Experimental searches for light exotica

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Indiana University

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Searching for Exotic Mesons

- We would like to understand how QCD gives rise to the properties of hadrons
- Discovering a spectrum of exotic *resonances* has the potential to expose new "rules" that QCD follows when "building" hadrons
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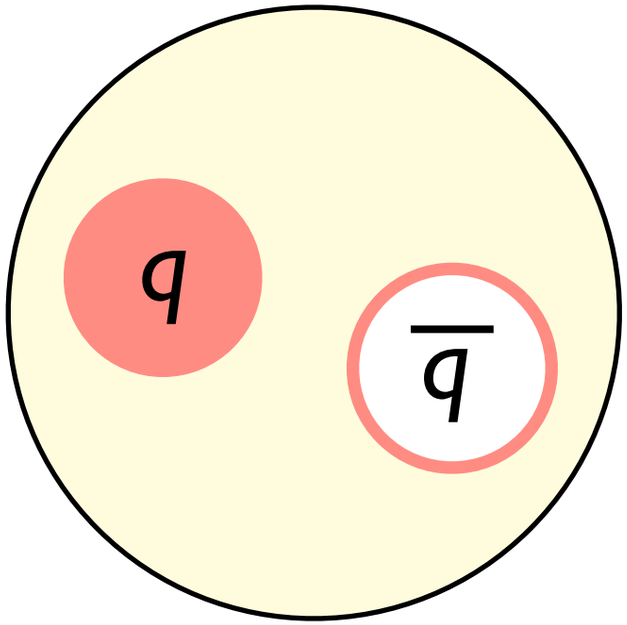
  - drives desire for theoretical understanding of how these rules arise from QCD
- Mesons are particularly well suited for this adventure:
  - notion of exotic J^{PC}
  - spectrum of "conventional" states is minimal
  - light and heavy quark sectors are complementary

Building Mesons

- Nature seems to prefer a very simple picture of mesons
  - how is this encoded in QCD?
- QCD suggests other "exotic" possibilities:
  - gluonic degrees of freedom (hybrids and glueballs)
  - tetraquarks, …

color singlet
quark anti-quark

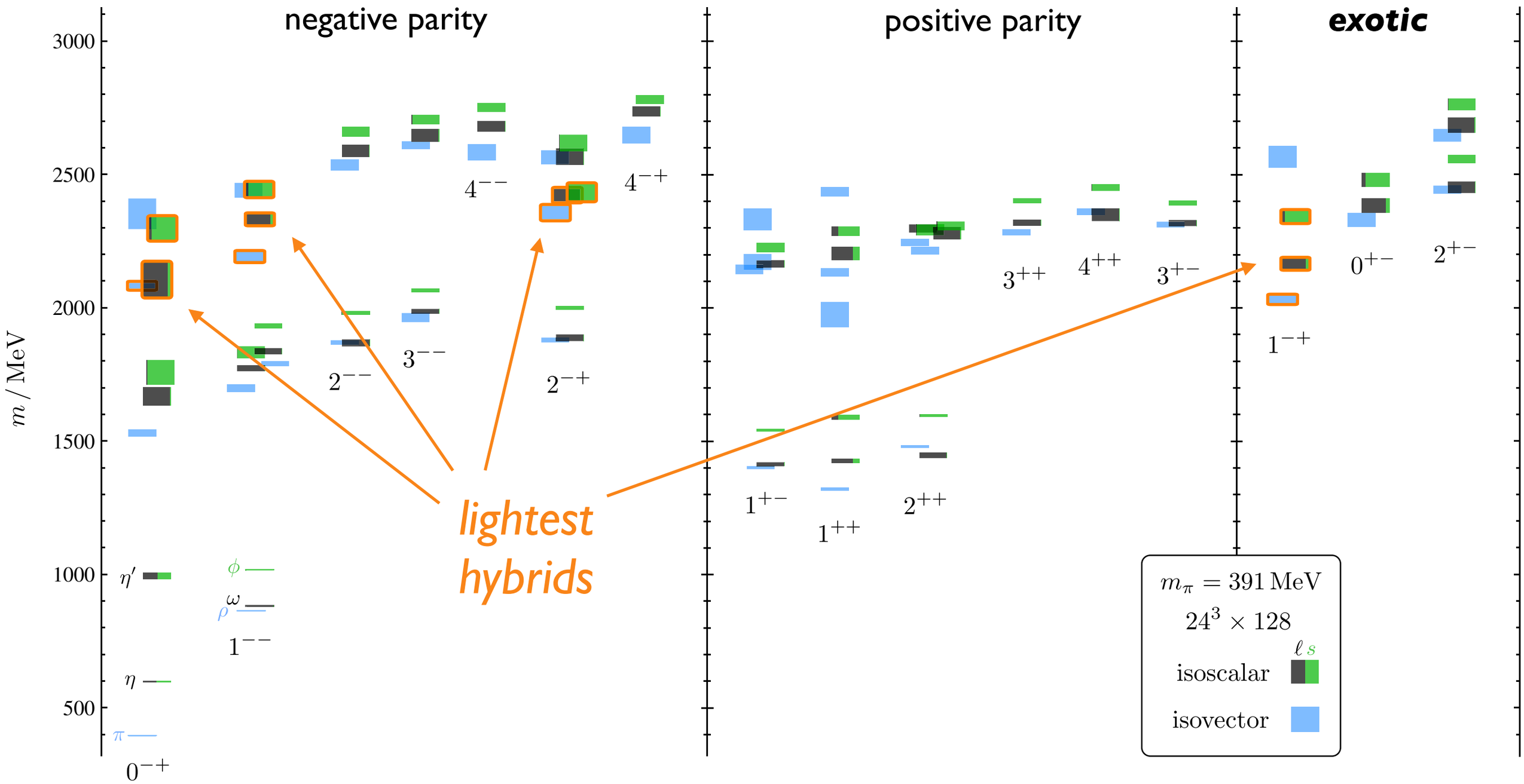


$J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$
Forbidden J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

Light Quark Mesons from Lattice QCD

Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



A Lattice QCD Motivated Model

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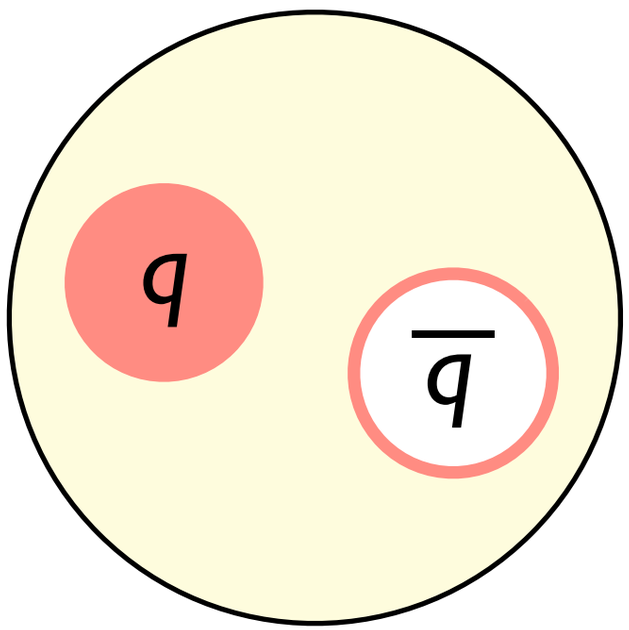

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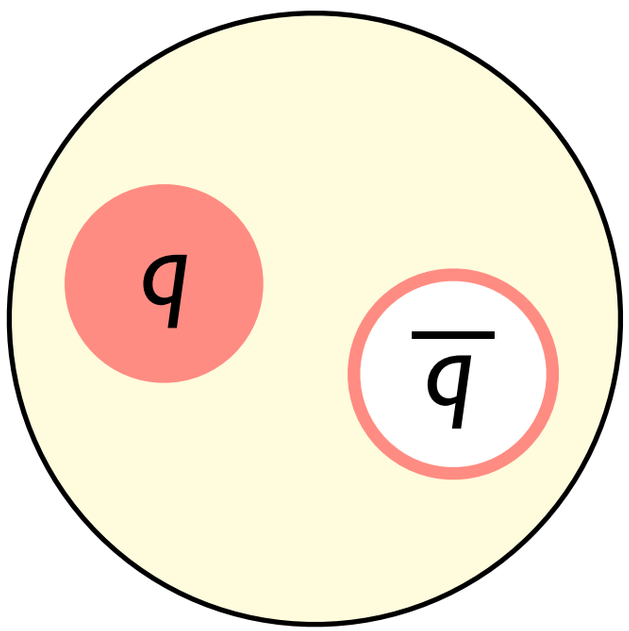

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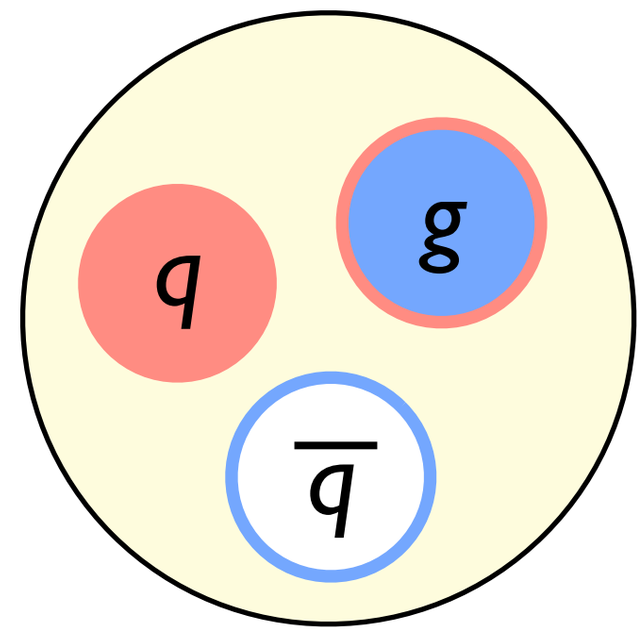
"gluonic field"
$(J^{PC})_g = 1^{+-}$
mass ≈ 1.0-1.5 GeV

color-octet
$q\overline{q}$ pair



Lightest Hybrids

	$S_{q\overline{q}} = 1$	$S_{q\overline{q}} = 0$
J^{PC}:	$0^{-+}, 1^{-+}, 2^{-+}$	1^{--}

"exotic hybrid"

Light Quark Exotic Mesons: Experiment

- Long history
  - reports of exotic J^{PC} mesons have been around for over twenty years
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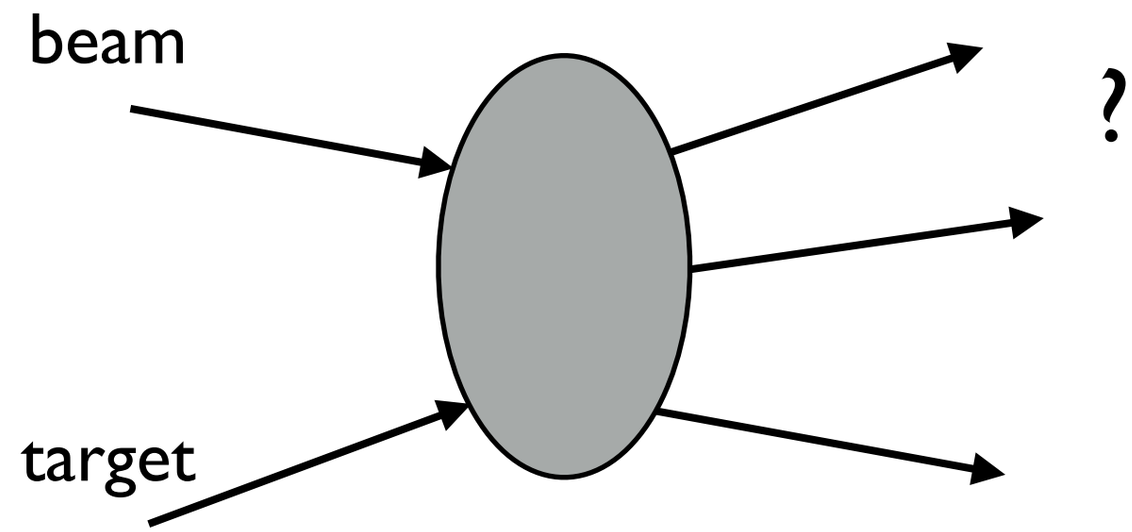
- Significant recent developments suggest exciting future:
  - a renewed focus on developing theoretical foundations of amplitude analysis
  - unprecedented statistical precision from experiment
  - new facilities coming online

Reunification of Theory and Experiment

- The hardest part about finding resonances with exotic properties is finding *resonances*.



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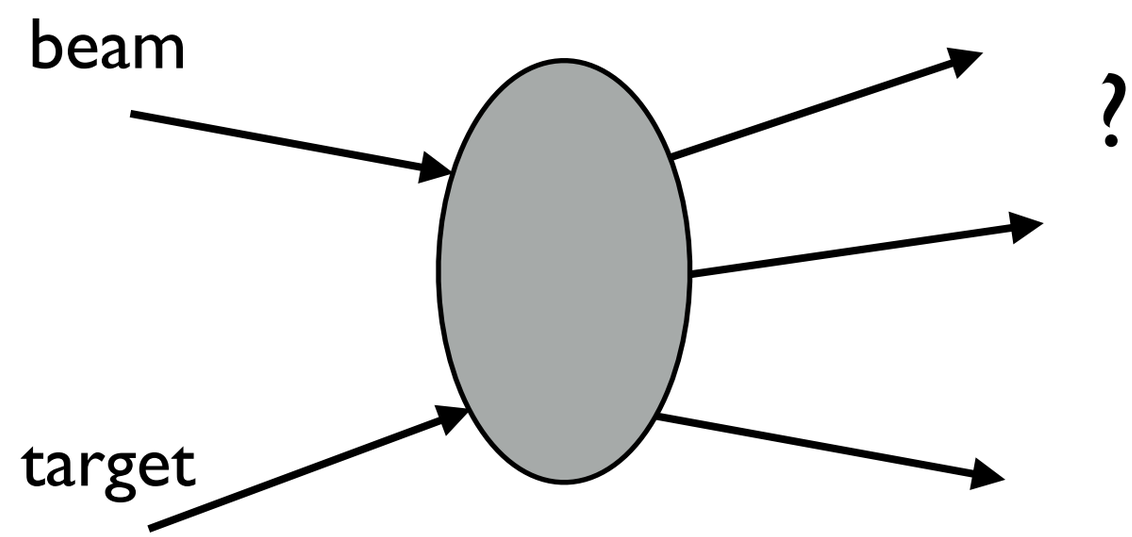

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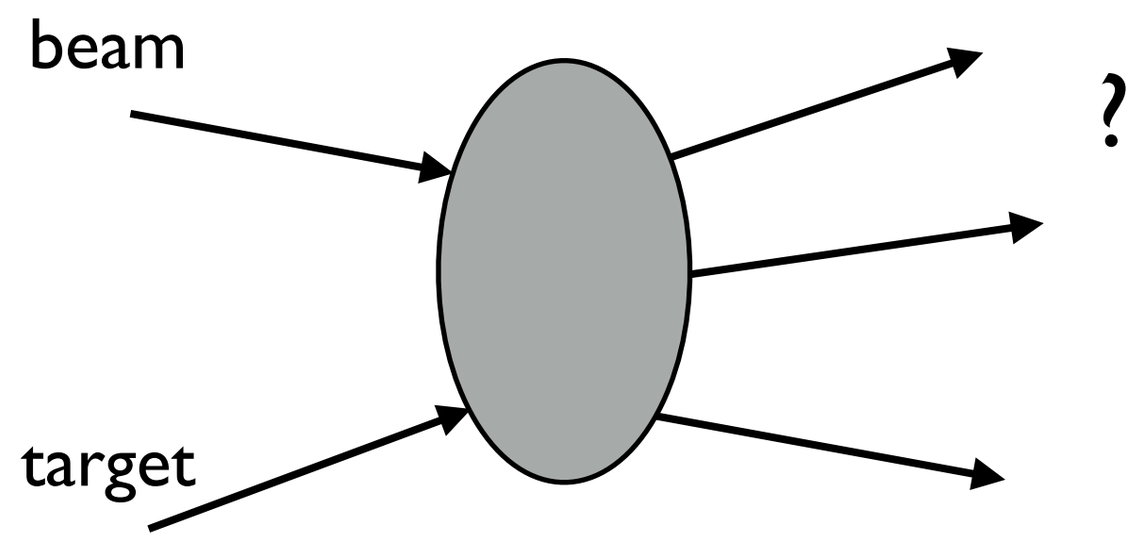
  - yields physically meaningful (universal) values for parameters



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- Need to systematically fit experimental data in way that
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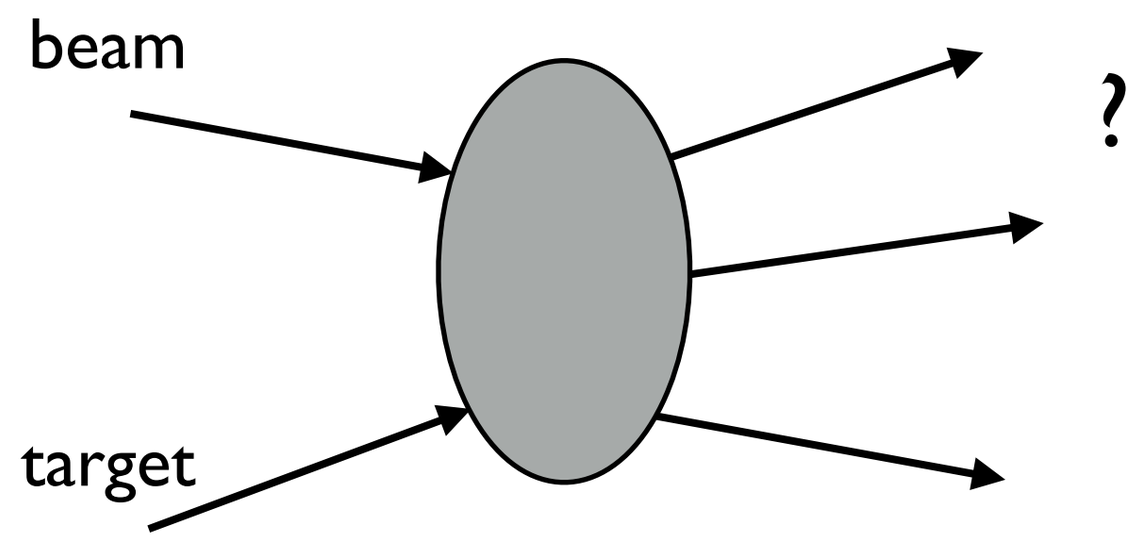
  - yields physically meaningful (universal) values for parameters
- Requires dedicated theory/experiment collaboration (see, for example, V. Mathieu's talk on Monday)



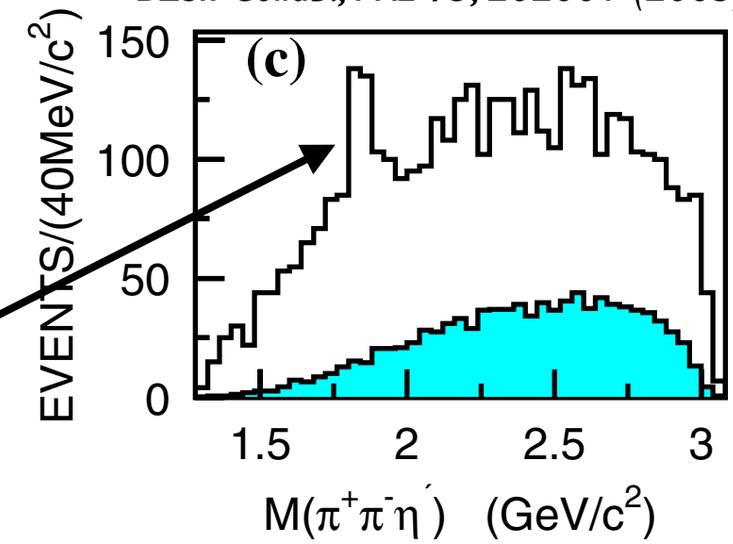
Joint Physics Analysis Center (JPAC) Analysis Meeting

Precision Brings Challenges

- Example from BESII and BESIII
  - Search for resonances in the channel $J/\psi \rightarrow \gamma \eta' \pi\pi$
  - Well-known enhancement at $p\bar{p}$ threshold in $J/\psi \rightarrow \gamma p\bar{p}$

BESII:
$X(1835)$
at 6σ with
58×10^6 J/ψ

BESII Collab., PRL 95, 262001 (2005)



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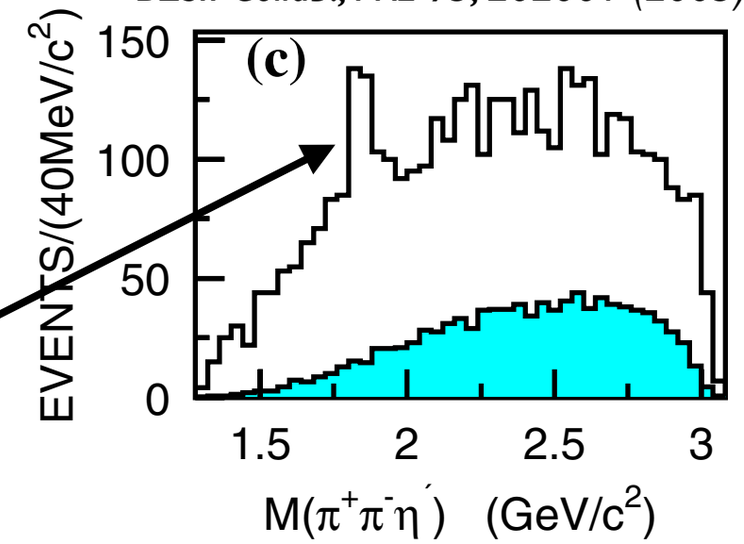
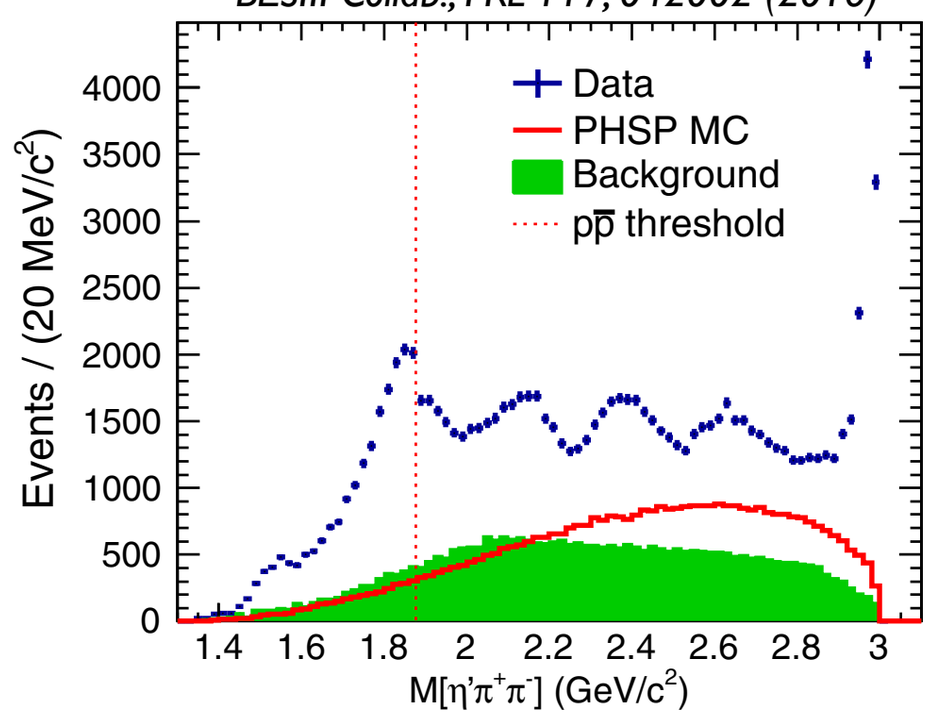


BESIII Collab., PRL 117, 042002 (2016)



Revisited with BESIII using 1.09×10^9 J/ψ

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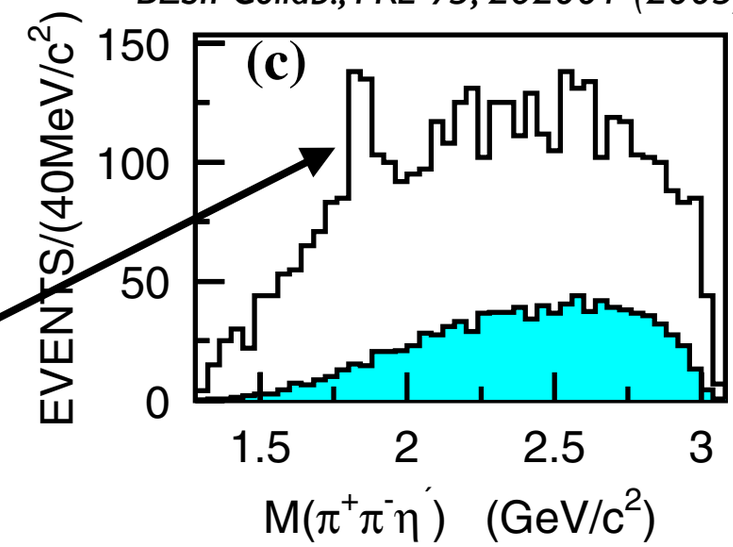

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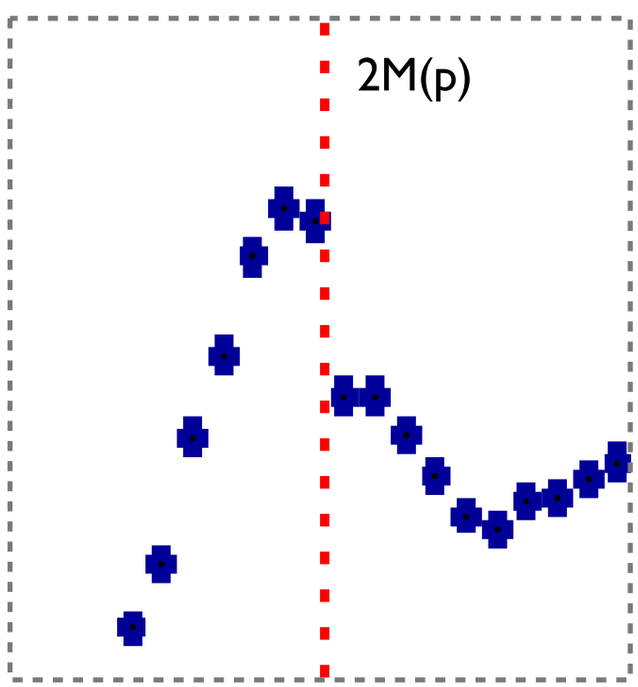

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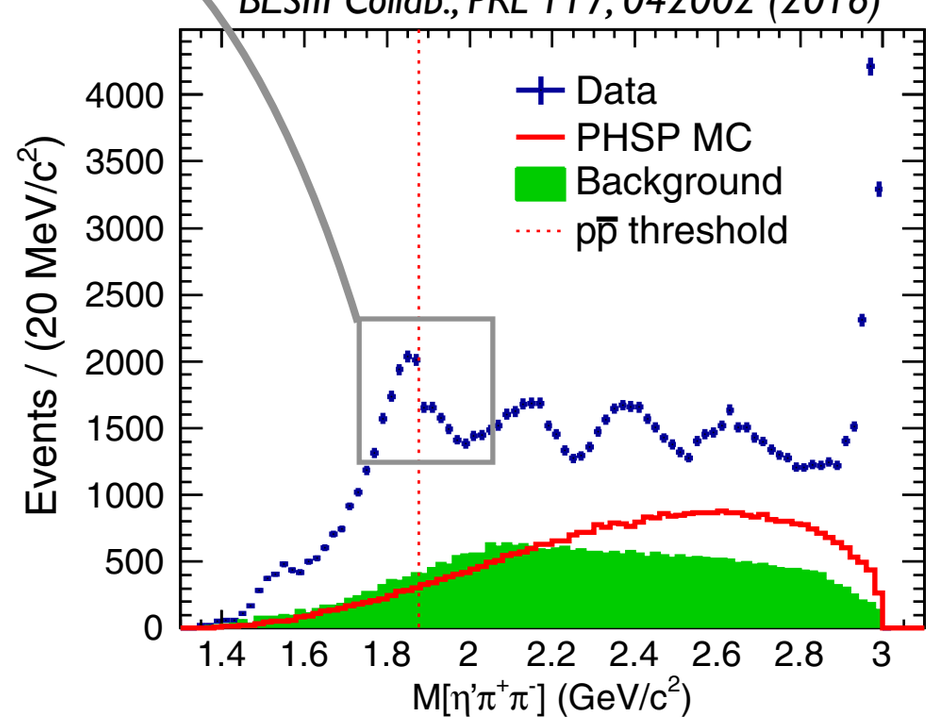

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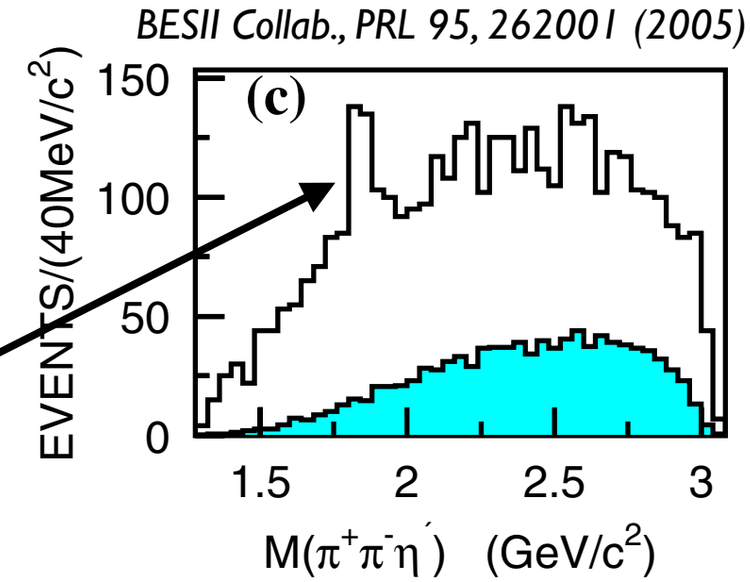

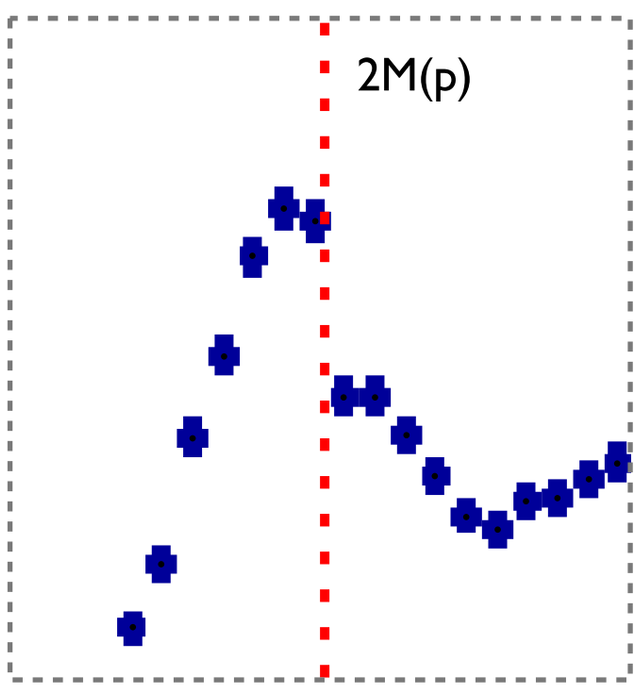

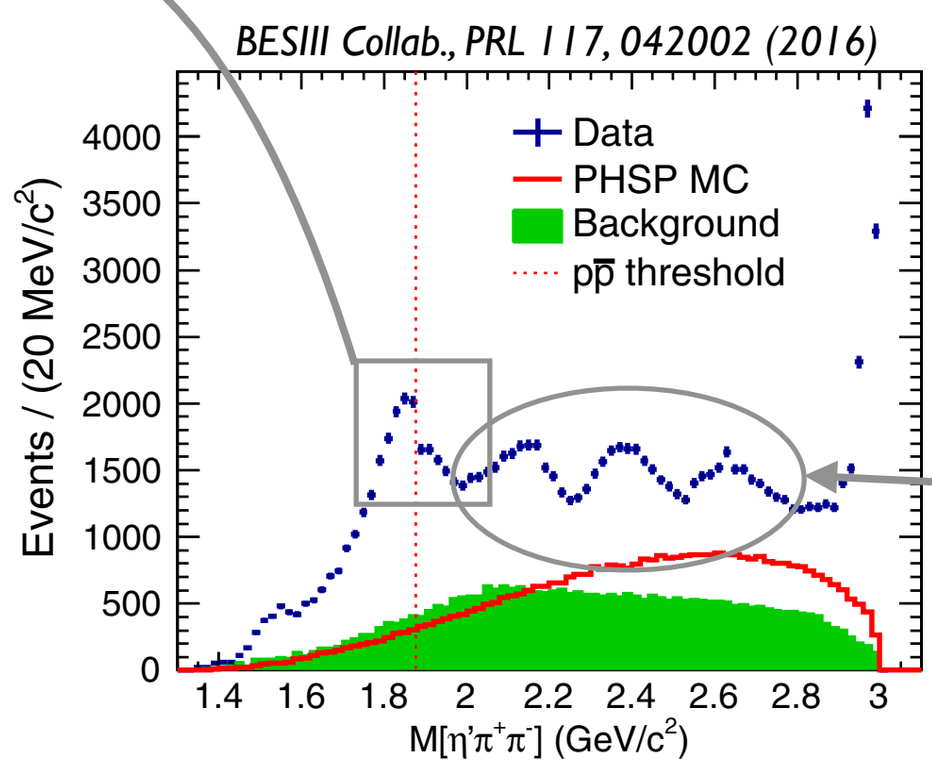

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Exotic J^{PC} Candidates

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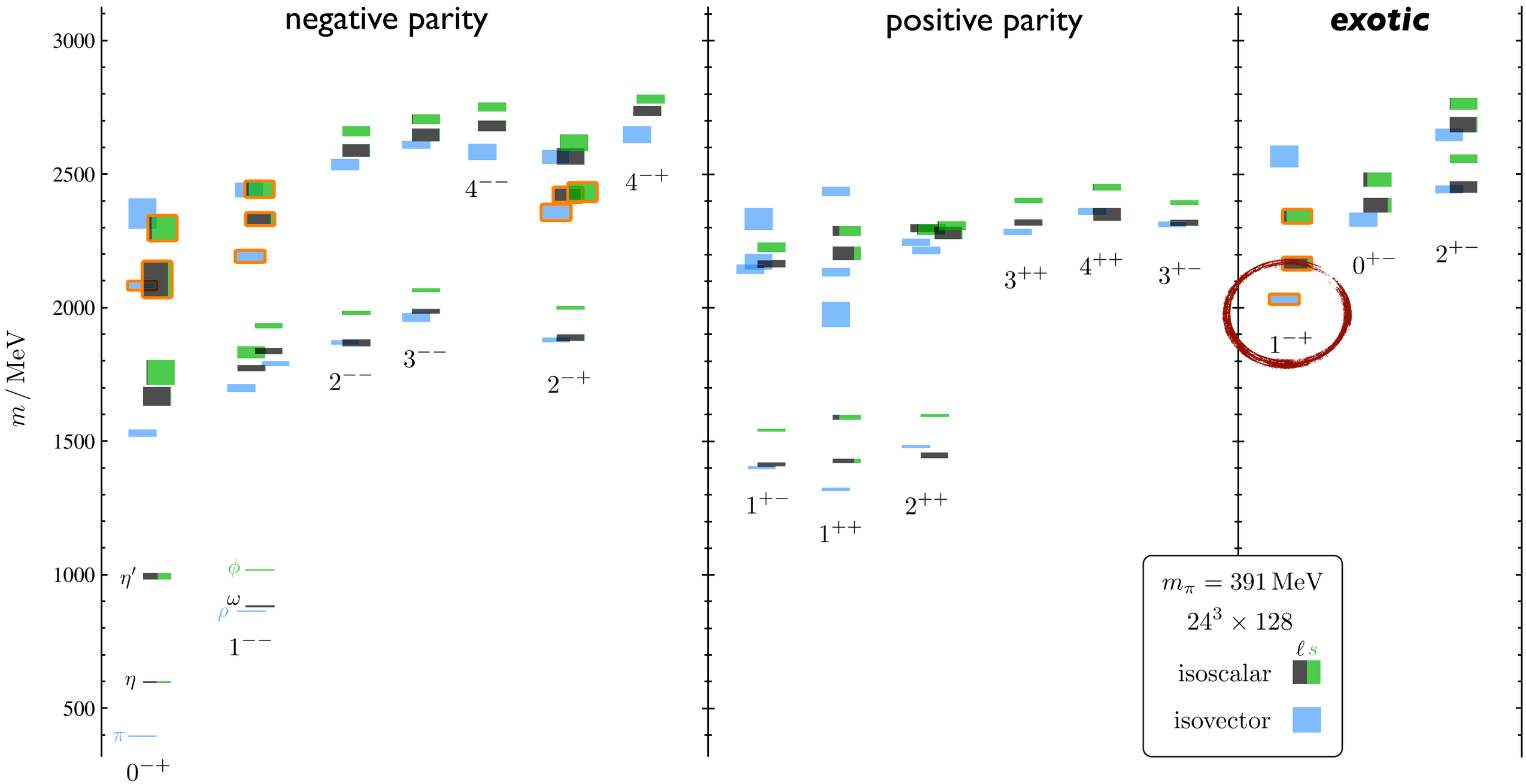

Exotic J^{PC} Candidates

- See PDG for references:
  - $\pi_1(1400) \to \eta\pi$
  - $\pi_1(1600) \to \eta'\pi$ and $\rho\pi$
  - $\pi_1(2015) \to f_1\pi$ and $\omega\pi\pi$
- Recent results most pertain to $\pi_1(1400)$ and $\pi_1(1600)$:
  - *P*-wave in $\eta^{(\prime)}\pi$
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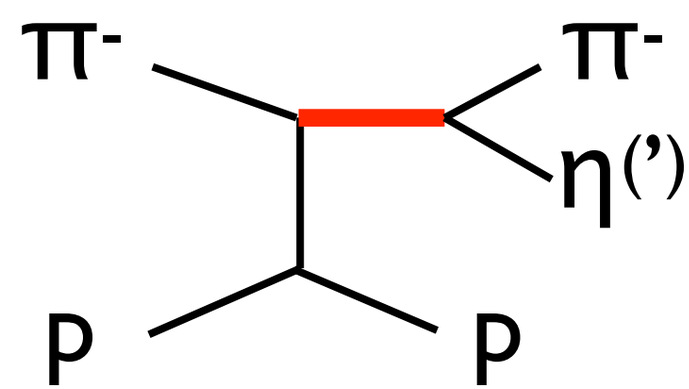
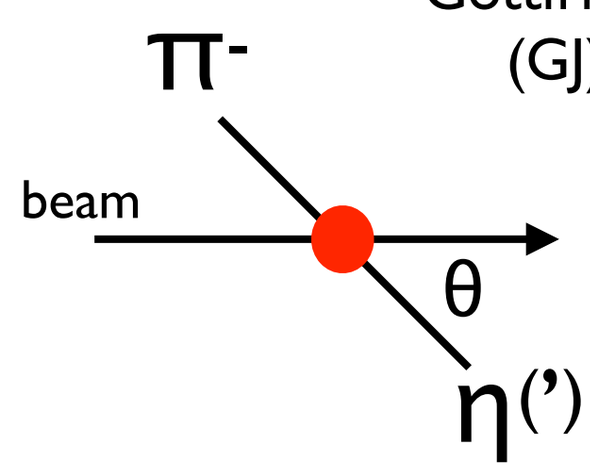
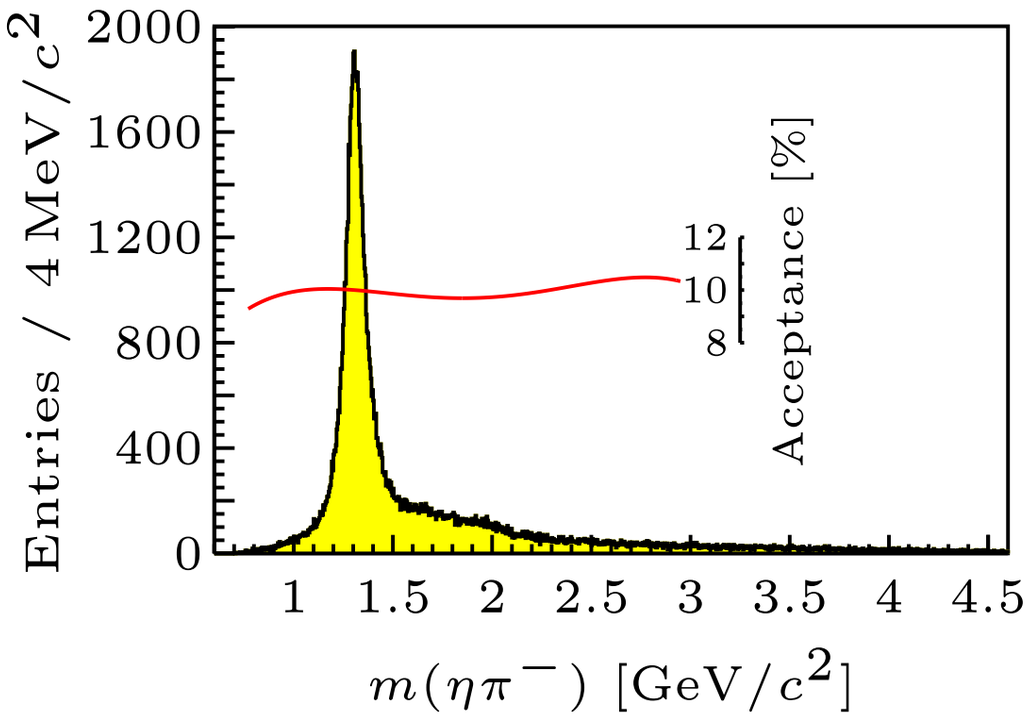
- Recent results most pertain to $\pi_1(1400)$ and $\pi_1(1600)$:
  - *P*-wave in $\eta^{(\prime)}\pi$
  - $\pi_1(1600) \rightarrow \rho\pi$
- Begin with $\eta^{(\prime)}\pi$ system:
  - isovector
  - L-odd implies neutral member has exotic J^{PC}: 1^{-+}, 3^{-+}, …
  - simple kinematics: L is encoded in a single angular distribution

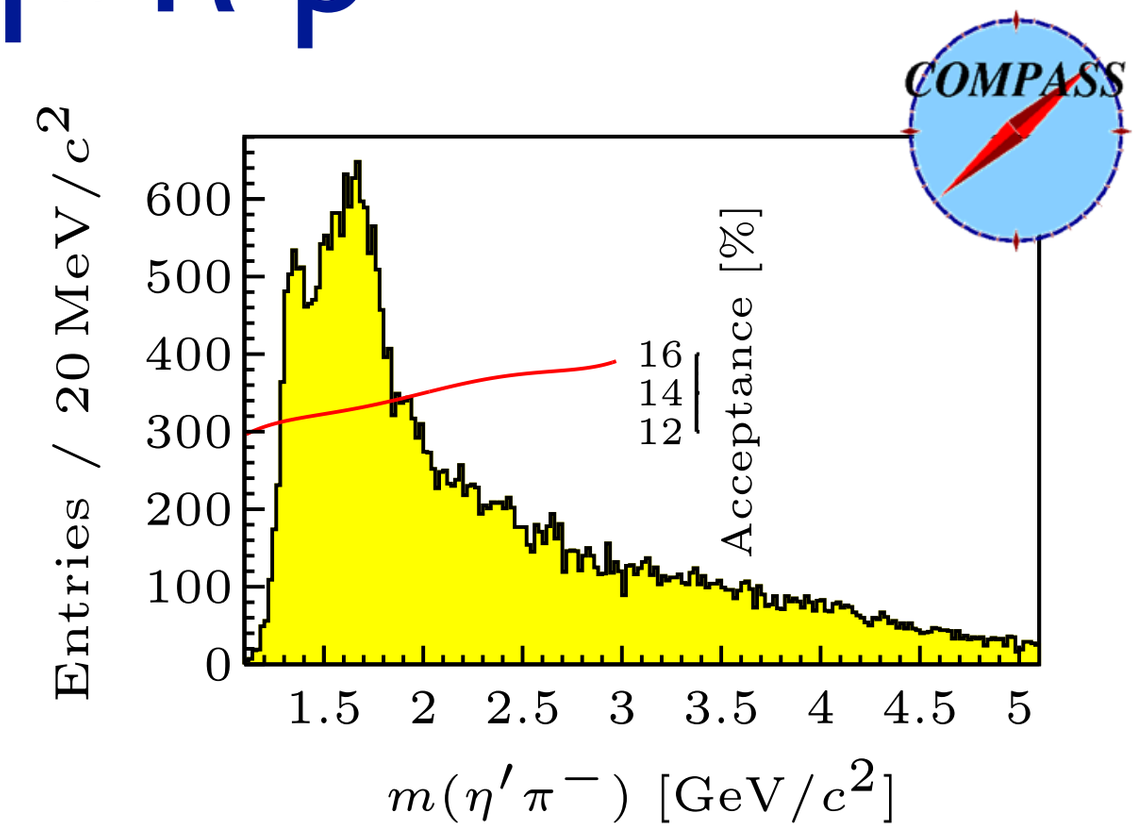


Gottfried-Jackson (GJ) Frame



$\pi^- p \rightarrow \eta^{(\prime)} \pi^- p$





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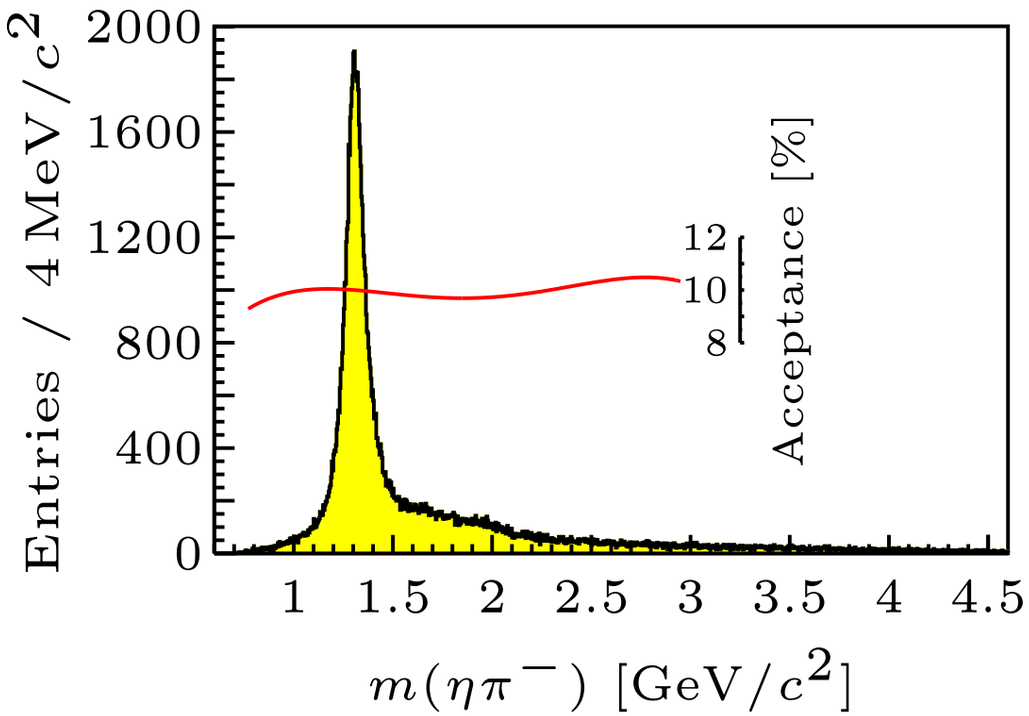
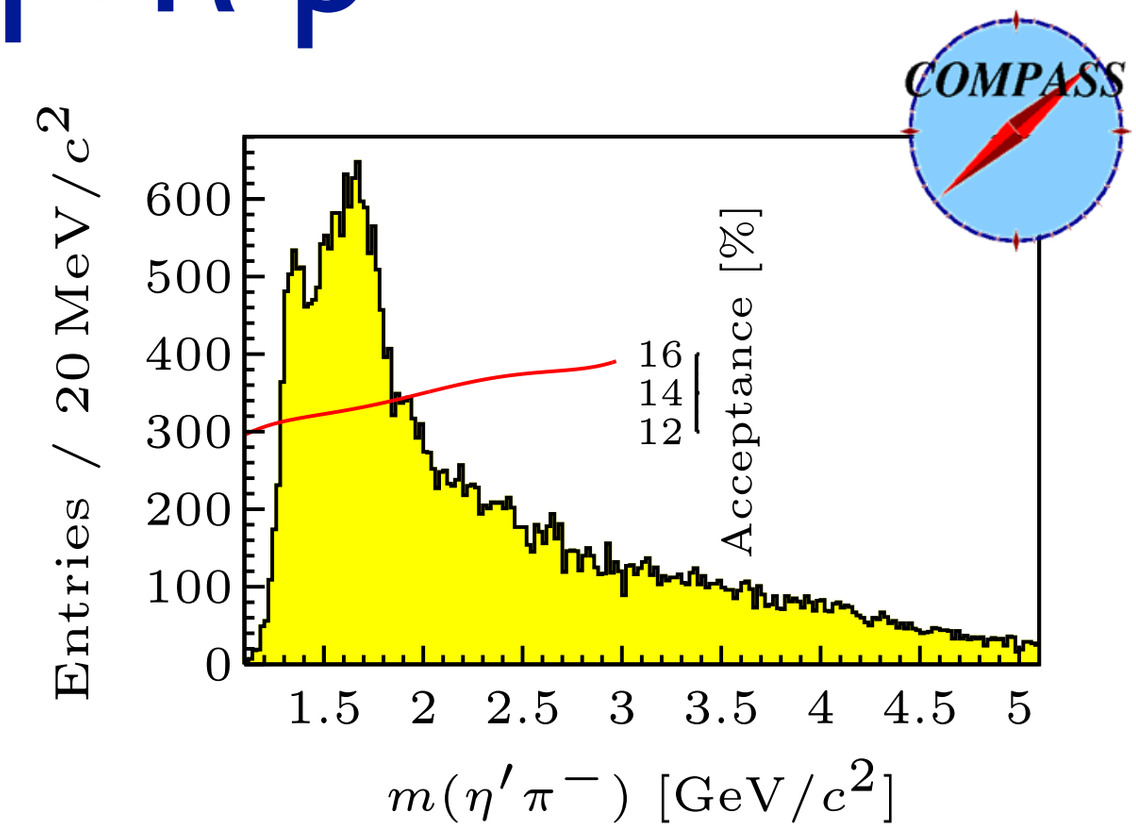
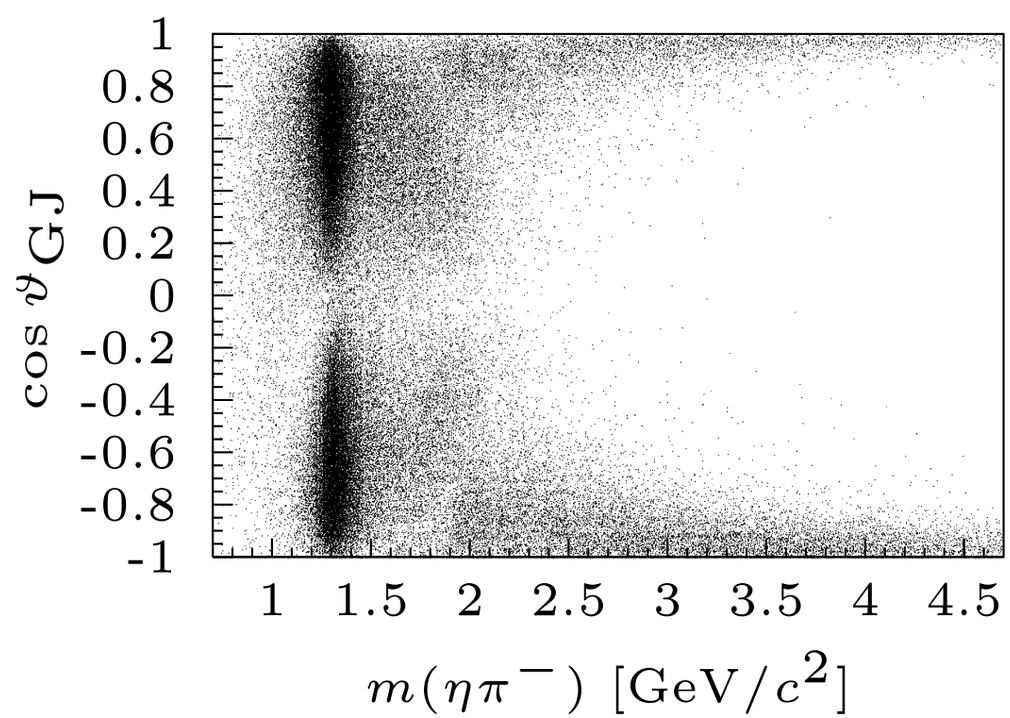
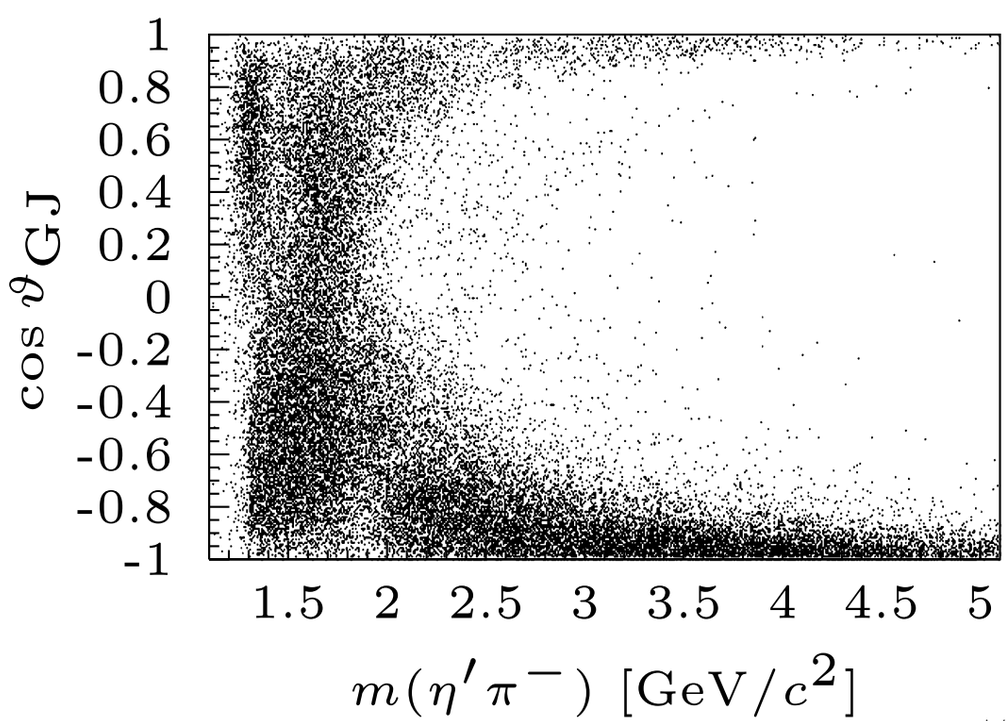


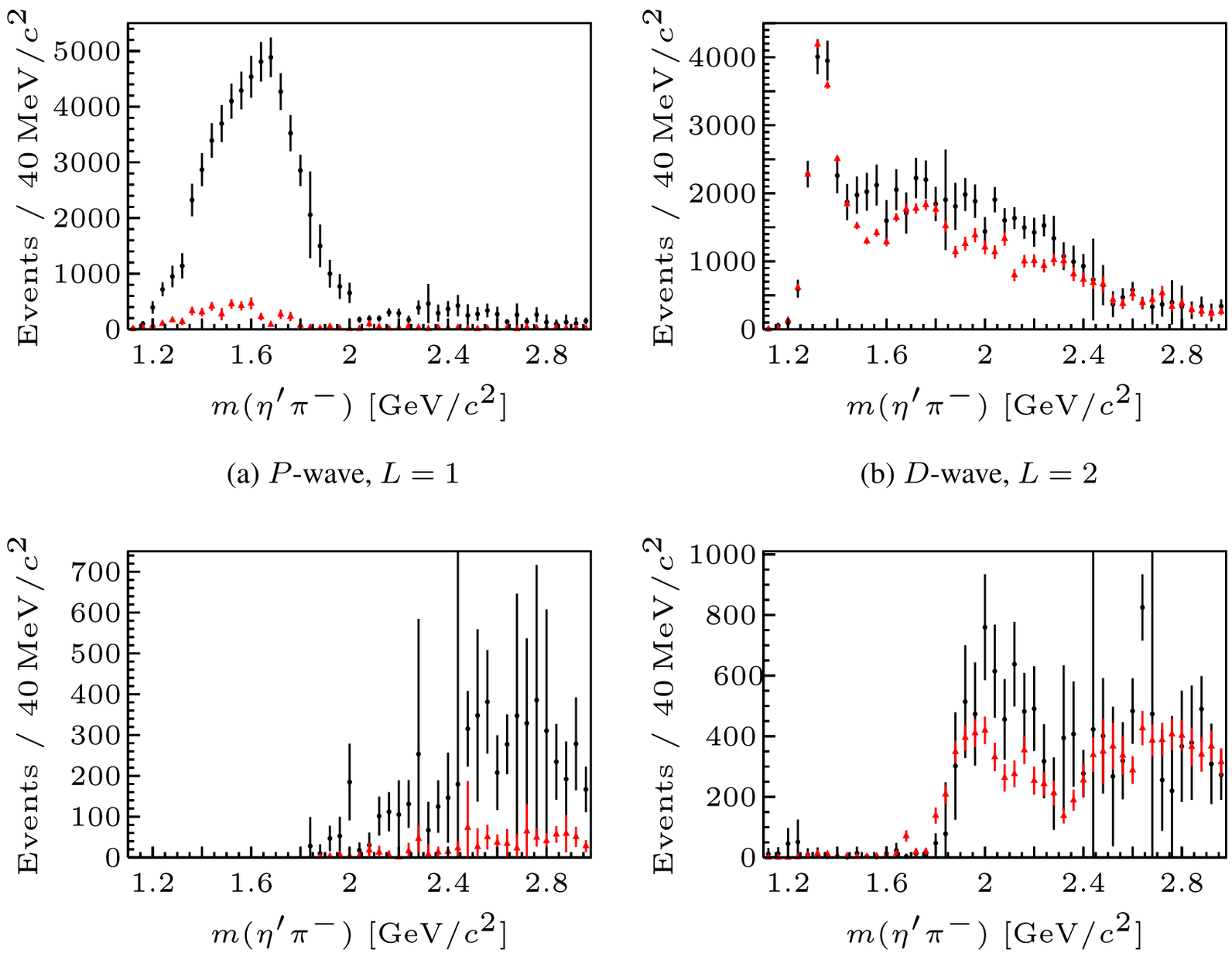






$\pi^- p \rightarrow \eta^{(\prime)} \pi^- p$

- Partial wave decomposition
  - black: $\eta'\pi$
  - red: $\eta\pi$ rescaled by kinematical factor
- Odd L waves (exotic) are enhanced in $\eta'\pi$ when compared with $\eta\pi$
  - resonant?
- Need well-constrained models to search for resonances



(a) P-wave, $L = 1$

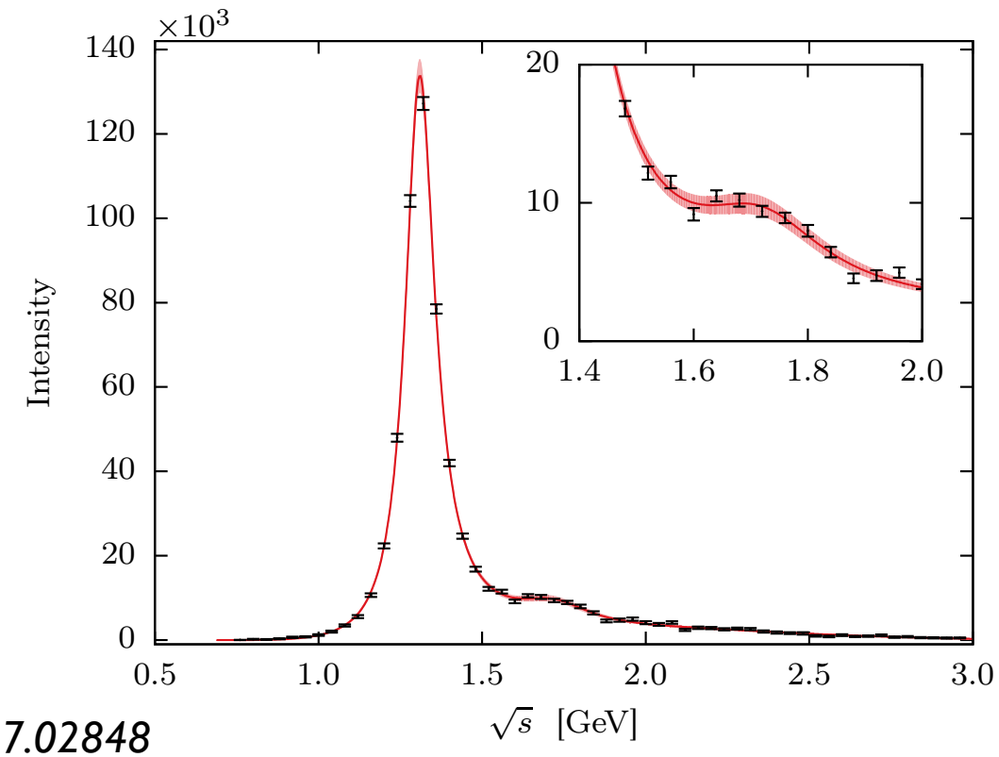
(b) D-wave, $L = 2$

(c) F-wave, $L = 3$

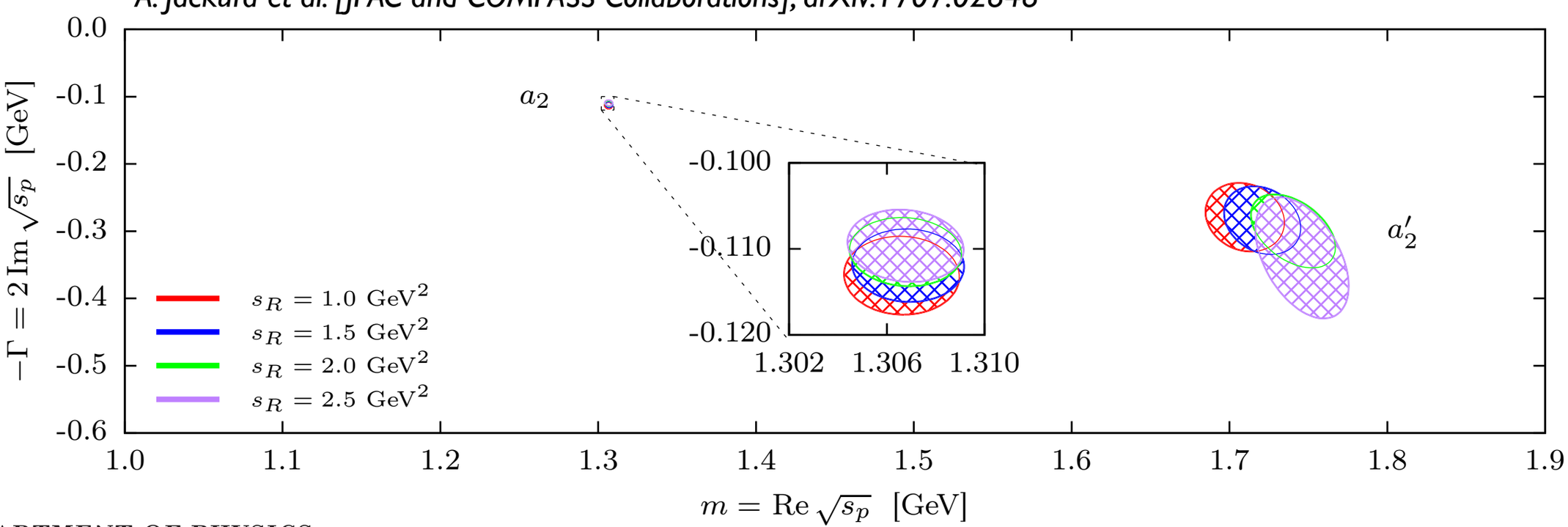
(d) G-wave, $L = 4$

Analysis of ηπ *D*-wave

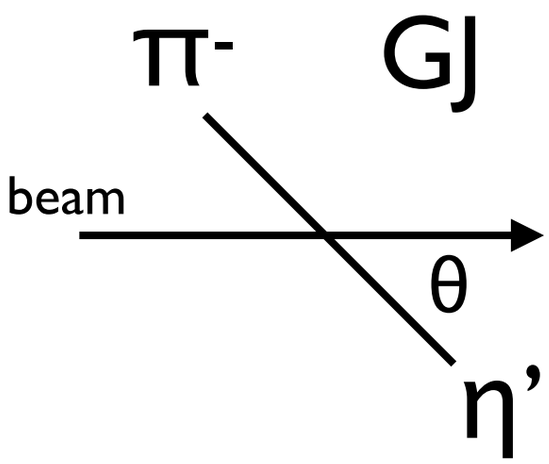
- Extract pole positions in a fit to published partial waves using unitary parameterization
- Strong evidence for a_2'
- Stepping stone to *P*-wave and η'π analyses (and others)



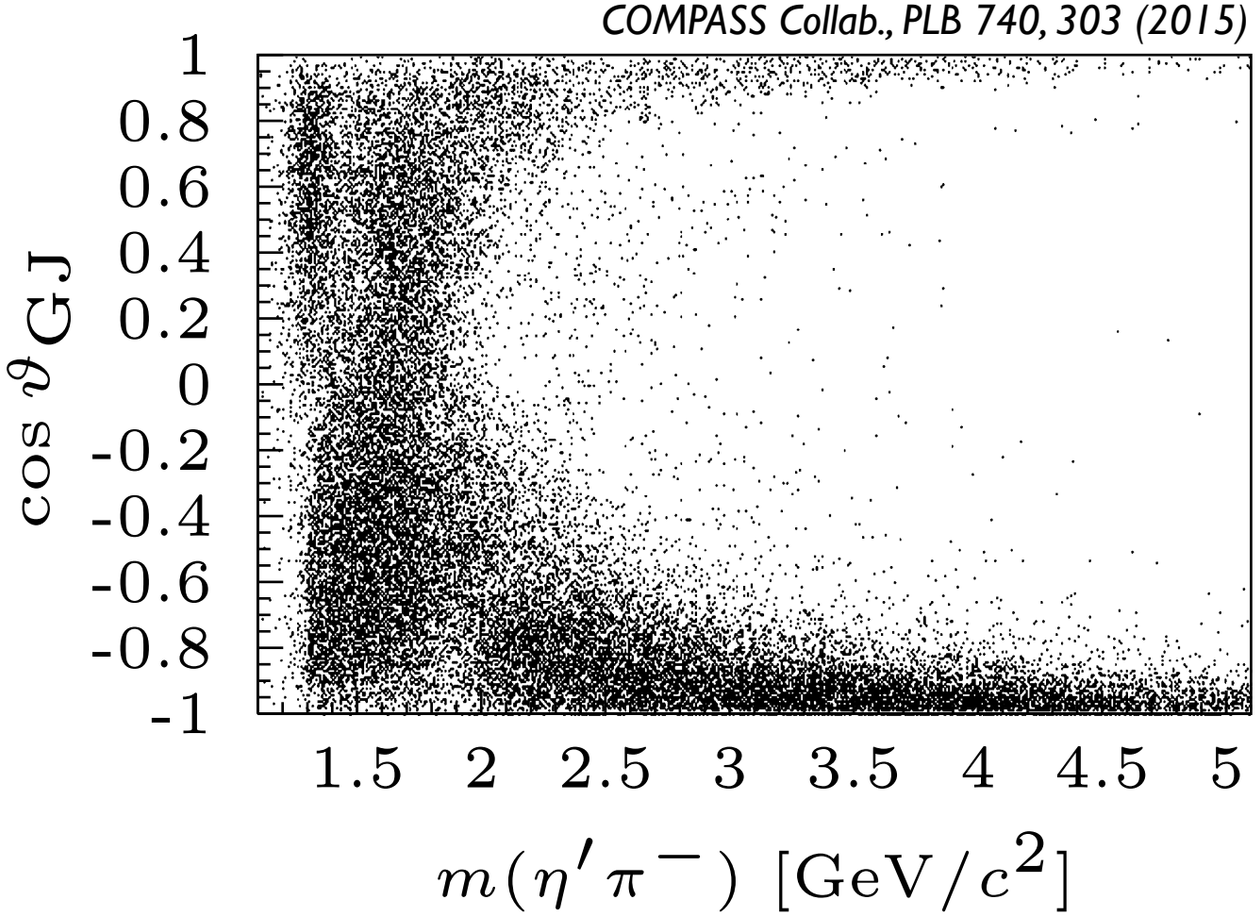
A. Jackura et al. [JPAC and COMPASS Collaborations], arXiv:1707.02848



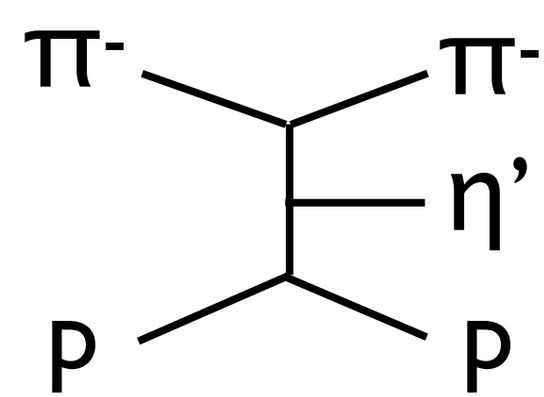
Constraining η'π *P*-wave



COMPASS Collab., PLB 740, 303 (2015)



Not-so-exotic scattering



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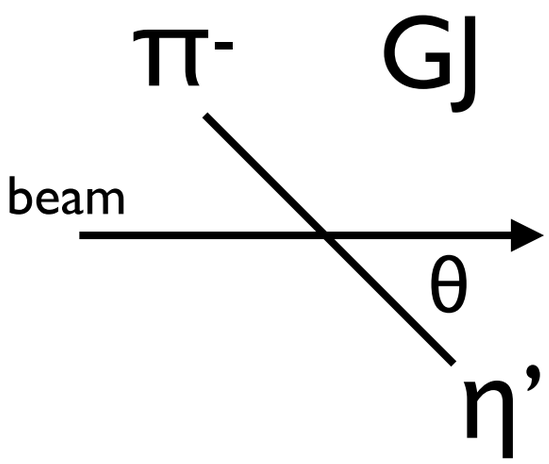

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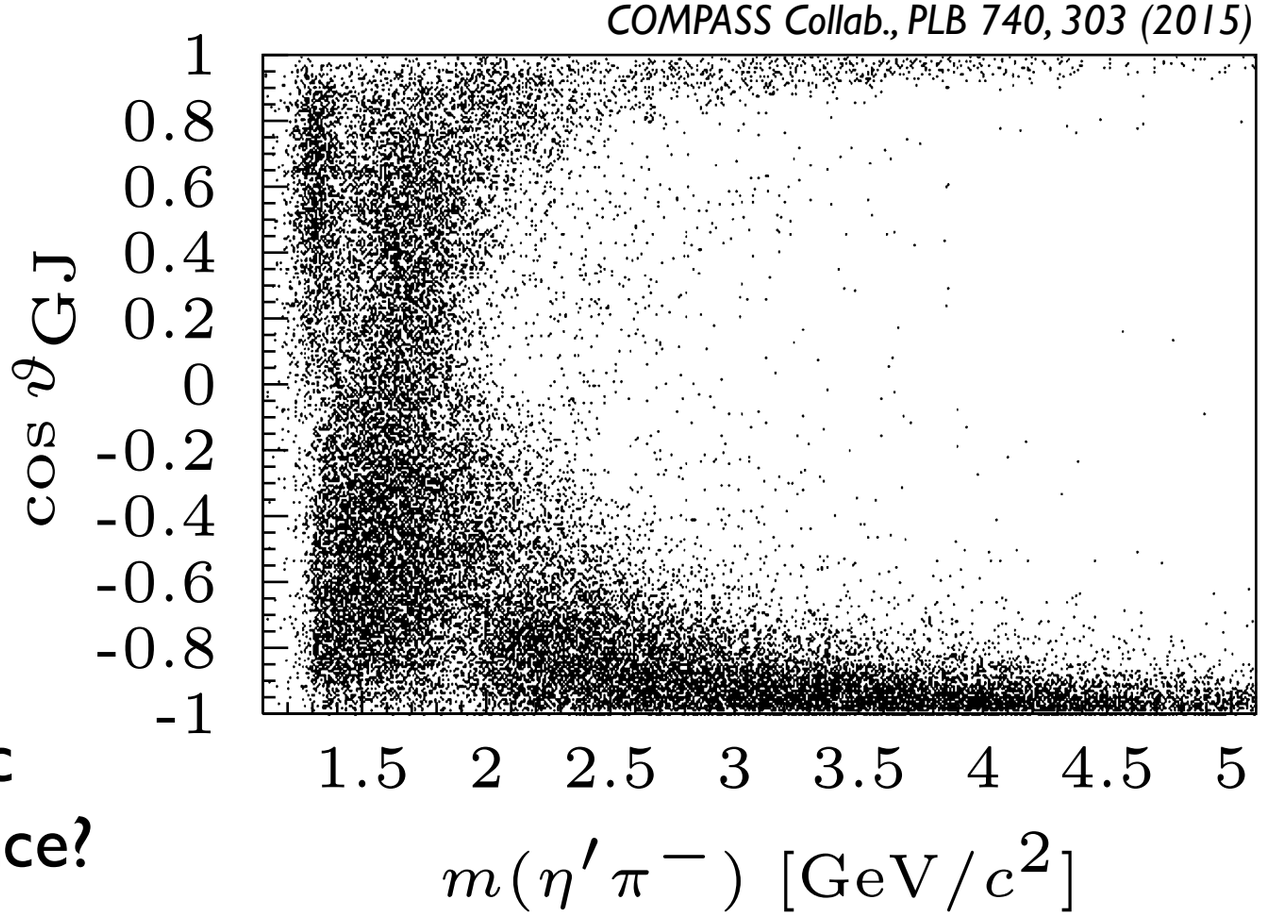
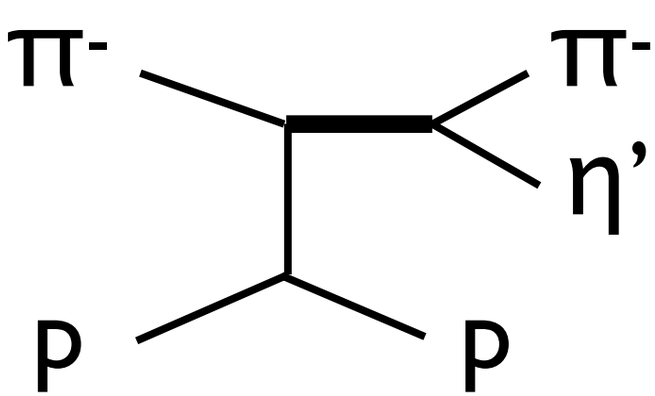
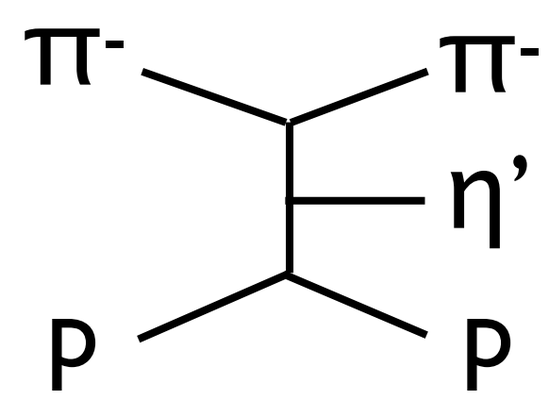


Exotic Resonance?



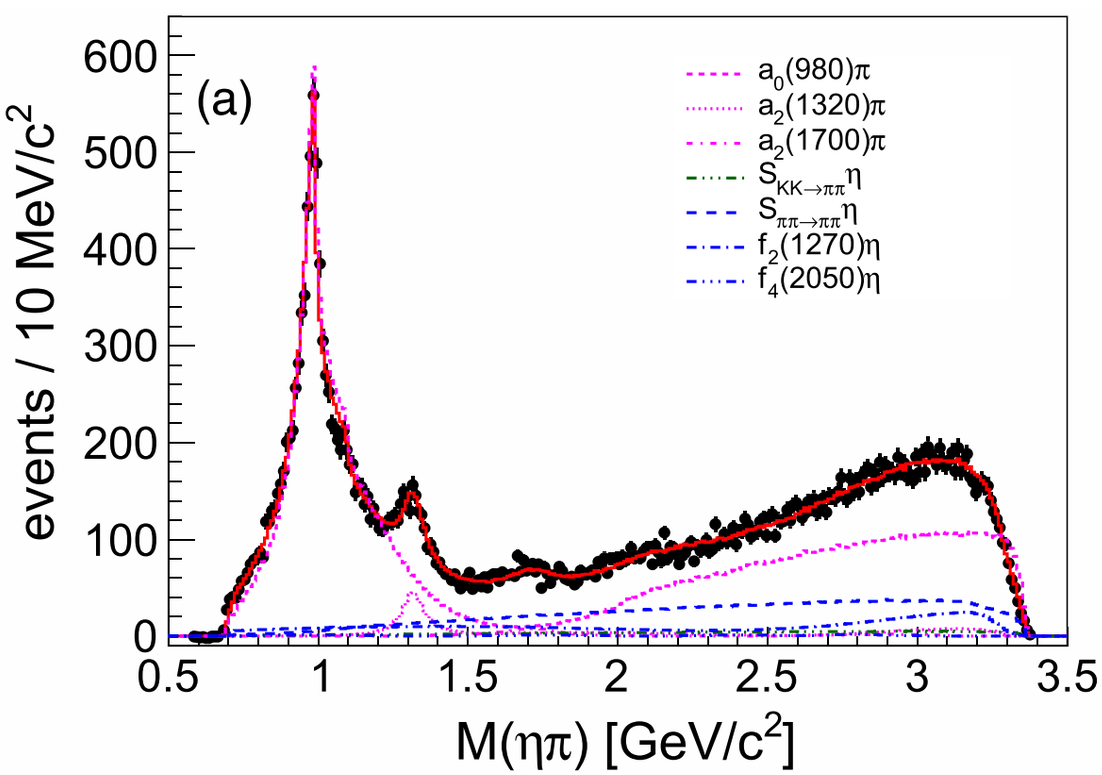
Extrapolate to resonance region

Not-so-exotic scattering

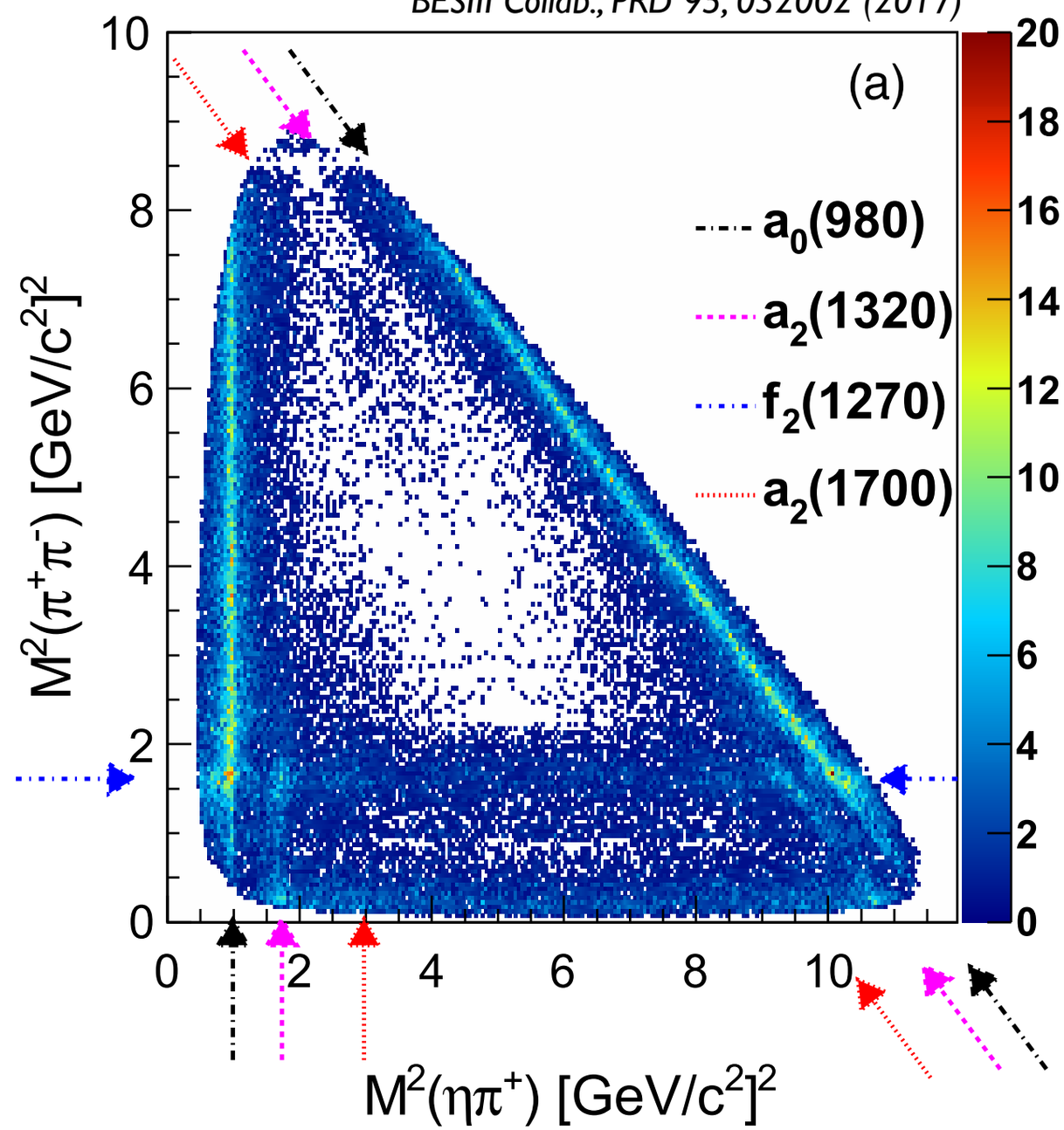


Complementary Production: $\chi_{c1} \rightarrow \eta\pi\pi$

- Additional evidence for the of a_2'
- No evidence for $\pi_1 \rightarrow \eta\pi$
- CLEO reported *P*-wave $\eta'\pi$ in $\chi_{c1} \rightarrow \eta'\pi\pi$ [*CLEO Collab., PRD 84, 112009 (2011)*]
  - can be explored at BESIII with better statistical precision



BESIII Collab., PRD 95, 032002 (2017)



$\pi_1 \rightarrow \eta^{(\prime)}\pi$ Summary

- Recent COMPASS observations consistent with previous experiments
  - $\eta\pi$ P-wave peaking at 1400 MeV
  - $\eta'\pi$ P-wave peaking at 1600 MeV
  - $\eta'\pi$ signal dominates $\eta\pi$
- Significant $\eta'\pi$ P-wave amplitude observed in complementary processes

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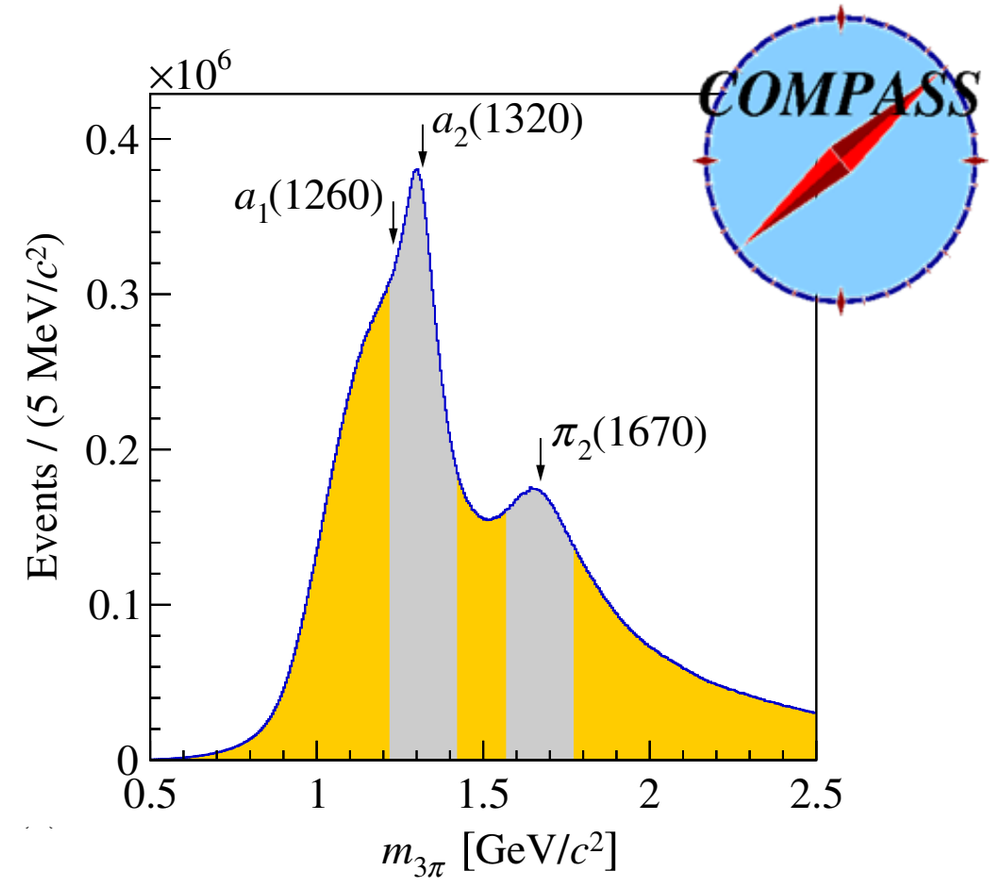
  - $\eta'\pi$ signal dominates $\eta\pi$
- Significant $\eta'\pi$ P-wave amplitude observed in complementary processes
- Very interesting but not quite yet at the threshold of passing the *duck test*
  - need to understand how peaks may be related to resonance poles

"When I see a bird that walks like a duck and swims like a duck and quacks like a duck, I call that bird a duck."

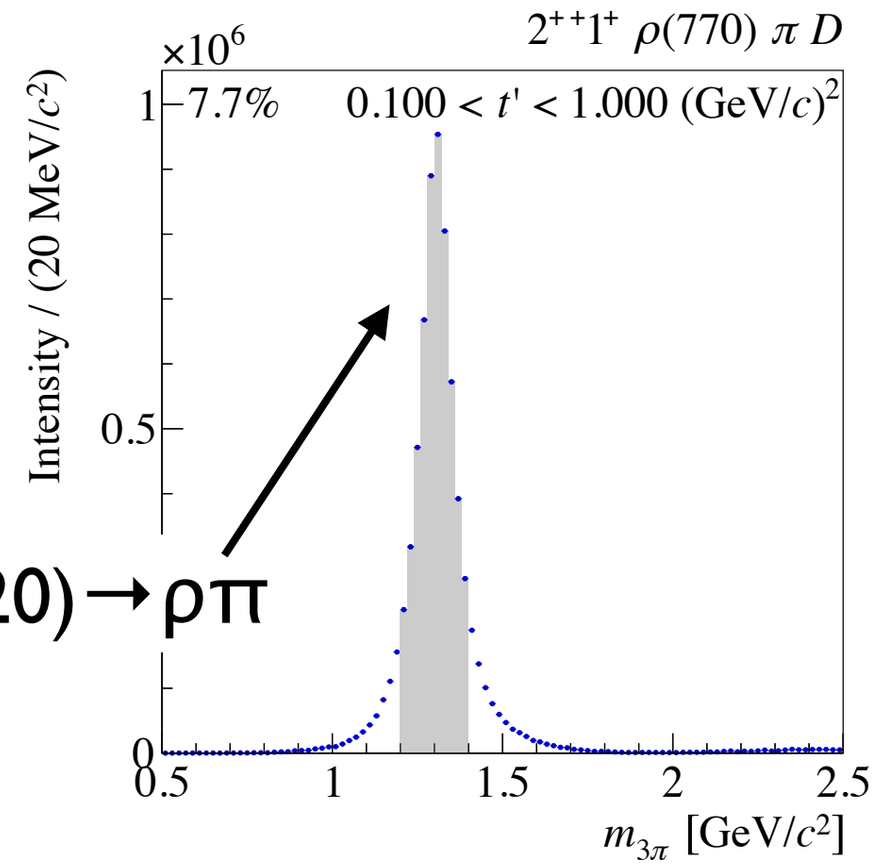
— James Whitcomb Riley
Indiana Poet

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

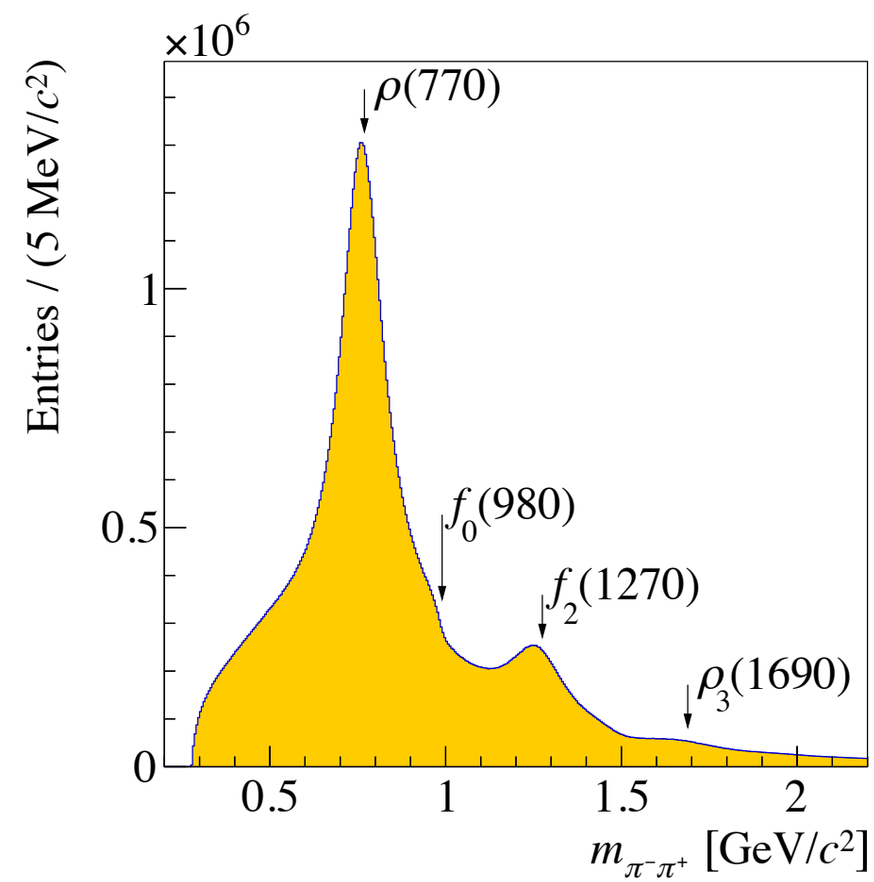
- 4.7 x 10^7 events
- Analysis of distribution 5D phase space to extract J^{PC} content (88 amplitudes) with minimal model dependence (result: O(10^5) parameters)
- statistics enables (and demands) innovations in analysis



See talks yesterday by S. Wallner and F. Krinner



$a_2(1320) \rightarrow \rho\pi$



COMPASS Collab., PRD 95, 032004 (2017)

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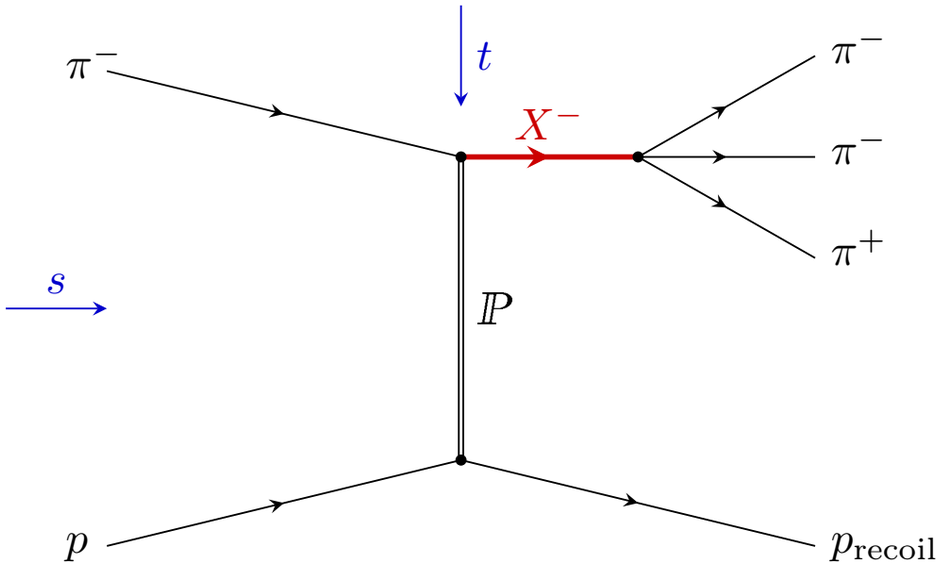
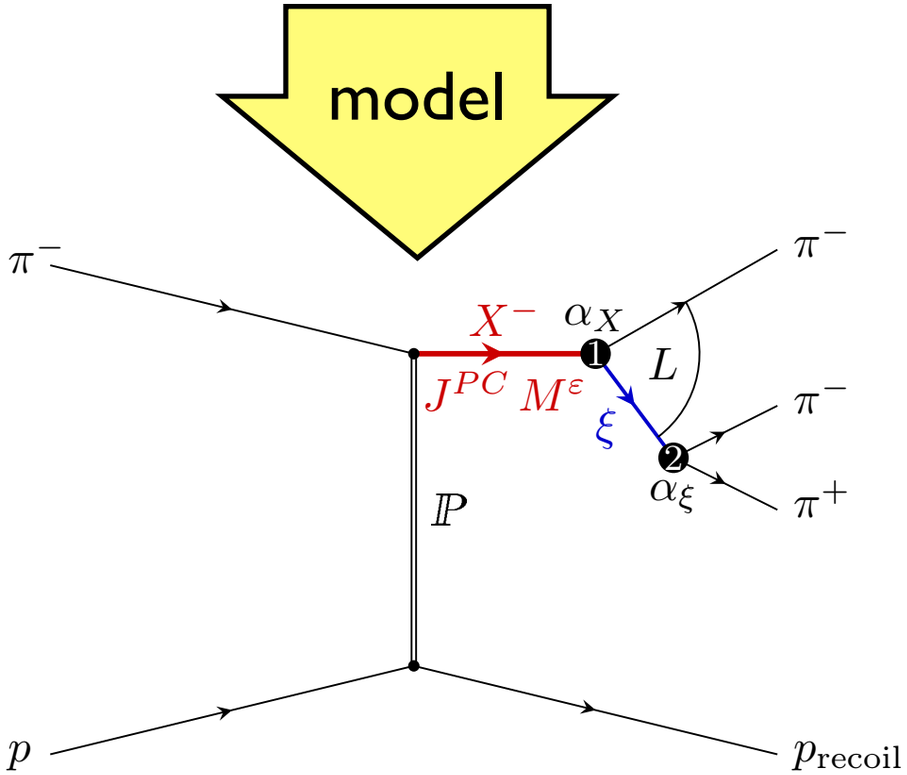
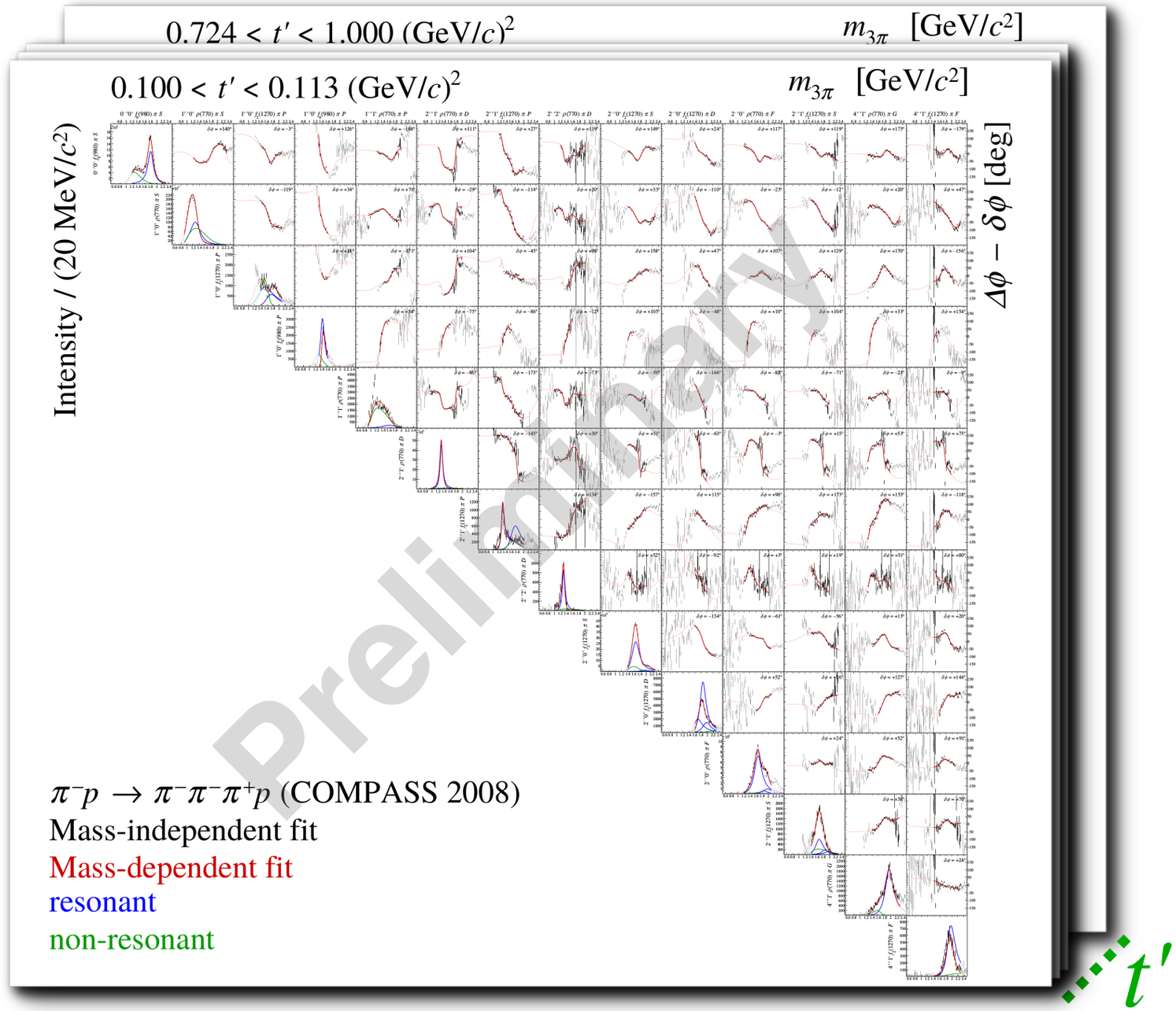


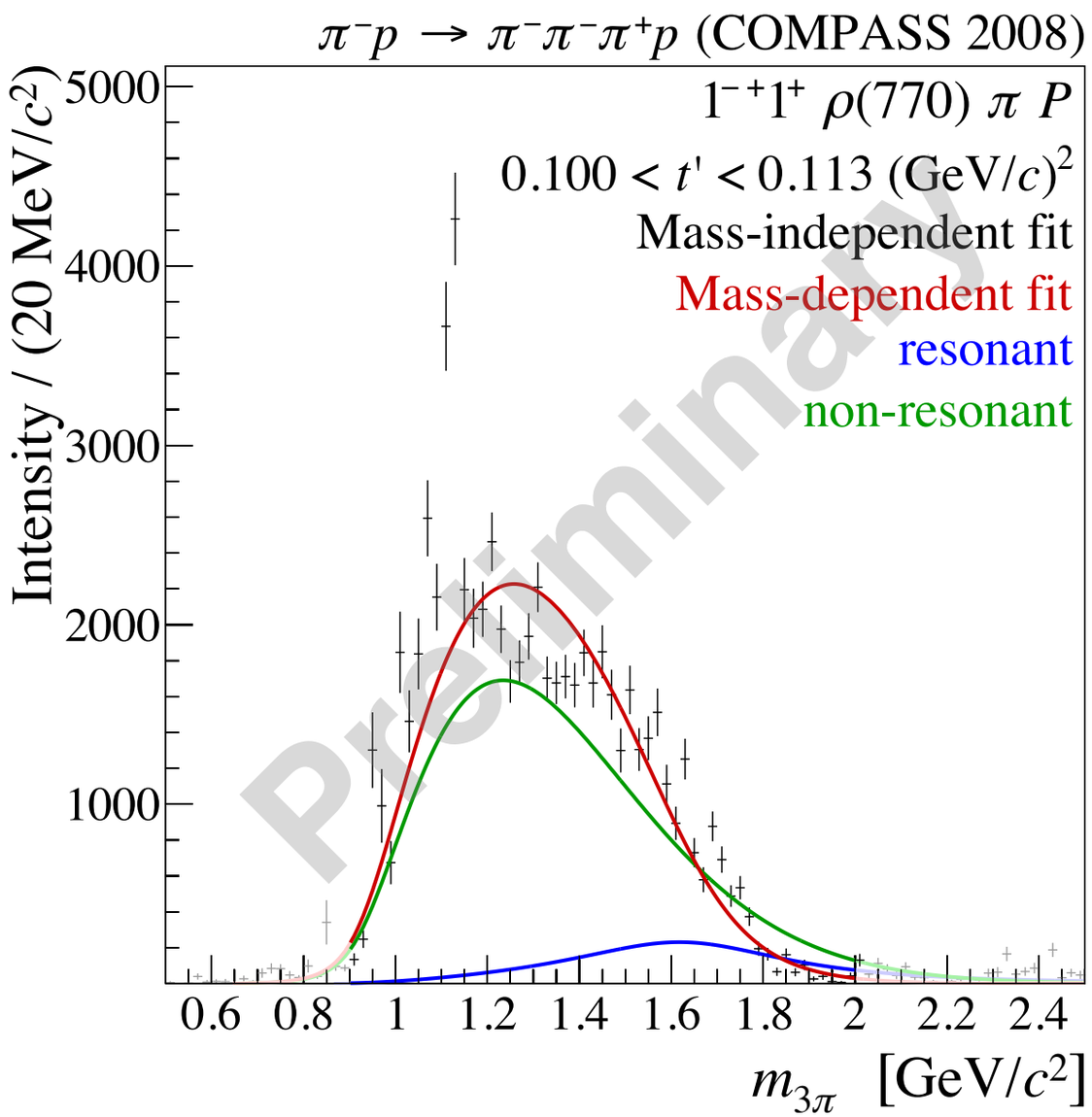




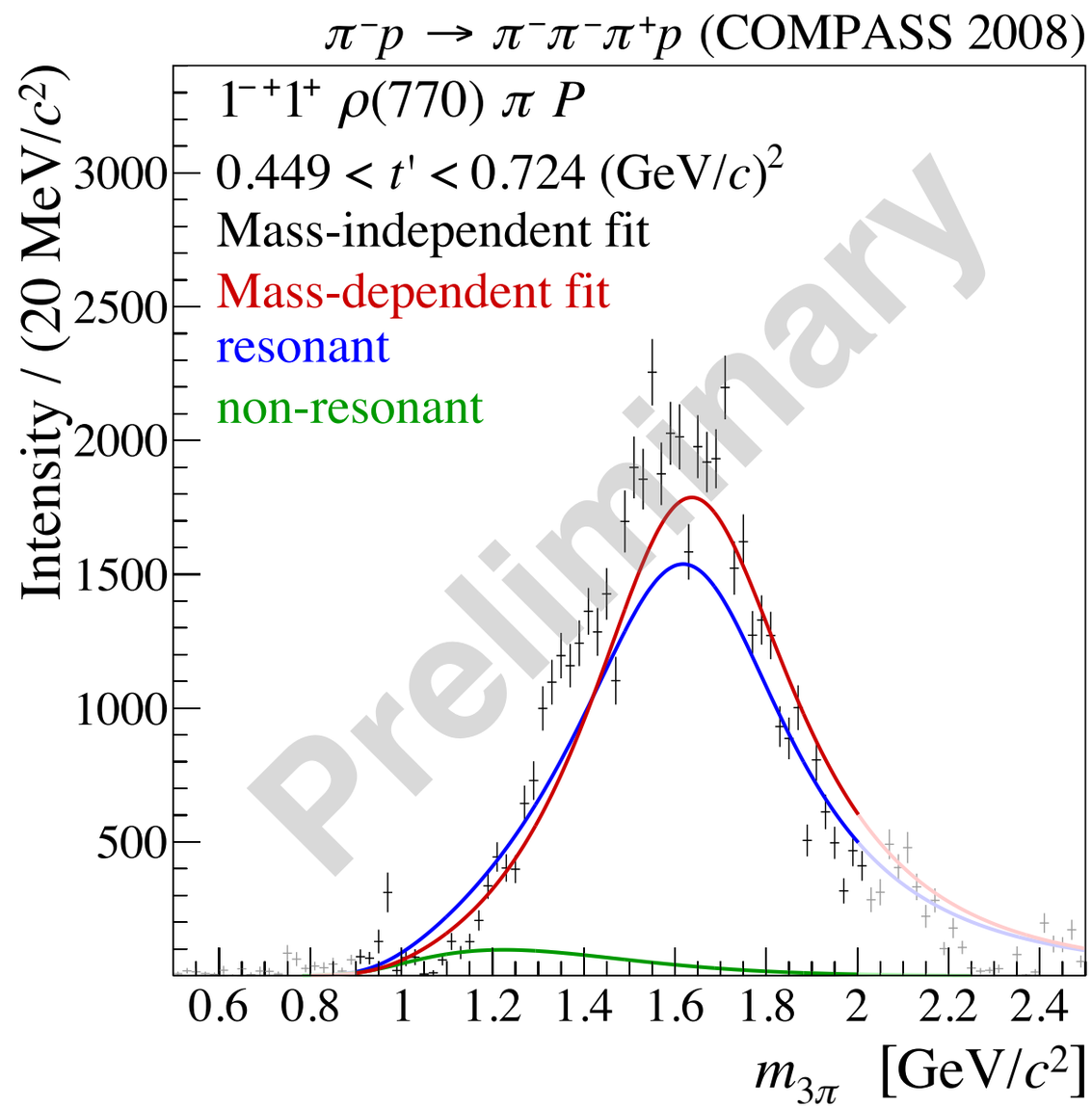
from S. Wallner yesterday

1^{-+} ρπ P-wave

low t



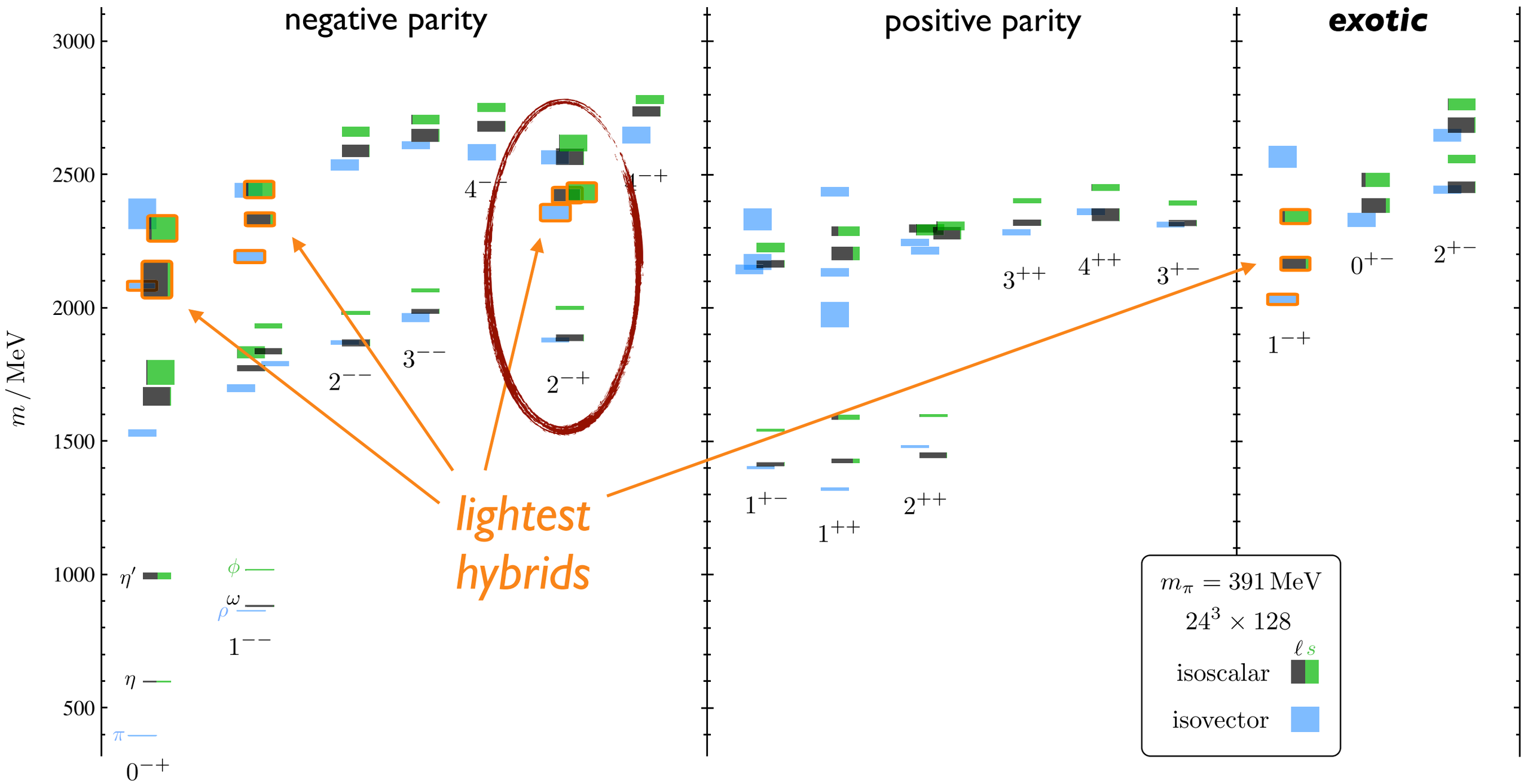
high t



See B. Ketzer tomorrow: resonant π_1 dominates exotic amplitude at high t

Light Quark Mesons from Lattice QCD

Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



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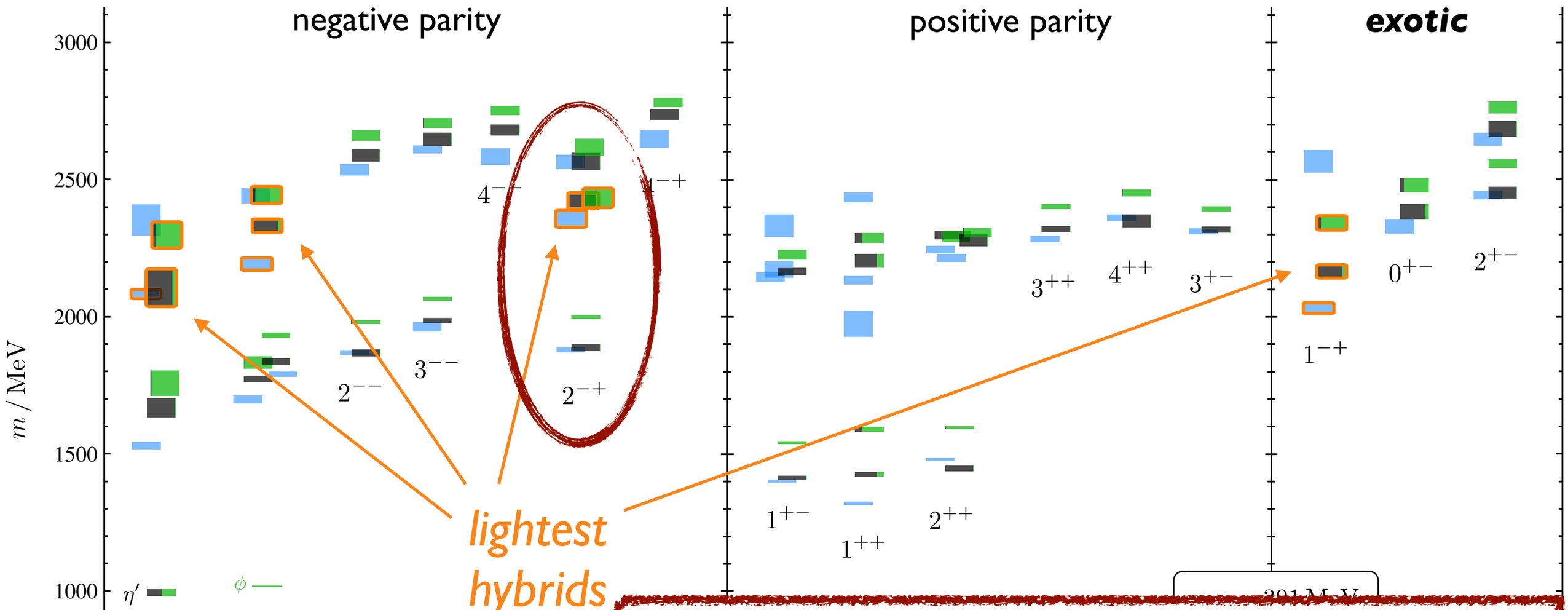
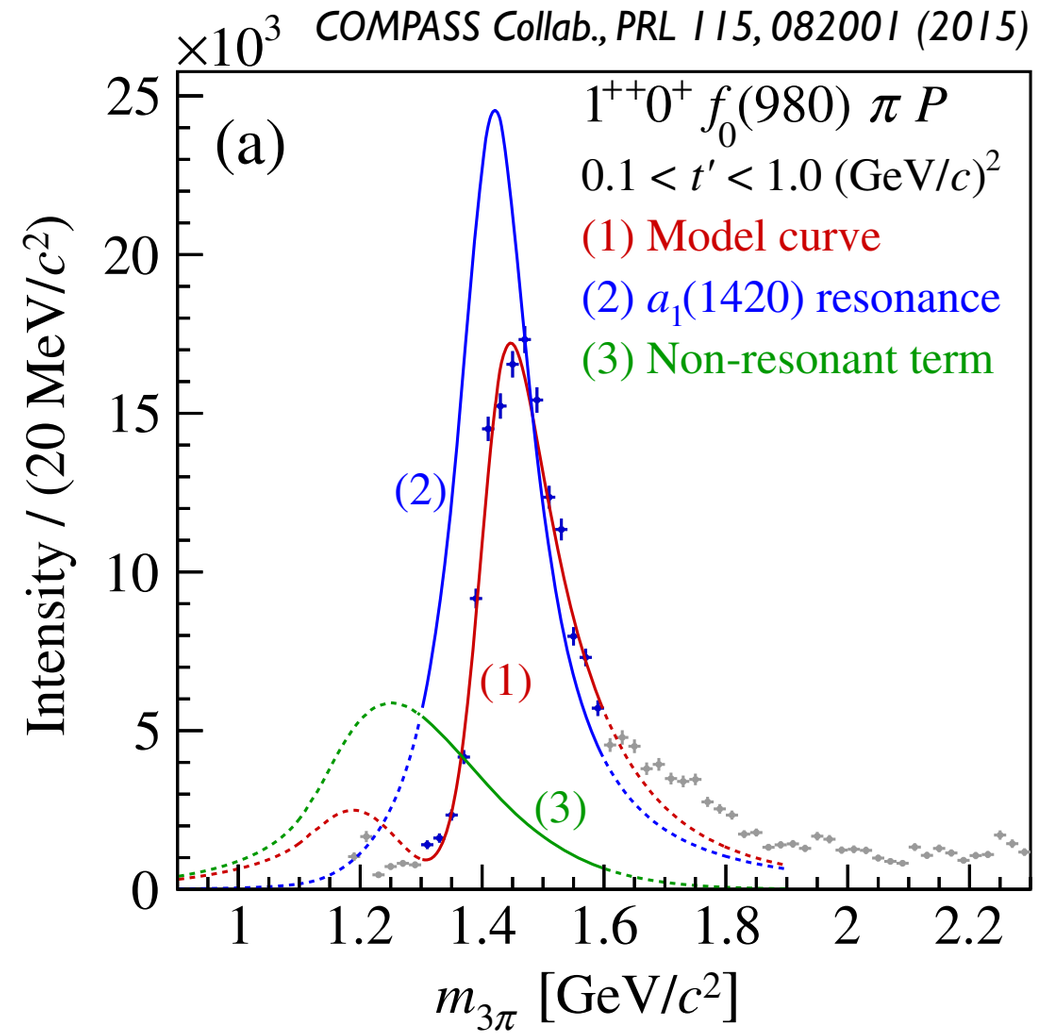


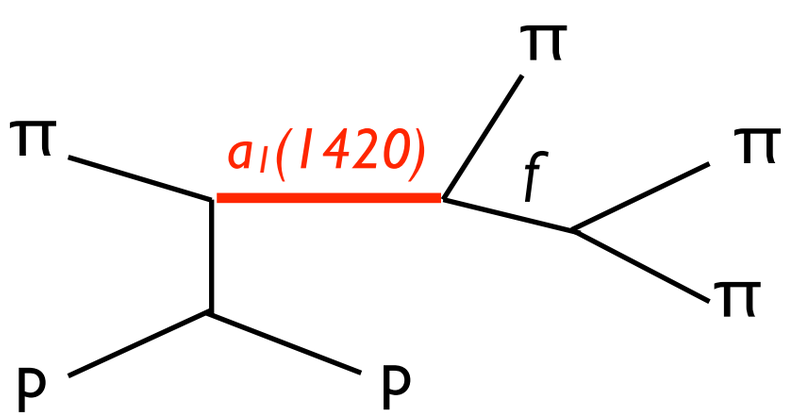
<u>Patterns are essential to establish the existence of hybrids</u>

- Hybrids should overpopulate conventional J^{PC}
- Understanding π_2 spectrum (e.g., using COMPASS data) is potentially just as interesting as the exotic π_1

$a_1(1420) \rightarrow f_0(980)\pi$

- Discovering patterns is crucial …but they must be patterns of resonances!
  - (Warning: sometimes Occam's razor kills the duck.)





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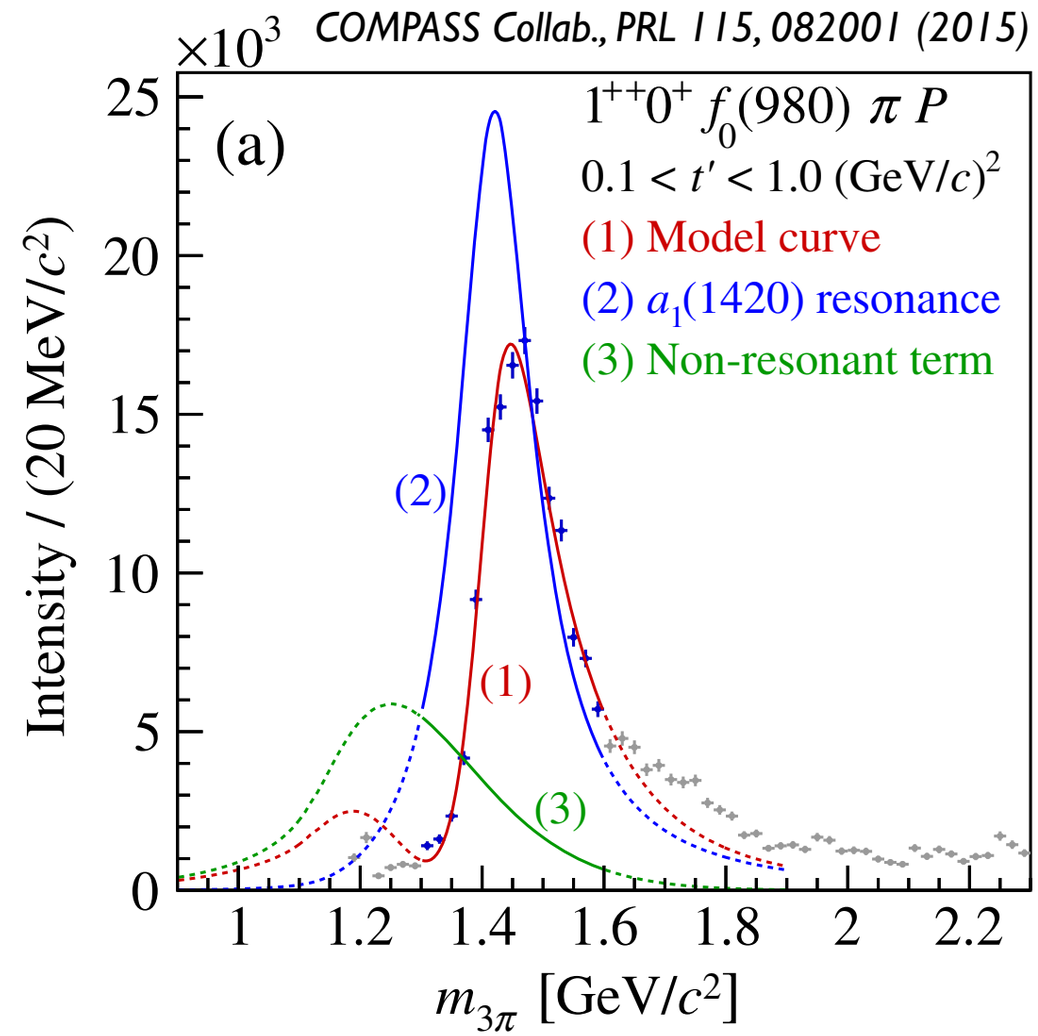
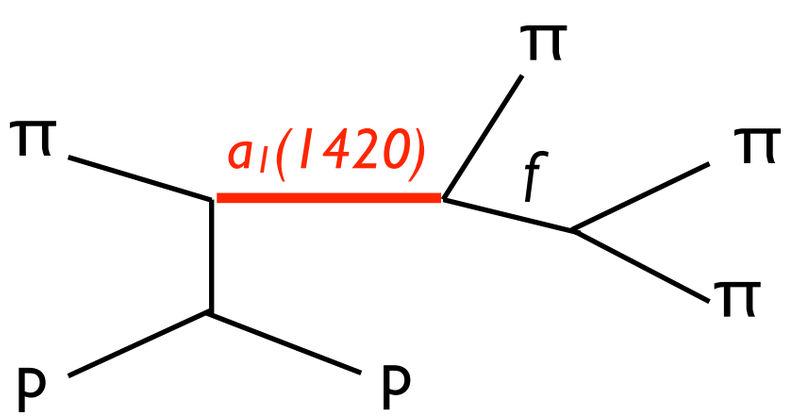
  - very narrow
  - only couples to $f_0(980)\pi$
  - mass doesn't fit the pattern with other qq states





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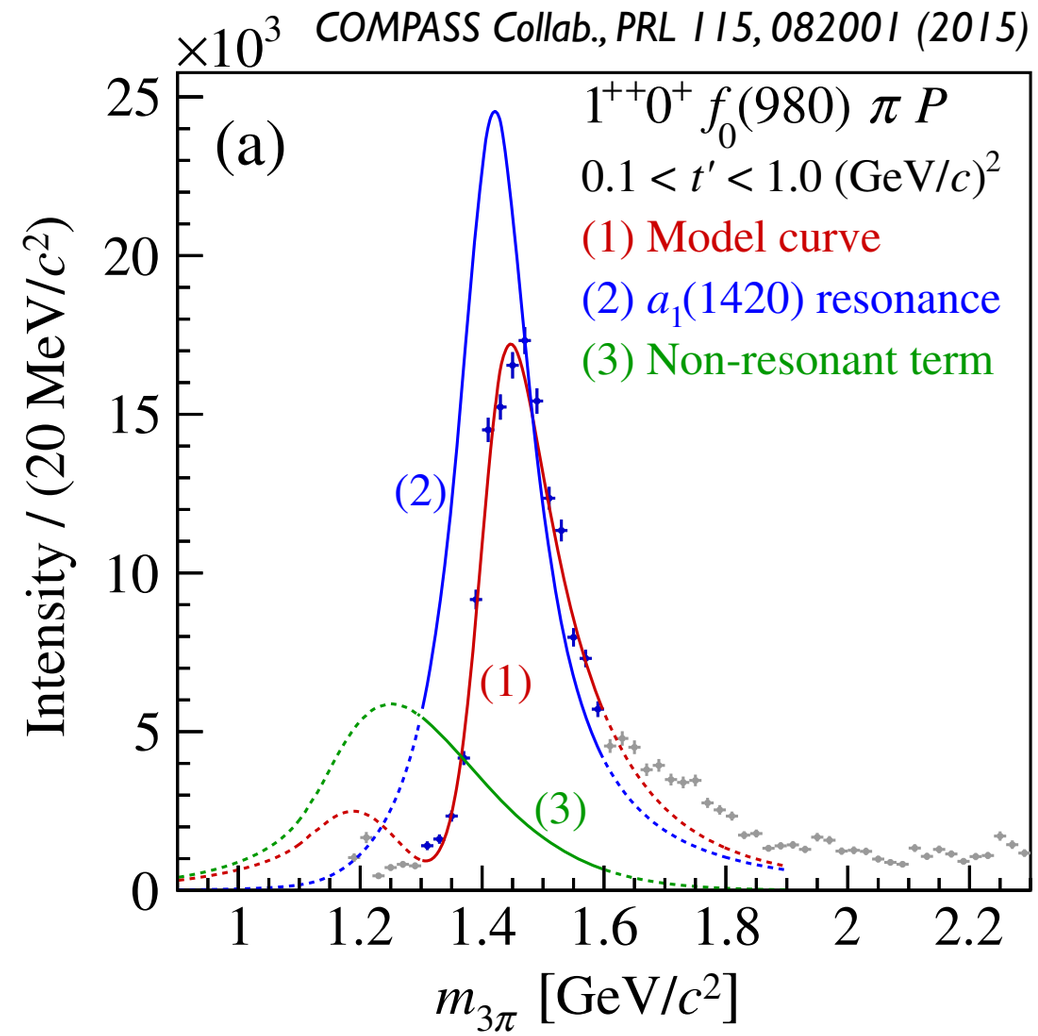
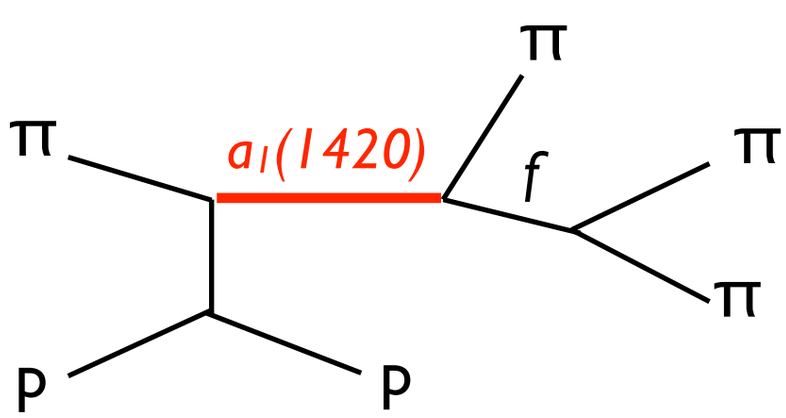
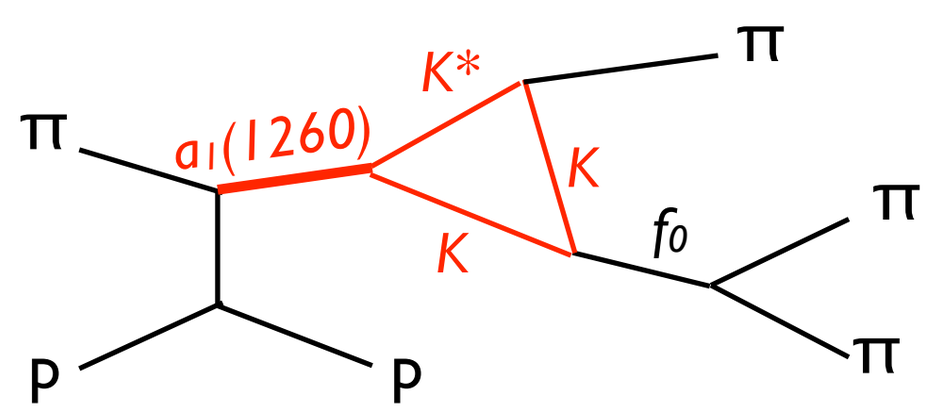
- All of the above can have a non-exotic origin…







$a_1(1420) \to f_0(980)\pi$

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  see M. Mikhasenko's talk (Tuesday) for references

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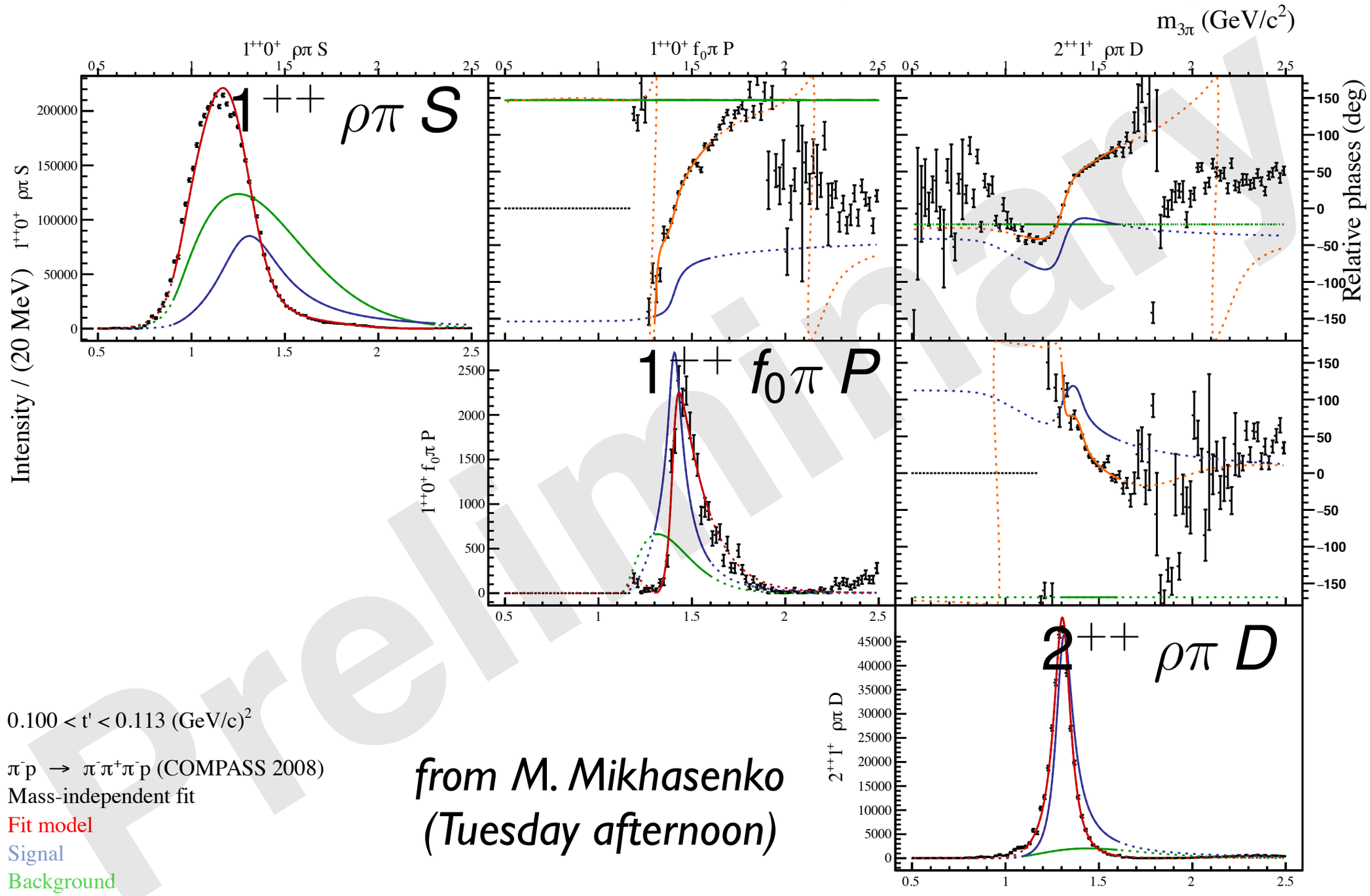
- An essential step: validating our understanding with high precision data

$a_1(1420) \to f_0(980)\pi$

Fit to the data, [COMPASS, in preparation]

Signal model for $1^{++} f_0\pi$ P-wave from the rescattering does not have free parameters



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

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

from M. Mikhasenko (Tuesday afternoon)

see also B. Ketzer tomorrow

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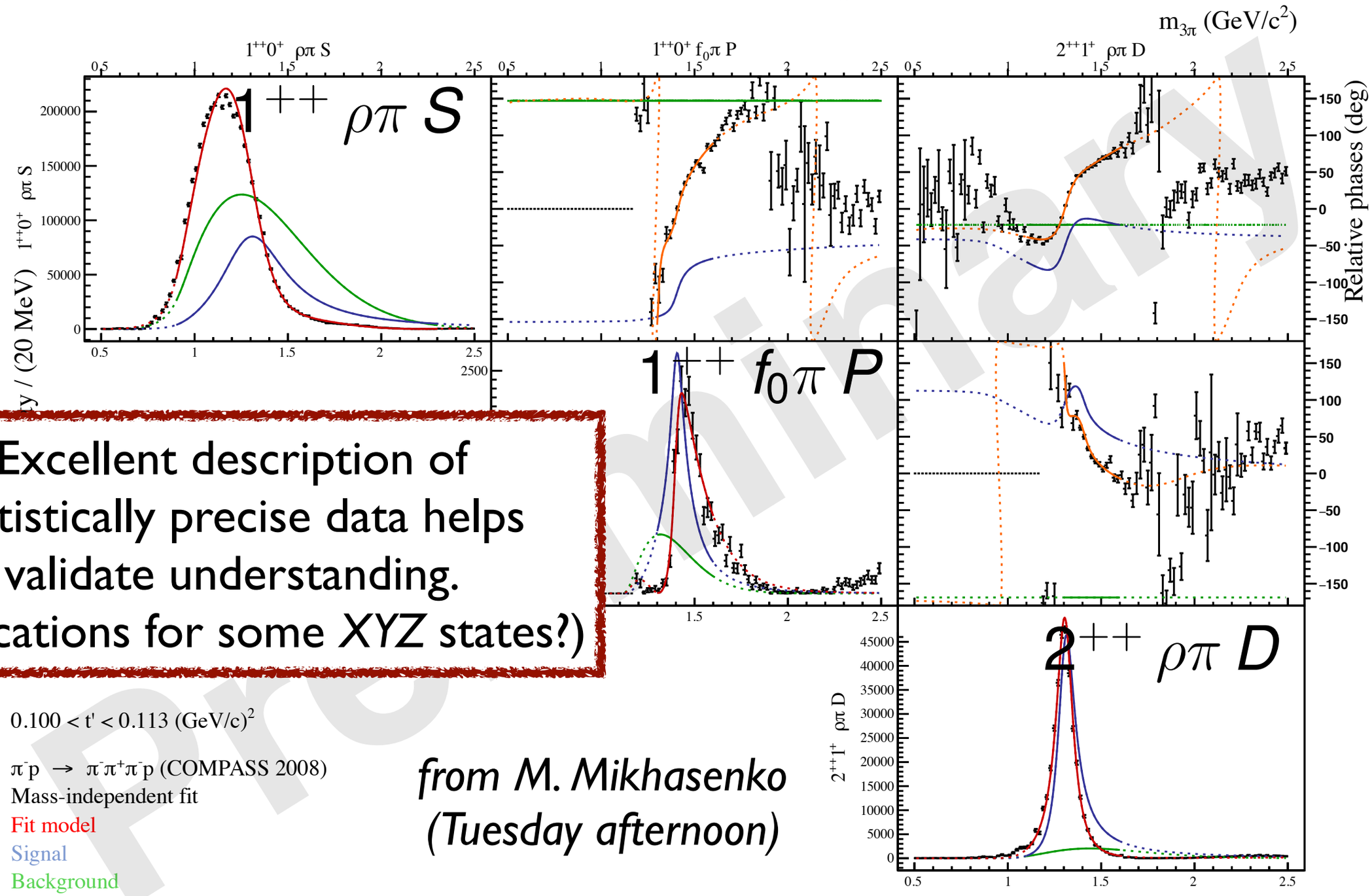

Excellent description of statistically precise data helps validate understanding.
(Implications for some *XYZ* states?)

from M. Mikhasenko (Tuesday afternoon)

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Summary and Outlook

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- Establishing patterns of resonances is essential: need detailed analysis of multiple channels using complementary production mechanisms in the 1.5 - 2.5 GeV region…

An exciting time: new experiments are expected to produce complementary results in coming years

GlueX

at Jefferson Lab

See talk by S. Dobbs tomorrow morning