Experimental Searches for Light Exotica
Precision and Progress

Sean Dobbs

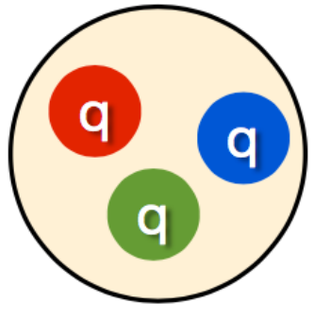
Florida State U.

8th Workshop of the APS Topical Group on Hadronic Physics
Denver, CO
April 11, 2019

QCD and Hadron Spectroscopy

- Recent decades have lead to new renaissance in hadron spectroscopy
  - New high-intensity experiments
  - More rigorous theoretical tools
  - New avenues in understanding QCD through bound states

meson



baryon

- Open questions:
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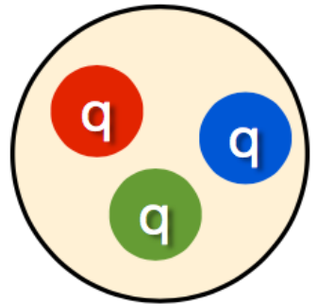

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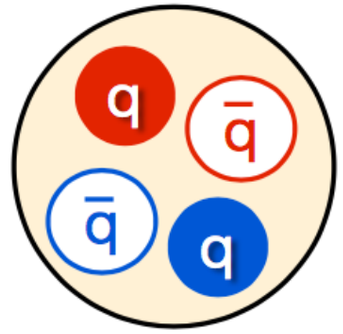
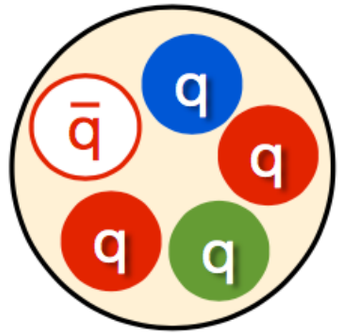
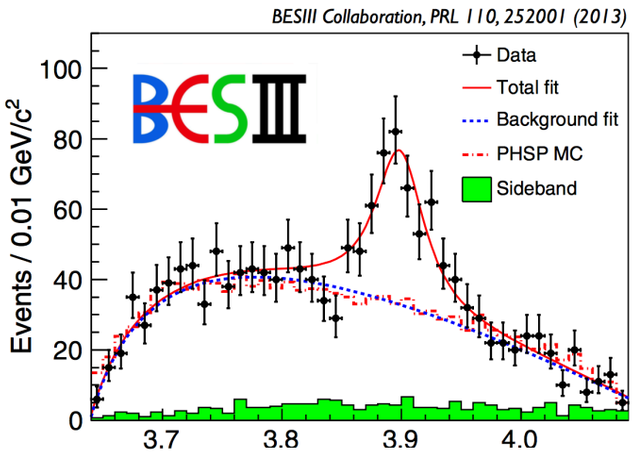


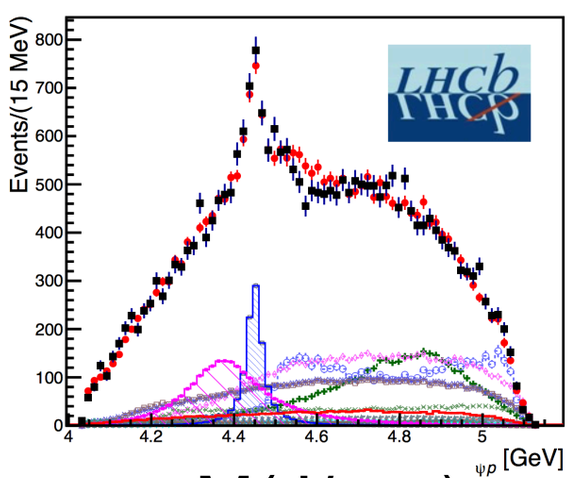
tetraquark



pentaquark



$M(J/\psi\ \pi^{\pm})$



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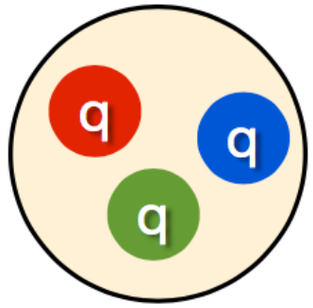

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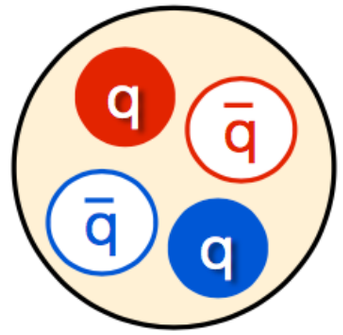

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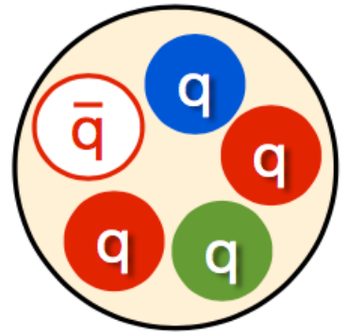

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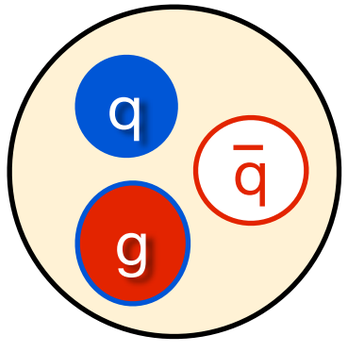
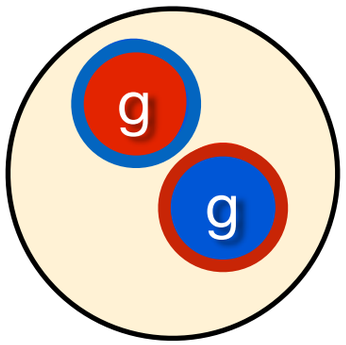


hybrid meson



glueball

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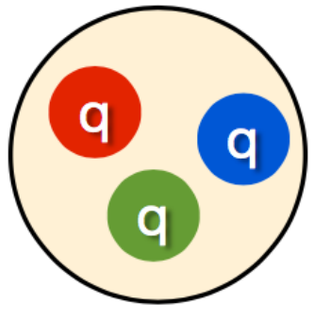

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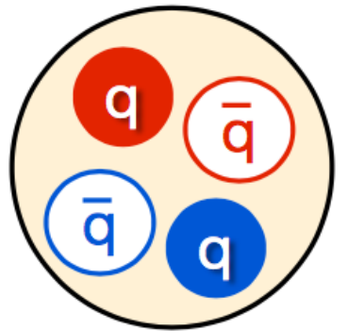

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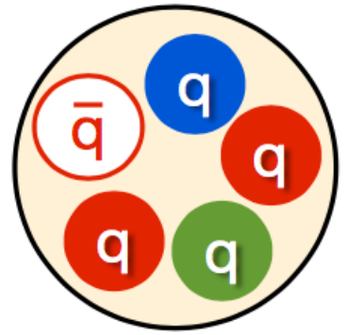

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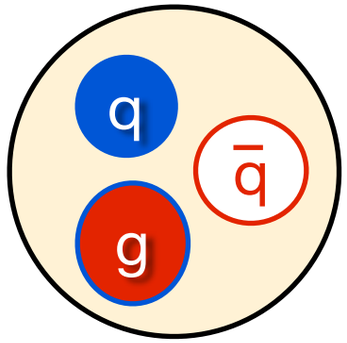

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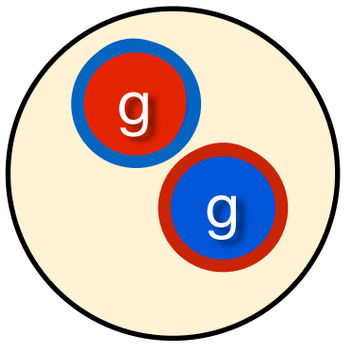
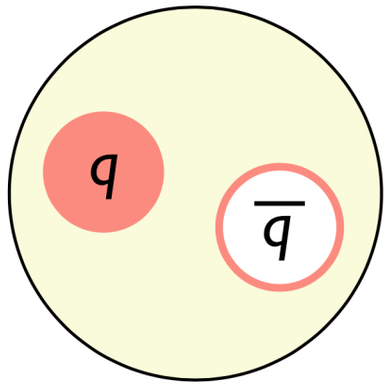


glueball

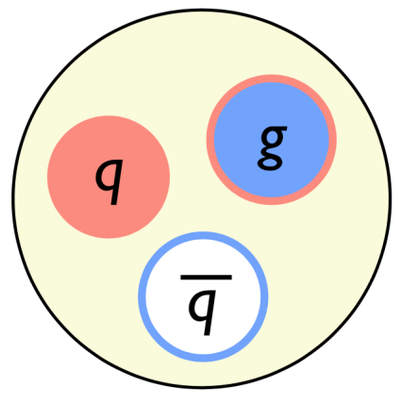
Searching For Hybrid Mesons

- **Wish:** Unambiguous narrow Breit-Wigner peaks in a mass spectrum
- **Reality:** Must establish resonance nature by identifying pole parameters
  - Requires high-quality data in multiple channels and rigorous models: **experimentalists and theorists working closely**
- Meson QNs
  - Allowed: **0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{-+},…**
  - Forbidden: **0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, …**
- Hybrid Meson QNs
  - **0^{-+}, 0^{+-}, 1^{--}, 1^{-+}, 2^{-+}, 2^{+-},** …
- Hybrid mesons can be found with **normal** and **exotic** quantum numbers

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



"Normal" Meson

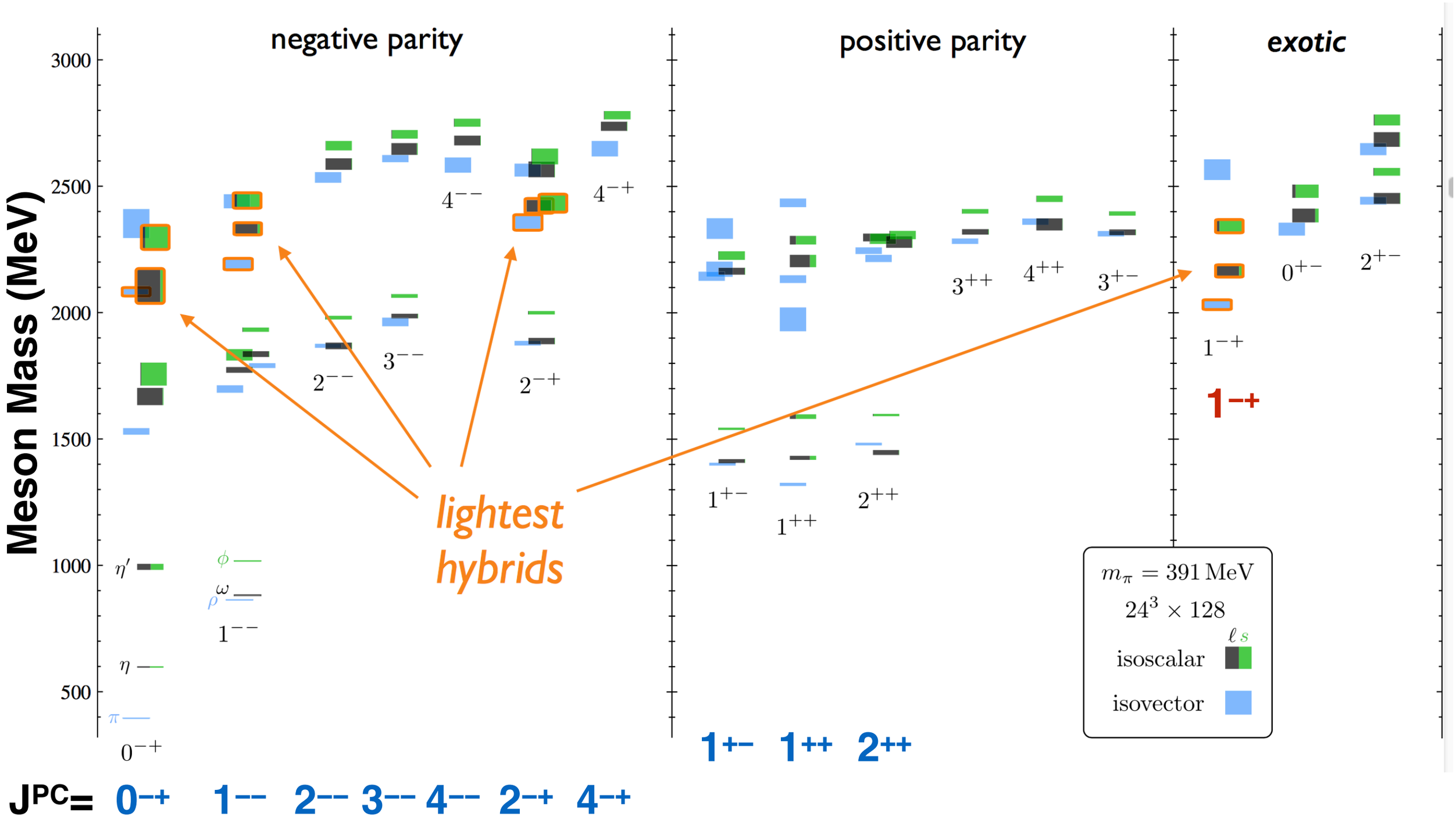


$(J^{PC})_g = 1^{+-}$

"Hybrid" Meson

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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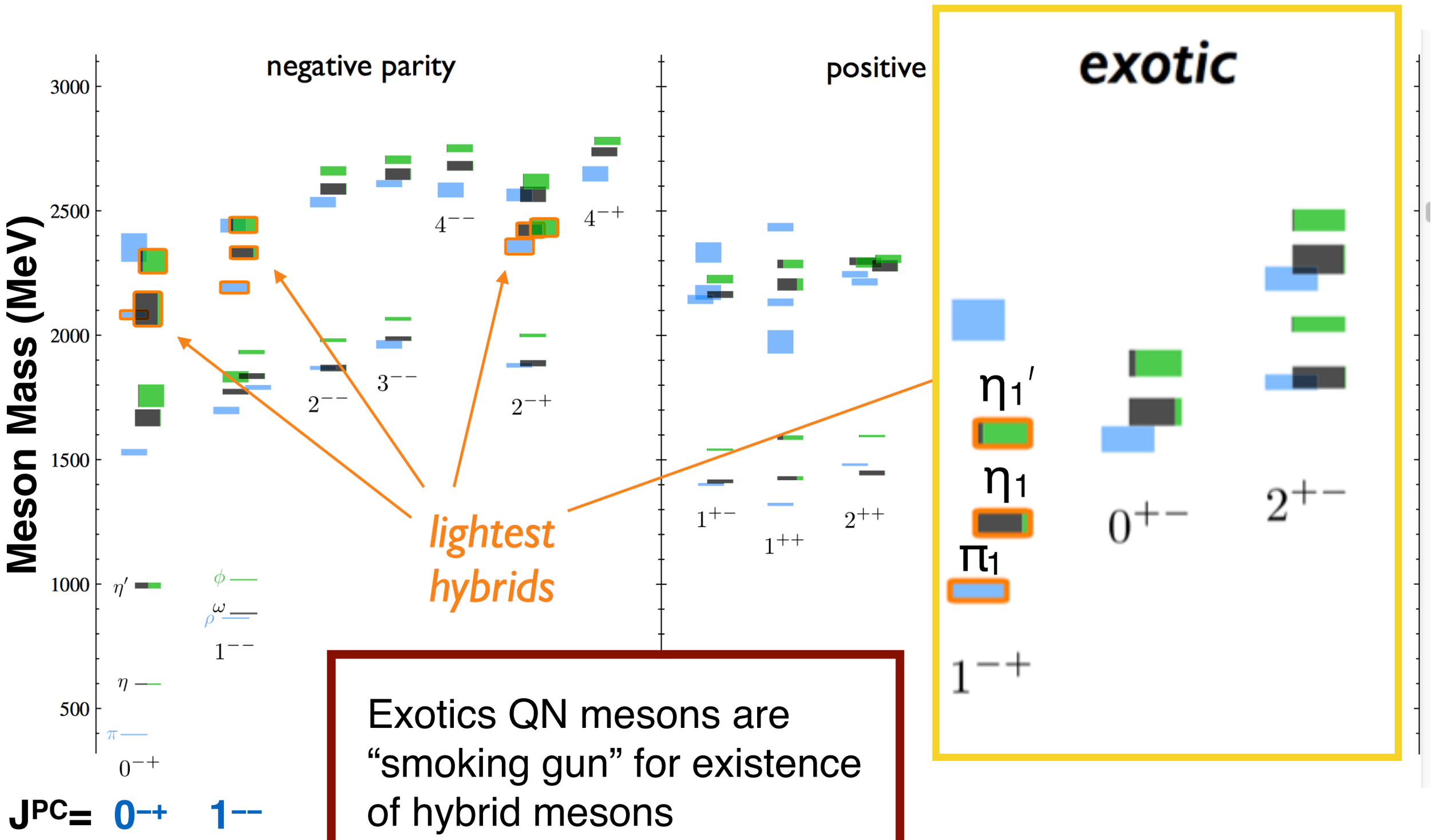

Exotics QN mesons are "smoking gun" for existence of hybrid mesons

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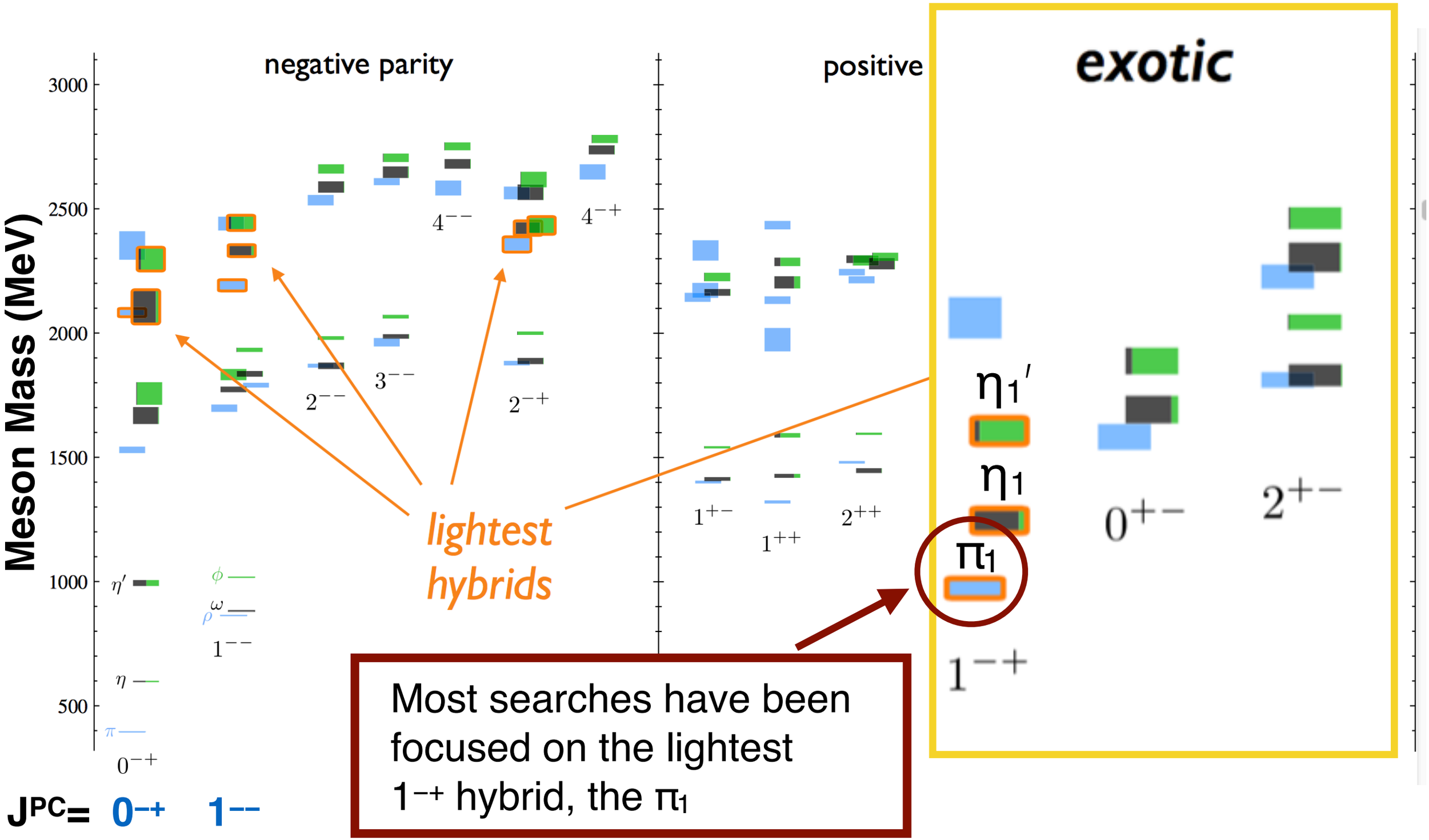

Most searches have been focused on the lightest 1^{-+} hybrid, the π_1

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

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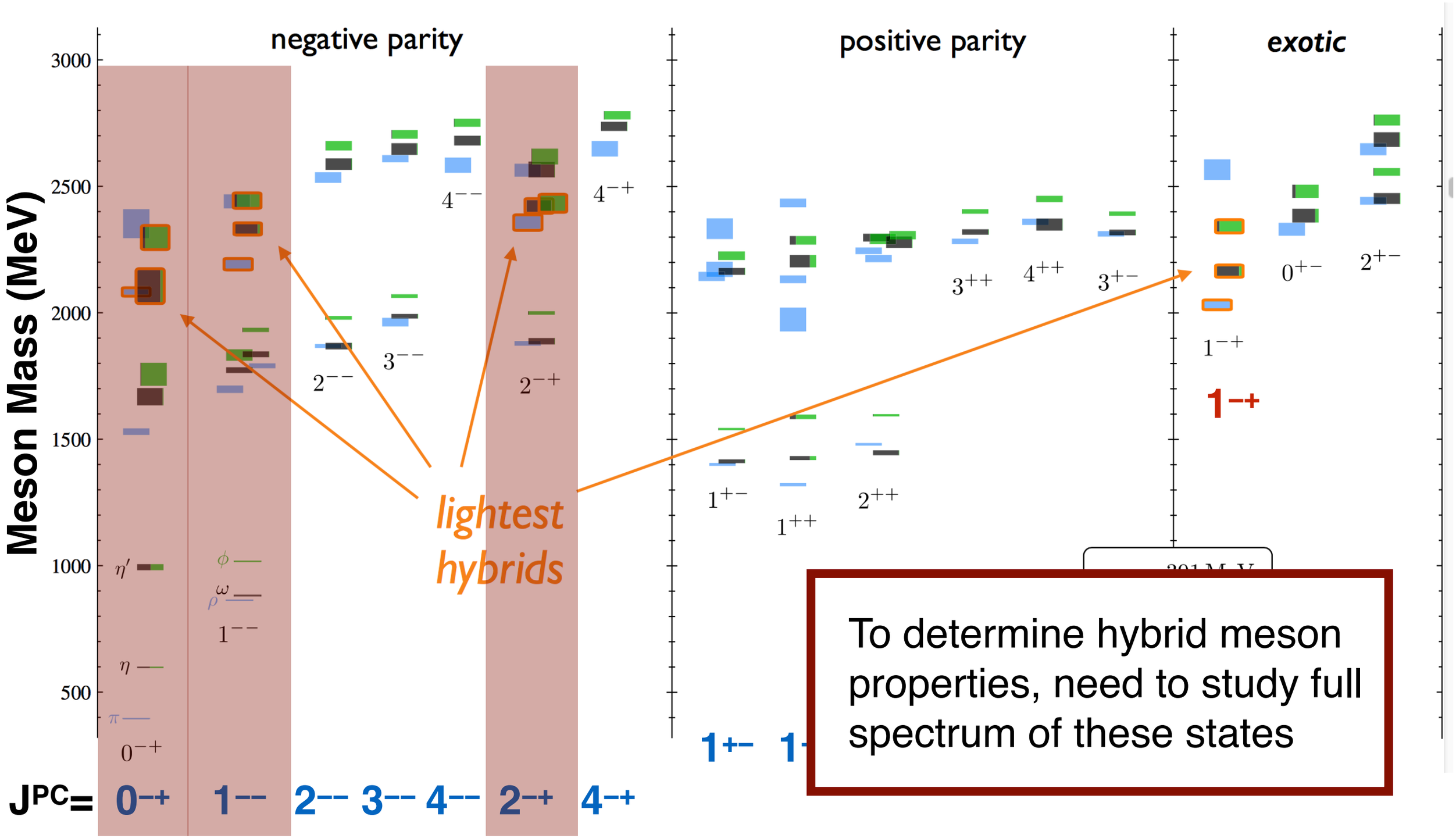

To determine hybrid meson properties, need to study full spectrum of these states

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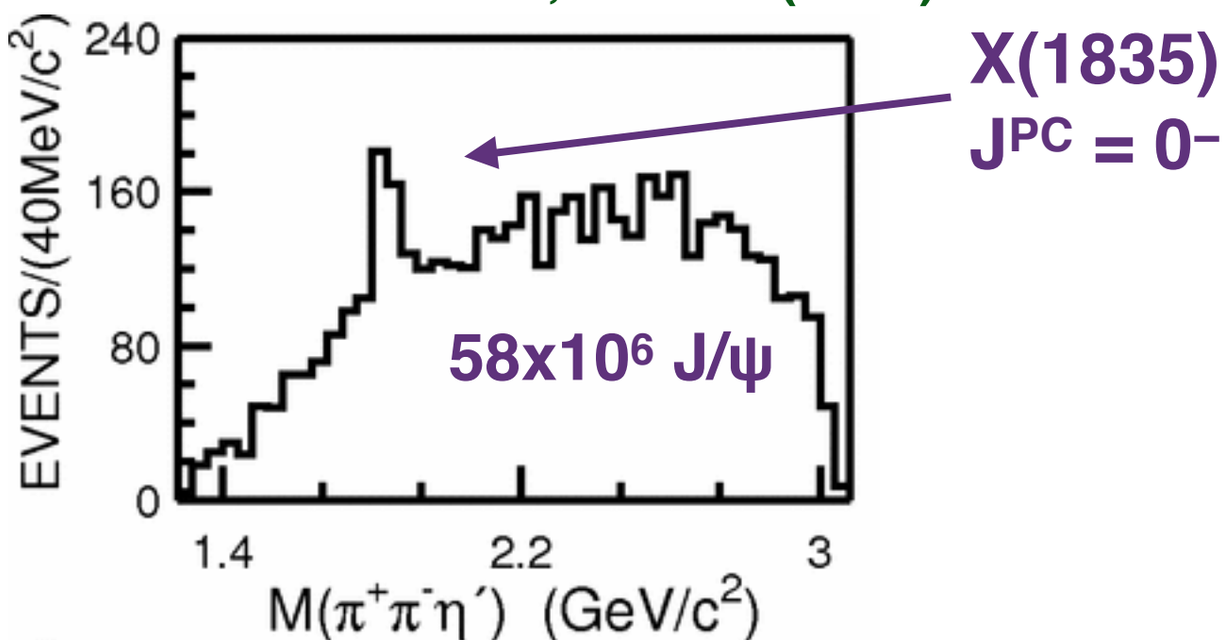
Precision and Spectroscopy: BES III & J/ψ → γ η′π⁺π⁻

- Search by BES for resonances in $J/\psi \to \gamma \eta'\pi^+\pi^-$ in e^+e^- annihilation
  - Structure seen near 2M(p)
  - More data suggests a richer spectrum of states

BES II: PRL 95, 262001 (2005)



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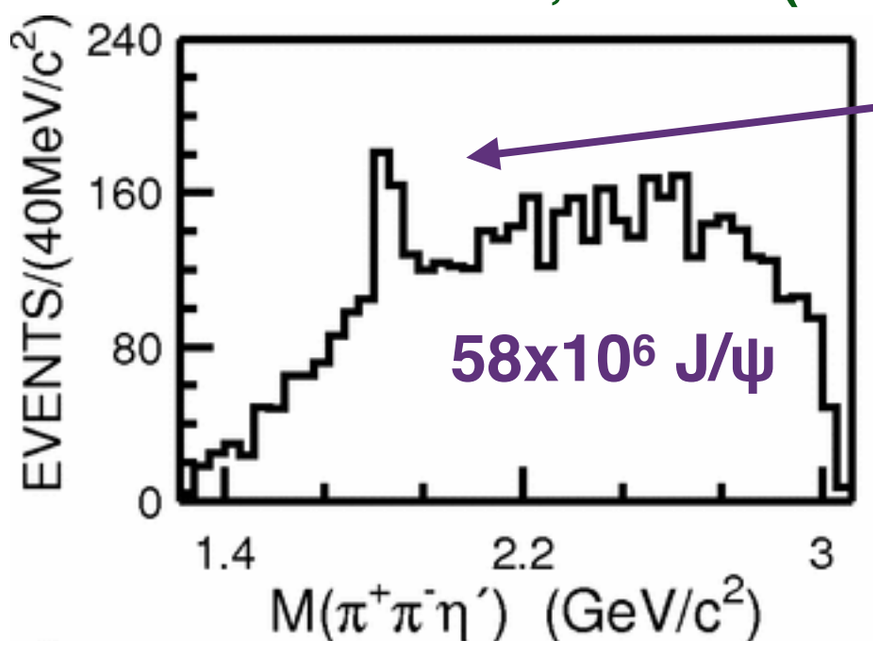
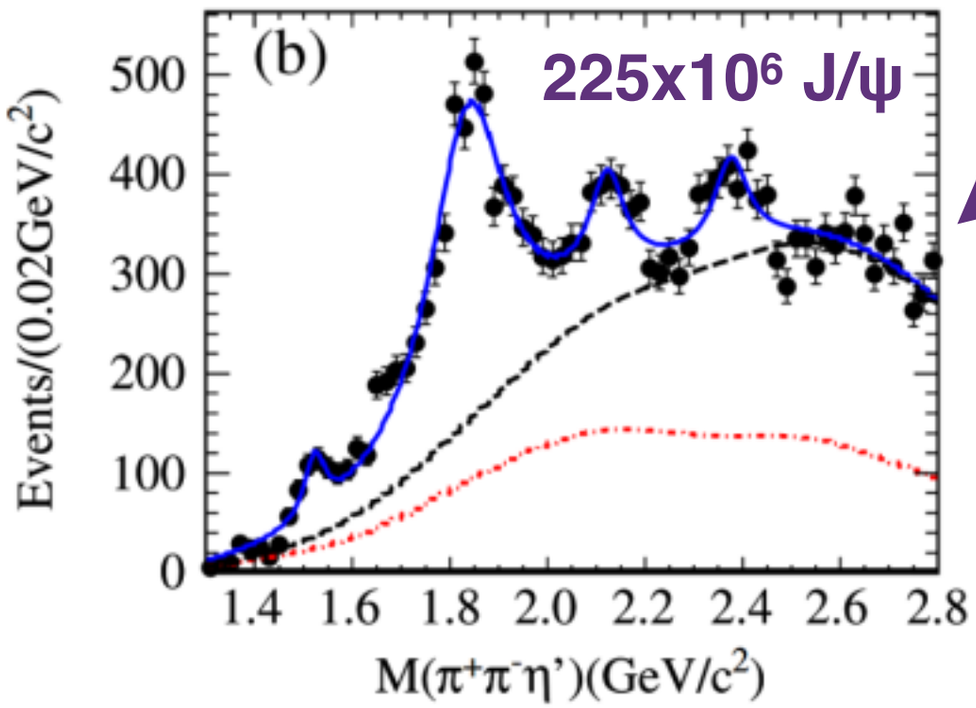


X(1835)
$J^{PC} = 0^-$

BESIII: PRL 106, 072002 (2011)



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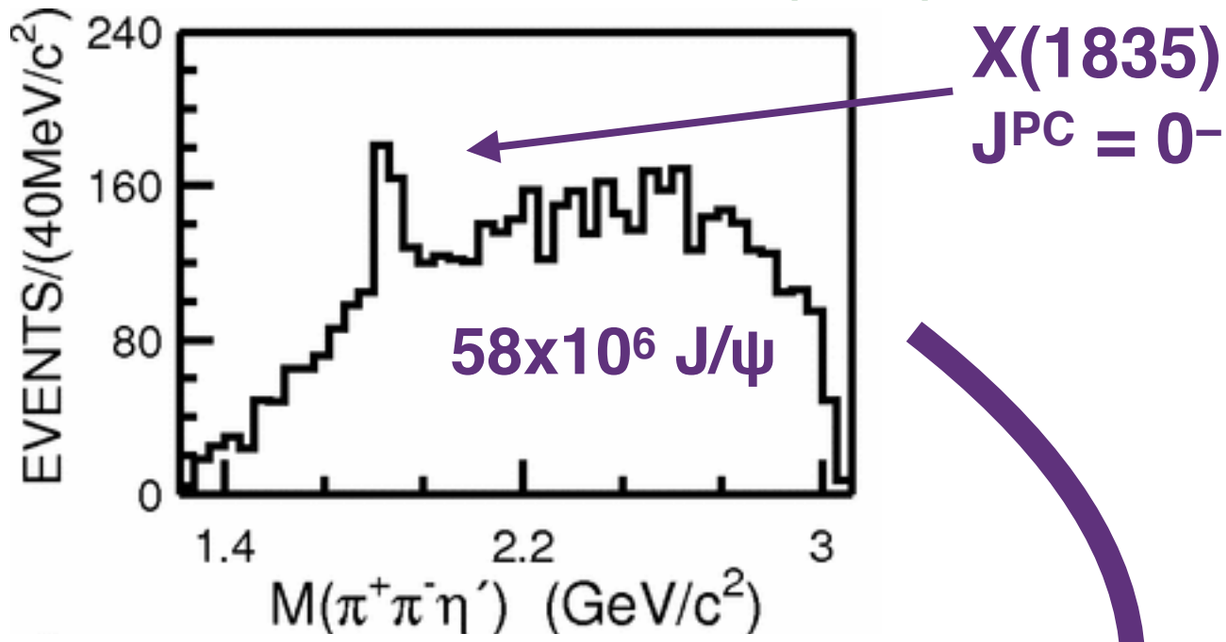

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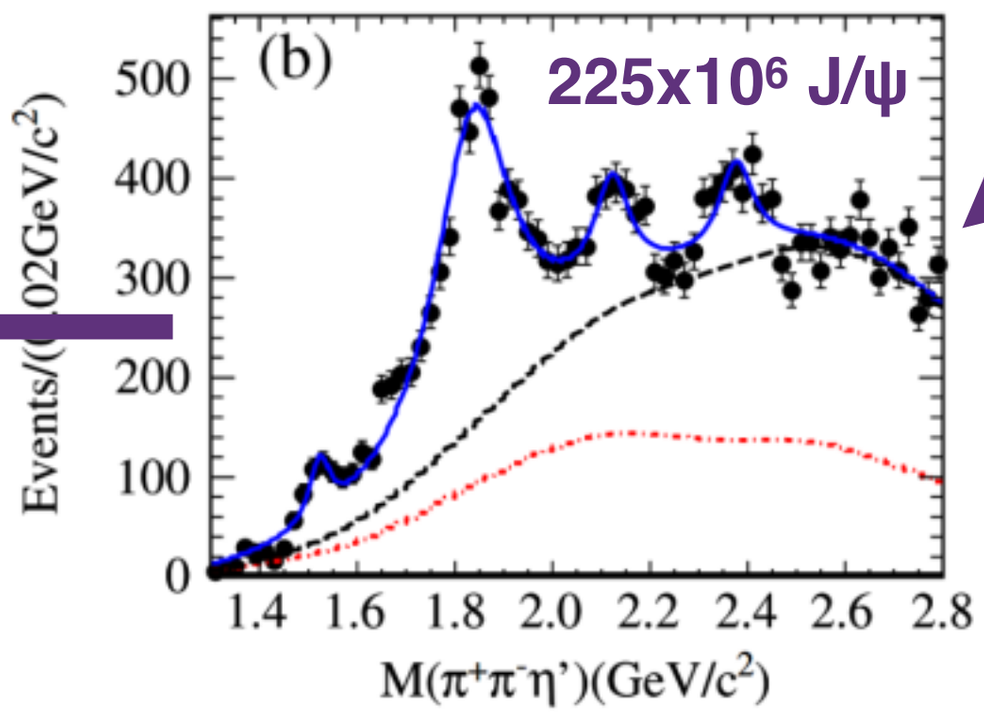

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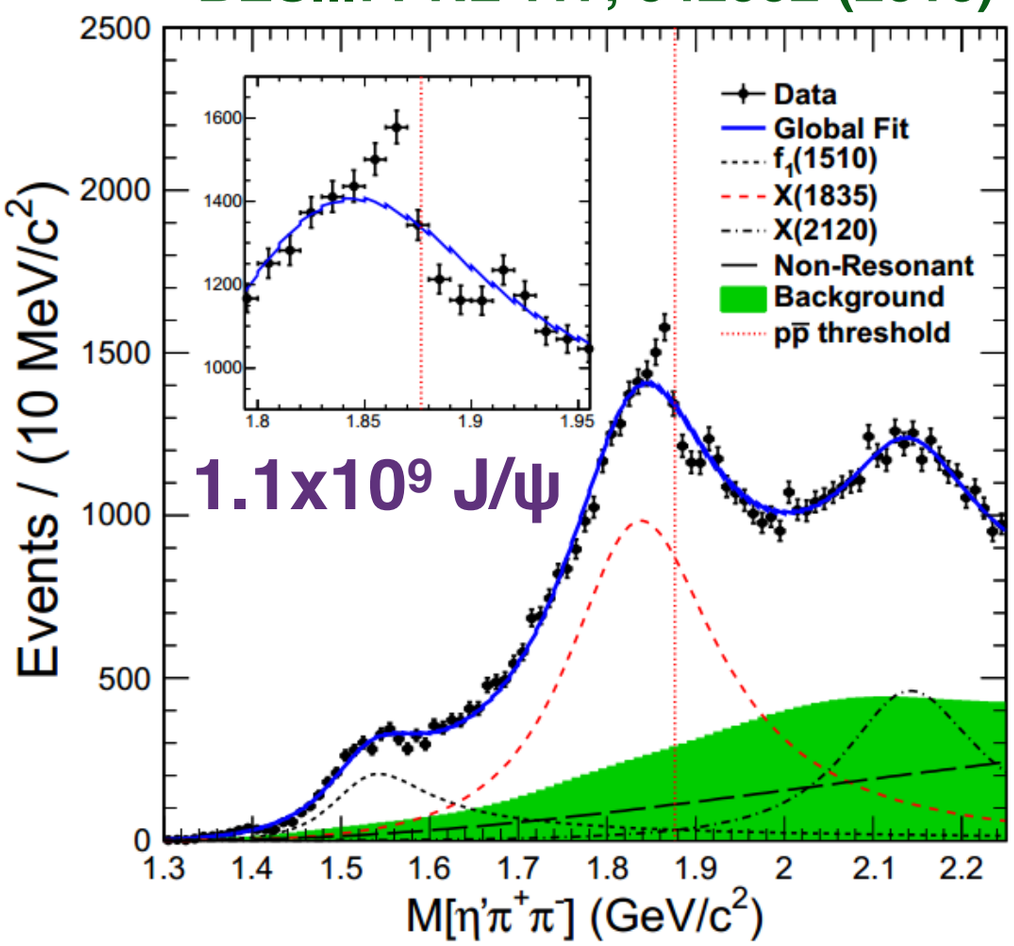

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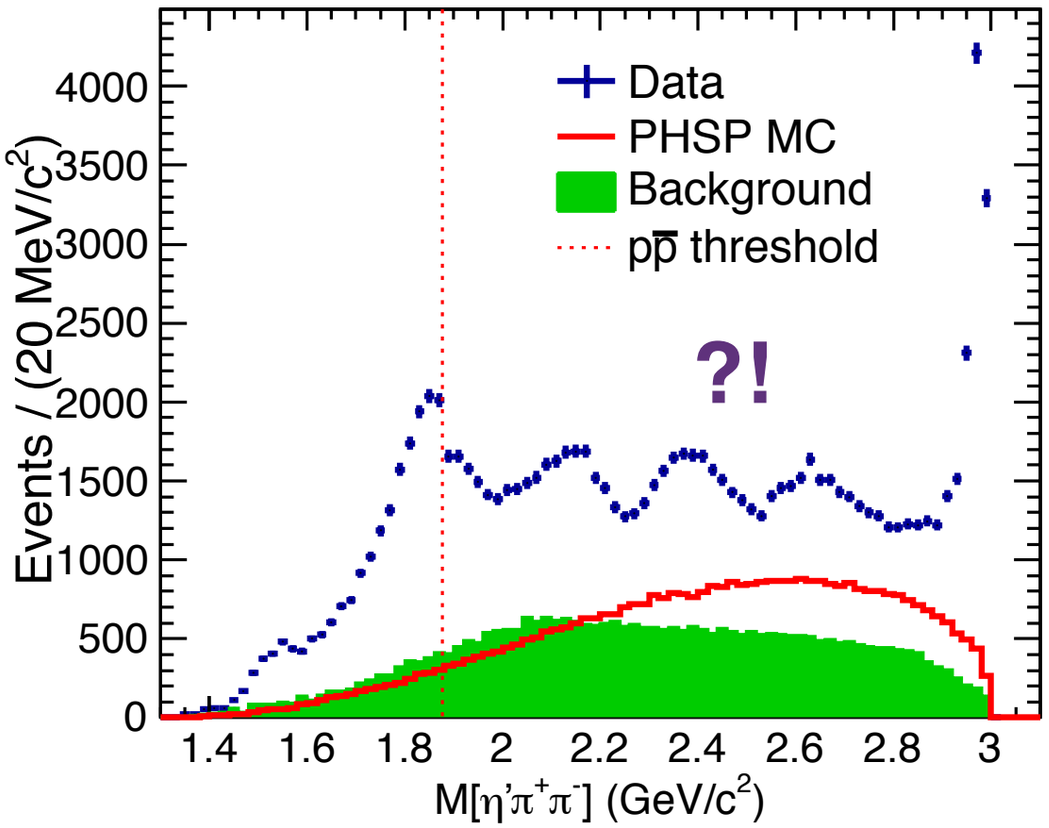

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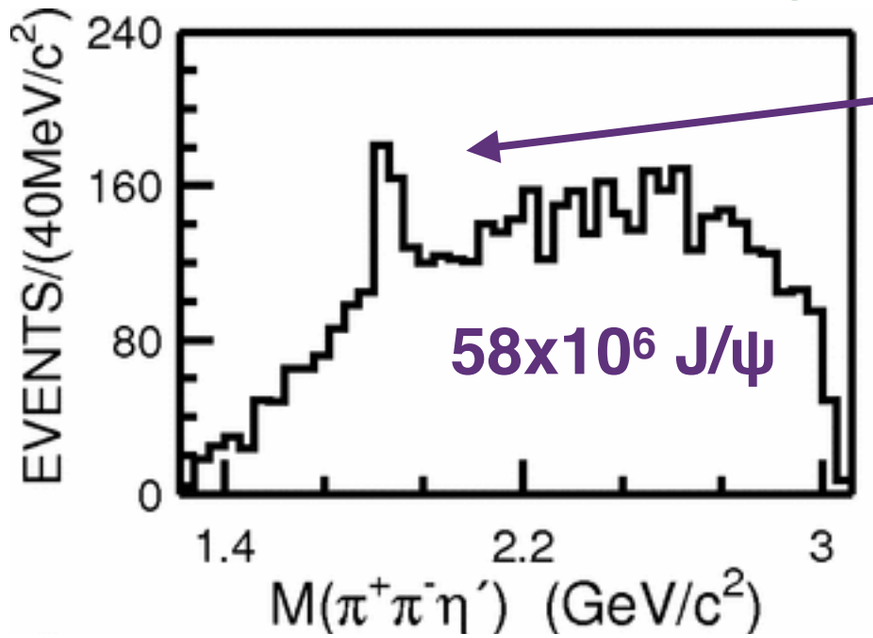

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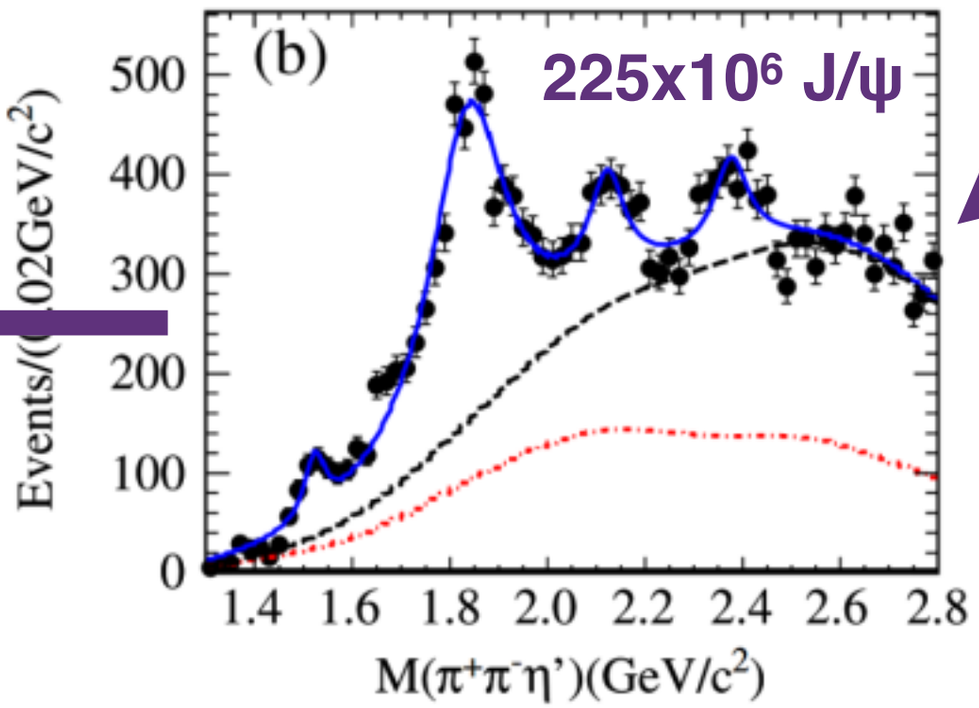

Searching in ηπ / η′π @ COMPASS

- Over 20 years of reported evidence for exotic J^{PC} mesons from many experiments.
  - Mass spectra generally look similar, but interpretations differ
  - $\pi_1(1400) \rightarrow \eta\pi$
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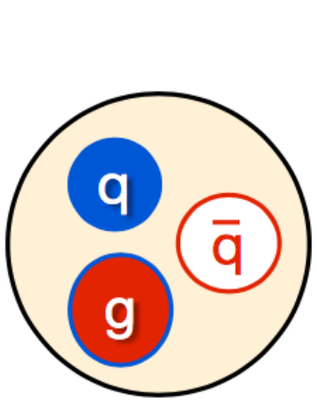
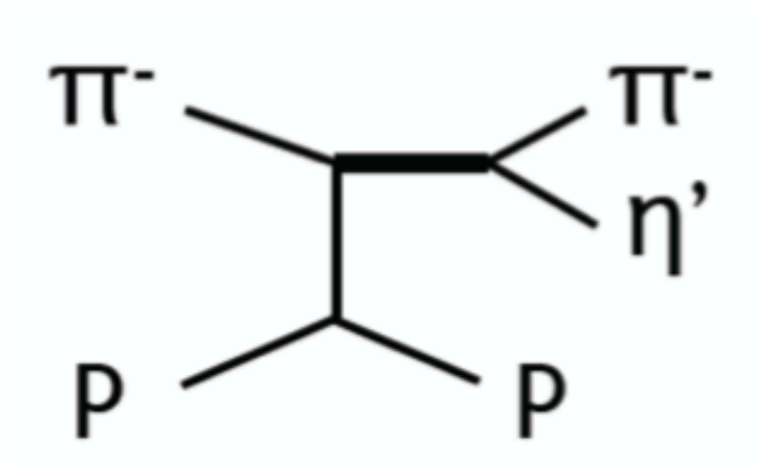
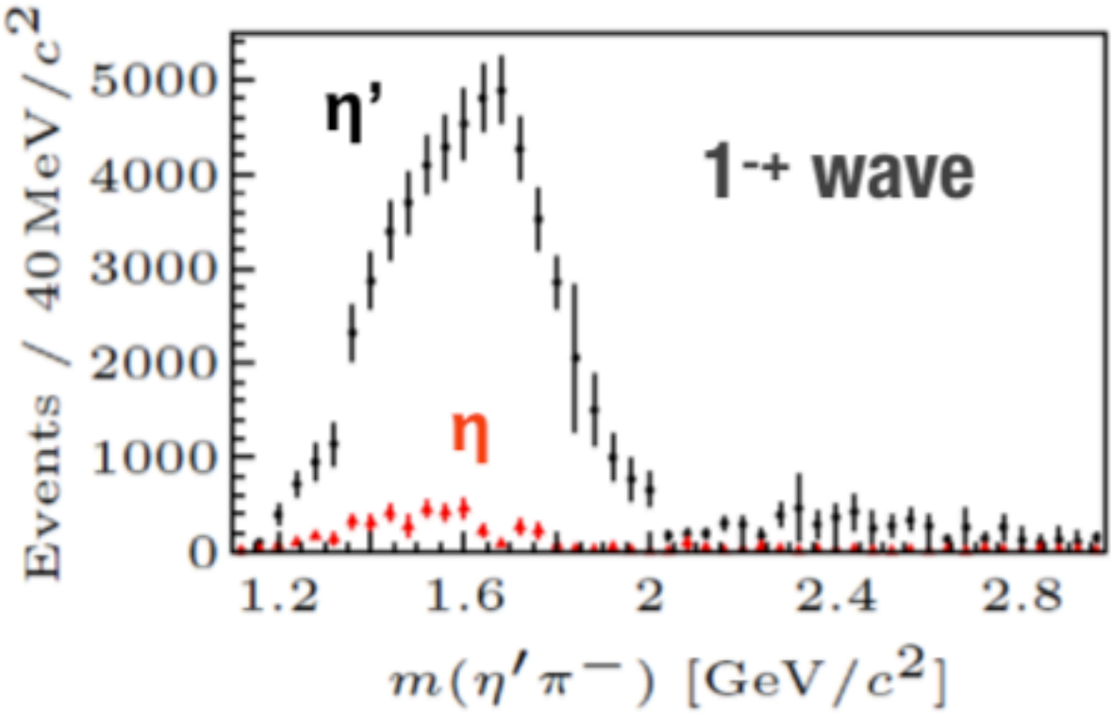




COMPASS: $\pi_1 \rightarrow \eta\pi$ / $\eta'\pi$

COMPASS: PLB 740, 303 (2015)



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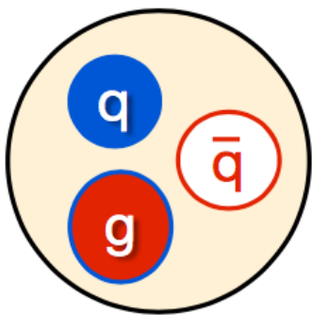

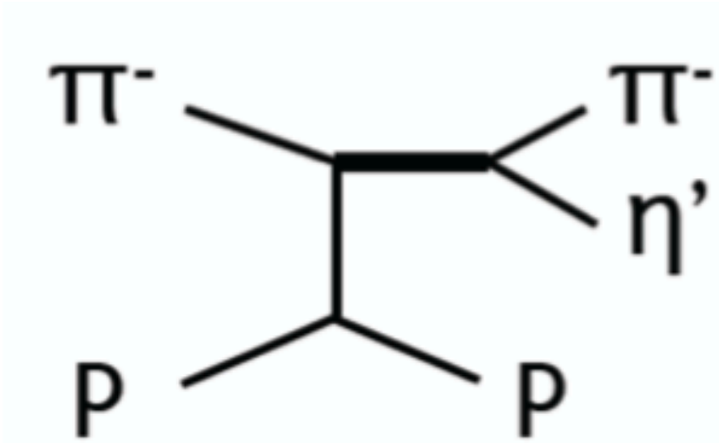

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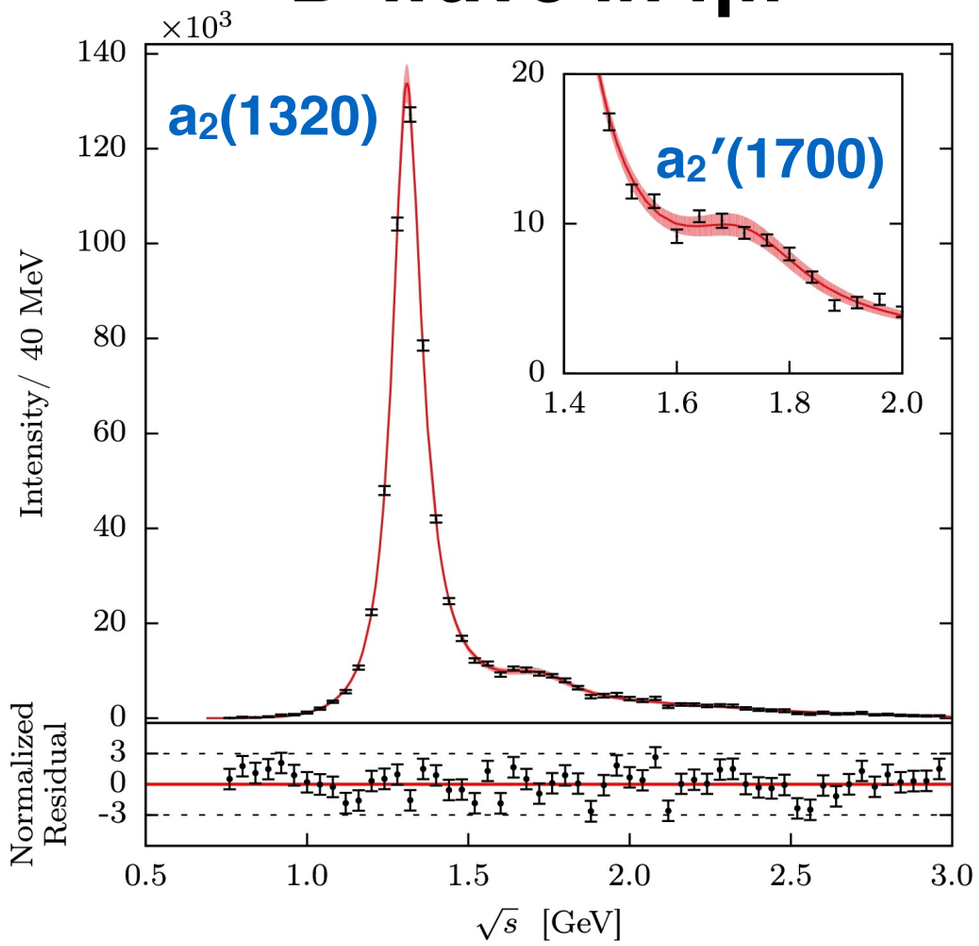
D-wave in ηπ



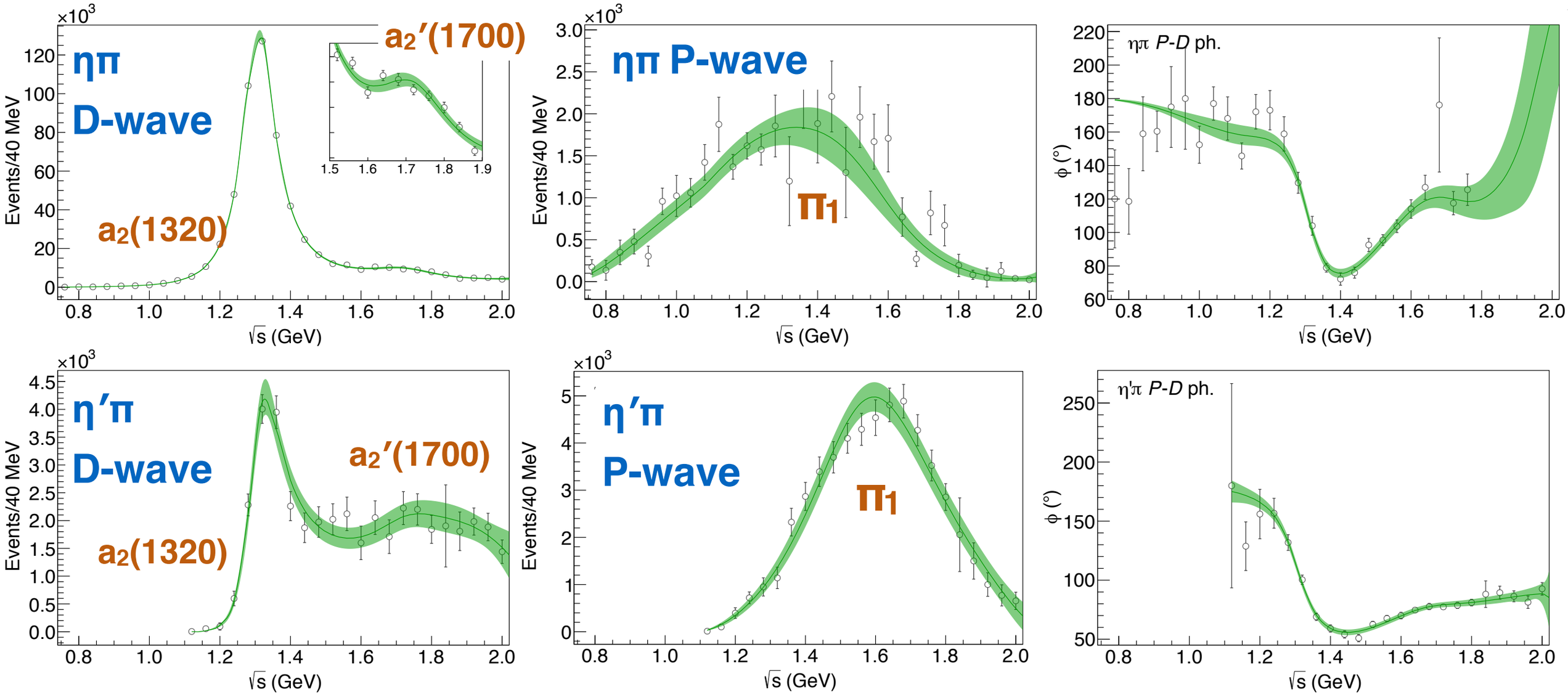
Extract resonance parameters with unitary reaction model

A. Jackura et al. [JPAC and COMPASS Collaborations], PLB 779, 464 (2017)

Coupled Channel Fits in ηπ / η′π @ COMPASS

- Coupled channel analysis for P-waves and D-waves
- High precision data & theoretical advances required to describe data

P/D-wave in ηπ / η′π



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

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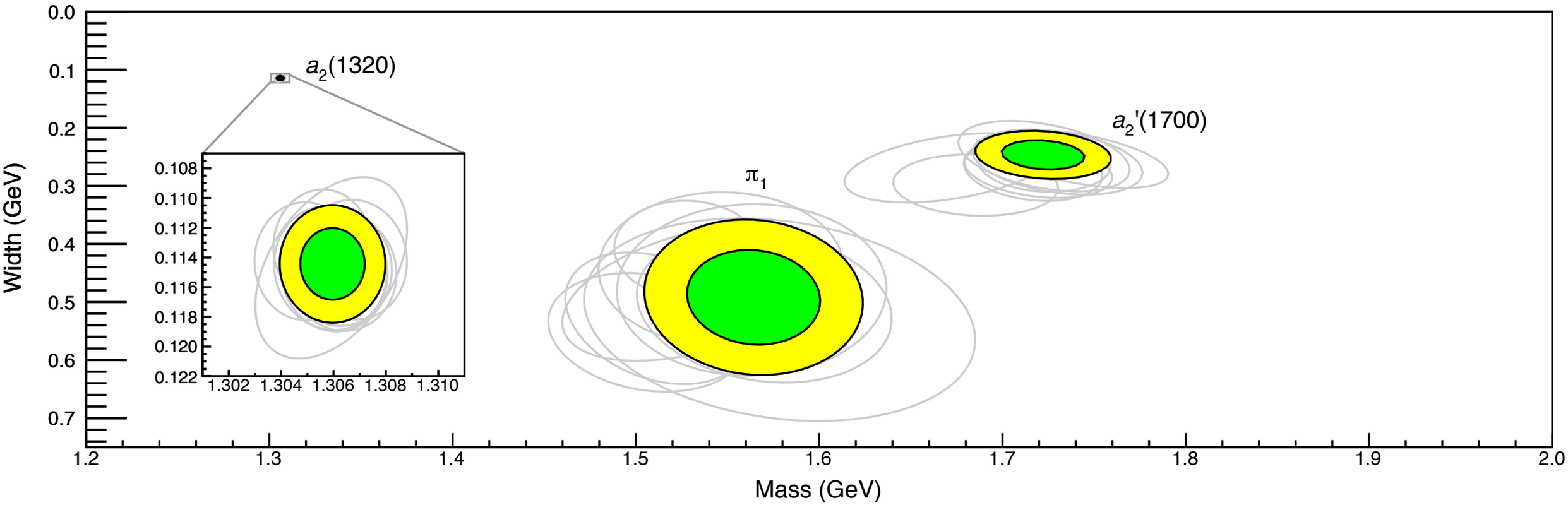


$M(\pi_1) = 1564 \pm 24 \pm 86$ MeV

$\Gamma(\pi_1) = 492 \pm 54 \pm 102$ MeV

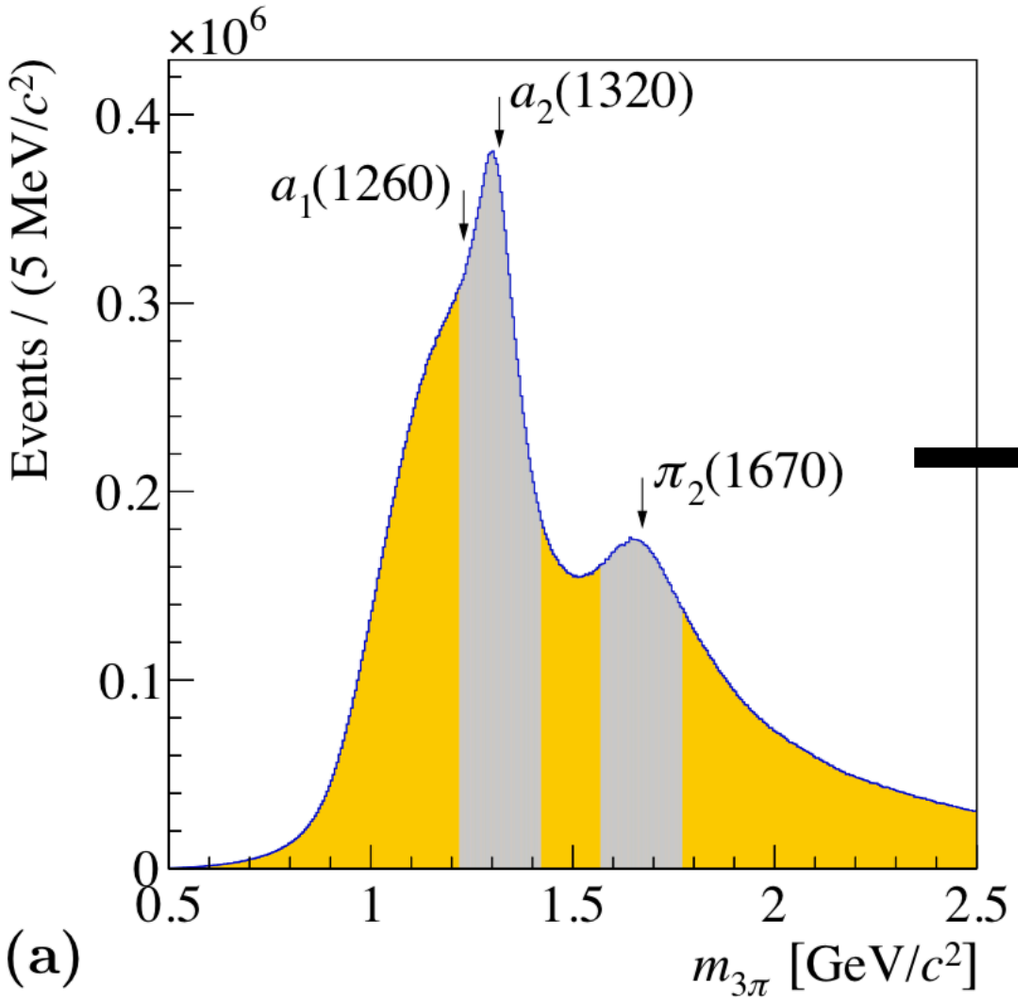
See: A. Rodas @ 10:30 AM Friday

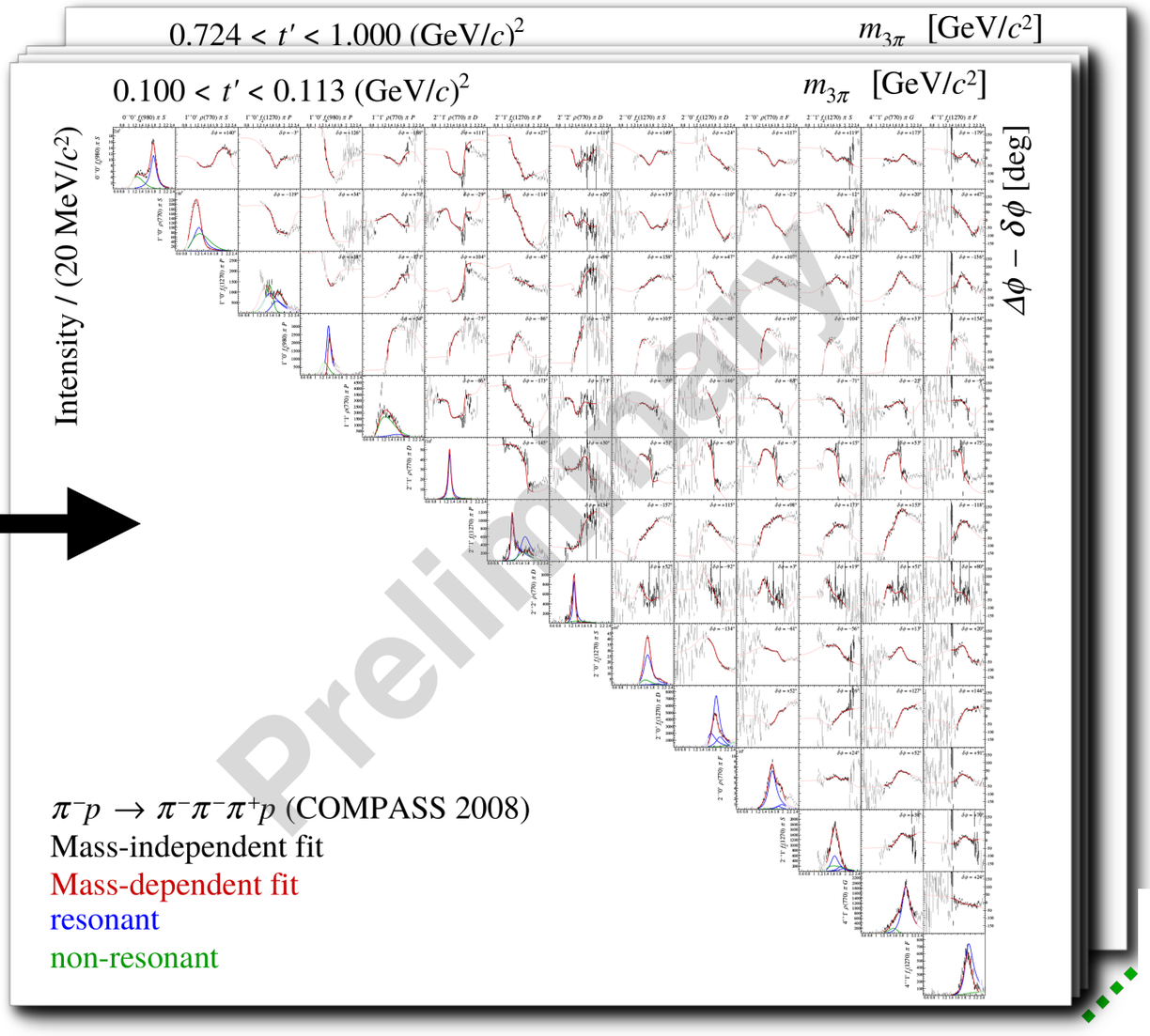
A. Rodas et al. (JPAC) [Phys. Rev. Lett. 122, 042002 (2019)]

Searching in $\pi^-\pi^-\pi^+$ @ COMPASS

- Huge data set of ~50 M exclusive π^- + p → π^- π^+ π^- + p_{recoil} events
- Partial wave decomposition using **88** waves in bins of t

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





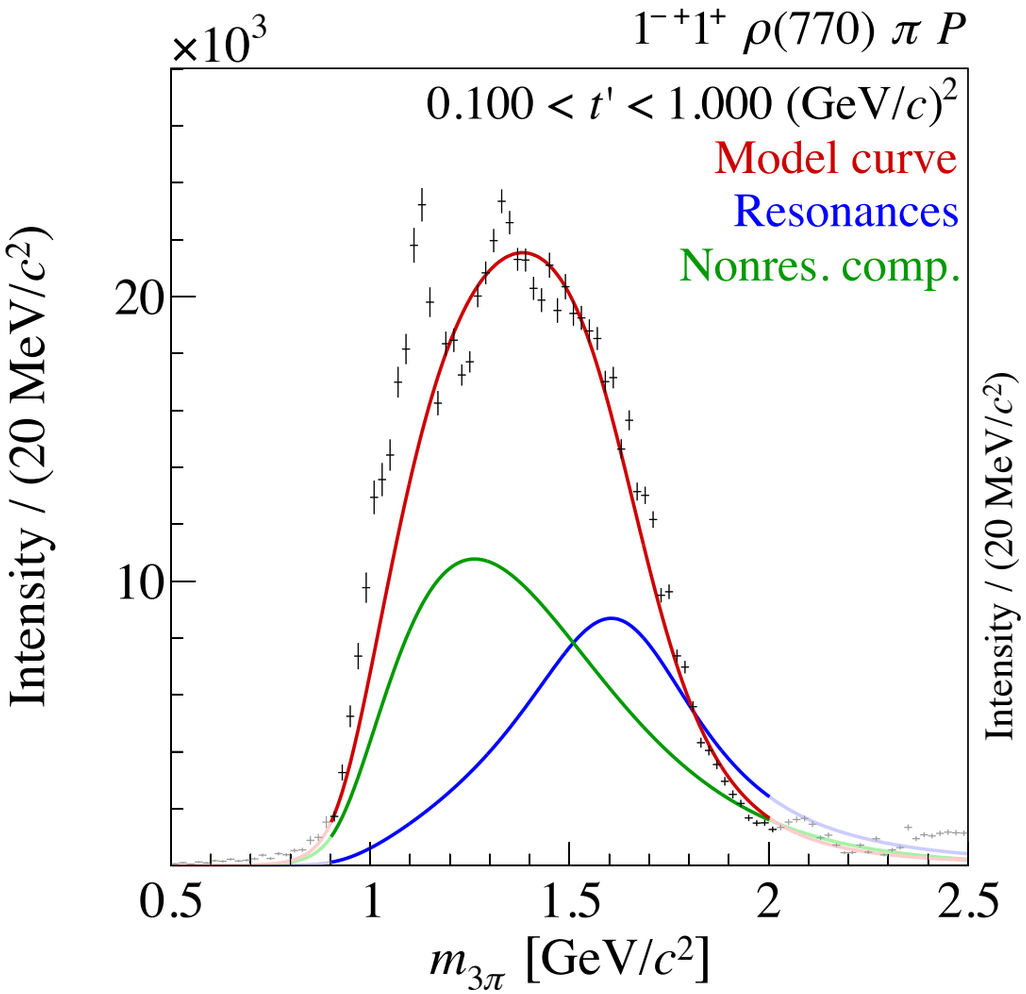
PRD 95, 032004 (2017)

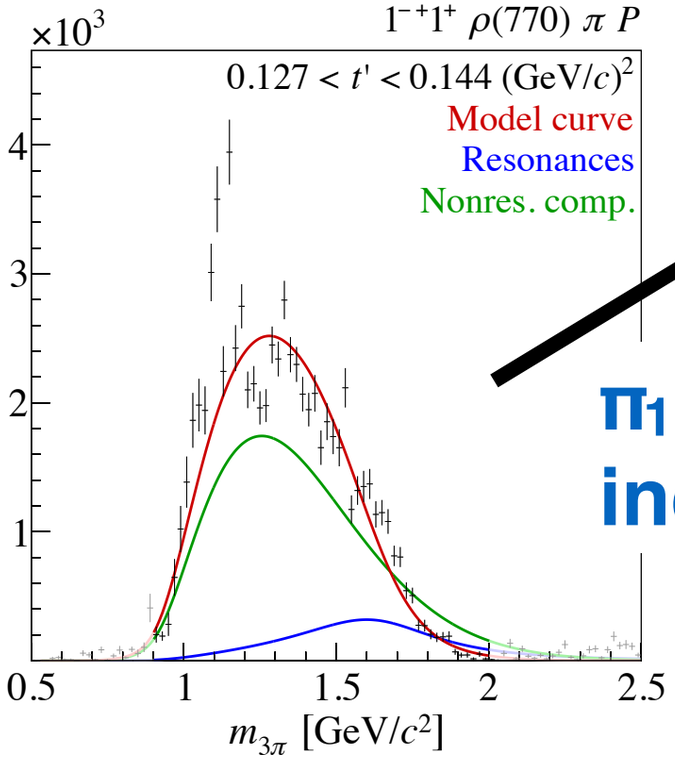
h/t S. Wallner, HADRON 2017

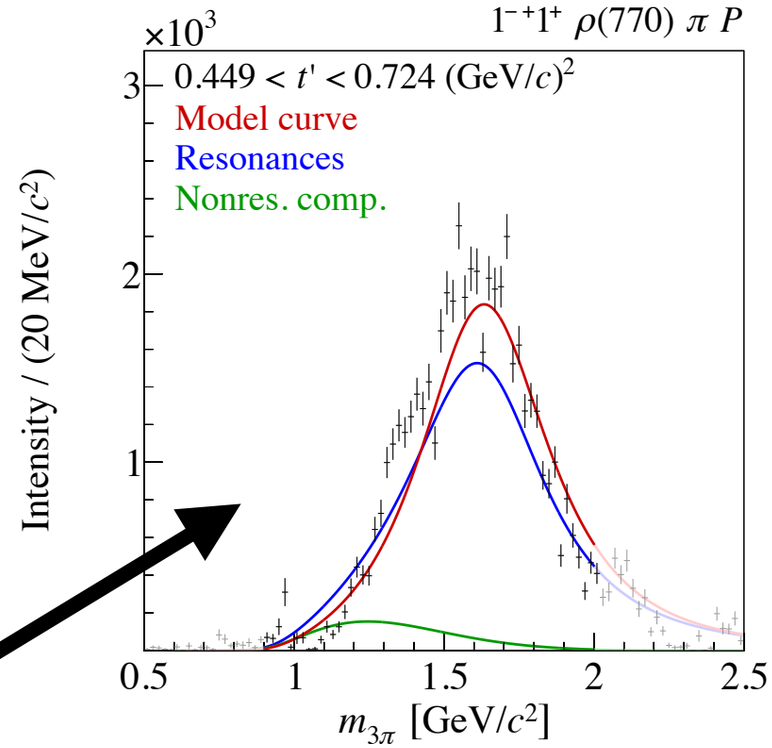
Searching in $\pi^-\pi^-\pi^+$ @ COMPASS

- Exotic 1^{-+} partial wave fit with strong resonant and non-resonant conts.
- π_1 contribution exhibits strong t-dependence

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







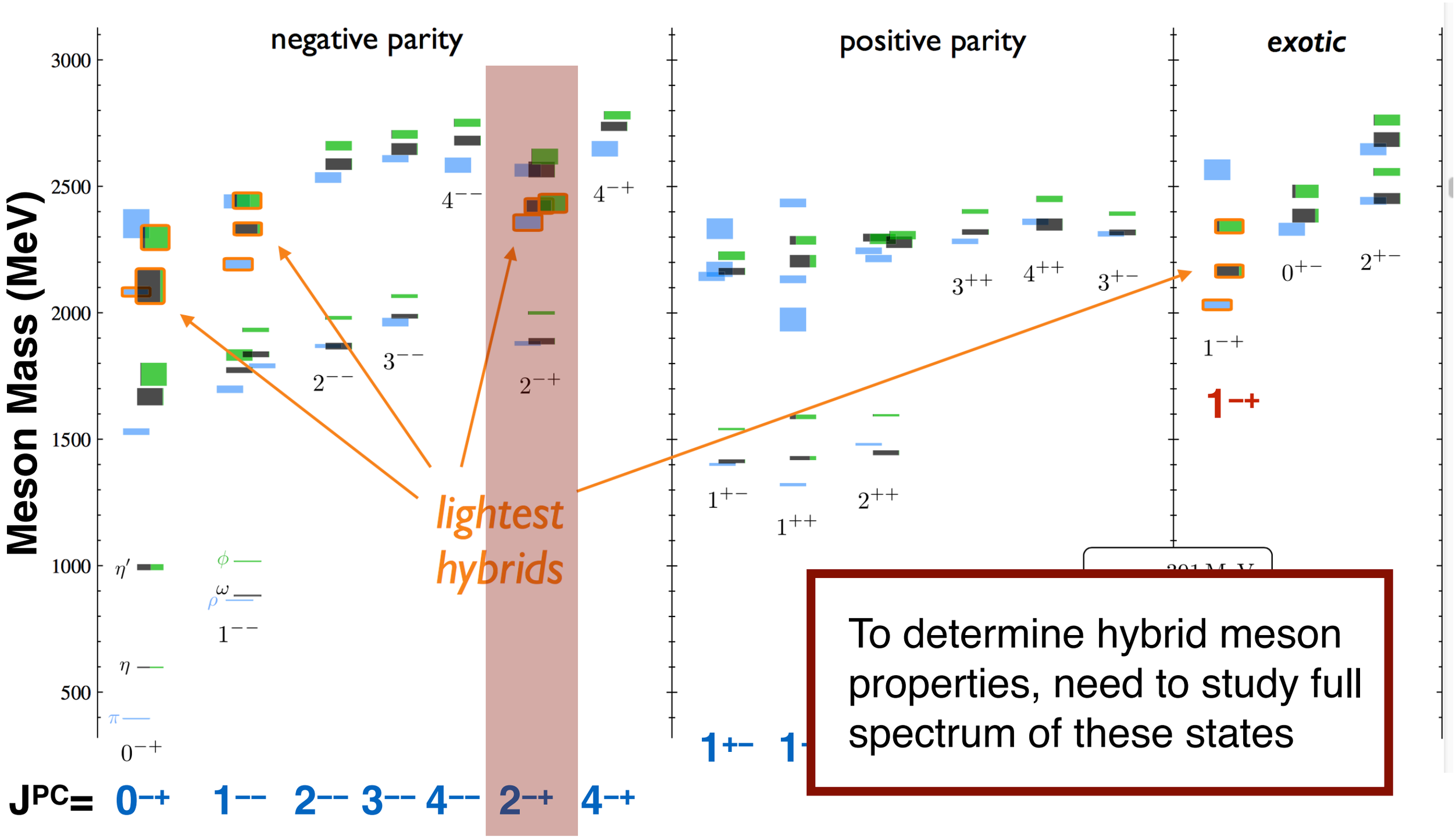
π_1 strength increases

PRD 98, 92003 (2018)

$M(\pi_1)$ = 1600+110–60 MeV

$\Gamma(\pi_1)$ = 580+100–230 MeV

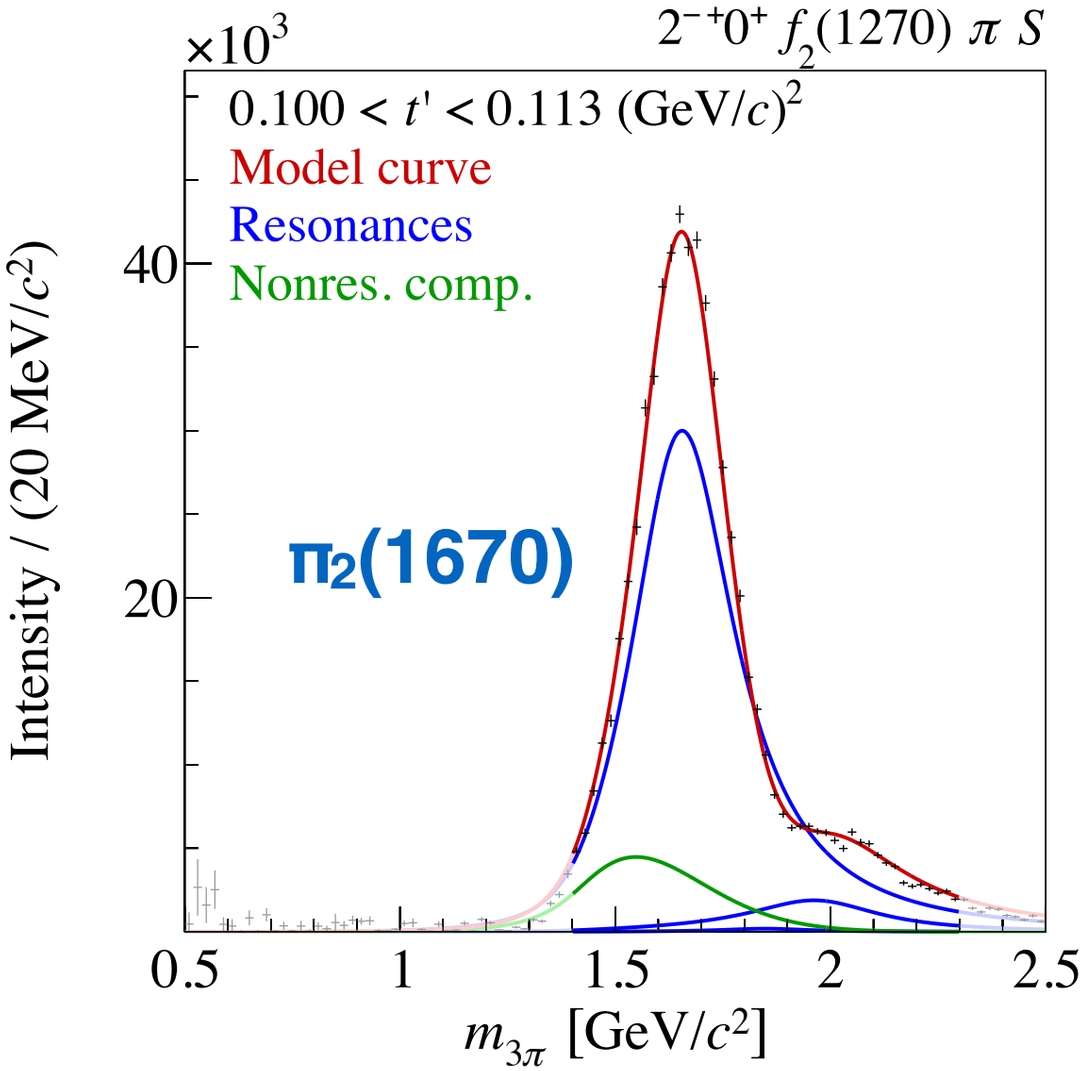
Light Meson Spectrum from Lattice QCD

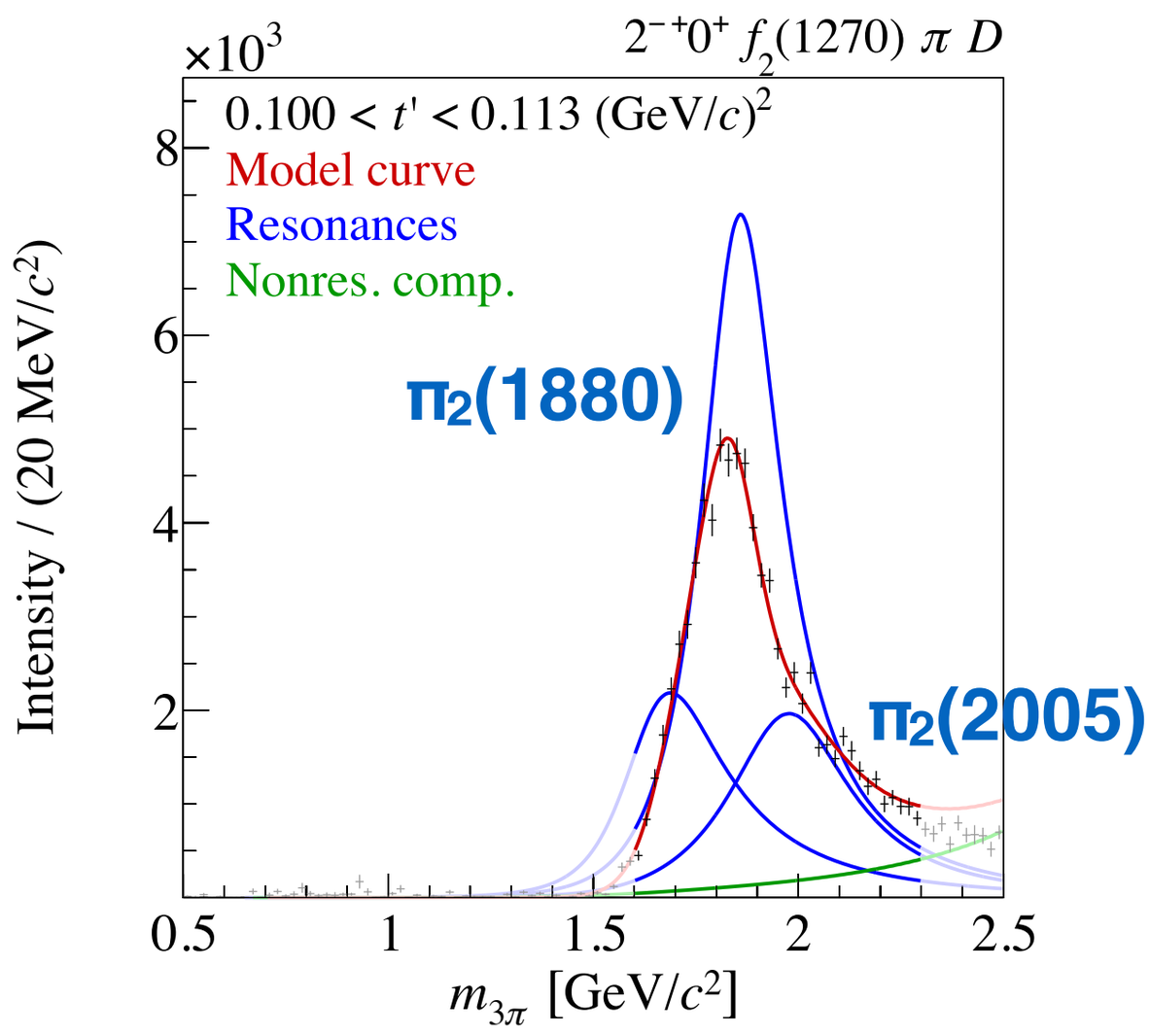


To determine hybrid meson properties, need to study full spectrum of these states

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

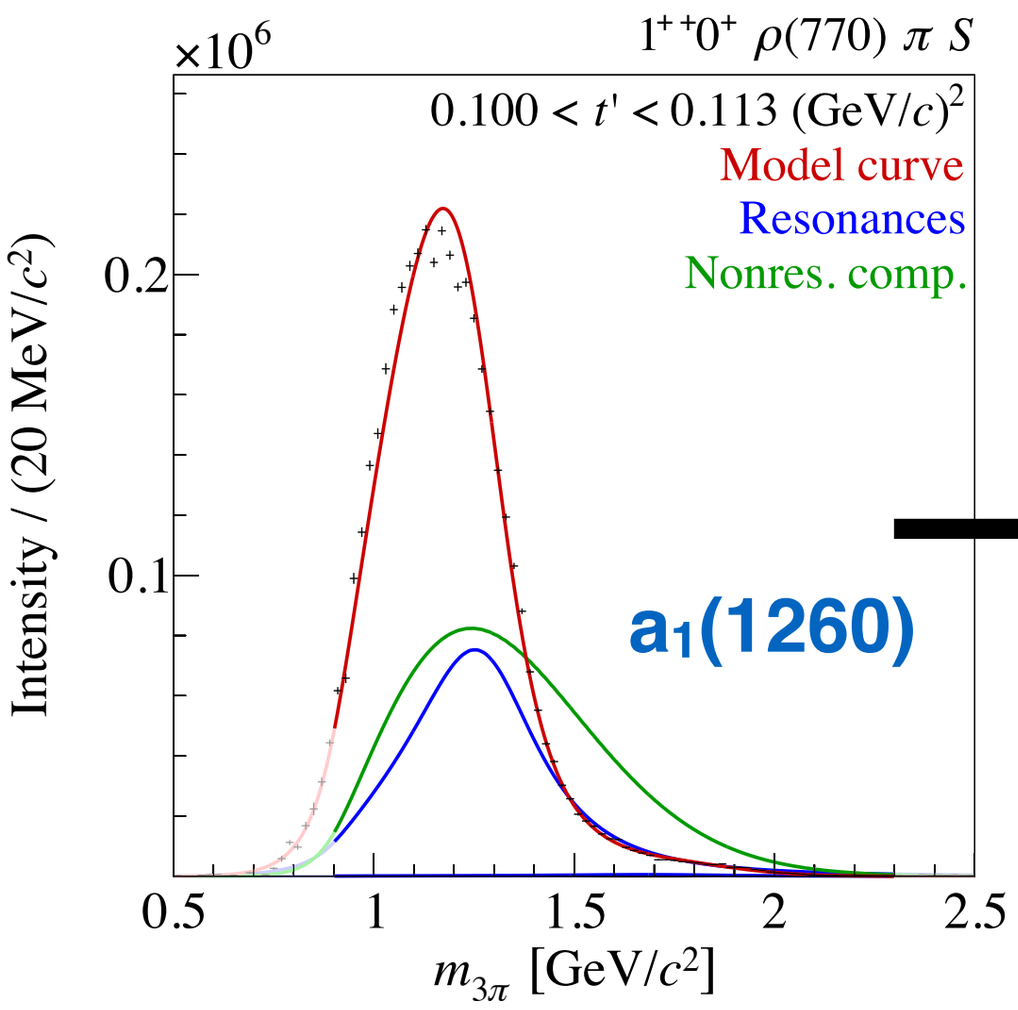
$\pi^-\pi^+\pi^-$ @ COMPASS: $J^{PC} = 2^{-+}$: $\pi_2(1670)$, $\pi_2(1880)$, $\pi_2(2005)$



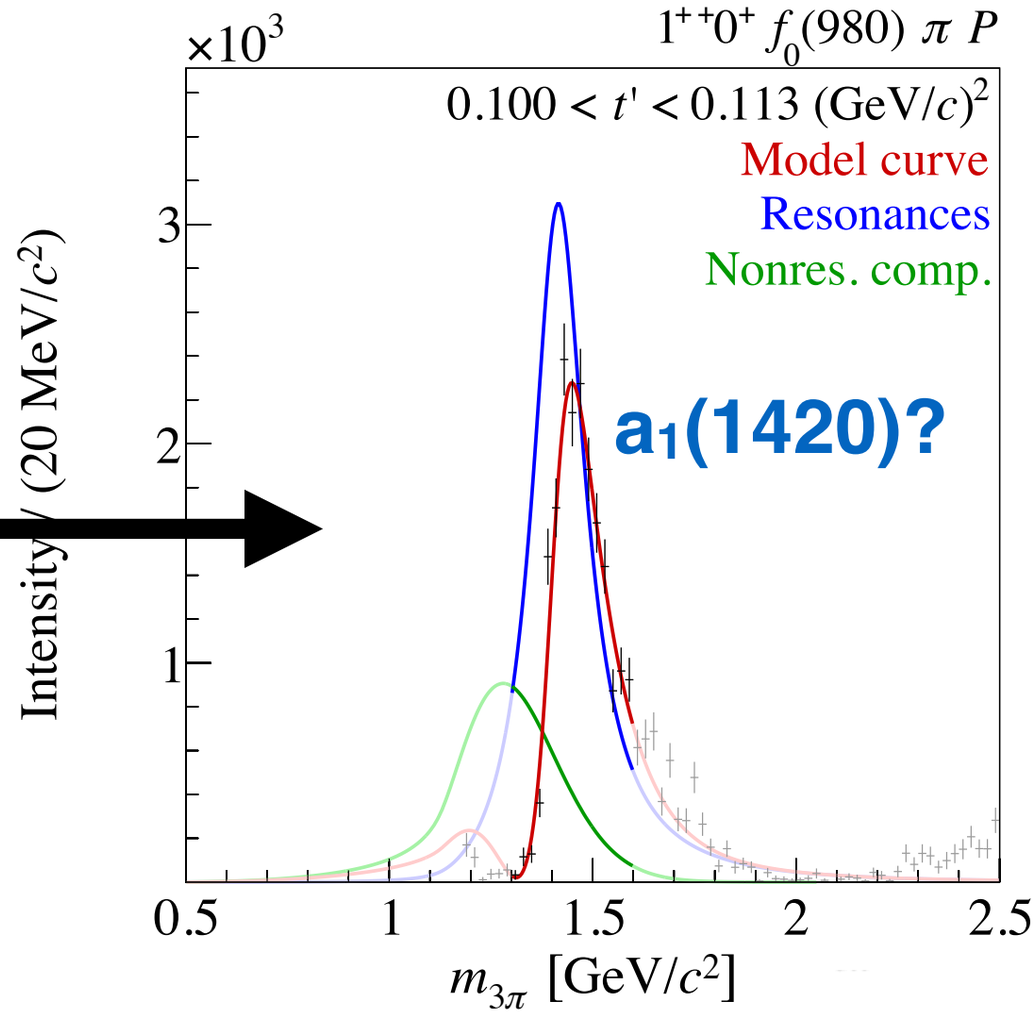


- Observed 3 π_2 states: $\pi_2(1670)$, $\pi_2(1880)$, $\pi_2(2005)$
- Are these supernumerary states? Non-resonant contributions complicate interpretation.
  - Need more input from theory and experiment.

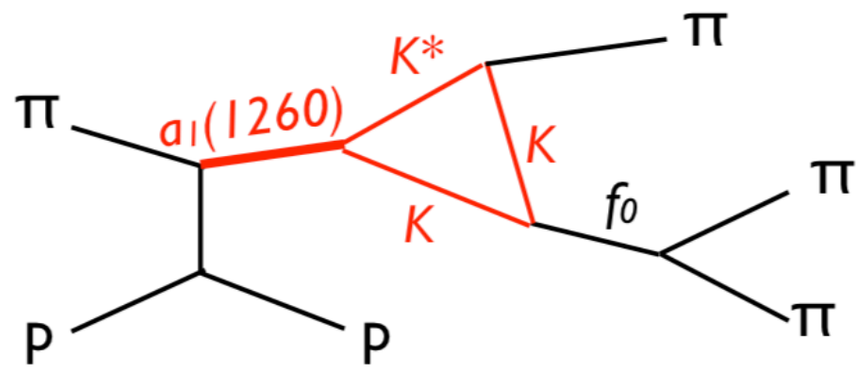
$\pi^-\pi^+\pi^-$ @ COMPASS: $J^{PC} = 1^{++}$: $a_1(1260)$, $a_1(1420)$



~1%

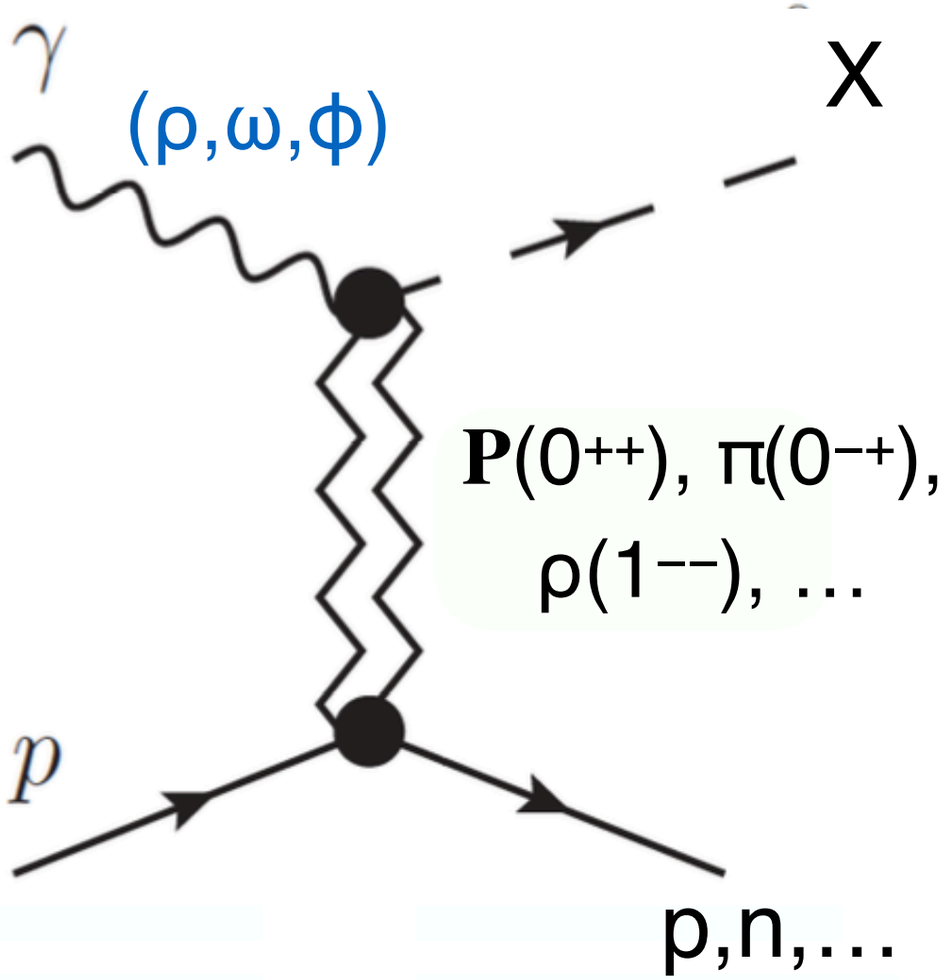


- Unexpected state seen in $f_0(980)$ π P-wave
  - Much theoretical interest
- Can be described as Breit-Wigner or anomalous triangle singularity



M. Mikhasenko et al., PRD 91, 094015 (2015)
F. Aceit et al., PRD 94, 09615 (2016)

Meson Photoproduction

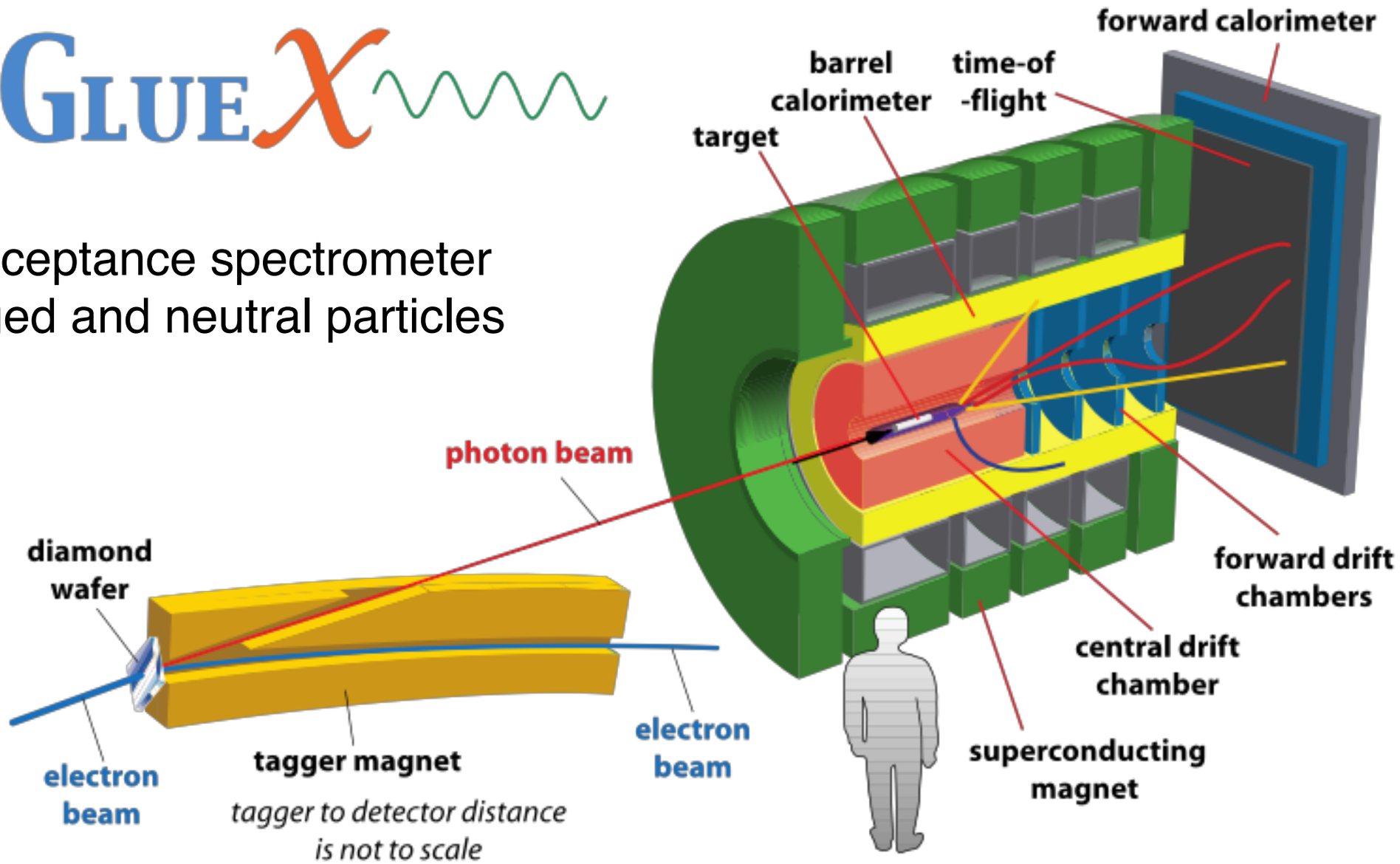


- Extend search for hybrids in fresh, **complementary** production mechanism
- **Photon** couples to exchanged QN via VMD, generates mesons with wide variety of J^{PC}: all expected hybrids can be produced
- Little existing photoproduction data. Neutral final states at these energies are mostly **unexplored**
- Photon polarization provides constraints on production processes
- Detailed models for amplitude analysis needed to understand spectra

The GlueX Experiment

GLUEX

Large acceptance spectrometer
for charged and neutral particles

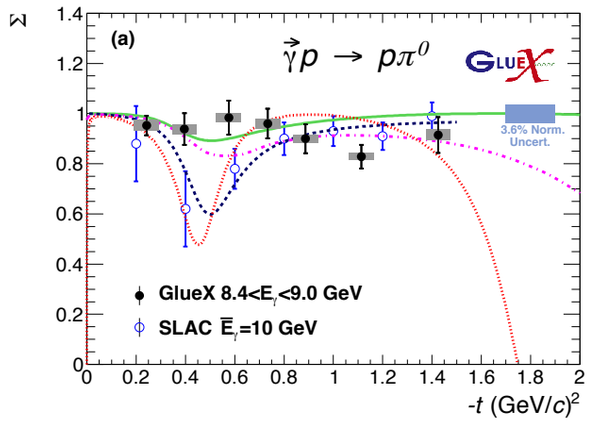


- **2016: 10 pb^{-1}** (~80 hours of physics-quality commissioning data)
- **2017: 45 pb^{-1}** (used for most public results)
- **2018: ~150 pb^{-1}** GlueX Phase-I **complete!**

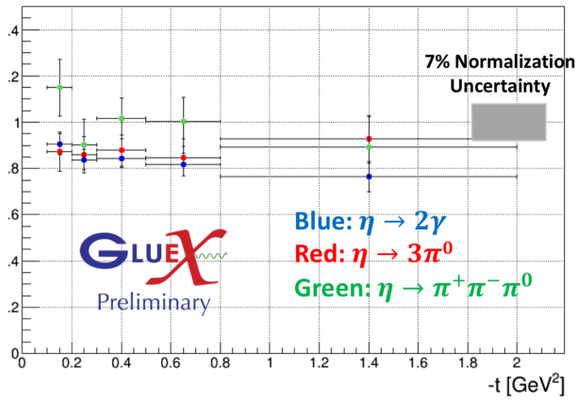
Polarization Observables at GlueX

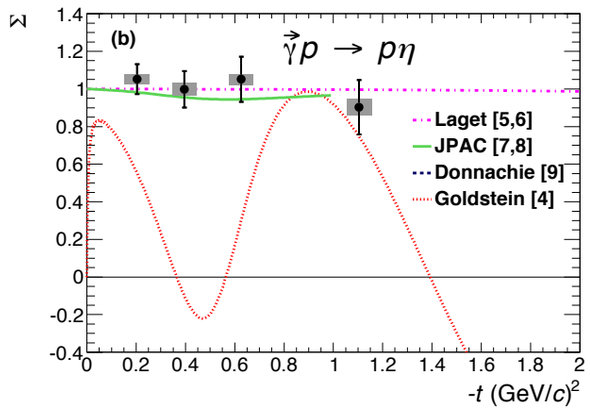
- Measurements of linearly polarized photon observables yield key info needed for hybrid meson searches
- Beam asymmetries
  - $\gamma p \to p \pi^0$
  - $\gamma p \to p \eta$
  - $\gamma p \to p \eta'$
  - $\gamma p \to \Delta^{++} \pi^-$
  - $\gamma p \to \Sigma^0 K^+$
- Spin-density Matrix Elements
  - $\gamma p \to p \rho^0$
  - $\gamma p \to p \omega$
  - $\gamma p \to p \phi$
  - $\gamma p \to \Lambda(1520) K^+$

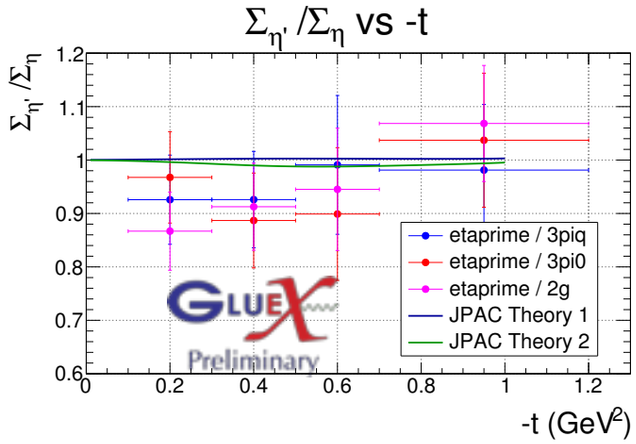
π^0 / η: PRC 95, 042201 (2017)



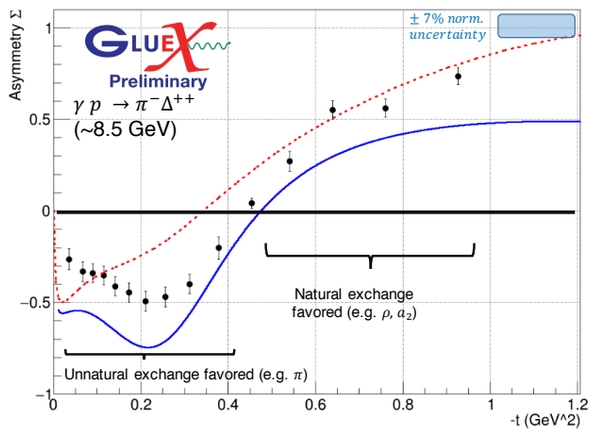
$\gamma p \to p \eta/\eta'$



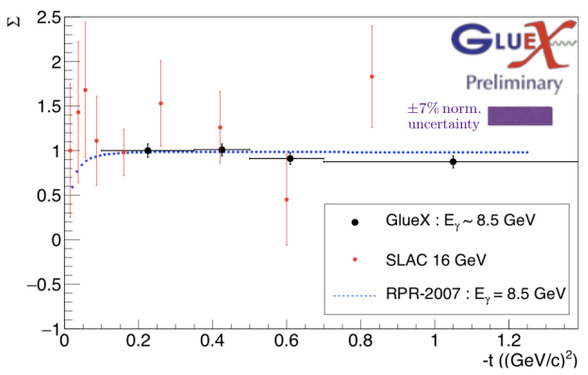




$\gamma p \to \Delta^{++} \pi^-$

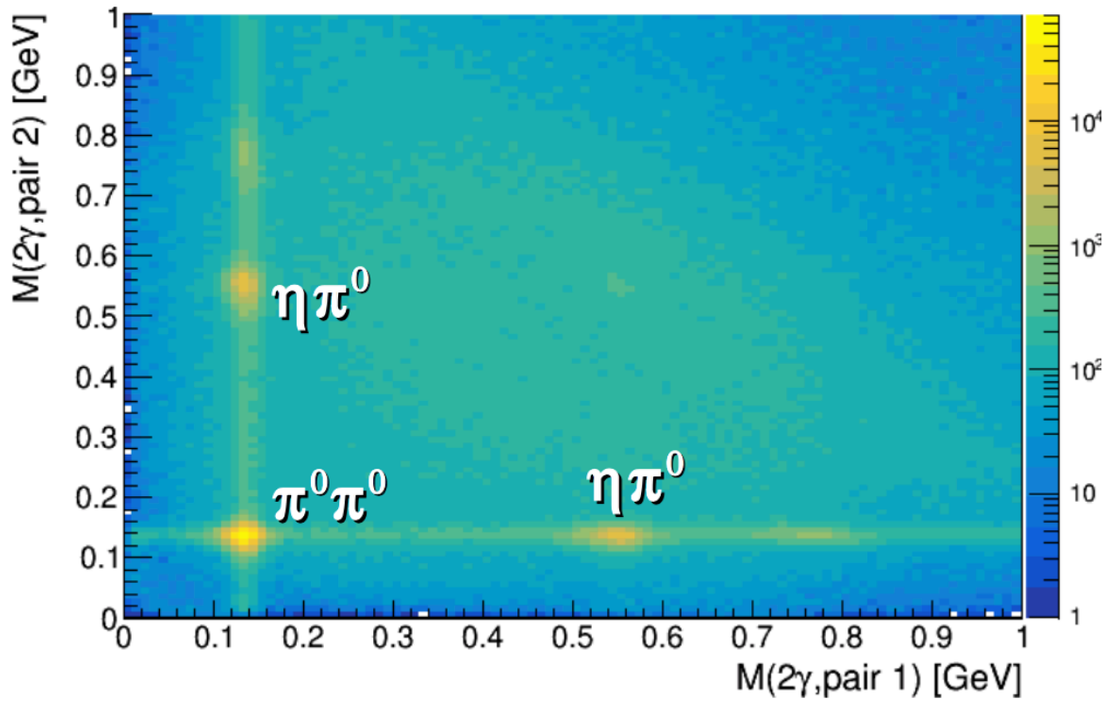


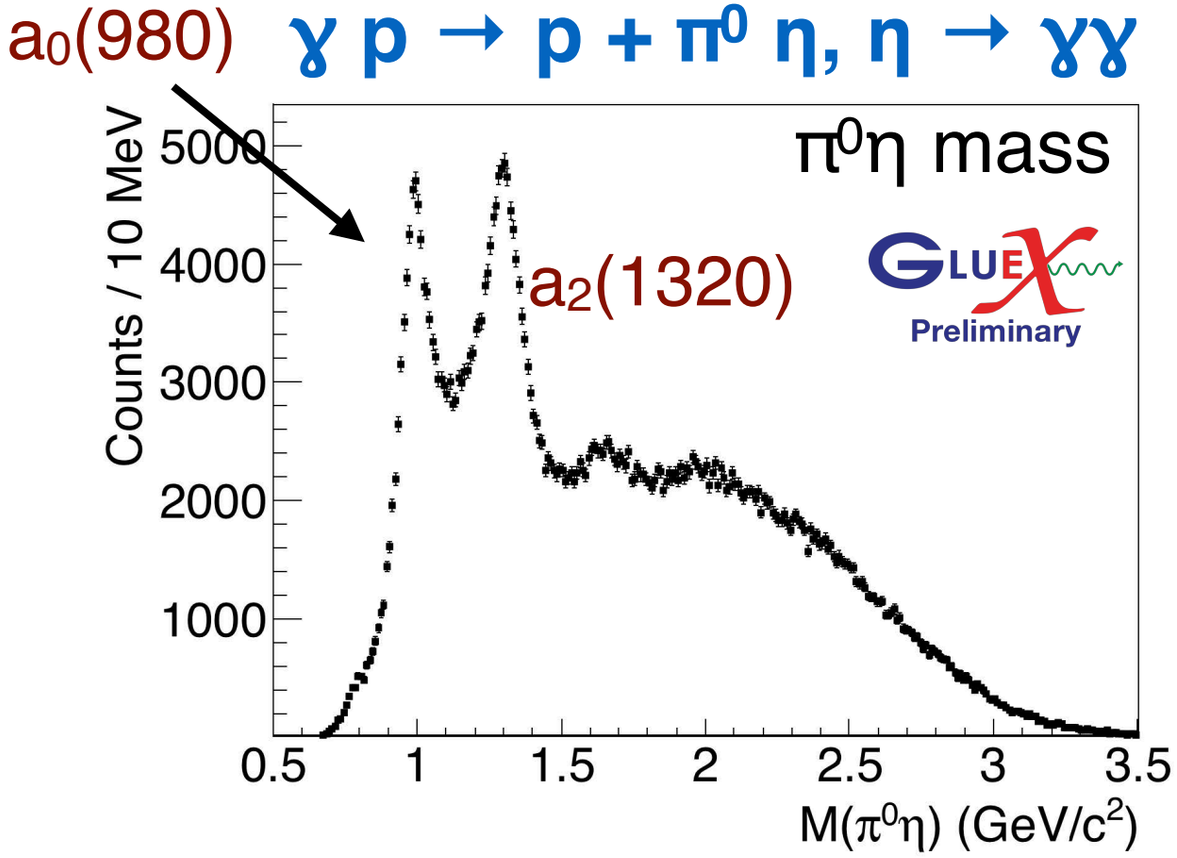
$\gamma p \to \Sigma^0 K^+$

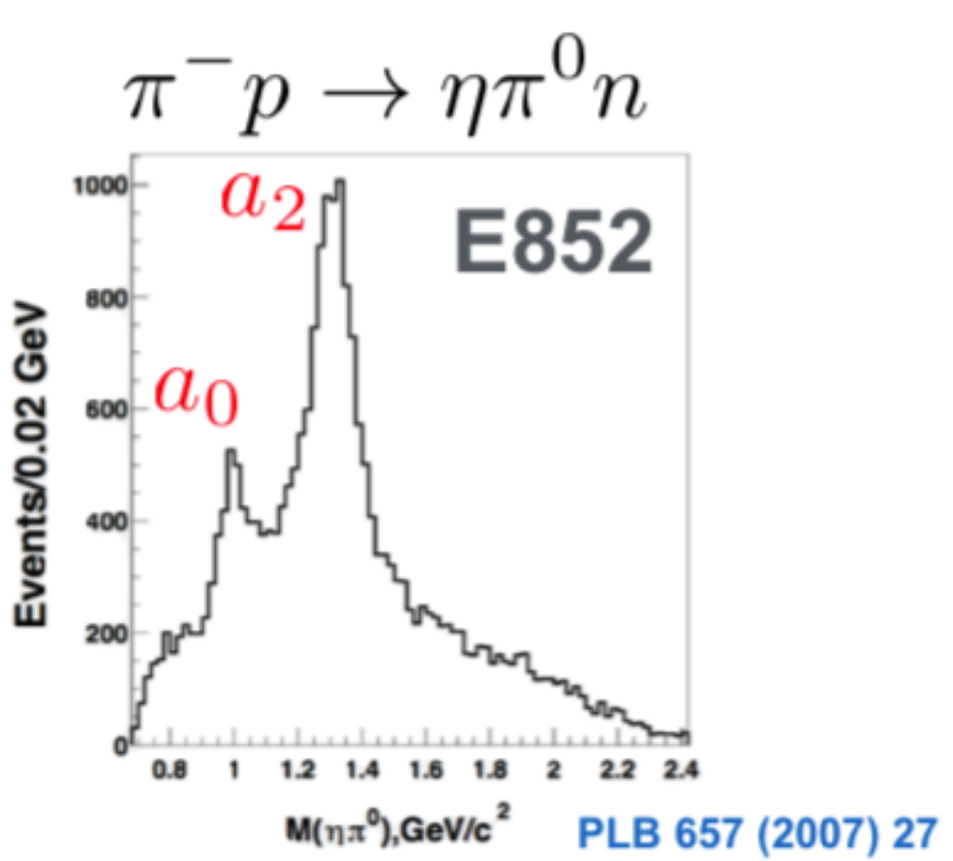


Spectroscopy Prospects @ GlueX: γ p → p + π η

- 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







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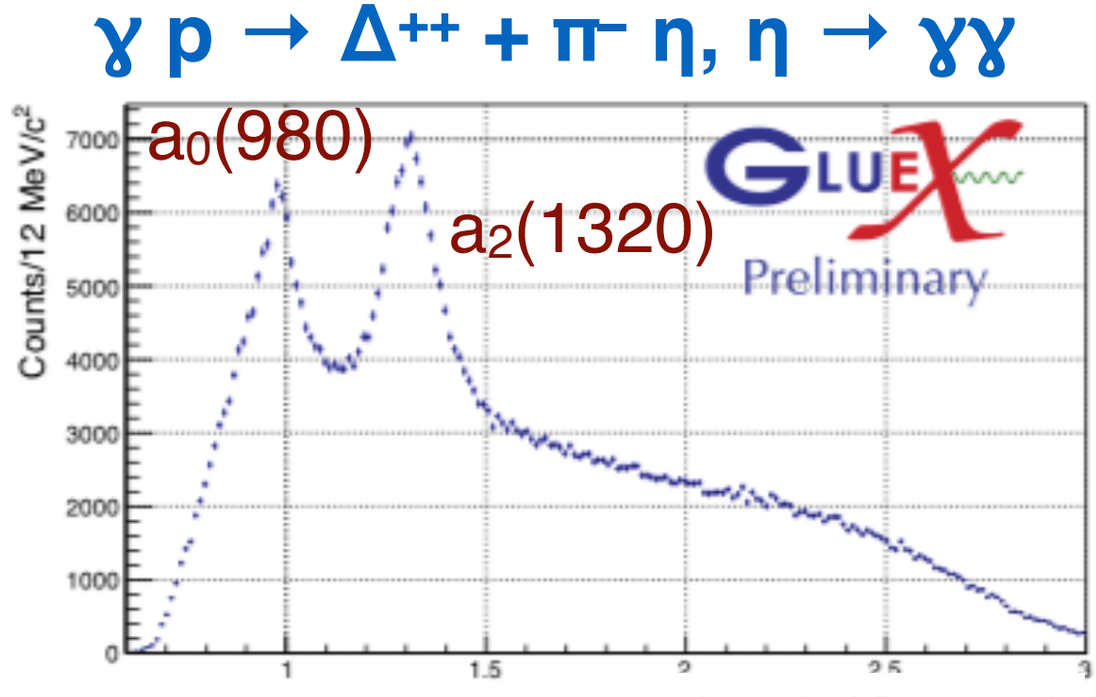
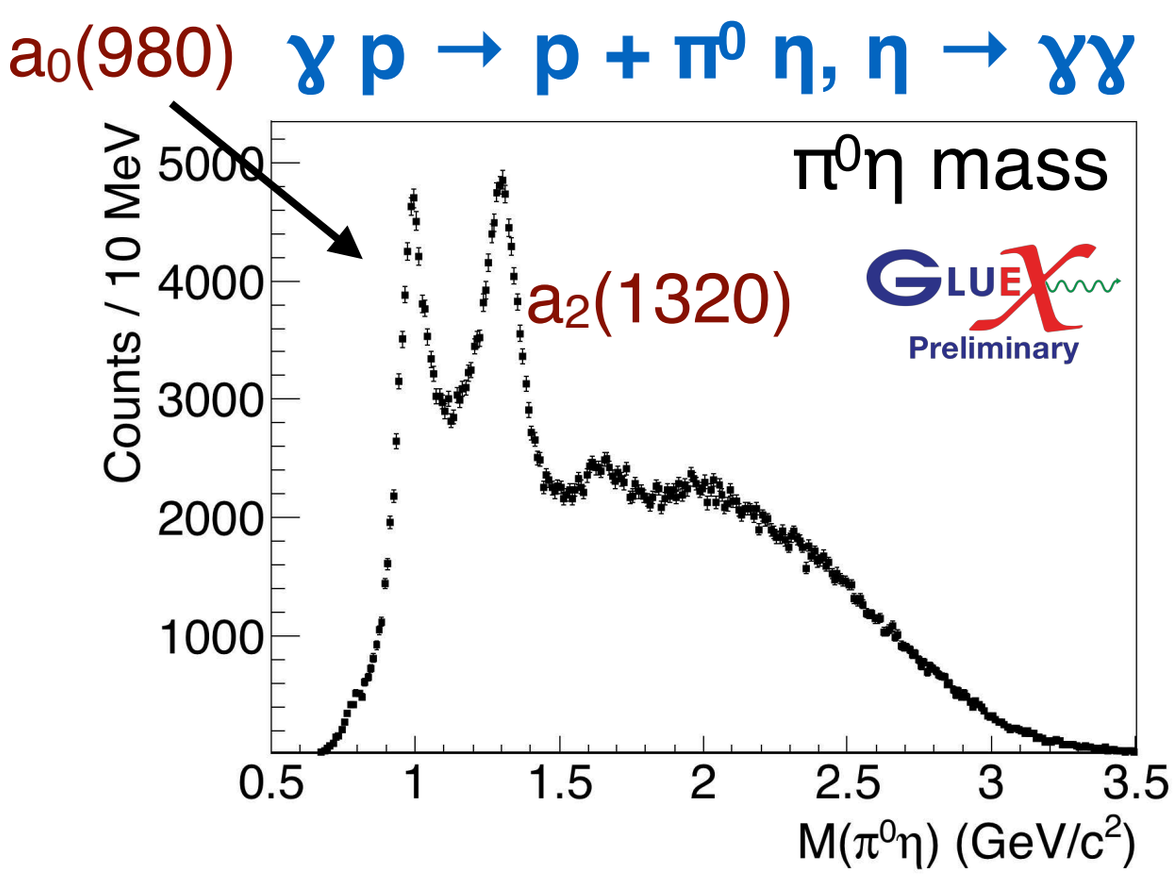
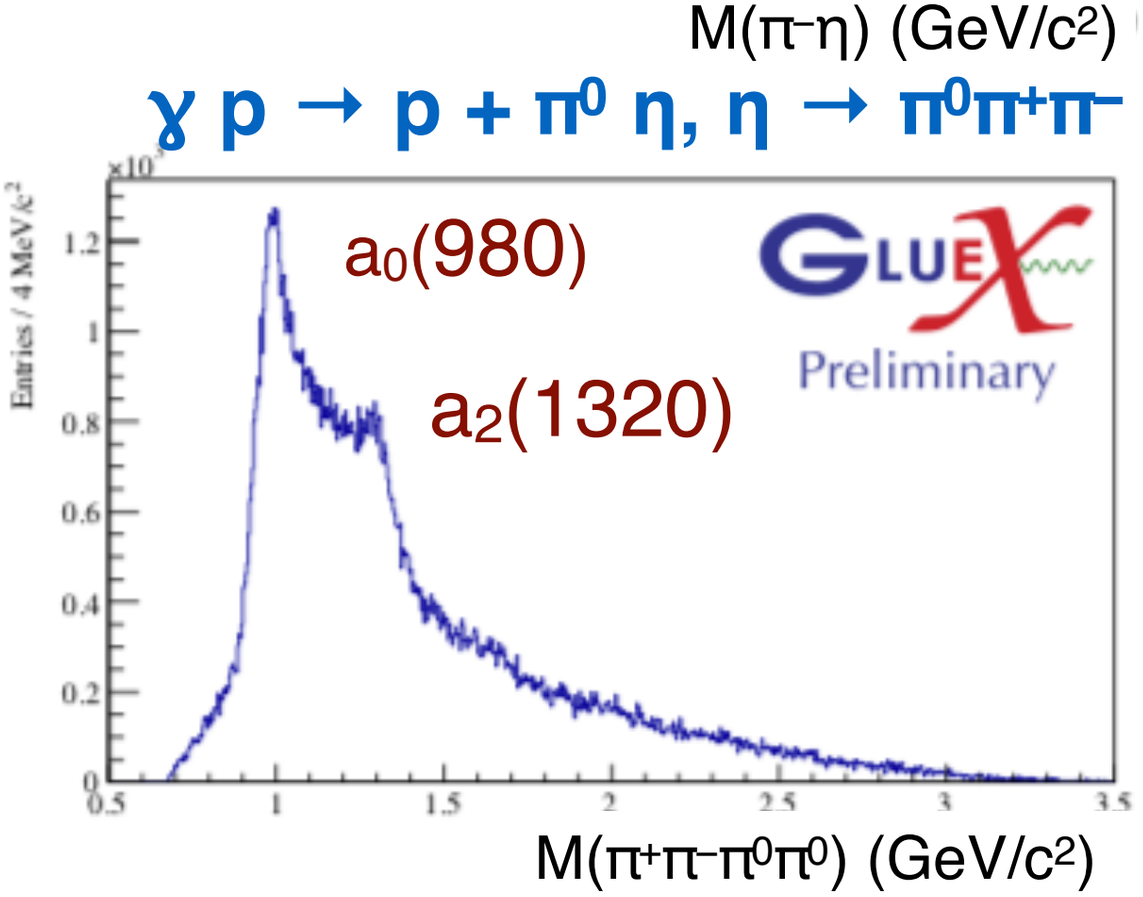
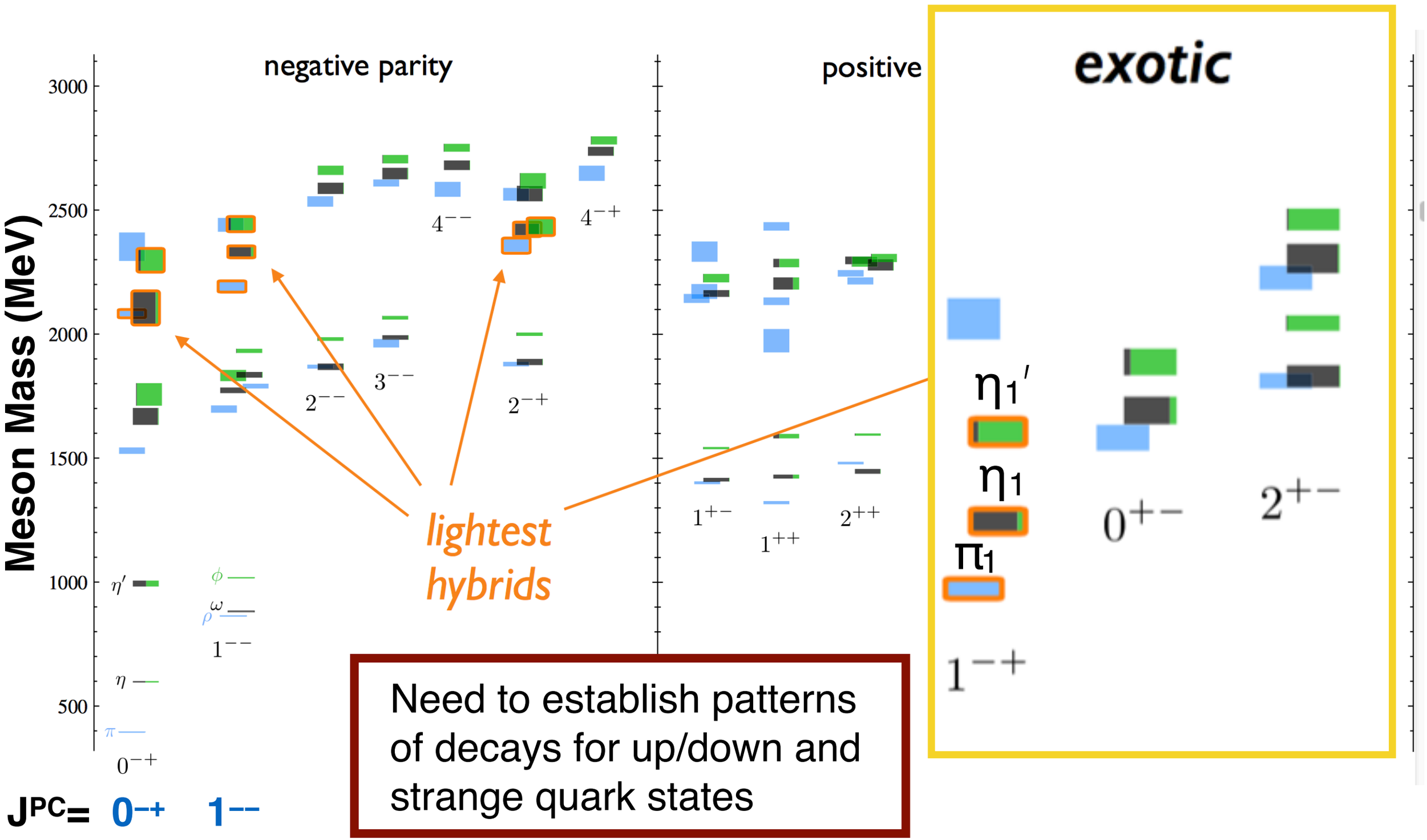






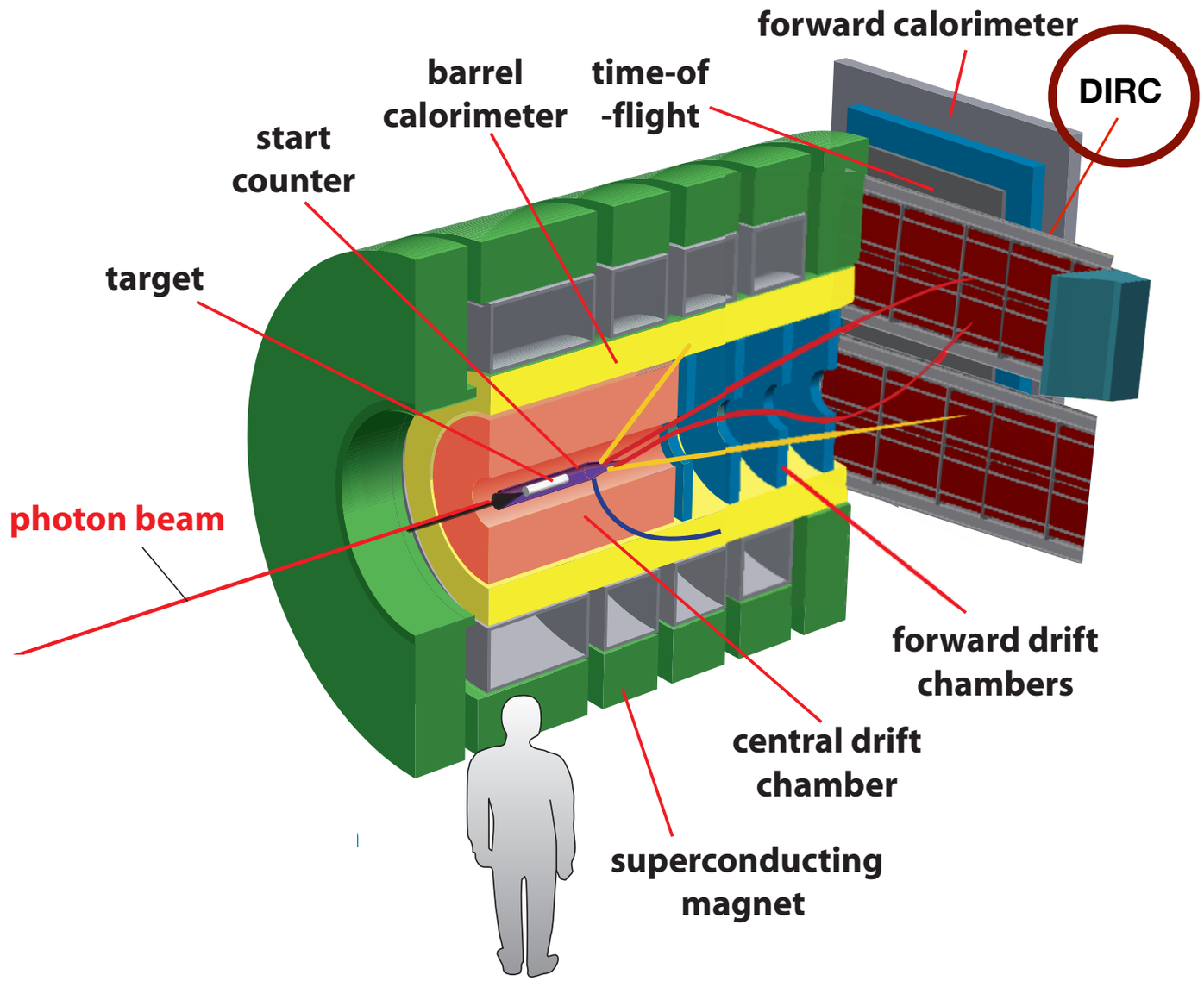
Light Meson Spectrum from Lattice QCD



Need to establish patterns of decays for up/down and strange quark states

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

GlueX-II: Enter the DIRC



SLAC NATIONAL ACCELERATOR LABORATORY

Jefferson Lab

- To study hybrids containing **strange quarks**, need clean identification of charged pions and kaons
- New addition: **DIRC** (**D**etection of **I**nternally **R**eflected **C**herenkov light)
- Installation & commissioning currently underway

Summary

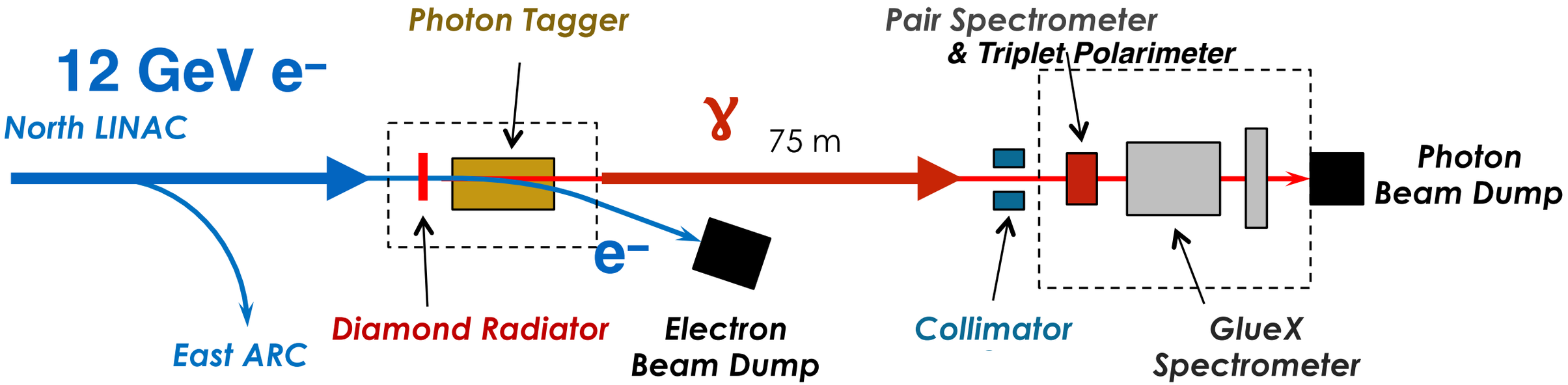
- New vistas have opened up in meson spectroscopy due to availability of large, high-quality data sets
- Close collaboration between experimentalists and theorists **essential** to map these spectra

See JPAC sessions Friday morning

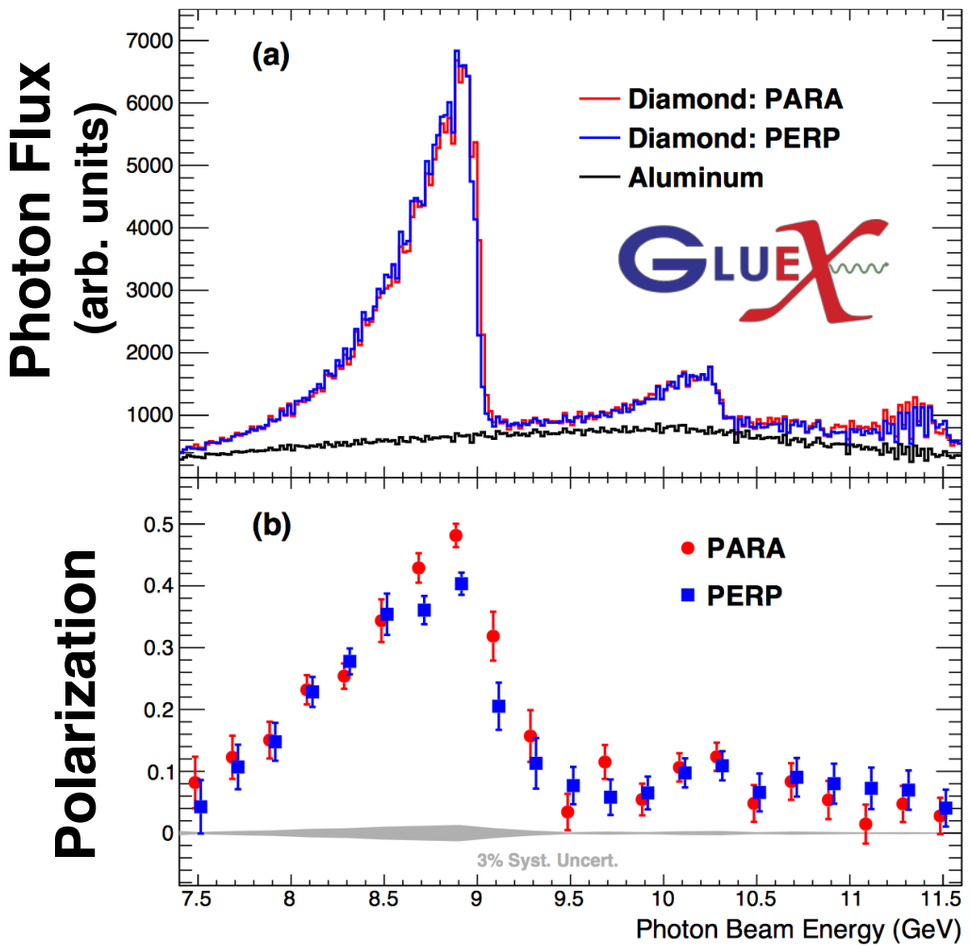
- Identification of hybrid mesons opens the door to establishing contribution of **gluonic excitations** to meson spectrum
  - **$\pi_1(1600)$** pole positions determined from COMPASS data
  - Need to map out spectra in complementary production mechanisms
  - **Photoproduction** provides powerful tool to establish the full spectrum of hybrid mesons
- Expect contributions from many new experiments
  - Current: GlueX (γ), CLAS12 (γ/e^-), BES-III (e^+e^-), …
  - Upcoming: Belle-II (e^+e^-), PANDA ($p\bar{p}$), ?

Backup Slides

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
- Intensity of ~1–5 × 10^7 γ/s in peak



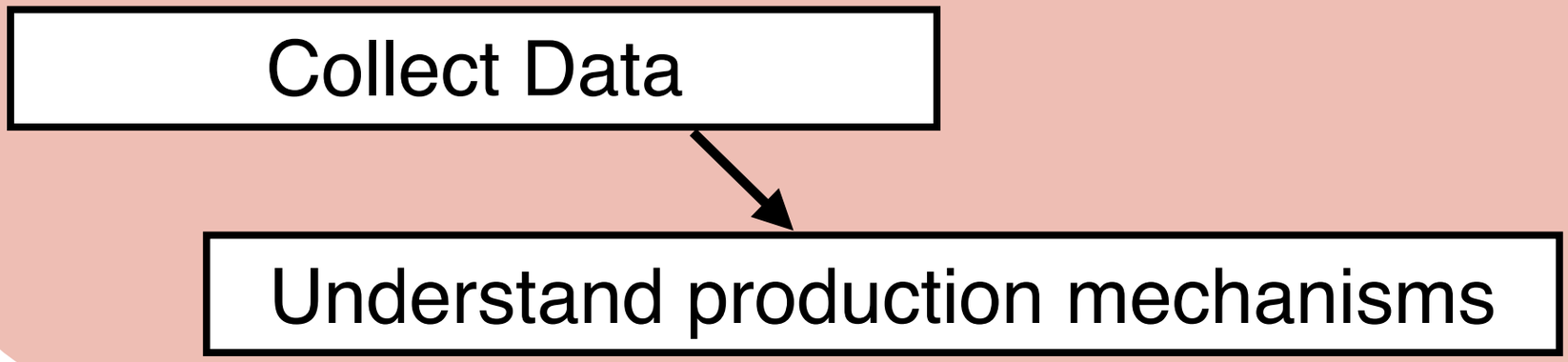
Searching for Exotics in Photoproduction

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

Collect Data

Searching for Exotics in Photoproduction

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



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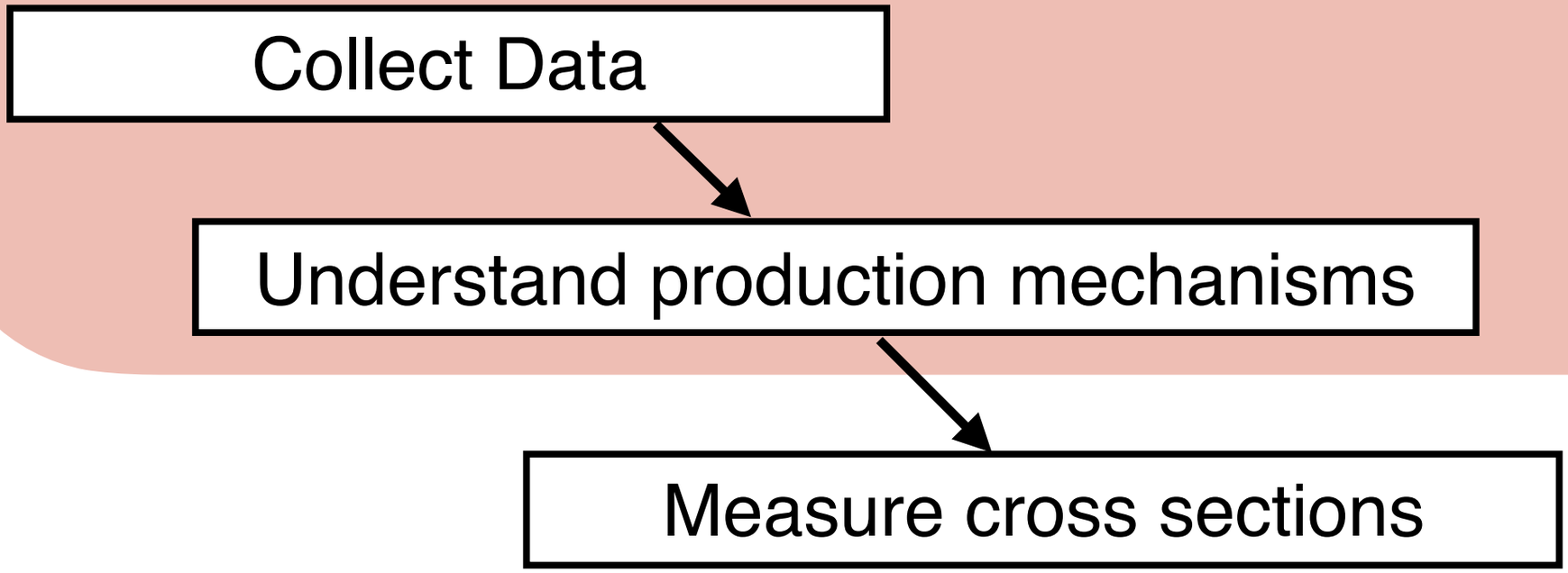

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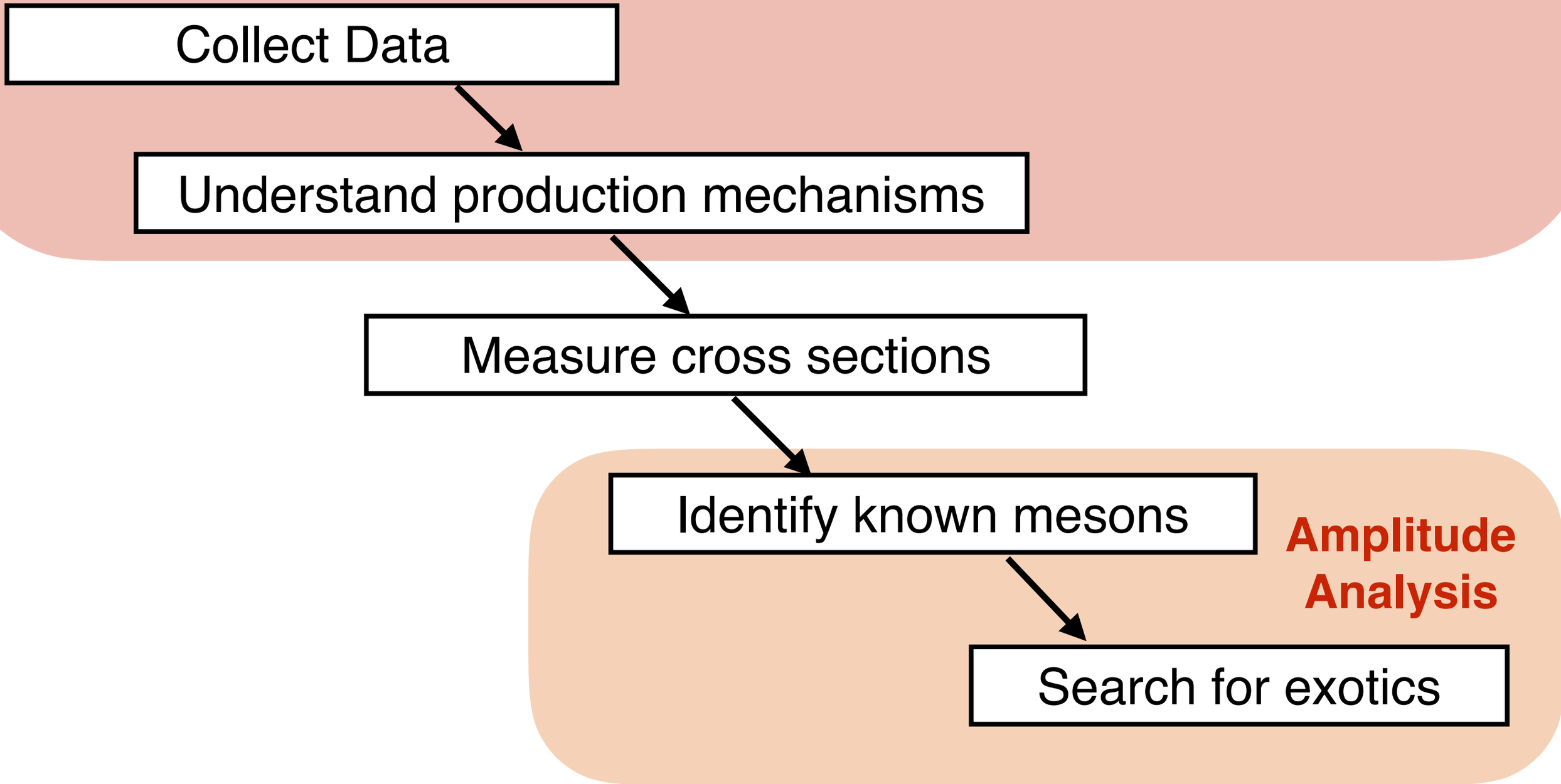

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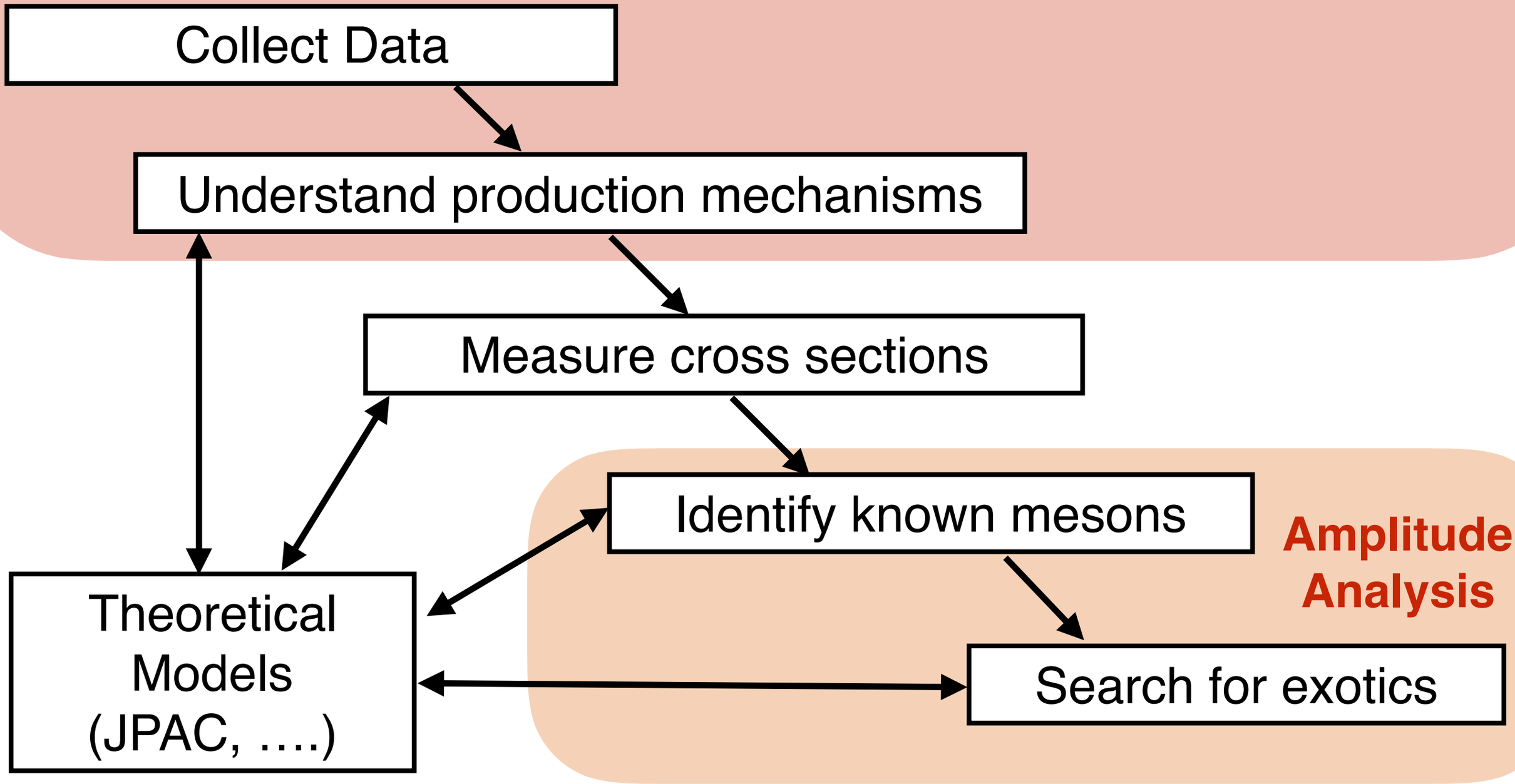

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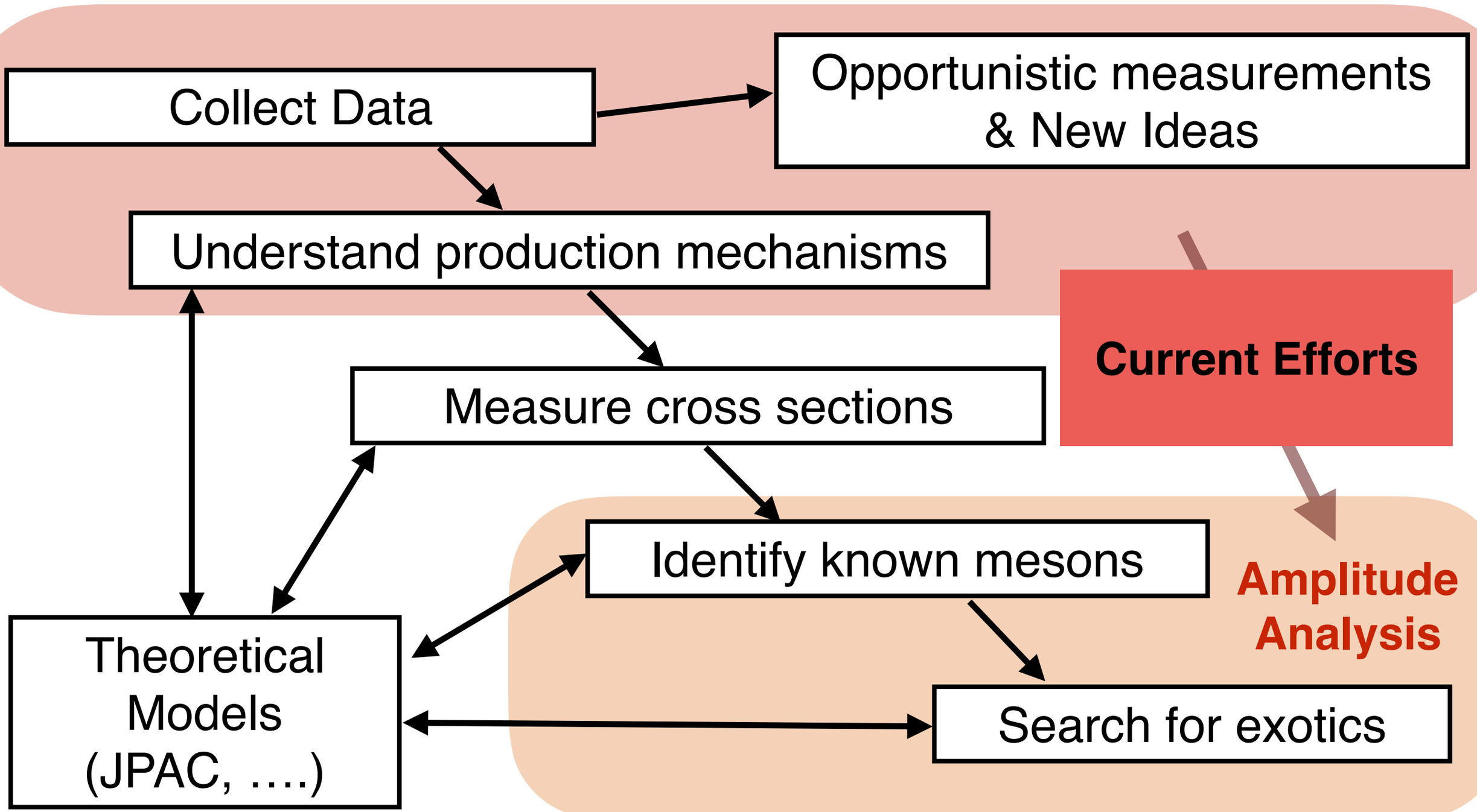
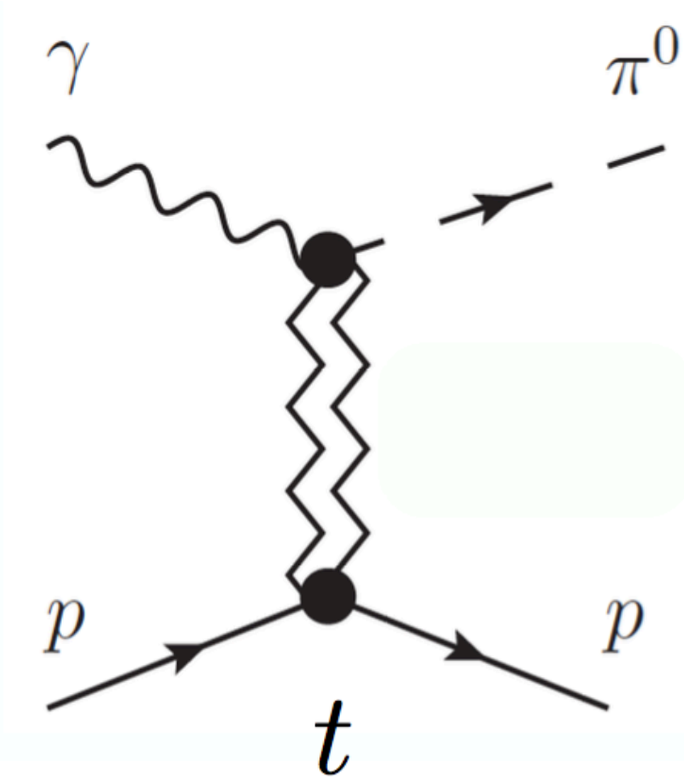


Beam Asymmetries: $\gamma p \to p + \pi^0 / \eta$

- 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

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



Exchange J^{PC}

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

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

JPAC: Mathieu et al., PRD 92, 074013

Beam Asymmetries: γ p → p + π⁰ / η

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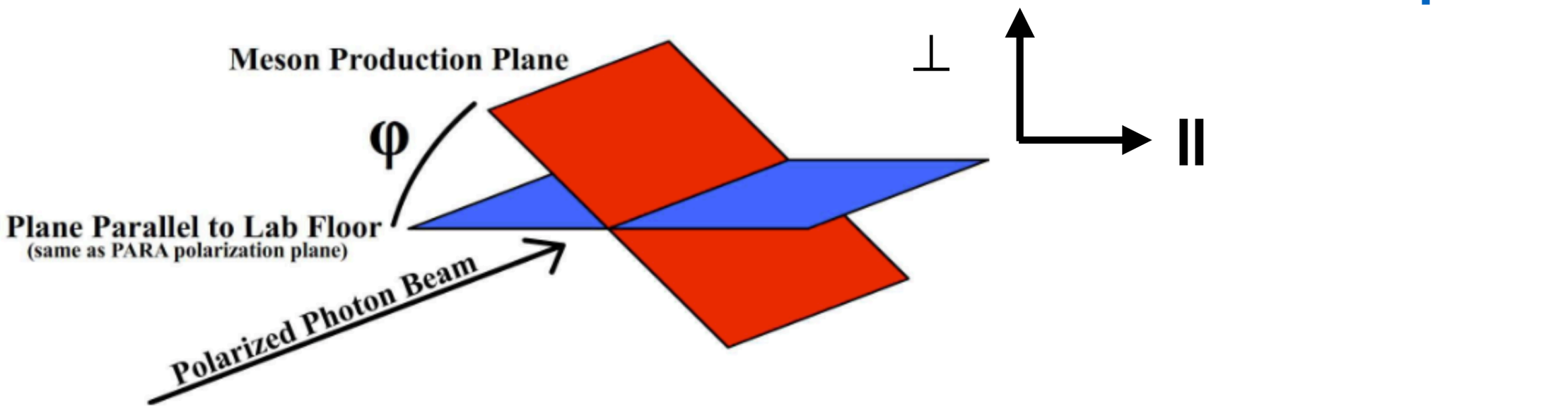
Production plane

$$\sigma = \sigma_0[1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_{\text{lin}})]$$

Polarization plane



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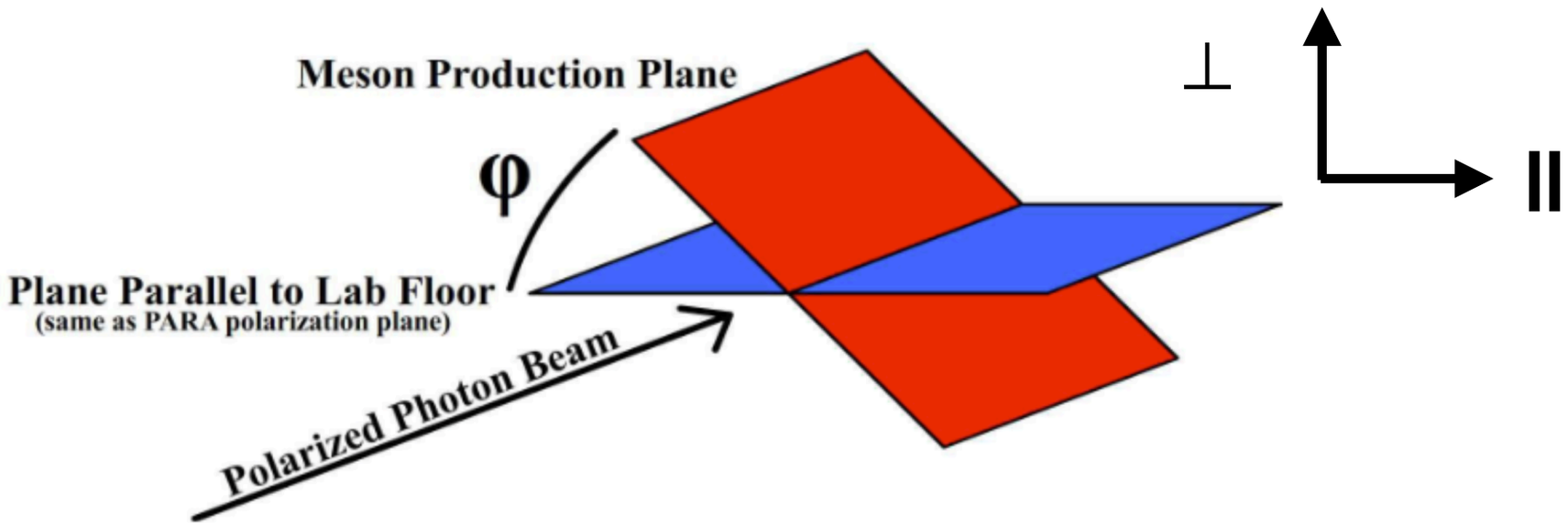
$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$



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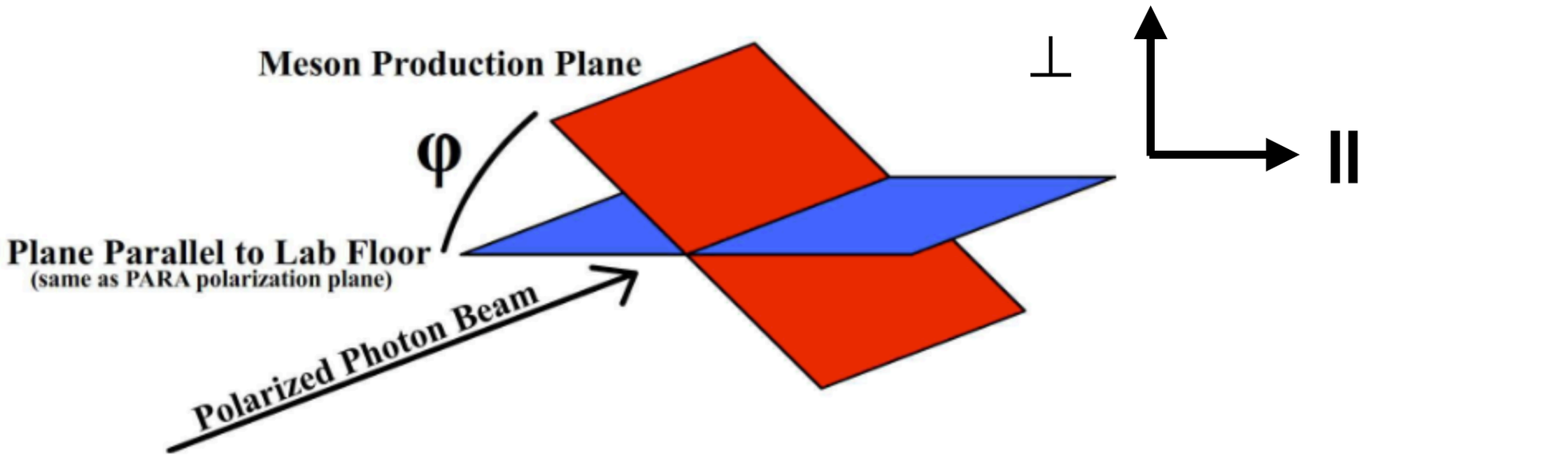
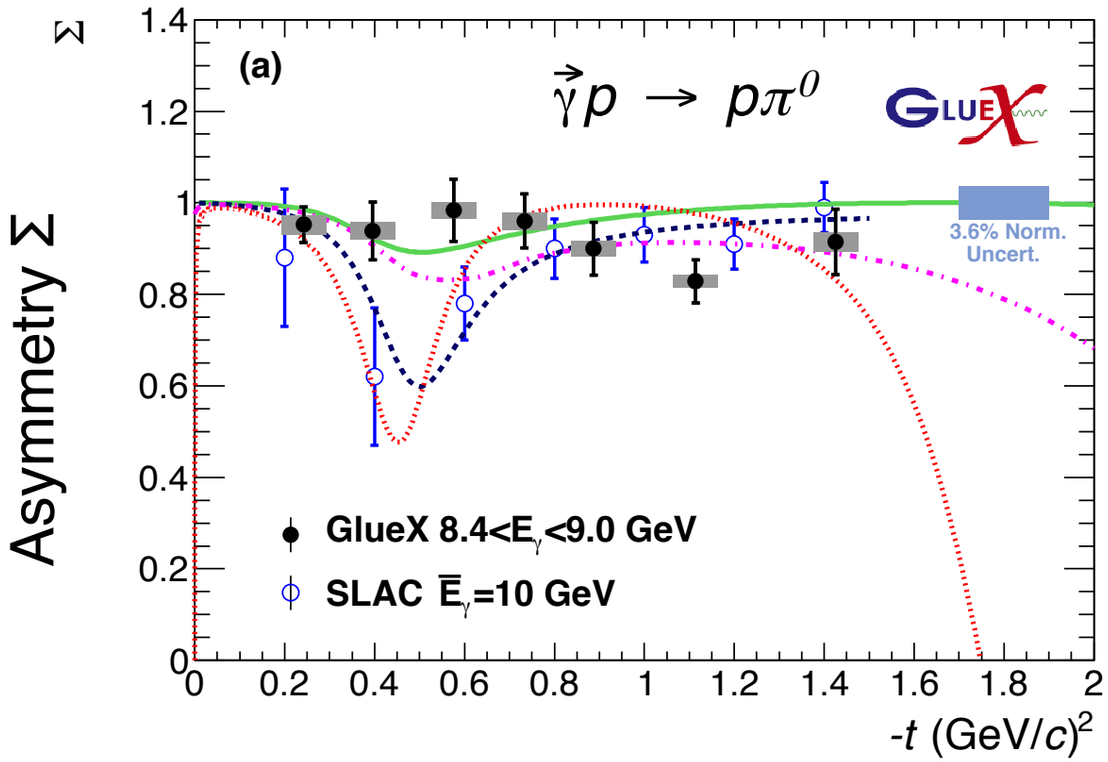
Measure with $\gamma e^- \to e^- e^+ e^-$

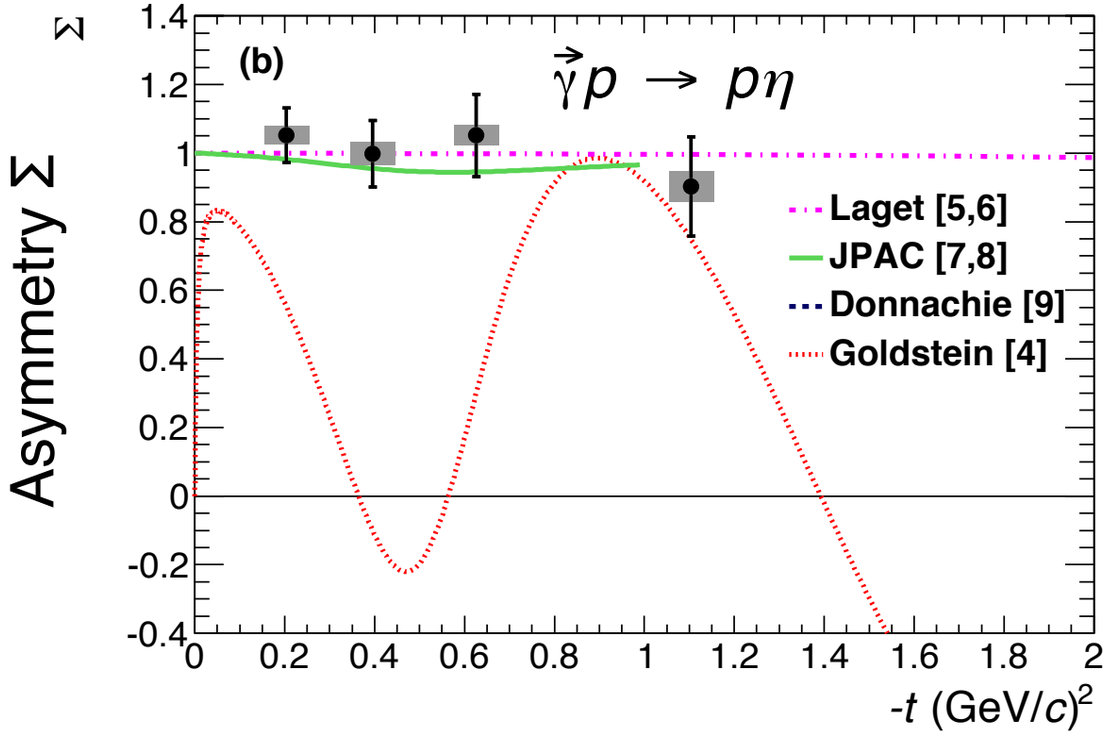
$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

Isolate Σ



Beam Asymmetries: γ p → p + π^0 / η

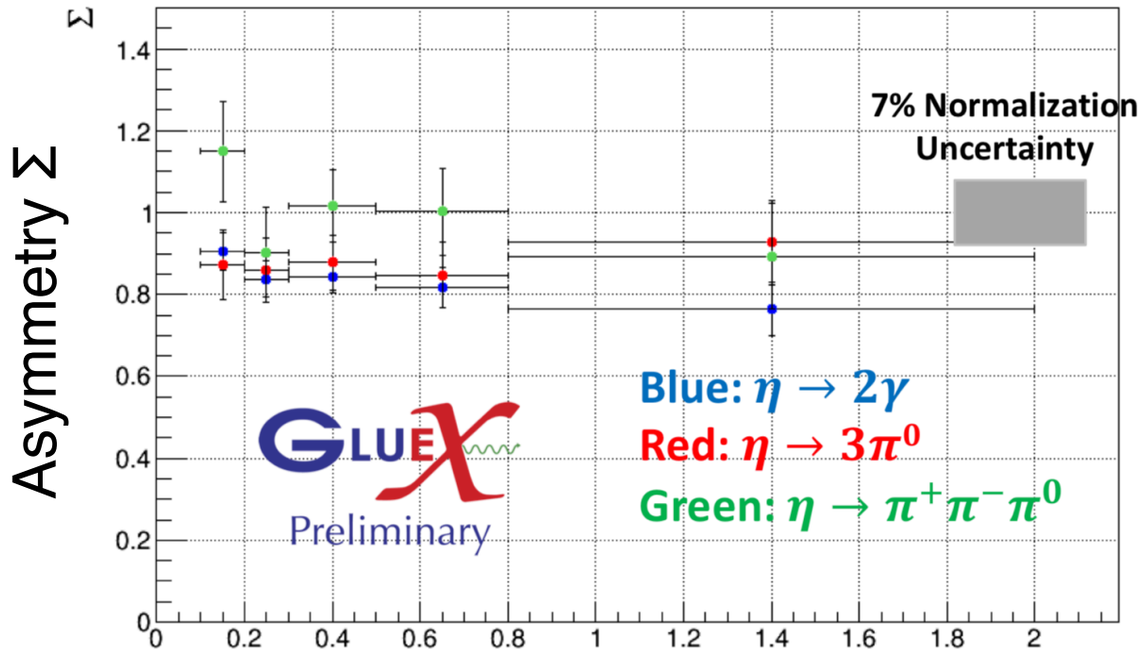


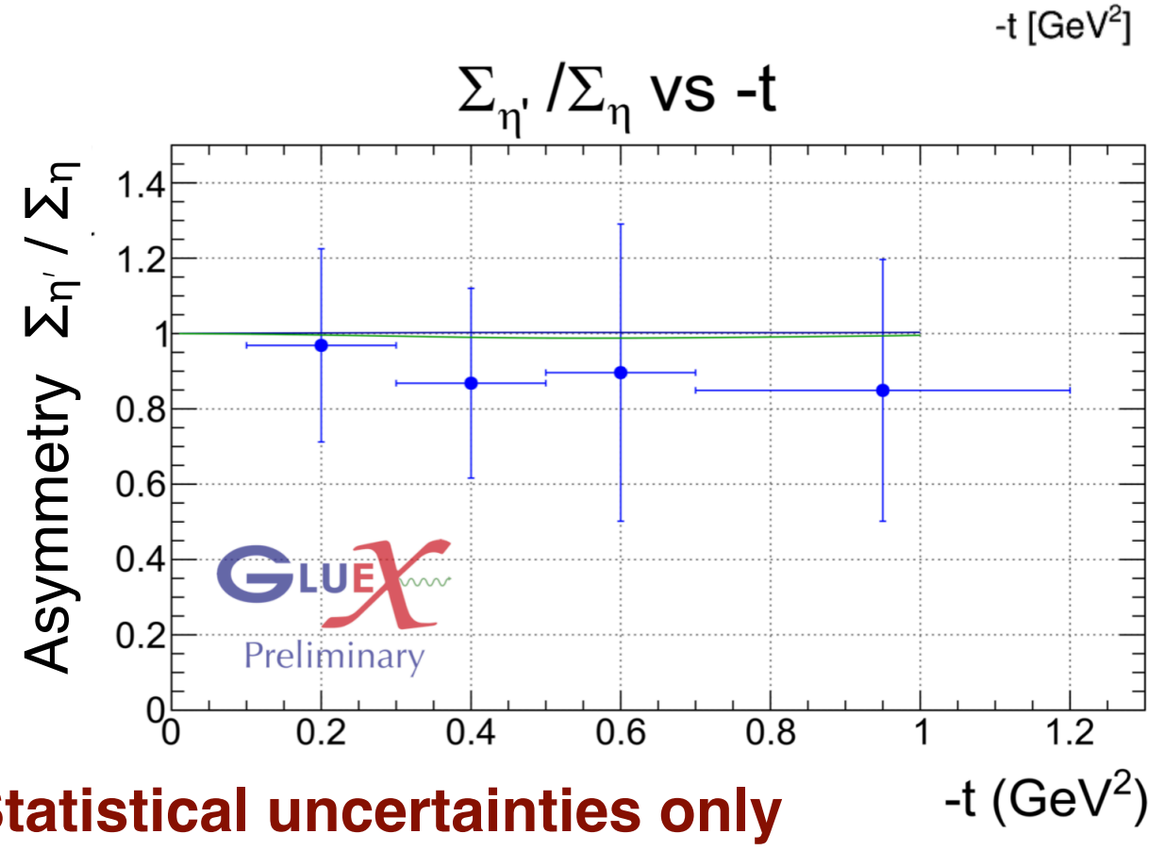


- First step towards study of photoproduction amplitudes made using 2016 data
- **Σ ≈ 1** indicates vector exchange dominates at this energy
- First **η** measurement at this energy
- Constrains background to baryon resonance production at lower energies [e.g. **arXiv:1708.07779**]

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

Beam Asymmetries: γ p → p + η / η′

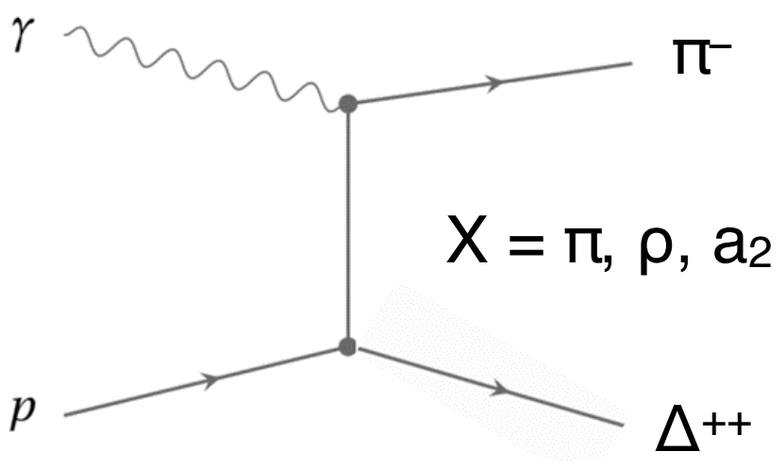




Statistical uncertainties only

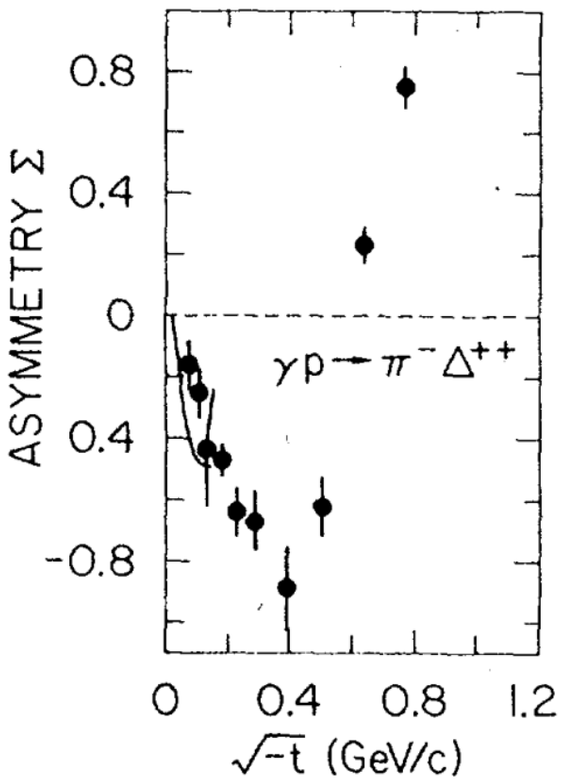
- Initial studies of η and η' beam asymmetries using 2017 data and additional decay modes
  - Expect similar mechanism for exotics
- Production is consistent with vector exchange dominance
  - Full GlueX-I data will provide a factor 5 more events
- Program of production amplitude studies is well underway

Beam Asymmetries: γ p → π⁻ Δ⁺⁺

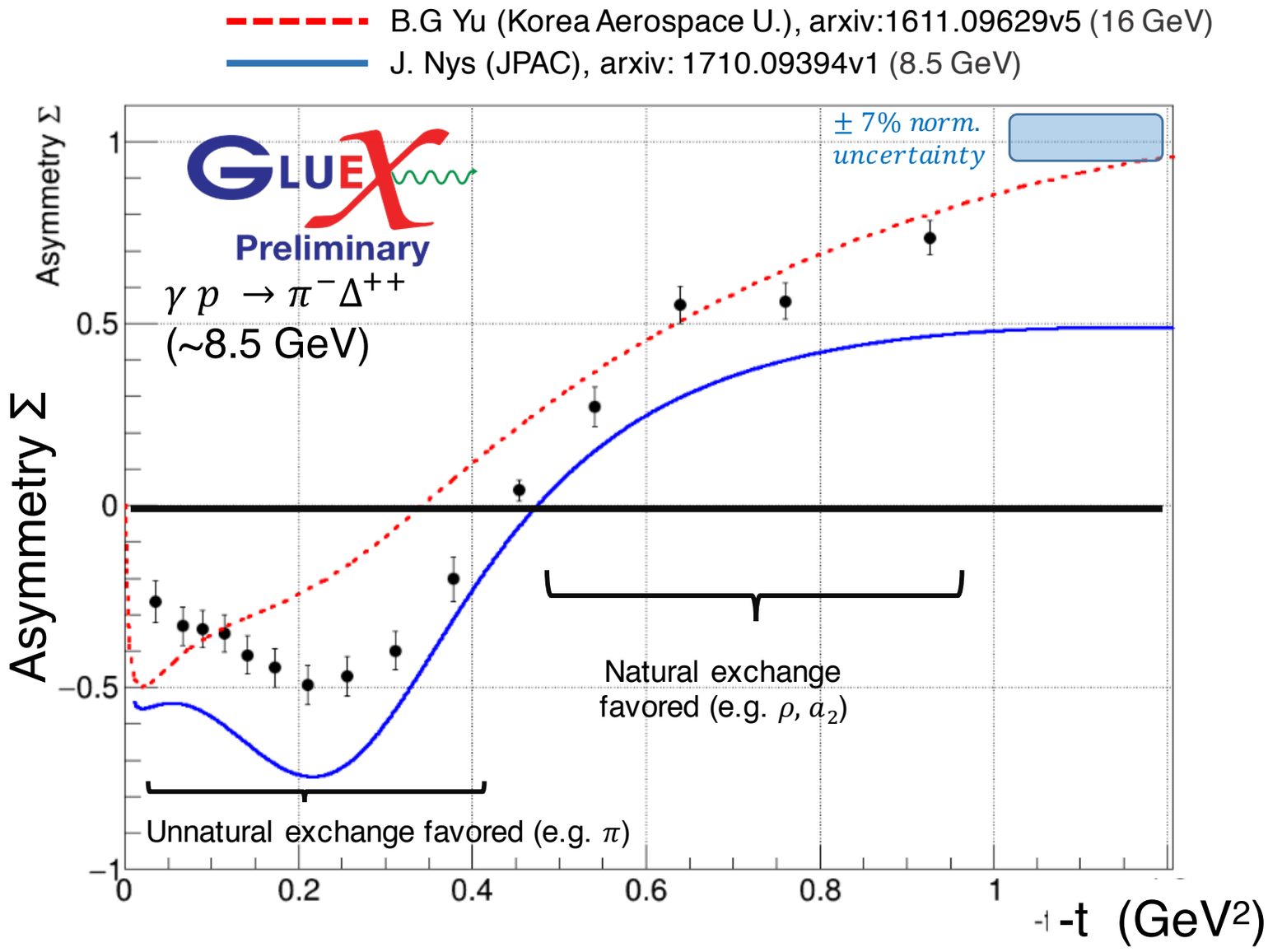


- Charged pseudoscalar beam asymmetry has more complicated t-dependance
- Preliminary results use order of magnitude more data than previous measurements

SLAC (16 GeV)

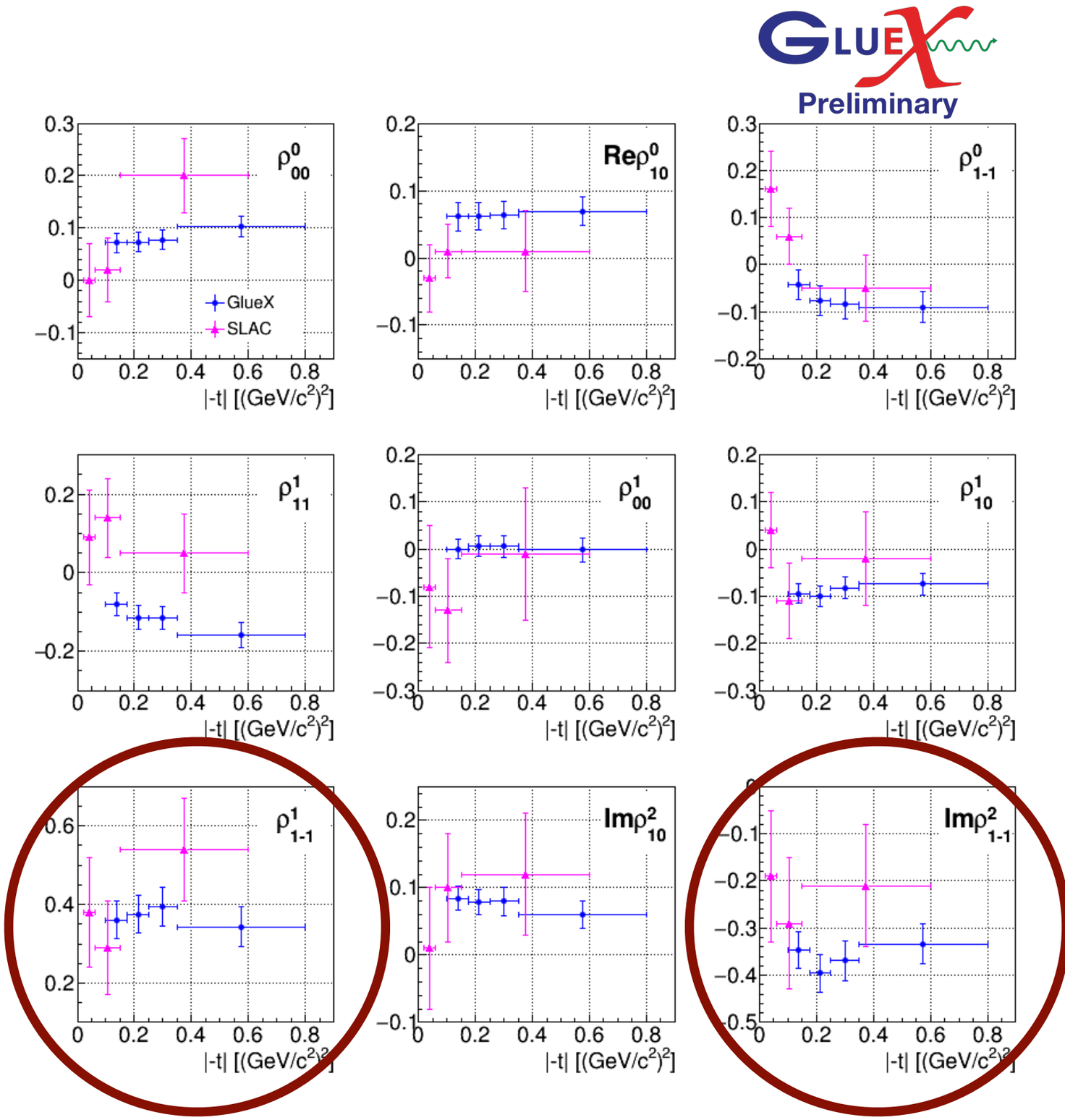


Phys. Rev. D **20**, 1553 (1979)

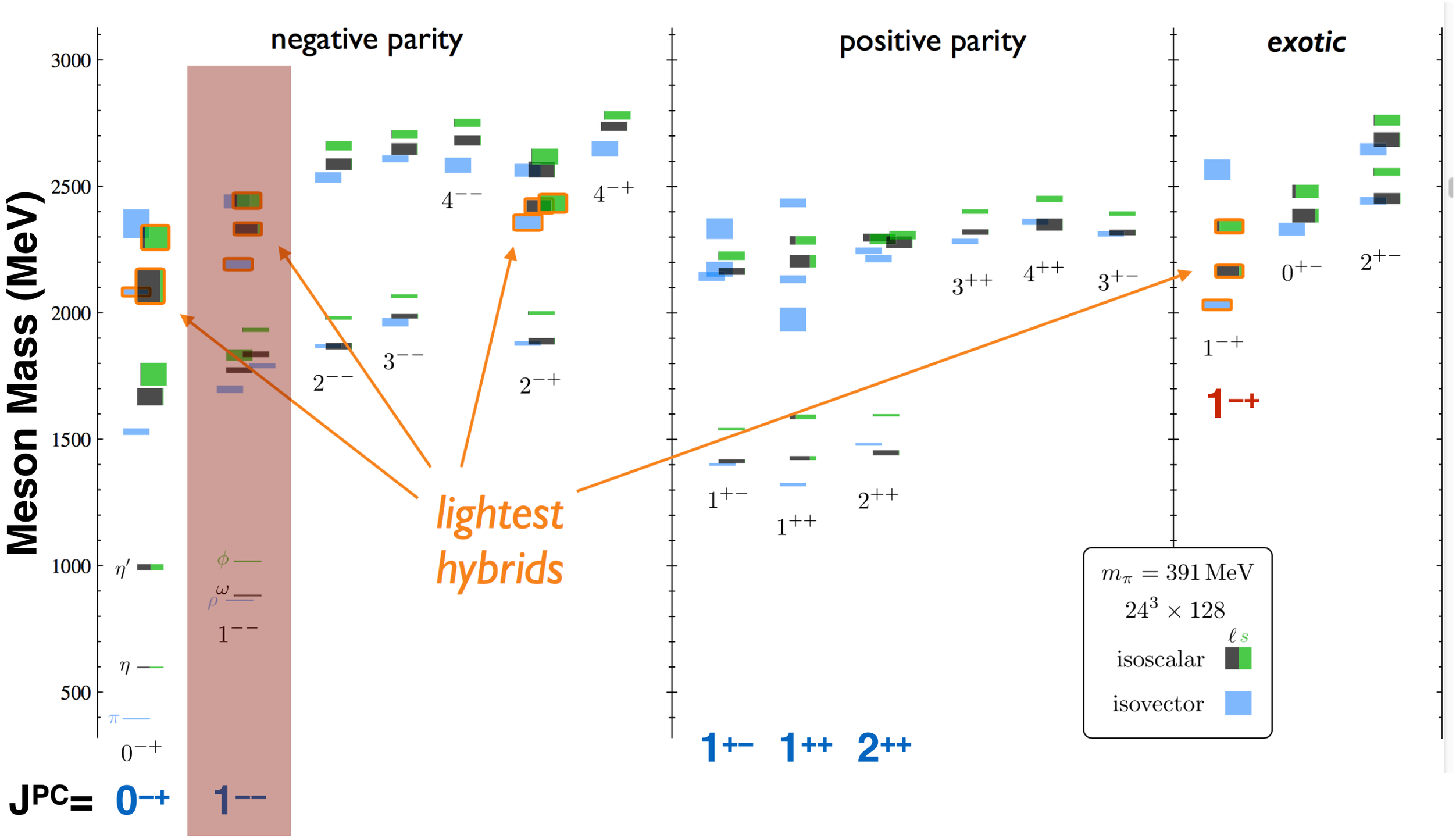


Spin Density Matrix Elements (SDMEs): γ p → p + ω

- SDMEs measure the transfer of polarization from the photon to the vector meson
- 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**
- Updating with full GlueX-I data
- **γ p → p + ϕ** and **p + ρ** also under analysis

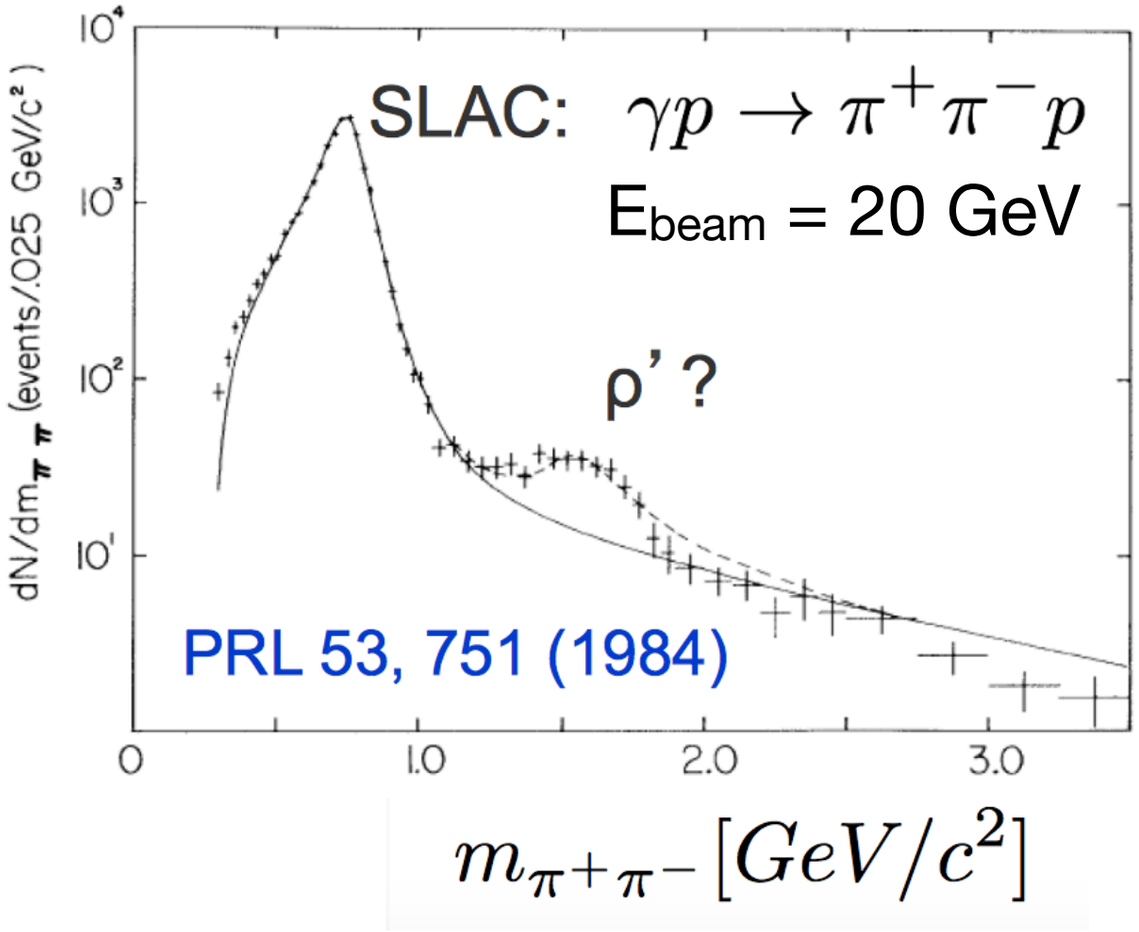


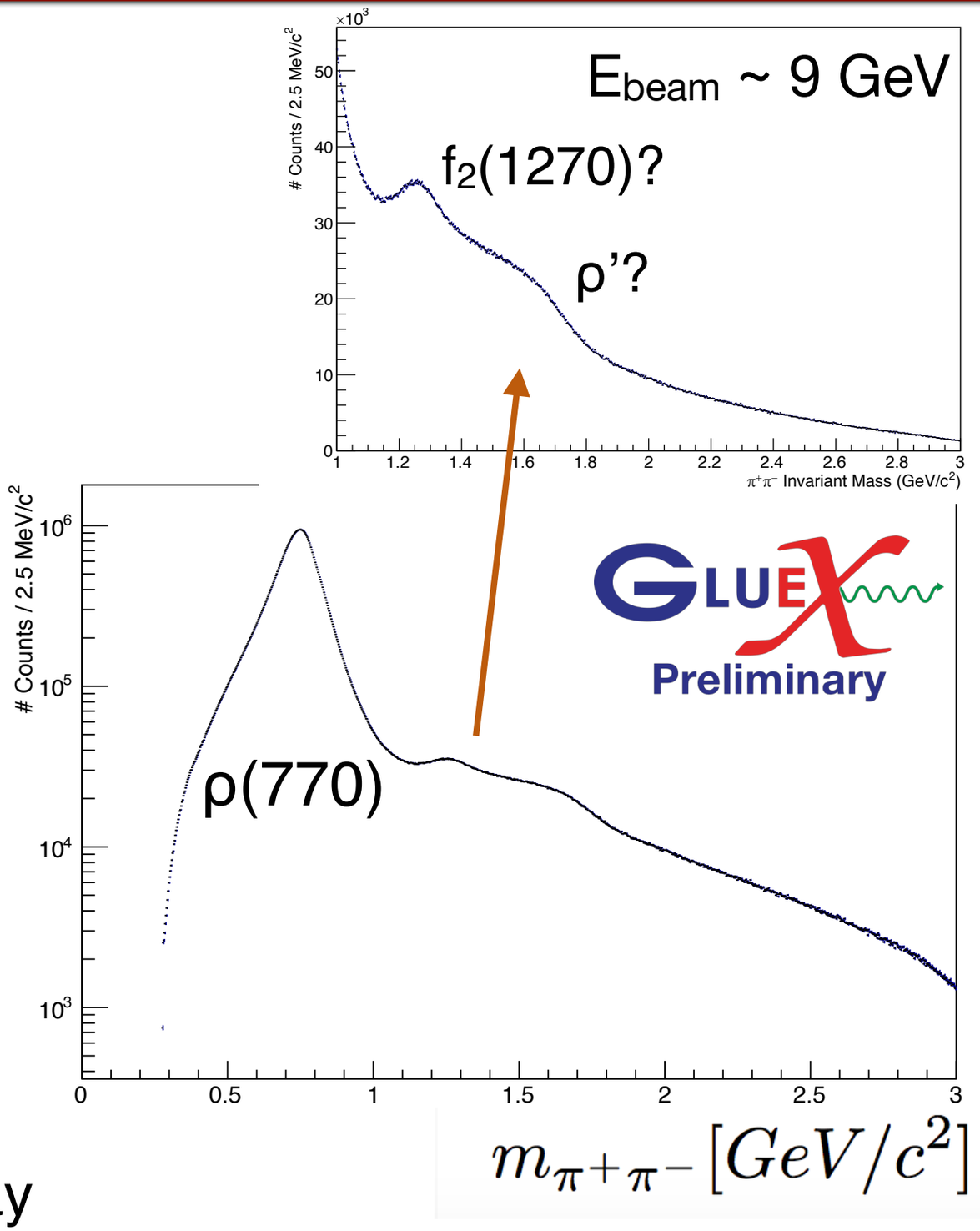
Light Meson Spectrum from Lattice QCD



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

GlueX Detector, October 2014 (w/ Curtis Meyer, Spokesman)

The GlueX Experiment in Hall D @ JLab

- The GlueX experiment is located in Hall D, newly constructed as part of the Jefferson Lab 12 GeV upgrade.
  - Large acceptance solenoidal spectrometer
  - Linearly polarized photon beam peaking at 9 GeV
  - Detects all decay products from full hadronic photoproduction rate
- 100+ Collaborators from 26 institutions

GlueX Detector, August 2014