Experimental spectroscopy

Precision and Exotics

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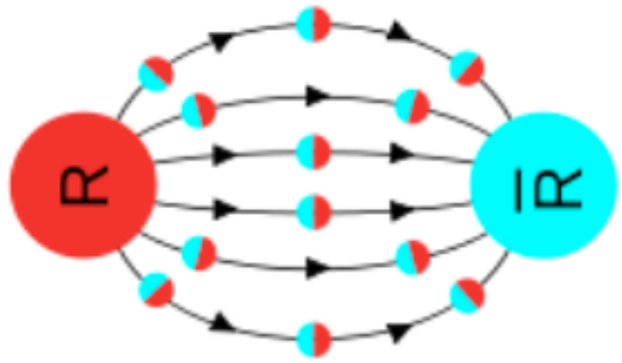
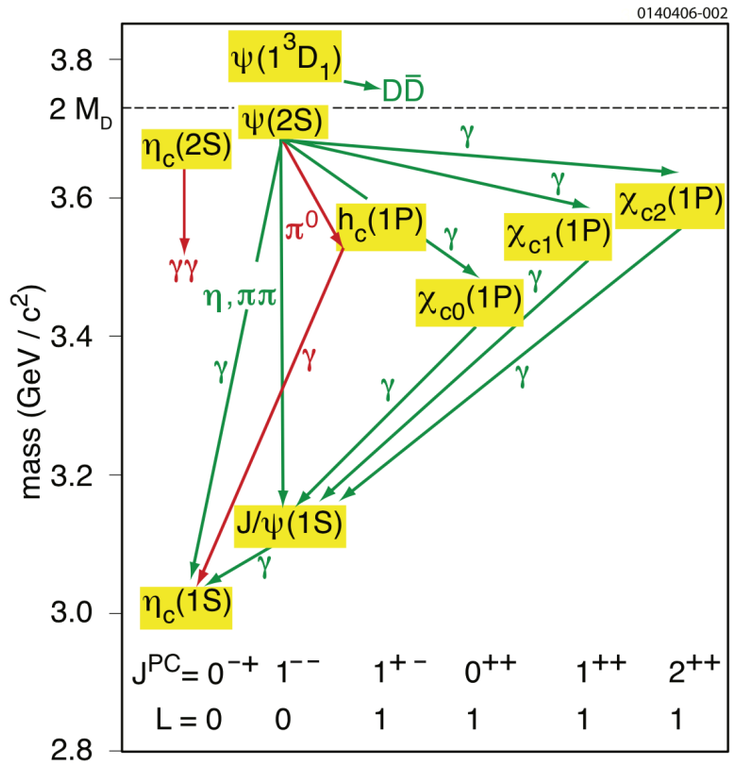
Newport News, VA
June 20, 2018

Introduction

- Quantum Chromodynamics (**QCD**)
  - Degrees of freedom: quarks and gluons
  - Rich spectrum of bound states predicted
  - Outstanding questions remain
    e.g., What is the nature of confinement?



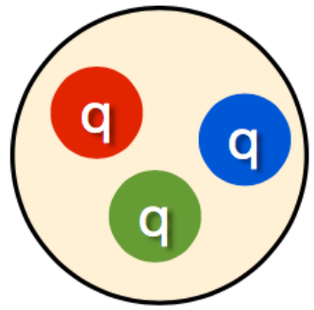
- New understanding gained by studying spectrum of bound QCD states
  - Recent progress in understanding hadron spectrum driven by large, high-quality data sets
  - New theoretical tools key for accurately interpreting this data



QCD and Hadron Spectroscopy

- Idea: study QCD through spectrum of bound states
  - Static properties of known hadrons well described by first-principals calculations
  - Modern experiments provide unprecedented data sets to push boundaries of our knowledge
- Open questions:
  - What is the origin of confinement?
  - Which color-singlet states exist in nature?

mesons



baryons

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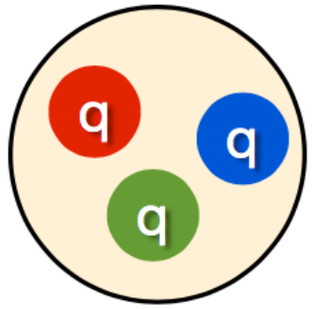
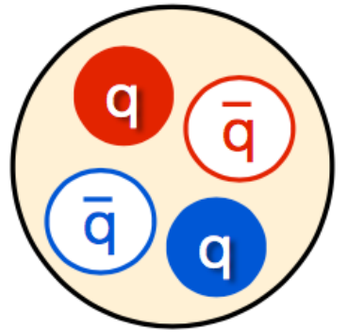
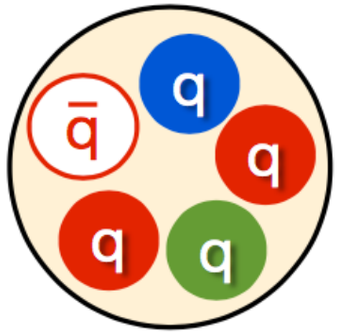


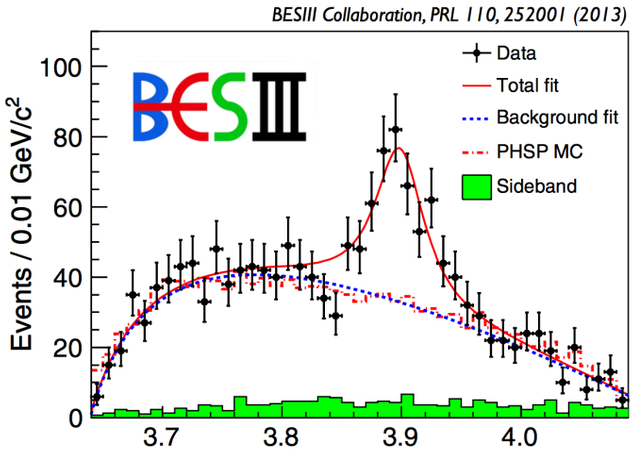
baryons



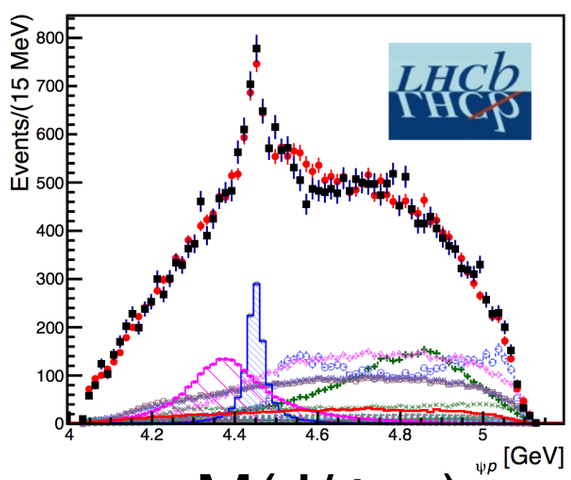
tetraquark



pentaquark



M(J/ψ π±)



M(J/ψ p)

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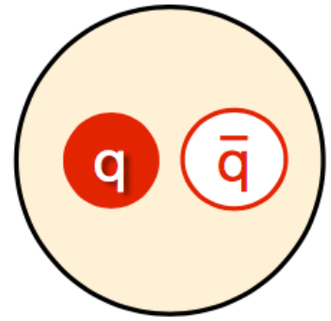
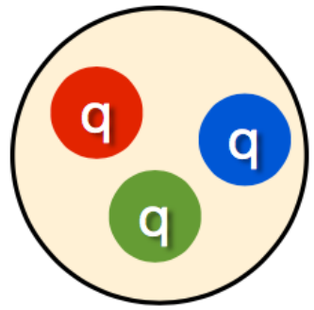
  - **Do gluonic degrees of freedom manifest themselves in the bound states that we observe?**



mesons



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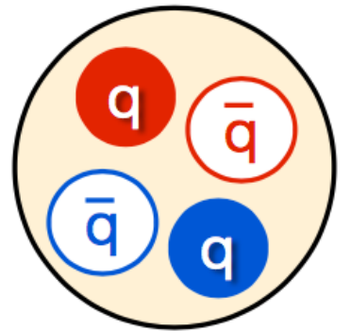

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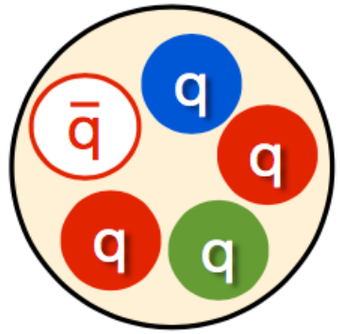

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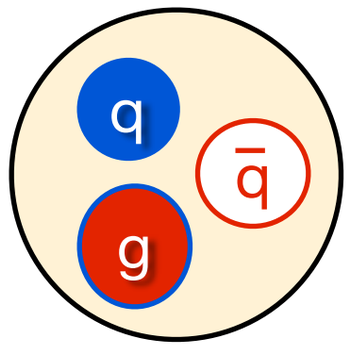
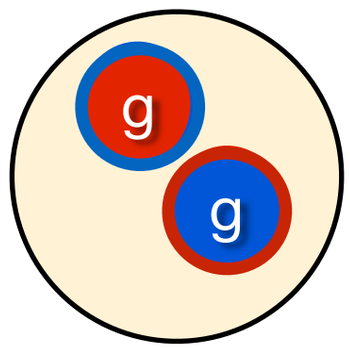


hybrid meson

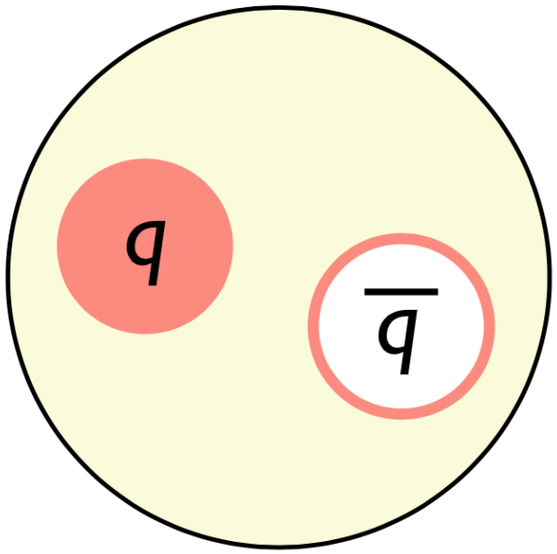


glueball

Meson Quantum Numbers

Mesons are arranged in groups of 9 (“nonets”) with same J^{PC}

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



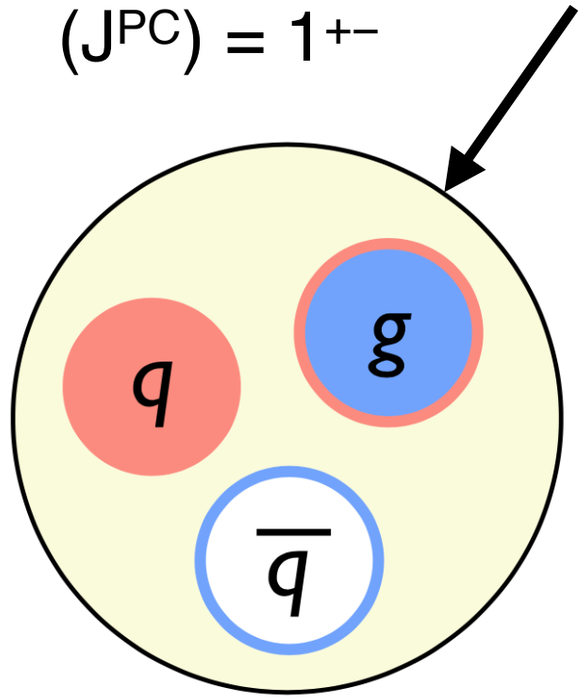
“Normal” Meson

Allowed J^{PC} : **0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{-+},…**

Forbidden J^{PC}: **0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, …**

gluonic field excitation → “constituent gluon”

$(J^{PC}) = 1^{+-}$

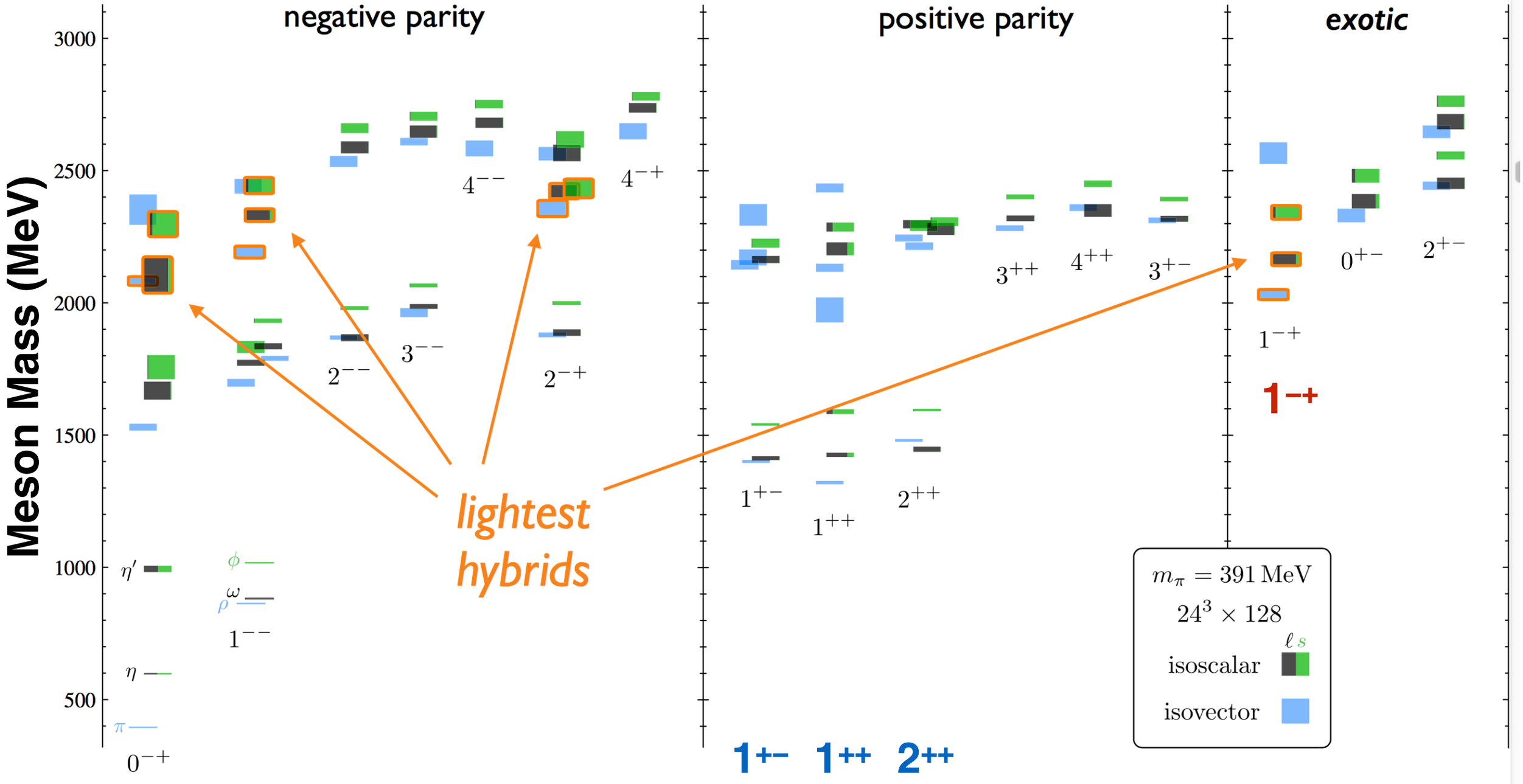


“Hybrid” Meson

Allowed J^{PC} : **0^{-+}, 0^{+-}, 1^{--}, 1^{-+}, 2^{-+}, 2^{+-},** …

Hybrid–Meson mass splitting ~ 1.0 – 1.5 GeV

Light Meson Spectrum from Lattice QCD



HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

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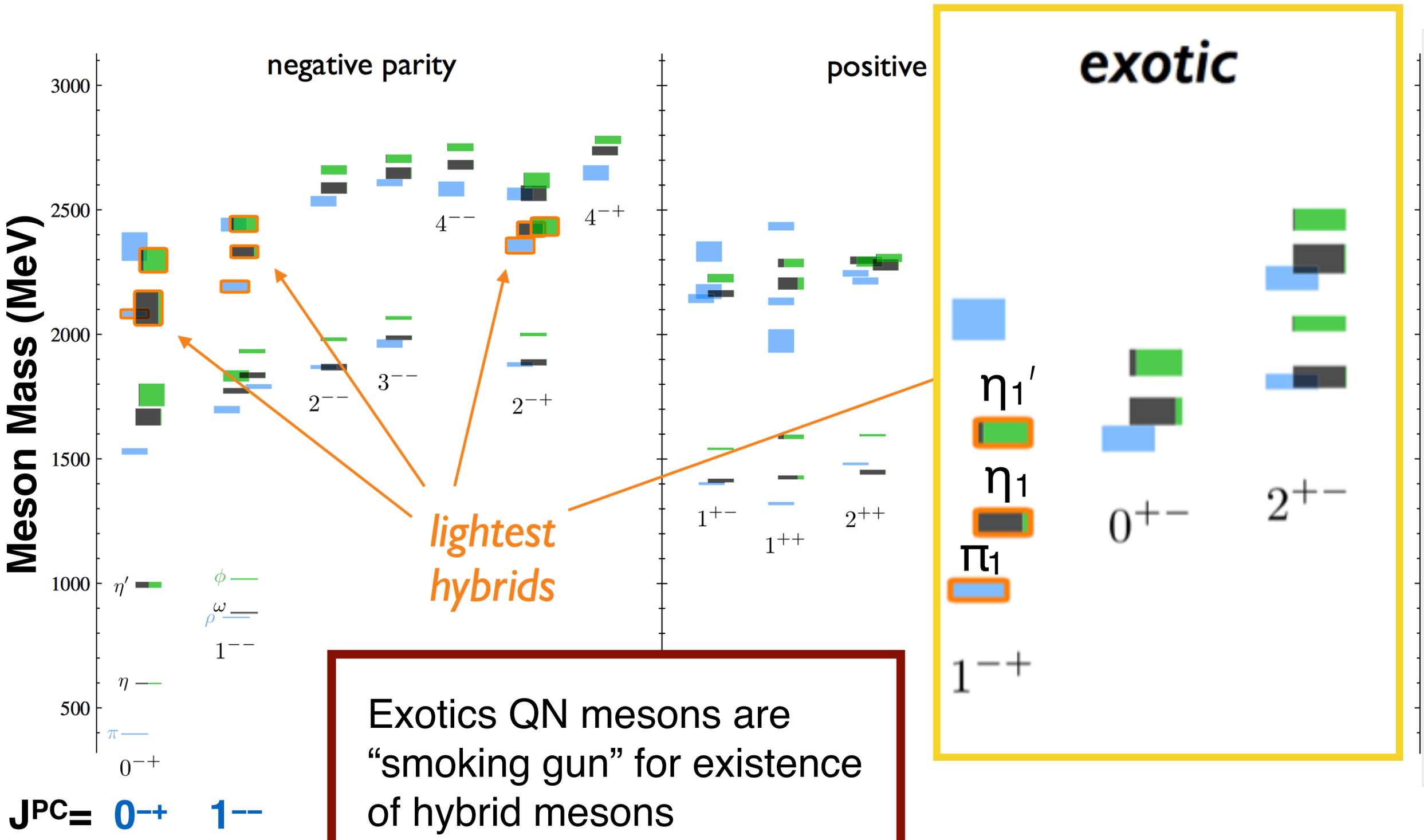

Exotics QN mesons are "smoking gun" for existence of hybrid mesons

HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

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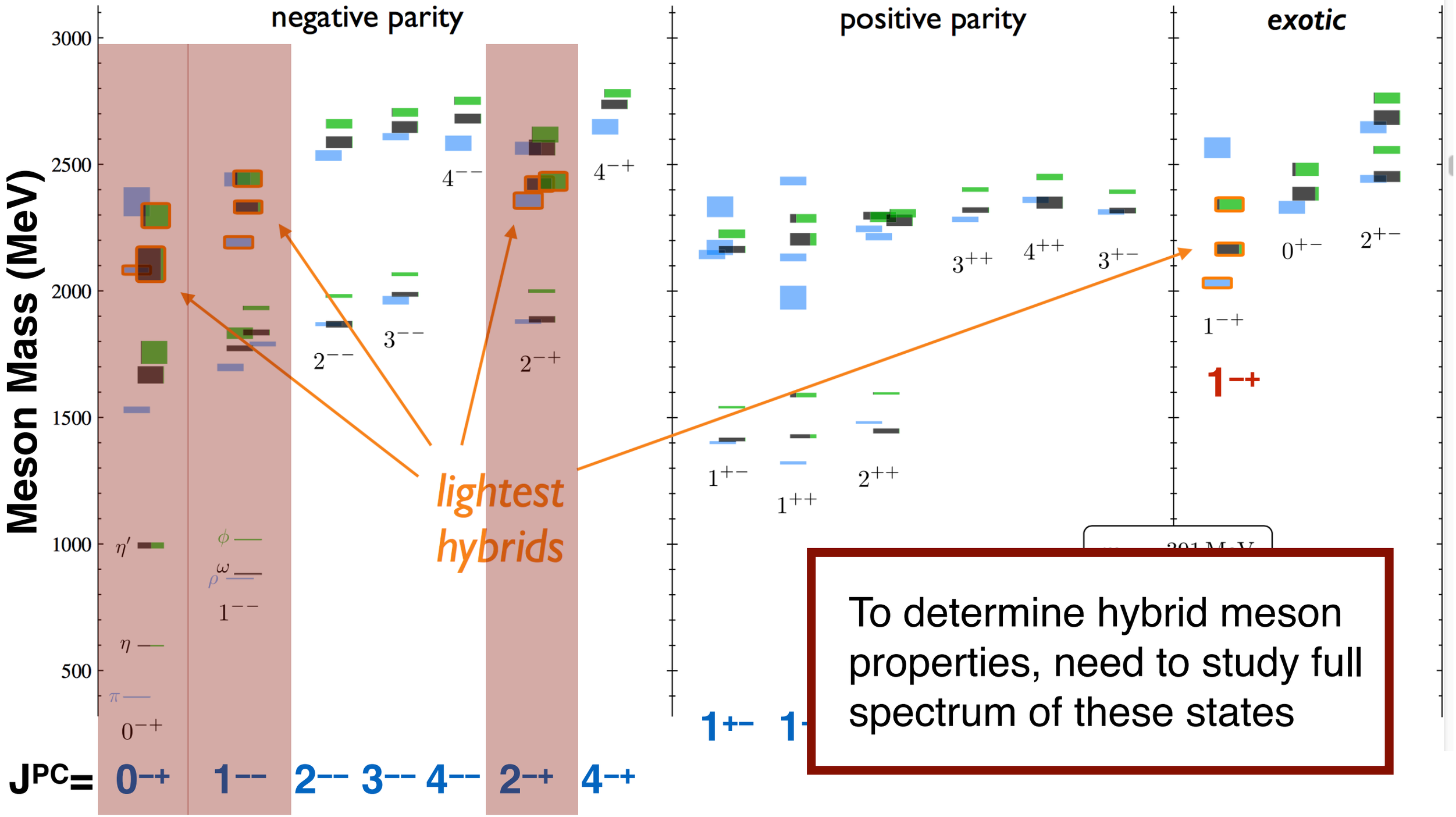


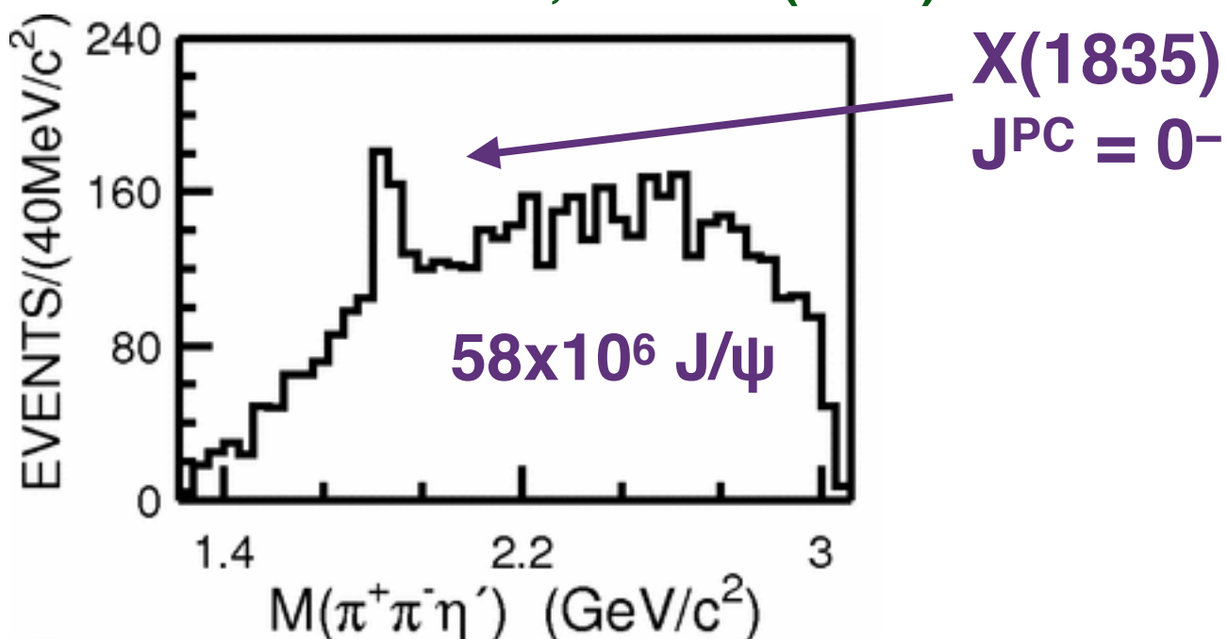
To determine hybrid meson properties, need to study full spectrum of these states

HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

Precision and Spectroscopy: BES III & J/ψ → γ η′π⁺π⁻

- Search by BES for resonances in $J/\psi \to \gamma\, \eta'\pi^+\pi^-$ in e^+e^- annihilation
  - Structure seen near 2M(p)
  - Understanding evolves as more data collected

BES II: PRL 95, 262001 (2005)



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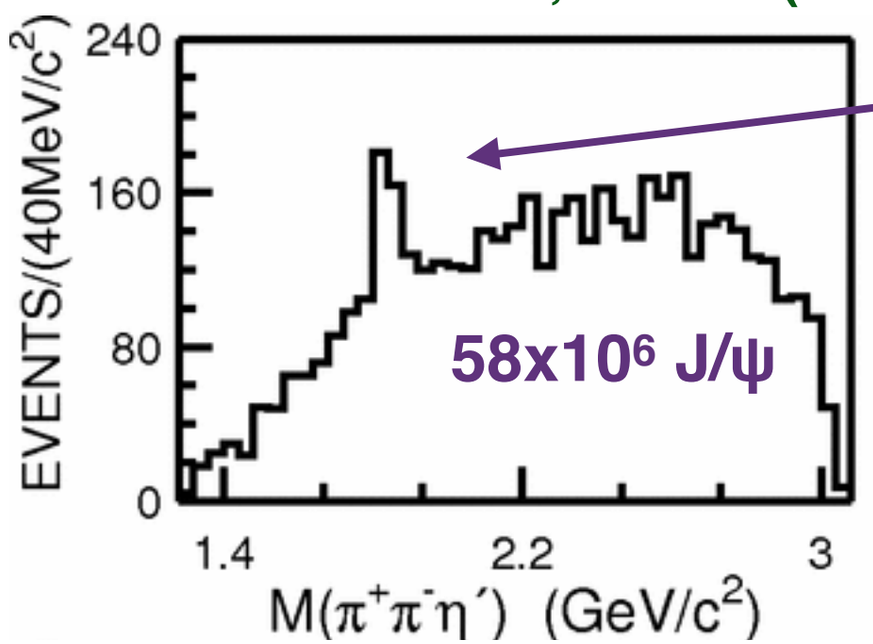

X(1835)
$J^{PC} = 0^-$

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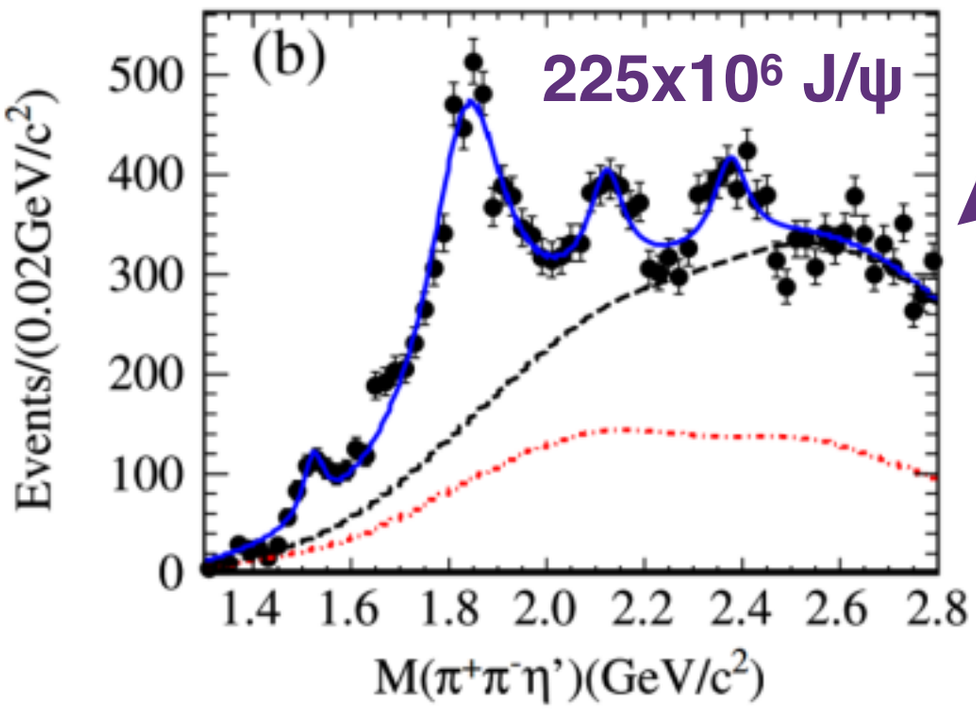

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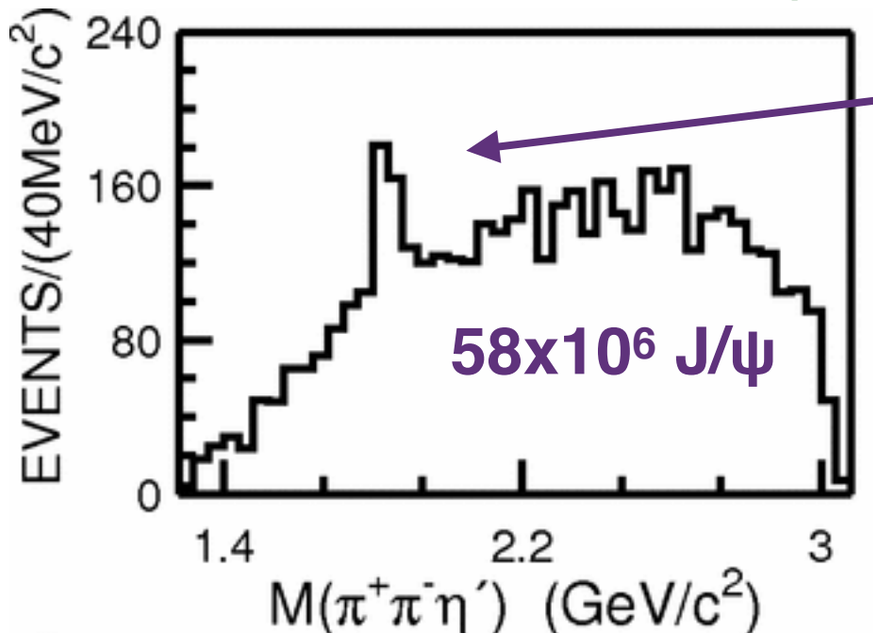

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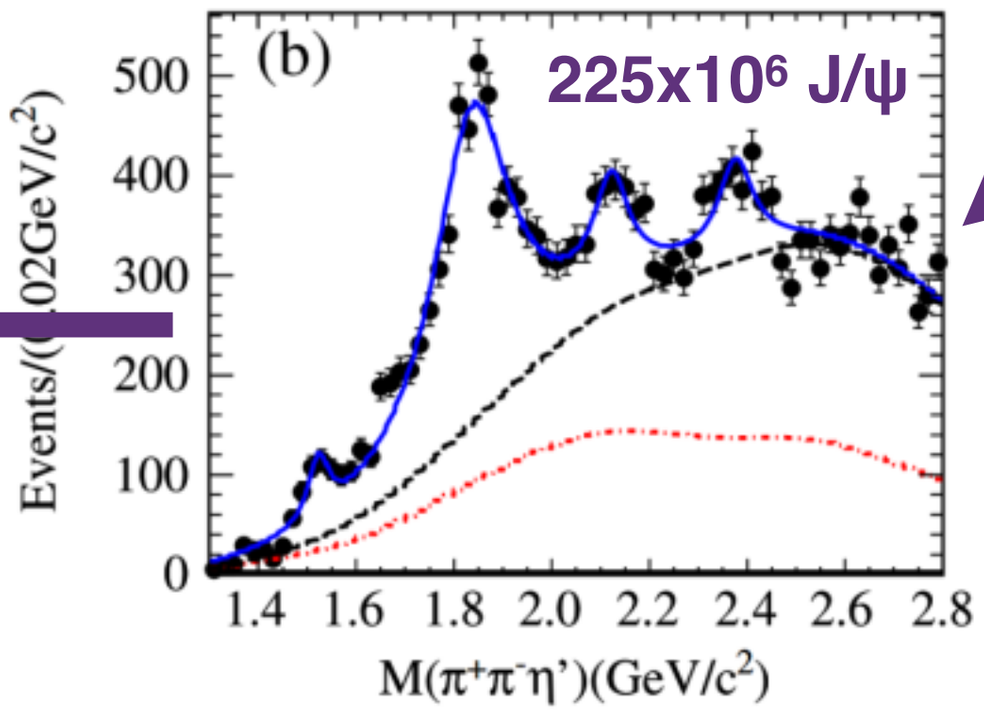

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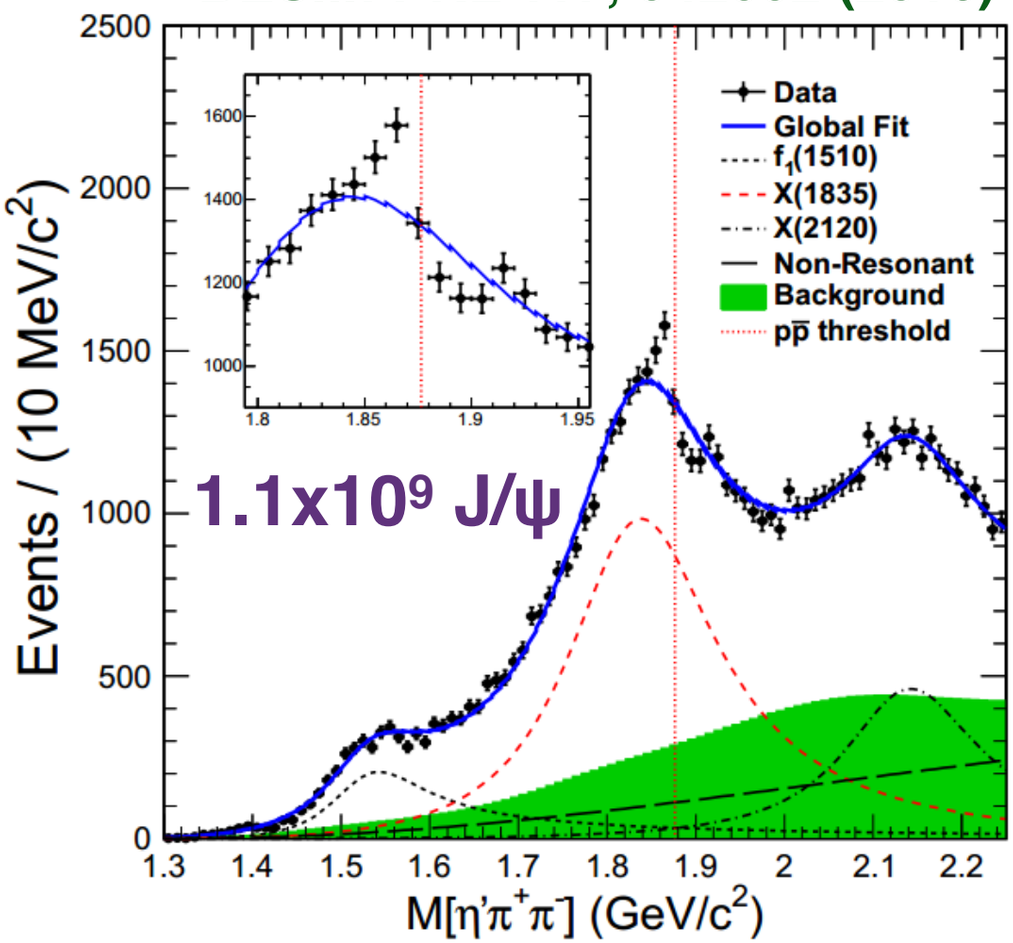

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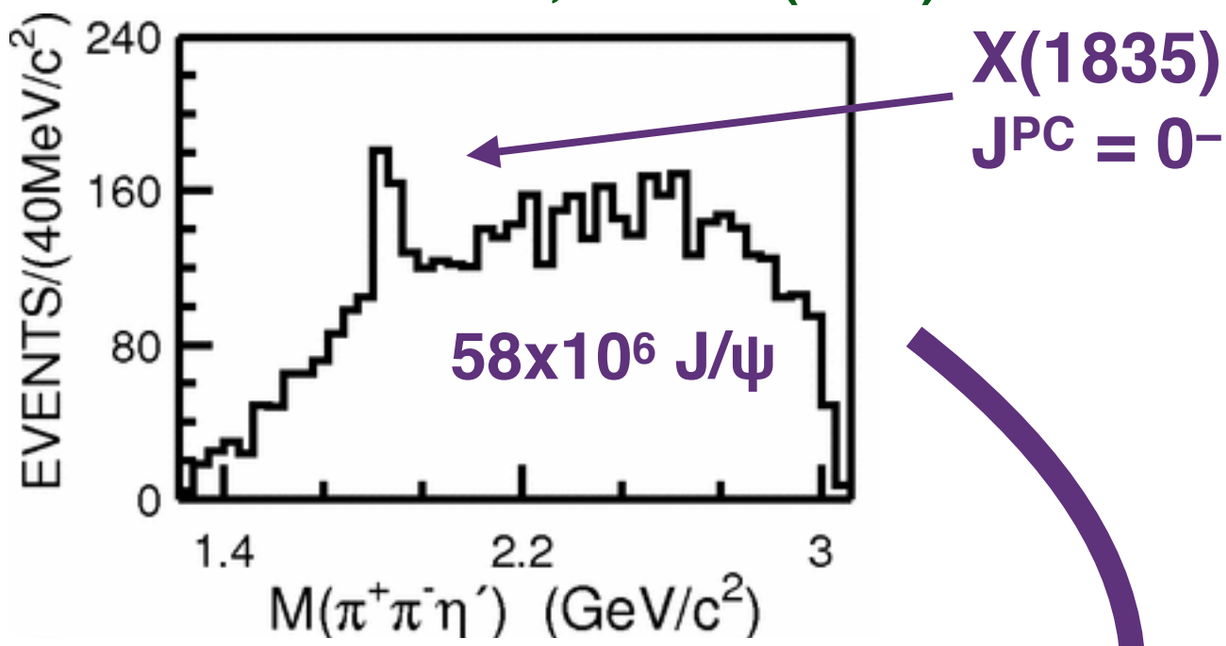

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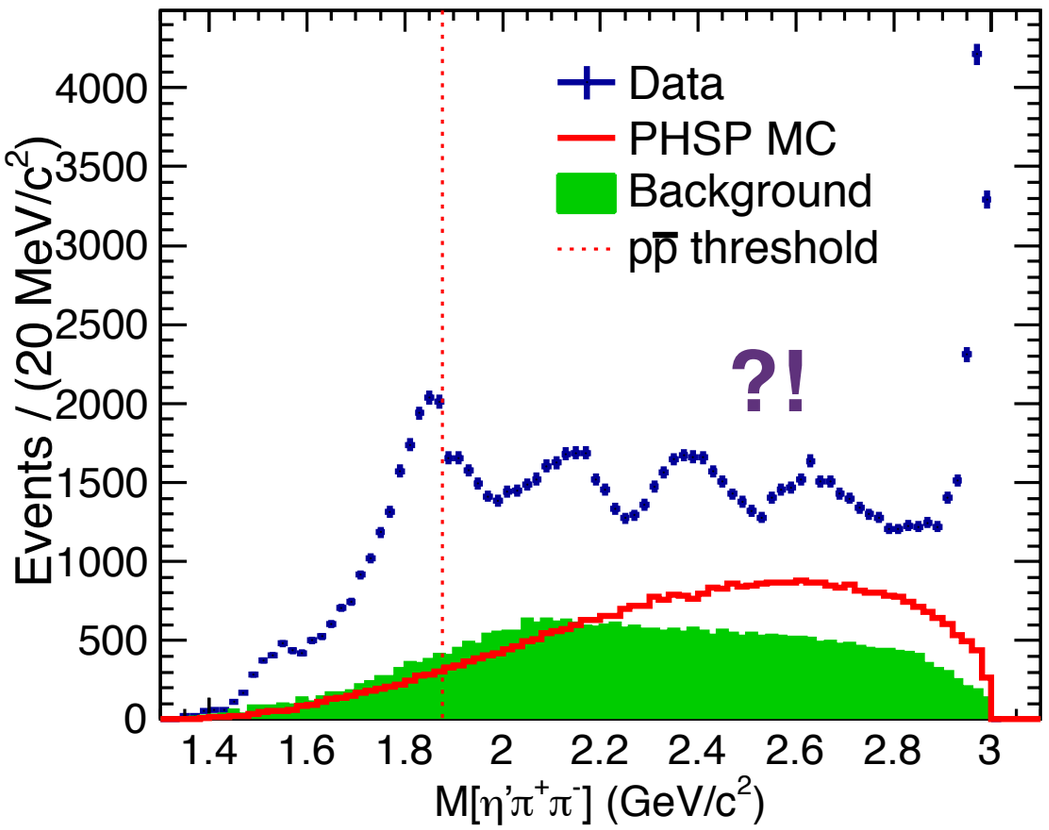

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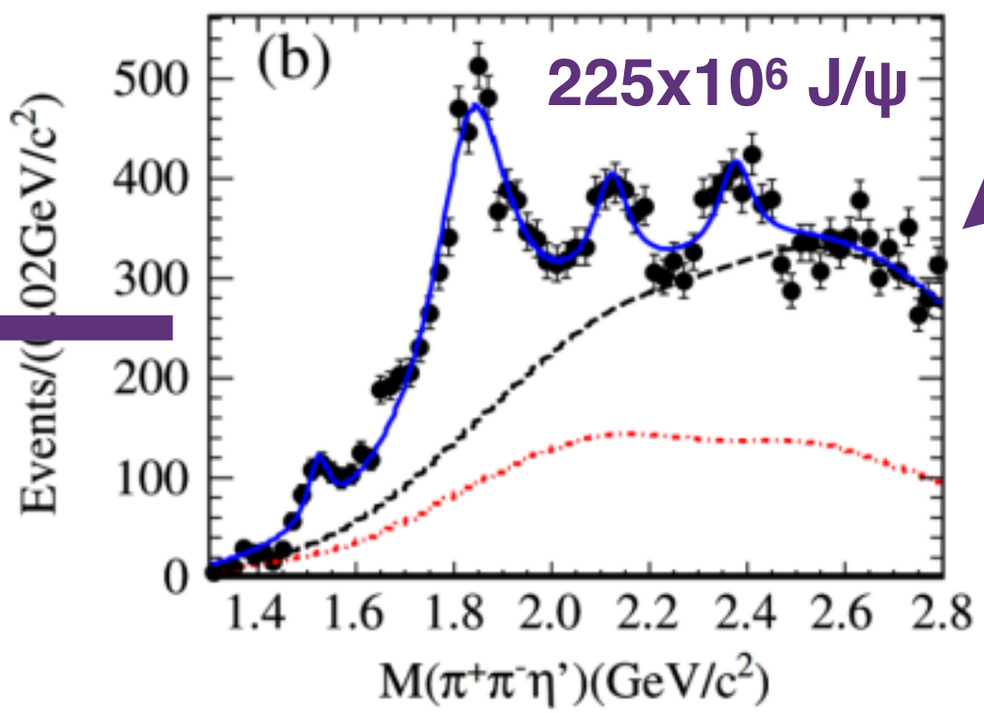
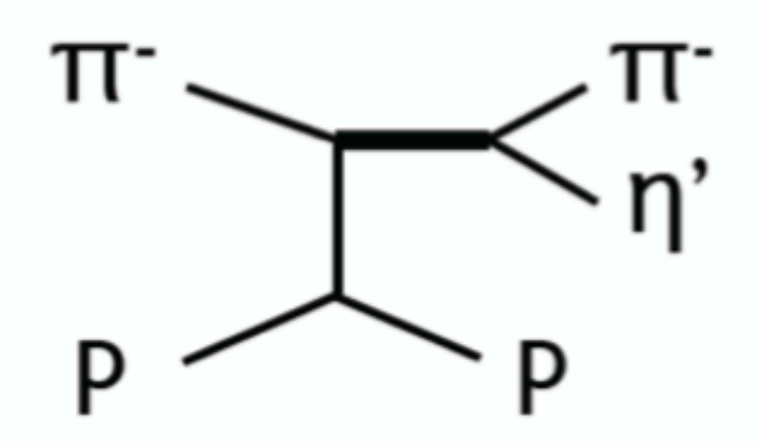
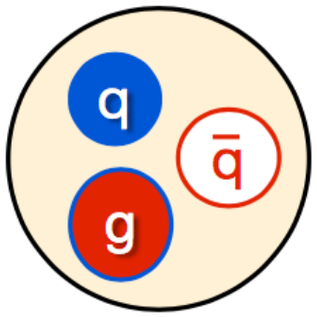


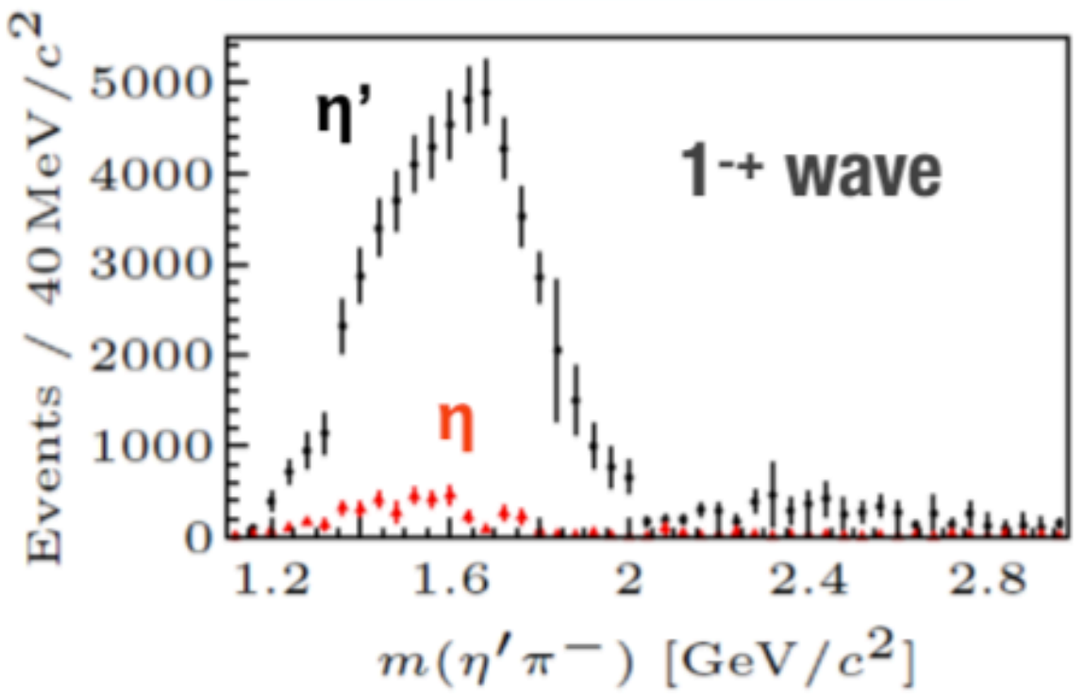
Evidence for exotic light-quark mesons

- Many searches, strongest evidence for π_1 in $\eta'\pi$ and $\rho\pi$ P-waves
- Resonance character not conclusively established

COMPASS: $\pi_1 \rightarrow \eta\pi$ / $\eta'\pi$

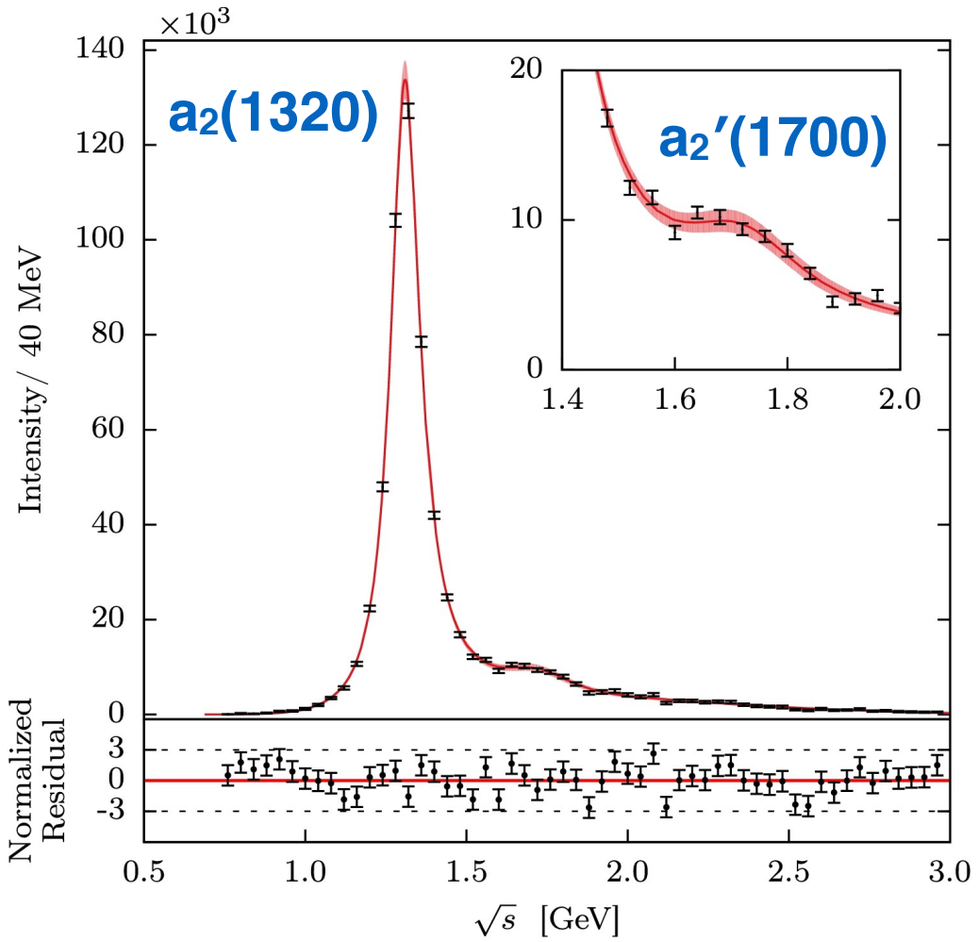






COMPASS: PLB 740, 303 (2015)

D-wave in η′π



Extract resonance parameters with unitary reaction model

A. Jackura et al. [JPAC and COMPASS Collaborations], PLB 779, 464 (2018)

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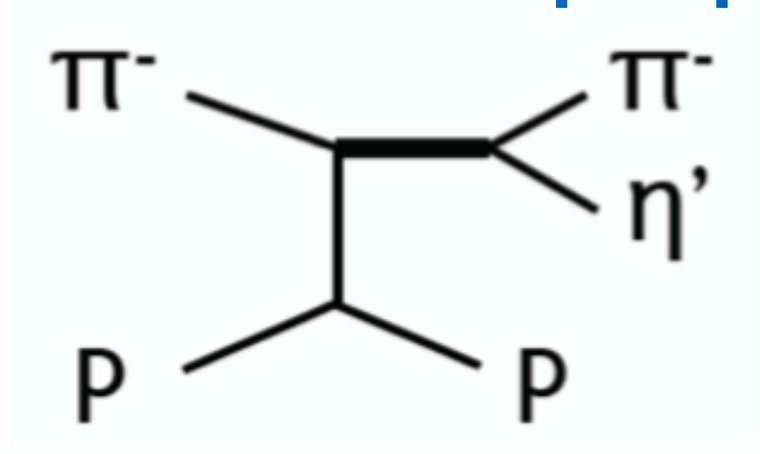
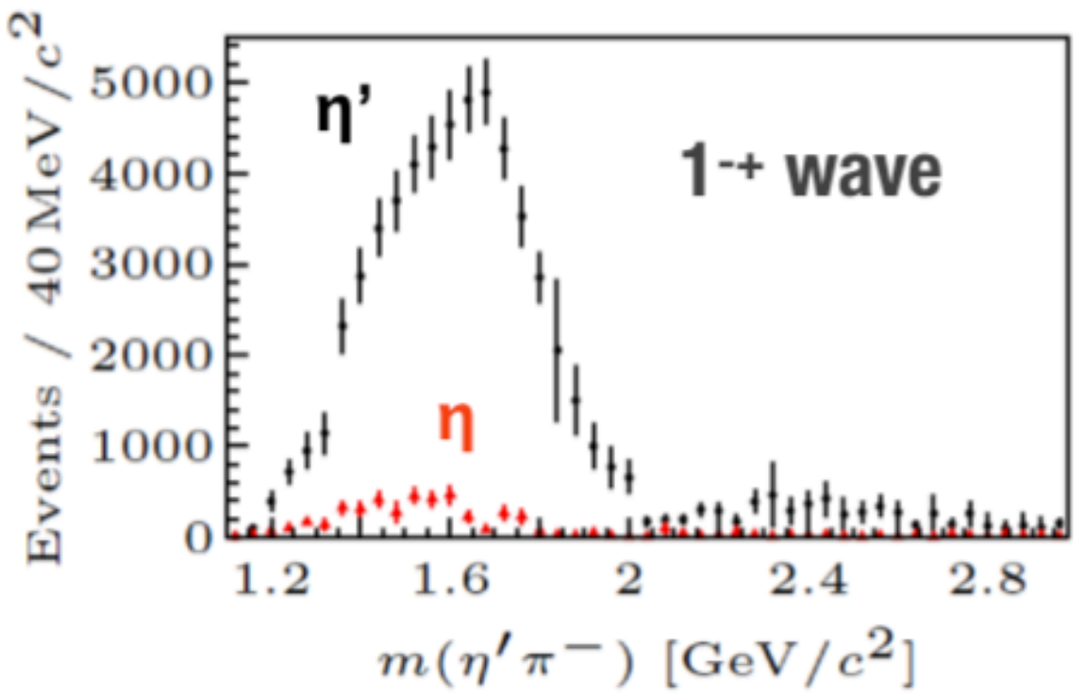
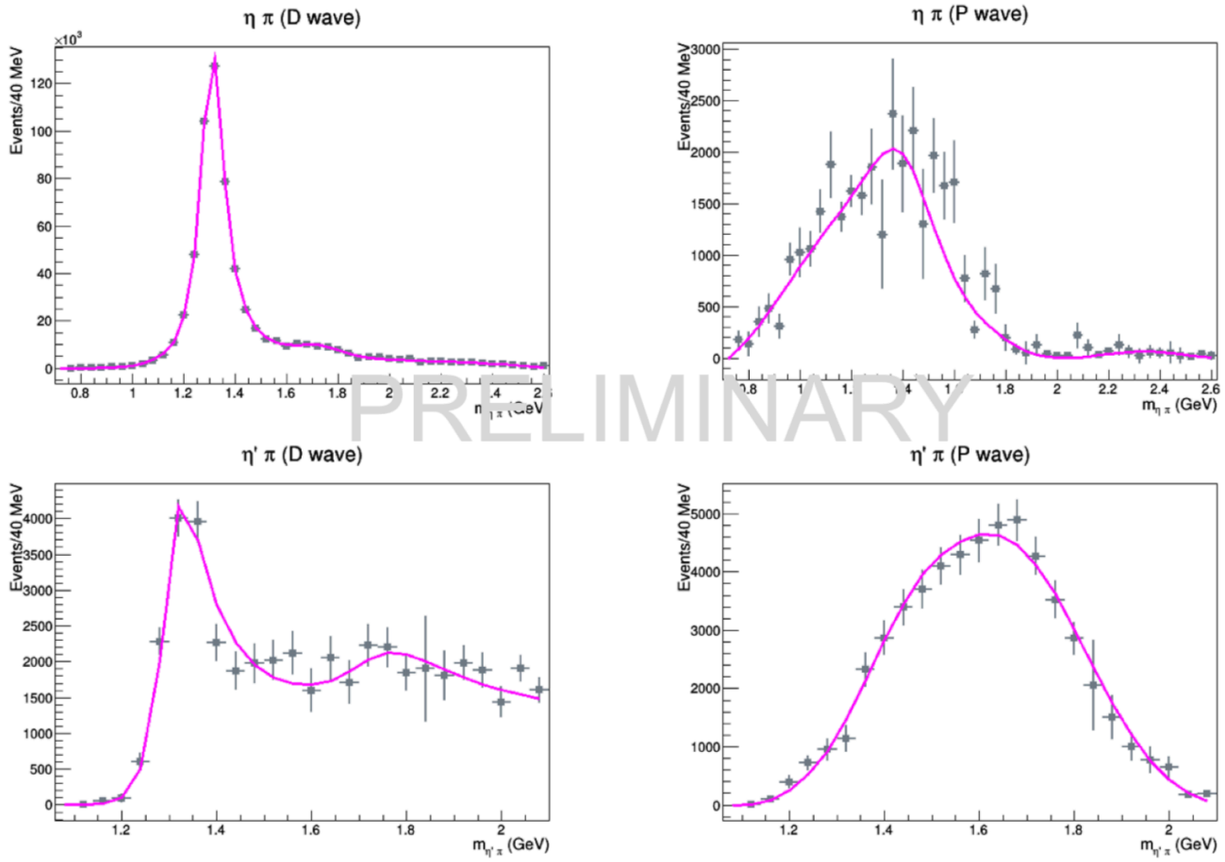




COMPASS: PLB 740, 303 (2015)

P/D-wave in $\eta\pi/\eta'\pi$ (preliminary)



A. Szczepaniak, MESON 2018

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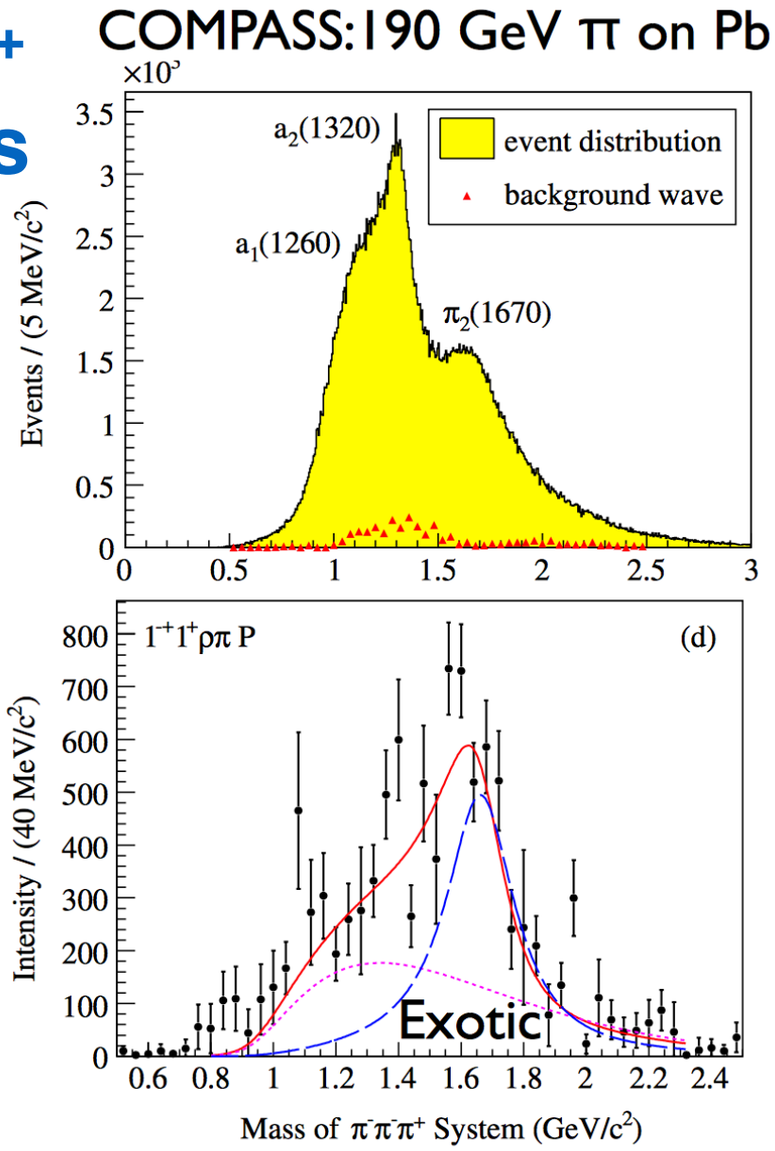
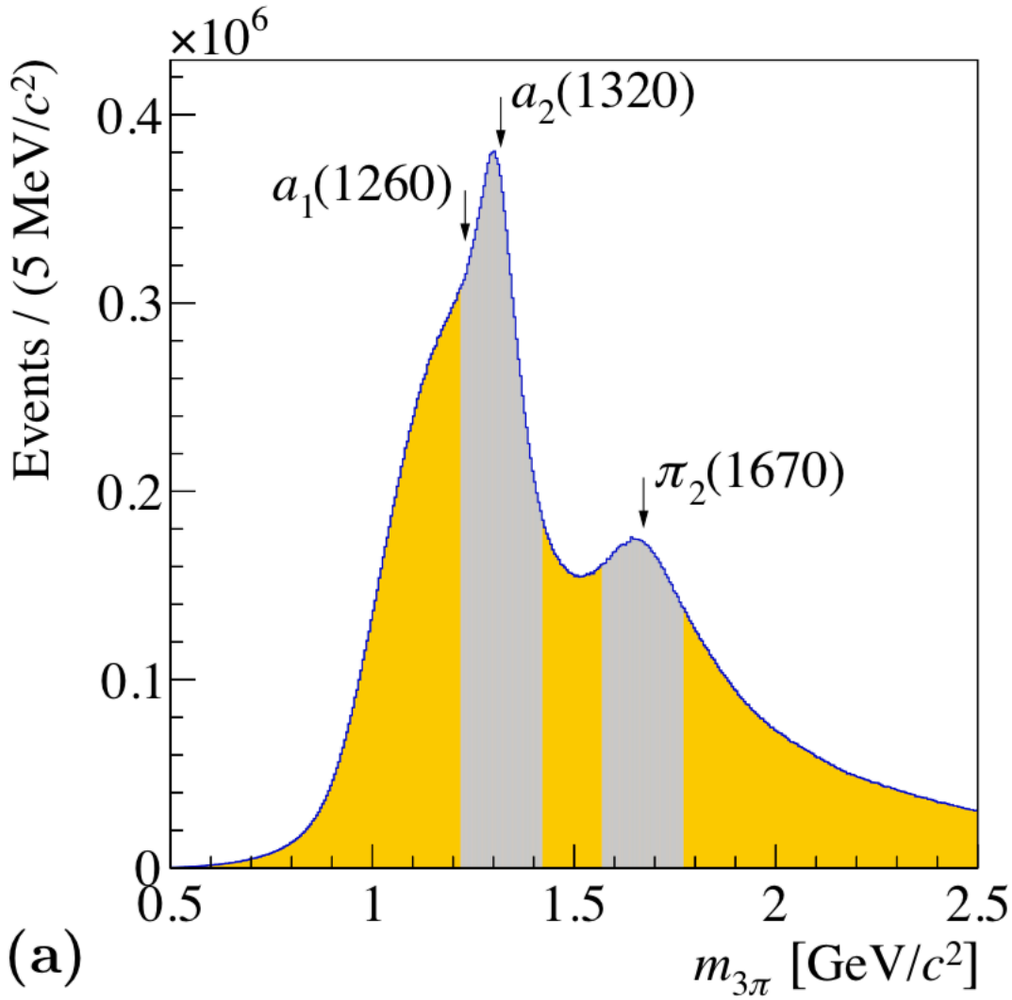
$$\pi_1 \rightarrow \rho\pi$$

420k $\pi^-\pi^-\pi^+$ events



COMPASS: PRL 104, 241803 (2010)

50M $\pi^-\pi^-\pi^+$ events



PRD 95, 032004 (2017)

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- Resonance cl

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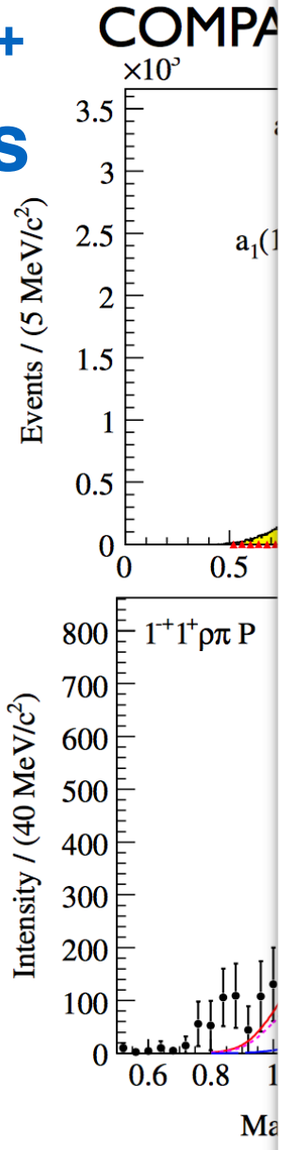
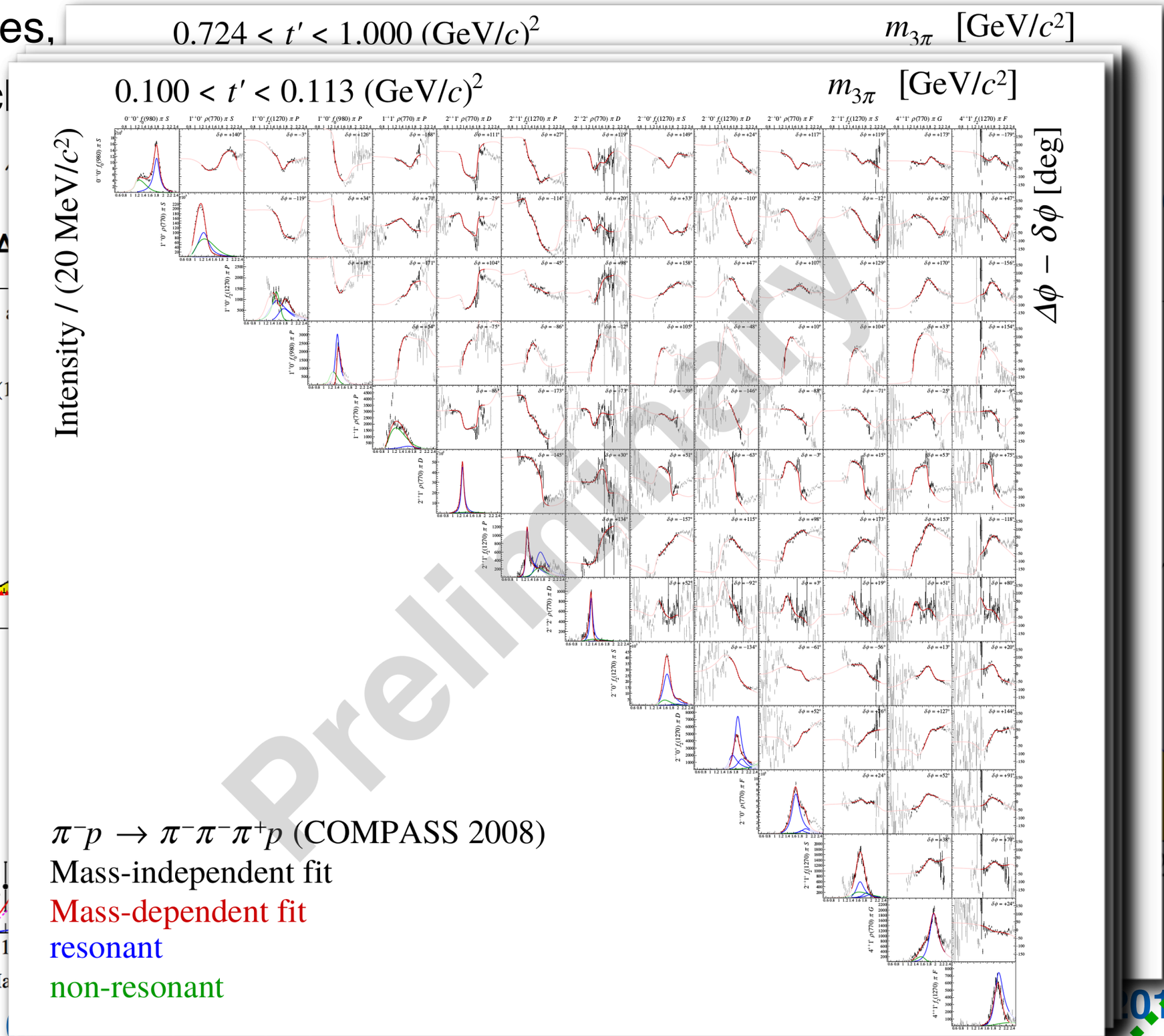
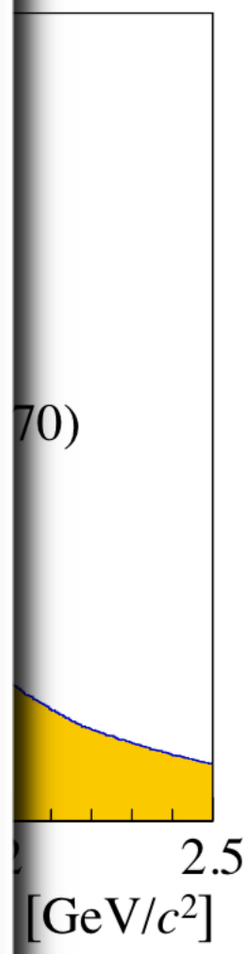




$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)
Mass-independent fit
Mass-dependent fit
resonant
non-resonant



COMPASS: PRL 1 **2017)**

t' bin

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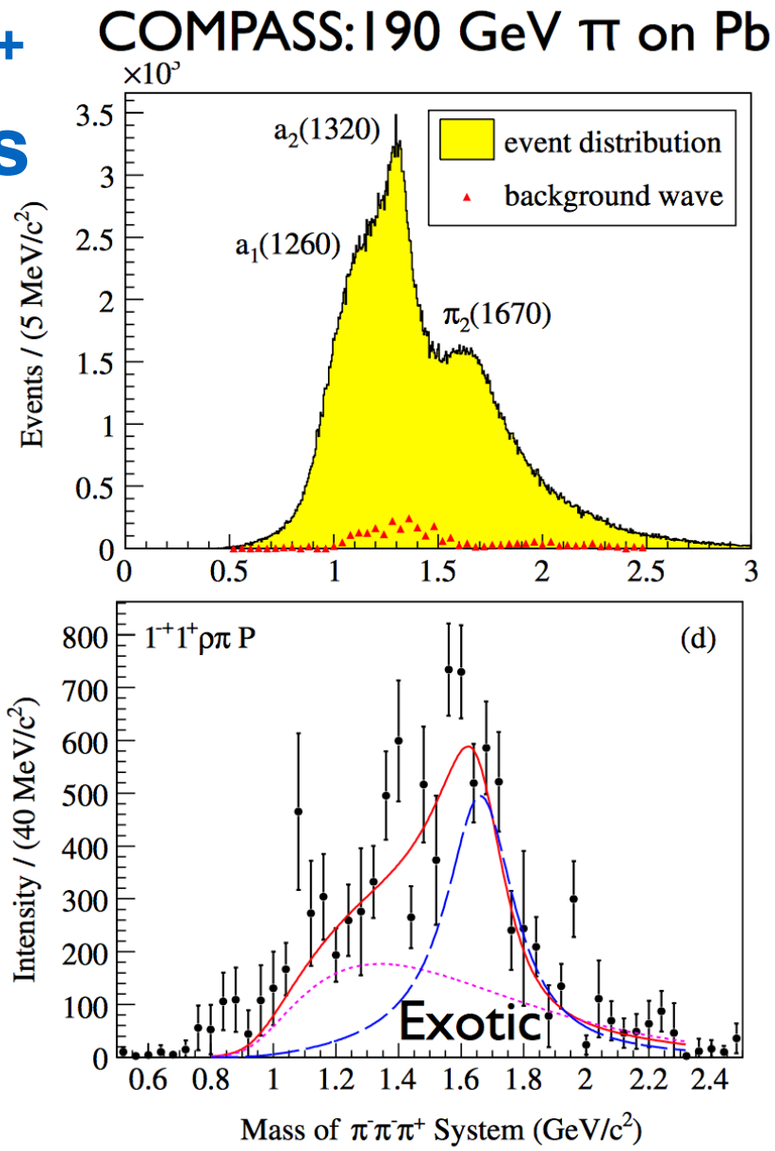

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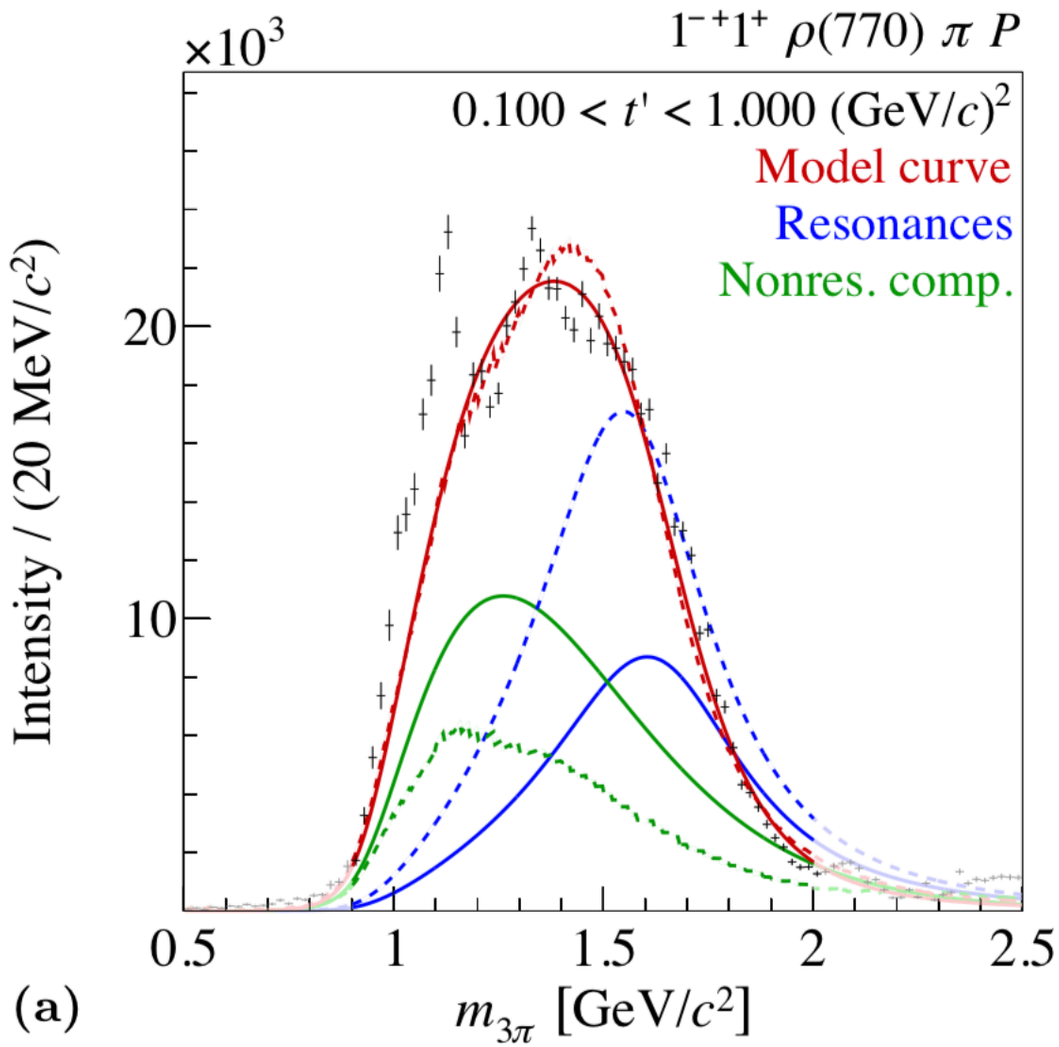

COMPASS: PRL 104, 241803 (2010)

arXiv:1802.05913

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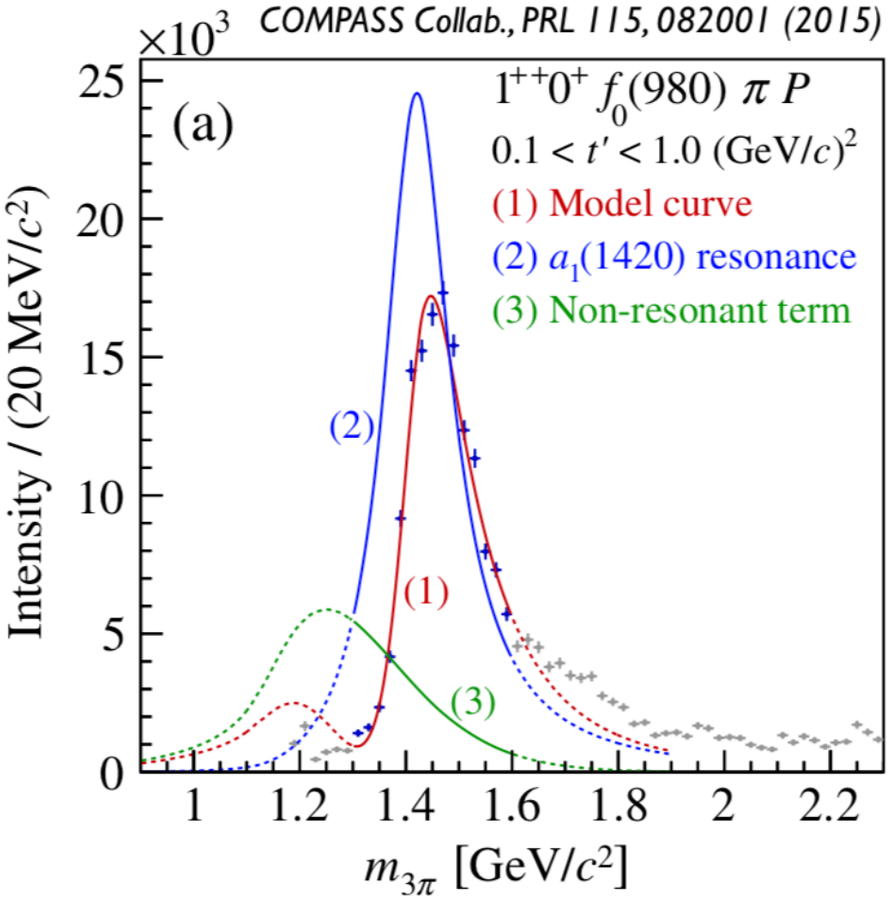
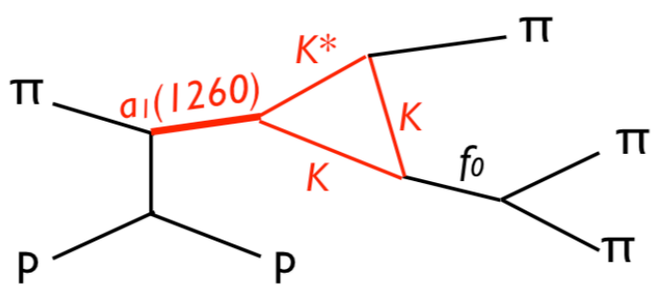
$a_1(1420) \to f_0(980)\,\pi$?



Describe non-$q\bar{q}$ candidate as triangle singularity



M. Mikhasenko, HADRON 2017

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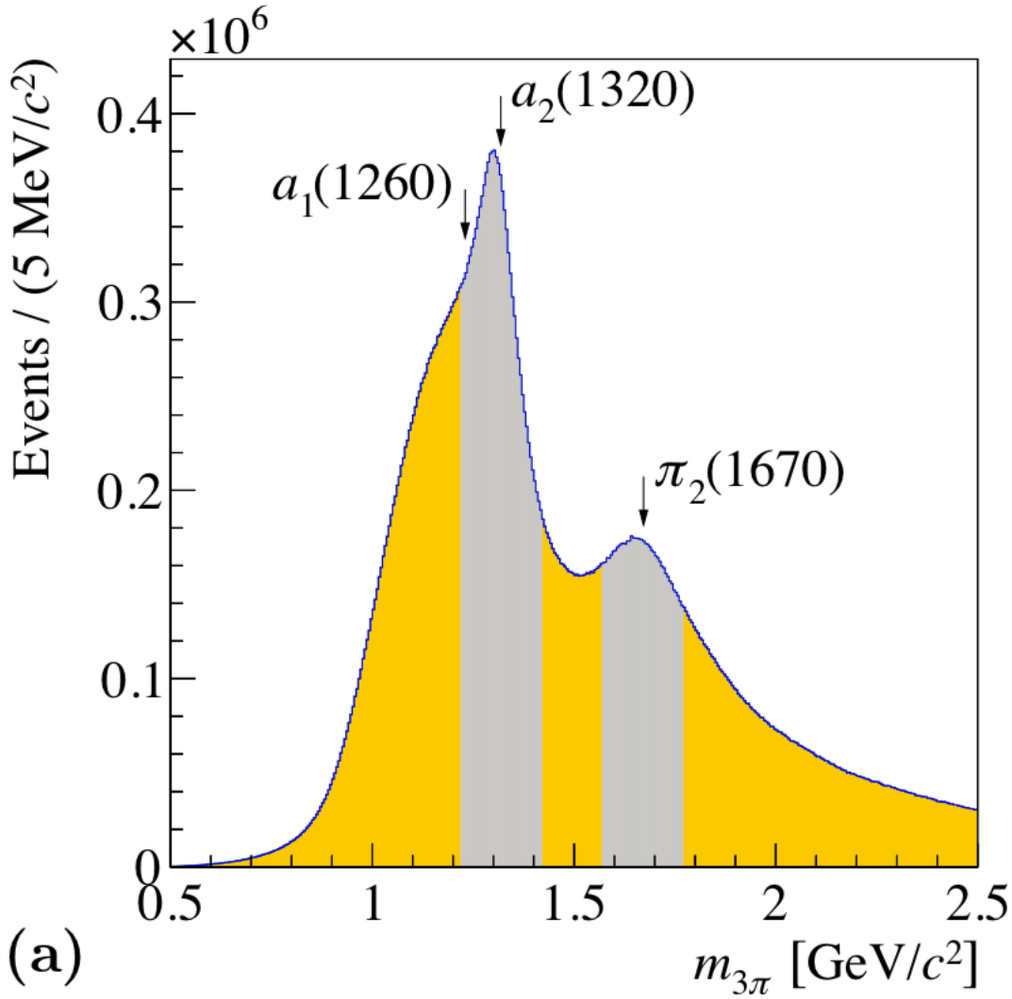
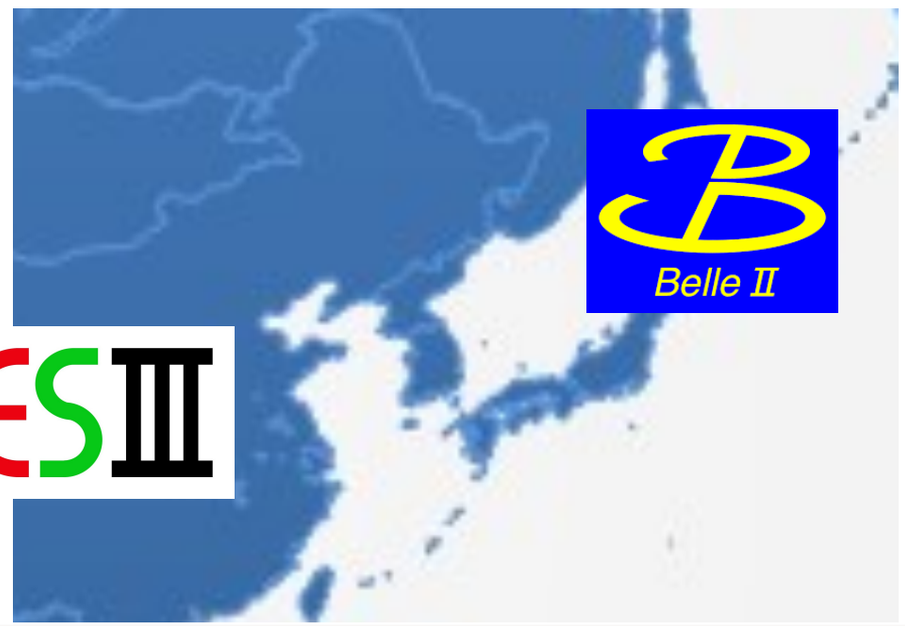


PRD 95, 032004 (2017)

Hadron Spectroscopy is Moving Forward Worldwide!

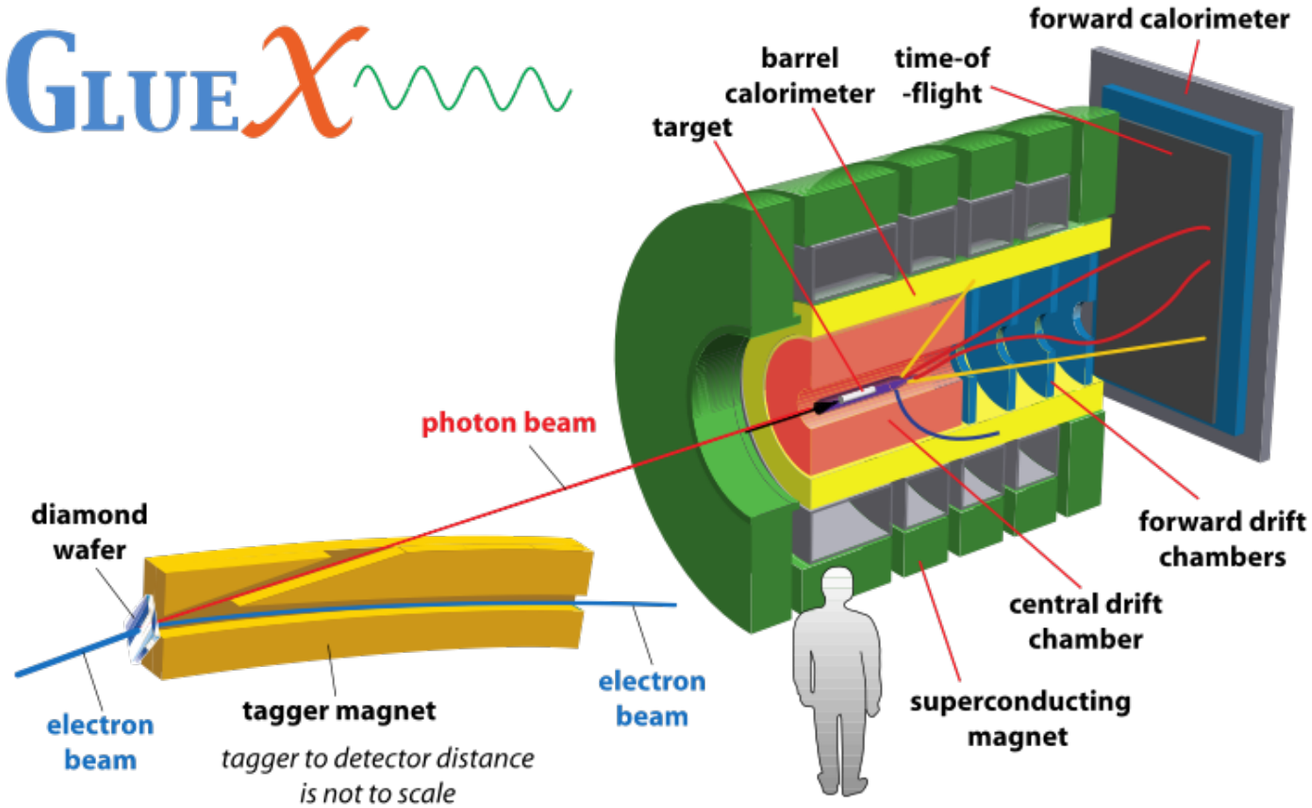
Moving into the high-precision era…



…collecting comprehensive data with orders of magnitude larger than previously available

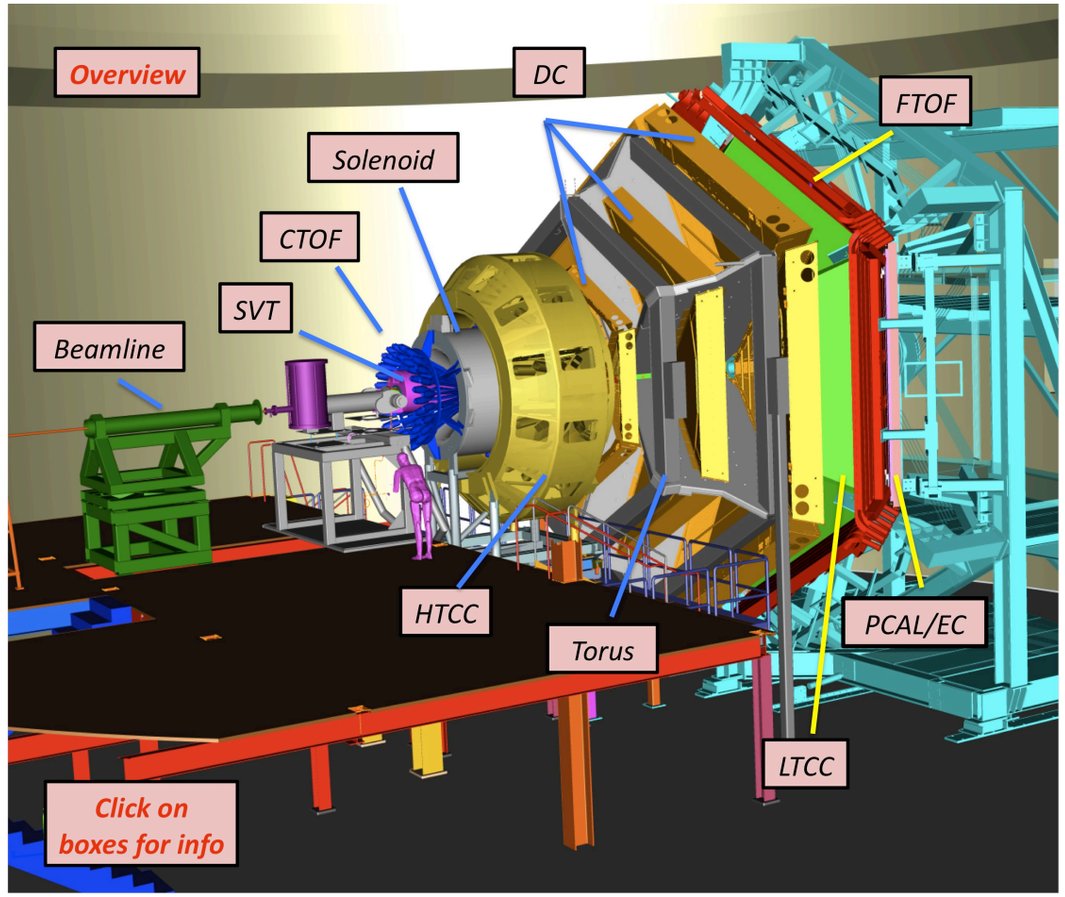
Hadron Spectroscopy at JLab

- Unique capability at JLab: hadron production with intense beams of electrons and photons



GlueX

- Photon beam with linear polarization
- Large acceptance and PID optimized for amplitude analysis

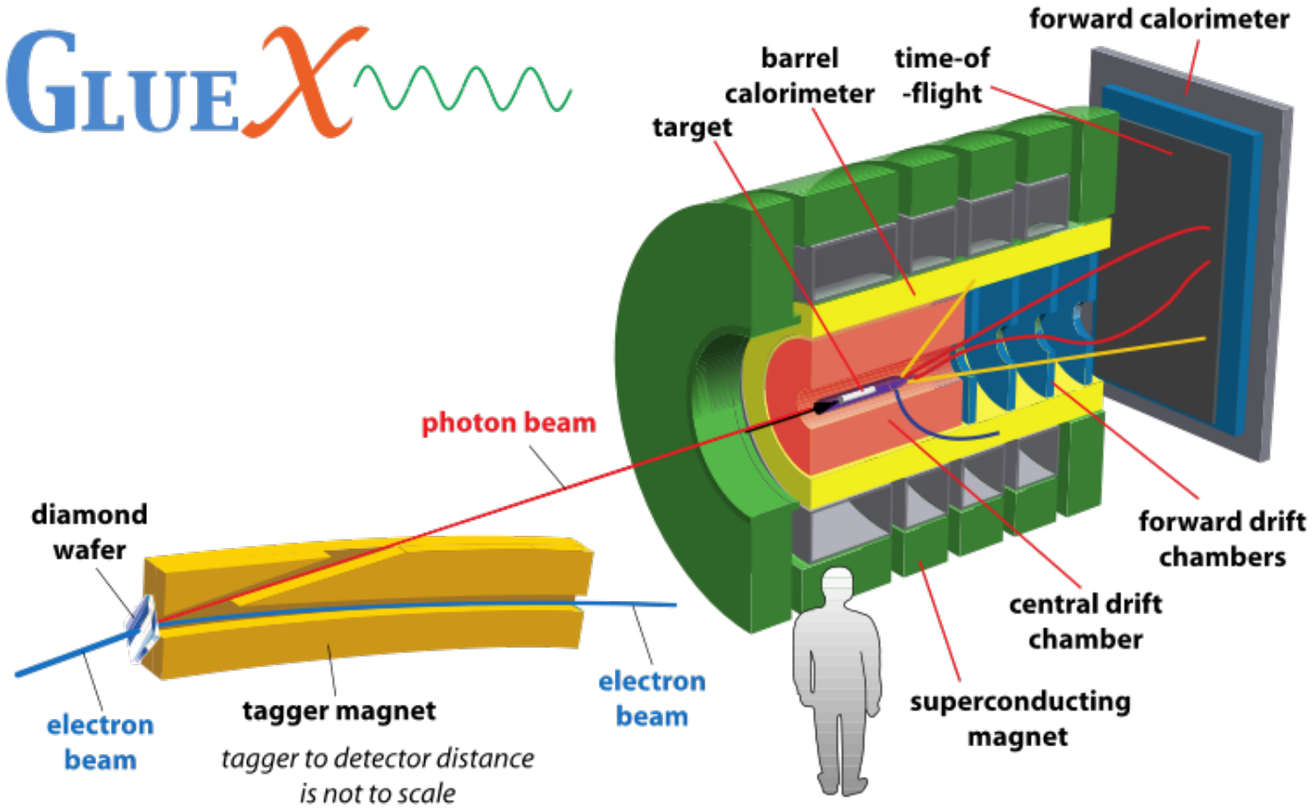


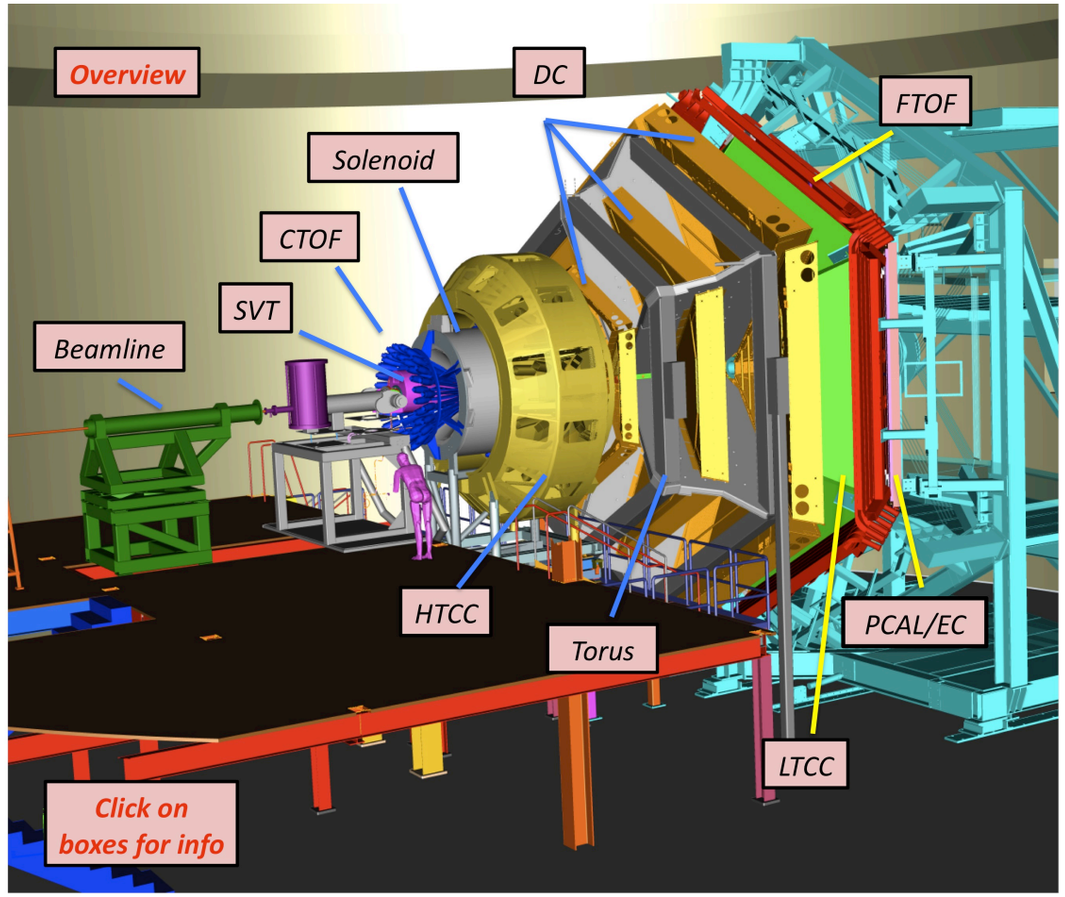
CLAS12

- Electron and photon beams with linear and circular polarization
- PID over large momentum range

Hadron Spectroscopy at JLab

- Unique capability at JLab: hadron production with intense beams of electrons and photons





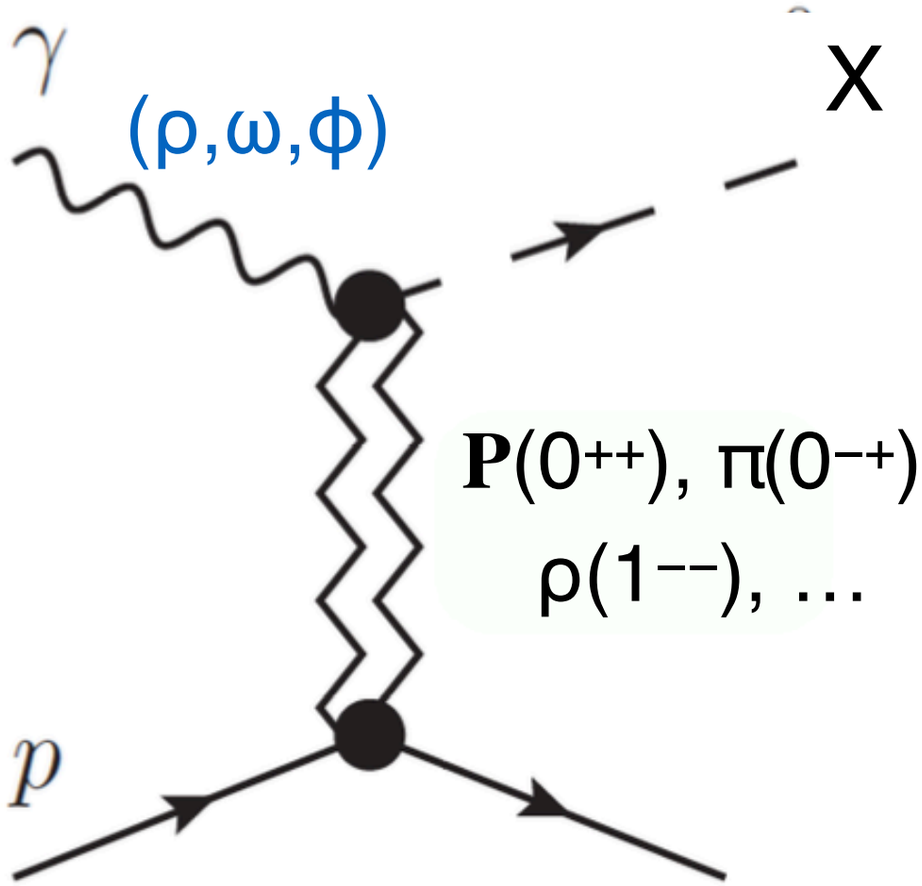
GlueX

- Commissioning: 2015–6
- Physics started 2017, GlueX-I 80% done
- DAQ rate: 400–700 MB/s
- Over 2.5 PB raw data to tape

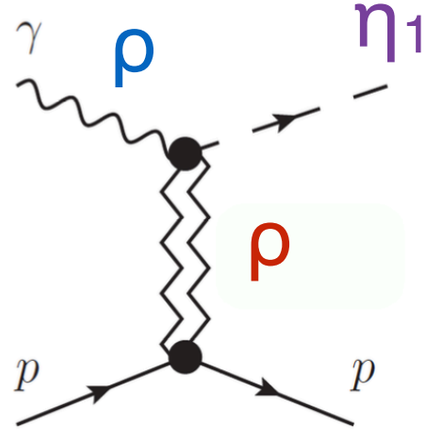
CLAS12

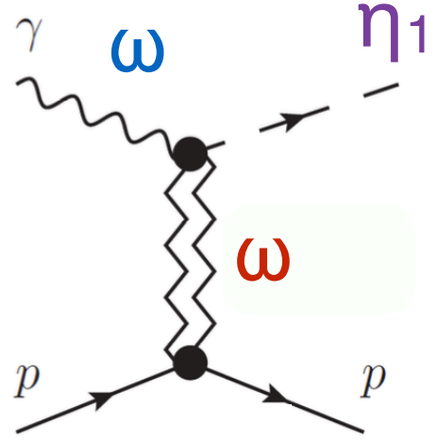
- Commissioning: 2017-8
- Physics started March 2018
- DAQ rate: 600 MB/s
- Over 800 TB raw data to tape

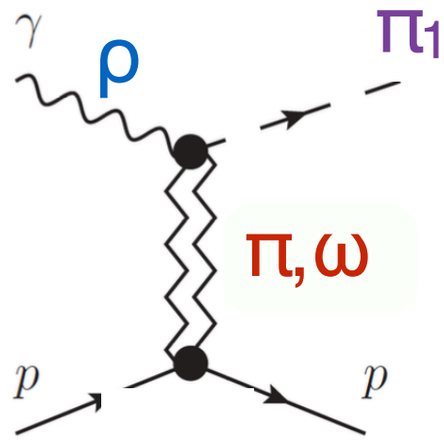
Meson Photoproduction



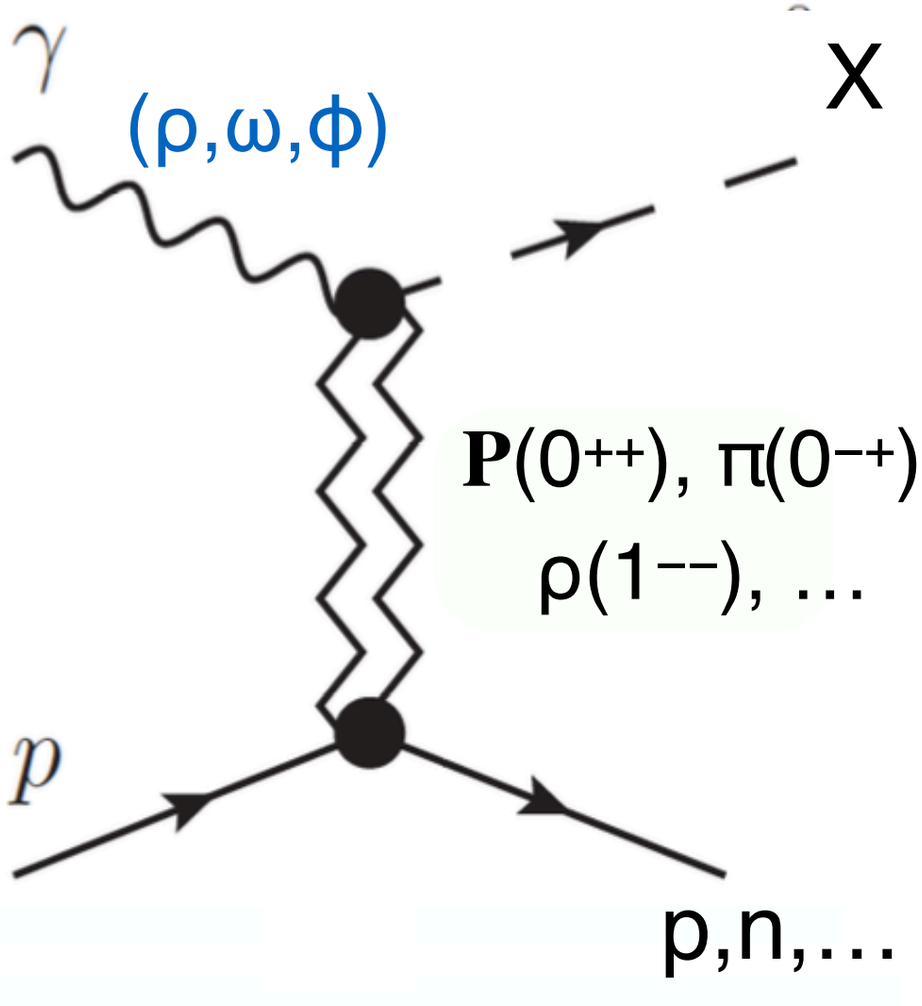
- Photon couples to exchanged QN via VMD, generates mesons with wide variety of J^{PC}
  - All expected hybrids can be produced!





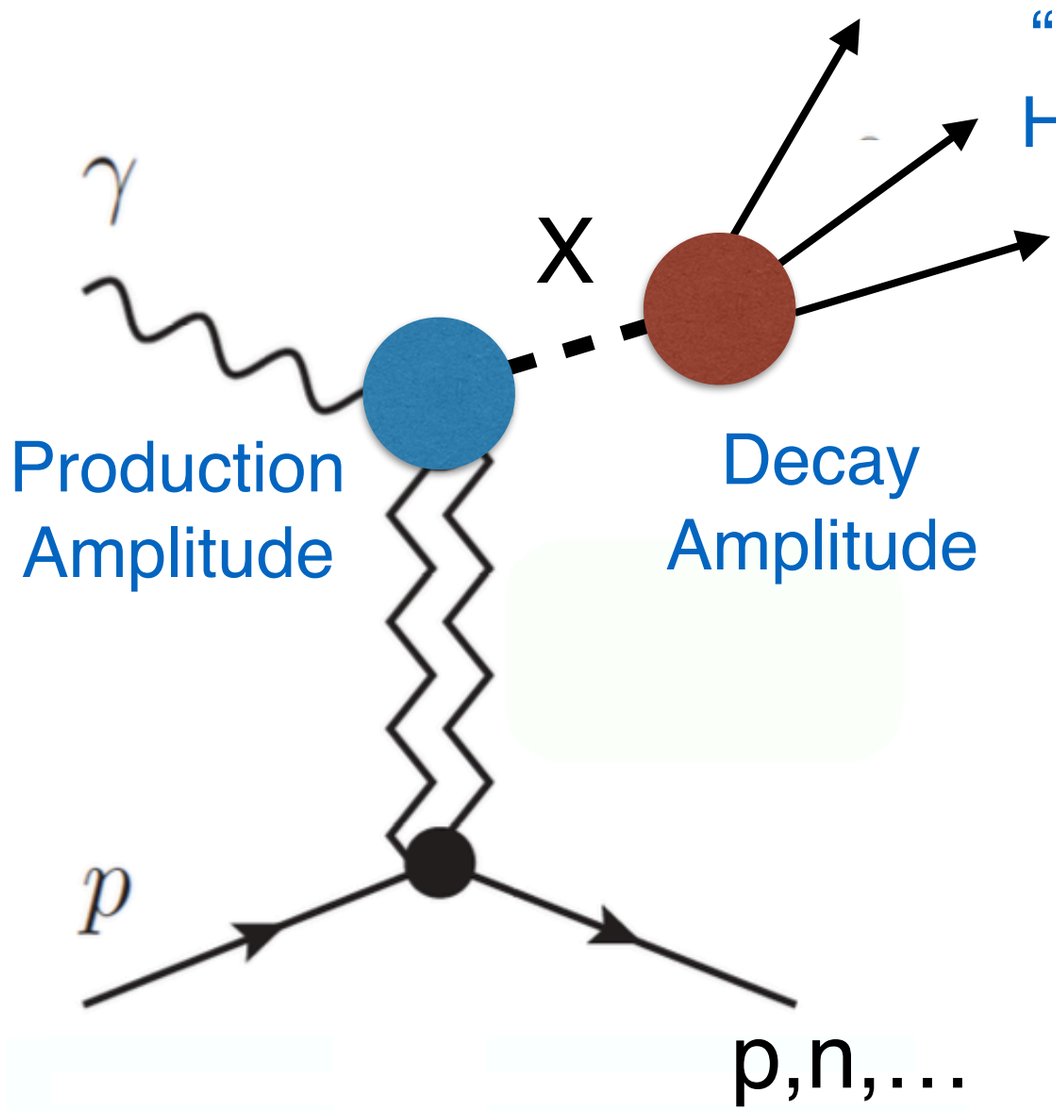


Meson Photoproduction



- Photon couples to exchanged QN via VMD, generates mesons with wide variety of J^{PC}
  - All expected hybrids can be produced
- Variety of hybrid decays expected:
  - $\pi_1 \rightarrow \rho\pi,\ \pi b_1,\ \pi f_1$
  - $\eta_1 \rightarrow \eta f_2,\ \pi a_2,\ \eta f_1$
- Little existing photoproduction data. Neutral final states at these energies are mostly unexplored
- Photon polarization provides constraints on production processes

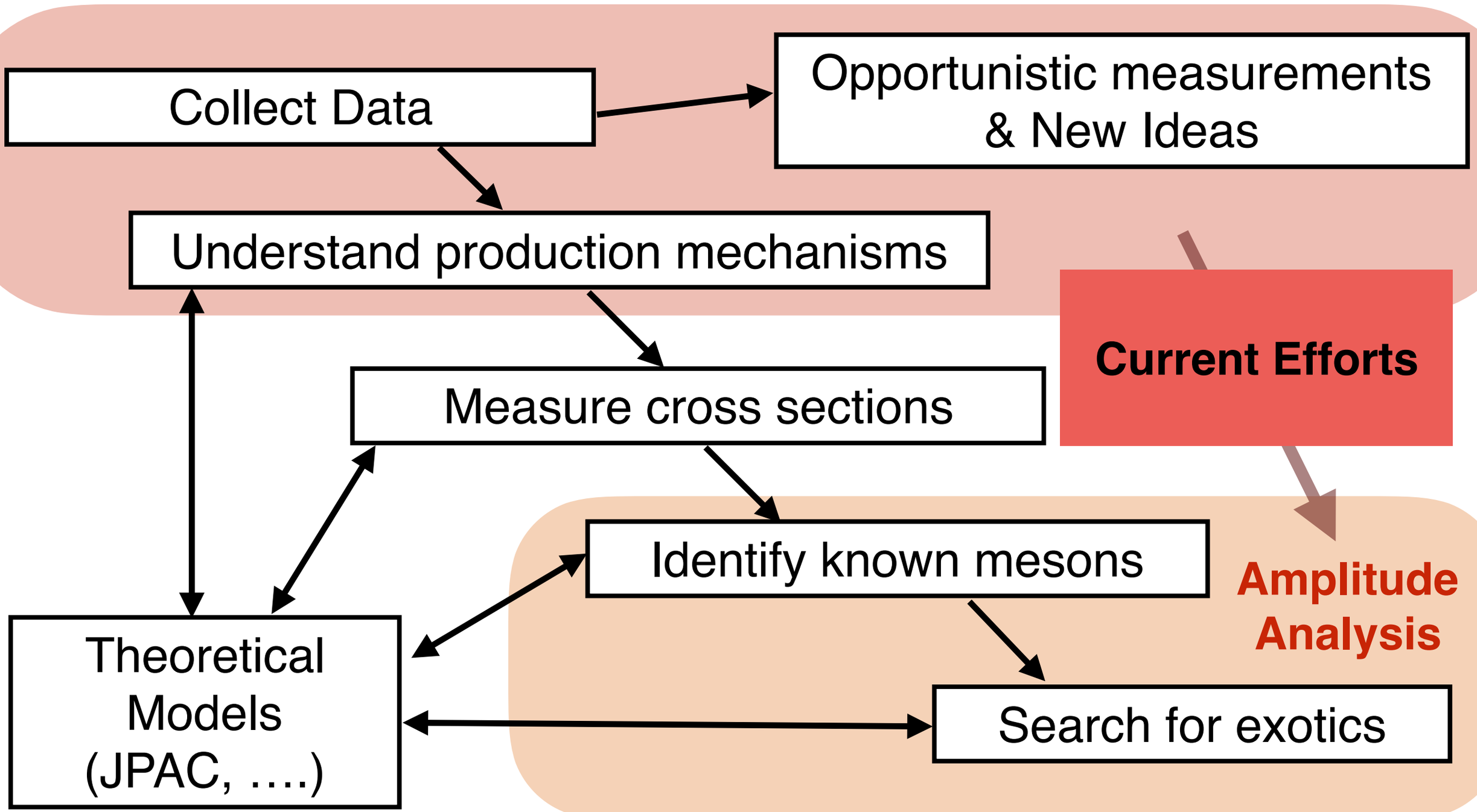
Meson Photoproduction & Amplitude Analysis



- Multiple states are produced which decay to the same set of particles and interfere
- Need to understand photon beam characteristics and have detailed detector model
- Improved theoretical models for amplitudes also needed, work closely with JPAC and others

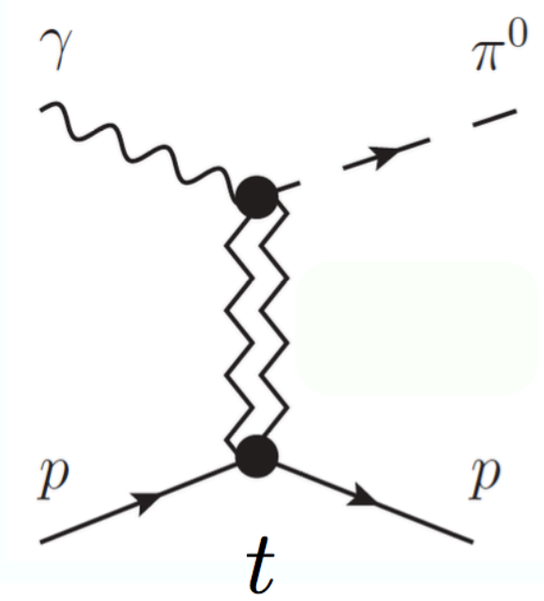
Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.



Beam Asymmetries: γ p → p + π⁰ / η

- Understanding production mechanisms necessary to determine J^{PC} of mesons in amplitude analyses, look at simplest reactions first
- Beam asymmetry Σ yields information on production mechanisms
- Combining data taken with different beam polarization cancels most acceptance effects



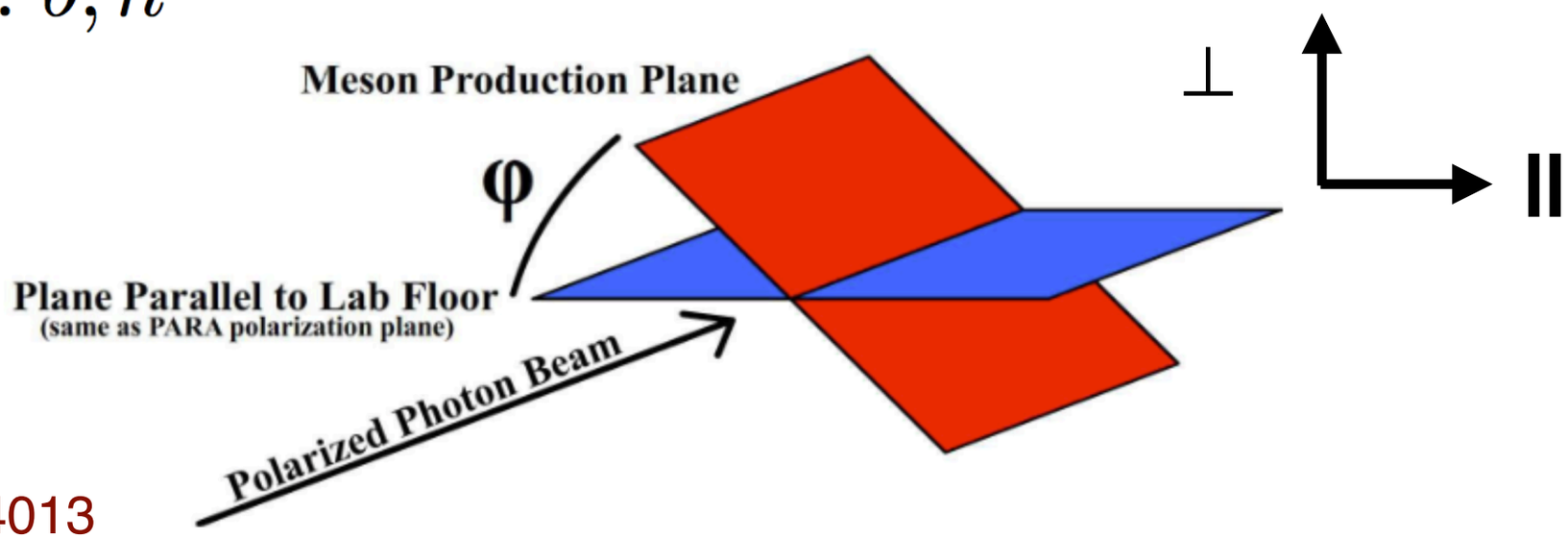
Exchange J^{PC}

$$1^{--} : \omega, \rho$$

$$1^{+-} : b, h$$

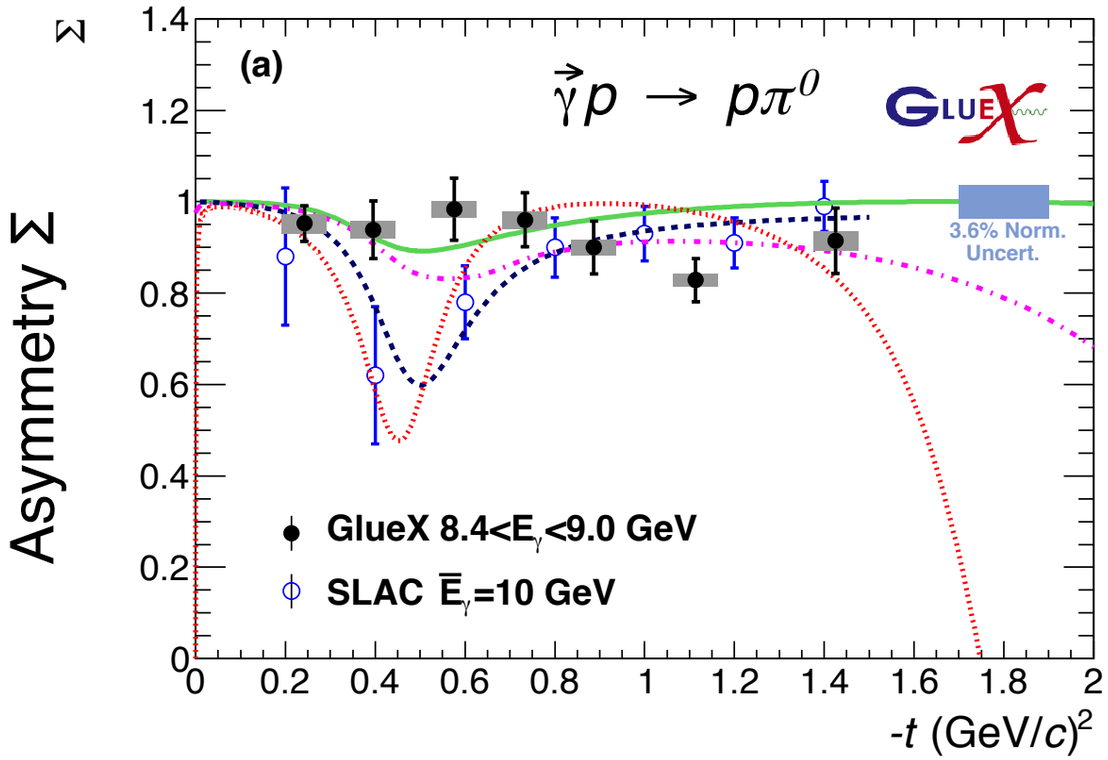
$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

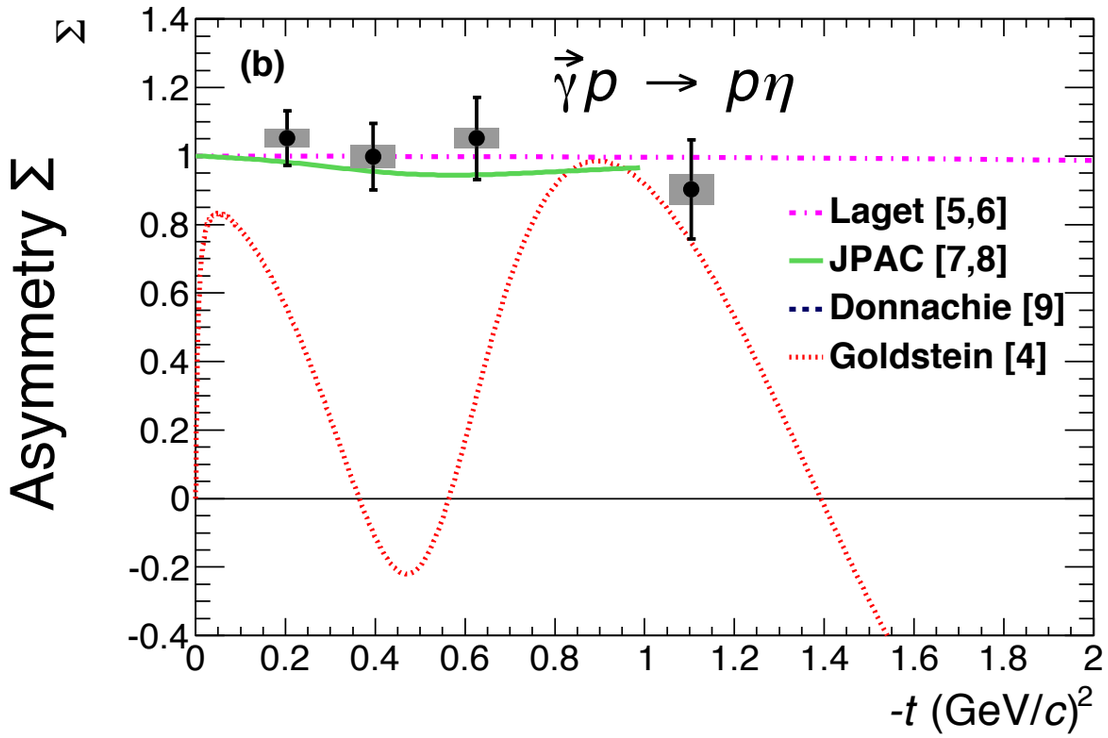
$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$



JPAC: Mathieu et al., PRD 92, 074013

Beam Asymmetries: $\gamma p \rightarrow p + \pi^0 / \eta$

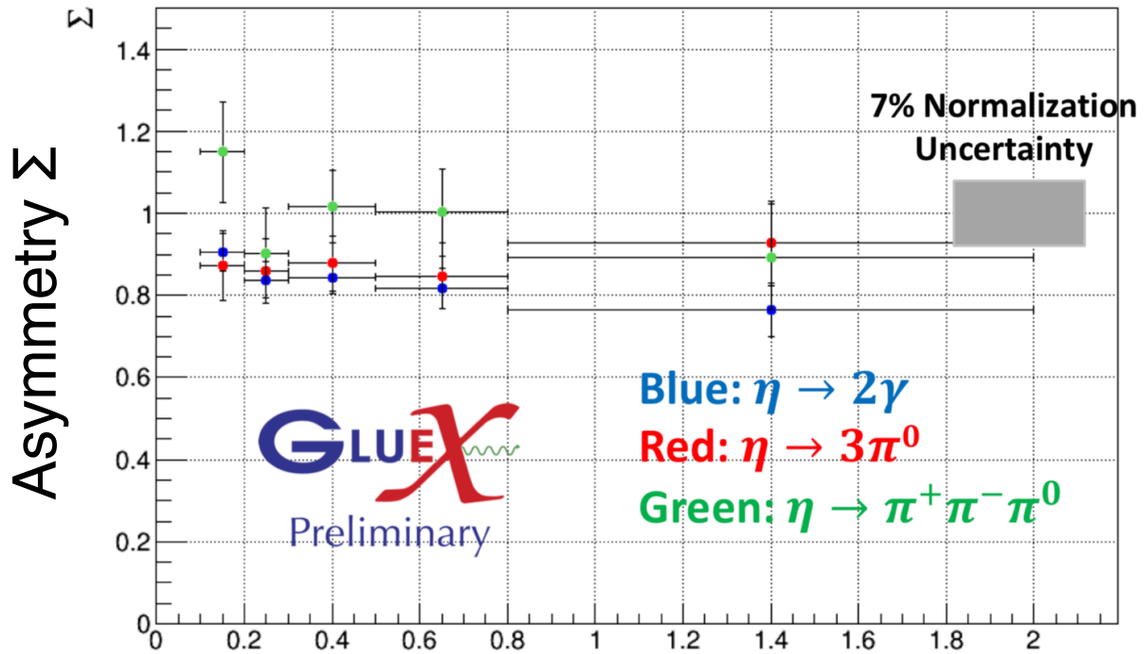


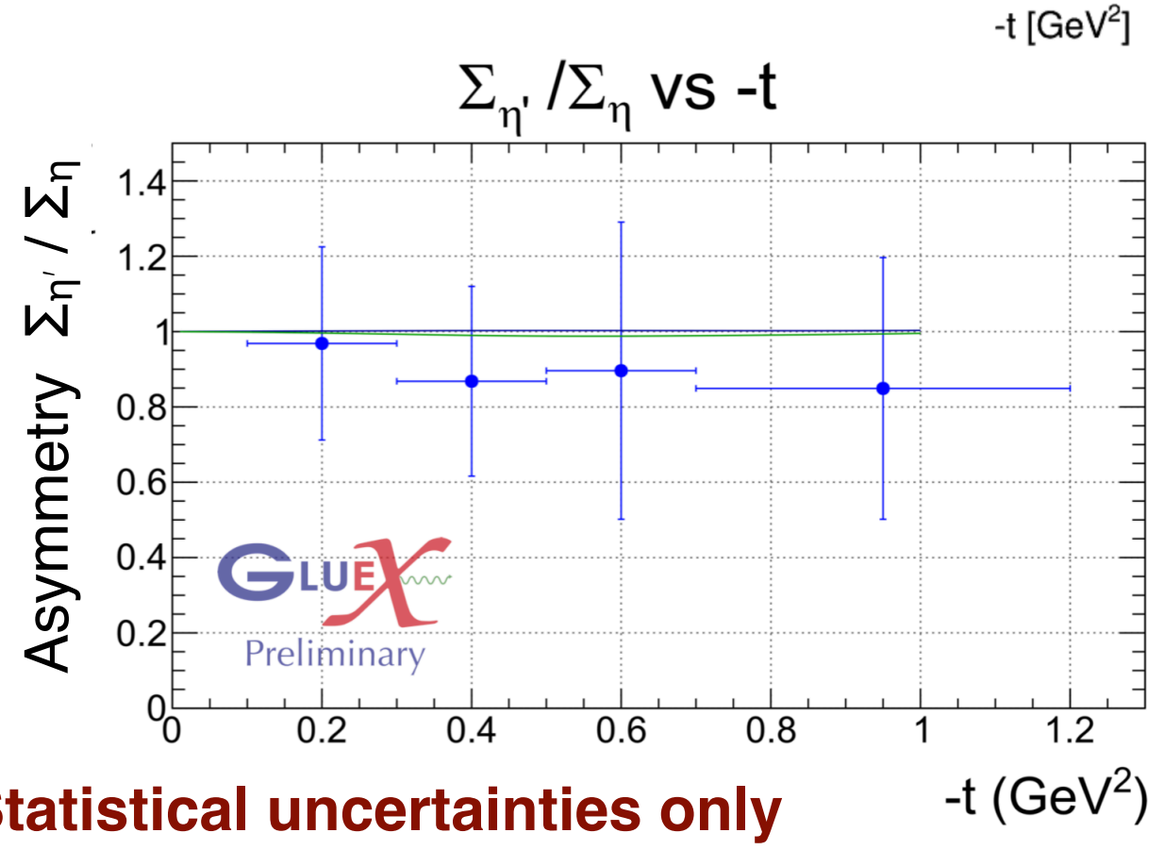


- First step towards study of photoproduction amplitudes using 2016 data
- **Σ ≈ 1** indicates vector exchange dominates at this energy
- First **η** measurement at this energy
- Constrains background to baryon resonance production at lower energies [e.g. **arXiv:1708.07779**]

First JLab 12 GeV publication:
Phys.Rev.C 95, 042201 (2017)

Beam Asymmetries: γ p → p + η / η′

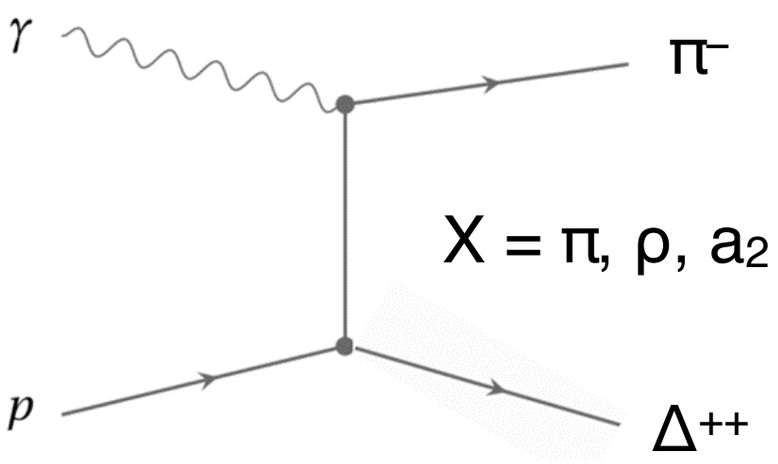




Statistical uncertainties only

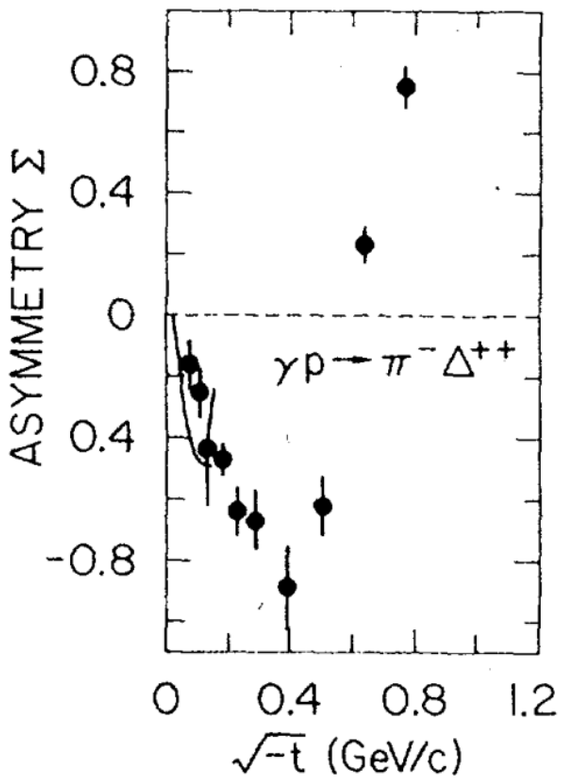
- Initial studies of η and η' beam asymmetries using 2017 data and additional decay modes
  - Production is consistent with vector exchange dominance
  - Expect similar mechanism for exotics
- Full GlueX-I data will provide a factor 5 more events
- Program of production amplitude studies is well underway

Beam Asymmetries: γ p → π⁻ Δ⁺⁺

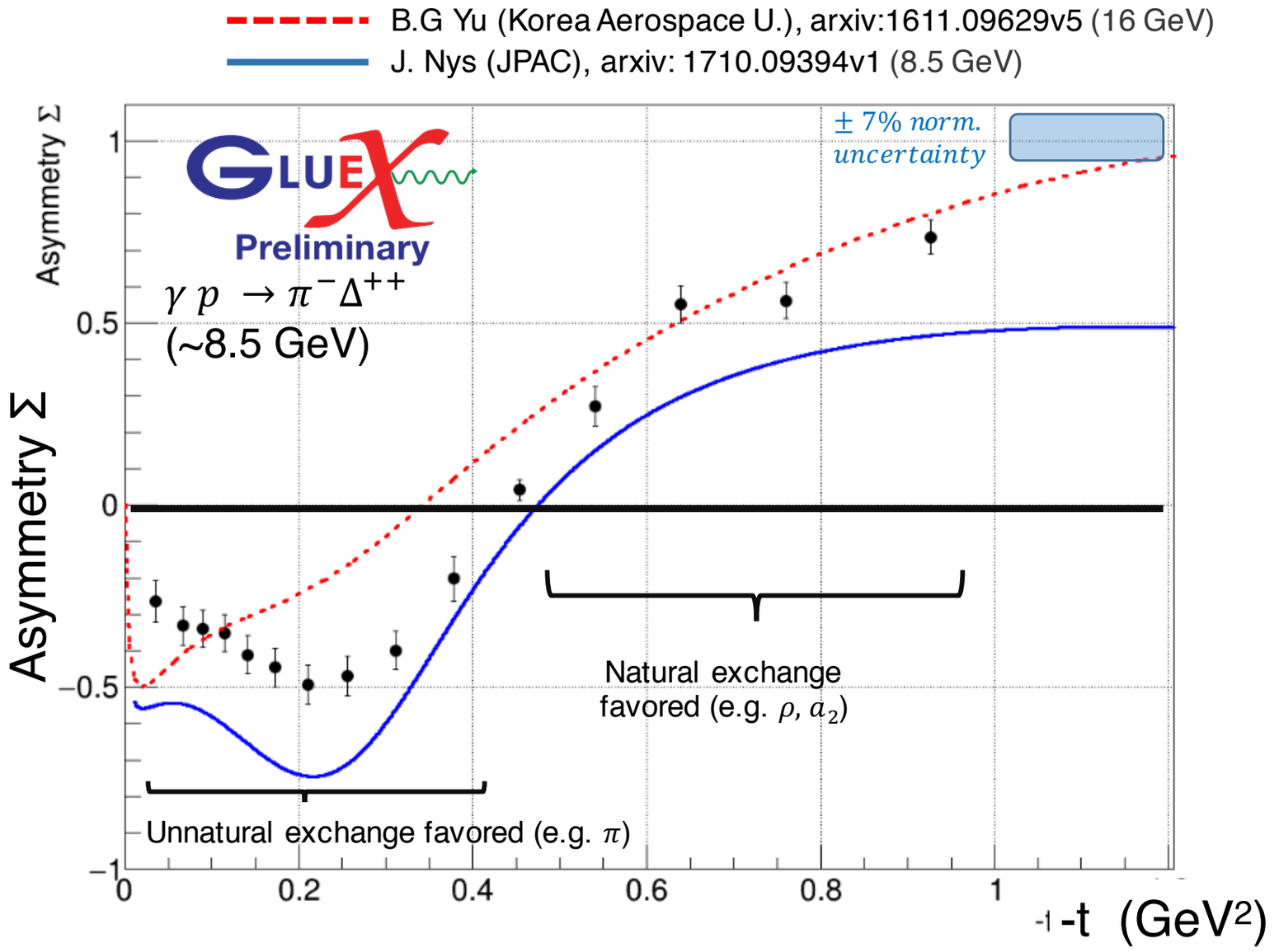


- Charged pseudoscalar beam asymmetry has more complicated t-dependance
- Preliminary results use order of magnitude more data than previous measurements

SLAC (16 GeV)

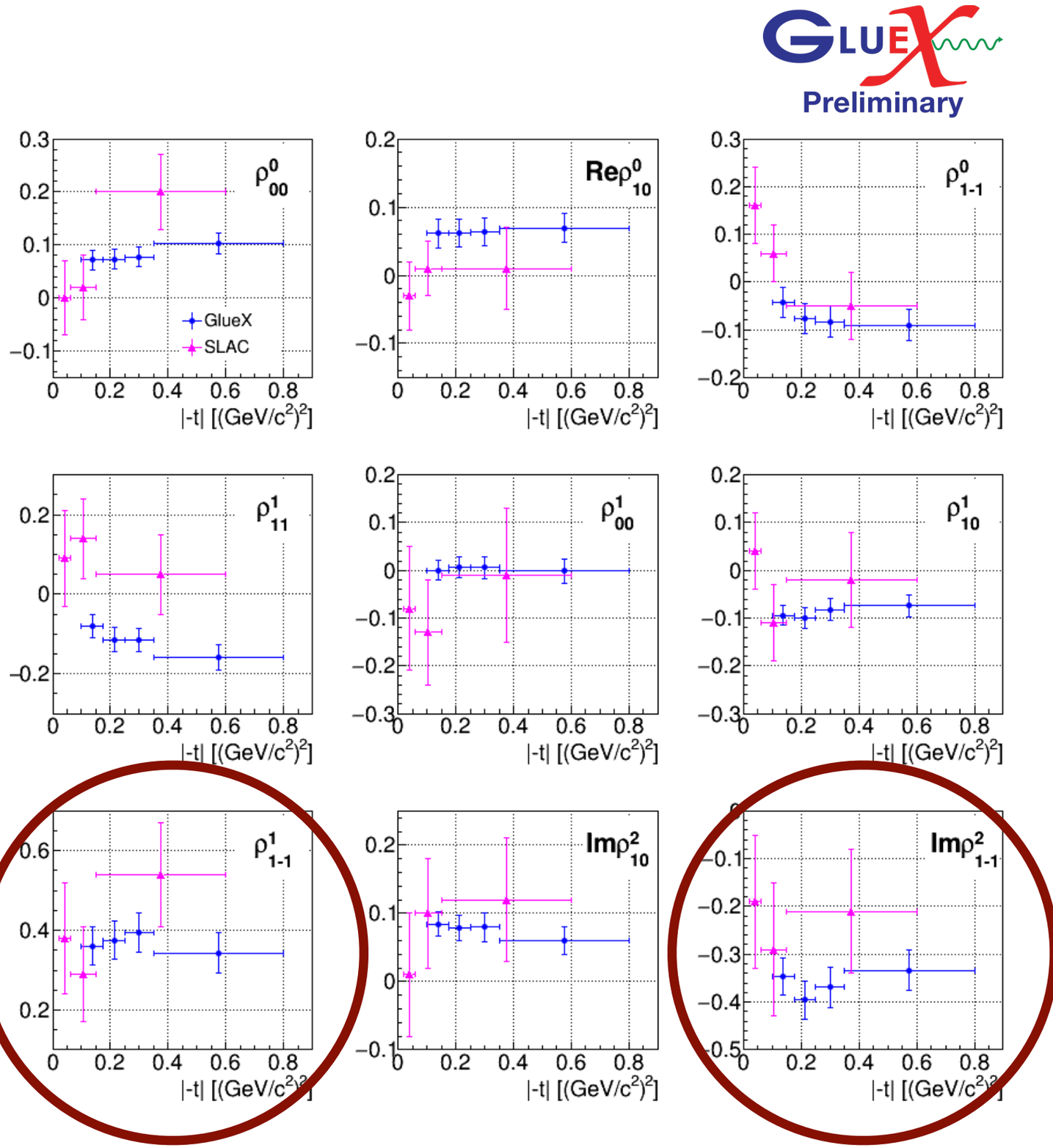


Phys. Rev. D **20**, 1553 (1979)

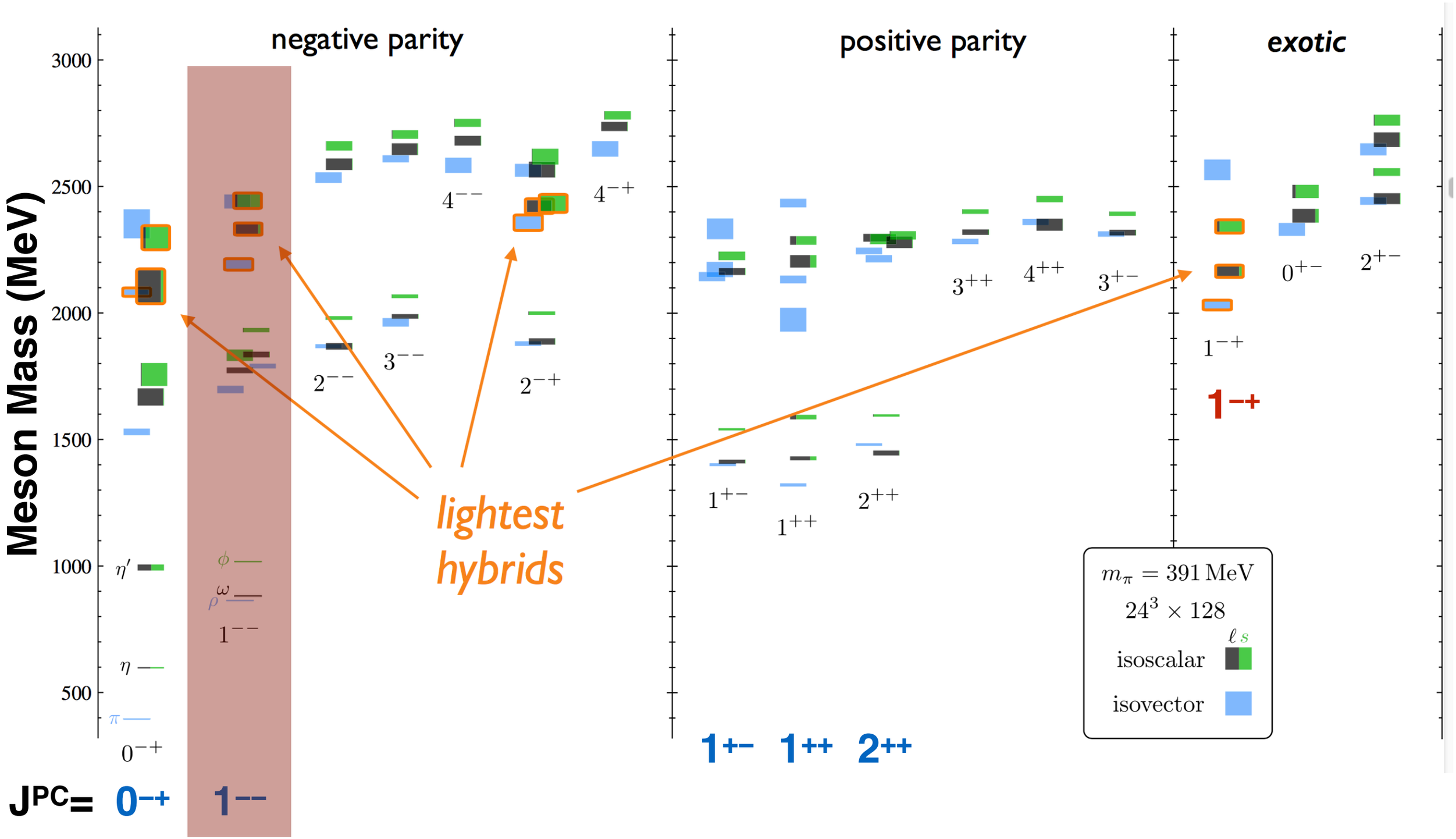


Spin Density Matrix Elements (SDMEs): γ p → p + ω

- SDMEs measure the transfer of polarization from the photon to the vector meson
  - Require understanding of detector acceptance
- Two matrix elements are particular sensitive to exchange particle in ω polarization transfer
  - Pomeron: **+1/2** and **–1/2**
  - Pion: **–1/2** and **+1/2**
- We observe around **+0.35** and **–0.35**
- **γ p → p + ϕ** and **p + ρ** also under analysis

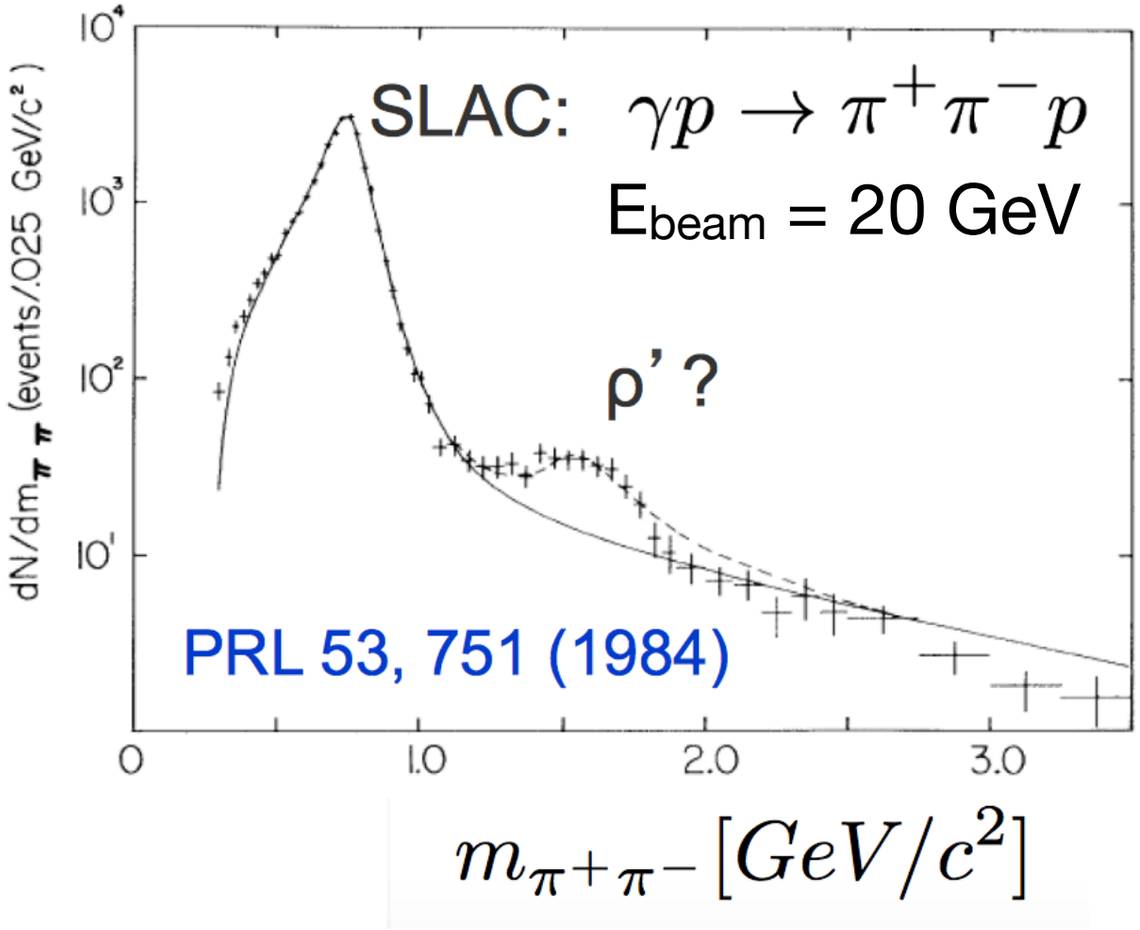


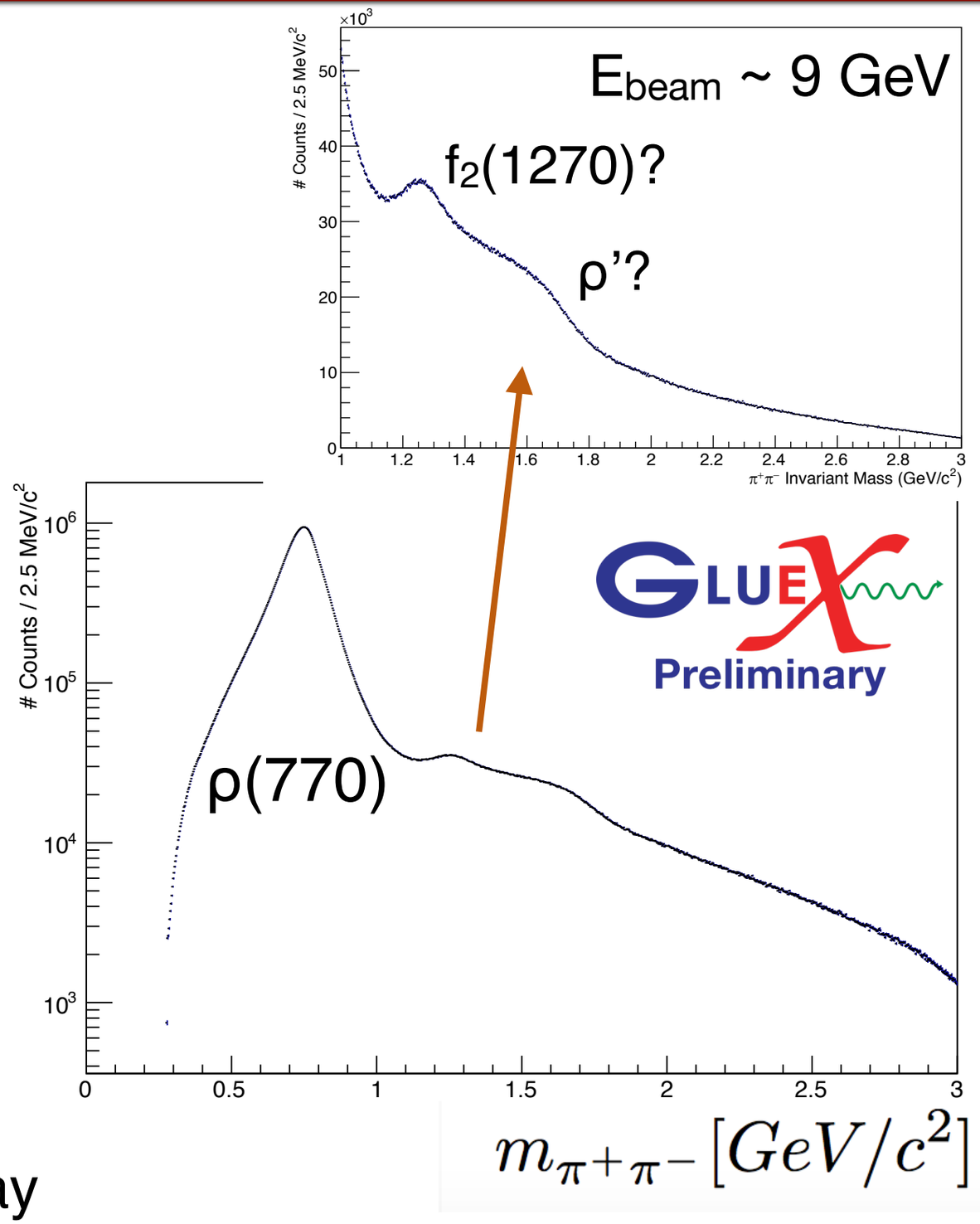
Light Meson Spectrum from Lattice QCD



HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

Spectroscopy Prospects: γ p → p + π⁺ π⁻

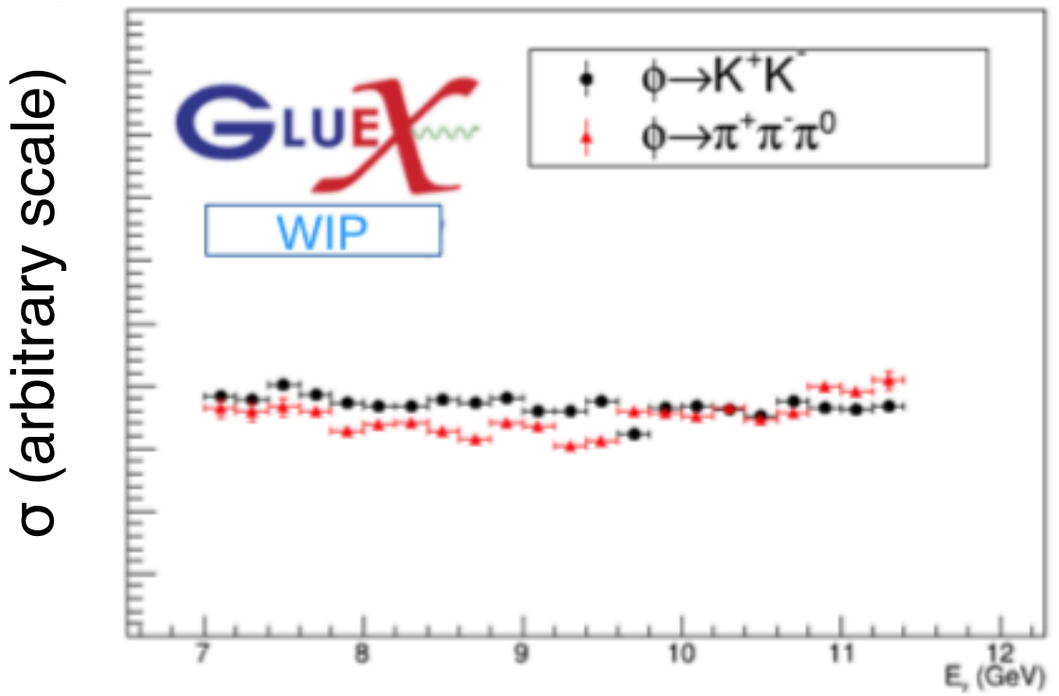


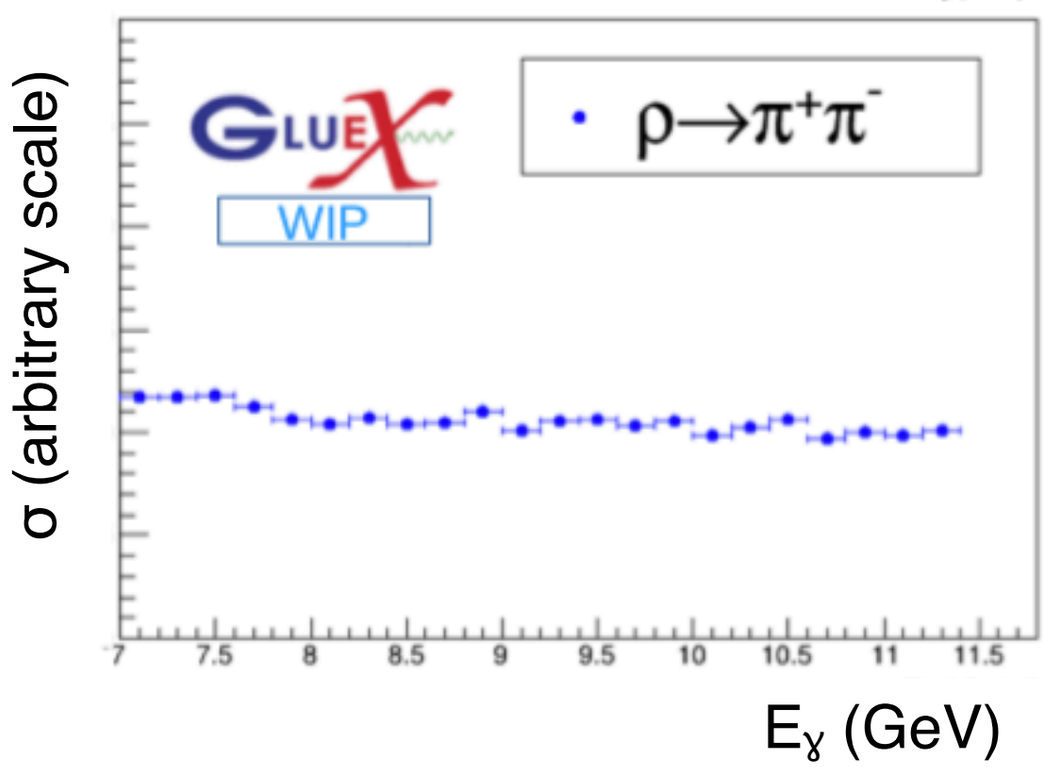


- Take fresh look at π⁺ π⁻ photoproduction
  - Using two-orders of magnitude more data than SLAC
  - Enhancements seen with M > 1 GeV
  - Moment / amplitude analysis underway
- K⁺ K⁻ photoproduction also being studied

Work Towards Vector Meson Production Cross Sections

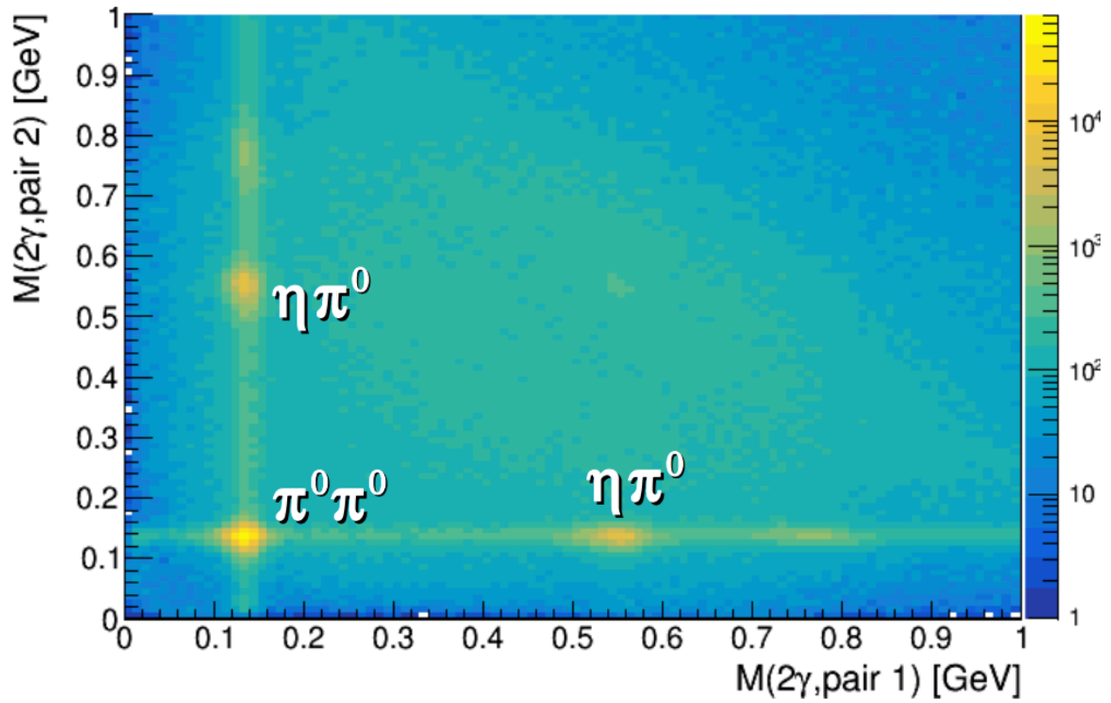
- Vector meson production cross sections provide important benchmarks
  - Require understanding of efficiencies and photon flux
  - Comparison with previous measurements
    - Photon energy and t dependence gives more insight into production mechanisms
- Very preliminary “Work In Progress” shows similar beam energy dependence to previous measurements

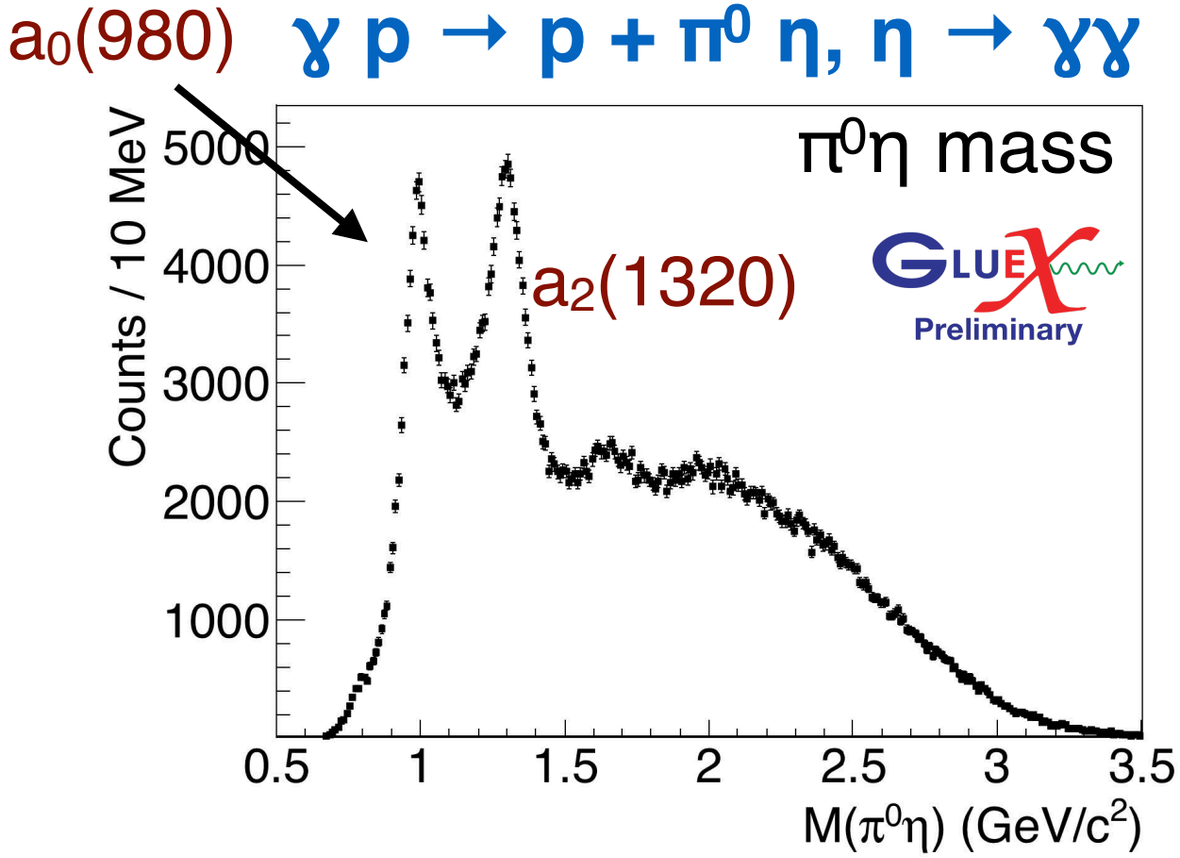


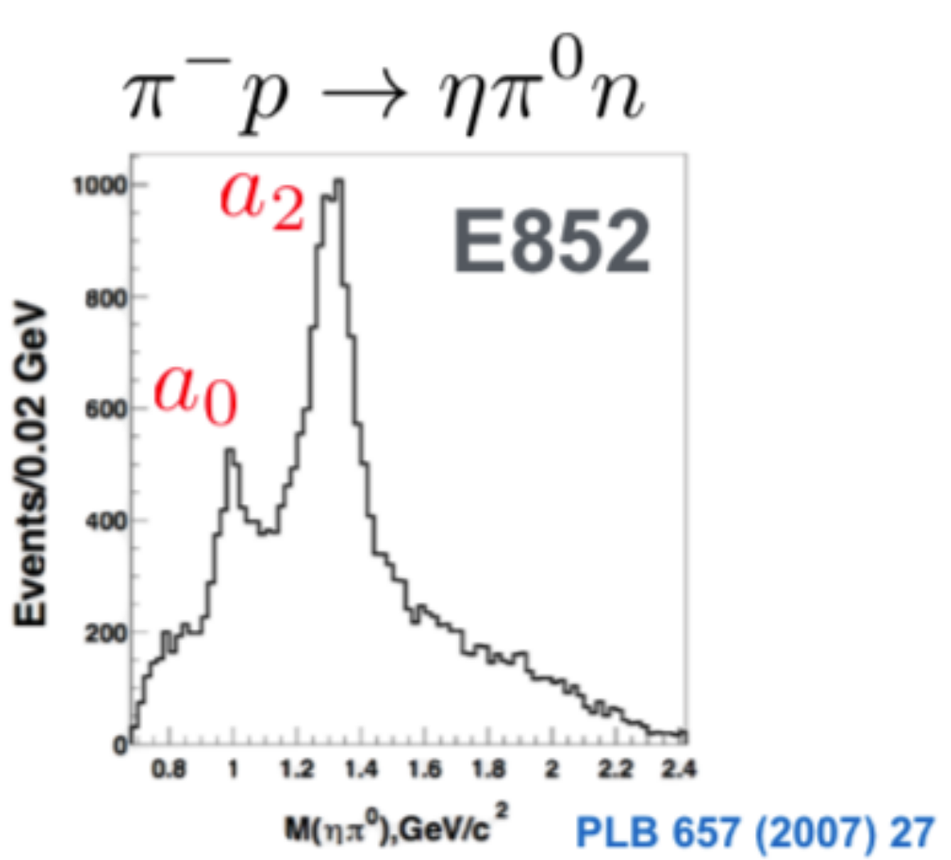


Spectroscopy Prospects: γ p → p + π⁰ η

- πη / πη′ promising channels for early hybrid searches
- With 20% of GlueX-I data, we see several well-known mesons
- Statistics are competitive with previous experiments



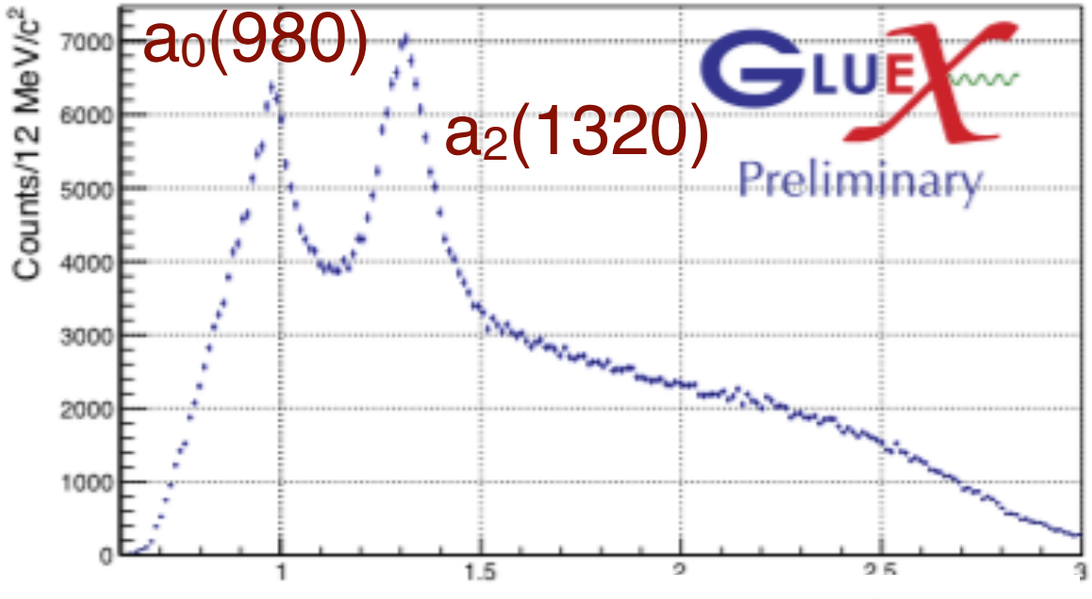




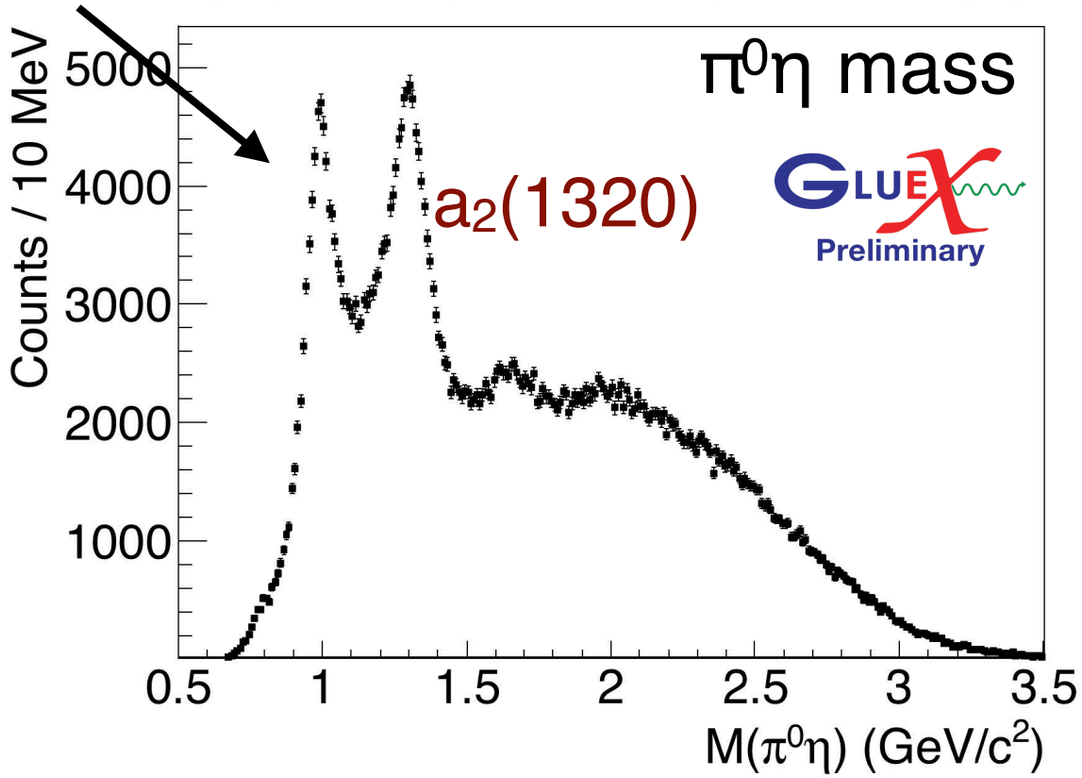
Spectroscopy Prospects: γ p → p + π^0 η

- $\pi^0\eta$ / $\pi^0\eta'$ promising channels for early hybrid searches
- With 20% of GlueX-I data, we see several well-known mesons
- Statistics are competitive with previous experiments

γ p → Δ^{++} + π^- η, η → γγ

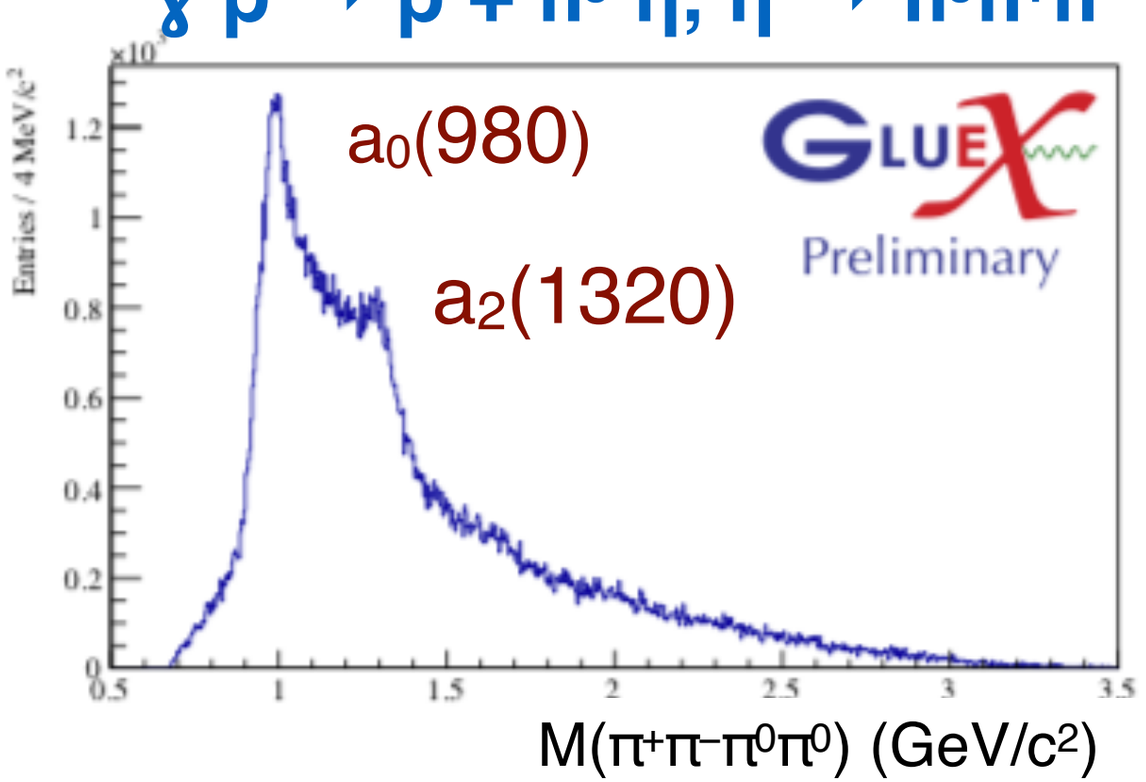


$a_0(980)$ γ p → p + π^0 η, η → γγ



M($\pi^-\eta$) (GeV/c²)

γ p → p + π^0 η, η → $\pi^0\pi^+\pi^-$



Spectroscopy Prospects: γ p → p + η π⁺ π⁻

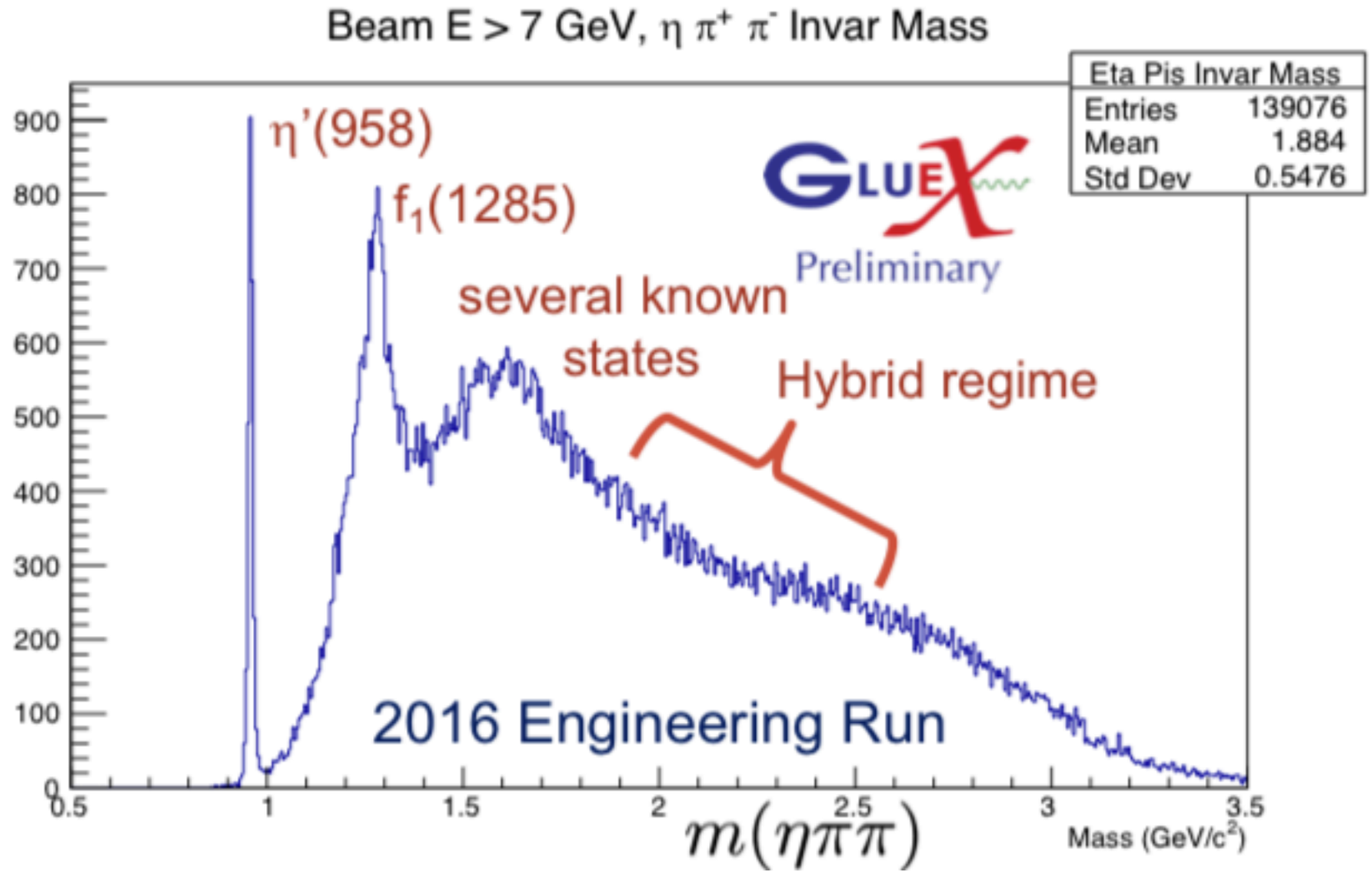
- Large sample of multiparticle decays collected as well
  - Example: η π⁺ π⁻ can have contributions from η_1 and b_1 hybrids
- Will analyze with models built from experience with 3-body reactions

Contributions from:

$\gamma p \rightarrow p\, a_2^{\pm} \pi^{\mp}$

$\gamma p \rightarrow p\, f_2\, \eta$

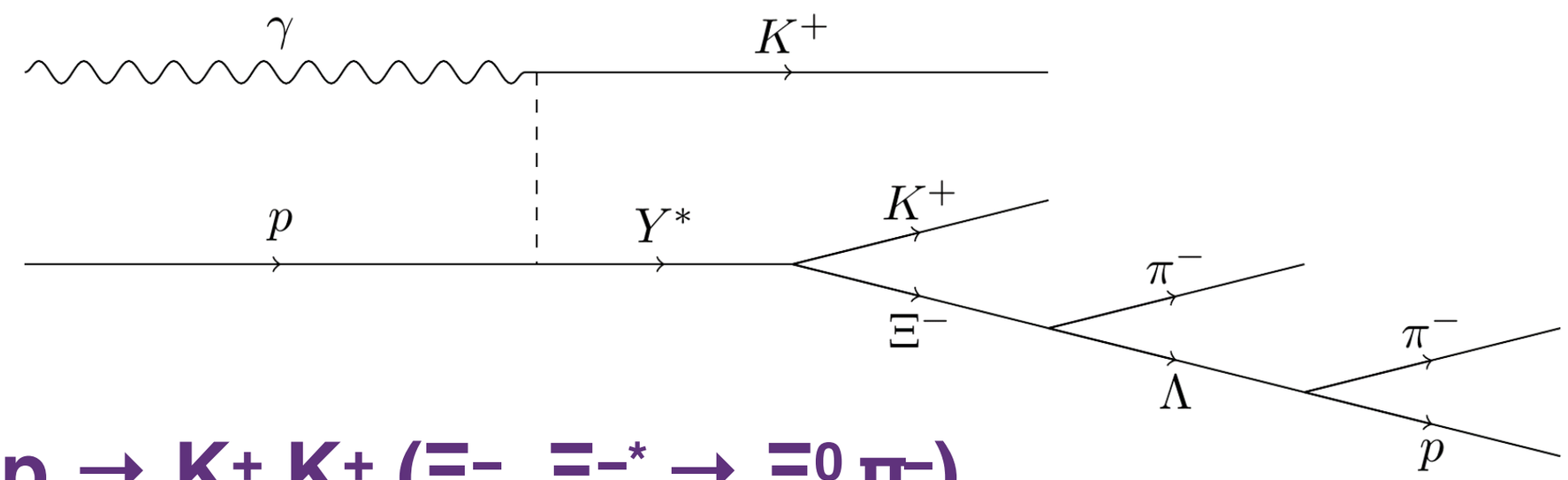
$\gamma p \rightarrow p\, \rho\, \eta$



Prospects for Cascade Spectroscopy

- The Cascade (ssd, ssu) spectrum is poorly known — nothing new since 1988!
  - LQCD predicts rich spectrum, many narrow states
- CLAS observed photoproduction of ground states
  - Production of excited cascades via a forward-going kaon?

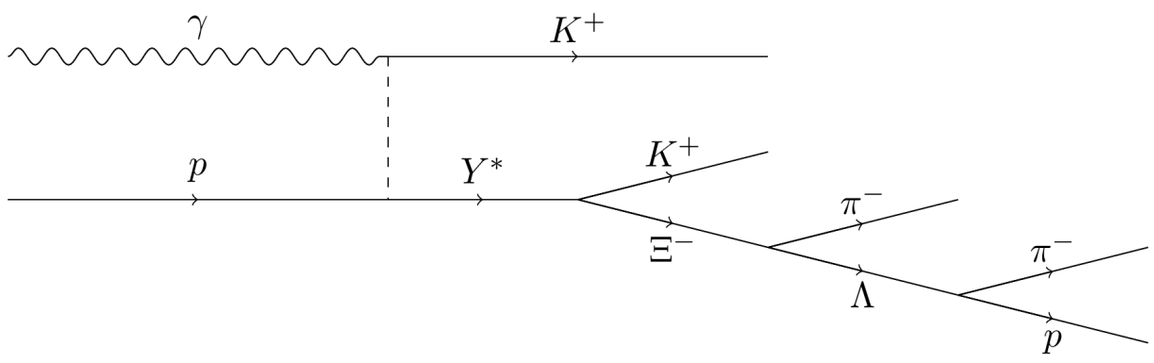
State		Quality
$\Xi(1320)$	$(1/2)^+$	****
$\Xi(1530)$	$(3/2)^+$	****
$\Xi(1690)$		***
$\Xi(1820)$	$(3/2)^-$	***
$\Xi(1950)$		***
$\Xi(2030)$		***

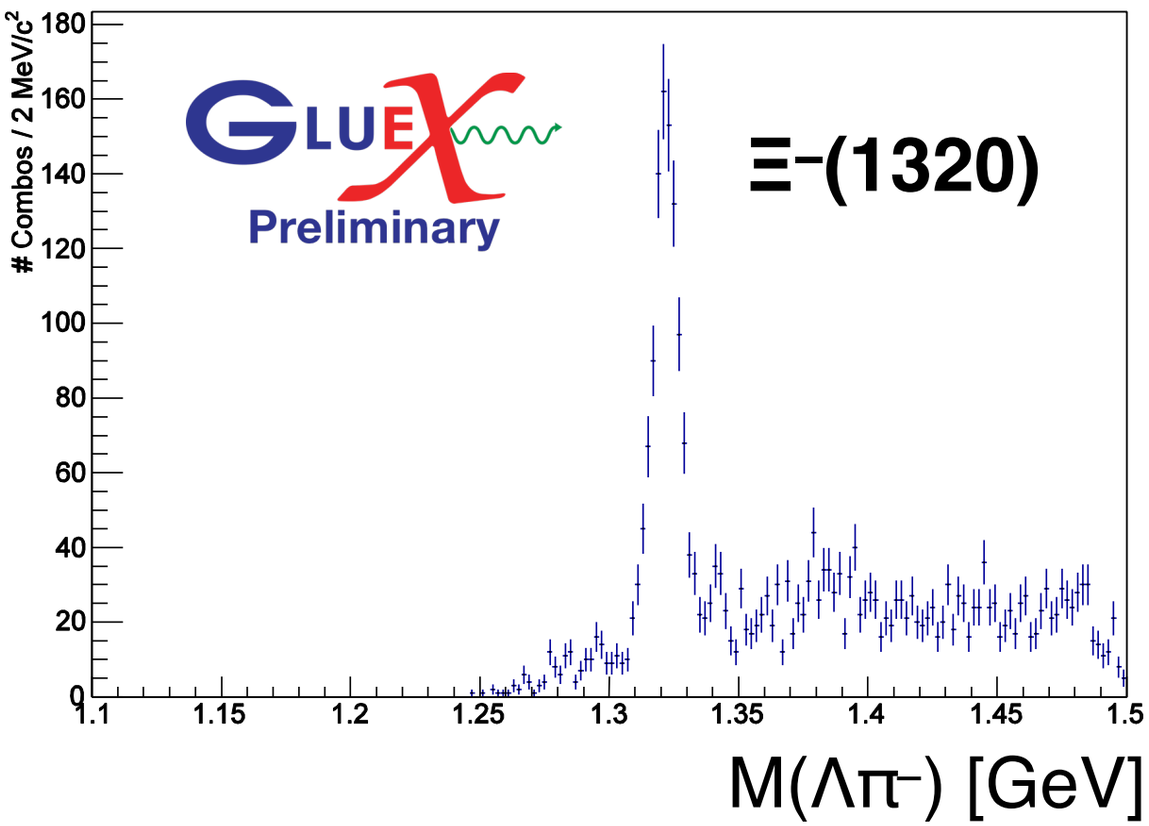


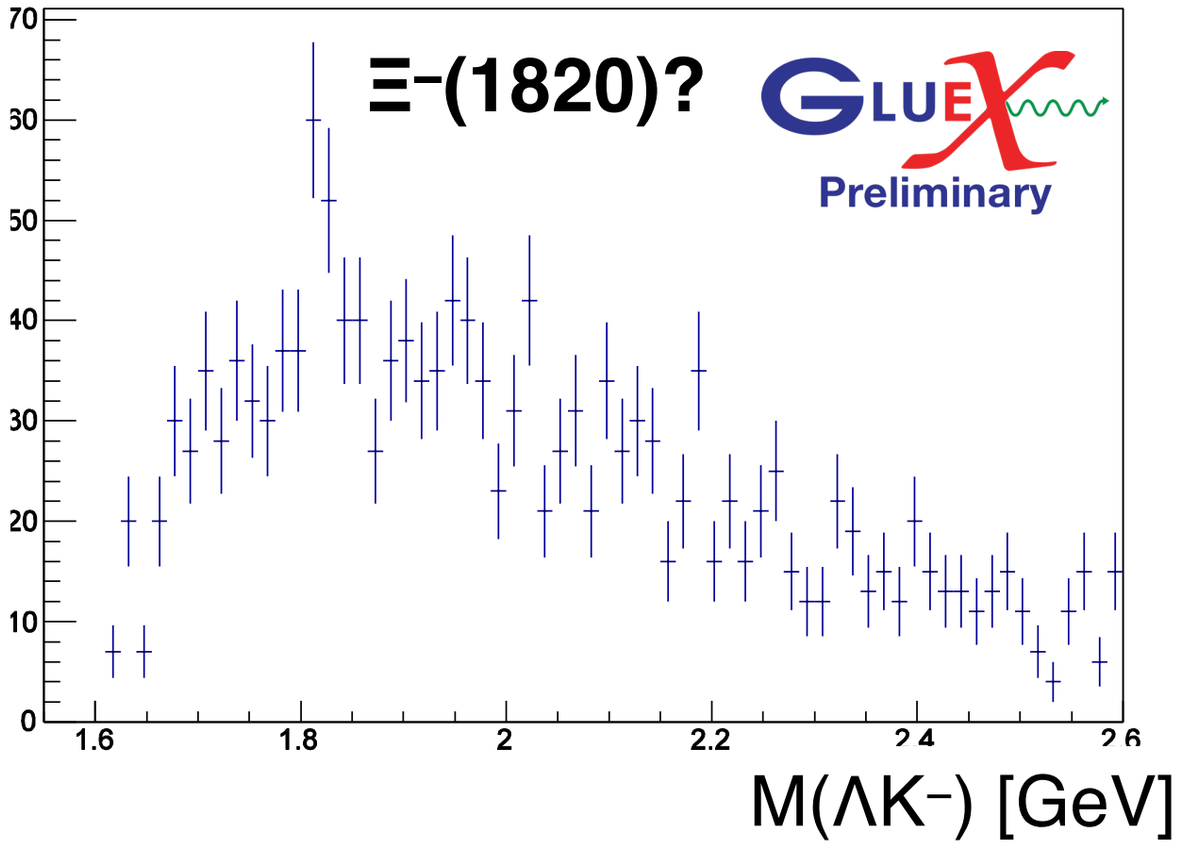
γ + p → K+ K+ (Ξ−, Ξ−* → Ξ0 π−)

Hunting for Excited Cascades

- GlueX can reconstruct these multi-step reactions
  - Full GlueX-I data opens door for more detailed studies
  - Searches in CLAS12 by Very Strange Group







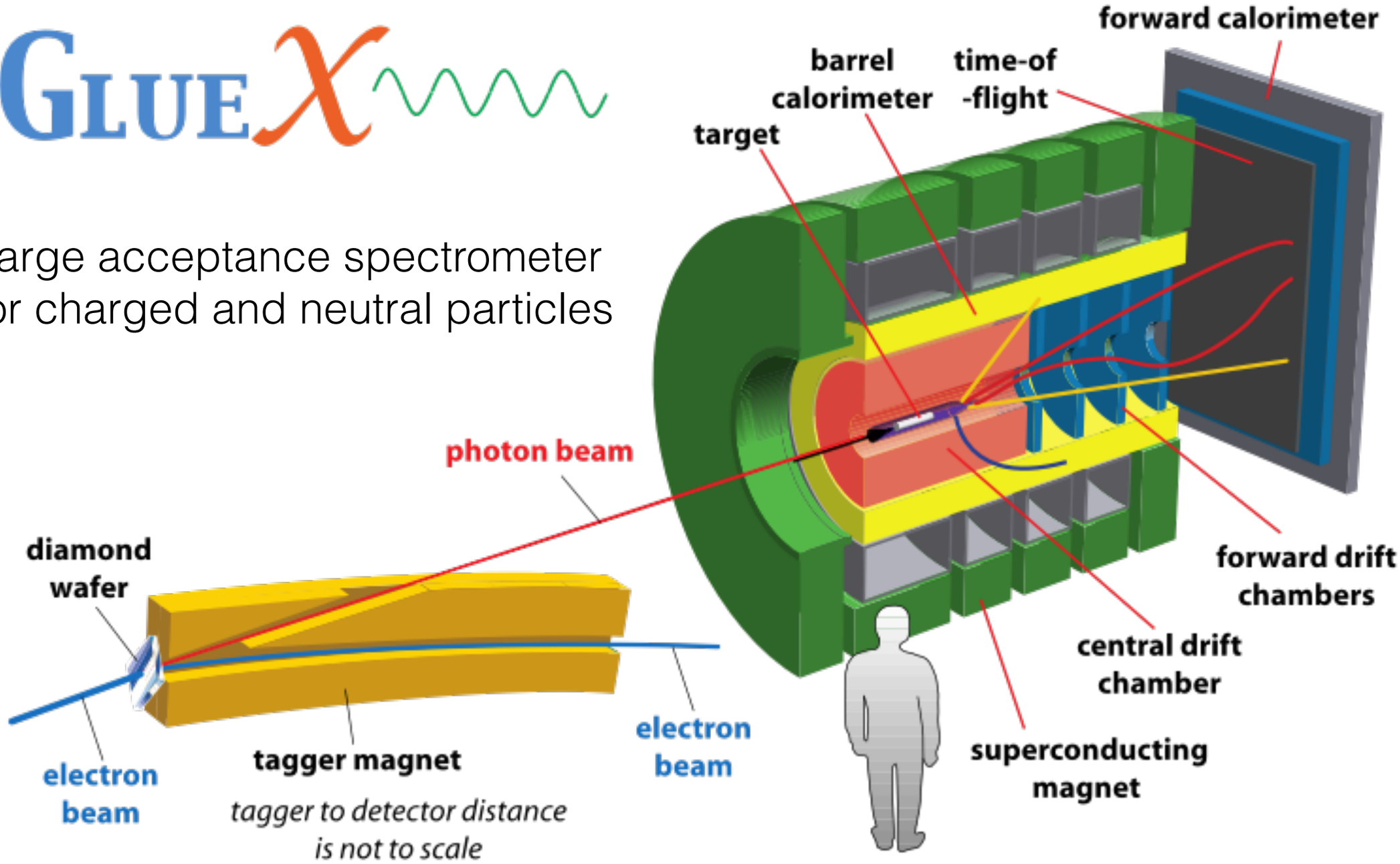
Summary

- Exciting time for light mesons! Confronting opportunities and challenge of new experiments is leading to new understanding.
- Entering era of large precision data
  - Unprecedented photoproduction data being collected by 12 GeV JLab experiments
  - Close collaboration between experiment and theory crucial for progress in understanding these data
- Hunt for hybrid mesons and other exotics at GlueX is on!
  - Many other opportunistic measurements being made: Cascade spectroscopy, J/ψ, B-boson, …
  - Expect many exciting results from CLAS12 as well!

Backup Slides

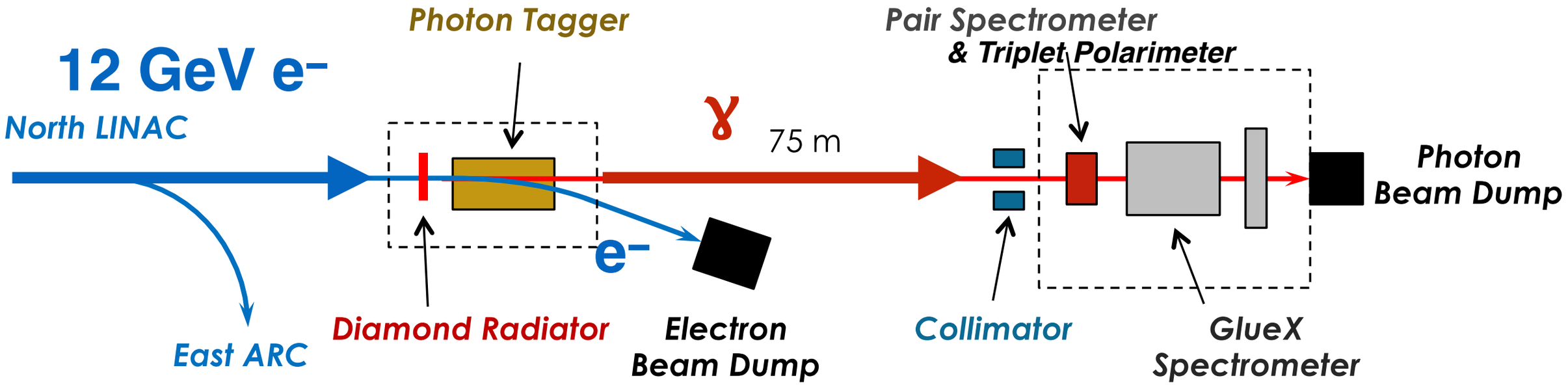
The GlueX Experiment

Large acceptance spectrometer
for charged and neutral particles

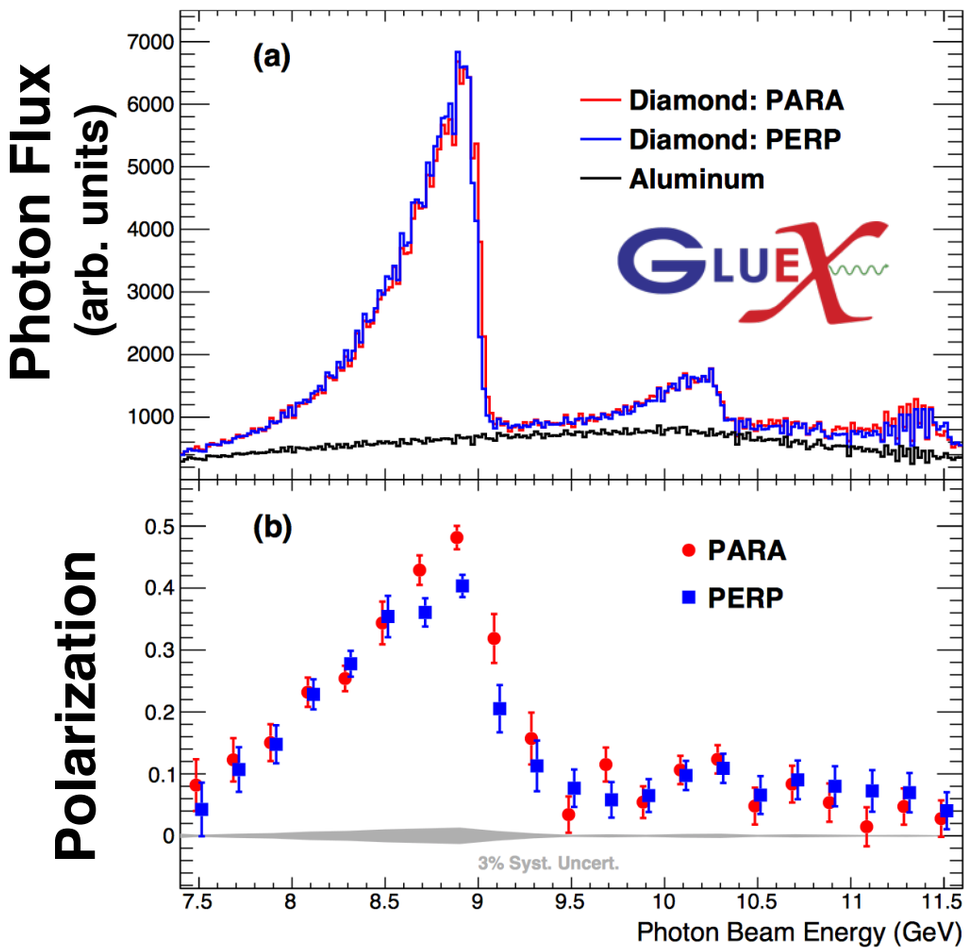


- 2016: ~80 hours of physics-quality commissioning data
- 2017: Start of data taking, ~8 times more data than 2016 (20% of GlueX-I)

The GlueX Experiment: Photon Beam

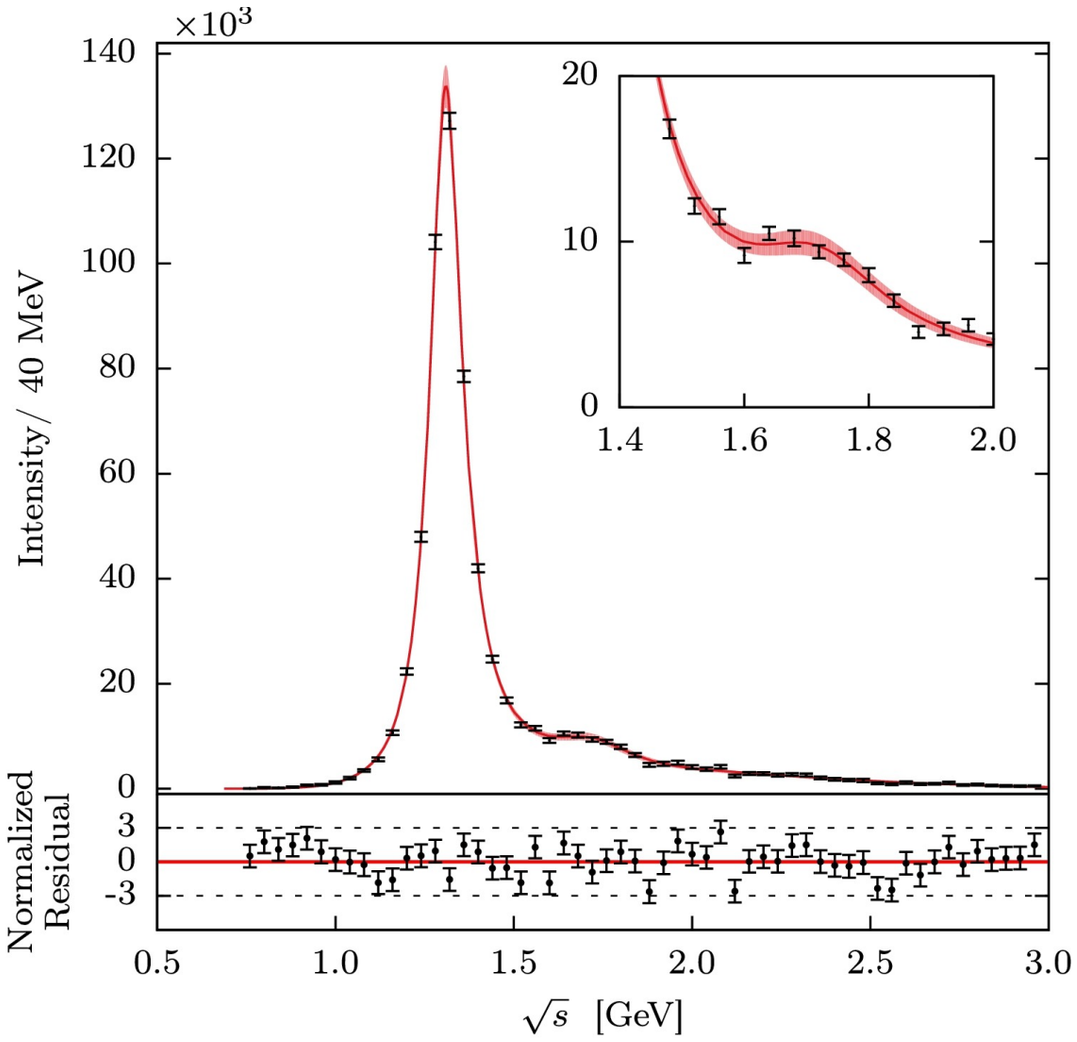


- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Design intensity of 10^8 γ/s in peak



Sidebar: Experiment and Theory Working Hand-in-Hand

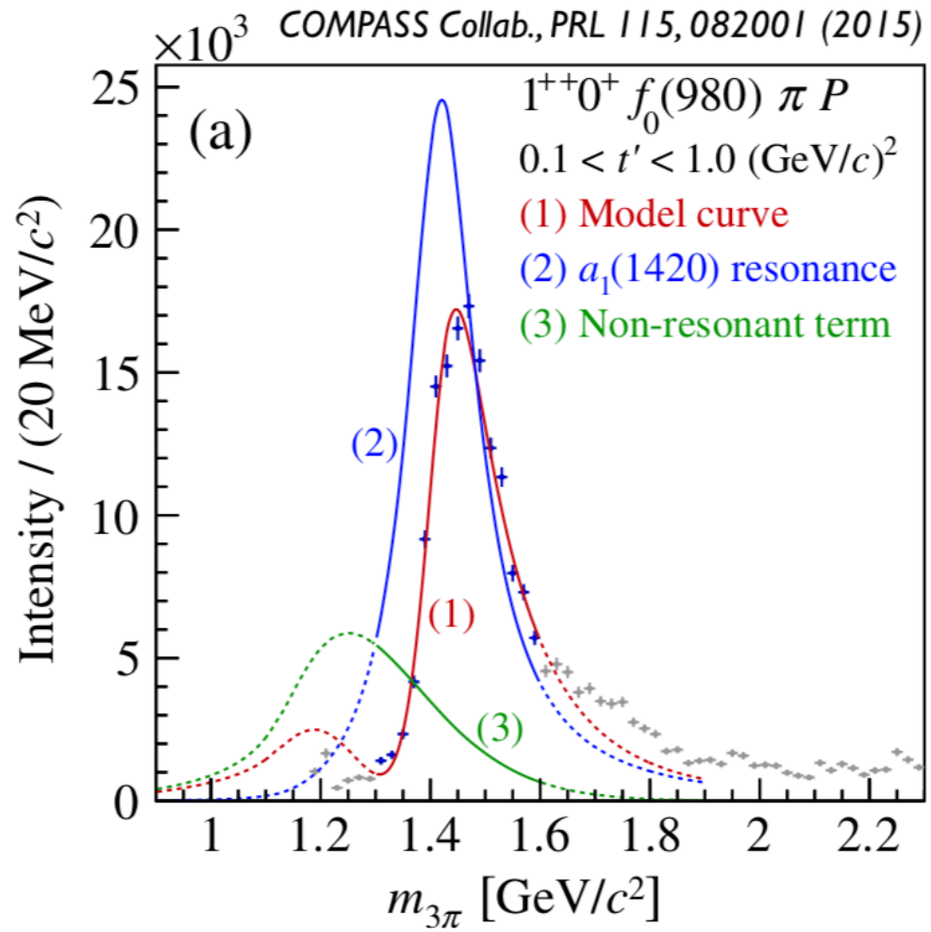
D-wave in $\pi^- p \to p\, \eta\pi^-$



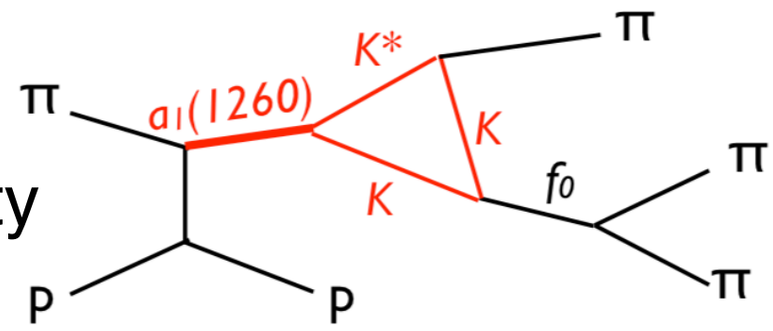
Extract resonance parameters with unitary reaction model

A. Jackura et al. [JPAC and COMPASS Collaborations], PLB 779, 464 (2018)

a1(1420) → f0(980) π



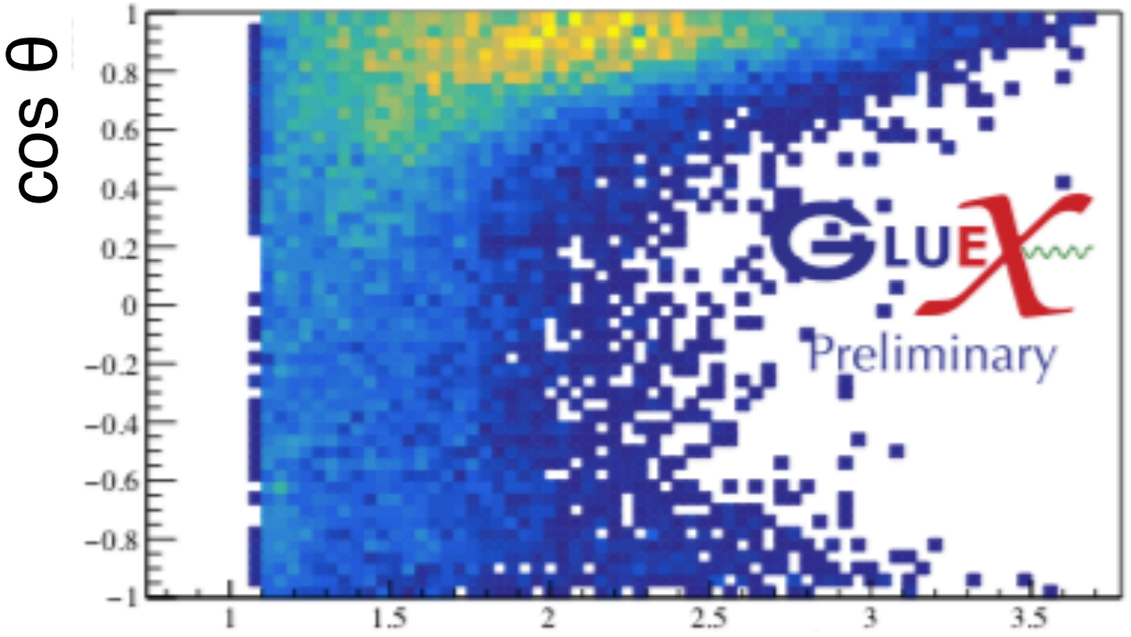
Describe non-qq candidate as triangle singularity



M. Mikhasenko et al. [JPAC and COMPASS Collaborations], in preparation

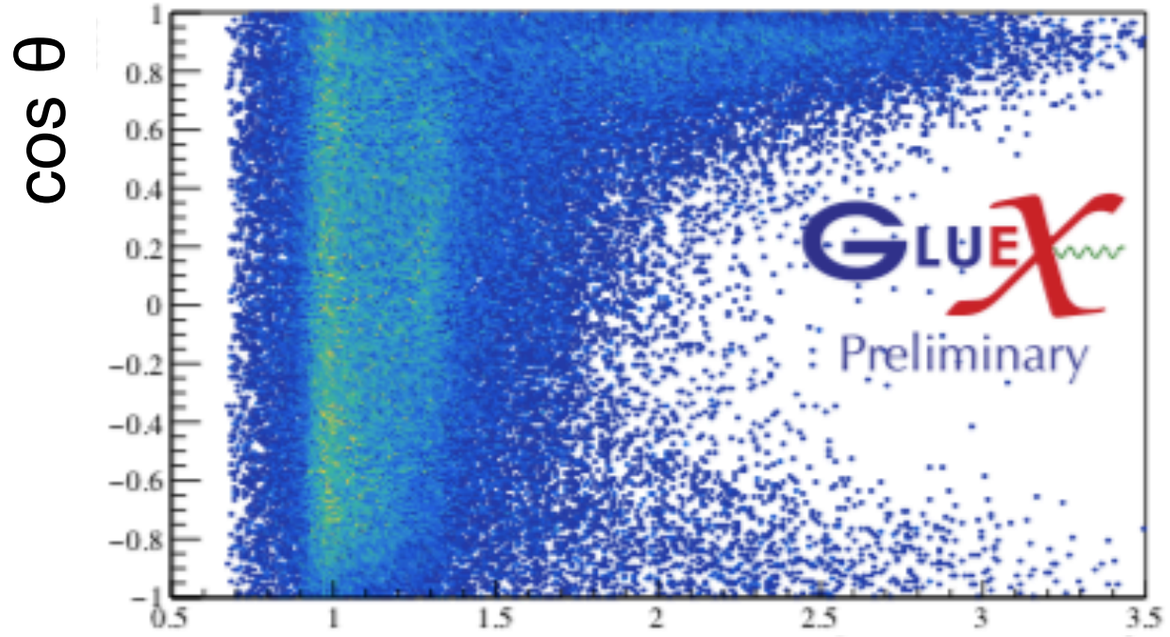
Angular Correlations in γ p → p + 4γ

$\eta'\pi^0$



η′π⁰ invariant mass (GeV)

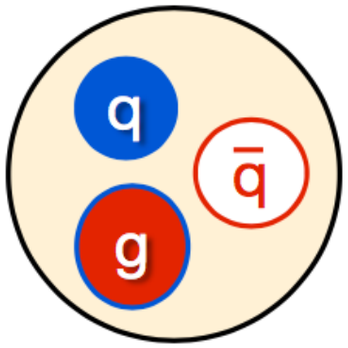
$\eta\pi^0$



ηπ⁰ invariant mass (GeV)

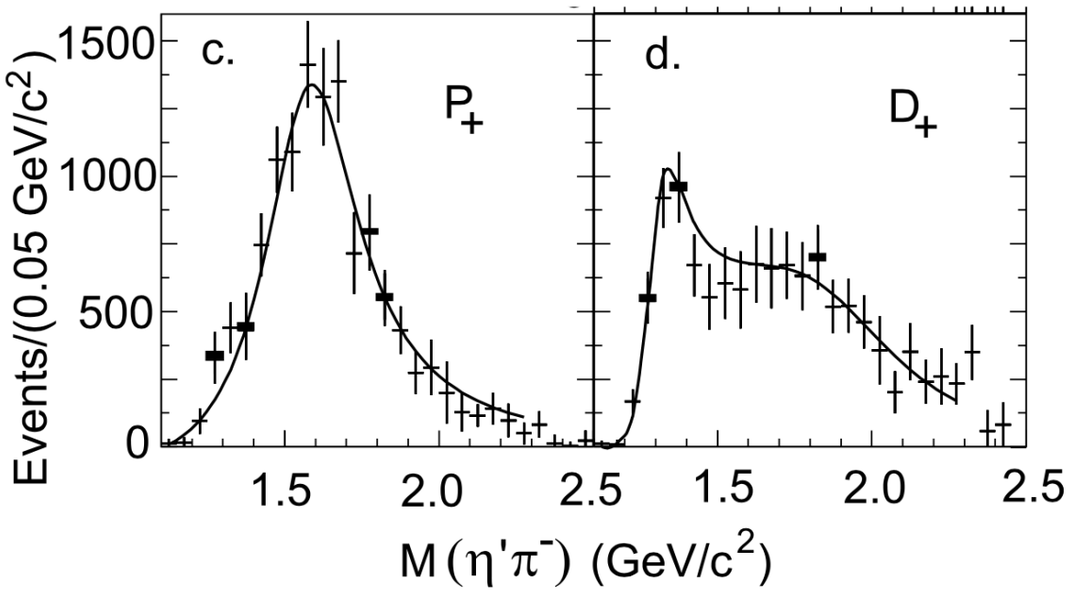
- Production near cos θ ~ 1 corresponds to meson production
- Stronger signal in η′π⁰ than ηπ⁰

Evidence for exotic light-quark mesons



$$\pi_1 \to \eta' \pi$$

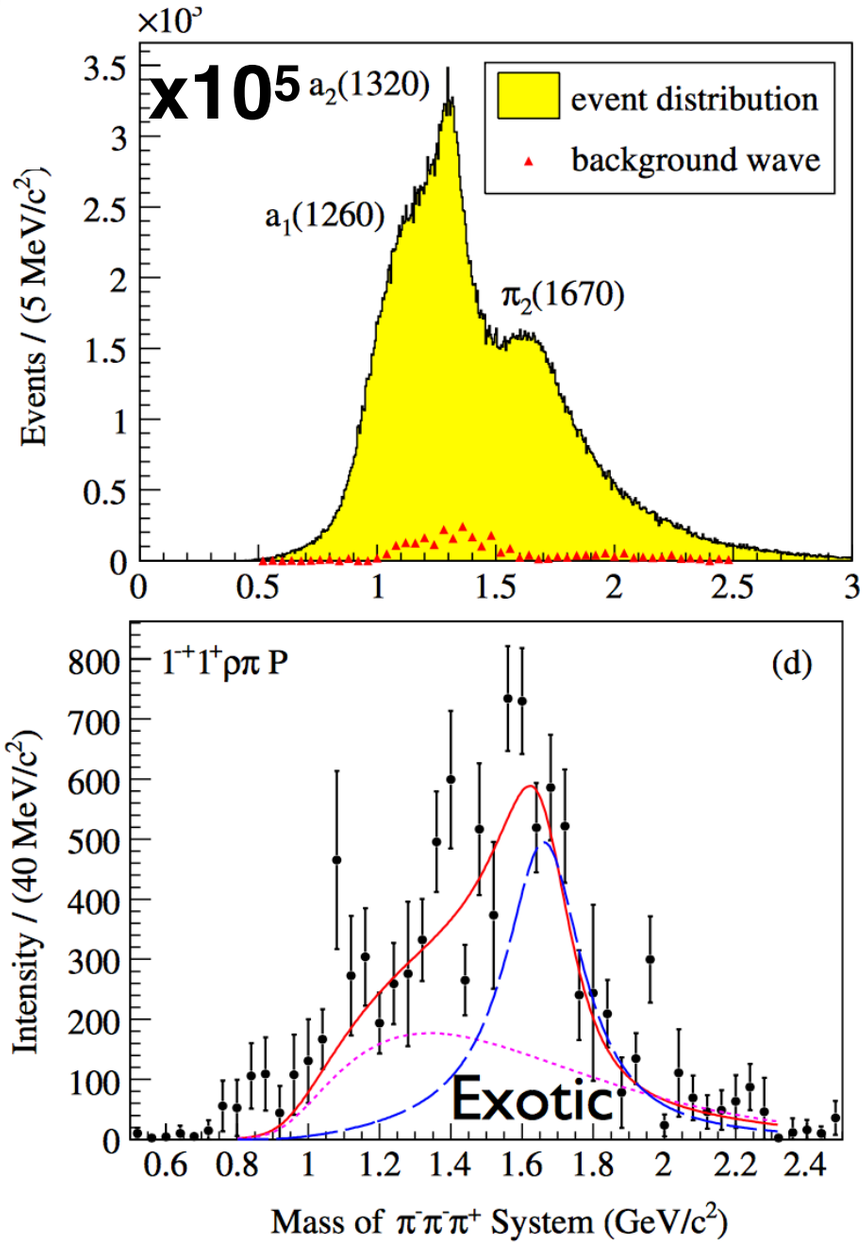
E852: 18 GeV π on p



PRL 86, 3977 (2001)

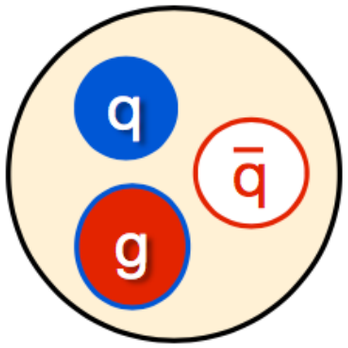
$$\pi_1 \to \rho\pi$$

COMPASS: 190 GeV π on Pb



PRL 104, 241803 (2010)

Evidence for exotic light-quark mesons



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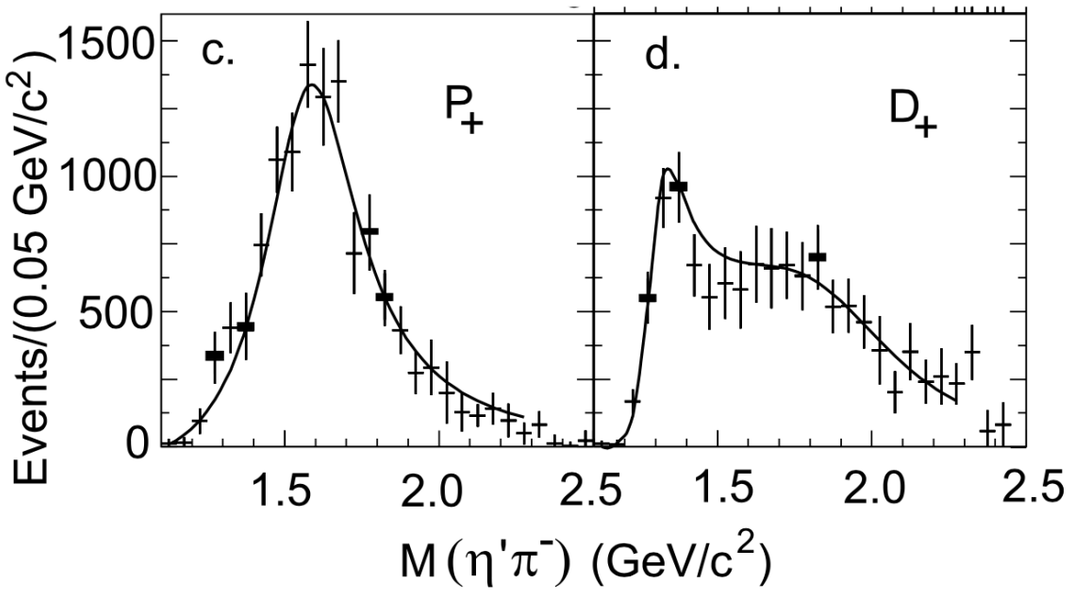
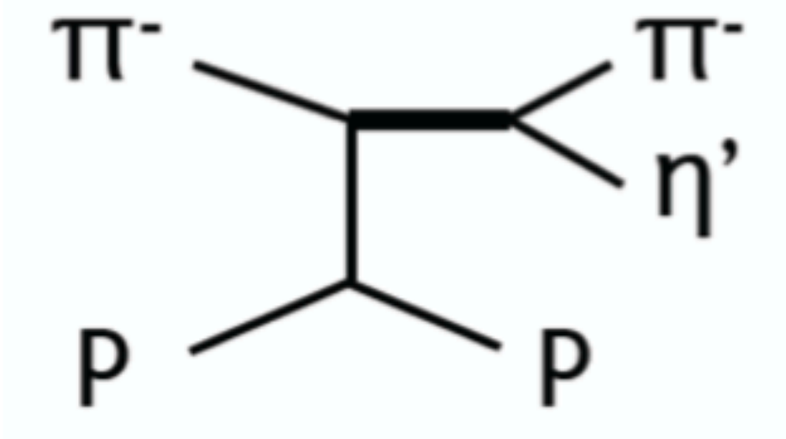
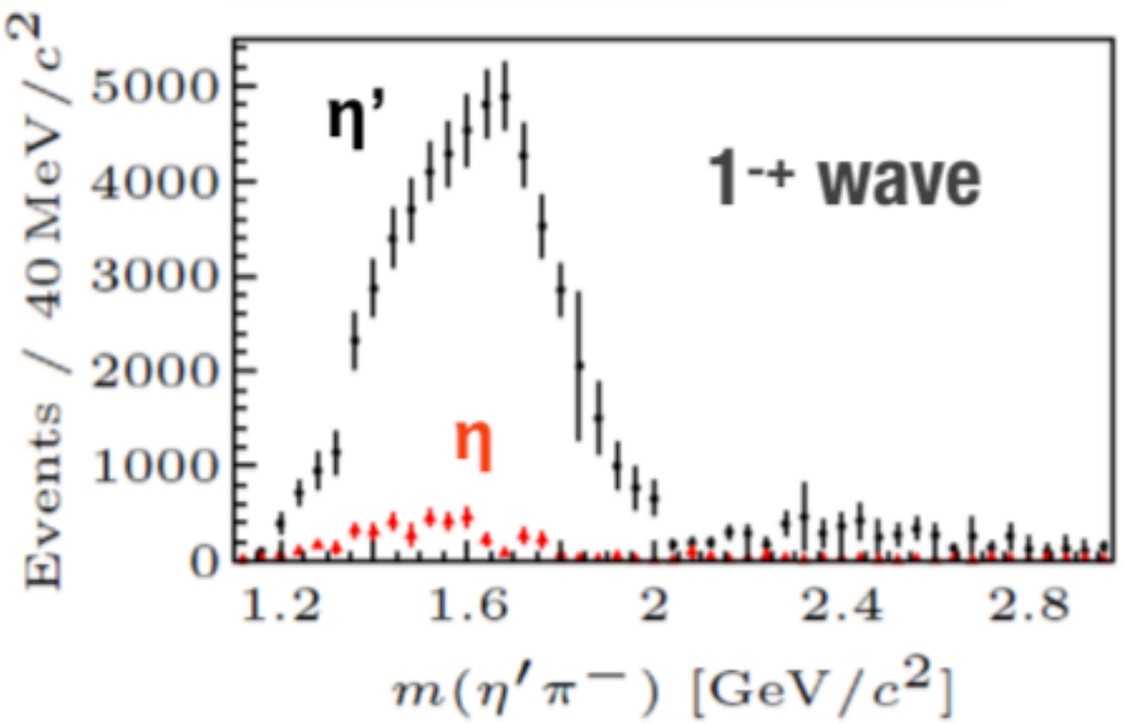


PRL 86, 3977 (2001)

Compass: PLB 740 (2015) 303



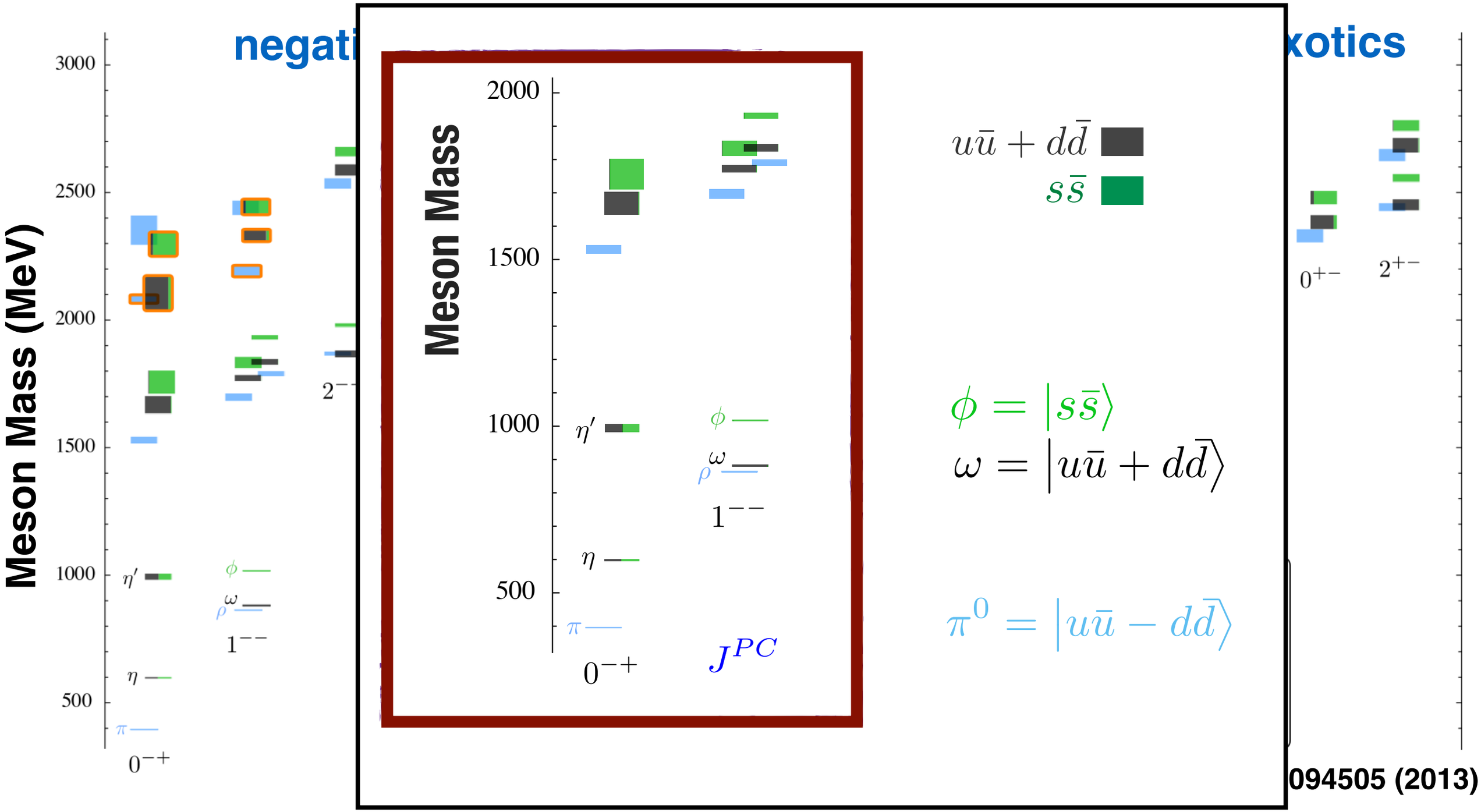


Evidence for exotic light-quark mesons

Experiment	Beam Momentum (GeV/c)	Reaction	Resonance
GAMS	32, 38, 100	$\pi^- p \to \pi^0 \eta n$	$\pi_1(1400)$
KEK	6.3	$\pi^- p \to \pi^- \eta p$	?
E852	18	$\pi^- p \to \pi^- \eta(') p$	$\pi_1(1400/1600)$
Crystal Barrel	Annihiation	$\bar{p} n \to \pi^- \pi^0 \eta$	$\pi_1(1400)$
VES	37	$\pi^- p \to \pi^- \eta(') p$	$\pi_1(1600)$?
COMPASS	190	$\pi^- p \to \pi^- \eta(') p$	?
CLAS	5.5	$\gamma p \to \pi^- \eta \Delta^{++}$	(not published)

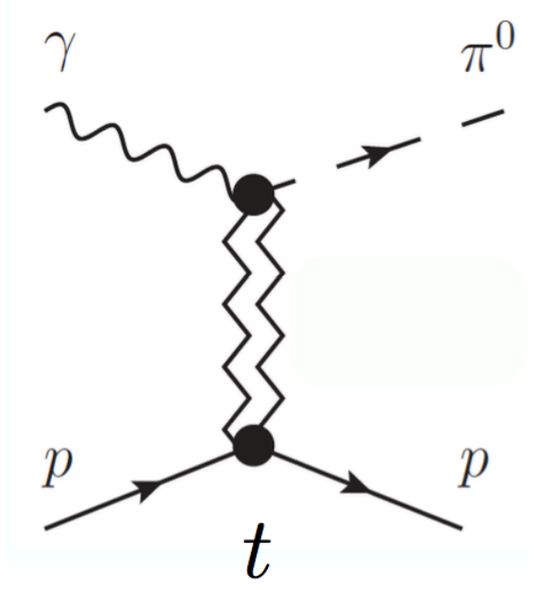
Exchange		Exotic Final States	
$\mathbb{P}$	0^{++}	b, h, h'	$2^{+-}, 0^{+-}$
π^0	0^{-+}	b_2, h_2, h_2'	2^{+-}
$\pi^\pm$	0^{-+}	$\pi_1^\pm$	1^{-+}
ω	1^{--}	π_1, η_1, η_1'	1^{-+}

Light Meson Spectrum from Lattice QCD



- Many broad, overlapping states. Overpopulation of states?
- Progress requires multiple channels, amplitude analysis…

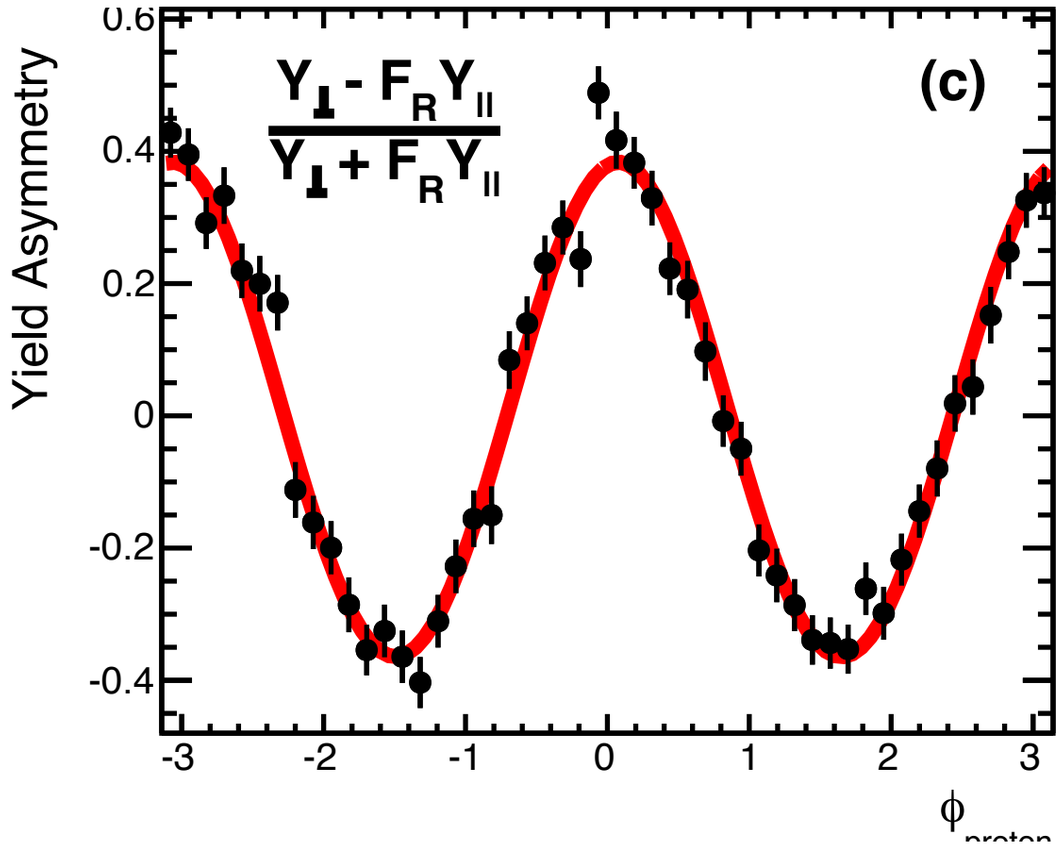
Beam Asymmetries: γ p → p + π⁰ / η



Exchange J^{PC}

$$1^{--} : \omega, \rho$$

$$1^{+-} : b, h$$



$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$

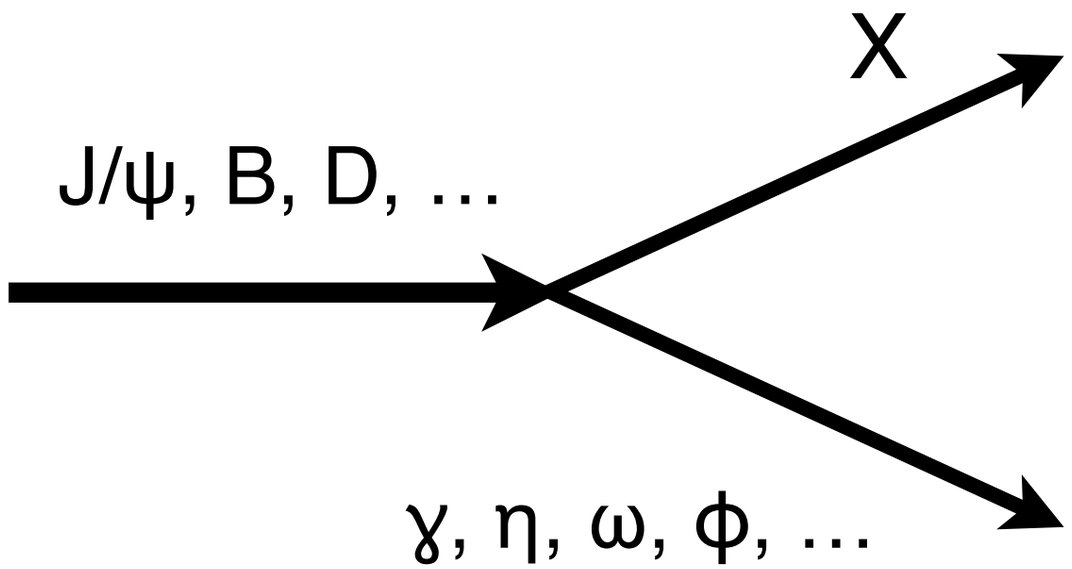
JPAC: Mathieu et al., PRD 92, 074013

$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

- Understanding production mechanisms necessary to determine J^{PC} of mesons in amplitude analyses
- Beam asymmetry Σ yields information on production mechanisms

How Do We Make Mesons?

- Production in Hadron Decays: BES, BaBar, Belle, CLEO, …
  - Simple initial state
  - Clean event samples
  - Small sample size



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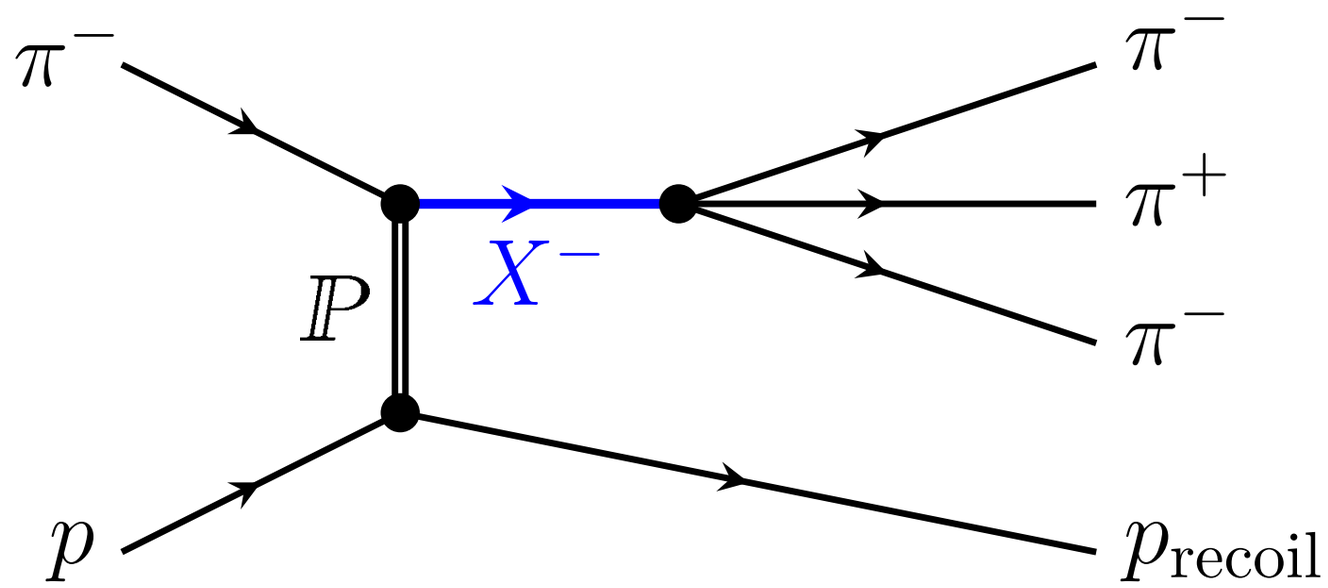
  - Large event samples, more complicated initial state
  - Need more sophisticated models of reaction



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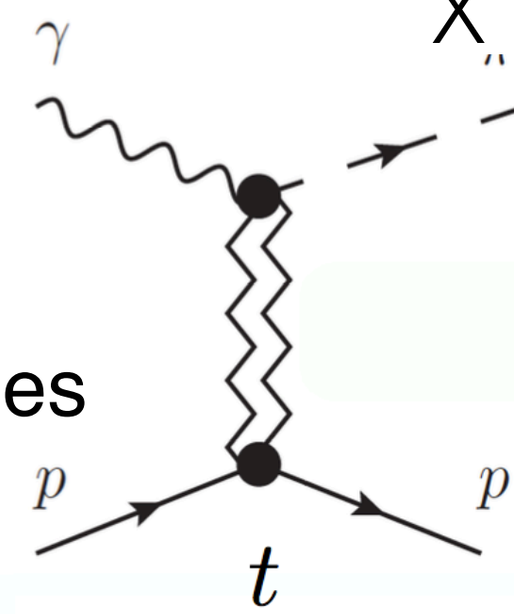
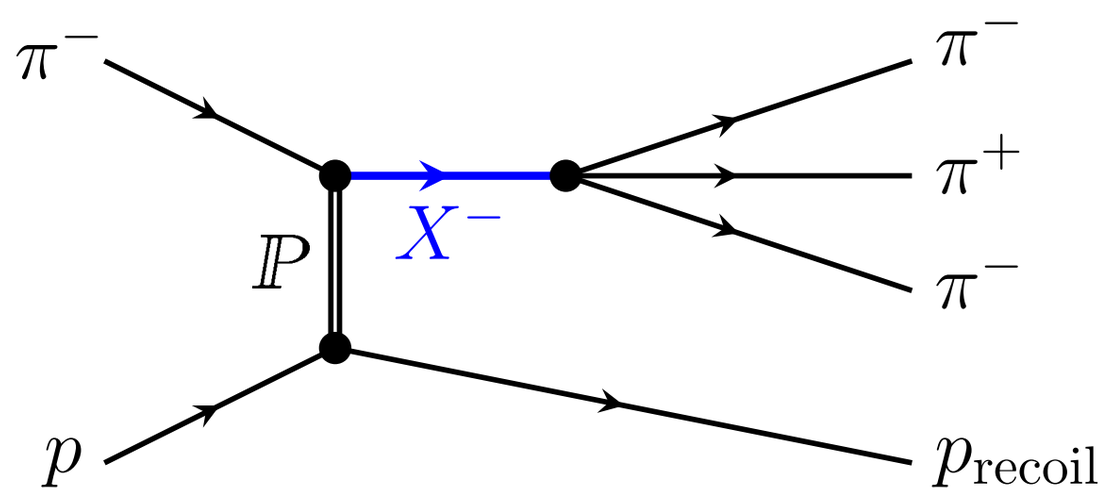
- Hadroproduction (π, K beams): COMPASS, E852, VES, …
  - Large event samples, more complicated initial state
  - Need more sophisticated models of reaction
- Photoproduction: CLAS12, GlueX, …
  - Large event samples, wide range of QN produced
    - Polarization gives extra info for amplitude analyses
  - Need to understand production mechanisms



Light Meson Spectroscopy at COMPASS

- Study of light meson spectrum $M \lesssim 2$ GeV using diffractive πp scattering
  - $\pi^- \pi^+ \pi^-$
  - $\eta \pi^-$, $\eta' \pi^-$
  - …

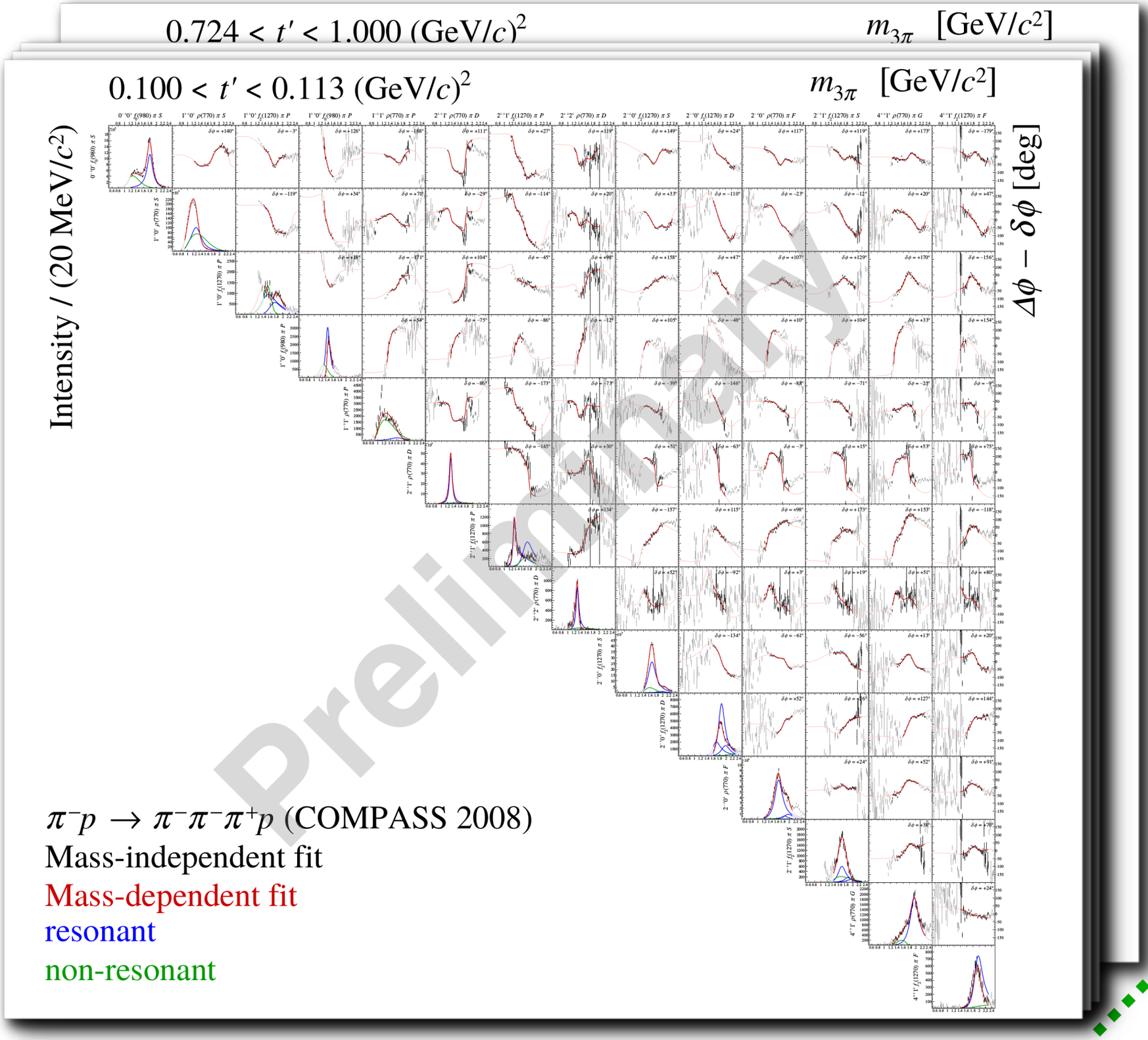


- Large data set of ~50 M exclusive $\pi^- + p \rightarrow \pi^- \pi^+ \pi^- + p_{\text{recoil}}$ events
  - Partial wave decomposition using **88** waves: *largest set to date*
  - Performed *t-resolved* analysis
- **Resonance model fit**

Talk by S. Wallner, Wed. 9:00

  - Modeling $M(\pi^-\pi^+\pi^-)$ dependence of partial waves
    - Resonant + non-resonant contributions, 11 ground + excited states
  - Simultaneous fit to 14 partial waves: *largest model so far*
  - Extensive systematic studies

π⁻ π⁺ π⁻ at COMPASS: Spin-density matrix of resonance fit



$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)

Mass-independent fit

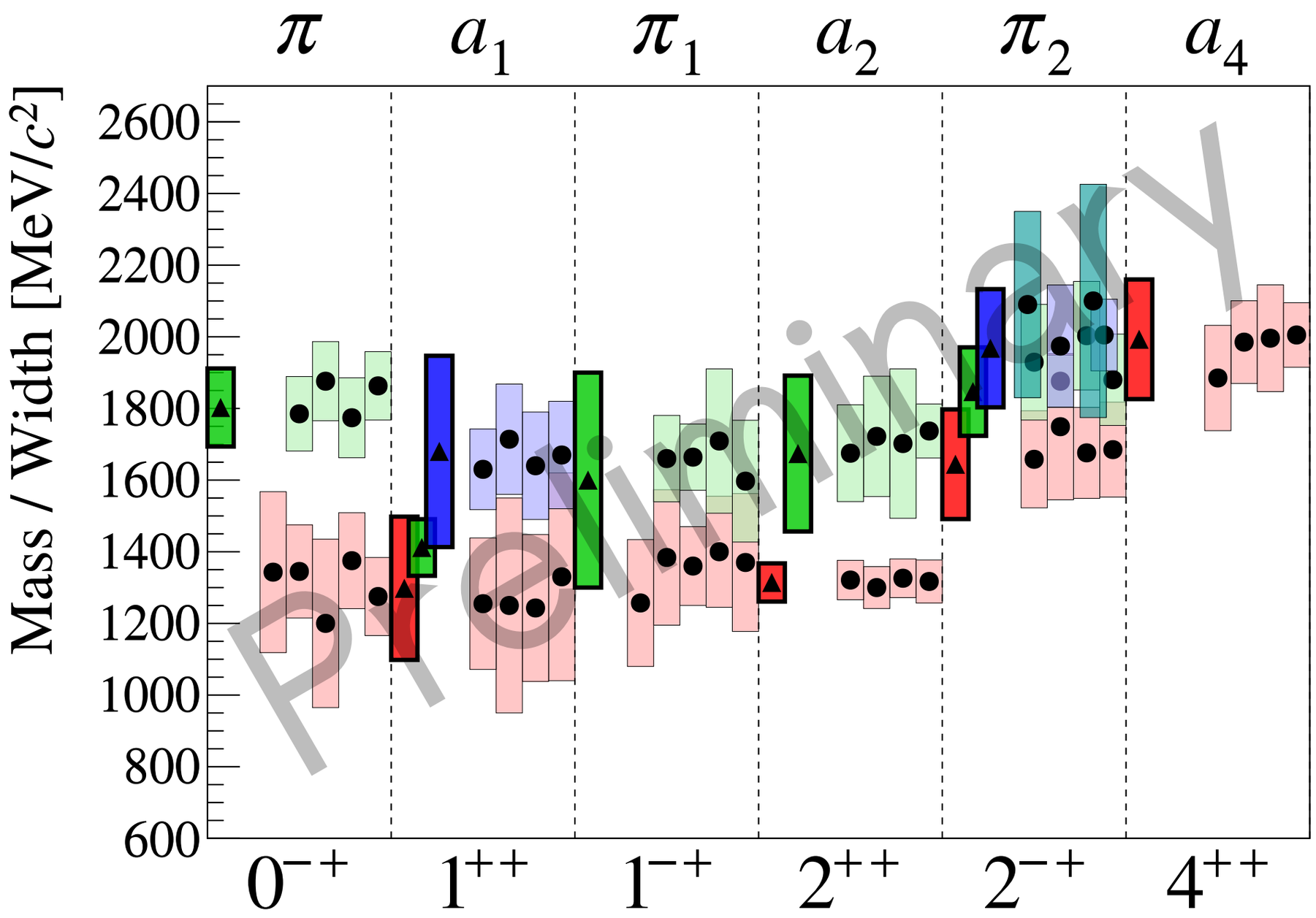
Mass-dependent fit

resonant

non-resonant

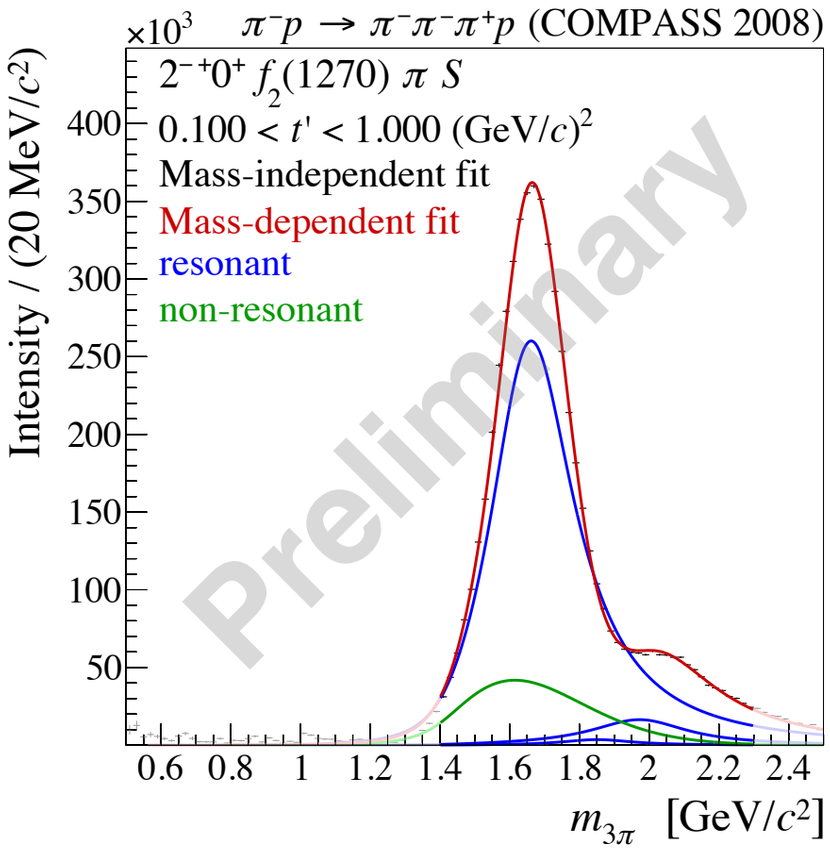
t' bins

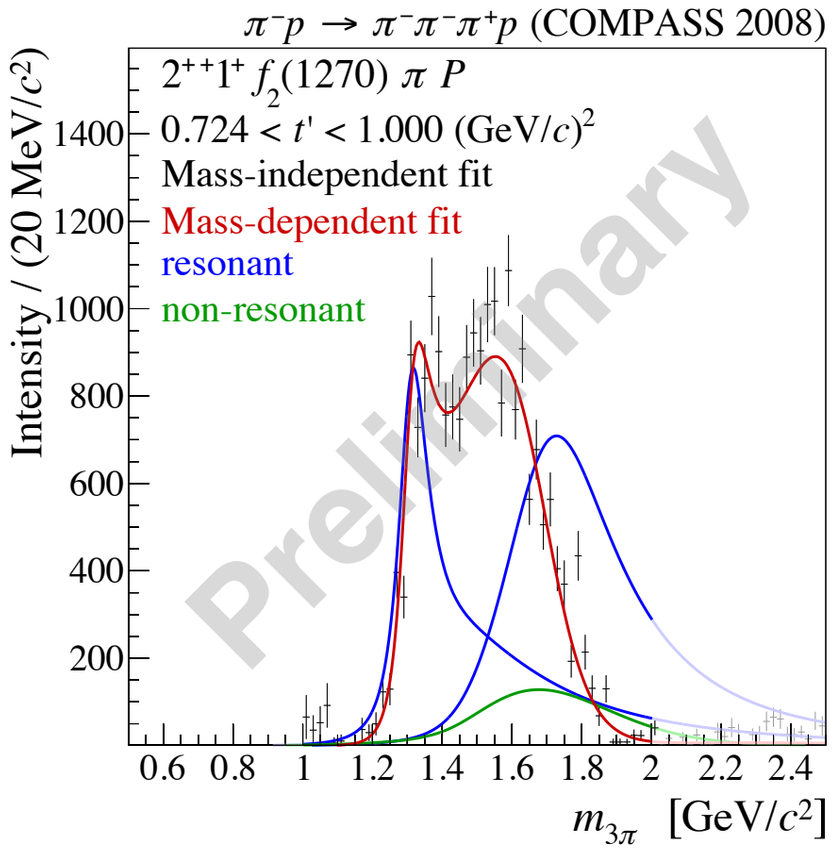
π⁻ π⁺ π⁻ at COMPASS: Results (triangles) and PDG (circles)

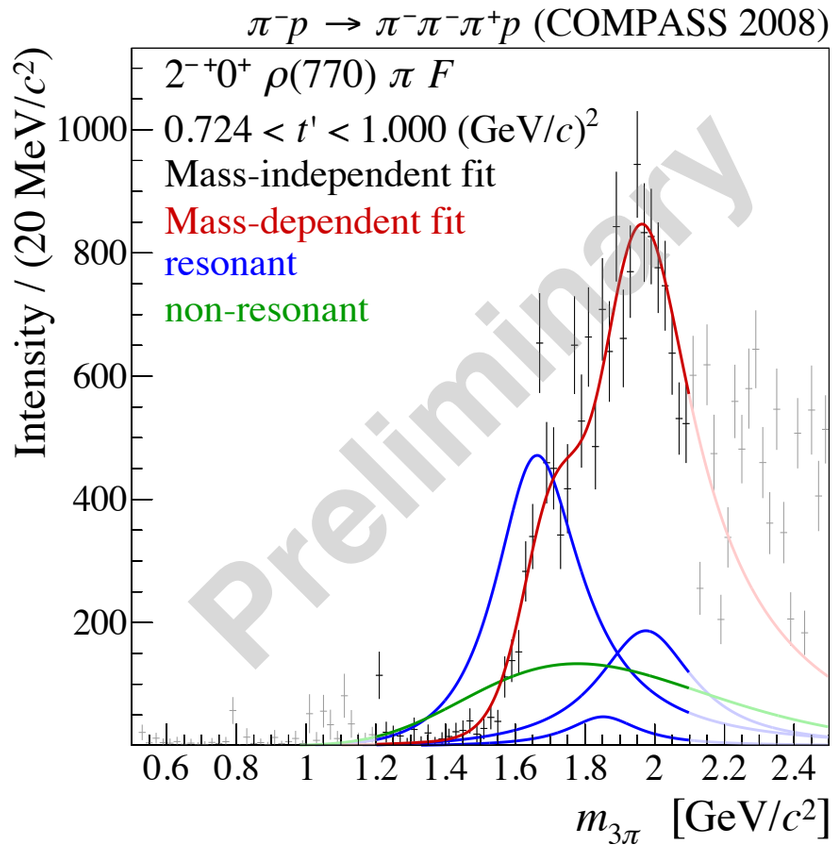


Center of the boxes represents the mass, height of the boxes the width of the states. The different colors show ground and excited states. The circles represent the latest measurements according to [PDG 2014], the triangles the results of this analysis.

$\pi^- \pi^+ \pi^-$ at COMPASS: $J^{PC} = 2^{-+}$: $\pi_2(1670)$, $\pi_2(1880)$, $\pi_2(2005)$







- Clear peak in $f_2(1270)\ \pi$ S decay, described by $\pi_2(1670)$ resonance
- Peak in $f_2(1270)\ \pi$ D decay at higher masses, described mainly by $\pi_2(1880)$
- Potential $\pi_2(2005)$ signal strongest in $\rho(770)\ \pi$ P decay