Meson spectroscopy at Jefferson Lab

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What we do not know

1. **What is the nature of the mass of hadrons?**

   Quarks account for only a small fraction of the mass of the proton (m_u=1.7-3.3 MeV, m_d=4.1-5.8 MeV): what leads to the ~GeV mass?

2. **Which are the relevant degrees of freedom?**

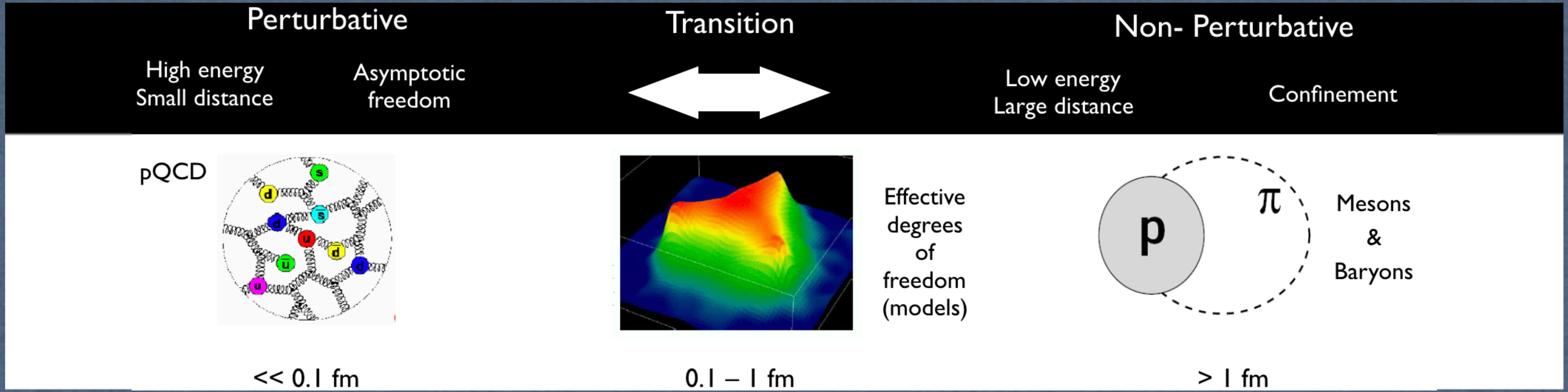
   At high energy, phenomena can be described in terms of quarks and gluons; at low energy, we observed baryons and mesons: what are the real degrees of freedom, and how does the transition from small to large distances occur?

3. **What is the origin of confinement?**

   Are quarks confined within colorless objects? Can we prove and explain it?

4. **Do quark configurations beyond qqq and qq-bar exist?**

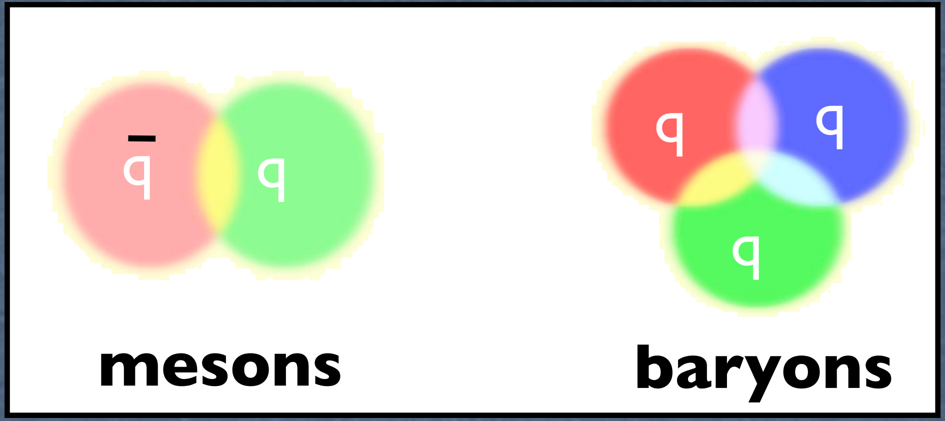
   The theory of strong interactions does not prohibit hadronic states with different quark configurations (*5q, gg, 2qg*). Can we find evidence of the existence of such states?



Studying the spectrum of hadrons is a fundamental step to understanding the characteristics of constituents and forces

What we know

Observed mesons and baryons well described by 1st principles QCD



Quarks are confined inside colorless hadrons
they combine to 'neutralize' color force

X	Experimental *(28)*	M_X (Ξ set)	M_X (Ω set)
ρ	0.775	0.775 (29) (13)	0.778 (30) (33)
*K**	0.894	0.906 (14) (4)	0.907 (15) (8)
N	0.939	0.936 (25) (22)	0.953 (29) (19)
Λ	1.116	1.114 (15) (5)	1.103 (23) (10)
Σ	1.191	1.169 (18) (15)	1.157 (25) (15)
Ξ	1.318	1.318	1.317 (16) (13)
Δ	1.232	1.248 (97) (61)	1.234 (82) (81)
Σ*	1.385	1.427 (46) (35)	1.404 (38) (27)
Ξ*	1.533	1.565 (26) (15)	1.561 (15) (15)
Ω	1.672	1.676 (20) (15)	1.672

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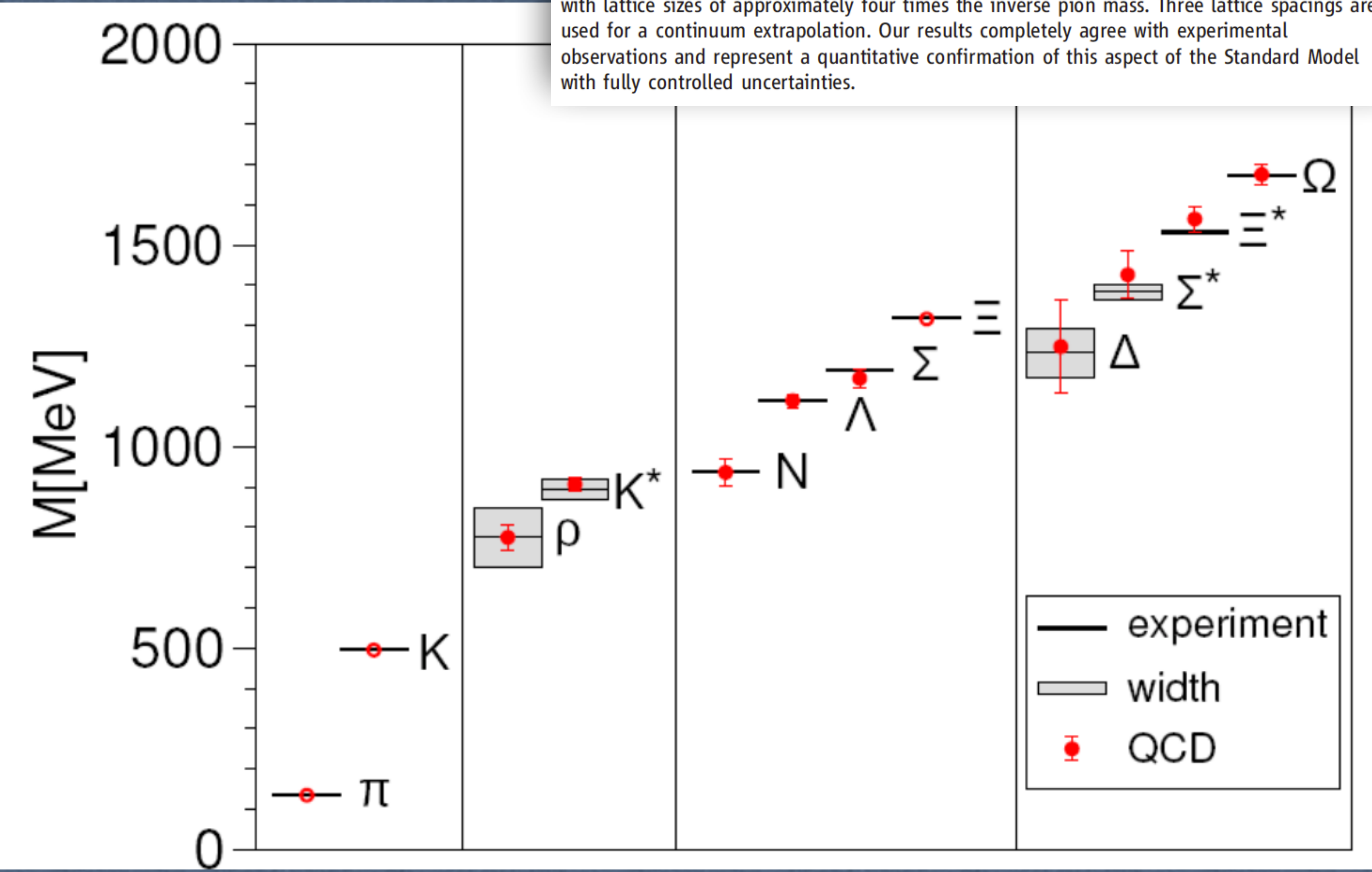
Ab Initio Determination of Light Hadron Masses

S. Dürr,[1] Z. Fodor,[1,2,3] J. Frison,[4] C. Hoelbling,[2,3,4] R. Hoffmann,[2] S. D. Katz,[2,3] S. Krieg,[2] T. Kurth,[2] L. Lellouch,[4] T. Lippert,[2,5] K. K. Szabo,[2] G. Vulvert[4]

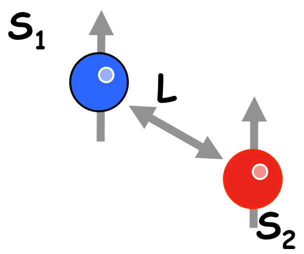
More than 99% of the mass of the visible universe is made up of protons and neutrons. Both particles are much heavier than their quark and gluon constituents, and the Standard Model o particle physics should explain this difference. We present a full ab initio calculation of the masses of protons, neutrons, and other light hadrons, using lattice quantum chromodynamics. Pion masses down to 190 mega–electron volts are used to extrapolate to the physical point, with lattice sizes of approximately four times the inverse pion mass. Three lattice spacings are used for a continuum extrapolation. Our results completely agree with experimental observations and represent a quantitative confirmation of this aspect of the Standard Model with fully controlled uncertainties.



What we know (light q)

Constituent Quark Model

- Quark-antiquark pairs with total spin S=0,1 and orbital angular momentum L



$S = S_1 + S_2$ $J = L + S$

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

Not all the J^{PC} combinations are allowed:

0^{++} 0^{+-} 0^{-+} 0^{--} 1^{++} 1^{+-} 1^{-+} 1^{--} 2^{++} 2^{+-} 2^{-+} 2^{--} 3^{++} 3^{+-} 3^{-+} 3^{--} …

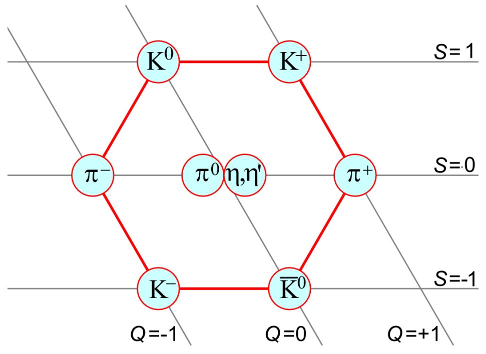
- SU(3) flavor symmetry → nonet (8⊕1) of degenerate states

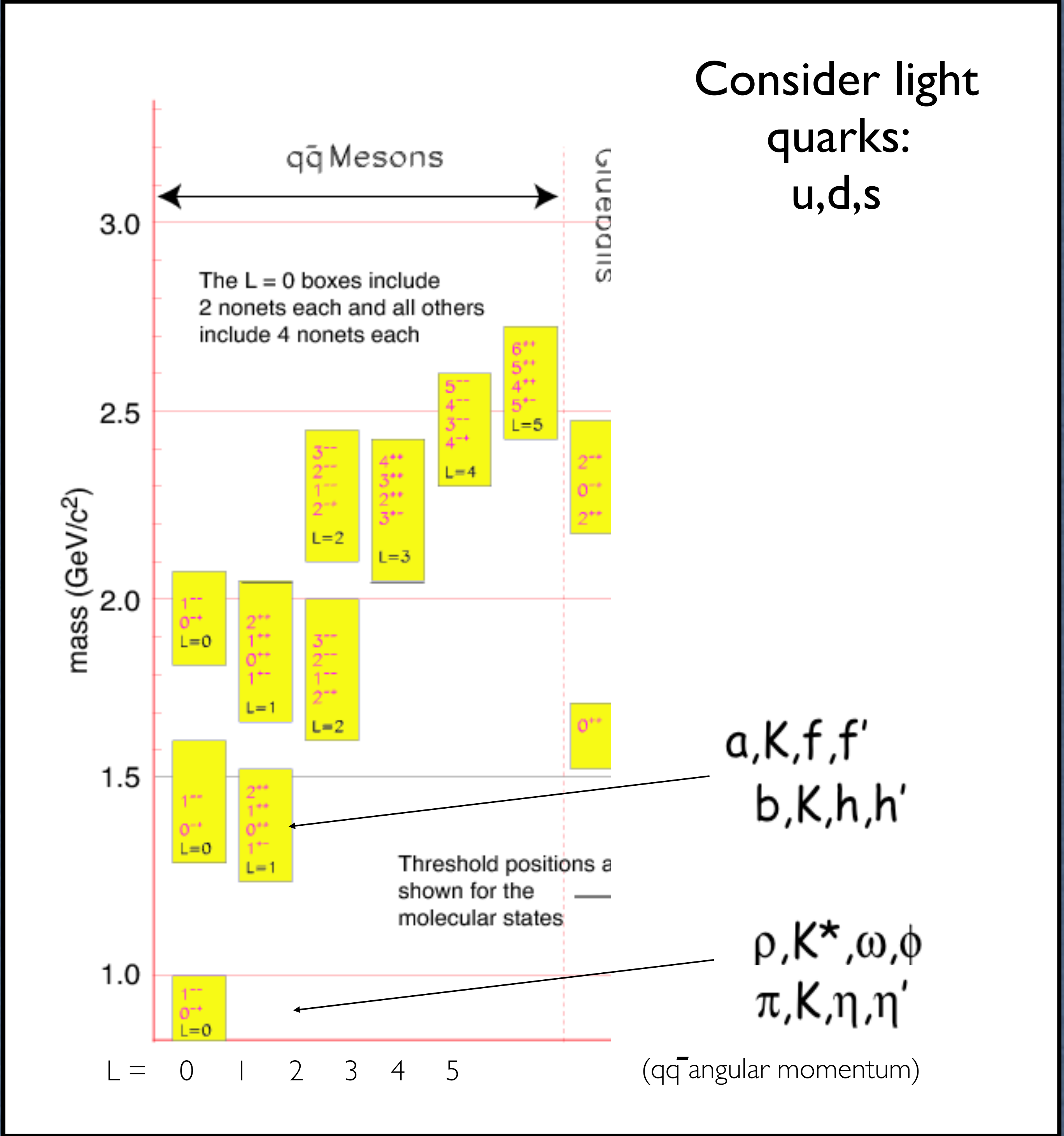
$J^{PC} = 0^{-+}$ ⇒ (π,K,η,η')

1^{--} ⇒ (ρ,K*,ω,Φ)

1^{+-} ⇒ (b_1,K_1,h_1,h_1')

…



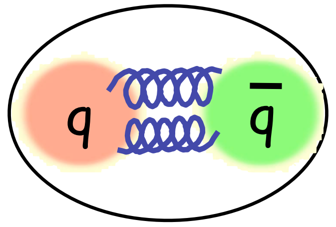


- Great success in describing the lower mass states
- …. but, a number of predicted states is not experimentally observed and assignments are uncertain

The gluons and the hadron spectrum

- Understanding gluonic excitations of mesons and the origin of confinement
- At high energy experimental evidence is found in jet production
- At lower energies the hadron spectrum carries information about the gluons that bind quarks
- Can we find hints of the glue in the meson spectrum?

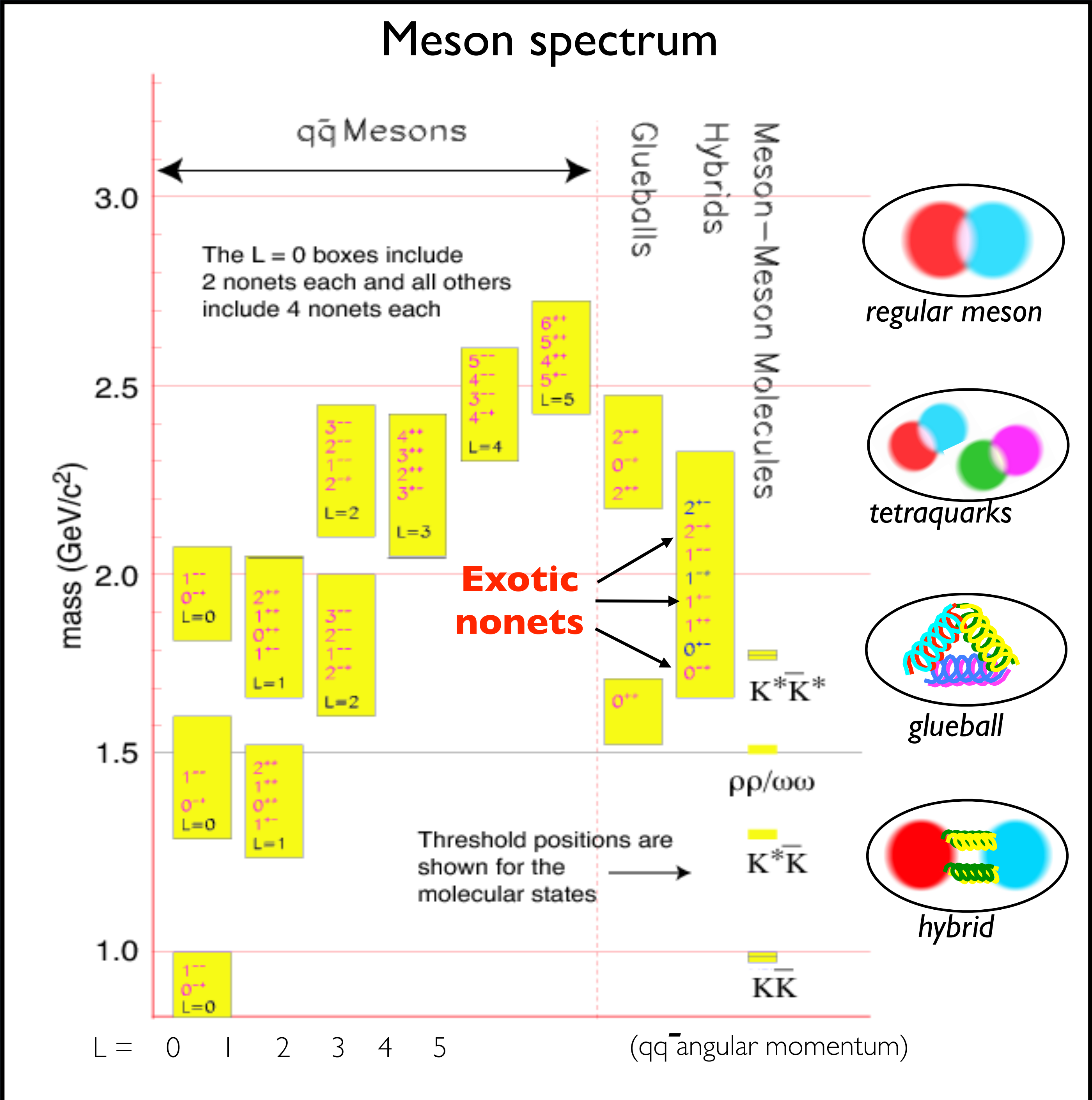
Search for non-standard states with explicit gluonic degrees of freedom



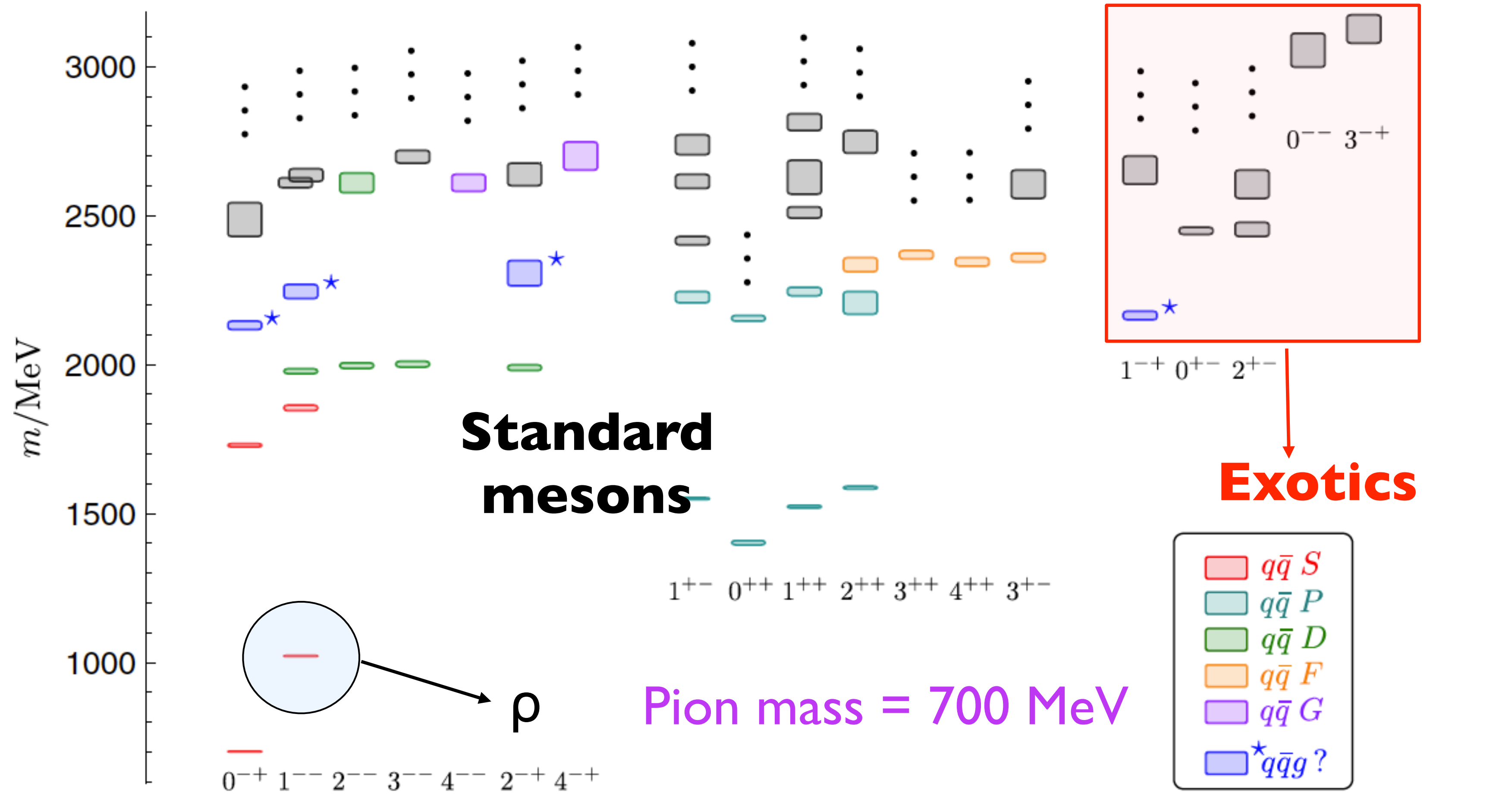
hybrid mesons

Not-allowed J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} ...

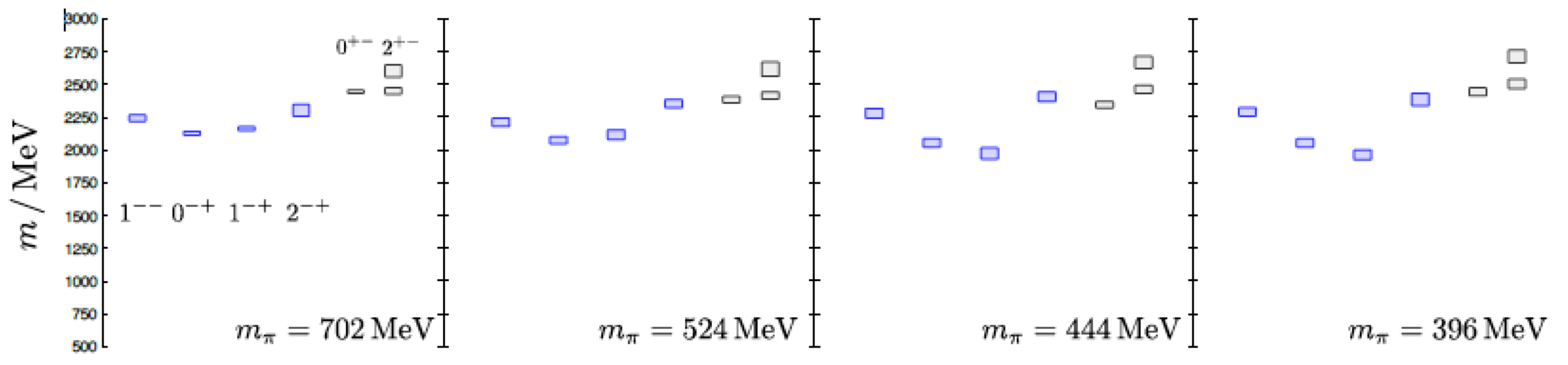
Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states



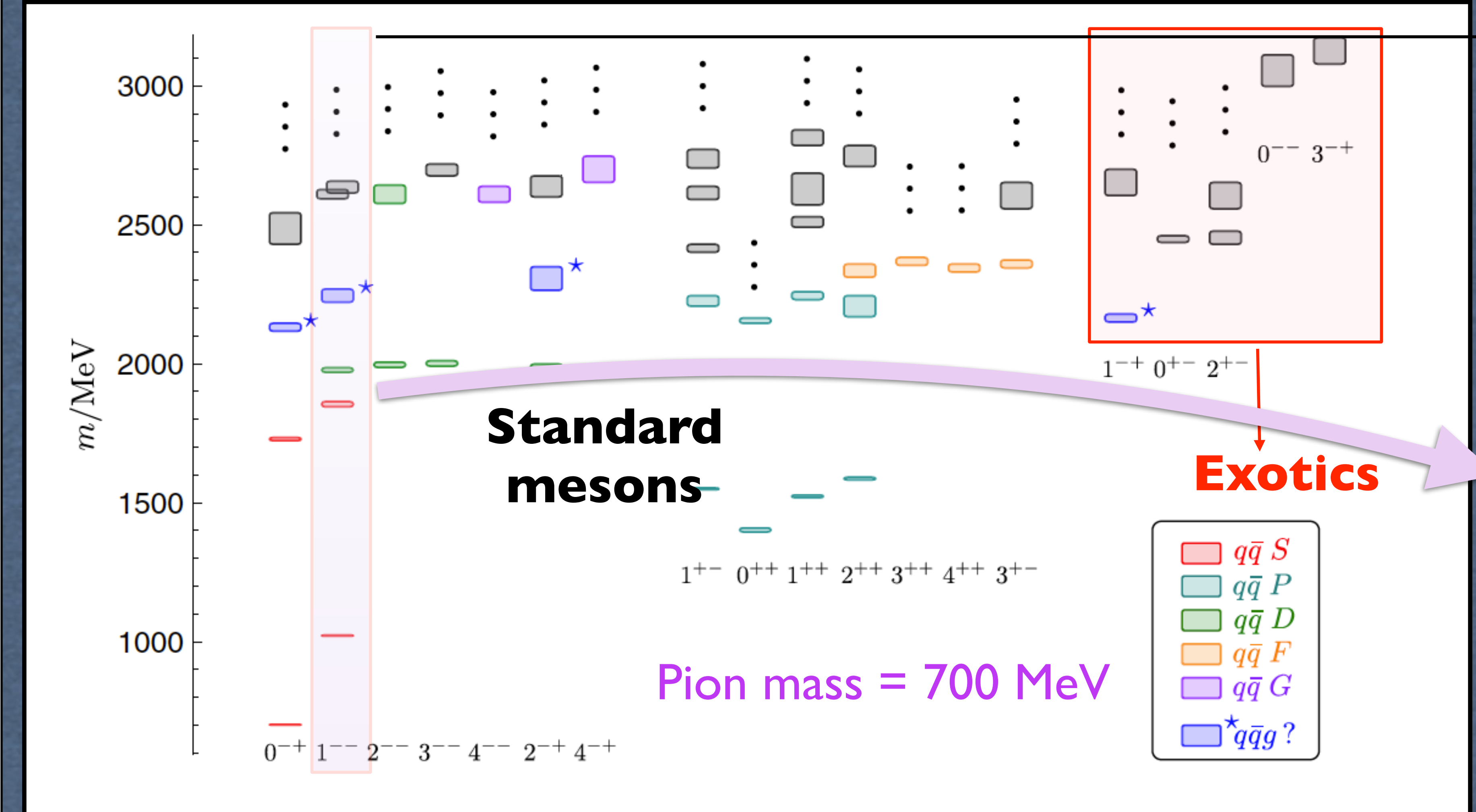
Light q spectrum from lattice QCD



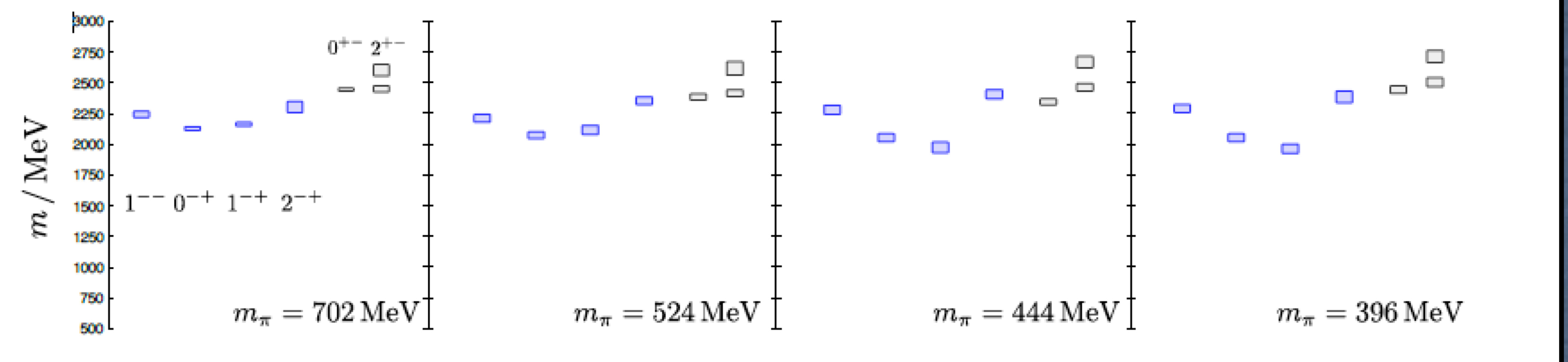
J.Dudek et al Phys.Rev.D82 (2010) 034508, Phys. Rev. D84, 074023 (2011), PysRev.D110 (2024) 034512

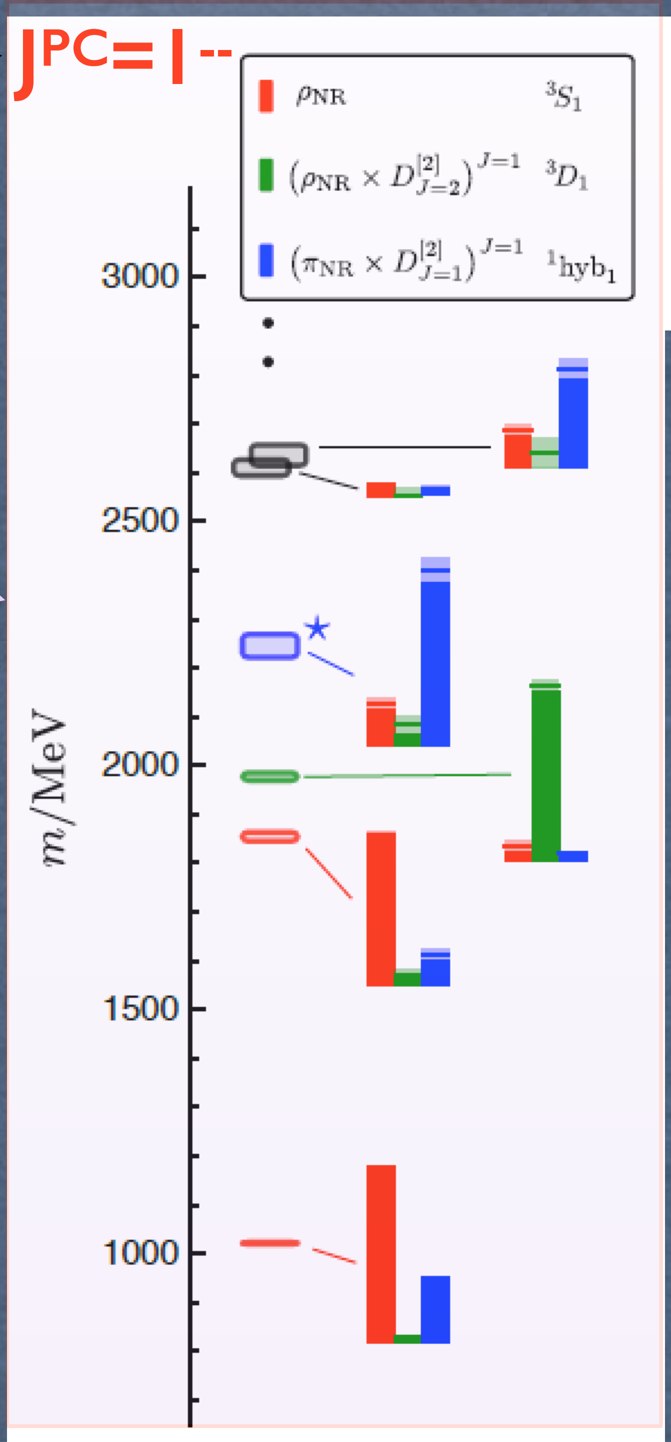


Light q spectrum from lattice QCD



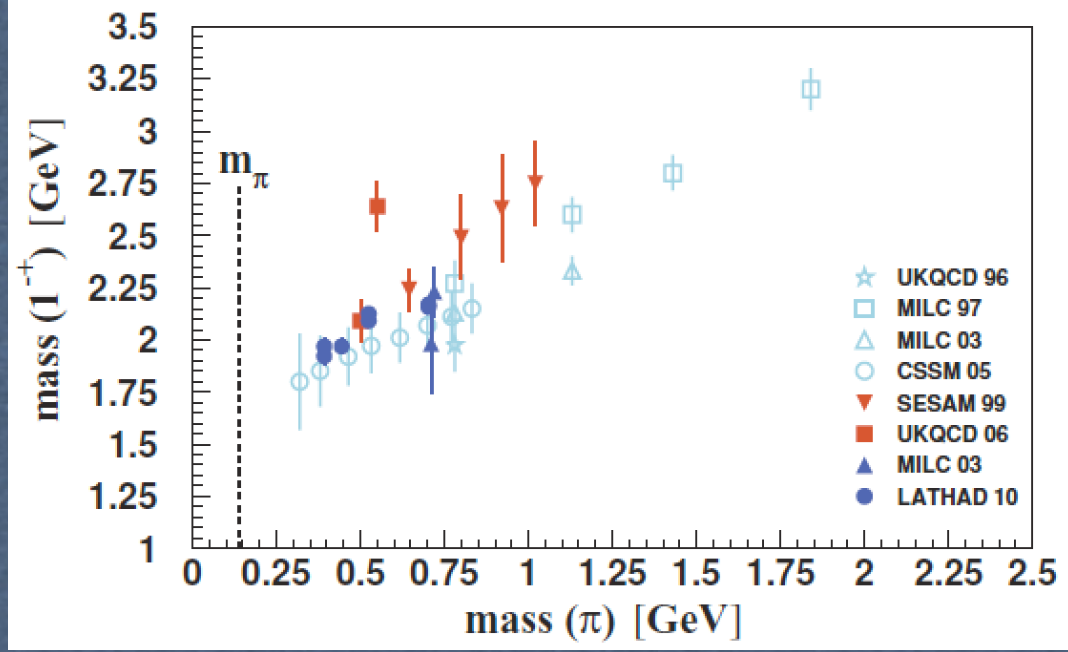
J.Dudek et al Phys.Rev.D82 (2010) 034508 J.Dudek et al., Phys. Rev. D84, 074023 (2011)



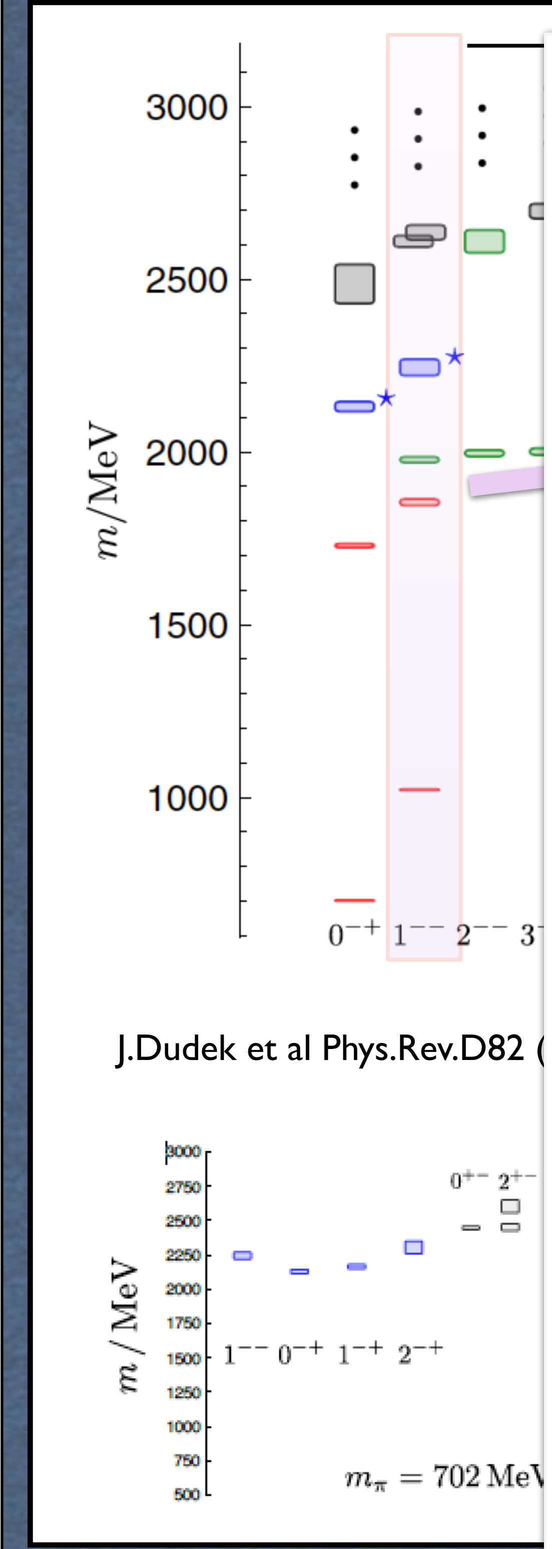


in blue: overlap with $J^{PC}=1^{-+}$ operator interpreted as qq-bar in S-wave + $J_g^{P_gC_g}=1^{+-}$ in P-wave

- Interpretation in term of CQM + Gluon field
- Dependence on Lattice size
- Dependence on pion mass



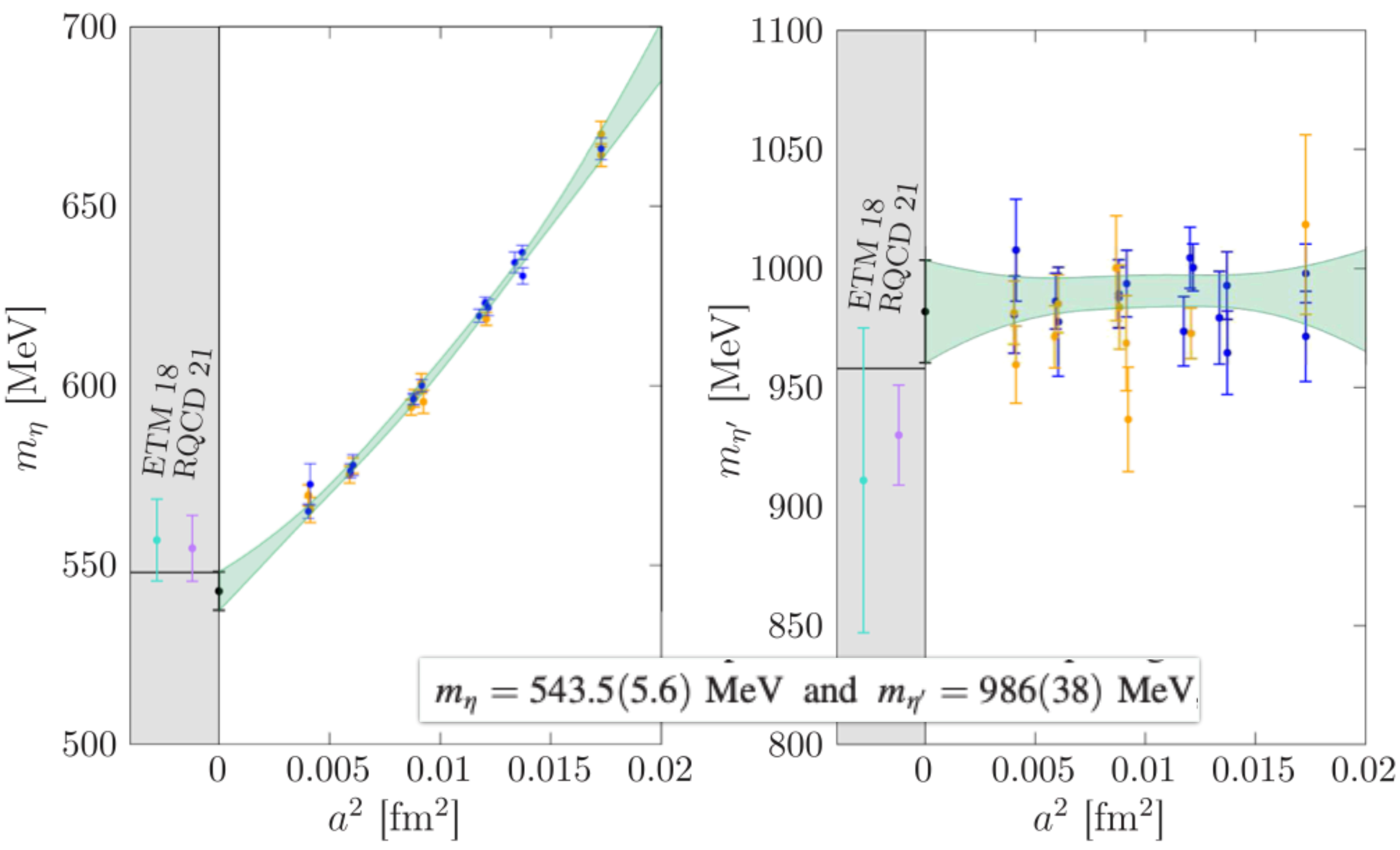
Light q spectrum from lattice QCD



J.Dudek et al Phys.Rev.D82 (

Lattice-QCD predictions for η and η' masses at the physical point

W.Verplanke et al. Phys Rev D 111, 094506 (2025)



$m_\eta = 543.5(5.6)$ MeV and $m_{\eta'} = 986(38)$ MeV

...verlap with $J^{PC}=1^{-+}$ operator

as qq-bar in S-wave +

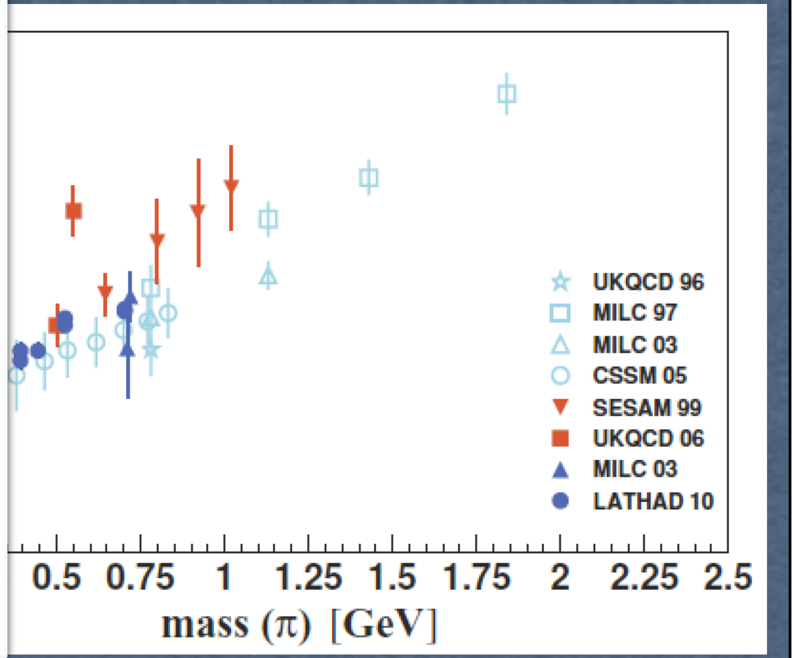
P-wave

...tation in term of CQM

field

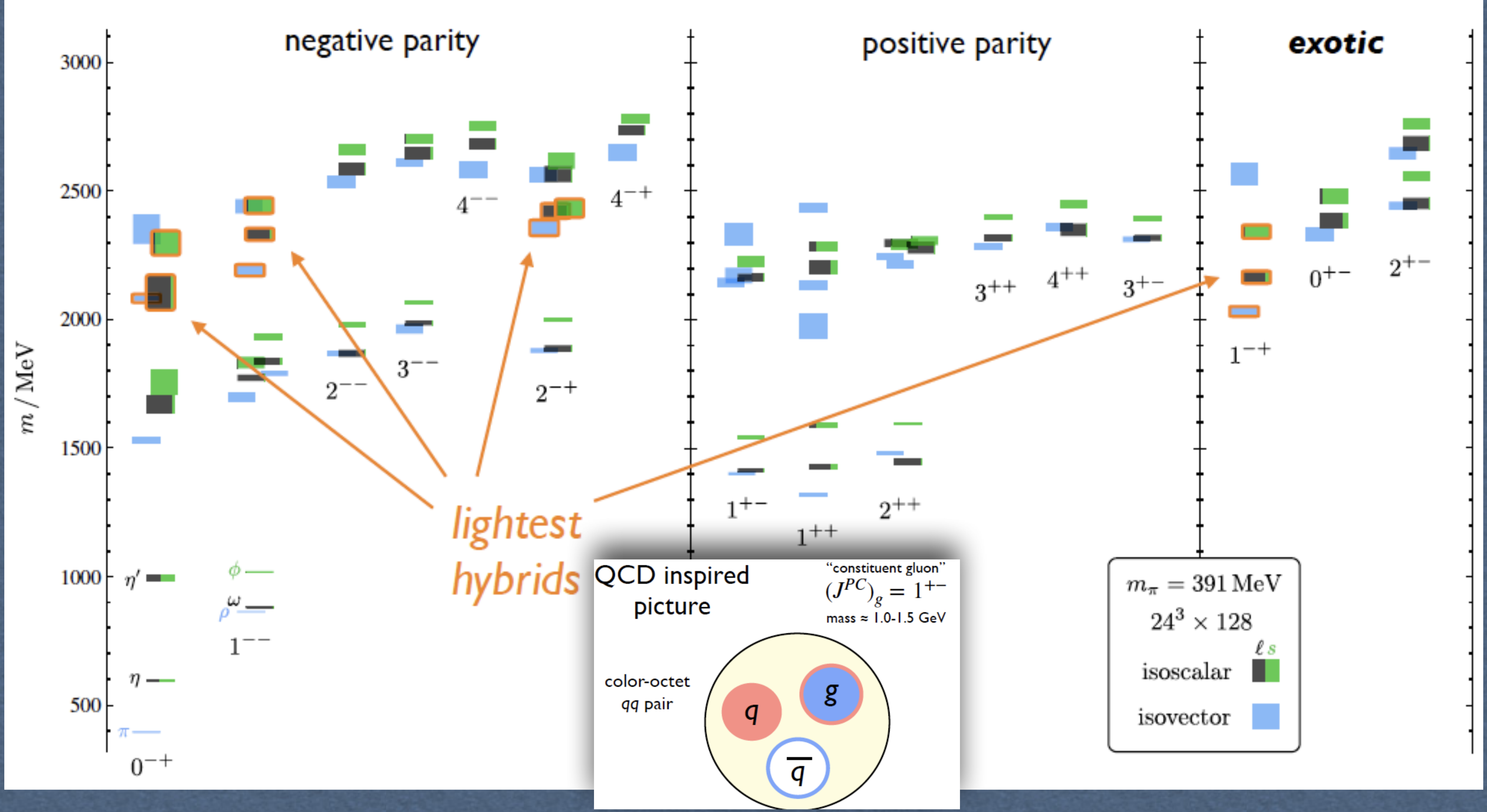
...ence on Lattice size

...ence on pion mass



Light q spectrum from lattice QCD

Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



Lattice-QCD predictions for the lowest hybrid states

0^{+-} ~ 2.0 GeV

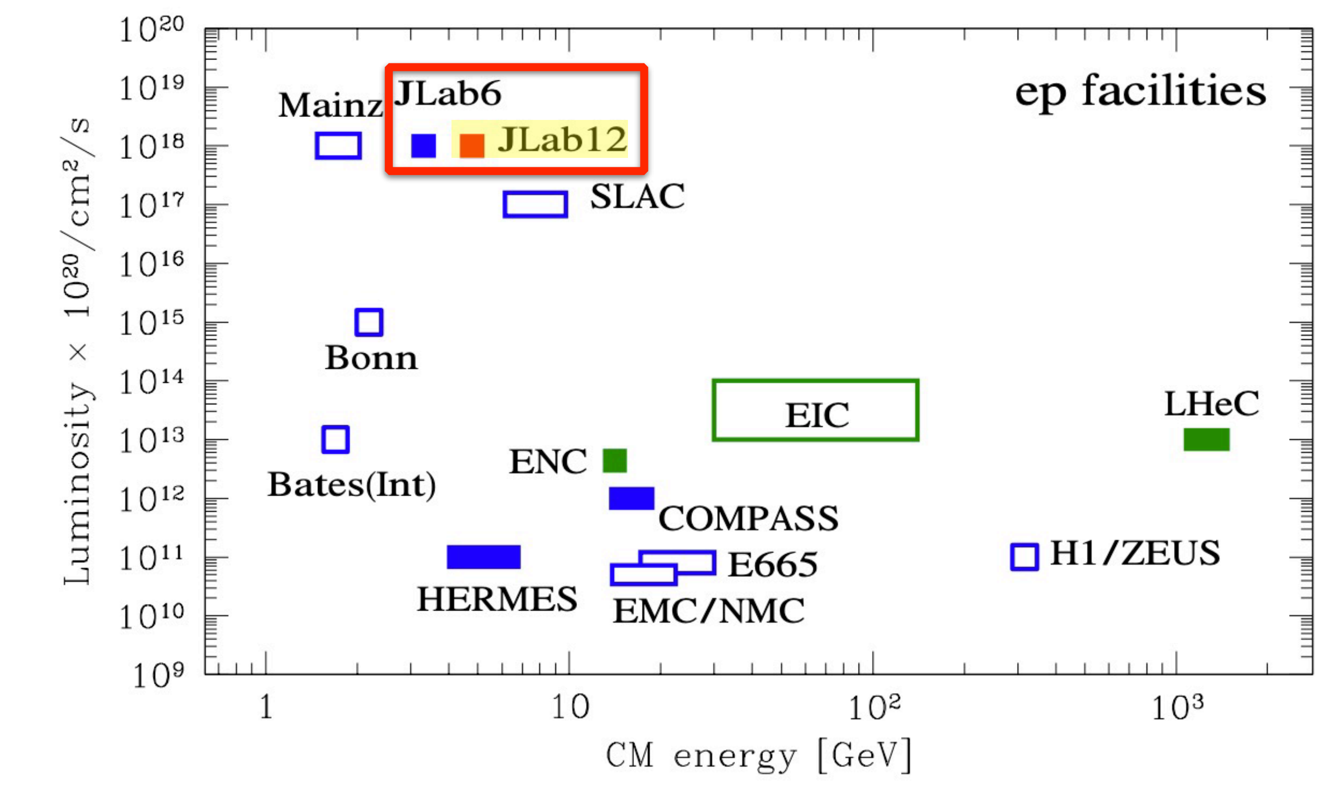
1^{-+} ~1.6 GeV

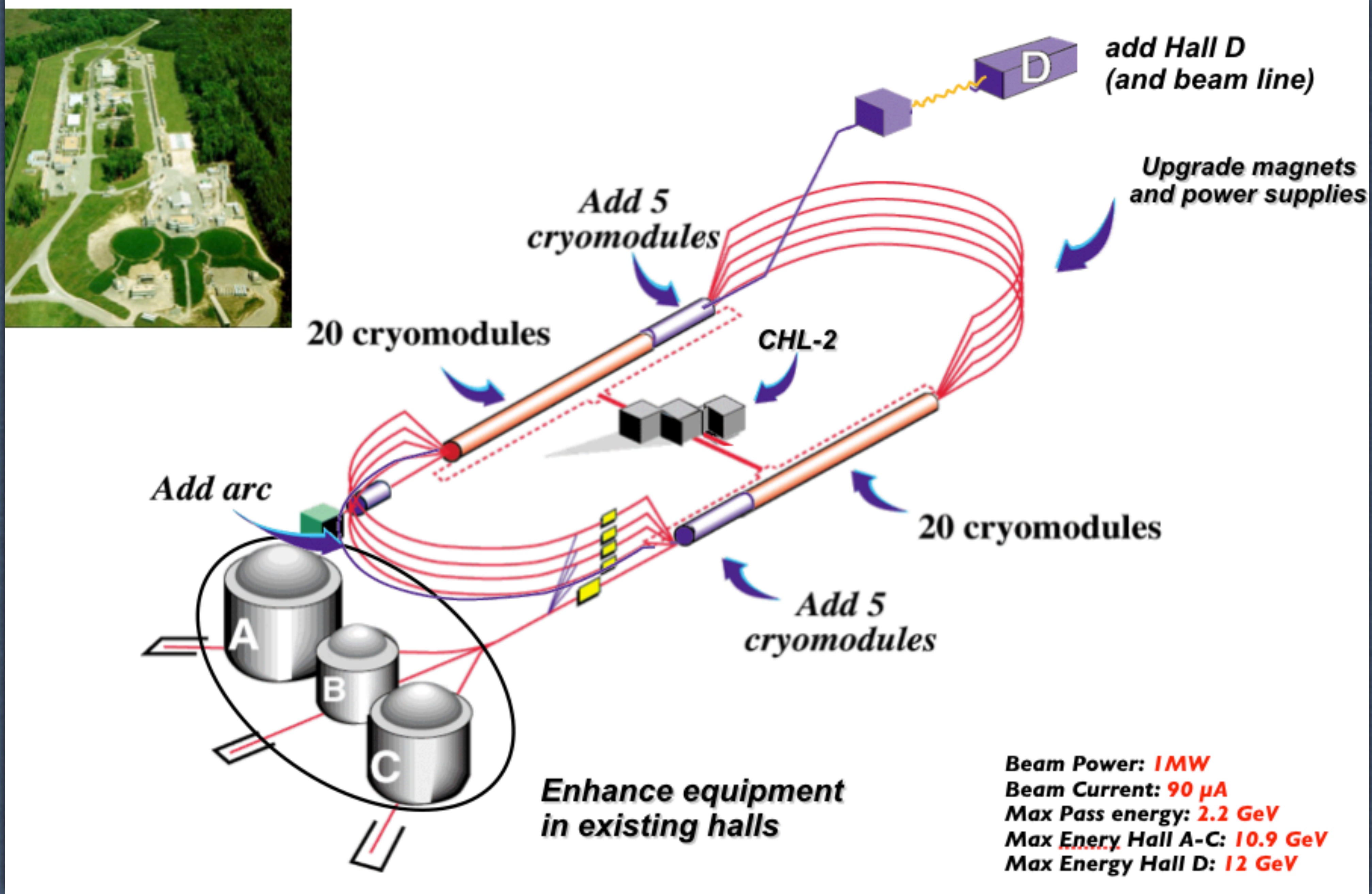
Hybrid mesons and glueballs mass range:

1.4 GeV - 3.0 GeV

This mass range is accessible in current experiments (CLAS12 and GLUEX @JLab)

Jefferson Lab
The intensity frontier





✴Primary Beam: Electrons

✴ Beam Energy: 12 GeV

- $10 > \lambda > 0.1$ fm
- nucleon → quark transition
- baryon and meson excited states

✴100% Duty Factor (CW) Beam

- coincidence experiments
- Four simultaneous beams
- Independent E and I

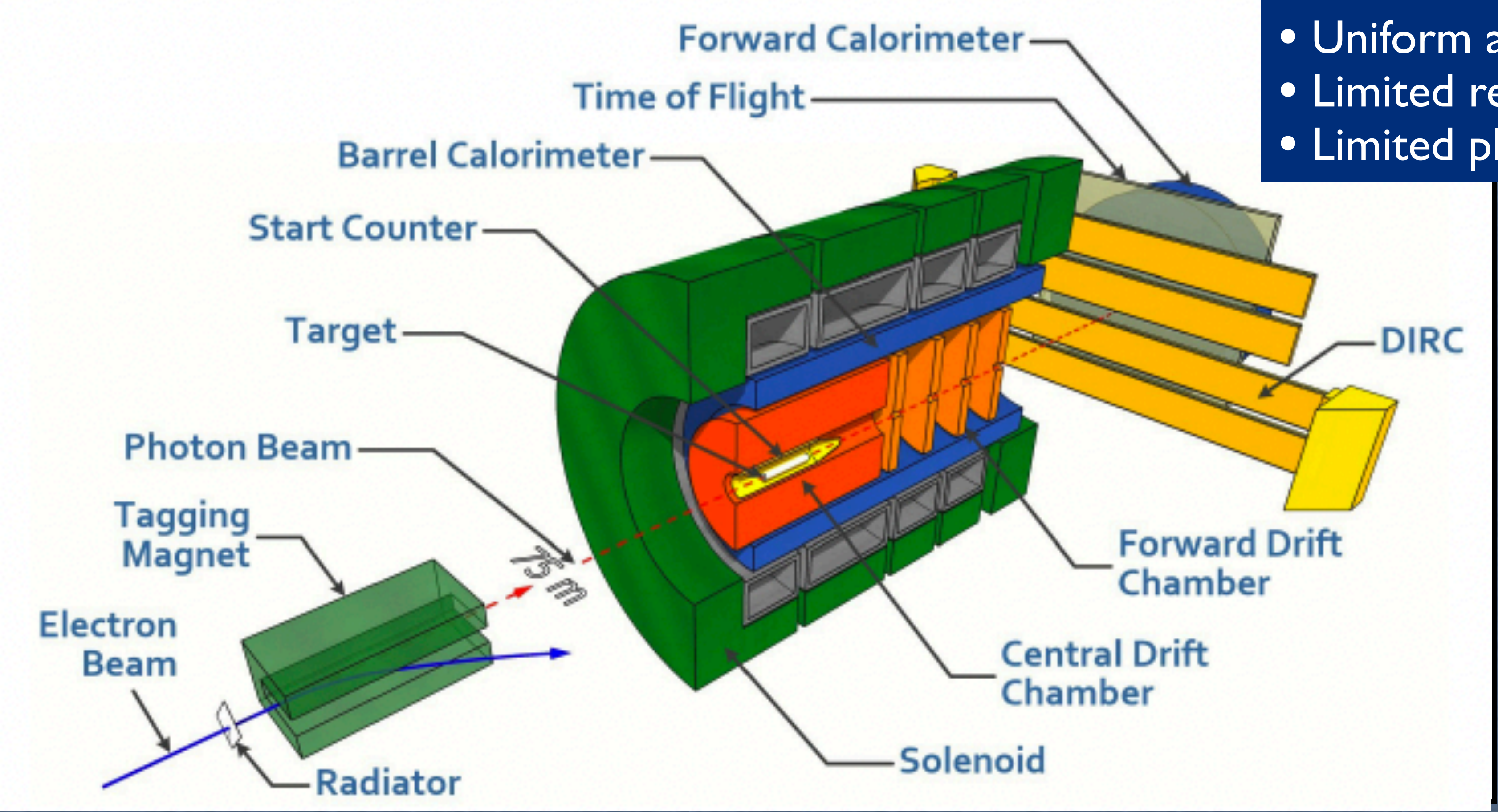
✴ Polarization

- spin degrees of freedom
- weak neutral currents

Meson spectroscopy with photons at JLab-12 GeV

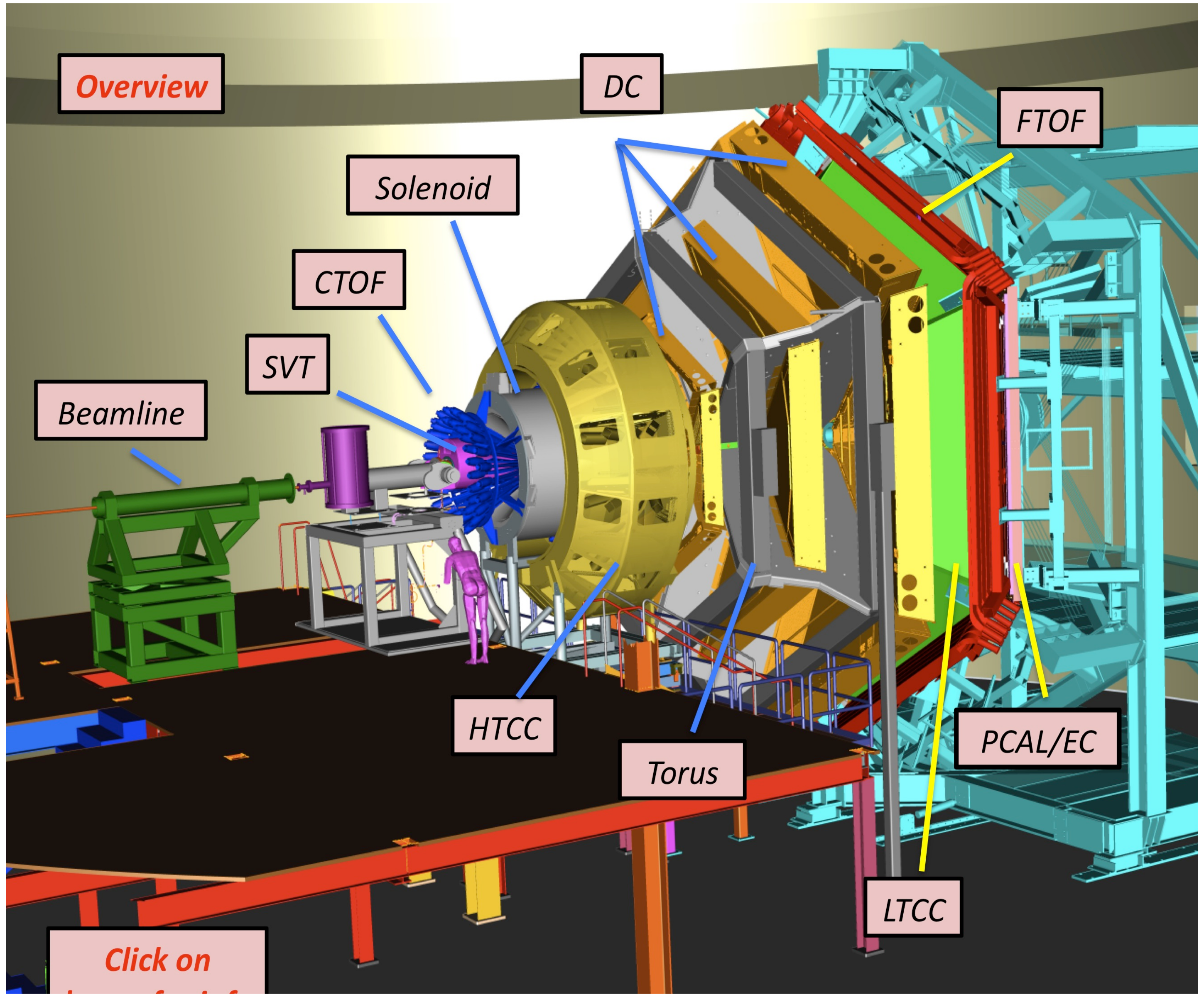
- Determination of JPC of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

Hall-D - GlueX Detector



- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

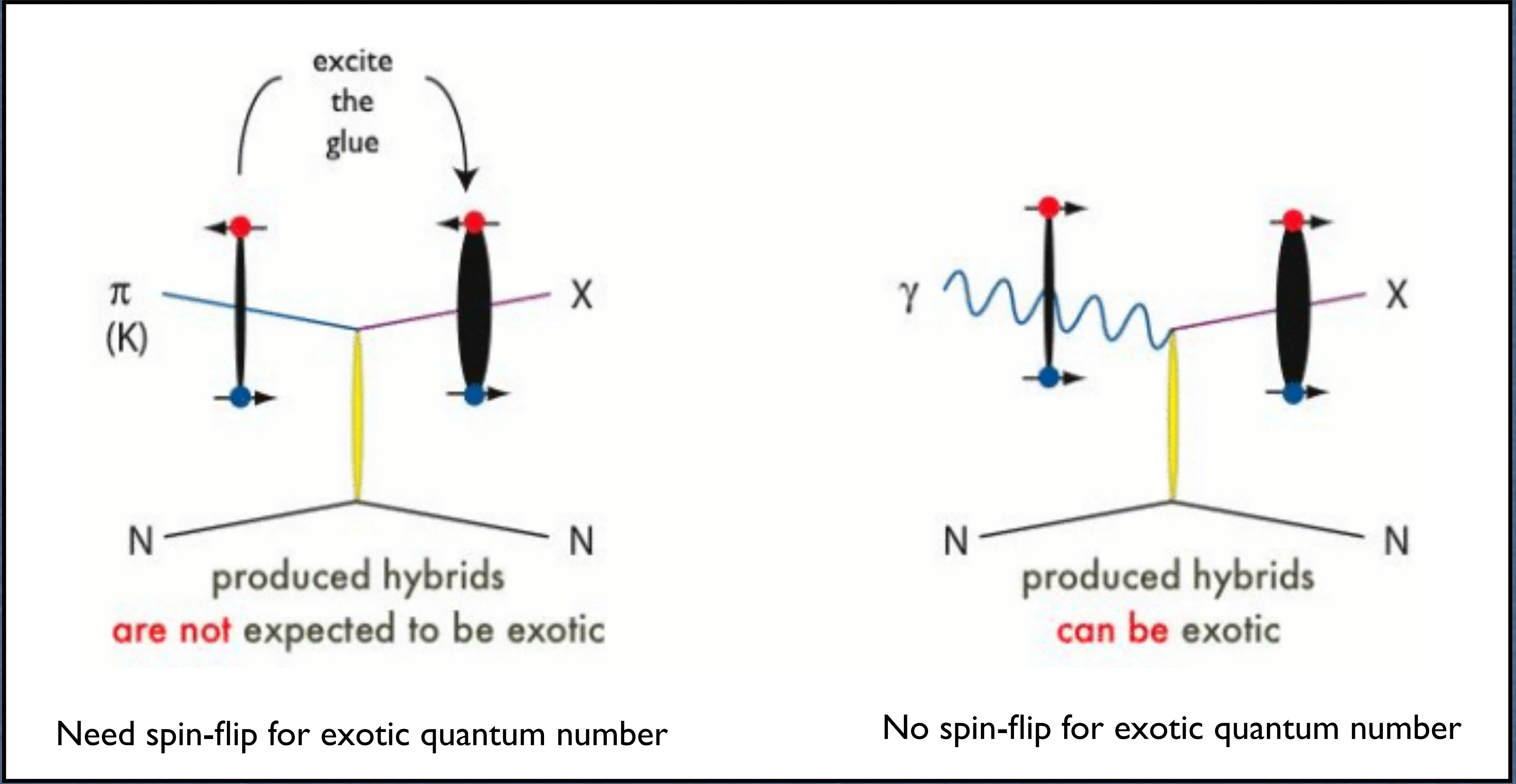
Hall-B - CLAS12 Detector



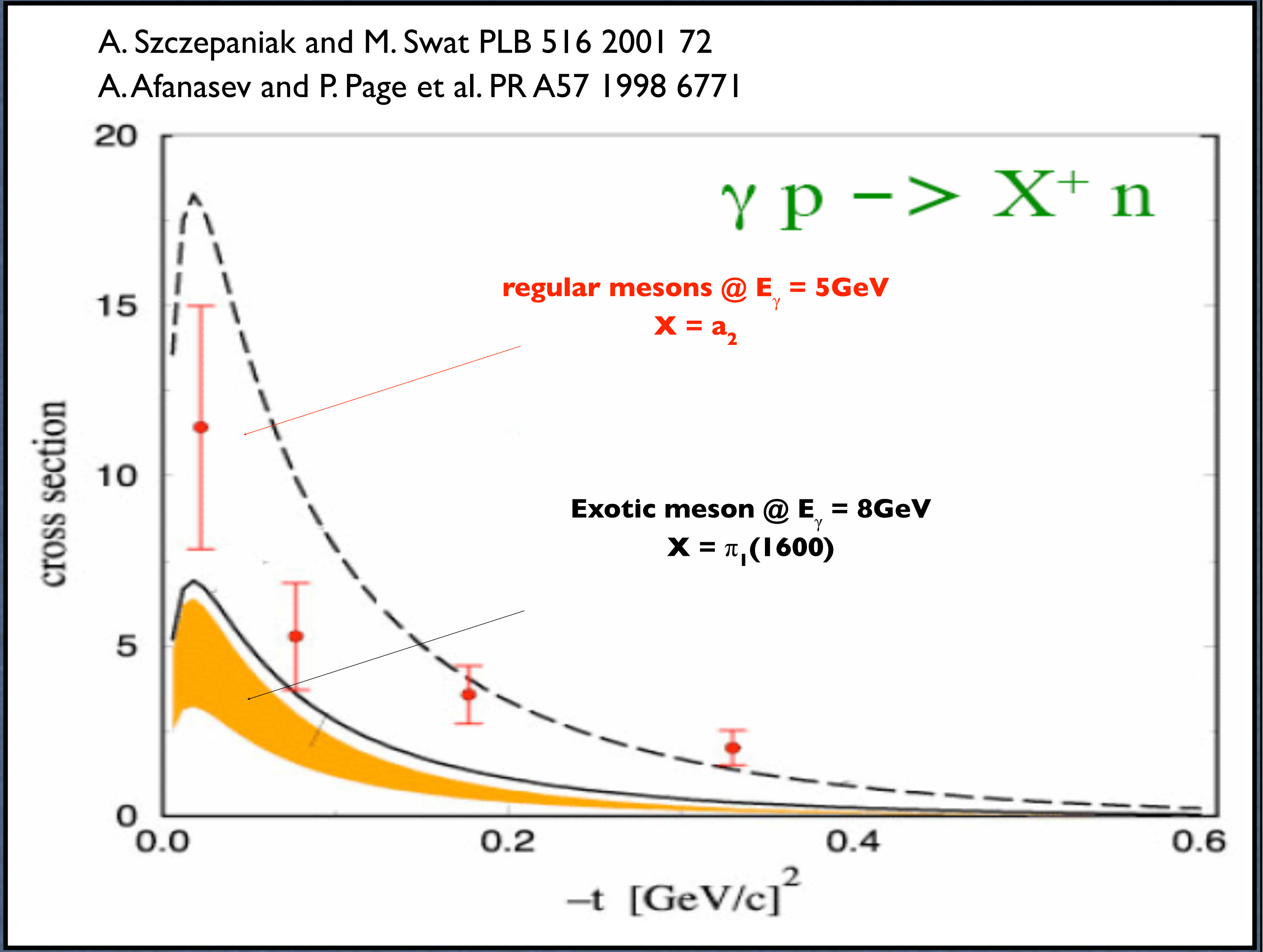
- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance

Why photoproduction?

★ Photoproduction: exotic J^{PC} are more likely produced by S=1 probe



★ Photoproduction is widely used to study hadron spectroscopy



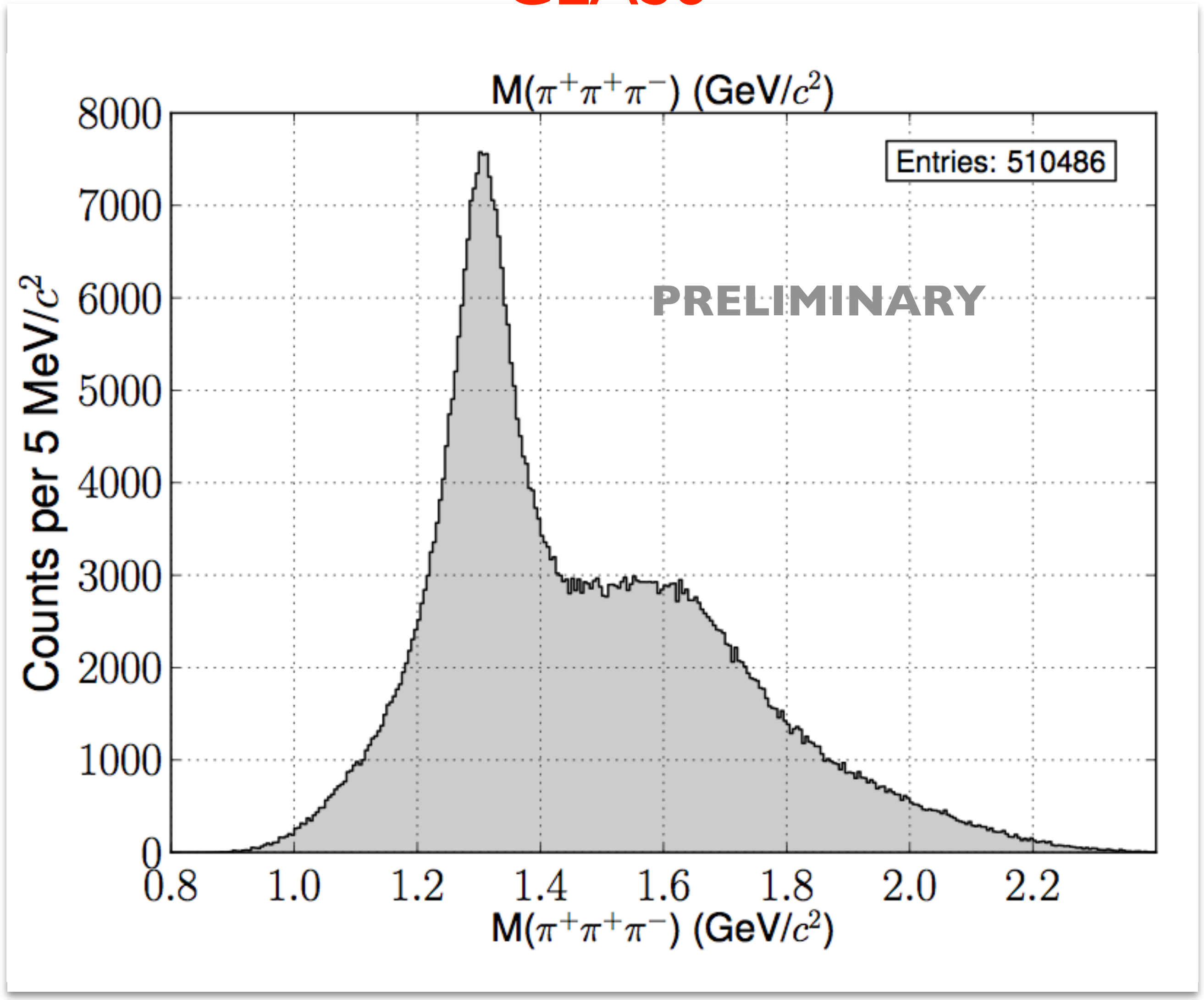
★ Linear polarization acts like a filter to disentangle the production mechanisms and suppress bg

★ Production rate for exotics is expected comparable as for regular mesons

nPQCD in action

A side note: invariant mass spectrum of (3π) system measured at:

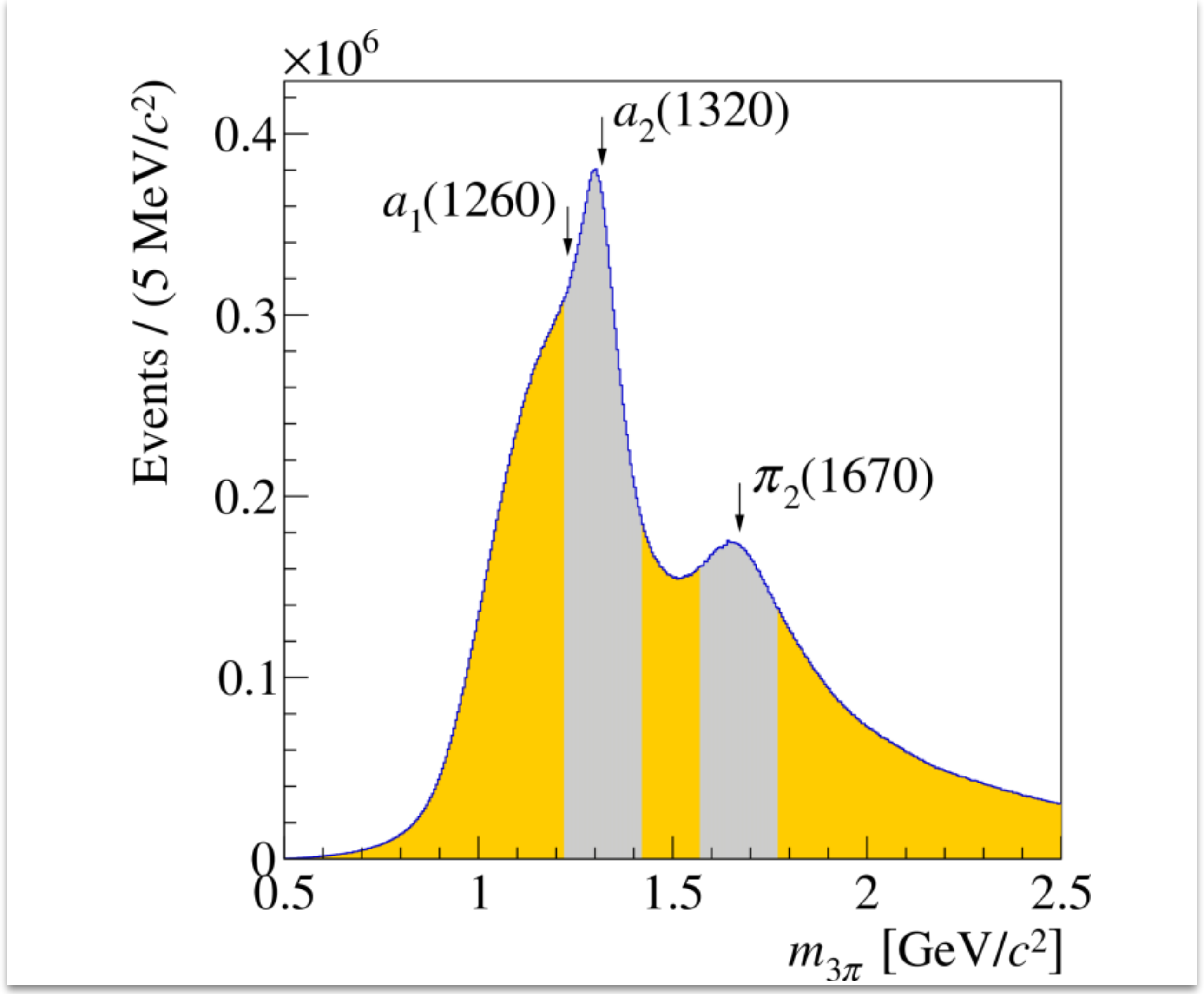
CLAS6



$\gamma\, p \rightarrow (n)\, \pi^+ \pi^+ \pi^-$

E_γ = 5 GeV

COMPASS

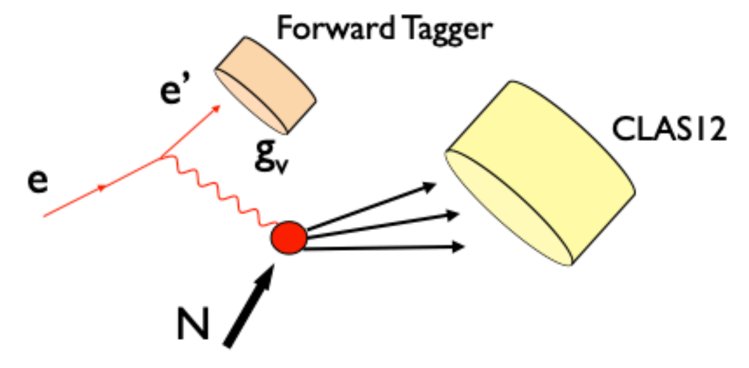


$\pi^- p \rightarrow (p)\, \pi^+ \pi^- \pi^-$

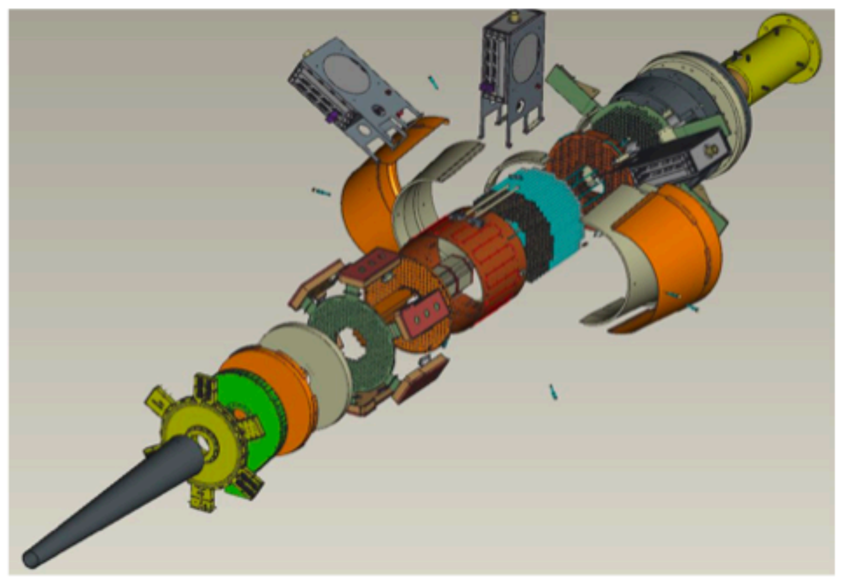
E_π = 191 GeV

Despite the significant difference in beam energy, the two spectra are similar showing the resonances dominate the spectrum below 2 GeV (low energy → non-pQCD)

Quasi-real photoproduction with CLAS12 (Low Q^2 electron scattering)



$E_{scattered}$	0.5 - 4.5 GeV
θ	2.5^o - 4.5^o
ϕ	0^o - 360^o
ν	6.5 - 10.5 GeV
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 >$ 0.1 GeV^2)
W	3.6 - 4.5 GeV



★ Electron scattering at "0" degrees (2.5° - 4.5°)

➤ low Q^2 virtual photon ⇔ real photon

★ Photon tagged by detecting the scattered electron at low angles

➤ High energy photons $6.5 < E_g < 10.5$ GeV

★ Quasi-real photons are linearly polarized

➤ Polarization ~ 70% - 10% (measured event-by-event)

★ High Luminosity (unique opportunity to run thin gas target!)

➤ Equivalent photon flux $N_\gamma \sim 5\ 10^8$ on 5cm H_2 ($L=10^{35}\ cm^{-2}s^{-1}$)

★ Multiparticle hadronic states detected in CLAS12

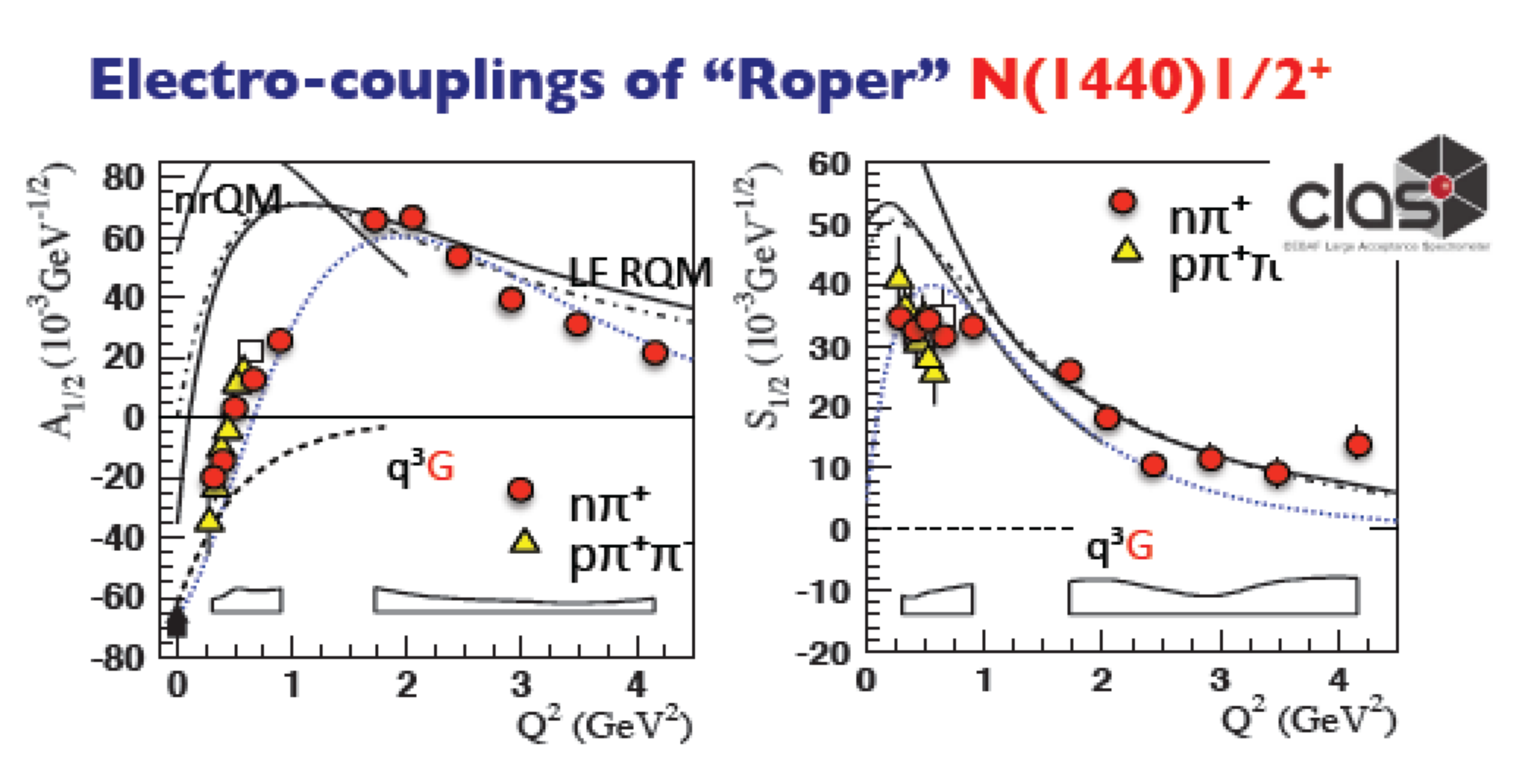
➤ High resolution and excellent PID (kaon identification)

Complementary to Hall-D GLUEX

Transition form factor evolution in Q^2 as a filter?

Electro-production can be used to explore the hadron structure at different wavelengths (Q2)

A drop of the transverse helicity amplitudes A1/2(Q2) faster than for ordinary three quark states, because of extra glue-component in valence structure



A suppressed longitudinal amplitude S1/2(Q2) in comparison with transverse electro-excitation amplitude Q3G
Q3G

- Nπ and Nππ give consistent results
- $A_{1/2}$ changes sign and has large magnitude at high Q^2
- QM fails to reproduce low Q^2 behavior, LFQM better at large Q^2
- Both $A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ inconsistent with hybrid model prediction

CLAS12 will map out the full meson/baryon spectrum and its evolution in Q2

The MesonEx physics program

Photoproduction of hyperons with CLAS12

Exp-12-008 "Very Strange Experiment"

Search for missing excited hyperon states

✴ Excited cascades
- Hyperon spectrum less know wrt N*
- How quark masse change the effective degrees of freedom in hadron spectra
- $\Xi^-(1530)$, $\Xi^-(1820)$
- $K^+K^+\pi^-$, $K^+K^+K^-p$

✴ Ω^- photoproduction
- 3 s quarks systemPoorly know
- Quantum number poorly known
- $K^+K^+K^0$, $K^+K^+K^0K^-$

✴ Quantum numbers and production dynamics determination
- Parity and polarisation measurement of $\Xi^-(1820)$
- Ω^- cross section

uirements

etector

Meson spectroscopy with photons in CLAS12

Exp-11-005 "MesonEx"

Study the meson spectrum in the 1-3 GeV mass range to identify gluonic excitation of mesons (hybrids) and other quark configuration beyond the CQM

✴ Hybrid mesons and Exotics
- Search for hybrids looking at many different final states
- Charged and neutral-rich decay modes
- $\gamma p \to p\,3\pi$, $\gamma p \to p\,\eta\,\pi$, ...

✴ Hybrids with hidden strangeness and strangeonia
- Intermediate mass of s quarks links long to short distance QCD potential
- Good resolution and kaon Id required
- $\gamma p \to p\,\phi\,\pi$, $\gamma p \to p\,\phi\,\eta$, $\gamma p \to p\,2K\,\pi$, ...

✴ Scalar mesons
- Poorly know f_0 and a_0 mesons in the mass range 1-2 GeV
- Theoretical indications of unconventional configurations (qqqq or gg)
- $\gamma p \to p\,2\pi$, $\gamma p \to p\,2K$, ...

ve reactions,

Requirements

Light Meson Decay

Exp-12-06-108b "LMD"

Transition Form Factor of the eta' Meson with CLAS

✴ Transition form factor of the eta' meson
- hadronic light-by-light (HLBL) contribution to the muon anomalous magnetic moment a_μ
- Dalitz decays of η' mesons, $\eta' \to \gamma\, e+\, e-$
- η' produced in $e\,p \to e\,p\,\eta'$
- 0.5% statistical uncertainties (disregarding higher order effects)

✴ Radiative decays o
✴ Access to the gam vertex
✴ Competition with experiments

- Studied in g12 (CLAS6)
- Detector requirements: high luminosity, lepton trigger capability, large angle acceptance
- External photon pair production background suppressed by exploiting the 1 mm vertex resolution

Requ

1) 4π

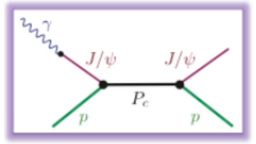
2) High electro

LHCb Pentaquark with CLAS12

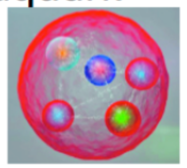
Exp-12-12-001a "Pentaquark"

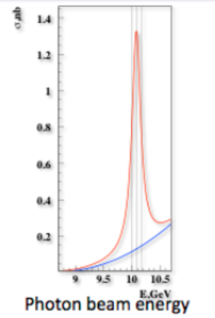
Near threshold J/psi photoproduction and study of LHCb pentaquarks with CLAS12

Search for LHCb Pentaquark



$$\gamma + p \to P_C \to J/\psi + p$$
$$J/\psi \to e^+e^-$$
$$J/\psi \to \mu^+\mu^-$$





$BR(P_c \to J/\psi p) = 1\%$ $L = 10^{35} cm^{-2} s^{-1}$

	$P_c(4380)$		$P_c(4450)$	
	Minimum	Maximum	Minimum	Maximum
Untagged mode	48	500	70	220
Tagged mode	20	600	28	880
Total	68	1100	98	1100

98 events/day for narrow $P_c(4450)$ pentaquark state at nominal CLAS12 luminosity

Requirements

1) 4π detector

2) High intensity 10 Ge electron beam

Nucleon resonances studies with CLAS12

Exp-12-009 "N" and Exp-12-06-108a "KY"*

Study the baryon spectrum to map the Q2 evolution of excited states in an unexplored domain

✴ Single and multi pions Xsec
- Extended kinematic coverage in the unexplored Q^2 region between 5-10 GeV
- Precise and abundant data for many final states

✴ Hyperon electroproduction
- Natural extension to single and multi K final states

✴ Photocoupling extraction
- Mapping the NN* transition form factors to pin down the underlying dynamics
- Phenomenological models to parametrize the data, and PWA for full interpretation
- Well established analysis procedure tested with CLAS data

- Isobar model and beyond
- Detector requirements: good acceptance, energy resolution, particle Id
- Identification of exotic configuration via PWA

Requirements

1) 4π detector

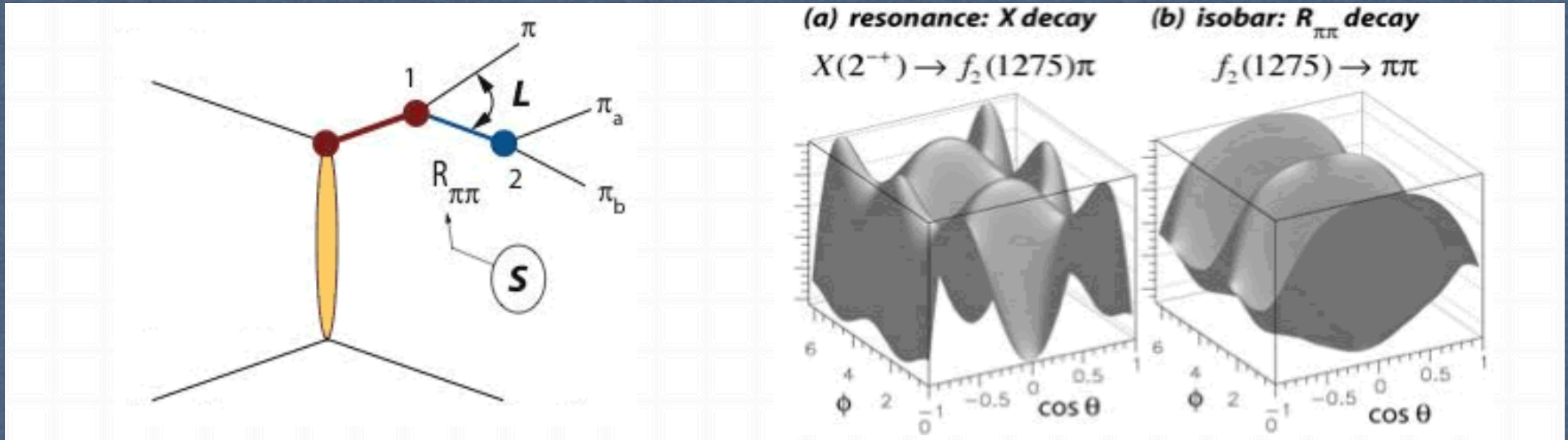
2) High intensity 10 GeV electron beam

Resonance detection

Two main experimental approaches to identifying and studying a hadron resonance

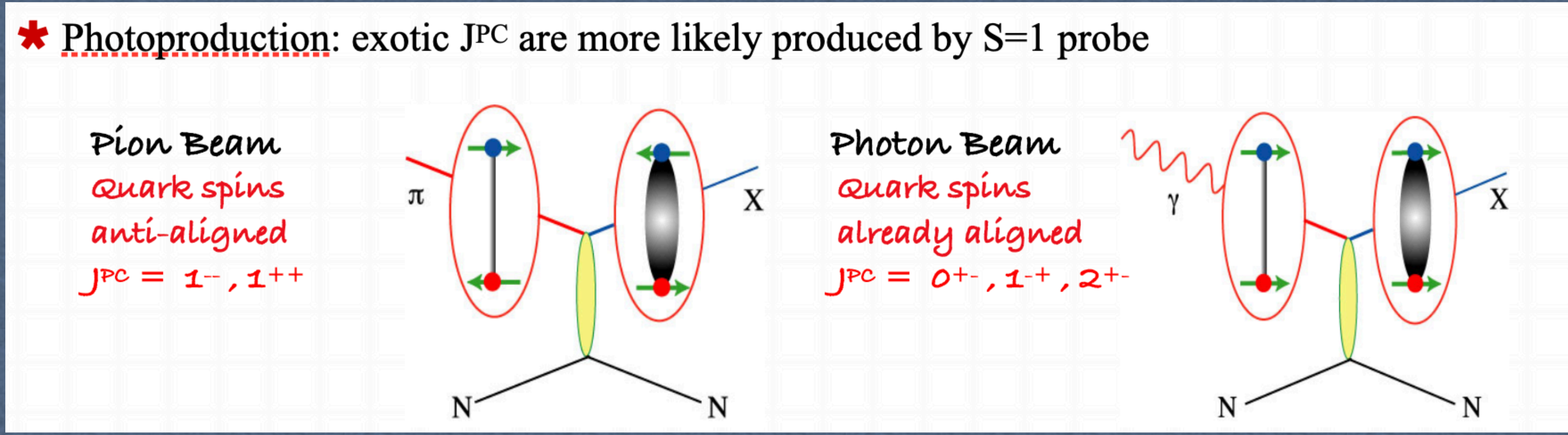
Decay

- Easier and straightforward
- Independent on production mechanisms
- Dalitz plot for 3-body decays
- Isobar Model for higher multiplicity



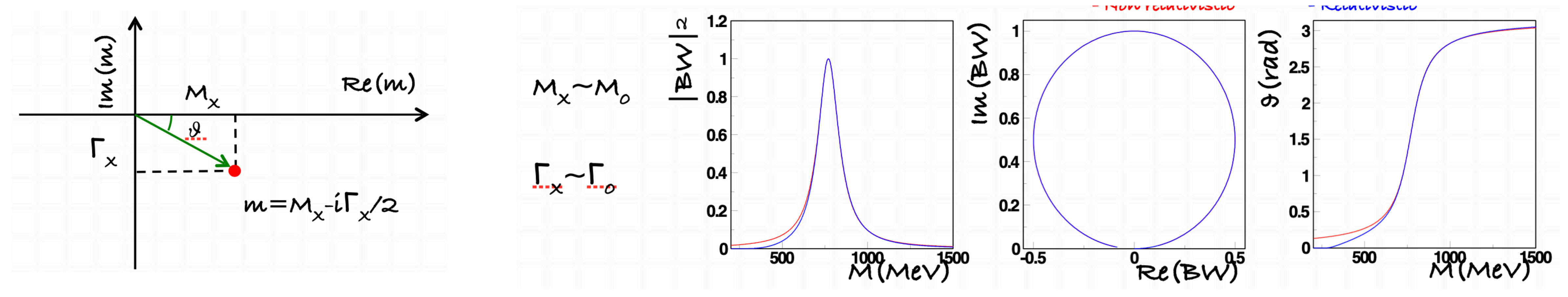
Production

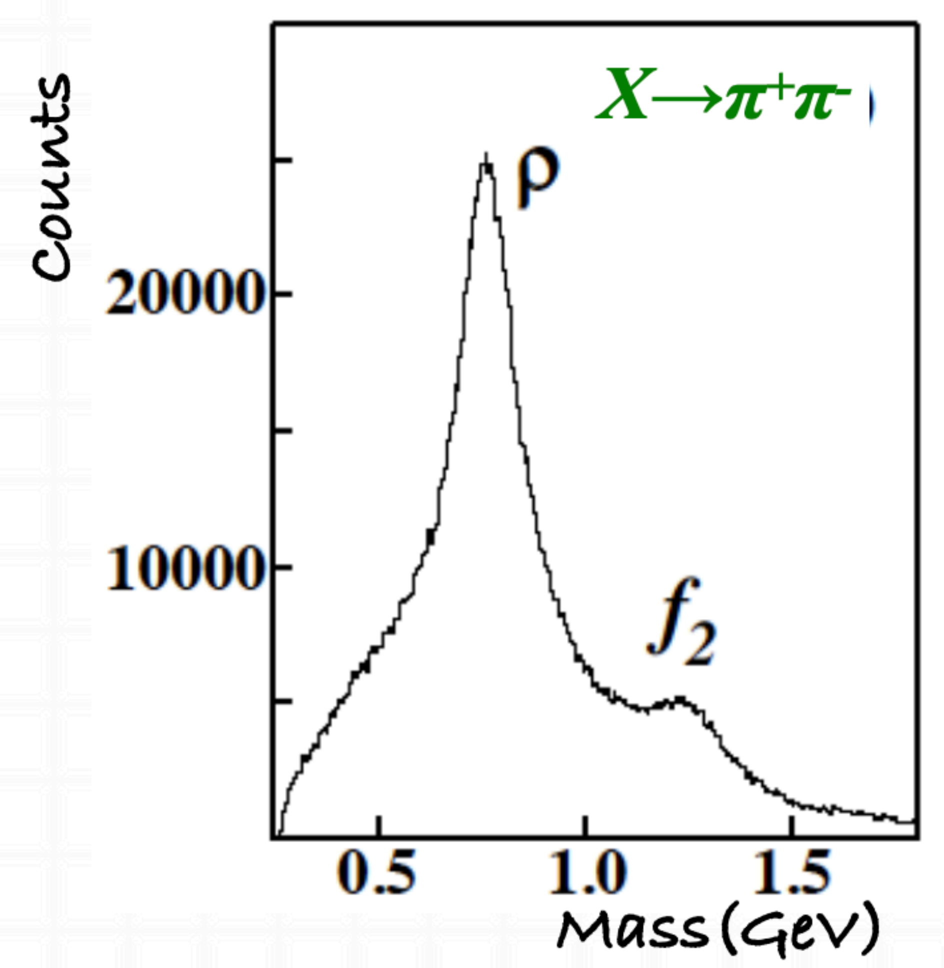
- Requires parametrisation of production vertex
- exclusive (or semi-inclusive) final state
- sensitive to the internal structure (nature)



From data to the spectrum

'resonance' is defined by the pole in the first Riemann sheet of the complex amplitude
... not every bump is a resonance and not every resonance is a bump!





- A hadron resonance can be observed by studying the **invariant mass spectrum** of its decay product.
- In real life, resonances do not always appear so clearly in a mass spectrum because they are **not isolated**
- A resonance has specific quantum numbers with defined decay angular momentum
- Each partial wave only includes the corresponding resonances

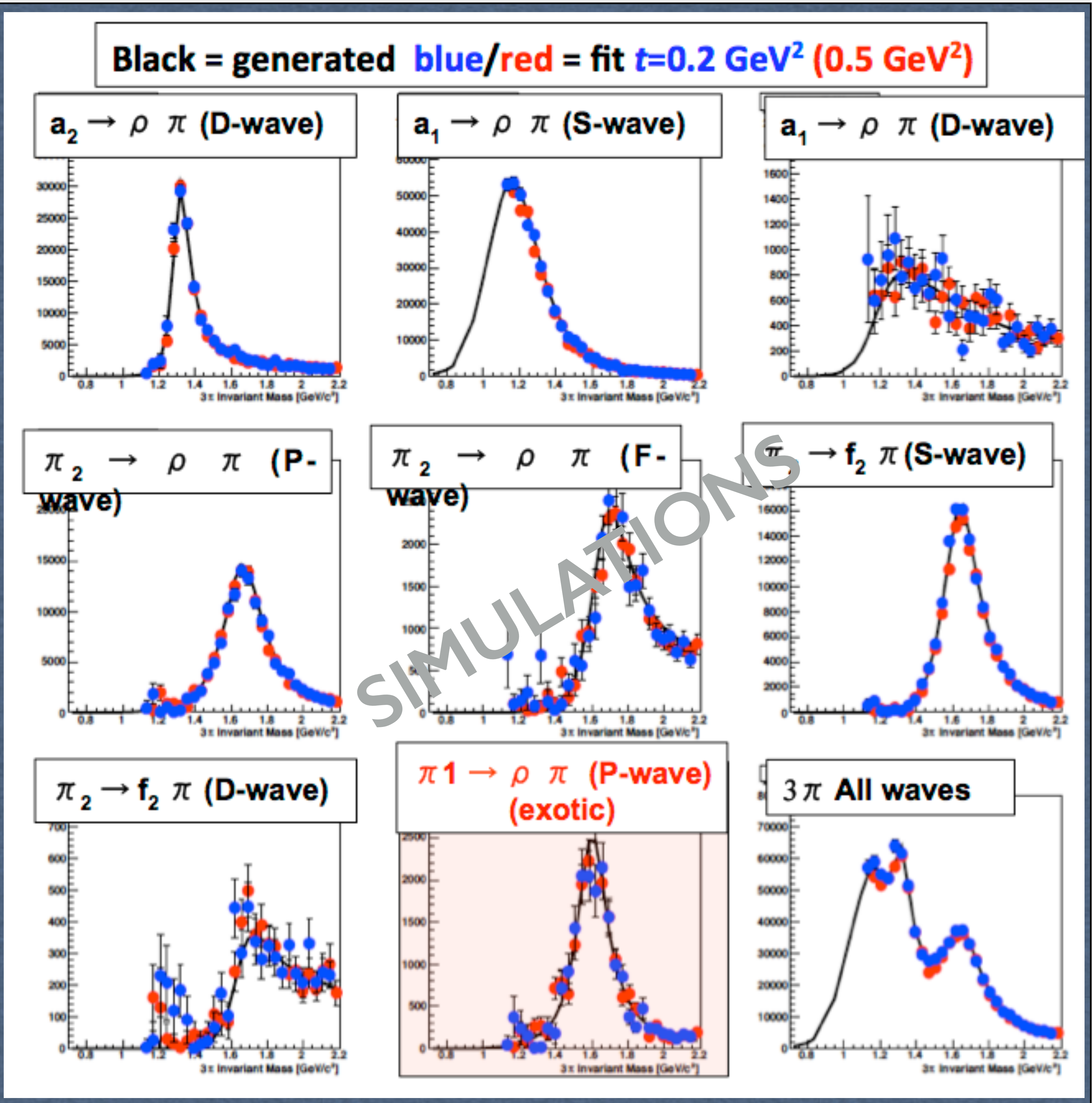
Partial Wave Analysis (PWA)

- Goal: extract the intensity of the different angular waves as a function of the invariant mass of the final state particles
- Measure events for the process of interest
- Build a model that describes the process
- Fit the model to the data

PWA with CLAS12

$\gamma\, p \rightarrow n\, \pi^+ \pi^+ \pi^-$

- The process is described as sum of 8 isobar channels:
  - $a_2 \rightarrow \rho\, \pi$ (D-wave)
  - $a_1 \rightarrow \rho\, \pi$ (S-wave)
  - $a_1 \rightarrow \rho\, \pi$ (D-wave)
  - $\pi_2 \rightarrow \rho\, \pi$ (P-wave)
  - $\pi_2 \rightarrow \rho\, \pi$ (F-wave)
  - $\pi_2 \rightarrow f_2\, \pi$(S-wave)
  - $\pi_2 \rightarrow f_2\, \pi$ (D-wave)
  - ~3% $\pi 1 \rightarrow \rho\, \pi$ (P-wave) (exotic)
- Amplitudes calculated by A.Szczepaniak and P.Guo
- CLAS12 acceptance projected and fitted
- PWA is stable against CLAS12 acceptance/ resolution distortion



D.Glazier

Modern AI-supported tools for data analysis

AI for NP/HEP

- Data collected by NP/HEP experiments are (always) affected by the detector's effects
- Before starting physics analysis the detector's effects unfolding are required
- Traditional observables may not be adequate to extract physics in multidimensional space (multi-particles in the final state)
- At High-Intensity frontiers, data sets are large and difficult to manipulate/preserve

Shall AI support NP/HEP experiments to extract physics from data in a more efficient way?

Develop AI-supported procedures to:

- Data preparation for unfolding detector effects
- Accurately fit data in multiD space
- Extract physics observables (xsec, asymmetries, …) from *synthetic* data (AI-generated)
- Interpret physics observables
- in all steps, quantifying the uncertainty (UQ)

A(i)DAPT

AI for Data Analysis and PreservaTion

Collaborative effort (regular meeting)

- ML experts (ODU, JLab)
- Experimentalists (JLab Hall-B, GlueX)
- Theorists (JPAC, JAM)

GANs for detector unfolding

Detector unfolding

Detector effects make measured observables (detector-level) DIFFERENT from 'true' observables (vertex-level)

Resolution

- Any detector has a finite resolution that spreads the measurement
- A spike could be not resolved
- The measurement may extend in an unphysical region (e.g. negative squared missing mass)

Acceptance

- Any measurement covers only a fraction of the reaction phase-space
- Difficulty: the cross section (Probability Density Function) can not be constrained by general rules (other than being positive) since it reflects the underlying (a-priori unknown) physics
- No model-independent extrapolation of PDF outside detector's acceptance is possible (based on measured phase space)

[Efficiency]

- Detection is a non-deterministic process provides different results in multiple measurements of the same observable

Use AI:

- INSIDE ACCEPTANCE to replace data with a synthetic replica statistically identical to the original but w/o smearing
- OUTSIDE ACCEPTANCE: to generate pseudo-data according a physics informed model

GANs for detector unfolding

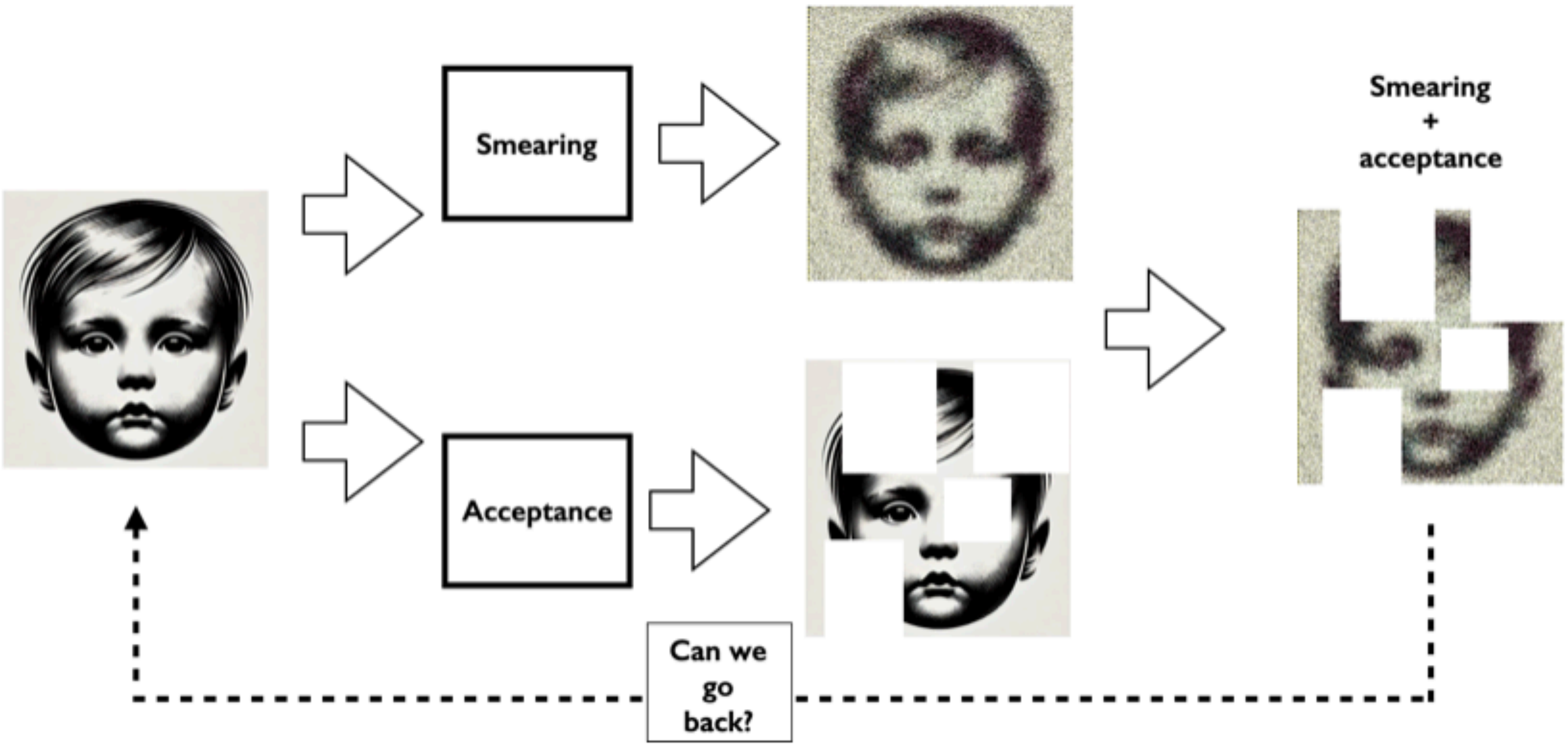
Detector unfolding

Detect
(vertex

Use AI:
- INSID
- OUTS

Detector unfolding

Can we recover the original image?



GANs for detector unfolding

Detector unfolding

Detect
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Use AI:
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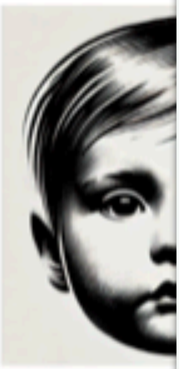
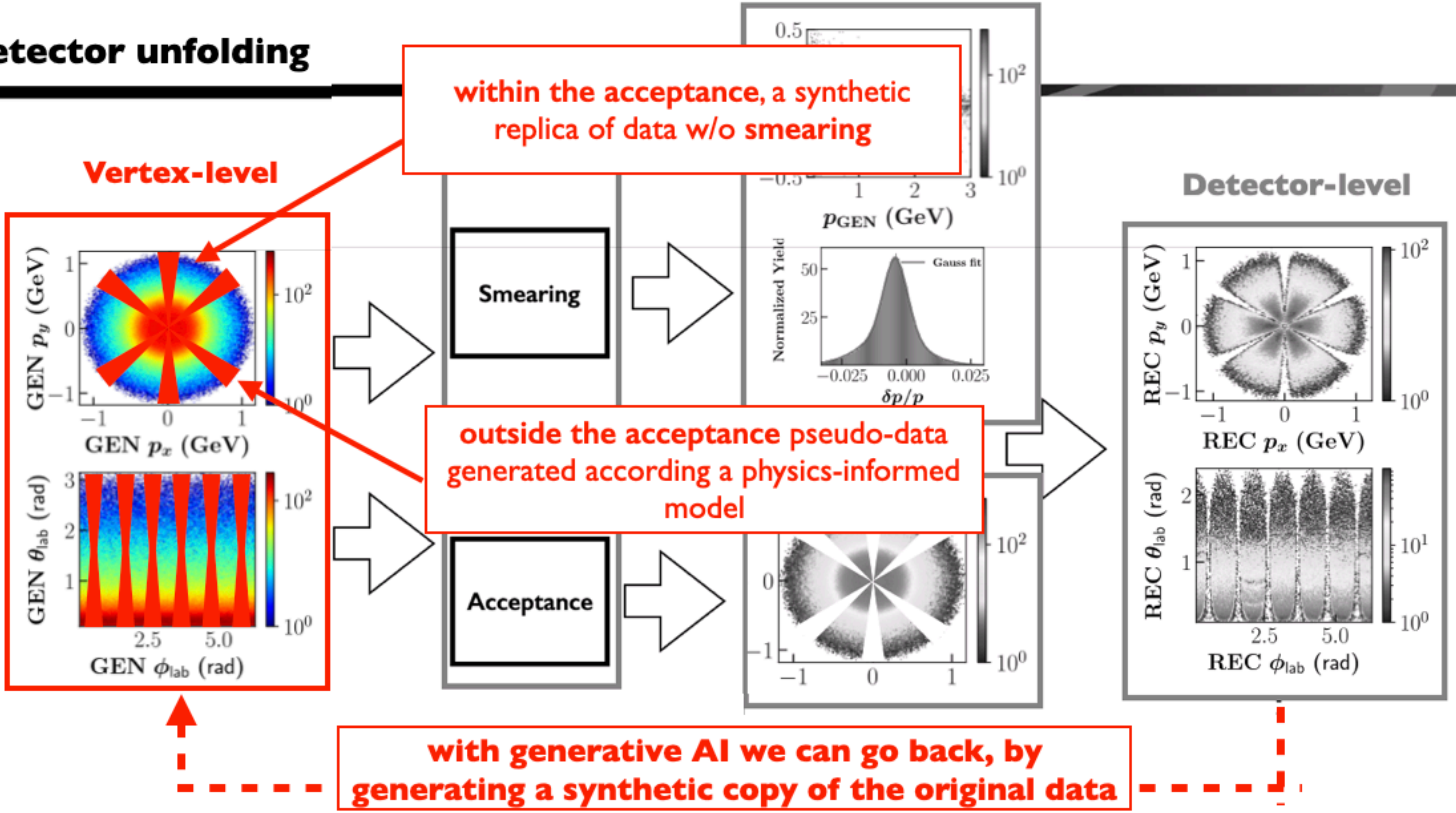
- OUTS

Detector unfolding



Detector unfolding

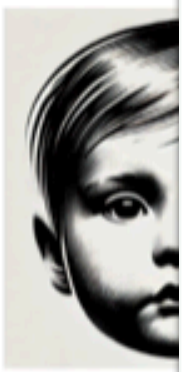


Detector unfol

Detector

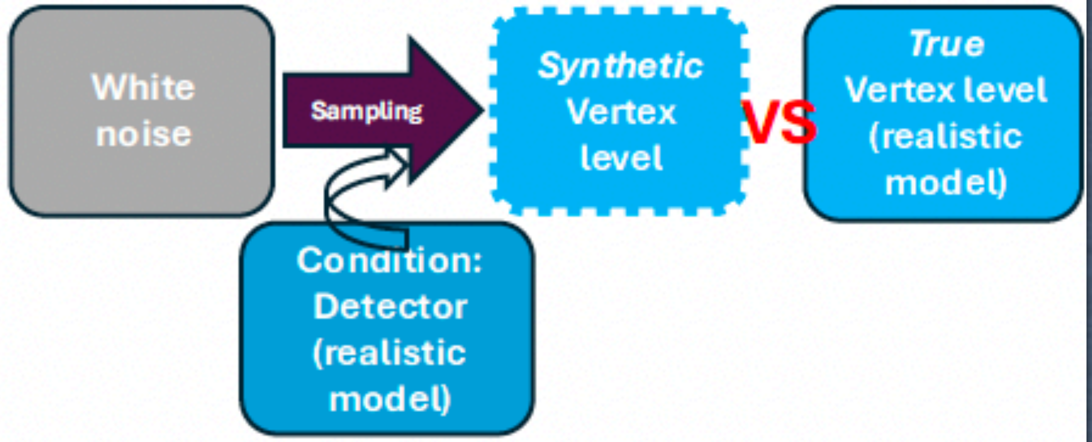
De

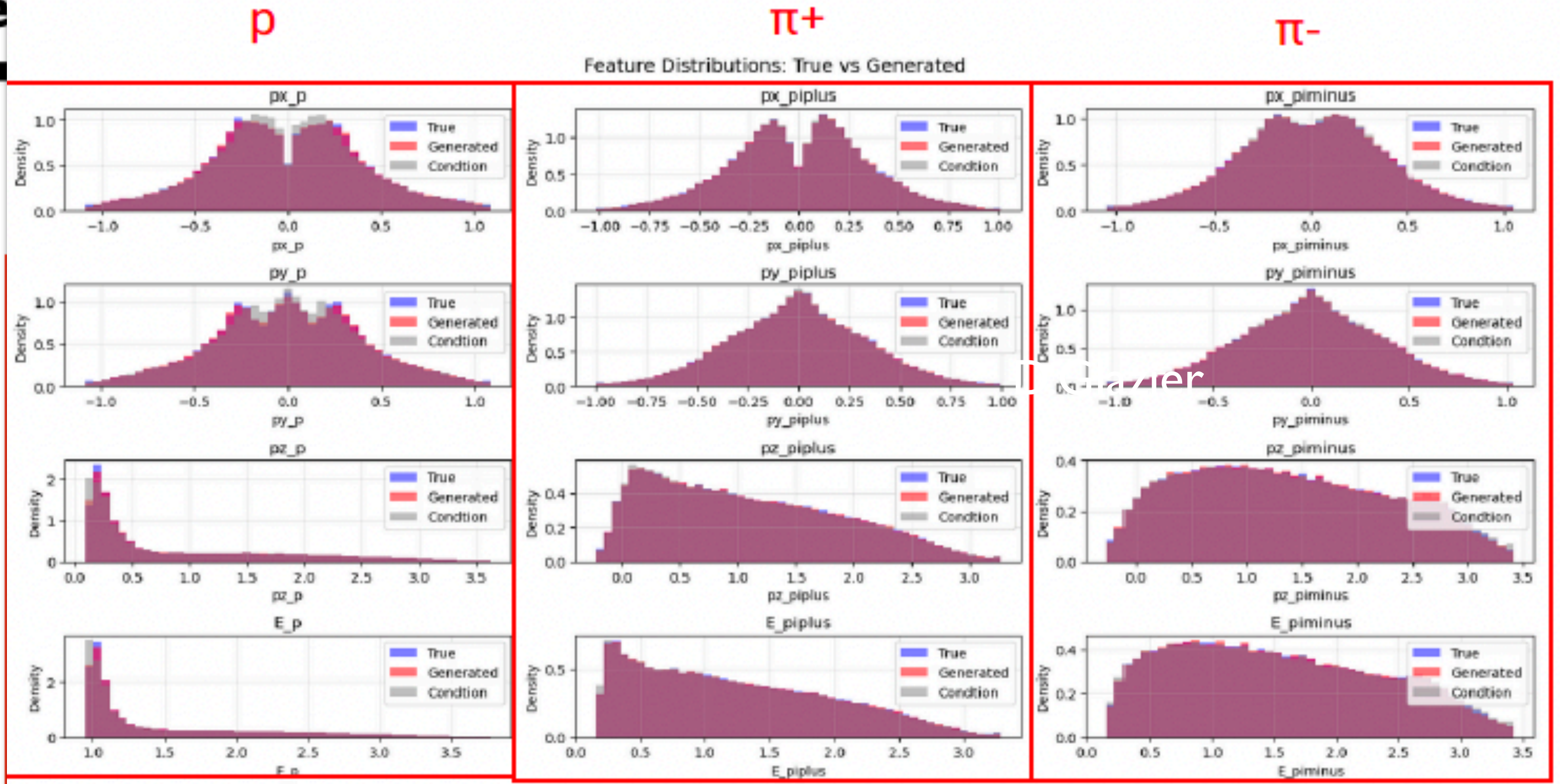
Detect
(vertex



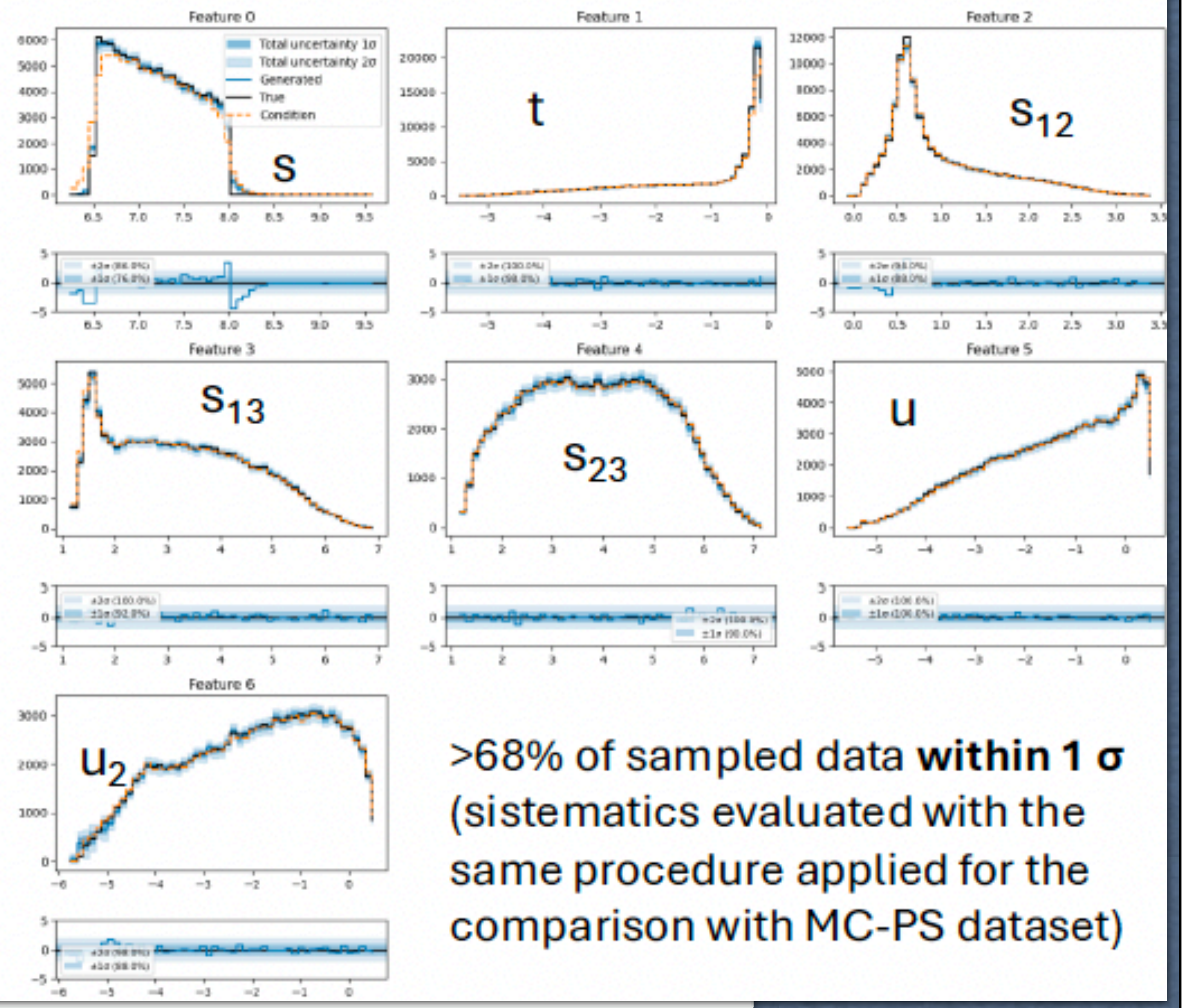
Use AI:
- INSID
- OUTS

A(i)DAPT: unfolding through diffusion models II





Correlations are preserved also in this case



>68% of sampled data **within 1 σ** (sistematics evaluated with the same procedure applied for the comparison with MC-PS dataset)

Using the same cDM trained just on MC-PS data, we manage to **satisfactorily sample the vertex from a realistic-MC dataset never seen by the model**: production is factorized and the model has really learned how to smear

G.Foti

Tools for data analysis from CLAS6 to CLAS12

- We want to extract the moments are calculated as fit parameters of the intensity:

$$\mathcal{I}(\Omega) = \sum_{JMS\Lambda} \left(\frac{2J+1}{4\pi}\right)\left(\frac{2S+1}{4\pi}\right) H(JMS\Lambda) \times D^{J*}_{M,\Lambda}(\phi_{GJ},\theta_{GJ},0) D^{S*}_{\Lambda,0}(\phi_{HF},\theta_{HF},0), \quad (1)$$

- The moments relate to partial waves:

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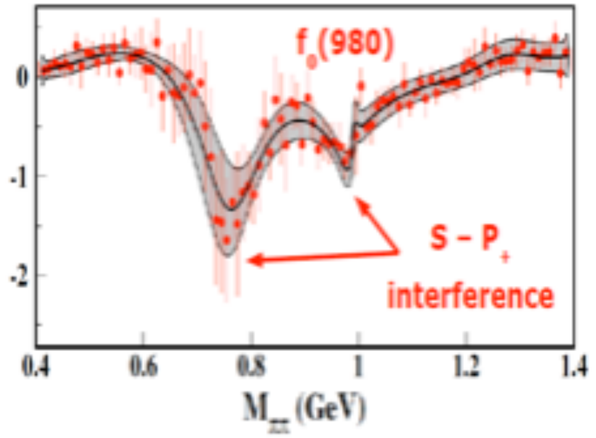
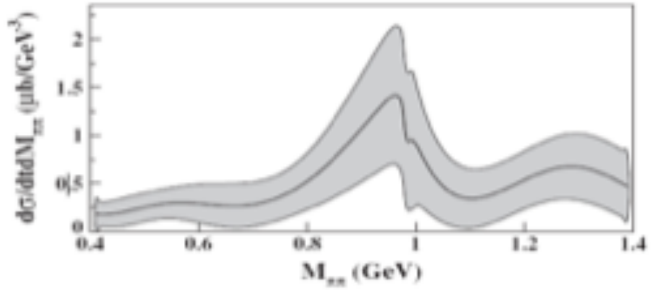
Strategy

- Moments of the angular distributions can be used as an intermediate step toward a full PWA

$$\langle Y_{\lambda\mu}\rangle(E_\gamma,t,M) = \frac{1}{\sqrt{4\pi}}\int d\Omega_\pi \frac{d\sigma}{dtdMd\Omega_\pi} Y_{\lambda\mu}(\Omega_\pi)$$

- Fit of amplitudes with moments lead to the first observation of the $f_0(980)$ using CLAS6 data



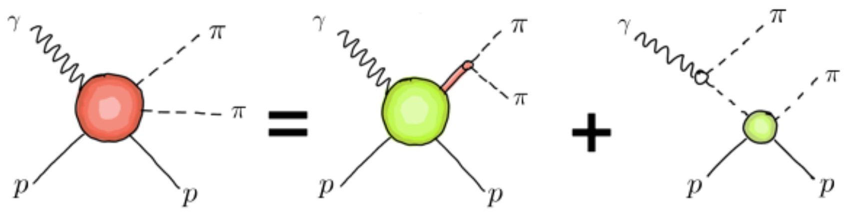


M($\pi^+\pi^-$) spectrum below 1.5 GeV:

- P-wave: ρ meson
- D-wave: $f_2(1270)$
- S-wave: σ, $f_0(980)$ and $f_0(1320)$

L.Bibrzycki

Regge-Amplitude Model for γp → π⁺π⁻p by JPAC, *PRD 111, 014002 (2025)*

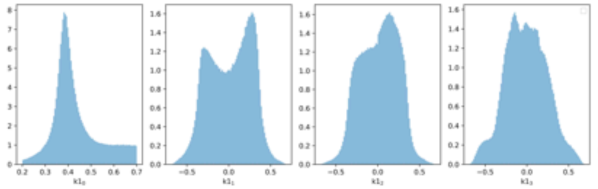


Physics Model:

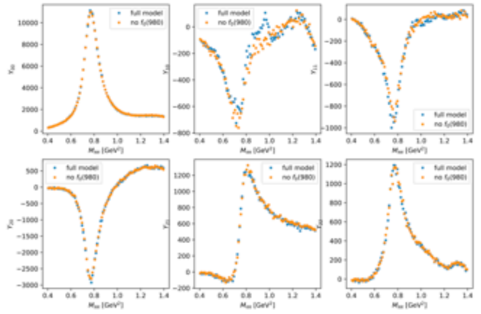
- Resonances: ρ(770), $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_2(1270)$
- Regge exchanges: Pomeron, a_2/f_2, ρ/ω
- Non-resonant Deck mechanism

Workflow:
Amplitude model → fit to angular moments → 4-fold cross section → MC generator

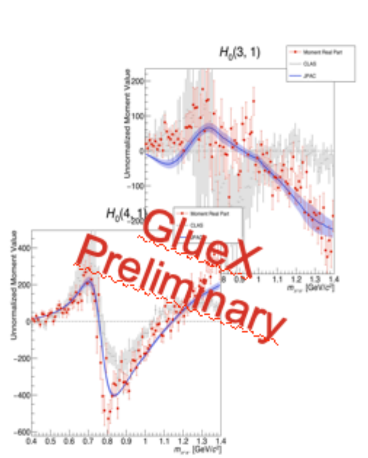
Deliverables:



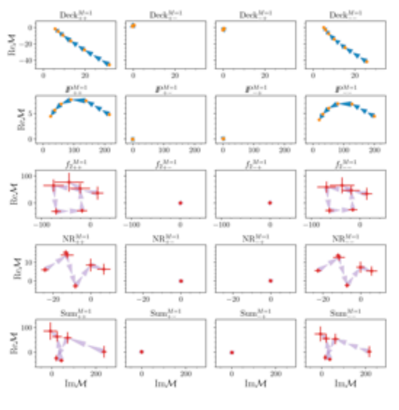
MC event samples (full 4-vectors)



Angular moments derived from the MC dataset



Higher moments



Amplitude phase motion

Tools for data analysis from CLAS6 to CLAS12

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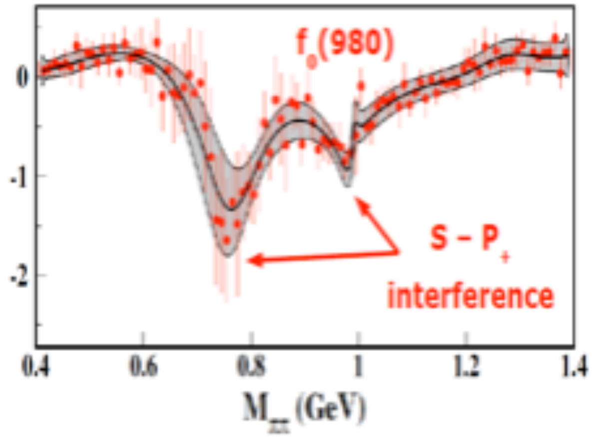

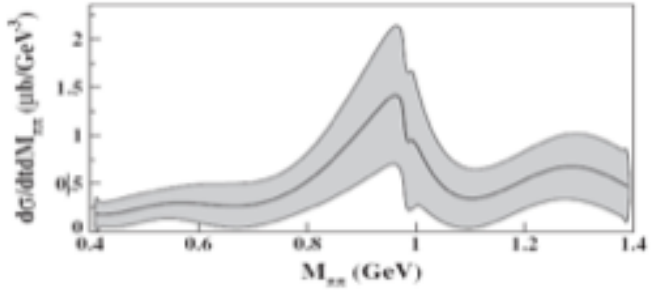

Key Framework Objectives

- **Model Independence I:** Experimental data can be completely summarised by Polarised Spherical Harmonic moments $H^\alpha(LM)$.
- **Unpolarised Experiments:** Relating these moments to underlying partial wave amplitudes of any contributing meson resonances reduces number of independent parameters.
- **Polarised nucleons**: We generalised to polarised nucleons, doubling the measureable amplitudes.
- **L/T seperation** Restricting the model dependence to Regge factorisation allows Single Energy L/T seperations. In principle polarised nucleon experiments allow fully model indepedent extractions.

Current Status & Next Steps

- **Formalism:** paper write up in progress.
- **Tools:**
  - Moment to amplitude invertor developed.
  - Moment fitting tools for electro-production under-development.
  - Inclusive Generator based on JPAC models under-development.

A Model-Independent Partial Wave Approach to Meson Photo- and Electroproduction

Spherical Harmonic Moments, Spin Density Matrices, Partial Wave Amplitudes

Derek Glazier
Dillon Leahy, Vincent Mathieu
and the Joint Physics Analysis Centre

Conclusion: Methods developed for complex amplitude analysis in photoproduction for Hadron Spectroscopy experiments are ready to be implemented in electro-production reactions.

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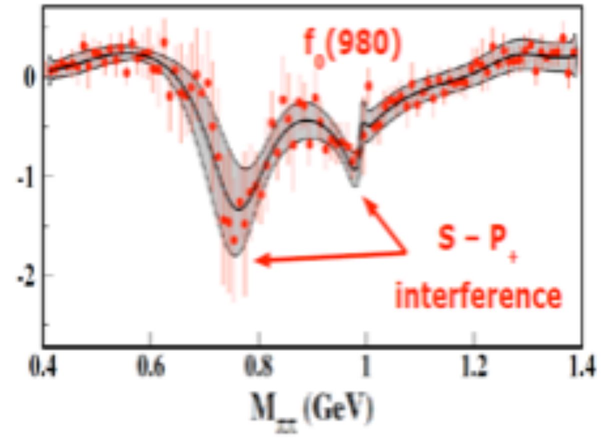

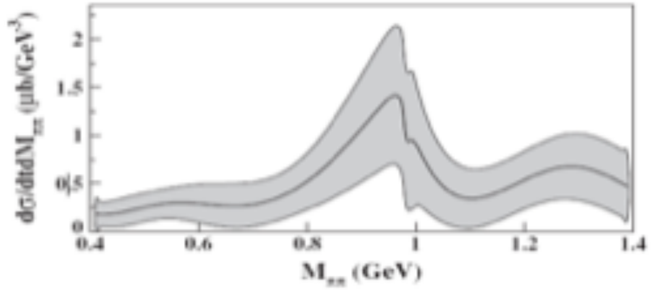

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- P-wave: ρ meson
- D-wave: $f_2(1270)$
- S-wave: σ, $f_0(980)$ and $f_0(1320)$

Polarised photoproduction of 2 spinless particles

Decay process can be studied in a number of related ways :

Moments of spherical harmonic distributions
Fourier analysis up to some truncation in L
CLAS results (Battaglieri et al, 2000)
still being analysed by JPAC

Spin Density Matrix Elements
Classic Schilling, Seybouth and Wolf paper for Vector mesons
Extended to electroproduction
Assumes only P-wave contributions
Recent GlueX results

Partial Wave Amplitudes
Allows multitude of contributing resonances of all l
Mass dependence allows pole extraction
GOAL for spectroscopy

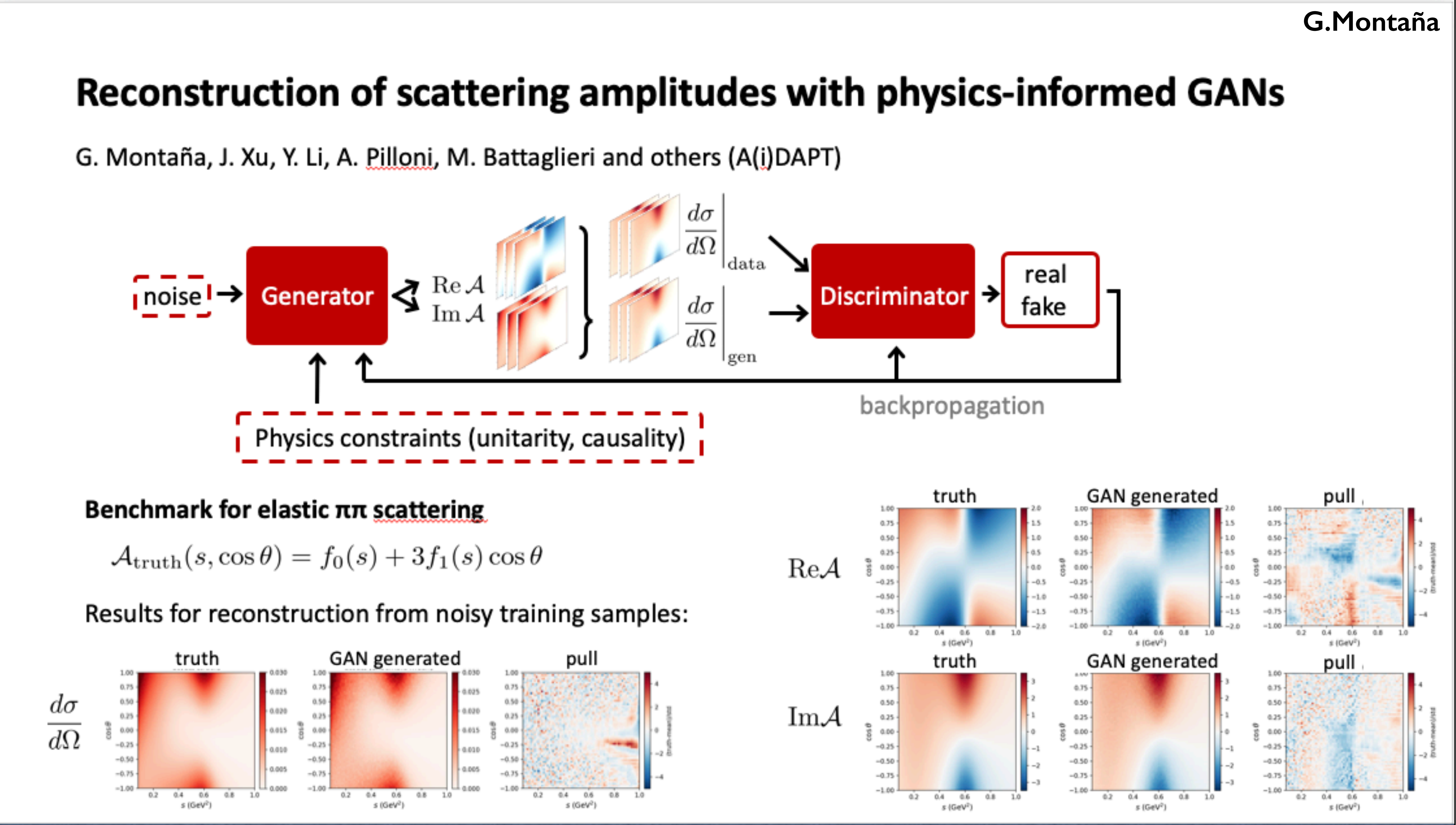
Greater connection to physics ↓

When analysing final states with CLAS12 that have > 2 particles (+ e')
We **must** consider the two-body decays when measuring cross sections
and beam spin asymmetries if we integrate over decay angle.
or else they are not reliable (they are a product of detector*physics)

AI for extracting amplitudes

Extract amplitude from differential cross sections, using unitarity constraint

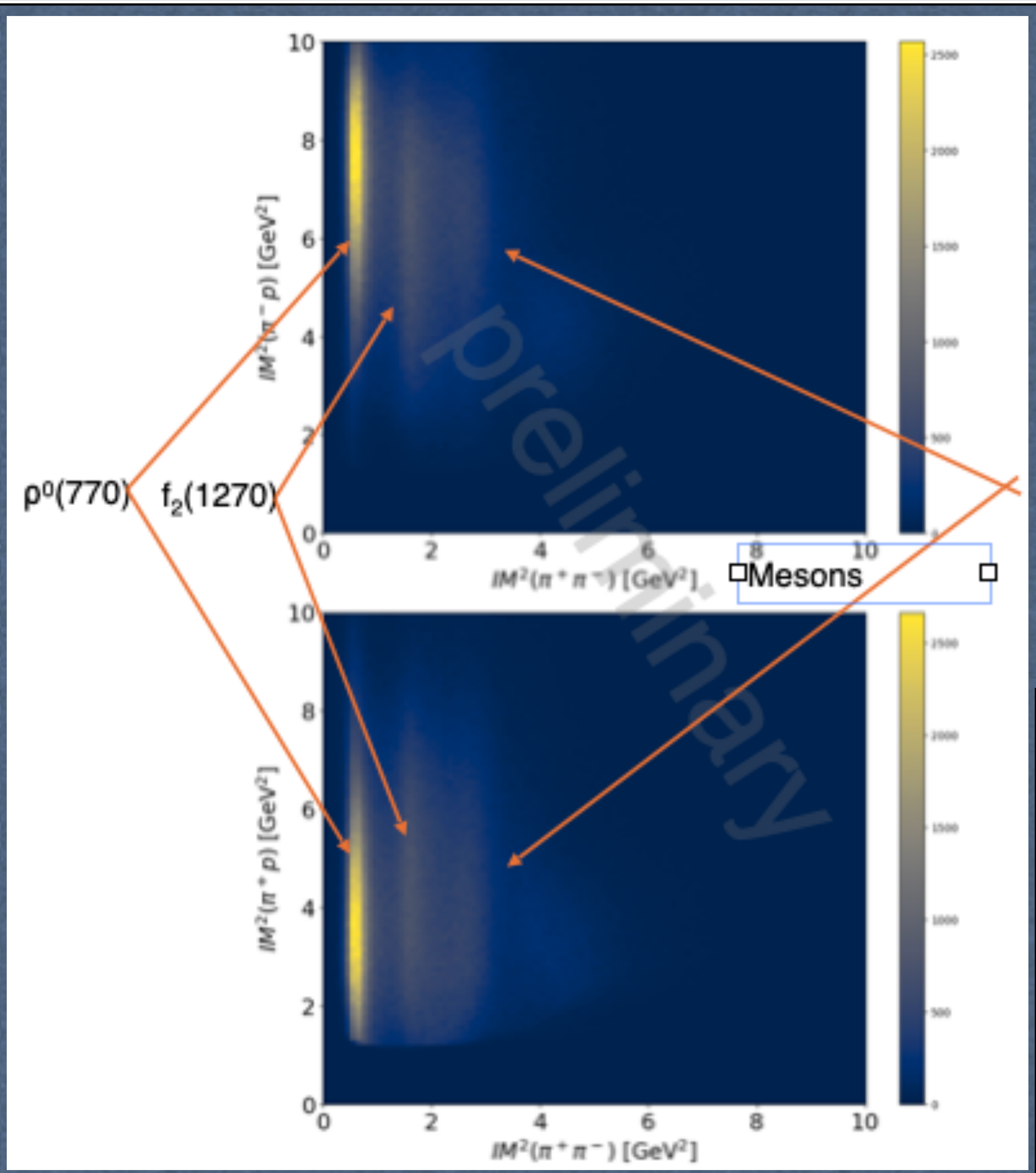
Train an AI model to extract amplitudes (complex numbers satisfying some physics constraints, e.g. unitarity) from events generated with Monte Carlo simulations according to a theoretical model (and eventually from experimental data)

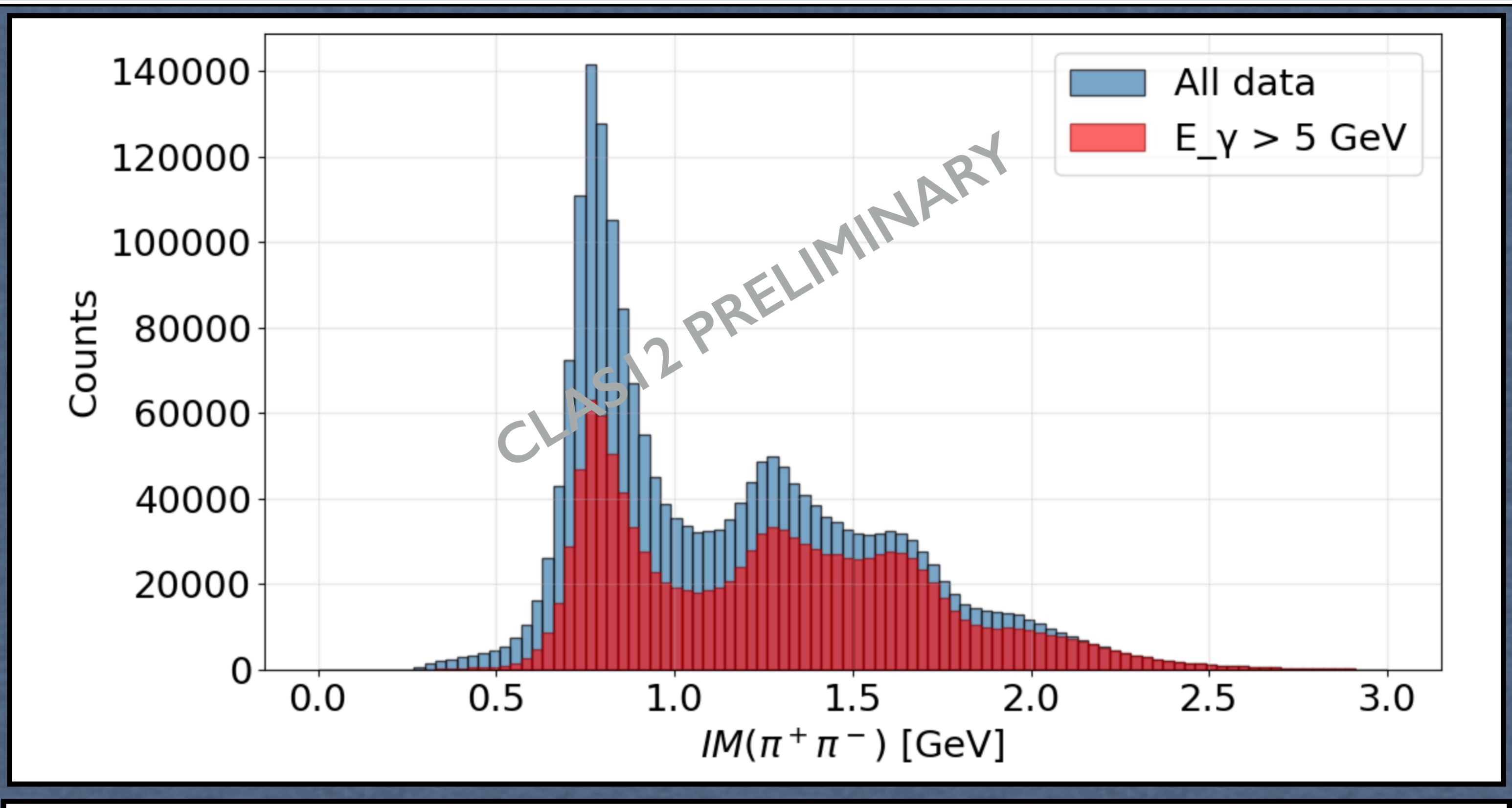


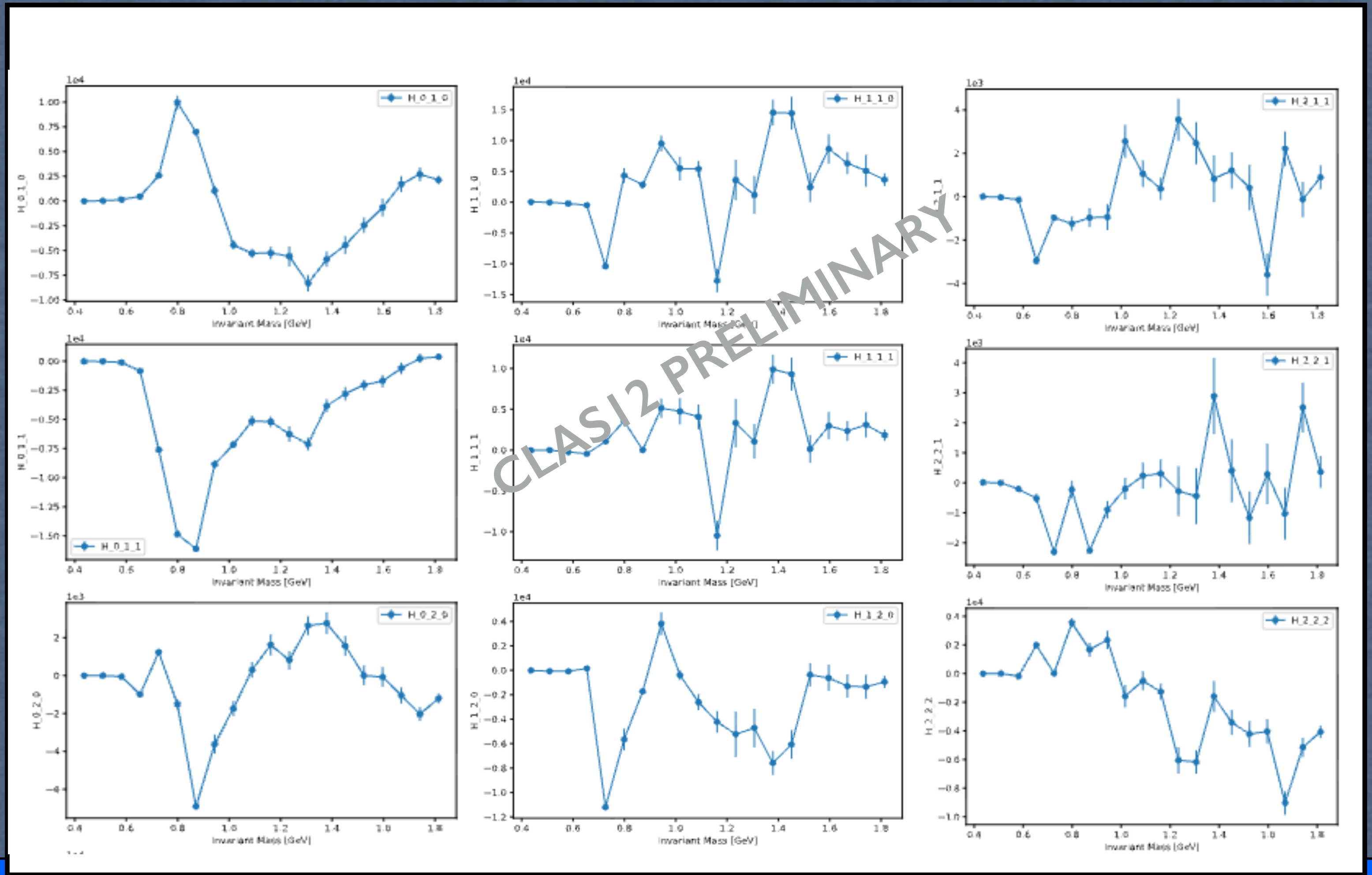
MesonEx data

$\gamma\, p \rightarrow p\, \pi^+ \pi^-$

- Use standard CLAS12 PID (FT based start time)
- $p\pi^+\pi^-$ exclusive reaction (all hadrons detected)
- All *-t*
- $<Q^2>=0.07\ GeV^2/c^2$
- E_{Beam} = 10.6 GeV → E_γ > 5 GeV







- Complementary cuts select baryons for further studies
- First extraction of angular moments

M.Filippini, D.Glazier

Absolute cross section

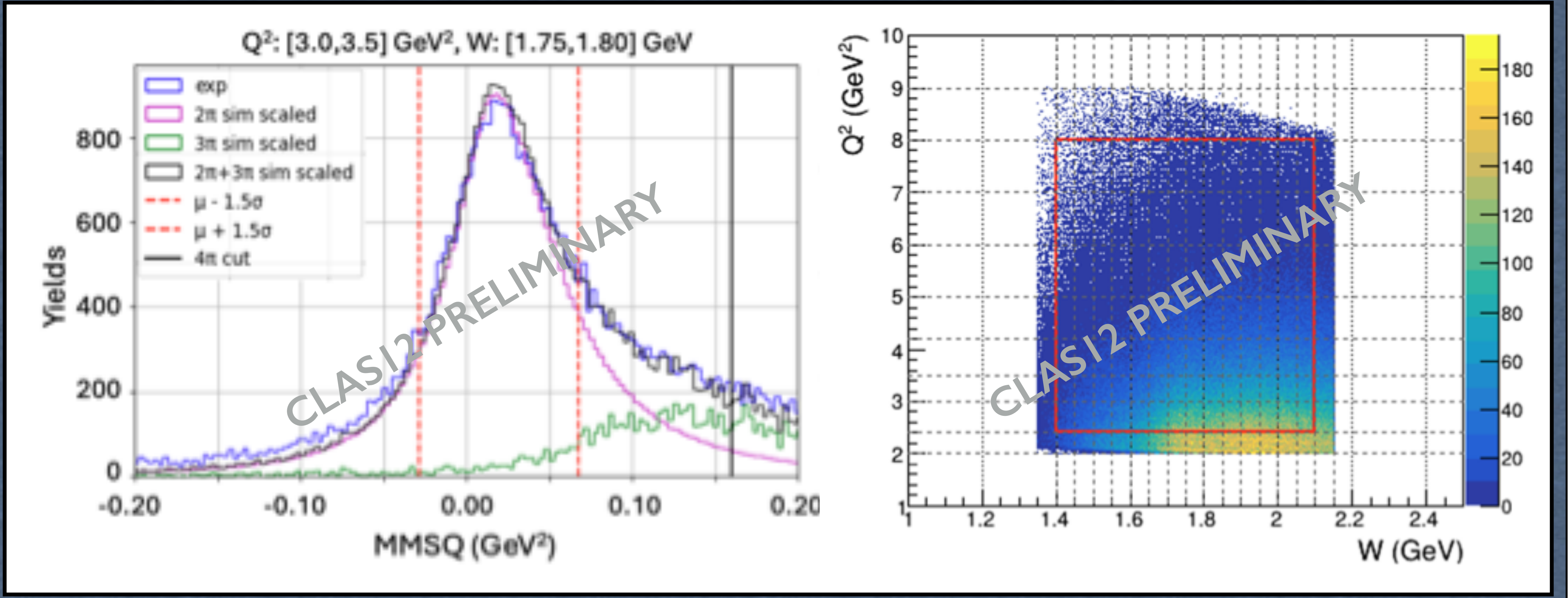
$e\,p \rightarrow e'\,p\,\pi^+\,\pi^-$

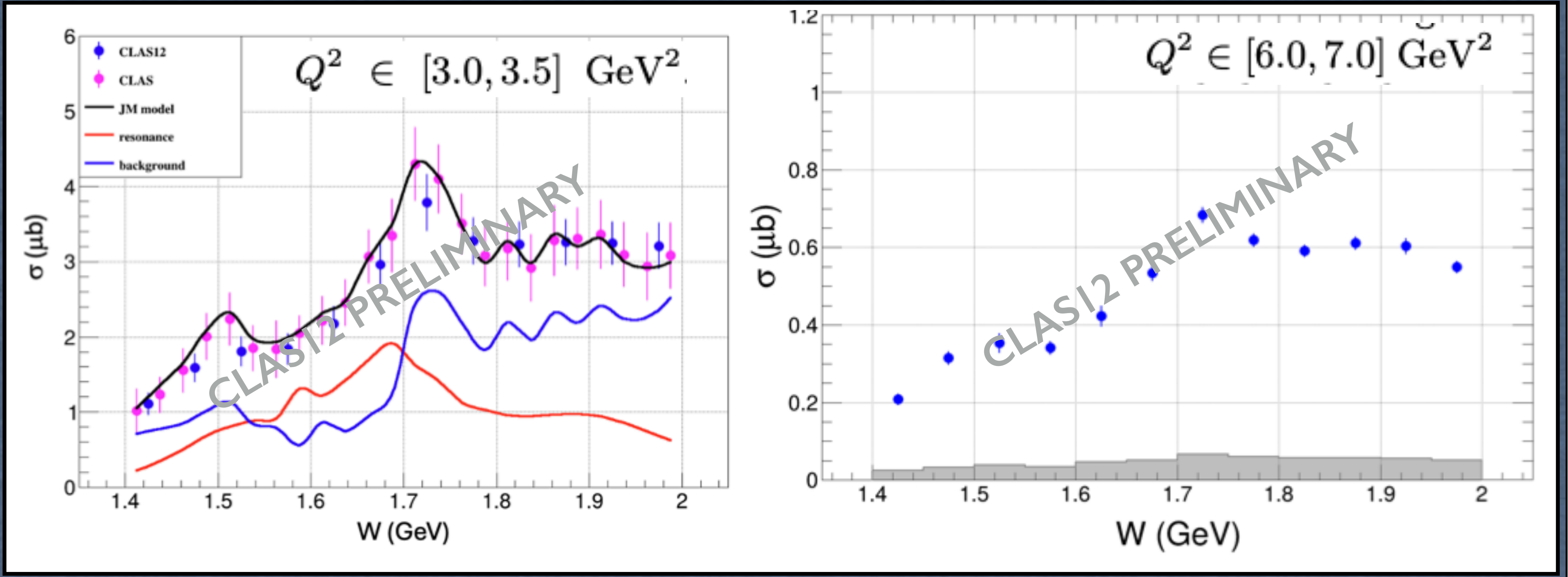
- $p\pi^+(\pi^-)$ exclusive reaction
- E_{Beam} = 10.6 GeV
- Q^2 = [2.4 - 8] GeV^2/c^2
- W = [1.4-2.1] GeV
- Absolute muti-d Xsec extraction

$$\frac{d^5\sigma}{dM_{h_1h_2}dM_{h_2h_3}d\Omega_{h_1}d\alpha_{[h_1p][h_2h_3]}} = \frac{1}{\Gamma_v}\frac{d^7\sigma}{dW\,dQ^2dM_{h_1h_2}dM_{h_2h_3}d\Omega_{h_1}d\alpha_{[h_1p][h_2h_3]}},$$

- Wide kinematic range covered
- Nucleon resonances photocoupling extraction
- Paper in preparation

K.Neupane

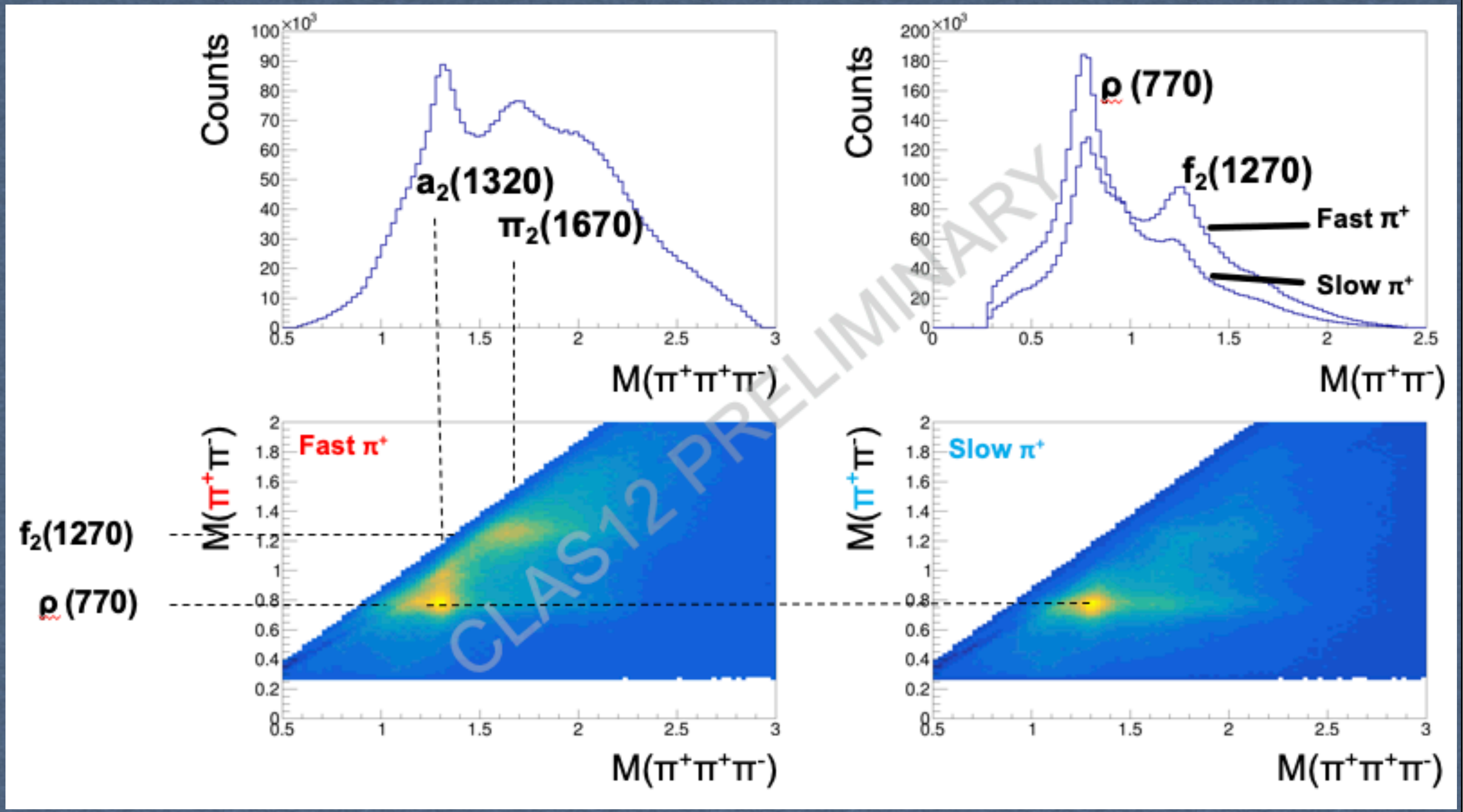




MesonEx data

$\gamma\, p \rightarrow (n)\, \pi^+ \pi^+ \pi^-$

- Search for $\pi_1(1600)$ exotic meson
- E_{beam}=10.6 GeV on LH2 target
  - *-t < -2 GeV*
  - $6<E_\gamma<10$ GeV
- Use standard CLAS12 PID (FT based start time)
- $p\pi^+\pi^-$ (missing n) exclusive reaction



- Need to include N*/Δ + 2π contributions in the analysis
- Trigger/Torus Field/Detector → Low acceptance for M < 1.3GeV

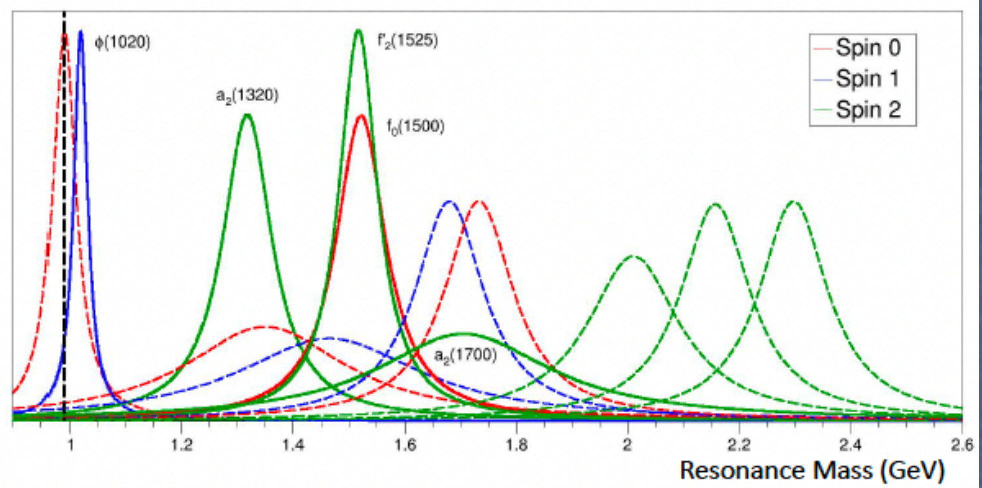
D.Glazier

MesonEx data

γ p → p K⁺ K⁻

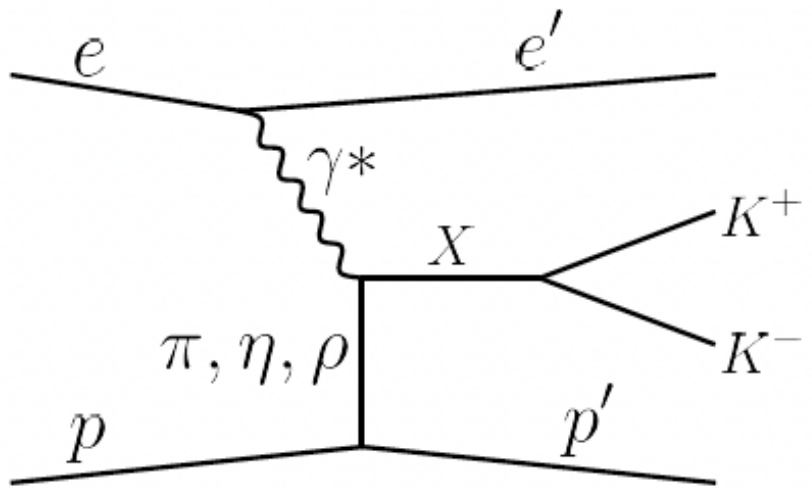
- E_{beam}=10.2 GeV on LH2 target
- Q^2 between 0.07 and 0.3 GeV
- e- in FT, hadrons in FD
- p and K^+ detected (K^- missing)

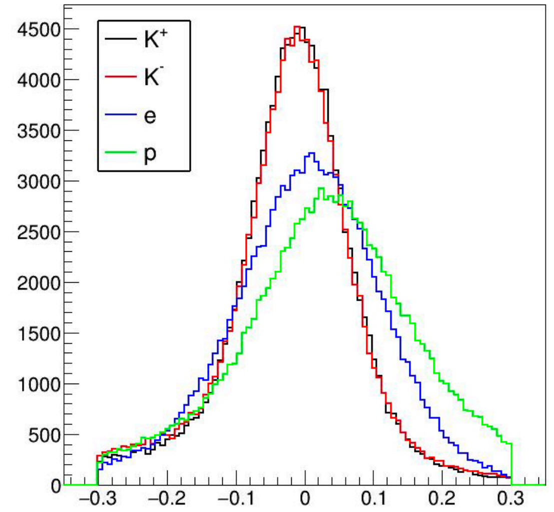
Resonances	Mass (MeV)	Width (MeV)	Spin
$\phi(1020)$	1019.5	4.3	1
$a_2(1320)$	1318.2	107.8	2
$f_0(1500)$	1522	108	0
$f'_2(1525)$	1517.3	84.4	2
$a_2(1700)$	1706	380	2

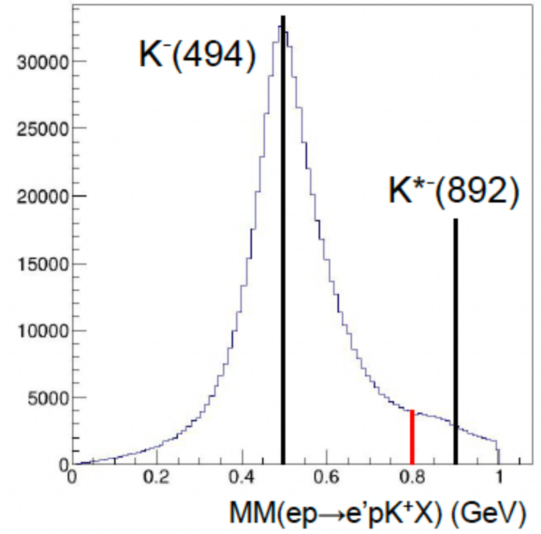


- Moment analysis

C.Velazquez

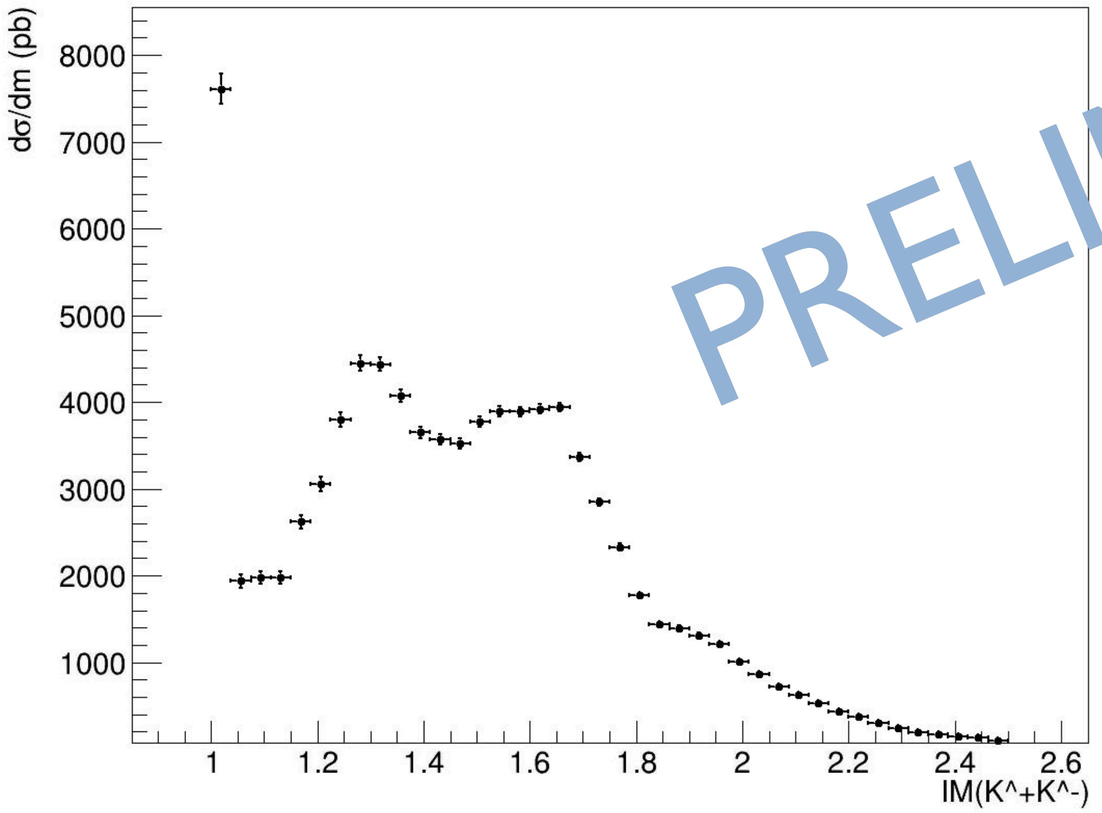






Differential cross-section

$$\frac{d\sigma}{dm_{K^+K^-}} = \frac{N_i}{\Gamma \epsilon_i \Delta m_i \, TBR_i}$$

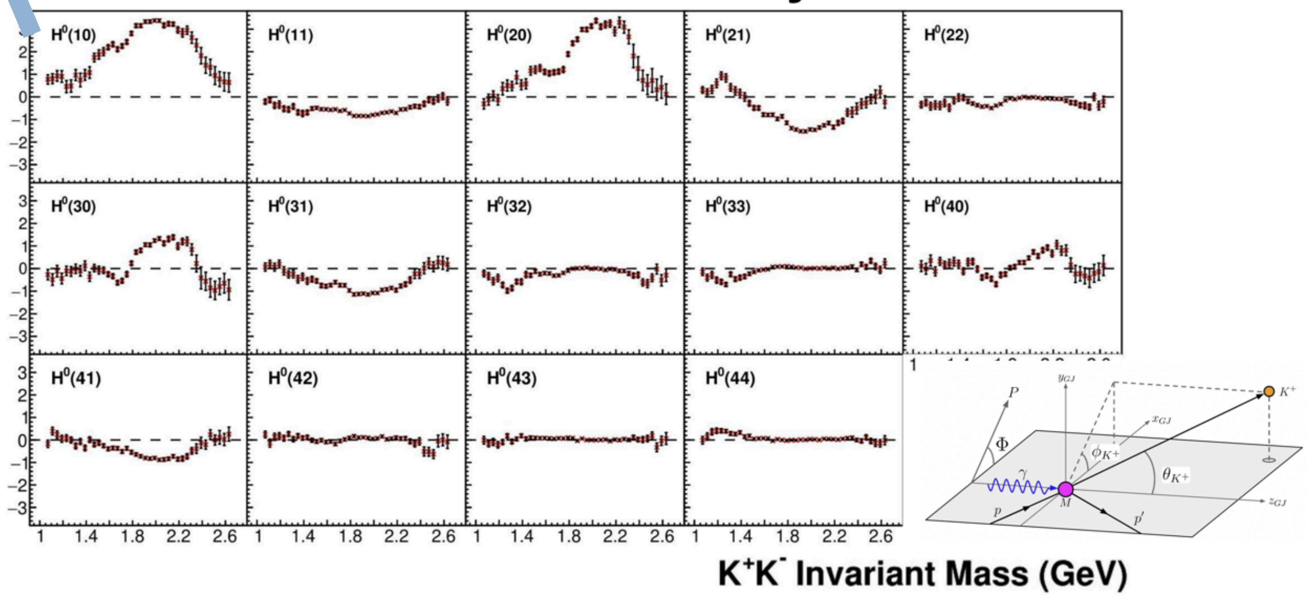


PRELIMINARY

$$H^0(LM) = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{2\pi}\int_{-1}^{1} I(\Omega,\Phi)\, d^L_{M0}(\theta)\cos M\phi \;d(\cos\theta)d\phi d\Phi$$

$$H^0(00) = H^1(00) + 2\left[|P_1^{(+)}|^2 + |D_1^{(+)}|^2 + |D_2^{(+)}|^2\right]$$

$$H^1(00) = 2\left[|S_0^{(+)}|^2 + |P_0^{(+)}|^2 + |D_0^{(+)}|^2\right]$$



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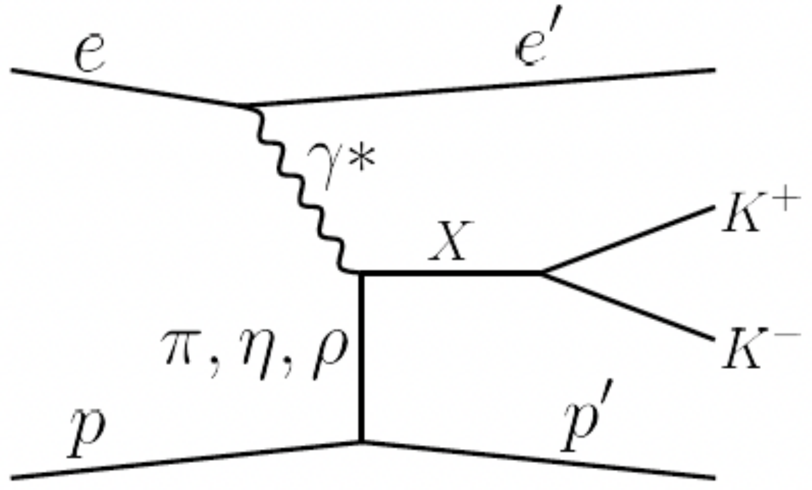

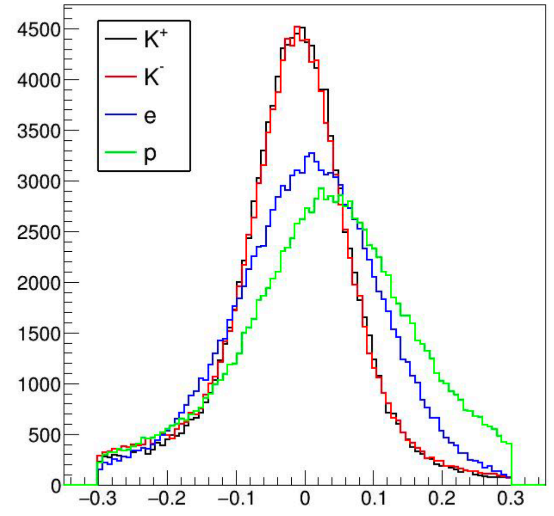

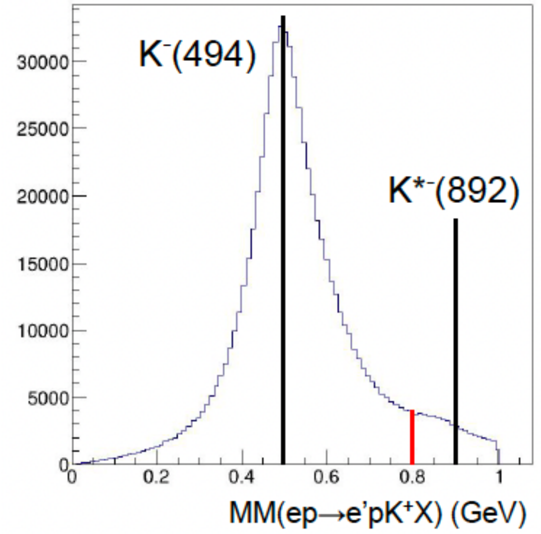

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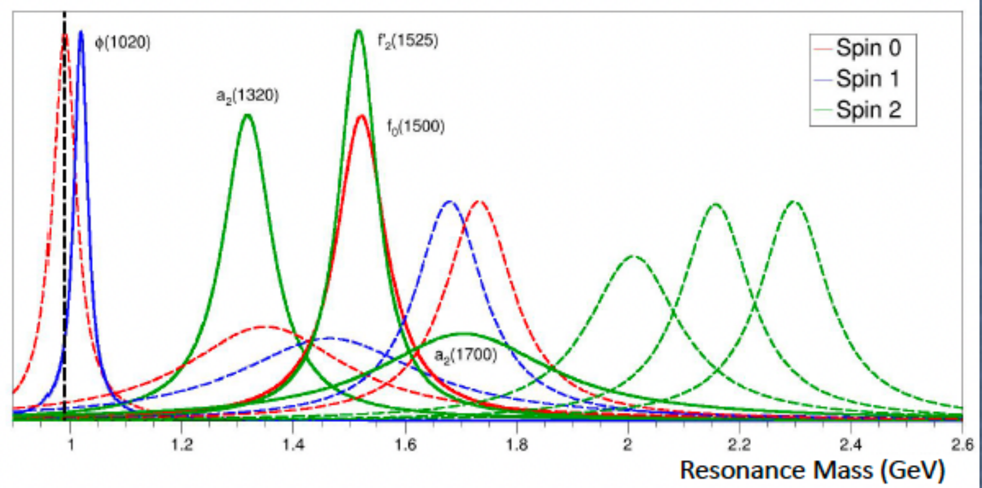
Monday 15:25

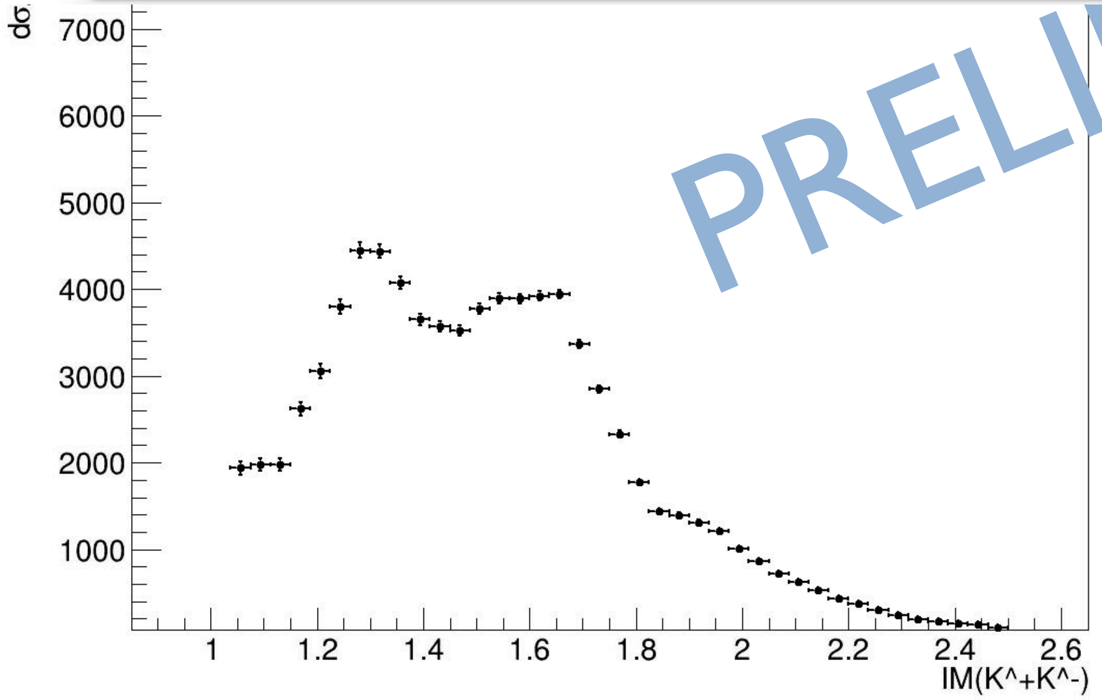
Partial Wave Analysis of Resonances in K+K- and KK* wit...

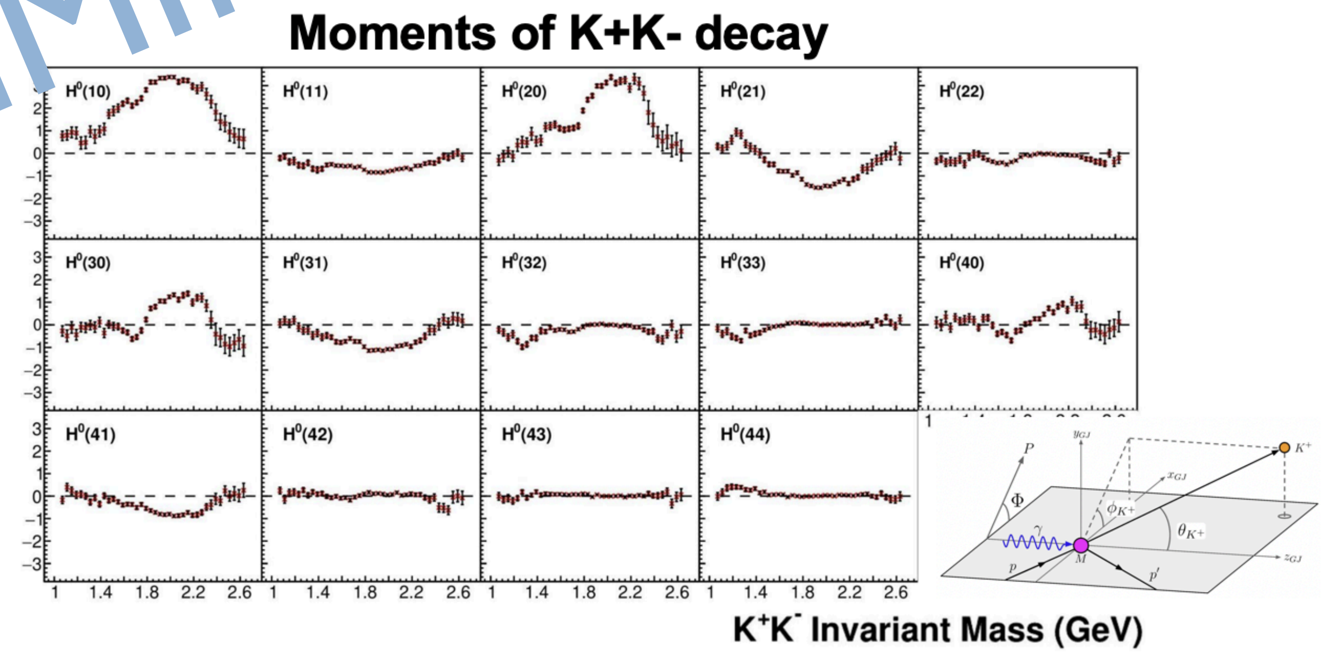
Charlie Velasquez



Differential cross-section

$$H^0(LM) = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{2\pi}\int_{-1}^{1} I(\Omega,\Phi)\, d^L_{M0}(\theta)\cos M\phi\ d(\cos\theta)d\phi d\Phi$$



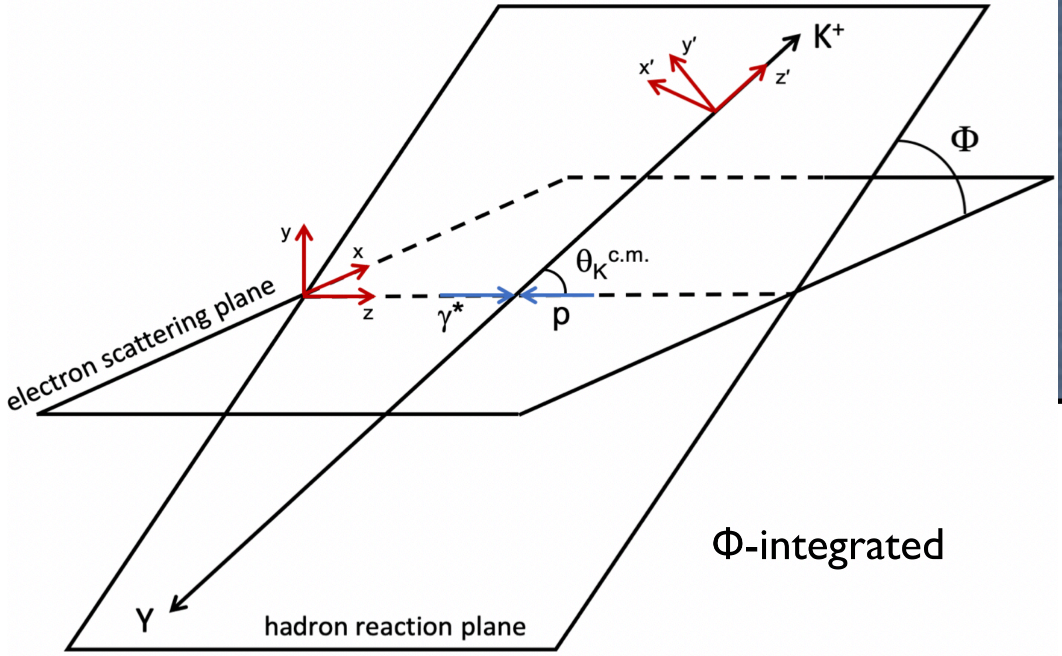


- Moment analysis

C.Velazquez

CLAS12 data analysis
e p → K^+ Y

- KY transferred and recoil polarisation
- K+ (Y=Λ^0) and K+ (Y=Σ^0)
- E_{beam}=6.5 GeV on LH2 target



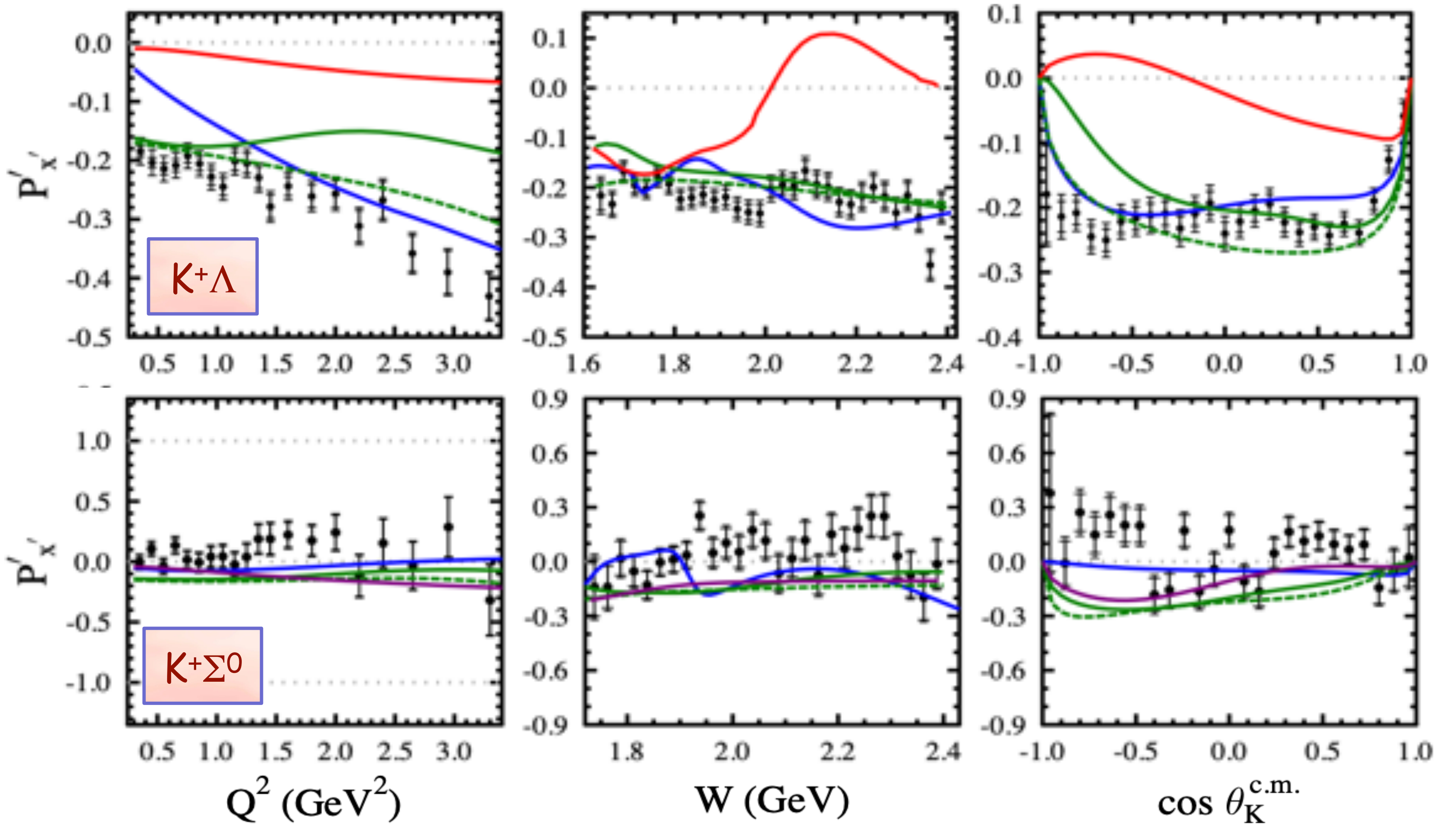
Φ-integrated

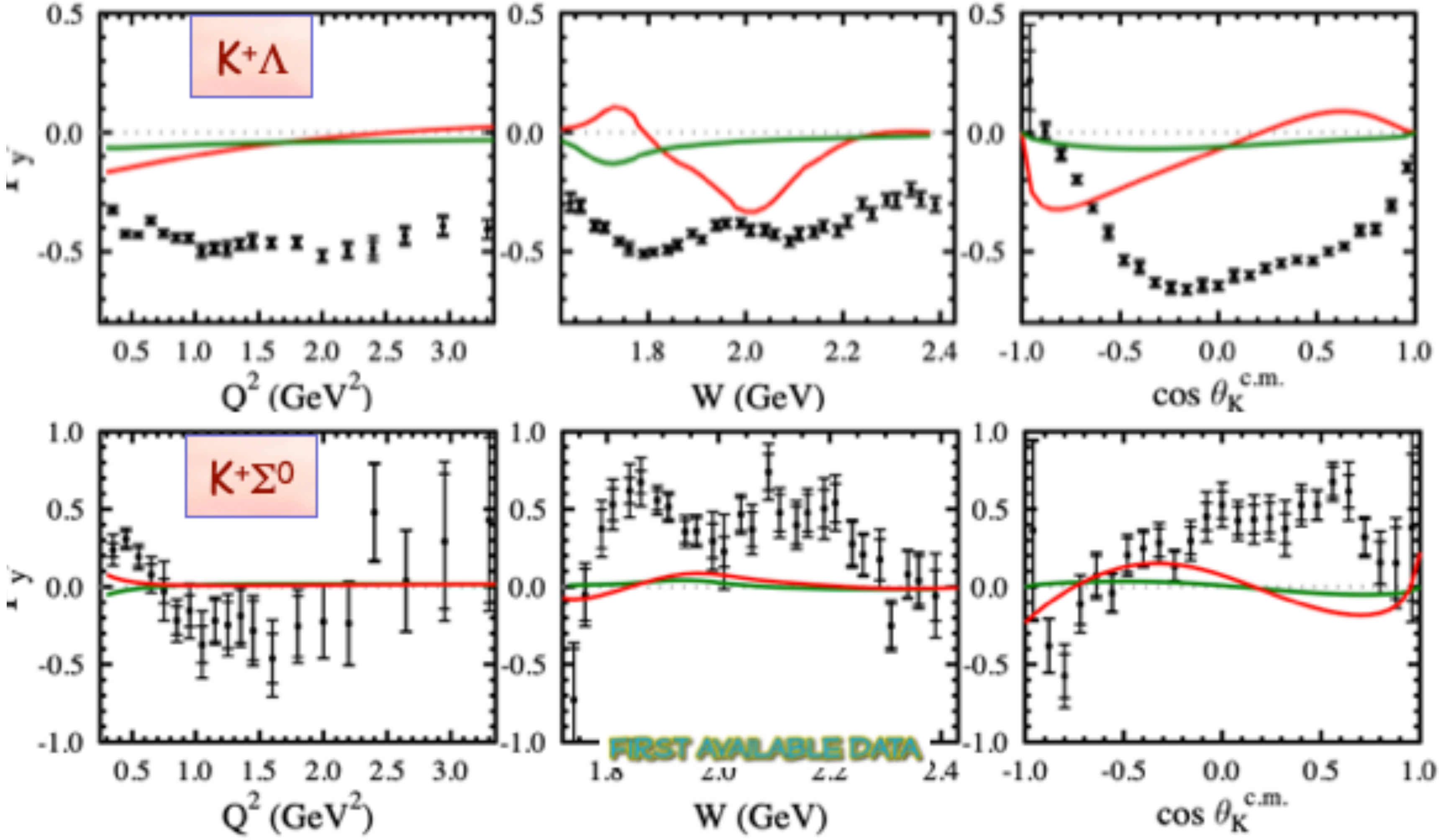
D.S. Carman et al. (CLAS12), PRC 105, 065201 (2022)
D.S. Carman et al. (CLAS), PRC 112, 035206 (2025)

- Single and couple channel analysis
- Fine tuning of isobar models

Isobar models:

BSΛ: D. Skoupil and P. Bydžovský, PRC 97, 025202 (2018)
BSΣ: D. Petrillis and D. Skoupil, PRC 110, 065204 (2024)
SL: J.C. David, C. Fayard, G.H. Lamont, and B. Saghai, PRC 53, 2613 (1996)





Conclusions and outlook

- ✳ Hadron spectroscopy (now as in the past) demonstrates to be an important tool to study strong forces
- ✳ Several new multi-quark states that do not fit into the Quark Model have been discovered
- ✳ Quark bound-states are genuine manifestation of non-perturbatibe regime of QCD
- ✳ Jefferson Lab has a comprehensive spectroscopy program (Gluex & CLAS12)
- ✳ Exotics and strangeness-rich mesons search exploit excellent resolution and particle ID
- ✳ CLAS12
  - Low Q^2 e- scattering for high intensity, linear pol, quasi-real photon beams
  - High Q^2 e- scattering to map out baryon/meson internal dynamics
- ✳ Abundant and precise data requires a solid PWA analysis framework
- ✳ New analysis tools based on AI are being developed in parallel to be ready for physics analyses

High-performance detectors, high intensity e/γ beams, strong analysis framework are the ingredients to make JLab a leading facility in modern hadron spectroscopy