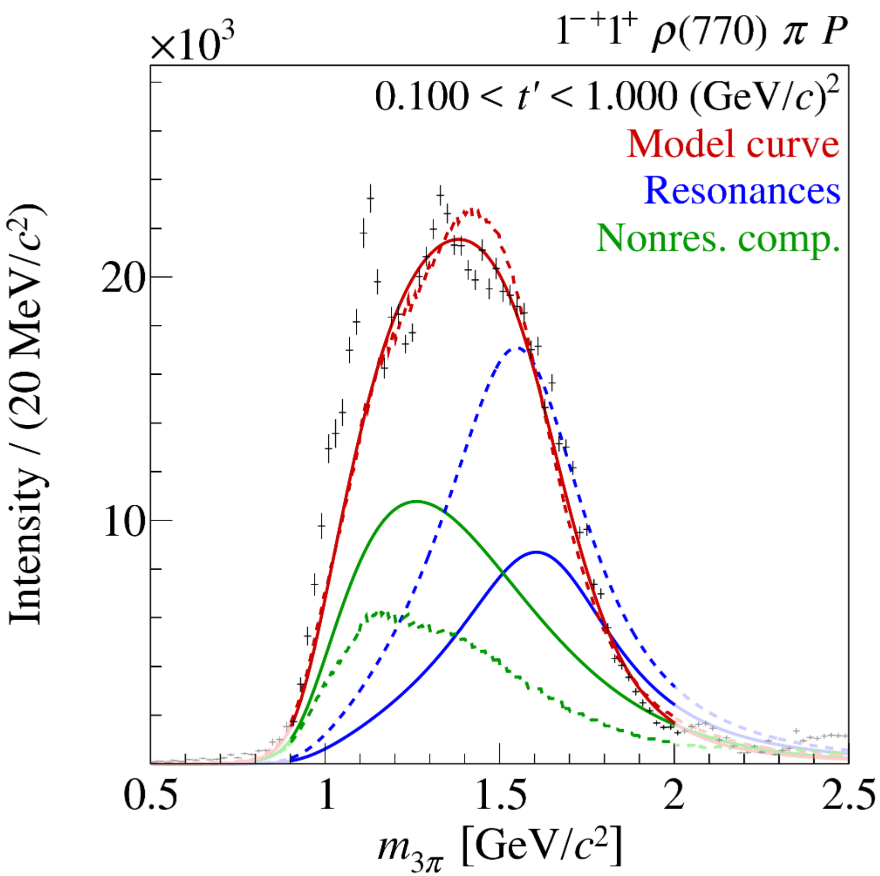
1^{-+} Partial Wave

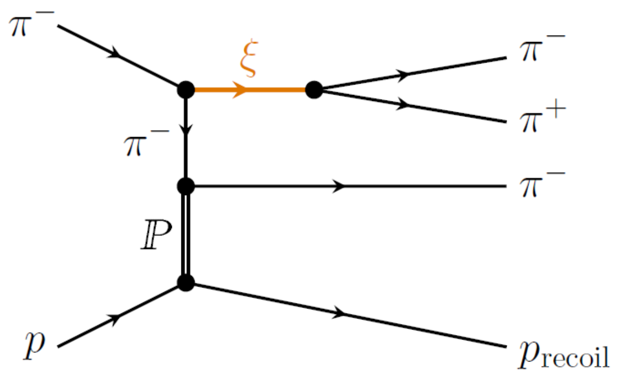


- Resonance-model fit to spin-density matrix: 14 waves
- Exploit t' dependence to separate resonant and non-resonant contributions

[R. Akhunzyanov et al. (COMPASS), Phys. Rev. D 98, 092003 (2018)]

1^{-+} Partial Wave





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

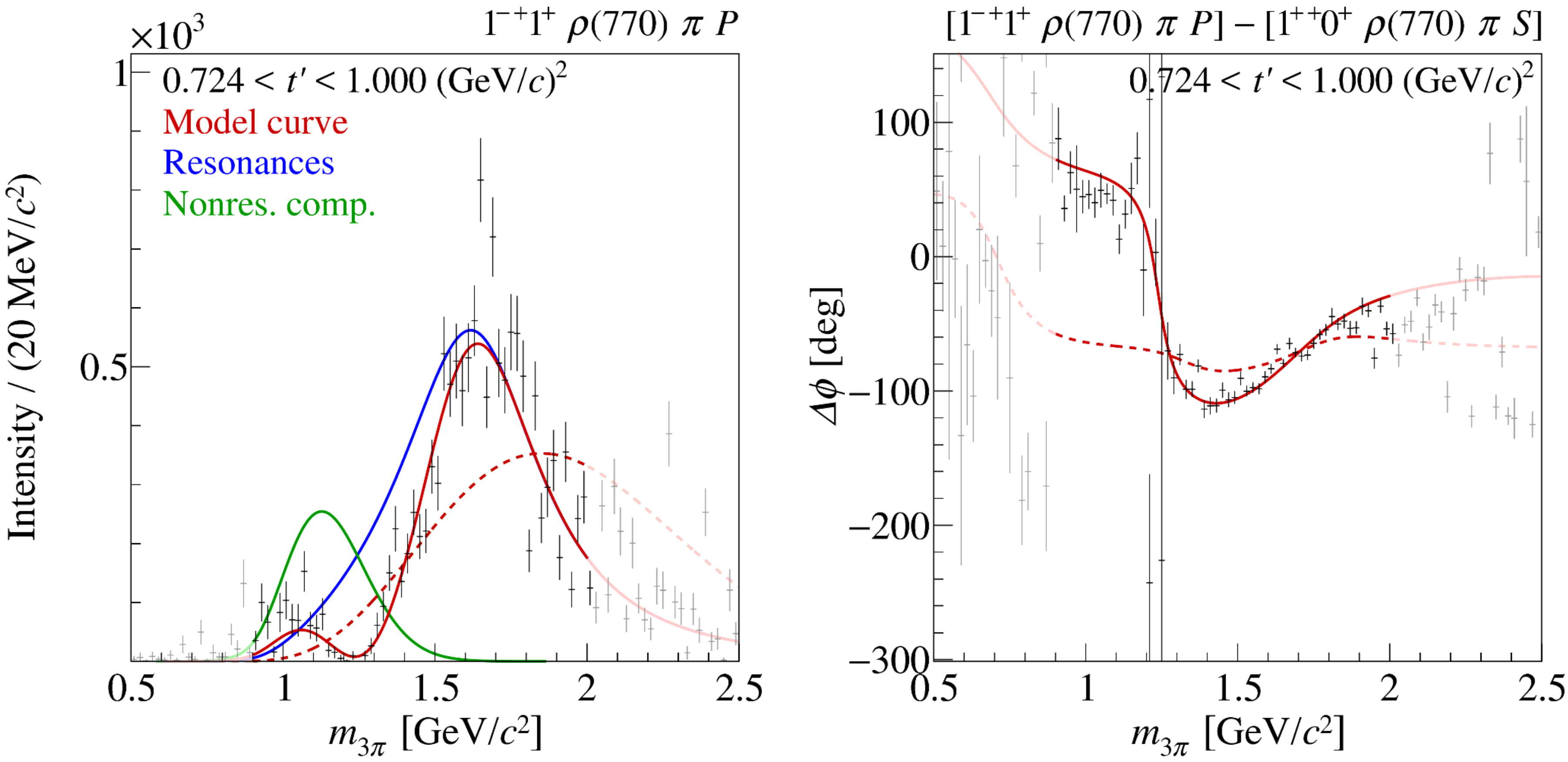
$$M_0 = 1600^{+110}_{-60}\ \mathrm{MeV}/c^2$$

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

- Bad description of data without resonance component

[R. Akhunzyanov et al. (COMPASS), Phys. Rev. D 98, 092003 (2018)]

1^{-+} Partial Wave

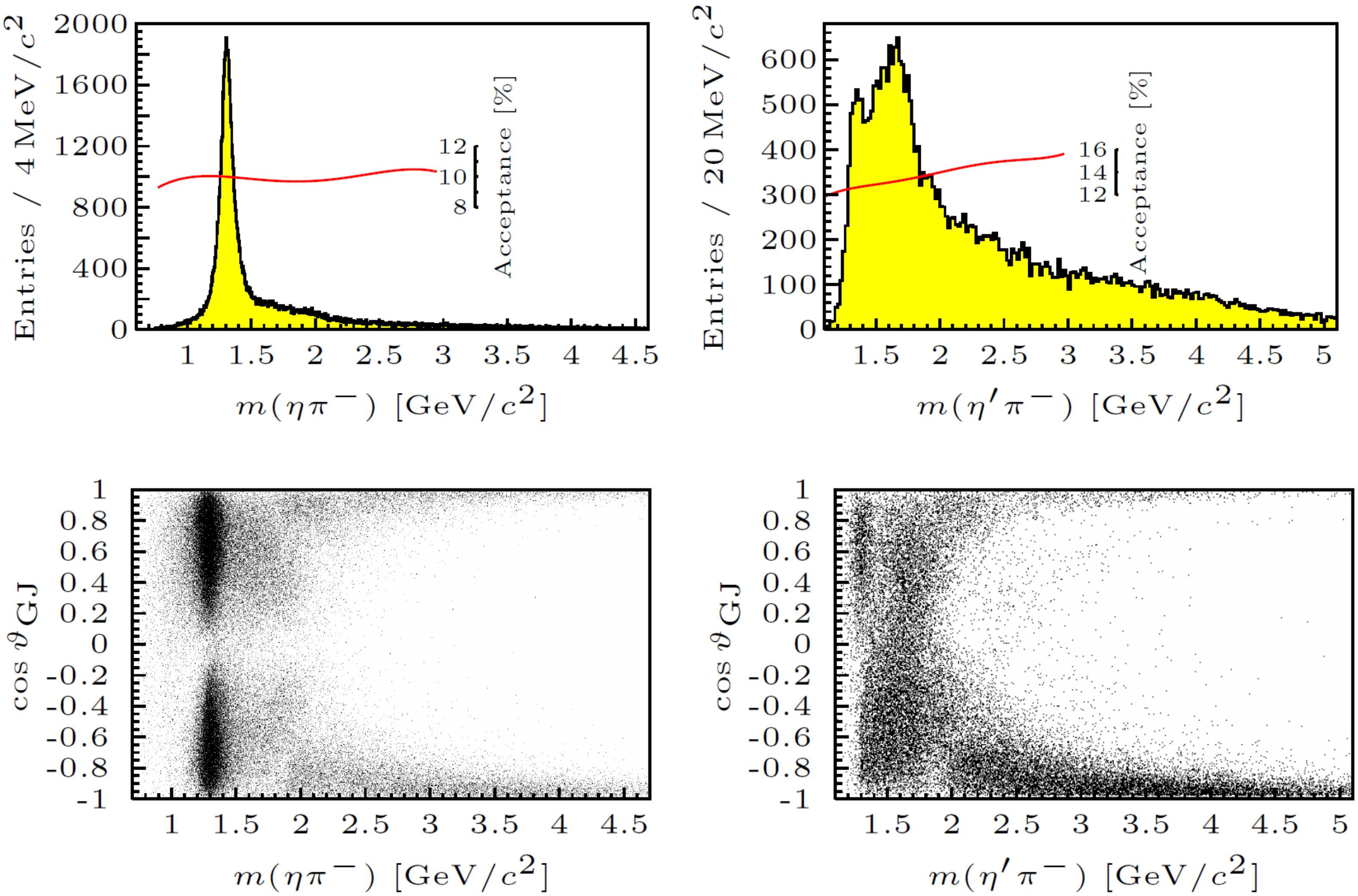


Bad description of data without resonance component

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

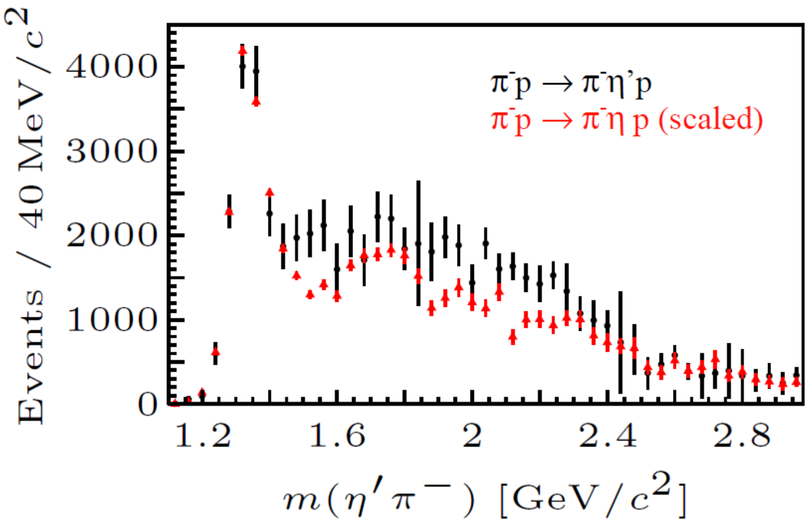
[R. Akhunzyanov et al. (COMPASS), Phys. Rev. D 98, 092003 (2018)]

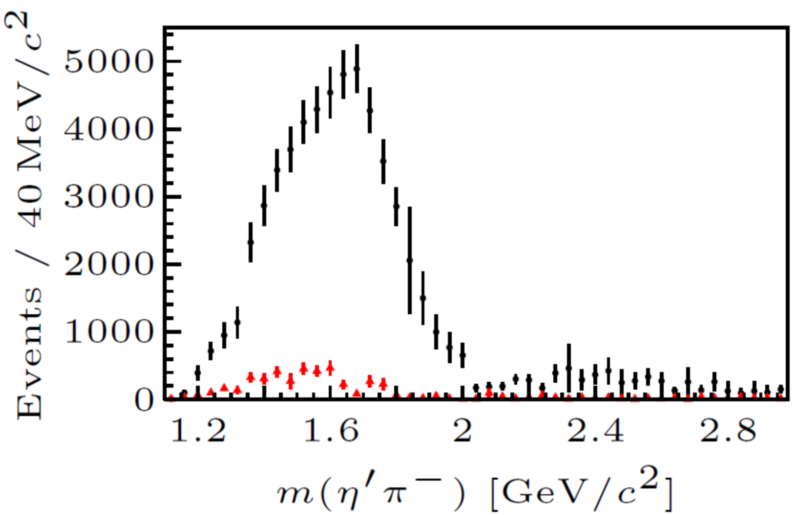
$\eta\pi^-$ / $\eta'\pi^-$ Final States

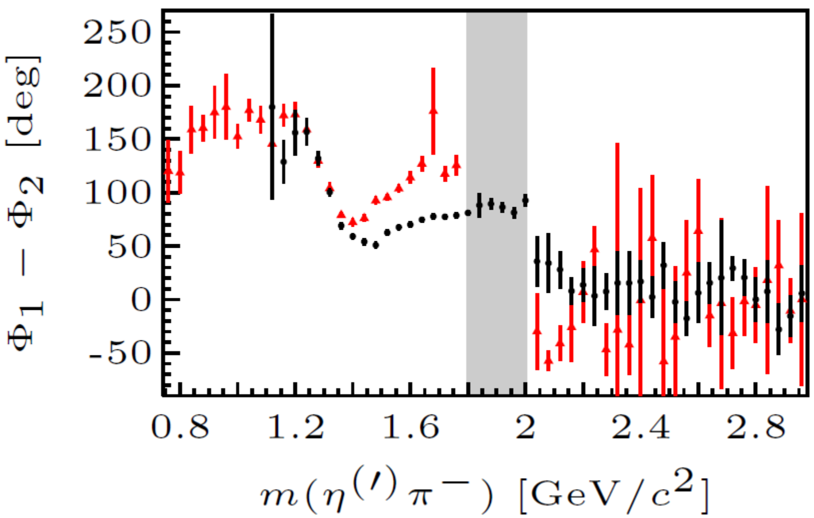


[C. Adolph (COMPASS), Phys. Lett. B 740, 303 (2015)]

ηπ⁻ / η'π⁻ Final States





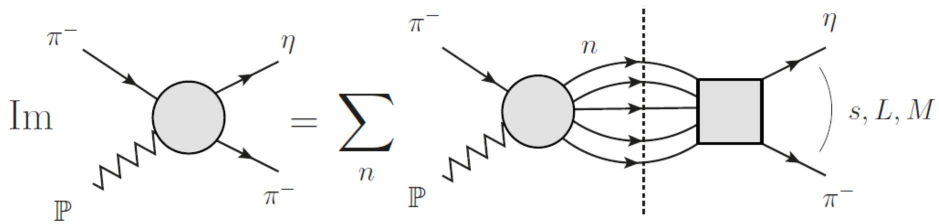


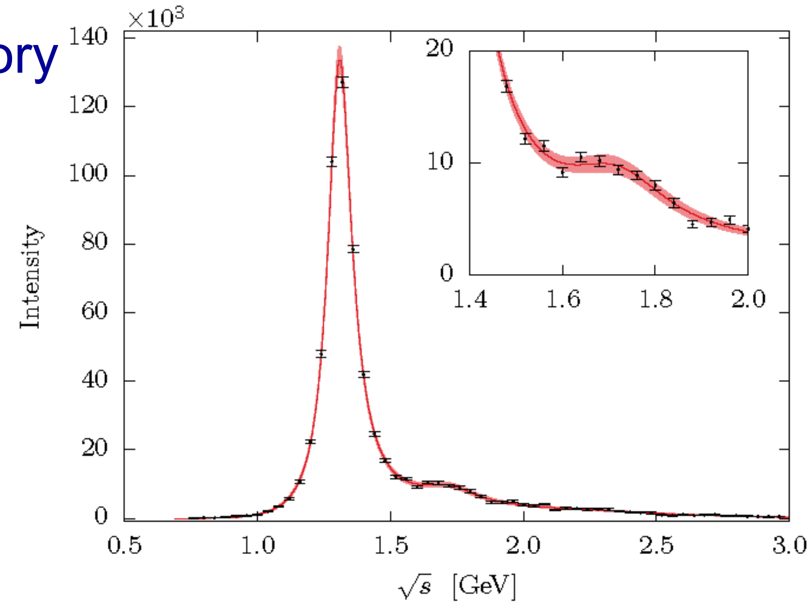
- ηπ⁻ waves scaled according to phase space and BR to final state
- *D*, *G* waves very similar
- *P* wave very different in ηπ and η'π
- Breit-Wigner model fit unstable

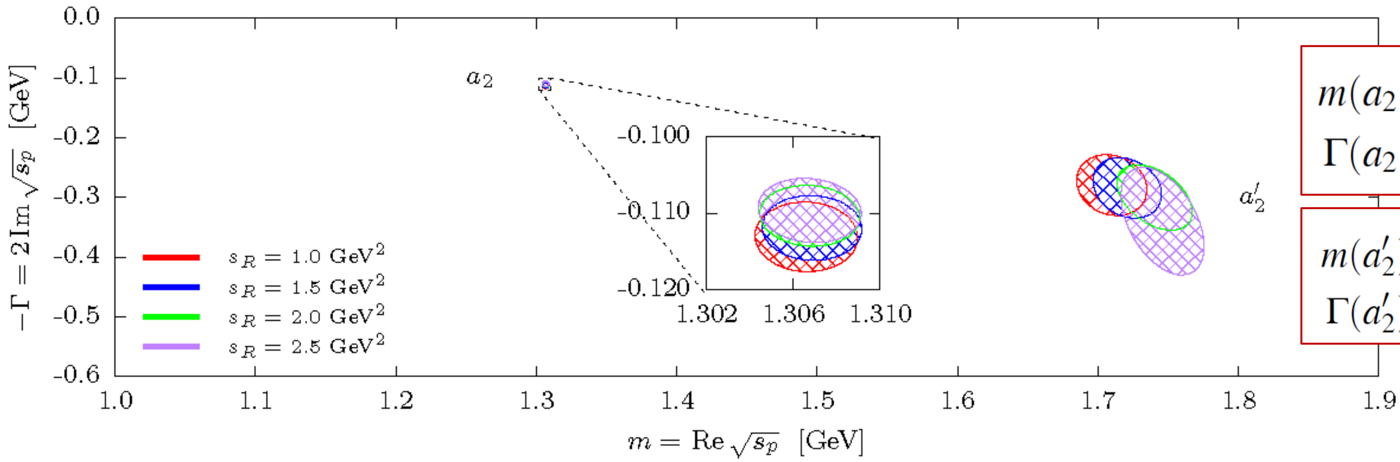
[C. Adolph (COMPASS), Phys. Lett. B 740, 303 (2015)]

Extraction of Poles

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





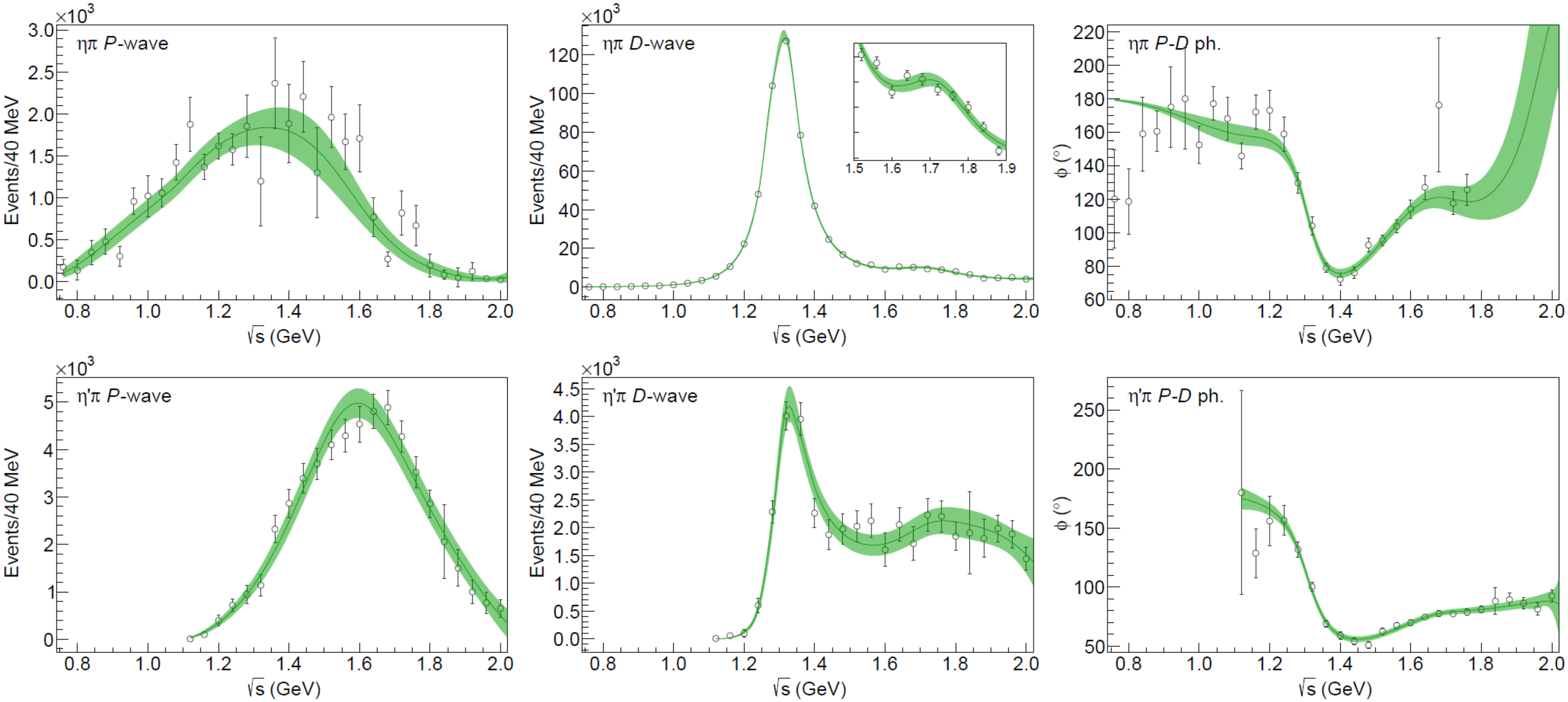


$$m(a_2) = (1307 \pm 1 \pm 6)\ \text{MeV},$$
$$\Gamma(a_2) = (112 \pm 1 \pm 8)\ \text{MeV},$$

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

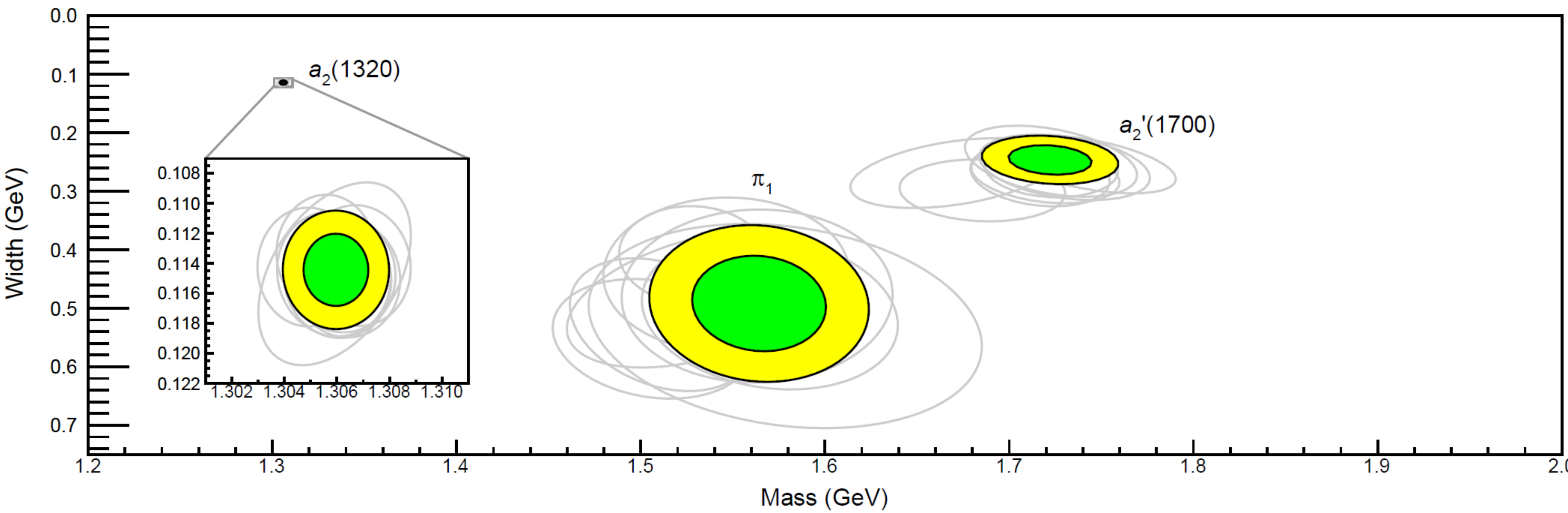
[A. Jackura et al. (JPAC, COMPASS), Phys. Lett. B 779, 464 (2018)]

ηπ–η′π Coupled Channels



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

$\eta\pi$–$\eta'\pi$ Coupled Channels



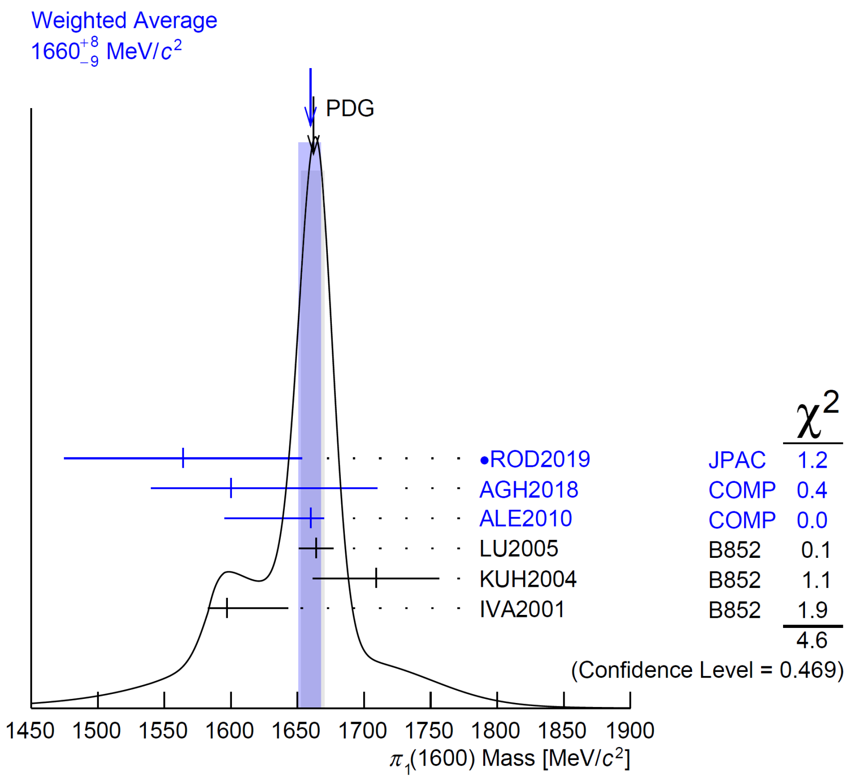
- only a single pole needed to describe both $\eta\pi$ and $\eta'\pi$ peaks
- consistent with π_1(1600)

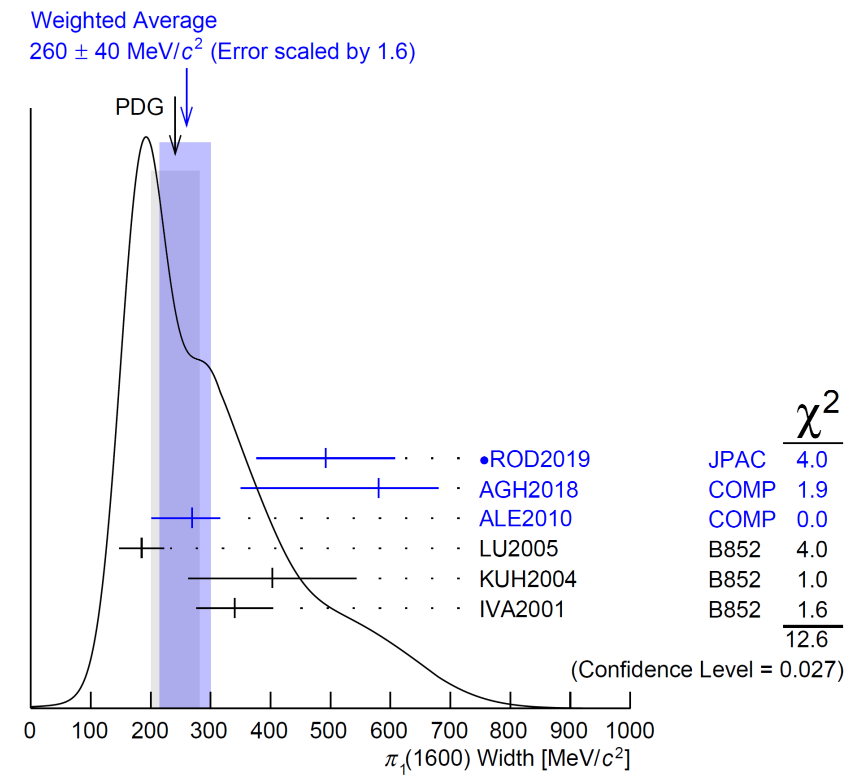
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

[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 a new era
- Statistical uncertainties very small, systematic model uncertainties dominate
- Large data sample on diffractive of COMPASS ⇨ PWA in bins of m_X and t'
- Spin-exotic $\pi_1(1600)$: (re-) observed by COMPASS
  - ⇨ $\rho\pi$ final states: resonance required to fit data, esp. at high t
  - ⇨ $\eta\pi - \eta'\pi$ coupled channel analysis: one single pole sufficient
  - ⇨ background due to Deck-like production important
- 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

COMPASS++ / AMBER

UNIVERSITÄT BONN

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN

Letter of Intent (Draft 2.0)

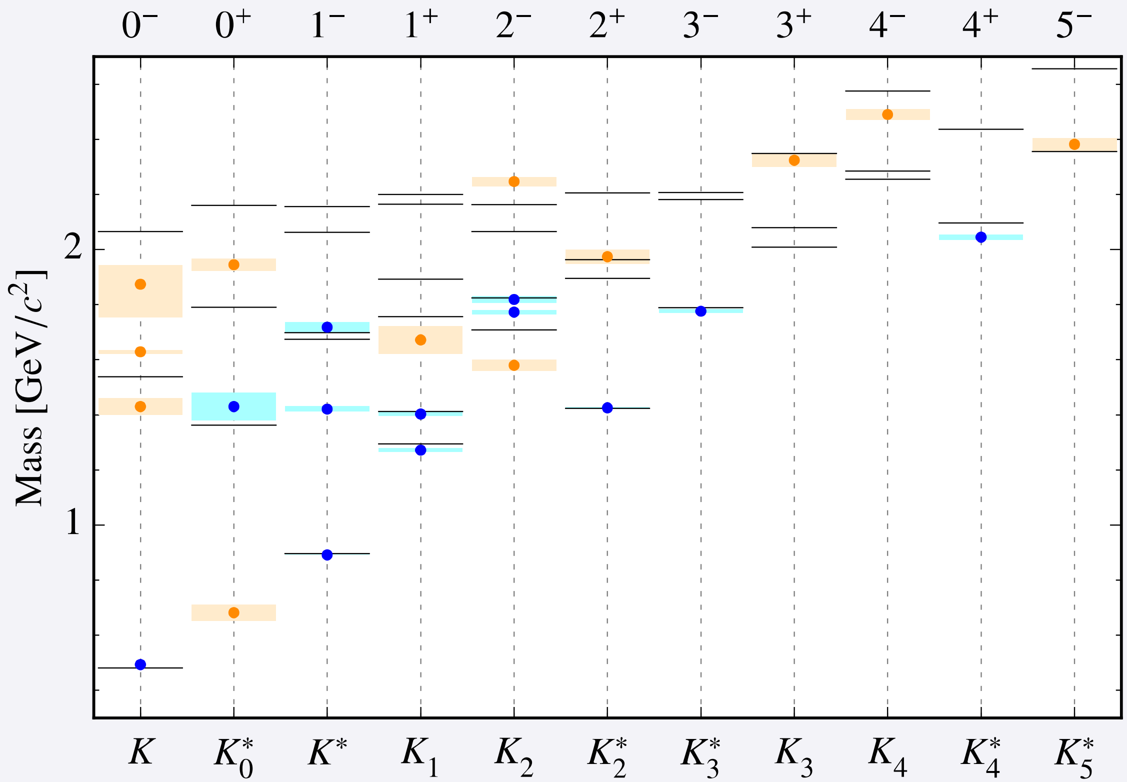
A New QCD facility at the M2 beam line of the CERN SPS

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

Kaon Excitation Spectrum



[Courtesy of S. Wallner, TUM]

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

New Beam: RF Separation

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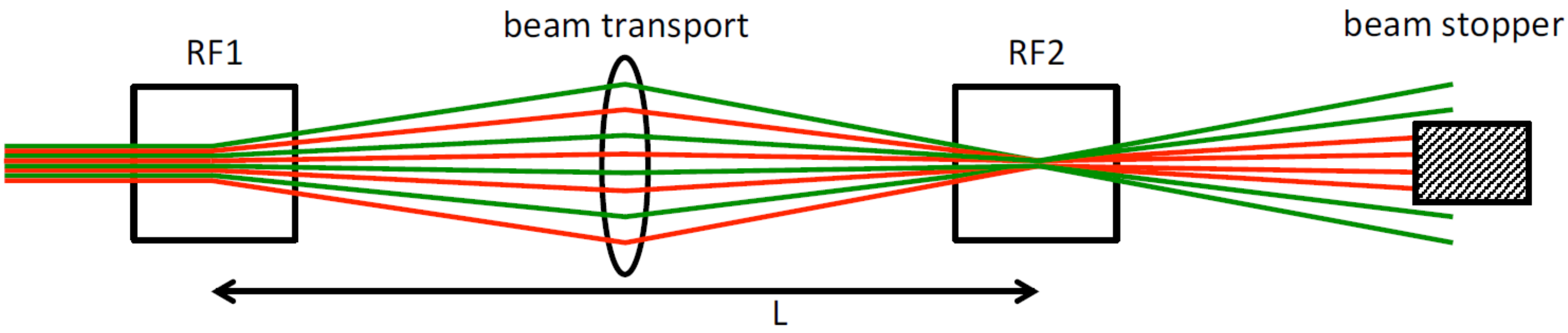
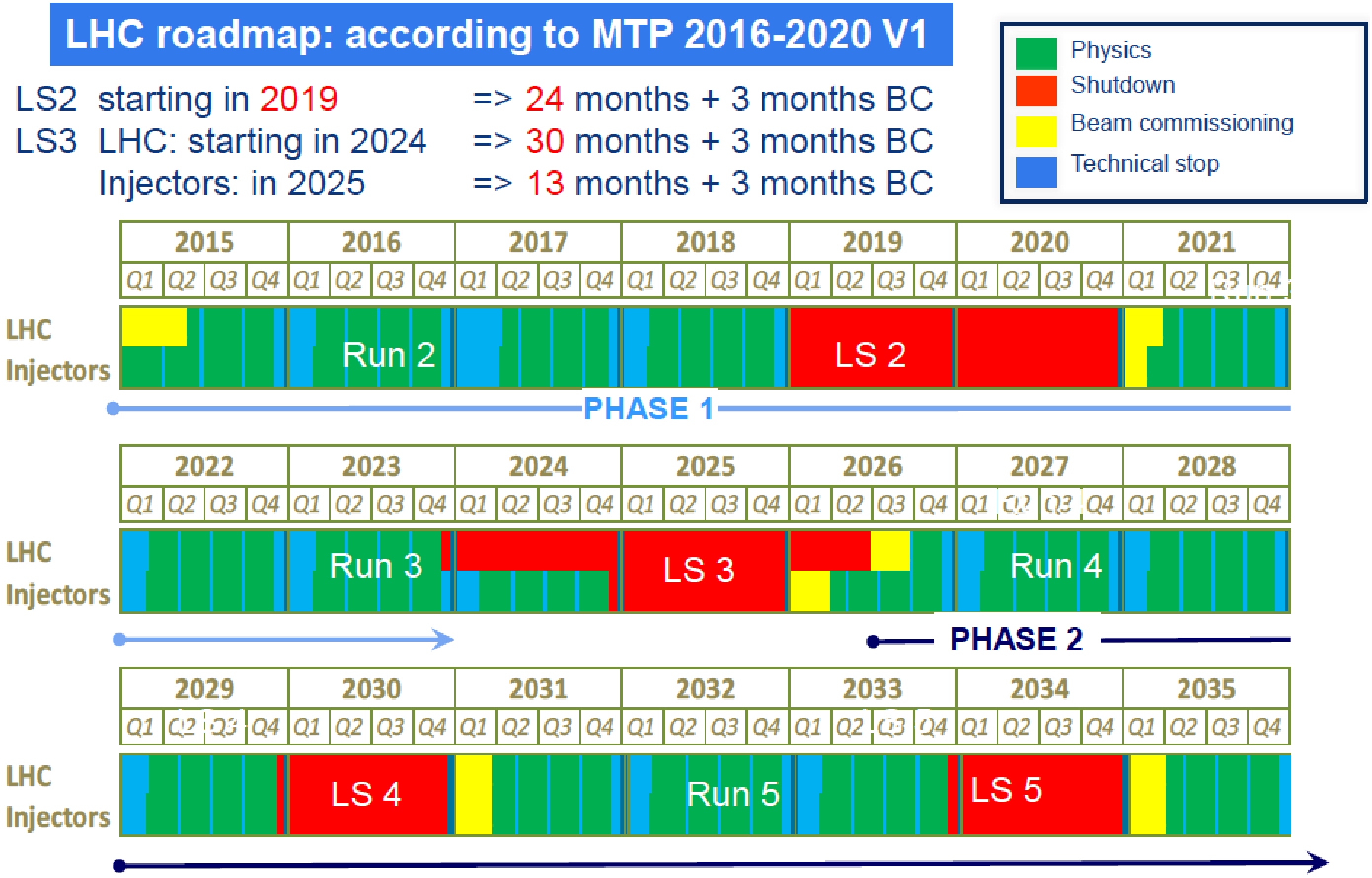
Reminder: Panofsky-Schnell-System with two cavities (CERN 68-29)



- 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: $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2\mathbf{p}^2$

Timelines



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

Overview of Physics Topics

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Interested?

- a diverse and exciting QCD physics programme is compiled for being carried out at a powerful future facility at the M2 beamline of CERN SPS
- further collaborators are welcome
- if interested sign up through our web page: