Exotic Meson Candidates from COMPASS

Bernhard Ketzer

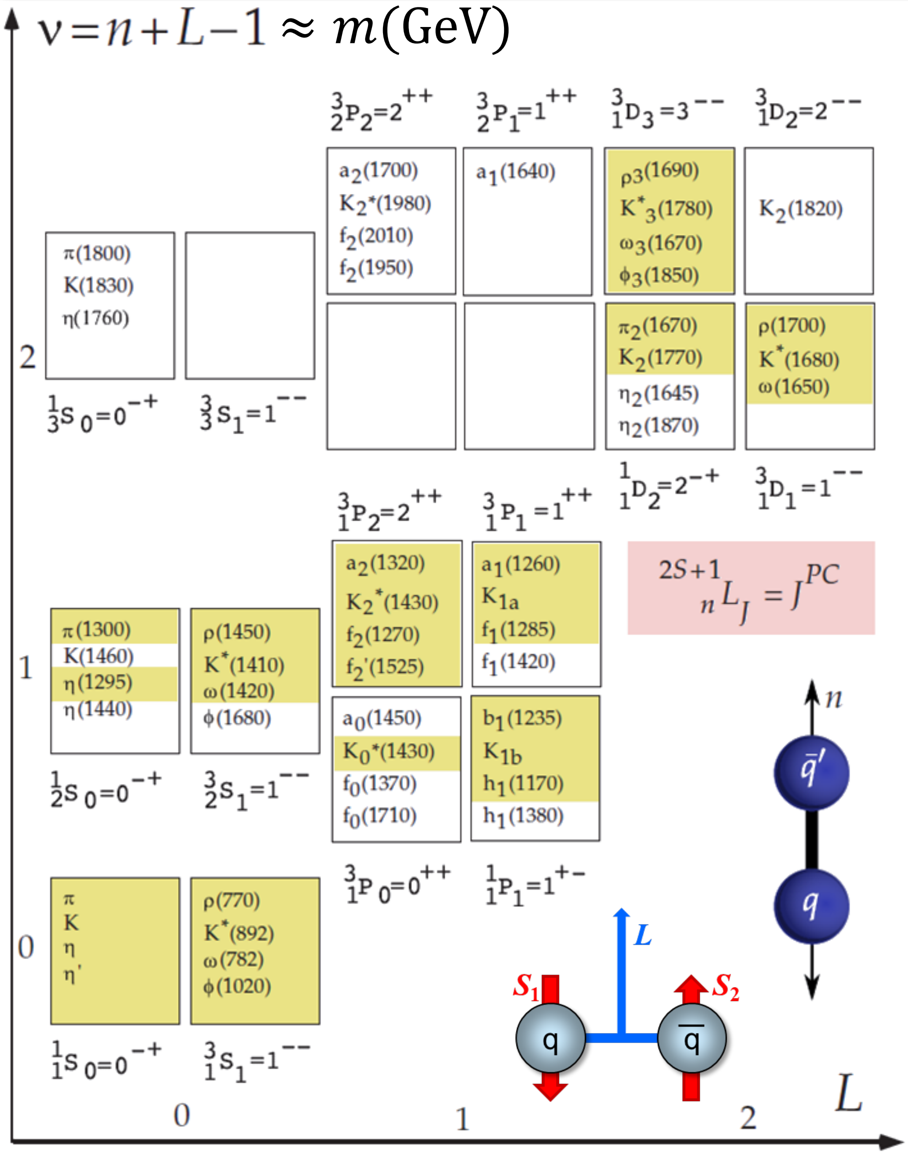
Rheinische Friedrich-Wilhelms-Universität Bonn

The Spectroscopy Program at EIC and Future Accelerators

Trento

20 December 2018

Light Meson Spectrum



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

Quark model:

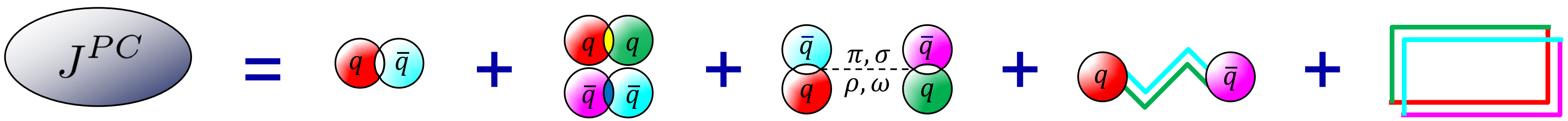
- SU(3)$_{flavor}$:

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

- color singlets

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

Exotic States



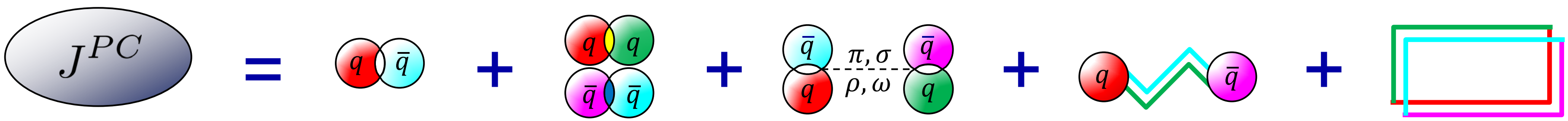
$(q\bar{q})_0$ $\quad (qq)_8(\bar{q}\bar{q})_8$ $\quad (q\bar{q})_0(q\bar{q})_0$ $\quad (q\bar{q})_8 g$ $\quad (gg)_0$

Tetraquark Molecule Hybrid Glueball

+ …

Where are they?

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?

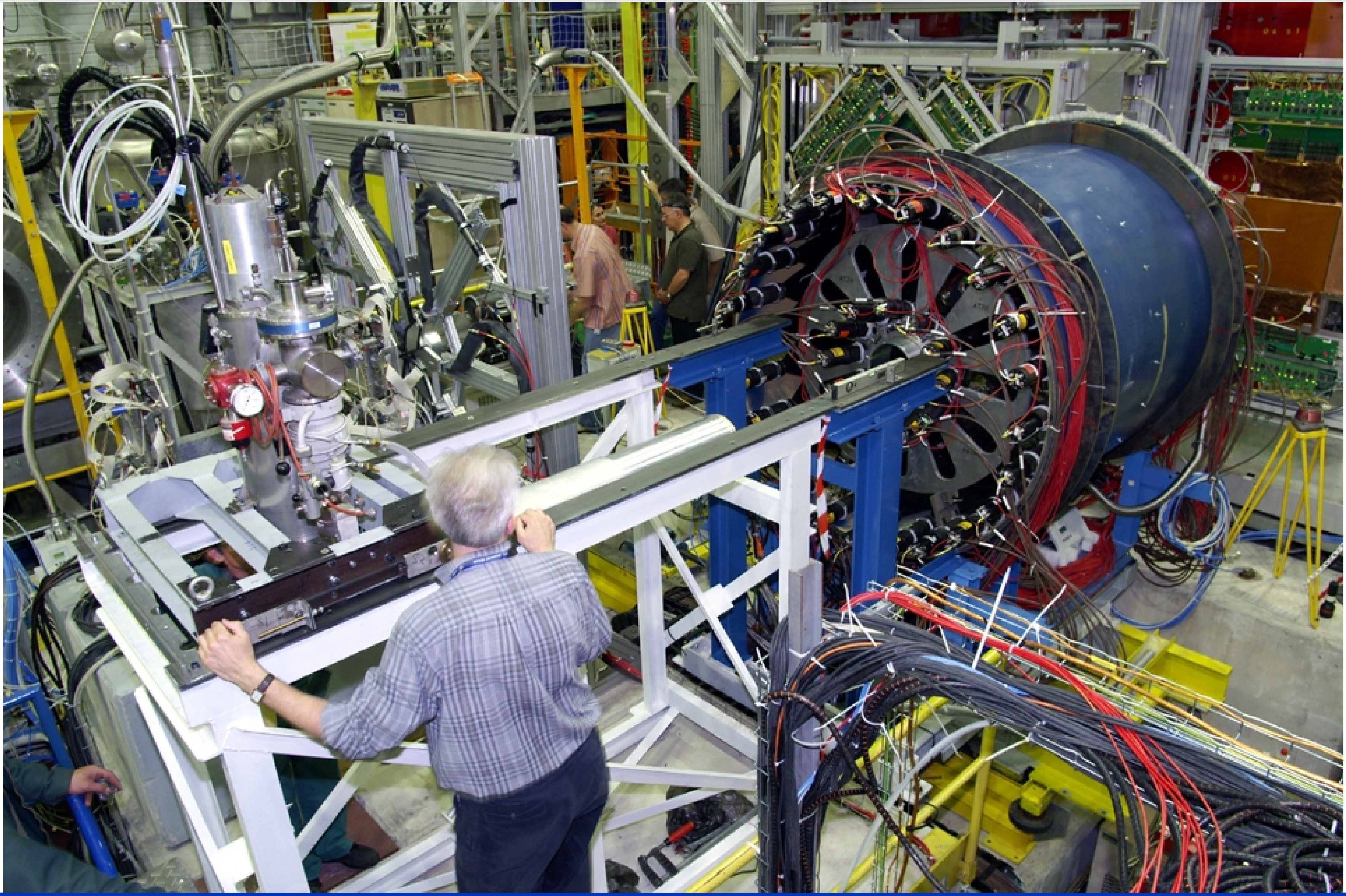
- Spin-exotic: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$
- Supernumerary states
- Charged QQbar, doubly charged QQ
- Comparison with models, lattice

Need:

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

The COMPASS Experiment

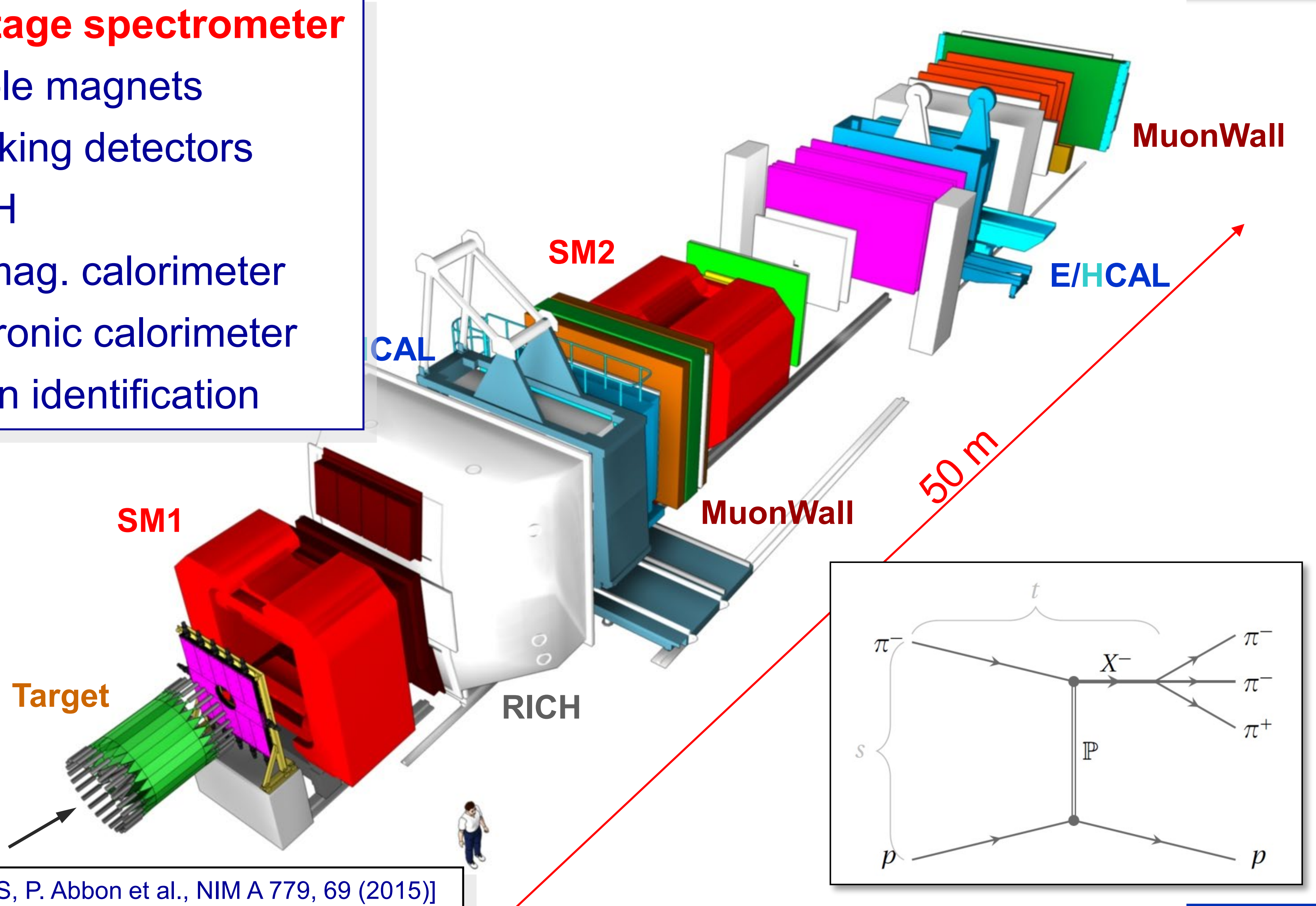
The COMPASS Experiment



The COMPASS Experiment

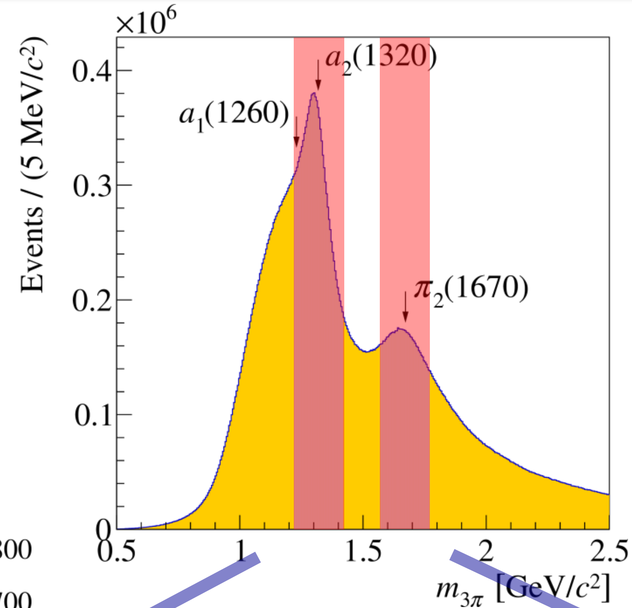
Two-stage spectrometer

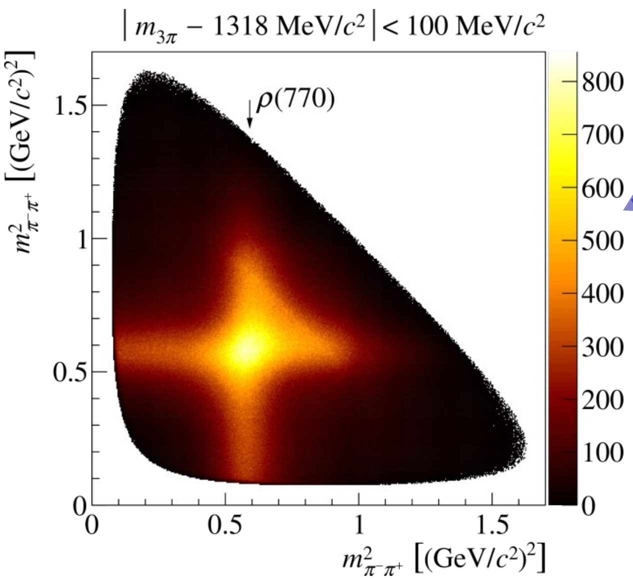
- Dipole magnets
- Tracking detectors
- RICH
- El.-mag. calorimeter
- Hadronic calorimeter
- Muon identification

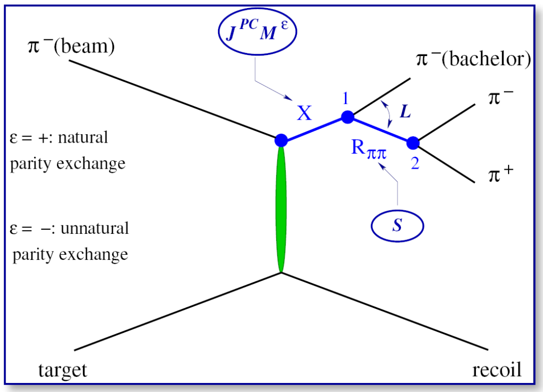


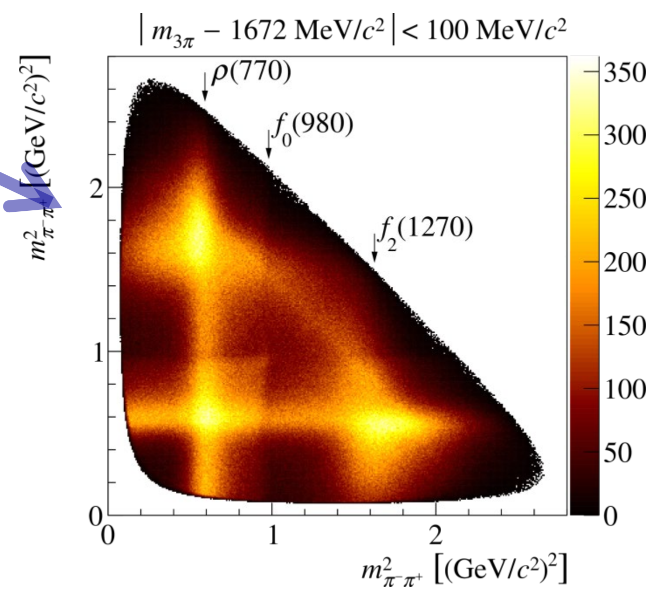
[COMPASS, P. Abbon et al., NIM A 779, 69 (2015)]

3π Final State



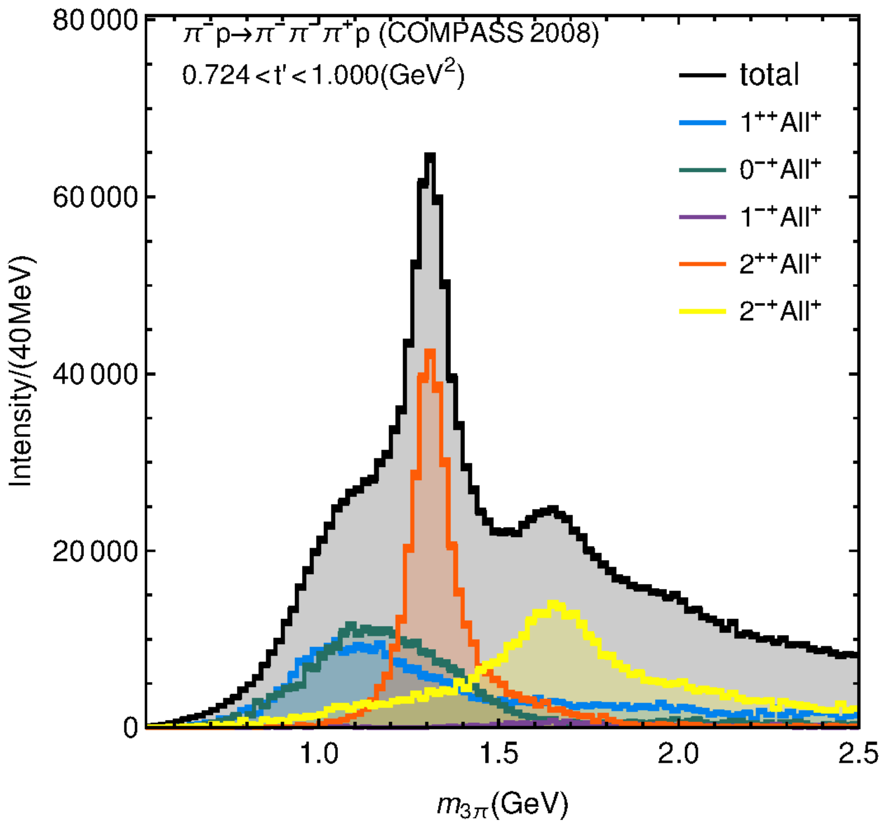




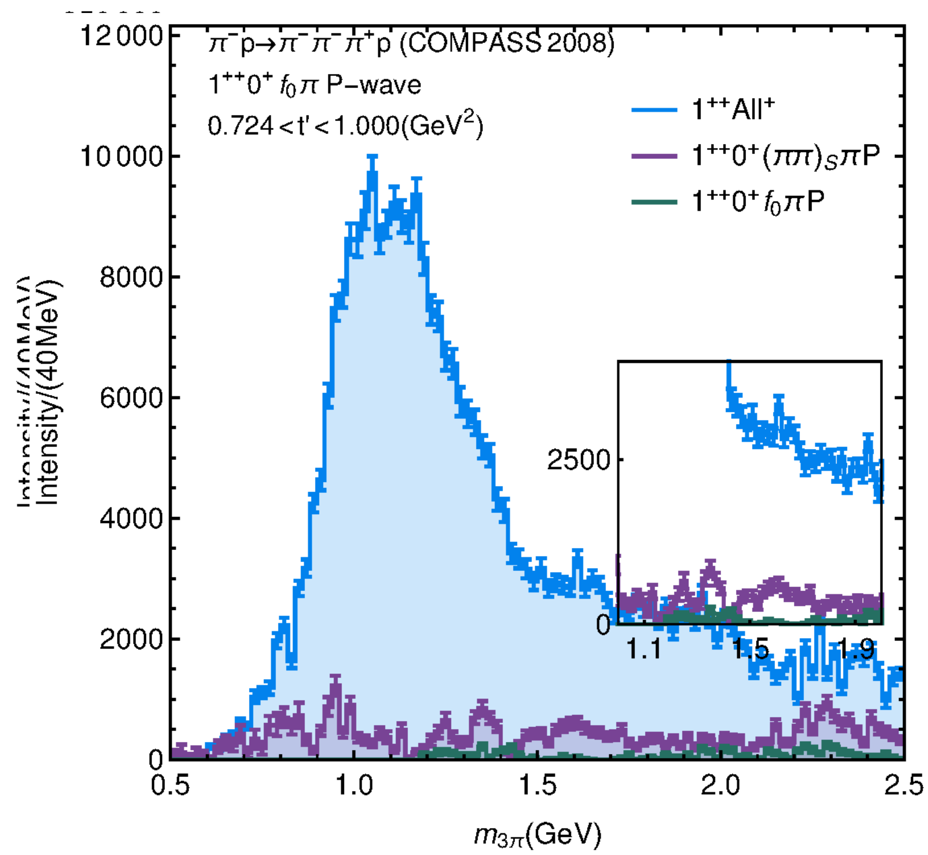


[C. Adolph et al., Phys. Rev. D 95, 032004 (2017)]

Total intensity



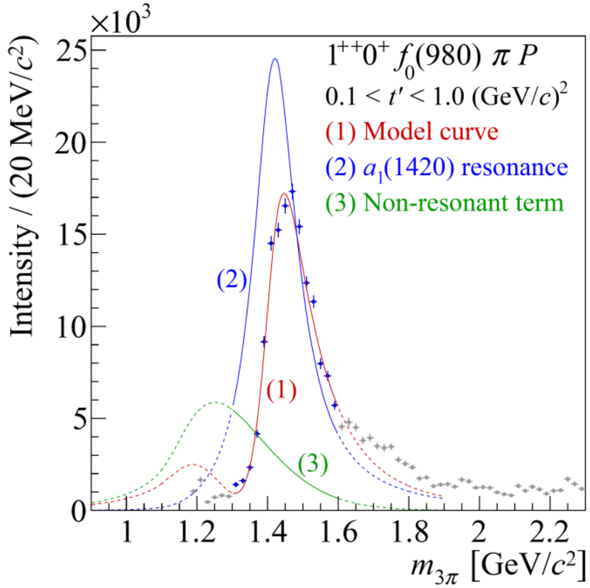
1^{++} Waves

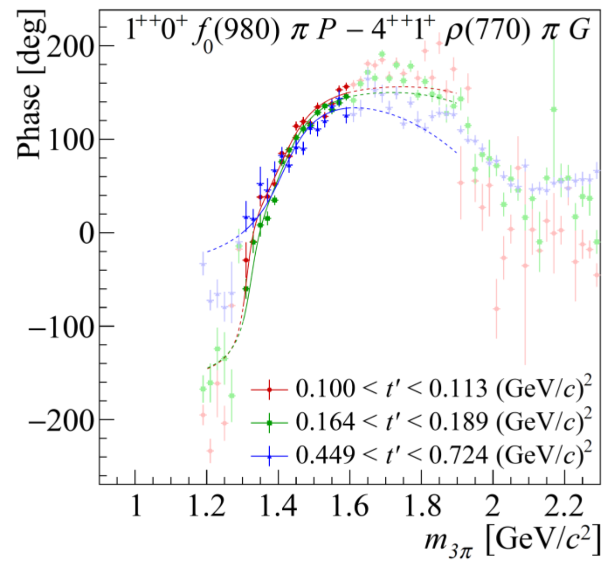


- Largest wave-set to date: 88 waves
- Independent fits in 100 bins (20 MeV) of $m_{3\pi}$ and 11 bins of t'

New $a_1(1420)$

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



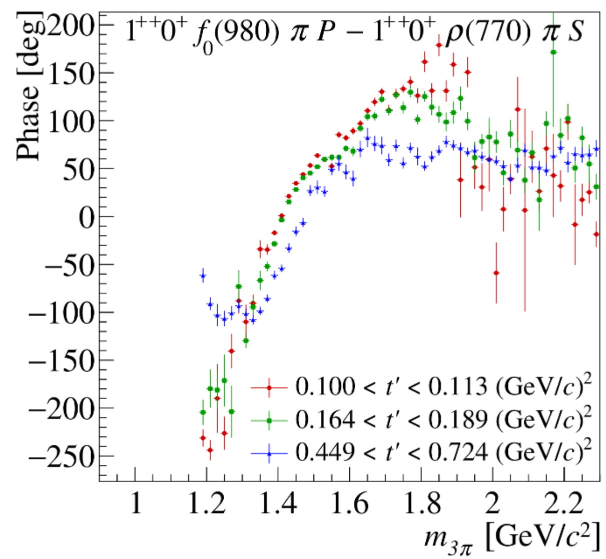


- Data described well by Breit-Wigner and non-resonant background
- Parameters for BW:

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

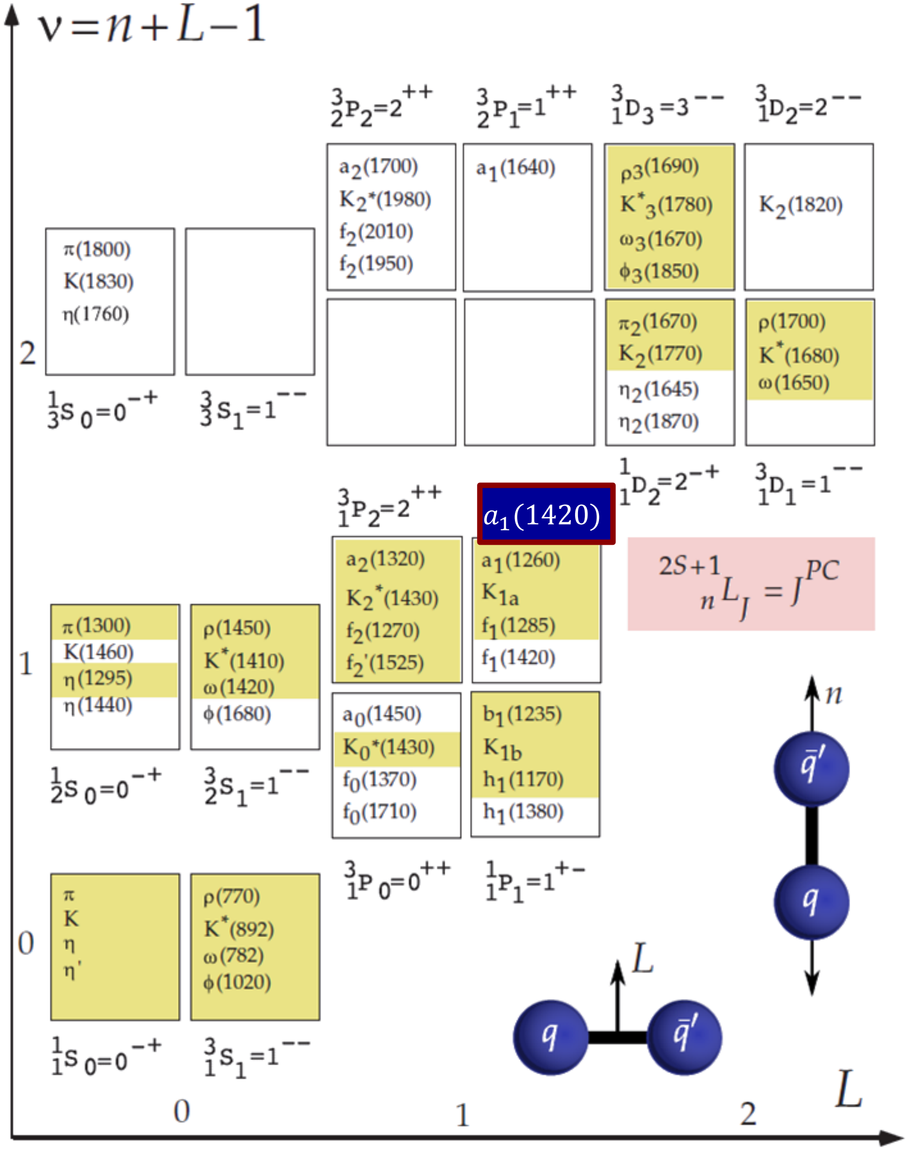
$$\Gamma_0 = 153^{+8}_{-23}\ \text{MeV}/c$$

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



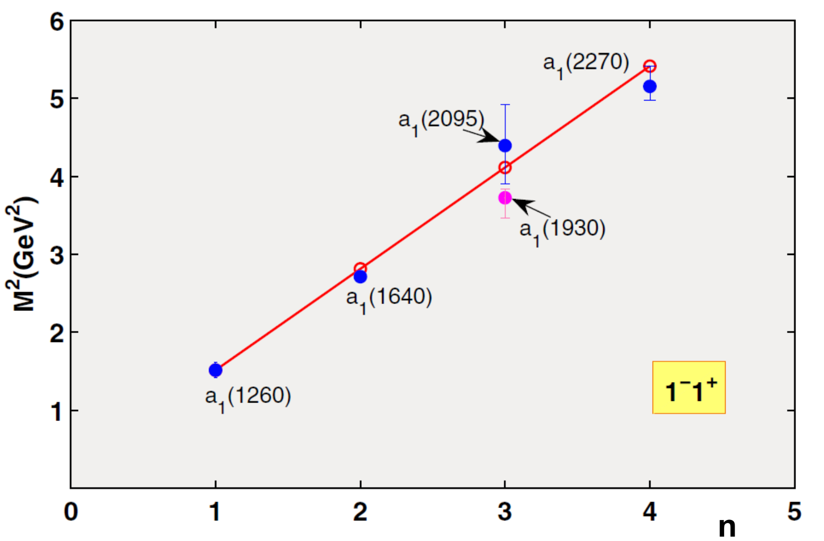
[C. Adolph et al., COMPASS, PRL 115, 082001 (2015)]

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 $\approx 1.38\ \mathrm{GeV}/c^2$



[Anisovich et al., PRD 62, 051502 (2000)]
[Chen et al., PRD 91, 074025 (2015)]

Press Echo

Science Ticker

Particle Physics

New particle may be made of four quarks

By Andrew Grant 4:48pm, February 2, 2015

CERN's COMPASS i

Das Physikportal pro-physik.de

Exotischer Teilchenzustand gibt Rätsel auf

01. September 2015

COMPASS-Kollaboration am CERN entdeckt neues Meson aus leichten Quarks

Eine exotische Kombination von leichten Quarks haben Wissenschaftler der COMPASS-Kollaboration am CERN beobachtet. Die Entdeckung gelang bei

scinexx.de Das Wissensmagazin

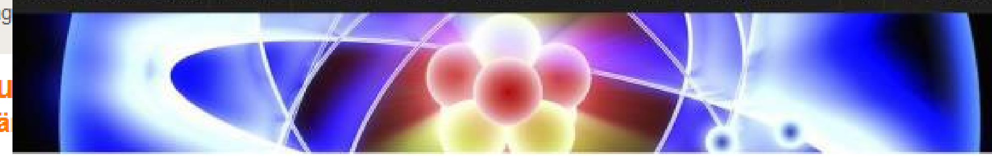
Rubriken | Freitag

Exotischer Teilchenzustand gibt Rätsel au

Neu entdecktes Zerfallsprodukt lässt sich nach gä Physik nicht erklären

Physikalisches Rätsel: Forscher des CERN h im Teilchenbeschleuniger ein unbekanntes Teilchen entdeckt. Noch ist unklar, ob es si eine exotische Kombination aus zwei Meson ein Partikel aus vier Quarks handelt. Klar ist dagegen, dass bisherige theoretische Erklär das Verhalten dieses Teilchens nicht ausrei beschreiben. Ein Physiker bezeichnete es da "neues Mitglied im Club der bisher unerklärt Zustände".

MOTHERBOARD Videos Maschinen Politik Zukunft Natur Kultur Entdeckungen



CERN entdeckt neues Teilchen für den „Club der unerklärten Zustände"

1 September 2015 // 09:31 AM CET

Autor CHRISTINE KEWITZ REDAKTEURIN

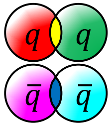
Ist es nicht schön, wenn man nach jahrelanger Partnerschaft noch unbekannte, aufregende Seiten an seinem Lebensgefährten entdeckt? So ähnlich muss es den Physikern des CERN, gegangen sein, die in einem schon sehr gut untersuchten Massebereich überraschenderweise ein neues Teilchen entdeckten.

Dem Standardmodell der Elementarteilchenphysik zufolge, welches alle bekannten Teilchen und ihre Wechselwirkungen aufführt, sind Quarks die fundamentalen

CONNECT TO MOTHERBOARD

Interpretations

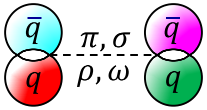
- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]



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

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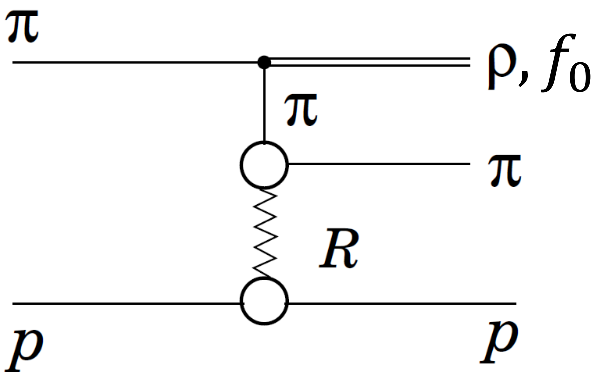
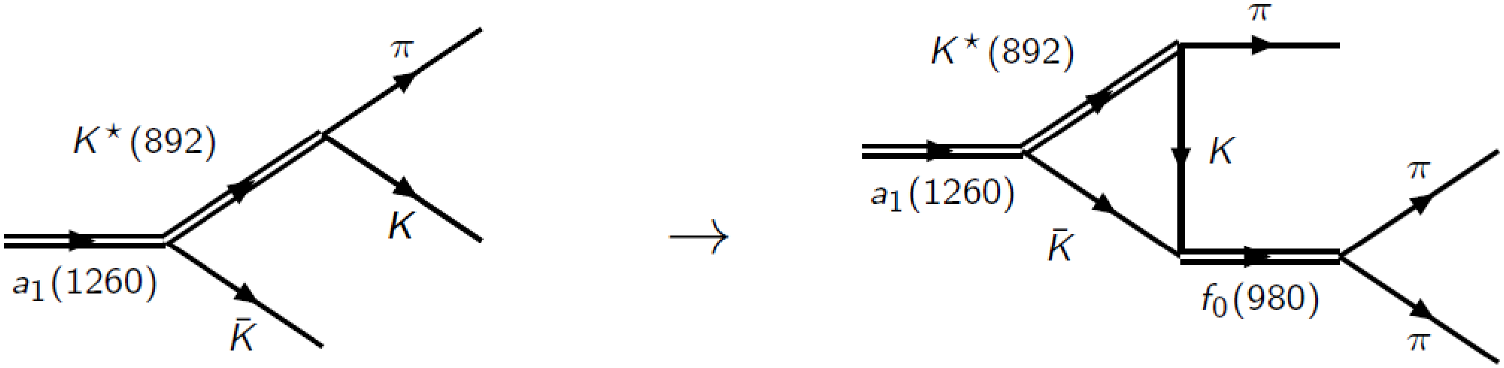
- $K^*\overline{K}$ molecule [T. Gutsche et al. (2017)]
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al. (2015)]



Interpretations

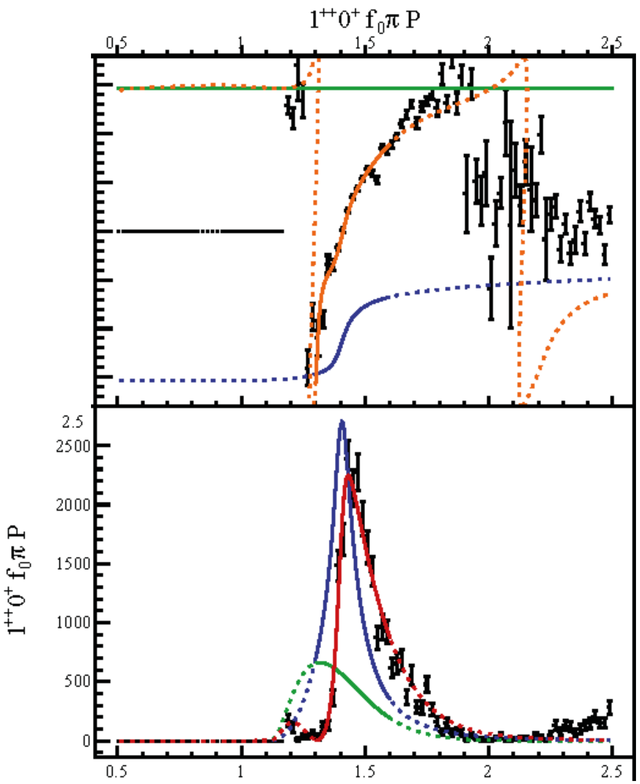
- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]
- $K^*\overline{K}$ molecule [T. Gutsche et al. (2017)]
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al. (2015)]
- Triangle singularity [Wu et al., PRL 108, 081803 (2012), M. Mikhasenko et al., PRD 91, 094015 (2015)]



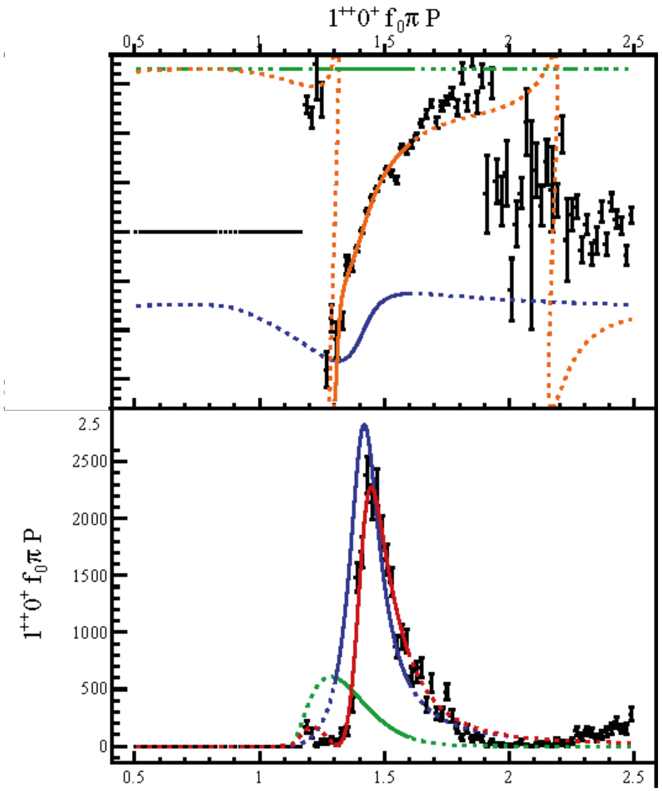
– Decay of $a_1(1260) \rightarrow K^*\overline{K}$ above threshold
– Final state rescattering of $K\overline{K}$ to $f_0(980)$
  ⇨ logarithmic singularity of amplitude if particles close to mass shell

Comparison TA - BW

Triangle Amplitude



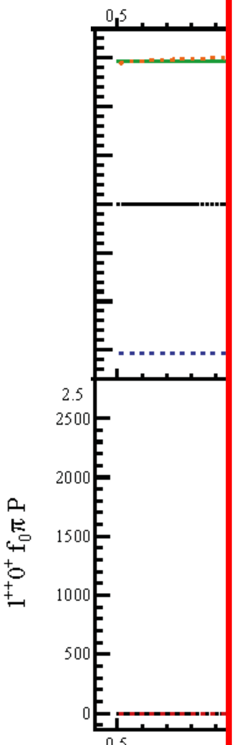
Breit-Wigner



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

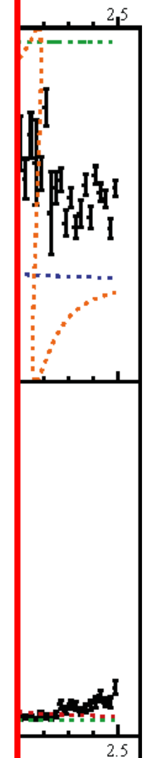
Comparison TA - BW

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 fully described 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

Ordinary $q\bar{q}$ mesons:

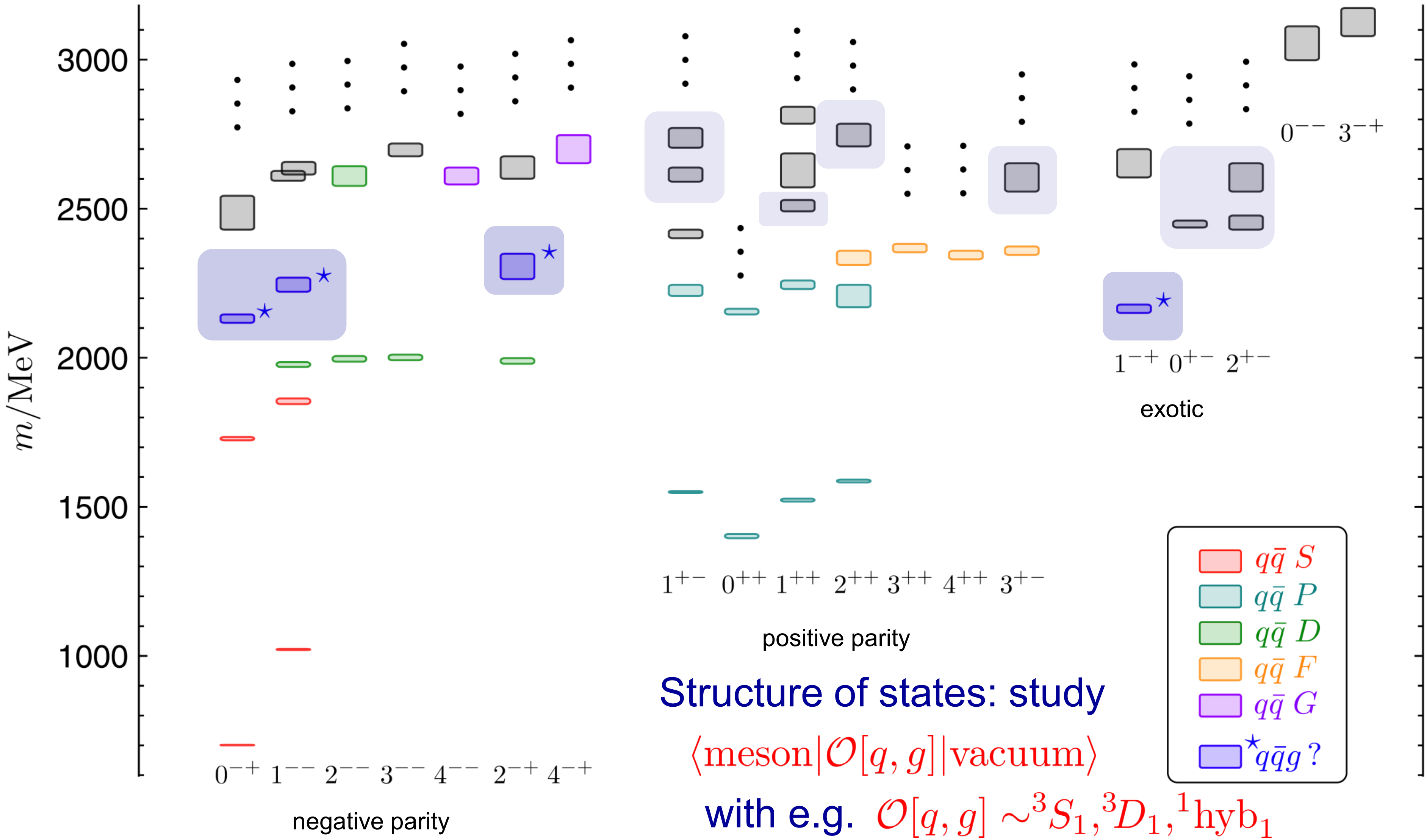
- orbital, radial excitations

Hybrids:

- excitation of gluonic degrees of freedom
- angular momentum in flux tube
- excited states also seen in L-QCD, bag,…

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

Hybrids: Lattice QCD



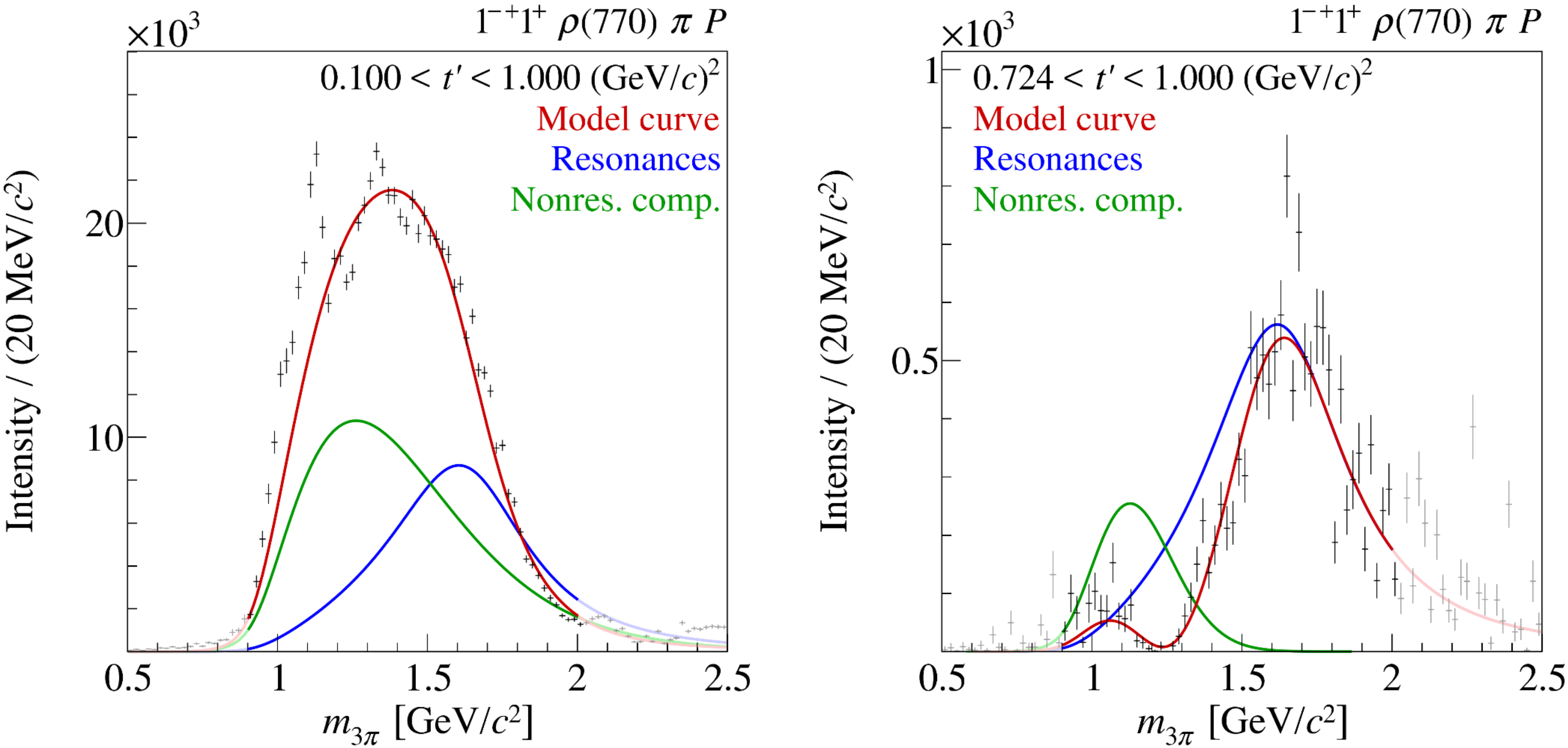
Structure of states: study

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

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

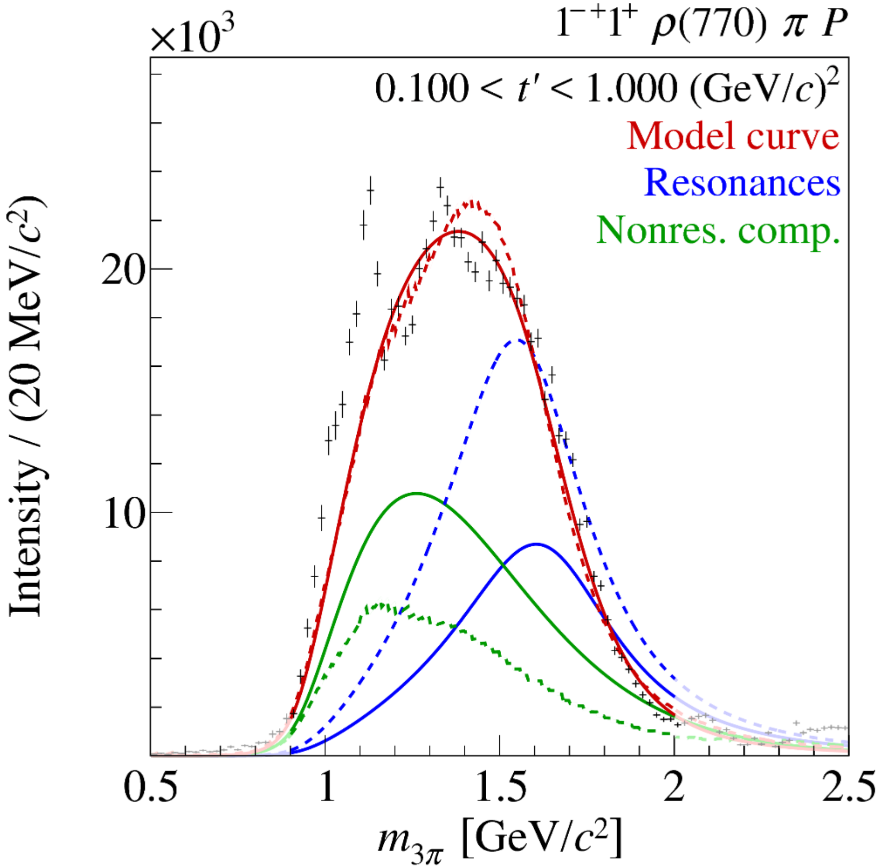
[J. Dudek, Phys. Rev. D 84, 074023 (2011), J. Dudek et al., Hadron Spectrum Collaboration, Phys. Rev. D 82, 034508 (2010)]

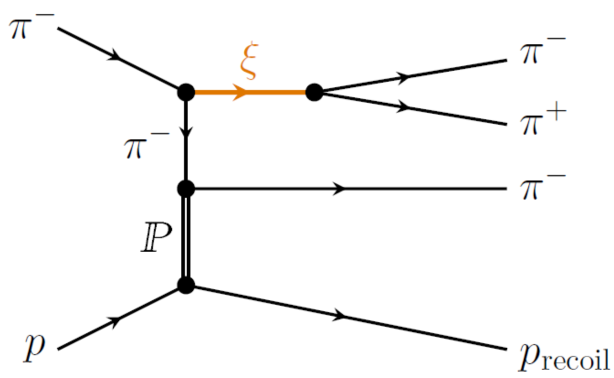
1^{-+} Partial Wave



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

[R. Akhunzyanov et al., arXiv: 1802.05913 (2018)]





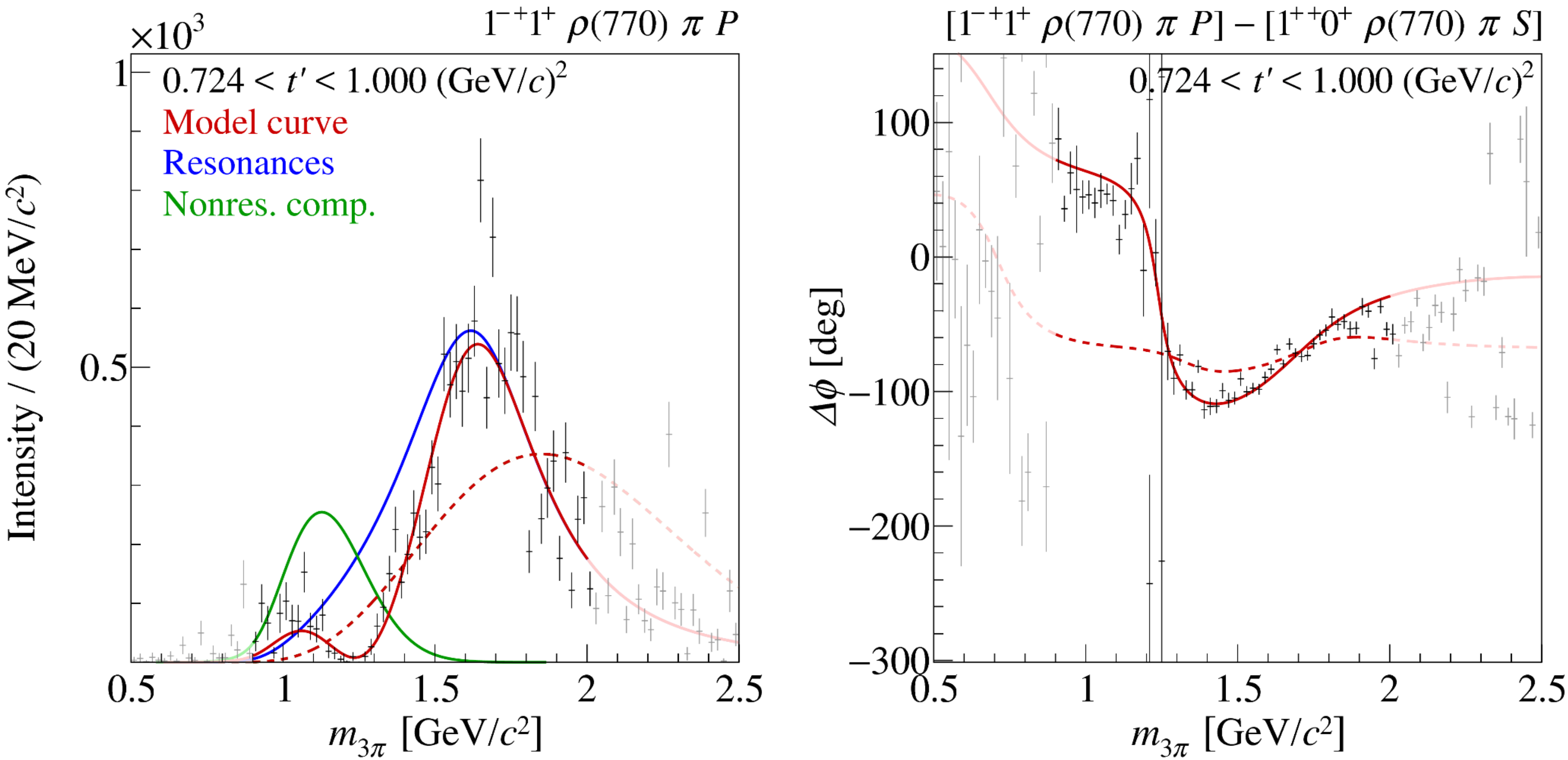
- Background shape in agreement with Deck-model studies
- Resonance parameters for $\pi_1(1600)$

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

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

[R. Akhunzyanov et al., arXiv: 1802.05913 (2018)]

1^{-+} Partial Wave

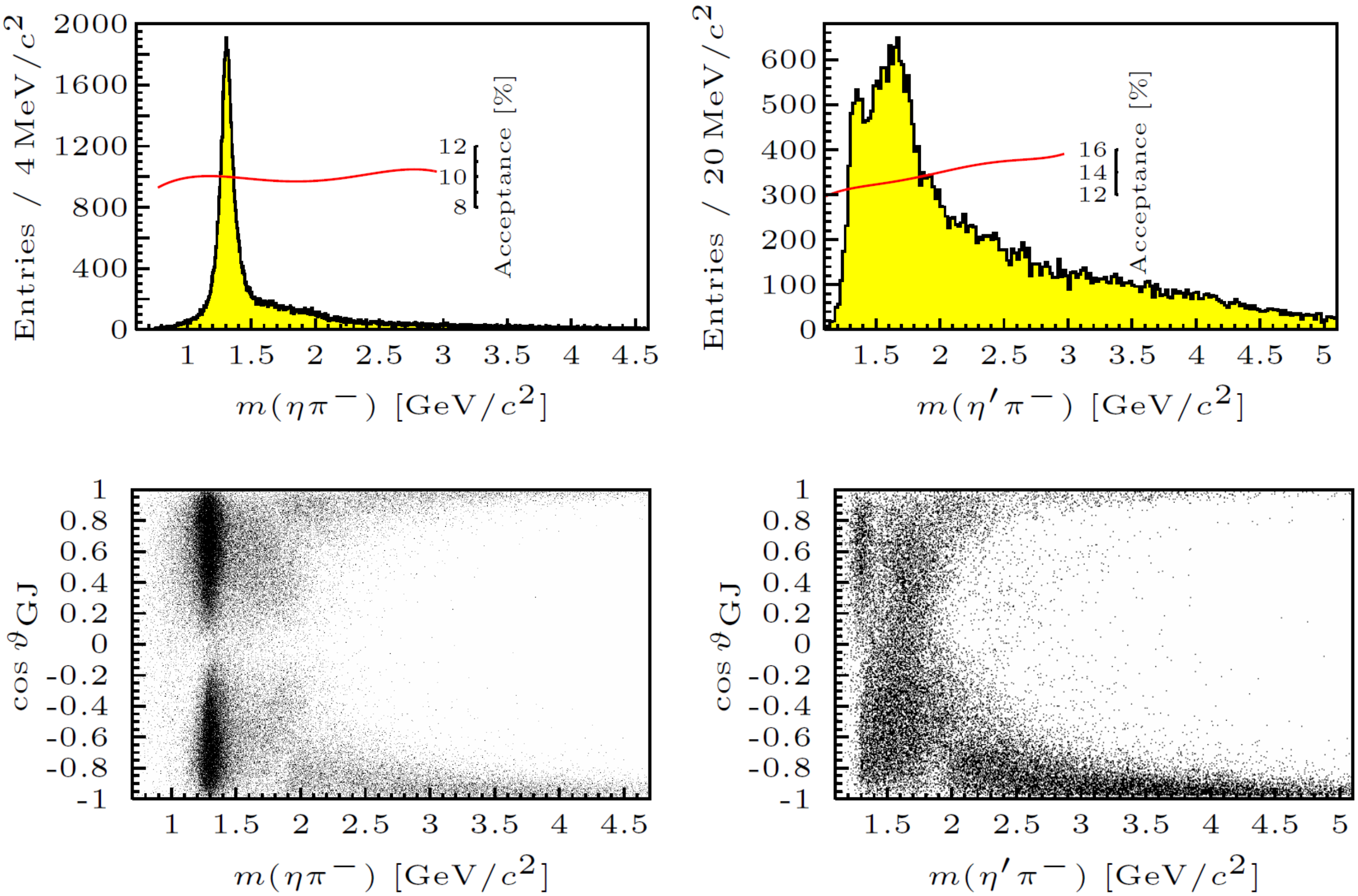


Bad description of data without resonance component

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

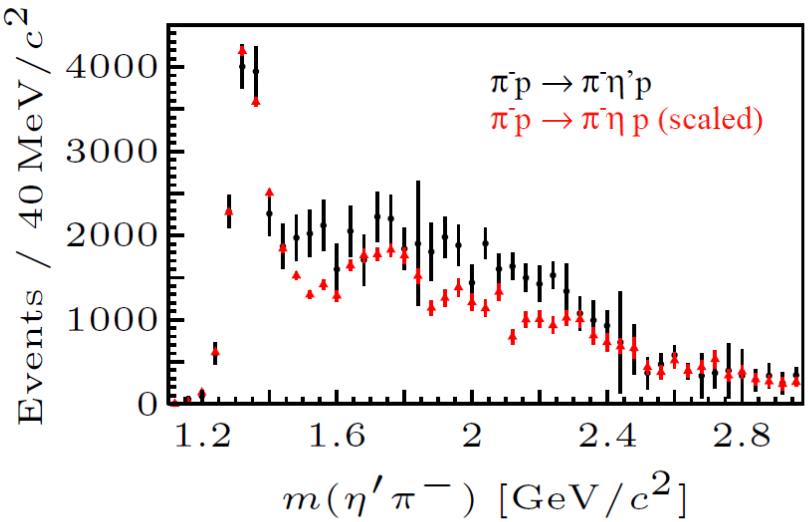
[R. Akhunzyanov et al., arXiv: 1802.05913 (2018)]

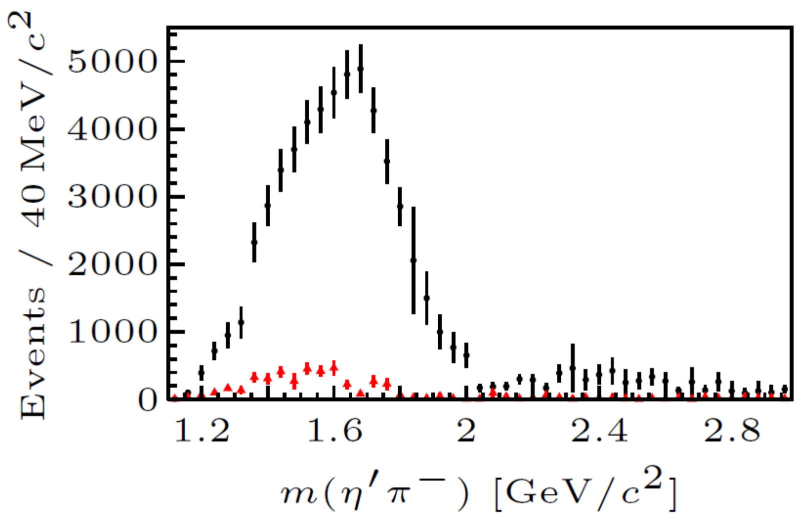
$\eta\pi^-$ / $\eta'\pi^-$ Final States

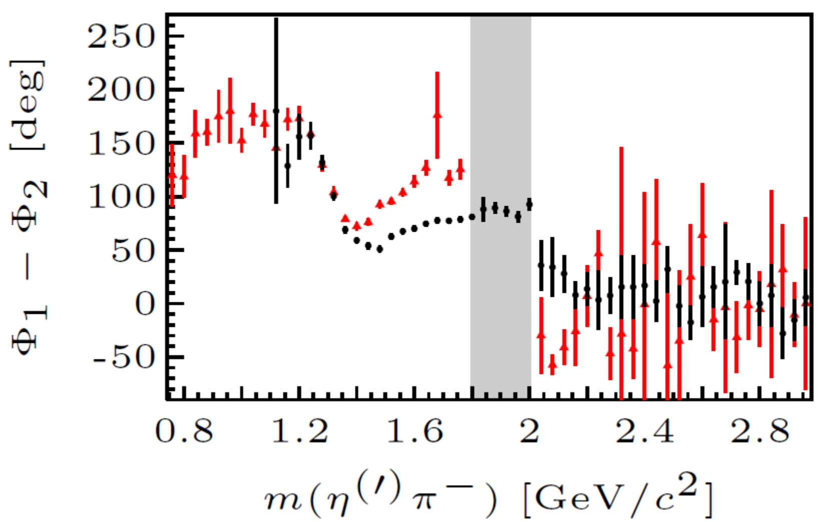


[C. Adolph (COMPASS), Phys. Lett. B 740, 303 (2015)]

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





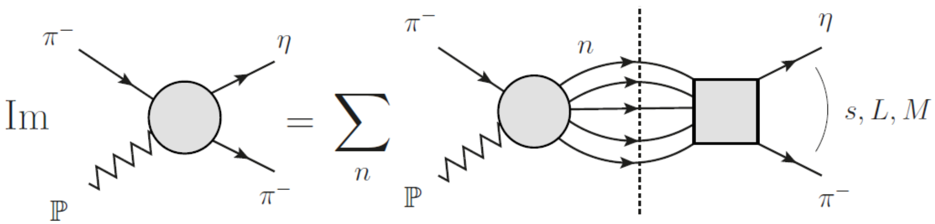


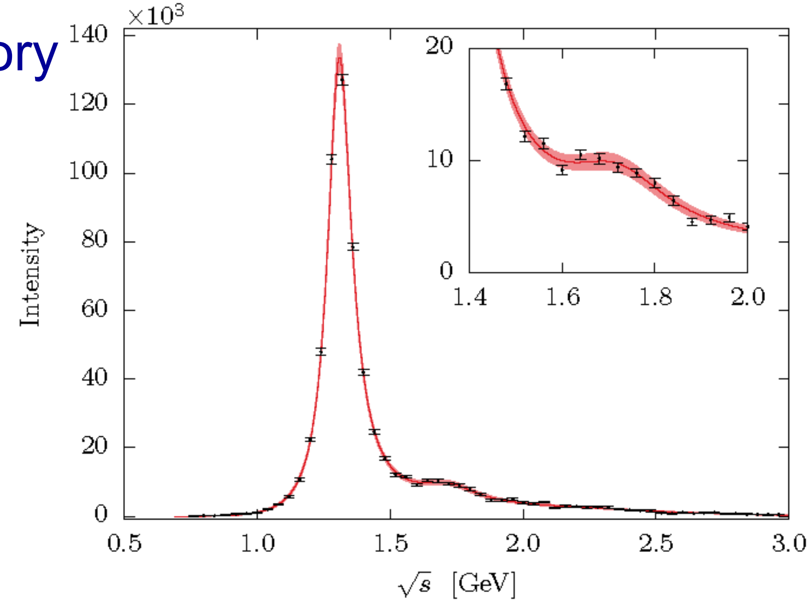
- $\eta\pi^-$ waves scaled according to phase space and BR to final state
- *D*, *G* waves very similar
- *P* wave very different in $\eta\pi$ and $\eta'\pi$
- Breit-Wigner model fit unstable

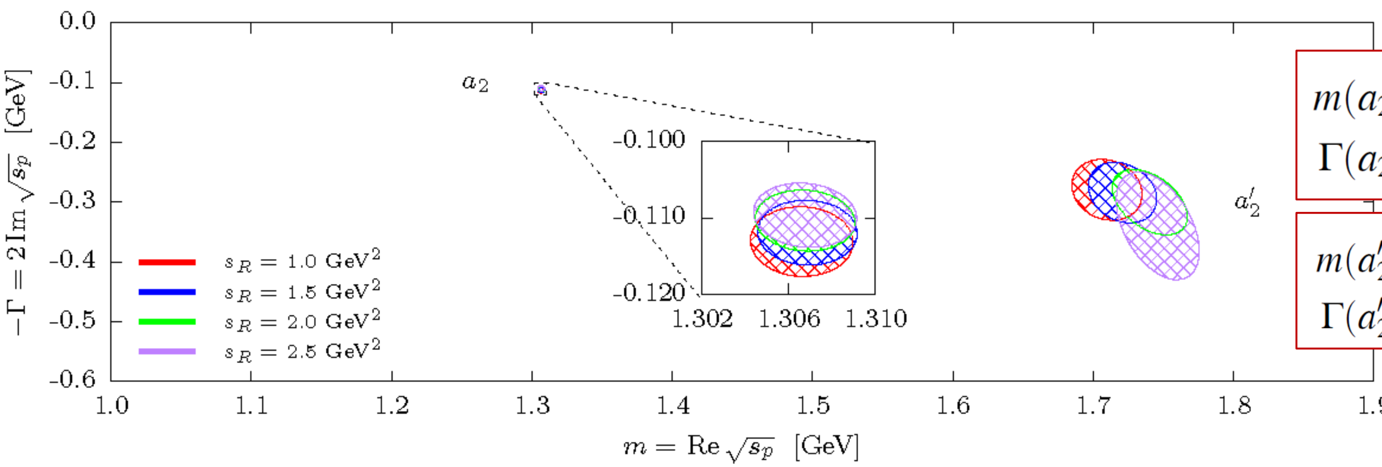
[C. Adolph (COMPASS), Phys. Lett. B 740, 303 (2015)]

Extraction of Poles

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





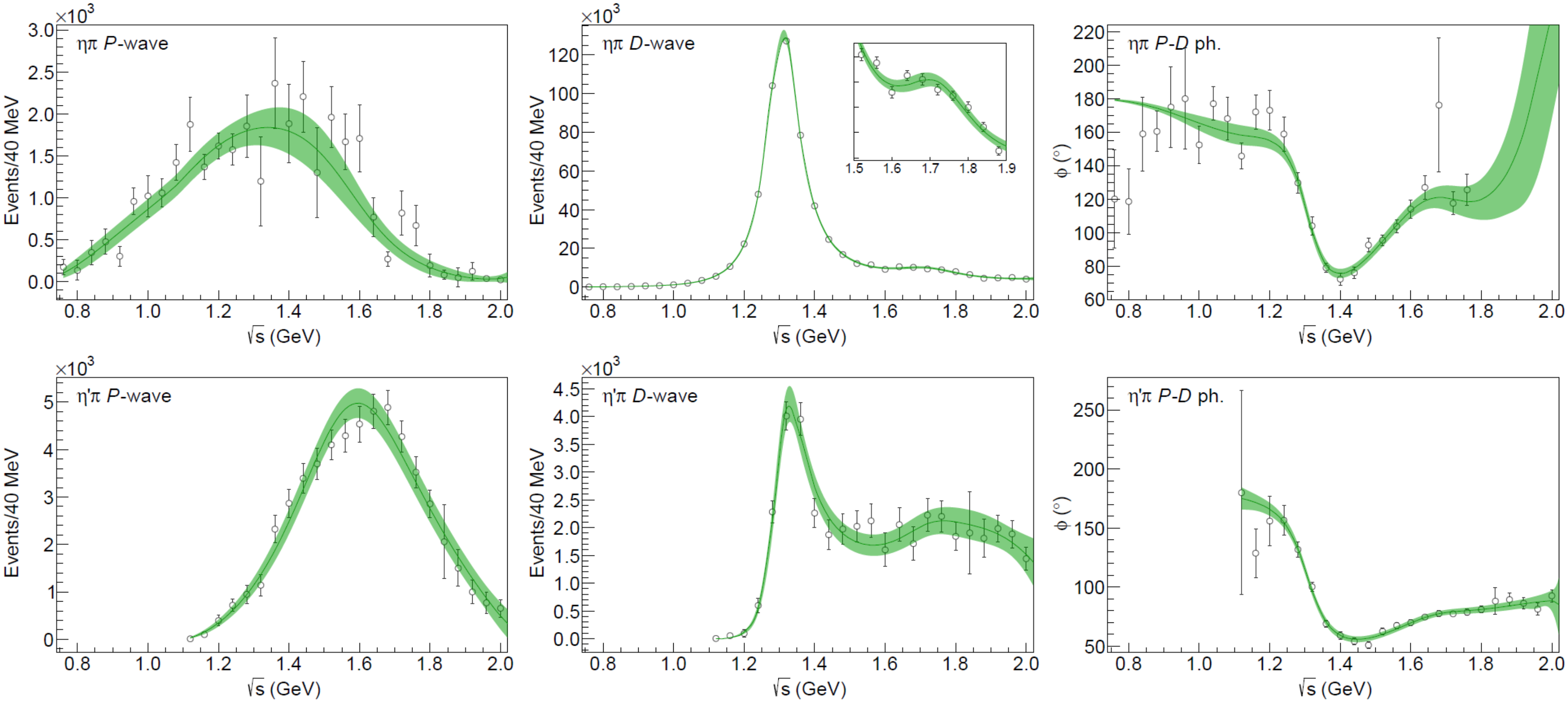


$$m(a_2) = (1307 \pm 1 \pm 6)\ \mathrm{MeV},$$
$$\Gamma(a_2) = (112 \pm 1 \pm 8)\ \mathrm{MeV},$$

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

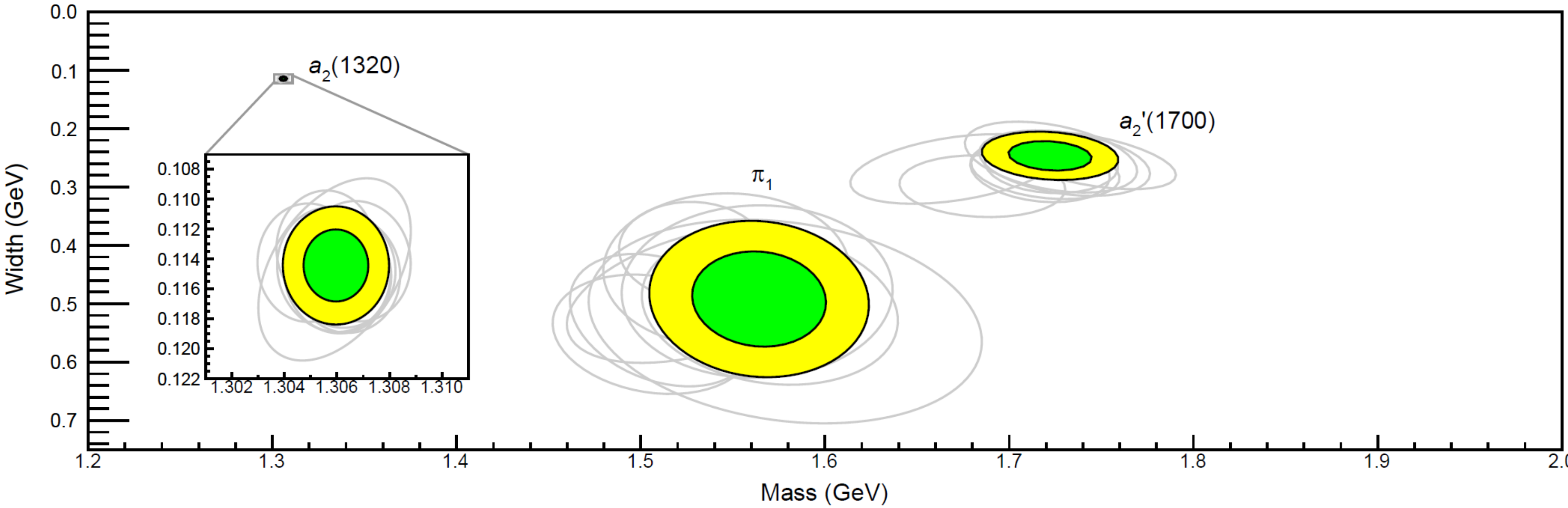
[A. Jackura et al. (JPAC, COMPASS), Phys. Lett. B 779, 464 (2018)]

ηπ–η′π Coupled Channels



[A. Rodas et al. (JPAC), subm. to PRL, arXiv:1810.04171]

$\eta\pi$–$\eta'\pi$ 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), subm. to PRL, arXiv:1810.04171]

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, more studies needed

- 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

Future Plans

arXiv:1808.00848v3 [hep-ex] 15 Oct 2018

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

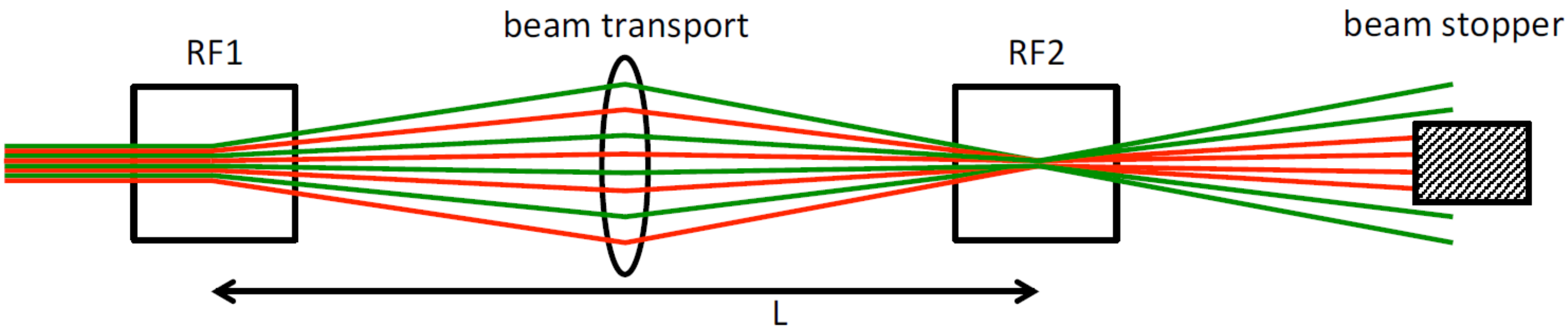
October 17, 2018

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

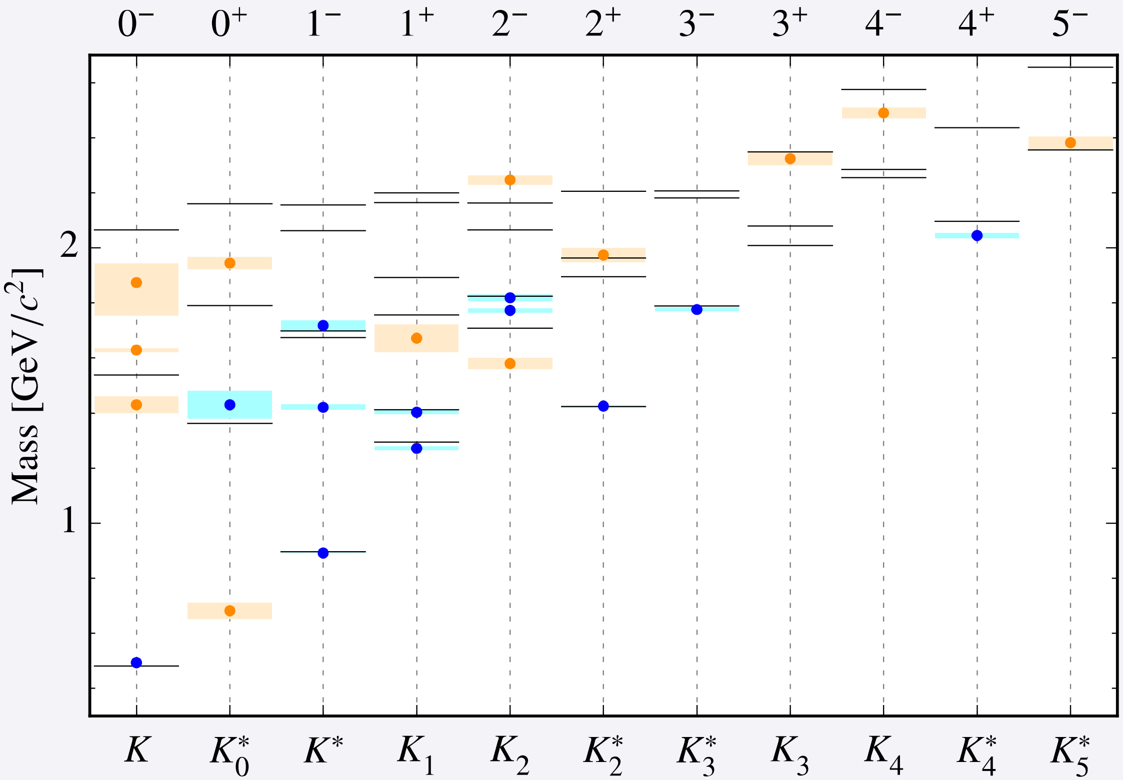
New Beam: RF Separation

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

Kaon Excitation Spectrum



[Courtesy of S. Wallner, TUM]

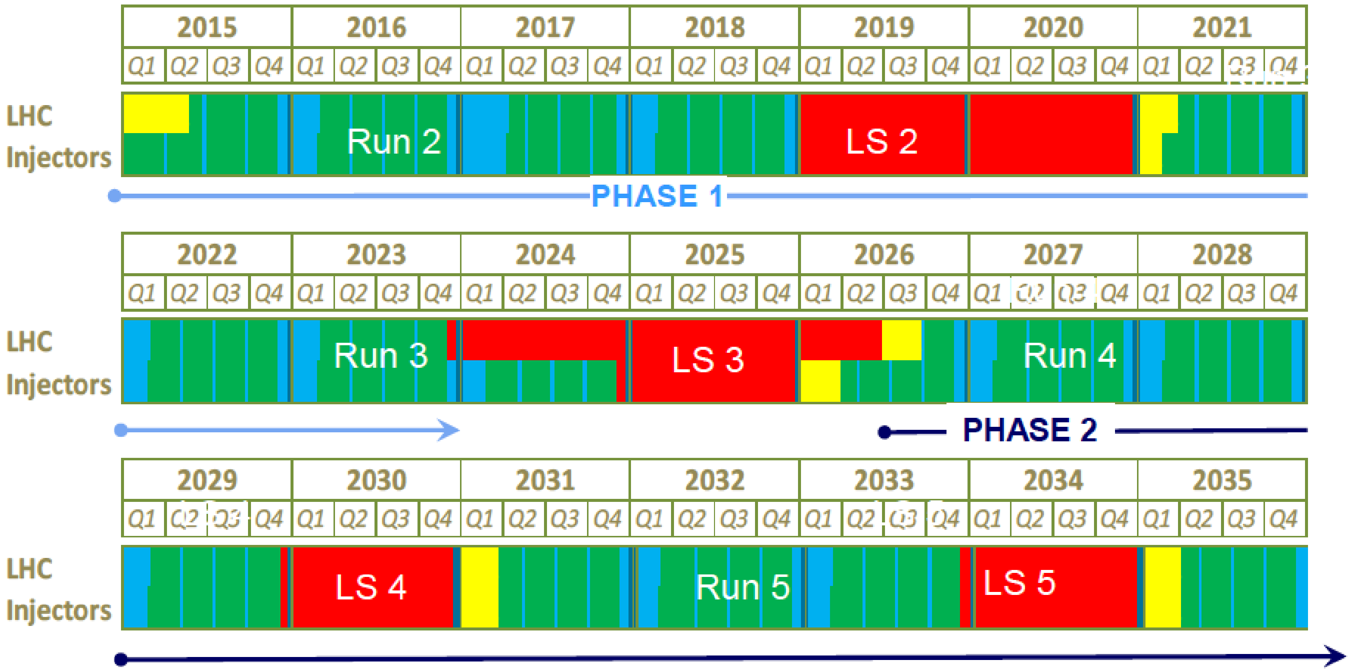
- 25 kaon states listed by PDG (<3.1GeV), 13 of those need confirmation
- many predicted quark-model states still missing
- some hints for supernumerary states

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

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
- nicely bridges the physics and time gap to EIC!
- further collaborators are currently searched for; signatures are collected until end of 2018
- if interested sign up through our web page: