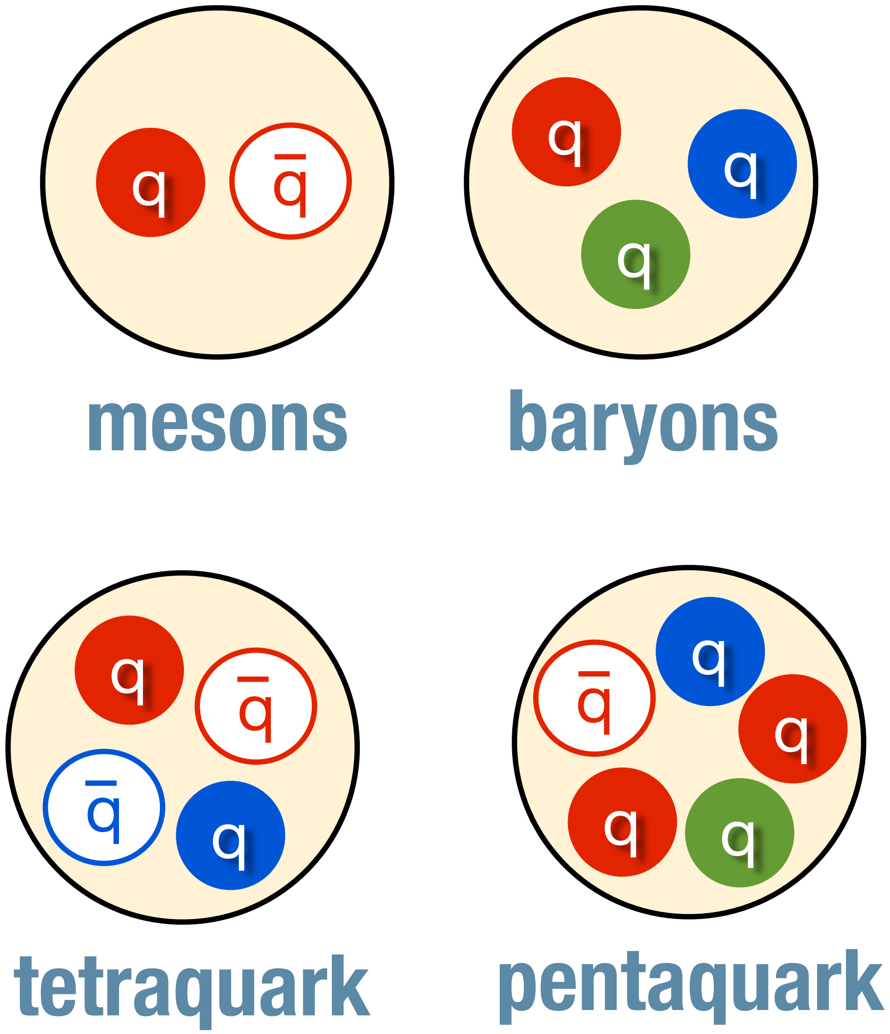
Meson spectroscopy at GlueX

Justin Stevens

William & Mary
CHARTERED 1693

Confined states of quarks and gluons



Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD

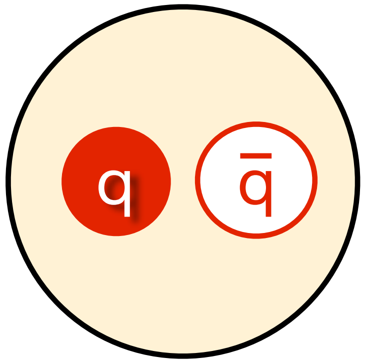
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

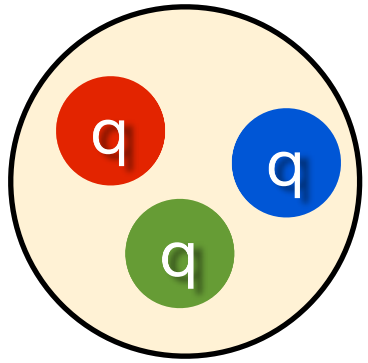
... Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. ...

Phys. Lett. 8 (1964) 214

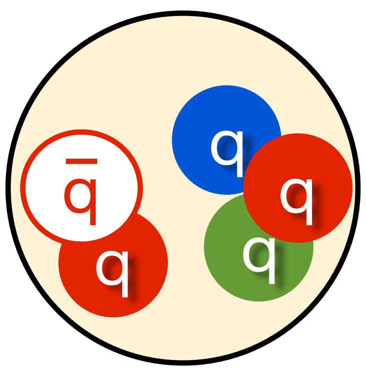
Confined states of quarks and gluons



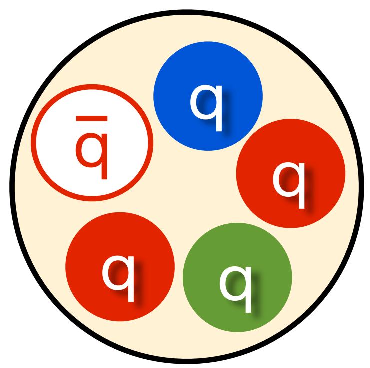
mesons



baryons



molecules



pentaquark

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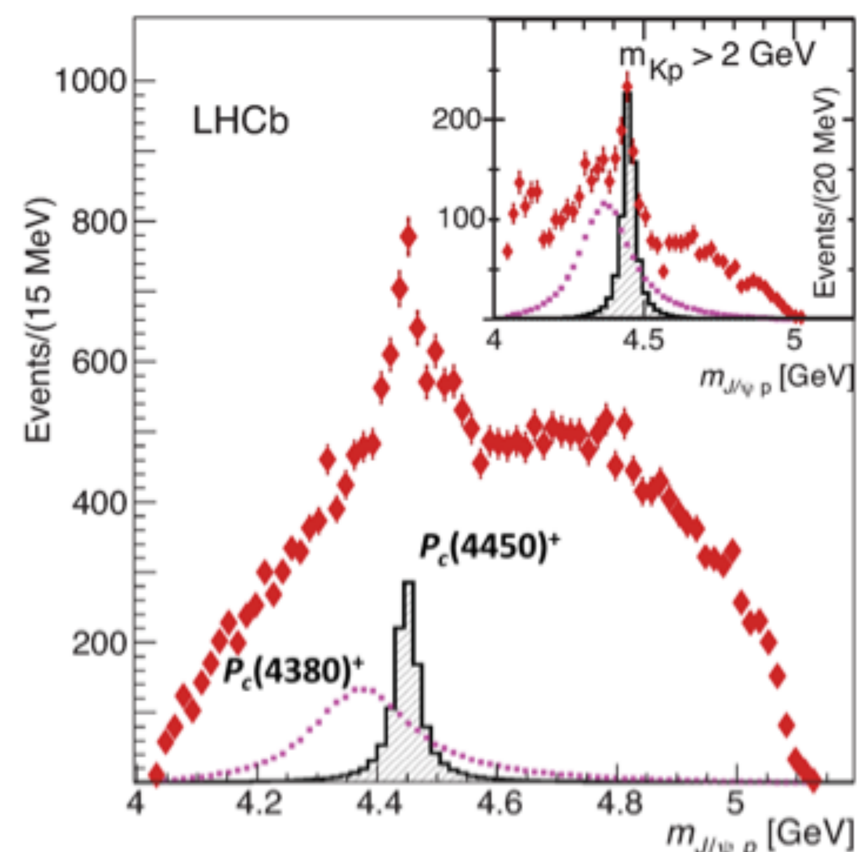
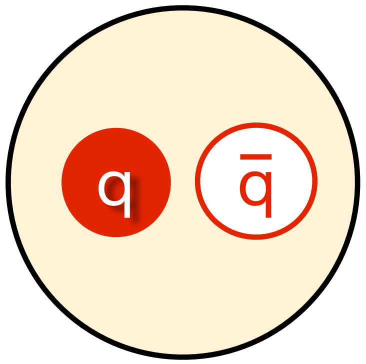
$$\Lambda_b \rightarrow J/\psi p K^-$$

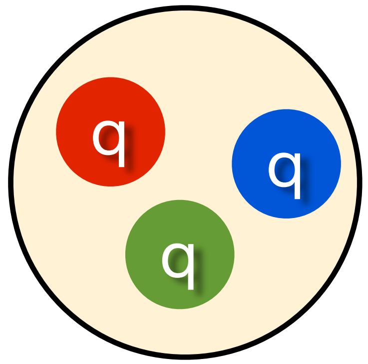


LHCb (2015)

Confined states of quarks and gluons



mesons



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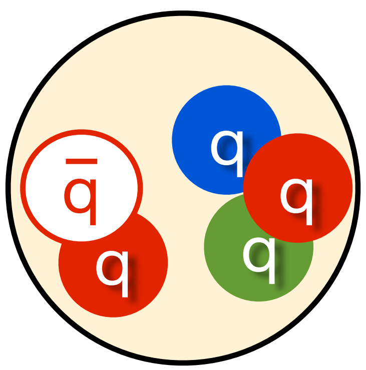
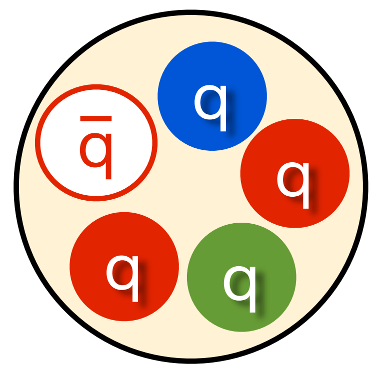


molecules



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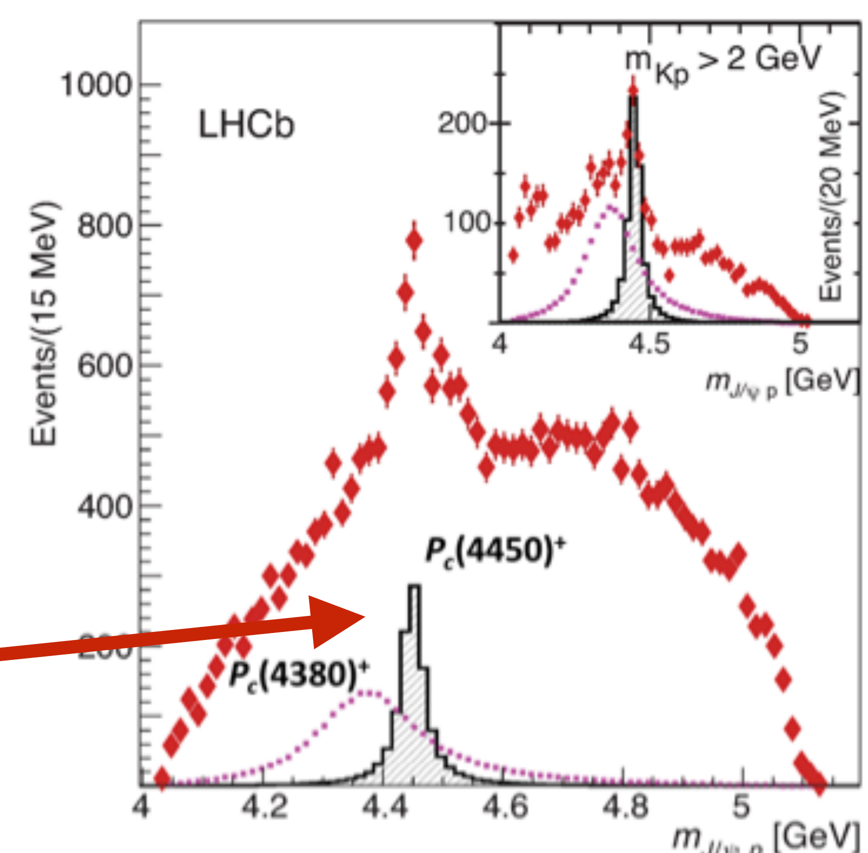
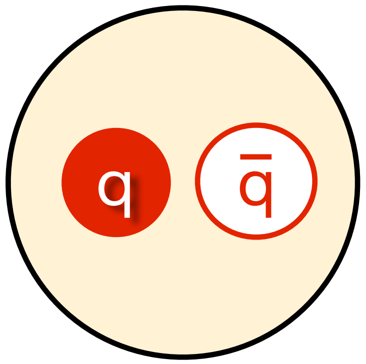


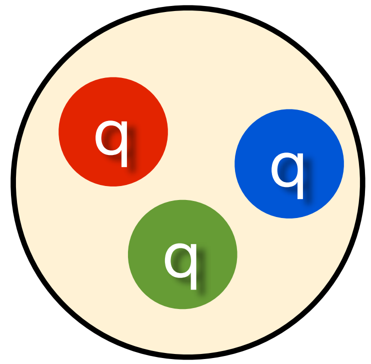
LHCb (2015)

Accessible at

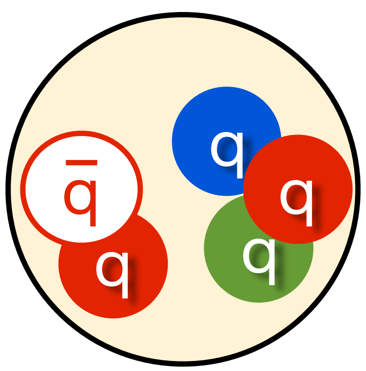
Jefferson Lab

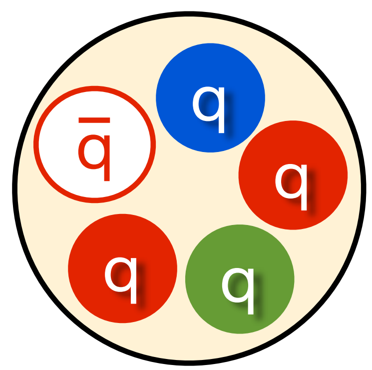
Confined states of quarks and gluons





mesons **baryons**





molecules **pentaquark**

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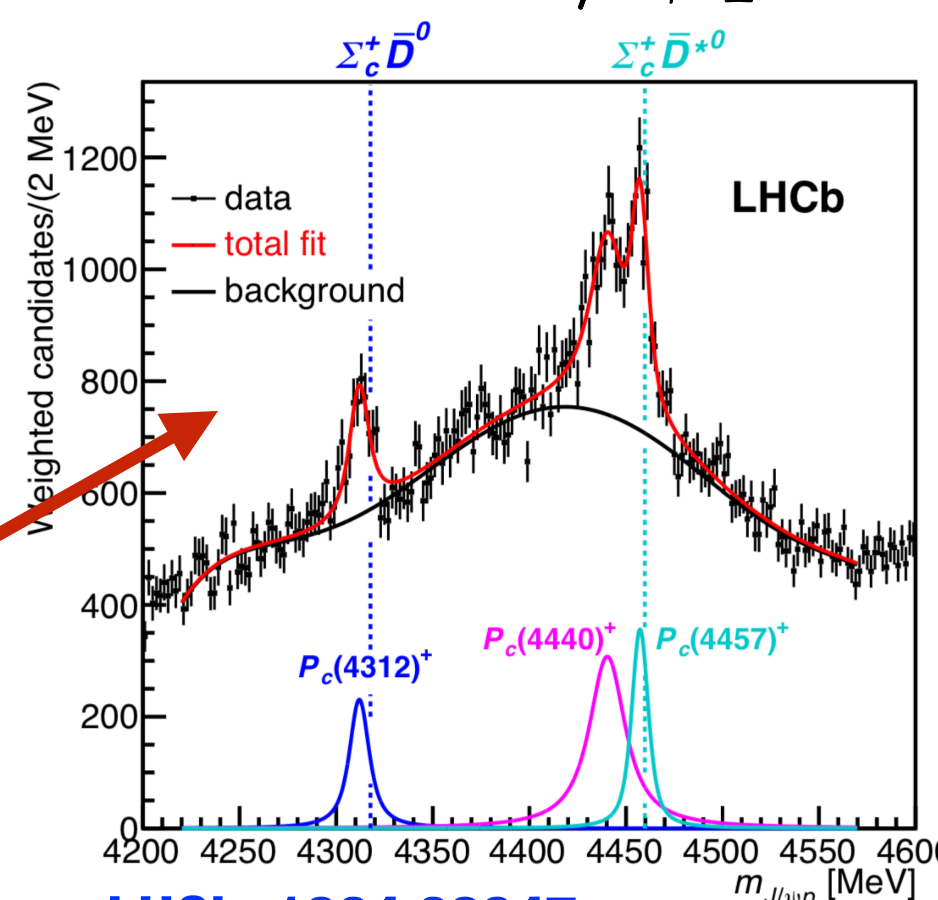

LHCb: 1904.03947

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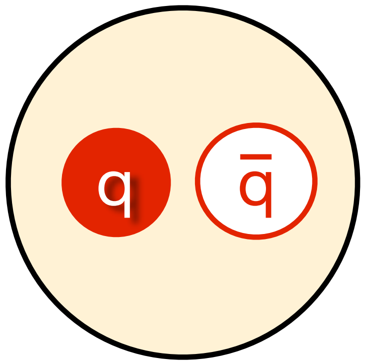

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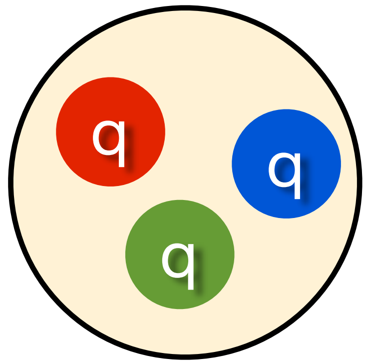

baryons

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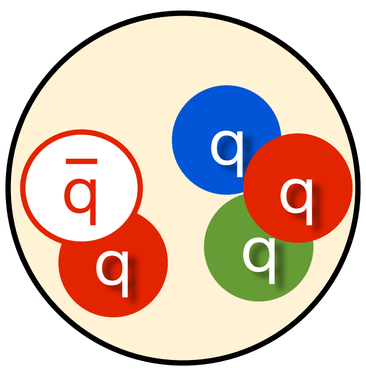

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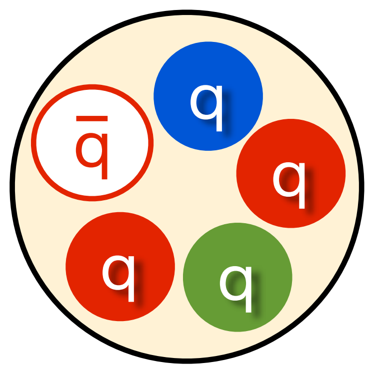
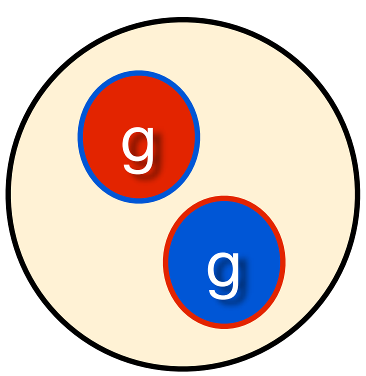
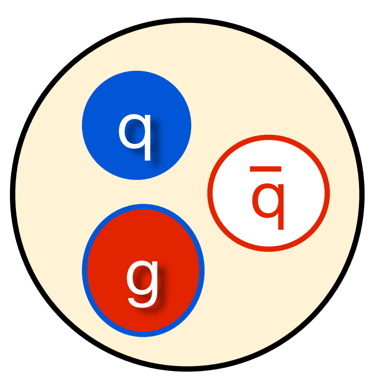


pentaquark



glueball

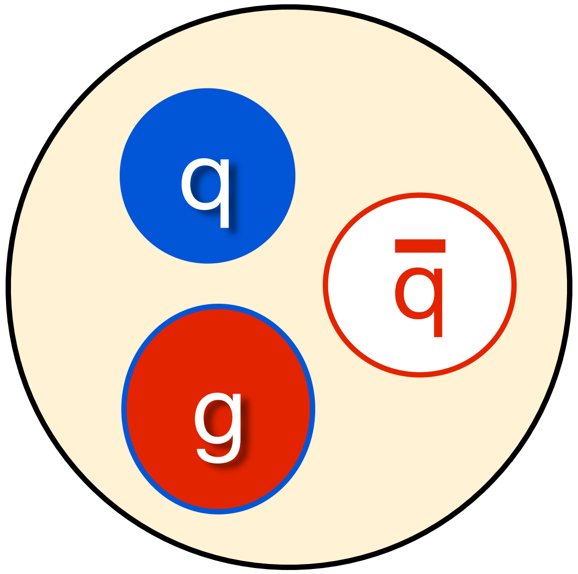


hybrid meson

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

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 scale ≈1-1.5 GeV



hybrid meson

Hybrid mesons and gluonic excitations

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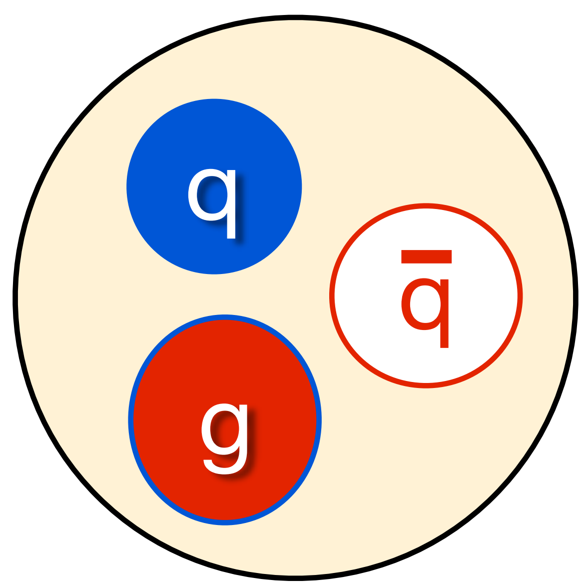
- Rich spectrum of hybrid mesons predicted by Lattice QCD
- Gluonic field with $J^{PC} = 1^{+-}$ and mass scale ≈1-1.5 GeV
- "Exotic" J^{PC} : not simple $q\bar{q}$ from the non-rel. quark model

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

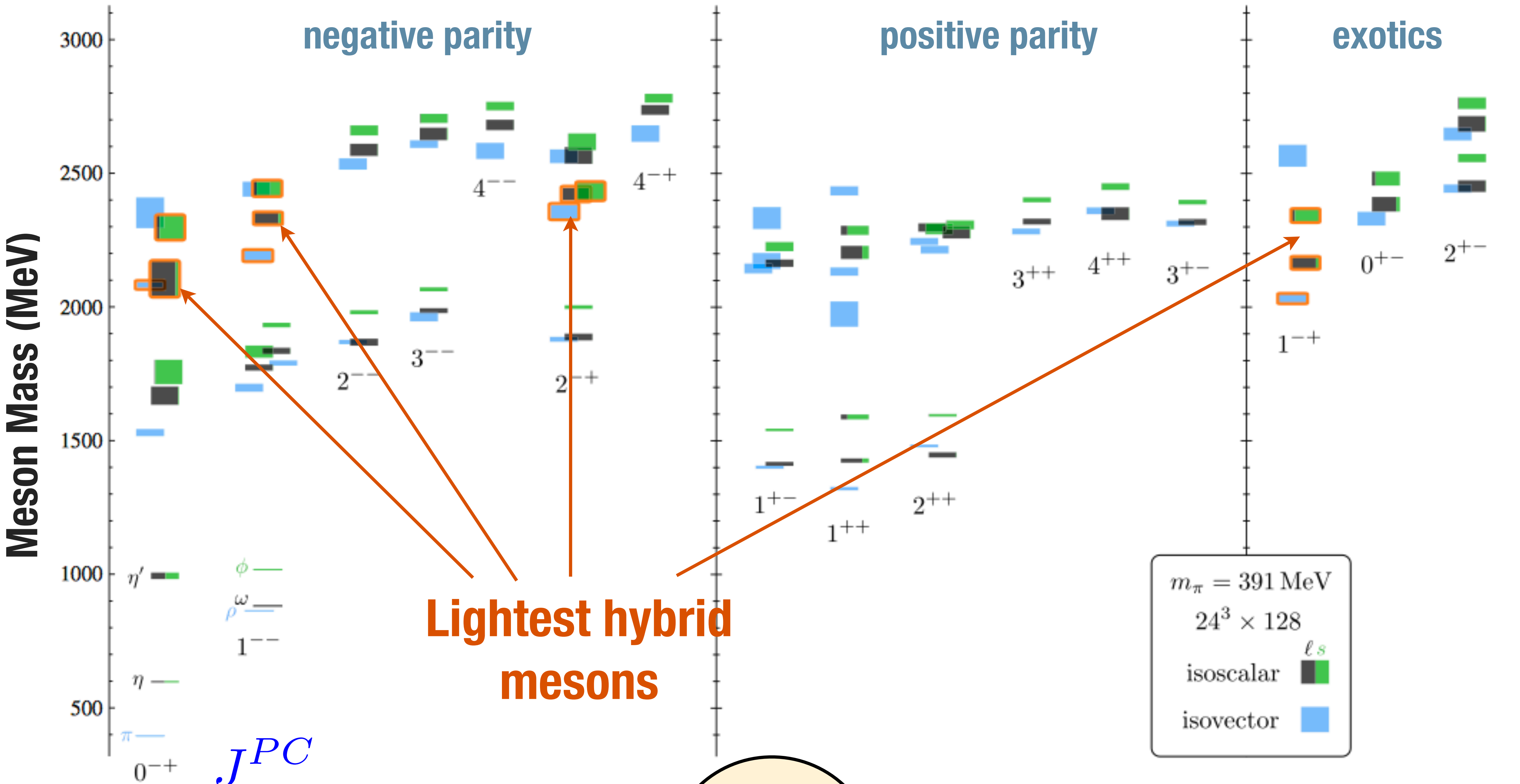


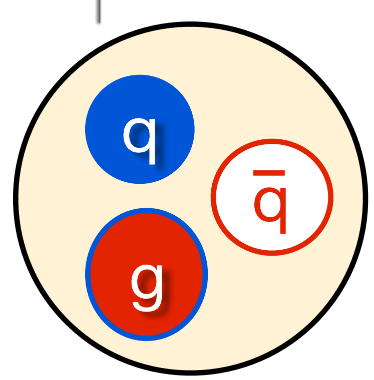
hybrid meson

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

Lattice QCD

Dudek et al. PRD 88 (2013) 094505





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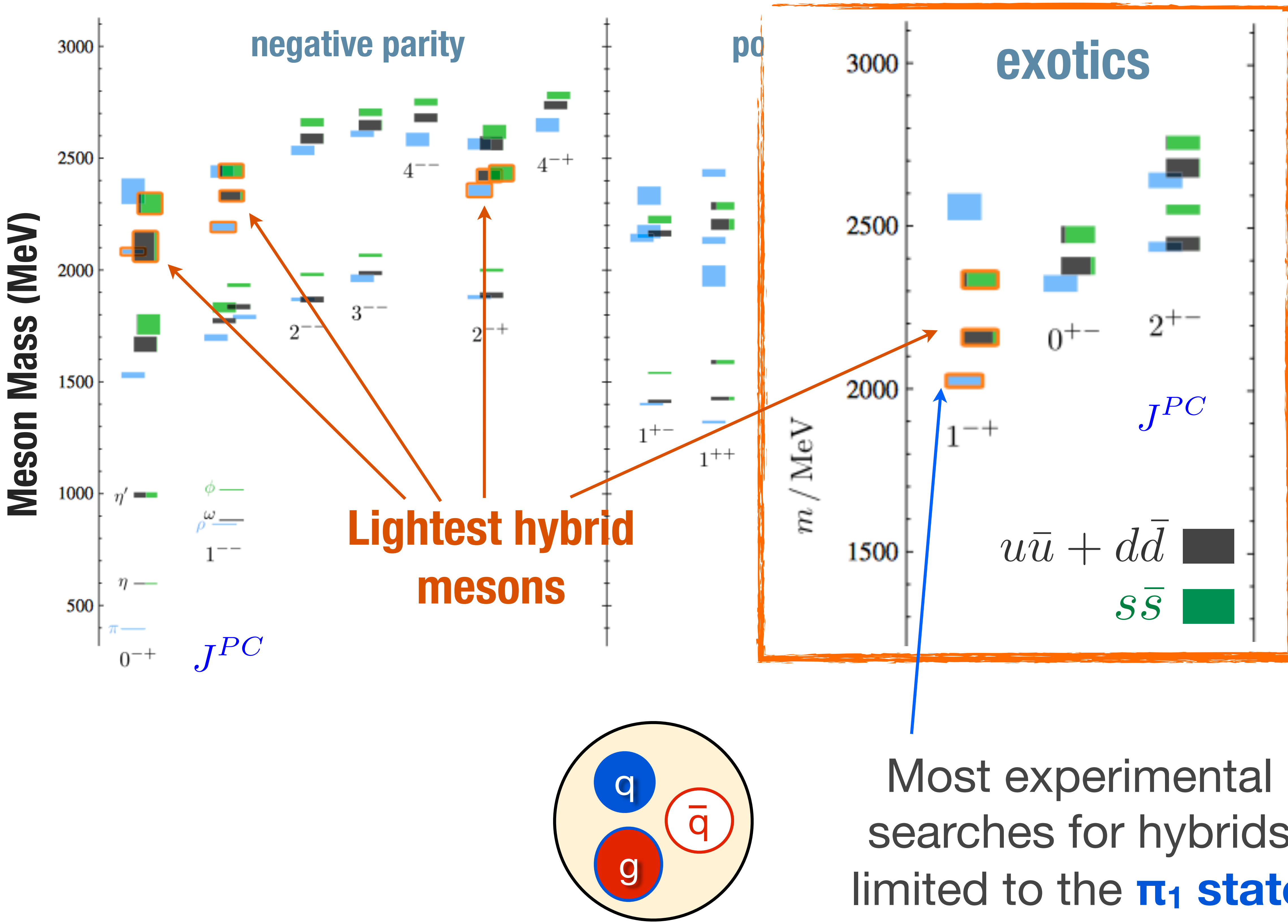
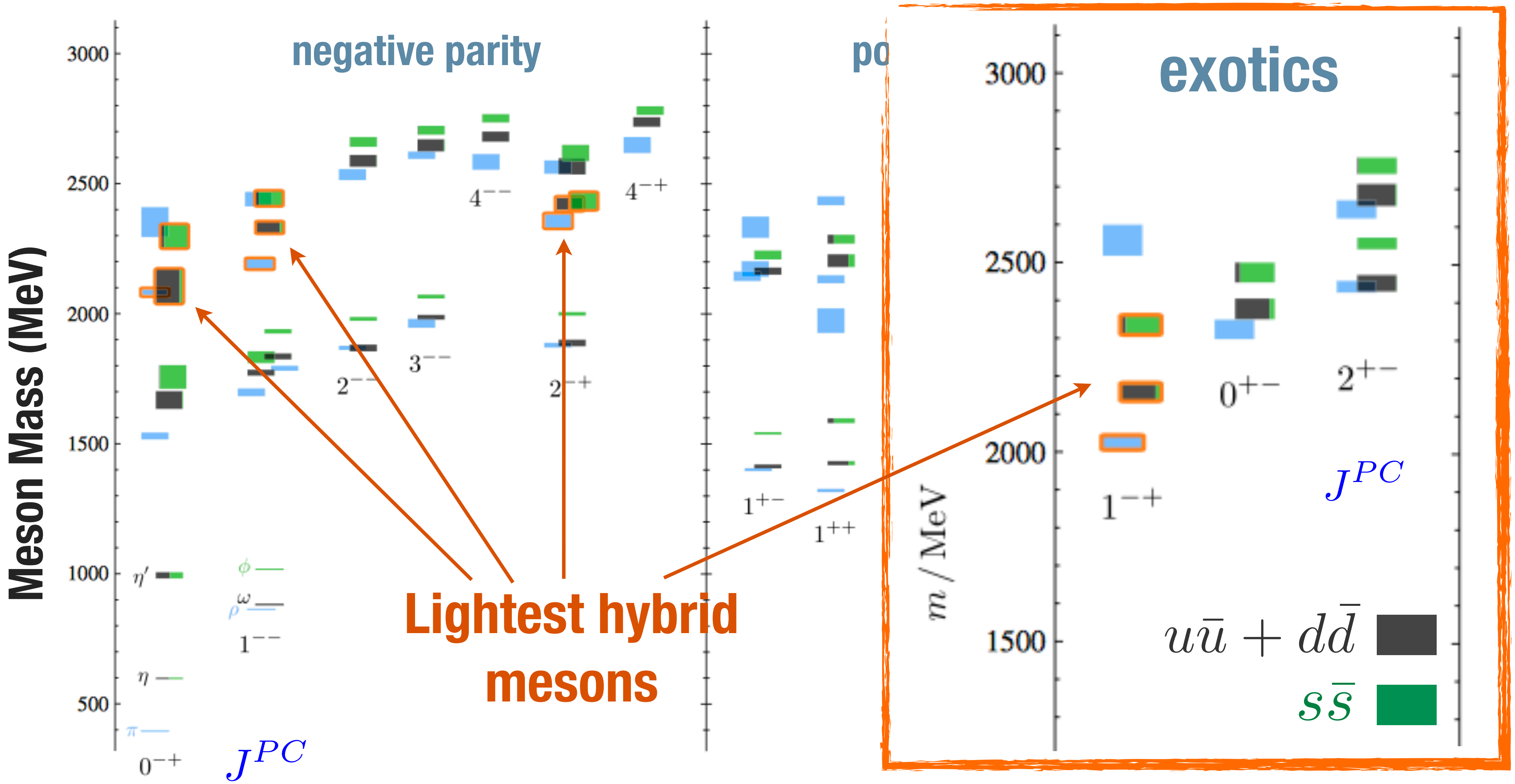


Most experimental searches for hybrids limited to the **π_1 state**

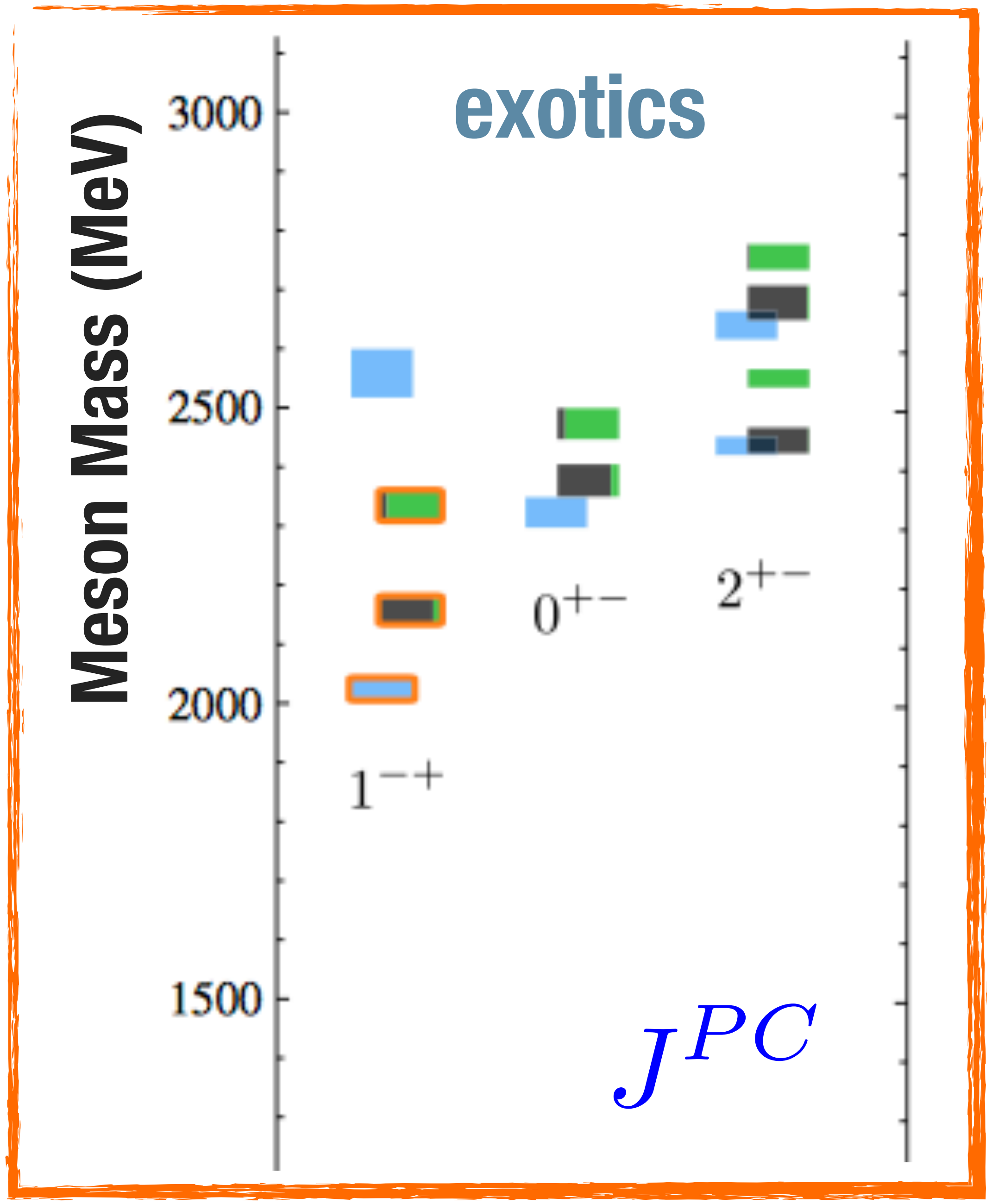
Lattice QCD: Mesons

Dudek et al. PRD 88 (2013) 094505

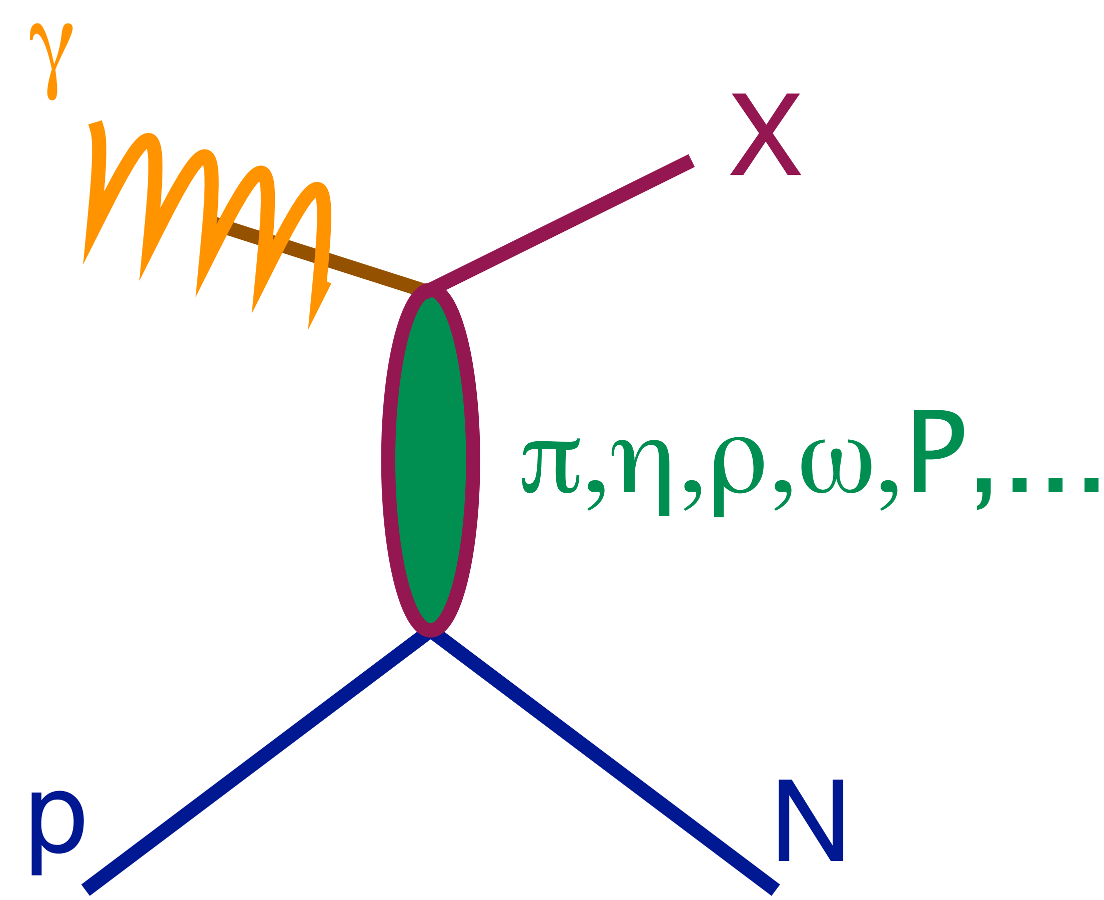


- Ideally look for a pattern of hybrid states in multiple decay modes
- Primary goal of the GlueX experiment is to search for and ultimately map out the spectrum of light quark hybrid mesons

Exotic J^{PC} in photoproduction



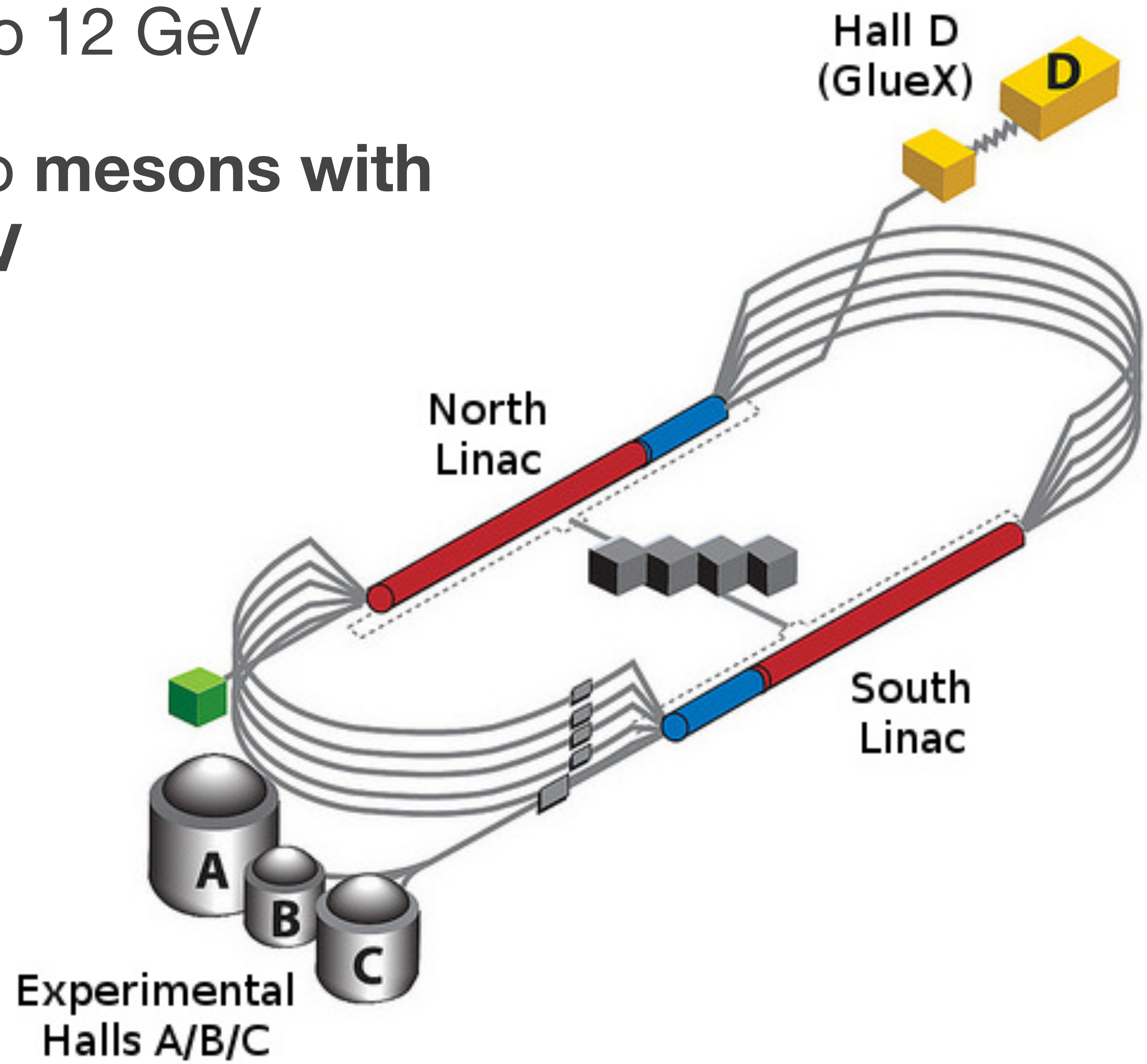
Meson X with particular J^{PC}



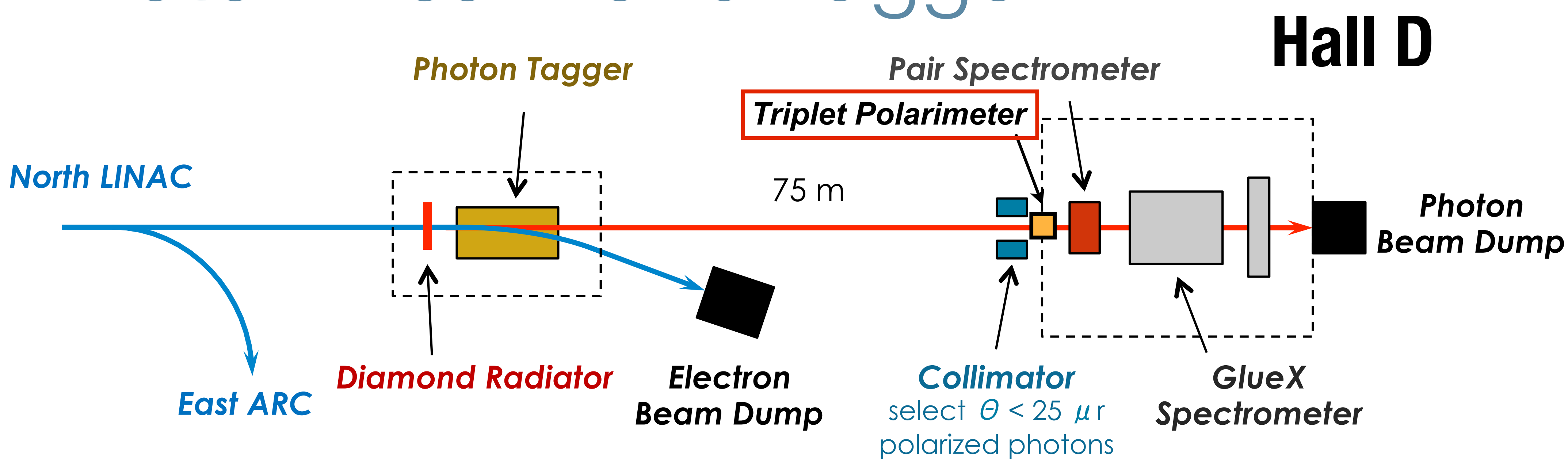
Production through t-channel "quasi-particle" exchange

Jefferson Lab 12 GeV Upgrade

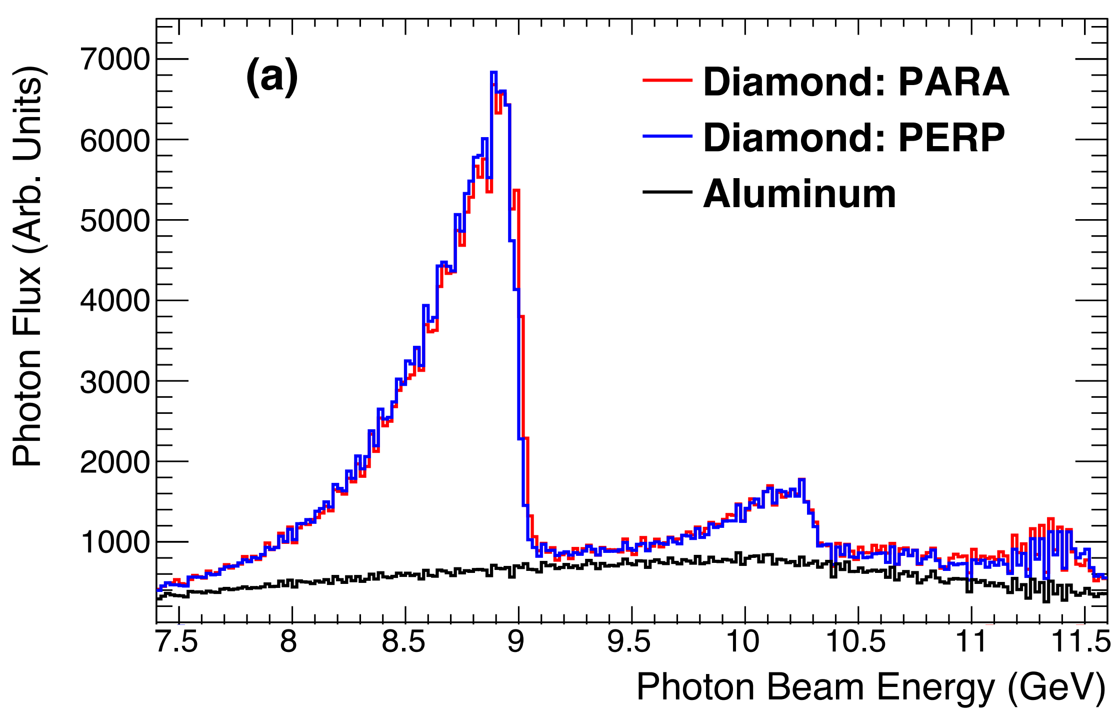
- Maximum electron beam energy upgraded from 6 to 12 GeV
- Provides access to **mesons with masses to ~3 GeV**



Photon Beam and Tagger

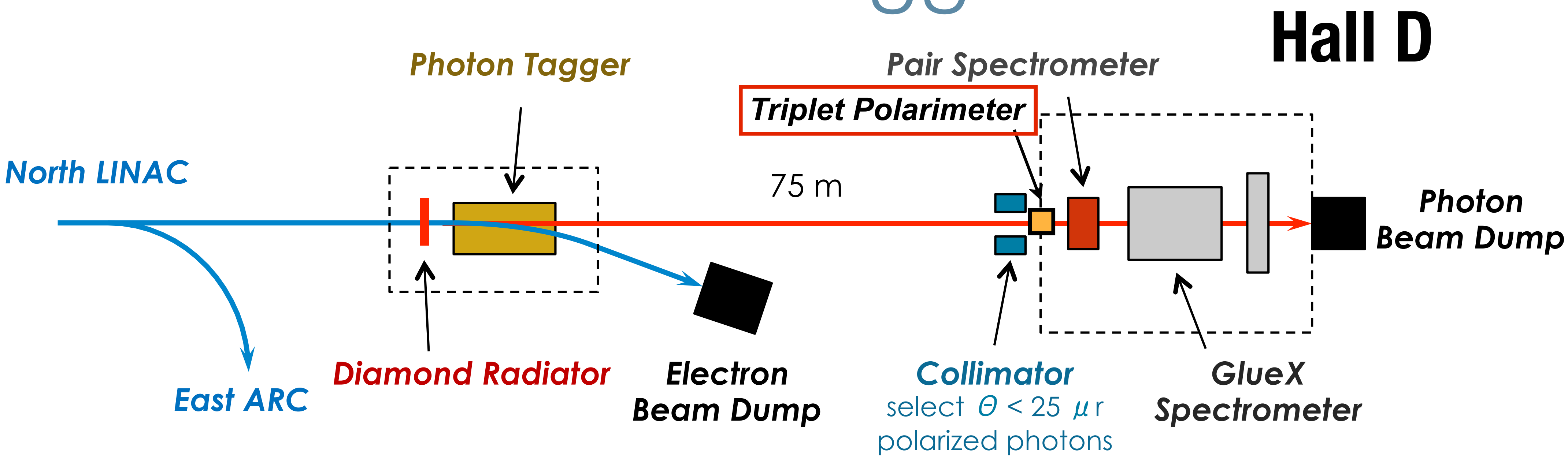


Measured Flux



Mesons up to ~3 GeV

Photon Beam and Tagger



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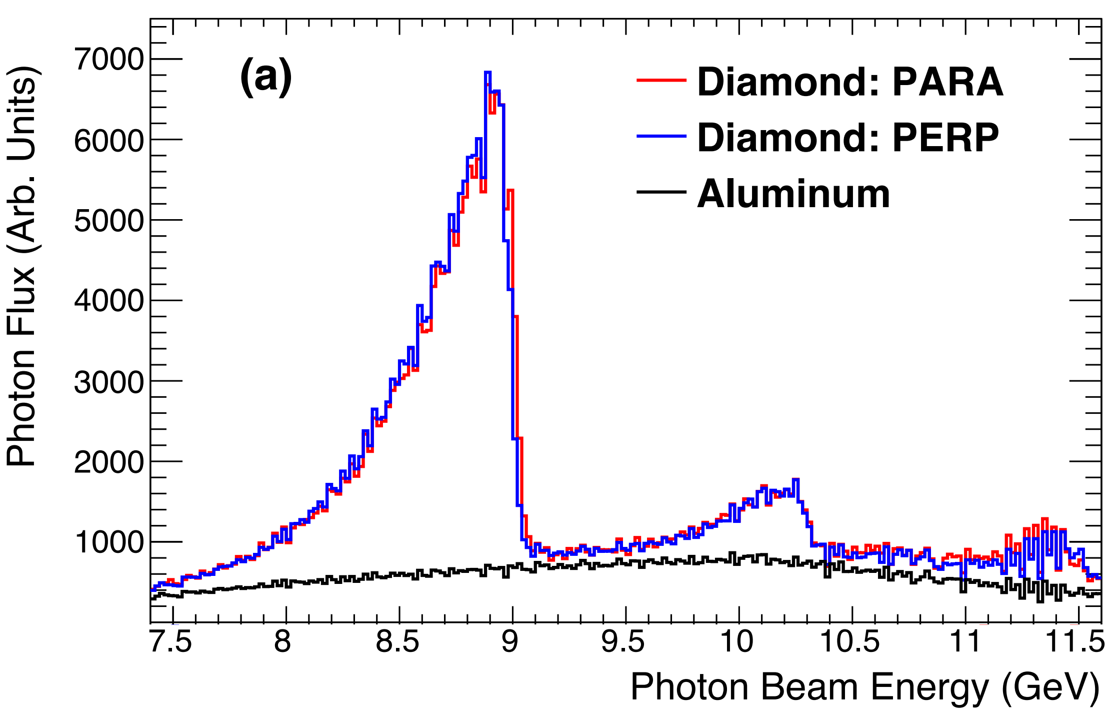
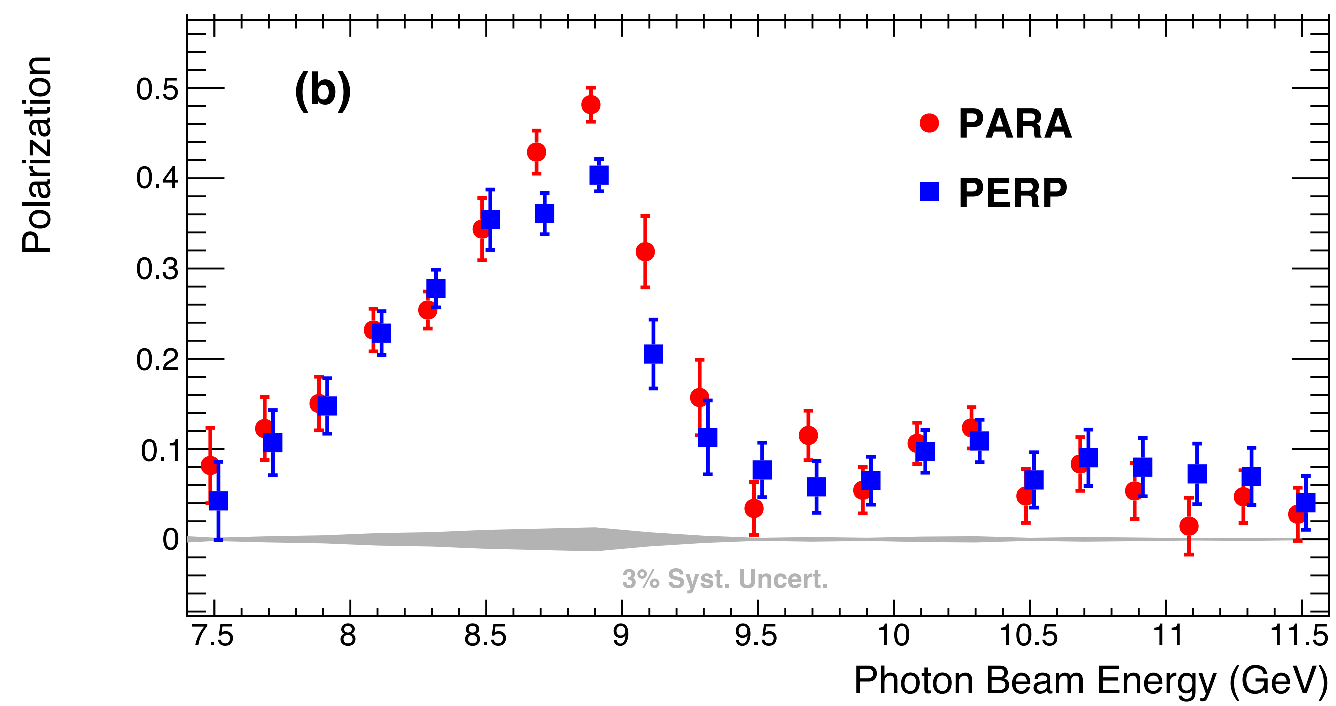


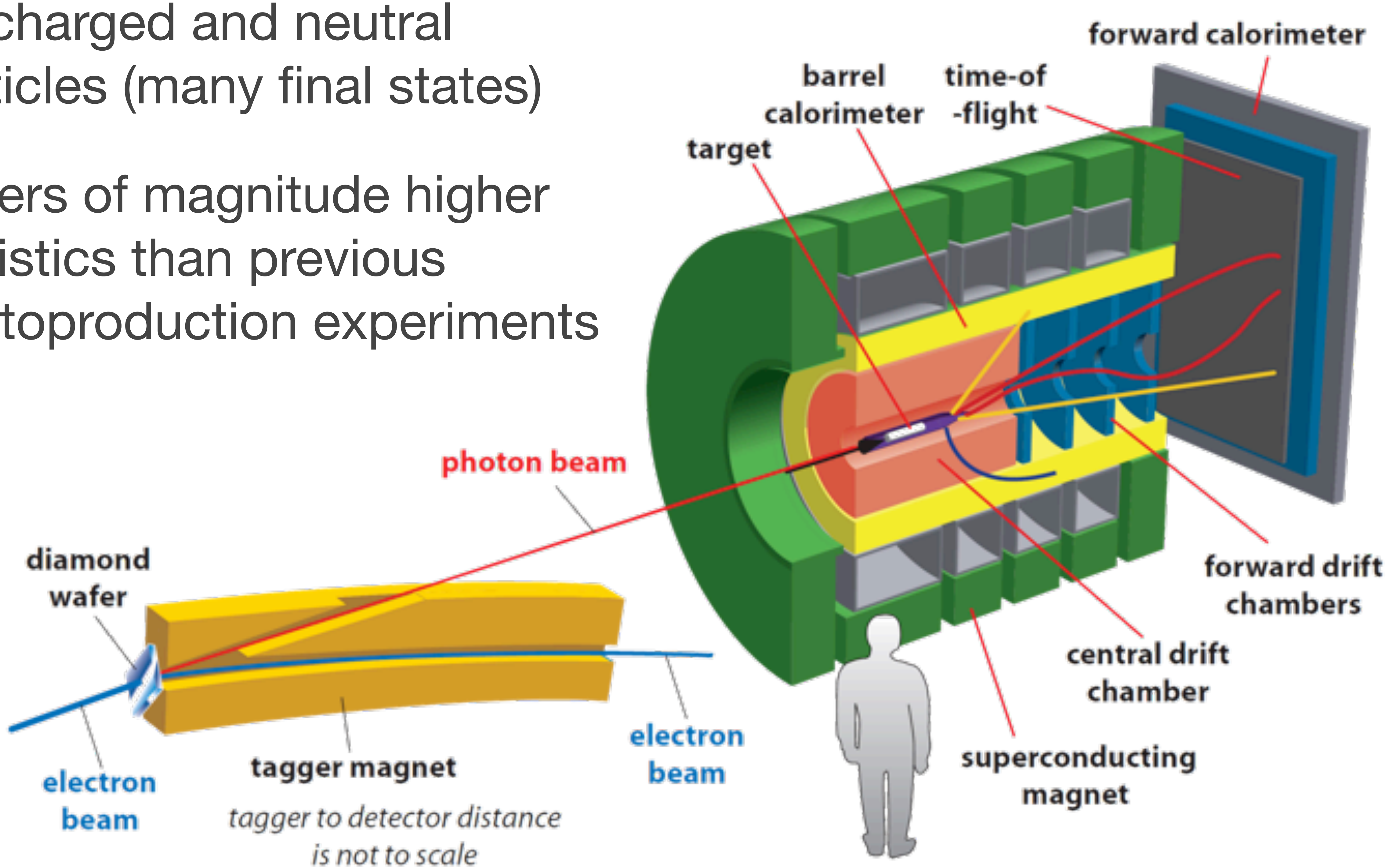
Measured Polarization



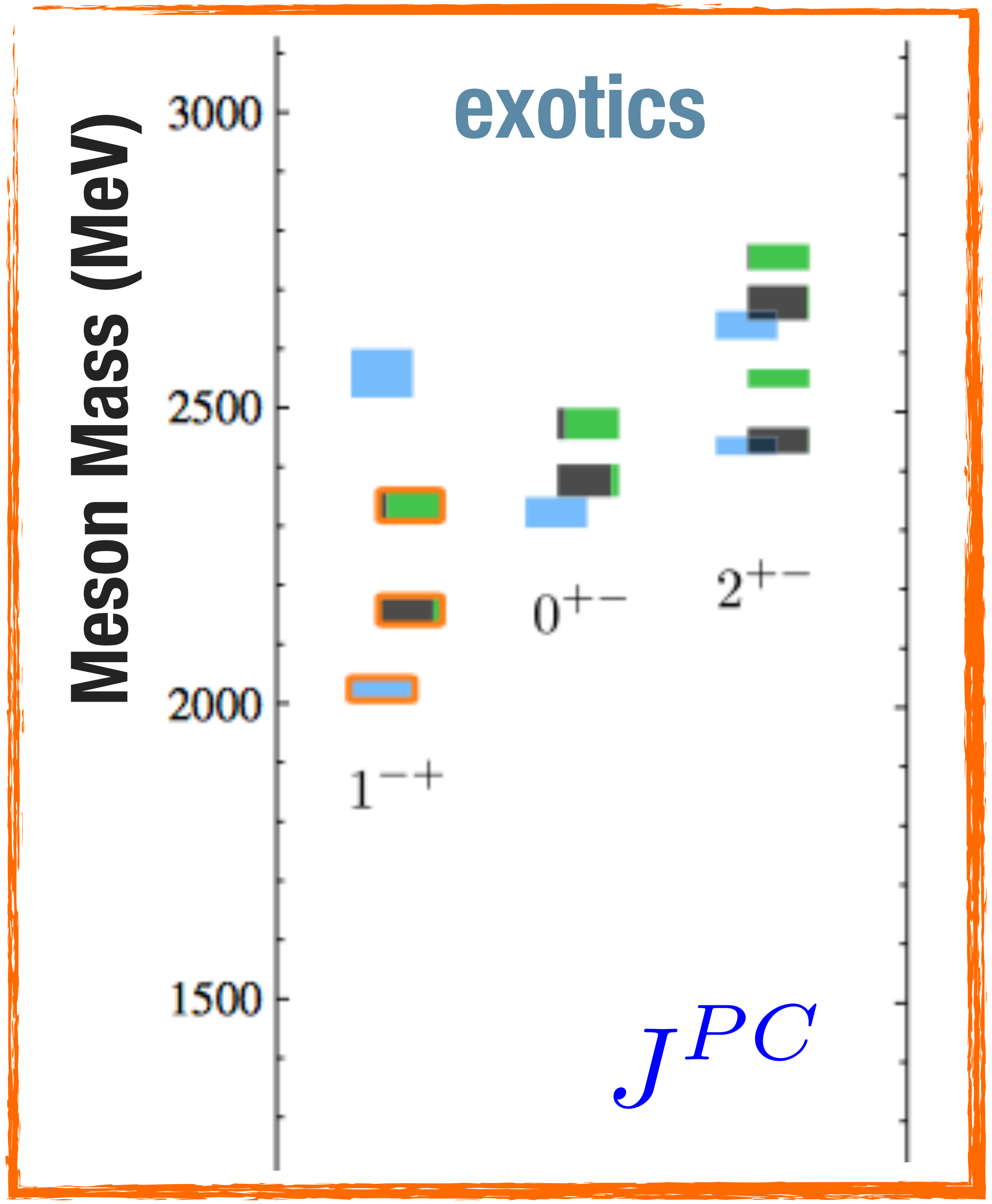
Filter on production mechanism

GlueX in Hall D

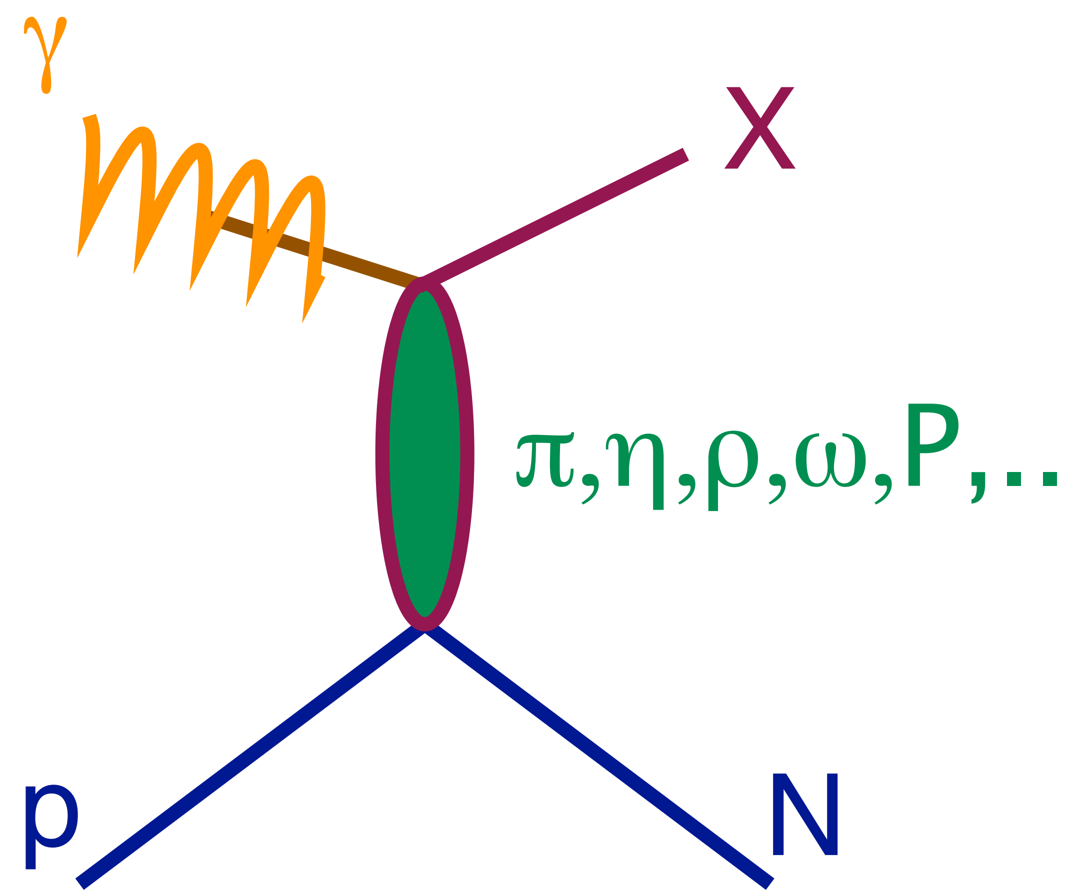
- Large acceptance detector for charged and neutral particles (many final states)
- Orders of magnitude higher statistics than previous photoproduction experiments



Exotic J^{PC} in photoproduction

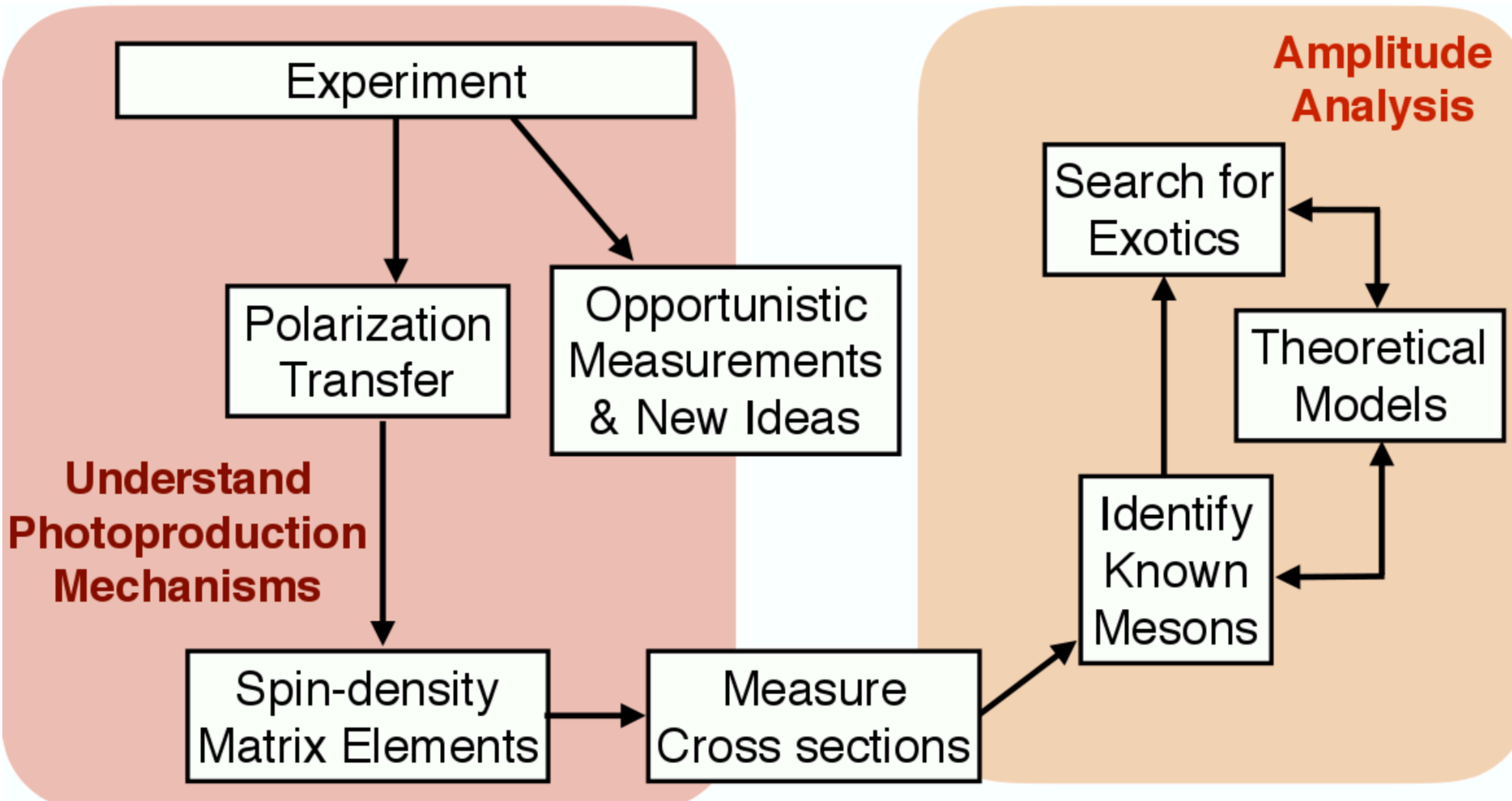


Meson X with particular J^{PC}



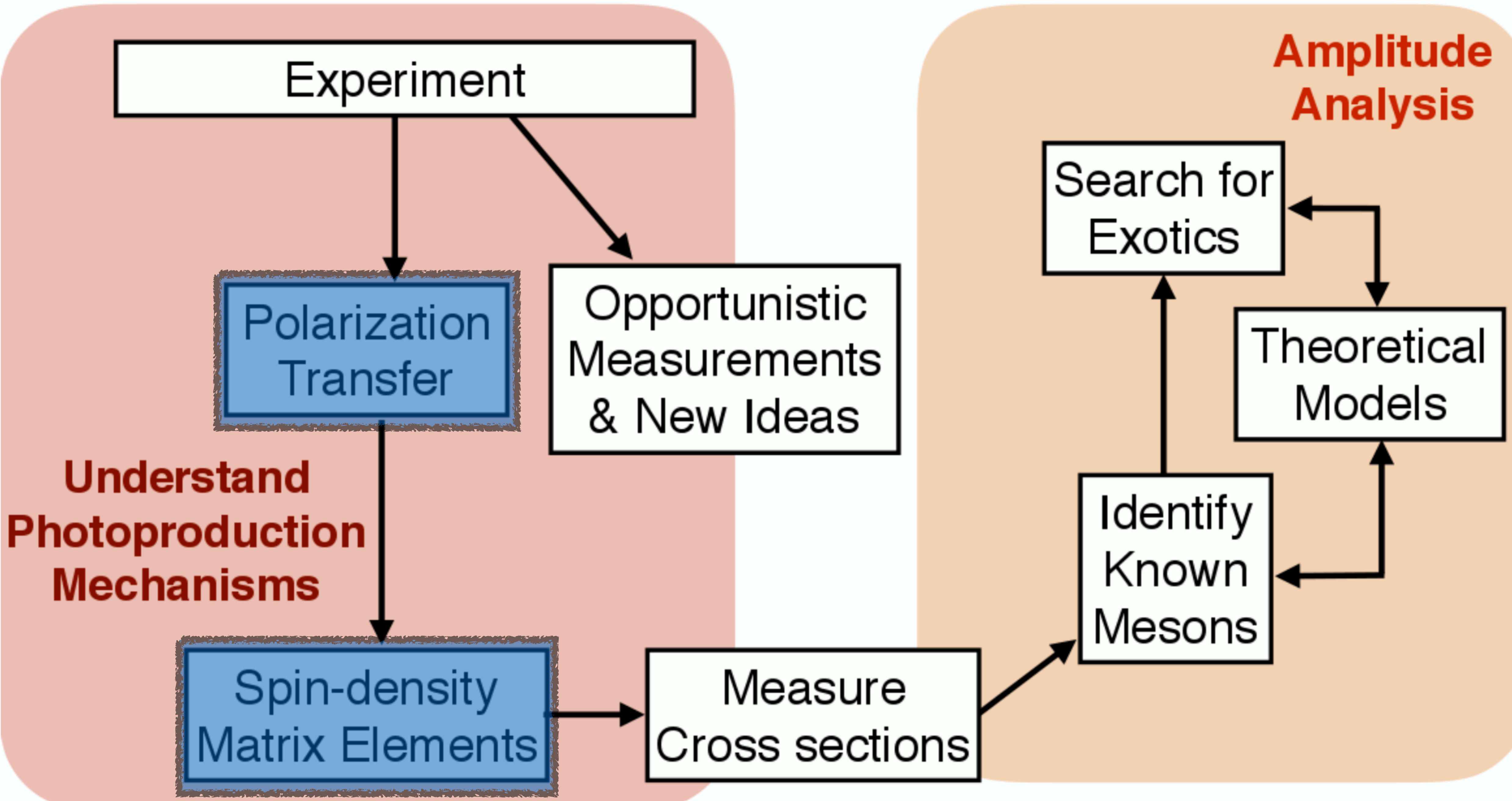
Production through t-channel "quasi-particle" exchange

GlueX Physics Program



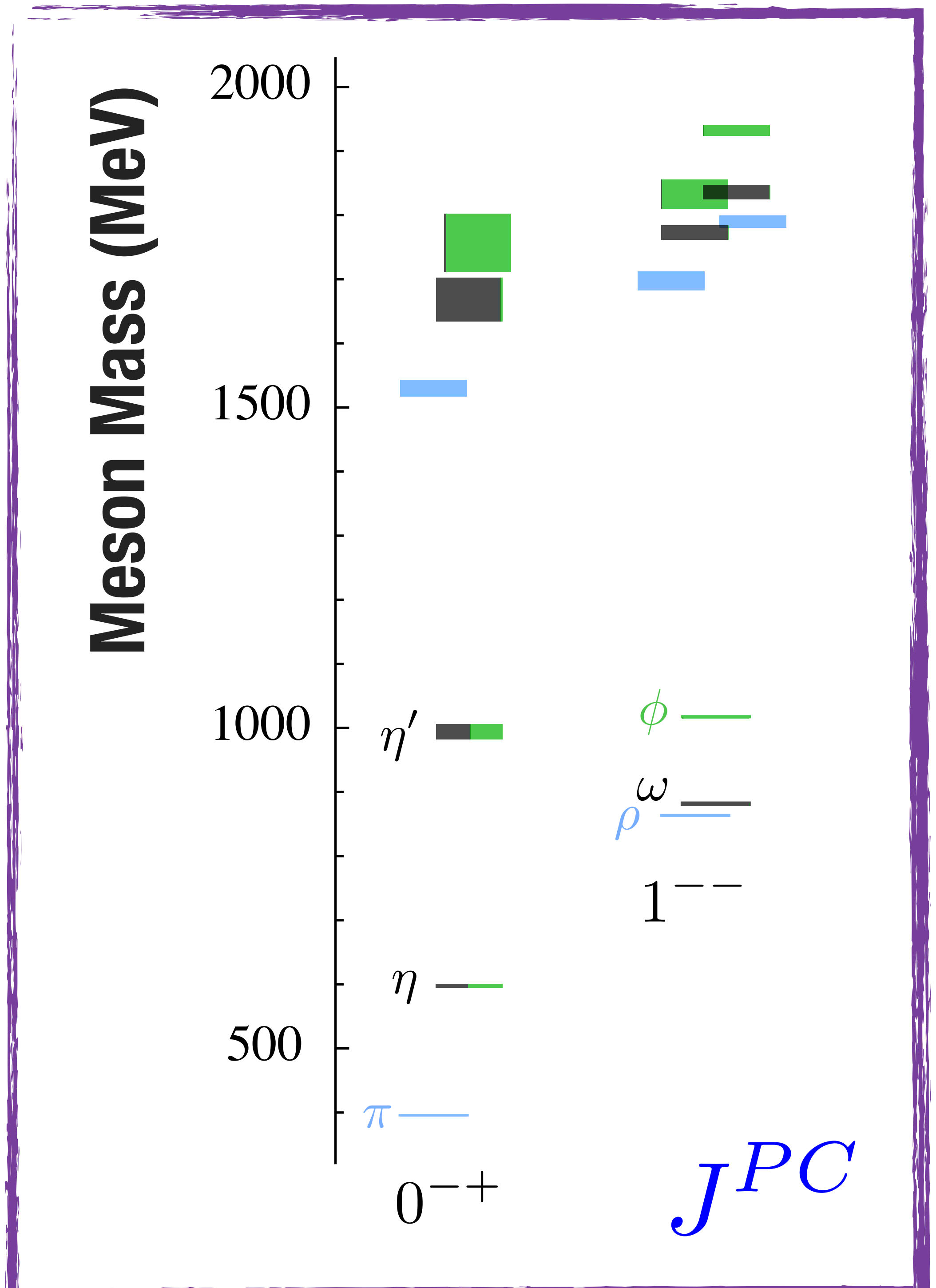
GlueX Physics Program

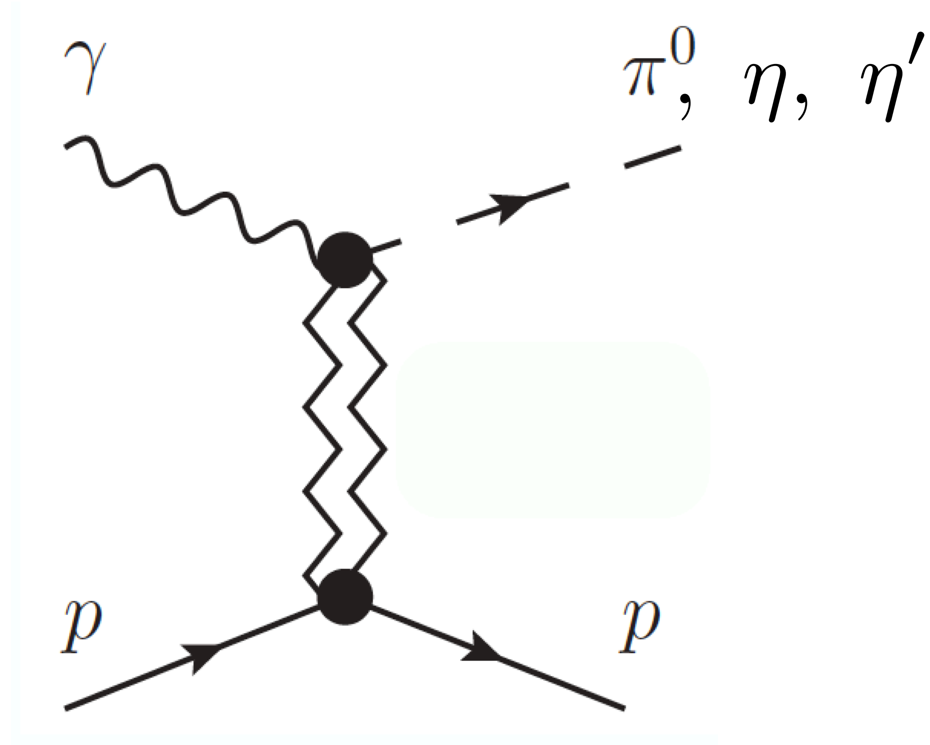
Strong collaboration with theory required: e.g. JPAC



Welcome more collaboration with theory!

Non-exotic J^{PC} in photoproduction





Exchange J^{PC}

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

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

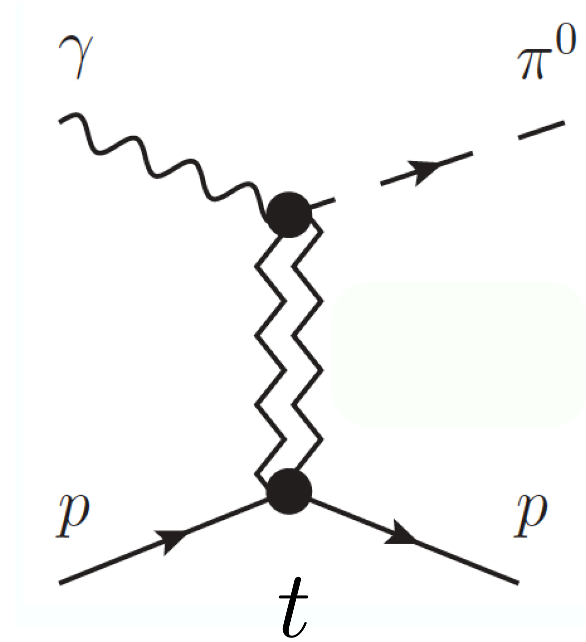
- Begin by understanding non-exotic production mechanism
- Linear photon beam polarization critical to filter out "naturality" of the exchange particle

$\gamma p \to \pi^0 p$ beam asymmetry Σ

- Beam asymmetry Σ provides insight into dominant production mechanism

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

- From experimental standpoint it's easily extended to $\gamma p \to \eta p$
  - **No previous measurements!**



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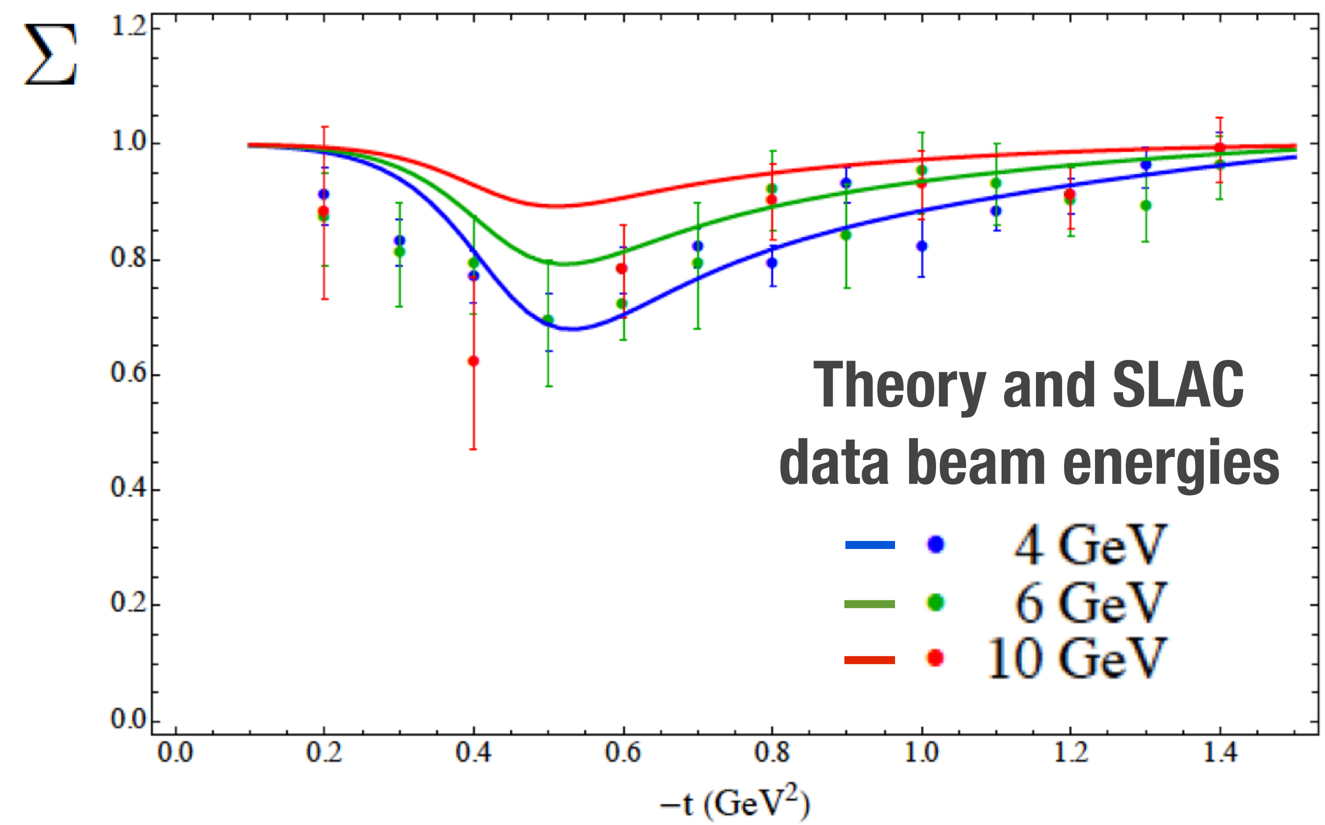
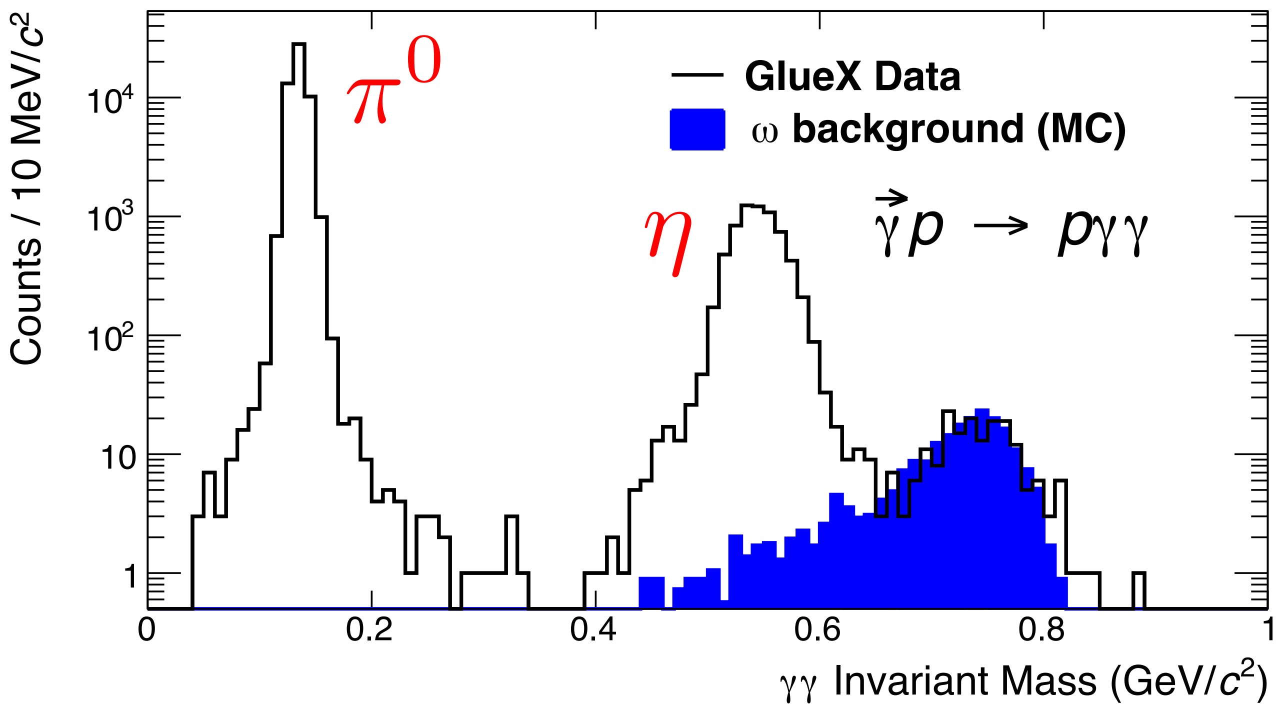
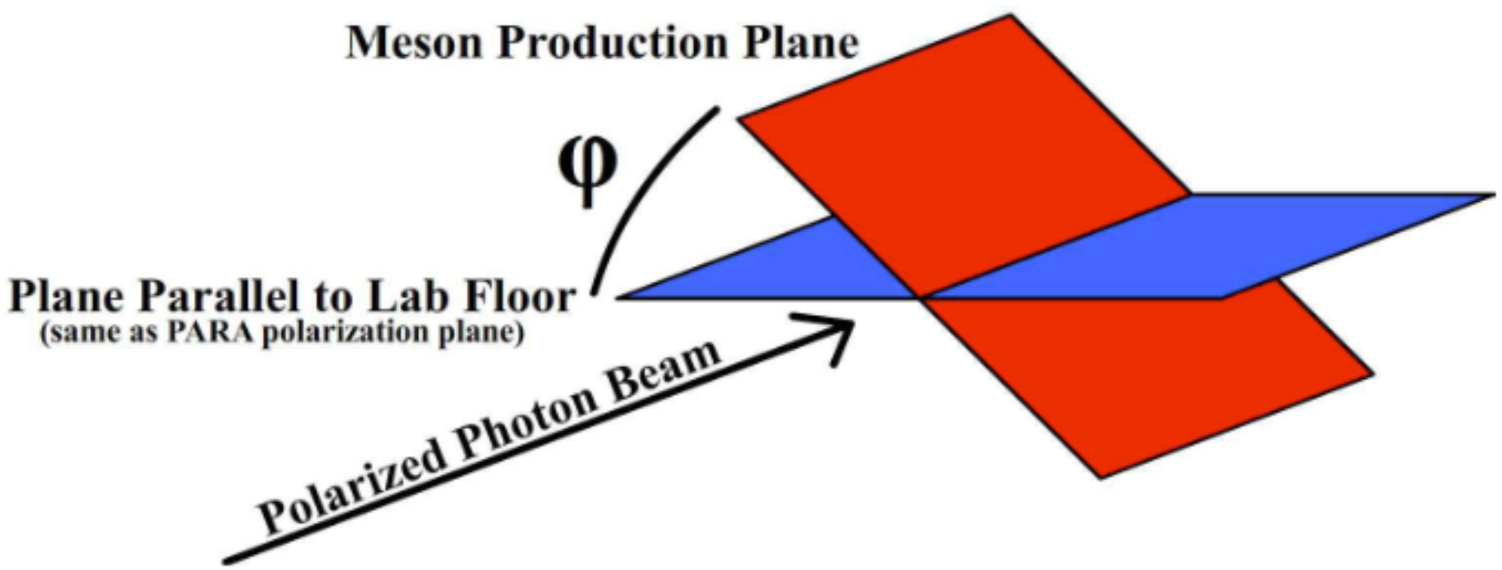


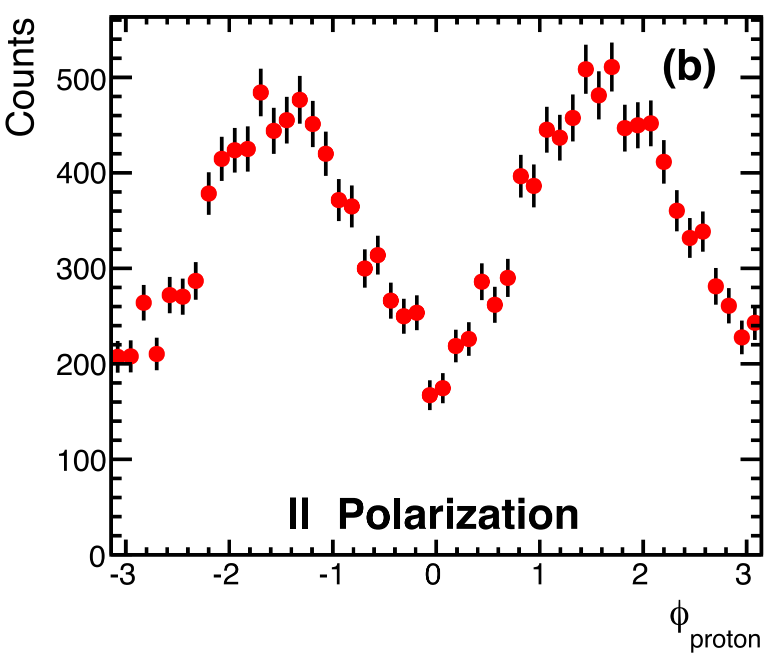
JPAC **Mathieu et al. PRD 92, 074013**

π^0 and η beam asymmetries

$$\gamma p \rightarrow p\gamma\gamma$$



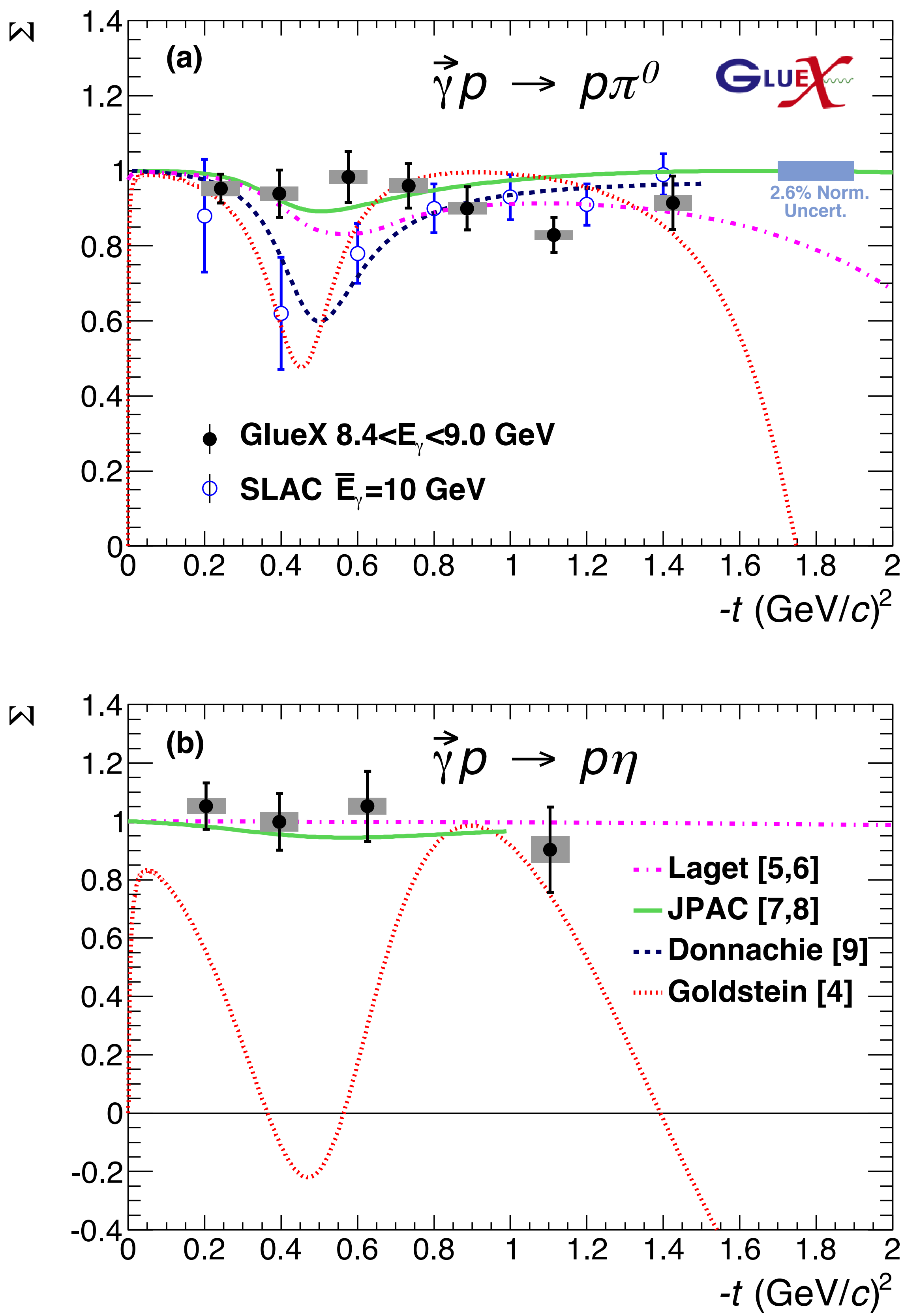




$$\sigma = \sigma_0 \left(1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_\gamma^{\text{lin}})\right)$$

Phys. Rev. C 95, 042201(R)

π⁰ and η beam asymmetries



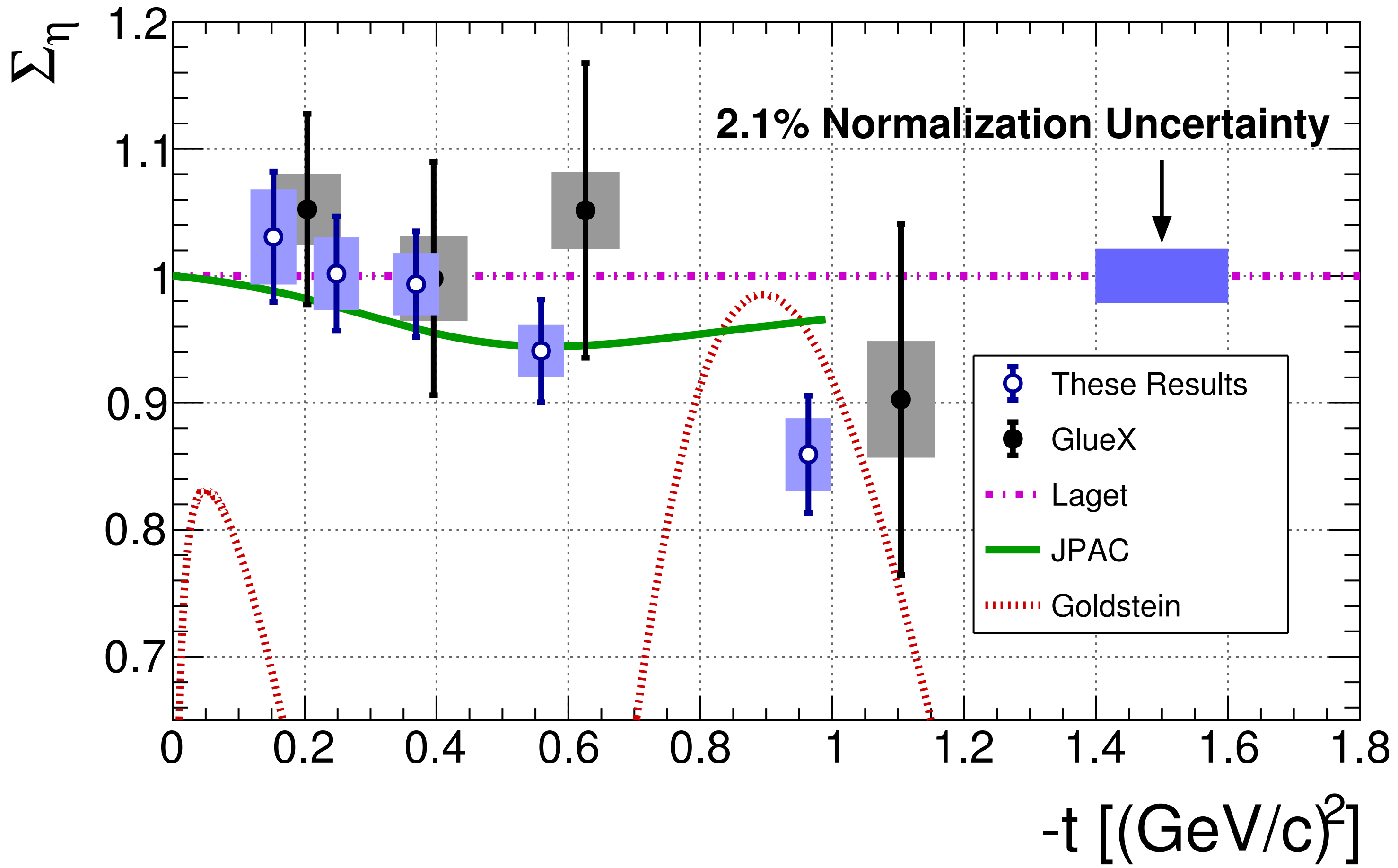
- Dip in multiple theory predictions not observed
- Indication of vector exchange dominance at this energy
- Additional asymmetry measurements ongoing with this dataset

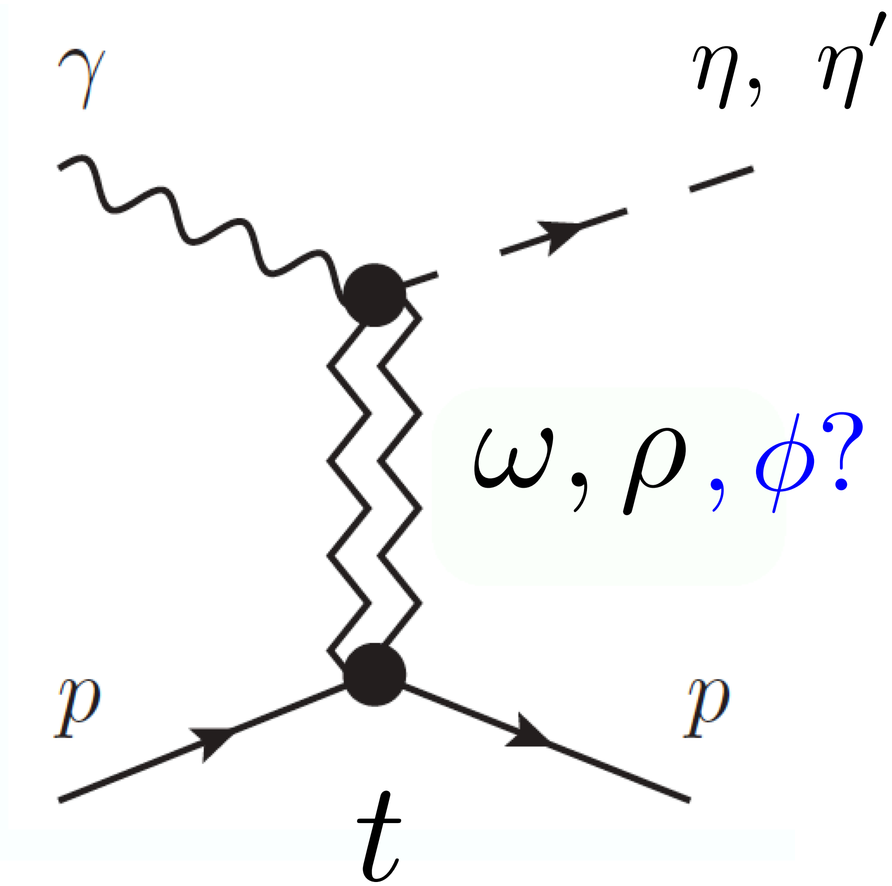
First 12 GeV publication!

Phys. Rev. C 95, 042201(R)

η/η' beam asymmetry

Recently submitted to PRC
arXiv:1908.05563



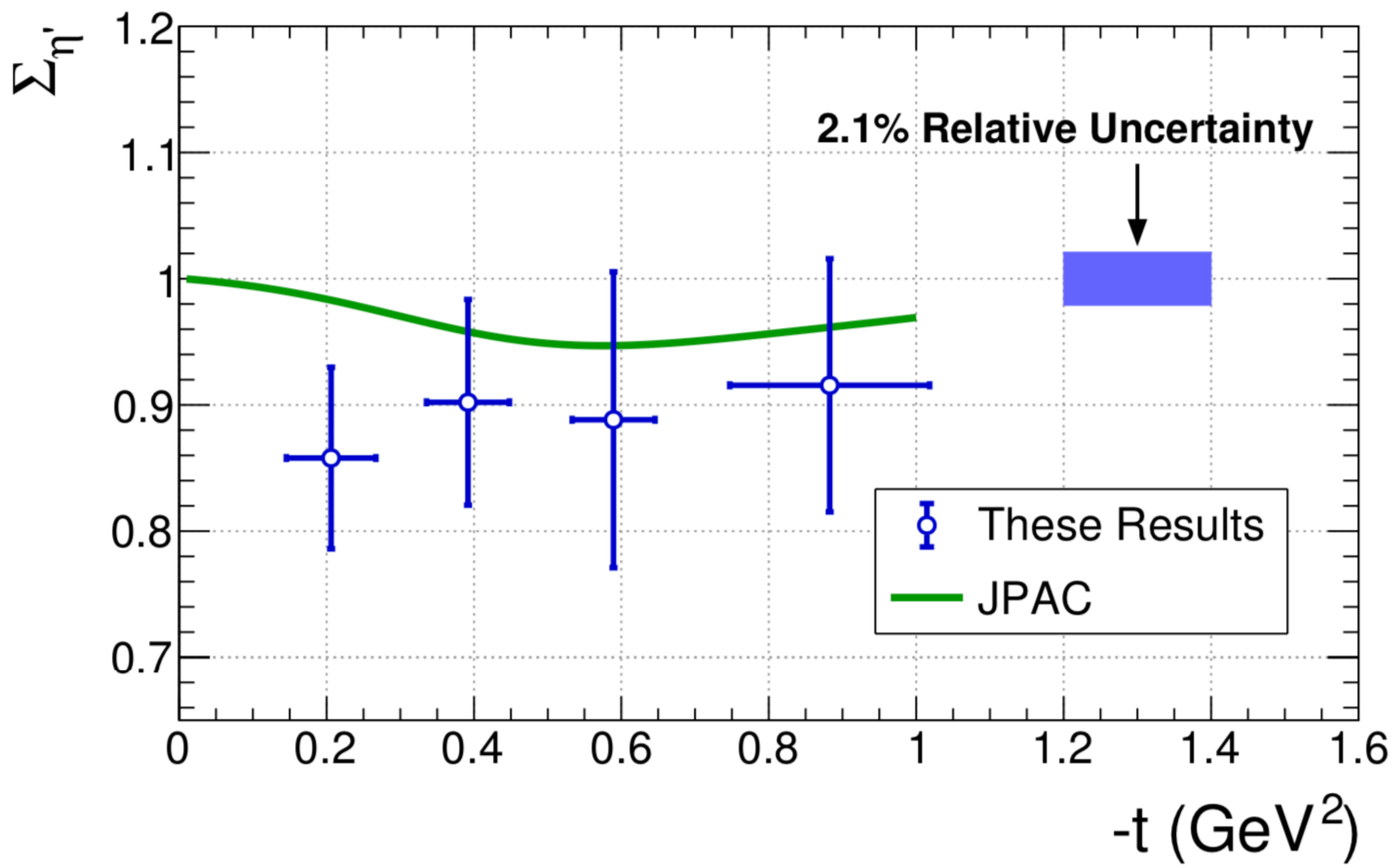


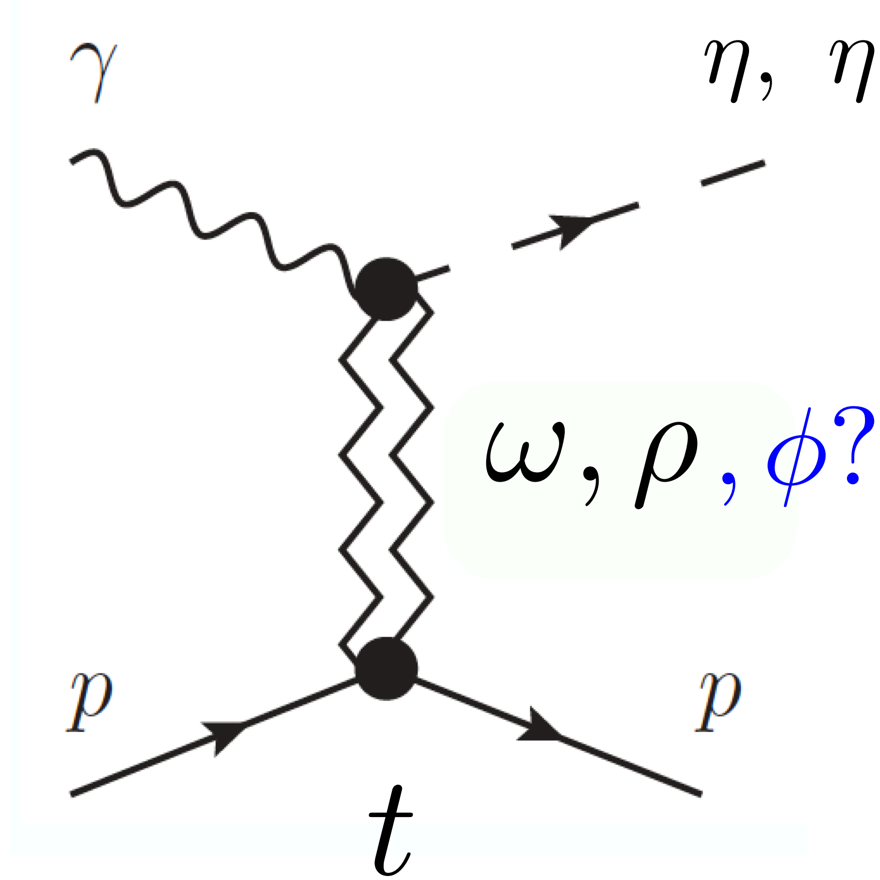
Consistent with prediction from JPAC: PLB 774 (2017) 362

Neutral pseudoscalars: Σ~1, dominated by vector exchange

η/η' beam asymmetry

Recently submitted to PRC
arXiv:1908.05563





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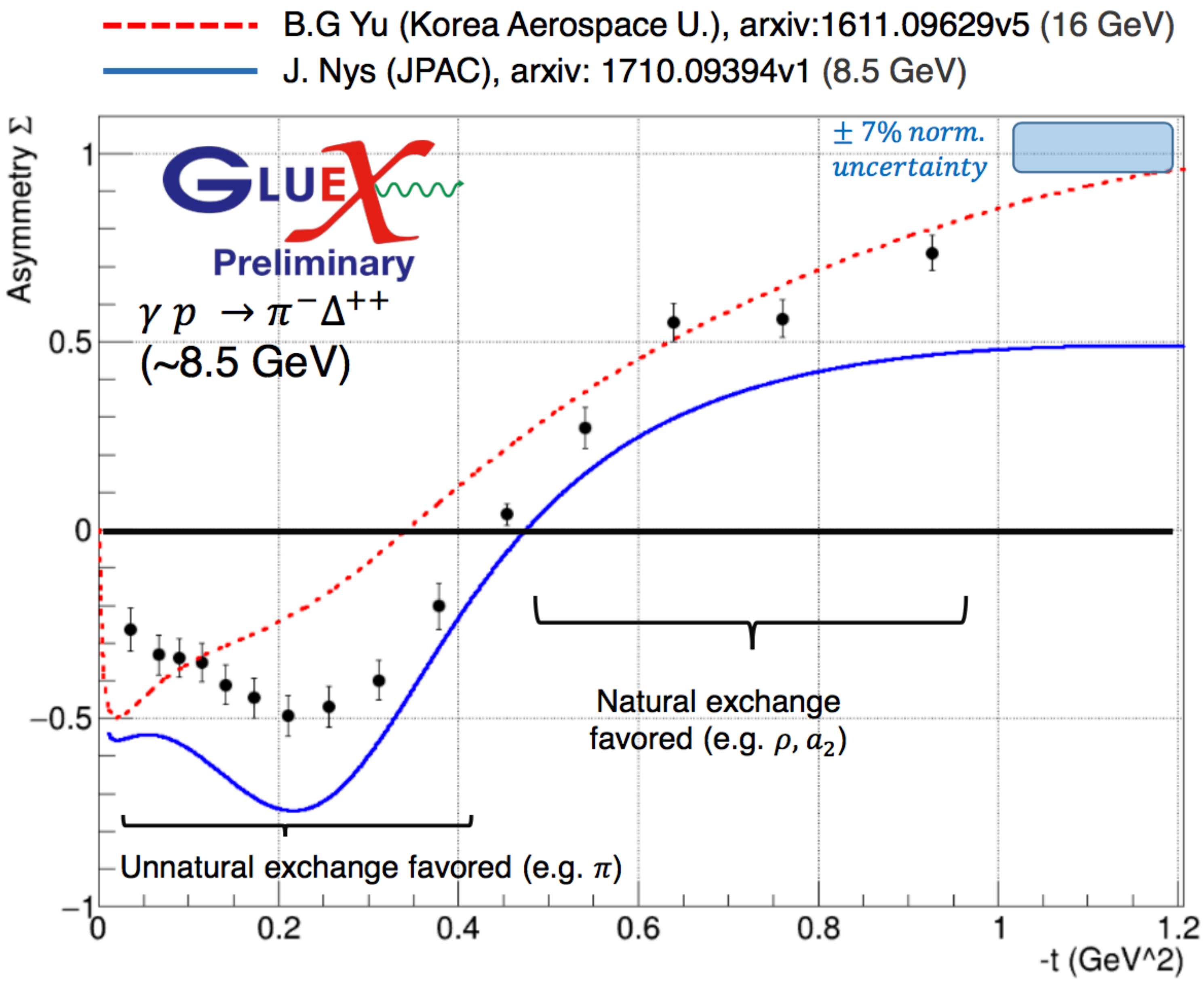
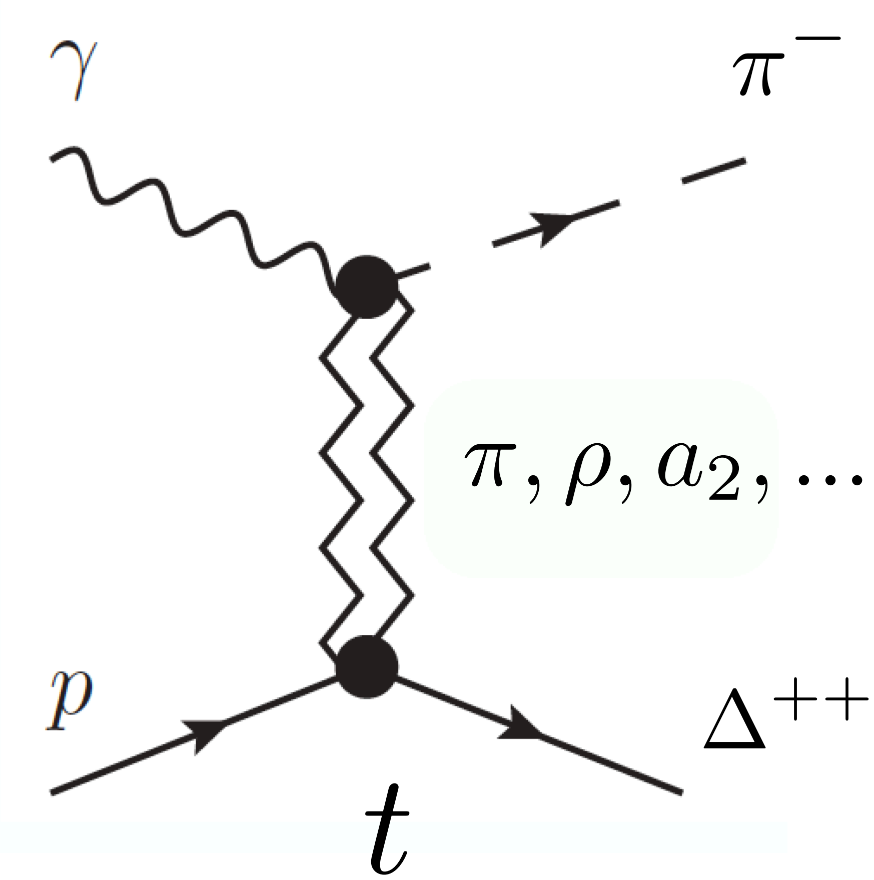
π- beam asymmetry





Charged pseudoscalars: more complicated -*t* dependence

Spin Density Matrix Elements

- Intensity expressed as function of production and decay angles for vector mesons: $\gamma p \to \rho p$

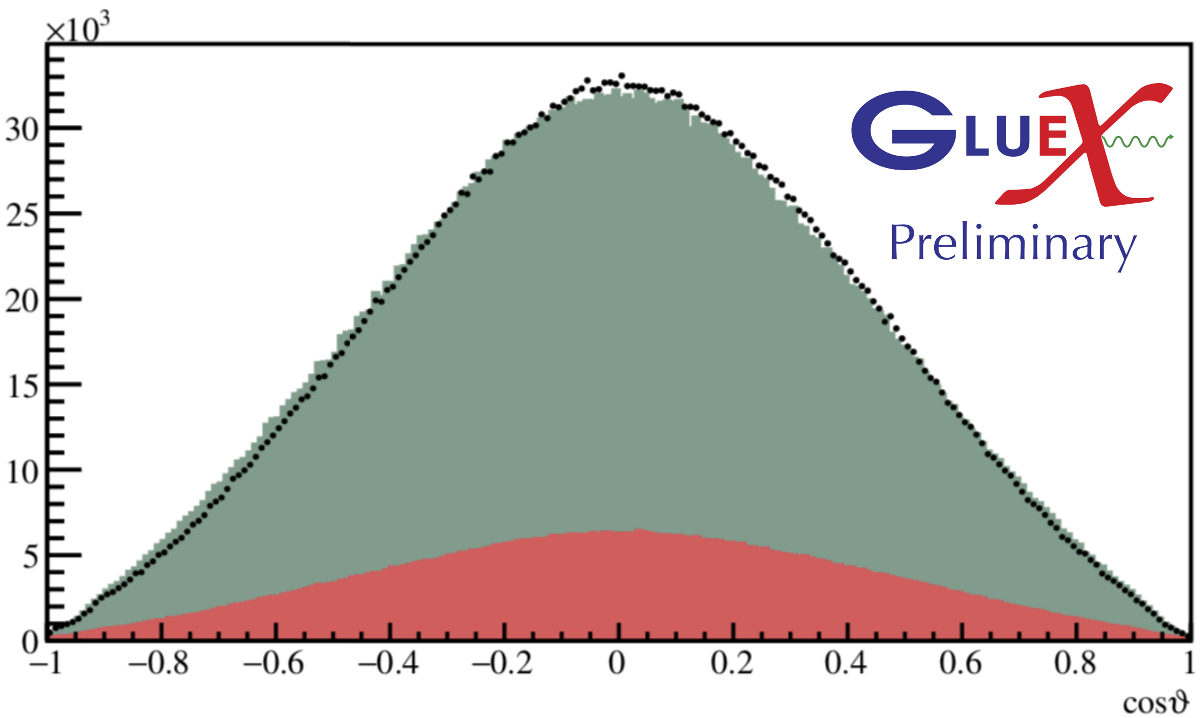
$$W^0(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

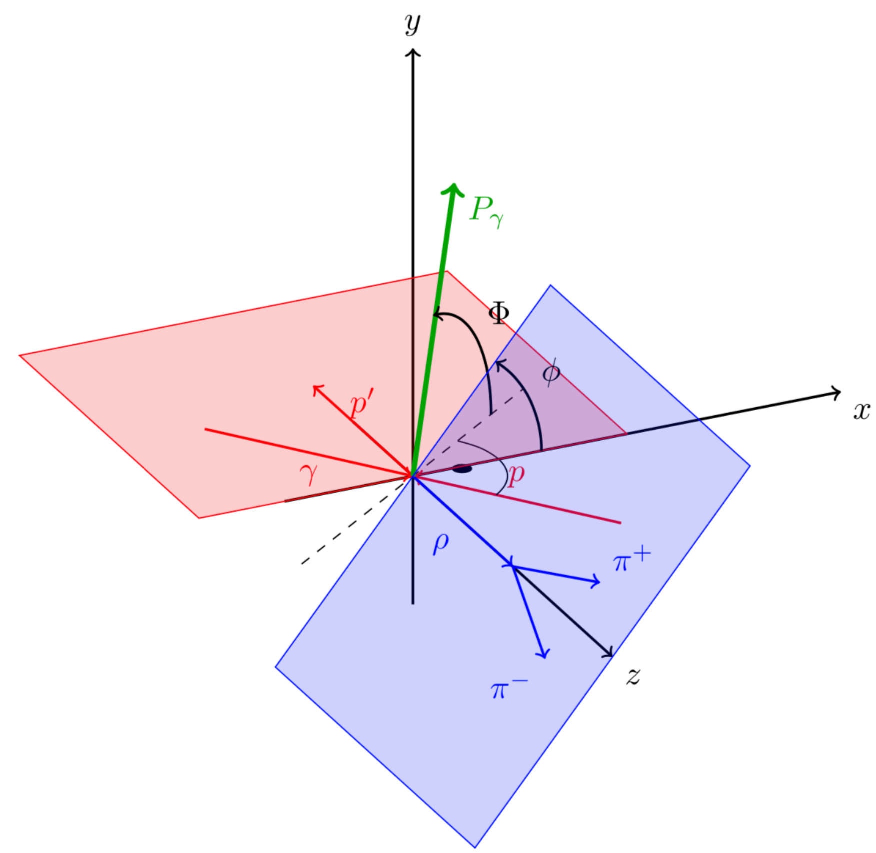
$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^2(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right)$$

$$W(\cos\vartheta,\varphi,\Phi) = W^0(\cos\vartheta,\varphi) - P_\gamma\cos(2\Phi)W^1(\cos\vartheta,\varphi) - P_\gamma\sin(2\Phi)W^2(\cos\vartheta,\varphi)$$

Schilling [Nucl. Phy. B, 15 (1970) 397]





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$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

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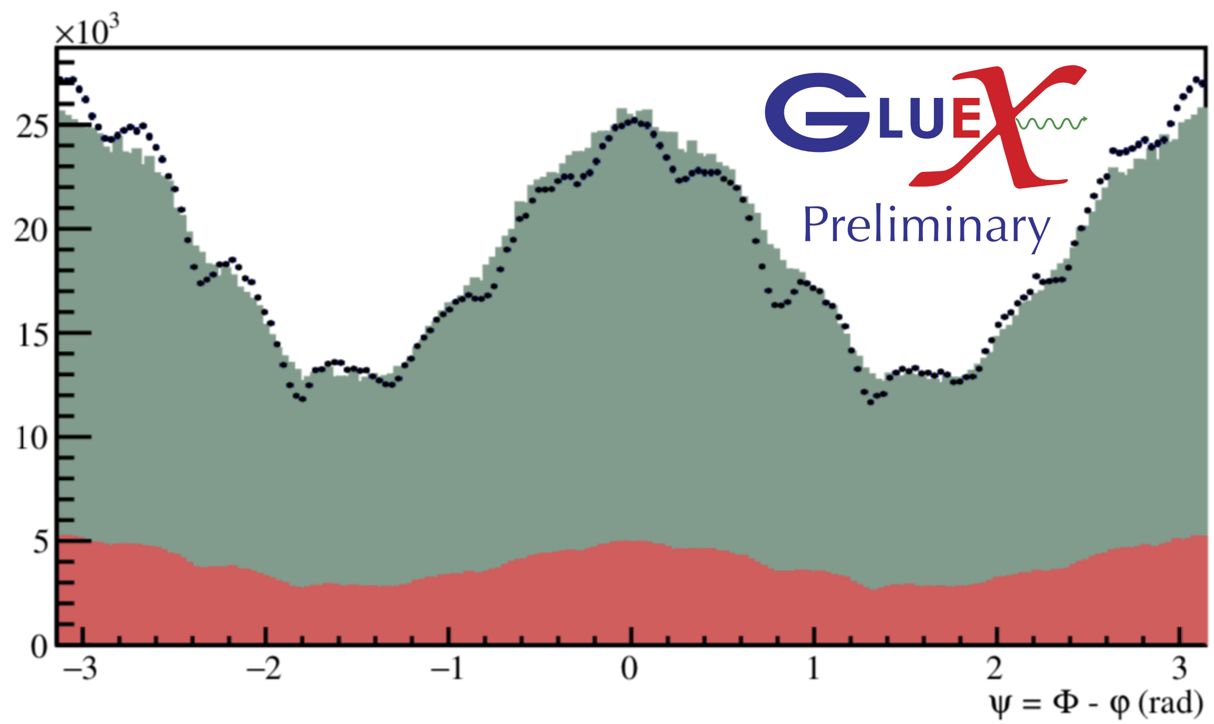
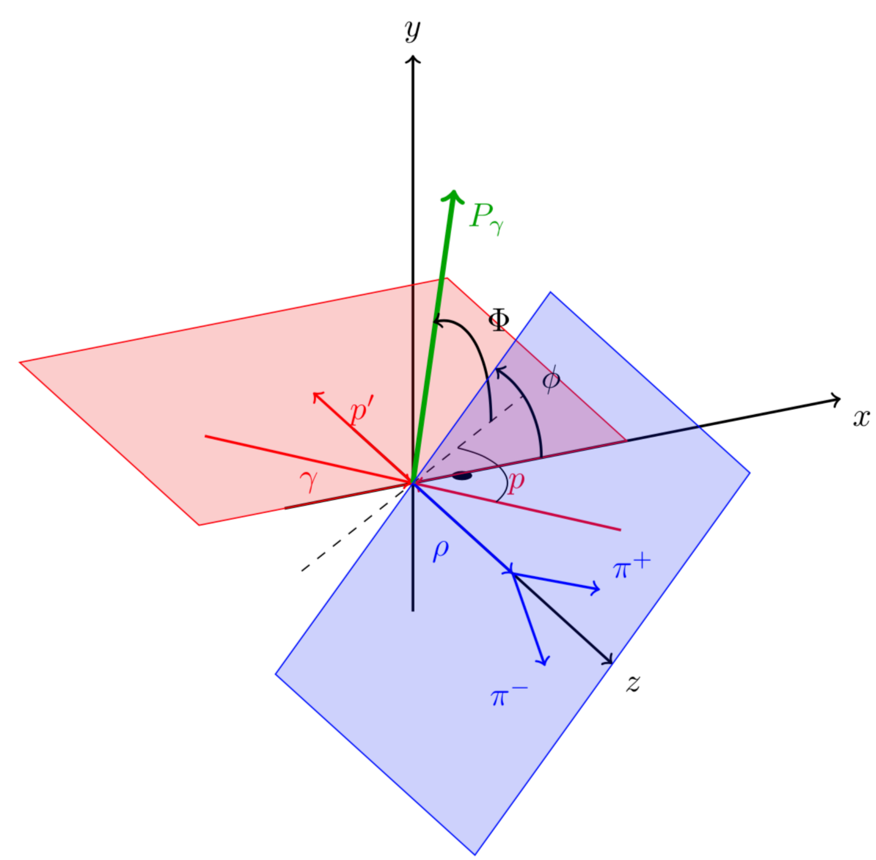
Schilling [Nucl. Phy. B, 15 (1970) 397]





Spin Density Matrix Elements

- Intensity expressed as function of production and decay angles for vector mesons: $\gamma p \to \rho p$

$$W^0(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

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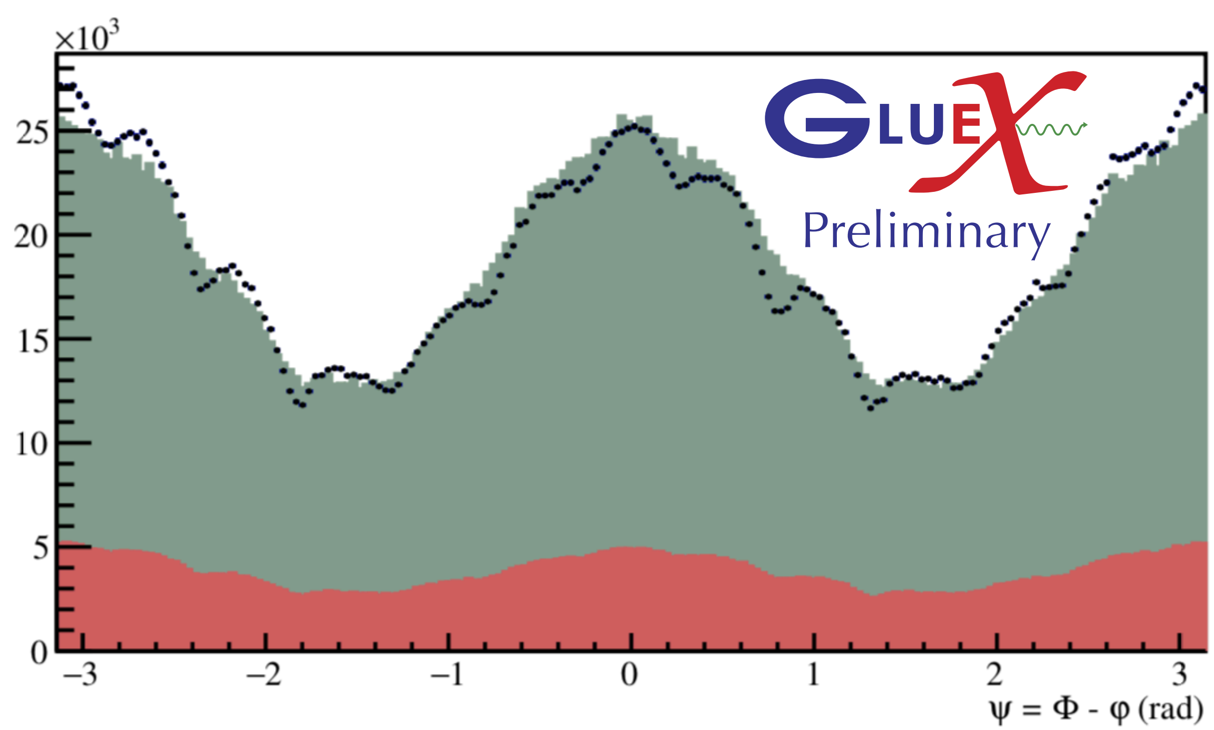
Schilling [Nucl. Phy. B, 15 (1970) 397]



- Requires control of angular acceptance distributions similar to PWA

$$\ln L = \sum_{i=1}^{N} \ln I(\Omega_i) - \sum_{j=1}^{M} \ln I(\Omega_j) - \int d\Omega\, I(\Omega)\,\eta(\Omega)$$

Signal **Bkgd.** **Accept.**

Spin Density Matrix Elements

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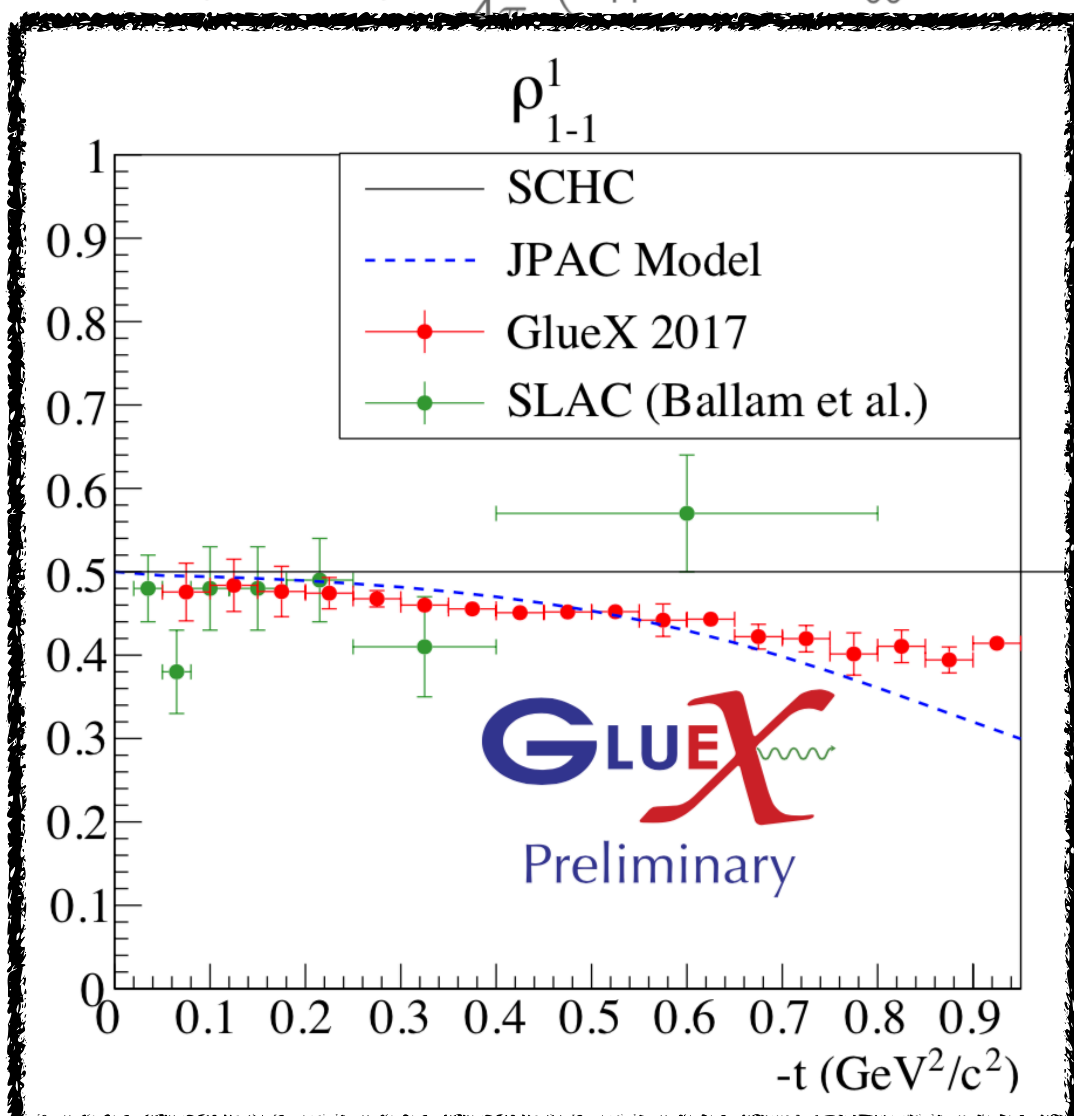
$$\ldots m\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right)$$

$$\ldots{}^1(\cos\vartheta,\varphi) - P_\gamma\sin(2\Phi)W^2(\cos\vartheta,\varphi)$$



- Good agreement with JPAC model in the low *-t* regime

- Natural parity exchange is dominant for ρ, ϕ, and ω

MENU2019 Proceedings arXiv:1908.07275

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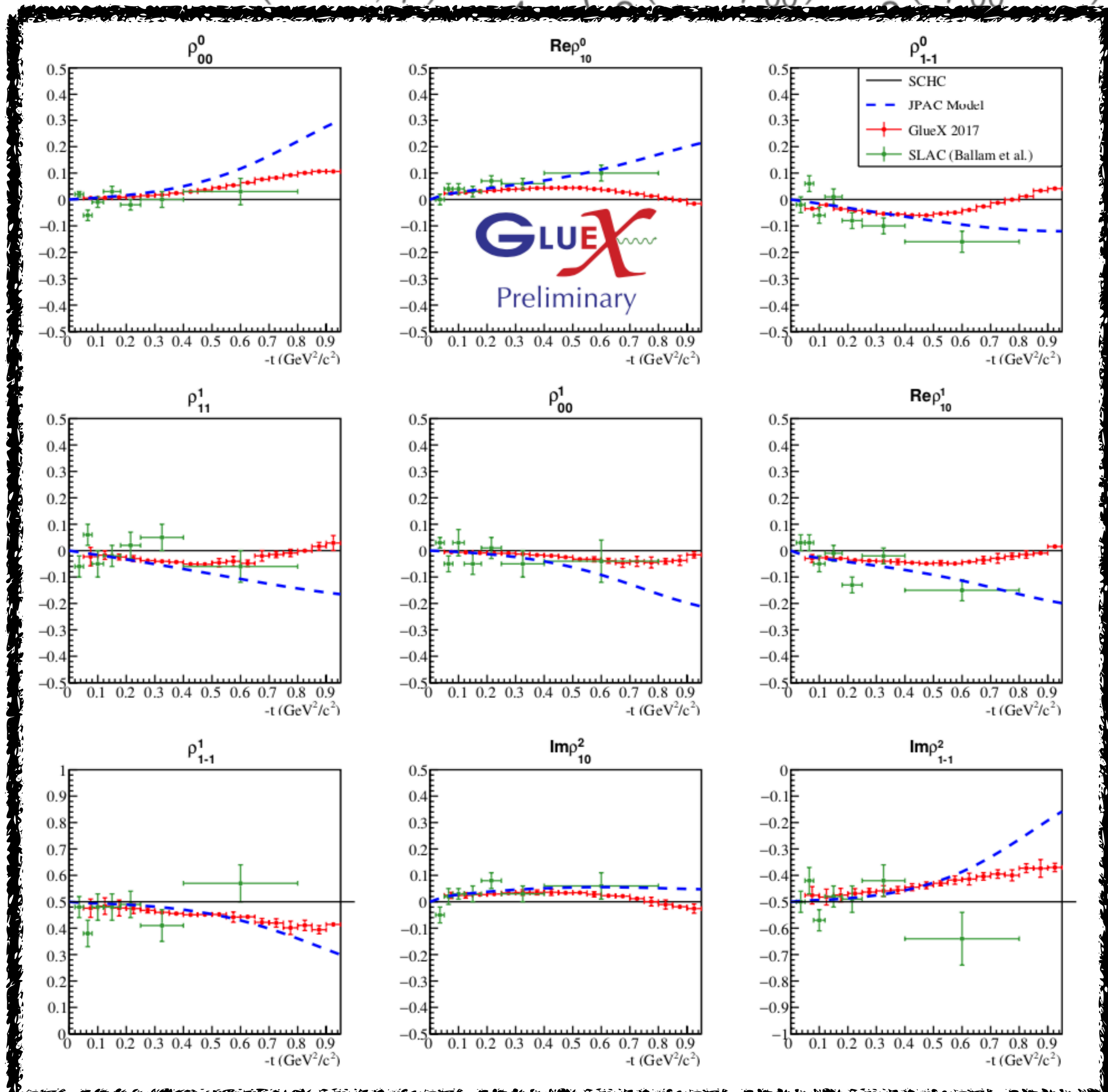
$$\ldots {}_{-1}\sin^2\vartheta\sin 2\varphi\right)$$

$$\ldots \mathrm{s}\,\vartheta,\varphi) - P_\gamma\sin(2\Phi)W^2(\cos\vartheta,\varphi)$$



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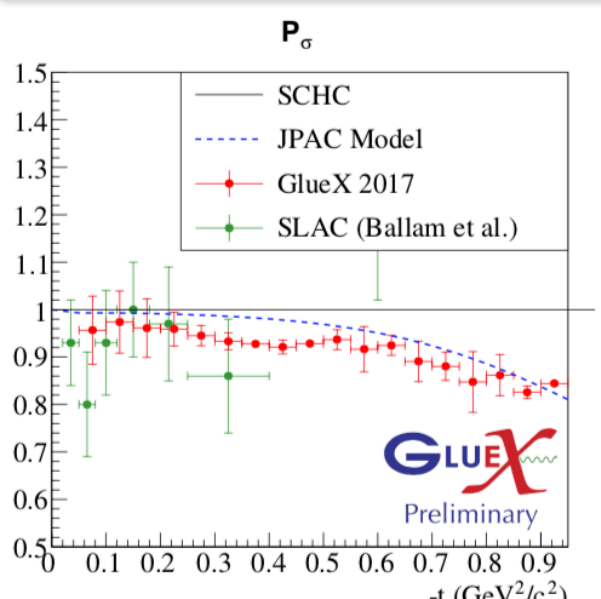
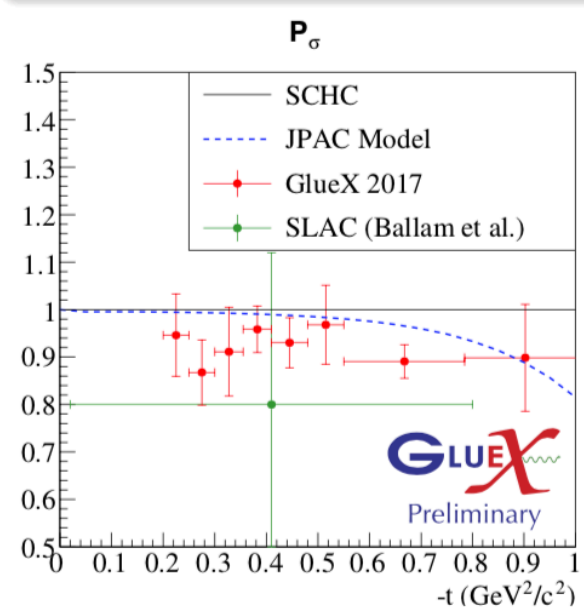
Schilling [Nucl. Phy. B, 15 (1970) 397]

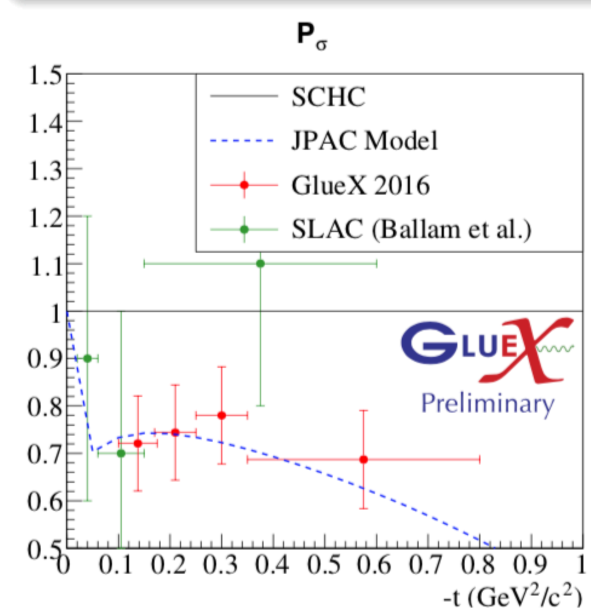
$\rho(770) \to \pi^+\pi^-$



$\phi(1020) \to K^+K^-$

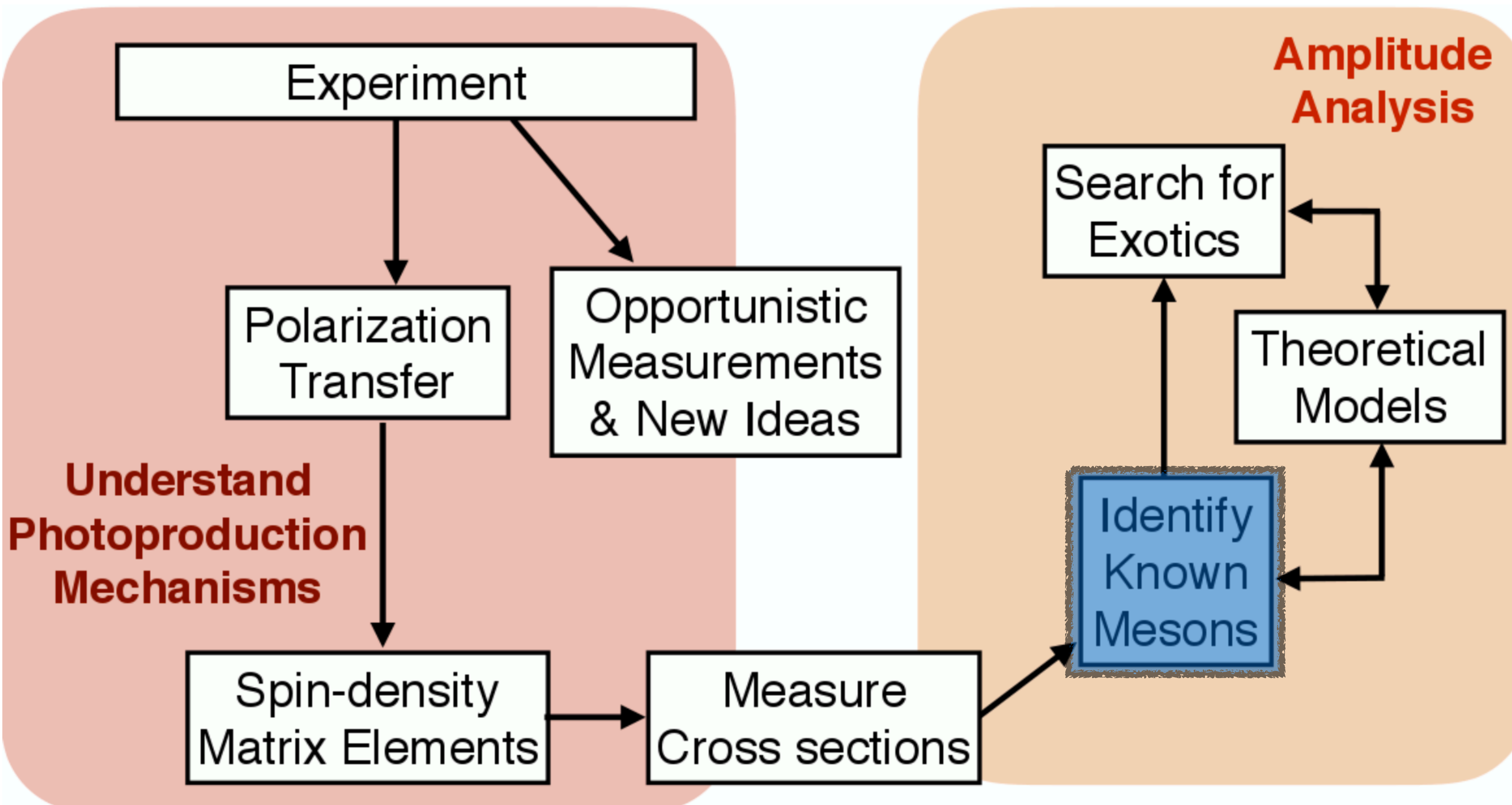


$\omega(782) \to \pi^+\pi^-\pi^0$



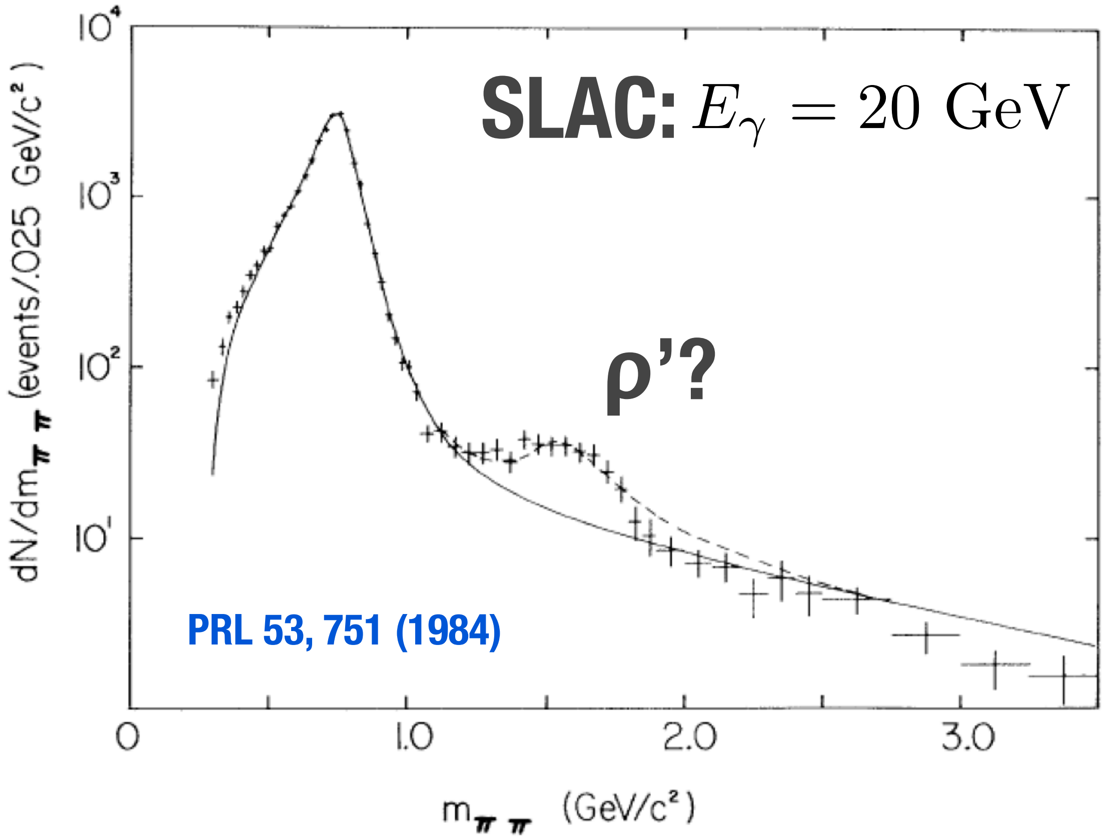
MENU2019 Proceedings arXiv:1908.07275

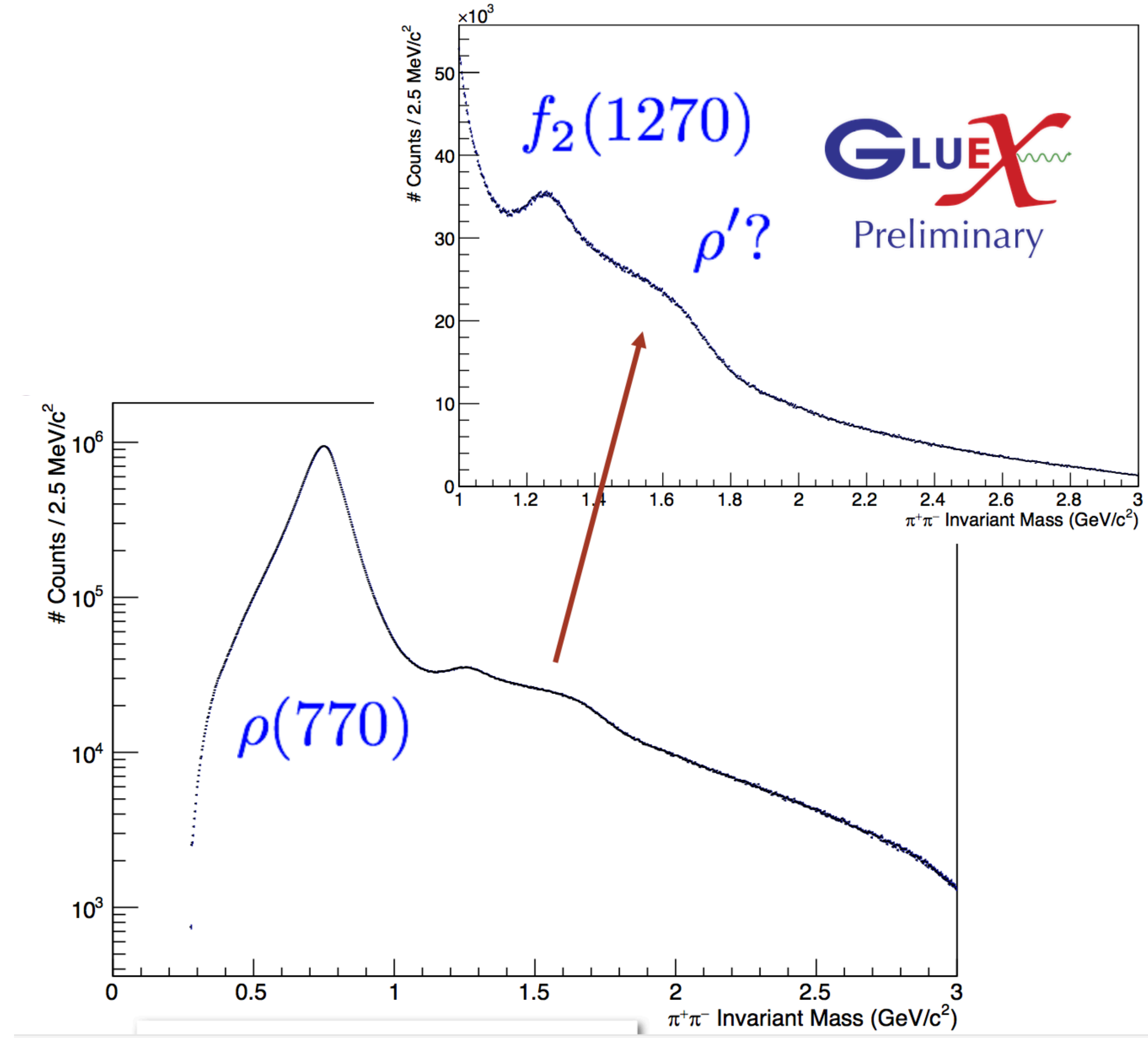
GlueX Physics Program



Early spectroscopy opportunities

$$\gamma p \to \pi^+ \pi^- p$$



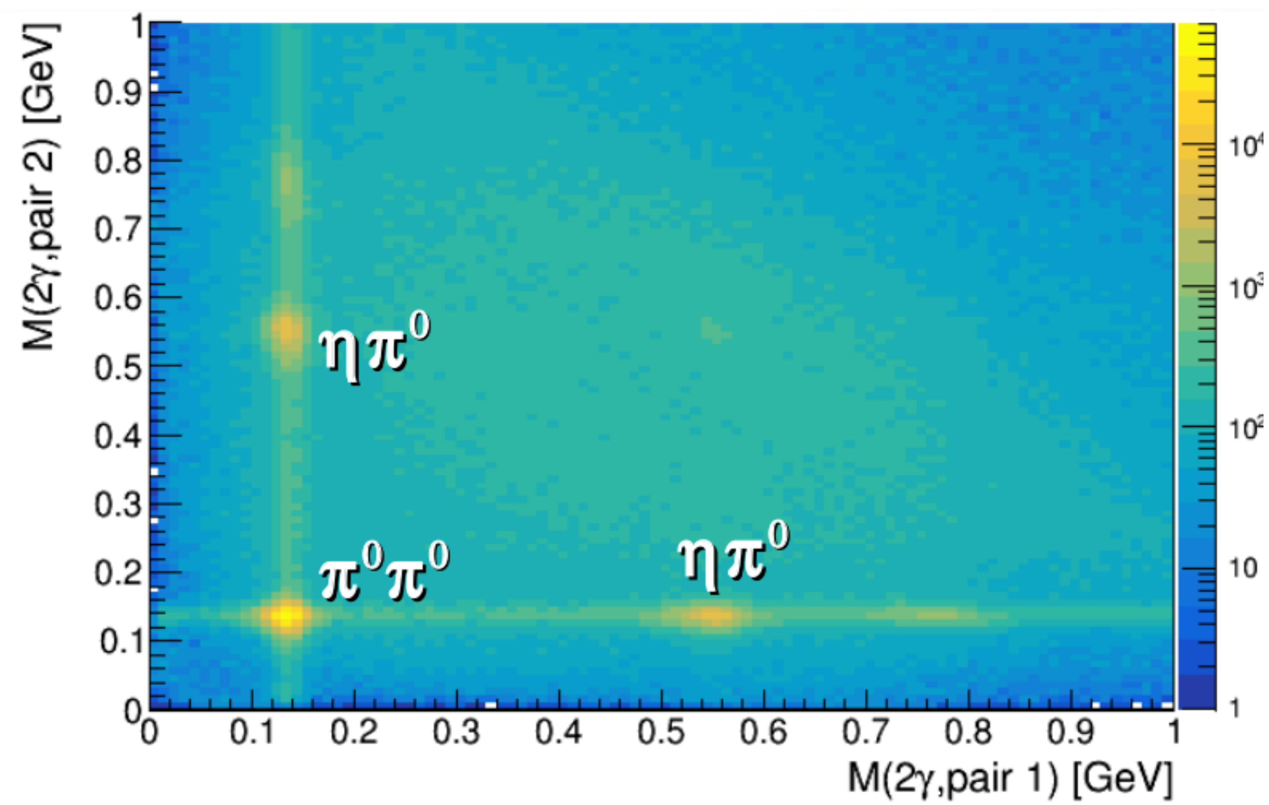


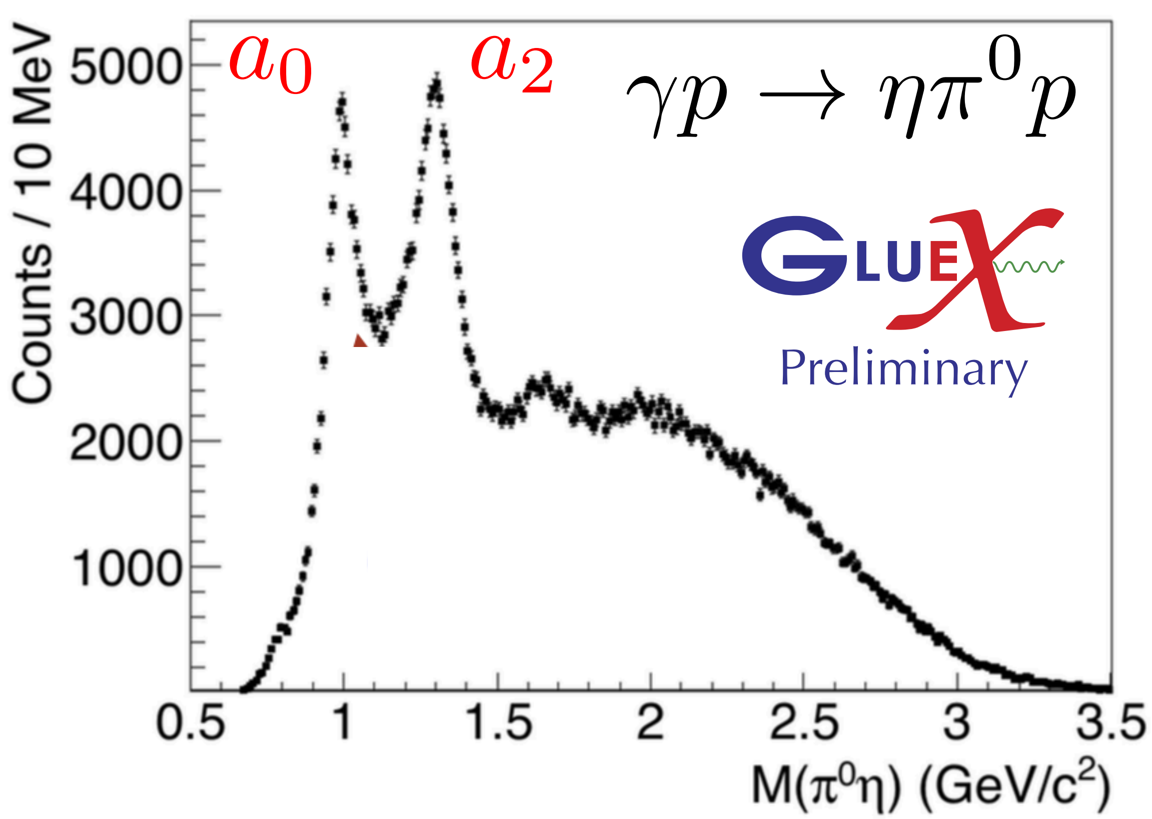
- Enhancement consistent with earlier SLAC measurement, but ~1000x more statistics with early GlueX data
- Polarization observables will provide further insight into the nature of this enhancement

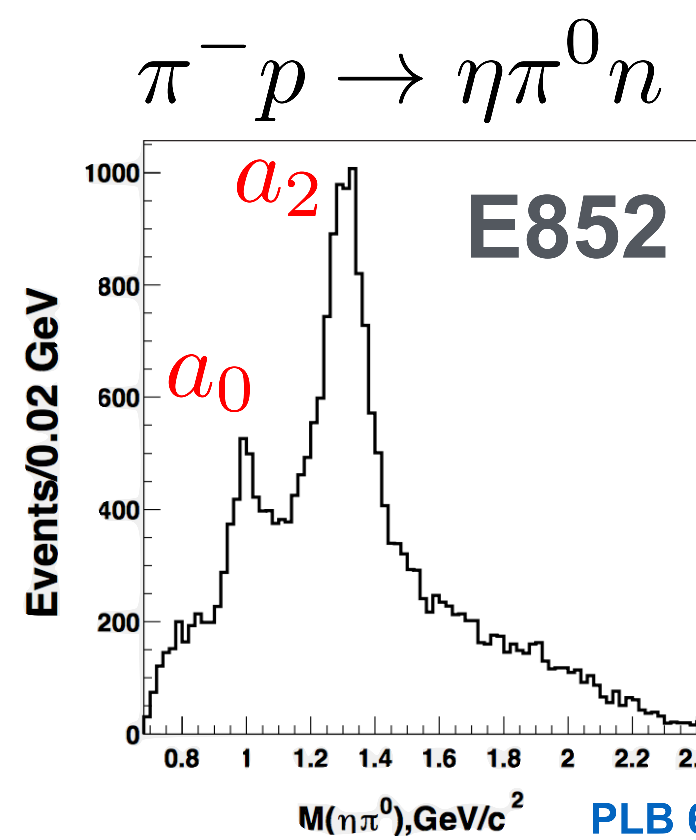
Early spectroscopy opportunities

$$\gamma p \rightarrow 4\gamma p$$

- Previous photoproduction data very sparse for channels with multiple neutrals particles
- Preliminary studies are already showing interesting features

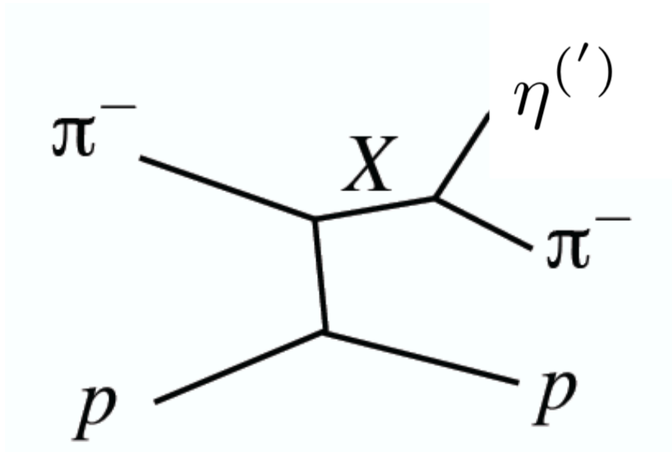






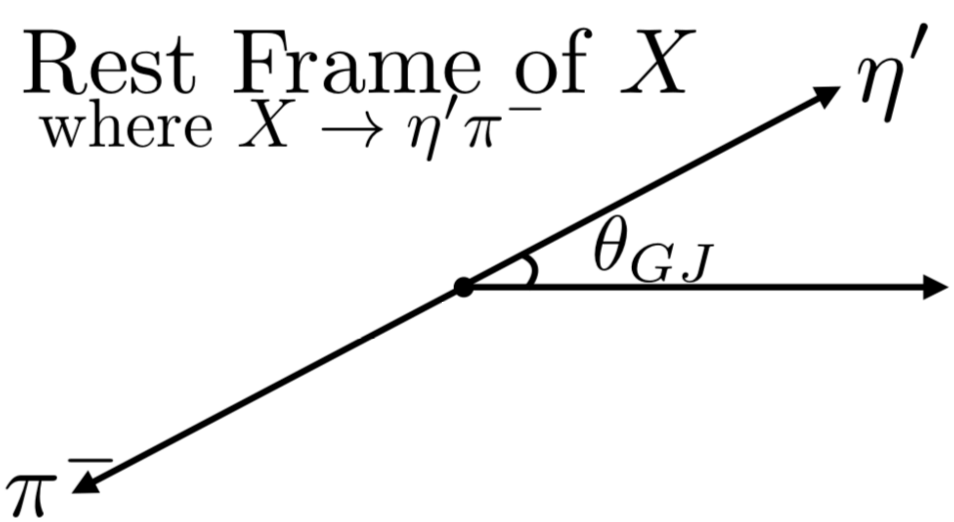
PLB 657 (2007) 27

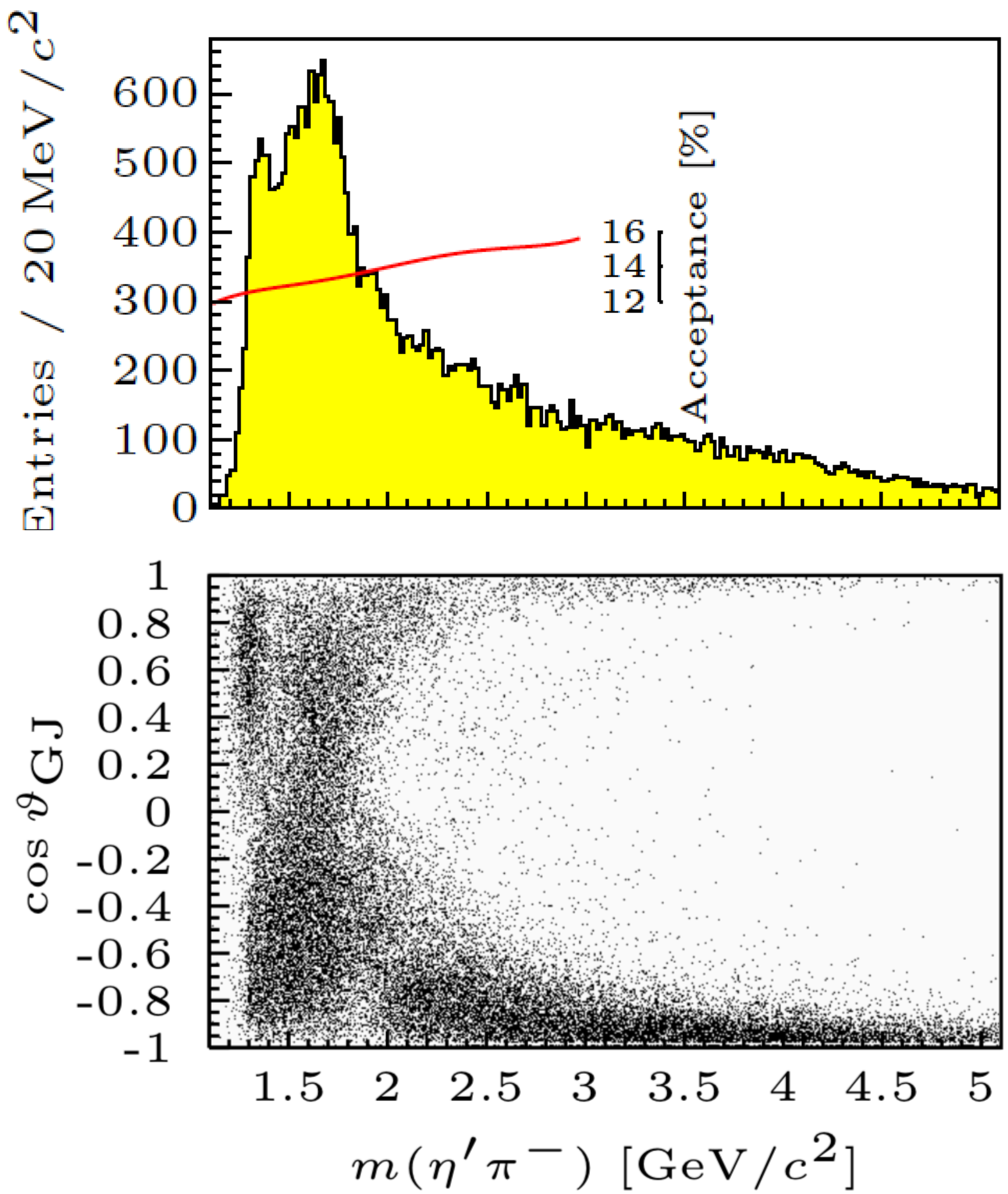
$\eta\pi/\eta'\pi$ spectroscopy at



Light quark resonances:

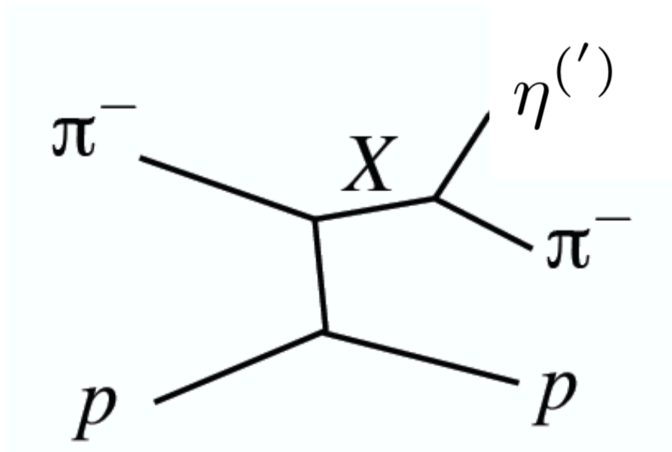
- Many broad overlapping resonances
- Identify different quantum numbers via their decay distributions

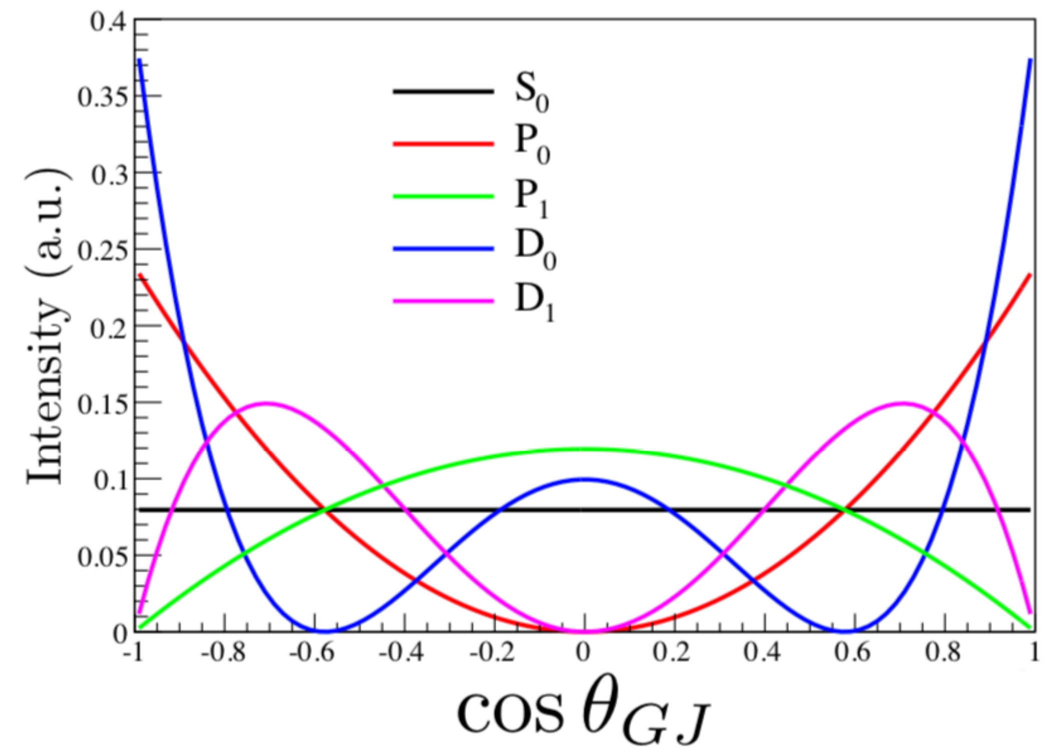




COMPASS: PLB 740 (2015) 303

ηπ/η’π spectroscopy at COMPASS





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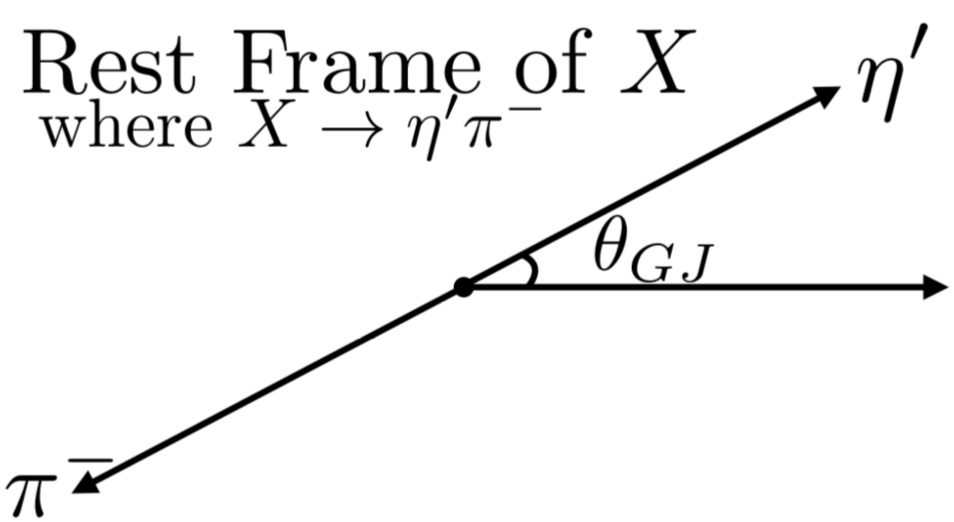

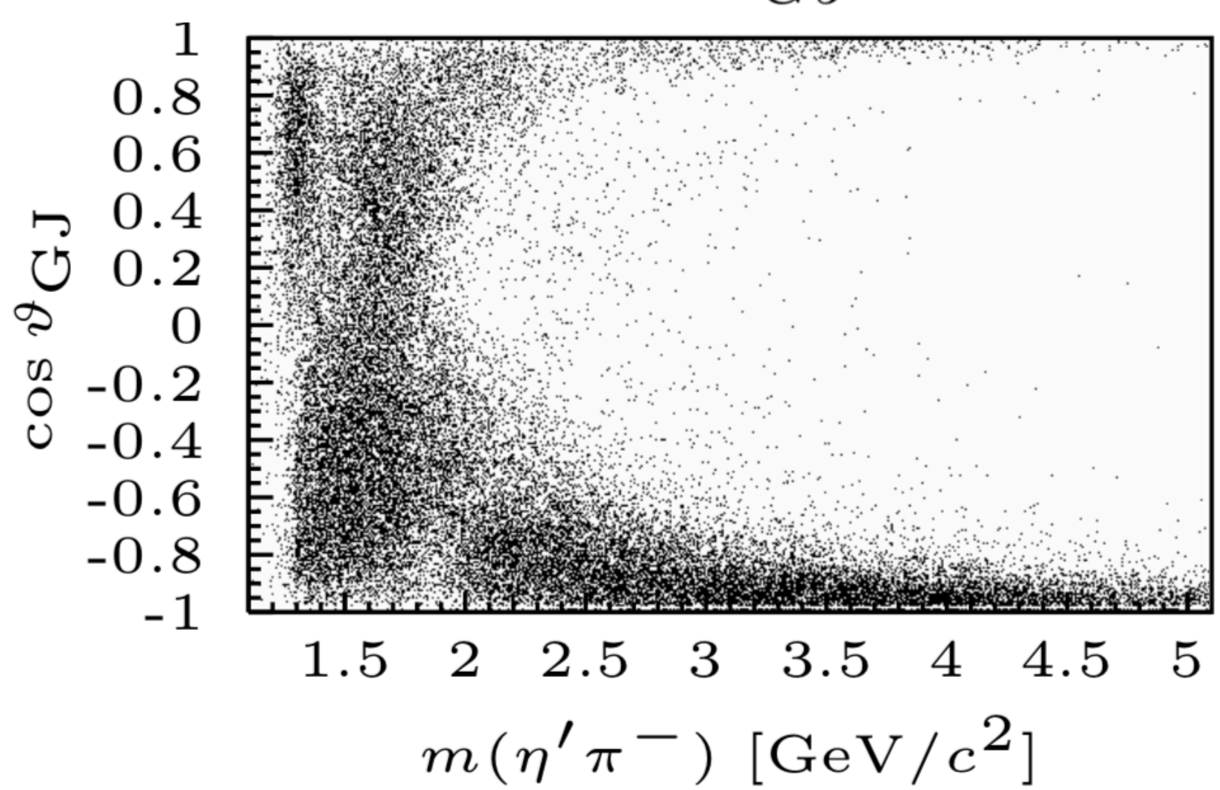

COMPASS: PLB 740 (2015) 303

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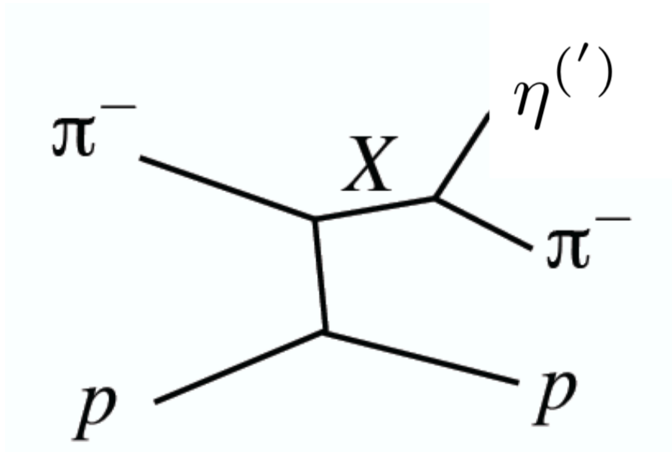

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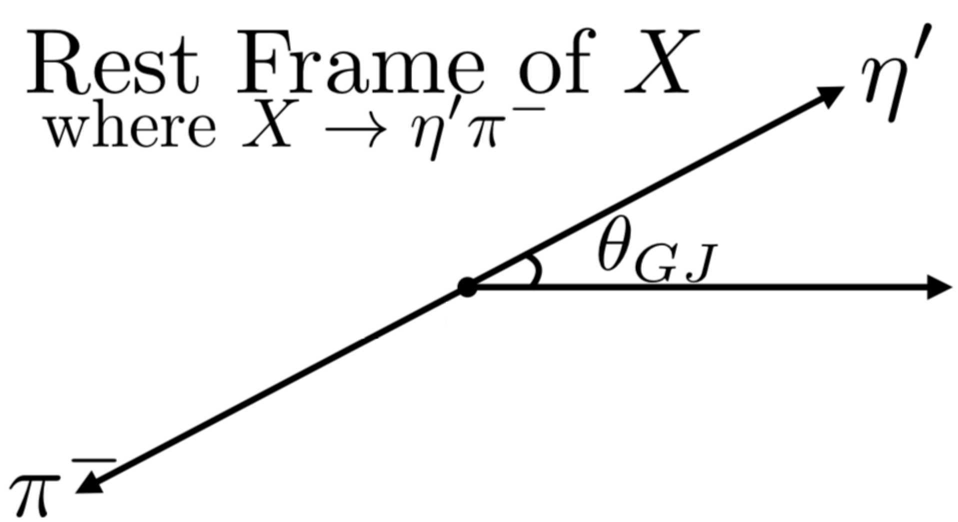
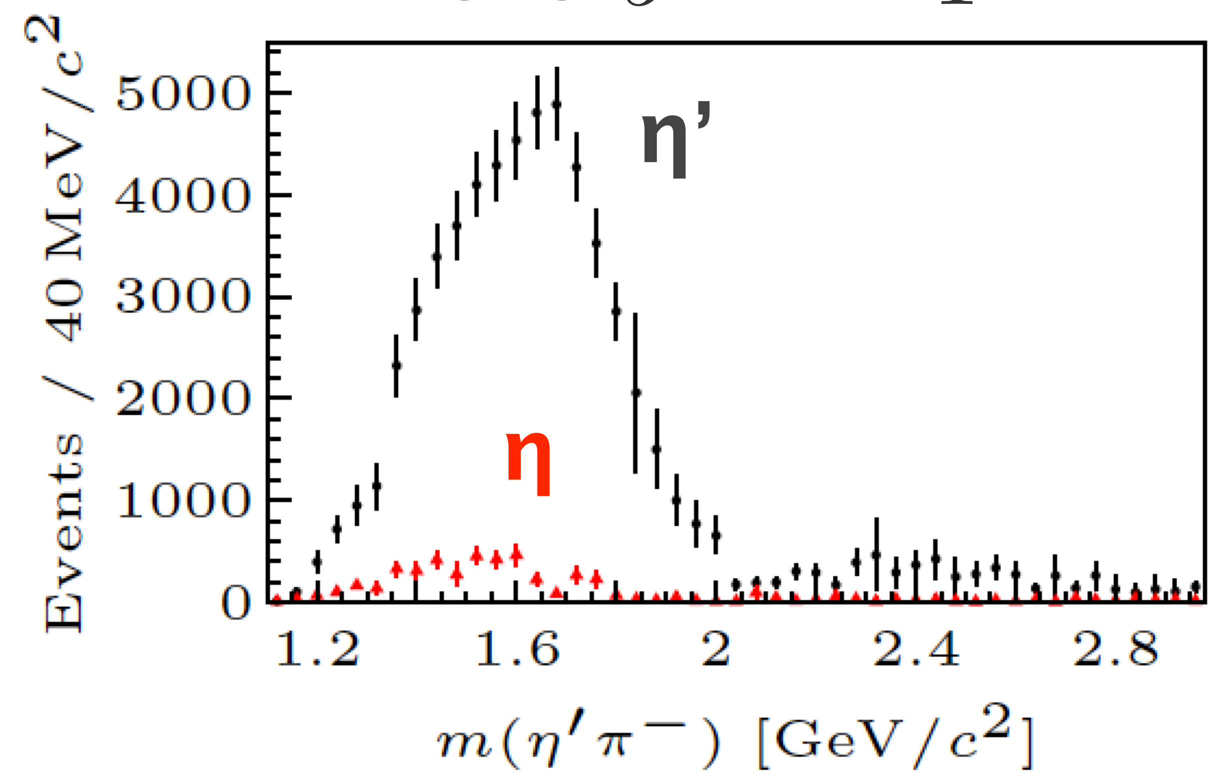


Exotic $J^{PC} = 1^{-+}$

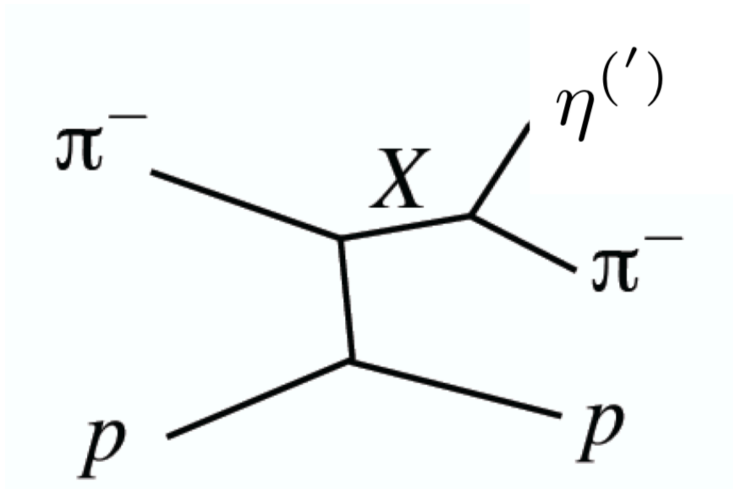


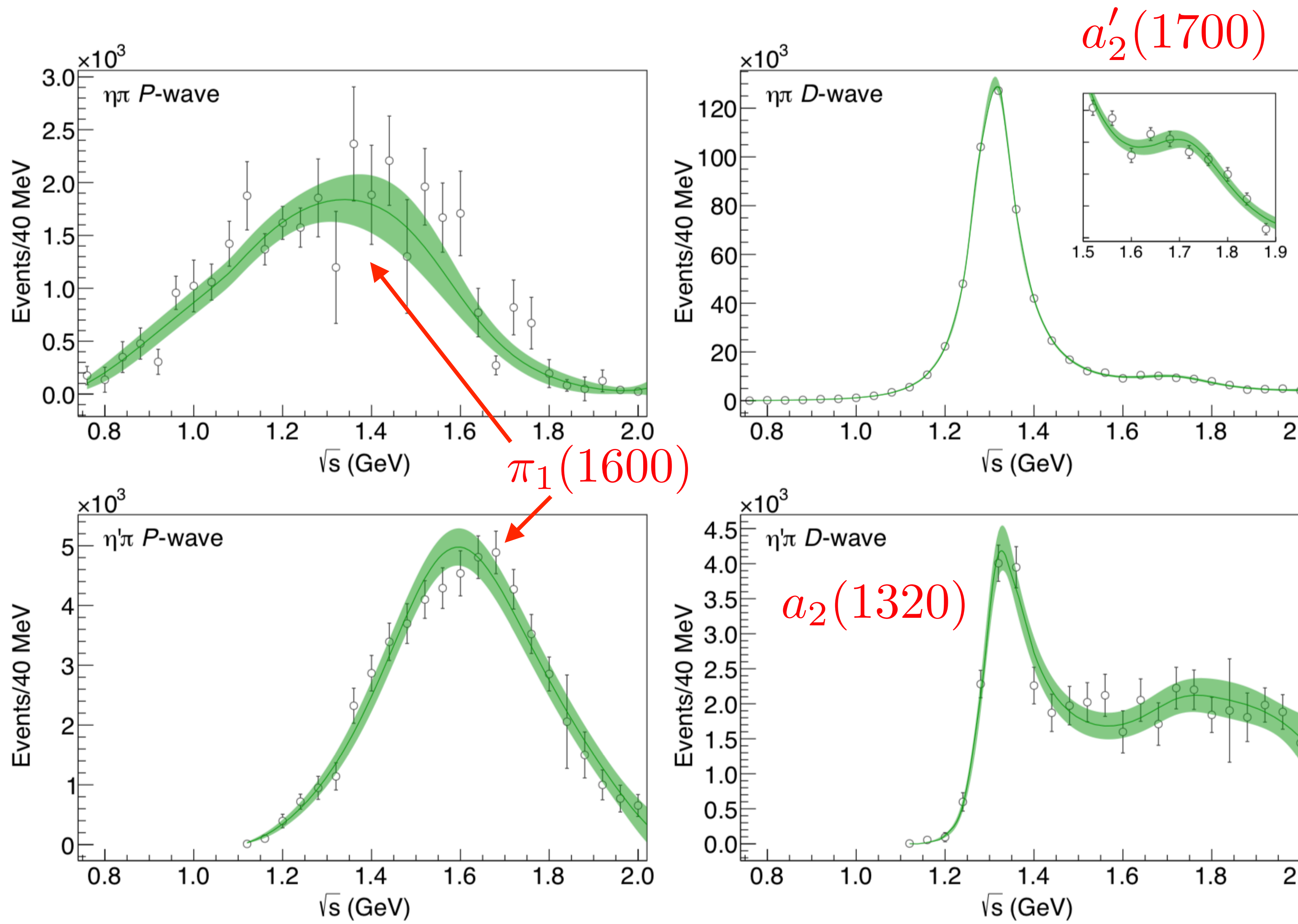
Need to work with theorists on better models to describe broad structures:

Joint Physics Analysis Center JPAC

COMPASS: PLB 740 (2015) 303

ηπ/η'π spectroscopy at COMPASS with JPAC

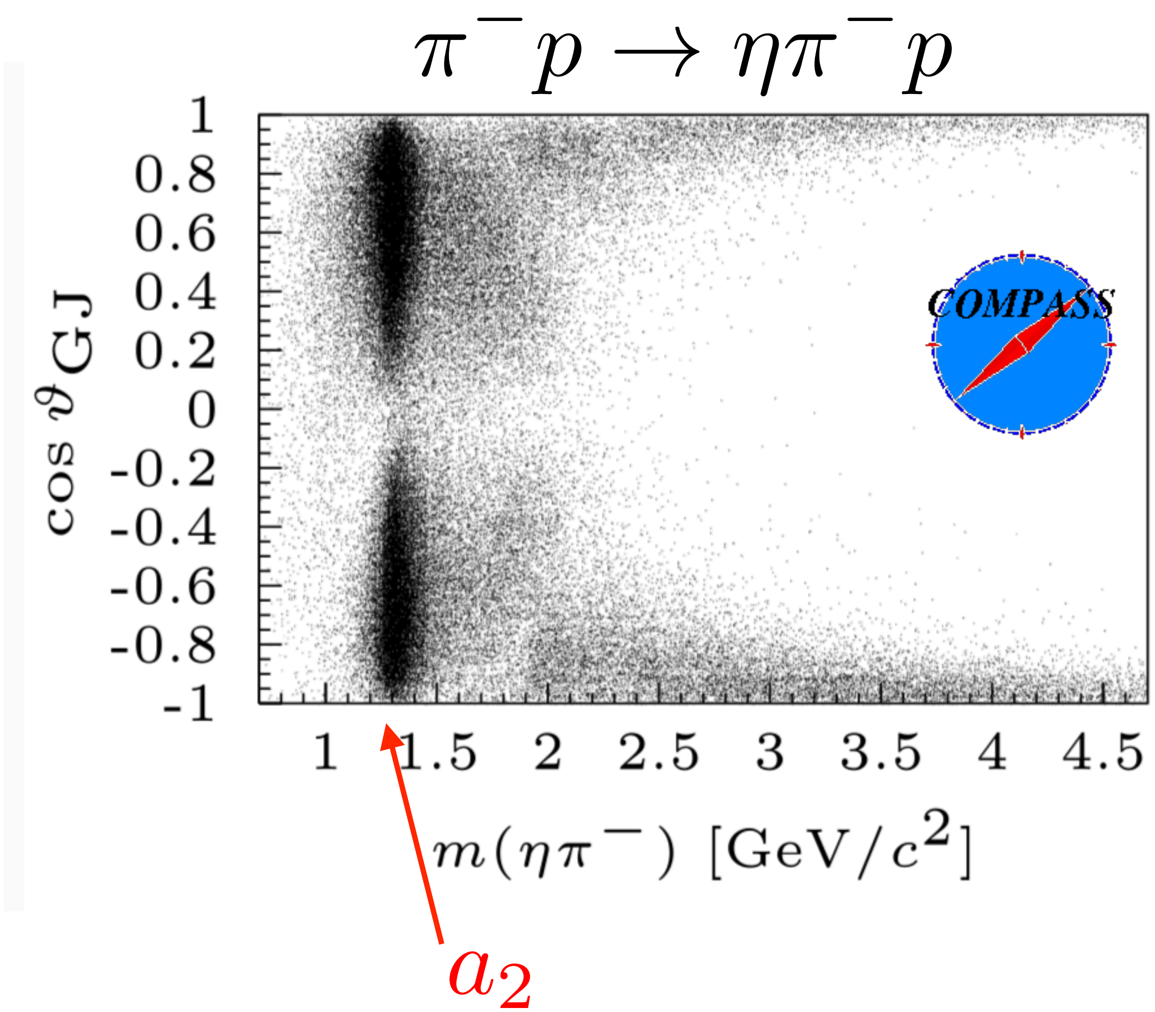


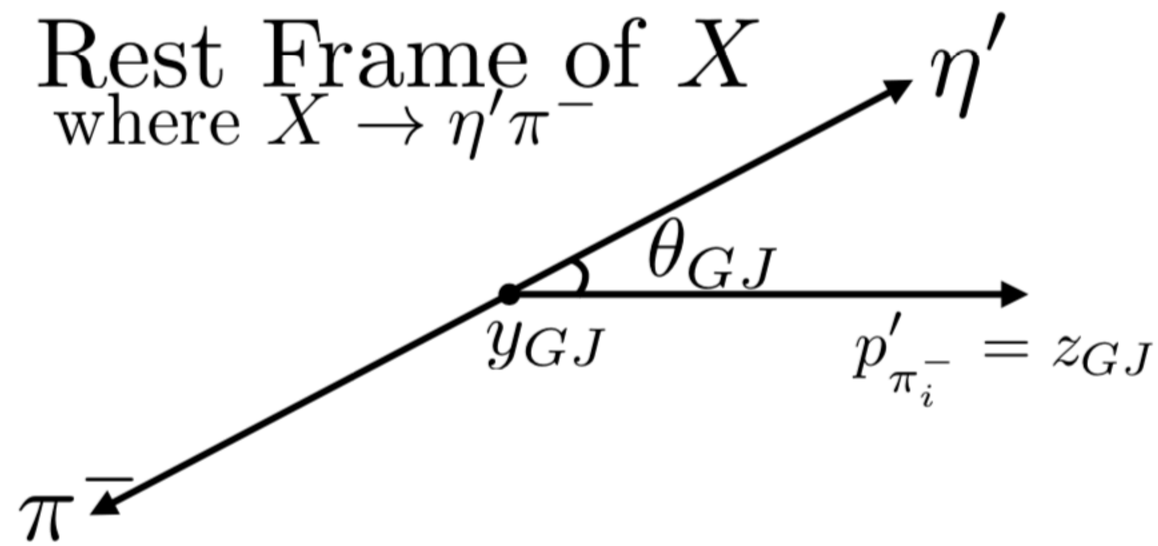


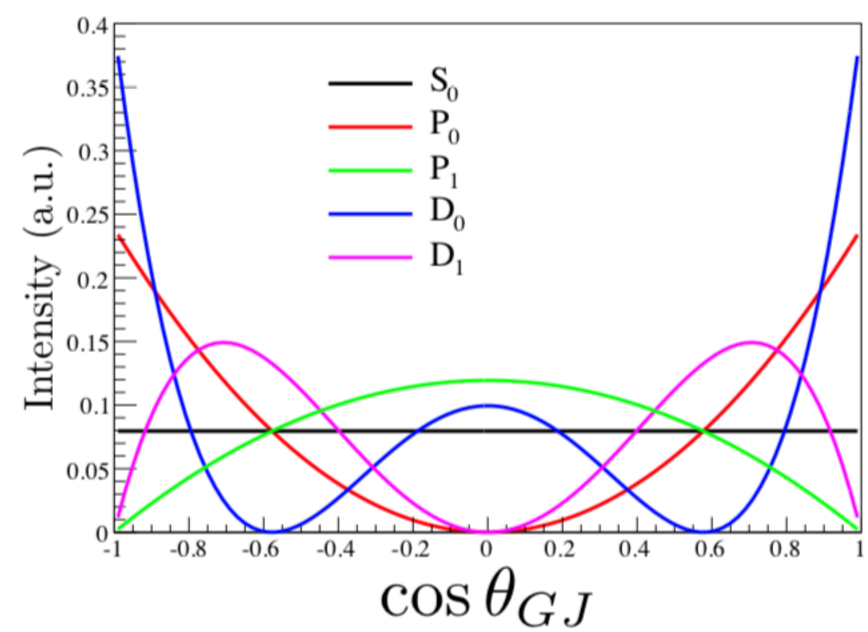
JPAC coupled channel fit to ηπ and η'π determine pole positions for a_2, a_2', and exotic π_1

COMPASS: PLB 740 (2015) 303
JPAC: PRL 122 (2019) 042002

ηπ spectroscopy

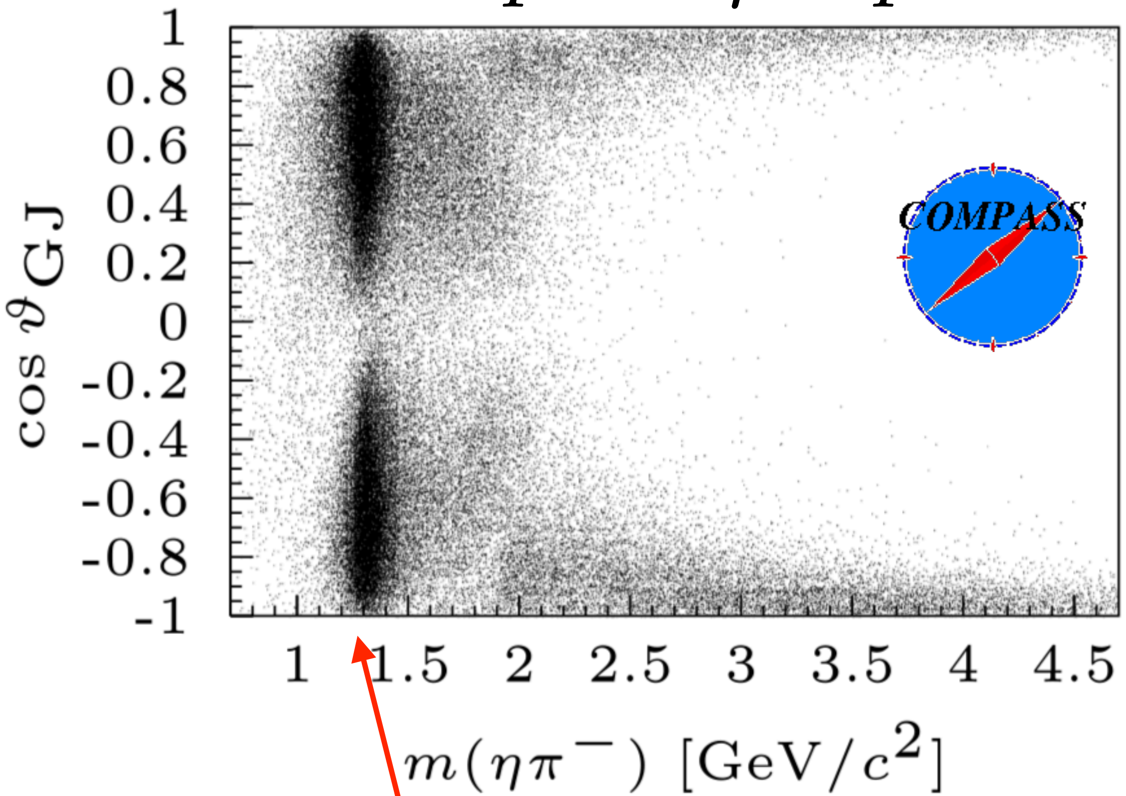






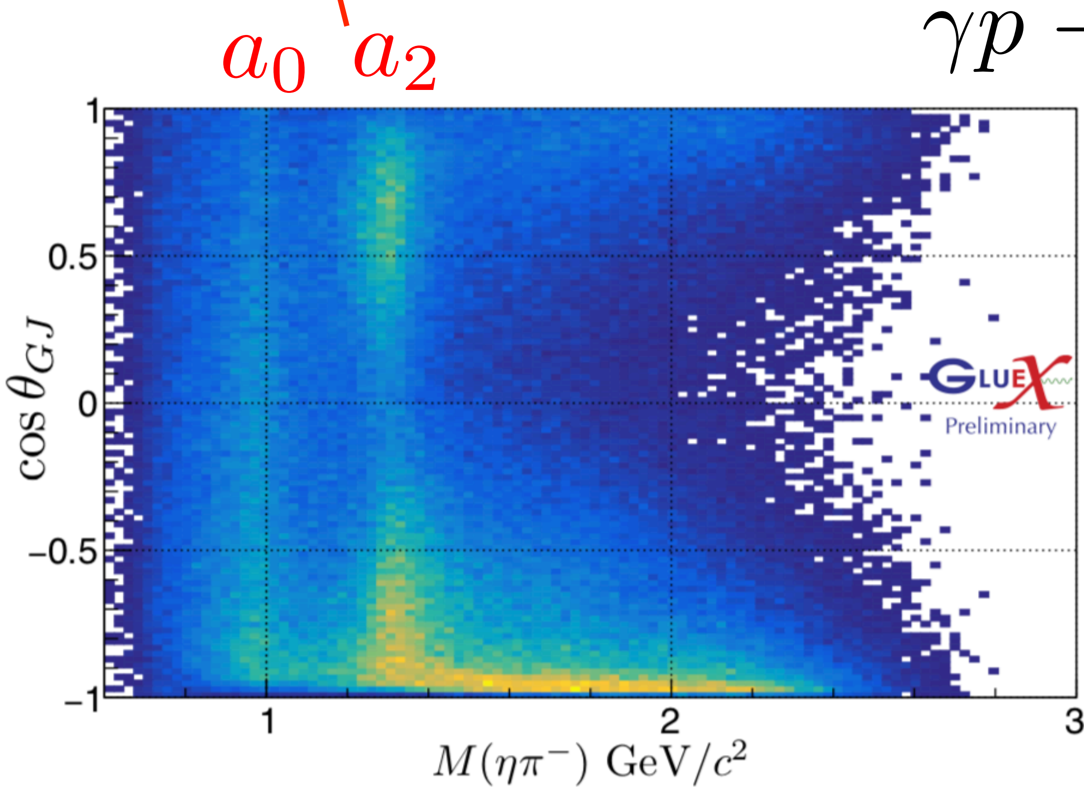
ηπ spectroscopy at GlueX

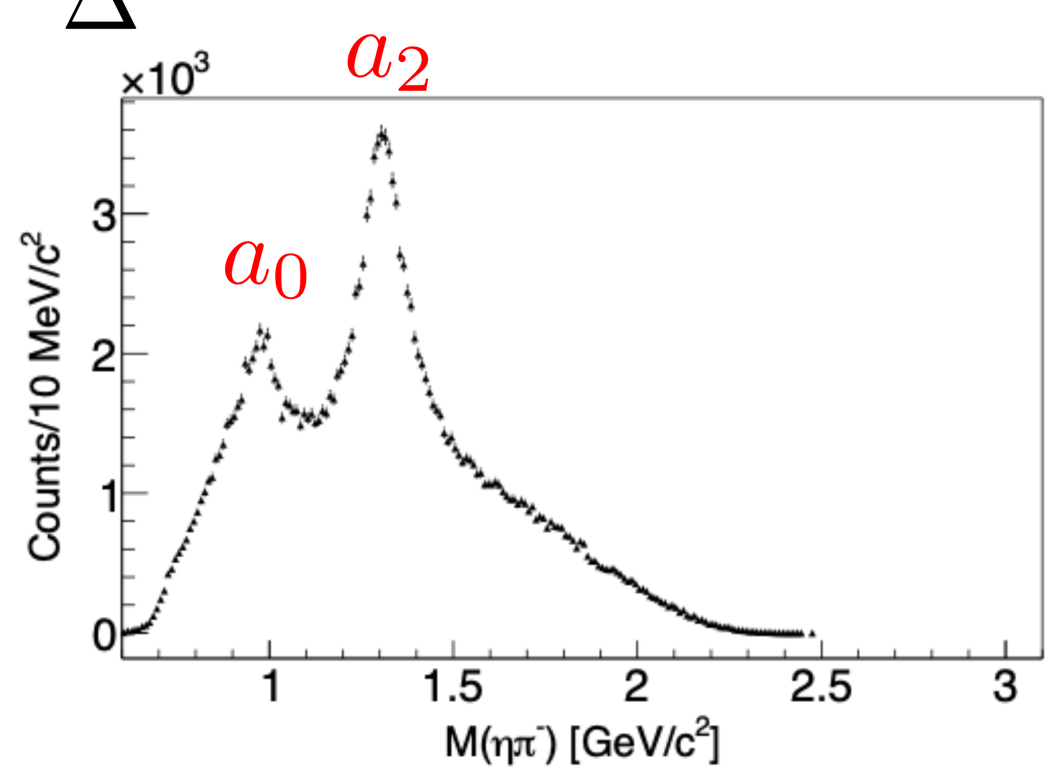
$\pi^- p \to \eta\pi^- p$



- Comparable statistical precision to Compass with single decay modes in **GlueX** dataset
- Different production mechanism and backgrounds to consider

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





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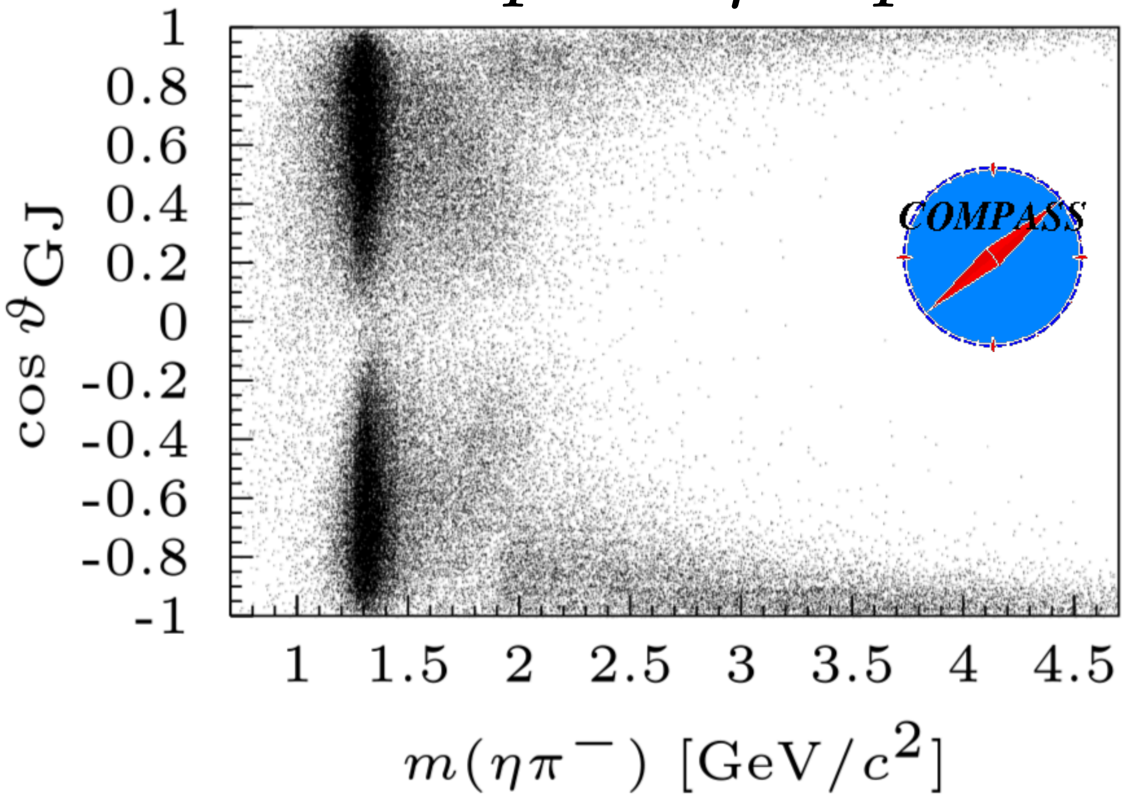

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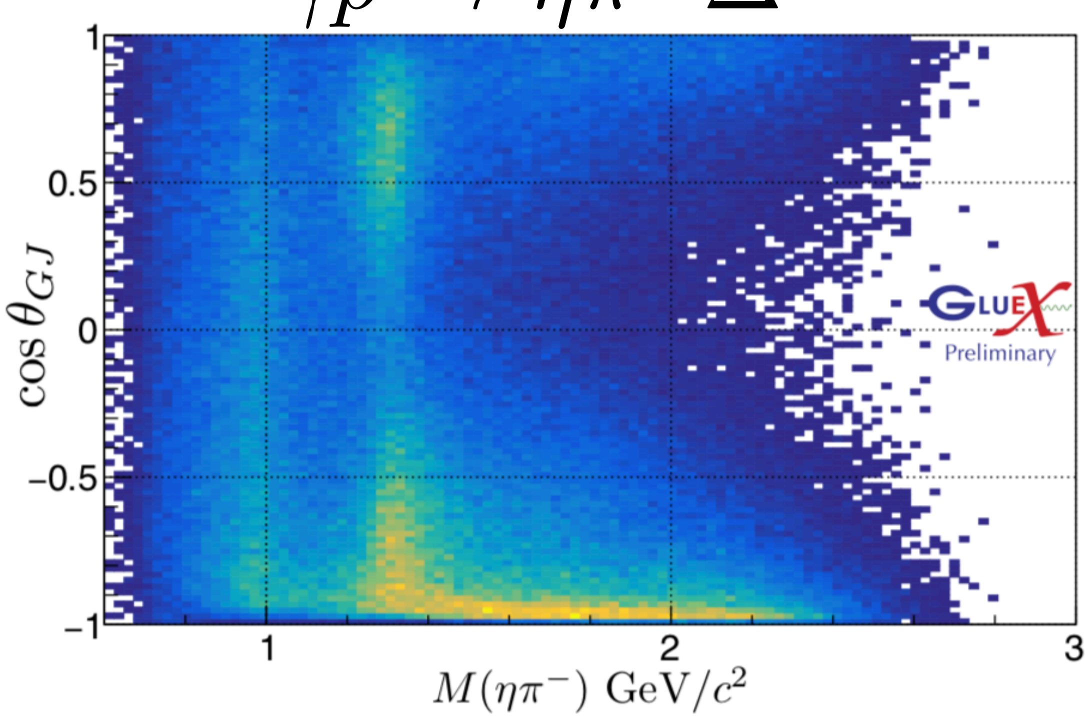
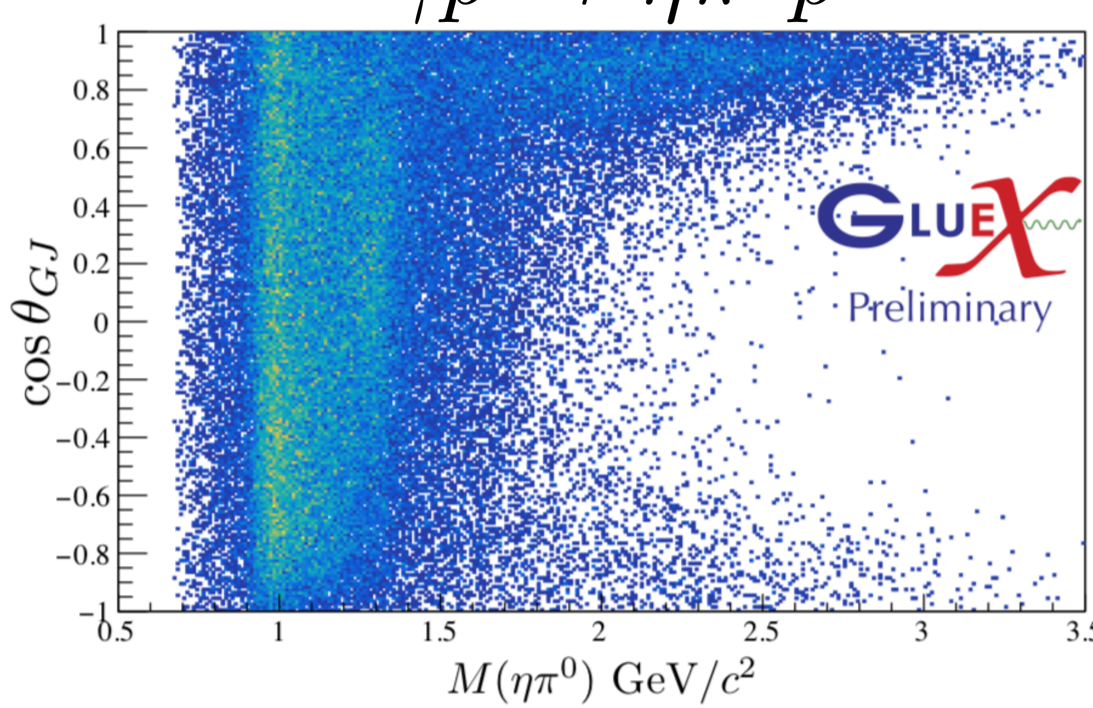
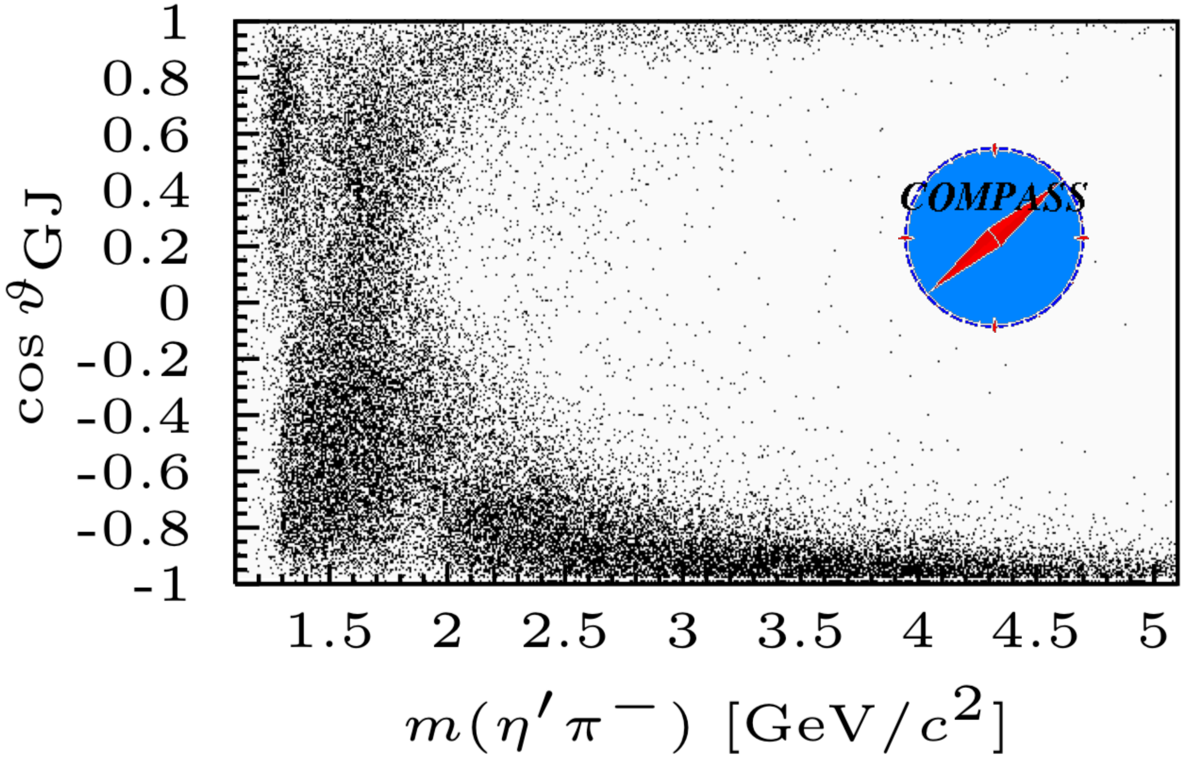


$\gamma p \to \eta\pi^0 p$

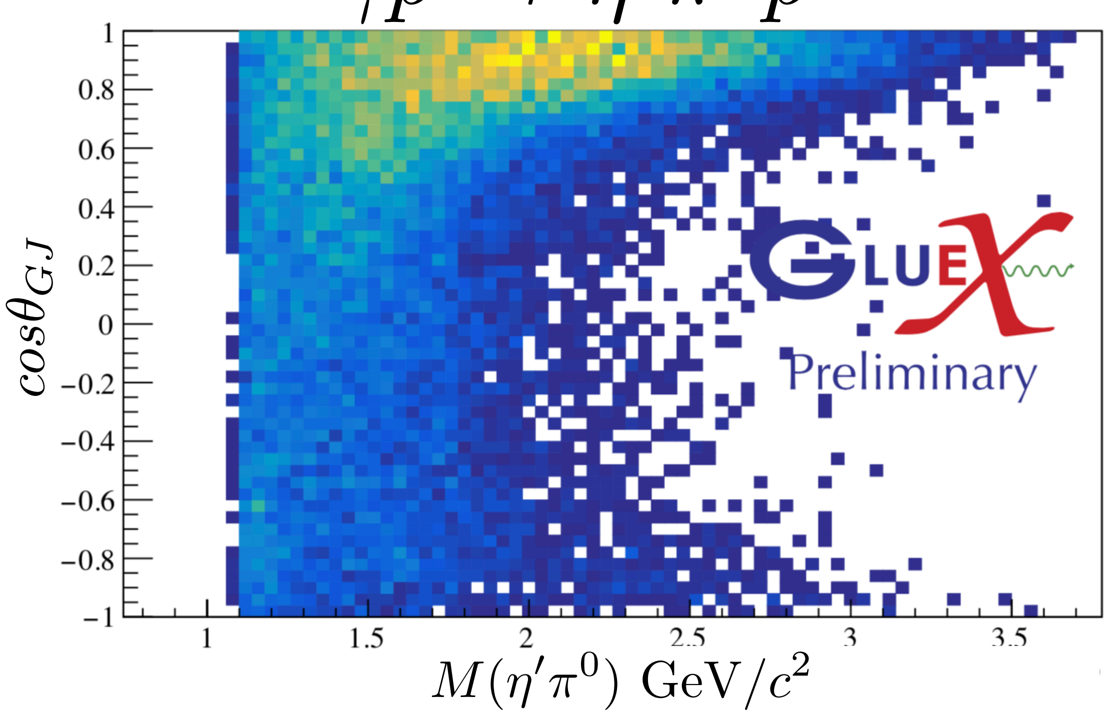


η’π spectroscopy at GlueX

$\pi^- p \to \eta' \pi^- p$



$\gamma p \to \eta' \pi^0 p$



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η'π spectroscopy at GlueX

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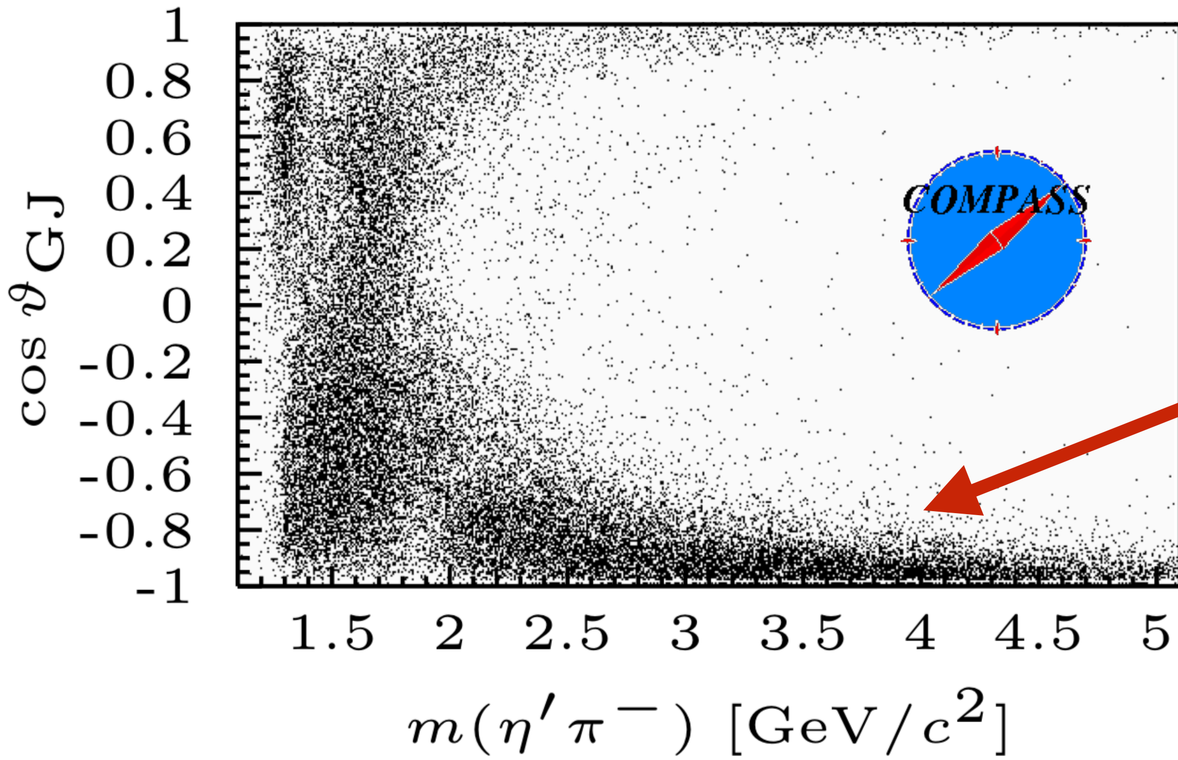
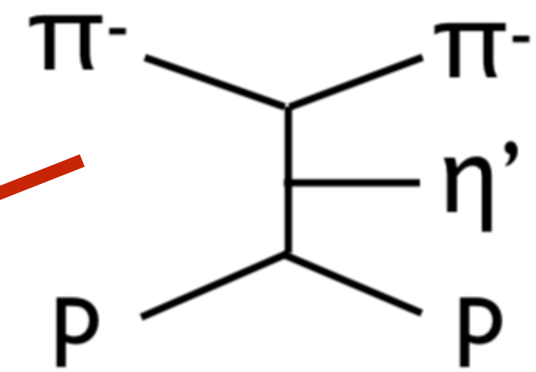
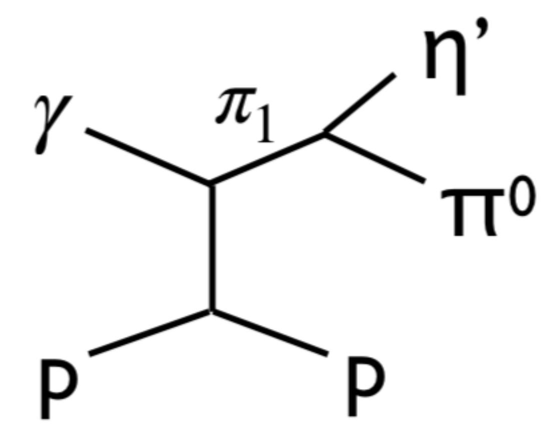


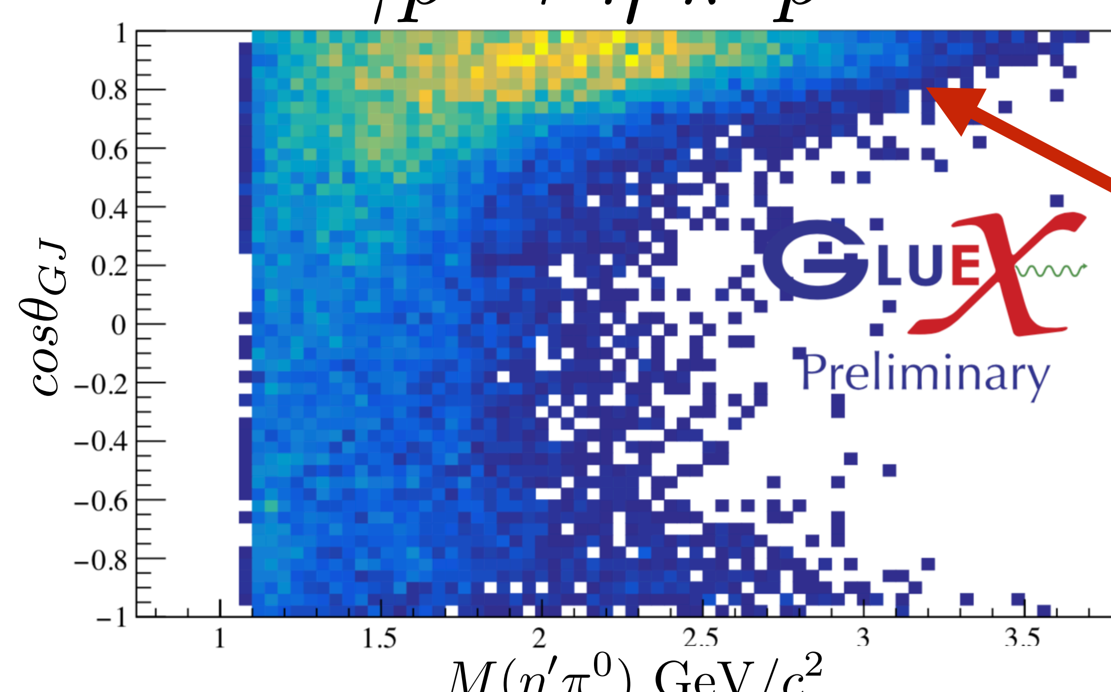
"Deck effect"



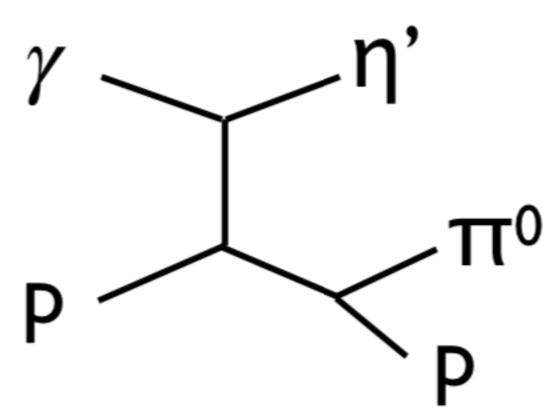
Exotic signal



$$\gamma p \to \eta' \pi^0 p$$



Baryon backgrounds

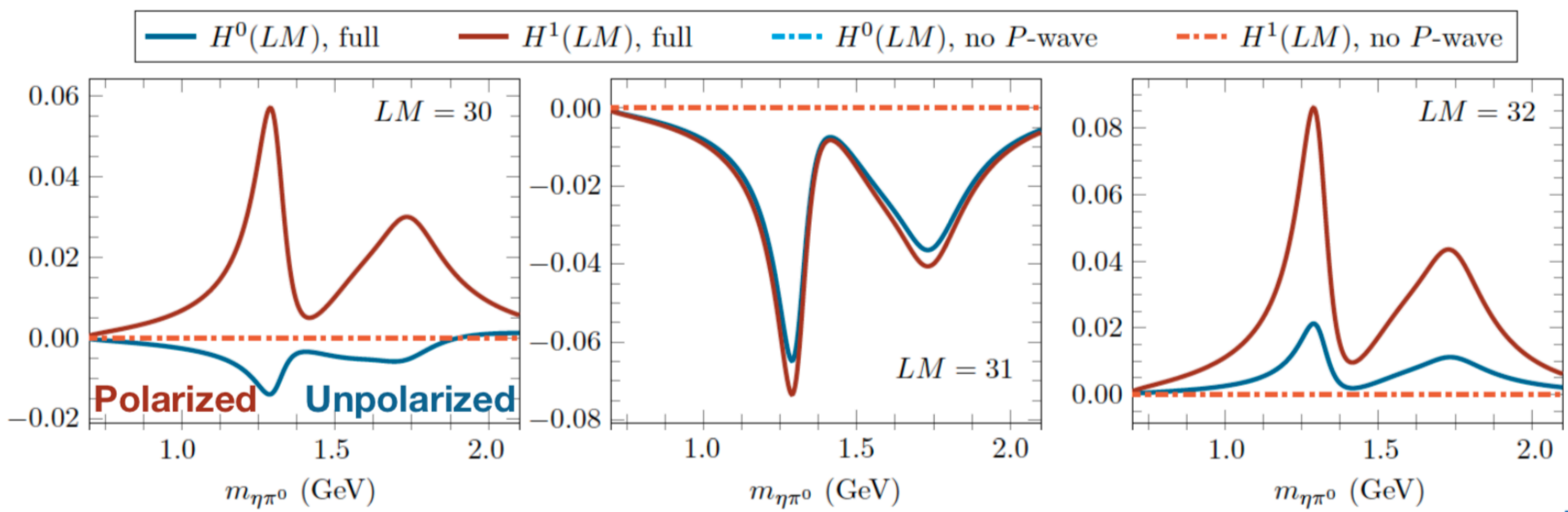


Polarization in ηπ spectroscopy

- Recent work by JPAC proposed "Moment Analysis" as model-independent approach

$$I(\Omega, \Phi) = I^0(\Omega) - P_\gamma I^1(\Omega) \cos 2\Phi - P_\gamma I^2(\Omega) \sin 2\Phi$$

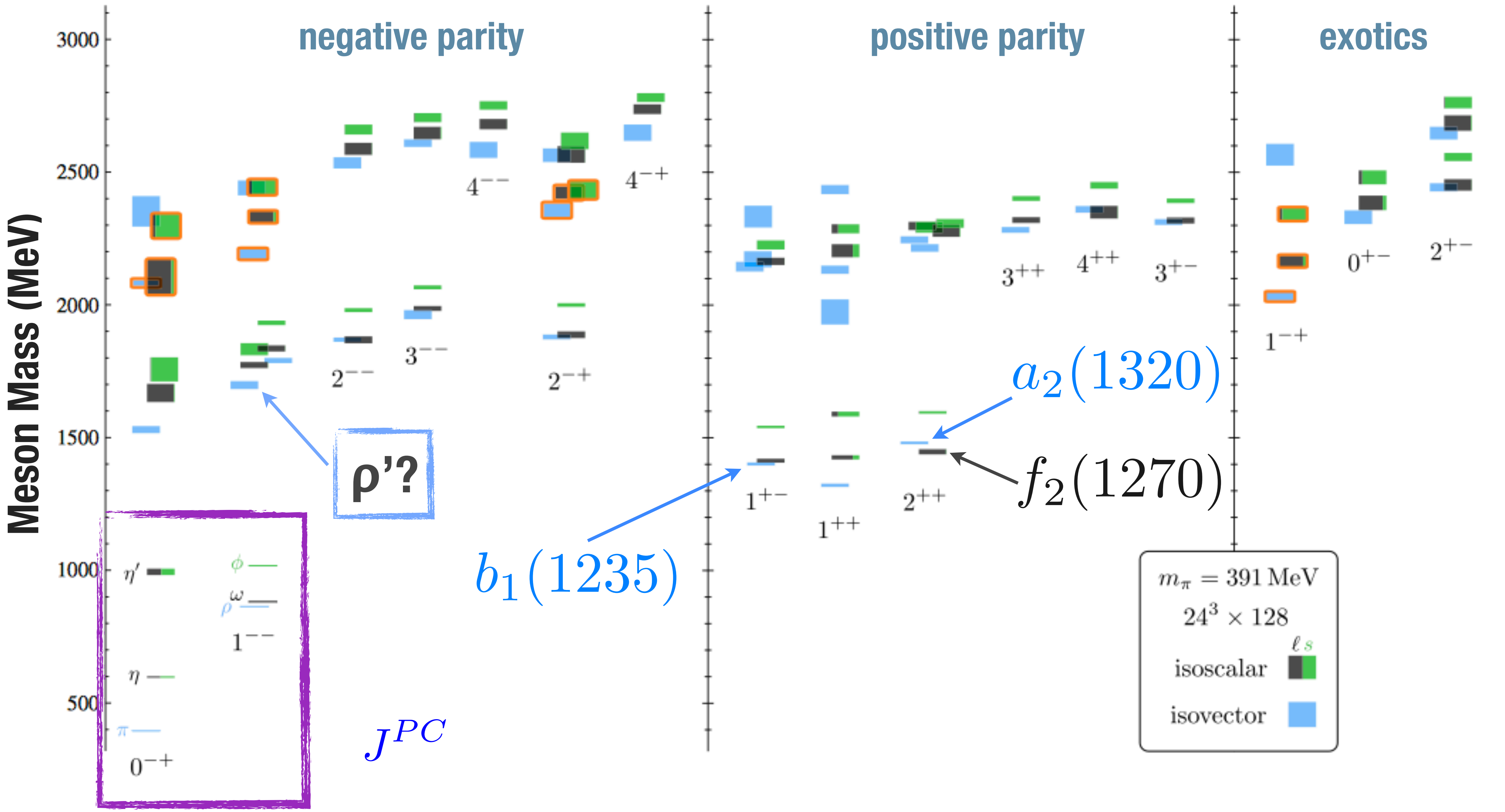
- Sensitivity to exotic *P-wave* through polarization



V. Mathieu *et al.* [JPAC], arXiv:1906.04841

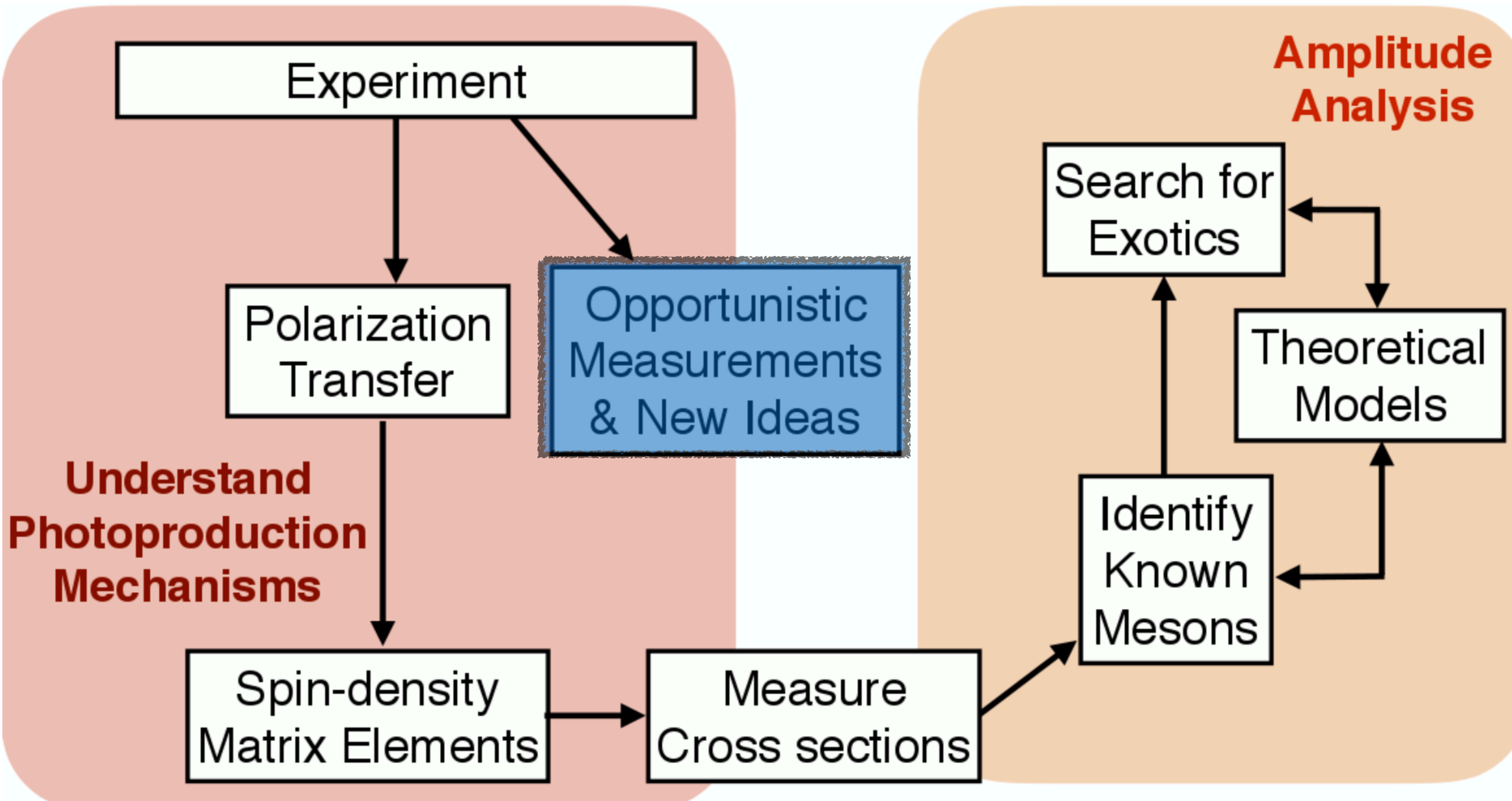
Mapping the meson spectrum

PRD 88 (2013) 094505

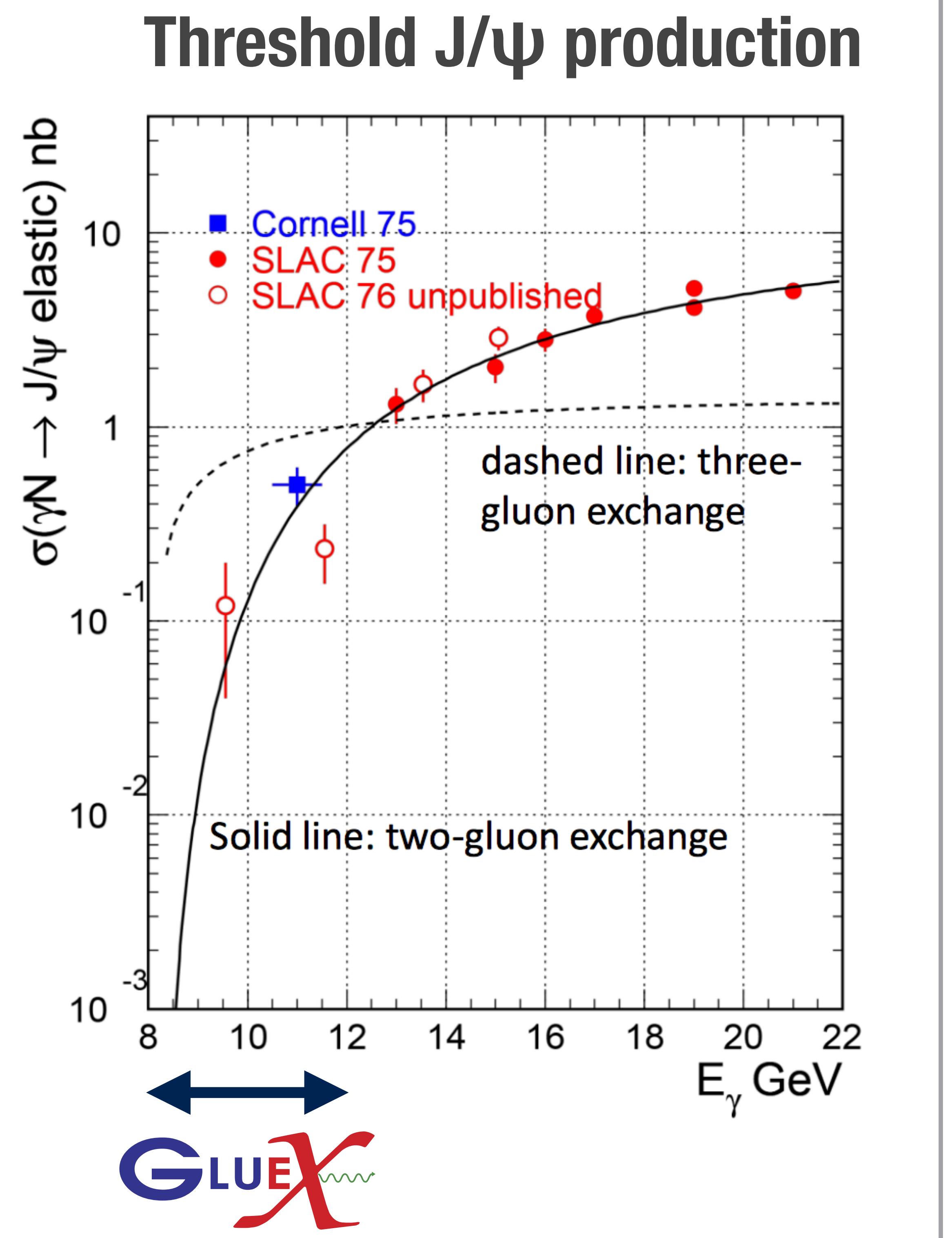


- Already studying polarization observables for **"simple" final states**
- Beginning to identify **known mesons** in multi-particle final states

GlueX Physics Program



Charmonium at JLab



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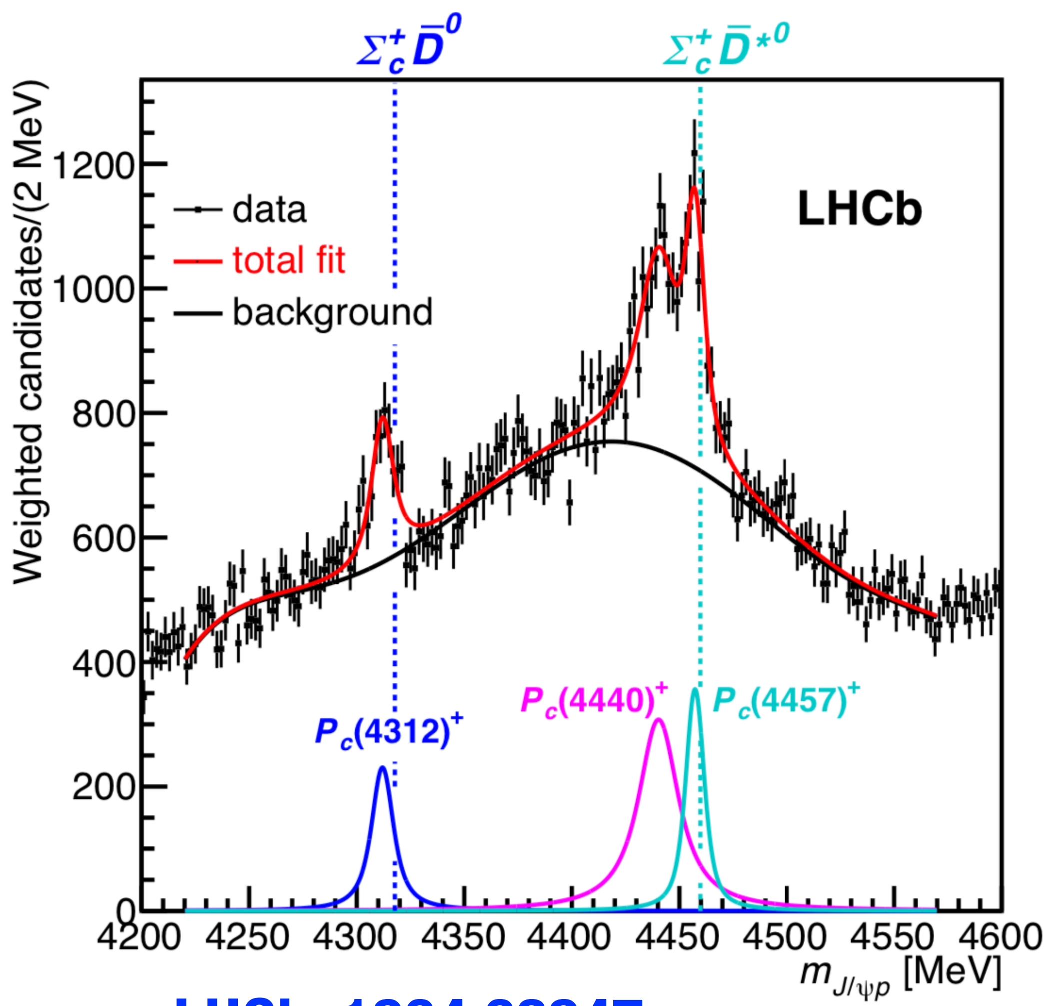
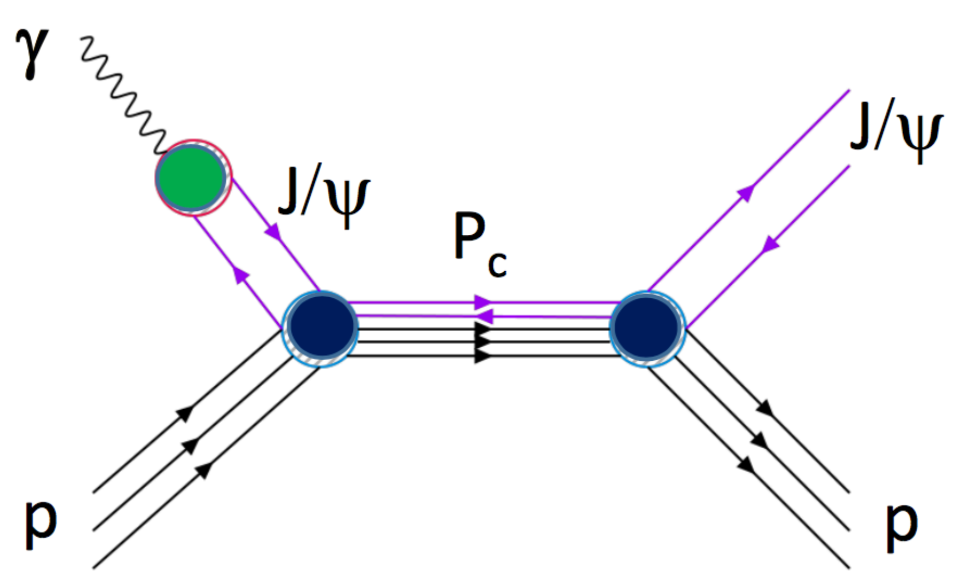
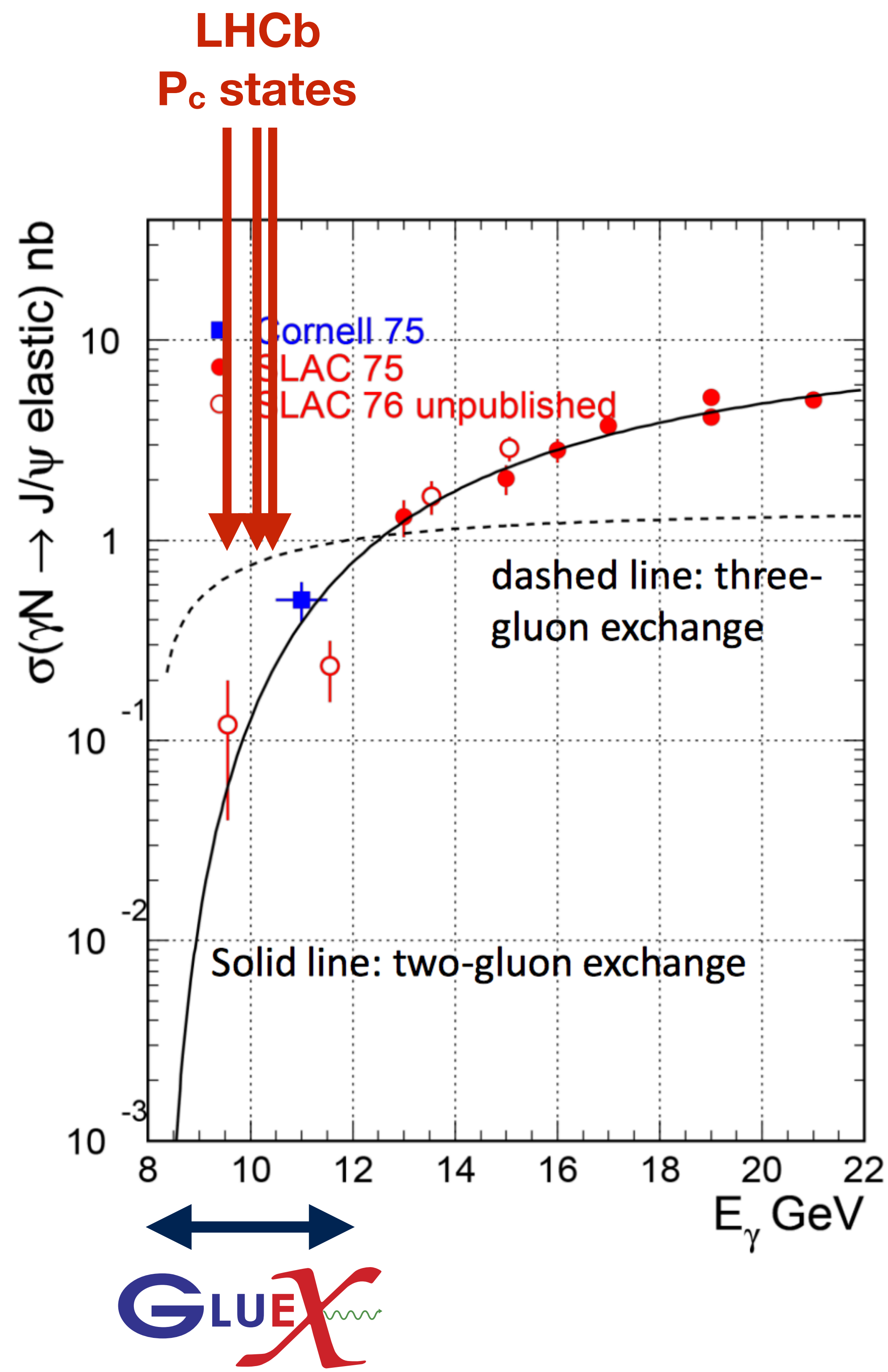


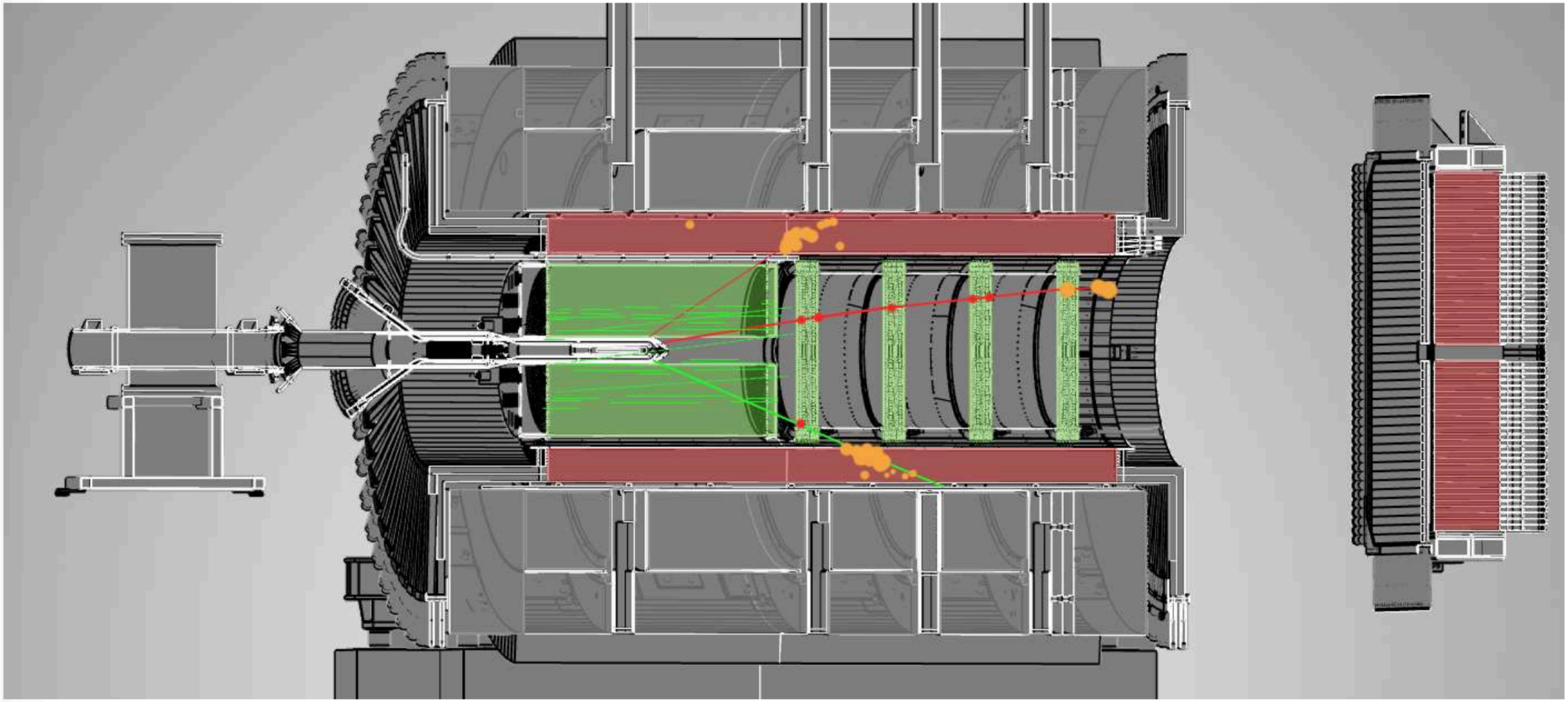
LHCb: 1904.03947





J/ψ photoproduction at GlueX

$$\gamma p \to p e^+ e^-$$



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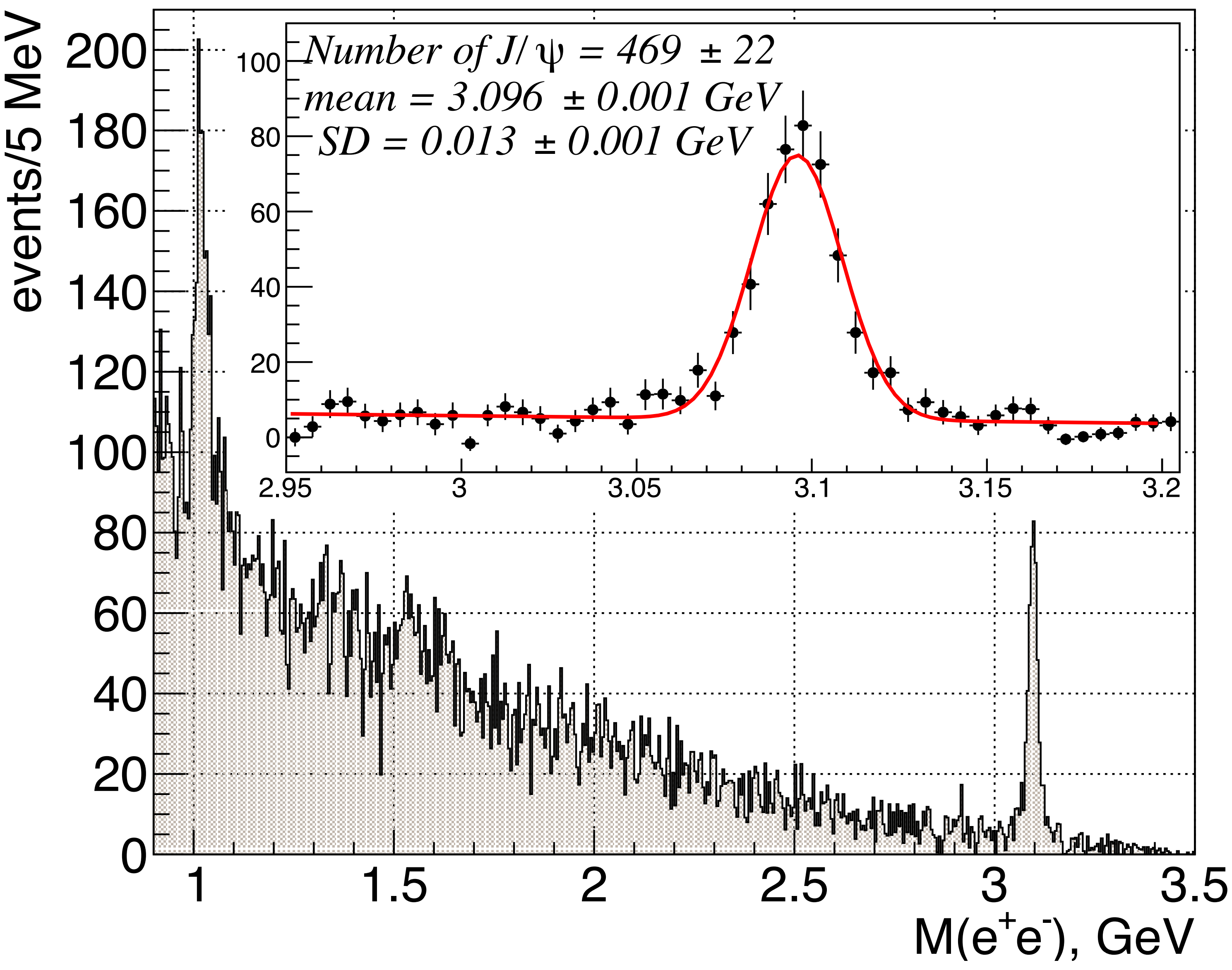
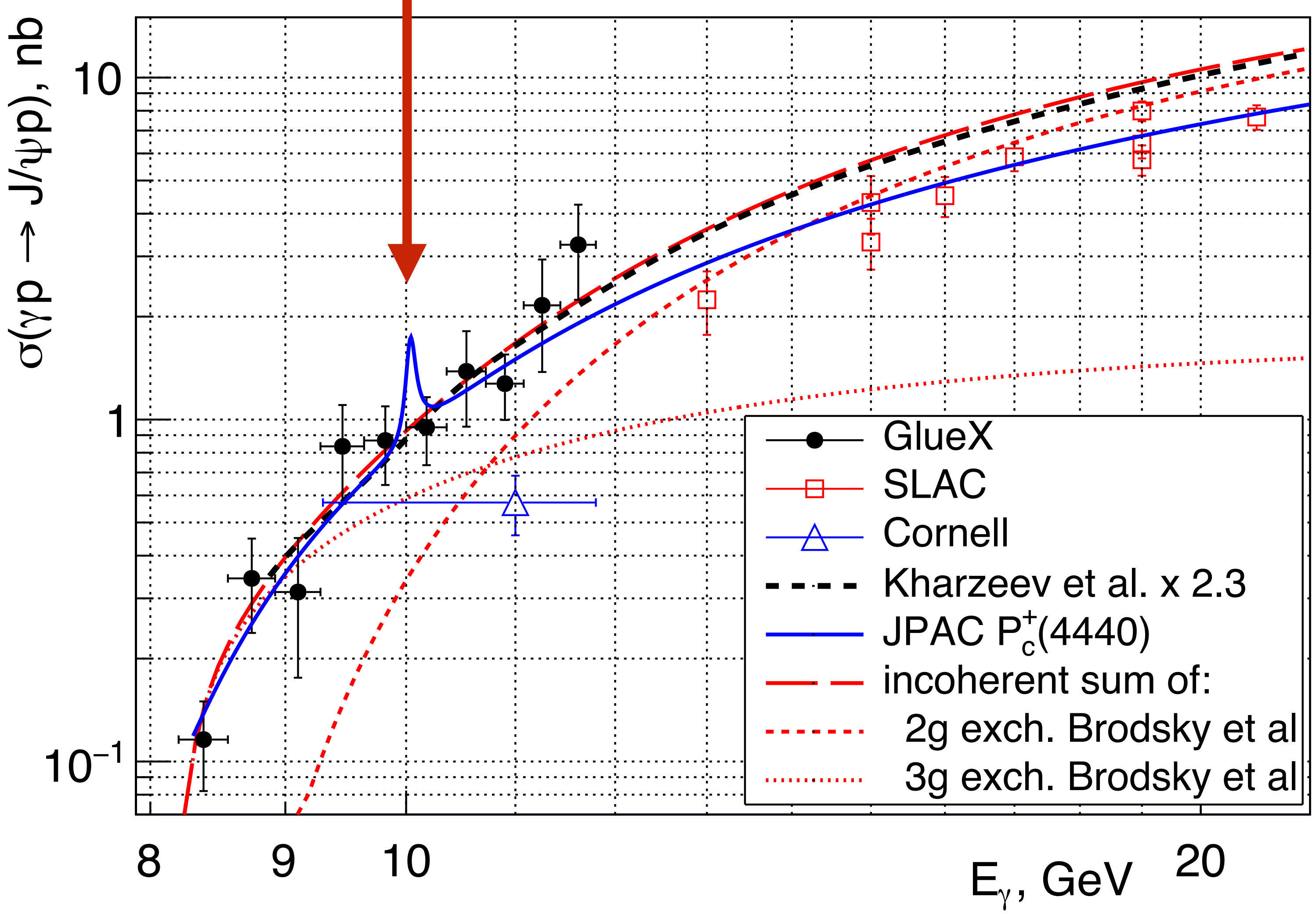


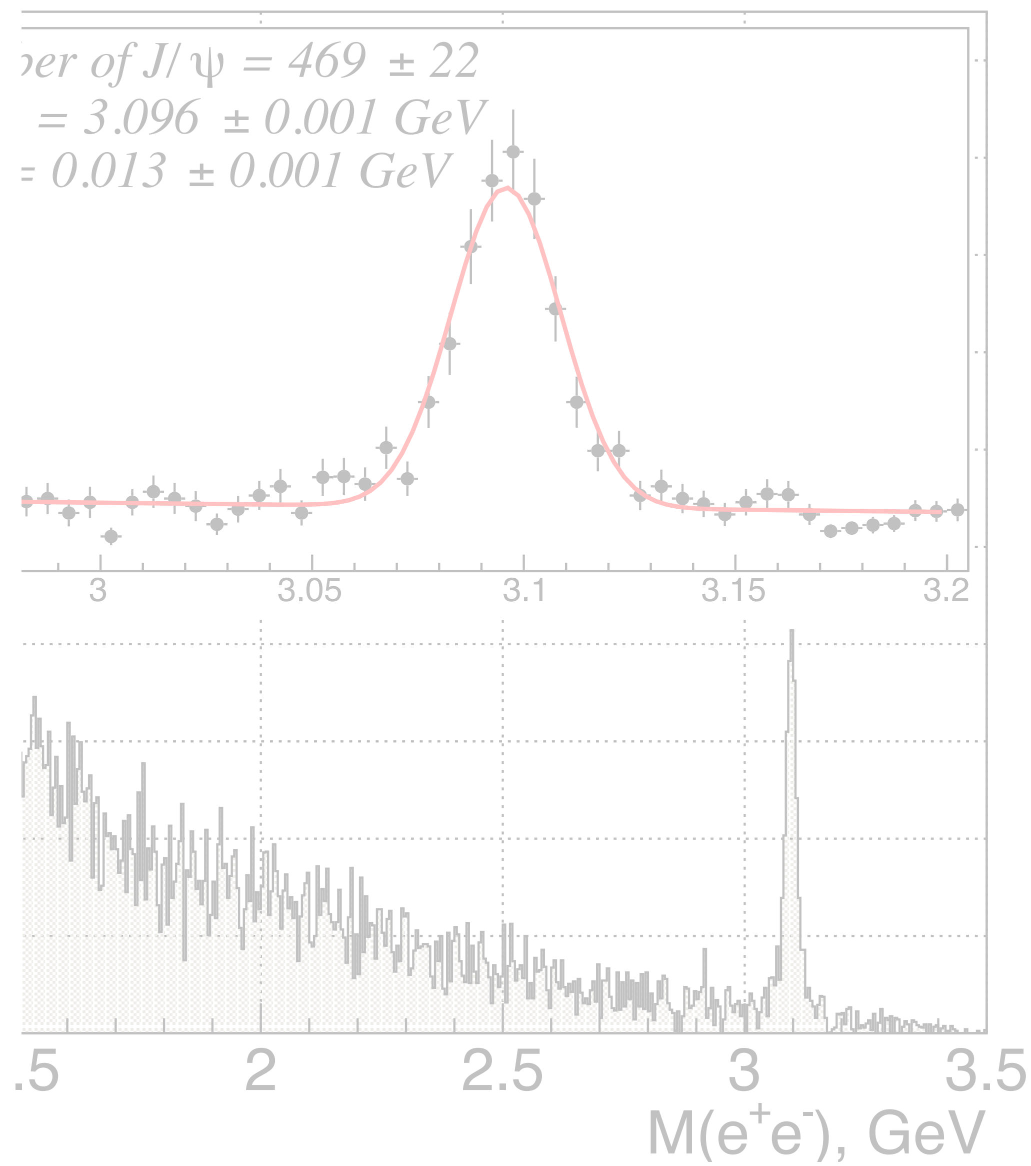
J/ψ photoproduction at GlueX

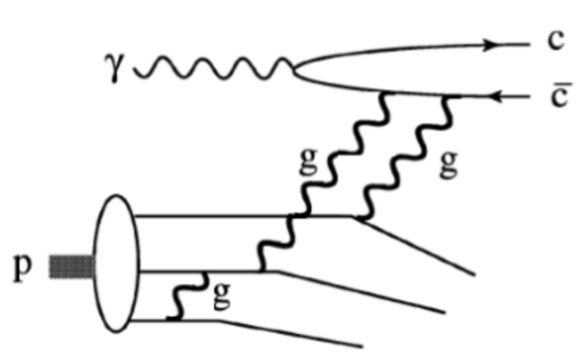
LHCb $P_c(4440)$

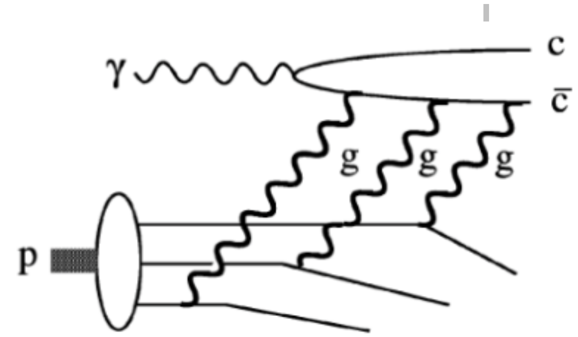
PRL 123, 072001 (2019)
Editor's Suggestion!

$$\gamma p \to p e^+ e^-$$









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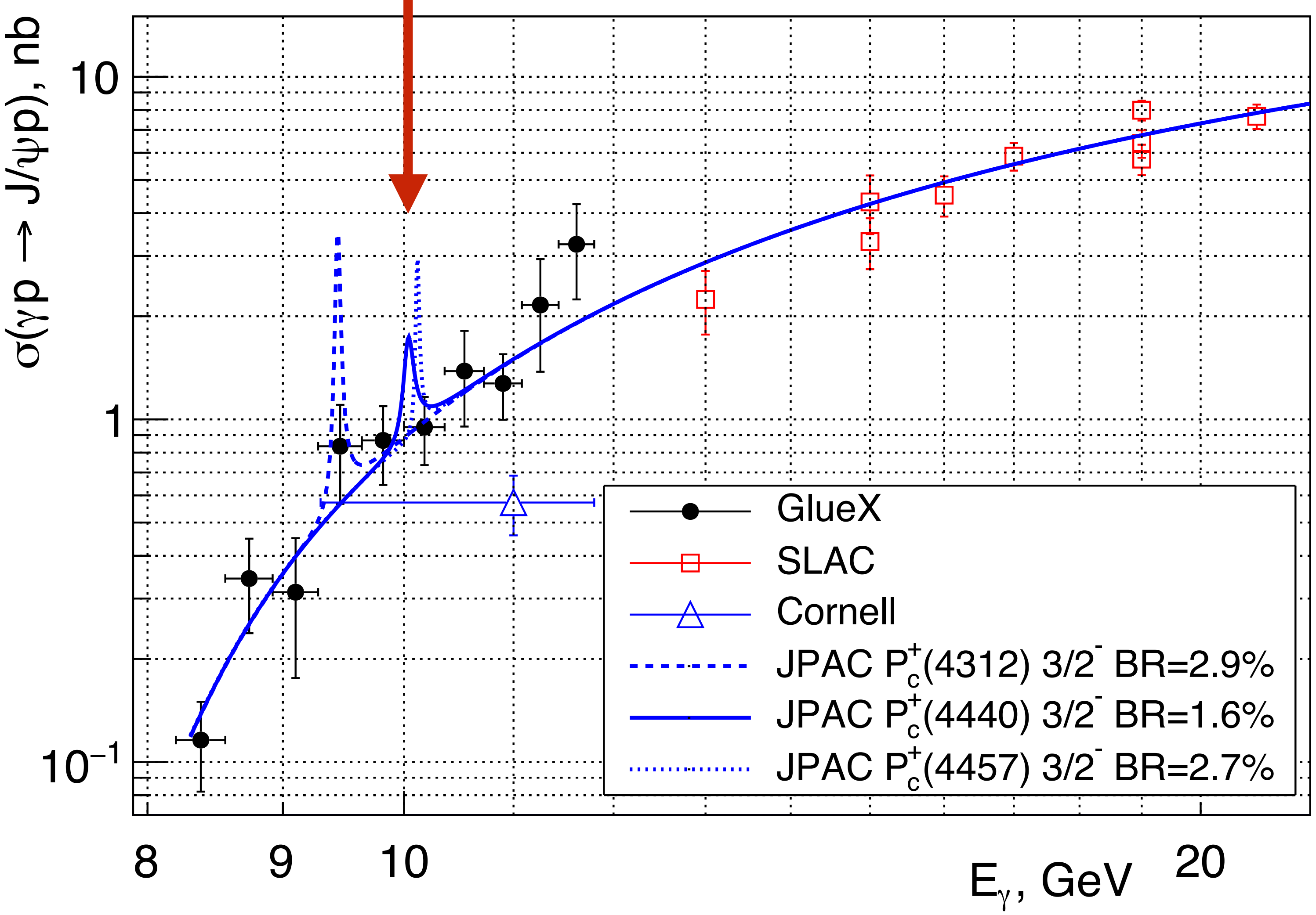
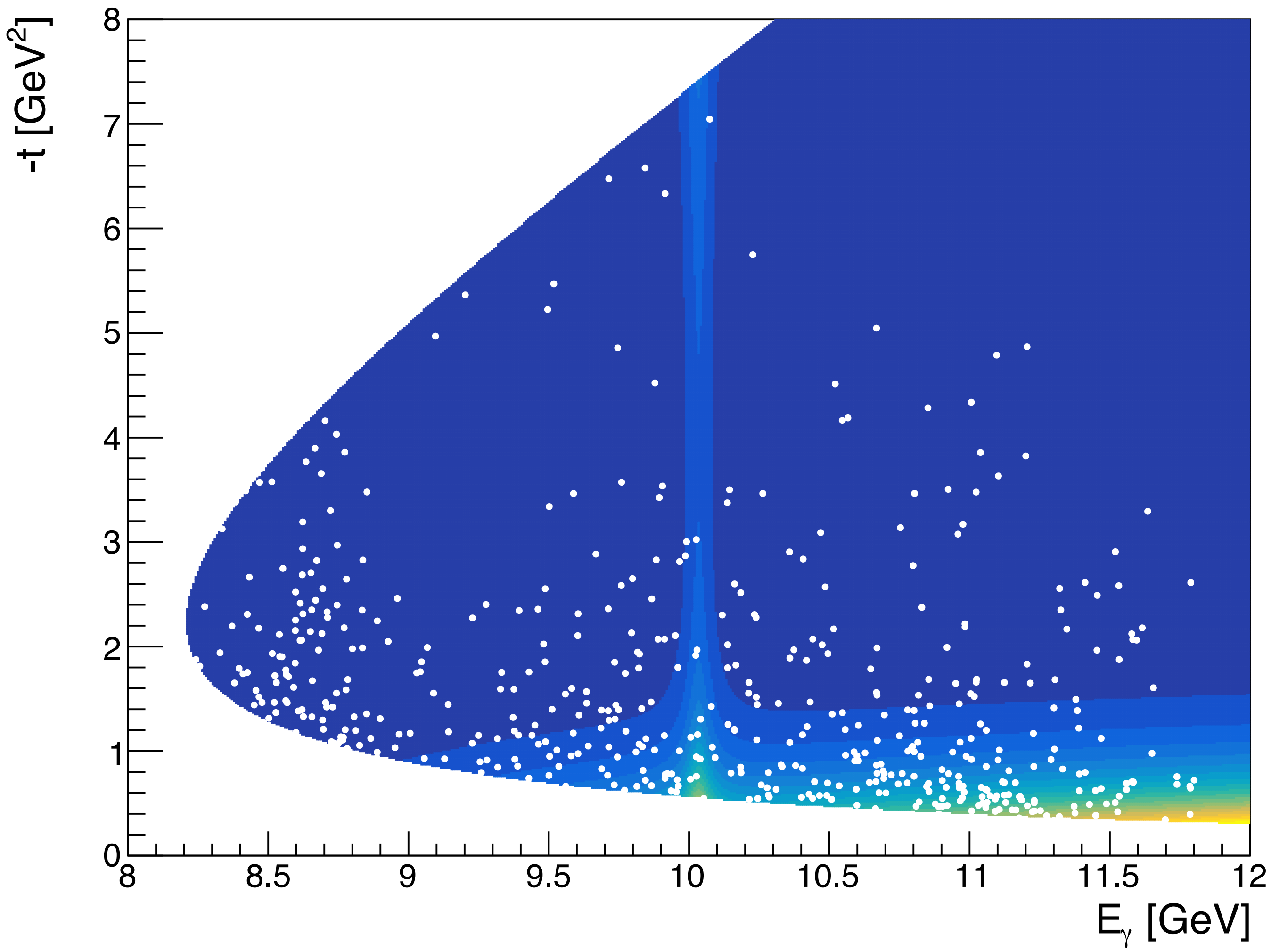


- No evidence of Pc states!
- Model-dependent upper limits at 90% CL (assuming $J^P=3/2^-$):
  - Br($P_c(4312)$ → J/ψ p) **< 4.6%**
  - Br($P_c(4440)$ → J/ψ p) **< 2.3%**
  - Br($P_c(4457)$ → J/ψ p) **< 3.8%**
    [ULs scale as (2J+1)]
- Disfavors hadrocharmonium and some molecular models. Pc's could preferentially couple to other channels?
  - Need consistent picture with Λ_b decays

JPAC model: PRD 94, 034002 (2016)

What's next for J/ψ photoproduction

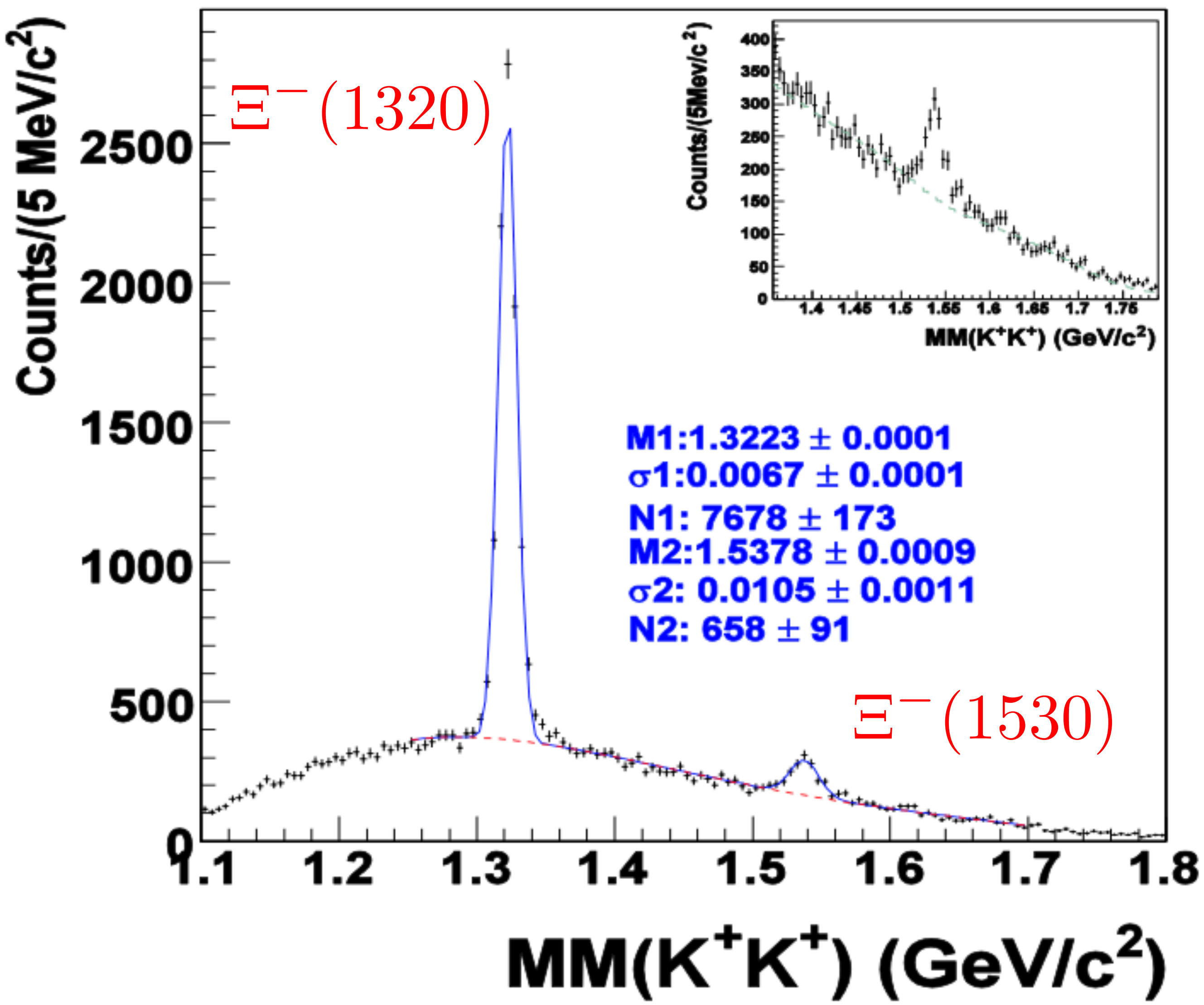


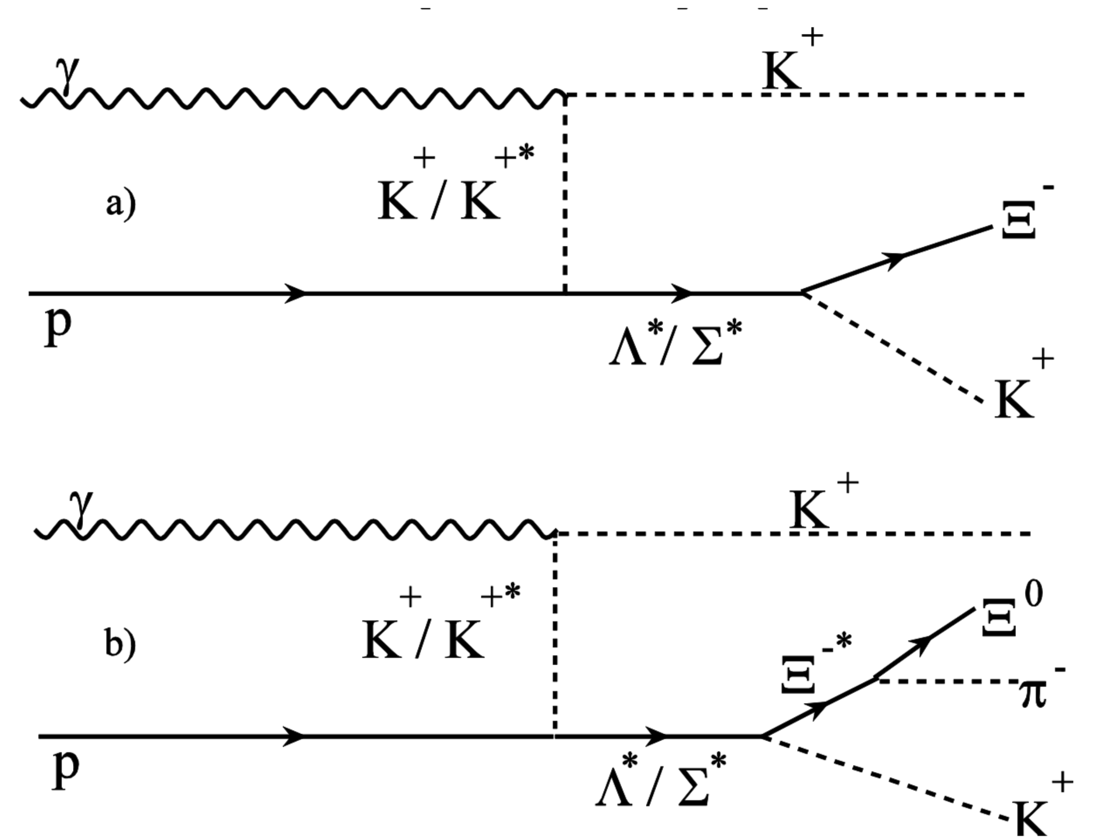
- GlueX "Low intensity" Phase-I program completed in 2018
  - Expect > 1500 J/ψ on tape
  - Fully utilize beam energy resolution with unbinned fit in E_γ and *-t*
- "High intensity" program to begin in Fall 2019

- Points: GlueX data in J/ψ mass region
- JPAC model: 5% $P_c(4440)$, $J^P = 3/2^-$

Hyperon Spectroscopy: $\Xi^-(dss)$

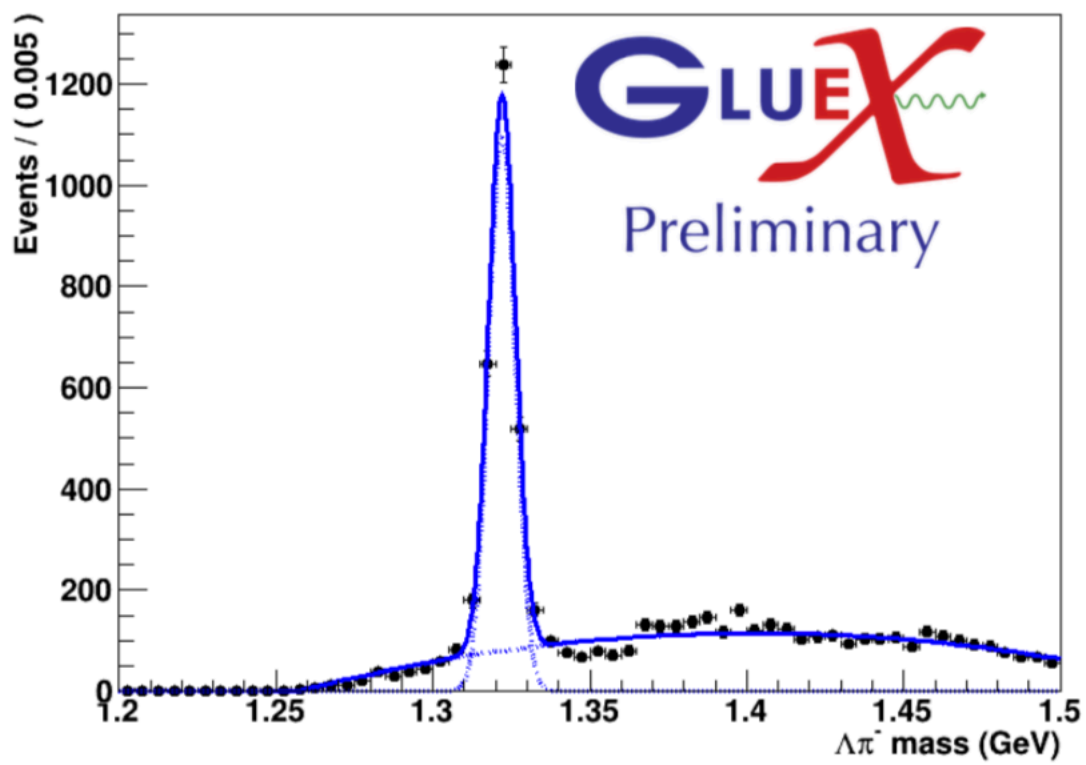
CLAS 6 GeV



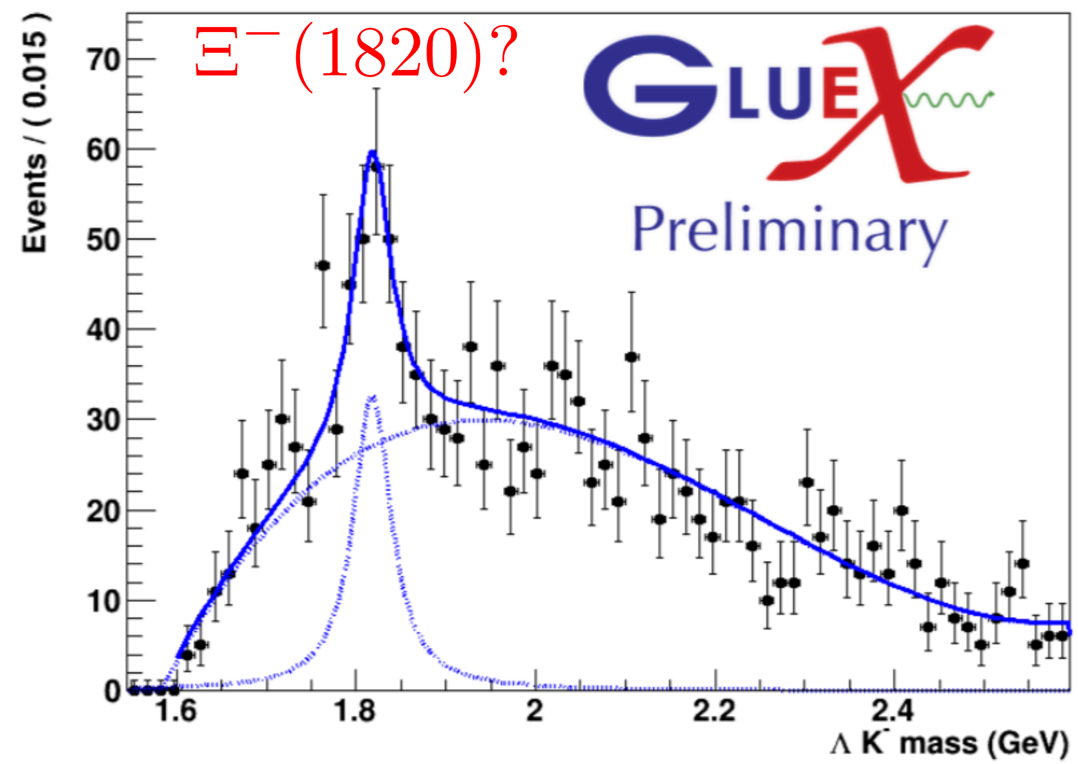


Hyperon Spectroscopy: $\Xi^-(dss)$

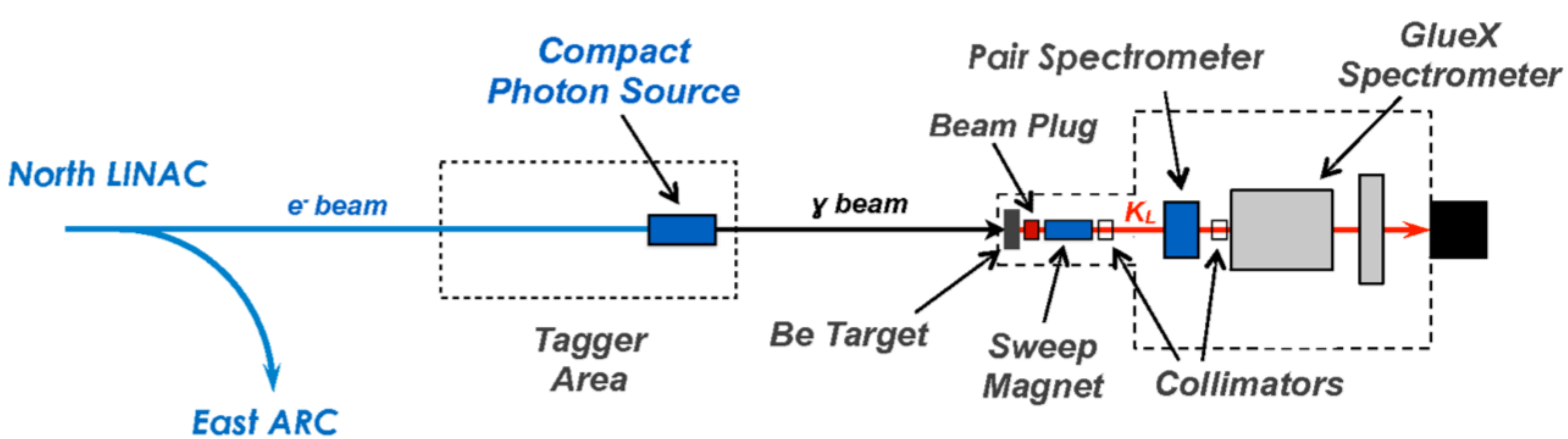
$\gamma p \to K^+ K^+ \Lambda \pi^-$



$\gamma p \to K^+ K^+ \Lambda K^-$



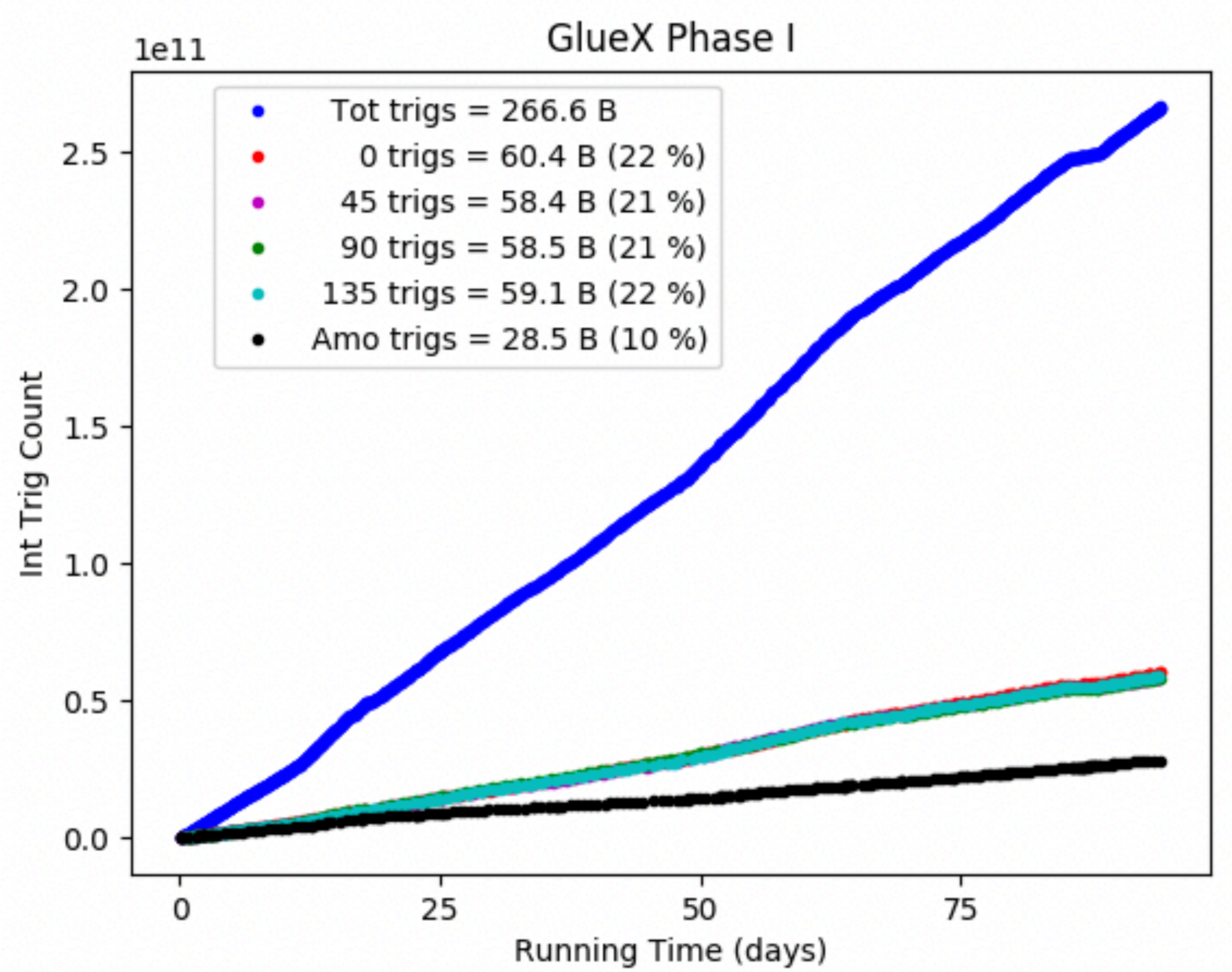
- **Longer term:** K_L beam ([PAC proposal]) cond. approved



GlueX Timeline

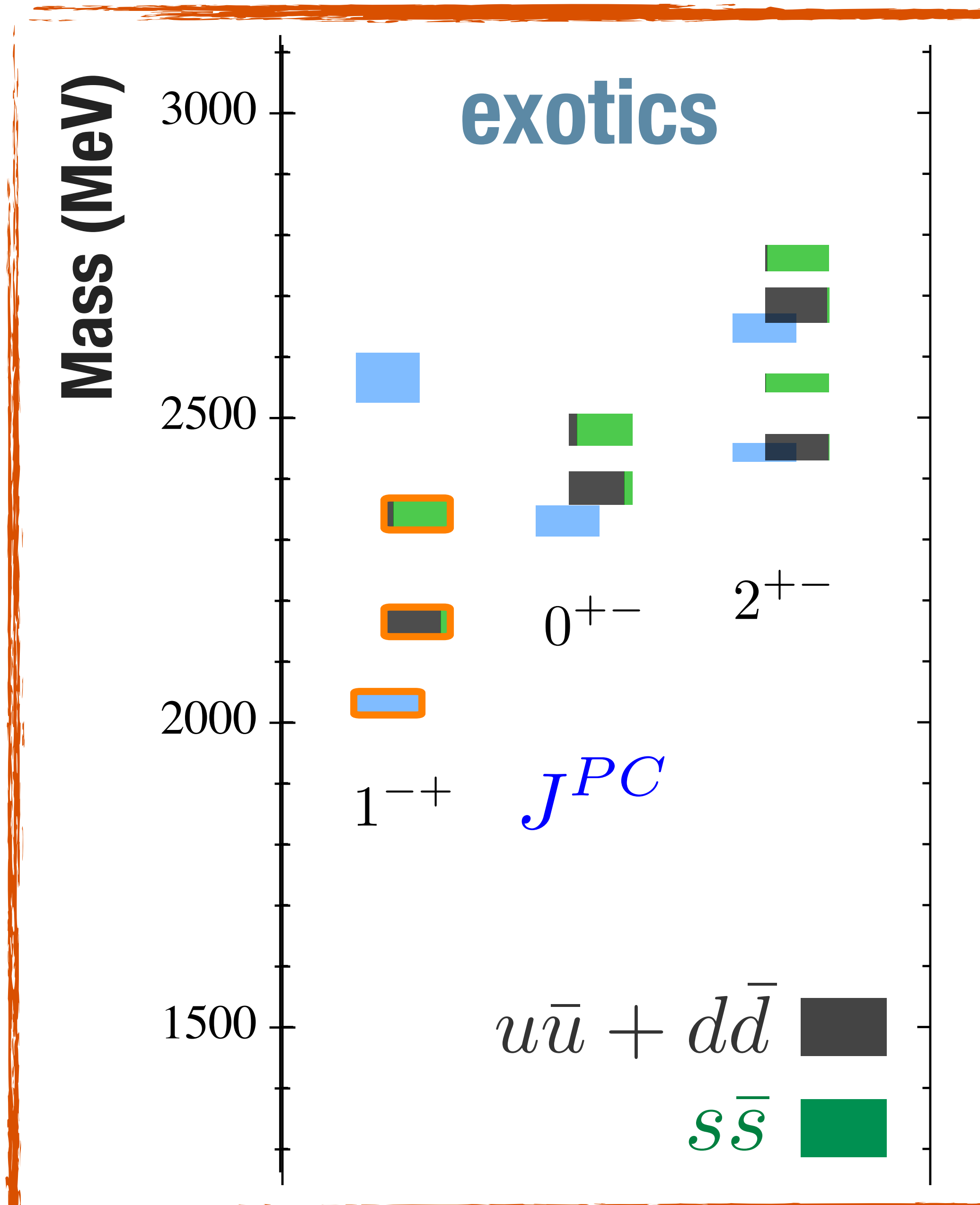
- GlueX “Low intensity” Phase-I program completed in 2018
  - Results presented here represent 21 pb^{-1} of polarized luminosity
  - Full statistics currently under analysis will add an additional 90 pb^{-1}
  - Identifying known mesons and begin exotic searches
- “High intensity” program to begin in Fall 2019

Phase-I dataset: 2016-2018
250 B events and ~8 PB of data



GlueX future

- Lattice predicts **strange** and **light** quark content for mesons
- Search for a **pattern** of hybrid states in many final states
- Requires clean identification of charged pions and kaons



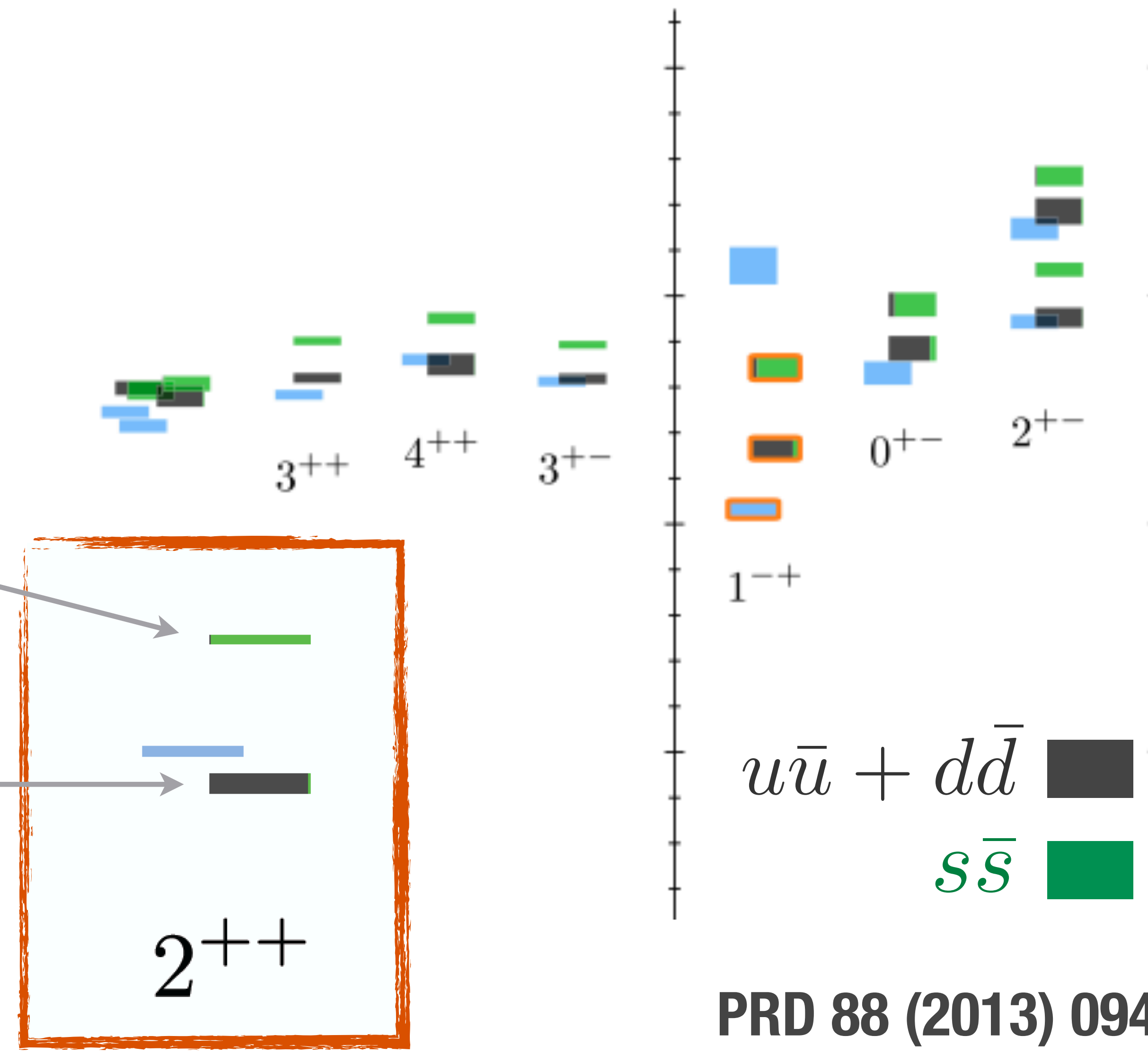
	Approximate Mass (MeV)	J^{PC}	Final States
π_1	1900	1^{-+}	$\omega\pi\pi^\dagger$, $3\pi^\dagger$, 5π, $\eta 3\pi^\dagger$, $\eta'\pi^\dagger$
η_1	2100	1^{-+}	4π, $\eta 4\pi$, $\eta\eta\pi\pi^\dagger$
η'_1	2300	1^{-+}	$KK\pi\pi^\dagger$, $KK\pi^\dagger$, $KK\omega^\dagger$

Strangeness program: decay patterns

- Experimentally infer quark flavor composition through branching ratios to strange and non-strange decays

$$\frac{\mathcal{B}(f_2'(1525) \to \pi\pi)}{\mathcal{B}(f_2'(1525) \to KK)} \approx 0.009$$

$$\frac{\mathcal{B}(f_2(1270) \to \pi\pi)}{\mathcal{B}(f_2(1270) \to KK)} \approx 20$$

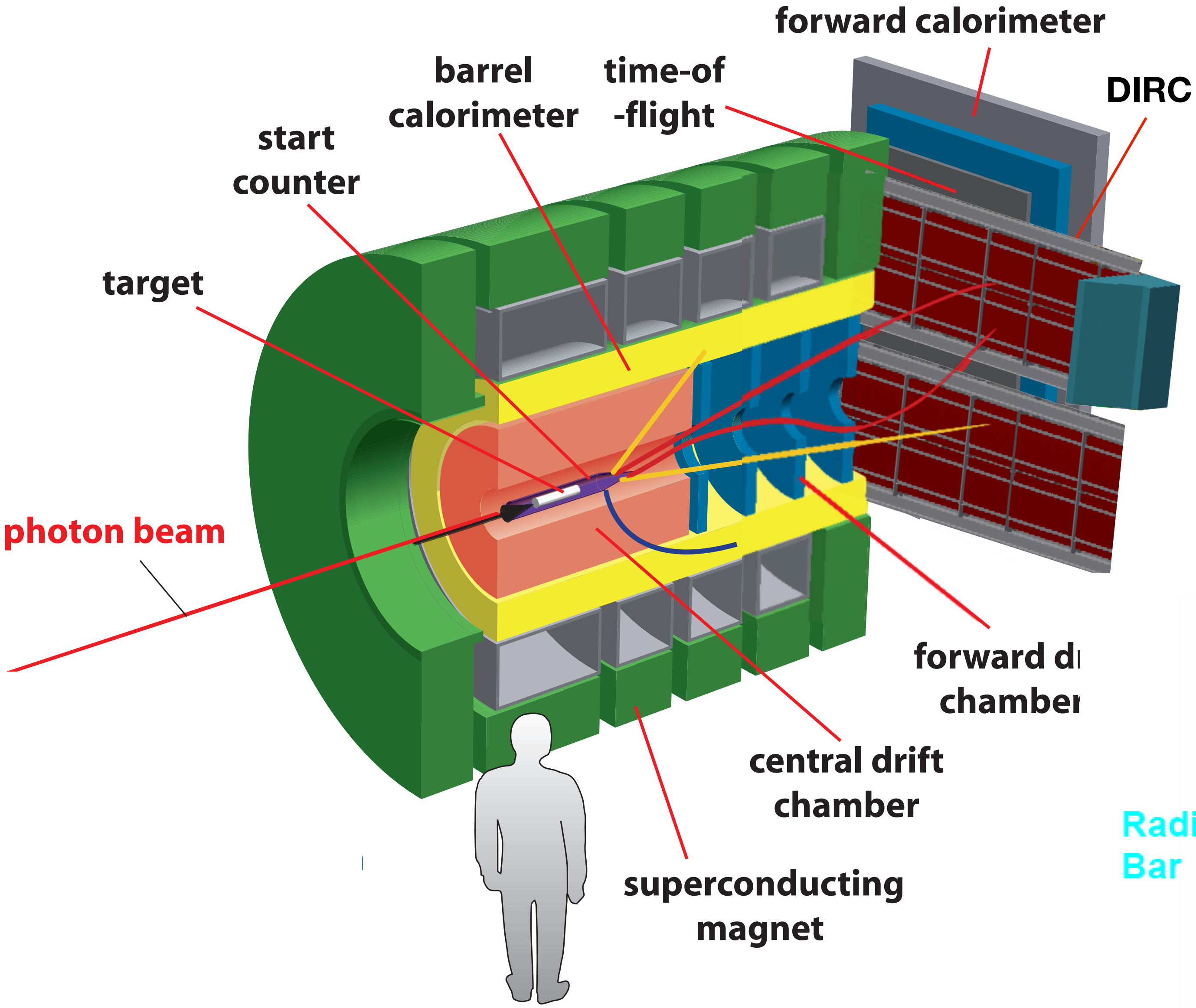


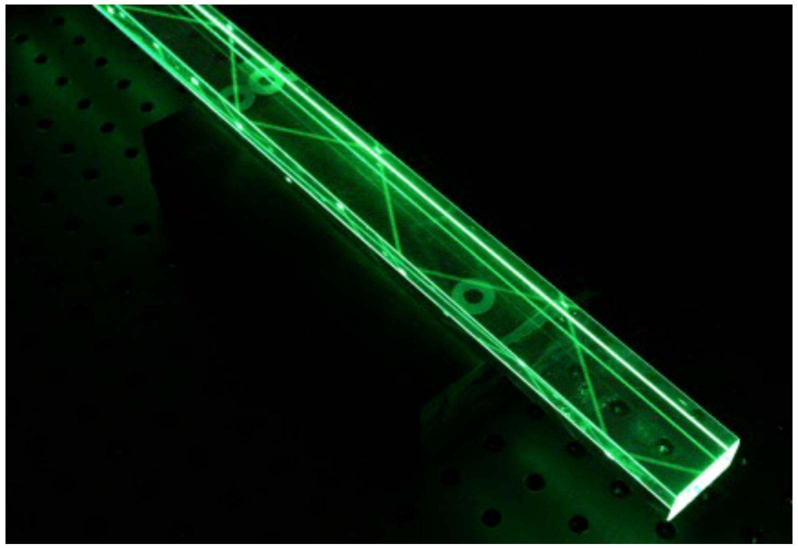
PRD 88 (2013) 094505

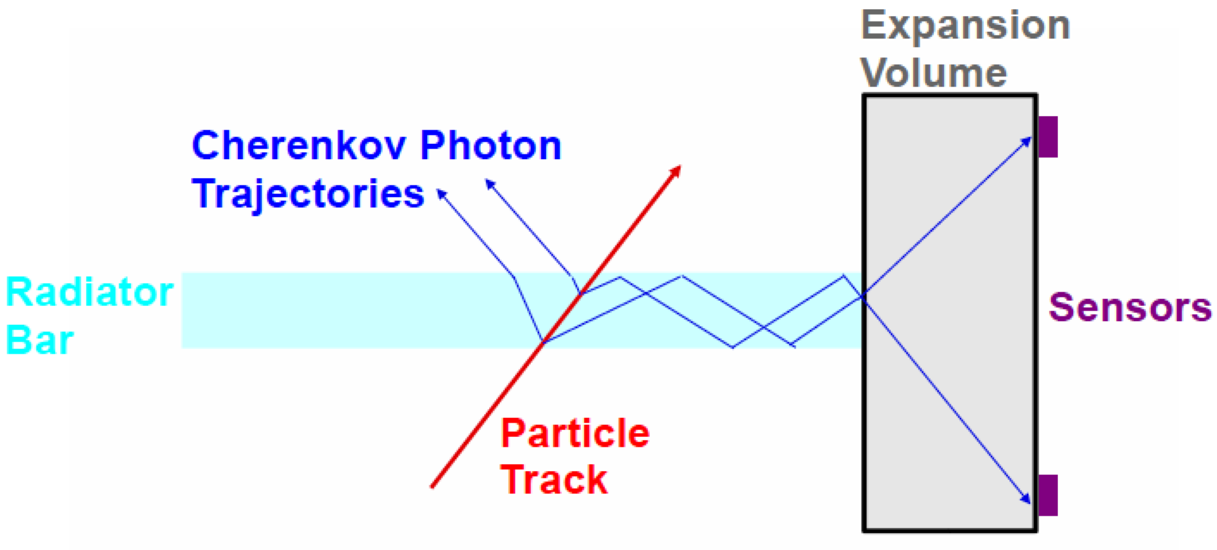
- Consistent with lattice QCD mixing angle for 2^{++}, and predictions for hybrids

- Need capability to detect strange and non-strange to infer hybrid flavor content

DIRC upgrade

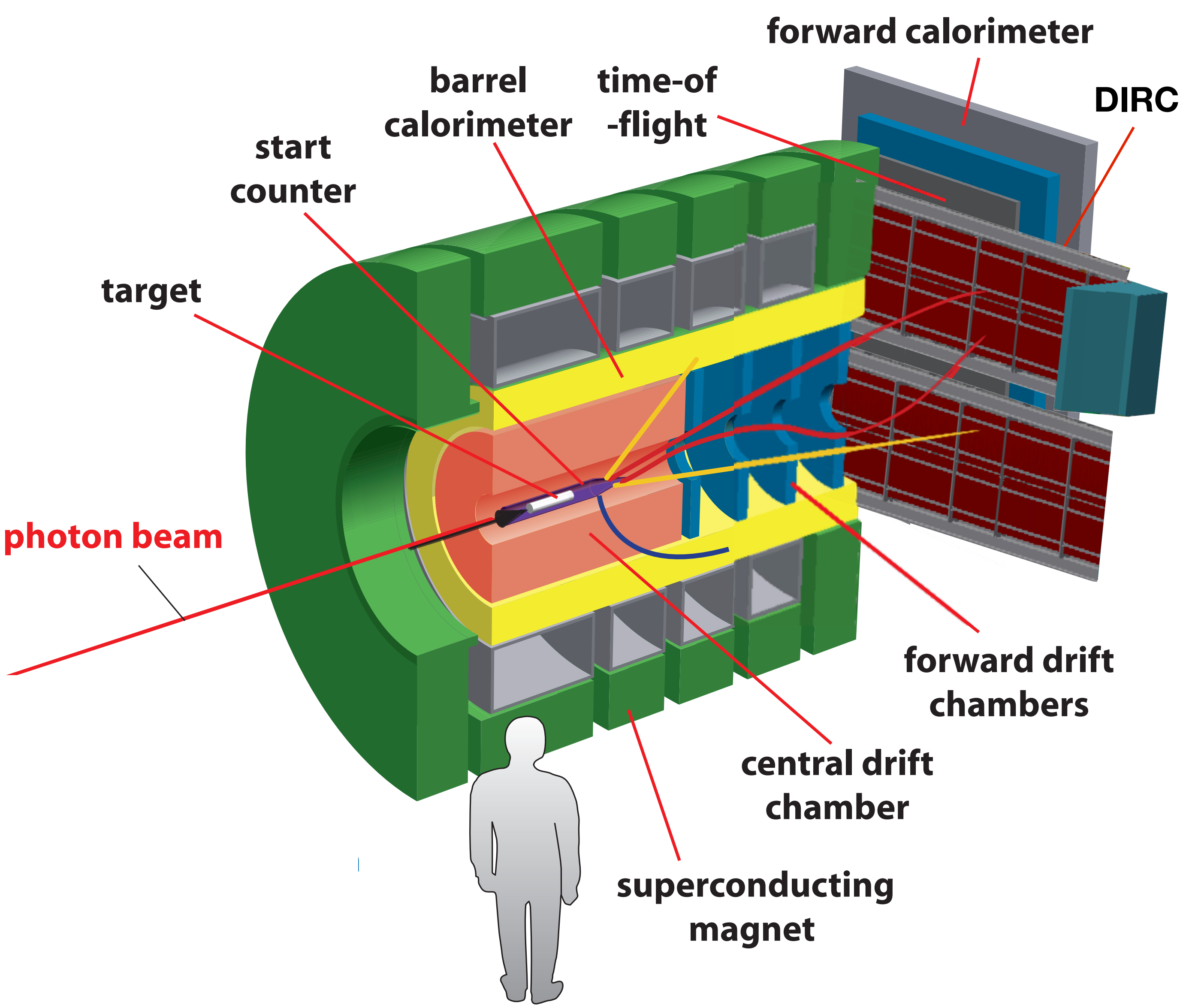


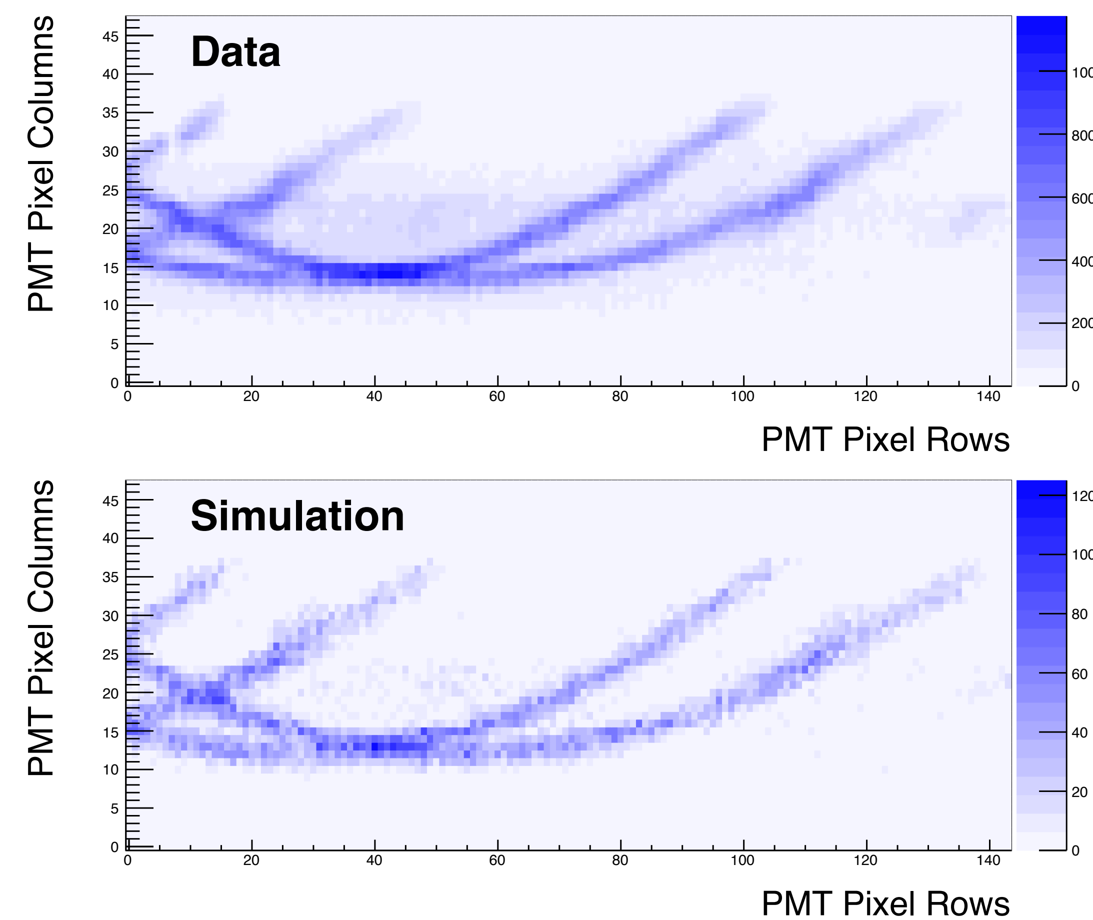




- The GlueX **DIRC** (**D**etection of **I**nternally **R**eflected **C**herenkov light) provides new K/π separation and will use components of the BaBar DIRC
- Installation and commissioning this year, physics data in 2019!

GlueX DIRC upgrade





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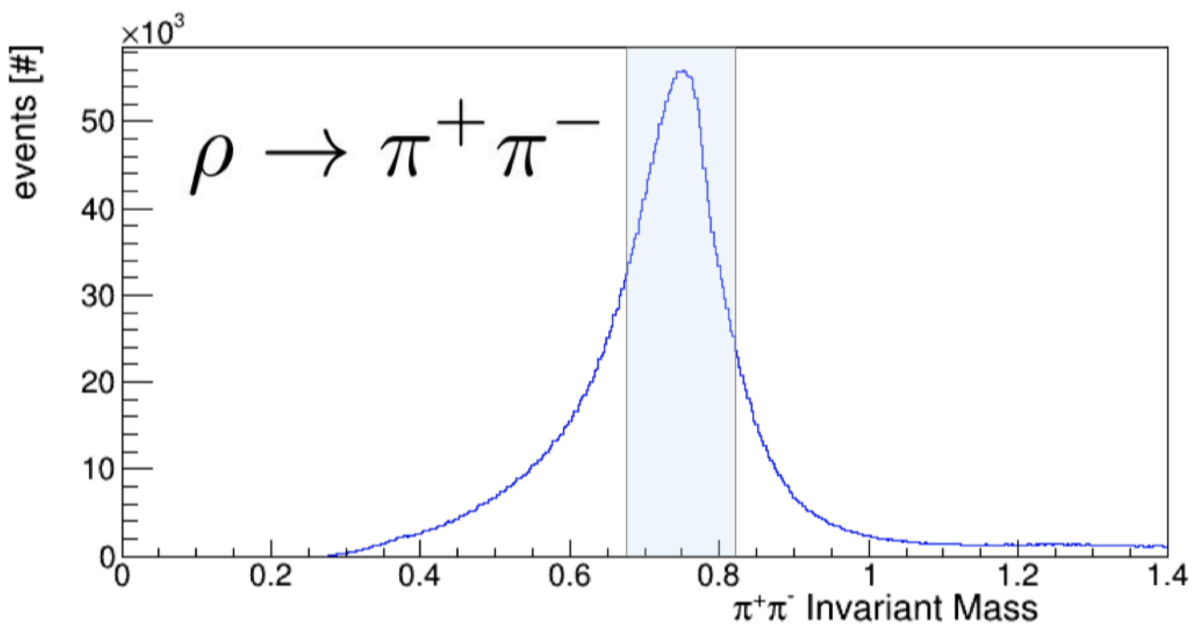
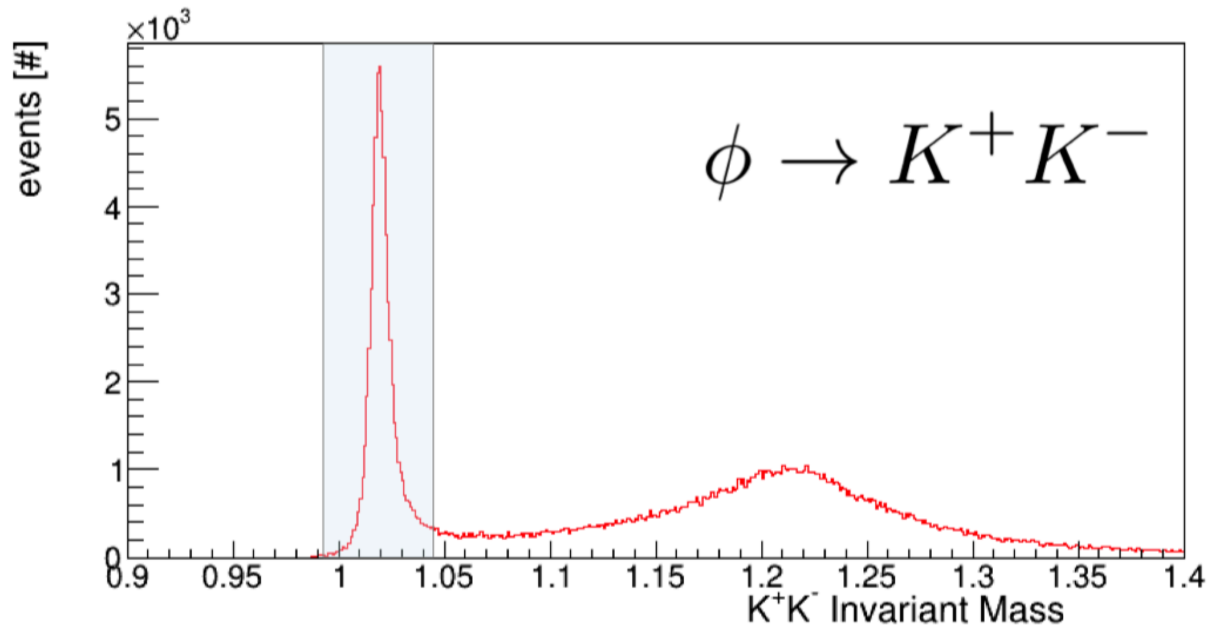
GlueX DIRC commissioning

- February 2019: 10 days of GlueX beamtime with 1/2 of DIRC installed for commissioning

- Samples of exclusive ρ and ϕ production provide pure samples of π and K tracks for PID studies

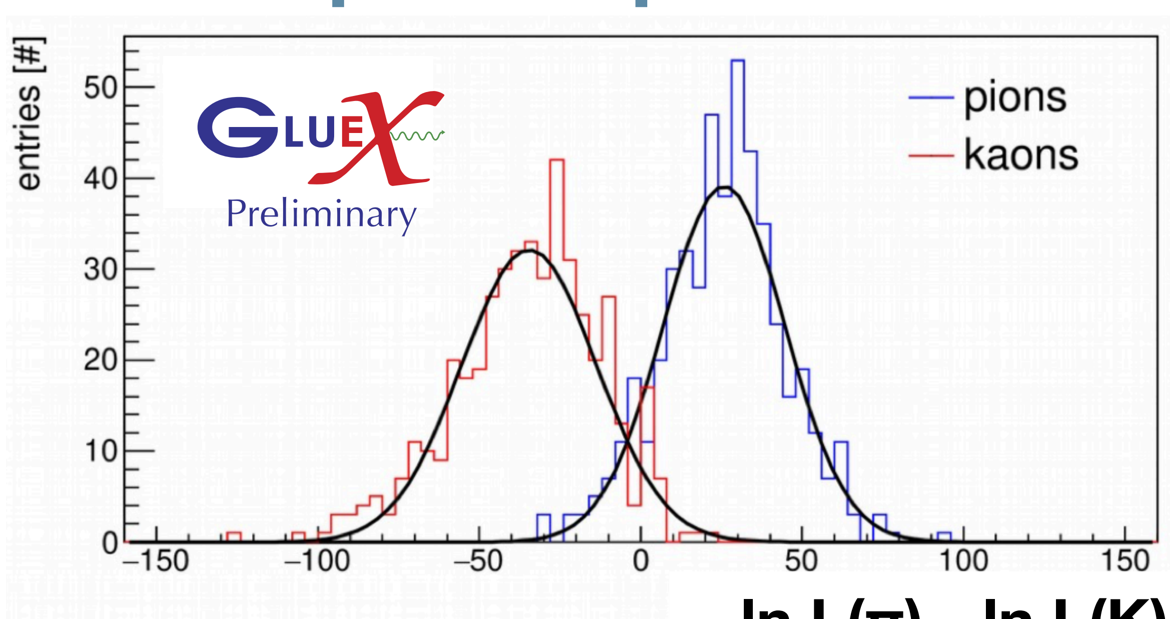




GlueX DIRC commissioning

- February 2019: 10 days of GlueX beamtime with 1/2 of DIRC installed for commissioning
- Samples of exclusive ρ and ϕ production provide pure samples of π and K tracks for PID studies
- Calibration and alignment in progress, but initial reconstruction studies show clear π/K separation

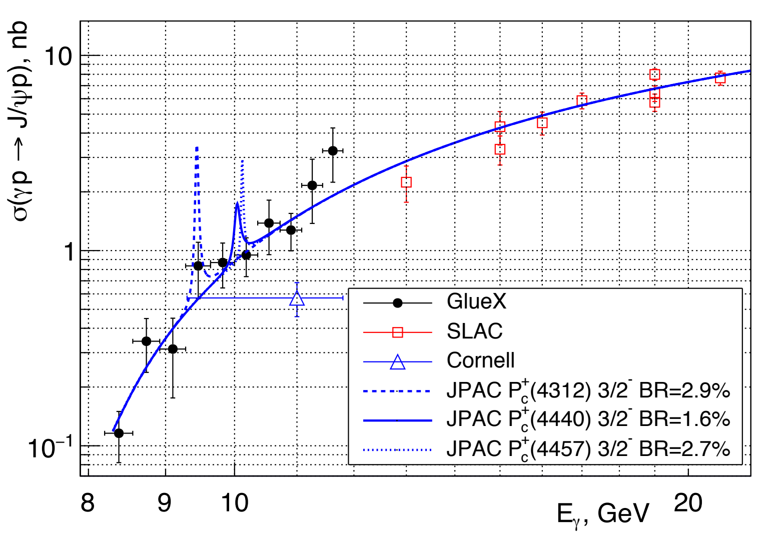
π/K separation power @ 3 GeV

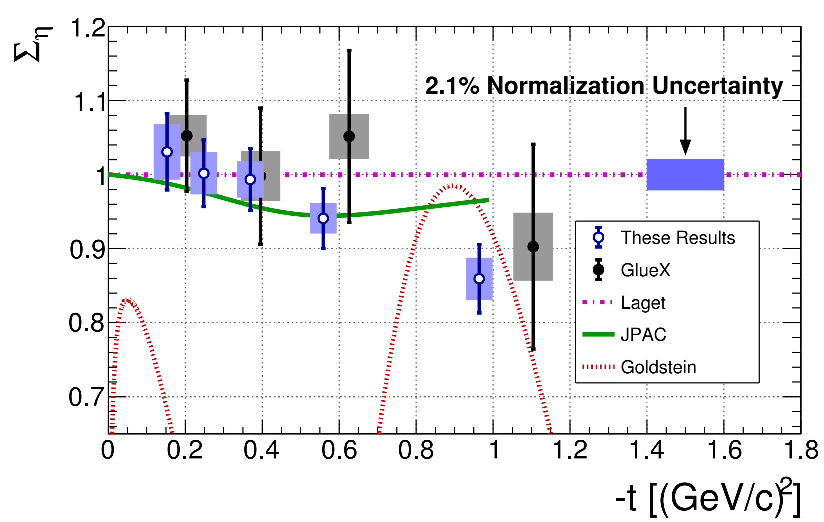


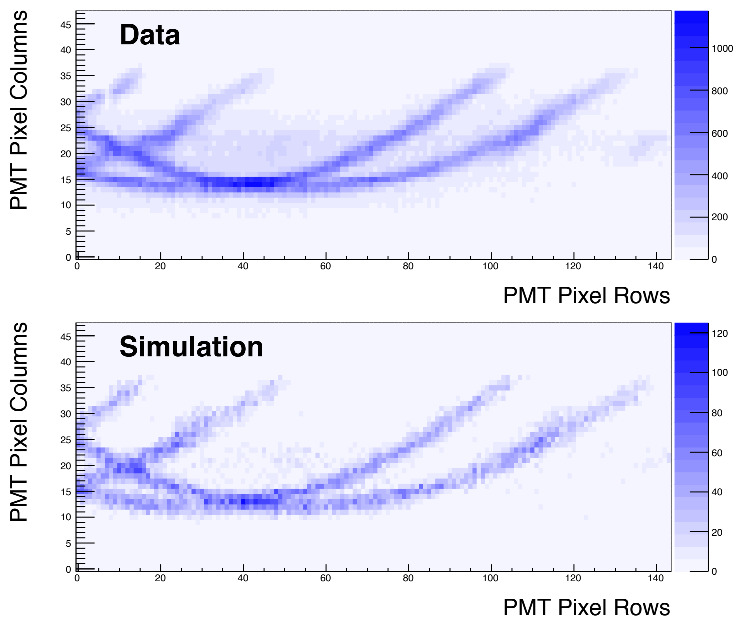
ln L(π) - ln L(K)

Summary

- The GlueX experiment is commissioned and the initial meson program is well underway
- First results aim at understanding the meson photoproduction mechanism through beam asymmetries and other polarization observables
- An upgrade is in progress to improve the identification of charged kaons to enhance the strange meson spectroscopy program







Supported by DE-SC0018224 U.S. DEPARTMENT OF ENERGY Office of Science