SEARCH FOR EXOTIC QUANTUM-NUMBER MESONS IN THE GLUEX EXPERIMENT

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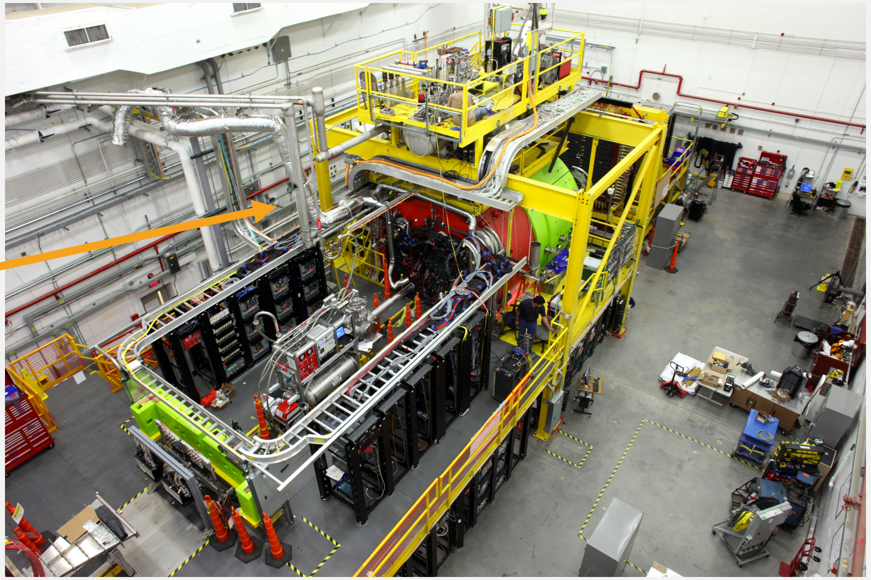
On behalf of the GlueX Collaboration

OUTLINE

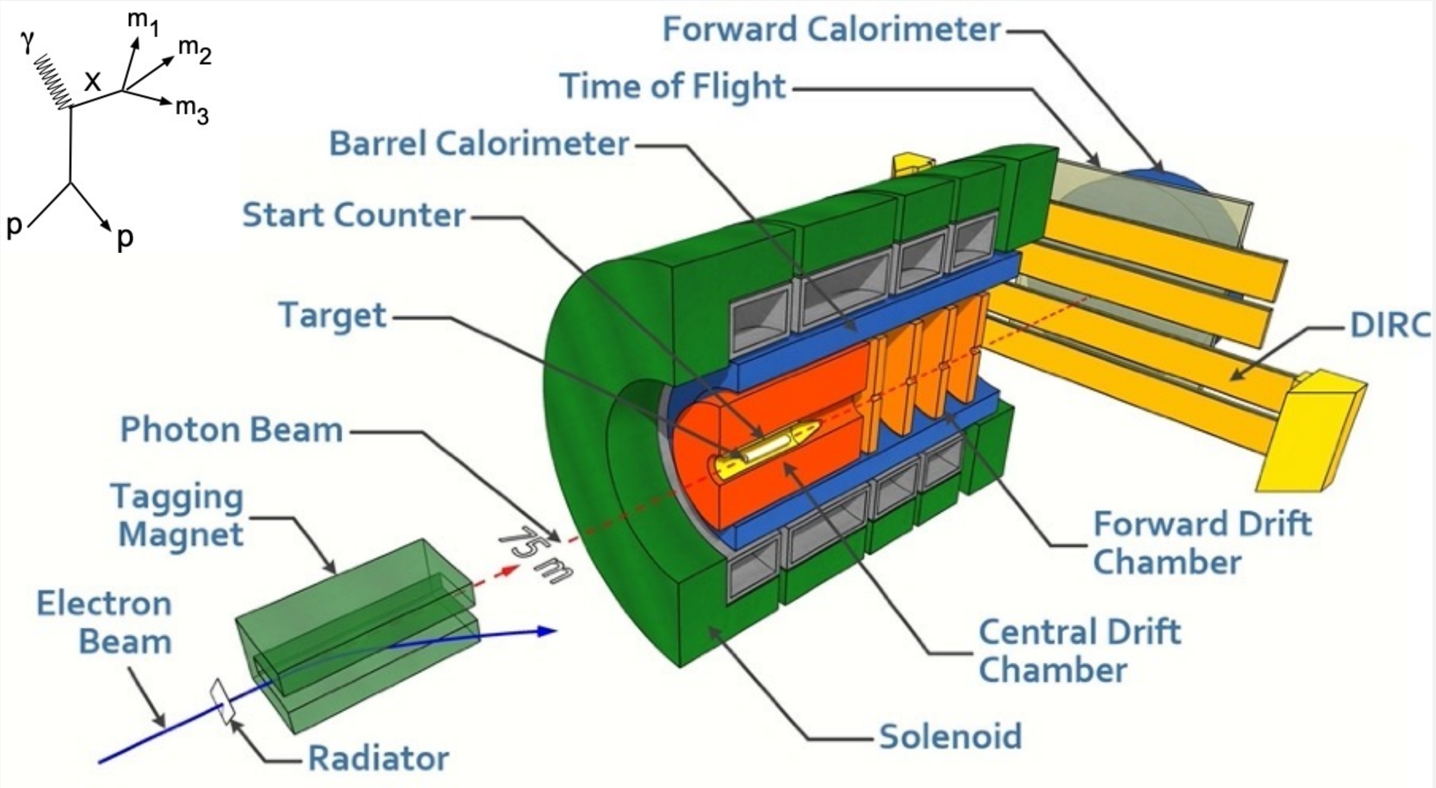
- The GlueX Experiment
- Exotic Quantum Number Mesons
- Photoproduction
- Searching for Exotics
- J/ψ Photoproduction



The GlueX Detector in HallD

THE GLUEX EXPERIMENT

- **Search for hybrid mesons.**
  - Gluonic DOF.
  - Predicted by LQCD.
- Linearly-polarized photon beam.
  - Unexplored regime.
- Hermetic detector.
  - Exclusive reaction.
- Very high statistics.
  - 125 pb^{-1} in Phase I

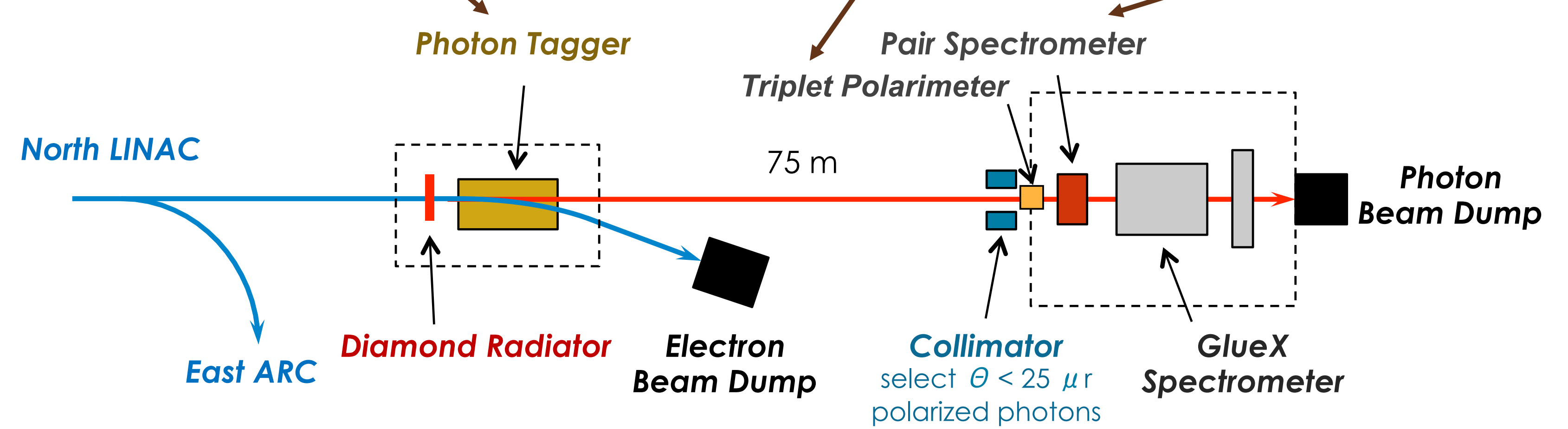


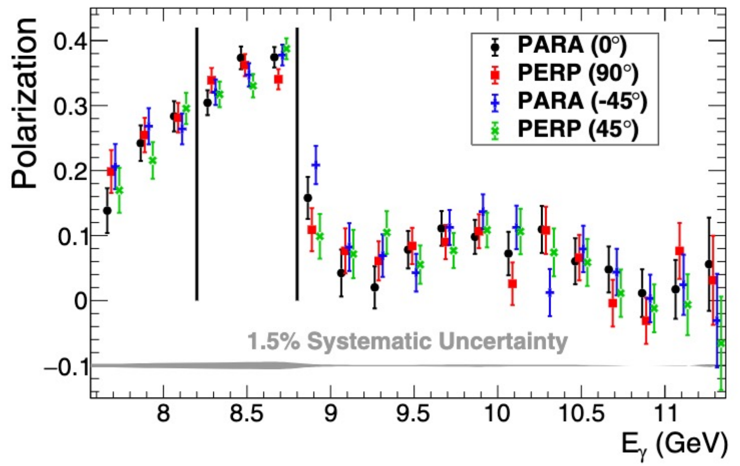
NIM A**987**, 164807 (2021)

HALL-D PHOTON COMPLEX

Coherent bremsstrahlung of 12 GeV electron beam on 50μm diamond radiator.
Linearly polarized photons in coherent peak (E_γ from 8.4 to 9 GeV).

The beam is energy tagged, has its polarization measured, and the flux is determination close to the GlueX detector.

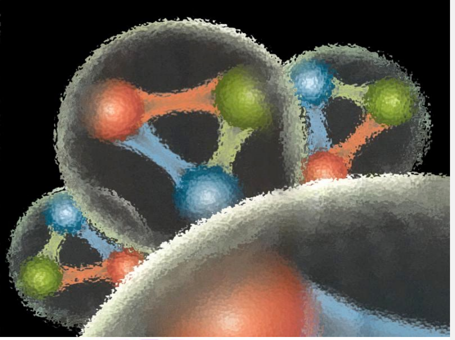


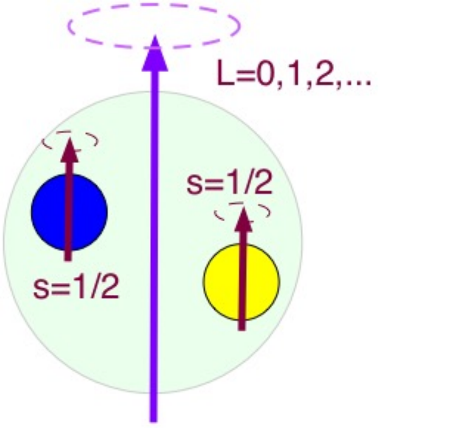


Linearly-polarized photons act as a filter on the naturality of the exchange mechanism.

Photon beams are unique: J=1, through VMD are effectively beams of ρ, ω and ϕ mesons.

NIM A**987**, 164807 (2021)





QUARK MODEL MESONS

Combine two spin **½** objects to S=**0** or S=**1**

Orbital angular momentum of two quarks: L=**0**,**1**,**2**,**3**,…

Total angular momentum, J=L+S: J=**0**,**1**,**2**,**3**,…

Spatial Reflection Symmetry: Parity **$P=-(-1)^L$**

Quark-antiquark Reflection: C-parity **$C=(-1)^{L+S}$**

Mesons are characterized by nonets of **$J^{P(C)}$**

Allowed J^{PC}

L=2, S=1,	$J^{PC}=3^{--}$
	$J^{PC}=2^{--}$
	$J^{PC}=1^{--}$
L=2, S=0,	$J^{PC}=2^{-+}$
L=1, S=1,	$J^{PC}=2^{++}$
	$J^{PC}=1^{++}$
	$J^{PC}=0^{++}$
L=1, S=0,	$J^{PC}=1^{+-}$
L=0, S=1,	$J^{PC}=1^{--}$
L=0, S=0,	$J^{PC}=0^{-+}$

Exotic Quantum Numbers: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$

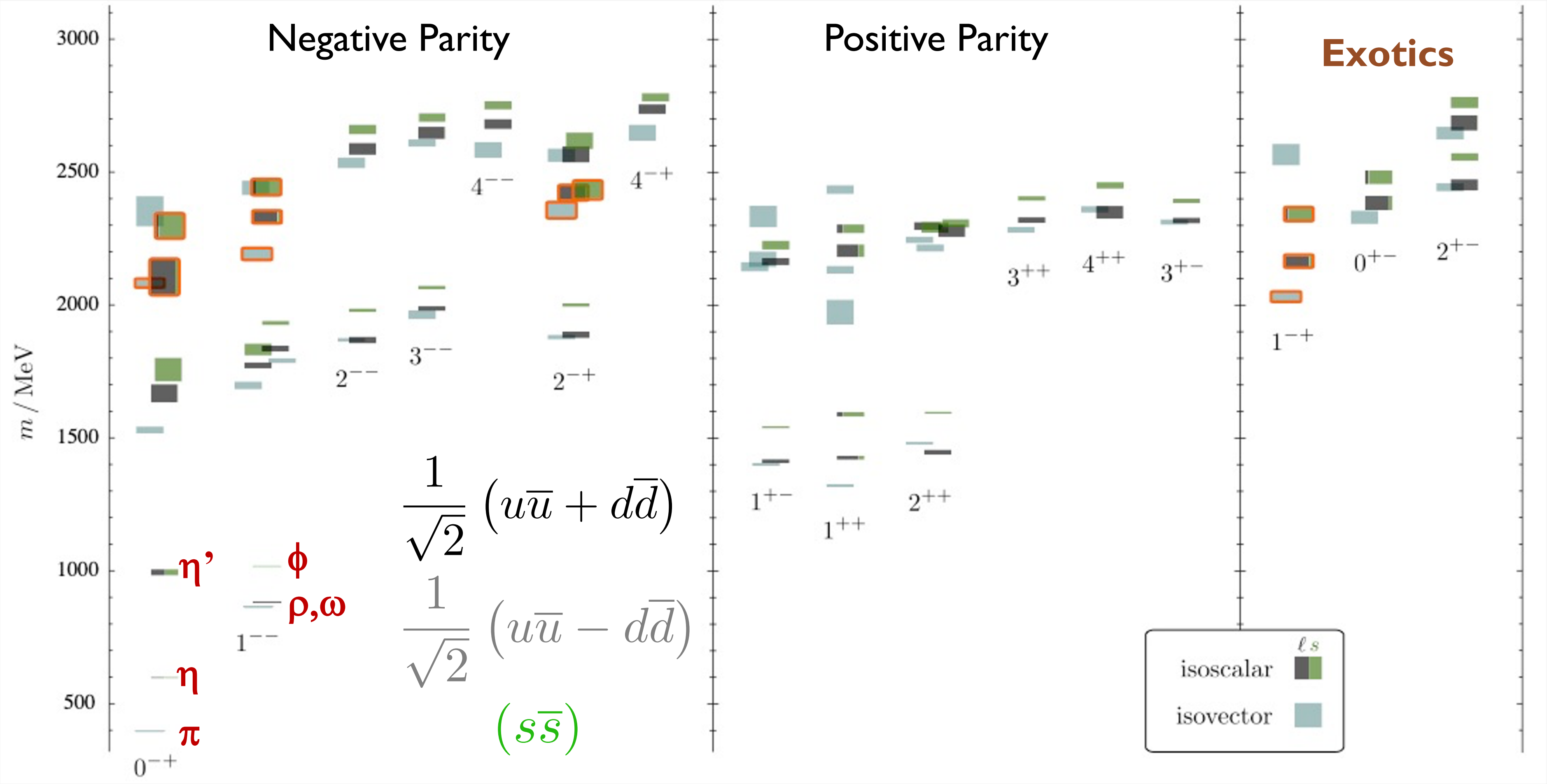
LATTICE QCD PREDICTIONS

Light-quark mesons, u,d,s and their antiquarks.

Shown are are I=0 and I=1 states.

Color shows mixing of I=0 states.

Large Gluonic Component



PRD83, 111502 & PRD88, 094505

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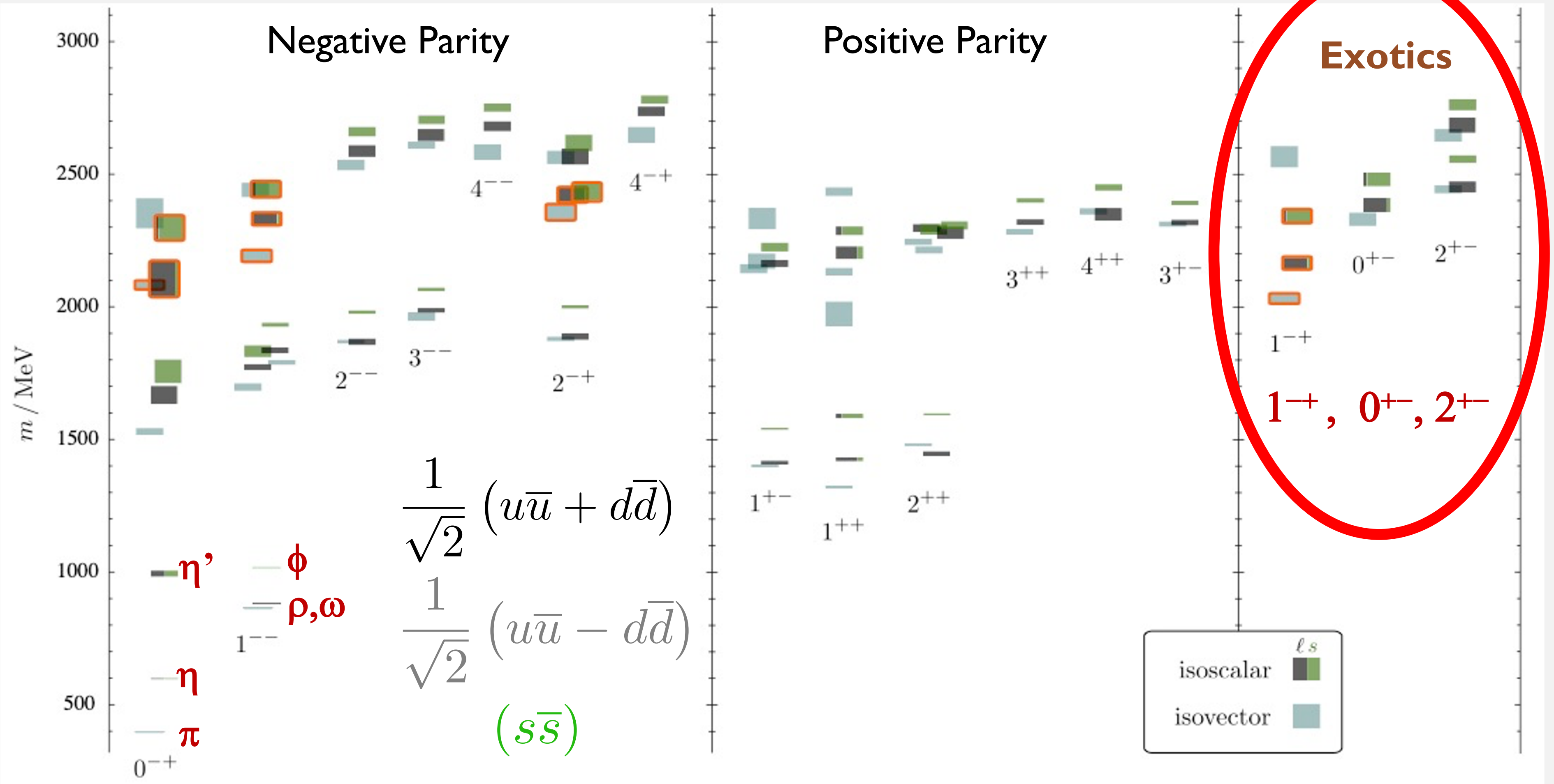
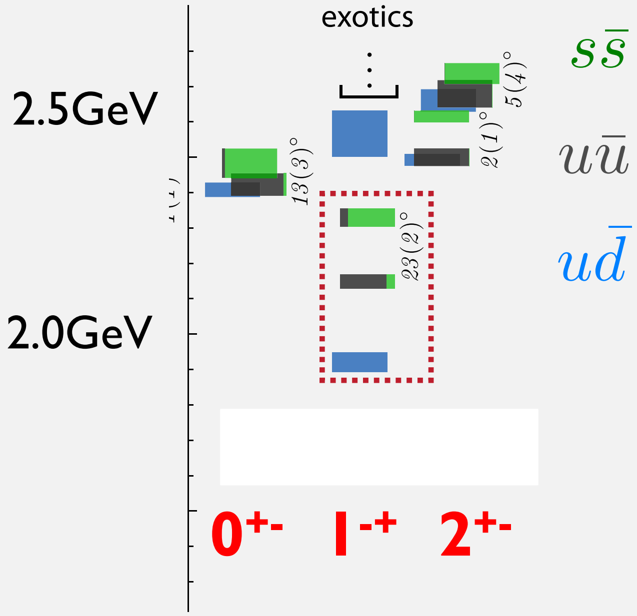


PRD83, 111502 & PRD88, 094505

EXOTIC HYBRID MESONS

Lattice QCD



Non quark-antiquark J^{PC} ,
Exotic Quantum Numbers!

Lattice QCD suggests 5 nonets with exotic quantum numbers:
1 nonet of 0^{+-} exotic mesons
2 nonets of 1^{-+} exotic mesons
2 nonets of 2^{+-} exotic mesons

Lattice QCD results are consistent with the gluonic field behaving like a $J^{PC}=1^{+-}$ constituent with a mass ~1-1.5 GeV/c^2.

EXOTIC HYBRID MESONS

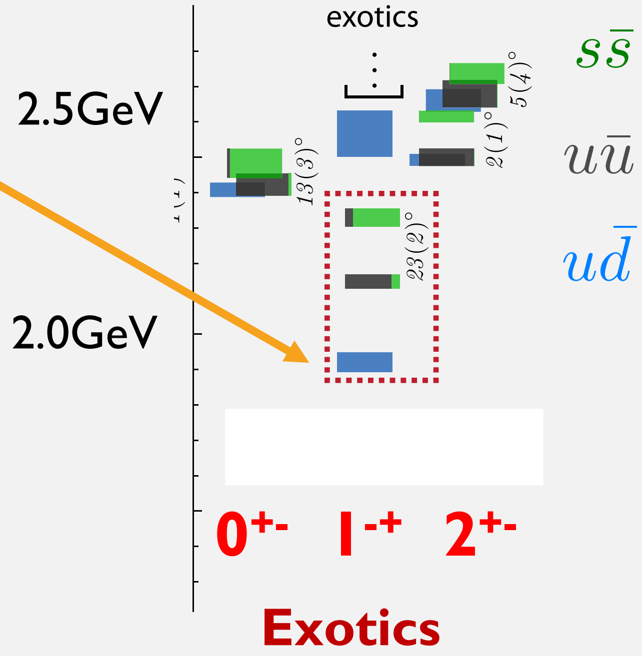
Experimental Evidence for the I=1 $\pi_1(1600)$.

$\pi_1(1600)$ reported in:

$\eta'\pi$: COMPASS/JPAC, E852, VES, CLEO-c
$\rho\pi$: COMPASS, E852
$b_1\pi$: VES, E852, CBAR
$f_1\pi$: VES, E852

JPAC $\eta\pi$ / $\eta'\pi$ coupled channel fit to and partial waves in pion production measured by COMPASS: $\pi_1(1600)$
Mass: $1564 \pm 24 \pm 86$ MeV/c^2
Width: $492 \pm 54 \pm 102$ MeV/c^2

Lattice QCD



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PRL 122, 042002 (2019)

WHERE DO WE LOOK?

Where are all the states?

- Spin 0: b_0, h_0, h_0'
- Spin 1: π_1, η_1, η_1'
- Spin 2: b_2, h_2, h_2'

Photoproduction could couple to all of these through simple exchange mechanisms: $\pi,\eta,\rho,\omega,P,b_1,h_1$

LQCD predicts the decays of the π_1, $b_1\pi$ dominant, much smaller rates to $\eta'\pi$, $\rho\pi$ and $f_1\pi$

Phys. Rev. D 103, 054502 (2021)

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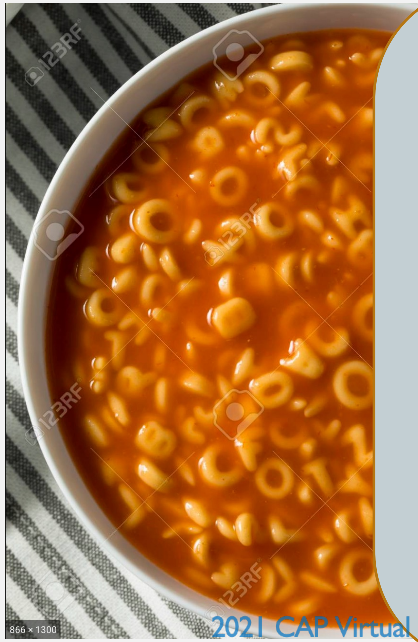
Phys. Rev. D 103, 054502 (2021)



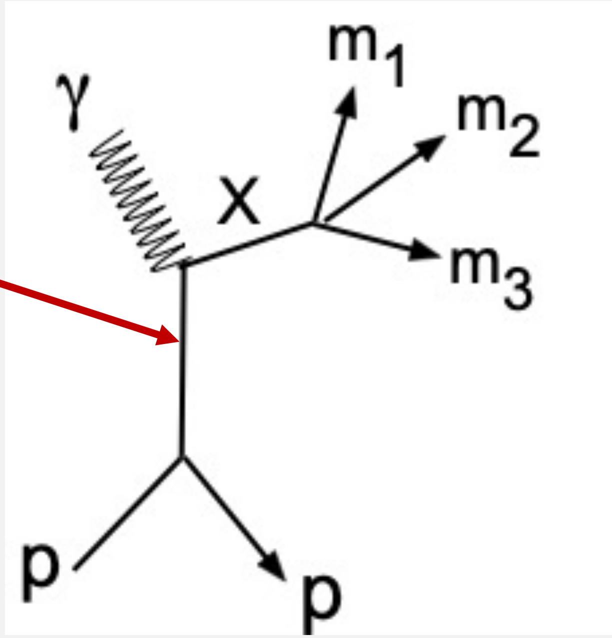
$b_0 \rightarrow \pi(1300)\pi$, $h_1\pi$, $f_1\rho$, $b_1\eta$
$h_0 \rightarrow b_1\pi$, $h_1\eta$
$h'_0 \rightarrow K_1(1270)K$, $K(1460)K$, $h_1\eta$
$\pi_1 \rightarrow \pi\rho$, πb_1 , πf_1, $\pi\eta'$, ηa_1
$\eta_1 \rightarrow \eta f_2$, $a_2\pi$, ηf_1, $\eta\eta'$, $\pi(1300)\pi$, $a_1\pi$,
$\eta_1' \rightarrow K^*K$, $K_1(1270)K$, $K_1(1410)K$, $\eta\eta'$
$b_2 \rightarrow \omega\pi$, $a_2\pi$, $\rho\eta$, $f_1\rho$, $a_1\pi$, $h_1\pi$, $b_1\eta$
$h_2 \rightarrow \rho\pi$, $b_1\pi$, $\omega\eta$, $f_1\omega$
$h'_2 \rightarrow K_1(1270)K$, $K_1(1410)K$, K_2^*K, $\phi\eta$, $f_1\phi$

For the others, look at "allowed" decay modes.

First searches
Need statistics
Difficult

SEARCHING FOR HYBRIDS

- **Understand production mechanisms:**
  - Natural $J^P=0^+, 1^-, 2^+$, … and unnatural $J^P=0^-, 1^+, 2^-$, … exchanges.
  - Linear Photon Polarization!
  - Beam asymmetry Σ, SDMEs ρ^i_{jk}, ….



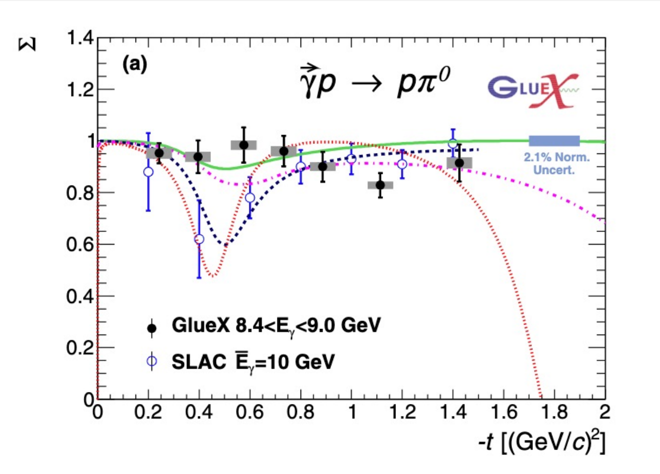
- **Understand Acceptance**
  - SDMEs, Cross sections , ….

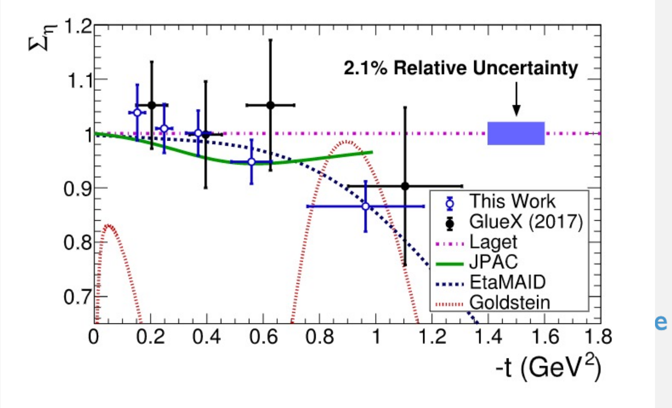
- **Reproduce known results**
  - Start with $\eta\pi$ and $\eta'\pi$

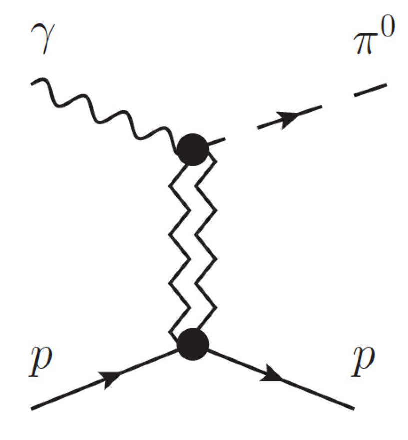
BEAM ASYMMETRY Σ

$$Y_{\parallel}(\phi, \phi_\gamma = 0) \propto \left(1 - P_{\parallel} \Sigma \cos 2\phi\right)$$

$$Y_{\perp}(\phi, \phi_\gamma = 90) \propto (1 + P_{\perp} \Sigma \cos 2\phi)$$





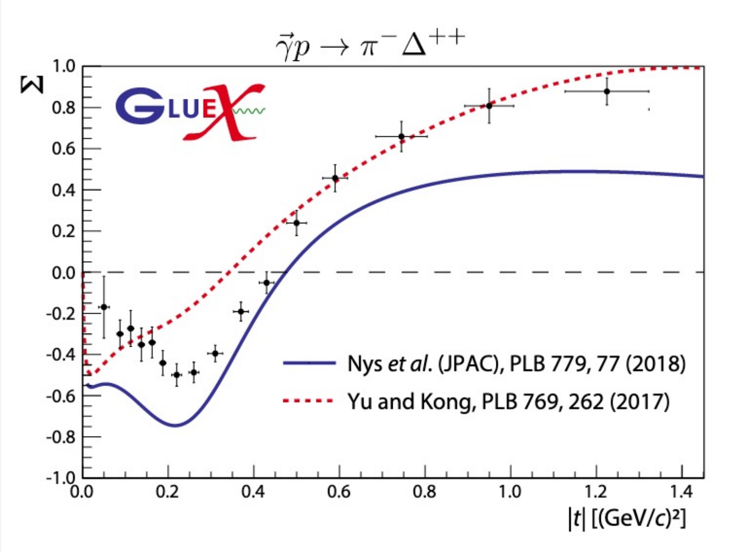


Exchange J^{PC}

1^{--} : ω, ρ

1^{+-} : b, h

Phys. Rev. C**95**, 042201(R), (2017)
Phys. Rev. C**100**, 052201(R) (2019)

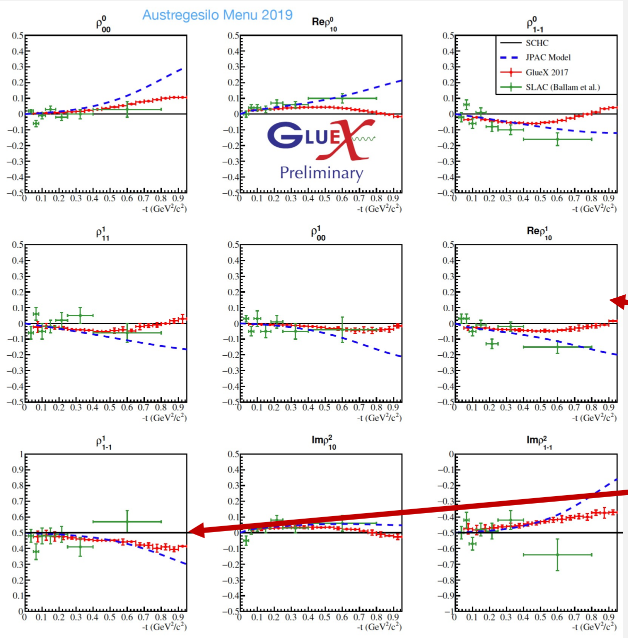


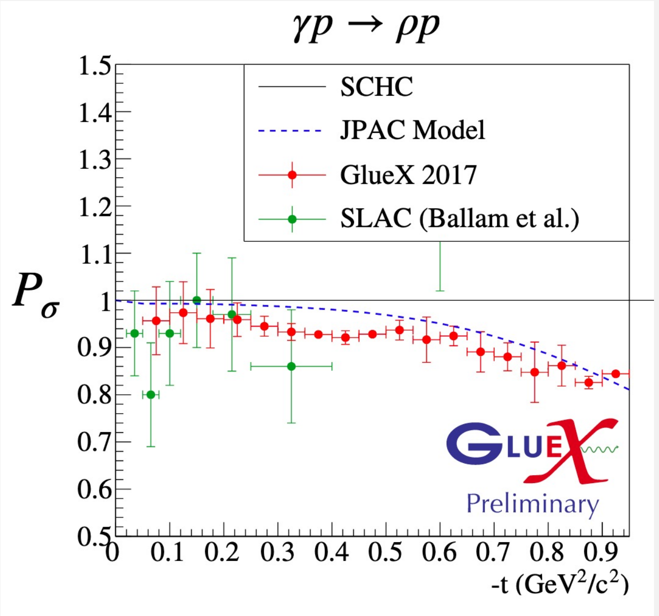
Production mechanism:
unnatural at low |t|,
natural at high |t|.

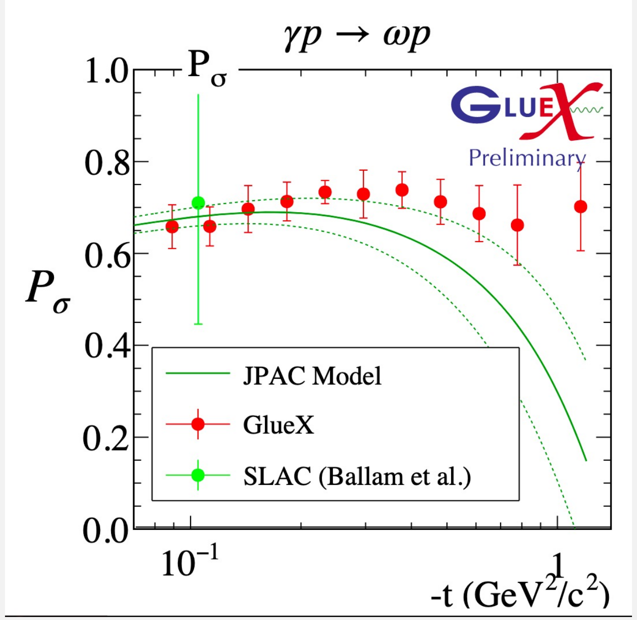
Phys. Rev. C 103, L022201 (2021)

SPIN DENSITY MATRIX ELEMENTS

- The Spin-Density matrix ρ of vector mesons describes the meson's polarization.
- Nine elements can be measured using decay angular distributions.
- Sensitive to production mechanisms.







$$P_\sigma = 2\rho^1_{1-1} - \rho^1_{10}$$

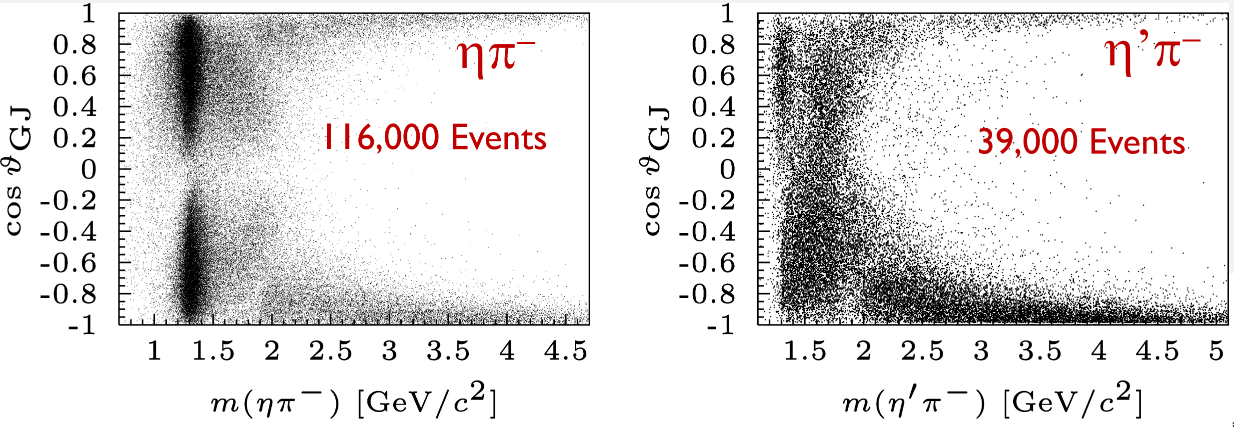
- P_σ = 1 Natural parity exchange:
  - 0^{++}, 1^{--}, 2^{++}, …
- P_σ = -1 Unnatural parity exchange:
  - 0^{-+}, 1^{+-}, 2^{-+}, …

SLAC: PRD 7, 3150 (1973) JPAC: PRD 97, 094003 (2018)

SEARCH FOR EXOTICS

Highest statistics on $\pi_1(1600) \to \eta'\pi$ from COMPASS

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

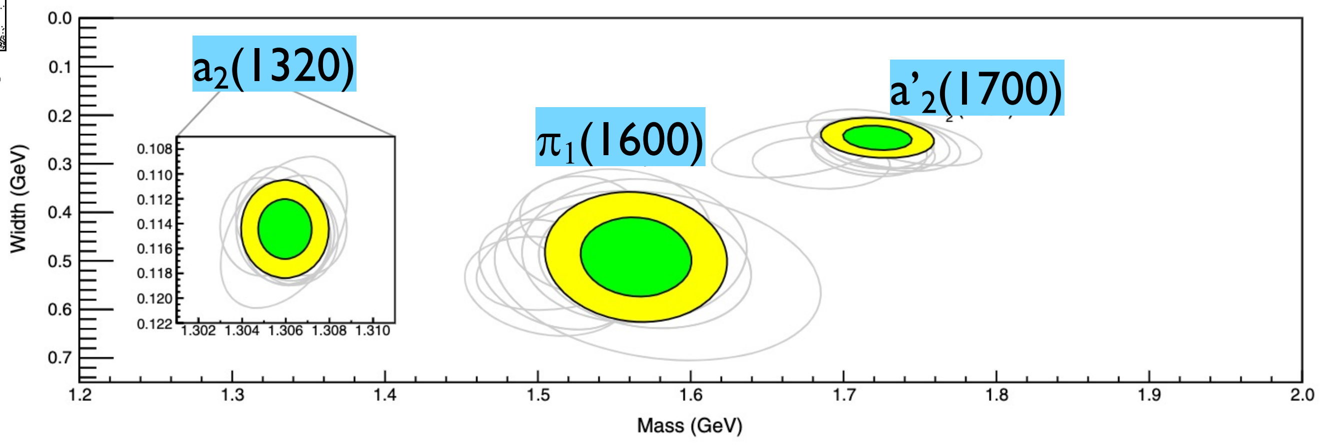


(a) $m(\eta\pi^-)$ vs. $\cos\vartheta_{GJ}$ (b) $m(\eta'\pi^-)$ vs. $\cos\vartheta_{GJ}$

COMPASS: strong exotic wave in the $\eta'\pi^-$, but not in the $\eta\pi^-$ data.

JPAC: Extracted the pole position of the $\pi_1(1600)$ from the COMPASS amplitudes.

Mass: 1564 +/- 24 +/- 86 MeV
Width: 492 +/- 54 +/- 102 MeV

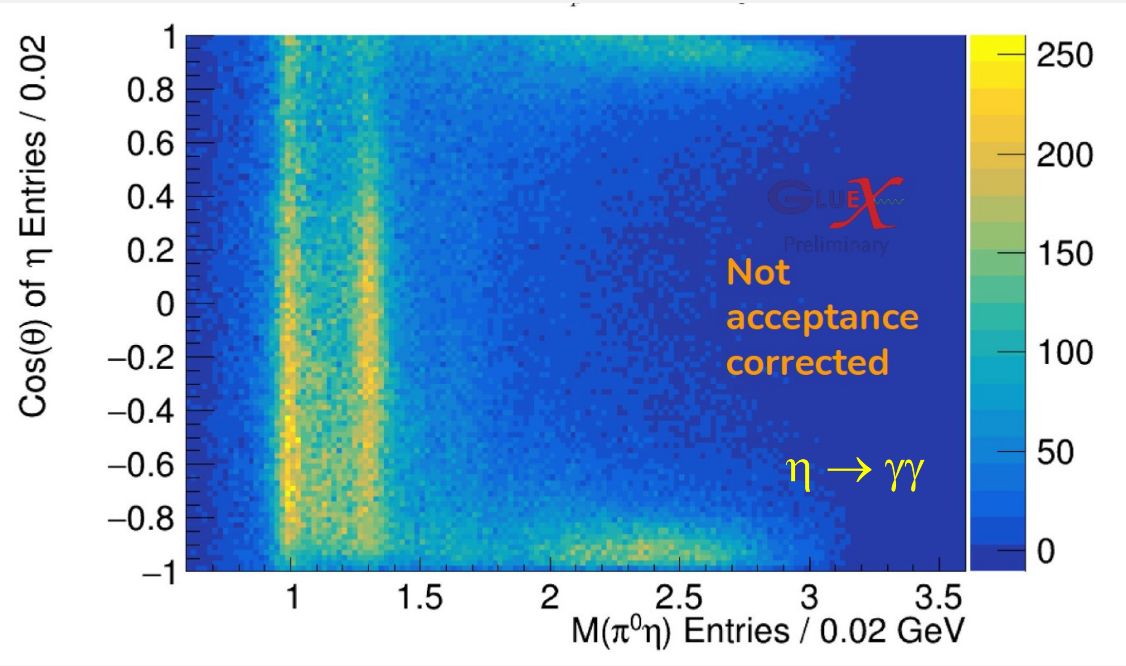


COMPASS: Phys. Lett. B 740, 303 (2015).

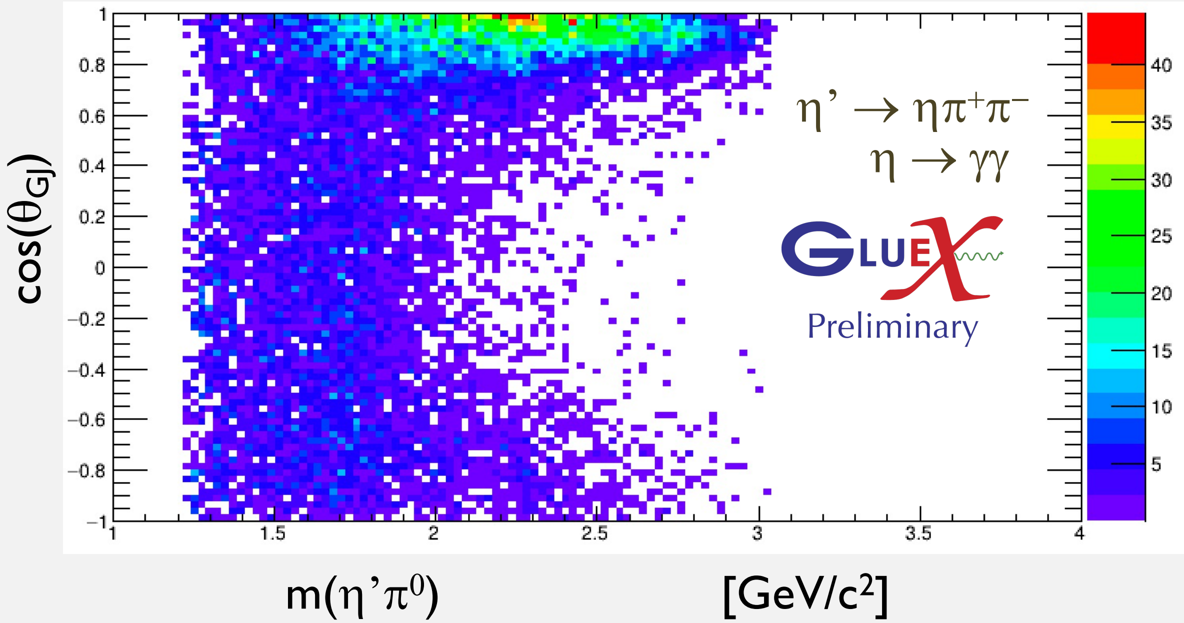
JPAC: Phys. Rev. Lett. 122, 042002 (2019).

SEARCH FOR EXOTICS

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



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



Comprehensive approach:

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

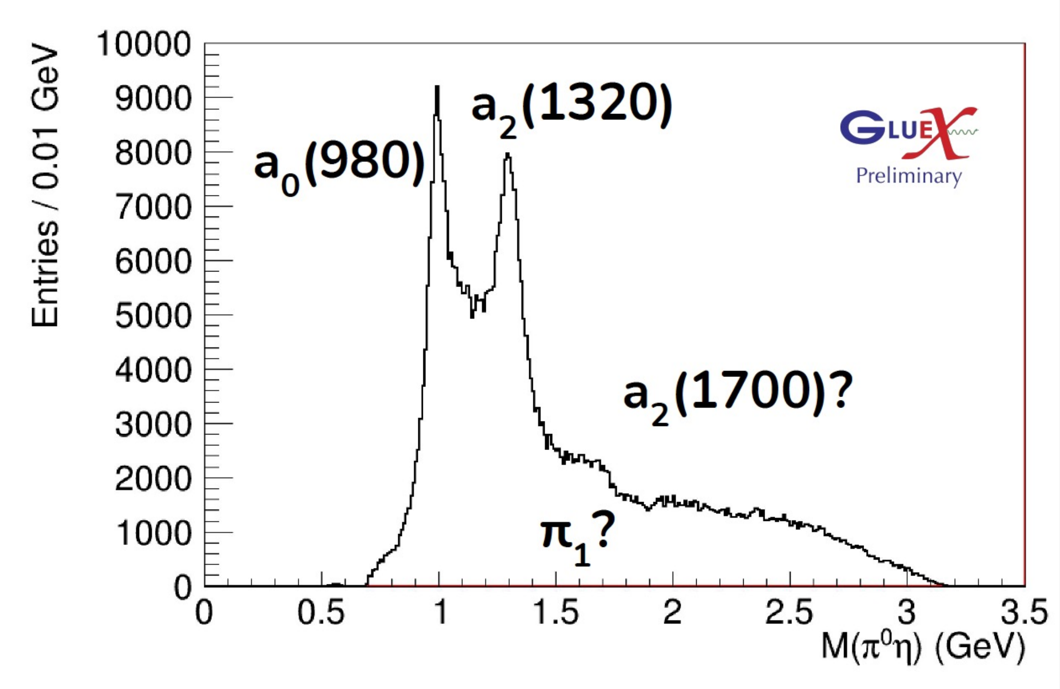
$\gamma p \to \Delta^{++}\ \eta/\eta'\pi^-$

$\eta \to \gamma\gamma\ ,\ \pi^+\pi^-\pi^0$

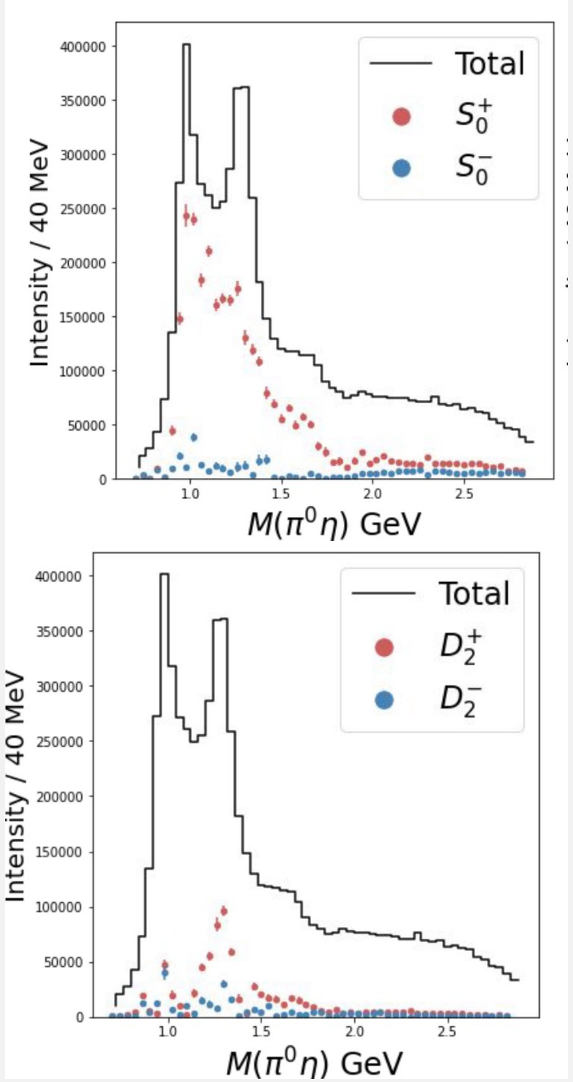
Close collaboration with theory to develop analysis tools.

SEARCH FOR EXOTICS

Amplitude Analysis of low-mass $\eta\pi^0$ system



Small wave set includes positive and negative reflectivity S and D waves.



- Large S-wave contributions.
- The $a_2(1320)$ produced dominantly in the D_2^+ partial wave.

OTHER CHANNELS

Exotic searches now looking at vector-pseudoscalar final states

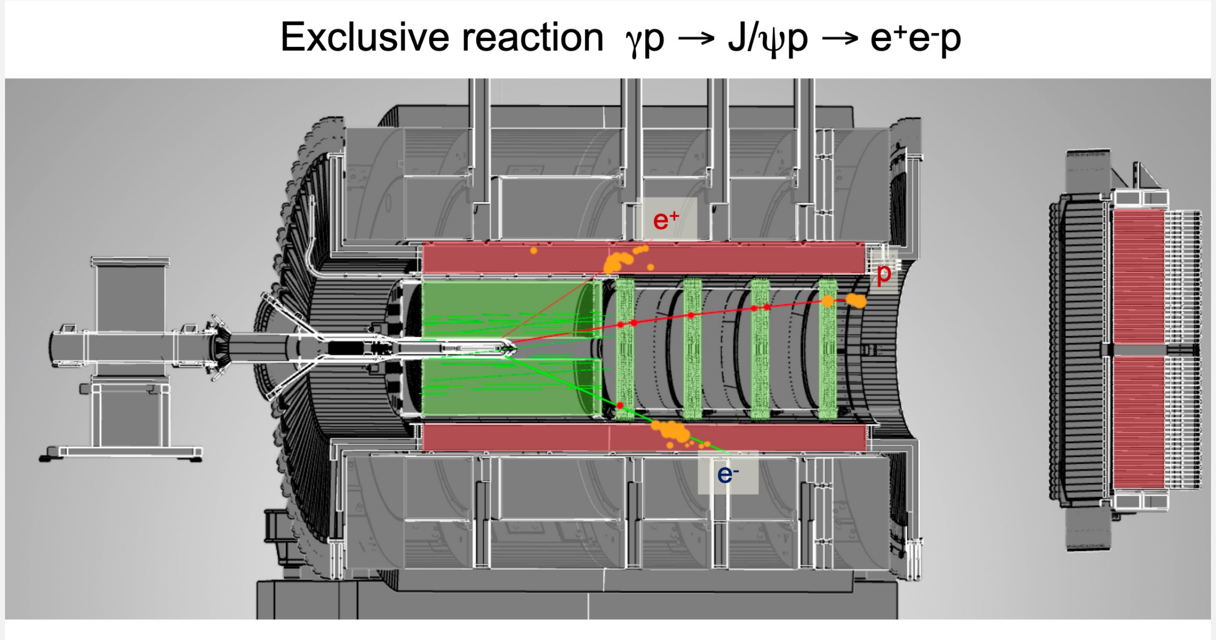
$\pi_1 \to \pi\rho$
$\eta_1' \to K^*K$
$b_2 \to \omega\pi, \rho\eta$
$h_2 \to \rho\pi, \omega\eta$

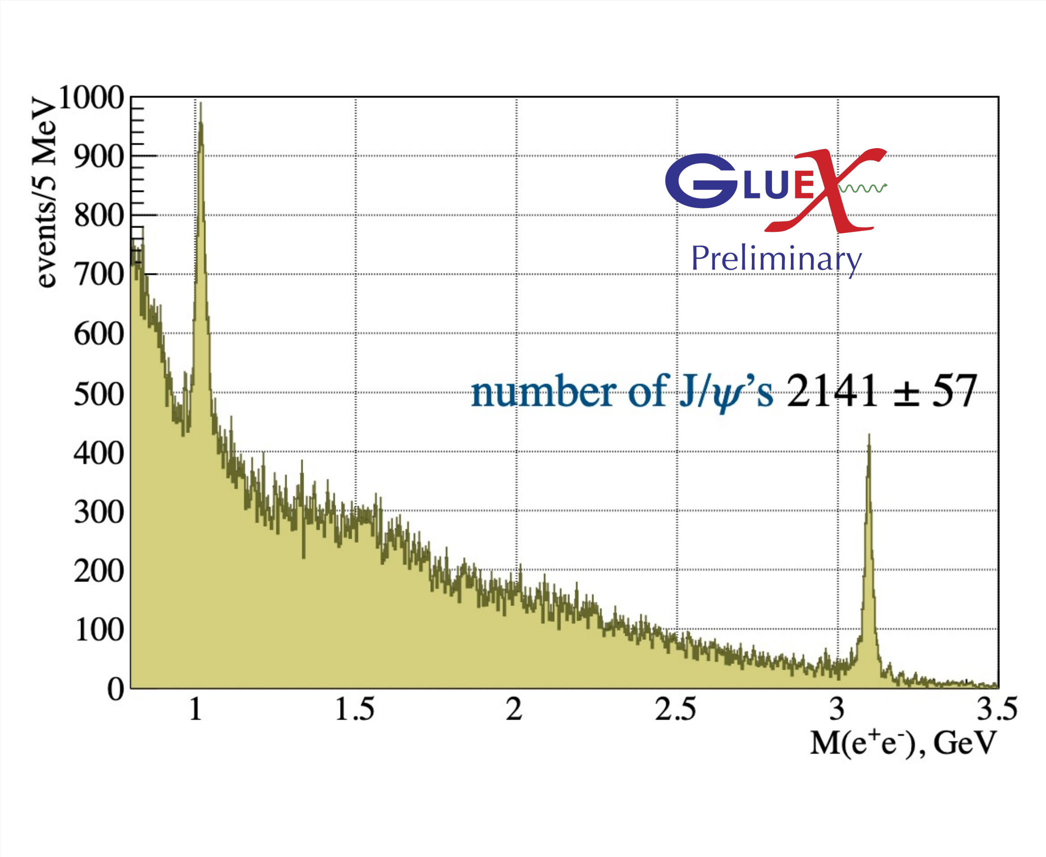
- Possible exotic decays.
- No narrow structures observed in the 1.8 to 2.3 GeV mass region.
- Partial wave analysis needed to search for broad states.
- Related talks:
  - Zisis Papandreou next: $\omega\pi$ cross sections.
  - Karthik Suresh earlier today: $\omega\pi$ amplitude analysis.

OPPORTUNISTIC PHYSICS

$\gamma p \rightarrow p\ J/\psi$

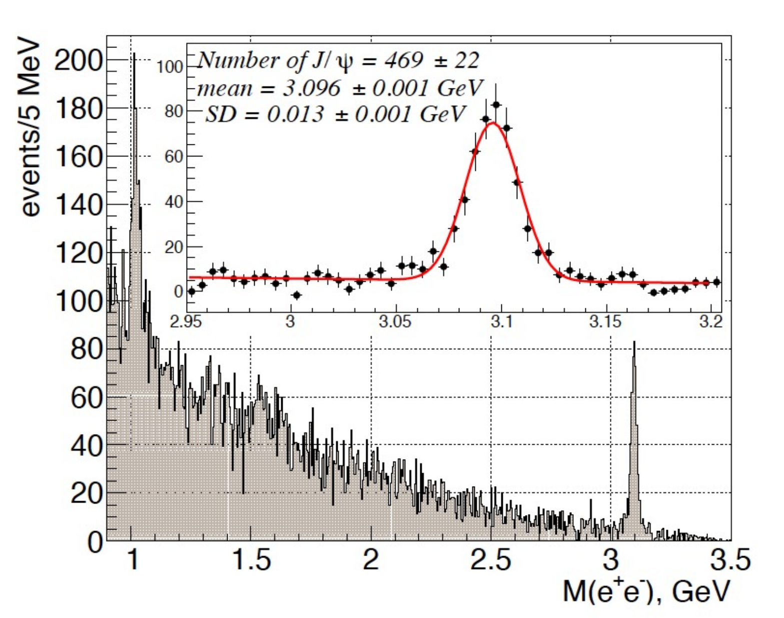
Measure cross section near threshold.





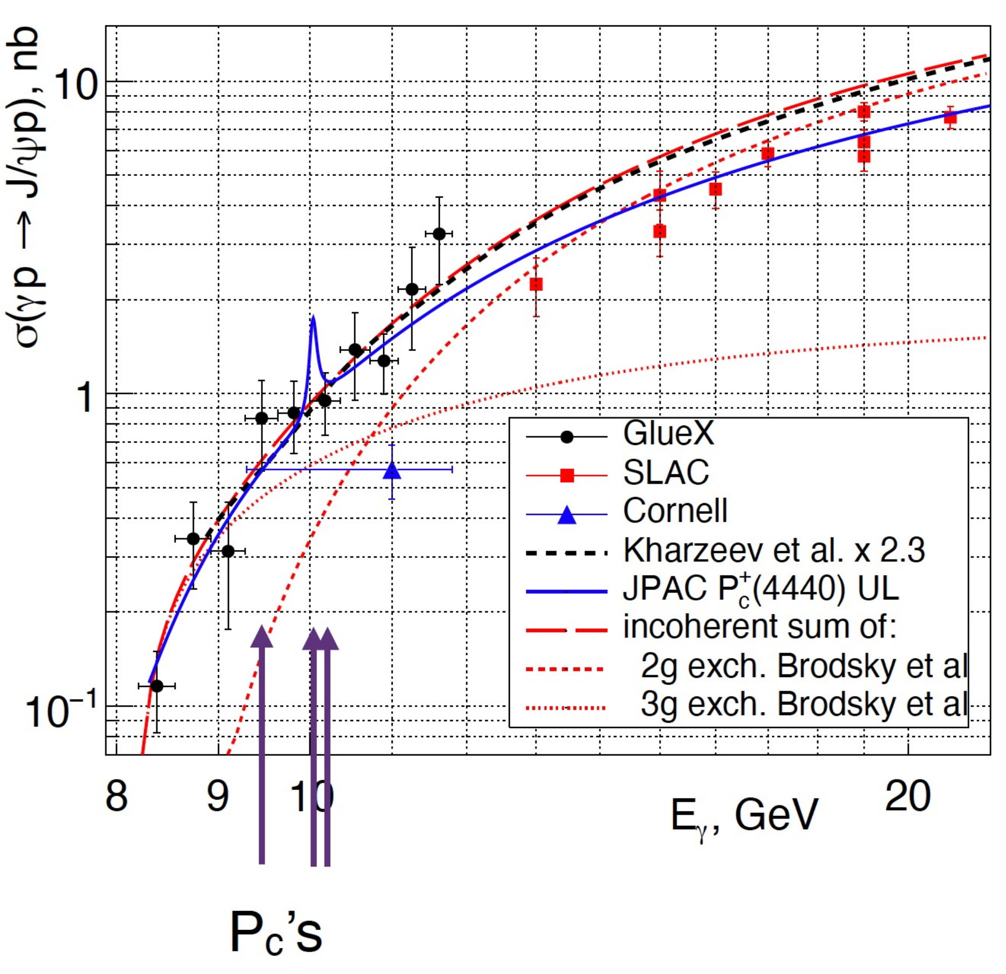
PRL 123, 072001 (2019)

OPPORTUNISTIC PHYSICS



$\gamma p \rightarrow p\ J/\psi$

- Published a portion (469 J/ψ events) of the Phase-I data.
- 27% Normalization uncertainty.
- Set upper limits on LHCb pentaquark production.
- The full data set is nearing publication.



PRL 123, 072001 (2019)

OPPORTUNISTIC PHYSICS

Kharzeev, arXiv:2102.00110 (2021)

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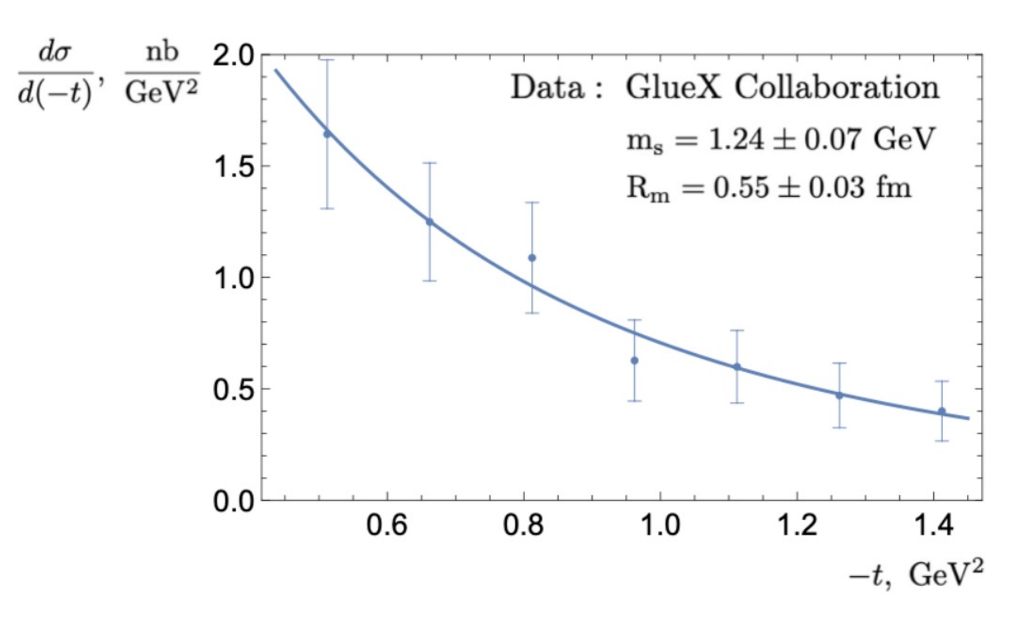
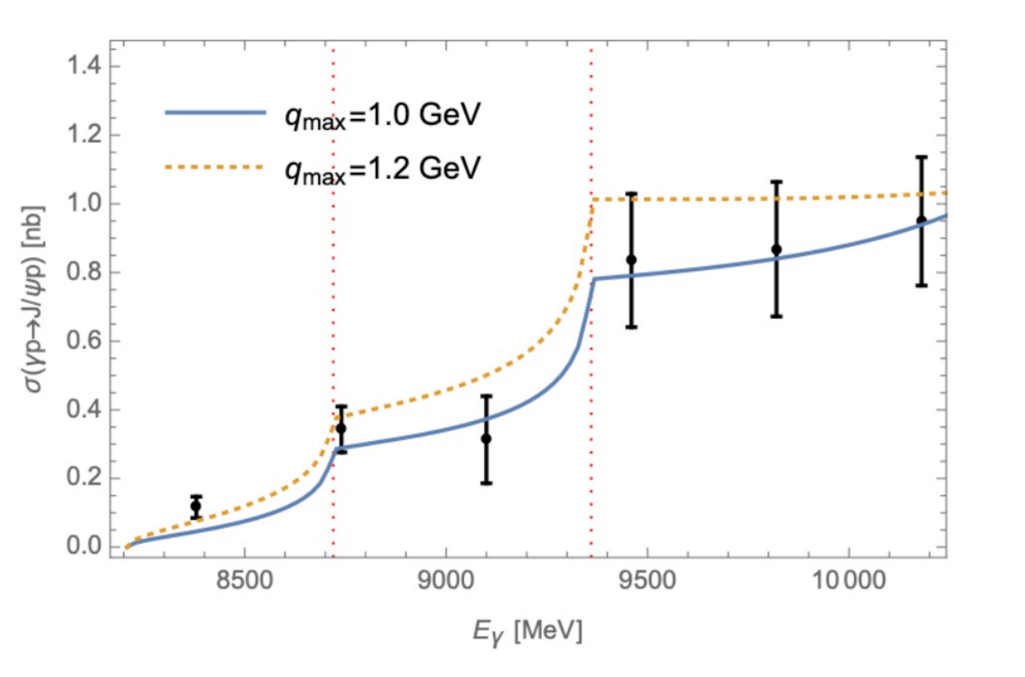


mass radius: R_m = 0.55 +/- 0.03 fm

charge radius: R_c = 0.8409 +/- 0.0004 fm

More data closer to the threshold is needed

Du et al., EPJC 80, 1053 (2020)



Calculated cross section energy dependence including open charm loops Higher precision data is needed

SUMMARY

- The GlueX Phase I 125 pb-1, Phase II with DIRC will be about a factor of 5.
- Beam asymmetry measurements allow us to study production mechanisms of simple final states.
- Spin-density matrix elements probe more complicated production.
- Initial results on the $\eta\pi$ and $\eta'\pi$ system, key first exotic search.
- Next searches focus of vector-pseudoscalar.
- Very interesting results on J/ψ photoproduction.

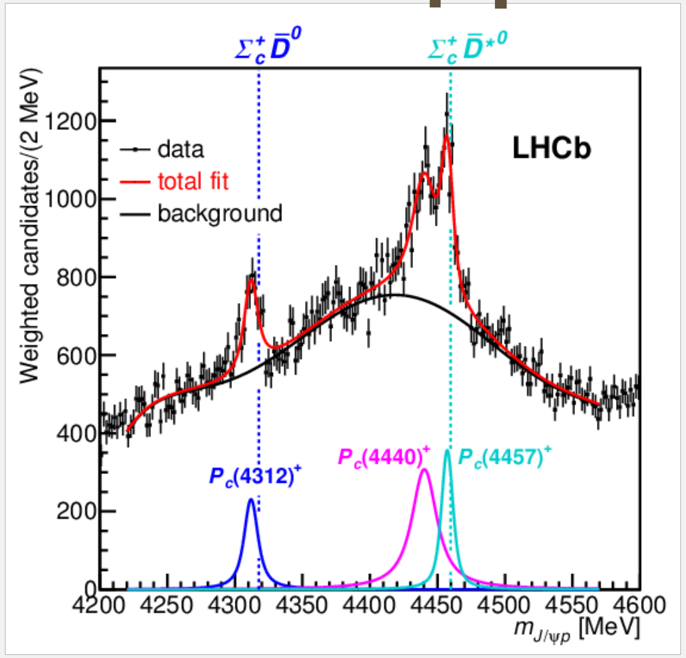
Acknowledgements
http://gluex.org/thanks/

Backup Slides

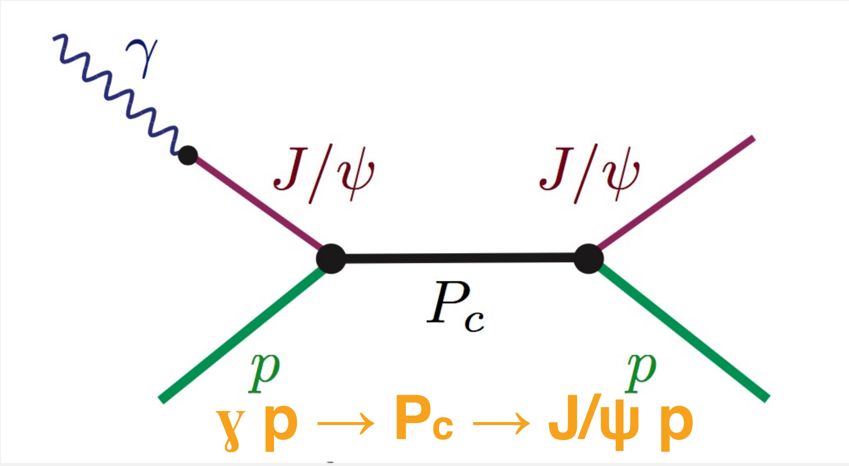
Threshold production is experimentally clean, ideal for studying J/ψ+N interaction.

Study coupling of resonant J/ψ+p states to photon.

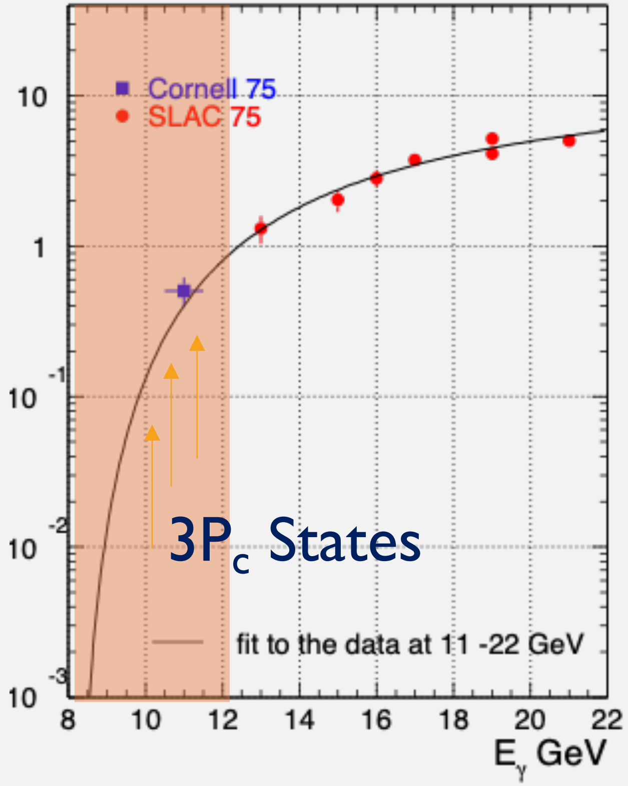
$\Lambda_b \rightarrow J/\psi\ p\ K^-$



Phys. Rev. Lett. 122, 222001 (2019)

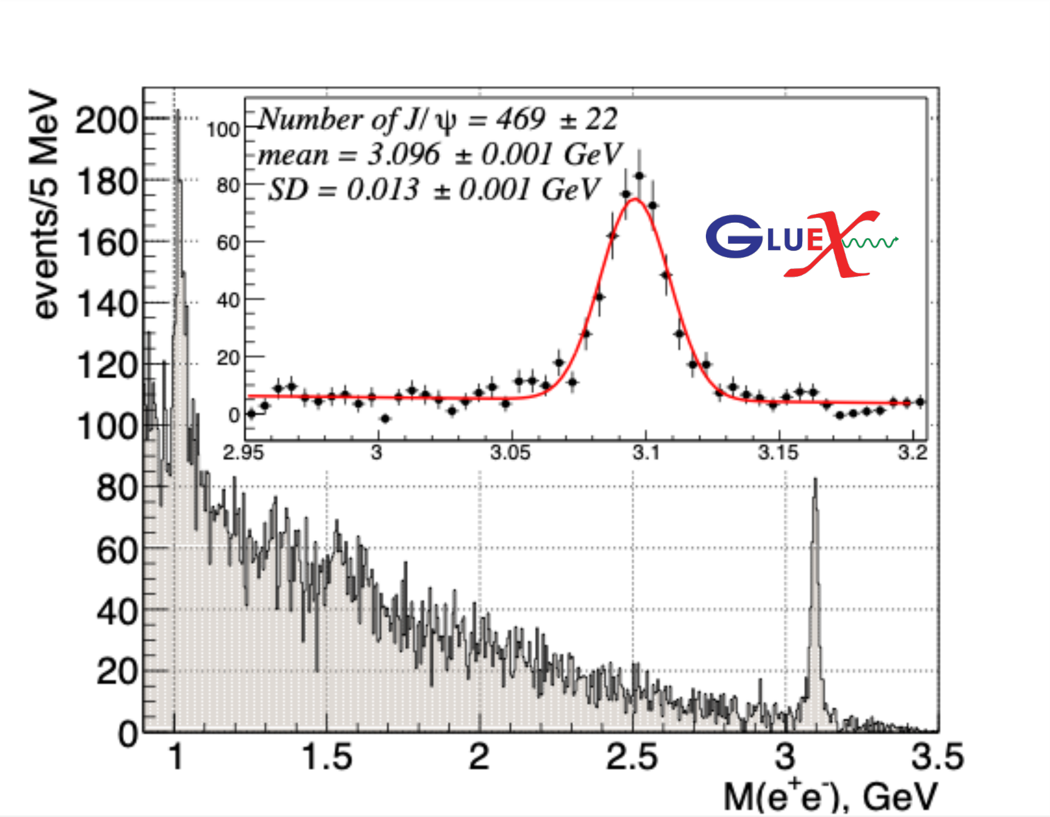


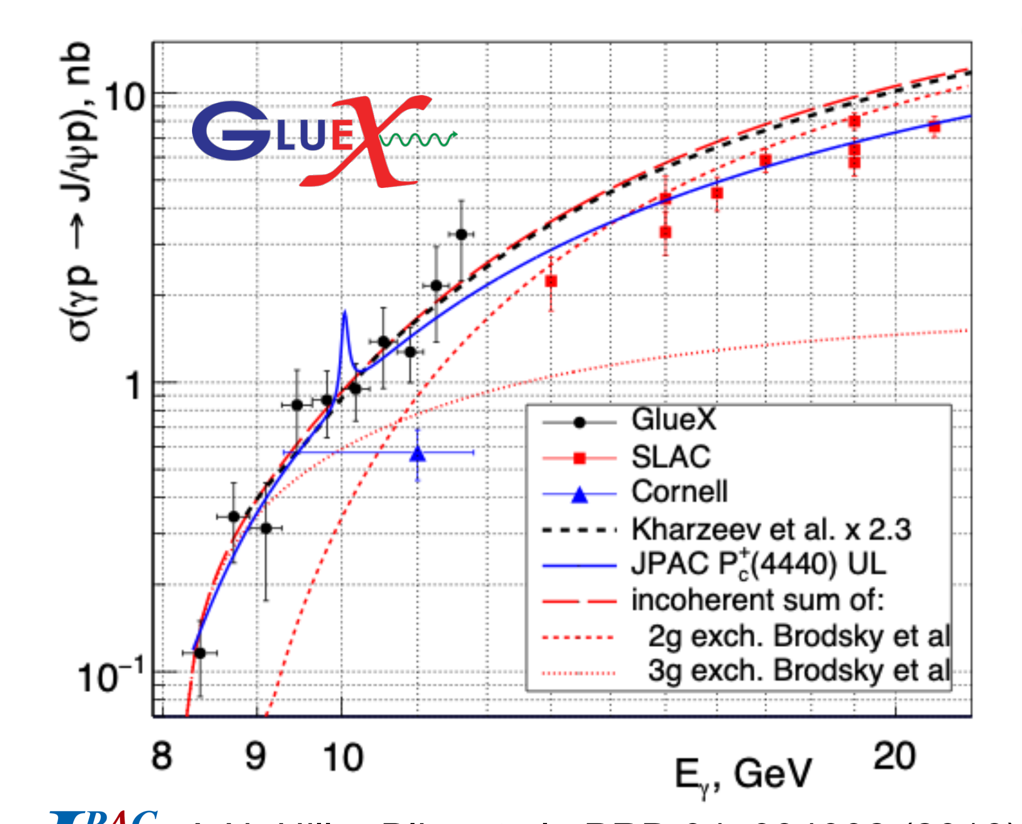
s-channel photoproduction probes nature of 5-quark interaction!



J/Ψ PHOTOPRODUCTION

First J/ψ cross section measurement at threshold, 27% normalization uncertainty, 3x as much data collected.





JPAC A.N. Hiller Blin, et al., PRD 94, 034002 (2016).

Model-dependent upper limits at 90% CL:

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%**

Phys. Rev. Lett. **123**, 072001 (2019)

JLab Hall has shown data for high |-t|.