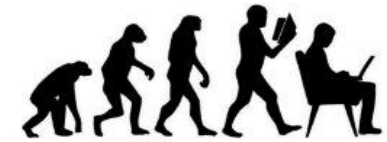
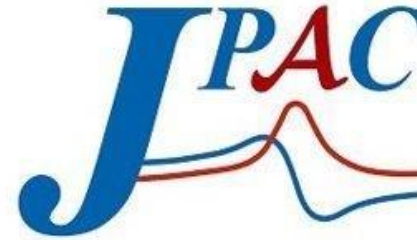




Università
degli Studi di
Messina



Istituto Nazionale di Fisica Nucleare



A(i)DAPT

AI for Data Analysis and Preservation

Hadron spectroscopy at JLab

Giorgio Foti

Phd student at **University of Messina, Italy** (Advisor:
Alessandro Pilloni)

*25th ZIMÁNYI SCHOOL - WINTER WORKSHOP ON
HEAVY ION PHYSICS*

December 1-5, 2025, Budapest

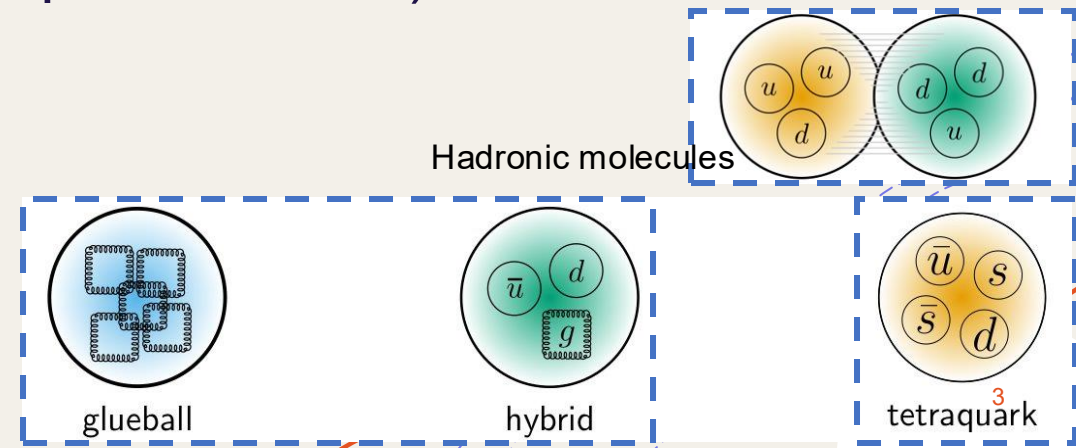
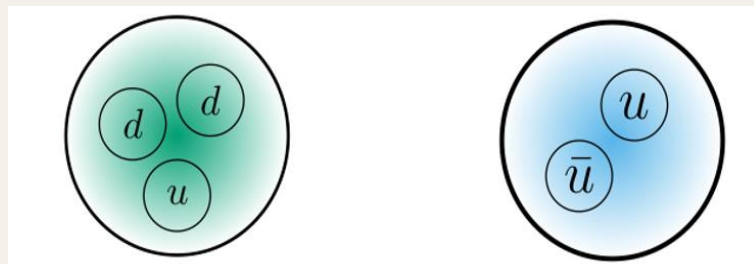
Outline

- + (Exotic) Hadron spectroscopy: an overview
- + Highlights of Hadron spectroscopy at Jlab: GlueX and MesonEx
- + Conclusions & Beyond

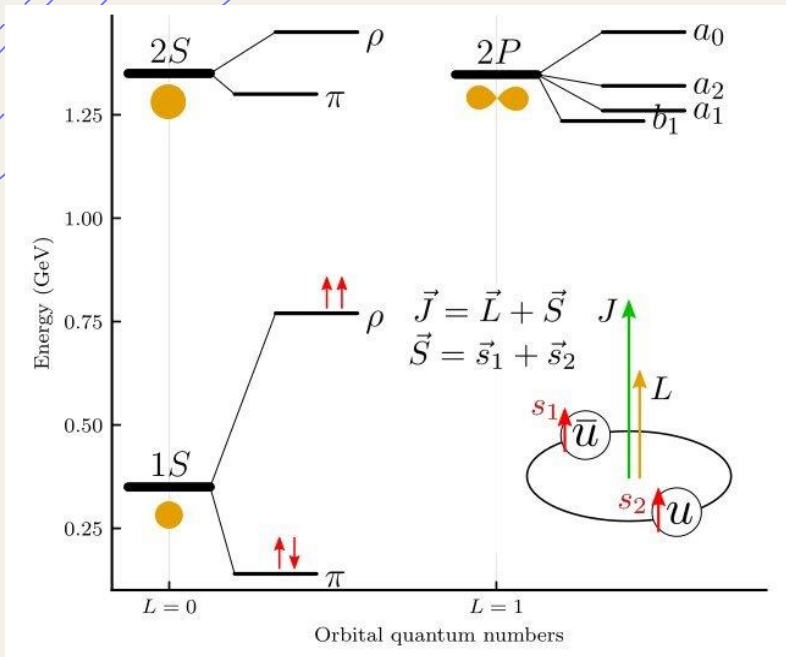


Why hadron spectroscopy is needed

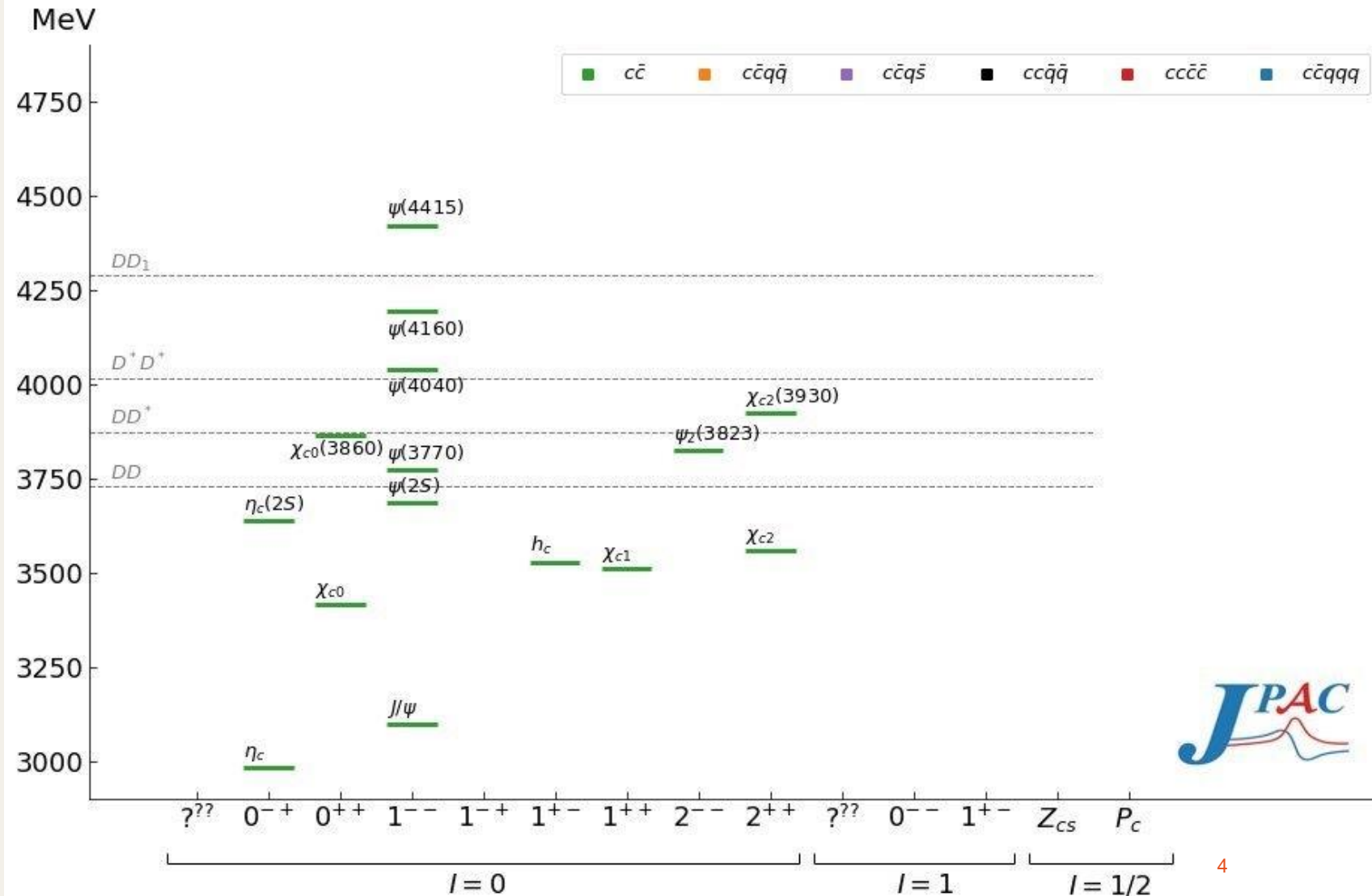
- + Is the study of the pattern of the excited states of hadrons (resonances)
- + Aim: shedding light on the low energy behaviour of strong interaction
- + Existence of charm quark, confinement, etc. come from this field
- + Before 2003: mesons as q -anti q and baryons as qqq
- + But then: $X(3872)$ first particle beyond ordinary quark model & a plethora of other "exotics" discovered since then (supernumerary states, spin-parity not allowed, cryptexotics, explicit exotic quark content)



Ordinary charmed mesons' spectrum

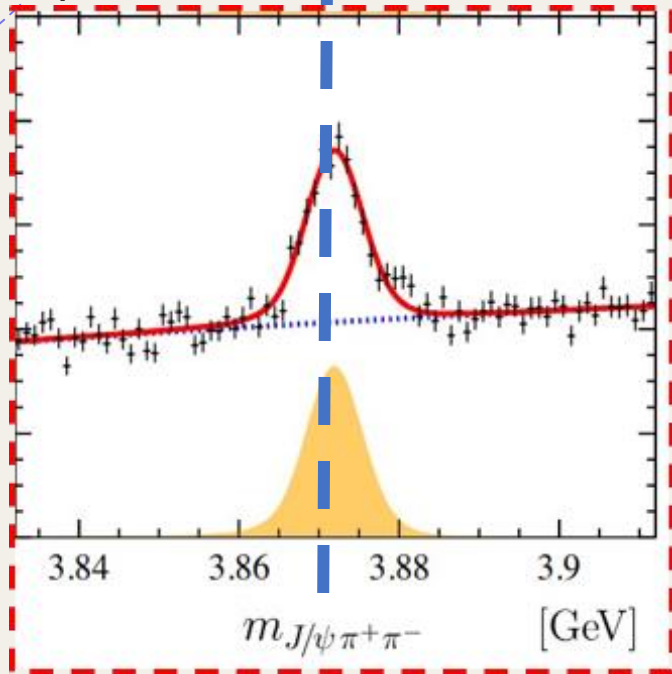


Study of qq system,
equivalently to the
hydrogen atom



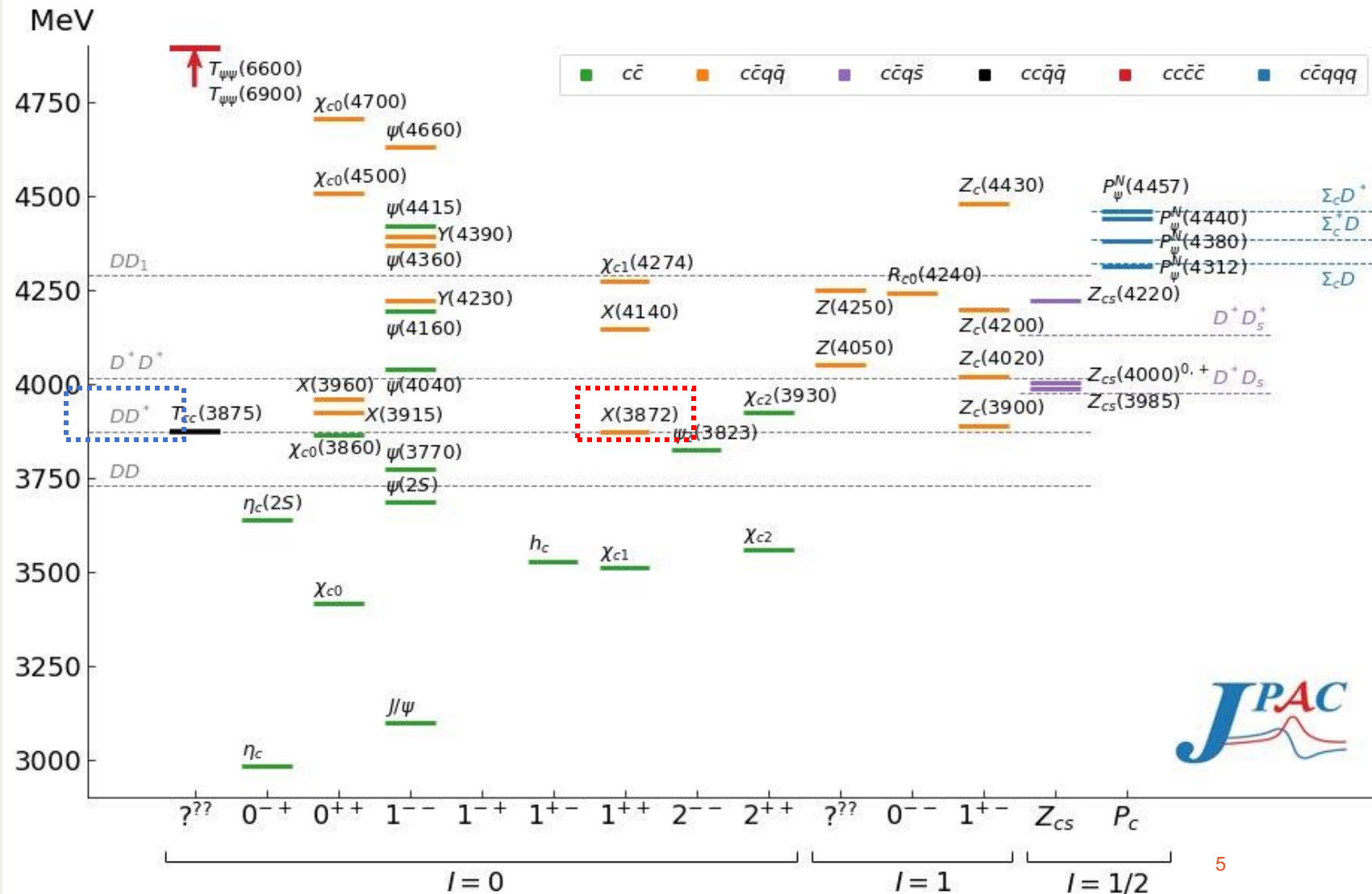
Current spectrum observed in the experiments

Proximity with DD threshold + Large isospin violation: is molecular hypotheses a viable explanation?



$$X \rightarrow J/\psi \omega$$

$$X \rightarrow J/\psi \rho$$



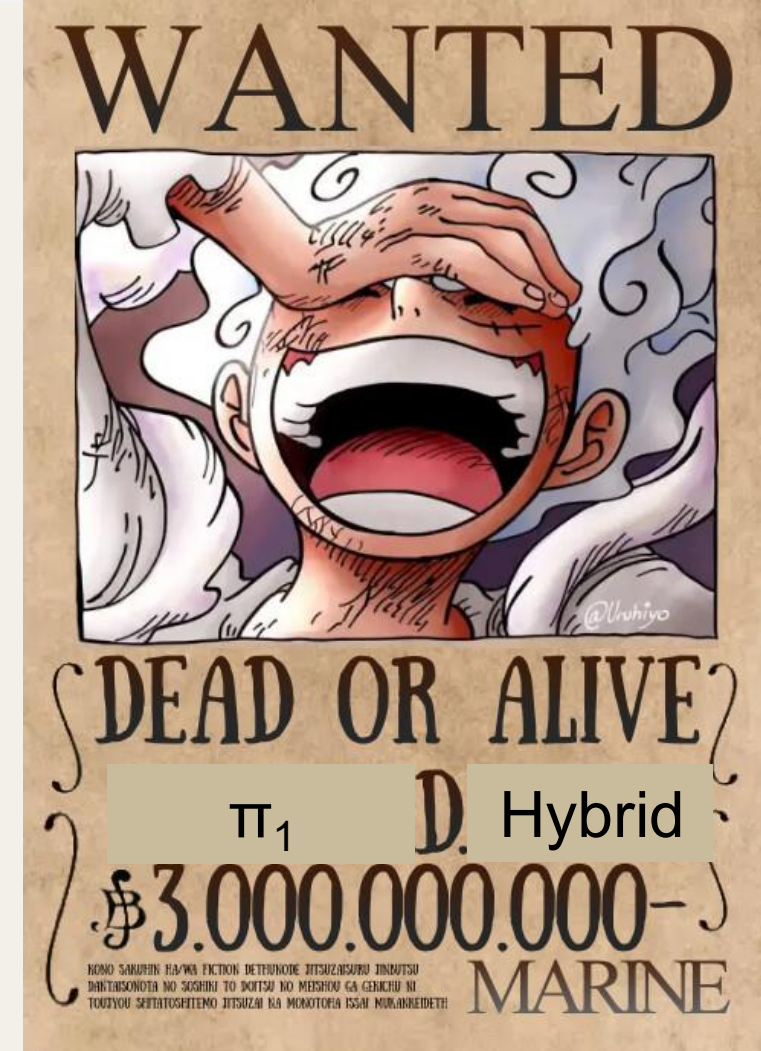
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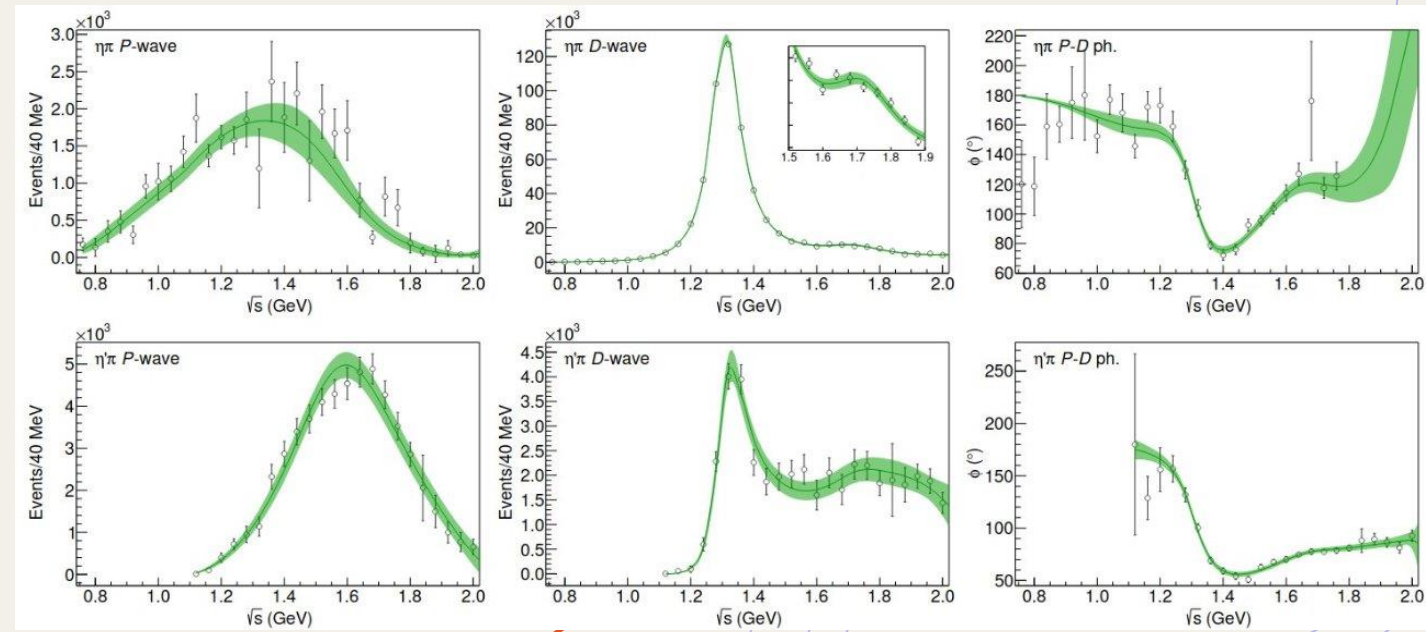
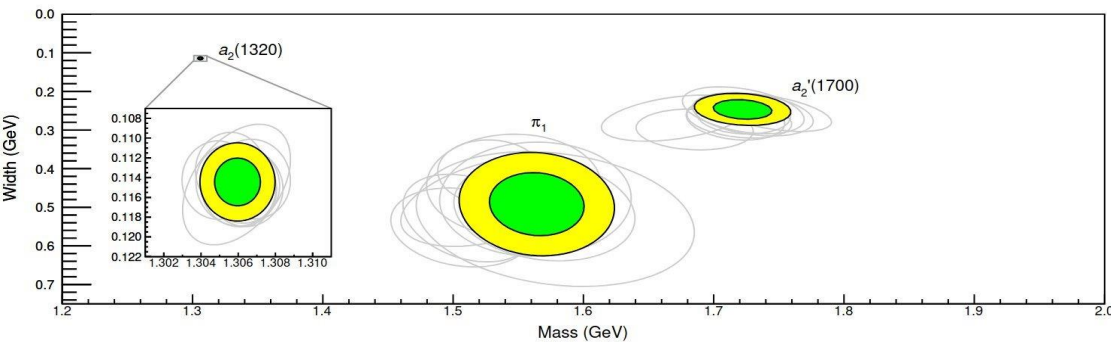
Chasing hybrids!

- + Hybrids are states with explicit excitations of the gluon field
- + The existence of a broad state with exotic quantum numbers $J^{PC} (I^G)=1^{-+} (1^{-})$ is supported by lattice and phenomenological QCD studies
- + Determination of hybrids properties provides a unique opportunity for a systematic study of low-energy gluon dynamic
- + This motivated COMPASS (CERN) program and the 12 GeV upgrade of JLab, with experiments dedicated to hybrid **photoproduction** (access to a wide variety of states & polarization acts as a filter) at CLAS12 and GlueX



The COMPASS case

- + The primary proton beam is steered on Be target producing secondary hadrons, mainly consisting of (anti-)protons, **pions** and kaons ~ 190 GeV
- + COMPASS experiment confirmed a peak in $\rho\pi$ and $\eta'\pi$ at around 1.6 GeV and an additional structure in $\eta\pi$, at ~ 1.4 GeV
- + The extraction of exotic signatures requires sophisticated partial-wave amplitude analyses (JPAC)
- + PDG: "Coupled channel analyses [Rodas et al.] favor the existence of only one broad isovector state consistent with in the MeV region"

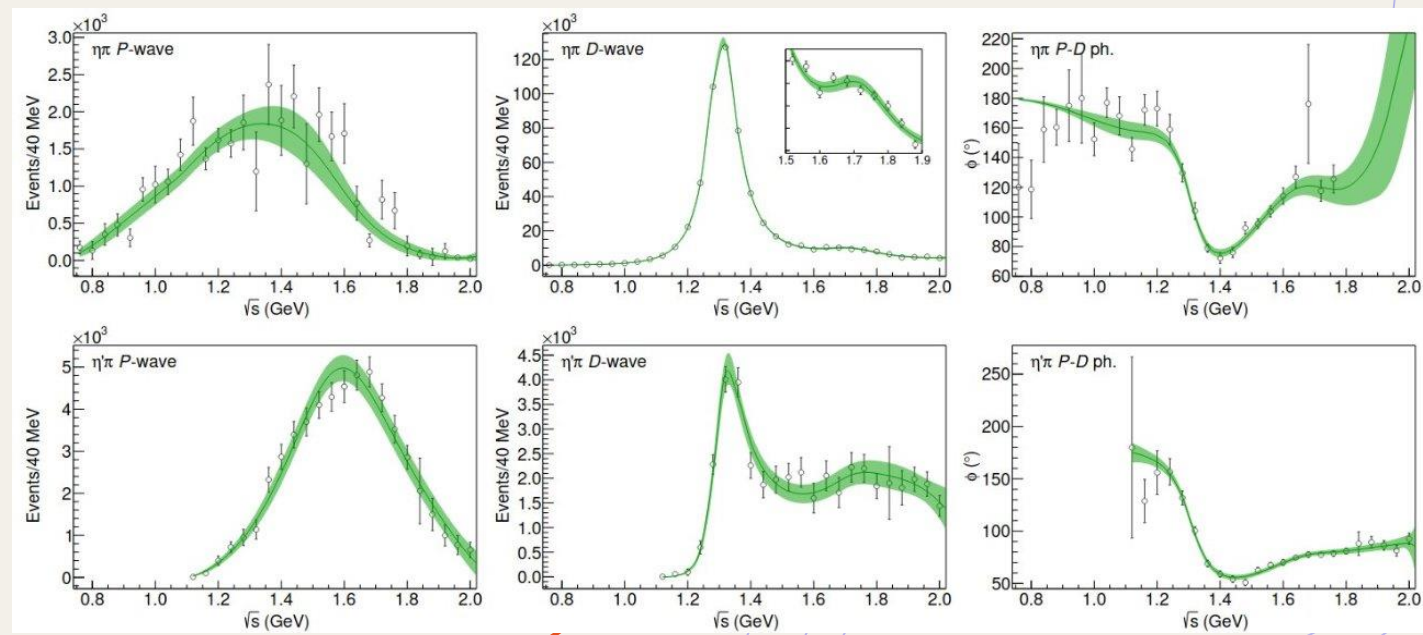
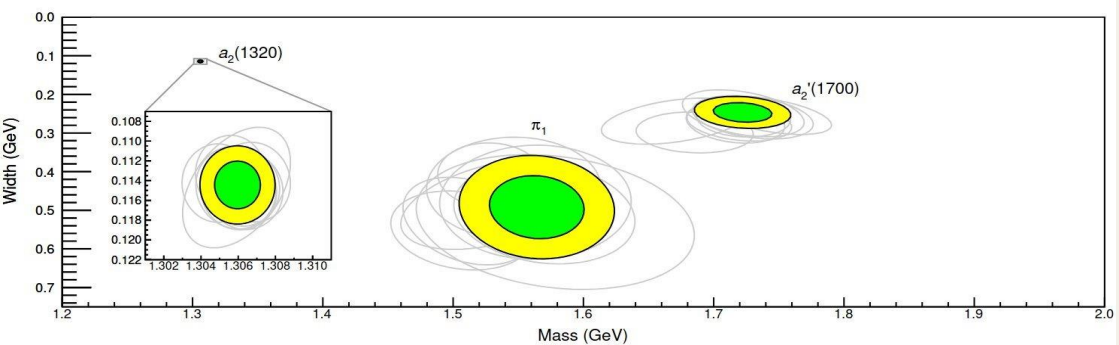


The COMPASS case

Solutions with two poles are possible, but:

- + fit quality does not improve the fit quality
- + the position of the second pole is unstable
- + peculiar behavior of the $\eta\pi$ phase in the > 2 GeV mass region, where no data exist

New data from GlueX and CLAS12 experiments at JLab in this and higher mass region needed

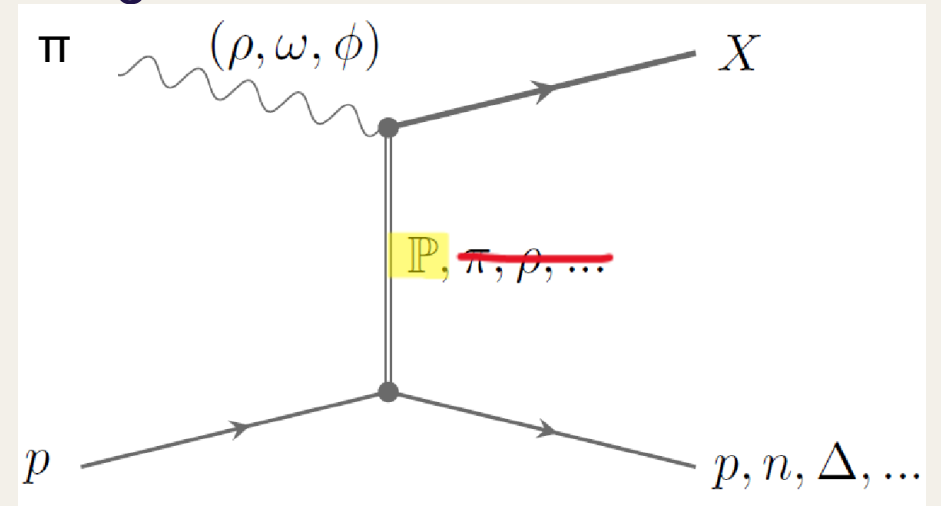


Understanding production mechanism is fundamental for many analyses

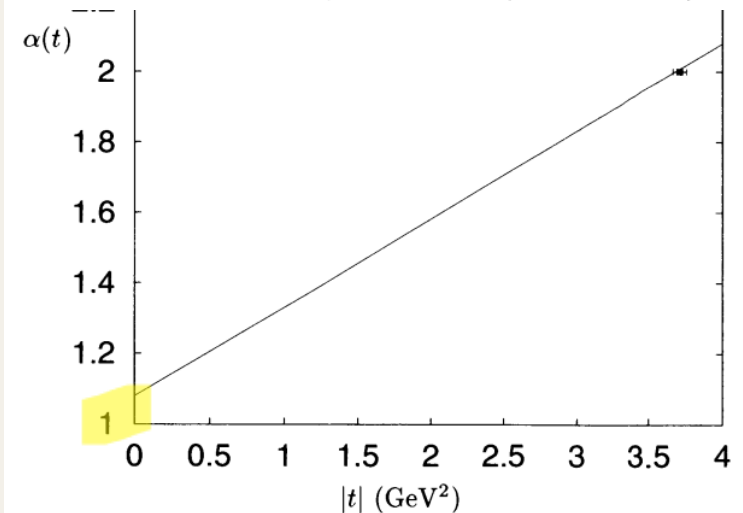
At COMPASS energies (pion beam $E \sim 190$ GeV), peripheral production of $\pi p \rightarrow \eta(\prime)\pi p$ can be modeled as a Pomeron (P) exchange:

- + The notion of Pomeron ("vacuum pole") exchange emerges from Regge theory
- + Regge theory tell us that for $s \rightarrow \infty$ and $-t \rightarrow 0$, the production amplitude can be modeled as $T(s,t) \sim \beta(t) s^{\alpha(t)}$
- + σ_{tot} is dominated by Pomeron exchange, because it has the highest intercept, $\alpha(t) = \alpha(0) + \alpha' t$:

$$\sigma_{\text{tot}} \underset{s \rightarrow \infty}{\simeq} \frac{1}{s} \text{Im} A(s, t = 0) \underset{s \rightarrow \infty}{\sim} s^{\alpha(0) - 1}$$



$\mathbb{P} : P = +1, C = +1, G = +1, I = 0, \xi = +1$



The challenging hybrids hunting at JLab

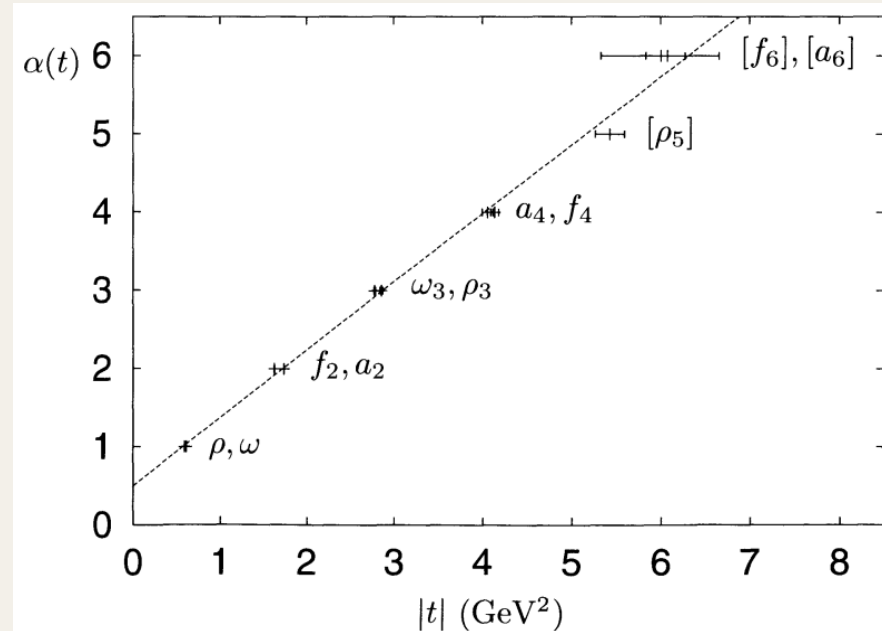
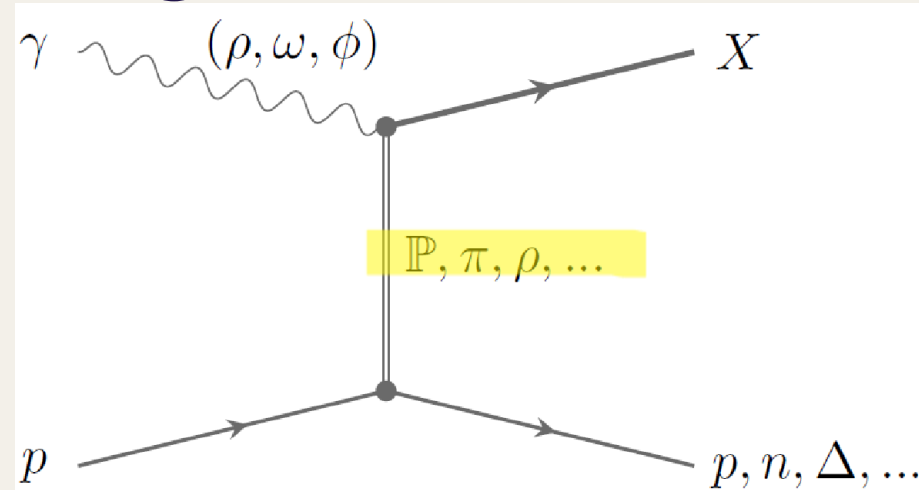
At JLab energies (e- beam $E \sim 12$ GeV) the situation is much more complicated because the previous single-pole approximation is no more realistic:

+ Other trajectories start to contribute

$$\sigma_{\text{tot}} \sim \sum_i A_i s^{\alpha_i(0)-1}$$

+ **A systematic approach is needed to understand production mechanisms whose complexity is progressively increasing**

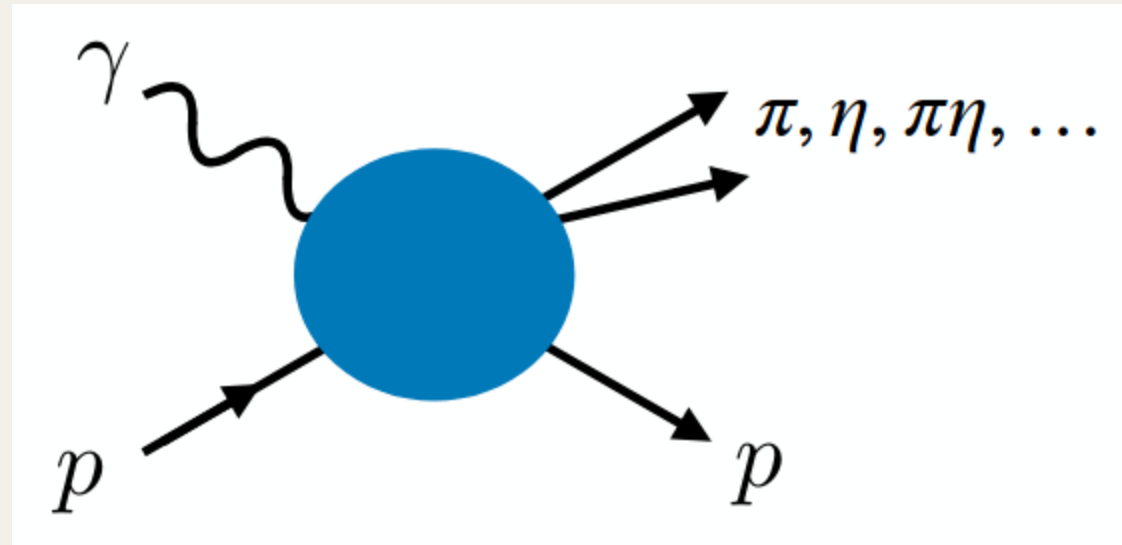
f_2 :	$P = +1, C = +1, G = +1, I = 0, \xi = +1,$
ρ :	$P = -1, C = -1, G = +1, I = 1, \xi = -1,$
ω :	$P = -1, C = -1, G = -1, I = 0, \xi = -1,$
a_2 :	$P = +1, C = +1, G = -1, I = 1, \xi = +1.$



Hadron spectroscopy program at JLab

Systematic increasing of complexity in studying the production mechanisms:

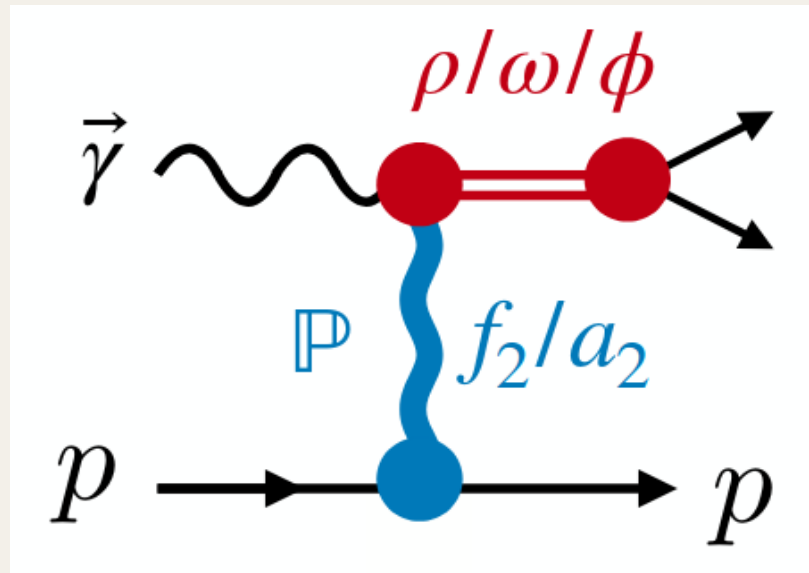
- + Top vertex: start with one meson production, and then two, three... and play with the spin: scalars, vectors, tensors



Hadron spectroscopy program at JLab

Systematic increasing of complexity in studying the production mechanisms:

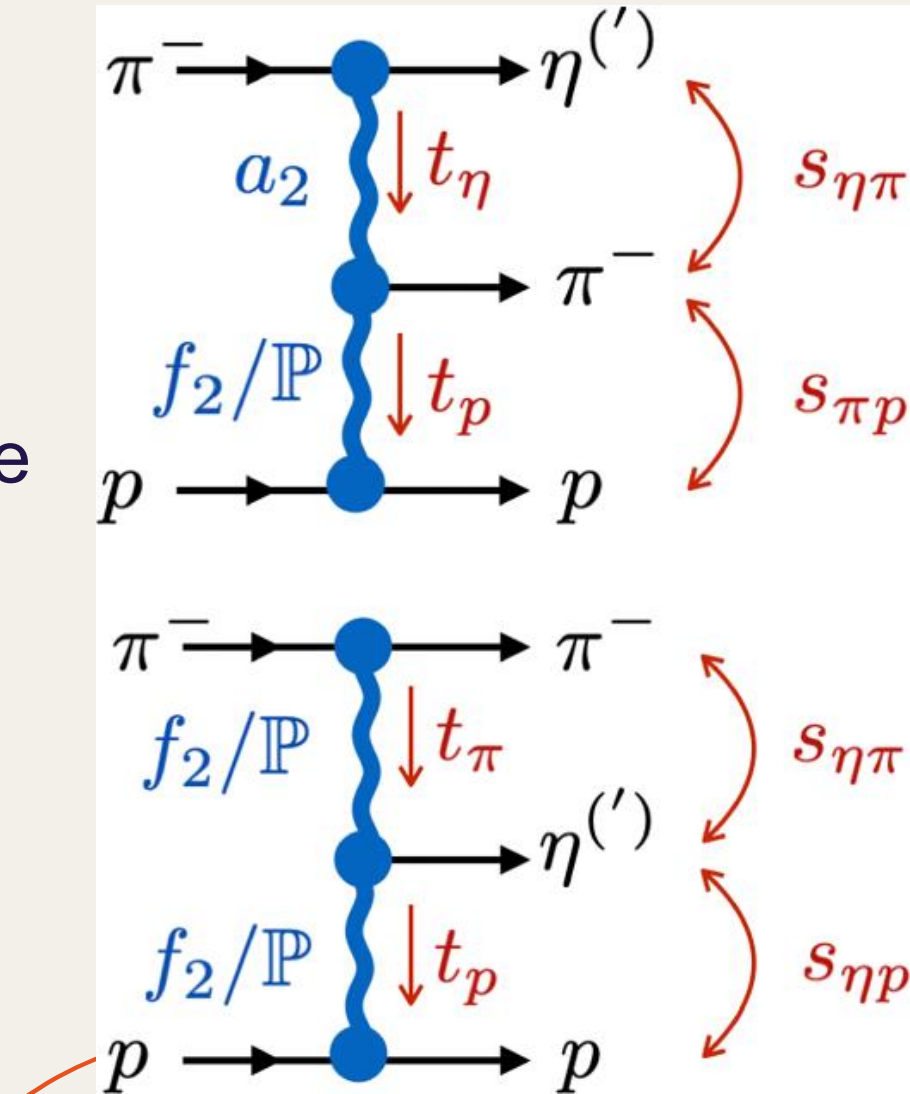
+ Top vertex: hit the resonance region in the top vertex



Hadron spectroscopy program at JLab

Systematic increasing of complexity in studying the production mechanisms:

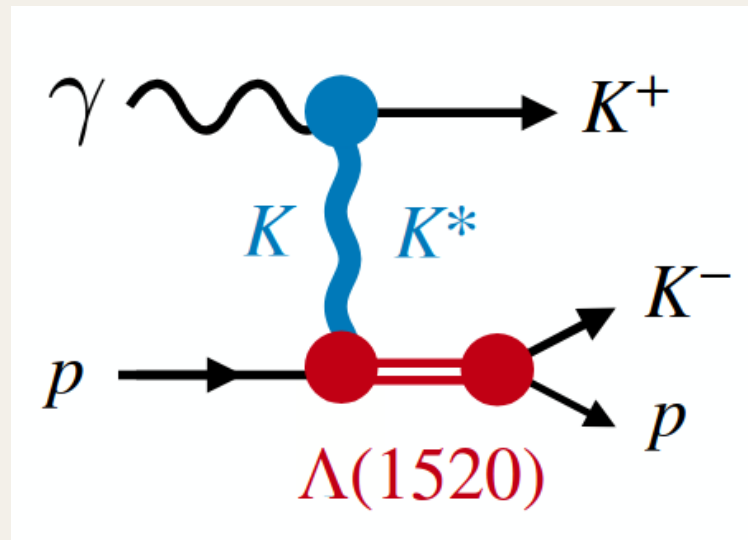
- + Top vertex: increase the invariant mass of the mesons' subsystem until Double Regge region



Hadron spectroscopy program at JLab

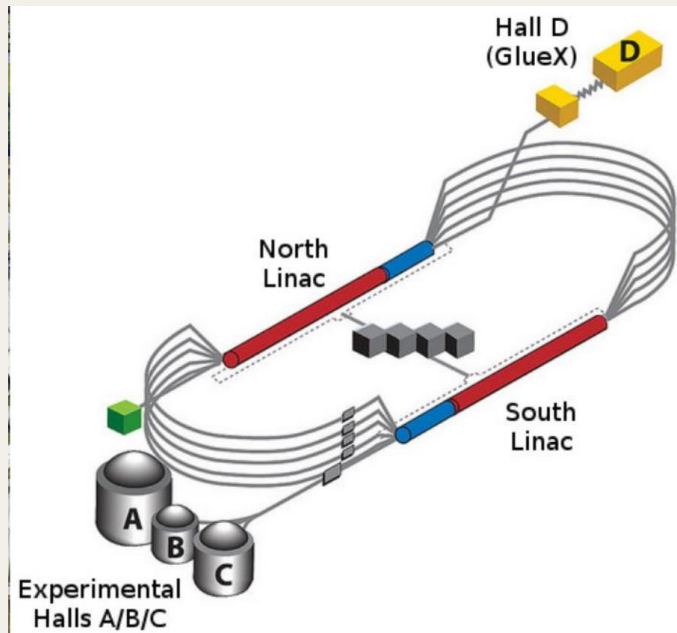
Systematic increasing of complexity in studying the production mechanisms:

+Bottom vertex: excite the target proton (baryon spectroscopy)

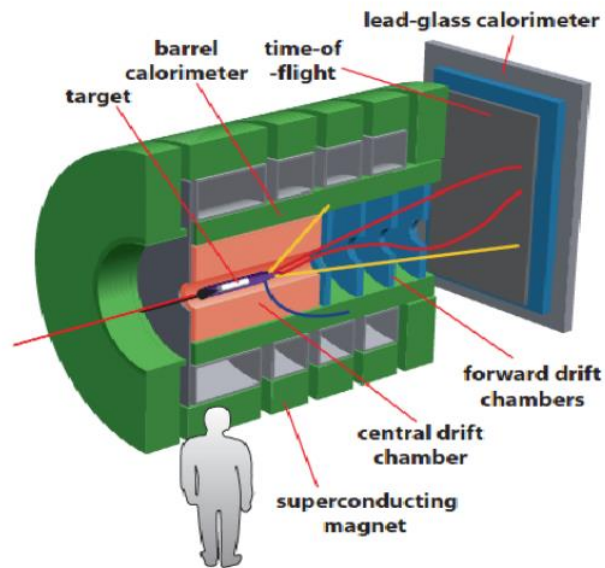


Complementary experiments to perform this analyses

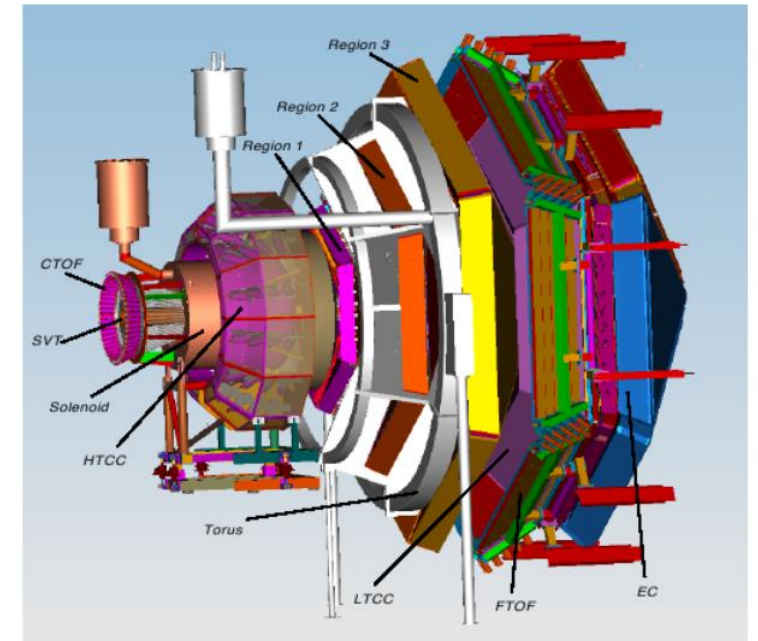
- + GlueX (Hall D): good for neutral particles detection, its main channel is $\eta(\prime)\pi$
- + MesonEx (CLAS12, Hall B): better performance in charged particles detection, 3π



GlueX Detector



CLAS12 Detector



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Current status & future directions

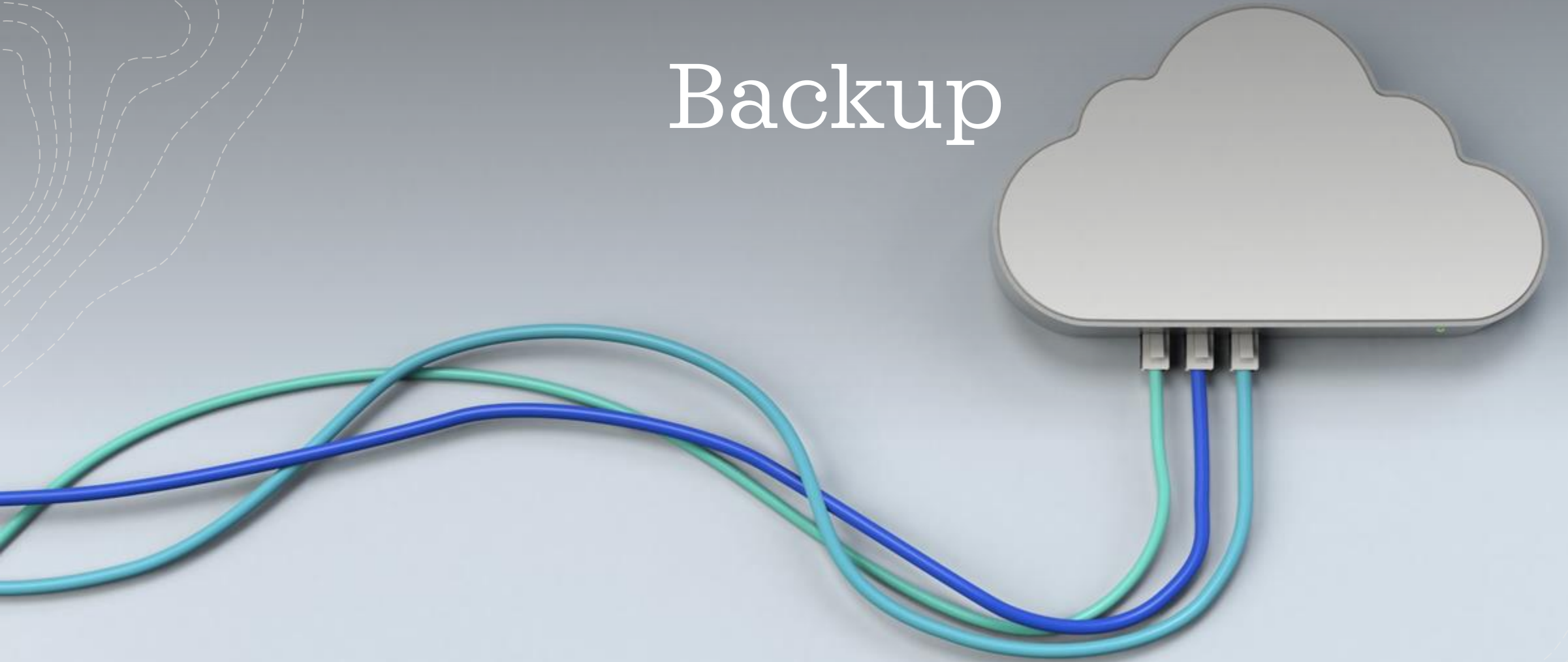


- + The systematic approach JLab is pursuing requires a joint effort from theorists and experimentalists, that is already well-established both for GlueX and CLAS collaborations
- + JPAC (Joint Physics Analyses Centre) was born to give theoretical support (S-matrix theory, Regge theory, amplitude analyses) to JLAB experiments; later expanded its range of interests to CERN (COMPASS, LHCb), B-factories, etc. e.g. an **amplitude analyses in the bottomonium sector**, using Belle (Japan) data
- + Actual status: GlueX already published some analyses, MesonEx not yet (currently dealing with 2π photo- and electro-production)
- + JLab spectroscopy program will be boosted by the planned upgrade from 12 to 22-24 GeV: multiquark candidates like the X(3872) will be accessible, matching JPAC theoretical interests (e.g. Developing an **S-matrix multi-particle formalism suitable for the X(3872)**)
- + AI is a tool we want to explore for many purposes: e.g. AiDAPT collaboration is applying **generative AI models for unfolding data**, amplitude analyses, data preservation



Thank you for your kind attention!

Backup



Hadron spectroscopy at Jlab: MesonEX

- The program goal is to probe the **spectrum** of excited meson states, in particular of **exotics** (pentaquarks, hybrids with extra constituent gluons),
to understand how quarks and gluons bind inside hadrons

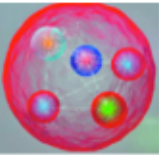
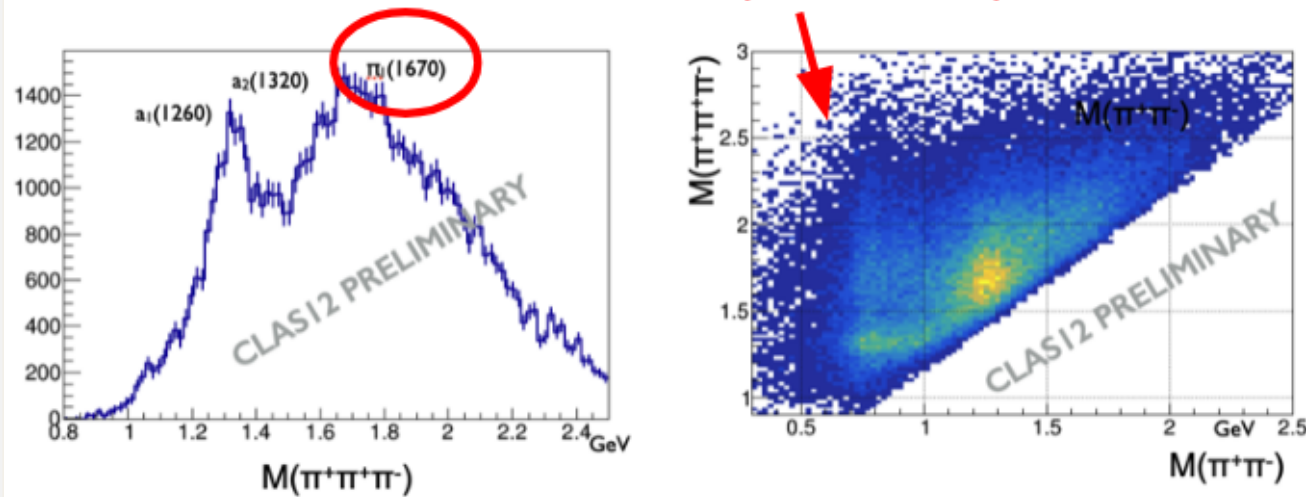
Example 1: $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$

Example 2: $\gamma p \rightarrow J/\psi p$

COMPASS has seen a hybrid $\pi_1(1670) \rightarrow 3\pi$
Needs confirmation in photoproduction
Sophisticated PW analysis to separate it

LHCb has observed pentaquarks in $J/\psi p$
Need confirmation in photoproduction
The channel is also used to extract
proton gravitational properties

Rich substructures, needs complicated amplitude model



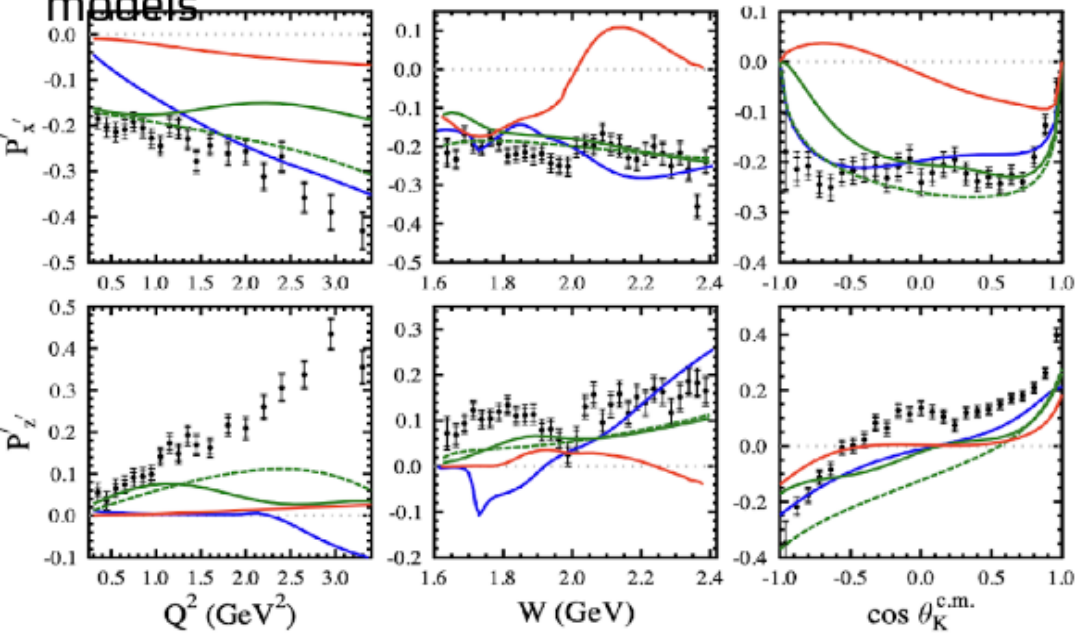
Requirements:

- 4π detector
- High intensity electron beam at 10 GeV
- Forward tagger to tag quasi-real photons

Hadron spectroscopy at Jlab: the N* and KY program

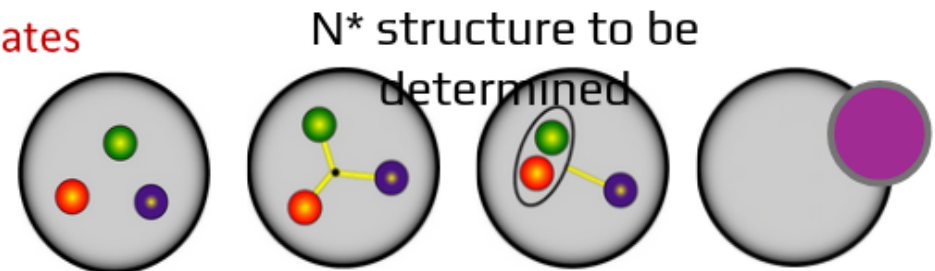
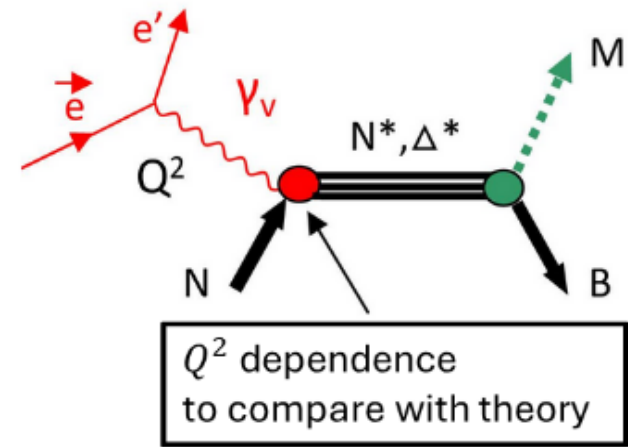
- The program goal is to probe the **spectrum** of excited baryons, and how it changes with the photon virtuality Q^2
- One can study excited nucleons (N*) and strange baryons (KY)
- The Q^2 dependence tell us how to distinguish ordinary and exotic baryons

The baryon spectrum is complicated
 new data on polarization observables can improve theoretical models.



D.S. Carman et al. (CLAS),
 PRC 105, 065201 (2022)

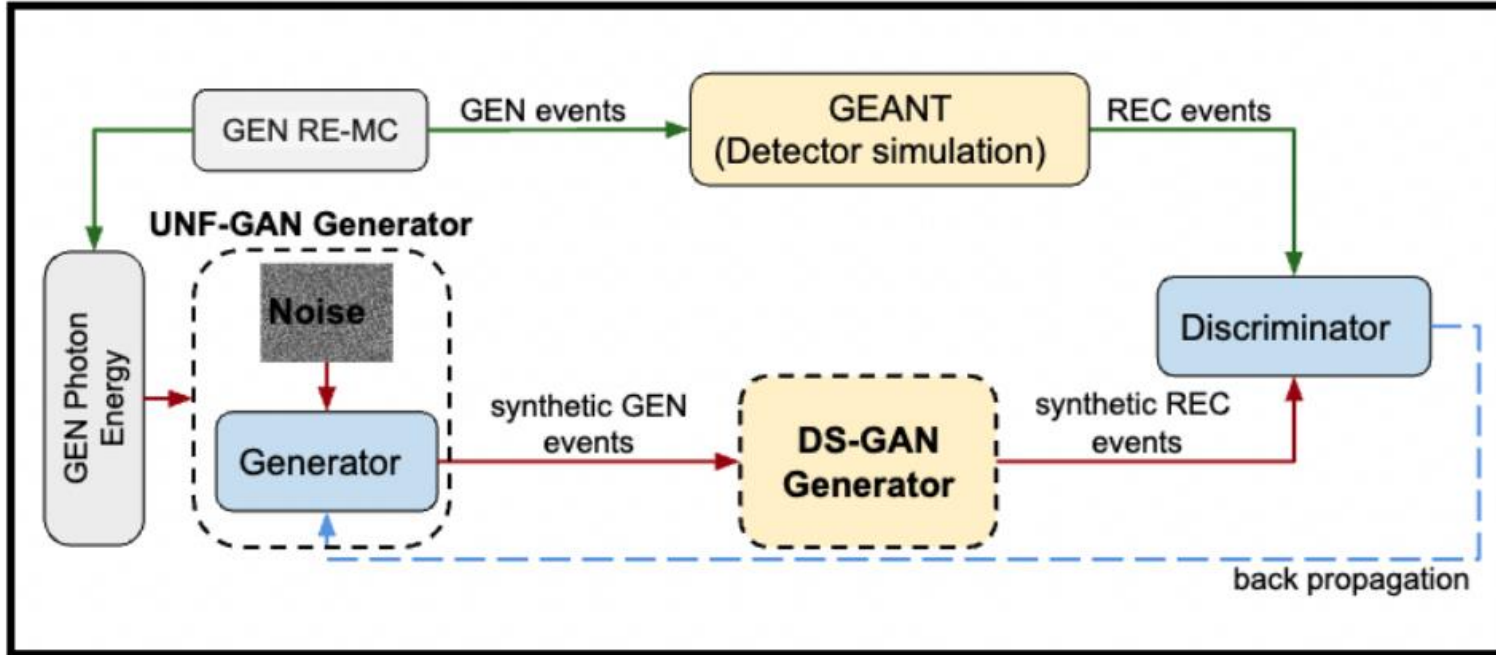
Polarization of Δ in
 $ep \rightarrow e' \Lambda K^+$
 Models could not predict it
 correctly and need updates



N* structure to be determined

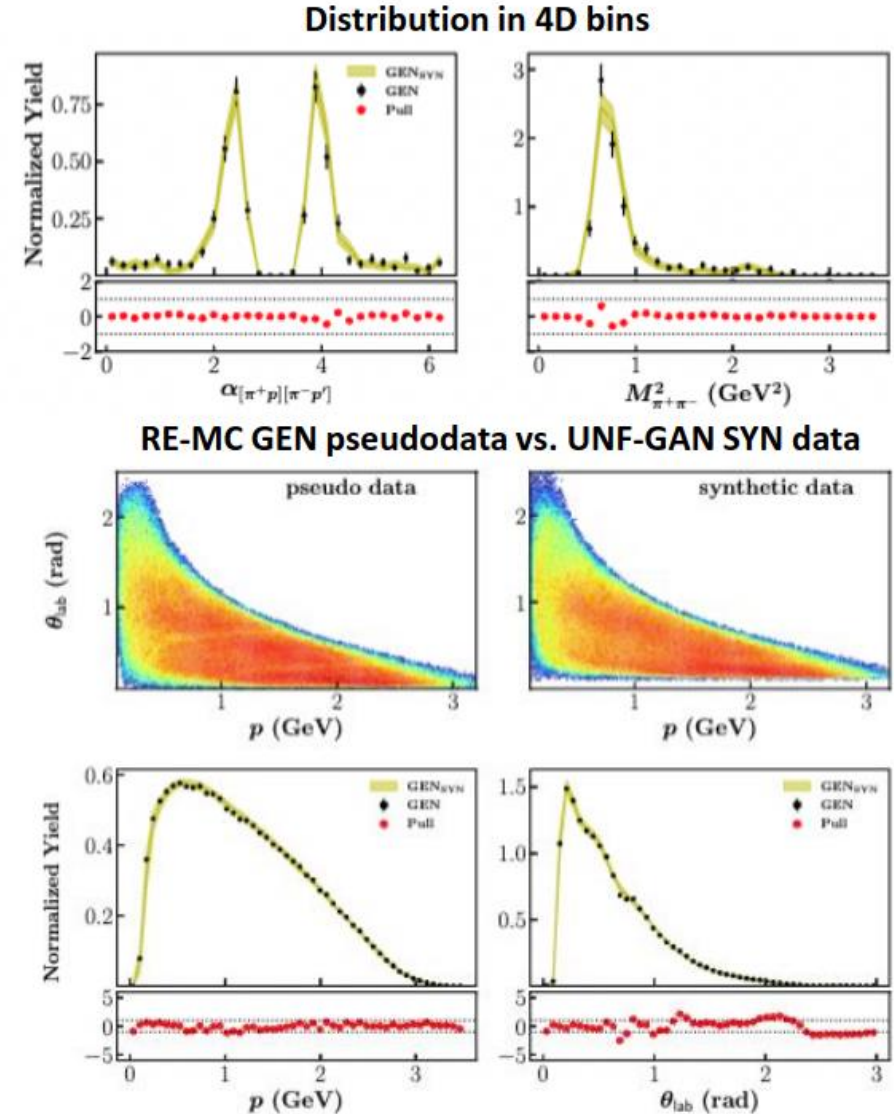
2π photoproduction closure test

- Deploy the unfolding GAN (UNF-GAN) that includes the DS-GAN and train it with RE-MC REC pseudodata
 - UNF-GAN trained with REC-MC pseudodata (experimental data proxy)
 - DS-GAN used to unfold CLAS detector effects (within acceptance)

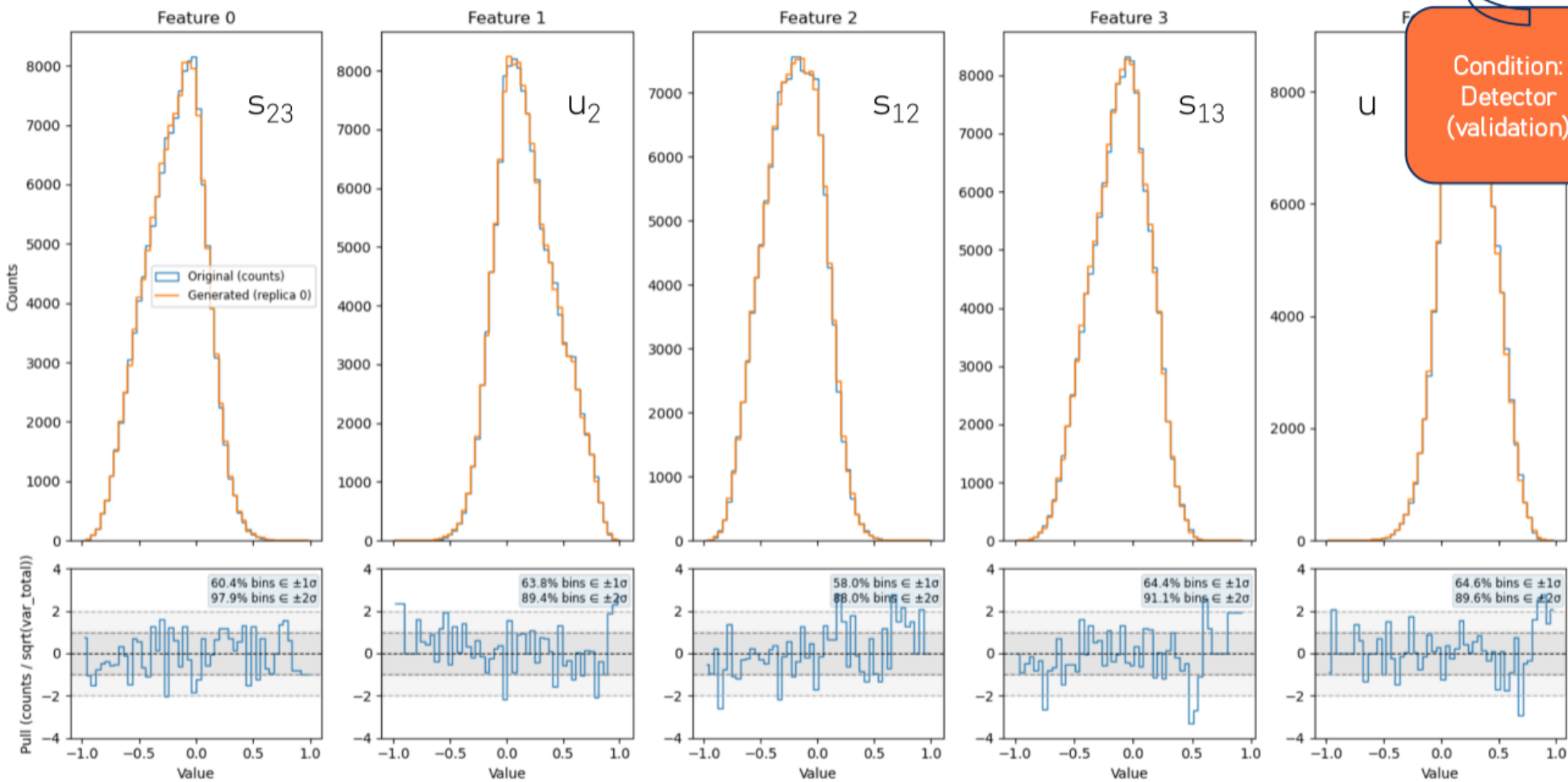
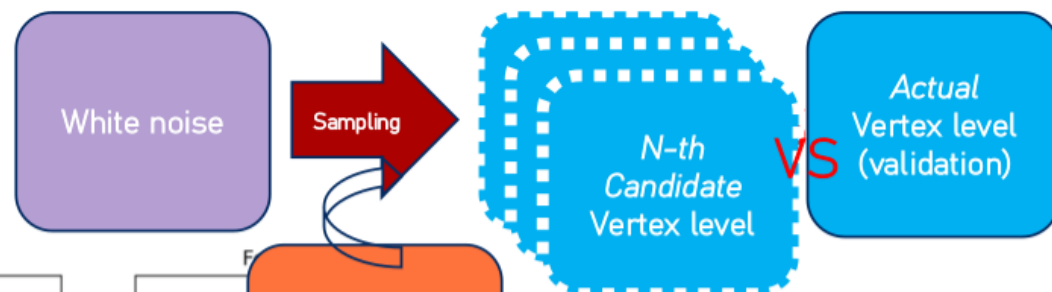


- Compare UNF-GAN GEN SYNT to RE-MC GEN pseudodata

Good agreement ($\pm 1\sigma$) for lab variables and in 4D bins



Current status of the project



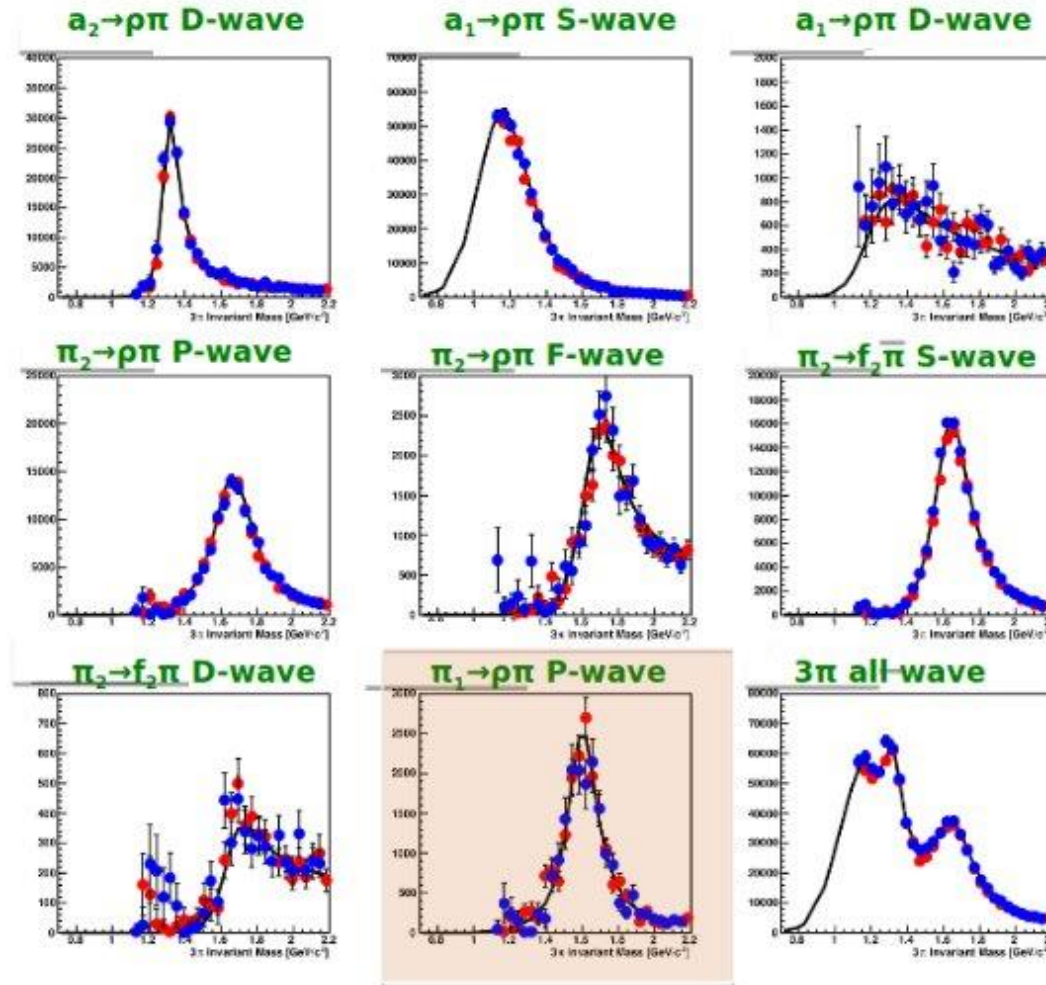
- This is a set of vertex replicas generated from the same detector level
- The statistical error associated to the sampling procedure is \ll statistical error
- The KS p-value is stably > 0.05 within the whole bunch of replicas

Feature 0: KS p-value mean=0.6699, 16-84% = [0.6121, 0.7614]
 Feature 1: KS p-value mean=0.6958, 16-84% = [0.6280, 0.7498]
 Feature 2: KS p-value mean=0.2347, 16-84% = [0.1418, 0.3123]
 Feature 3: KS p-value mean=0.8966, 16-84% = [0.8750, 0.9413]
 Feature 4: KS p-value mean=0.4086, 16-84% = [0.3372, 0.4870]

Benchmark 3π Simulations

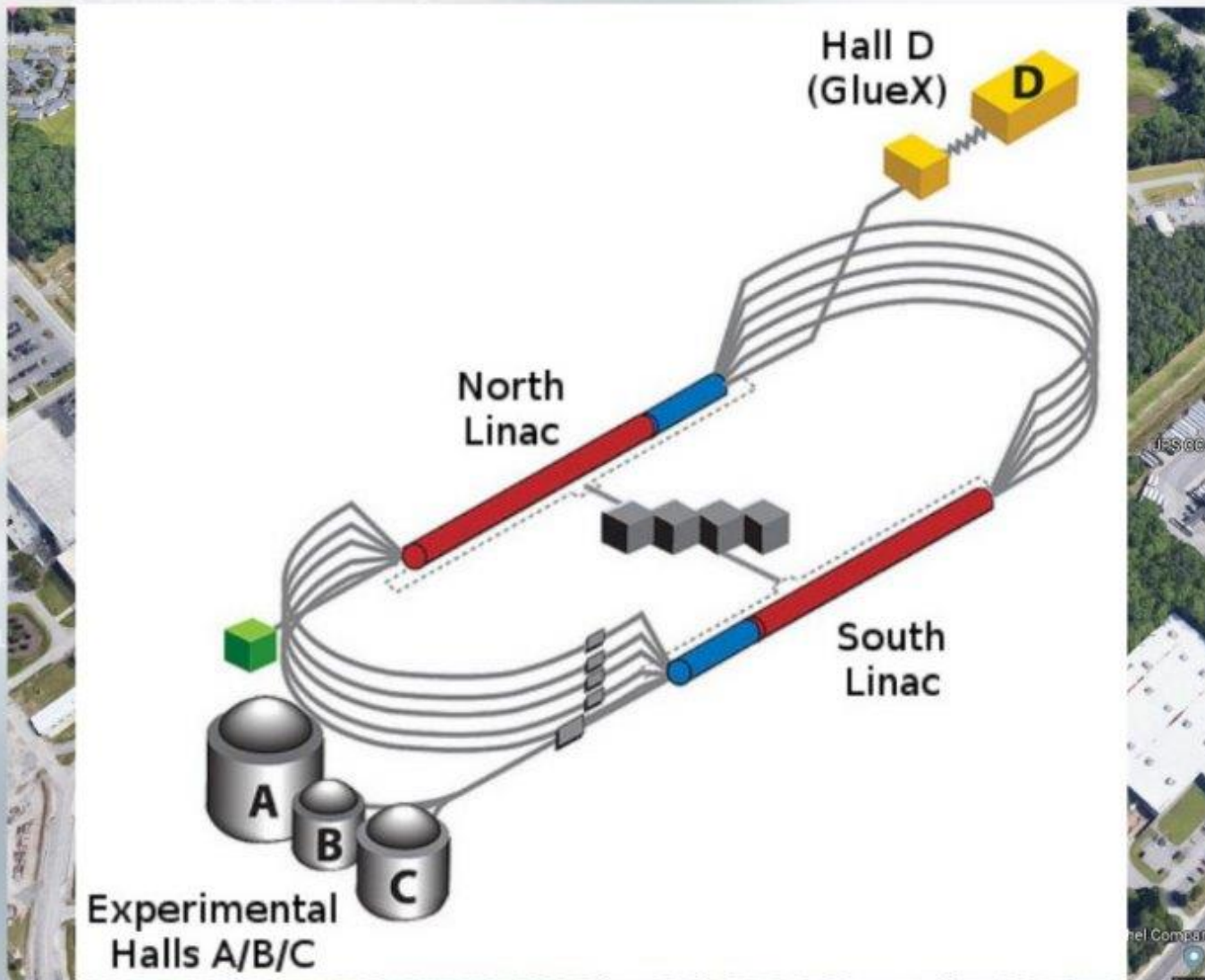
Meson spectroscopy in the light-quark sector:

- Investigating of the meson spectrum up to masses of 2.5 GeV
- Search for rare or poorly known states (strangeness-rich, scalars, ...)
- Search states with unconventional quark-gluon configurations

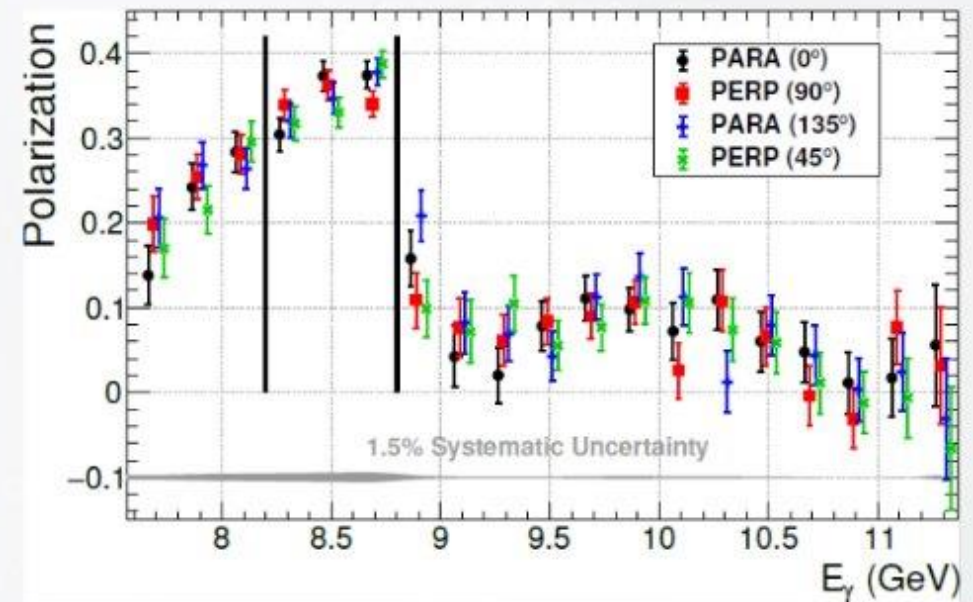


Note poor acceptance below 1.3GeV (half field)

Continuous Electron Beam Accelerator Facility



- Thomas Jefferson National Accelerator Facility in Newport News, Virginia, USA
- CEBAF delivers electron beam with energies up to 12 GeV
- Coherent Bremsstrahlung on thin diamond radiator
- Linear polarization: 40% in peak (8 - 9 GeV)
- Beam intensity up to $5 \times 10^7 \gamma/s$ in peak



JPAC publications on JLab physics (in this talk)

Single Meson Photoproduction:

$$\vec{\gamma}p \rightarrow \pi N$$

VM et al **PRD92 074013 (2015)**

VM et al **PRD98 014041 (2018)**

$$\vec{\gamma}p \rightarrow \eta p$$

Nys et al **PRD95 034014 (2017)**

VM et al **EPL122 41001 (2018)**

$$\vec{\gamma}p \rightarrow \eta' p$$

VM et al **PLB774 362 (2017)**

$$\vec{\gamma}p \rightarrow \pi\Delta$$

Nys et al **PLB779 77 (2018)**

Vector and Tenson Meson Photoproduction:

$$\vec{\gamma}p \rightarrow (\rho^0, \omega, \phi)p$$

VM et al **PRD97 094003 (2018)**

$$\vec{\gamma}p \rightarrow (f_2, a_2^0)p$$

VM et al **PRD102 014003 (2020)**

Double Mesons Photoproduction:

$$\vec{\gamma}p \rightarrow \eta\pi p$$

VM et al **PRD100 054017 (2019)**

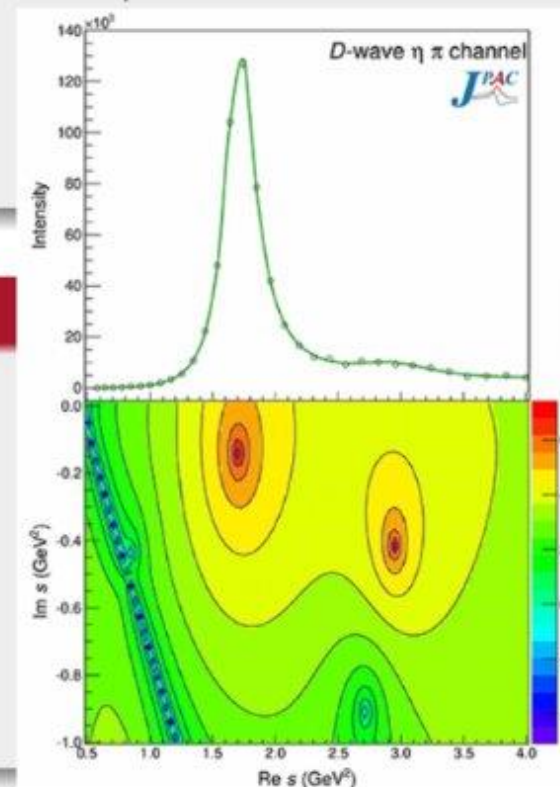
2 publications with GlueX and 3 publications with CLAS

Simulations and codes available: <http://www.jpac-physics.org/>

Step 1: Mass-Independent Partial-Wave Analysis

- Partial wave $\psi_w(\tau)$: Complex-valued amplitude which describes angular distribution of decay products
- Constant in a narrow mass bin: model-independent
- Total intensity distribution \mathcal{I} in each mass bin: coherent sum of amplitudes with production coefficients T_w

$$\mathcal{I}(\tau) = \left| \sum_w T_w \psi_w(\tau) \right|^2$$



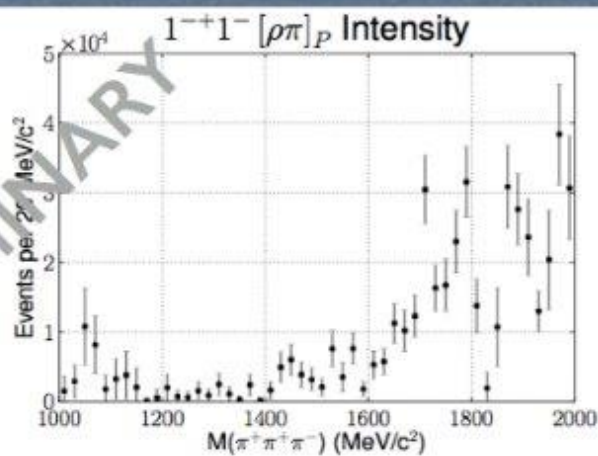
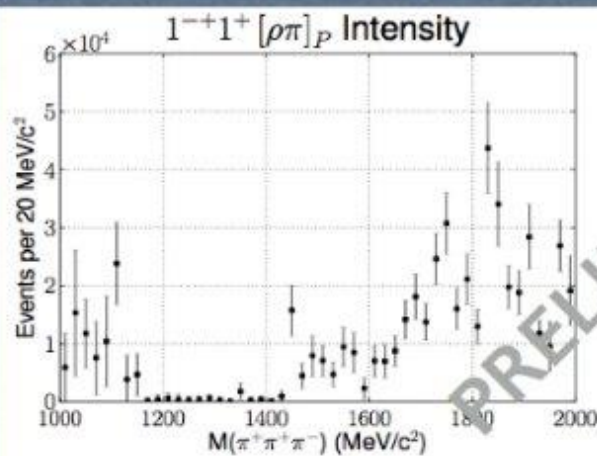
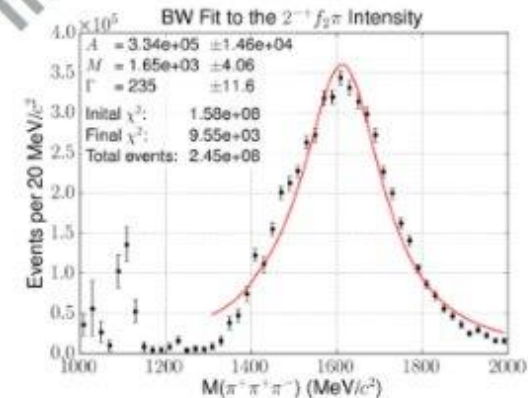
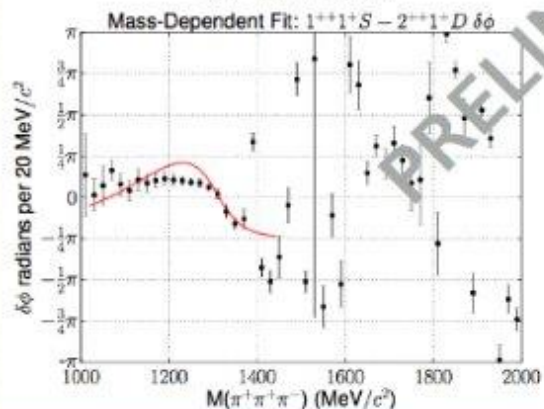
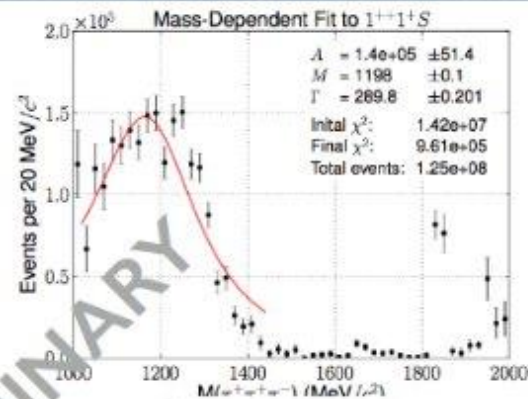
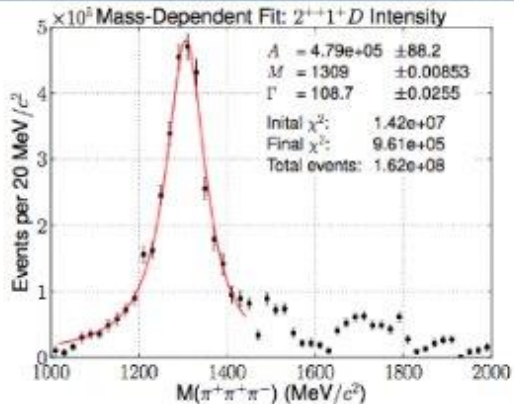
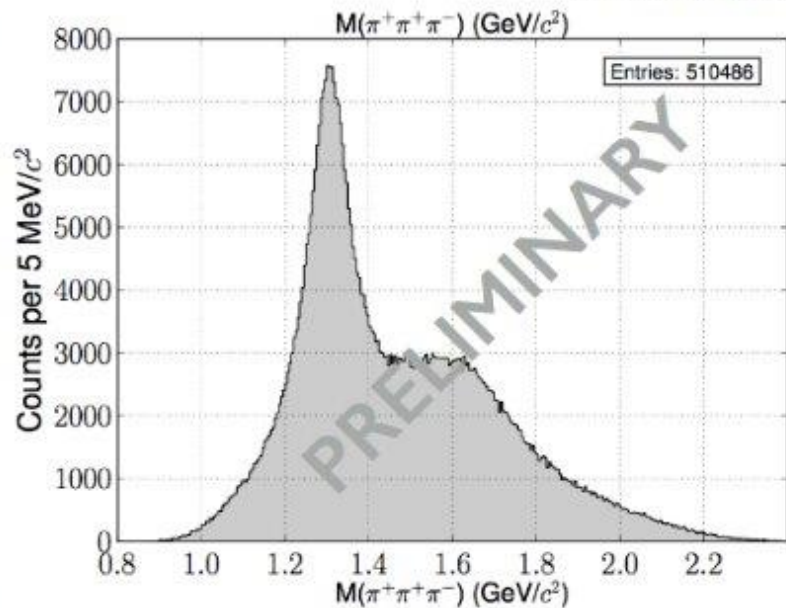
Step 2: Model for Mass Dependence for Results from Step 1

- Breit-Wigner function for narrow, isolated resonances
- Approximations for coupled channels: Flatté, K-matrix, ...
- Amplitudes for dynamical effects: triangle singularity, ...
- Treatment of background

Extraction of physical quantities: pole positions, coupling constants

The 3π system from CLAS-g12 data set

C.Bookwalter (FSU)



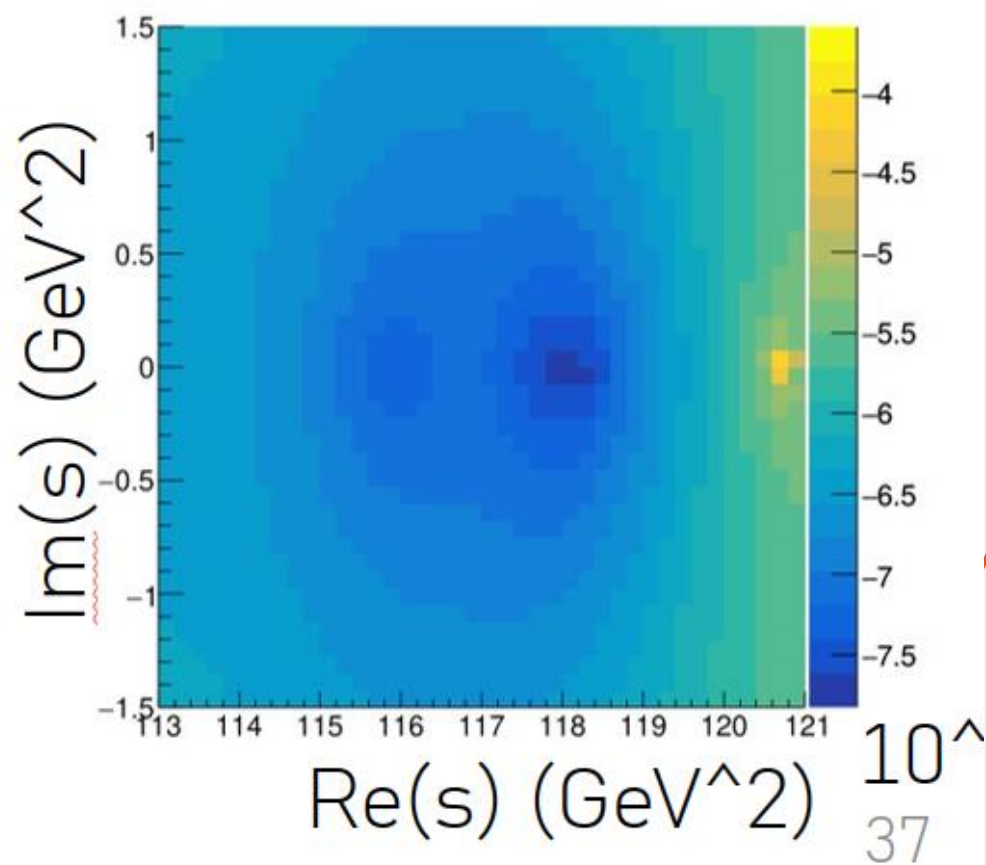
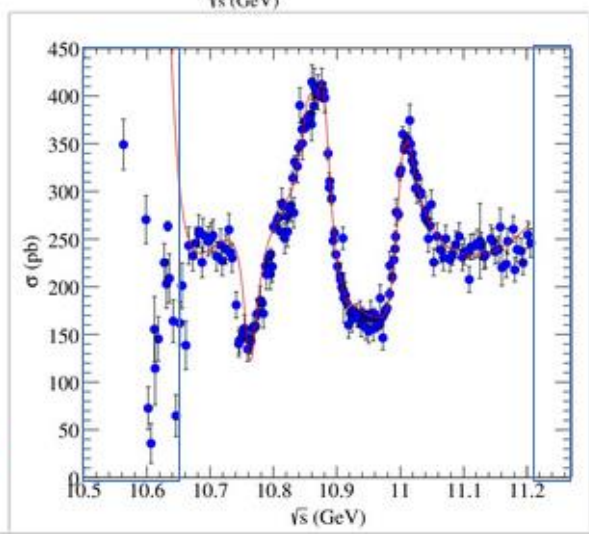
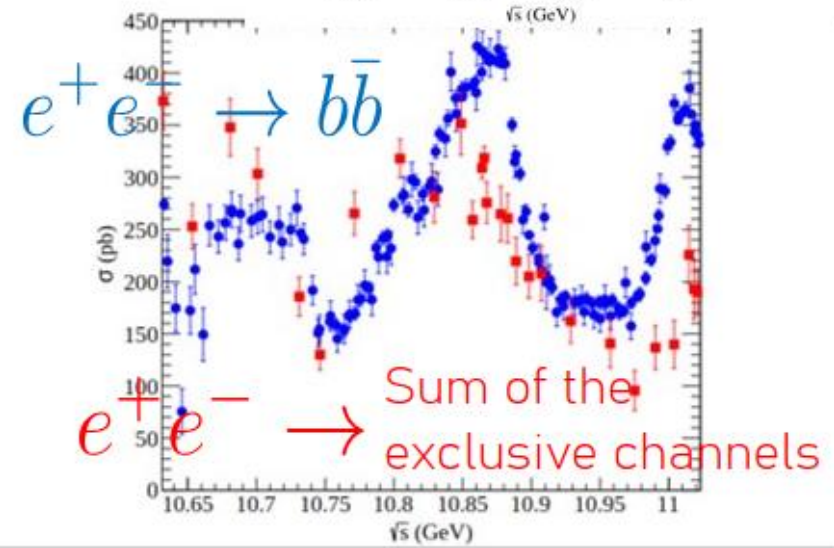
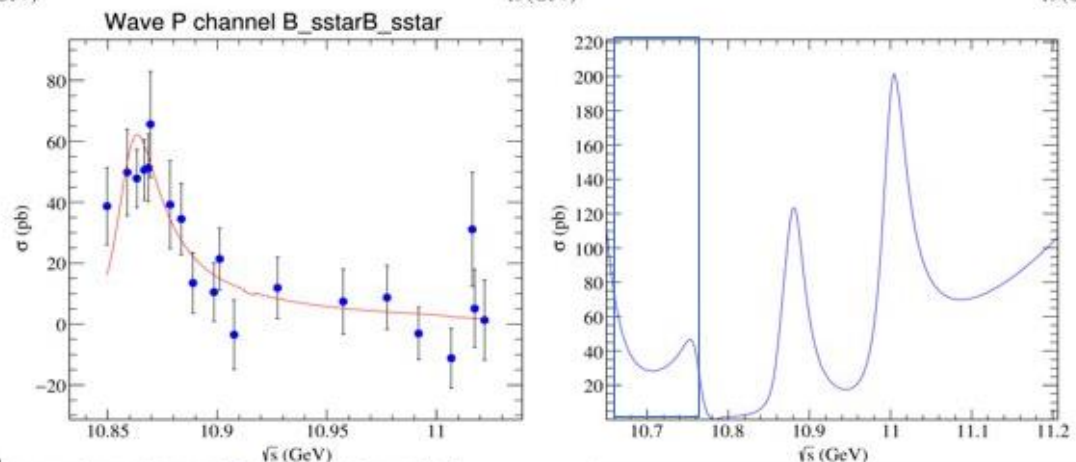
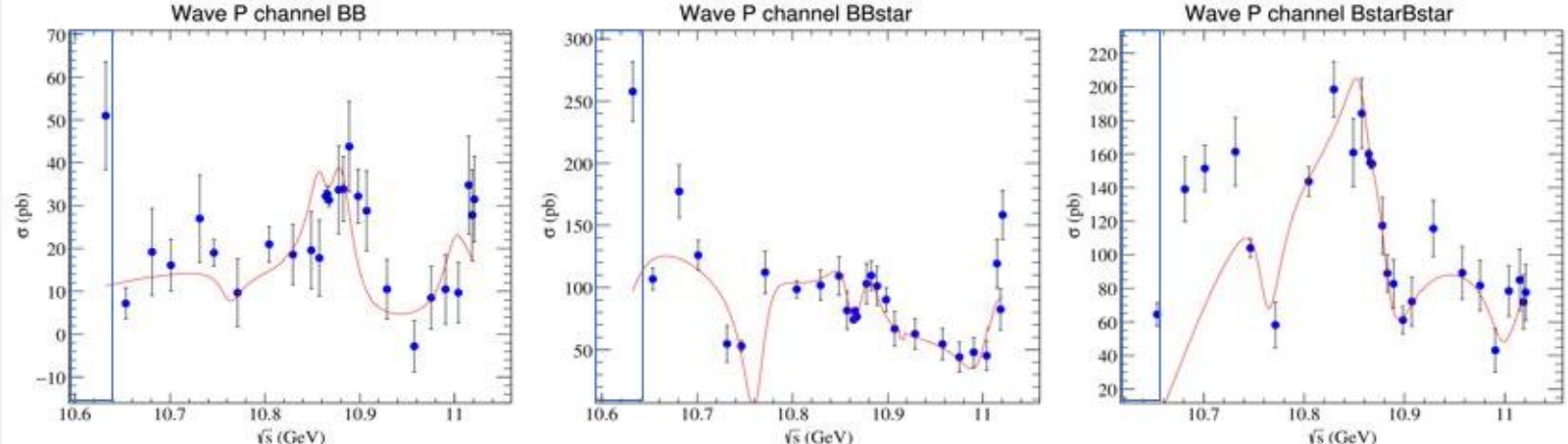
Evidence of dominant resonances and no-evidence of exotic state confirmed

PWA in CLAS is feasible!

Needs to have higher energy, higher statistics and and test other final states

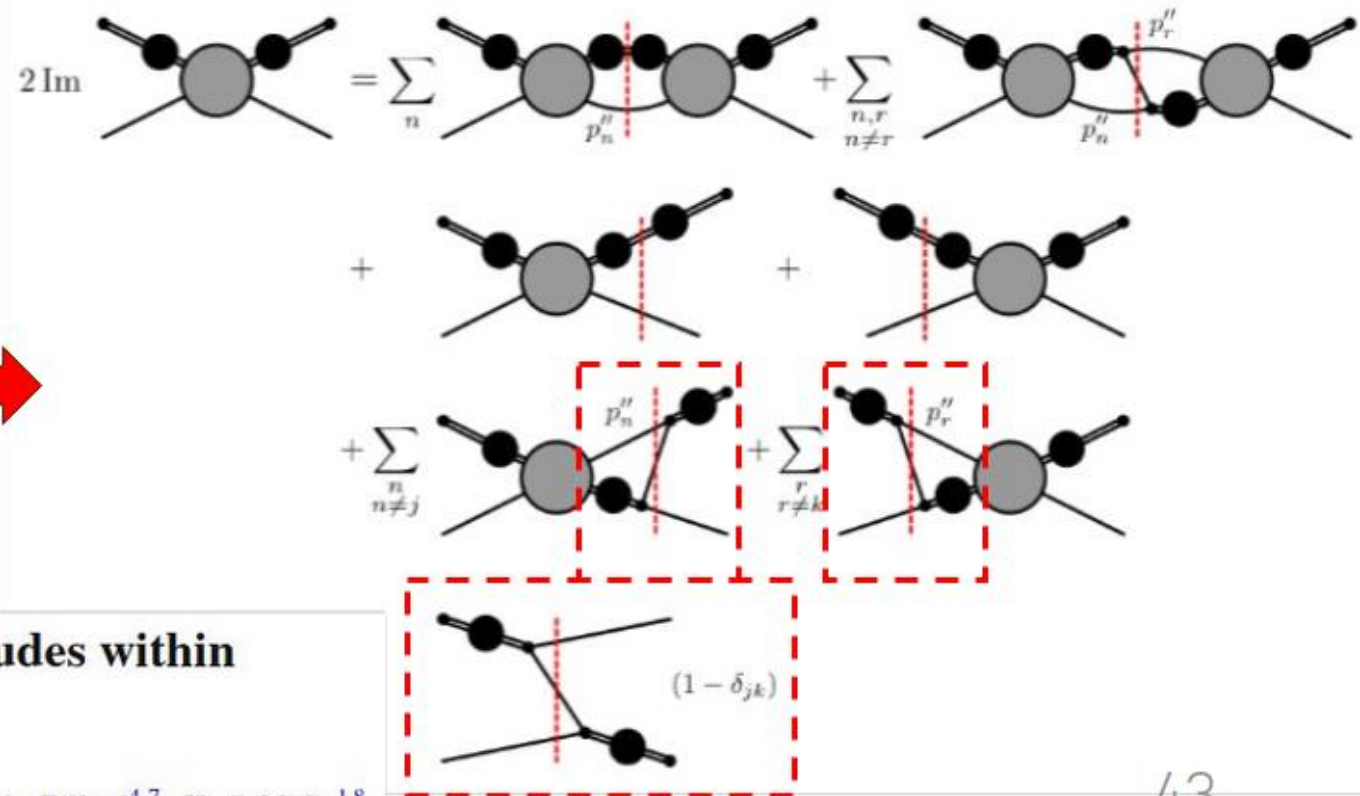
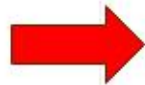
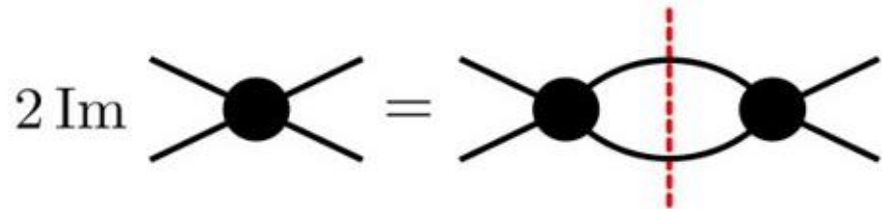
→ CLAS12

Fit + pole search procedure: preliminary results



3-BODY UNITARITY

$$2 \operatorname{Im} T(s, t) = \sum_{\text{physical}} T_{i \rightarrow n} T_{n \rightarrow f}^\dagger$$



Phenomenology of relativistic $3 \rightarrow 3$ reaction amplitudes within the isobar approximation