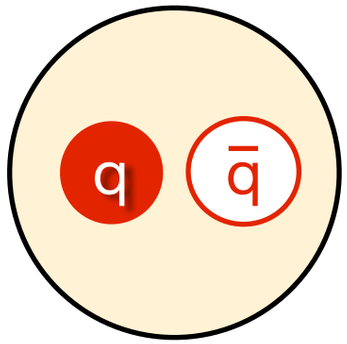
Hadron Spectroscopy at GlueX and Beyond (3)

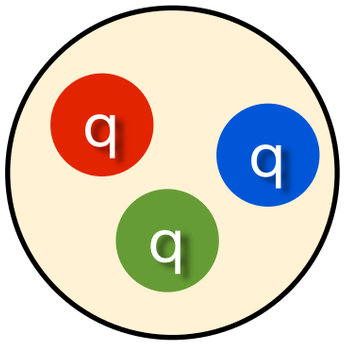
Justin Stevens

WILLIAM & MARY
CHARTERED 1693

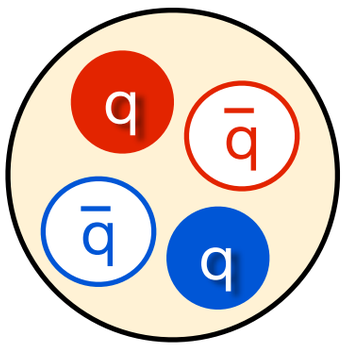
Confined states of quarks and gluons



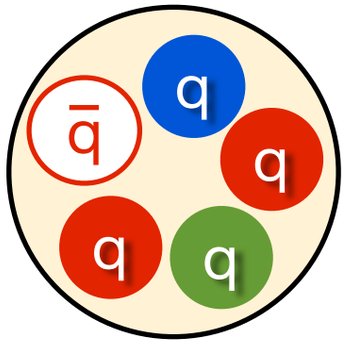
mesons



baryons



tetraquark

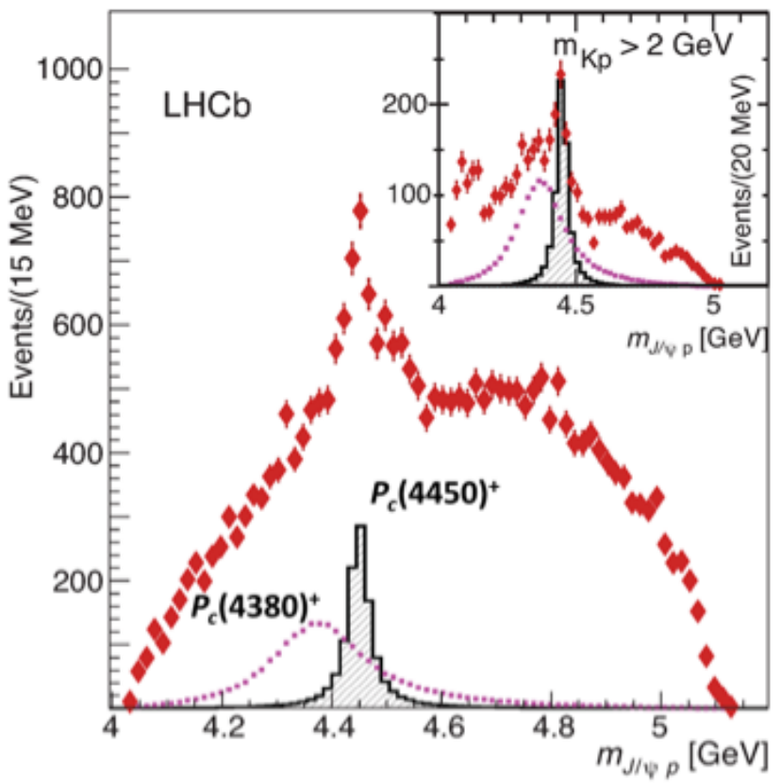


pentaquark

Observed mesons and baryons well described by 1st principles QCD

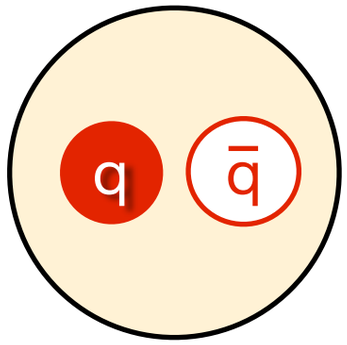
But these aren't the only states permitted by QCD

$$\Lambda_b \to J/\psi p K^-$$

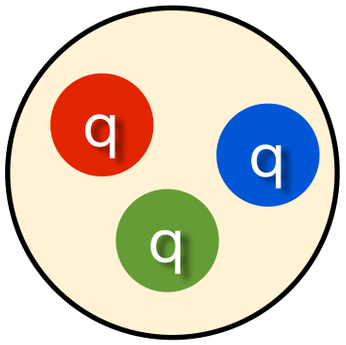


PRL 115, 072001 (2015)

Confined states of quarks and gluons



mesons



baryons

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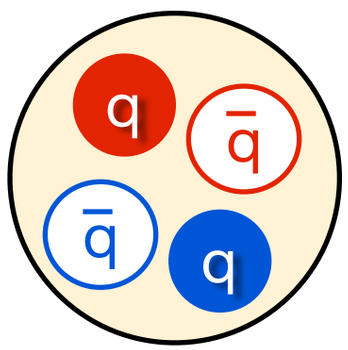

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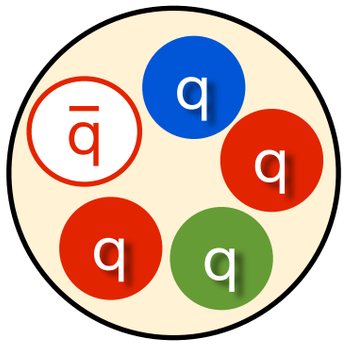

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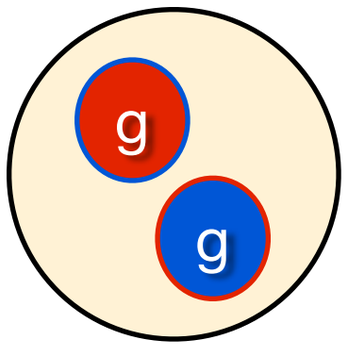
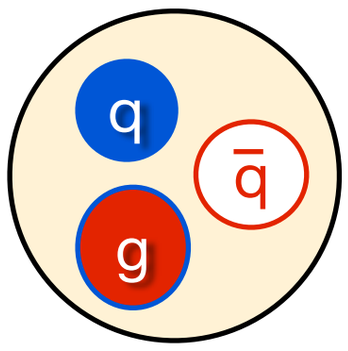


glueball



hybrid meson

Do gluonic degrees of freedom manifest themselves in the bound states we observe in nature?

Classifying mesons

- General properties: mass, electric charge, quark flavor
- Grouped by quantum numbers: J^{PC}
  - Angular momentum: $\vec{J} = \vec{L} + \vec{S}$
  - Parity: Invert spatial coordinates

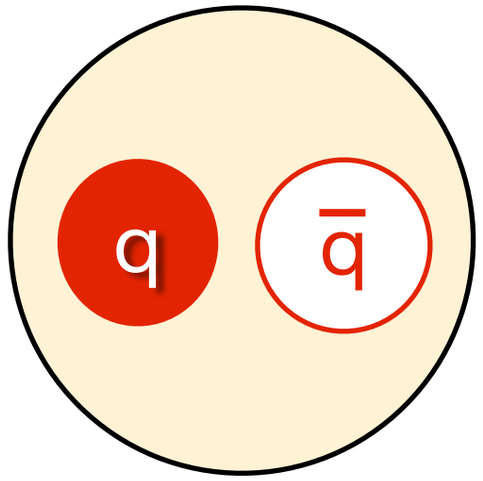
$$P = (-1)^{L+1}$$

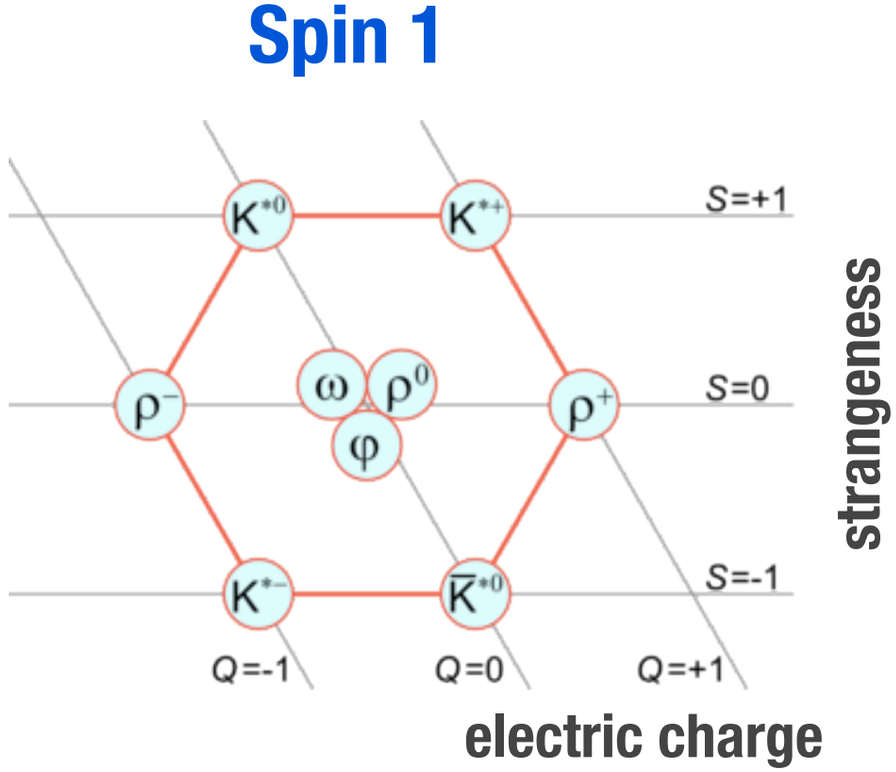
  - Charge conj.: particle ↔ antiparticle

$$C = (-1)^{L+S}$$

- Allowed **J^{PC}** for $q\bar{q}$ mesons:

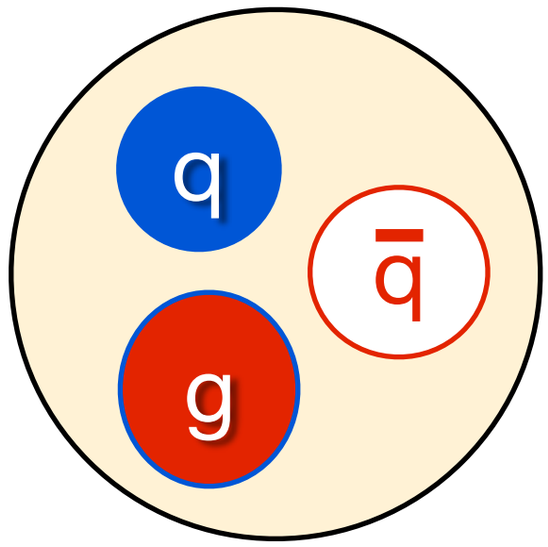
$$J^{PC} = 0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 2^{++} ...$$





Hybrid mesons and gluonic excitations

- Excited gluonic field coupled to $q\bar{q}$ pair
- Rich spectrum of hybrid mesons predicted by Lattice QCD
- Gluonic field with $J^{PC} = 1^{+-}$ and mass = 1-1.5 GeV

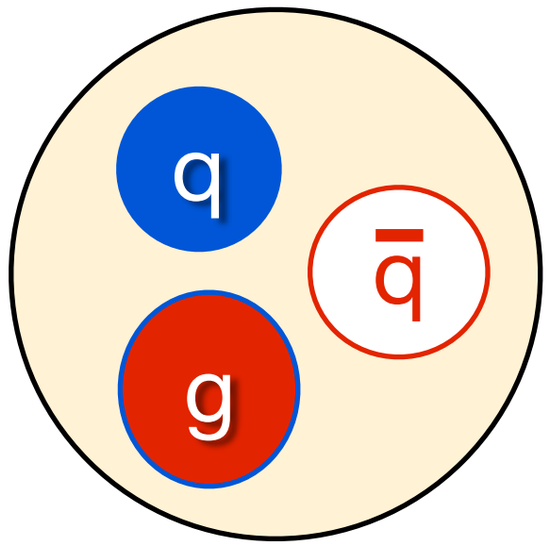


hybrid meson

Hybrid mesons and gluonic excitations

- Excited gluonic field coupled to $q\bar{q}$ pair
- Rich spectrum of hybrid mesons predicted by Lattice QCD
- Gluonic field with $J^{PC} = 1^{+-}$ and mass = 1-1.5 GeV
- "Exotic" J^{PC} : not simple $q\bar{q}$ from the non-rel. quark model

$$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} ...$$



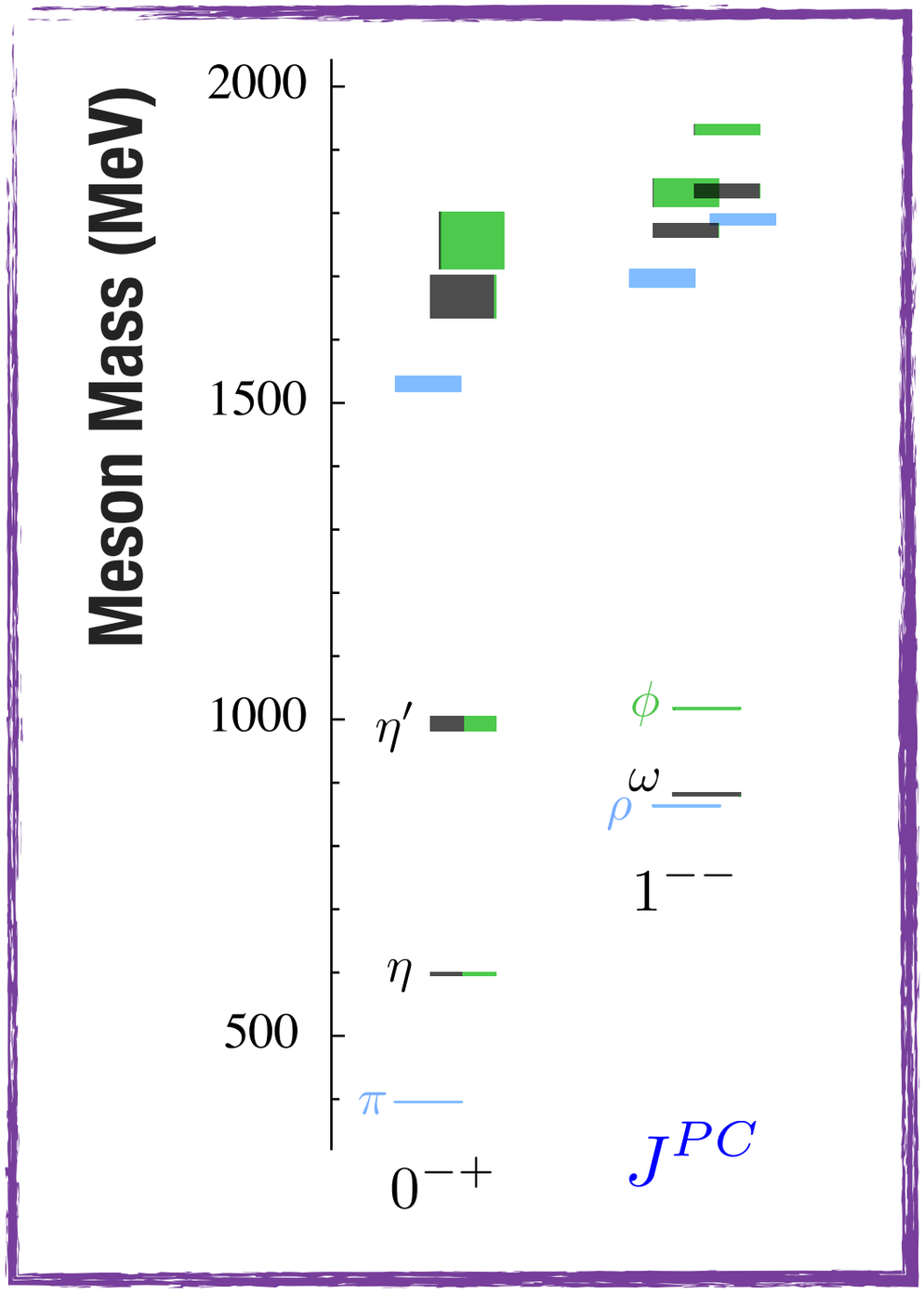
hybrid meson

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

Lattice QCD

had spec
hadron spectrum collaboration

PRD 88 (2013) 094505



$u\bar{u} + d\bar{d}$

$s\bar{s}$

$\phi = |s\bar{s}\rangle$

$\omega = |u\bar{u} + d\bar{d}\rangle$

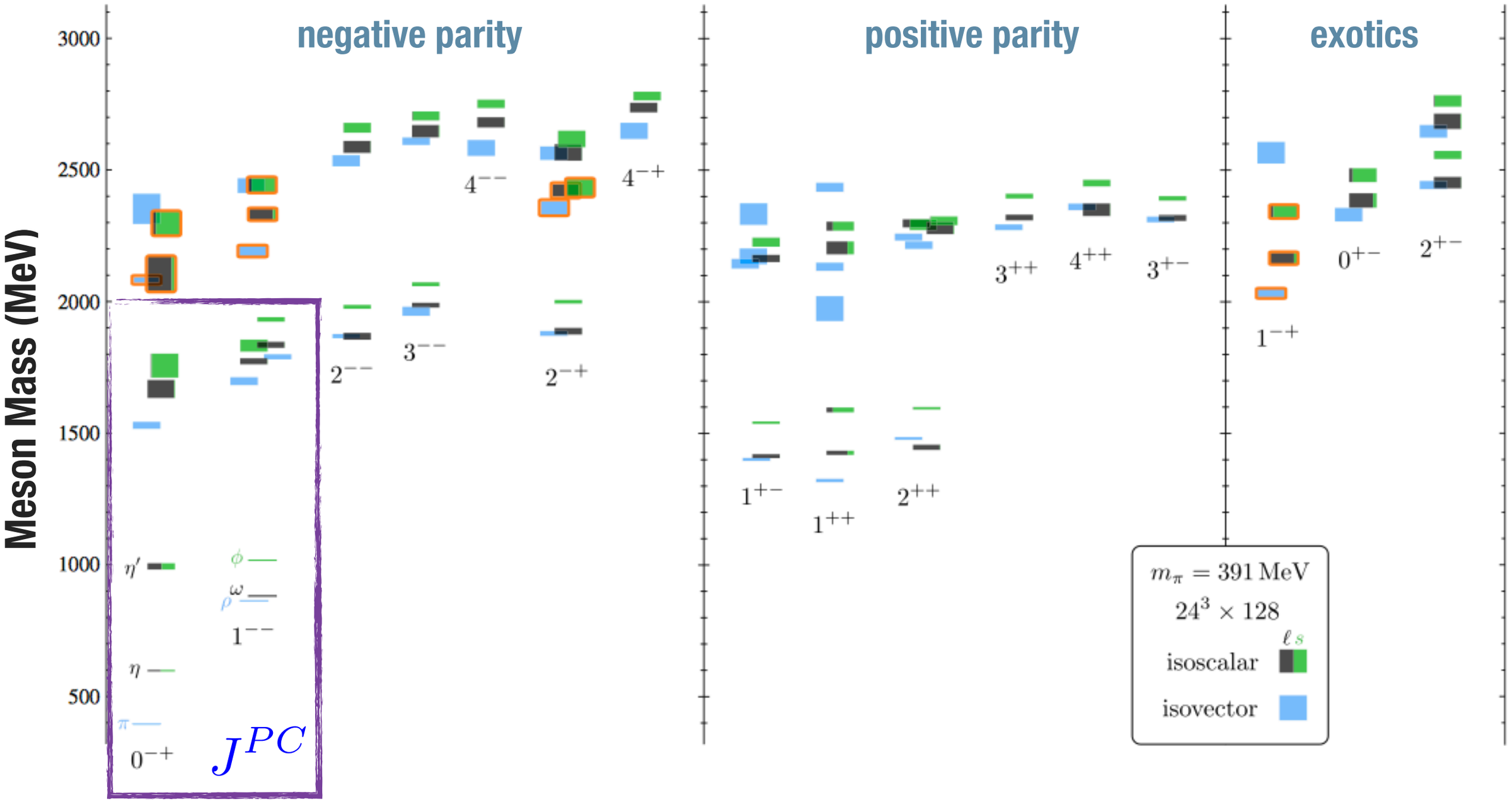
$\pi^0 = |u\bar{u} - d\bar{d}\rangle$

Note: $m_\pi = 392\,\mathrm{MeV}$

Lattice QCD

hadspec
hadron spectrum collaboration

PRD 88 (2013) 094505



Lattice QCD

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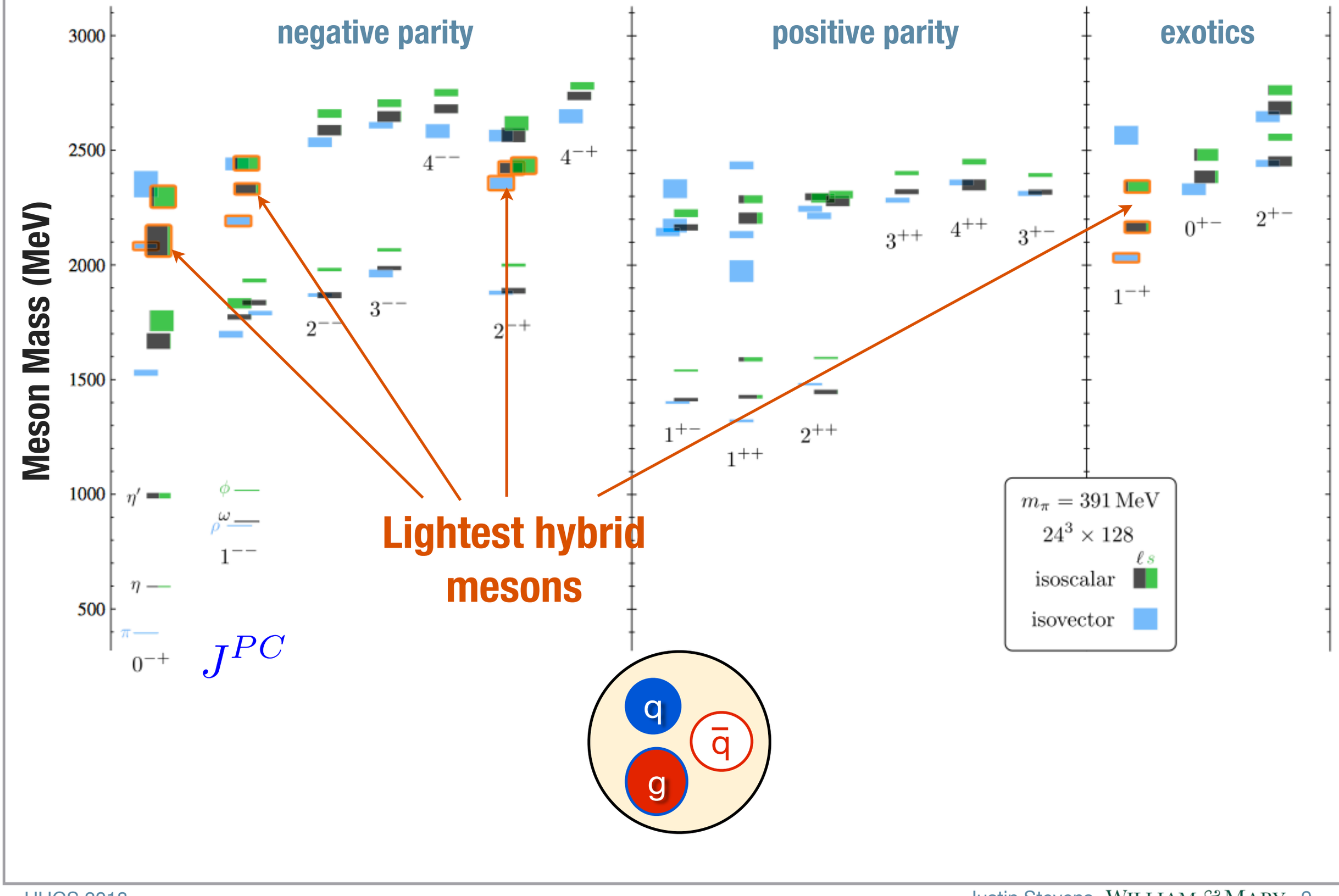

Lightest hybrid mesons

Lattice QCD

had spec
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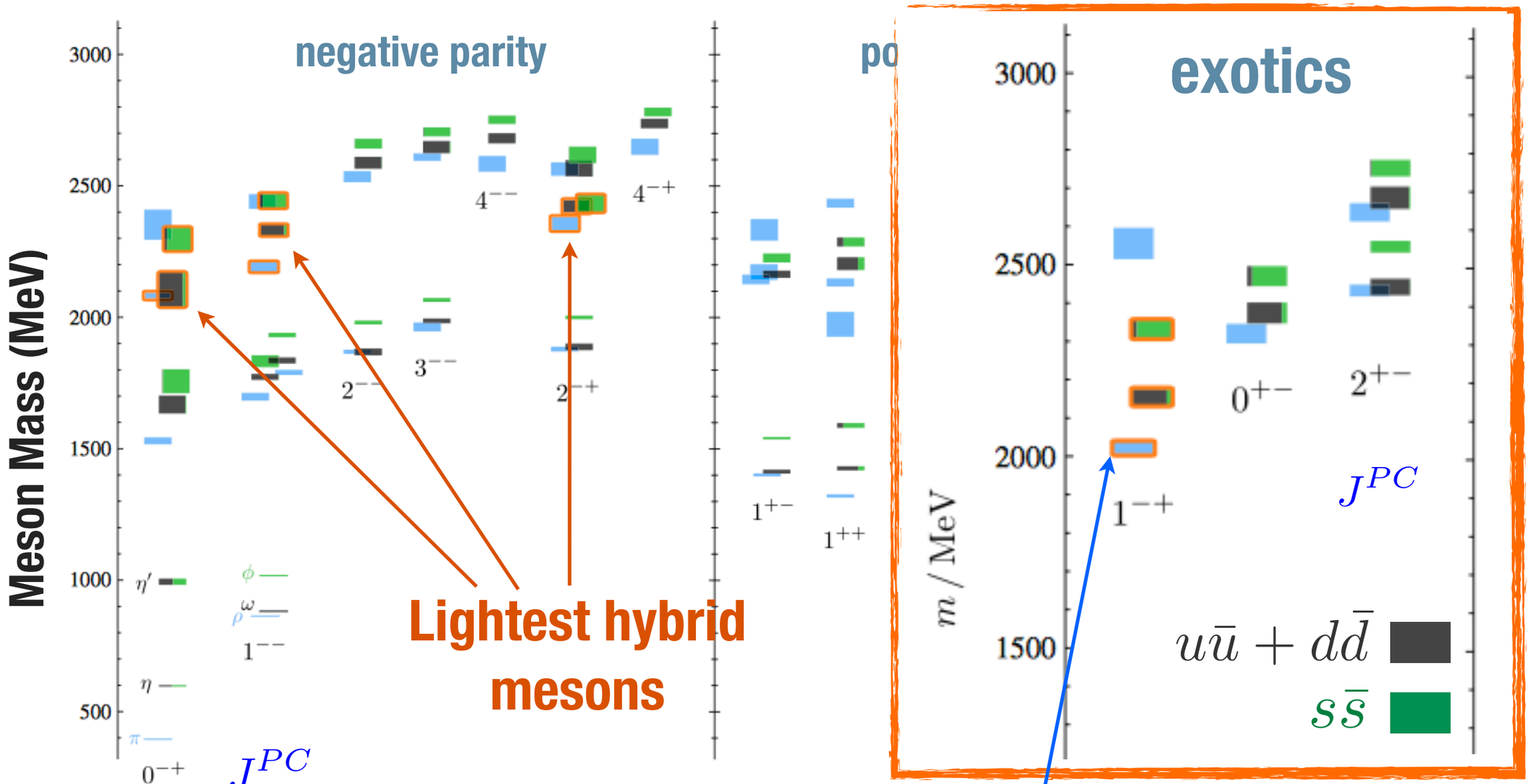
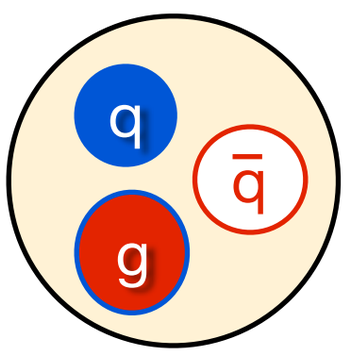
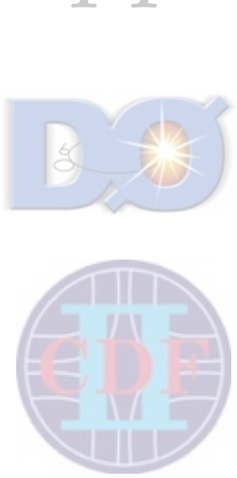


Lightest hybrid mesons



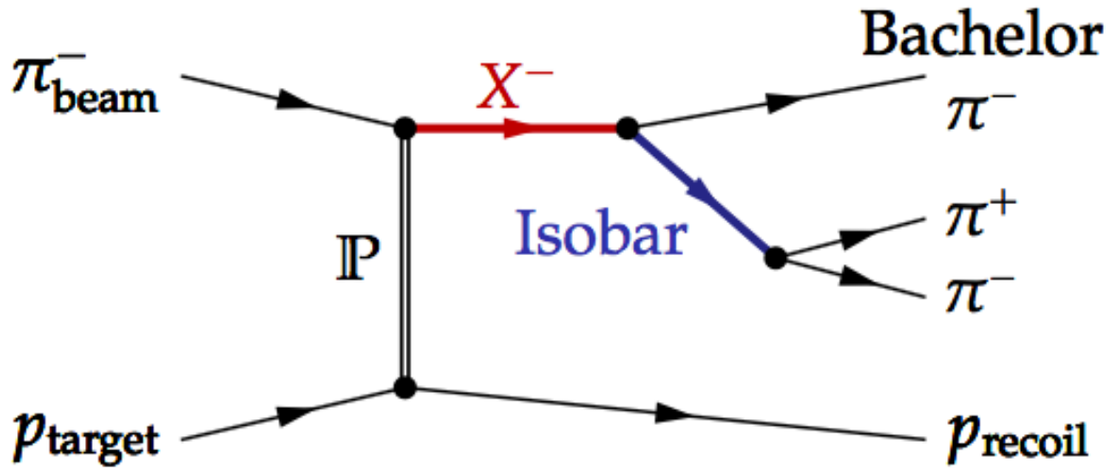
Most experimental searches for hybrids limited to the π_1 state

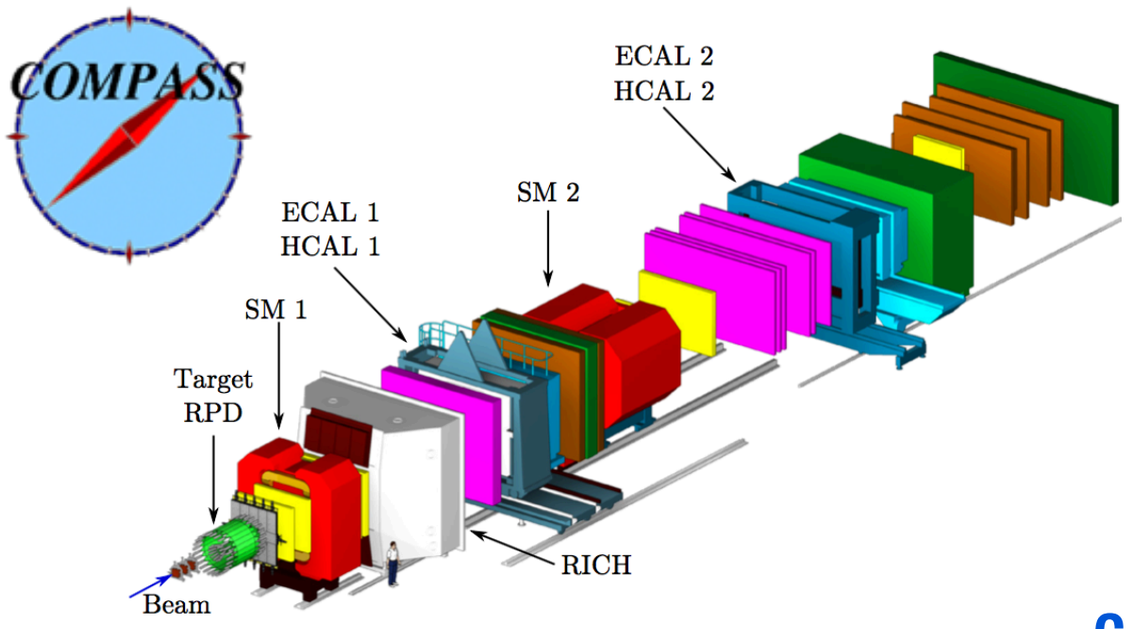
Light quark experiments

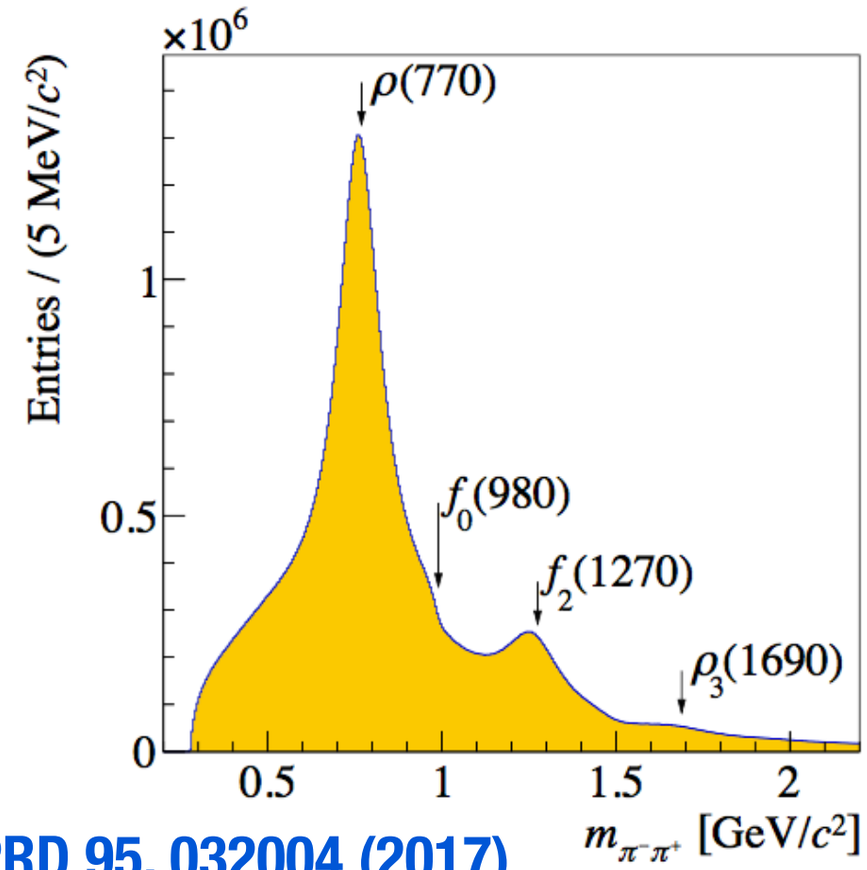
	Heavy quarks	**Light quarks**
Electromagnetic probes	e^+e^- 	γp 
Hadronic probes	$\bar{p}p$  pp	$\bar{p}p$  πp 

Compass: Diffractive πp scattering

- Long history of hadron spectroscopy in pion production experiments
- Rich structure in $\pi^-\pi^+\pi^-$ spectrum, modeled as intermediate resonances ***X***$^-$ and $\pi^+\pi^-$ **Isobars**







Compass: PRD 95, 032004 (2017)

Compass: Diffractive πp scattering

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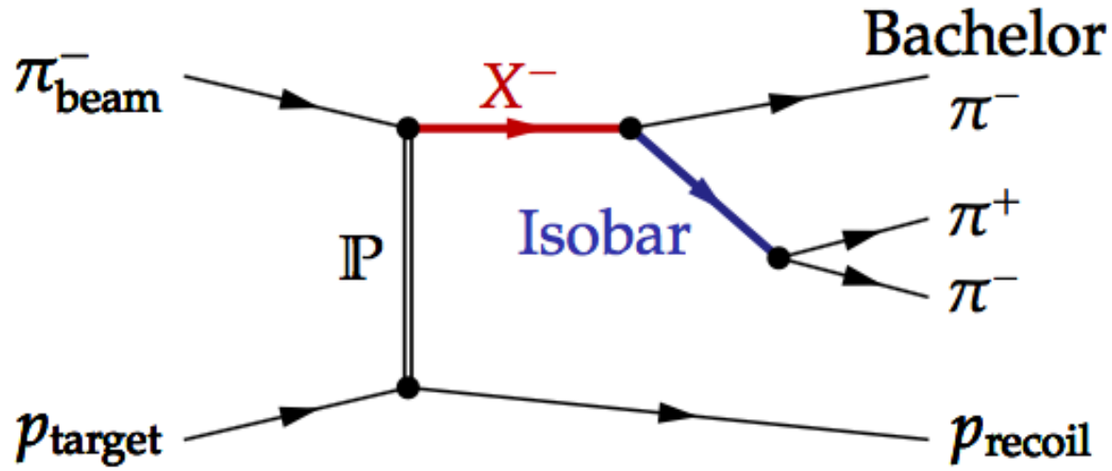
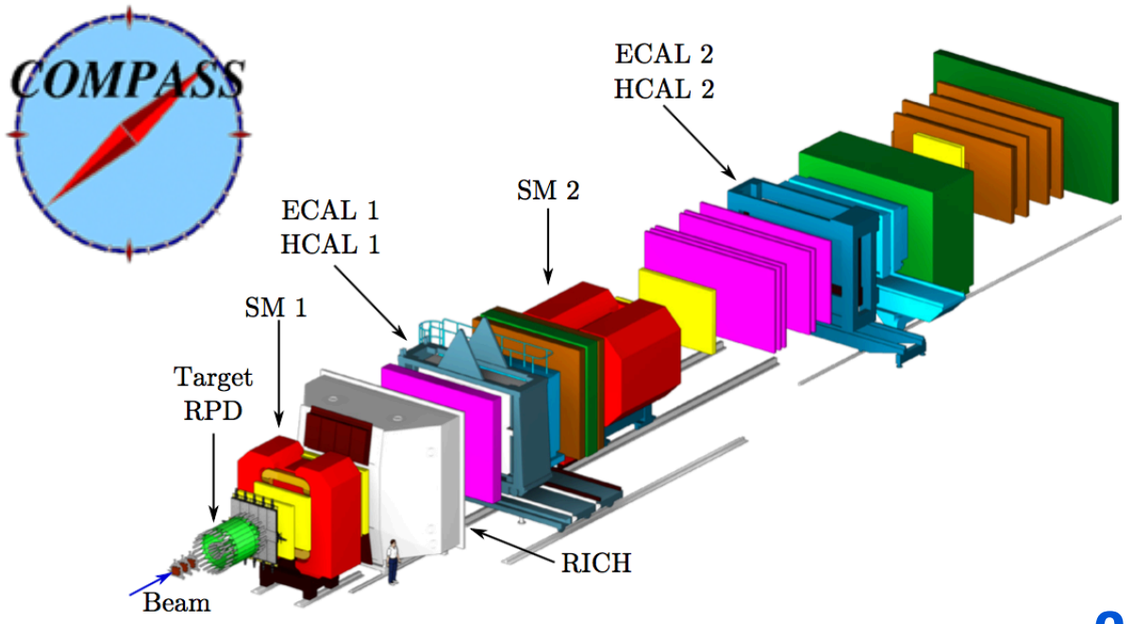
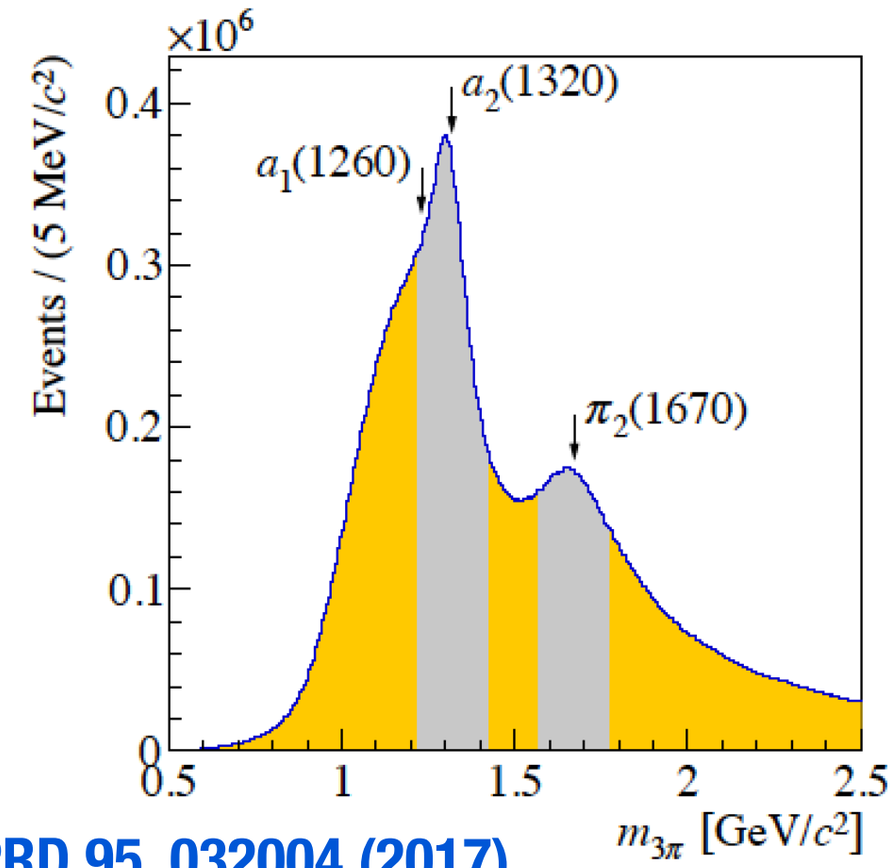




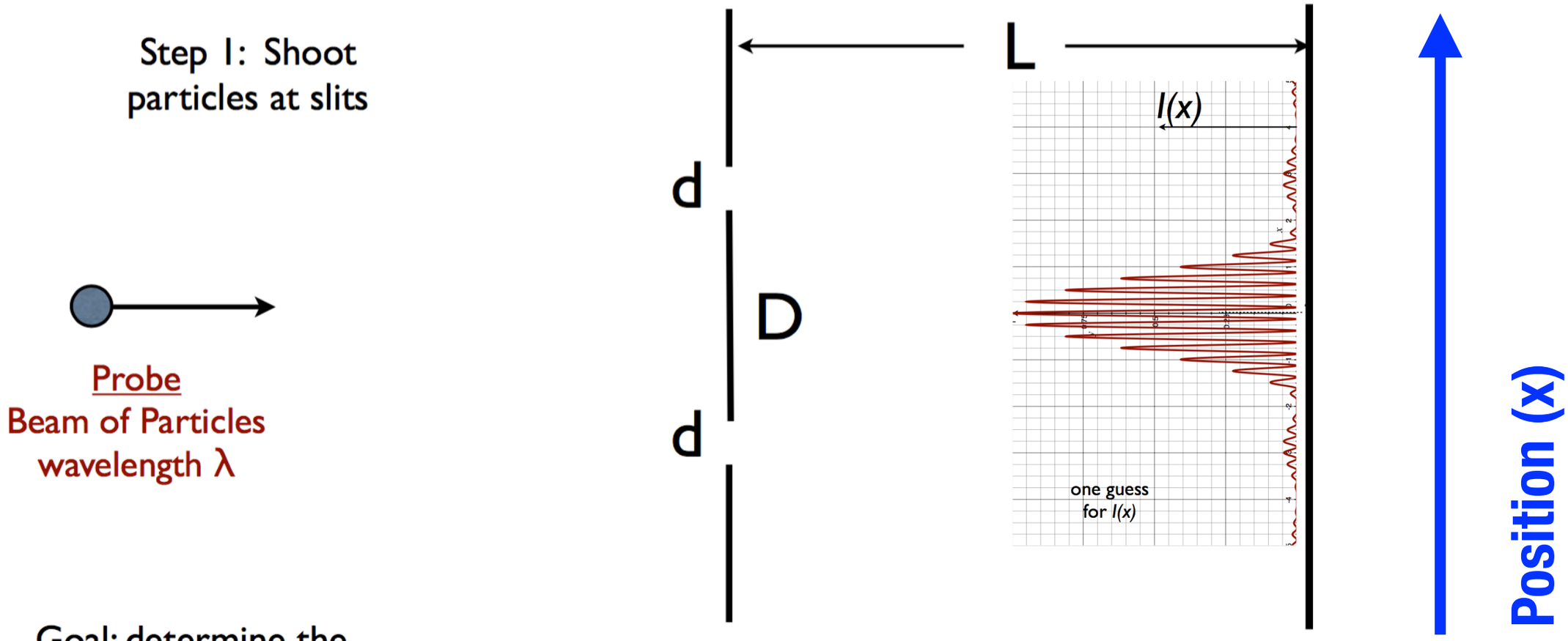


Compass: PRD 95, 032004 (2017)

Double Slit Experiment

Step 1: Shoot particles at slits

Step 2: For each particle record location *x* where it was detected



Probe
Beam of Particles
wavelength λ

Goal: determine the values of *d* and *D*

Physical System Under Study
Two Slits: width d, separation D

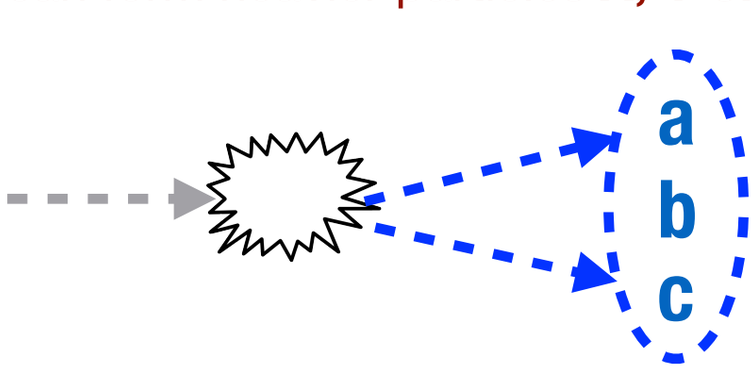
Detector
Measures location x_i for each arriving particle

Physical Model: $$I(x) = I_0 \left(\frac{\sin(d\pi x/\lambda L)}{d\pi x/\lambda L} \right)^2 \cos^2(2D\pi x/\lambda L)$$

Particle physics “many slits”

Step 1: Create particles
a, b and **c** in some collision

Probe: particles **a, b** and **c** which can form heavier particles **X, Y or Z**



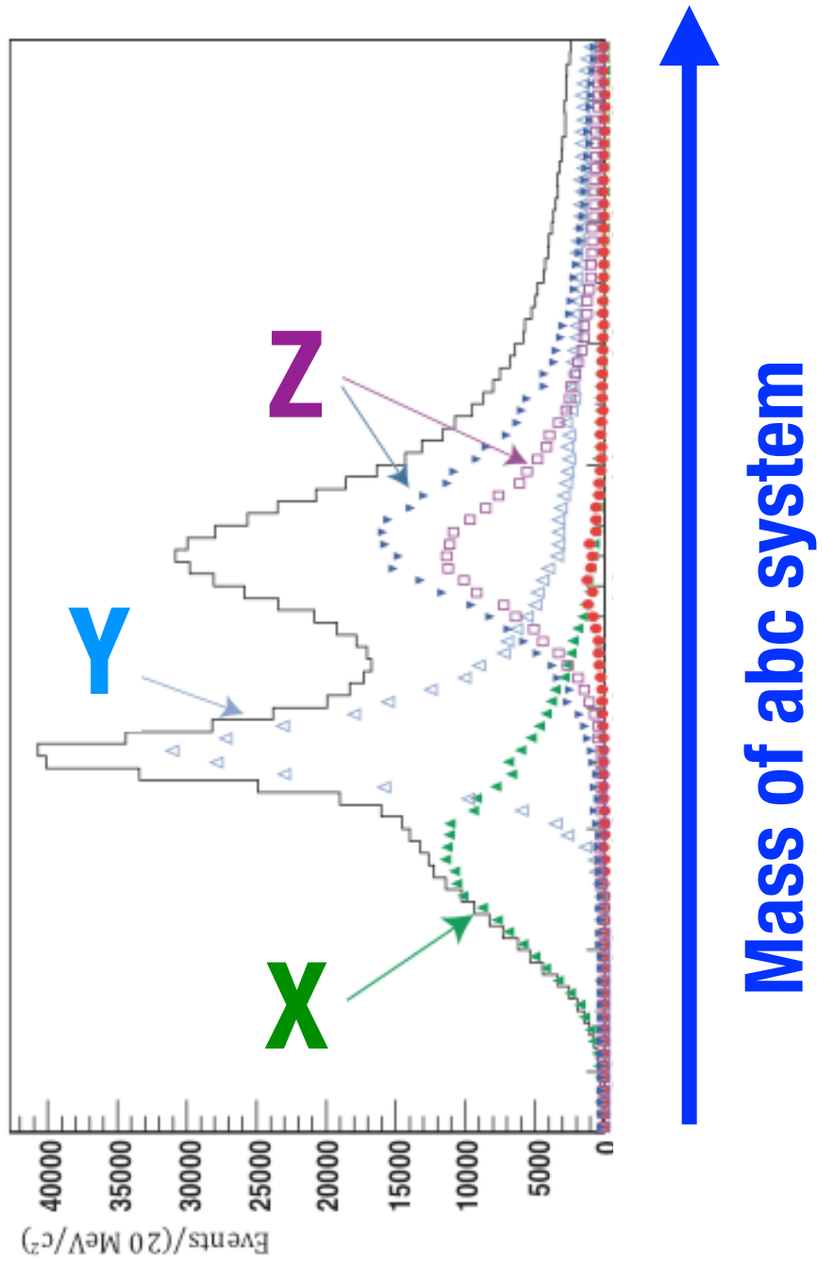
Physical Model:

$$I(M) = \left| \sum_{i=X,Y,Z} V_i A_i(M) \right|^2$$

Goal: determine properties of X, Y, and Z

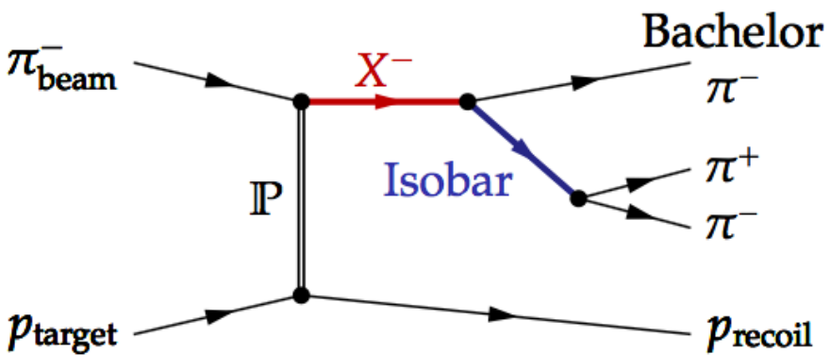
Physical System Under Study: intermediate particles X, Y, and Z

Step 2: For each collision record the **mass of the abc system**



Detector: Measure mass of abc system for each collision

Amplitude Analysis



- **Goal:** Identify J^{PC} of $X \longrightarrow \pi^+\pi^-\pi^+$
- Model the intensity of events at the level of QM amplitudes (allow for interference)

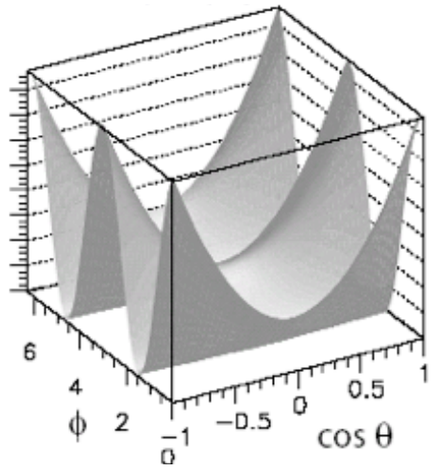
$$I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha}^{N_{\text{amps}}} V_\alpha A_\alpha(\vec{x}) \right|^2$$

- 5-dimensional problem: two new angles at each decay step (X and l)

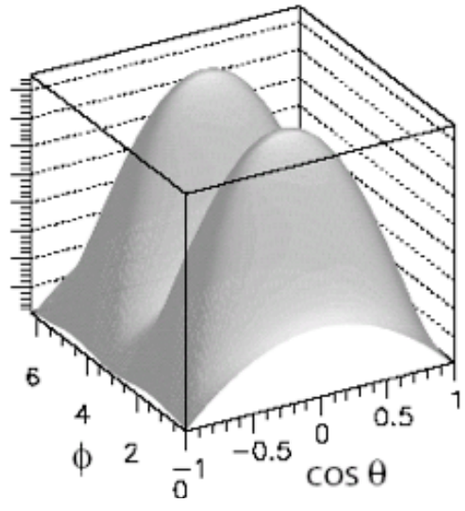
Example Intensity:

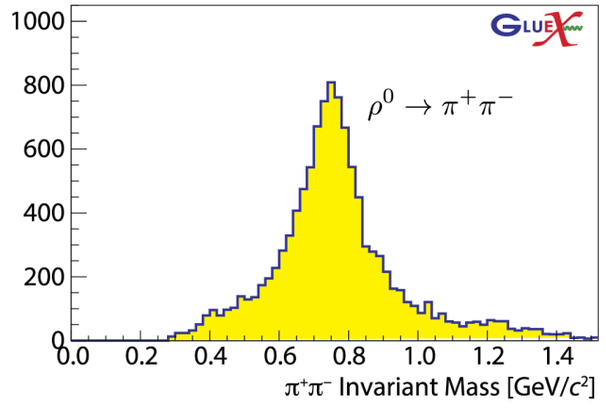
$$X(1^{++}) \rightarrow \rho\pi^+ \text{ (S wave)}$$

$X \rightarrow \rho\pi^+$



$\rho \rightarrow \pi^+\pi^-$





Amplitude Analysis

$$I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha}^{N_{\text{amps}}} V_\alpha A_\alpha(\vec{x}) \right|^2$$

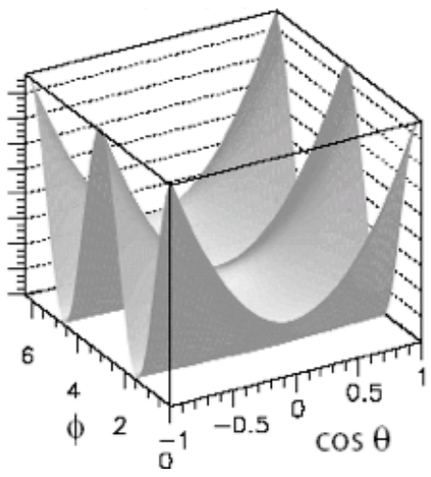
- Expand set of possible amplitudes over many X and I, and determine V_α via maximum likelihood fit
- Good angular acceptance critical for disentangling J^{PC}

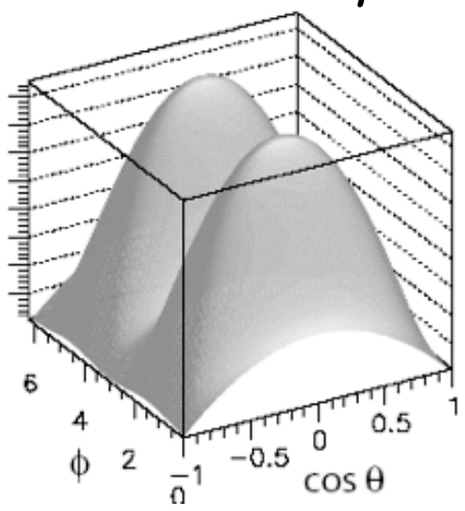
Example Intensities:

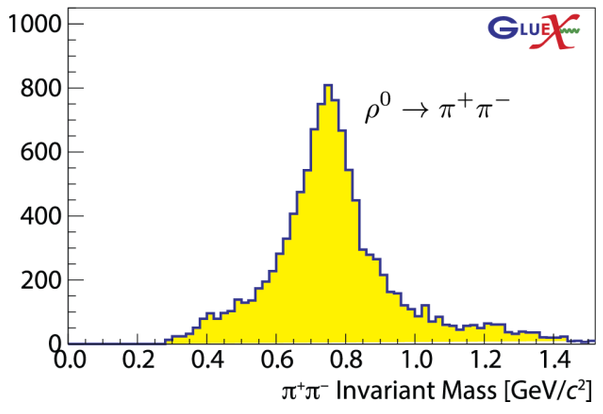
$X \to \rho\pi^+$

$\rho \to \pi^+\pi^-$

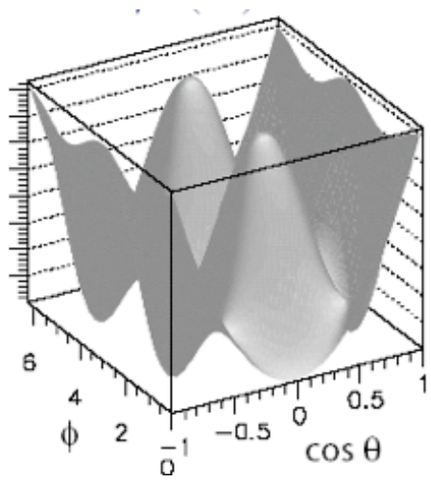
$X(1^{++})$
$\to \rho\pi^+$ (S wave)

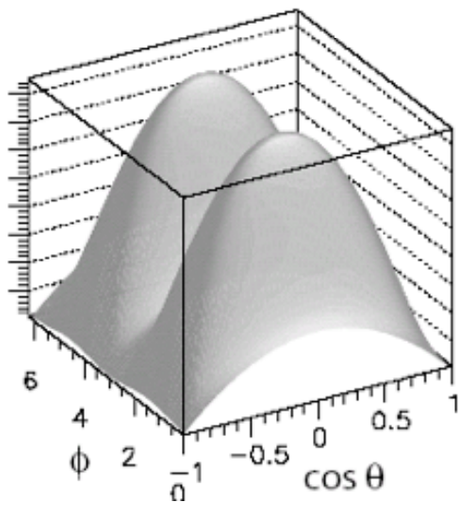


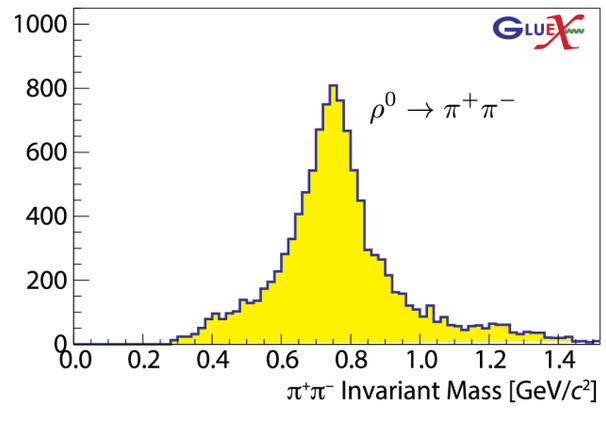




$X(2^{++})$
$\to \rho\pi^+$ (D wave)







Resonance phase motion expectations

$M = 1.26$ GeV

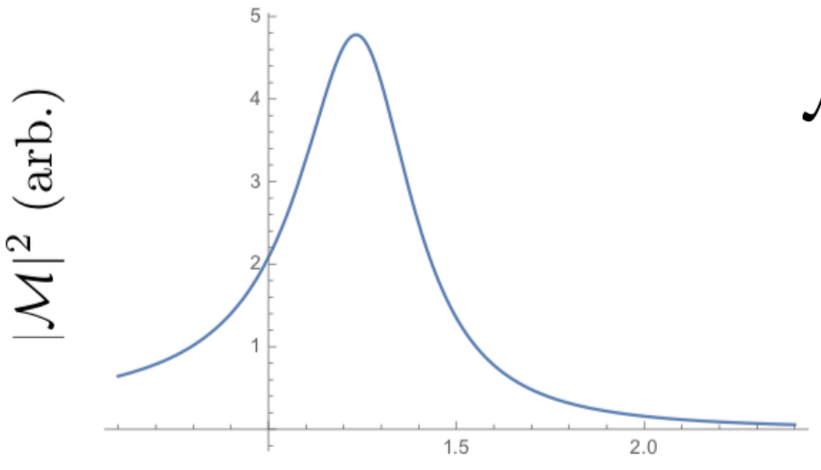
$\Gamma = 0.37$ GeV

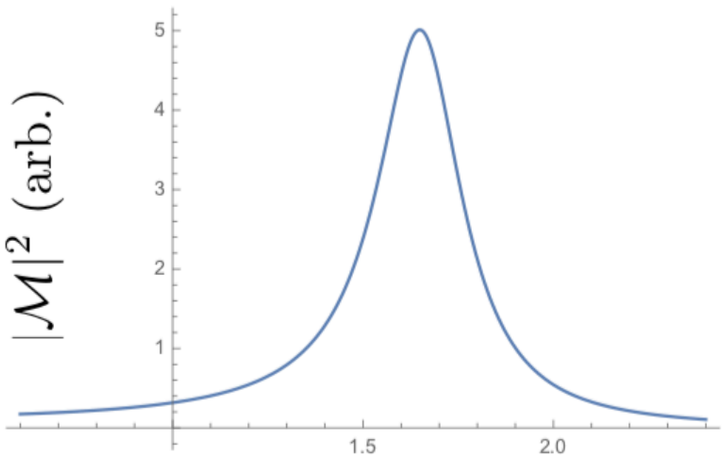
Assuming a Breit-Wigner mass-dependent amplitude:

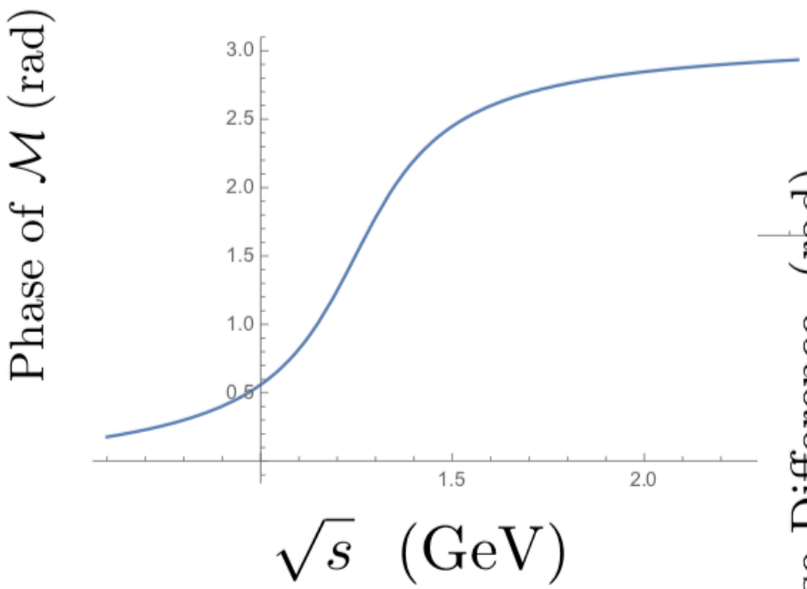
$$\mathcal{M} \propto \frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

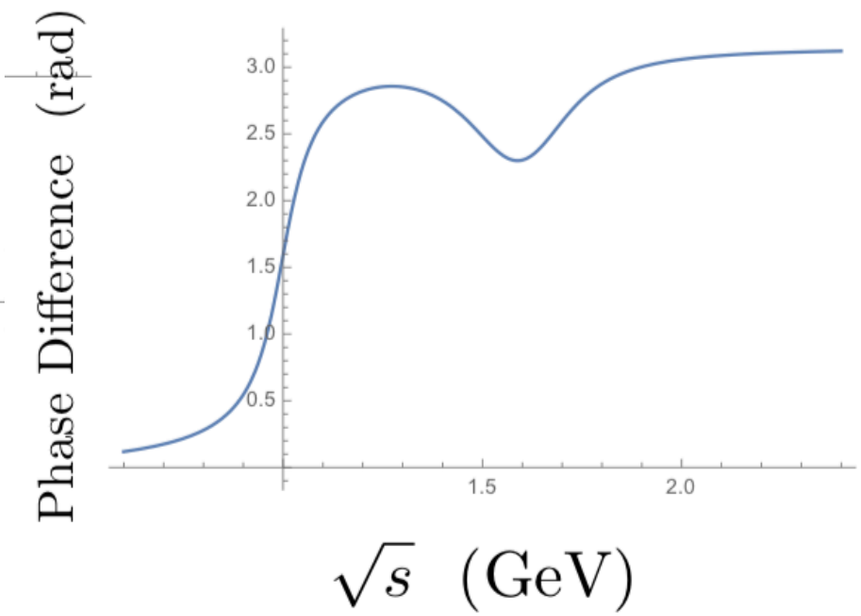
$M = 1.66$ GeV

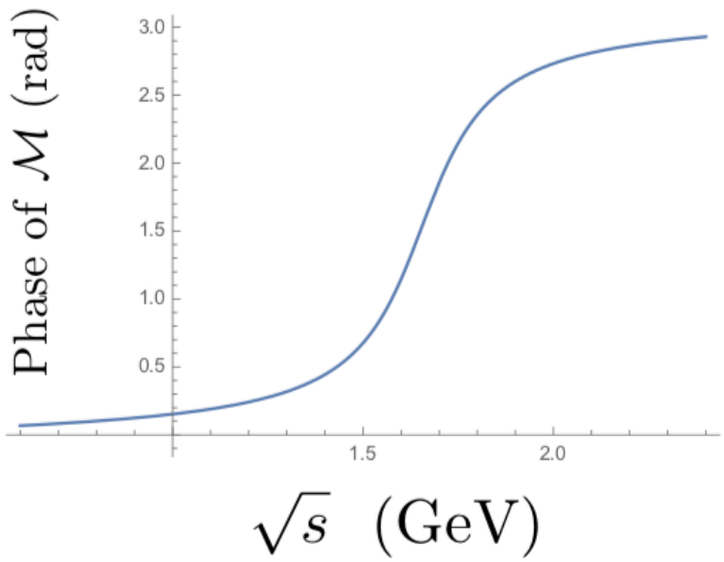
$\Gamma = 0.27$ GeV







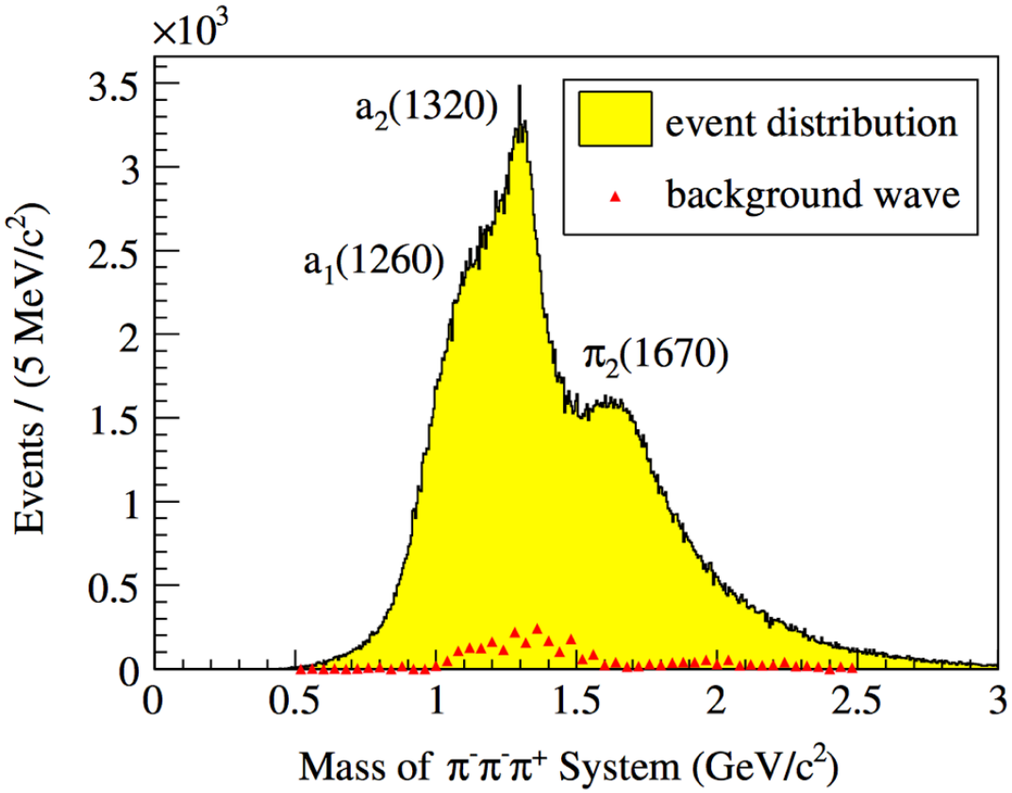


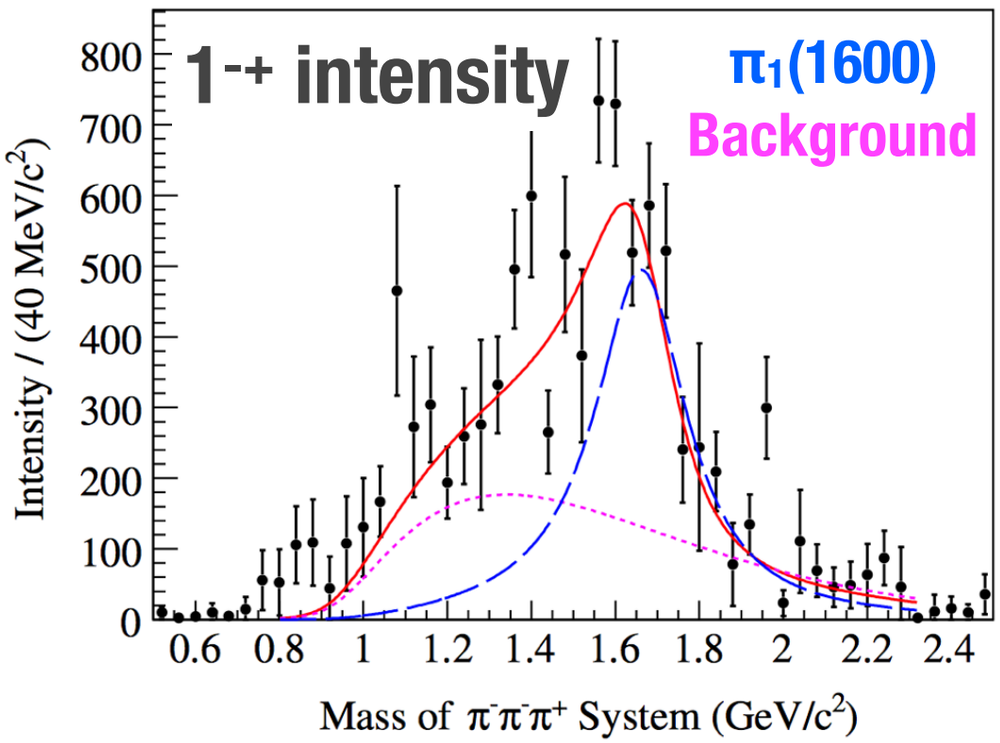


Matt Shepherd

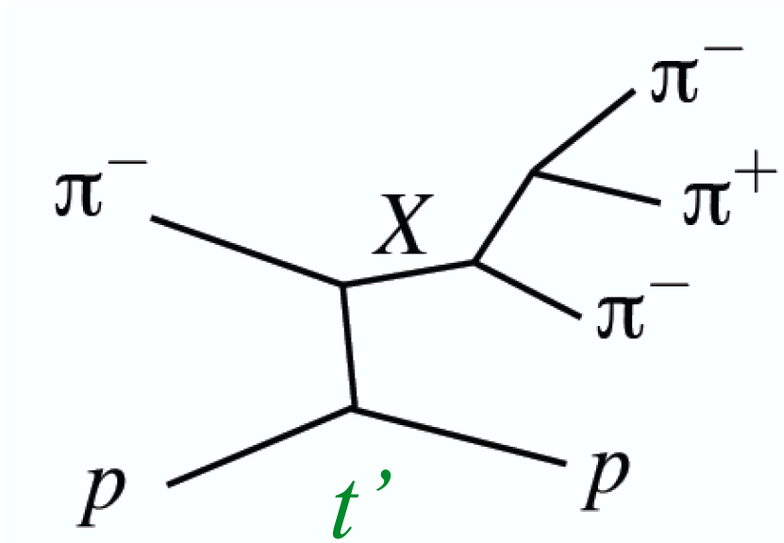
Early evidence for 1^{-+} exotics: $\pi_1(1600)$

COMPASS: $\pi^- p \to \pi^- \pi^+ \pi^- p$



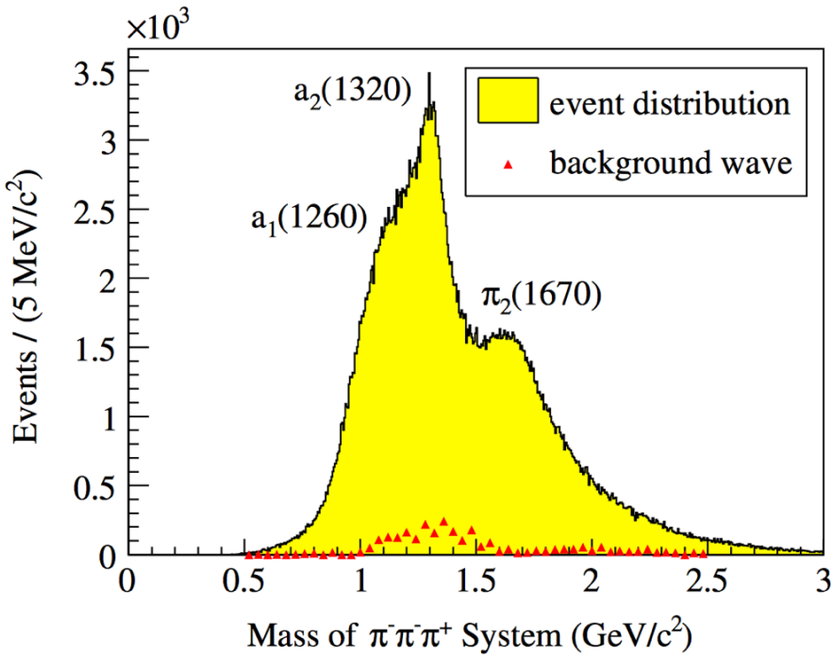


PRL 104, 241803 (2010)



Compass πp amplitude analysis

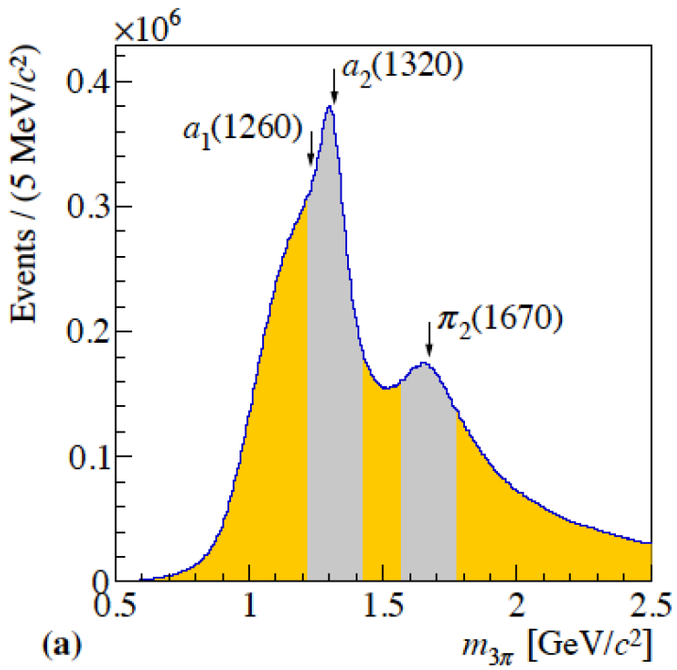
Compass: PRL 104, 241803 (2010)



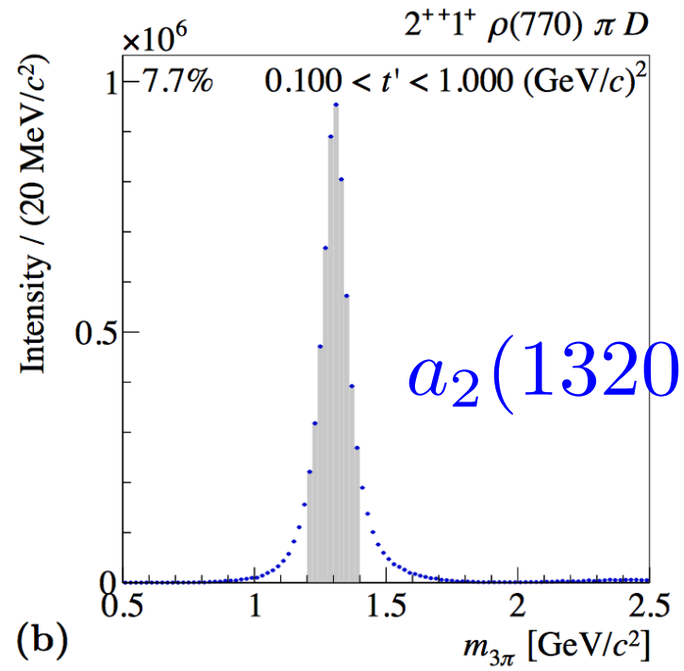
Unprecedented statistics:

~50M exclusive events

Compass: PRD 95, 032004 (2017)



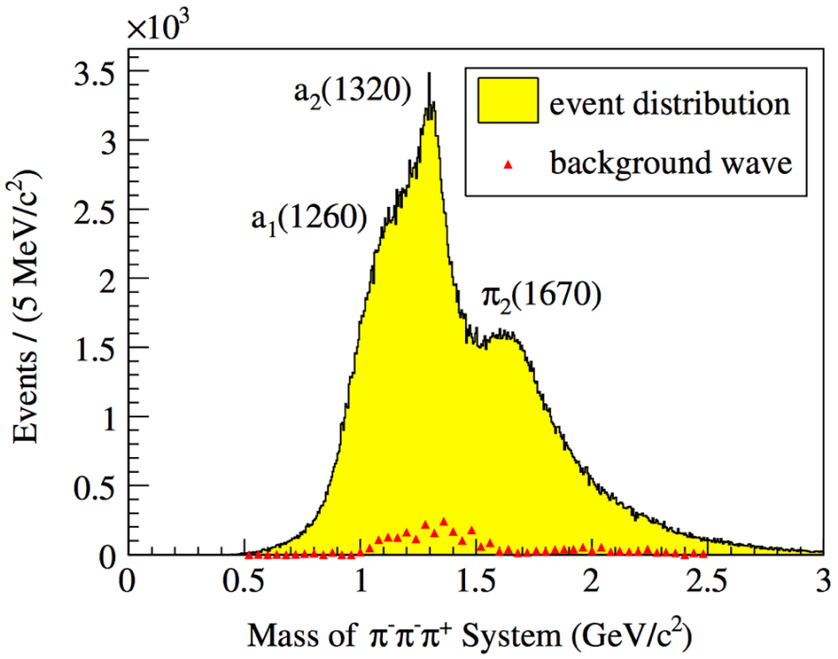
- Decompose into 88 amplitudes representing ***X***⁻, **Isobars**, ***L***, and ***M***
- Extract amplitude intensity and phase in bins of π⁻π⁺π⁻ mass



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

Compass πp amplitude analysis

Compass: PRL 104, 241803 (2010)



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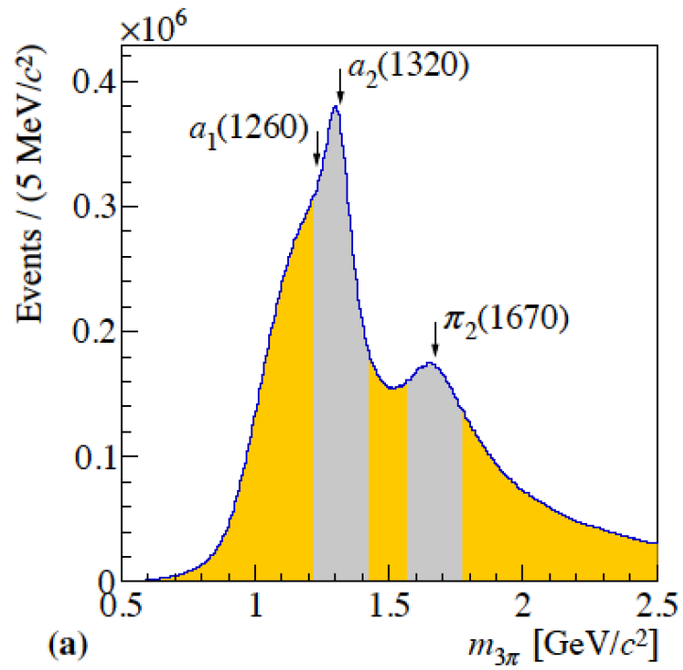

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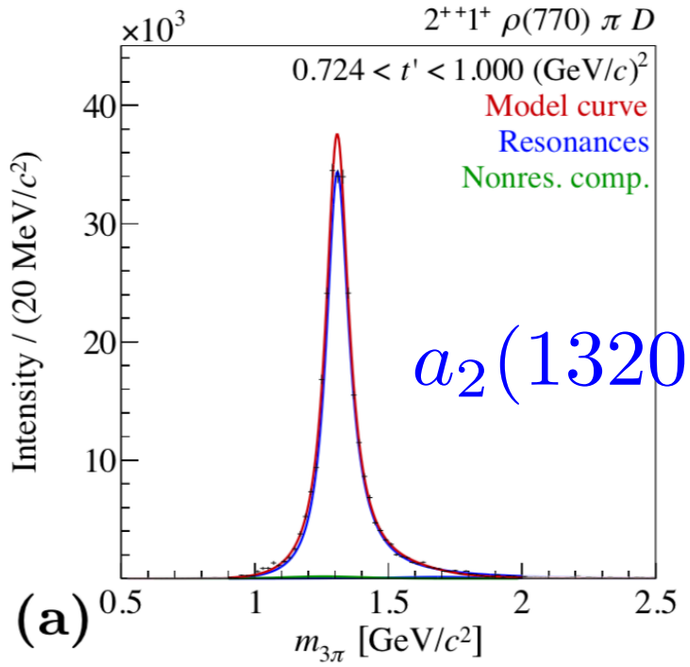

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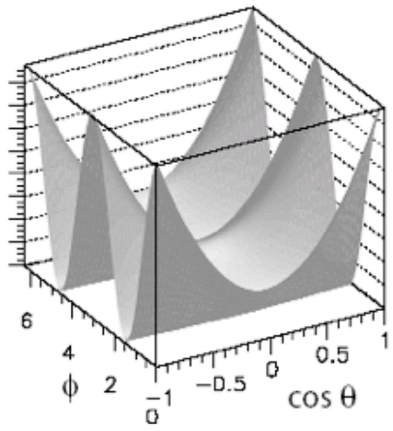
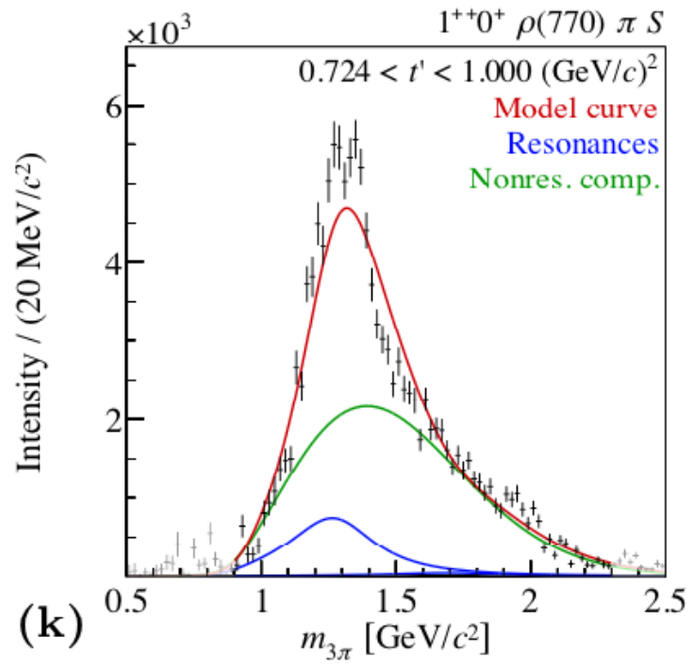
Compass πp: example amplitudes

$X(1^{++})$

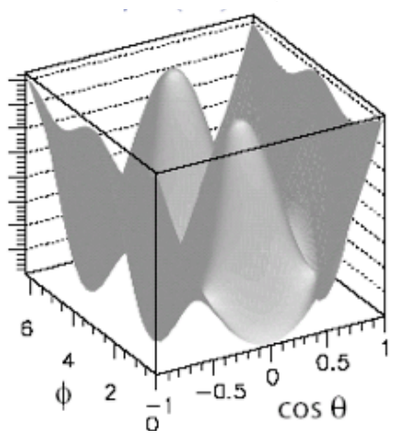
$\rightarrow \rho\pi^-$ (S wave)

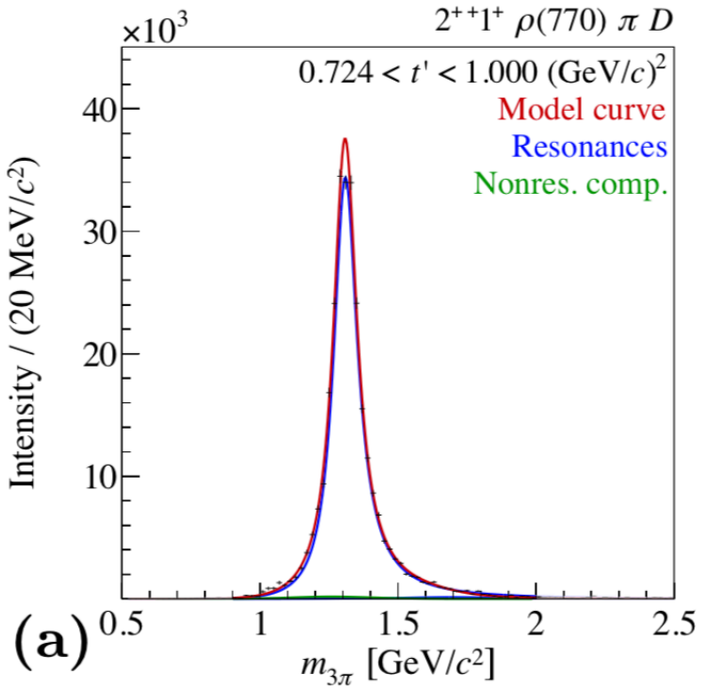




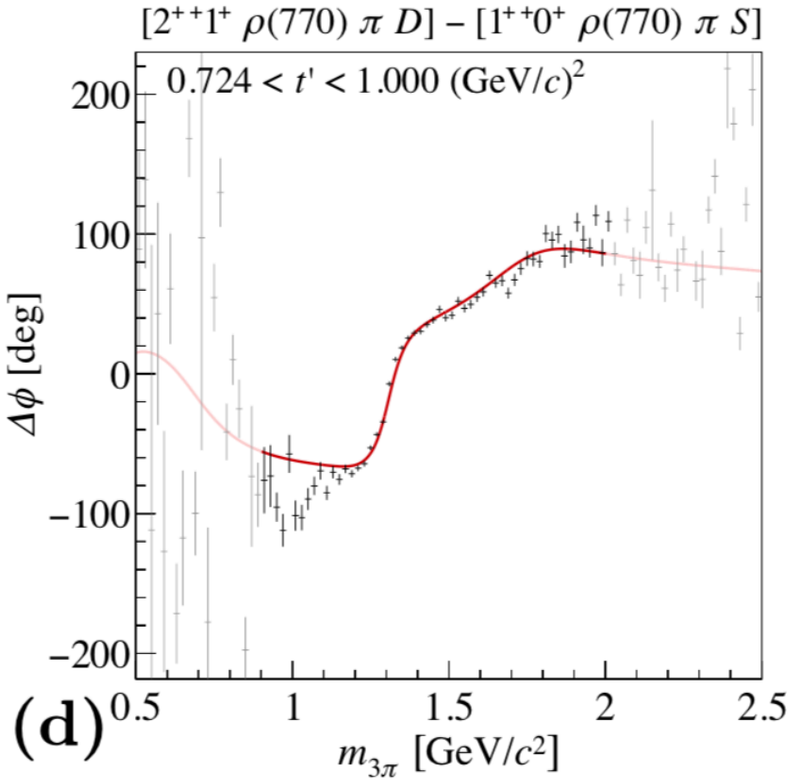
$X(2^{++})$

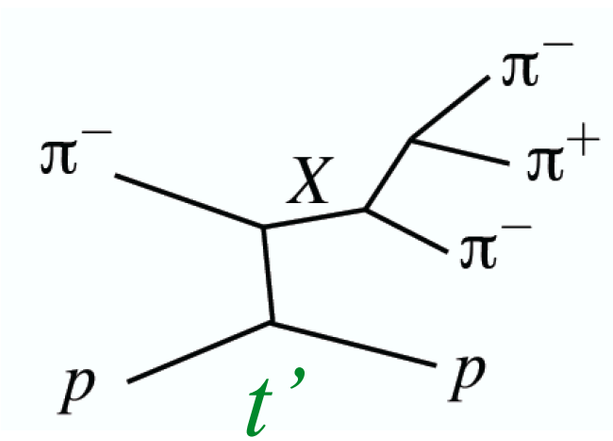
$\rightarrow \rho\pi^-$ (D wave)





Interference

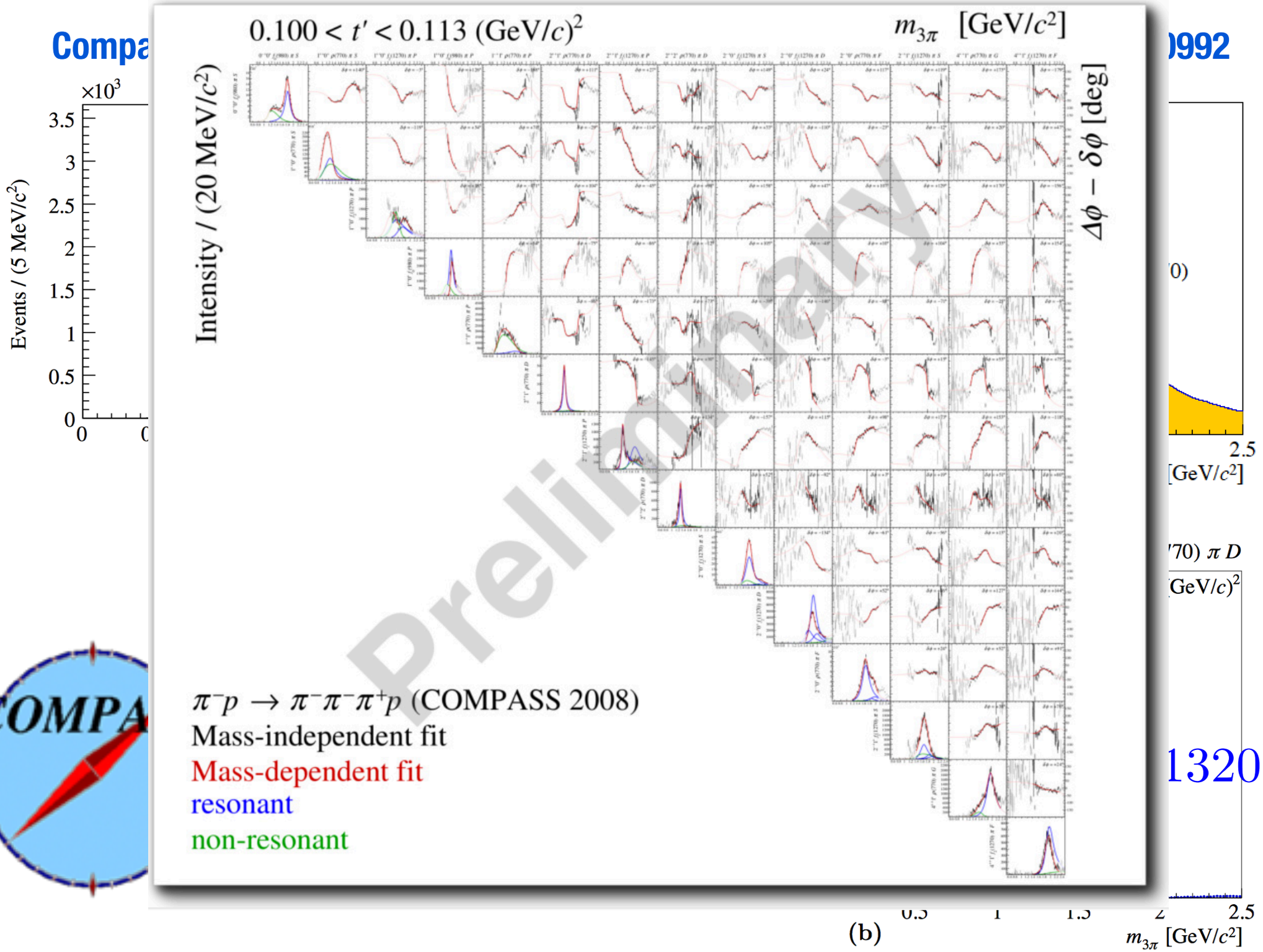




COMPASS

arXiv:1802.05913

Compass πp amplitude analysis



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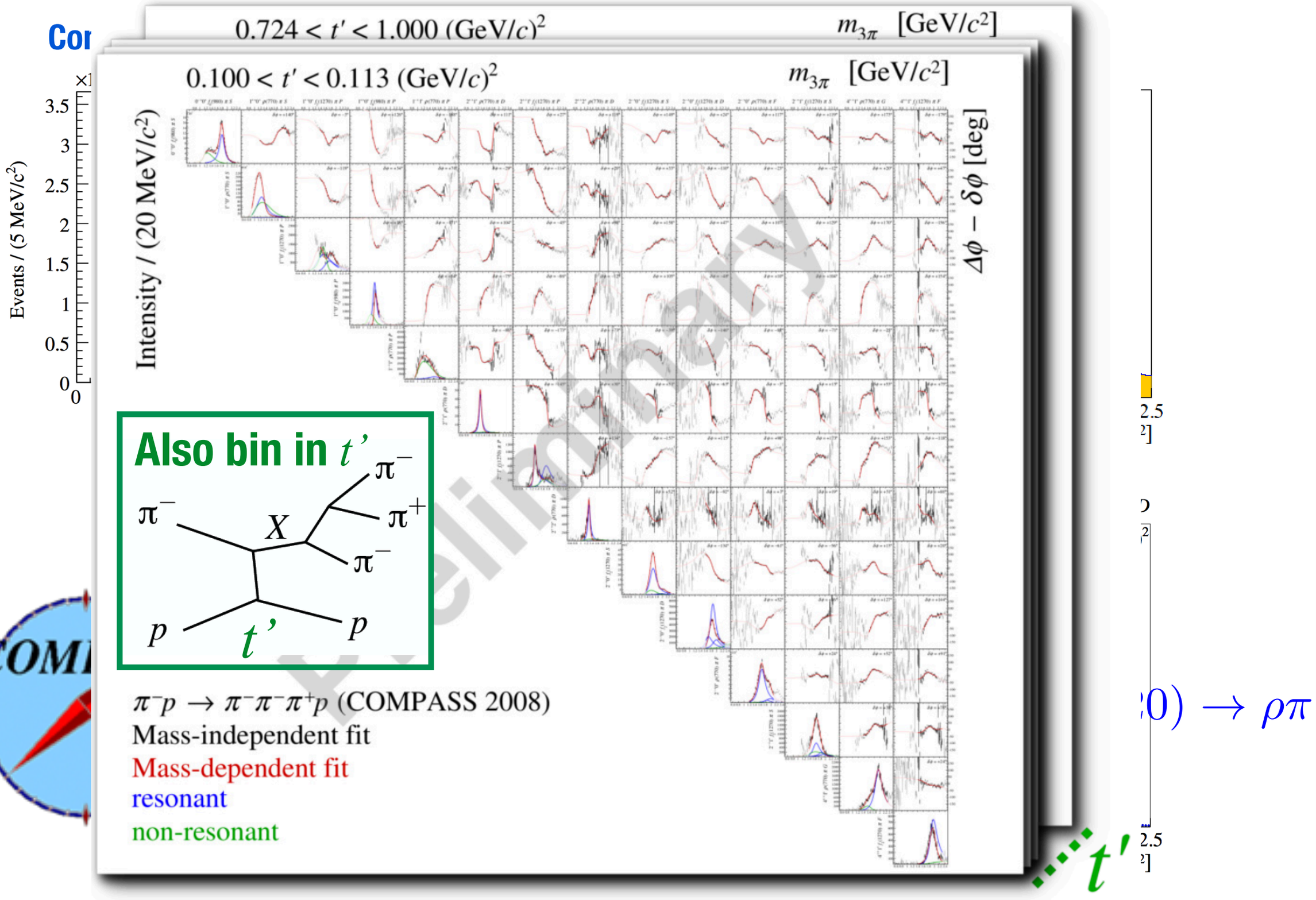
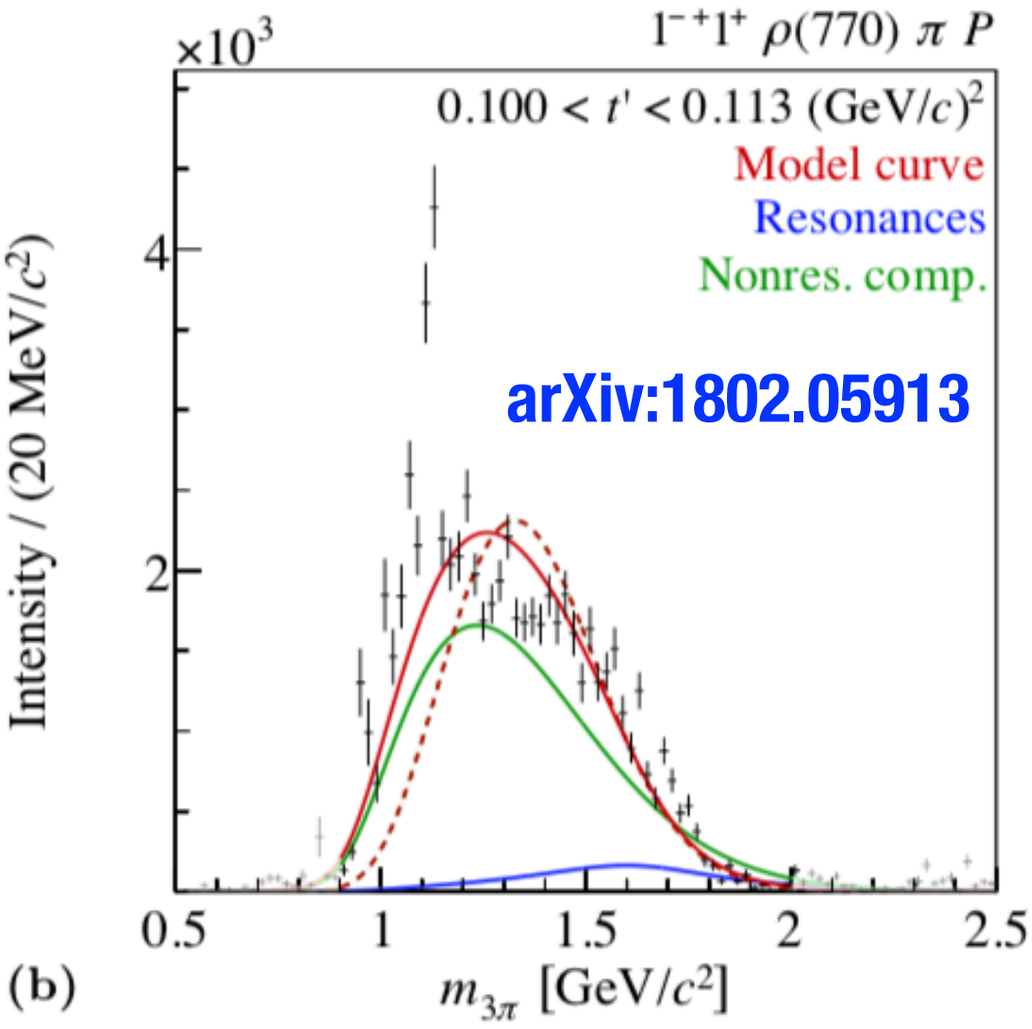
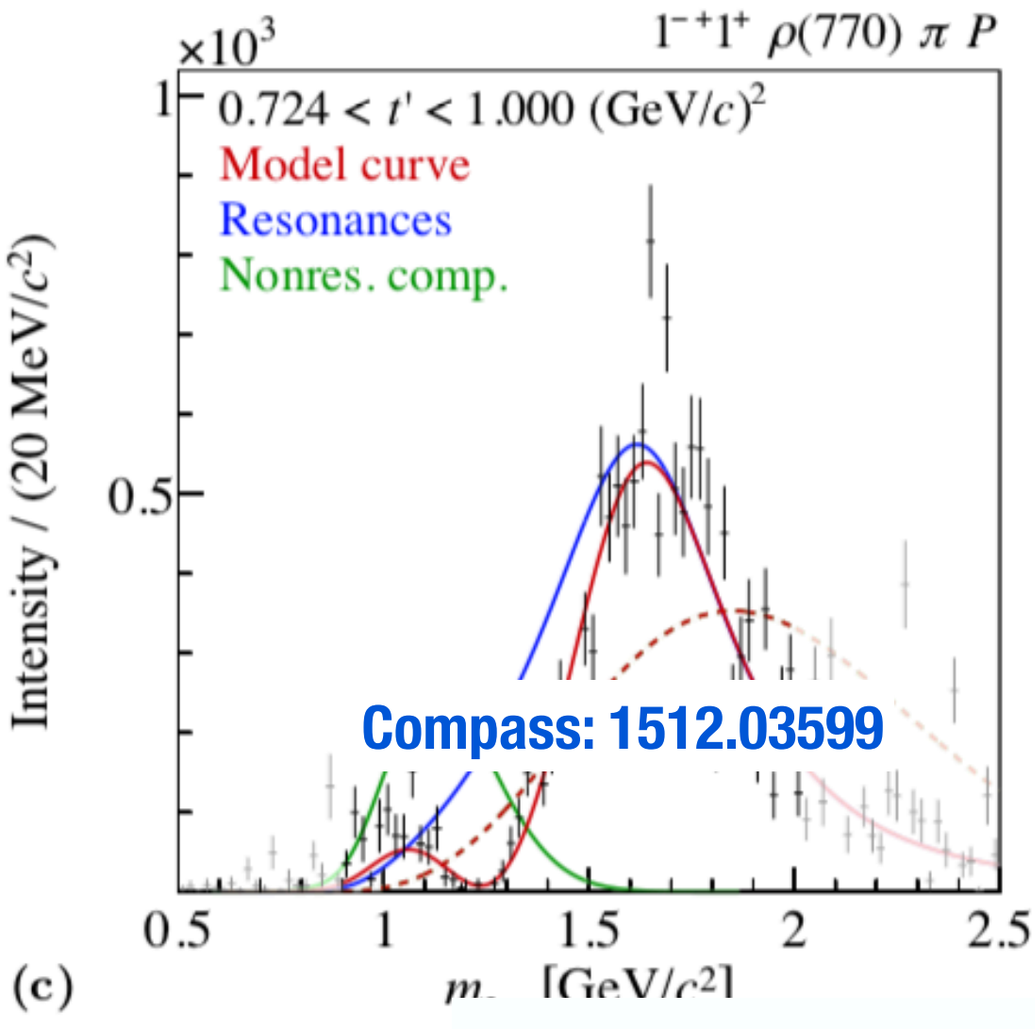


Evidence for 1^{-+} $\pi_1(1600)$ in $\rho\pi$

Low t'



High t'

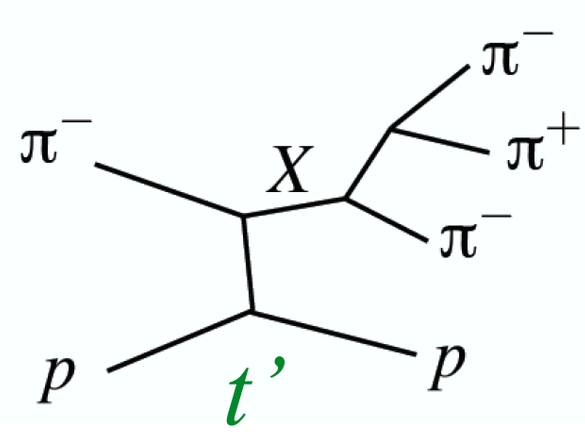


arXiv:1802.05913

Compass: 1512.03599

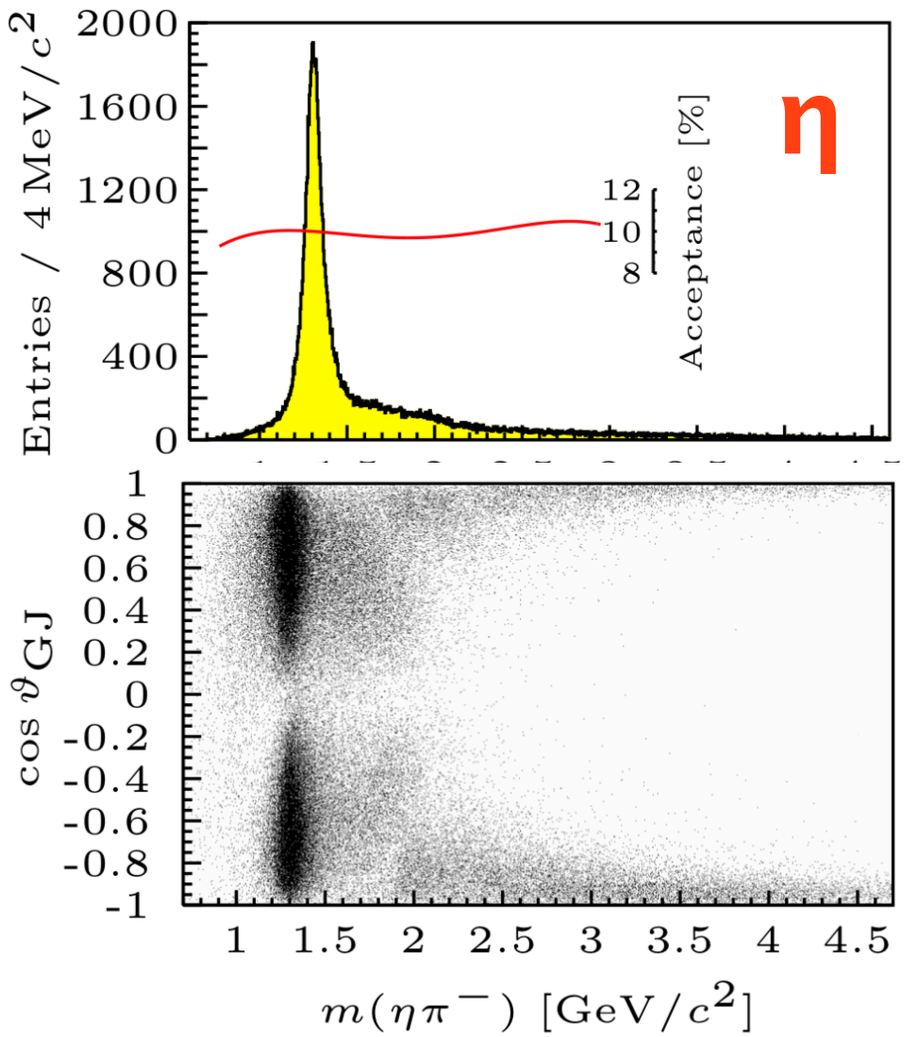
Need to work with theorists on better models for resonant and non-resonant:

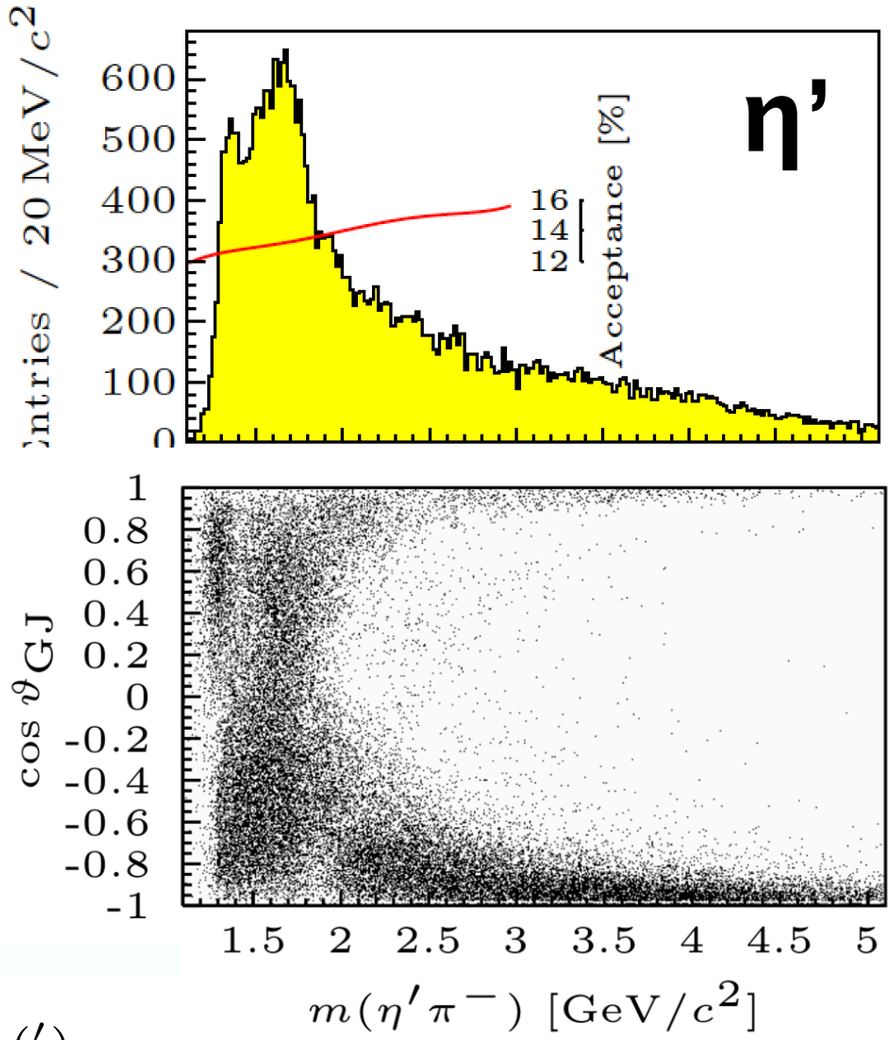
Joint Physics Analysis Center

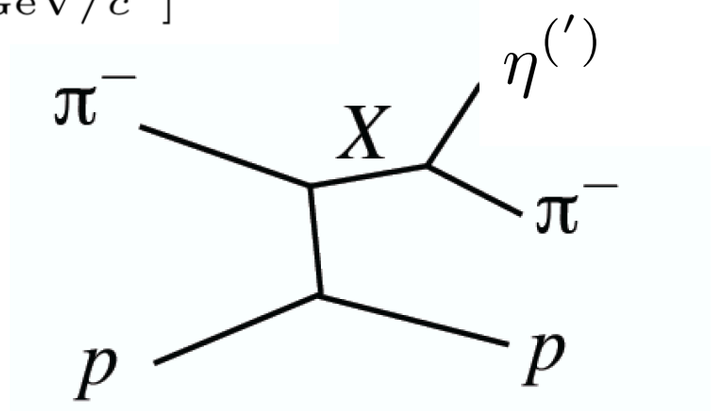


Evidence for 1^{-+} exotics: $\pi_1(1600)$

COMPASS: $\pi^- p \to \eta^{(\prime)} \pi^- p$







PLB 740 (2015) 303

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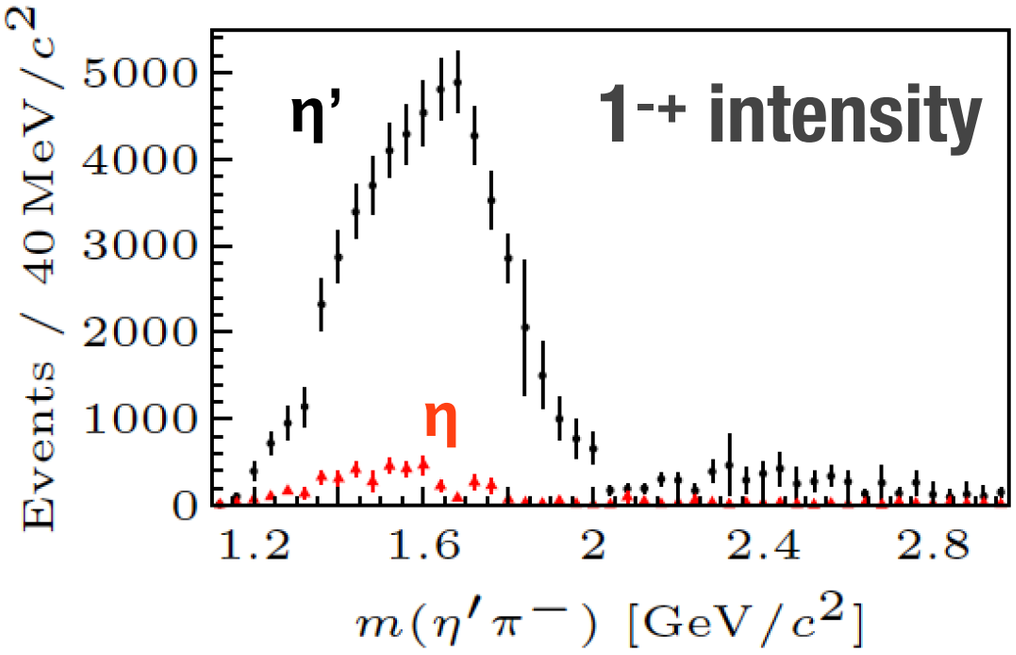
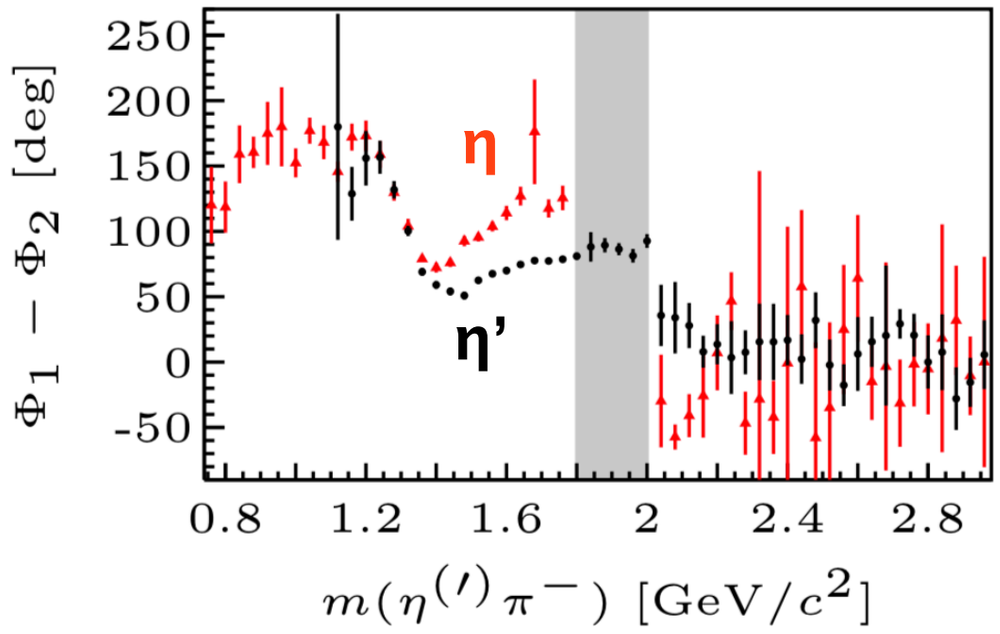
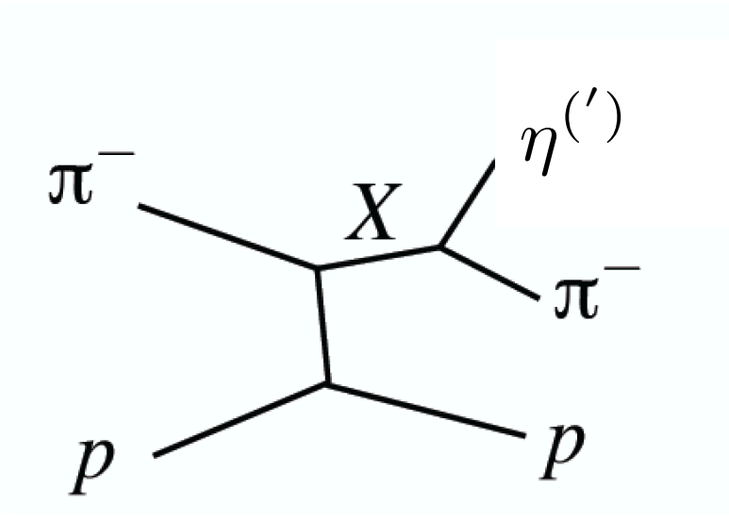




PLB 740 (2015) 303



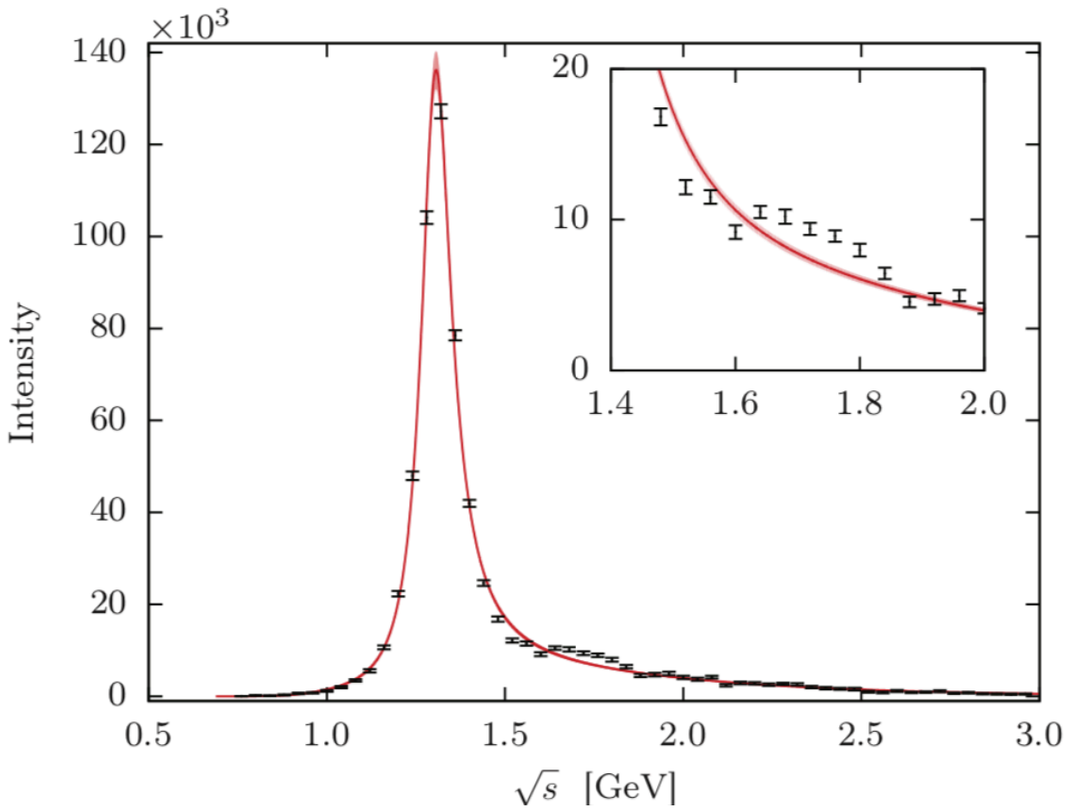
Need to work with theorists on better models to describe broad structures:

Joint Physics Analysis Center

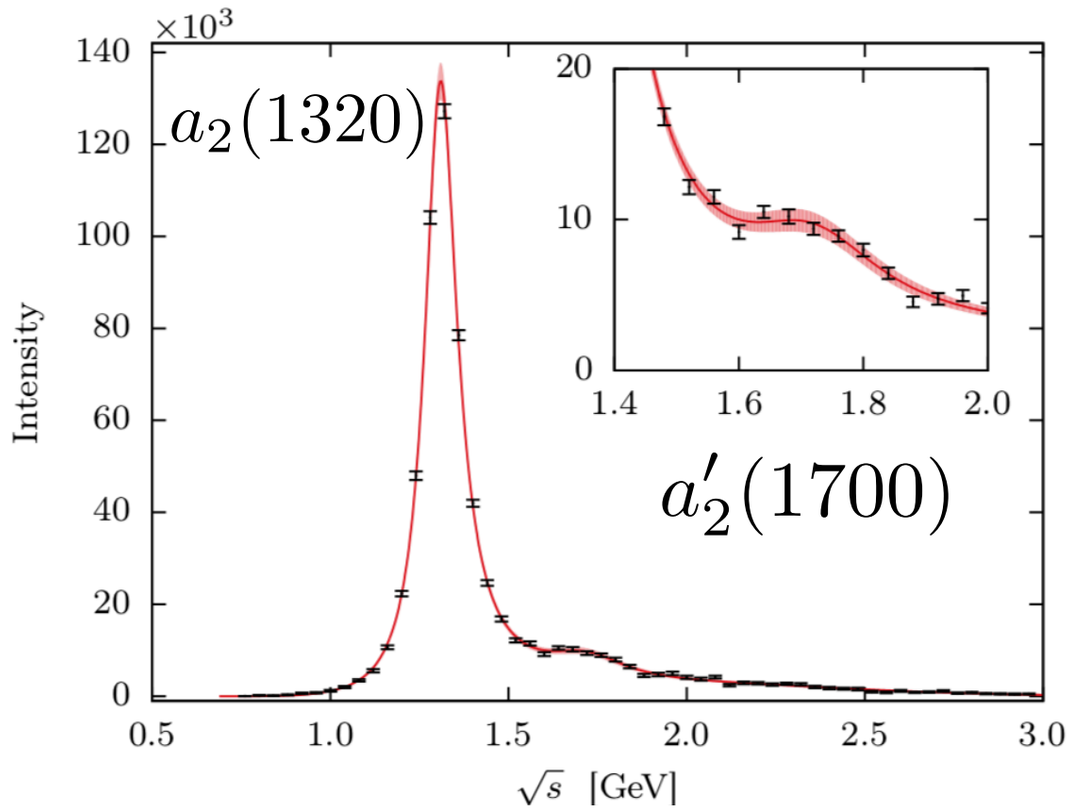
Tensor mesons with JPAC

$$\pi^- p \to \eta\pi^- p: \; 2^{++} \text{ Intensity}$$

PLB779 (2018) 464



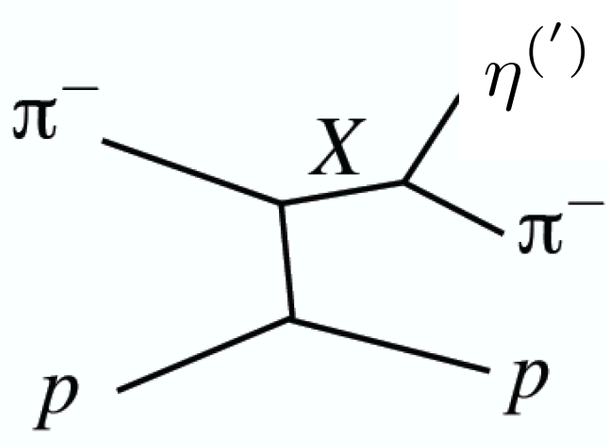
Fit with single a_2 resonances



Find additional a'$_2$ is required

Need to work with theorists on better models to describe broad structures:

Joint Physics Analysis Center JPAC



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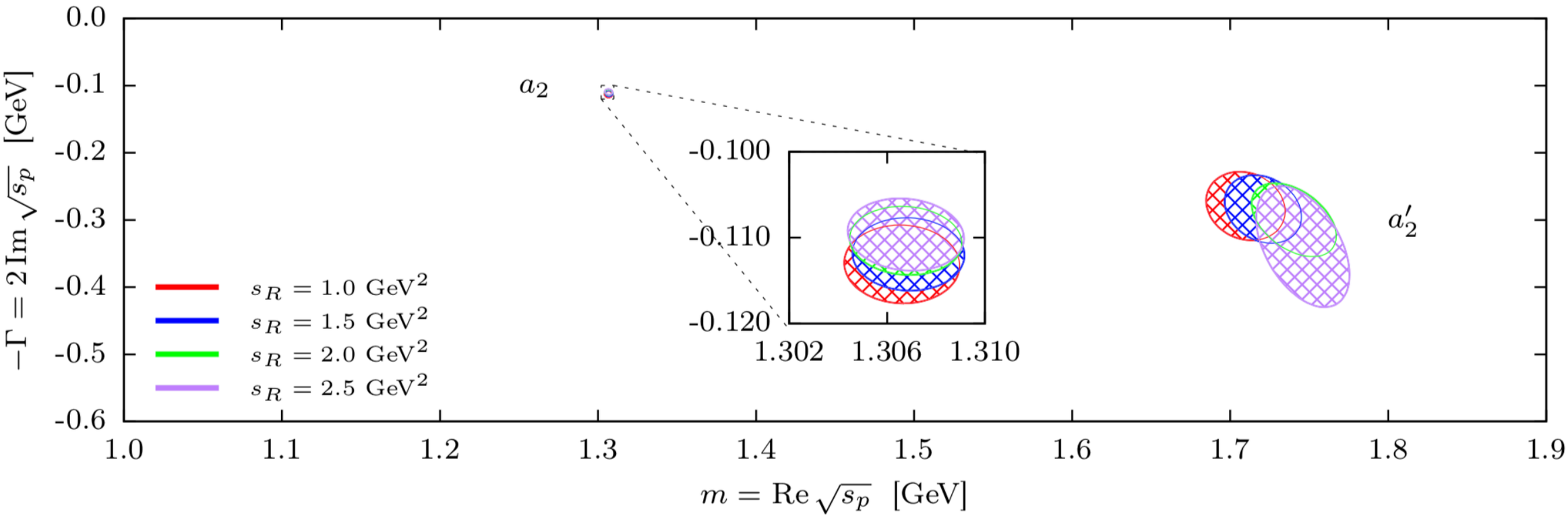
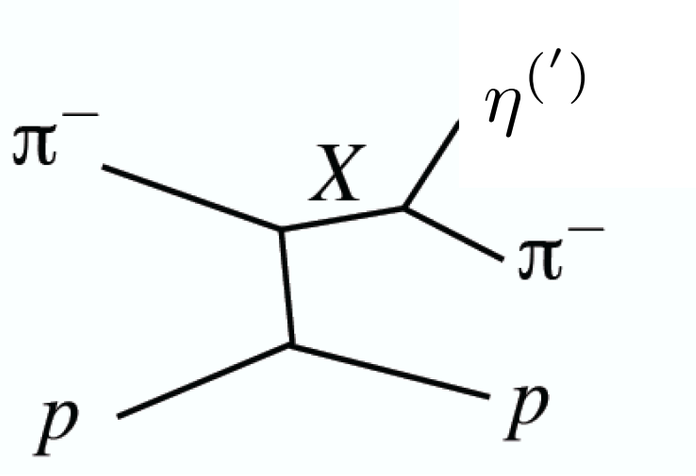
PLB779 (2018) 464



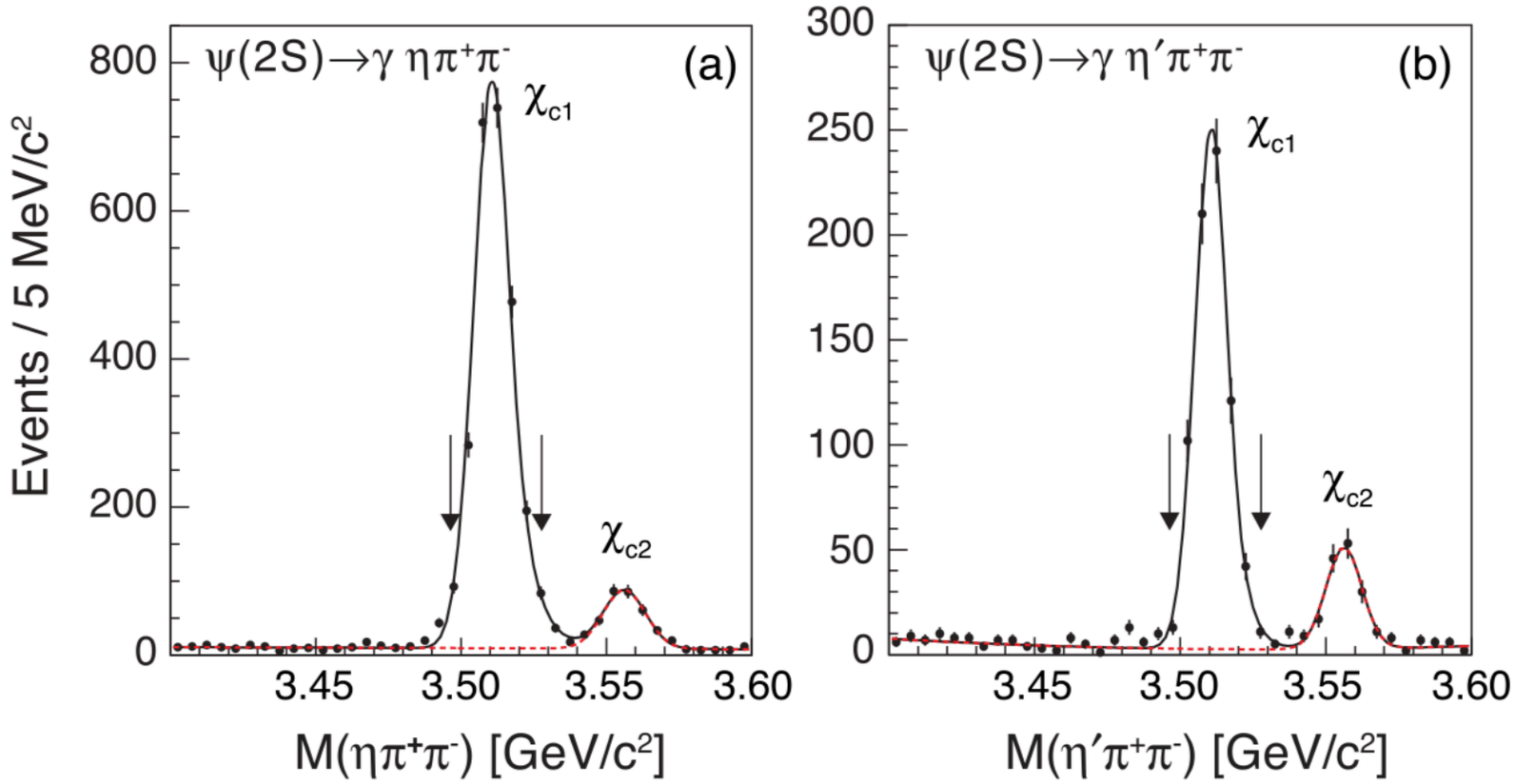


Need to work with theorists on better models to describe broad structures:

Joint Physics Analysis Center

Exotics from charmonium decays

$$\psi(2S) \to \gamma\chi_{c1}$$

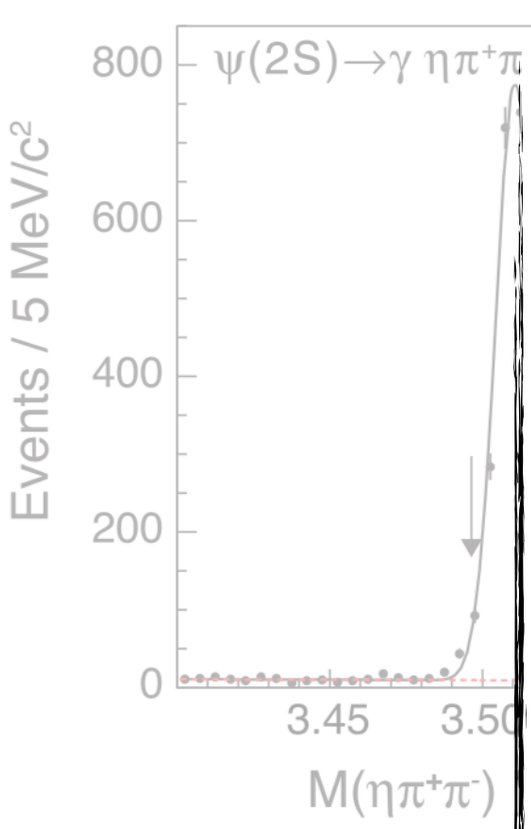


- Produce vector charmonium in e^+e^- CLEO, BESIII, etc.
- Study decay products through amplitude analysis

Phys. Rev. D 84, 112009

Exotics from charmonium decays

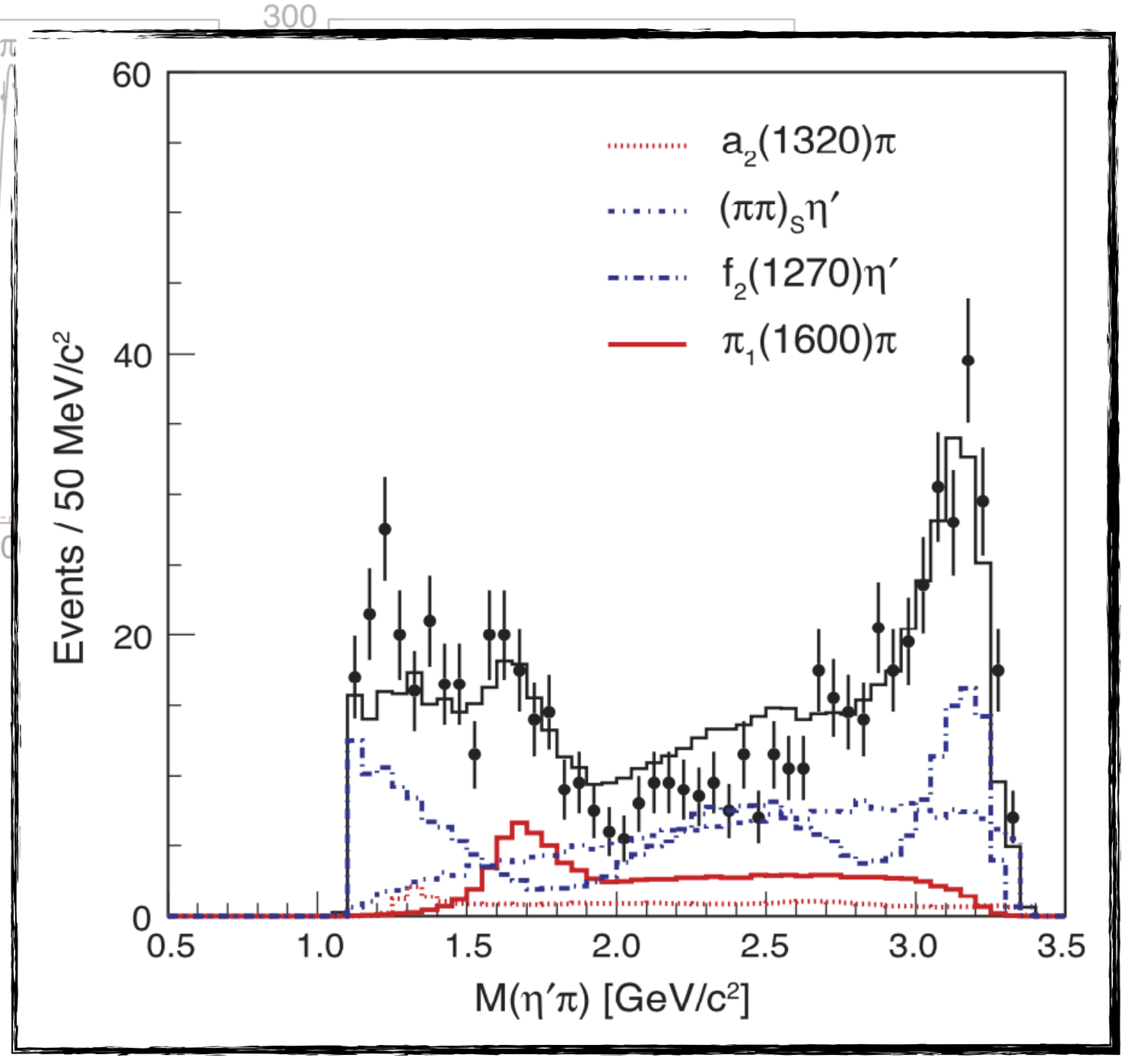
$$\psi(2S) \to \gamma\chi_{c1}$$



$$\chi_{c1} \to \eta'\pi\pi$$

$$\chi_{c1} \to X\pi$$

$$\chi_{c1} \to X\eta'$$

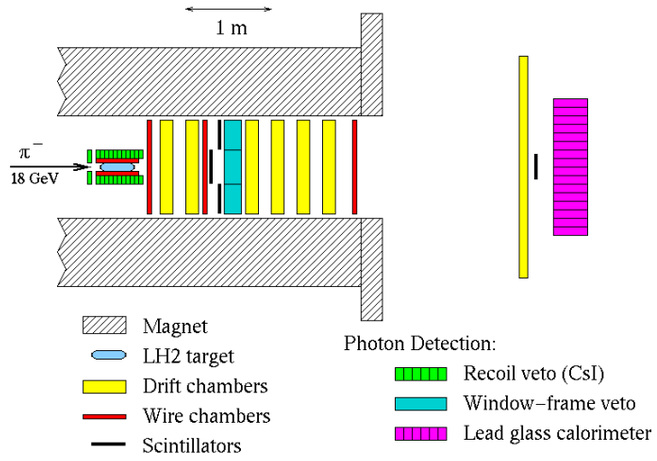


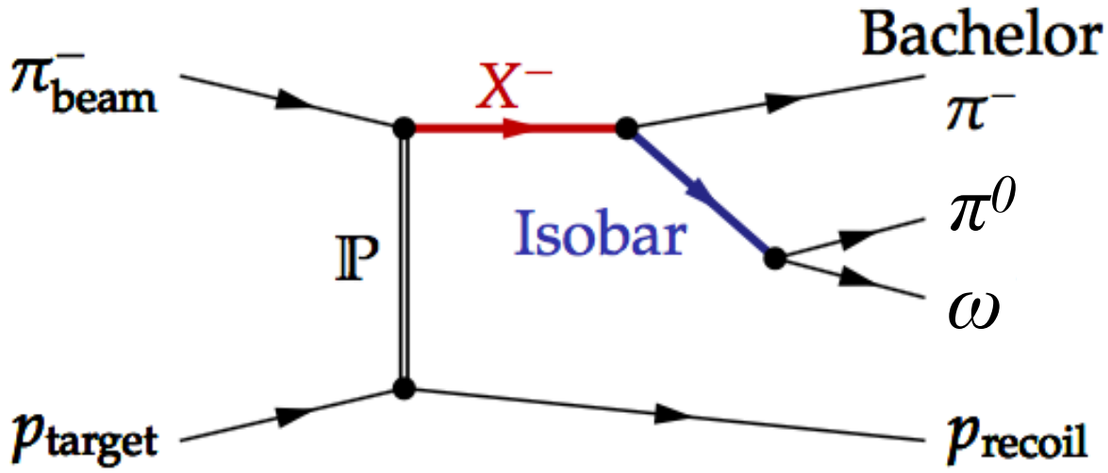
Phys. Rev. D 84, 112009

Exotics in other decay modes

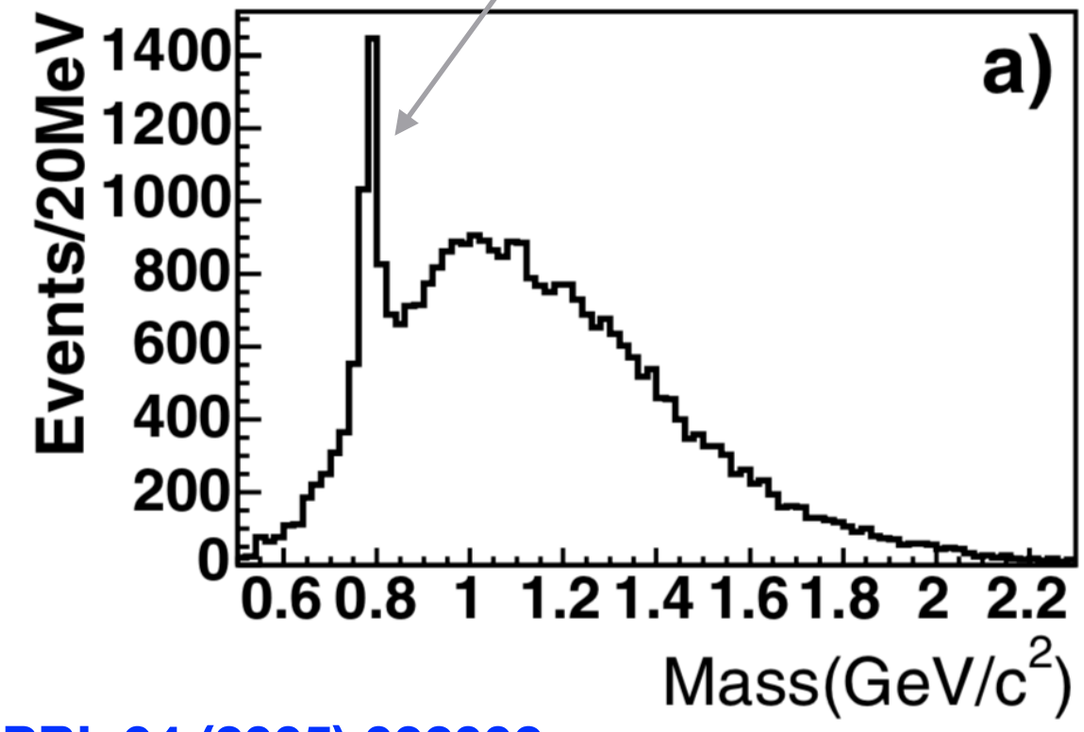
$$\pi^- p \to \omega \pi^0 \pi^- p$$

E852

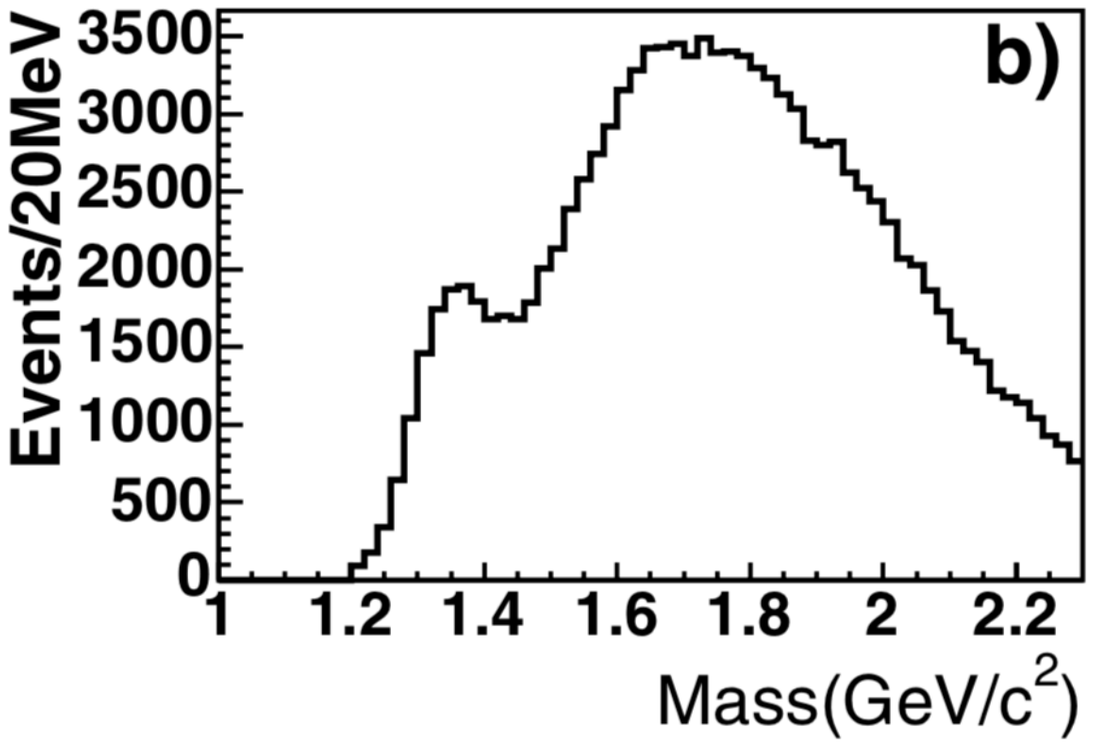




$$\omega \to \pi^+ \pi^- \pi^0$$



$$X \to \omega \pi^0 \pi^-$$



PRL 94 (2005) 032002

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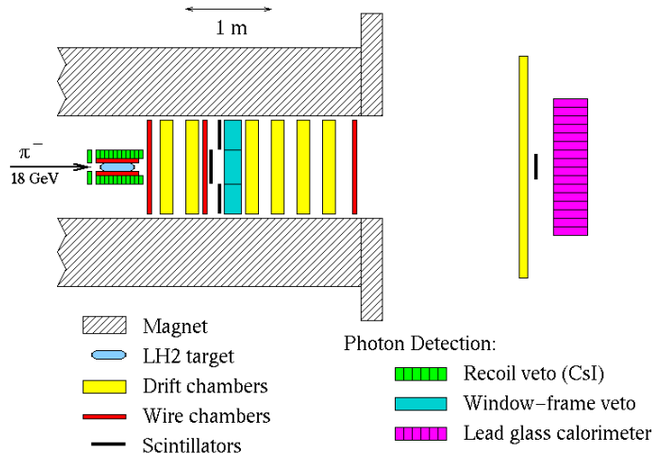
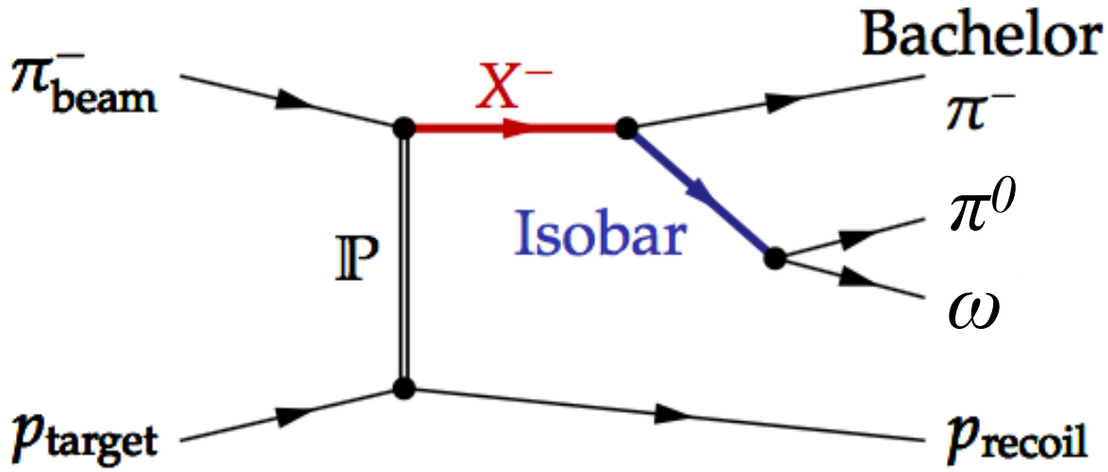
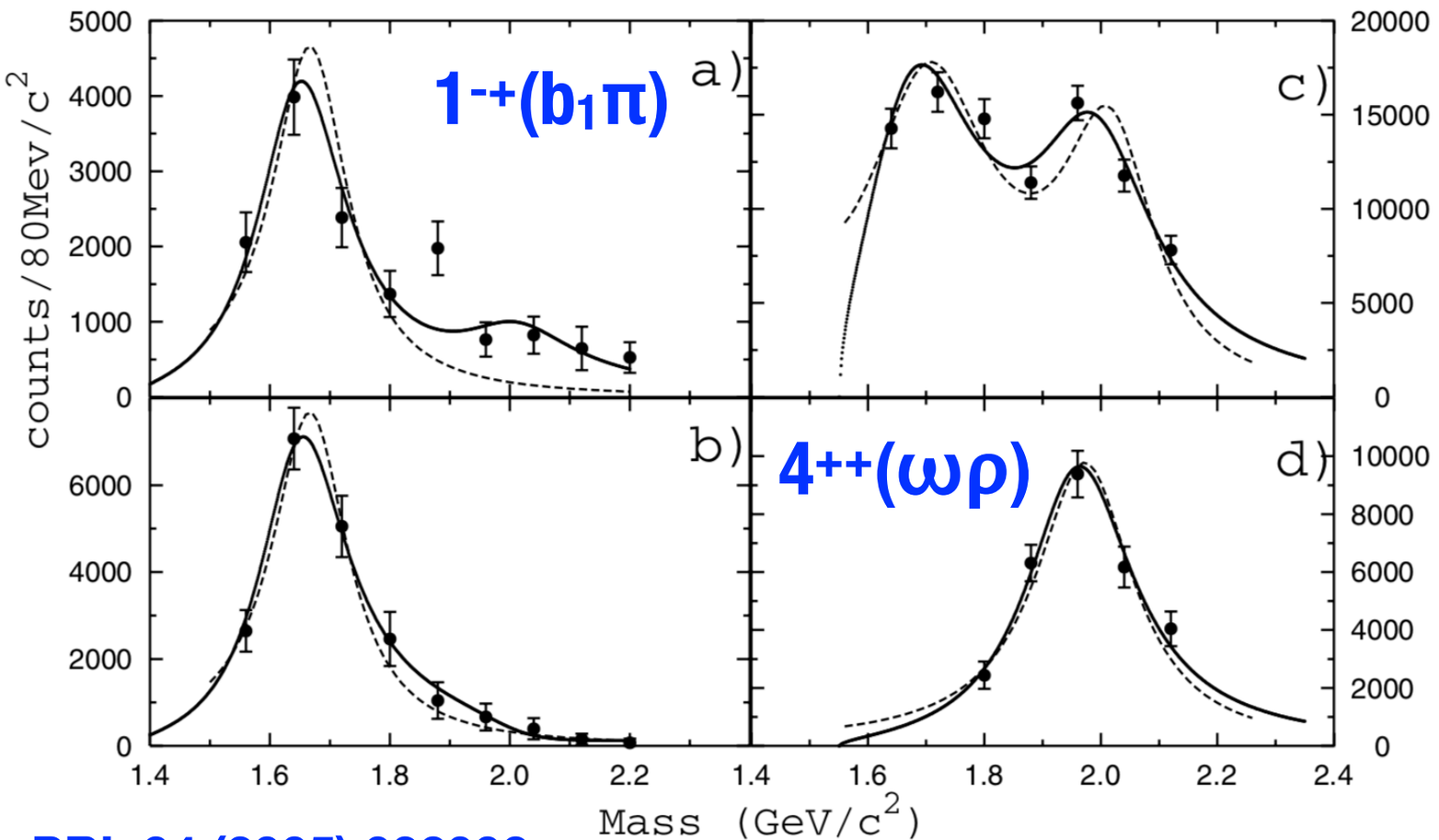
E852

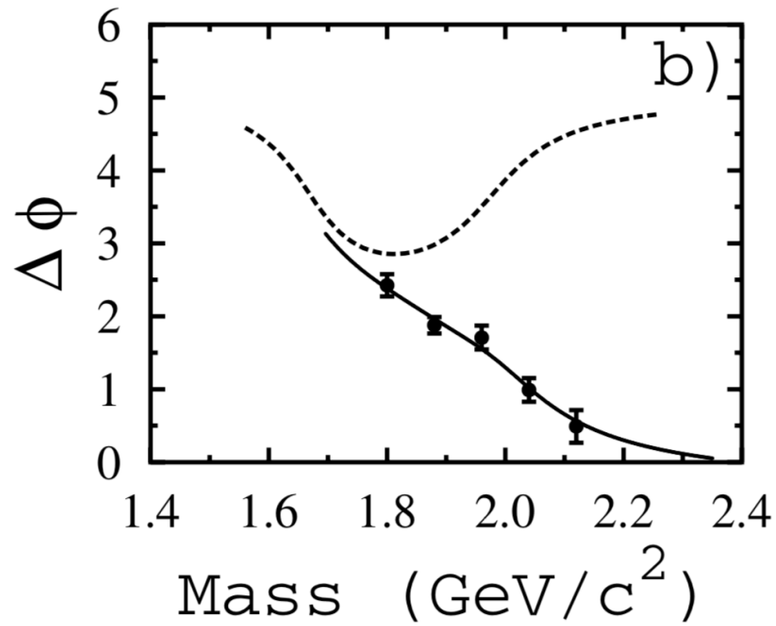






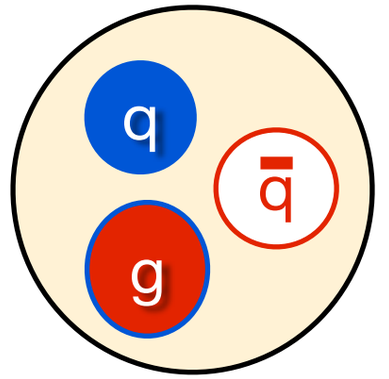
PRL 94 (2005) 032002

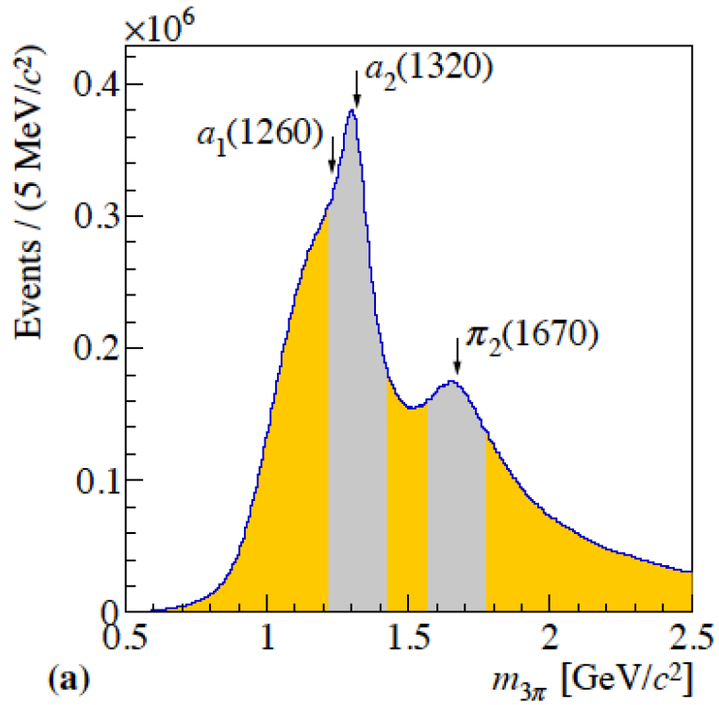
Phase motion: $1^{-+}(b_1\pi)$ - $4^{++}(\omega\rho)$

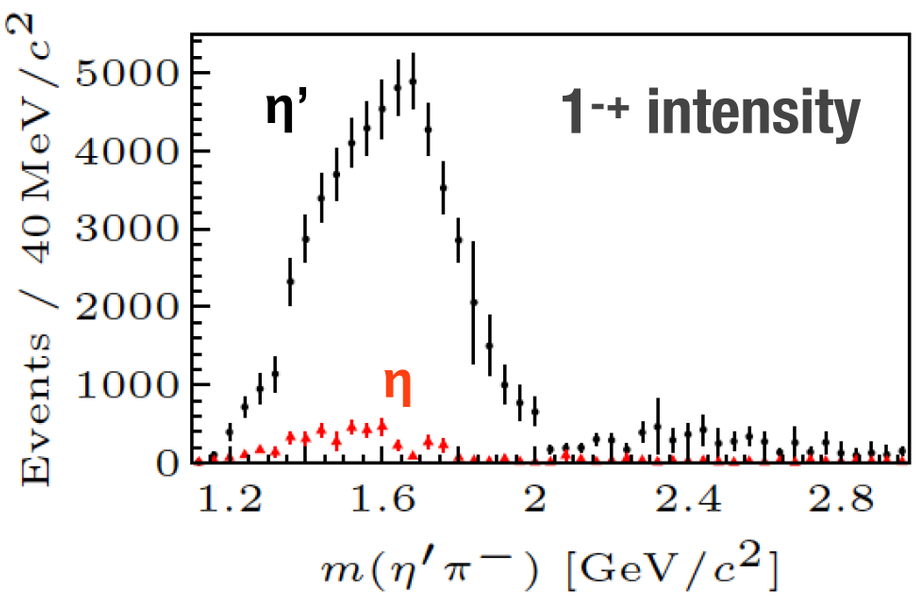


Summary

- Hybrid mesons provide unique access to gluonic degrees of freedom in bound states
- Lattice QCD predicts a rich spectrum of hybrid mesons, some with exotic J^{PC}
- Significant evidence for exotic $J^{PC} = 1^{-+}$ in the literature, but interpretation is murky
- The search for a coherent pattern of gluonic excitations continues…







Further Reading

- **Light isovector resonances in $\pi^- p \to \pi^- \pi^- \pi^+$**
  Compass Collaboration
  [arXiv:1802.05913]

- **Searching for the rules that govern hadron construction**
  Matt Shepherd, Jozef J. Dudek, and Ryan Mitchell
  Nature 534 (2016) 487

- **Hybrid mesons**
  Curtis A. Meyer and Eric S Swanson, Progress in Particle and Nuclear Physics 82, 21-58 (2015)

Backup

Exotic J^{PC} decays

C. A. Meyer and E. S. Swanson,
Progress in Particle and Nuclear Physics B82, 21, (2015)

	Approximate Mass (MeV)	J^{PC}	Total Width MeV PSS	IKP	Allowed Decay Modes
π_1	1900	1^{-+}	81 – 168	117	$b_1\pi$, $\pi\rho$, πf_1, $\pi\eta$, $\pi\eta'$, ηa_1, $\pi\eta(1295)$
η_1	2100	1^{-+}	59 – 158	107	πa_1, πa_2, ηf_1, ηf_2, $\pi\pi(1300)$, $\eta\eta'$, KK_1^A, KK_1^B
η_1'	2300	1^{-+}	95 – 216	172	KK_1^B, KK_1^A, KK^*, $\eta\eta'$
b_0	2400	0^{+-}	247 – 429	665	$\pi\pi(1300)$, πh_1, ρf_1, ηb_1
h_0	2400	0^{+-}	59 – 262	94	πb_1, ηh_1, $KK(1460)$
h_0'	2500	0^{+-}	259 – 490	426	$KK(1460)$, KK_1^A, ηh_1
b_2	2500	2^{+-}	5 – 11	248	πa_1, πa_2, πh_1, $\eta\rho$, ηb_1, ρf_1
h_2	2500	2^{+-}	4 – 12	166	$\pi\rho$, πb_1, $\eta\omega$, ωb_1
h_2'	2600	2^{+-}	5 – 18	79	KK_1^B, KK_1^A, KK_2^*, ηh_1

- Predictions for the spectrum of hybrids from lattice, **but decay predictions are model dependent**

1^{-+} channels observed

$$\pi\rho \to \pi\pi\pi$$
$$\pi\eta' \to \eta\pi\pi\pi$$
$$\pi b_1 \to \omega\pi\pi$$

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$$\pi\eta' \to \eta\pi\pi\pi$$
$$\pi b_1 \to \omega\pi\pi$$

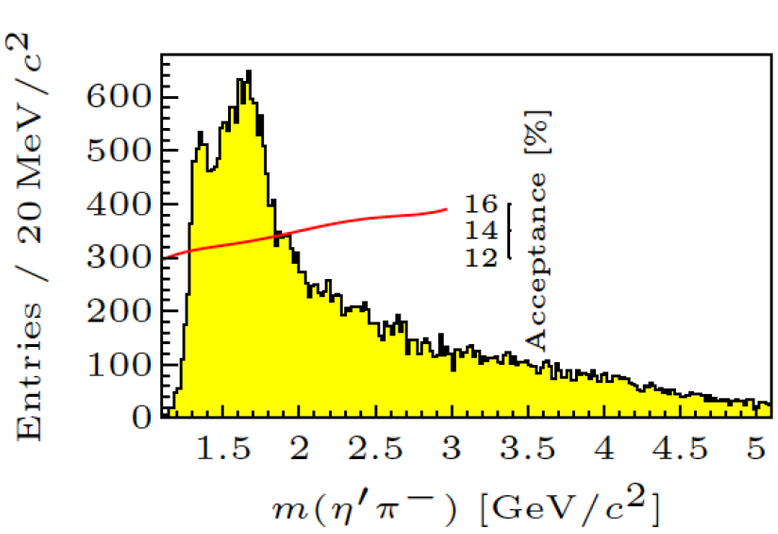
Some additional 1^{-+} channels

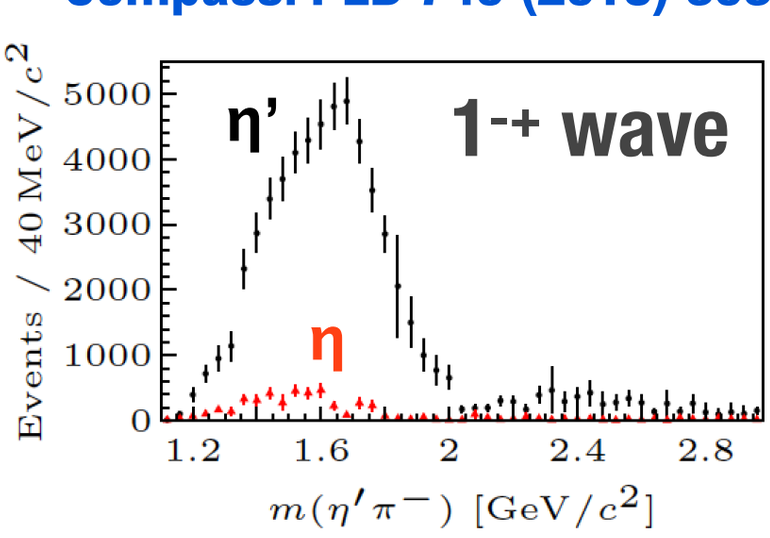
$$\pi a_2 \to \eta\pi\pi \qquad \eta f_1 \to \eta\eta\pi\pi$$
$$KK^* \to KK\pi$$
$$KK_1(1270) \to KK\pi\pi$$

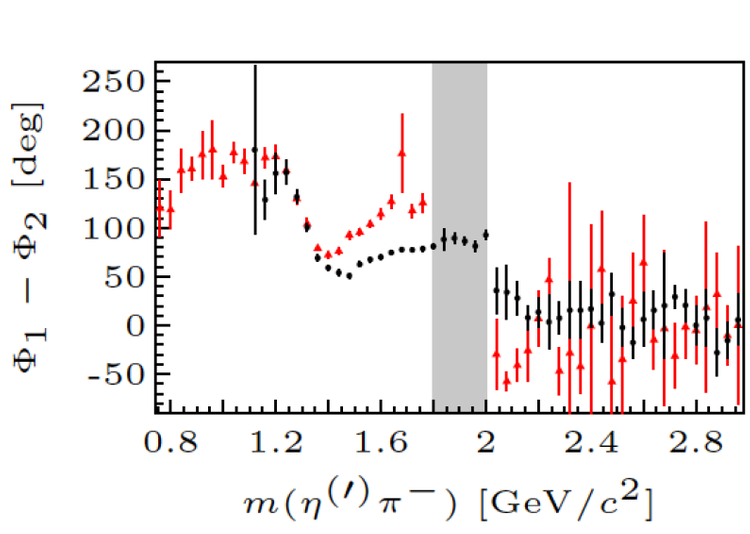
Evidence for 1^{-+} exotics

- **$\pi_1(1400) \rightarrow \eta\pi$**
  - Not likely a hybrid: dynamical origin or 4-quark state?
- **$\pi_1(1600) \rightarrow \pi\pi\pi$, $\eta'\pi$, $b_1\pi$, etc.**

Compass: PLB 740 (2015) 303







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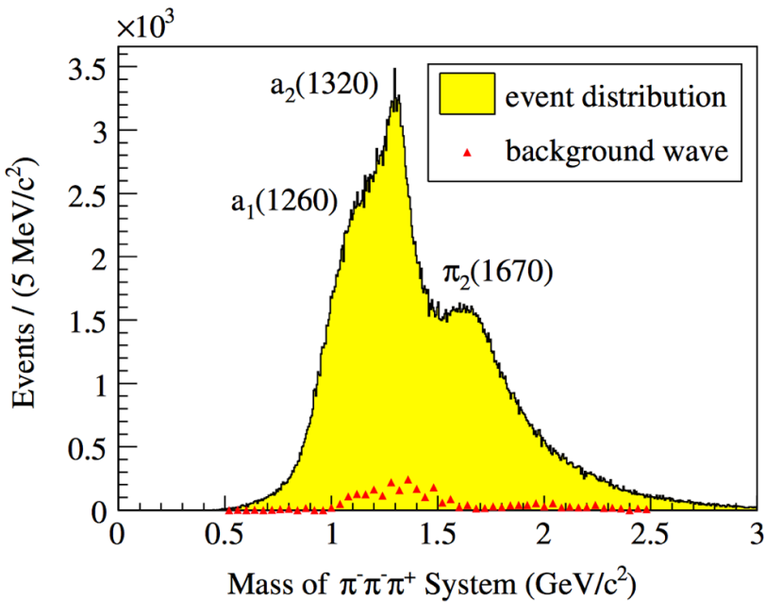
- **$\pi_1(1600) \rightarrow \pi\pi\pi$, $\eta'\pi$, $b_1\pi$, etc.**

Compass: PRL 104, 241803 (2010)

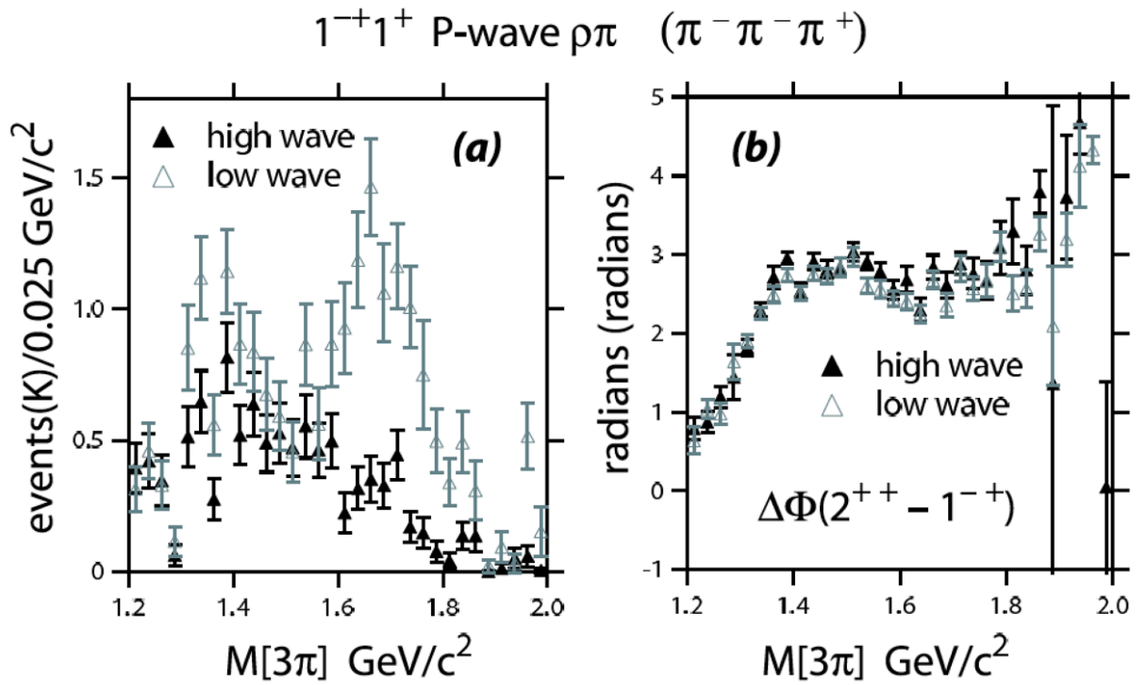


Evidence for 1^{-+} exotics

- **$\pi_1(1400) \rightarrow \eta\pi$**
  - Not likely a hybrid: dynamical origin or 4-quark state?
- **$\pi_1(1600) \rightarrow \pi\pi\pi$, $\eta'\pi$, $b_1\pi$, etc.**

E852: PRD 73 (2006) 072001

Found no exotic when using a larger set of partial waves (ie. “high wave”) than previous analysis



- **Not** observed in $\gamma p \rightarrow n\,\pi^+\pi^-\pi^+$ at CLAS: charged vs neutral exchange?