Exotic Mesons at COMPASS

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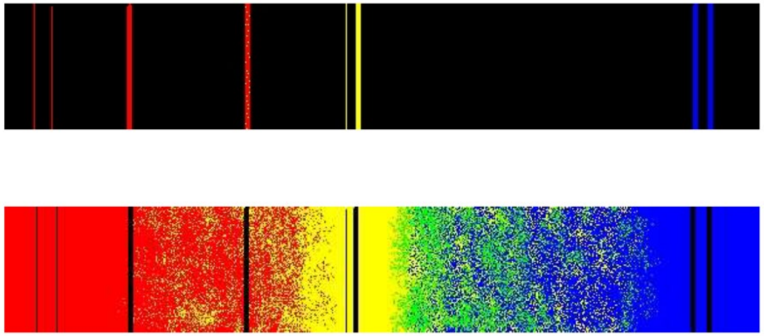
EMMI Hadron Physics Seminar

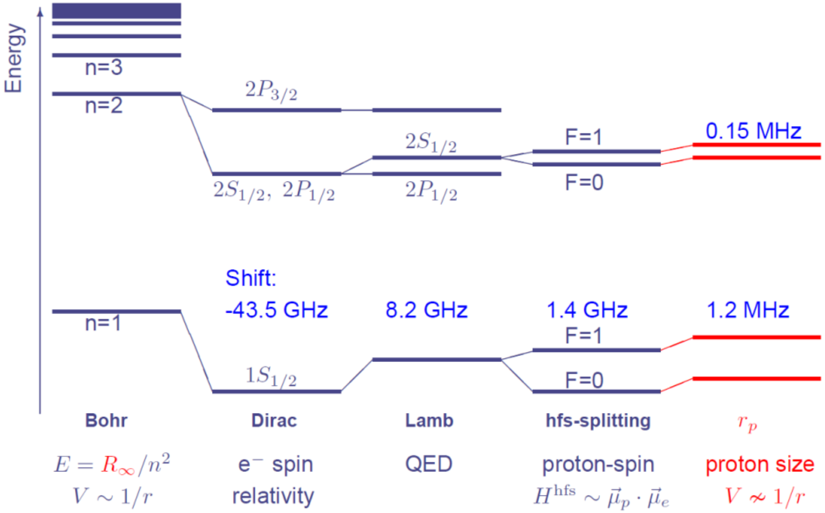
GSI

05 June 2019

Why Hadron Spectroscopy?

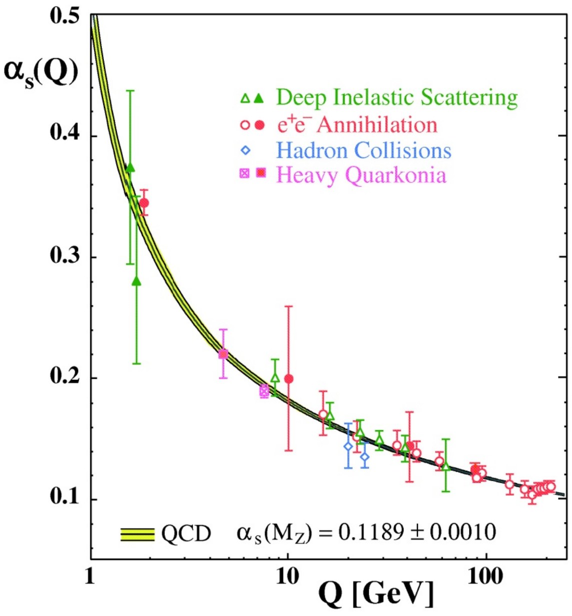
Remember the hydrogen atom…





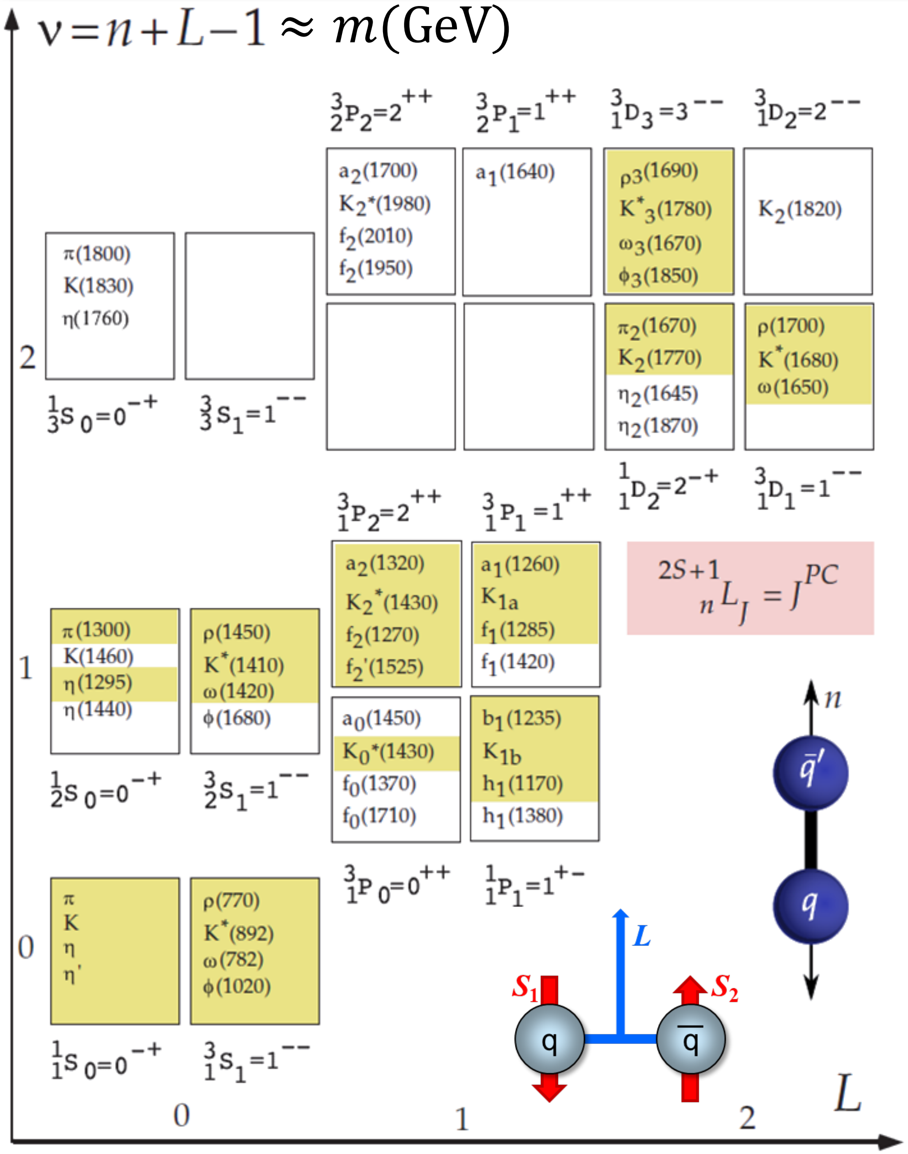
Similarly: study QCD through the excitation spectrum of strongly interacting particles

- 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)$_{\text{flavor}}$:

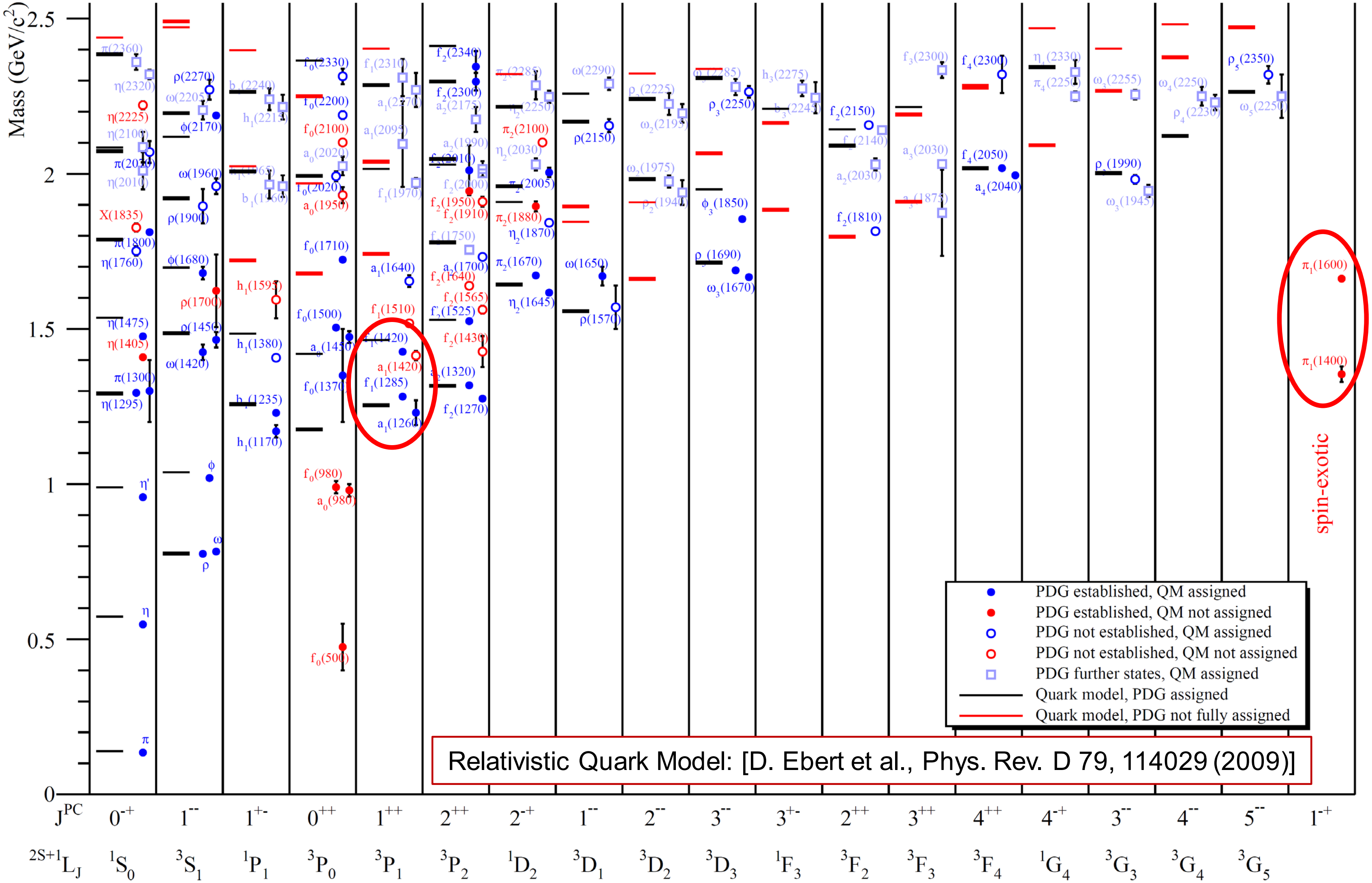
$$q\otimes\overline{q}' = 3\otimes\overline{3} = 8\oplus 1$$

- color singlets

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

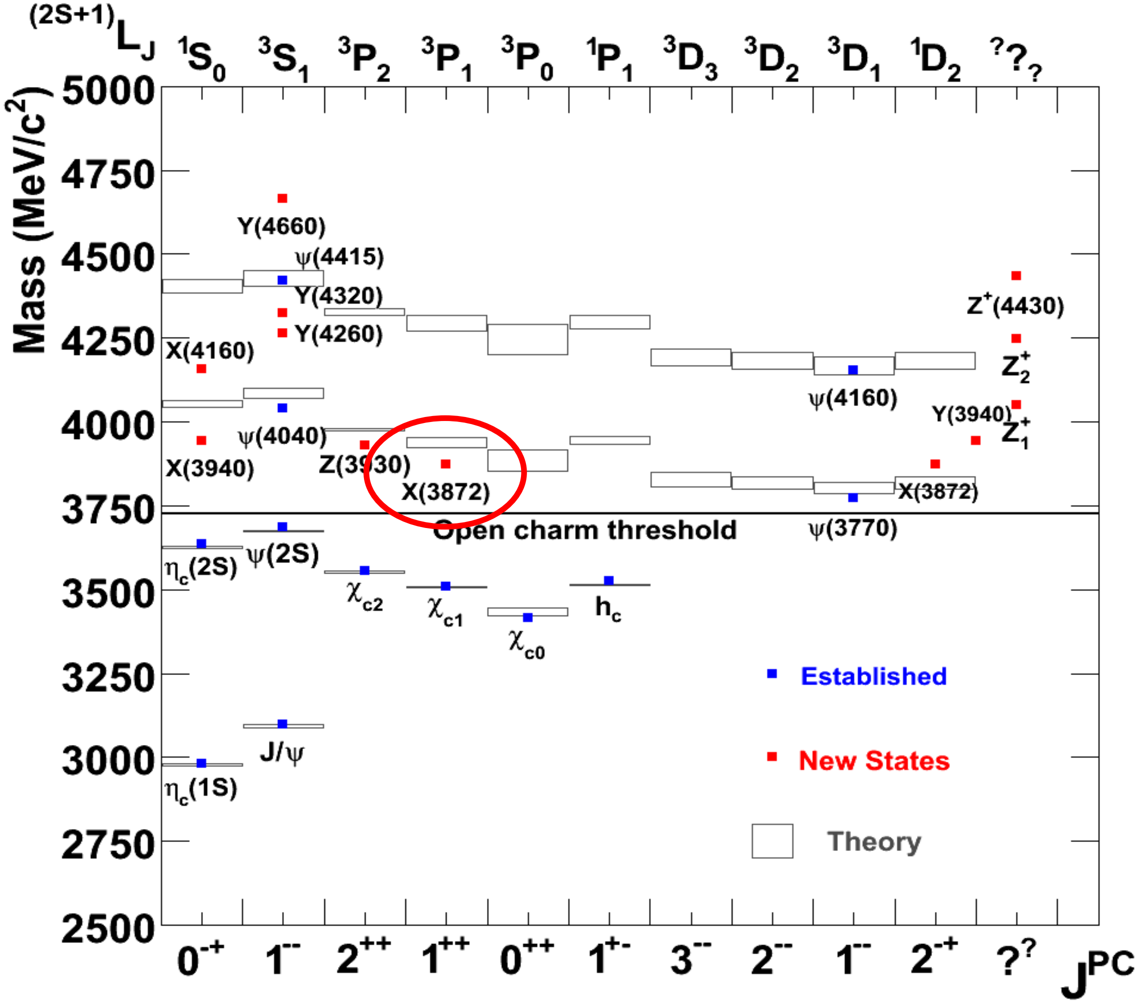
[Amsler et al., Phys. Rept. 389, 61 (2004)]

Light Meson Spectrum



Relativistic Quark Model: [D. Ebert et al., Phys. Rev. D 79, 114029 (2009)]

Charmonium Spectrum



[V. Santoro, Hadron 2015]

Quark model:

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

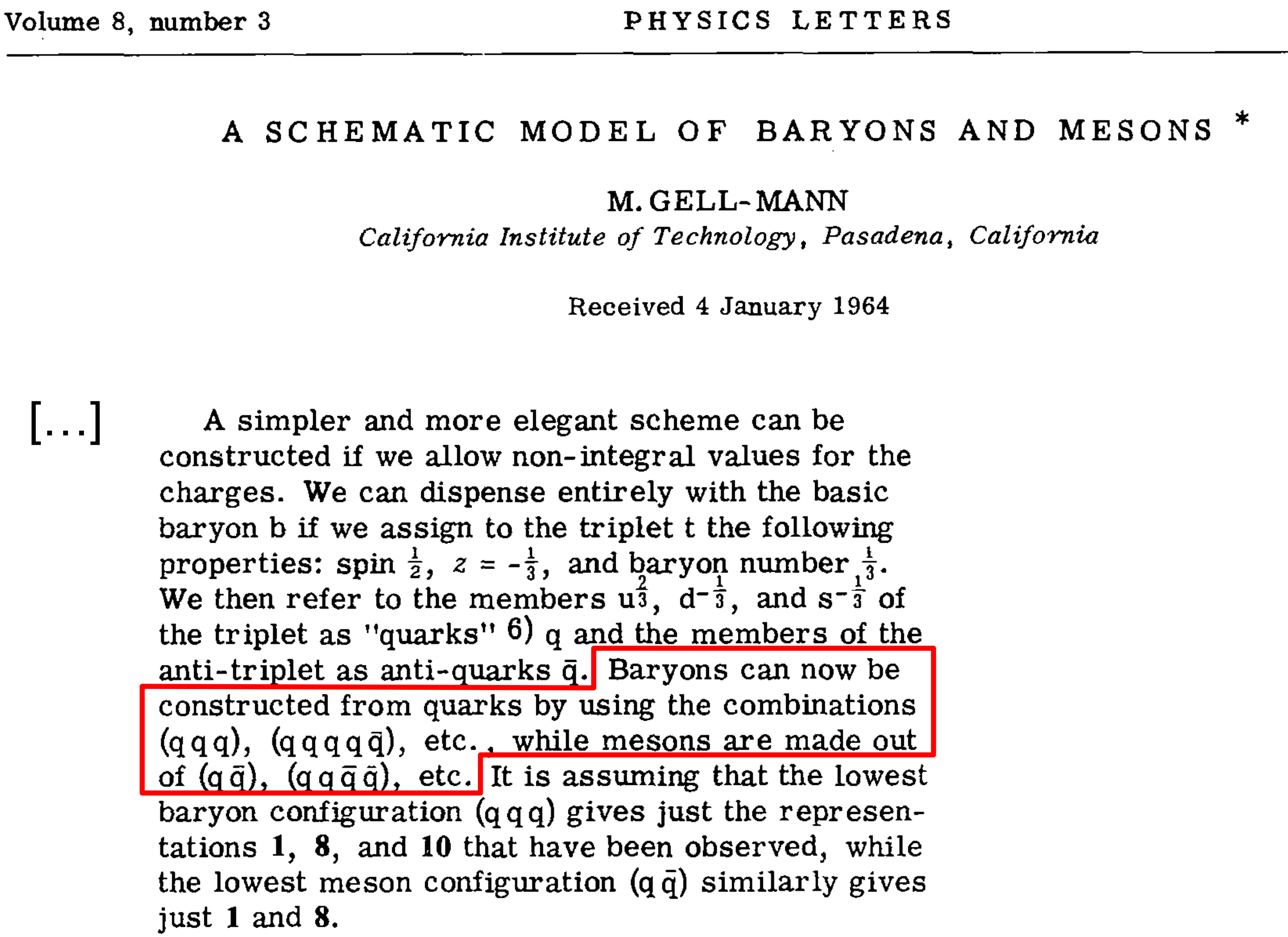
$$q \otimes \overline{q}' = 3 \otimes \overline{3} = 8 \oplus 1$$

- 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)]

Exotic States



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

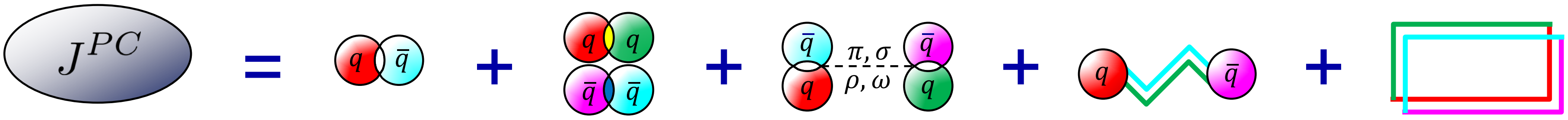
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

[...]

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

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?

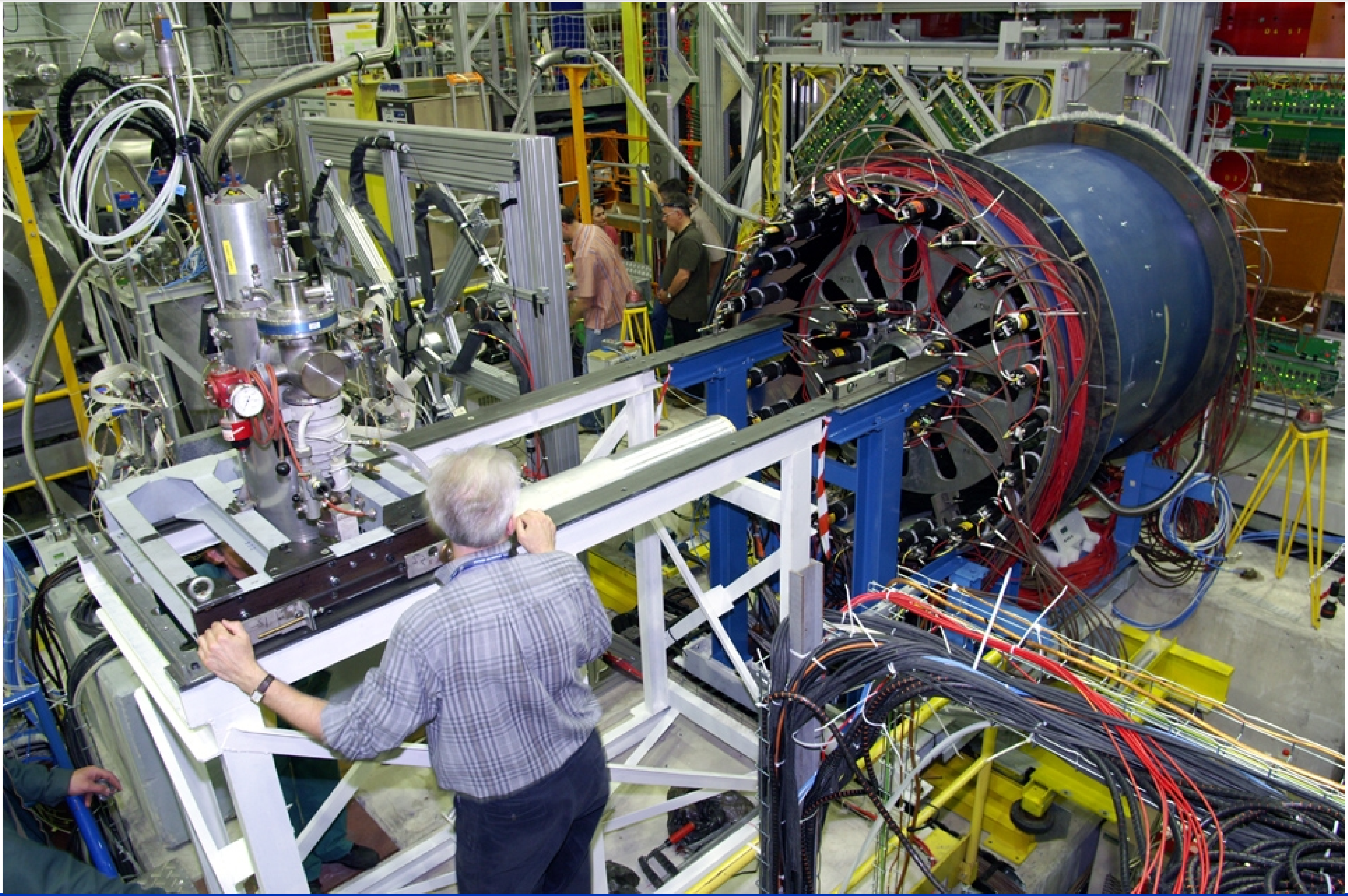
- Spin-exotic: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$
- Supernumerary states
- Flavor-exotic: $|Q|, |I_3|, |S|, |C| \geq 2$
- Comparison with models, lattice

Need:

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

The COMPASS Experiment

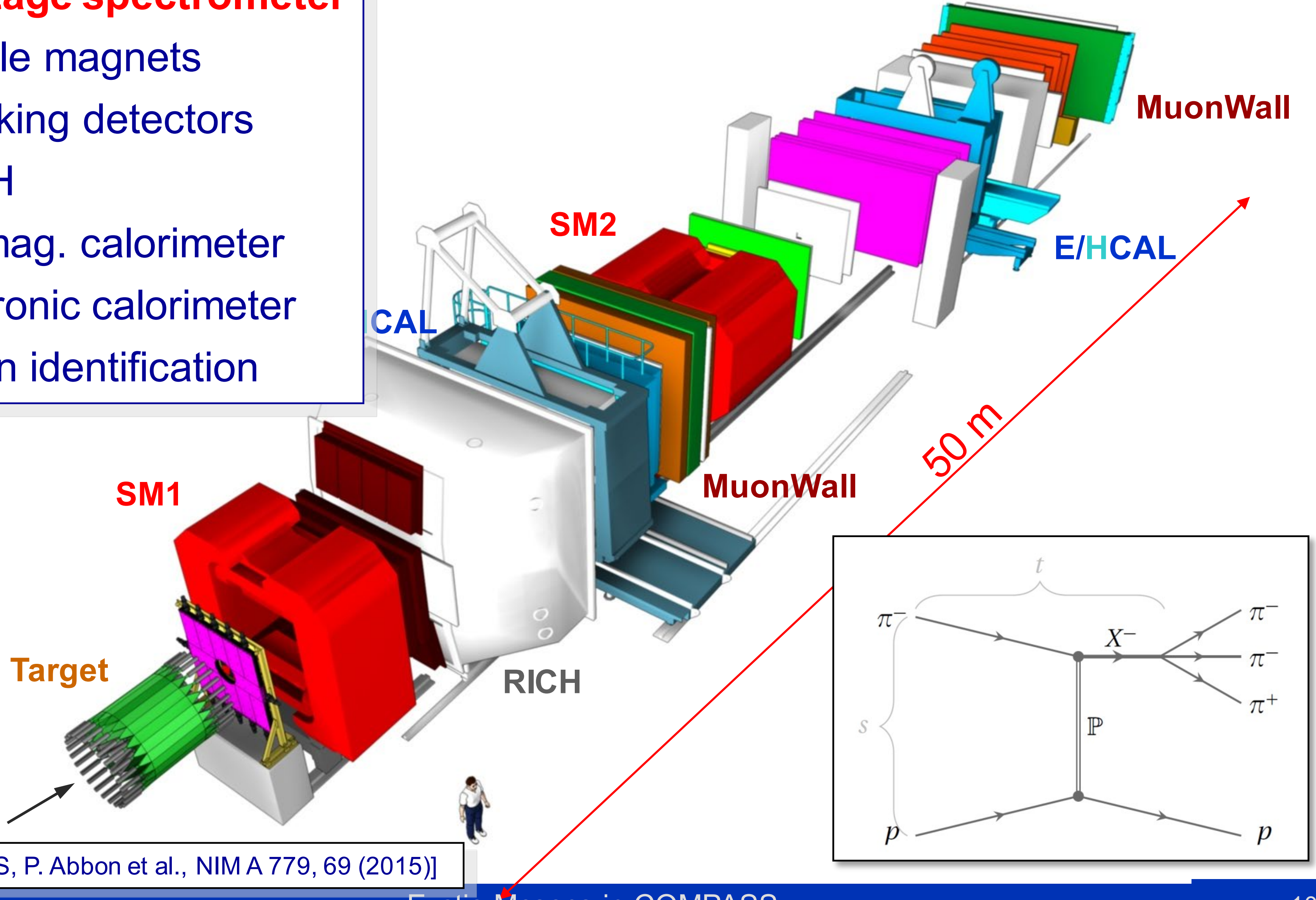
The COMPASS Experiment



The COMPASS Experiment

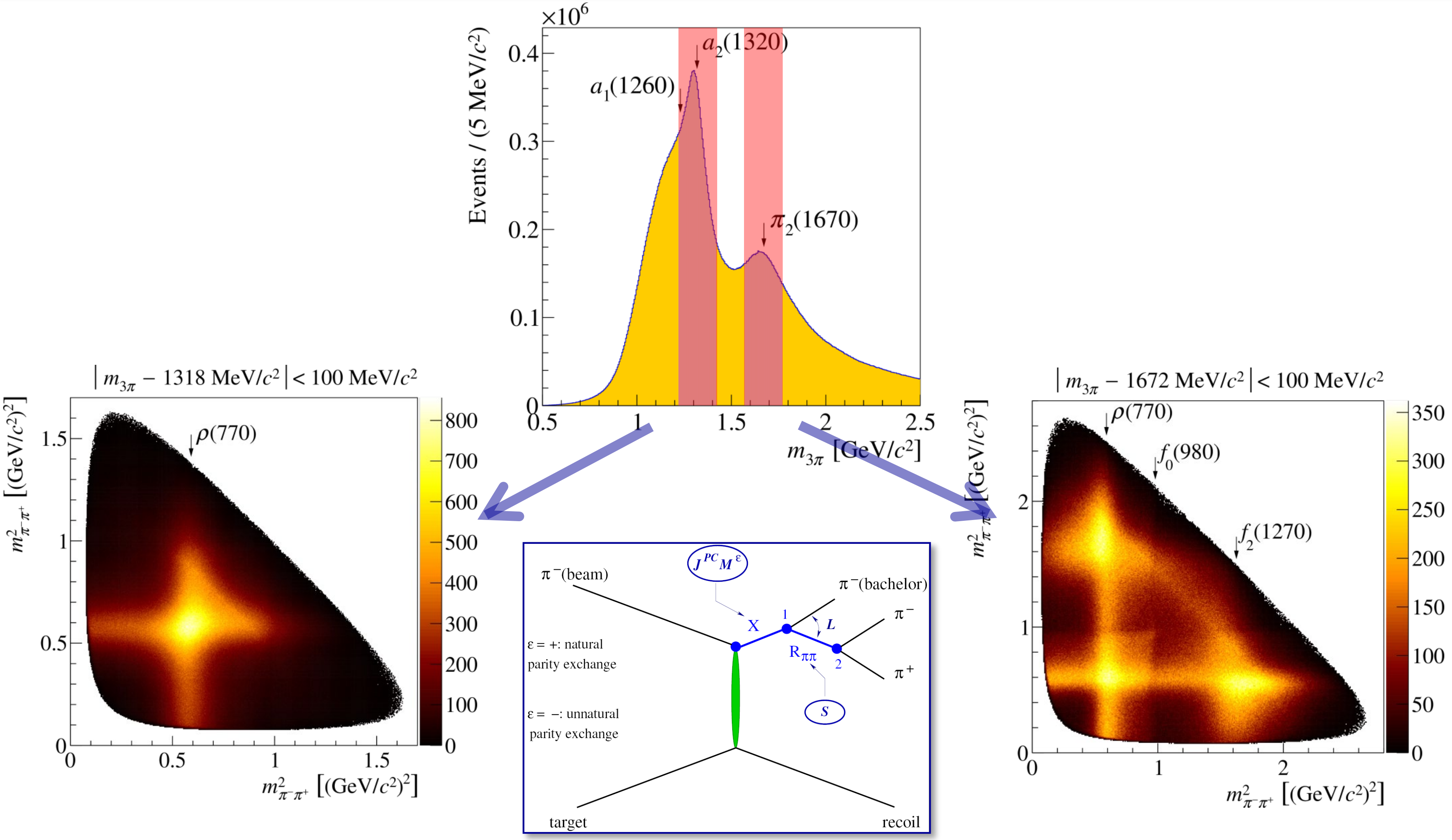
Two-stage spectrometer

- 🟥 Dipole magnets
- 🟩 Tracking detectors
- ⬜ RICH
- 🟦 El.-mag. calorimeter
- 🟦 Hadronic calorimeter
- 🟫 Muon identification



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

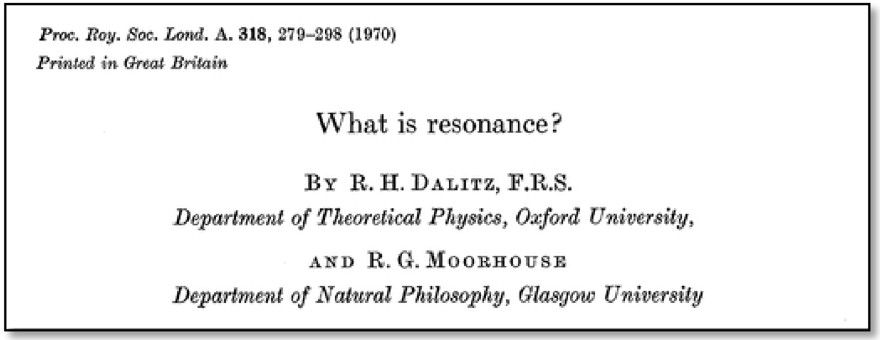
3π Final State



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

What is a Resonance?

- “Not every bump is a resonance, and not every resonance is a bump”
- Resonances have complex properties like mass and width, which do not depend on the experiment or the specific model
- Resonances correspond to poles in the S-matrix on unphysical Riemann sheets

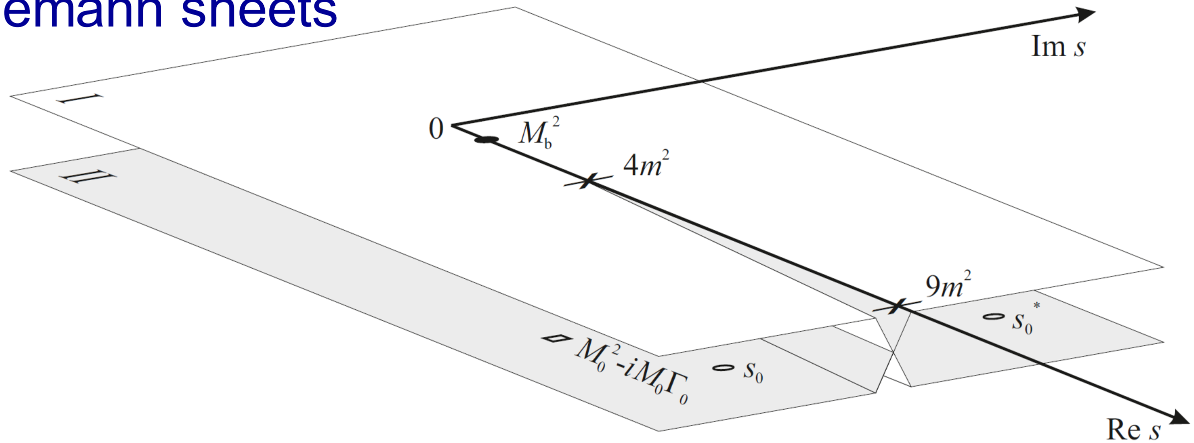


Proc. Roy. Soc. Lond. A. **318**, 279–298 (1970)
Printed in Great Britain

What is resonance?

By R. H. Dalitz, F.R.S.
Department of Theoretical Physics, Oxford University,
and R. G. Moorhouse
Department of Natural Philosophy, Glasgow University

- S-matrix: $\mathbb{S} = \mathbb{I} + i\mathbb{T}$
  - unitary
  - analytic



Transition (reaction) matrix:

$$T_{fi} = (2\pi)^4 \delta^{(4)}\left(\sum_{m=1}^{M} p_m - \sum_{n=1}^{N} p_n\right) \prod_{m=1}^{M} \frac{1}{\sqrt{2E_m}} \prod_{n=1}^{N} \frac{1}{\sqrt{2E_n}} \mathcal{M}_{fi}$$

Partial Wave Expansion

For a 2-body reaction: expand scattering amplitude in partial waves

$$\mathcal{M}_{fi} \equiv A(s,t) = \sum_{\ell=0}^{\infty} (2\ell+1) A_\ell(s) P_\ell(\cos\theta)$$

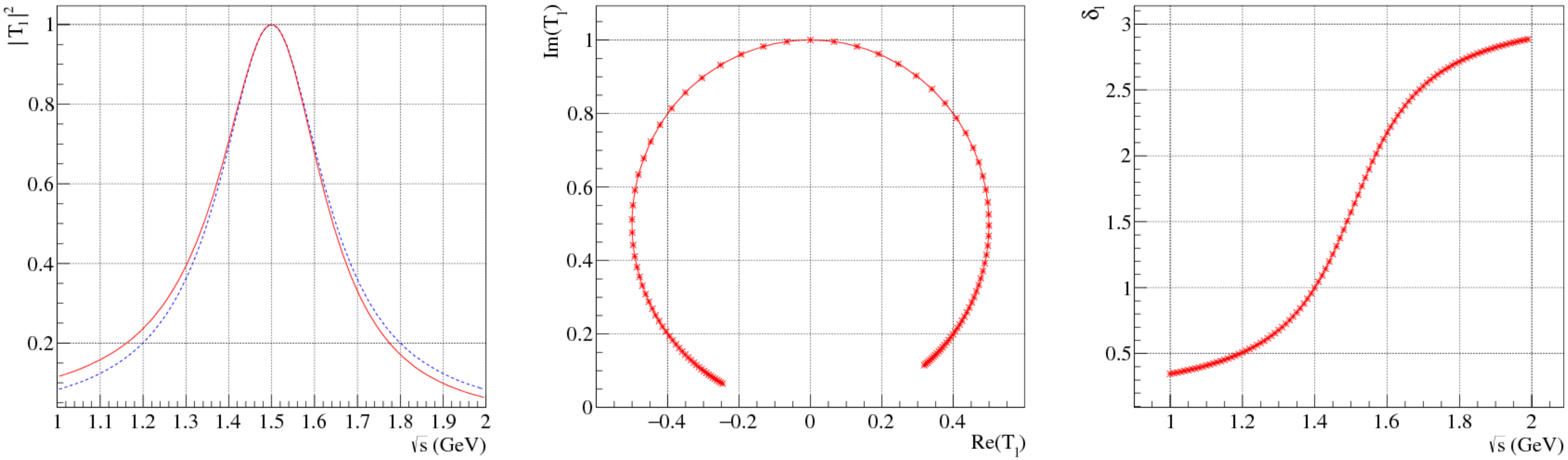
- P_ℓ Legendre polynomials ⇨ angular distribution
- A_ℓ transition amplitudes ⇨ dynamics
- General parameterization for elastic scattering through resonance

$$A_\ell(s) = \frac{8\pi\sqrt{s}}{k} \cdot \frac{\eta_\ell(s) e^{2i\delta_\ell(s)} - 1}{2i} = \frac{8\pi\sqrt{s}}{k} T_\ell(s)$$

- For isolated, narrow resonance: Breit-Wigner parameterization

$$T_\ell(s) \simeq \frac{m_0 \Gamma}{m_0^2 - s - i m_0 \Gamma}$$

Partial Wave Expansion



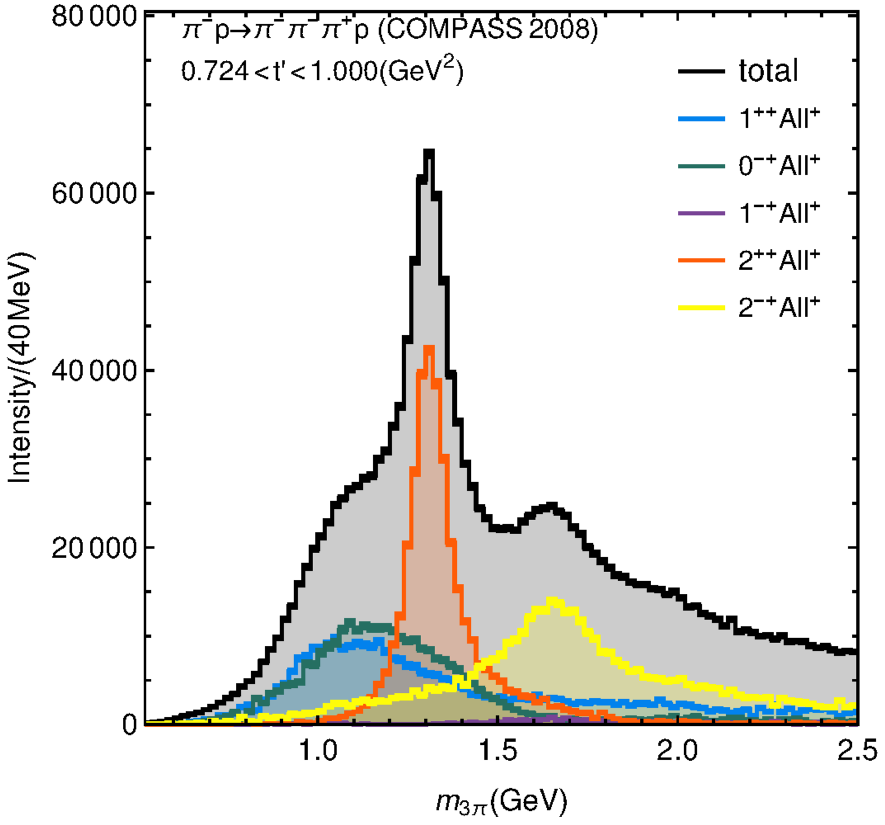
$$A_\ell(s) = \frac{8\pi\sqrt{s}}{k} \cdot \frac{\eta_\ell(s)e^{2i\delta_\ell(s)} - 1}{2i} = \frac{8\pi\sqrt{s}}{k} T_\ell(s)$$

- For isolated, narrow resonance: Breit-Wigner parameterization

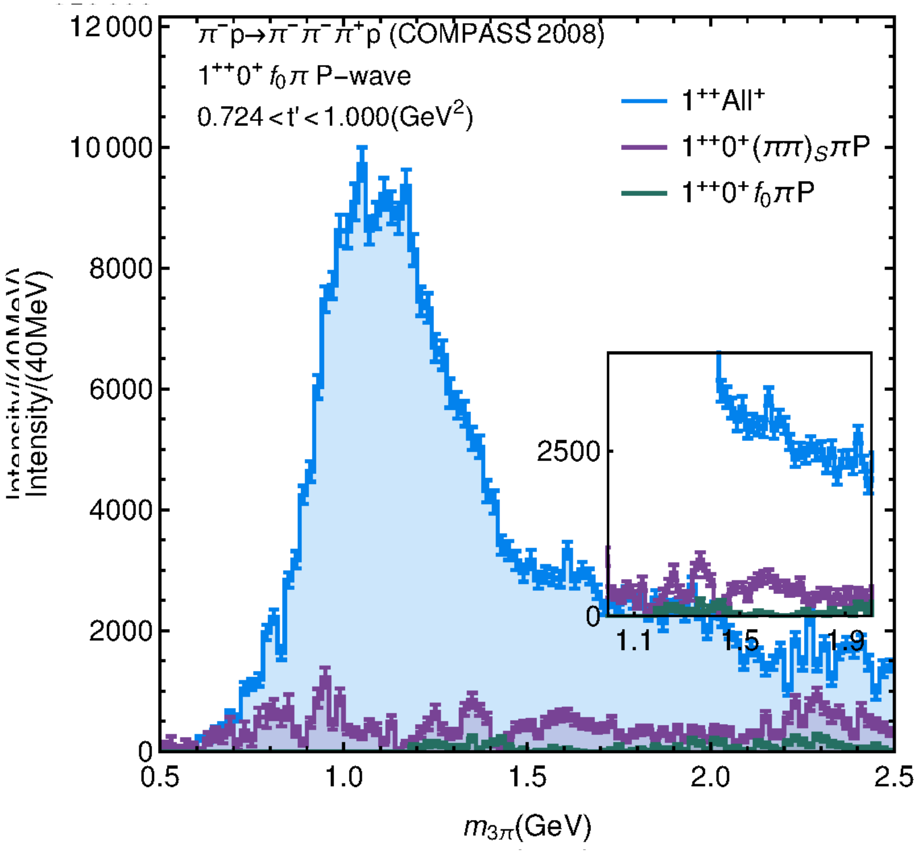
$$T_\ell(s) \simeq \frac{m_0\Gamma}{m_0^2 - s - im_0\Gamma}$$

Partial-Wave Analysis

Total intensity



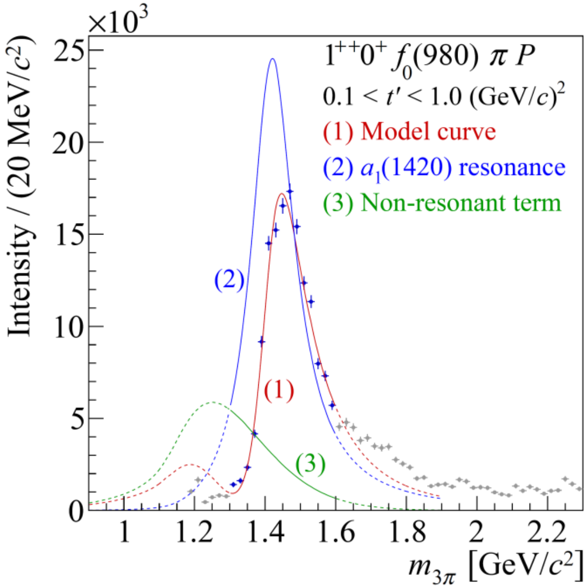
1^{++} Waves

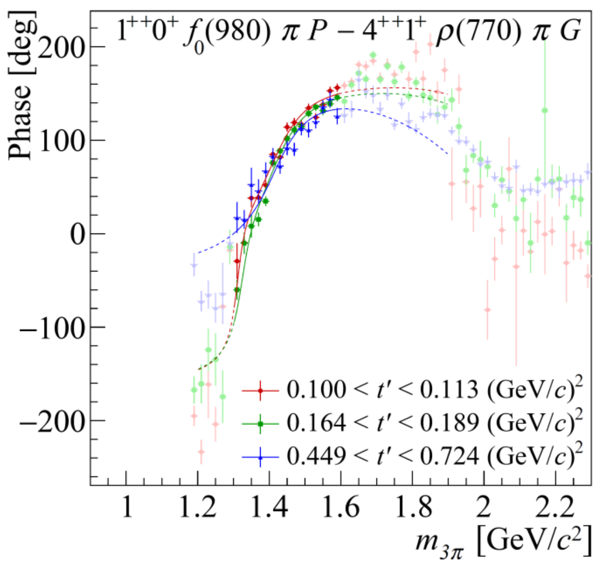


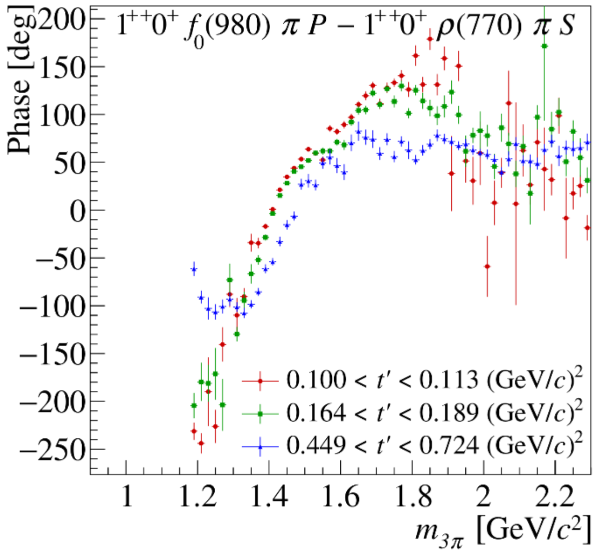
- Largest wave-set to date: 88 waves
- Independent fits in 100 bins (20 MeV) of $m_{3\pi}$ and 11 bins of t'

New $a_1(1420)$

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







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

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

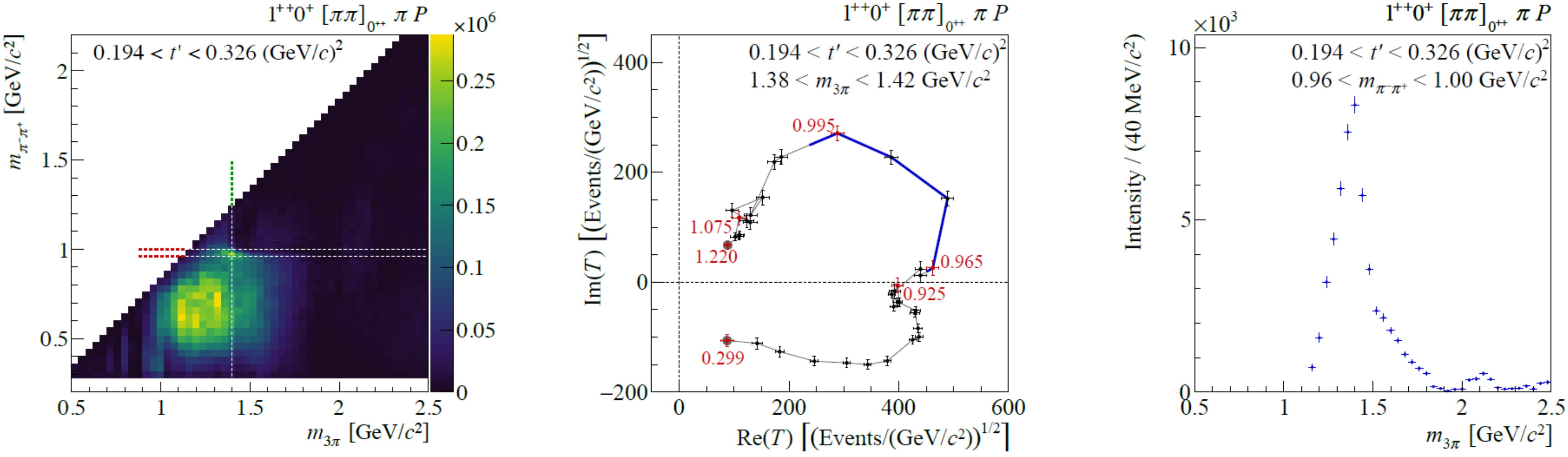
$$\Gamma_0 = 153^{+8}_{-23}\ \mathrm{MeV}/c$$

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

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

New $a_1(1420)$

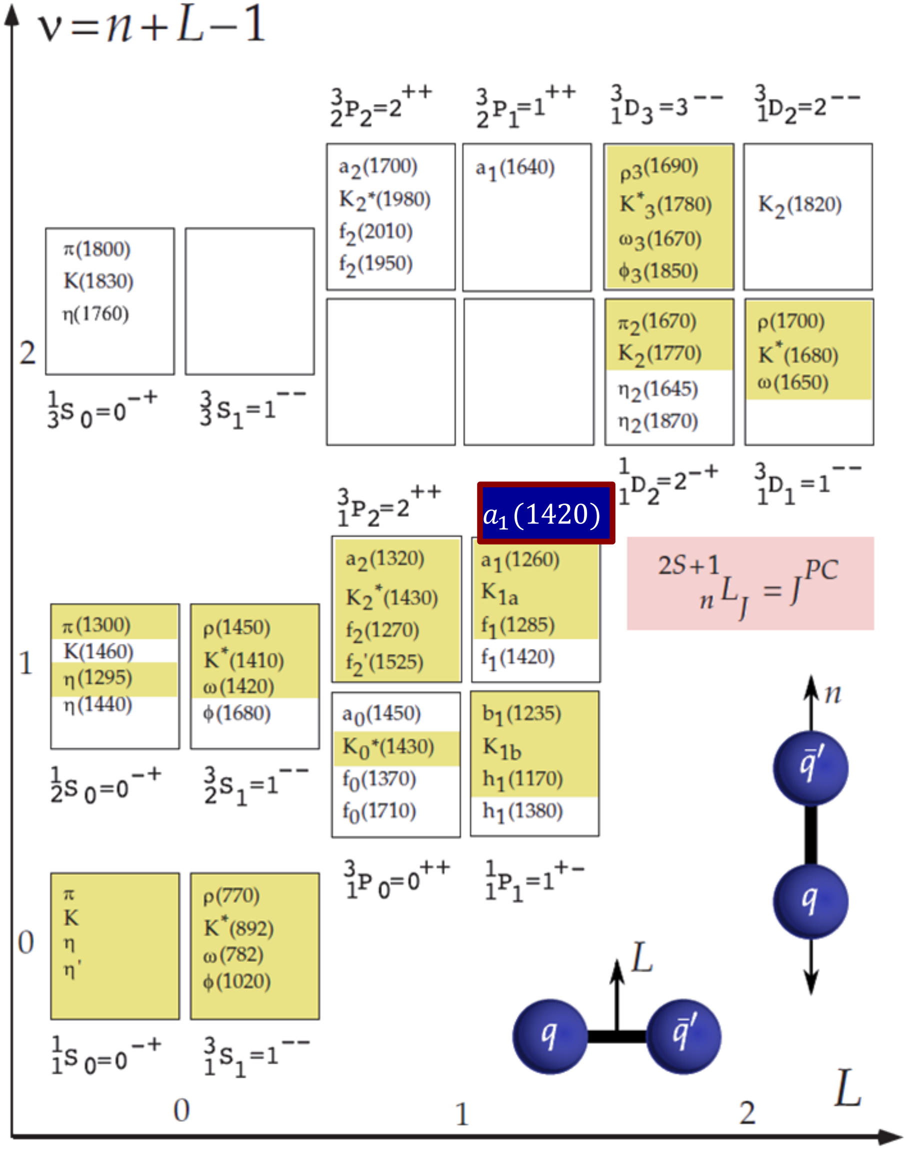
[C. Adolph, et al. (COMPASS Collaboration), Phys. Rev. D 95 (2017) 032004]



Freed isobar analysis (model-independent isobar amplitude):

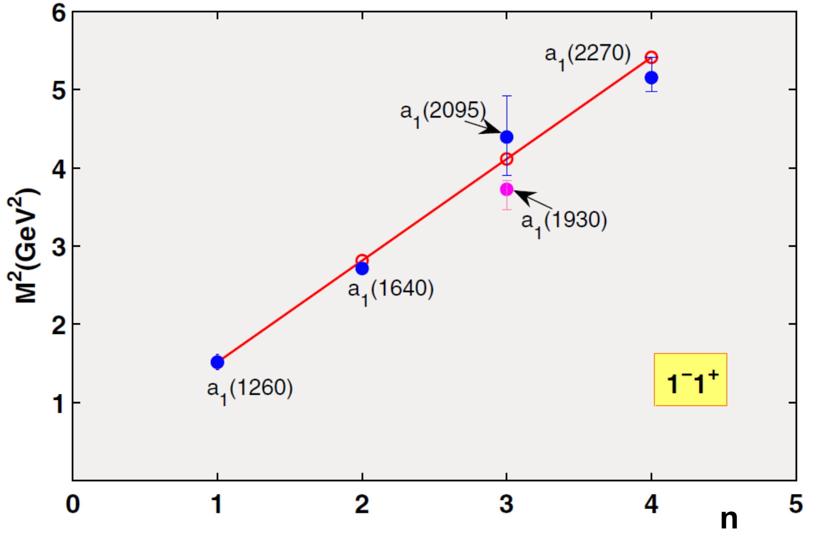
- Replace fixed parameterization of 2-body amplitude $J^{PC}_{\text{iso}} = 0^{++}$ by set of free (complex) parameters in 2-body mass bins
- No separation into several isobars
- Amplitude for $J^{PC}_{\text{iso}} = 0^{++}$ isobars determined from data for three $J^{PC}_{3\pi} = 0^{-+},\ 1^{++},\ 2^{-+}$

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

Exotischer Teilchenzustand gibt Rätsel au

Neu entdecktes Zerfallsprodukt lässt sich nach gä Physik nicht erklären

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

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

1 September 2015 // 09:31 AM CET

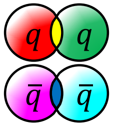
Autor
CHRISTINE KEWITZ
REDAKTEURIN

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

Interpretations

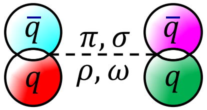
- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]



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

Interpretations

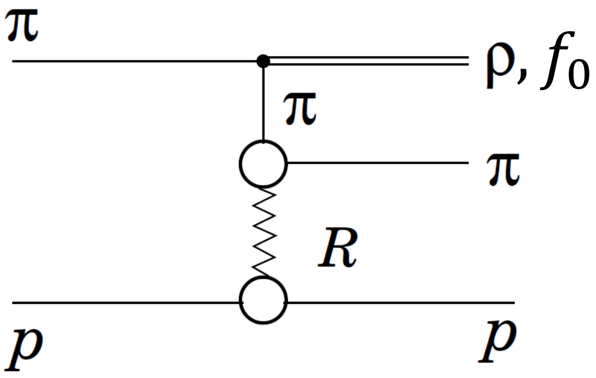
- Tetraquark state [Z.-G. Wang (2014), H.-X.Chen et al. (2015), T. Gutsche et al. (2017)]
- $K^*\overline{K}$ molecule [T. Gutsche et al. (2017)]



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

Interpretations

- 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)]



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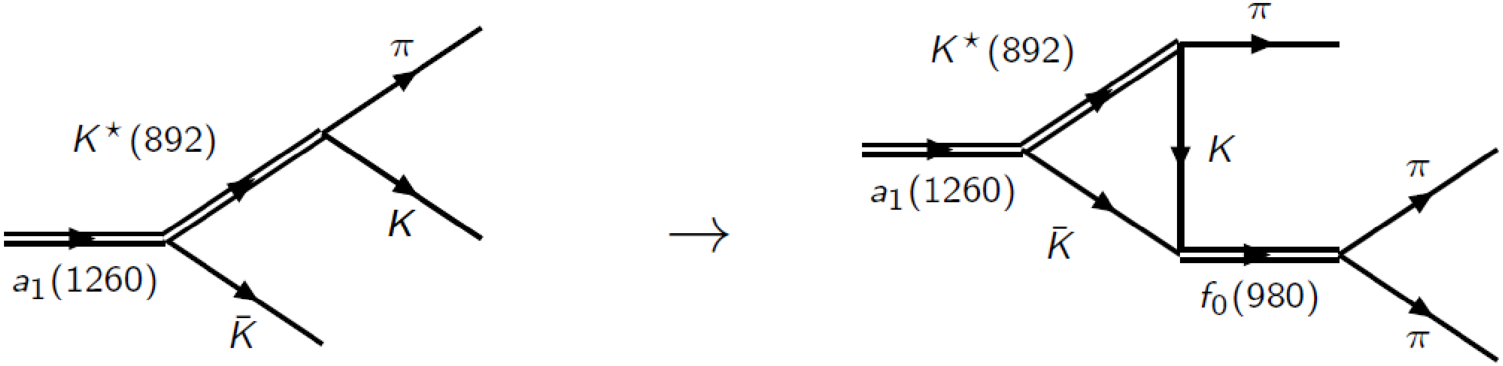
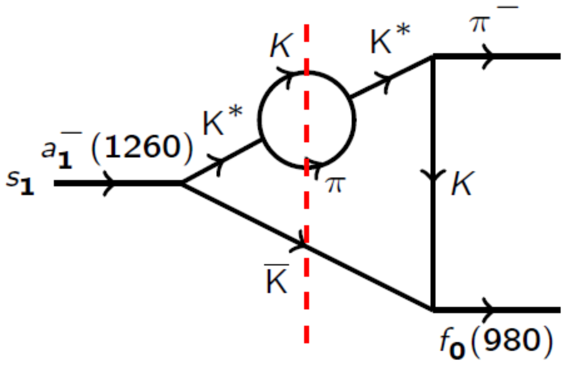
- $K^*\overline{K}$ molecule [T. Gutsche et al. (2017)]
- Interference of Deck $\rho\pi$ S and $f_0\pi$ P-wave [J.-L. Basdevant et al. (2015)]
- Triangle singularity [M. Mikhasenko et al., PRD 91, 094015 (2015), F. Aceti, PRD 94, 096015 (2016)]

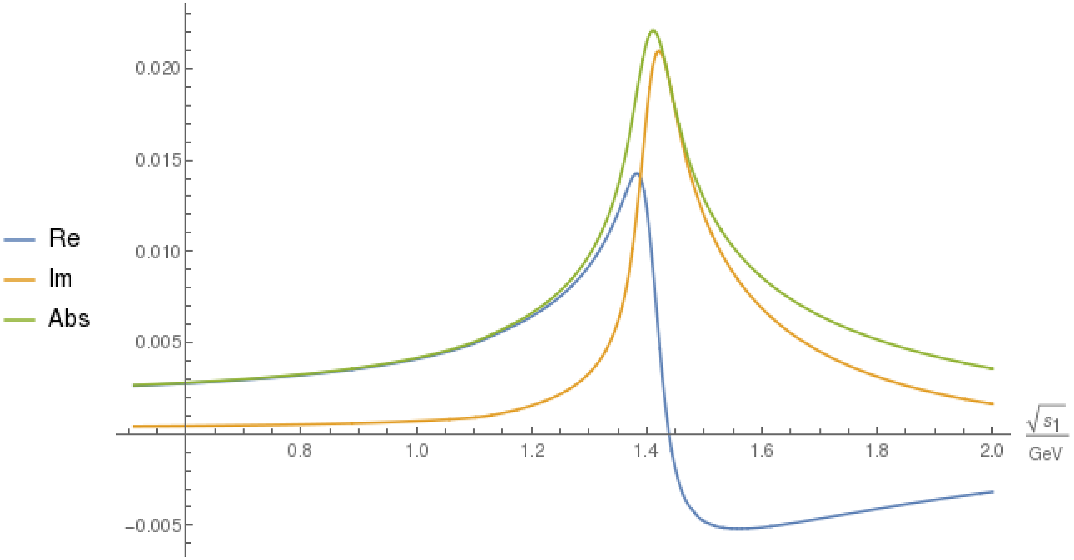


  - Decay of $a_1(1260) \rightarrow K^*\overline{K}$ above threshold
  - Final-state rescattering of $K\overline{K}$ to $f_0(980)$

    ⇨ logarithmic singularity of amplitude if particles close to mass shell

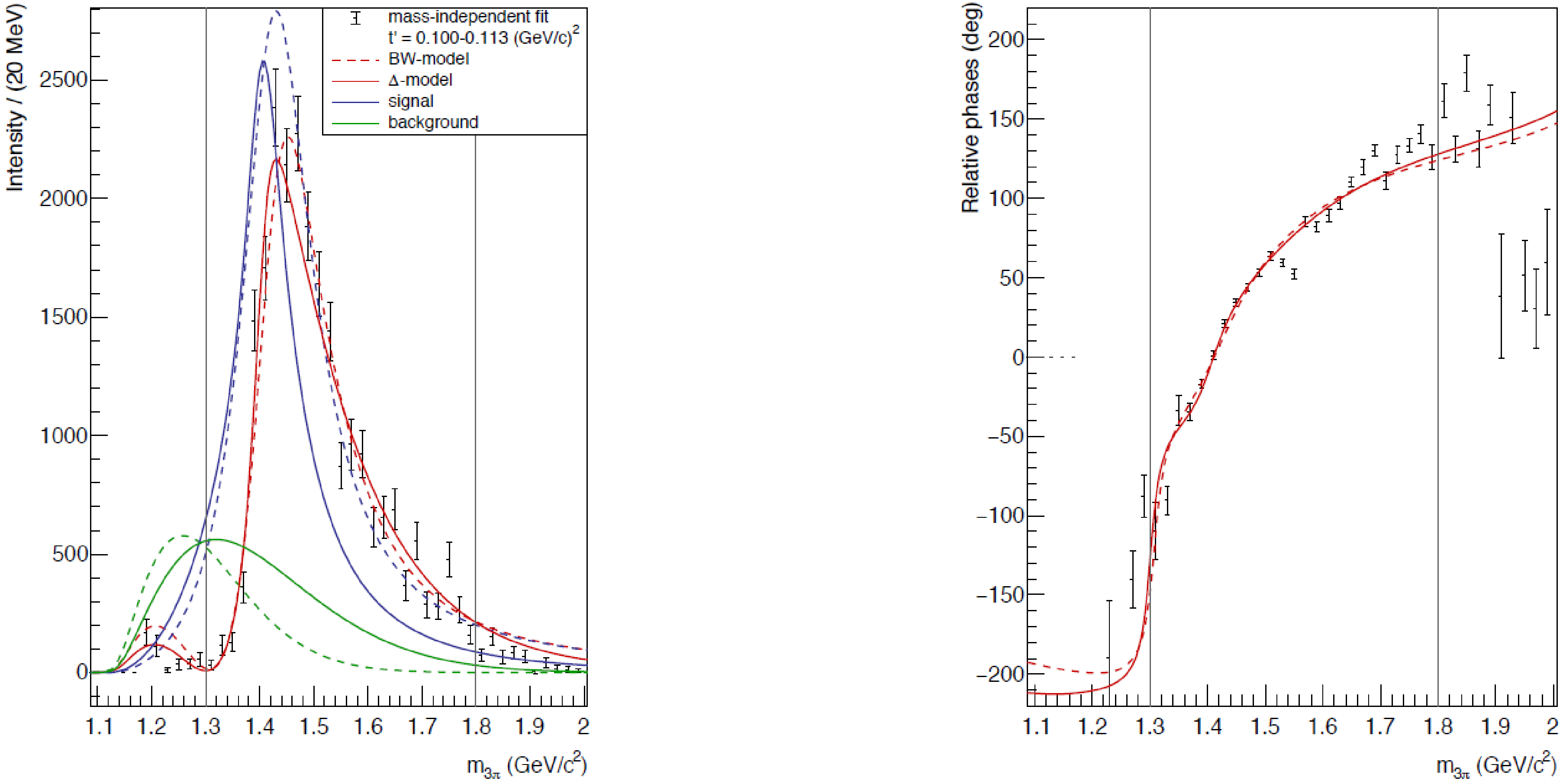
Triangle Amplitude





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

Comparison TS - BW

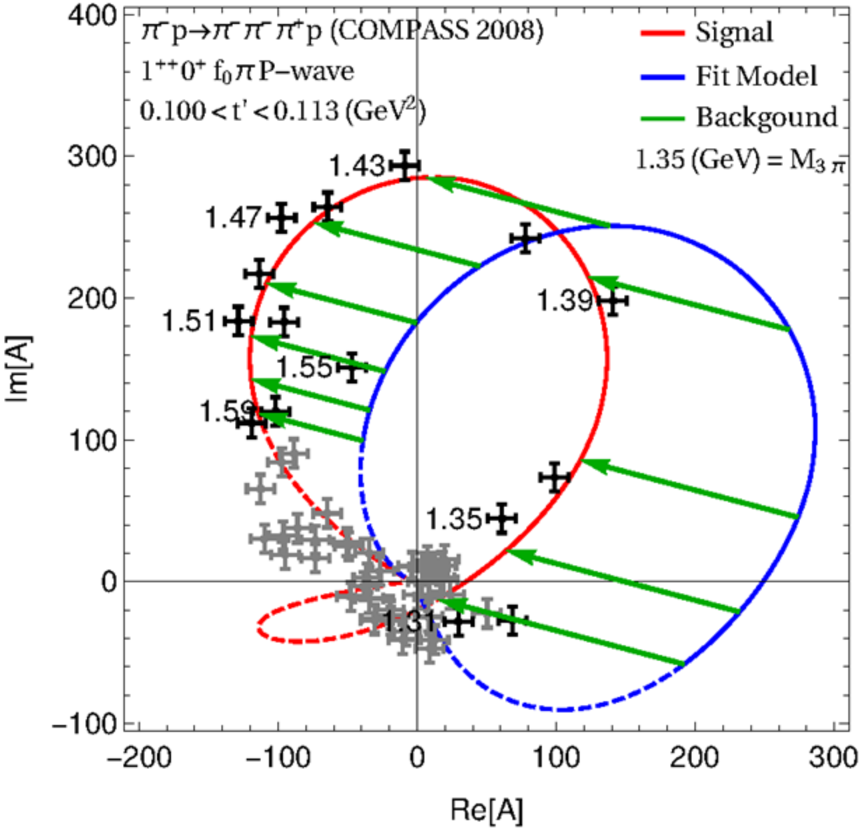


- Similar χ^2_{red} for both fits (slightly better for triangle)
- No new free parameters for $a_1(1420)$ signal by triangle mechanism

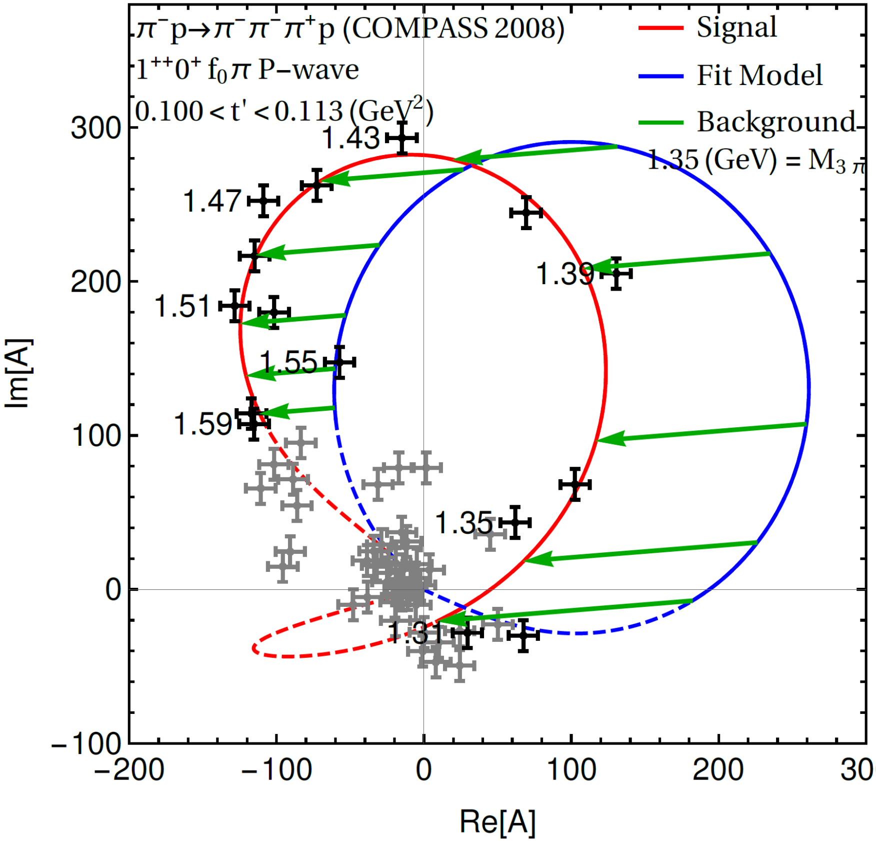
Comparison TS - BW

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

Triangle



Resonance

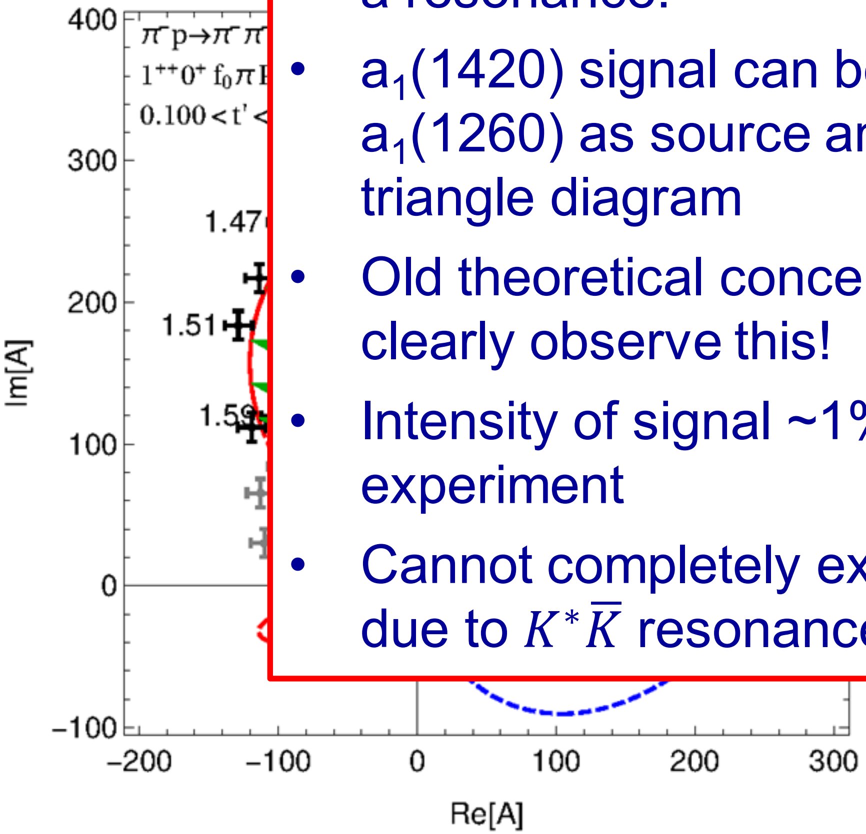


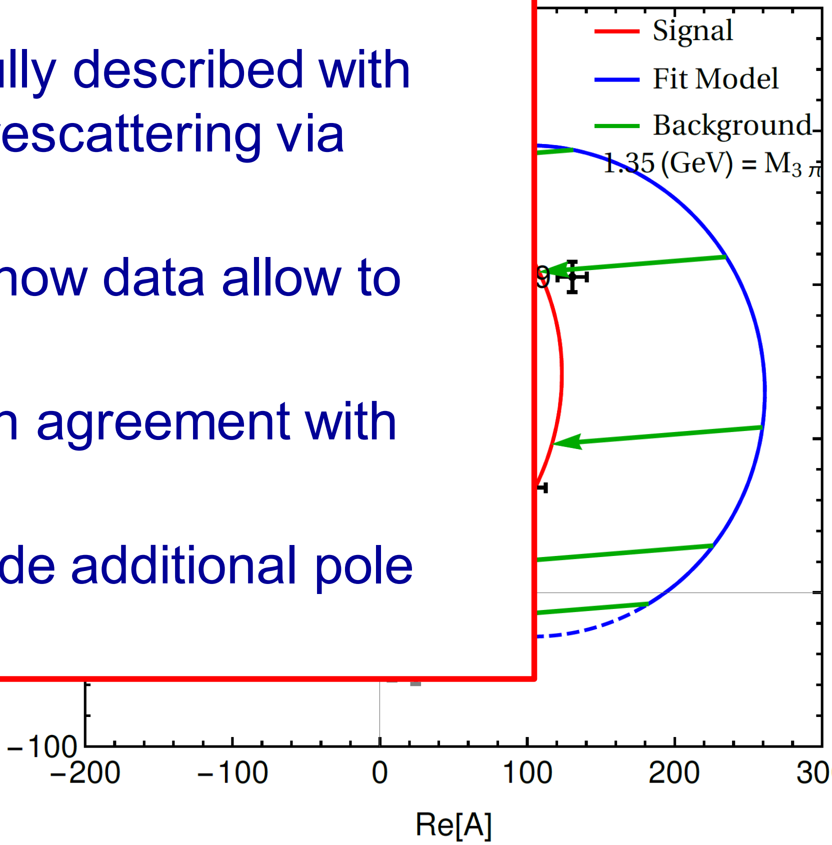
Comparison TS - BW

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

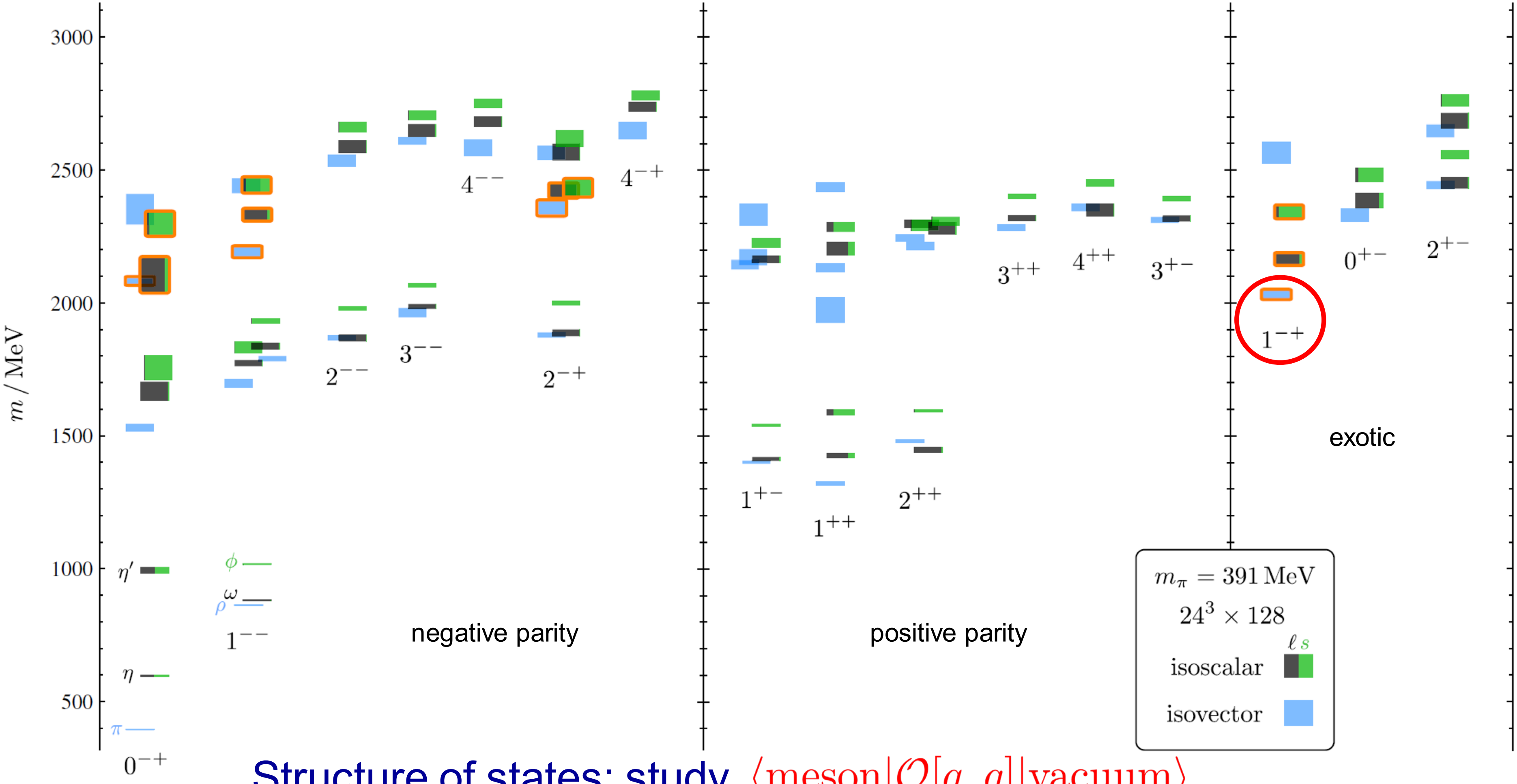
Summary for $a_1(1420)$

- 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

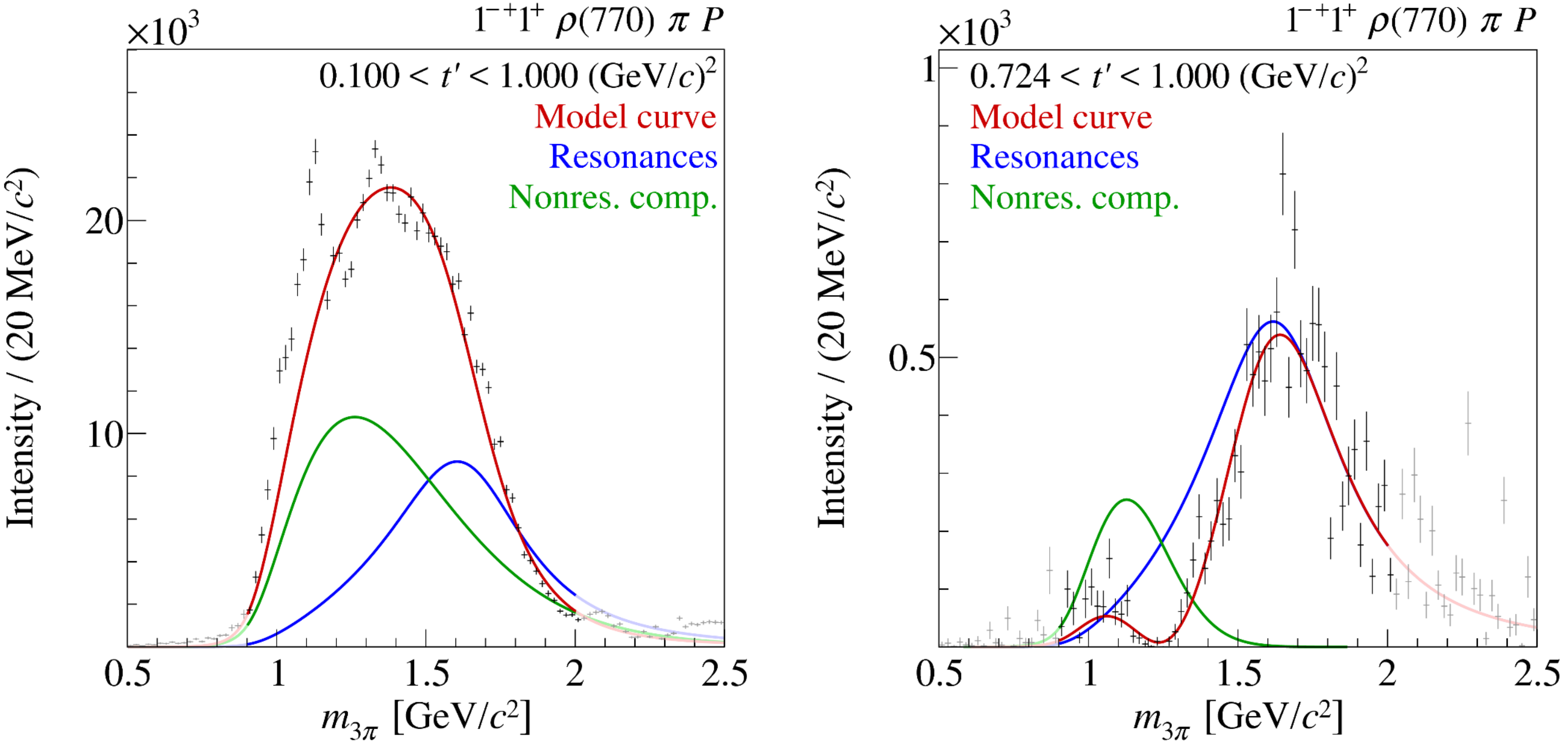


Structure of states: study $\langle \text{meson} | \mathcal{O}[q,g] | \text{vacuum} \rangle$

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)]

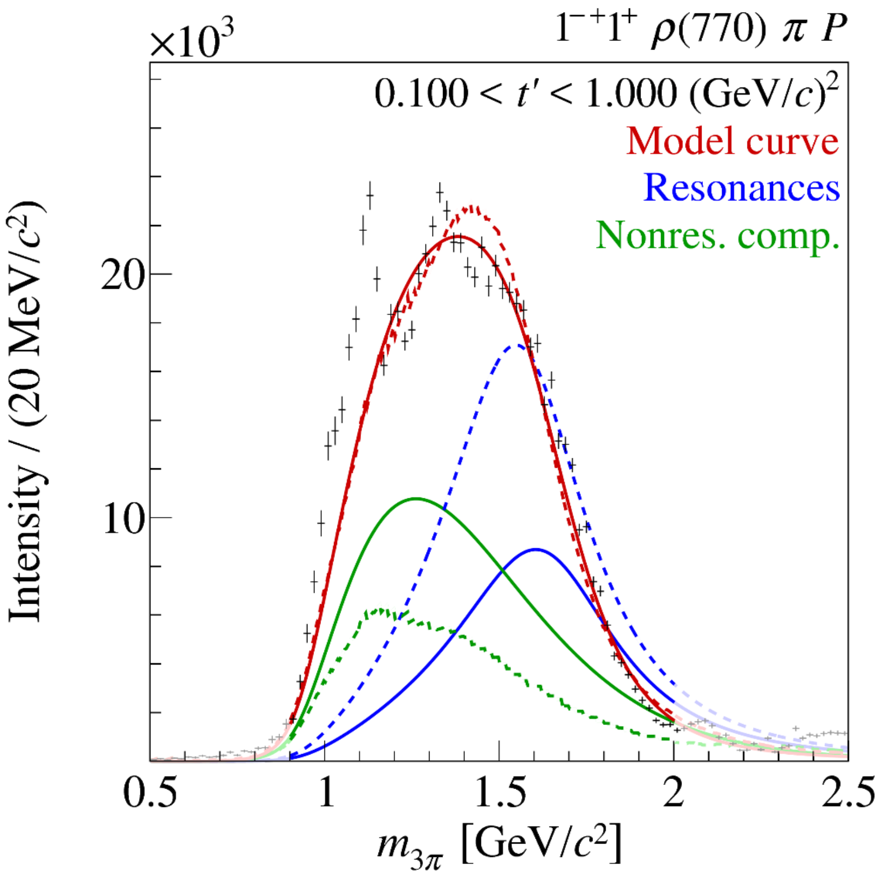
1^{-+} Partial Wave

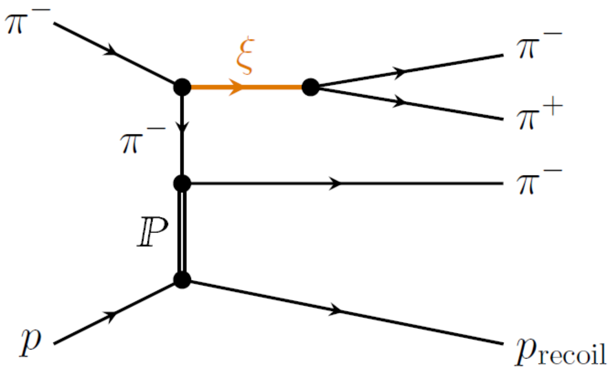


- Resonance-model fit to spin-density matrix: 14 waves
- Exploit *t´* dependence to separate resonant and non-resonant contributions

[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 $\pi_1(1600)$

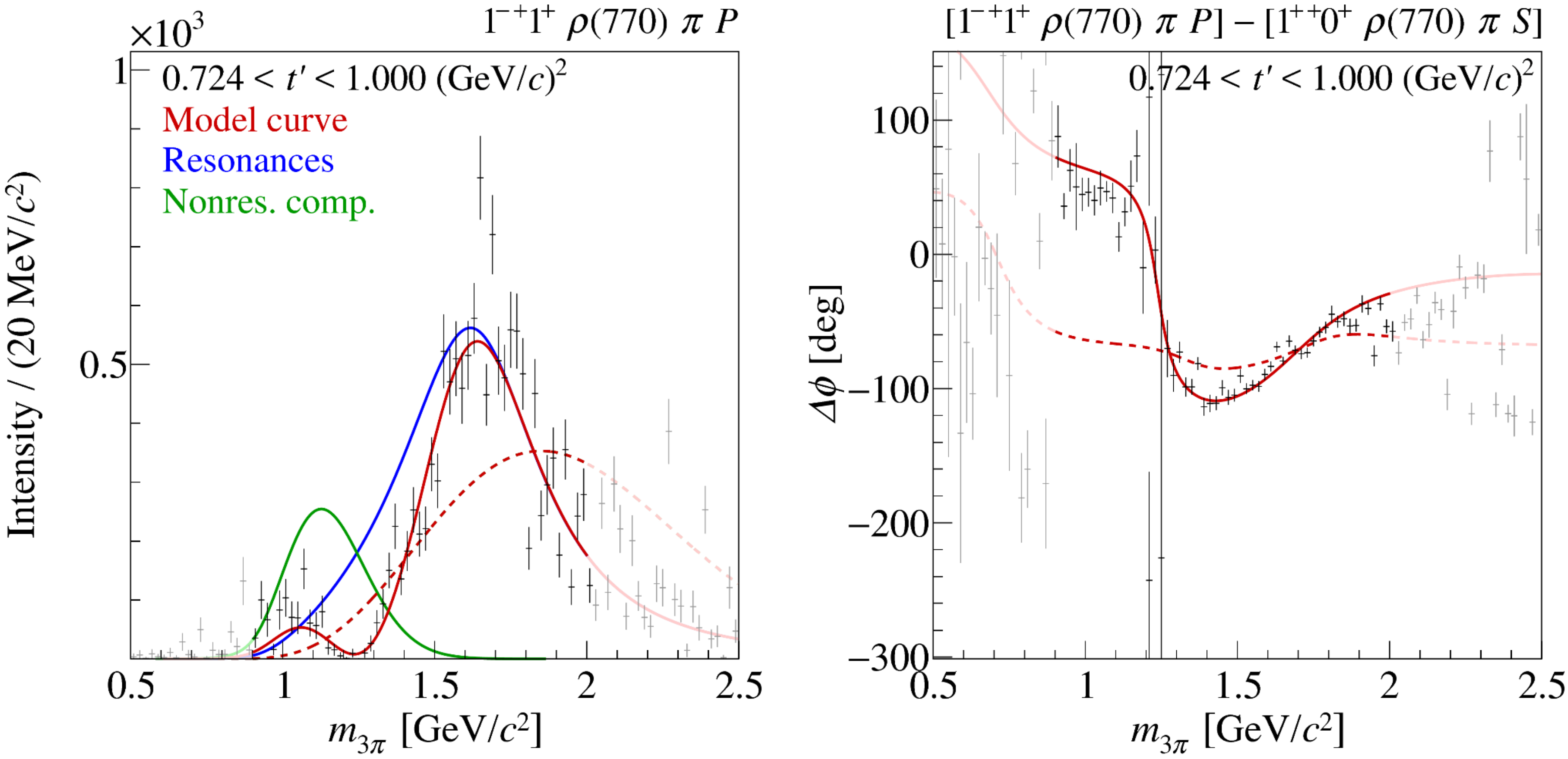
$$M_0 = 1600^{+110}_{-60}\ \text{MeV}/c^2$$

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

- Bad description of data without resonance component

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

1^{-+} Partial Wave

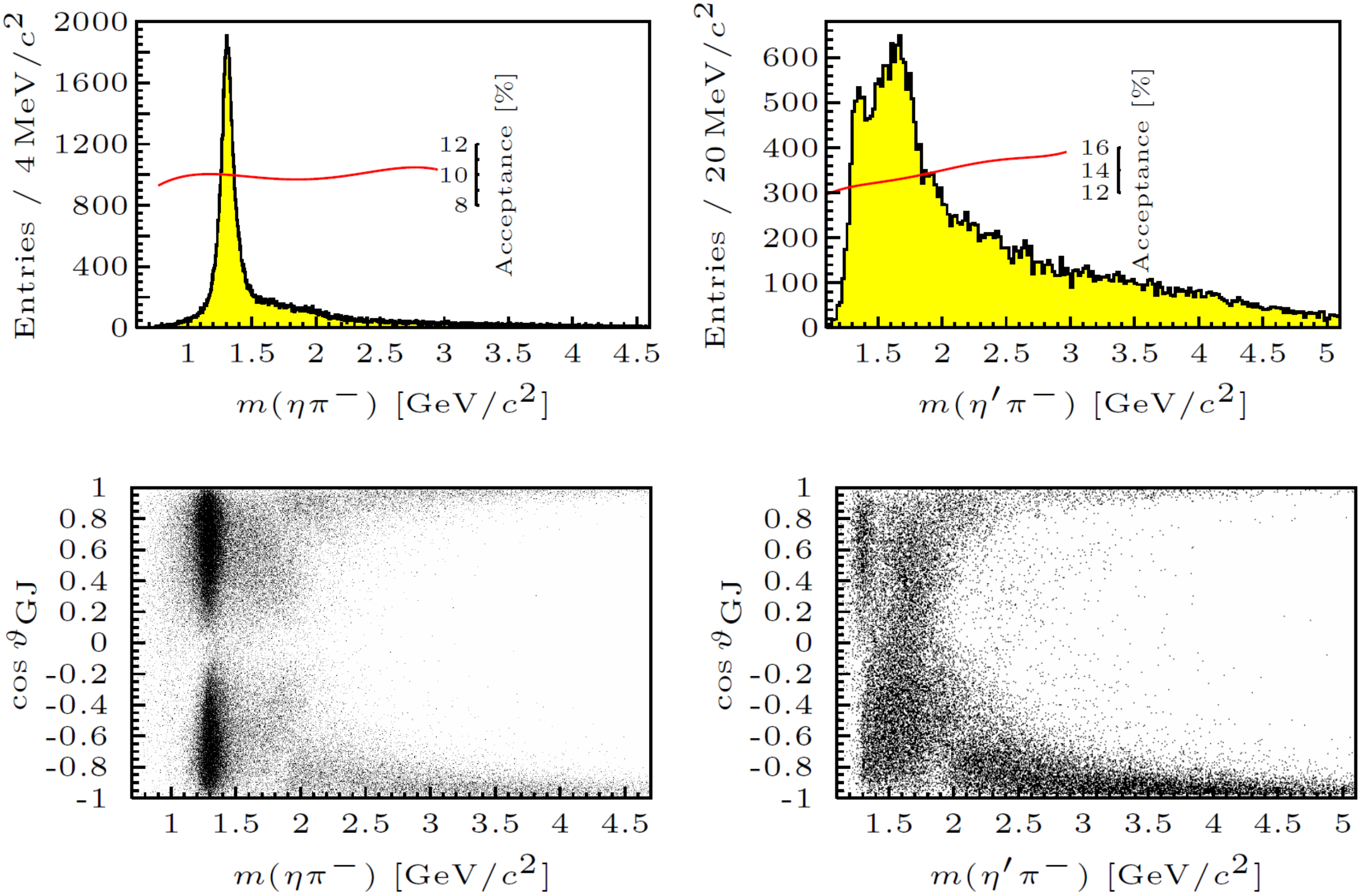


Bad description of data without resonance component

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

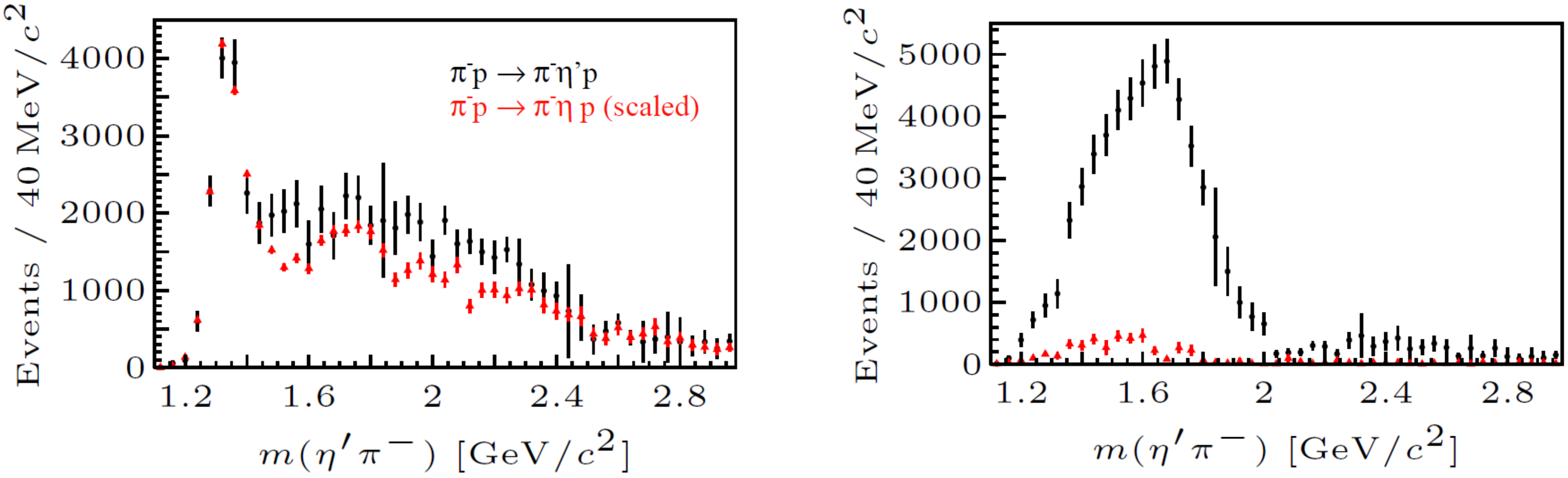
[R. Akhunzyanov et al. (COMPASS), Phys. Rev. D 98, 092003 (2018)]

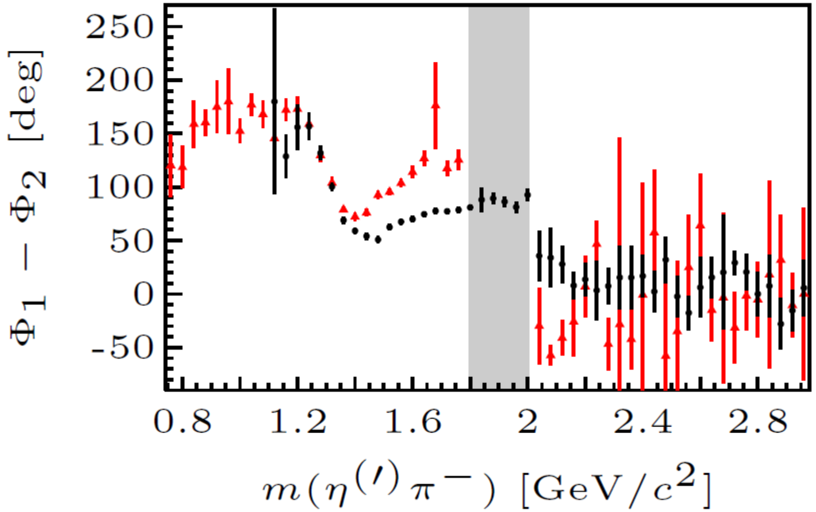
$\eta\pi^-$ / $\eta'\pi^-$ Final States



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

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



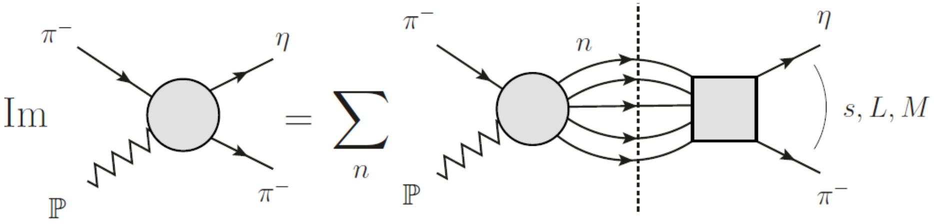


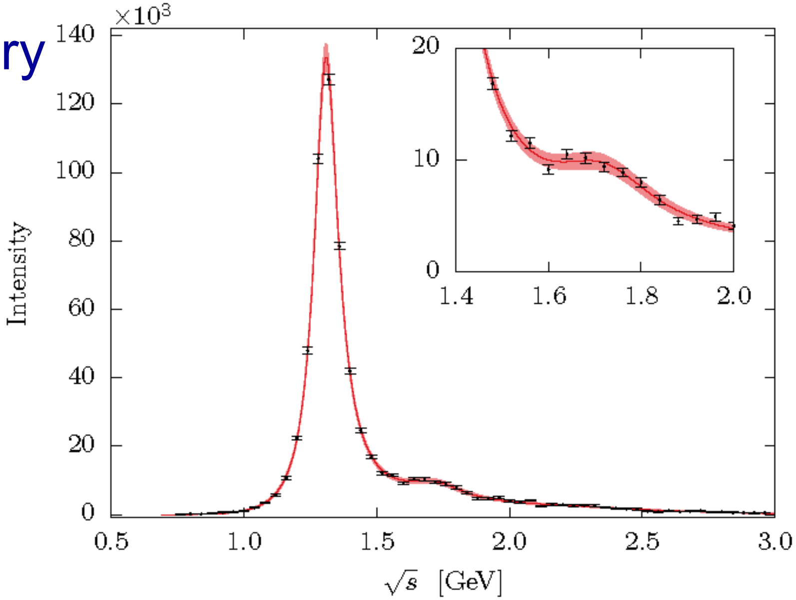
- $\eta\pi^-$ waves scaled according to phase space and BR to final state
- *D*, *G* waves very similar
- *P* wave very different in $\eta\pi$ and $\eta'\pi$
- Breit-Wigner model fit unstable

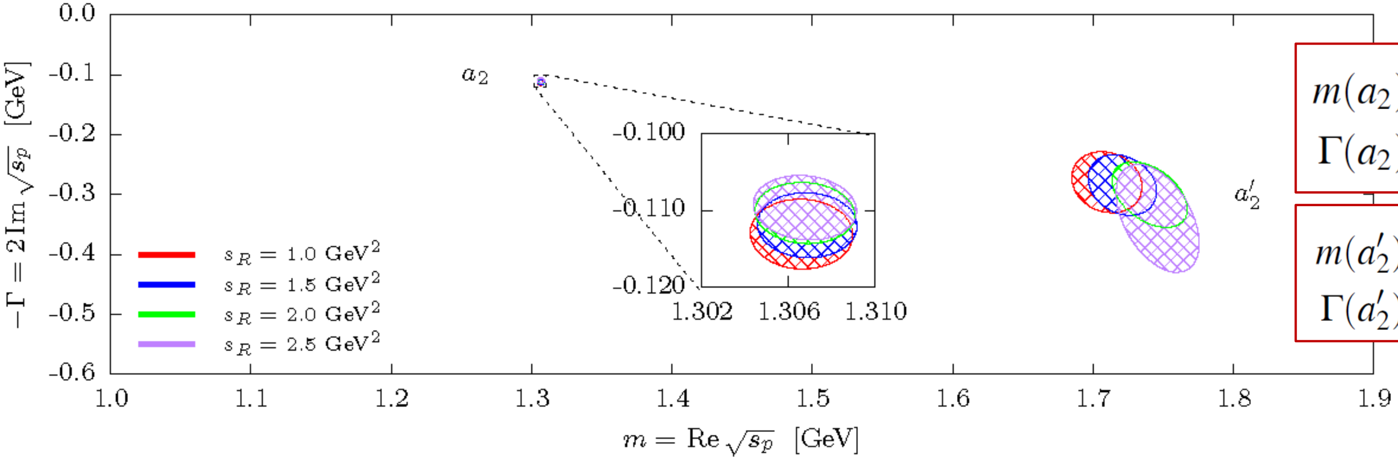
[C. Adolph (COMPASS), Phys. Lett. B 740, 303 (2015)]

Extraction of Poles

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





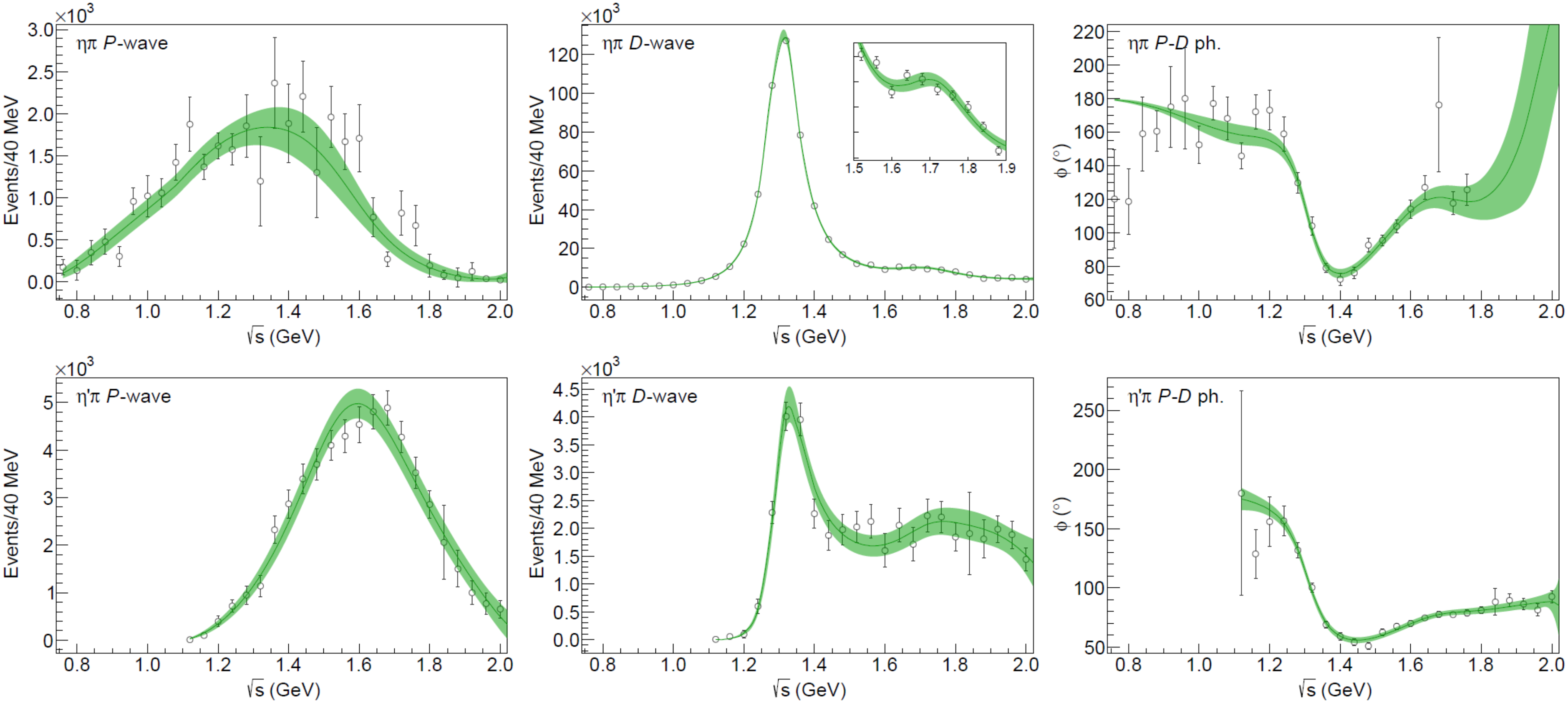


$$m(a_2) = (1307 \pm 1 \pm 6)\ \mathrm{MeV},$$
$$\Gamma(a_2) = (112 \pm 1 \pm 8)\ \mathrm{MeV},$$

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

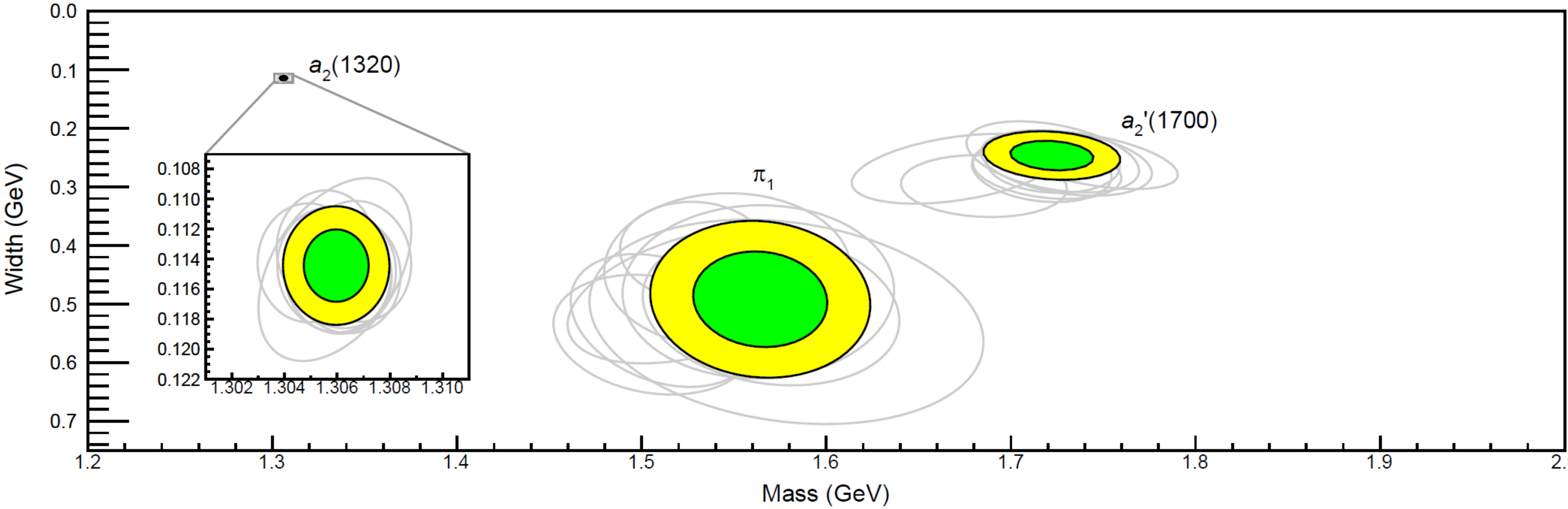
[A. Jackura et al. (JPAC, COMPASS), Phys. Lett. B 779, 464 (2018)]

ηπ–η′π Coupled Channels



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

ηπ–η′π Coupled Channels



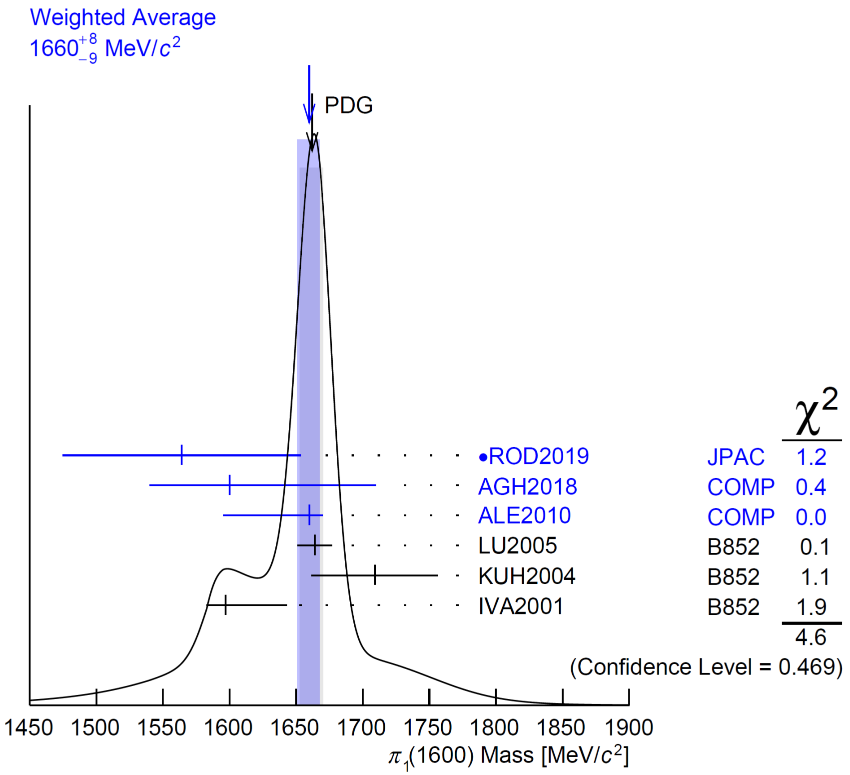
- only a single pole needed to describe both ηπ and η′π peaks
- consistent with $\pi_1(1600)$

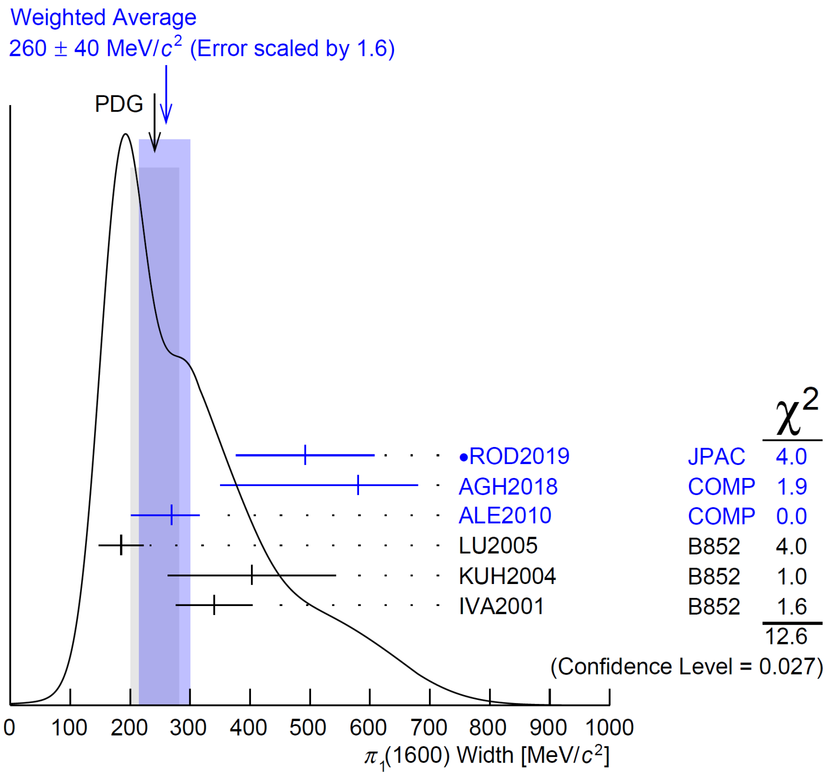
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

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

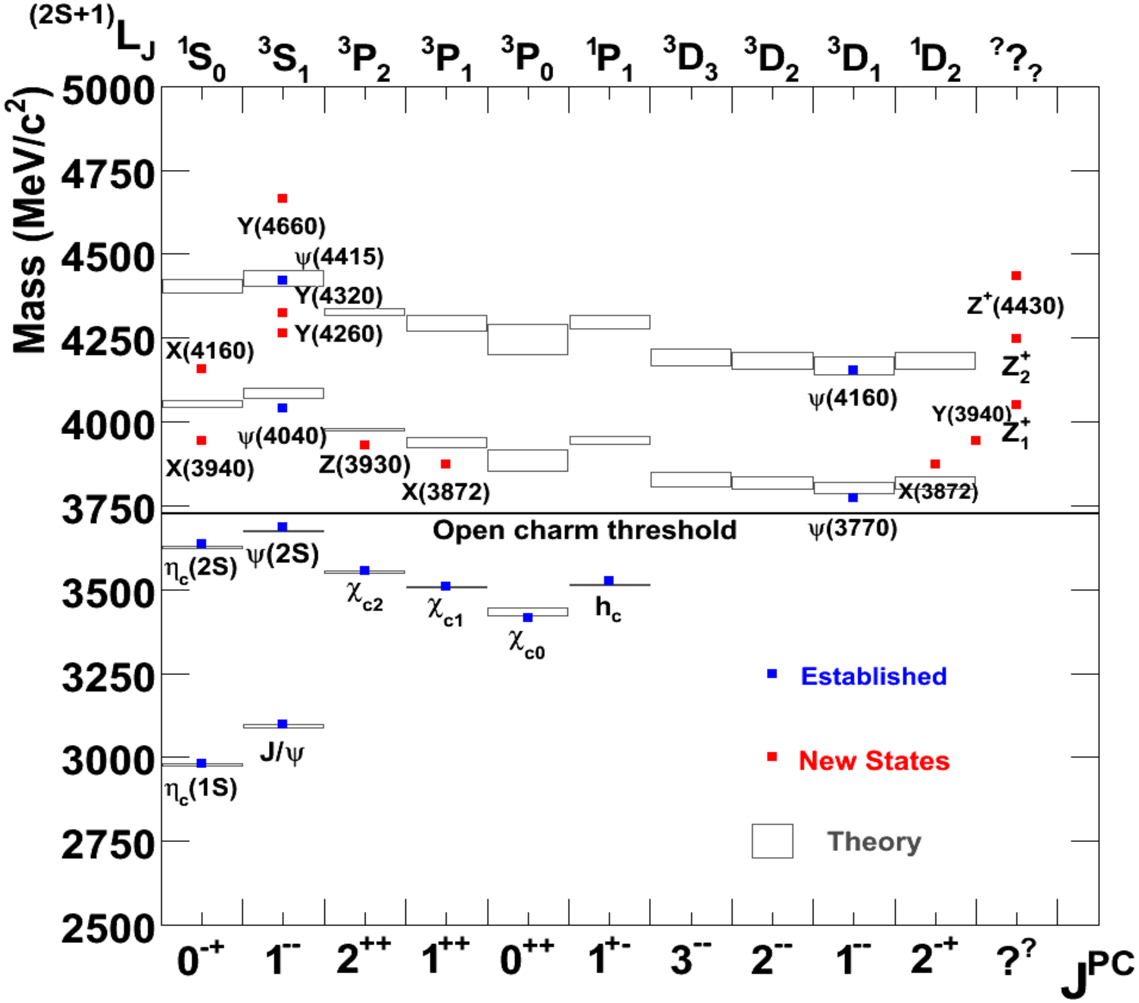
Summary for π_1

- 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





Charmonium Spectrum



[V. Santoro, Hadron 2015]

Quark model:

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

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

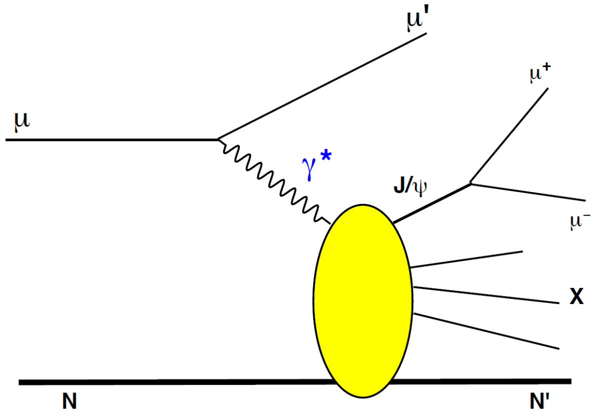
- color singlets

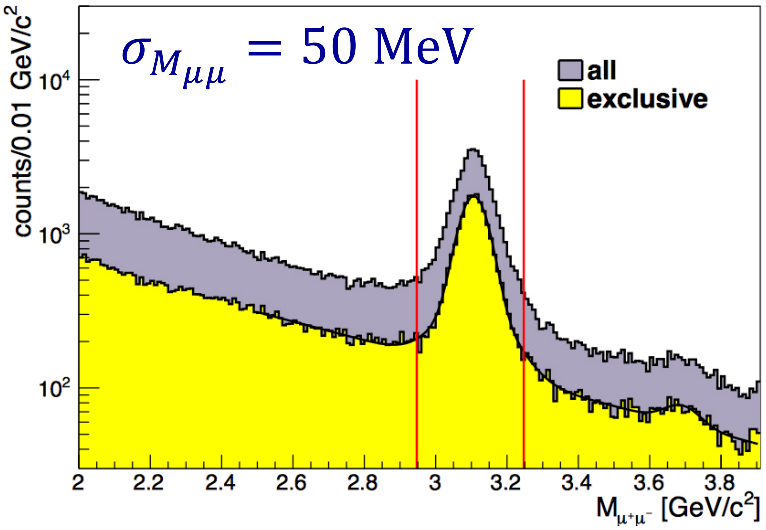
- Many new (narrow) states discovered in recent years
- Assignment not clear
- Some definitively not charmonium-like

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

Muoproduction of Charmonia

Deep inelastic scattering with muons:



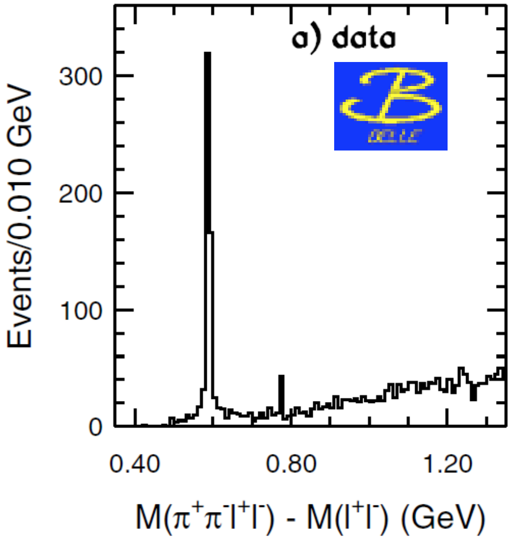


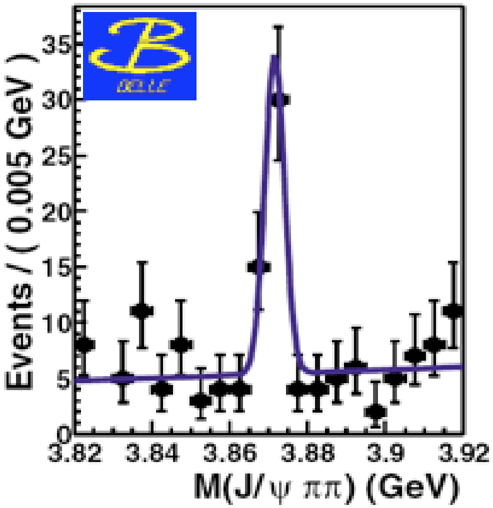
Year	Beam ($p/\ GeV/c$)	Target
2002	μ^+ (160)	^{6}LiD
2003	μ^+ (160)	^{6}LiD
2004	μ^+ (160)	^{6}LiD
2006	μ^+ (160)	^{6}LiD
2007	μ^+ (160)	NH_3
2010	μ^+ (160)	NH_3
2011	μ^+ (200)	NH_3
2016	$\mu^\pm$ (160)	Liq. H_2
2017	$\mu^\pm$ (160)	Liq. H_2

- ~50 k $J/\psi \to \mu^+\mu^-$ events (until 2011)
- corresponds to $\mathcal{L}_{\text{int}} \sim 14\ \text{pb}^{-1}$

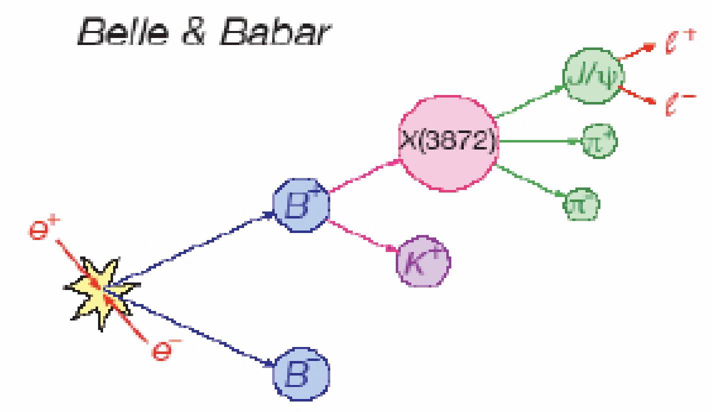
X(3872)

Discovered by BELLE in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-} J/\psi$





[BELLE, S.-K. Choi et al, PRL 91, 262001 (2003)]

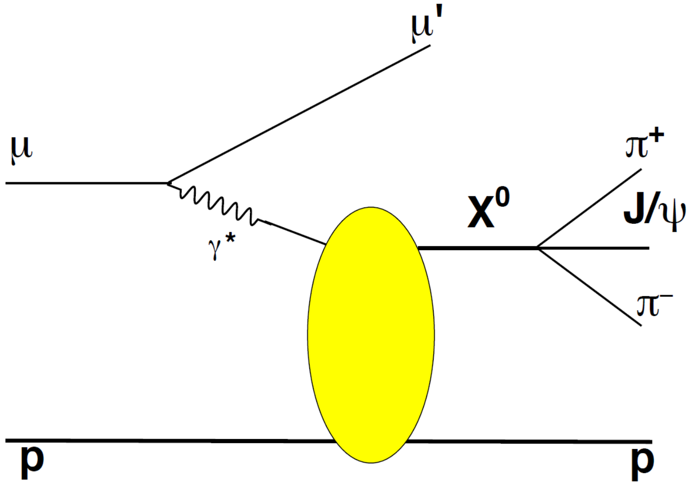


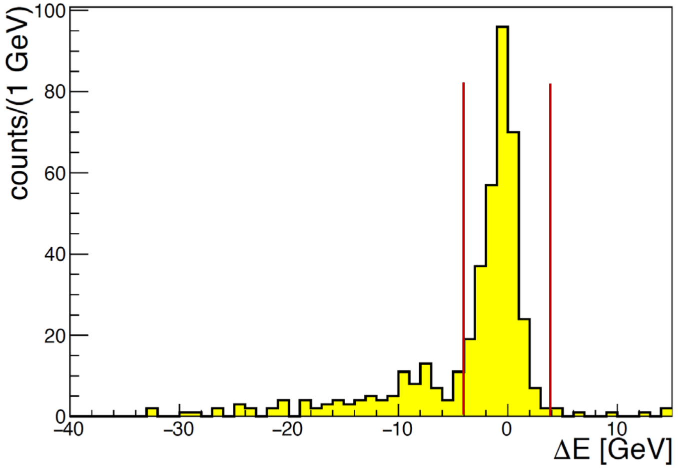
Most-cited paper by BELLE!

Higher Charmonia in COMPASS

Exclusive reaction with neutral exchange

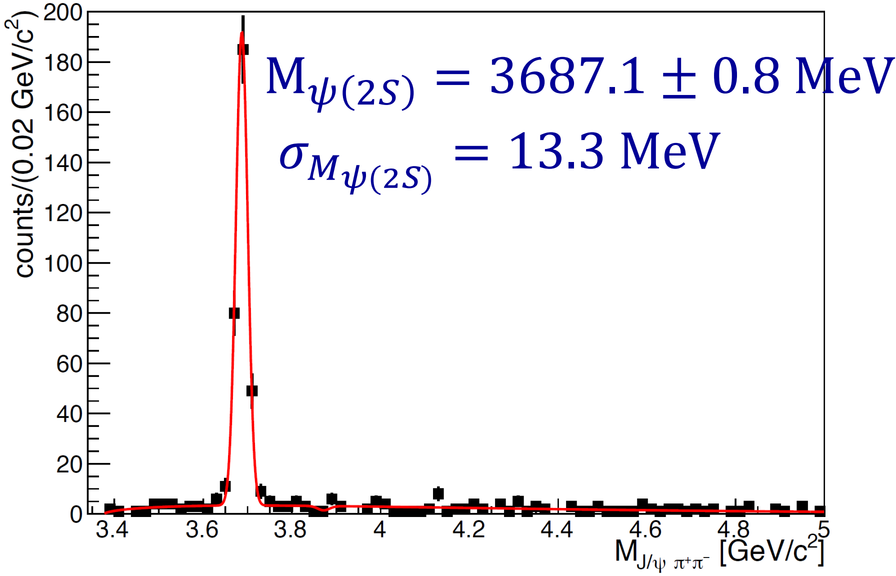
$$\mu^+ N \to \mu^+ X^0 N' \to \mu^+ (J/\psi \pi^+ \pi^-) N'$$
$$\to \mu^+ (\mu^+ \mu^- \pi^+ \pi^-) N',$$





⇨ no sign of a peak at 3.87 GeV

< 0.9 ev. (90% CL)

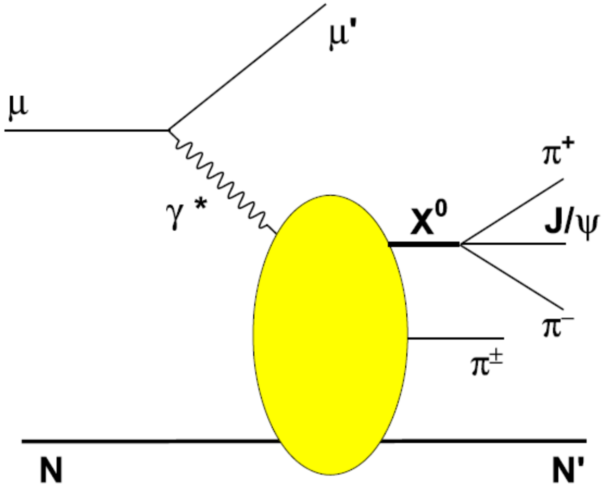


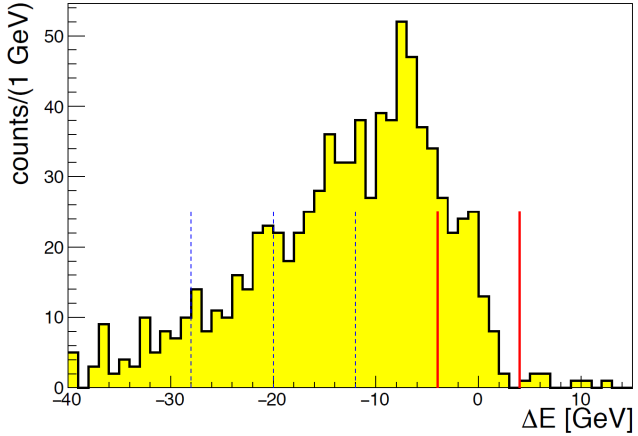
$$M_{\psi(2S)} = 3687.1 \pm 0.8 \text{ MeV}$$
$$\sigma_{M_{\psi(2S)}} = 13.3 \text{ MeV}$$

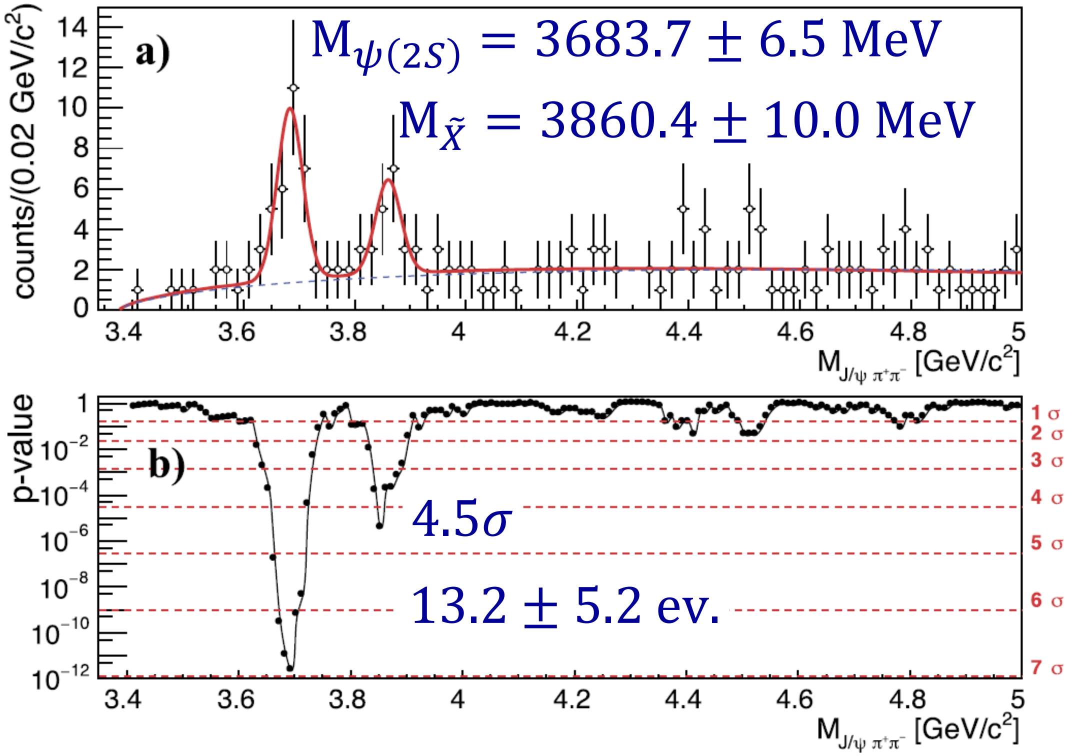
Higher Charmonia in COMPASS

Exclusive reaction with charge exchange and additional $\pi^{\pm}$

$$\mu^+ N \to \mu^+ X^0 \pi^{\pm} N' \to \mu^+ (J/\psi \pi^+ \pi^-) \pi^{\pm} N'$$
$$\to \mu^+ (\mu^+ \mu^- \pi^+ \pi^-) \pi^{\pm} N',$$







$M_{\psi(2S)} = 3683.7 \pm 6.5$ MeV

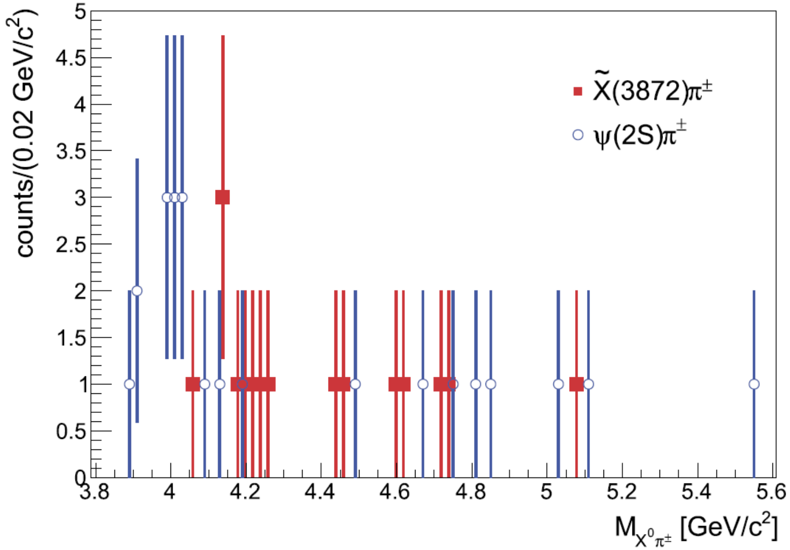
$M_{\tilde{X}} = 3860.4 \pm 10.0$ MeV

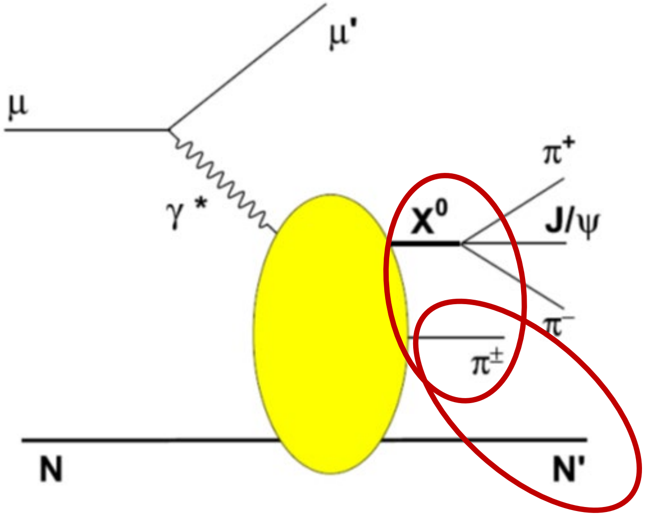
4.5σ

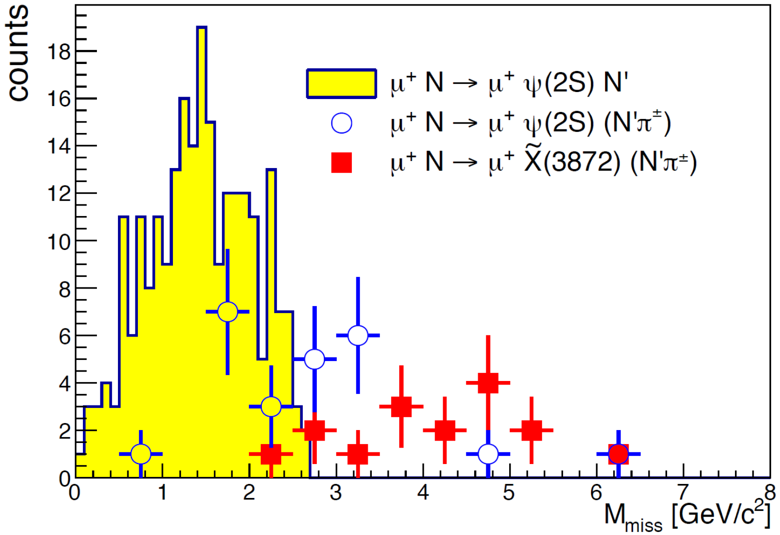
13.2 ± 5.2 ev.

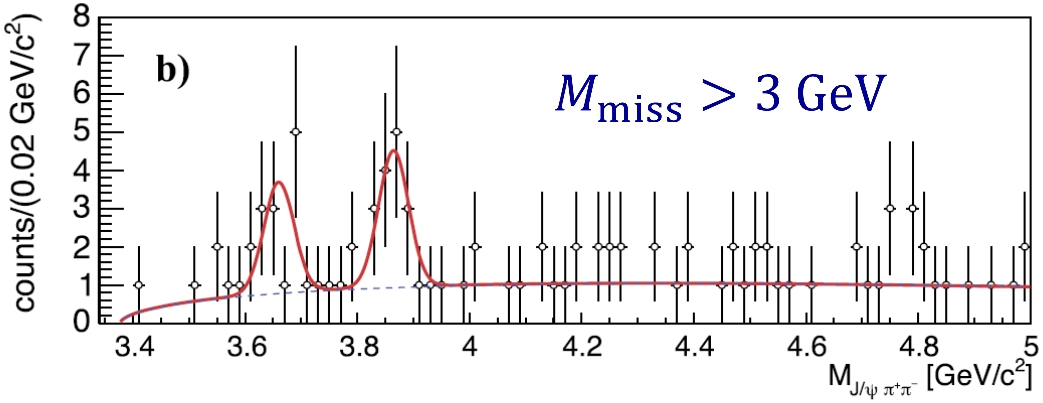
[COMPASS, M. Aghasyan, PLB 783, 334 (2018)]

Production Mechanism?

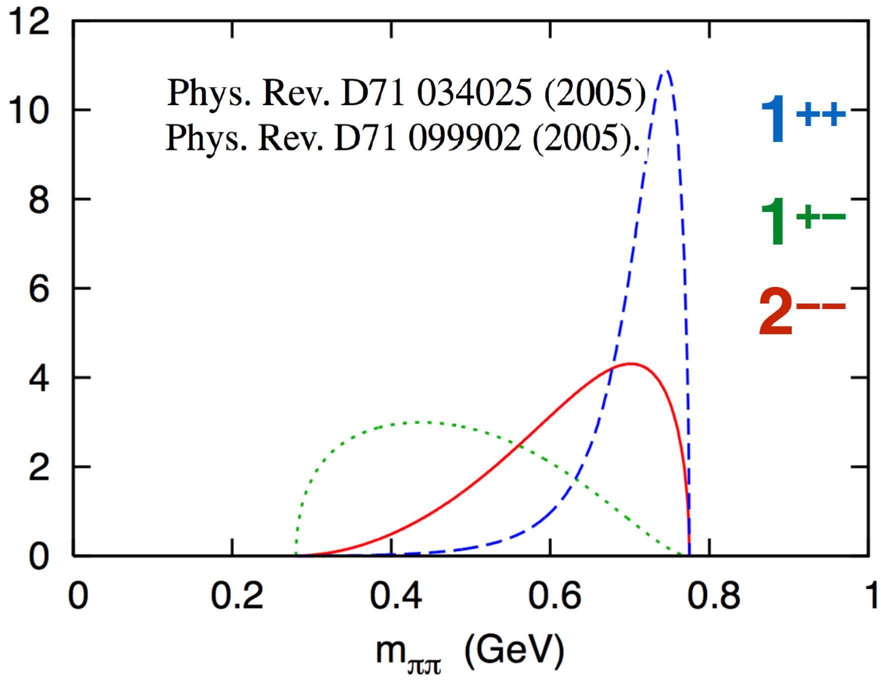




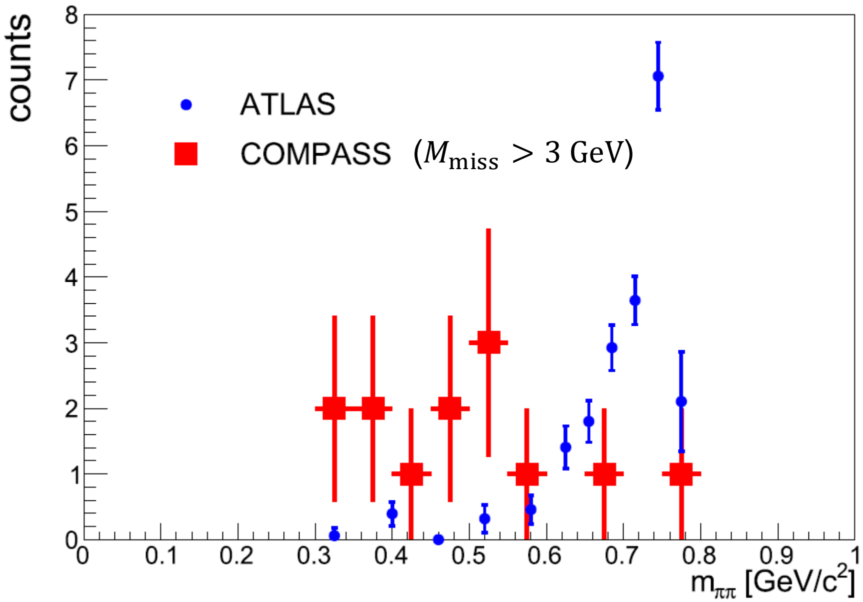




Di-pion Subsystem


Phys. Rev. D71 034025 (2005)

Phys. Rev. D71 099902 (2005).



- COMPASS mass spectrum of di-pion system from $\psi(2S)$ consistent with previous results
- Mass spectrum of di-pion system from decay of $X(3872)$ studied by BELLE, CDF, CMS, ATLAS ⇨ favors high masses ($J/\psi\,\rho$ decay)
- COMPASS mass spectrum very different, consistent with $J^{PC} = 1^{+-}$
- A neutral partner of $X(3872)$ decaying to $J/\psi\,\sigma$ is predicted by tetraquark models (L. Maiani et al.)

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'

Conclusions

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- Extremely large data samples with π and μ beams from COMPASS
- Very small statistical uncertainties for dominating resonances
- 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

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- Spin-exotic $\pi_1(1600)$: (re-) observed by COMPASS
- 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

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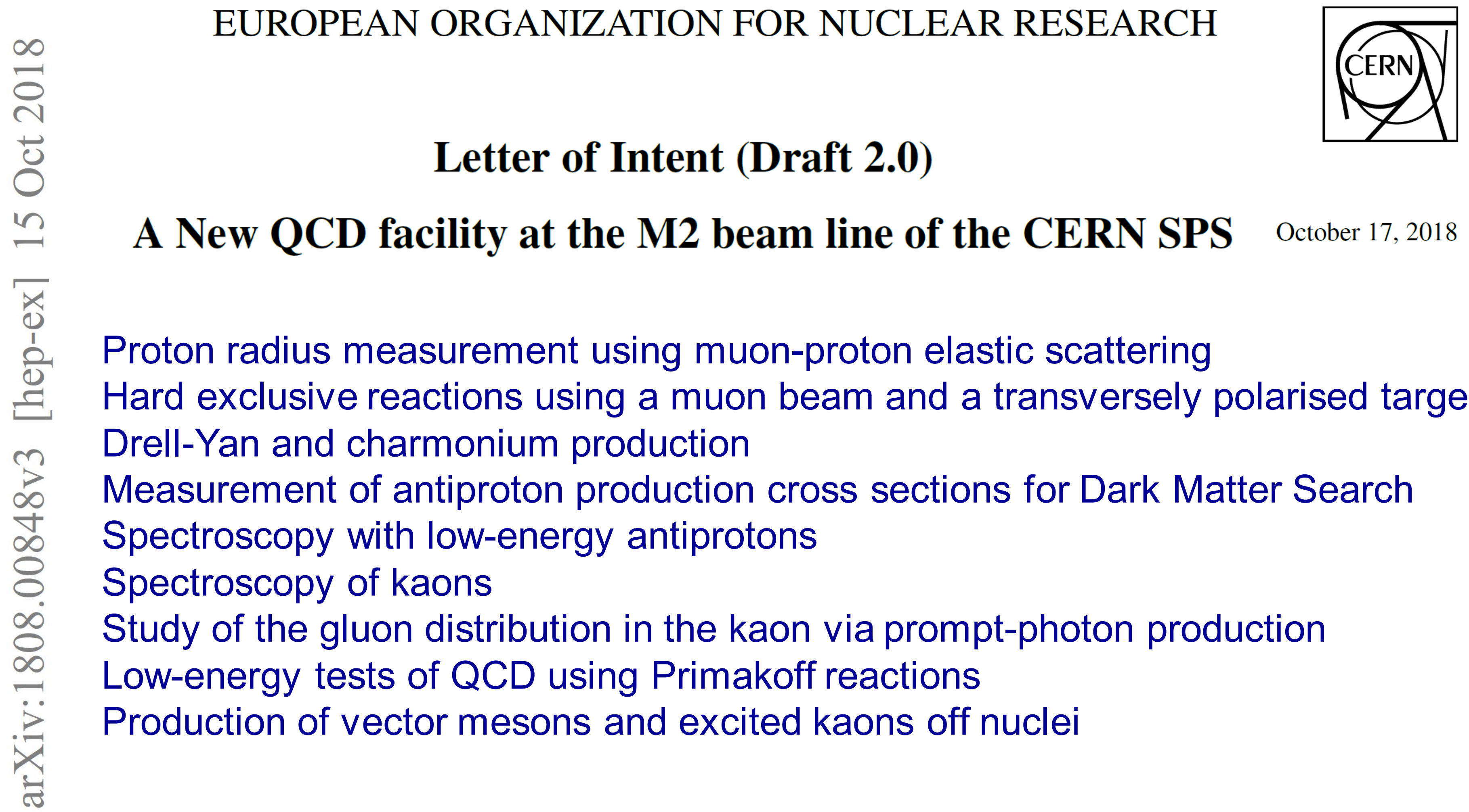
- Small signals and effects can be studied for the first time
- Spin-exotic $\pi_1(1600)$: (re-) observed by COMPASS
- New axial vector signal observed in $a_1(1420) \rightarrow f_0(980)\pi$
- Muoproduction of $\tilde{X}(3872)$ observed in $\mu N \rightarrow \mu\tilde{X}(3872)\pi N'$
  - ⇨ mass, width, decay mode compatible with $X(3872)$
  - ⇨ two-pion mass spectrum in disagreement with previous results
  - ⇨ could be $C = -1$ partner of $X(3872)$ in tetraquark models
  - ⇨ needs confirmation by other experiments

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



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