The MesonEx experiment

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(for the MesonEx working group)

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?

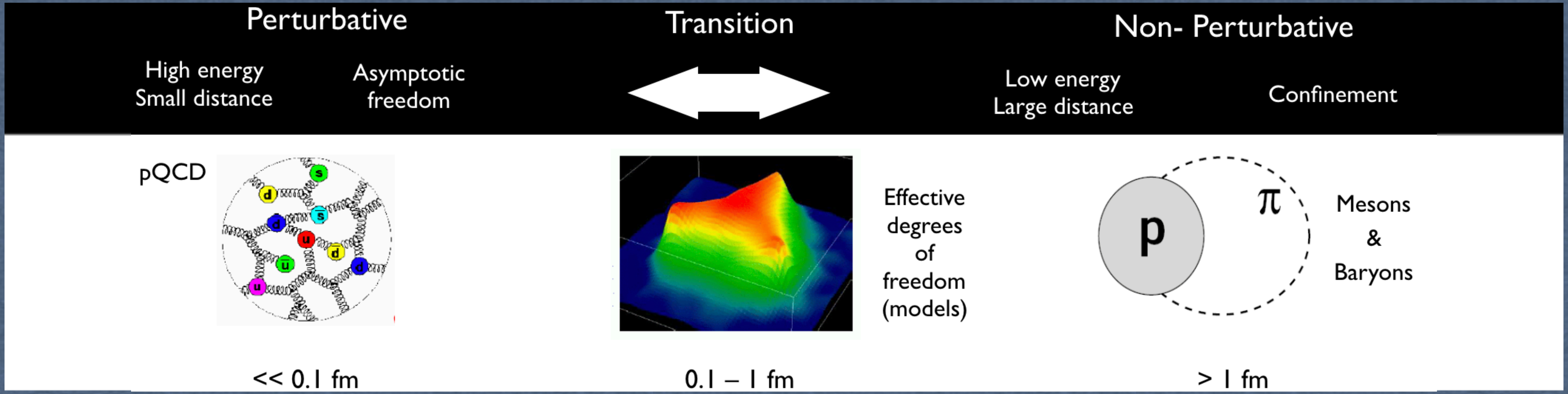
At high energy, phenomena can be described in terms of quarks and gluons; at low energy, we observed baryons and mesons: what are the real degrees of freedom, and how does the transition from small to large distances occur?

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?

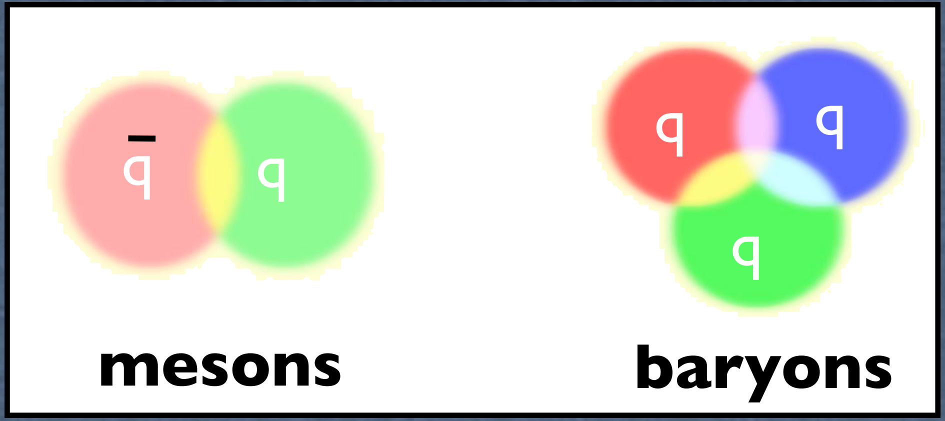
The theory of strong interactions does not prohibit hadronic states with different quark configurations (*5q, gg, 2qg*). Can we find evidence of the existence of such states?



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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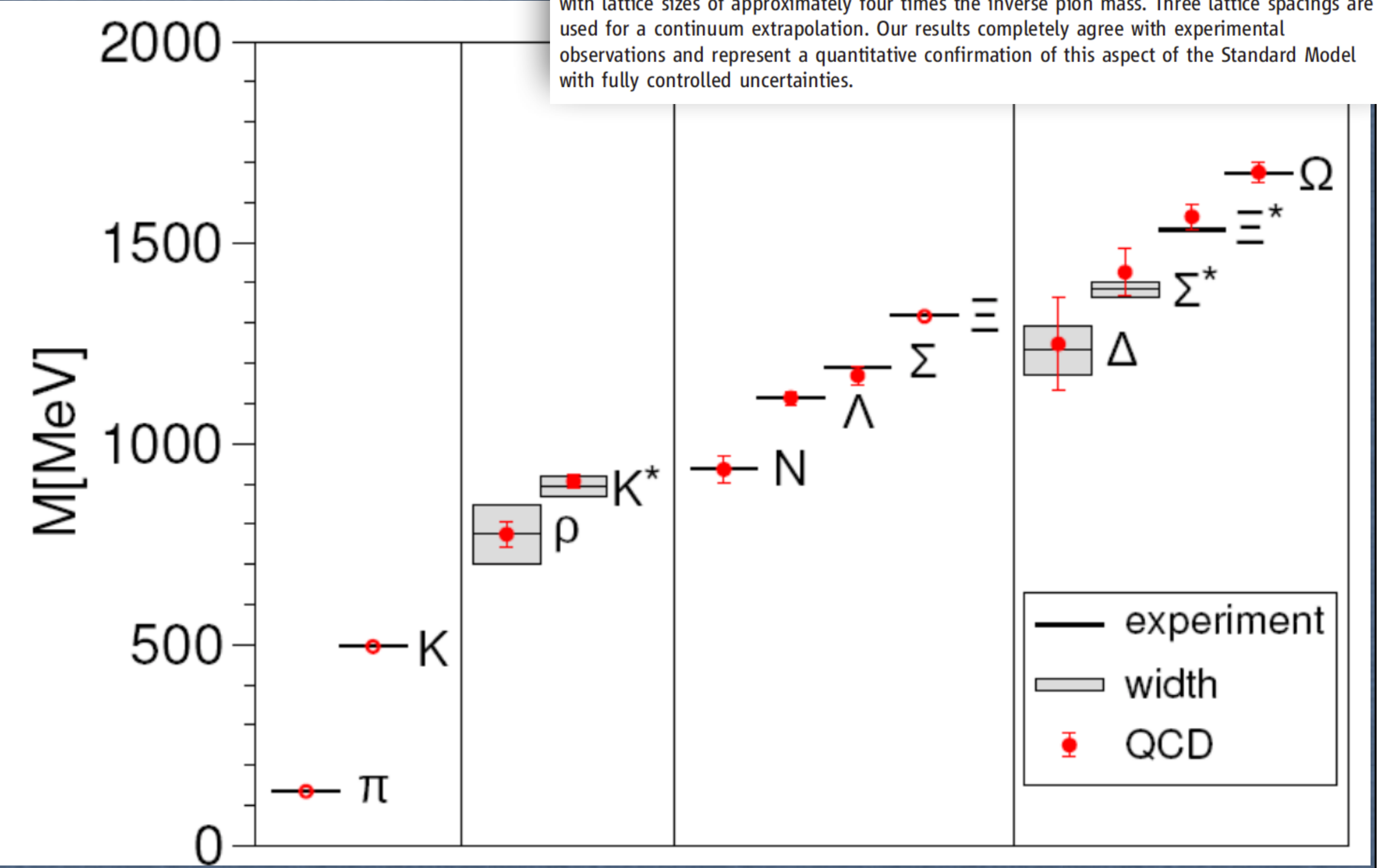
DOI: 10.1126/science.1163233

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]

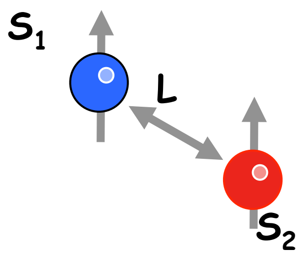
More than 99% of the mass of the visible universe is made up of protons and neutrons. Both particles are much heavier than their quark and gluon constituents, and the Standard Model o particle physics should explain this difference. We present a full ab initio calculation of the masses of protons, neutrons, 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^{--} …

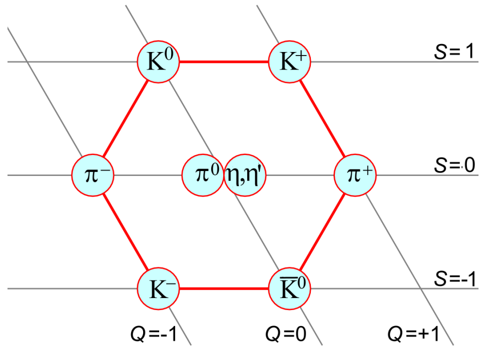
- SU(3) flavor symmetry → nonet ($8\oplus1$) of degenerate states

J^{PC}= 0^{-+} ⇒ (π,K,η,η')

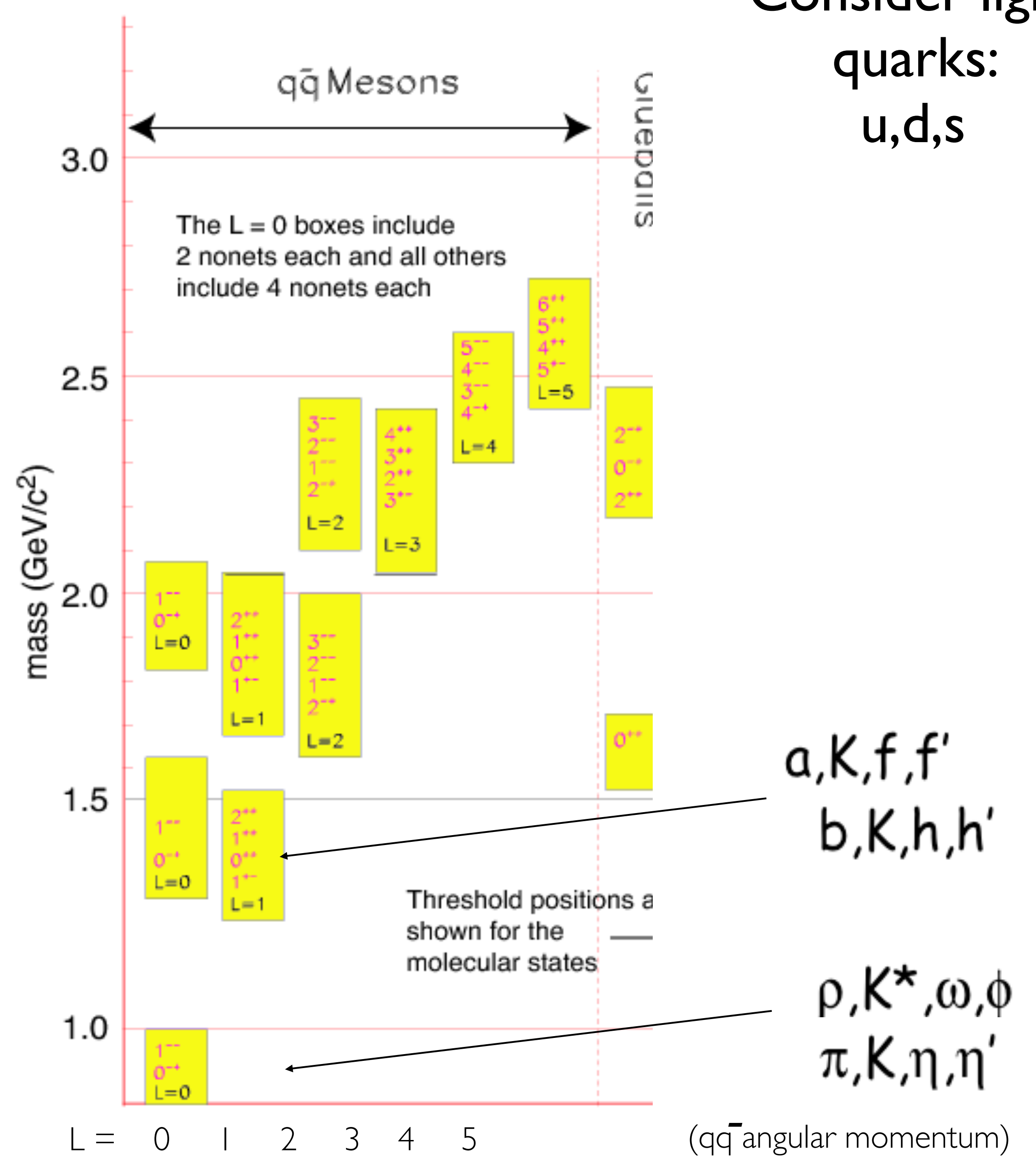
1^{--} ⇒ (ρ,K*,ω,Φ)

1^{+-} ⇒ (b_1,K_1,h_1,h_1')

...



Consider light quarks: u,d,s

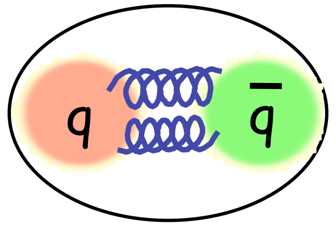


- Great success in describing the lower mass states
- …. but, a number of predicted states is not experimentally observed and assignments are uncertain

The gluons and the hadron spectrum

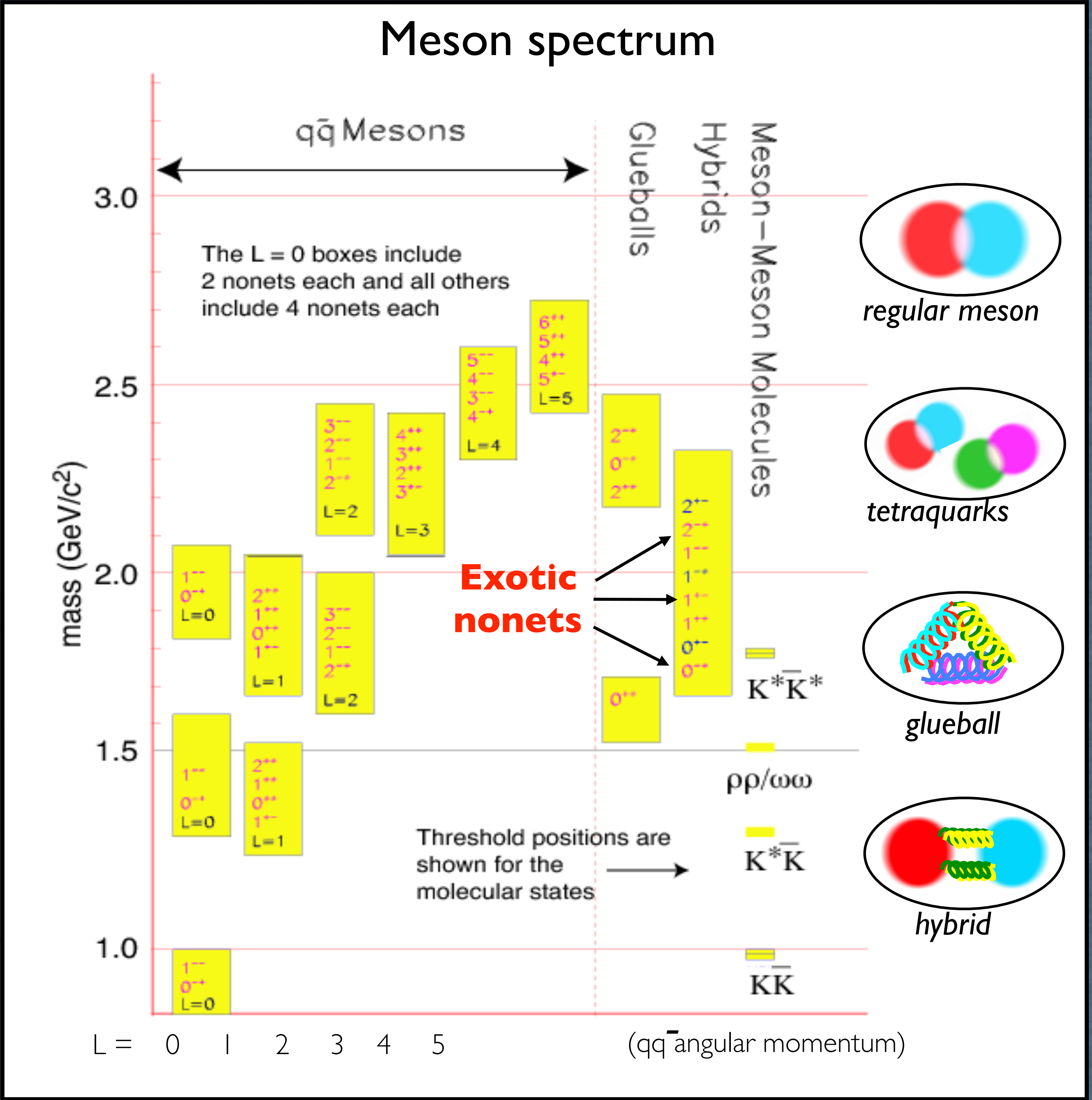
- Understanding gluonic excitations of mesons and the origin of confinement
- At high energy experimental evidence is found in jet production
- At lower energies the hadron spectrum carries information about the gluons that bind quarks
- Can we find hints of the glue in the meson spectrum?

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

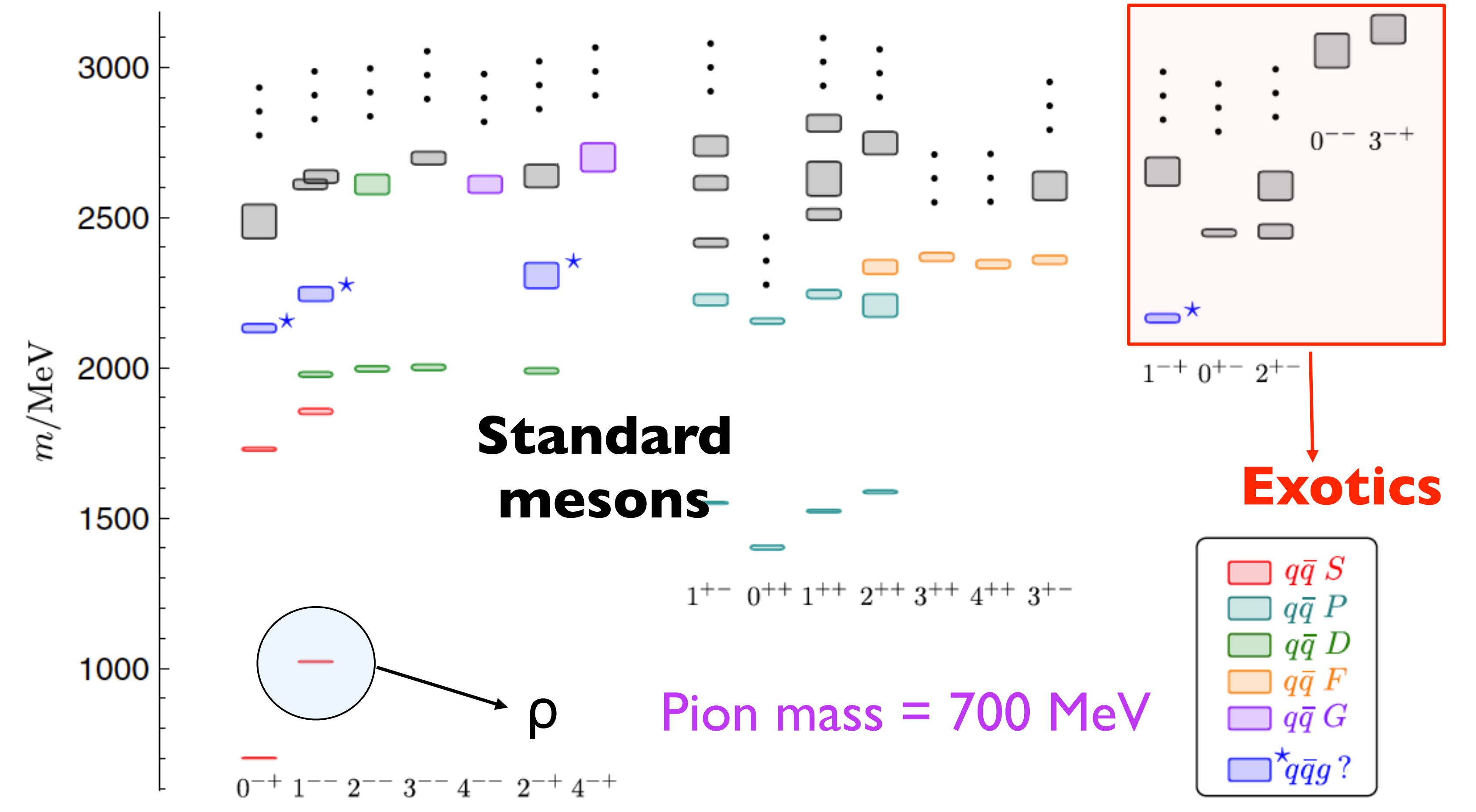


Not-allowed J^{PC} = $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ ...

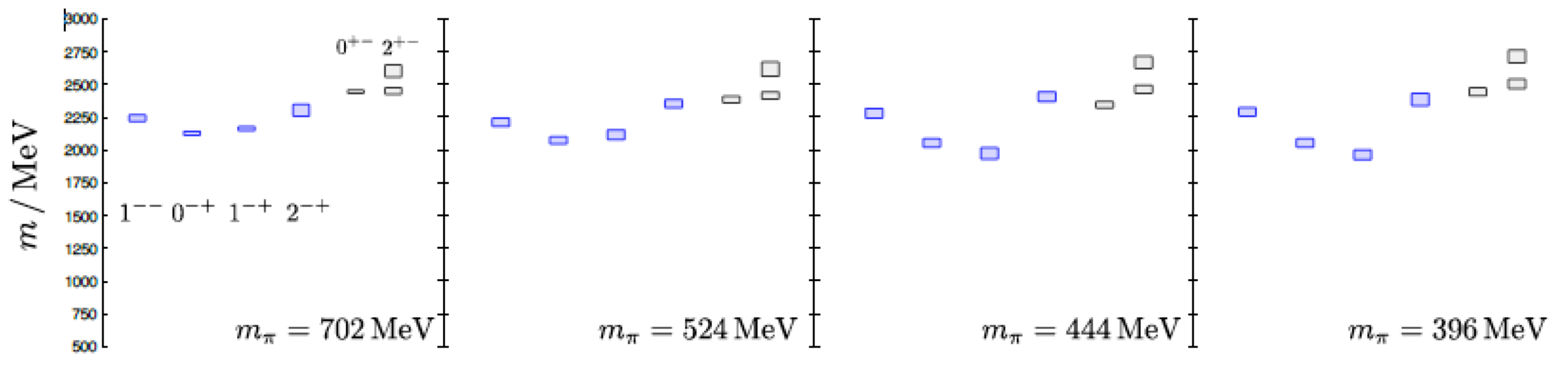
Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states



Light q spectrum from lattice QCD



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



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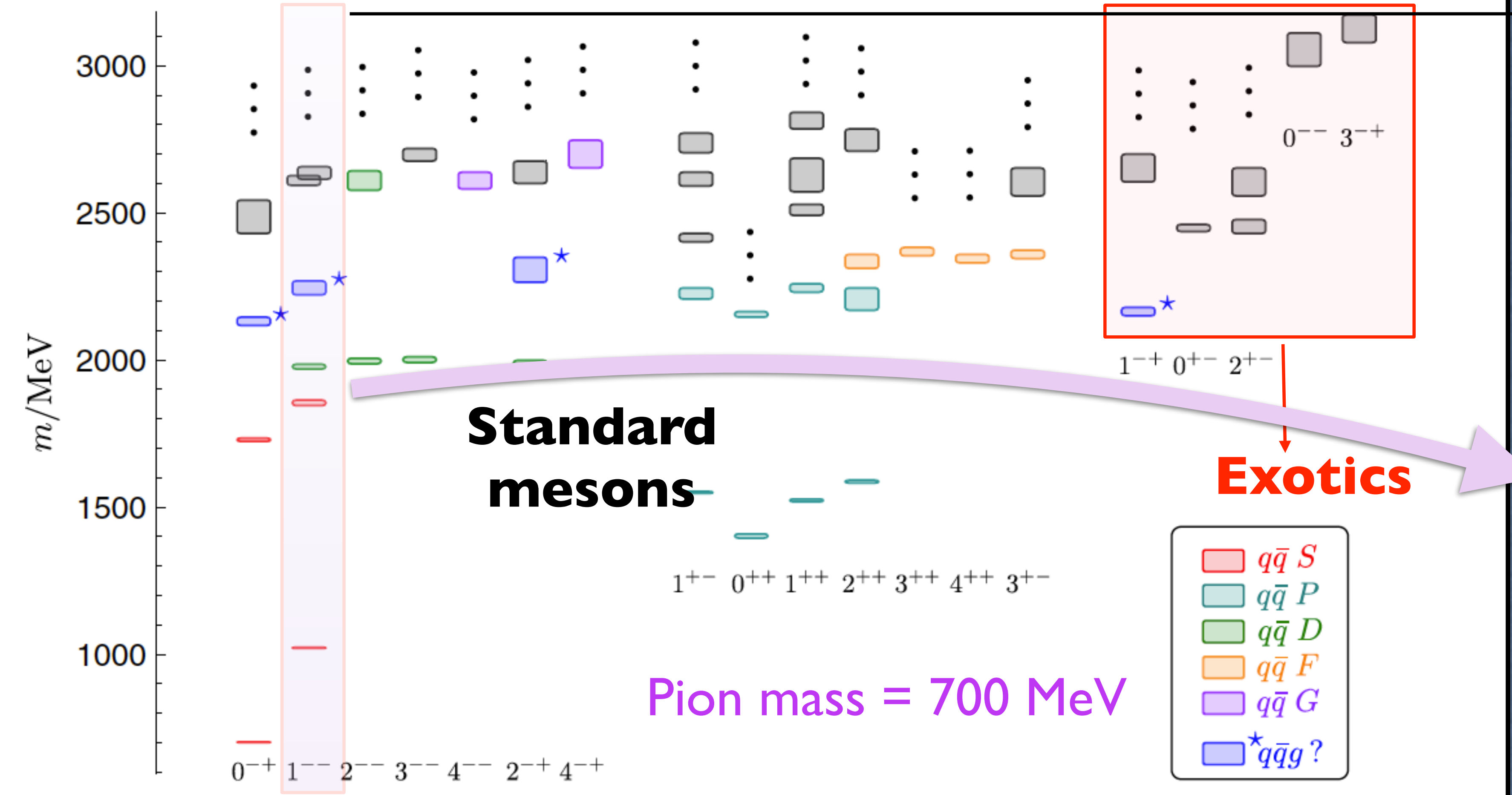

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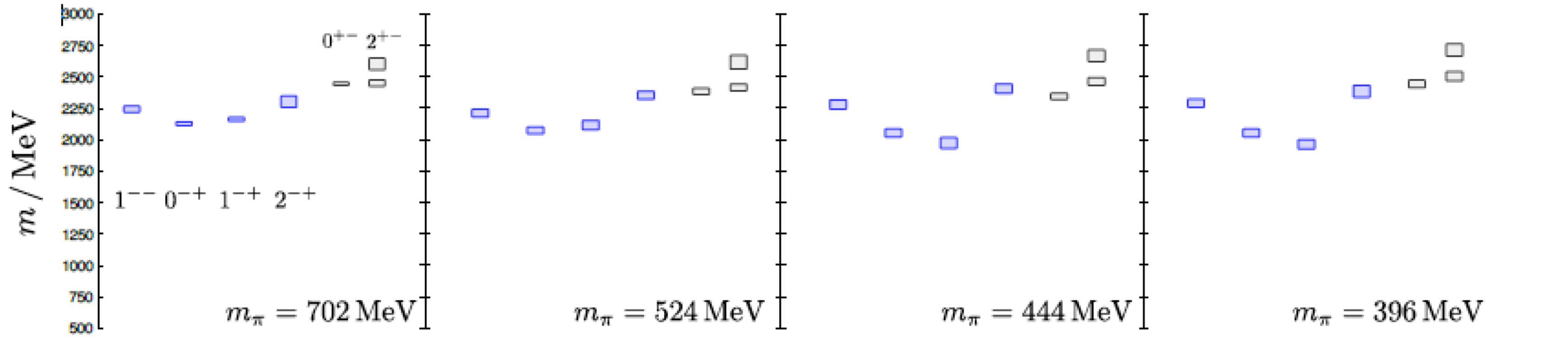
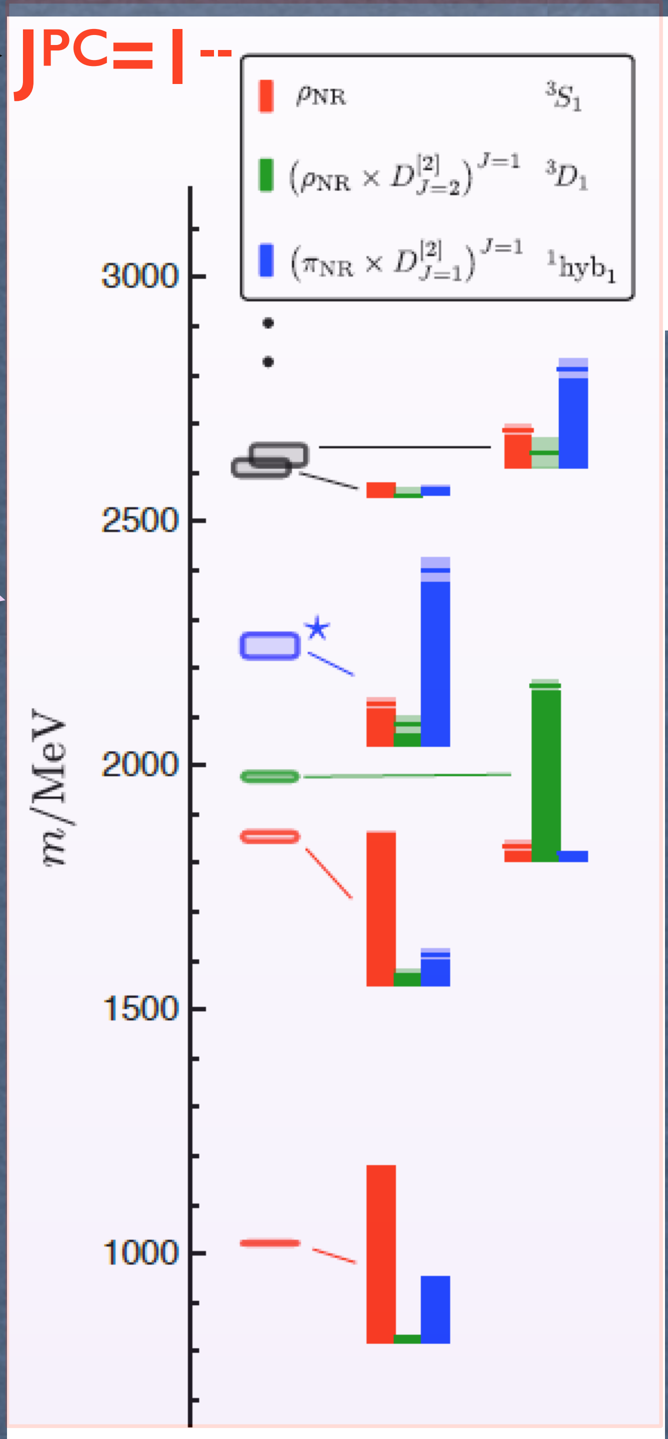
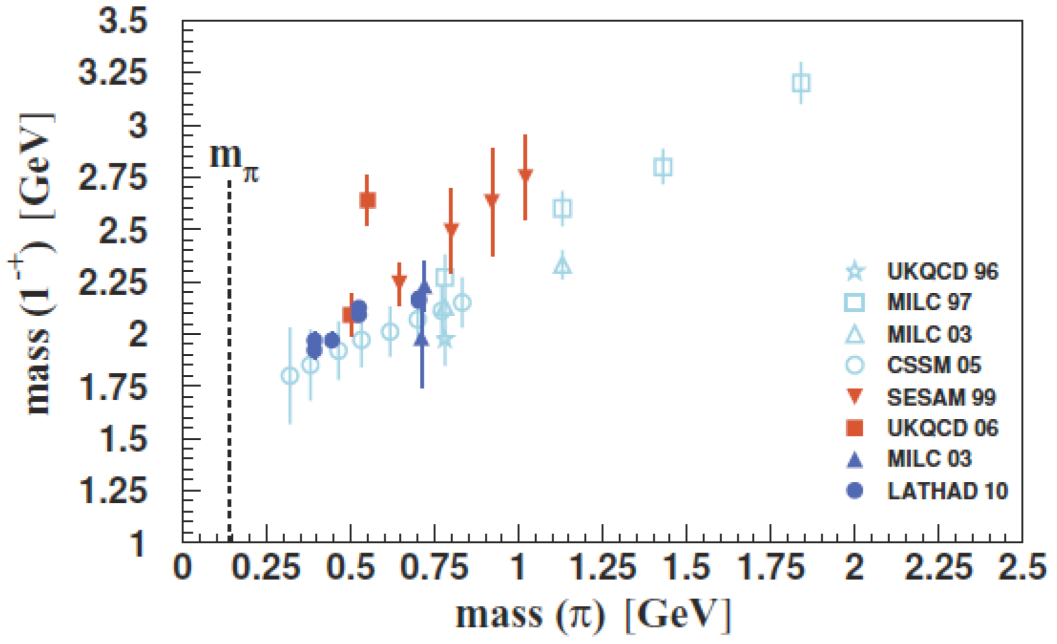




in blue: overlap with $J^{PC}=1^{-+}$ operator interpreted as qq-bar in S-wave + $J_g^{P_gC_g}=1^{+-}$ in P-wave

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



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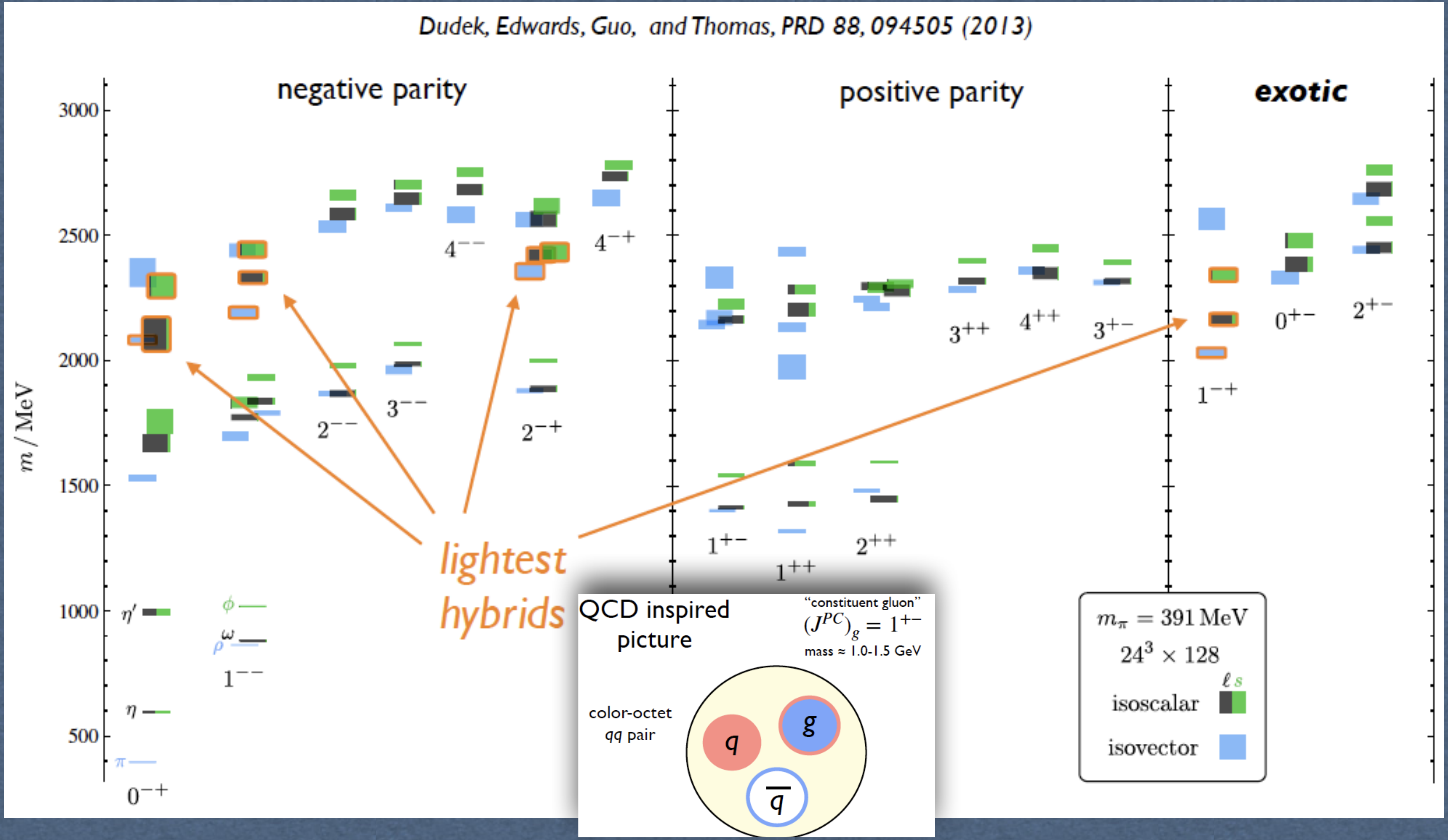


Lattice-QCD predictions for the lowest hybrid states

0^{+-} ~ 2.0 GeV
1^{-+} ~1.6 GeV

Hybrid mesons and glueballs mass range:

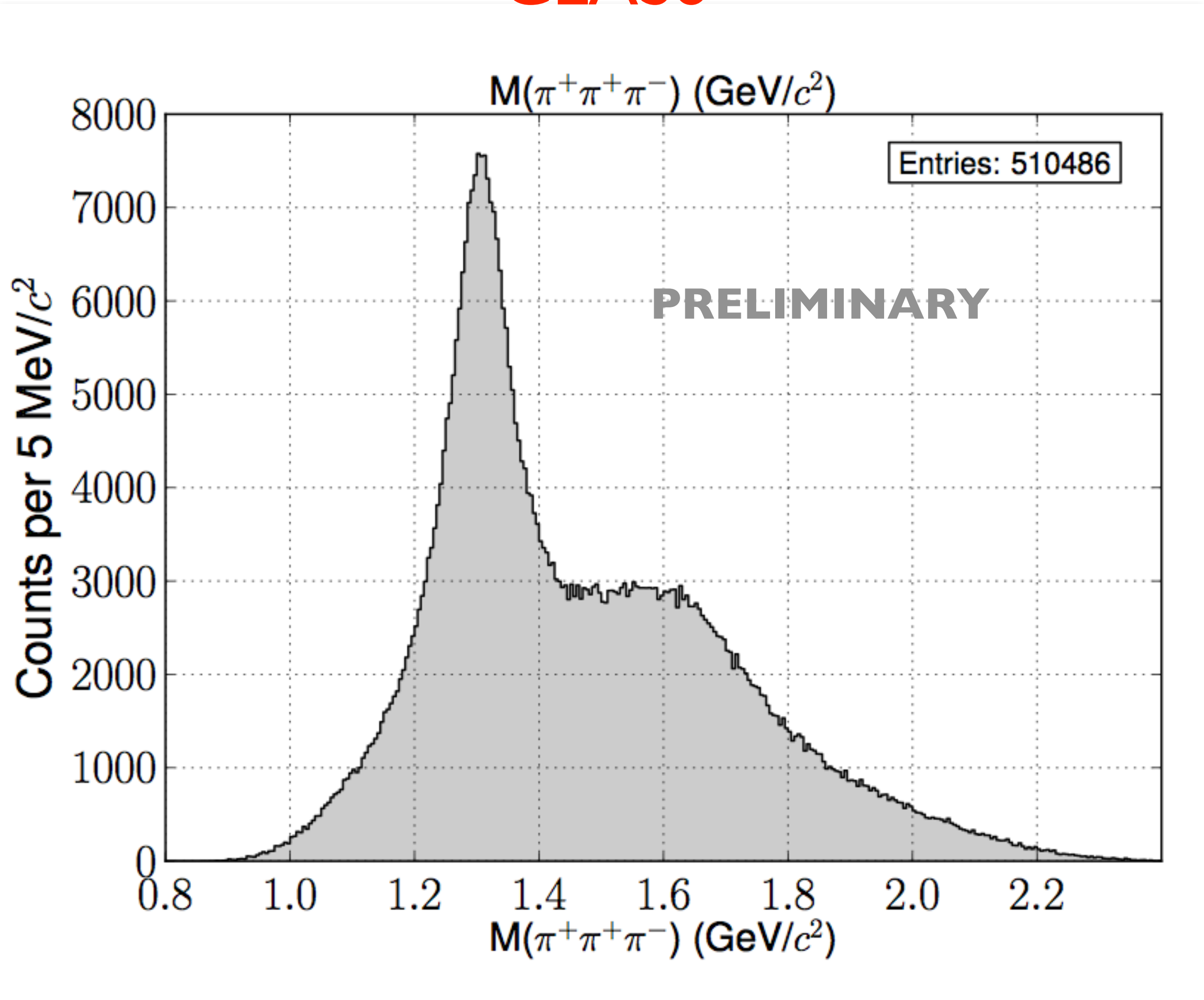
1.4 GeV - 3.0 GeV

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

nPQCD in action

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

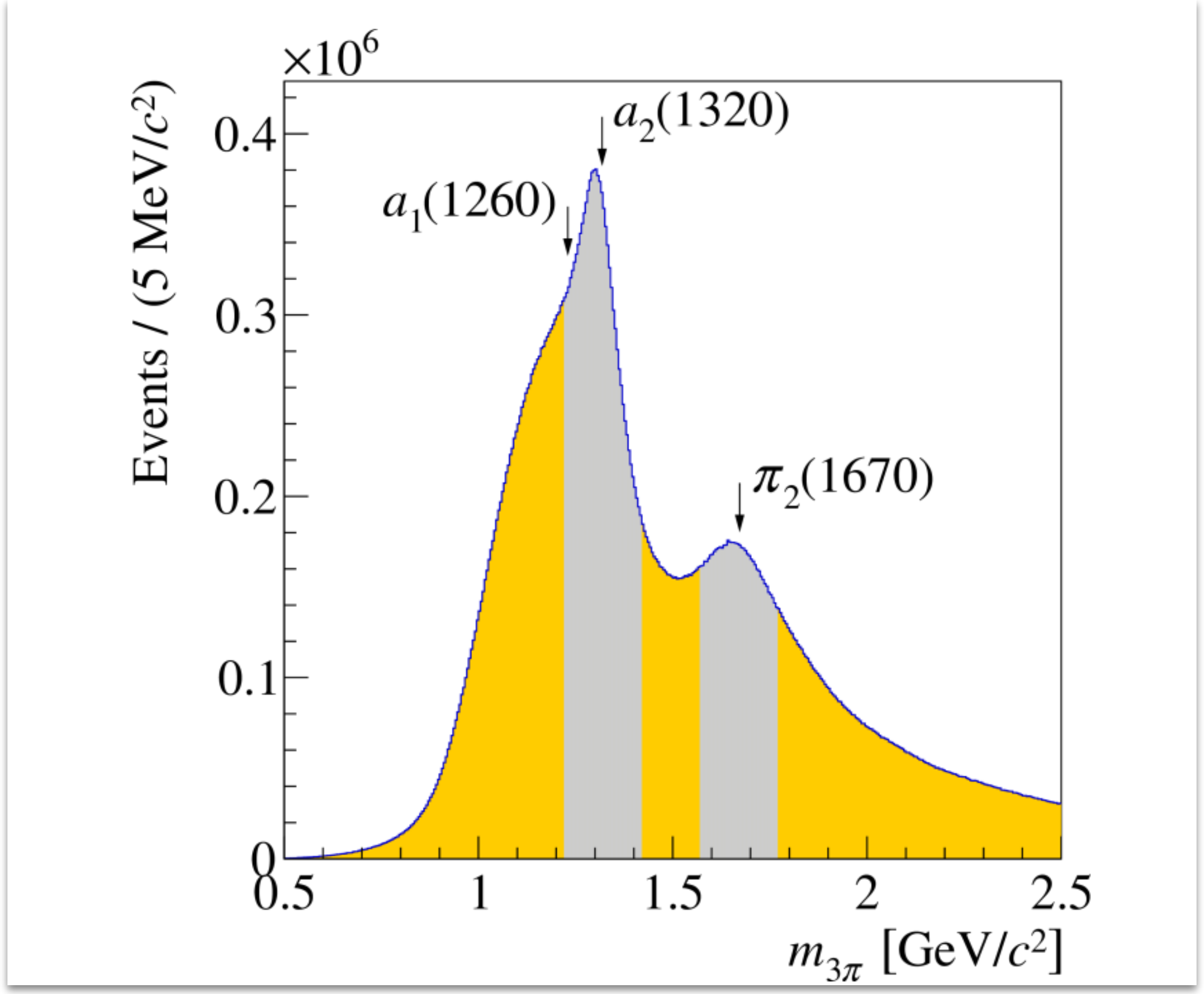
CLAS6



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

$E_\gamma = 5$ GeV

COMPASS

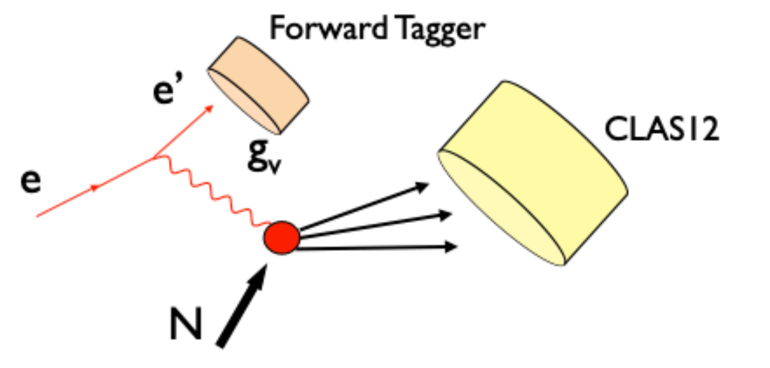


$\pi^- p \rightarrow (p)\, \pi^+ \pi^- \pi^-$

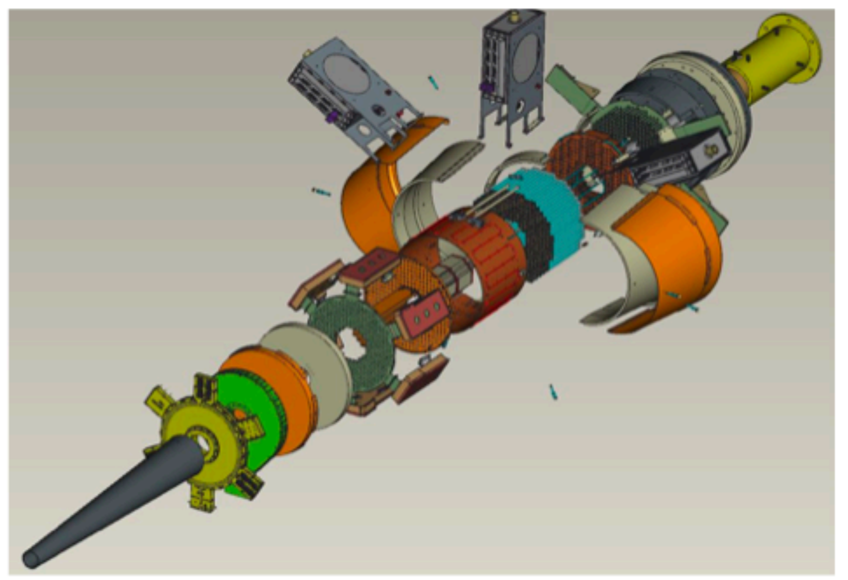
$E_\pi = 191$ GeV

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)

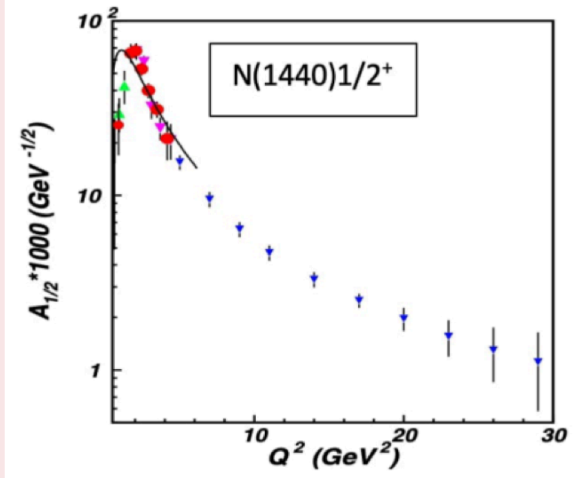
Complementary to Hall-D GLUEX

Bringing Q² into the game

D.Dean, this workshop

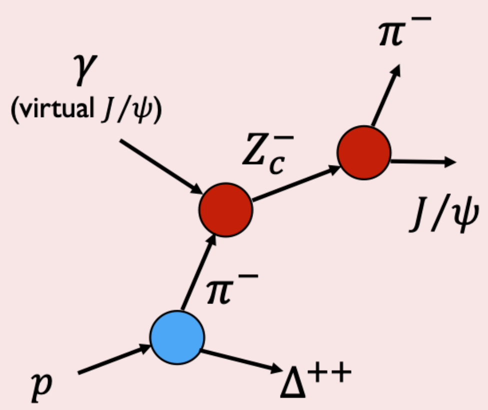
Scientific vignettes for the 22 GeV upgrade

How does QCD generate hadrons?



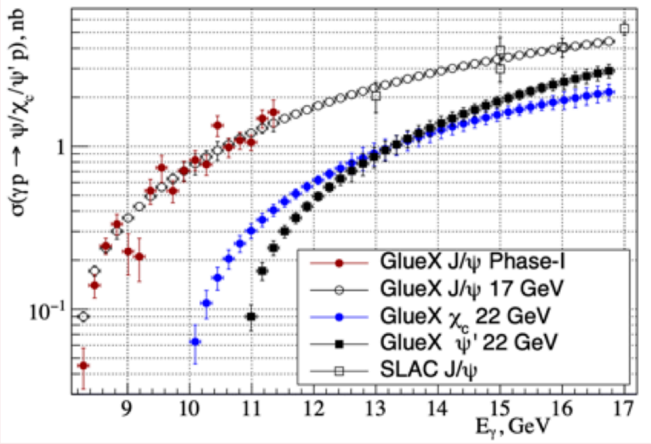
- Q^2 evolution of the $\gamma_v pN^*$ electrocouplings could offer an insight into hadron mass generation and the emergence of the N* structure from QCD
- Simulations indicate JLab22 is the only foreseeable facility to extend these measurements up to 30 GeV² and down to α_s/π=0.15 where non-and perturbative QCD coexist.

Are there pure exotic states?



Direct (photon) probe of the $Z_c \to J/\psi\pi$ coupling without rescattering effects provides unique complementary data to constrain interpretation of e^+e^- data.

Can we harness threshold charmonium production to probe proton/gluon properties?



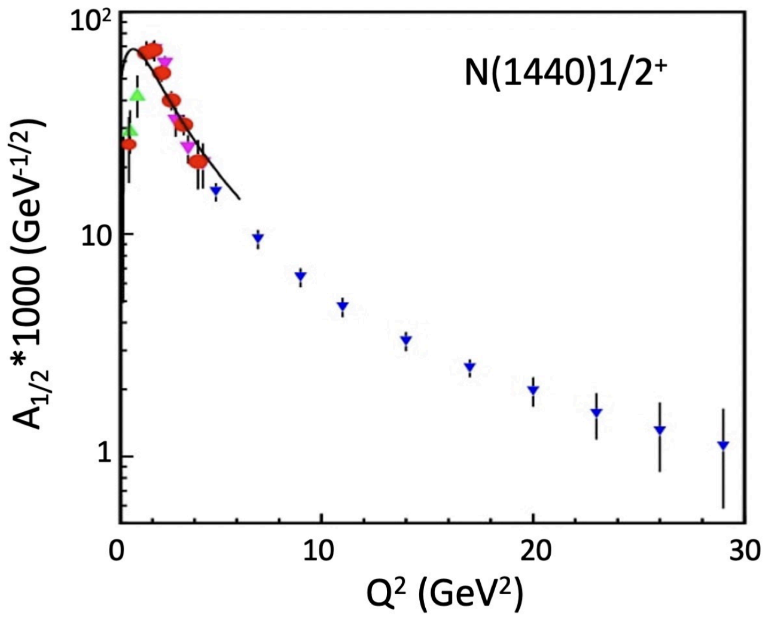
Exclusive charmonium production near threshold probes gluon/mass properties of proton (mass radius, gravitational form factors, D-term, anomalous contribution to proton mass), however

- assuming factorization
- assuming two-gluon exchange

CLAS 12 Workshop, Paris 20 Jefferson Lab

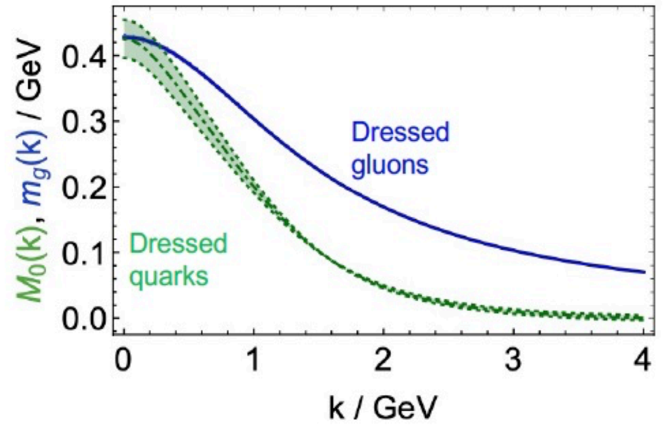
P.Rossi, this workshop

Bound 3 Quark Structure of N*s and Emergence of Mass



Continuum Schwinger Method

- the solution of the QCD equations of motion for q/g fields reveals existence of dressed q/g with momentum-dependent masses.



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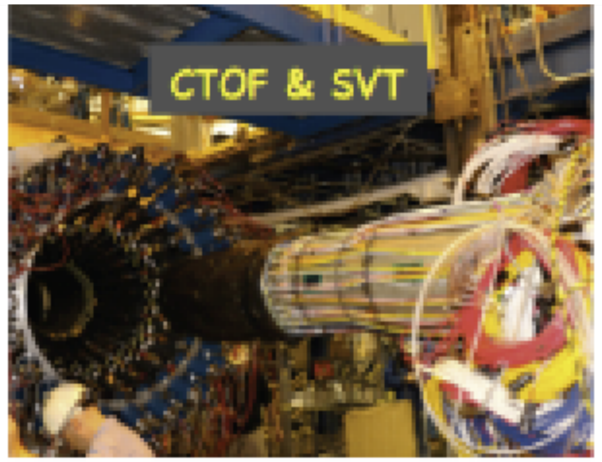
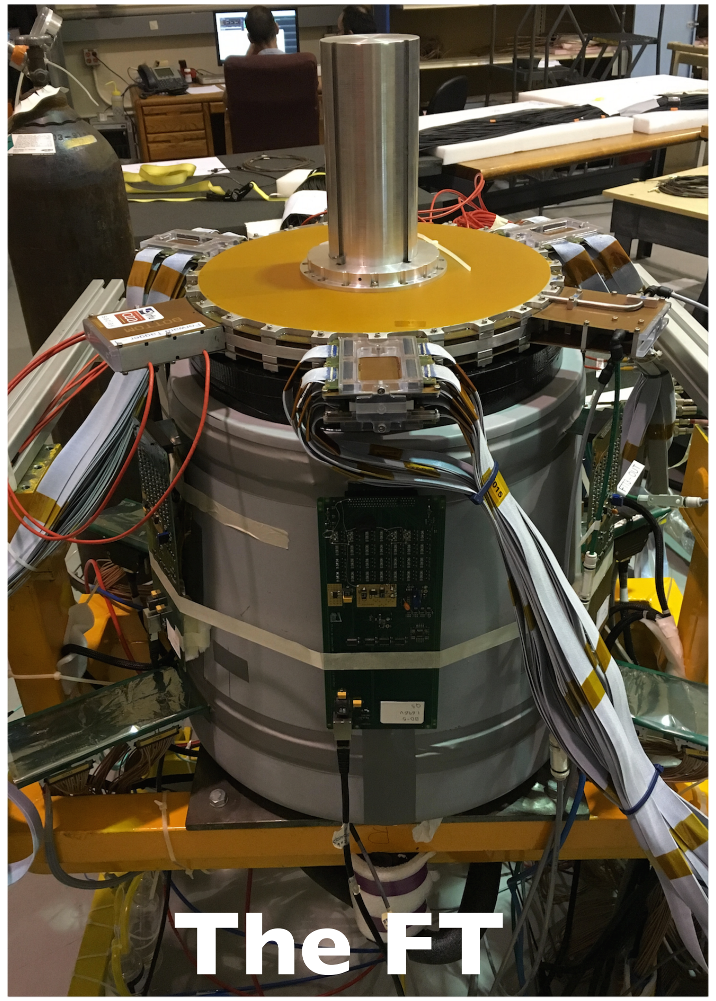
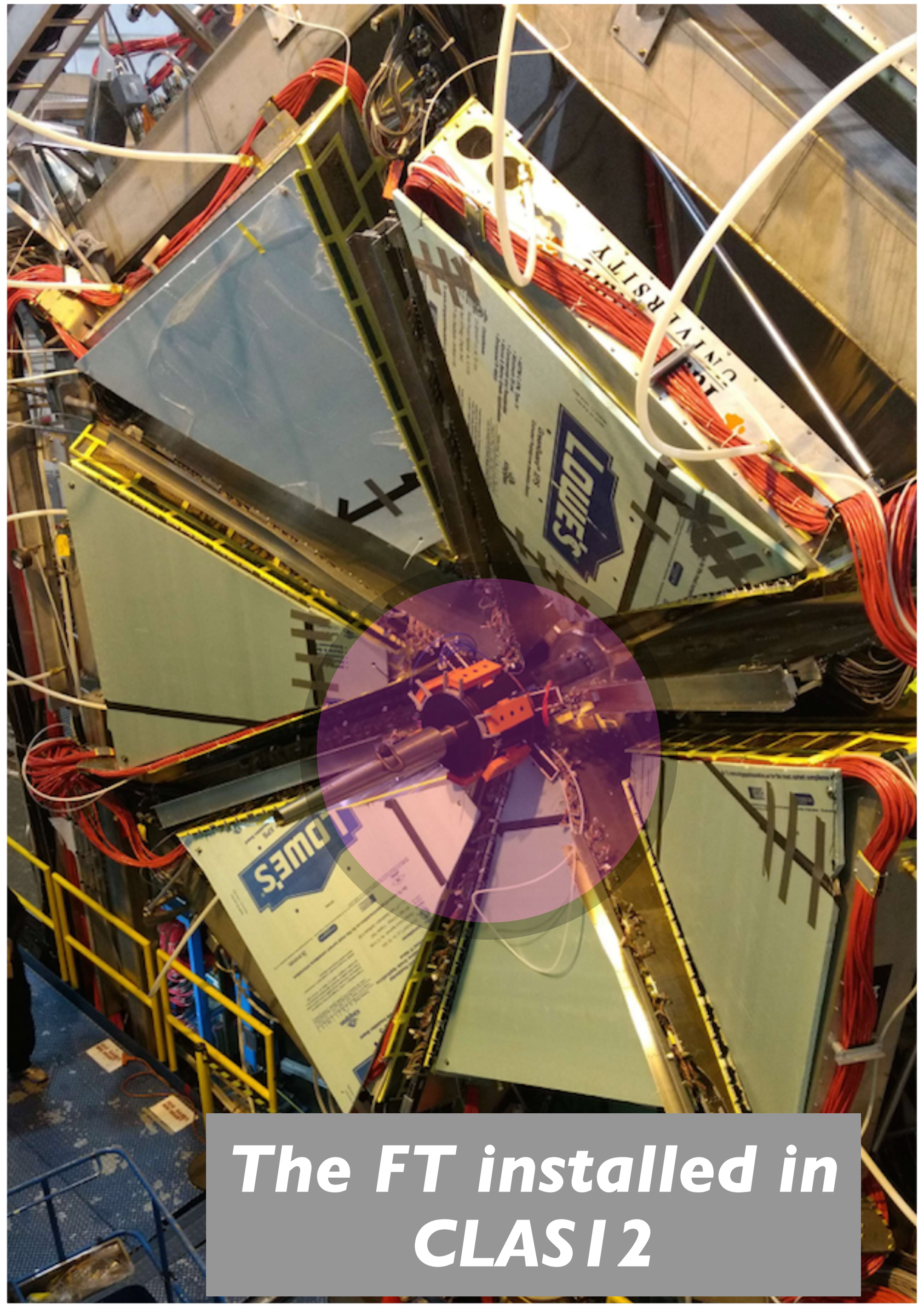
10 Jefferson Lab

★ Q² evolution is a key-tool to understand meson structure
★ CLAS12 MesonEx will demonstrate the technique
★Future JLab at 20+ GeV will fully exploit it

The Forward Tagger and CLAS12







FT-Hodo: Scintillator tiles
veto for photons
EdinburghU+JMU+NSU+Jlab

FT-Trck: MicroMegas
electron angles and polarization plane
Saclay + OhioU+Jlab

FT-Cal: $PbWO_4$ calorimeter
electron energy/momentum
Photon energy (ν=E-E')
Polarization $\varepsilon^{-1} \approx 1 + \nu^2/2EE'$
INFN-GE, INFN-RM2, INFN-TO, JLab

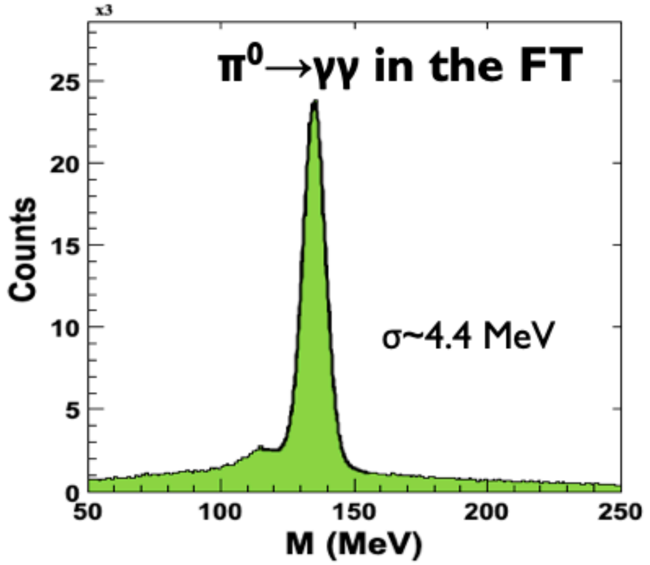
CLAS12 FT performance

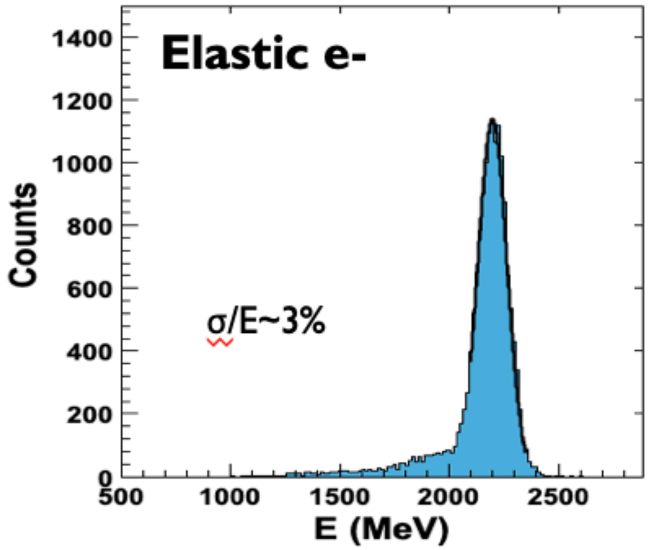
- Full Forward Tagger installed in CLAS12 in July 2017
- Commissioned with cosmic ray data in July-November 2017 to study:
  - Response of individual detectors
  - Efficiency and energy calibration
  - Relative timing
- On-beam commissioning during CLAS12 engineering run in January 2018

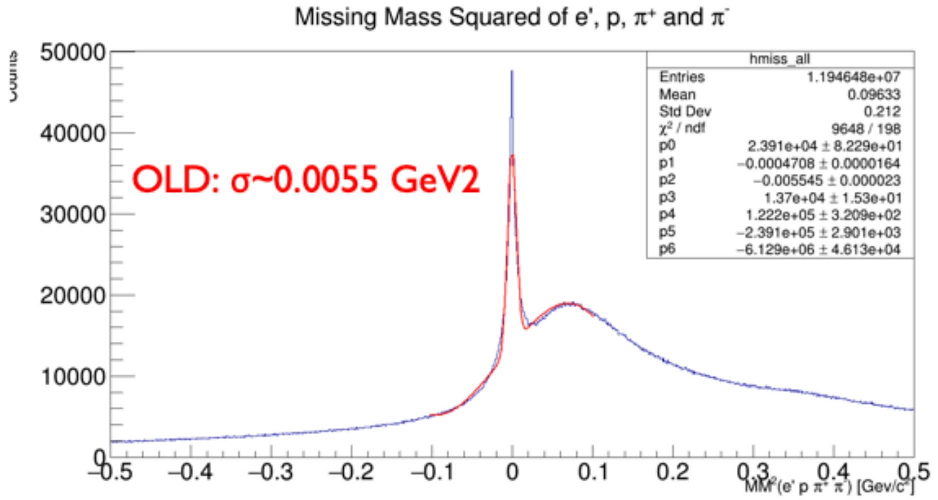
- Physics running since February 2018:
  - 10.2-10.6 GeV on LH2 from in 2018/2019
  - 7.5 GeV on LH2 in Fall 2018
  - 10.2-10.5 GeV on LD2 in 2019 and 2020
  - 10.5 GeV in RGC

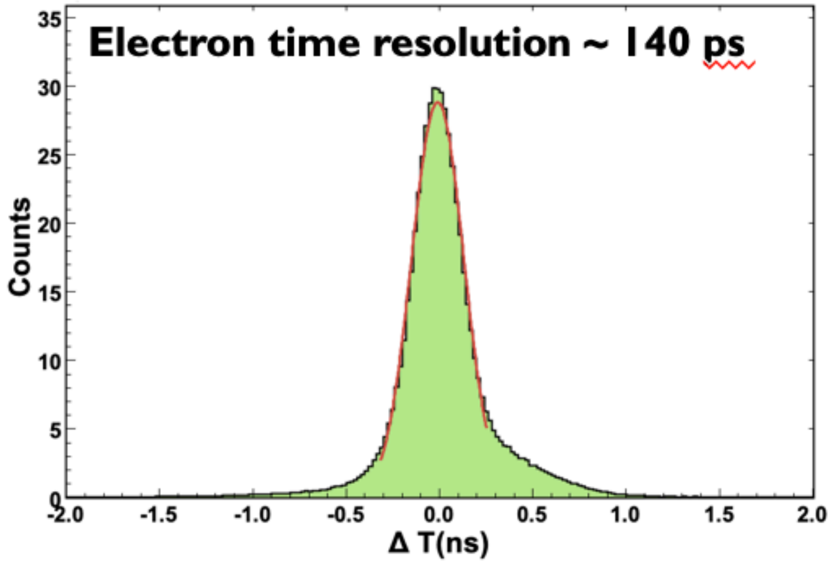
R.De Vita

- Detector performance assessed on different data set after calibrations based on beam data:
  - Energy calibration based on π^0 2-photon decay
  - Timing calibration based on events with e-γ events with e- detected in CLAS12 forward detector
- Timing calibration exceed specifications (300 ps)
- Energy resolution ~ 3%@2GeV still ±1% higher than specs due to SICCAS crystal properties but improved significantly in accuracy and stability thanks to updates to the calibration procedure

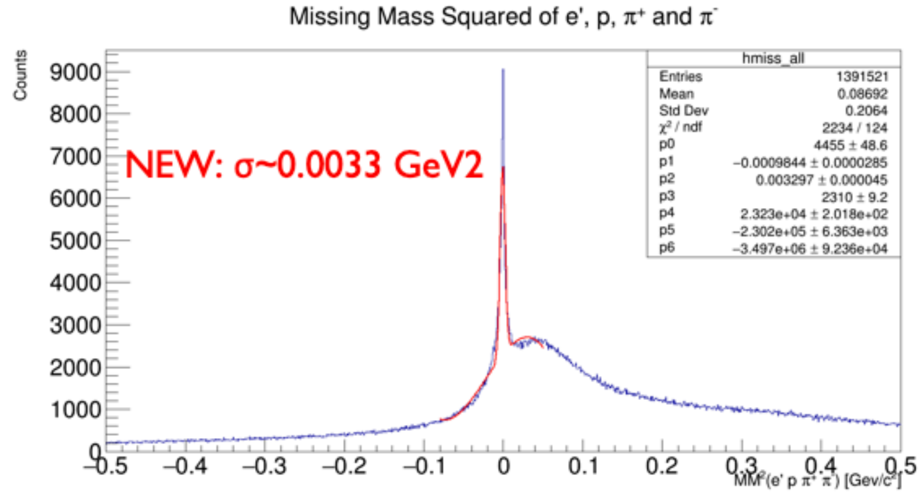








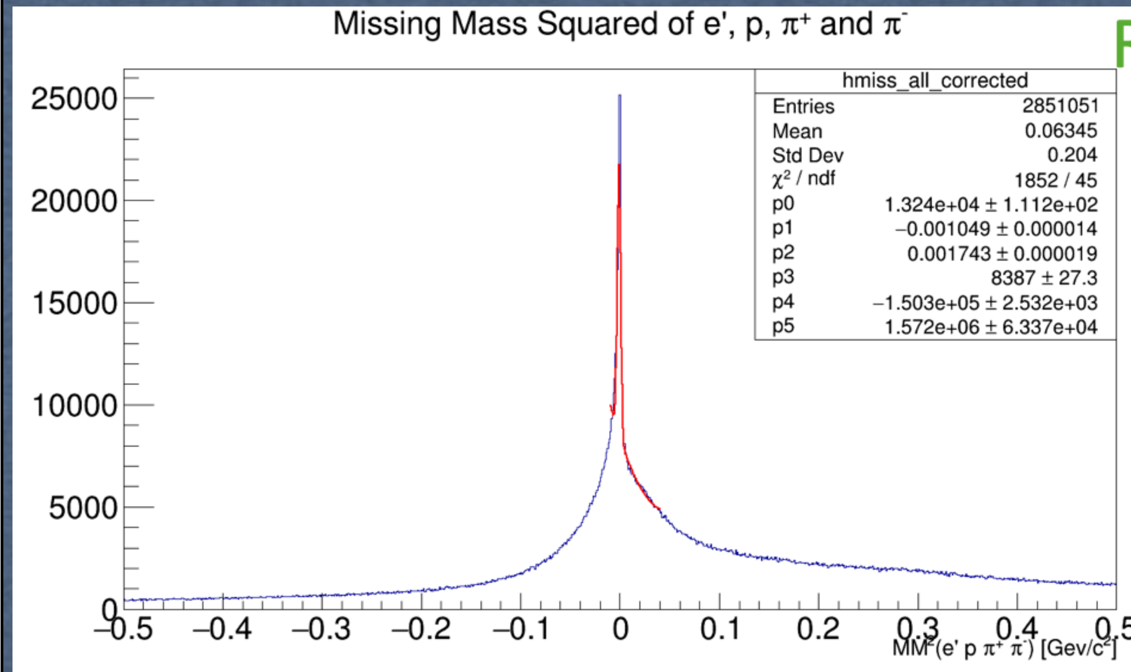
Improvements in energy calibration have sizable effect in missing mass resolution from different final states



FT Electron Corrections

Geraint Clash
University of York

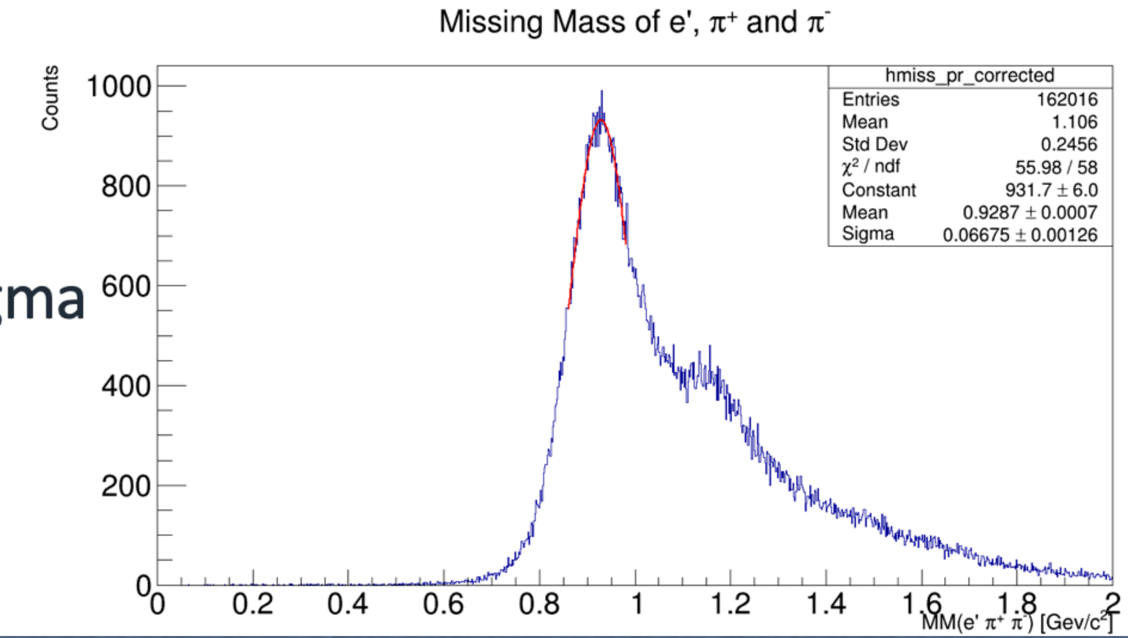
RGK (7.5)



0 ±3 sigma

	MM all	Proton
Mean	-0.0010	0.9287
Sigma	0.0017	0.0668

Mean±3 sigma



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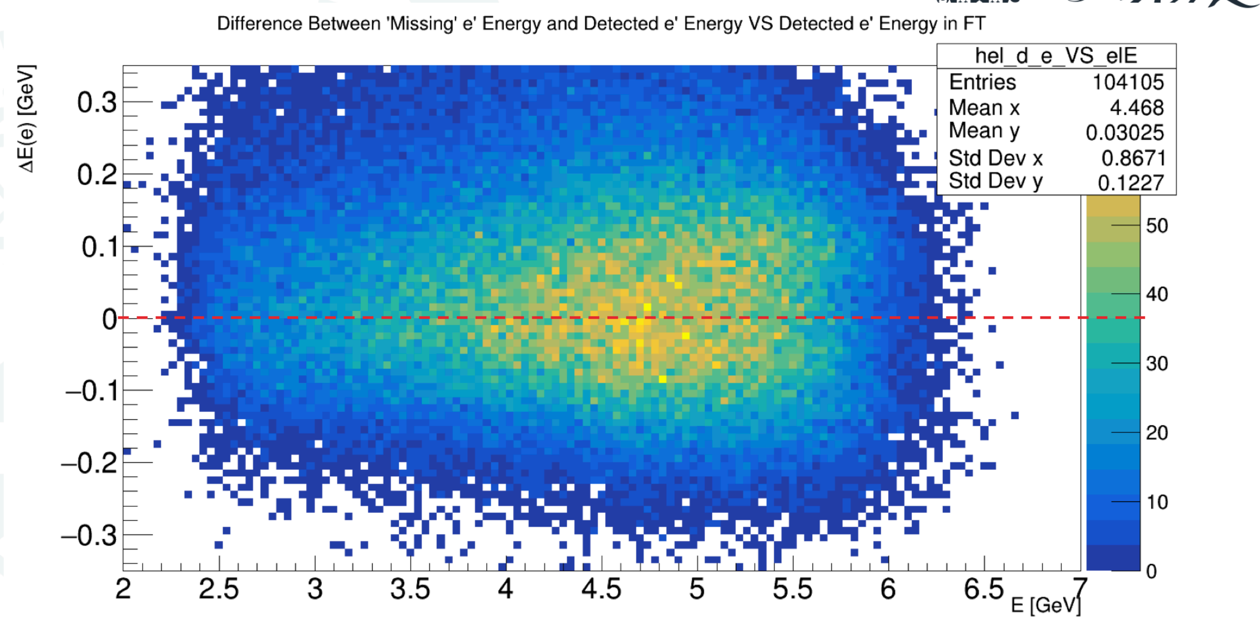


Use two pion exclusive electroproduction to check FT calibration and corrections

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

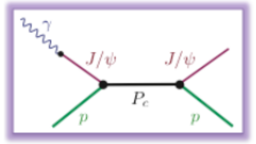
Req...
1) 4π...
2) High... electr...

LHCb Pentaquark with CLAS12

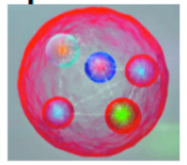
Exp-12-12-001a "Pentaquark"

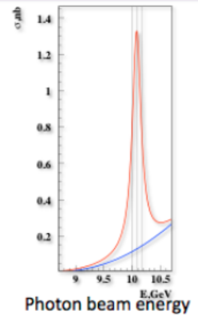
Near threshold J/psi photoproduction and study of LHCb pentaquarks with CLAS12

Search for LHCb Pentaquark



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





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

	$P_c(4380)$		$P_c(4450)$	
	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

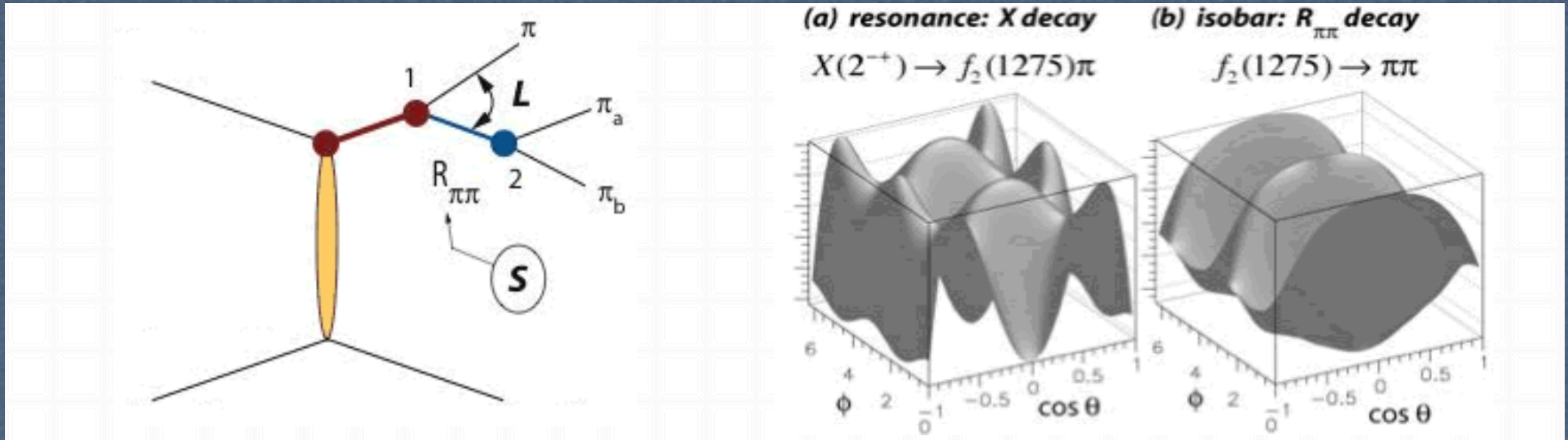
Requirements
1) 4π detector
2) High intensity 10 GeV electron beam

Resonance detection

Two main experimental approaches to identifying and studying a hadron resonance

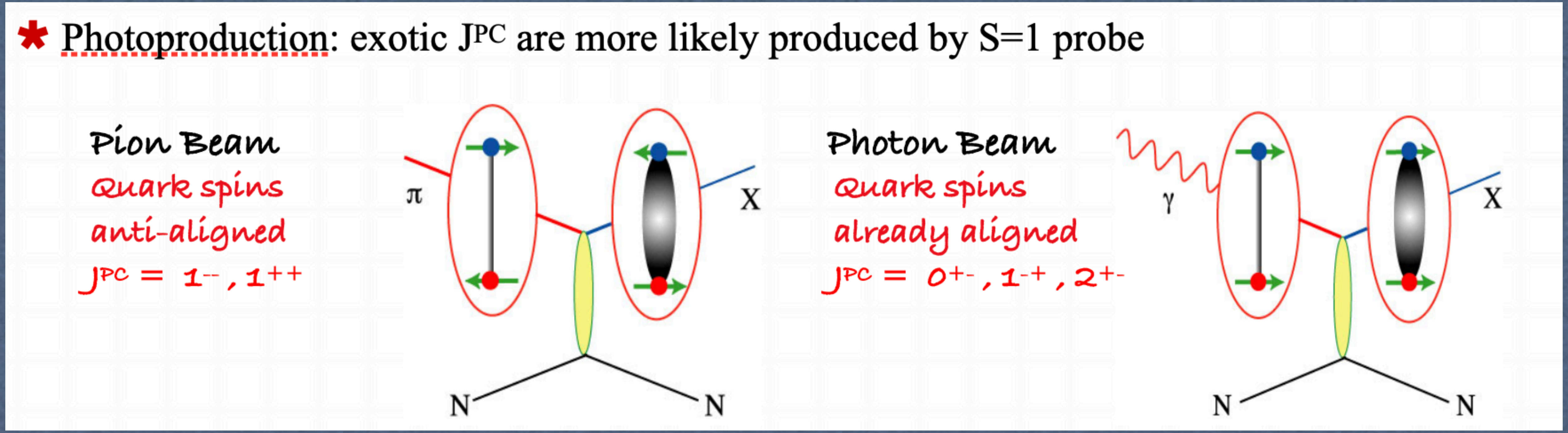
Decay

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



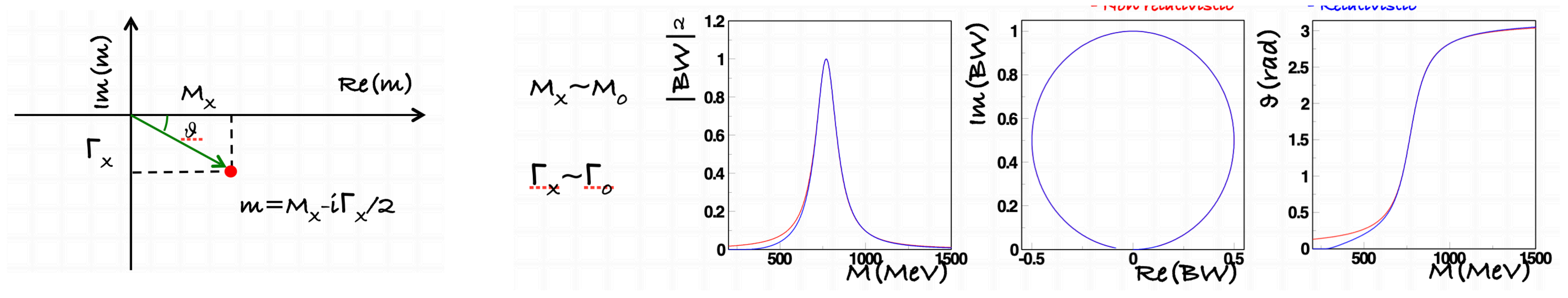
Production

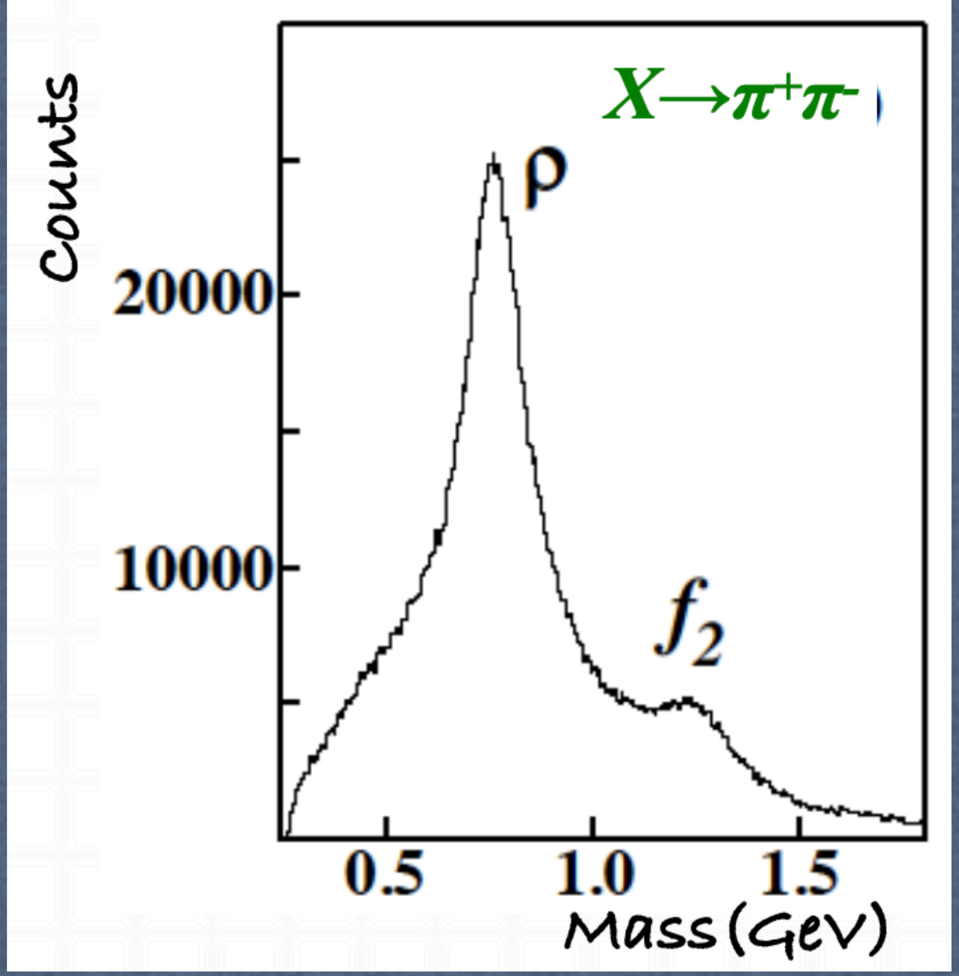
- Requires parametrisation of production vertex
- exclusive (or semi-inclusive) final state
- sensitive to the internal structure (nature)



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)

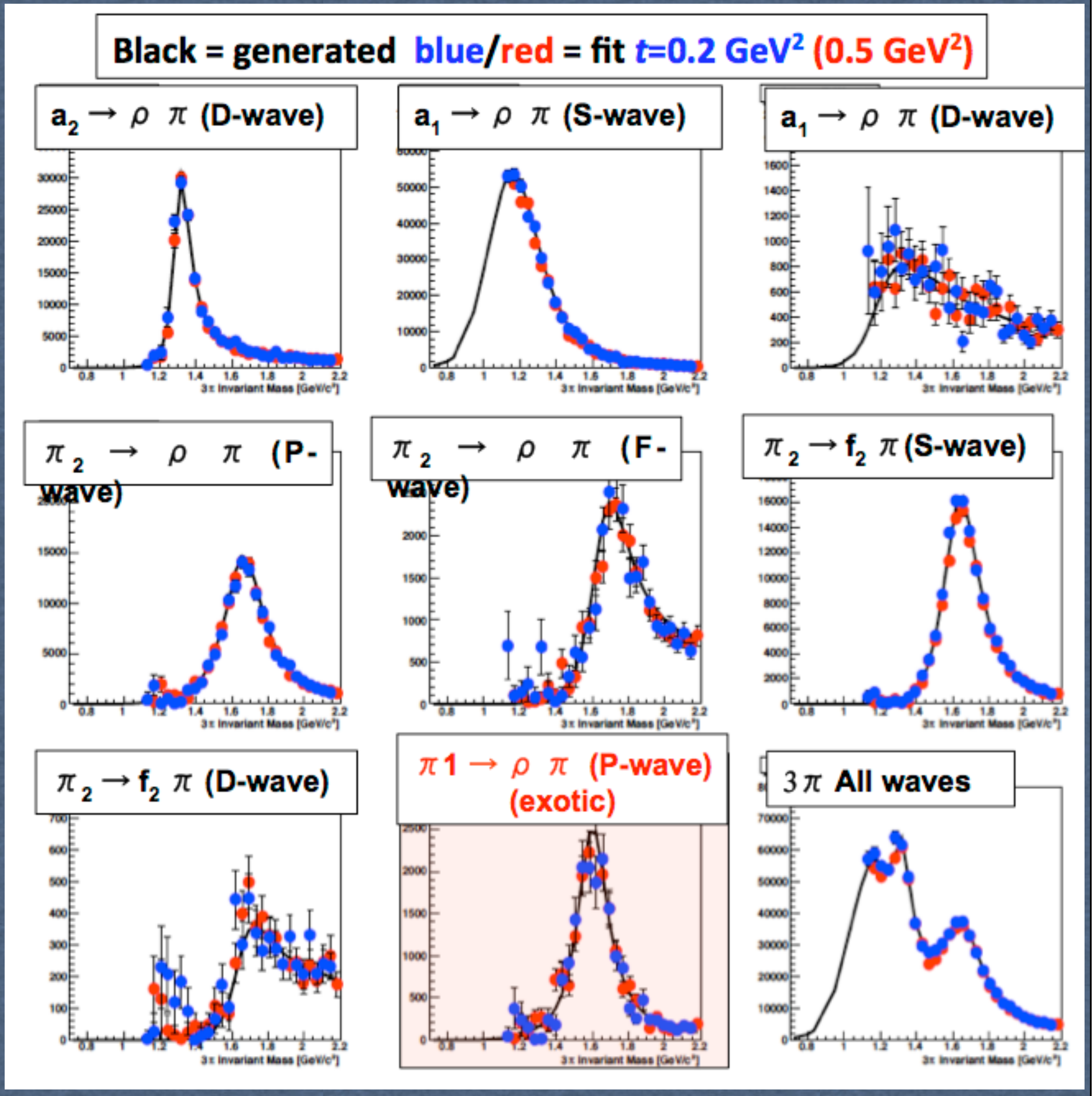
  $\pi_2 \rightarrow \rho \pi$ (F-wave)

  $\pi_2 \rightarrow f_2 \pi$(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

CLAS12 data analysis

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

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

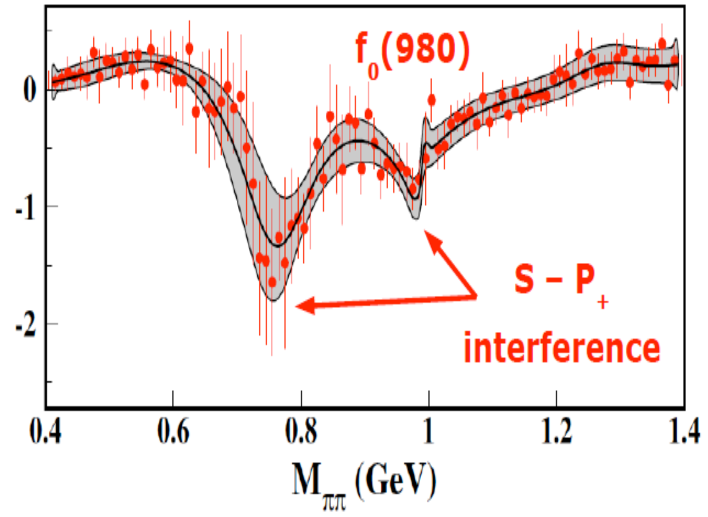
- P-wave: ρ meson
- D-wave: $f_2(1270)$
- S-wave: σ, $f_0(980)$ and $f_0(1320)$

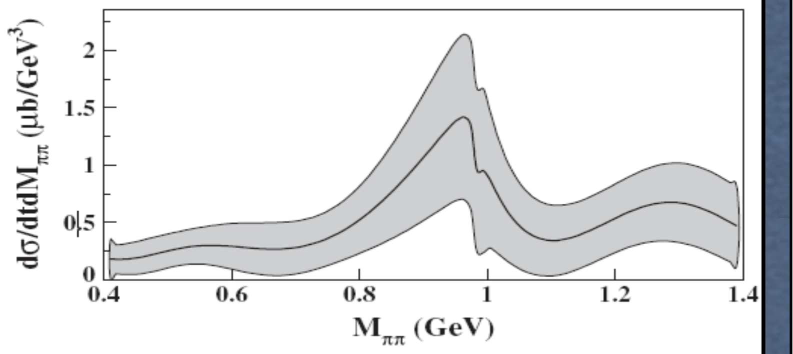
Strategy

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

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

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





Pseudo Data from Amplitudes

$$H^0(11) = H^1(11) + 2\sqrt{\frac{2}{5}}\,\mathrm{Re}(P_1^{(+)} D_2^{(+)*}) \,,$$

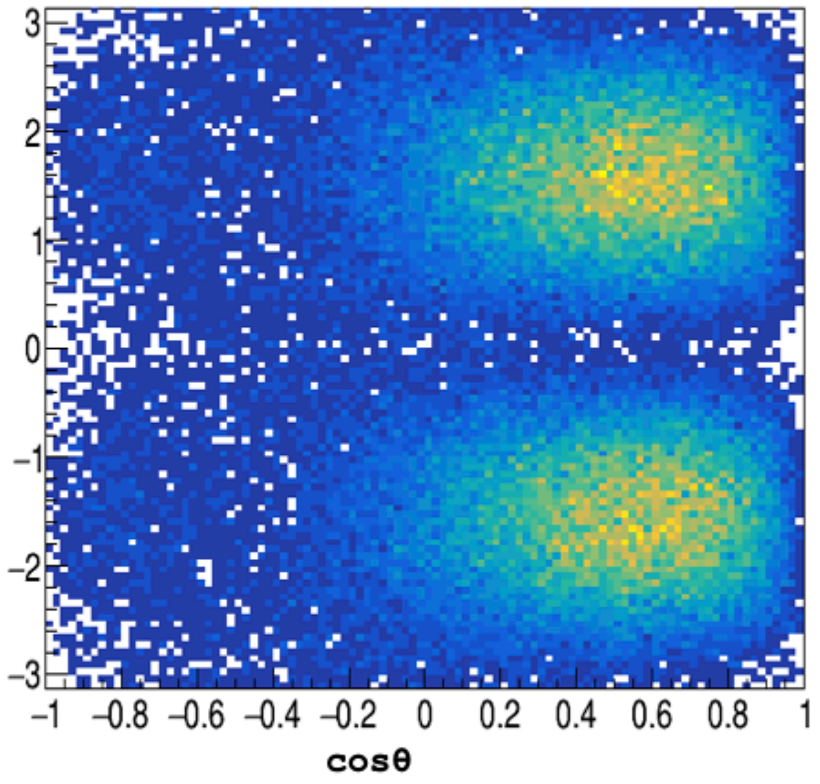
$$H^1(11) = \frac{2}{15}\left[3\sqrt{5}\,\mathrm{Re}(P_0^{(+)} D_1^{(+)*}) - \sqrt{15}\,\mathrm{Re}(P_1^{(+)} D_0^{(+)*}) + 5\sqrt{3}\,\mathrm{Re}(S_0^{(+)} P_1^{(+)*})\right] \,,$$

$$H^0(20) = H^1(20) - \frac{2}{35}\left[7|P_1^{(+)}|^2 - 5|D_1^{(+)}|^2 + 10|D_2^{(+)}|^2\right] \,,$$

$$H^1(20) = \frac{4}{35}\left[7|P_0^{(+)}|^2 + 5|D_0^{(+)}|^2 + 7\sqrt{5}\,\mathrm{Re}(S_0^{(+)} D_0^{(+)*})\right] \,,$$

$$H^0(21) = H^1(21) + \frac{2}{7}\sqrt{6}\,\mathrm{Re}(D_1^{(+)} D_2^{(+)*}) \,,$$

$$H^1(21) = \frac{2}{35}\left[7\sqrt{5}\,\mathrm{Re}(S_0^{(+)} D_1^{(+)*}) + 7\sqrt{3}\,\mathrm{Re}(P_0^{(+)} P_1^{(+)*}) + 5\,\mathrm{Re}(D_0^{(+)} D_1^{(+)*})\right] \,,$$

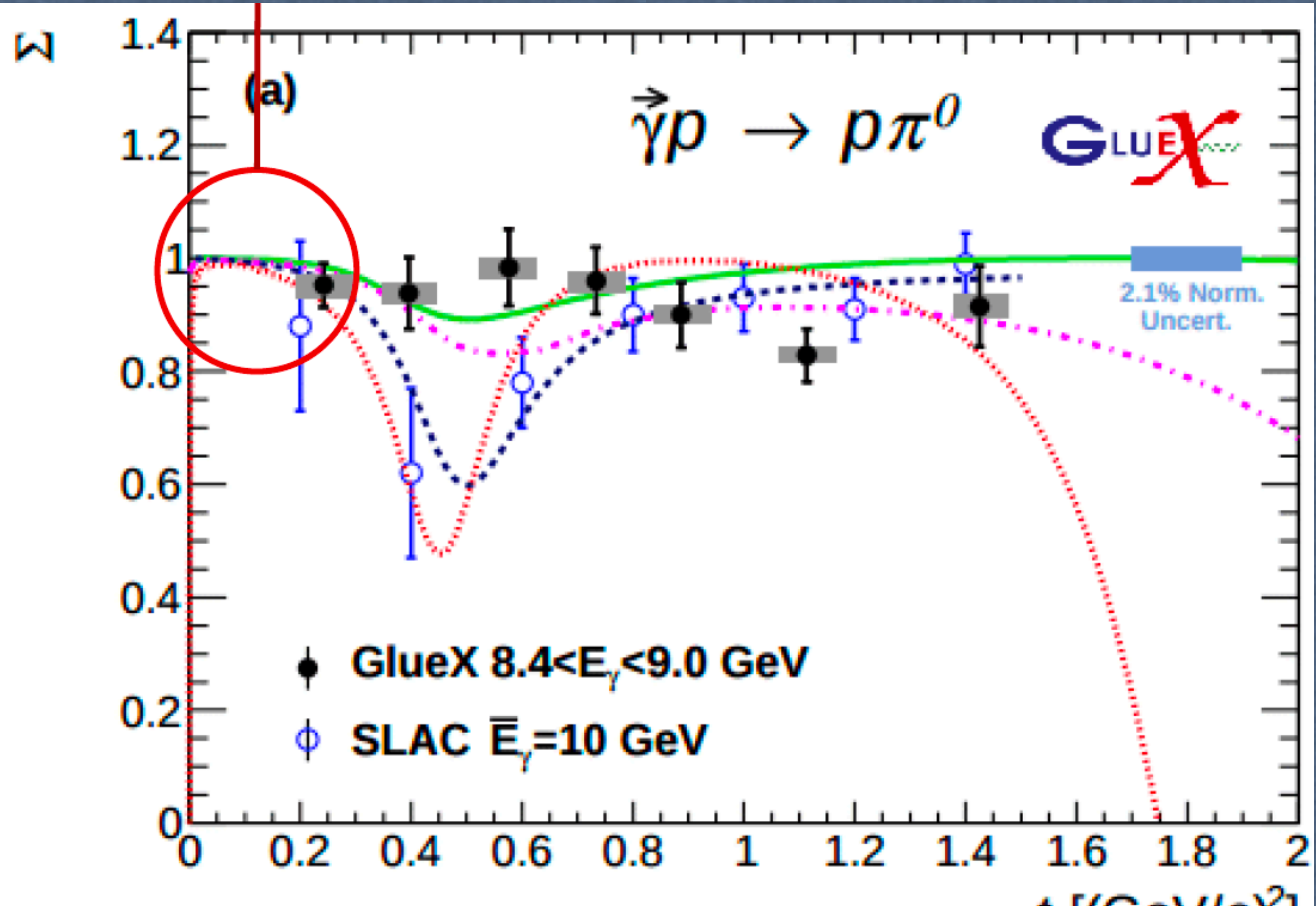


Generated	Fit result
(L,M) = (1,0): H0 = 0.3578 ;	H_0_1_0 = 0.358 +/- 0.008
(L,M) = (1,1): H0 = 0.0000 ;	H_0_1_1 = -0.0007 +/- 0.0007
(L,M) = (2,0): H0 = -0.0629 ;	H_0_2_0 = -0.0624 +/- 0.0005
(L,M) = (2,1): H0 = 0.0000 ;	H_0_2_1 = -0.0005 +/- 0.0005
(L,M) = (2,2): H0 = -0.1680 ;	H_0_2_2 = -0.169 +/- 0.0009
(L,M) = (3,0): H0 = -0.1533 ;	H_0_3_0 = -0.153 +/- 0.005
(L,M) = (3,1): H0 = 0.0000	H_0_3_1 = -0.0002 +/- 0.0003
(L,M) = (3,2): H0 = -0.1400 ;	H_0_3_2 = -0.140 +/- 0.001
(L,M) = (3,3): H0 = 0.0000 ;	H_0_3_3 = 0.0003 +/- 0.0006
(L,M) = (4,0): H0 = -0.0762 ;	H_0_4_0 = -0.0765 +/- 0.0007
(L,M) = (4,1): H0 = 0.0000 ;	H_0_4_1 = 0.0002 +/- 0.0003
(L,M) = (4,2): H0 = -0.0602 ;	H_0_4_2 = -0.0605 +/- 0.0004
(L,M) = (4,3): H0 = 0.0000 ;	H_0_4_3 = -0.0001 +/- 0.0004
(L,M) = (4,4): H0 = 0.0000 ;	H_0_4_4 = 0.0001 +/- 0.0005

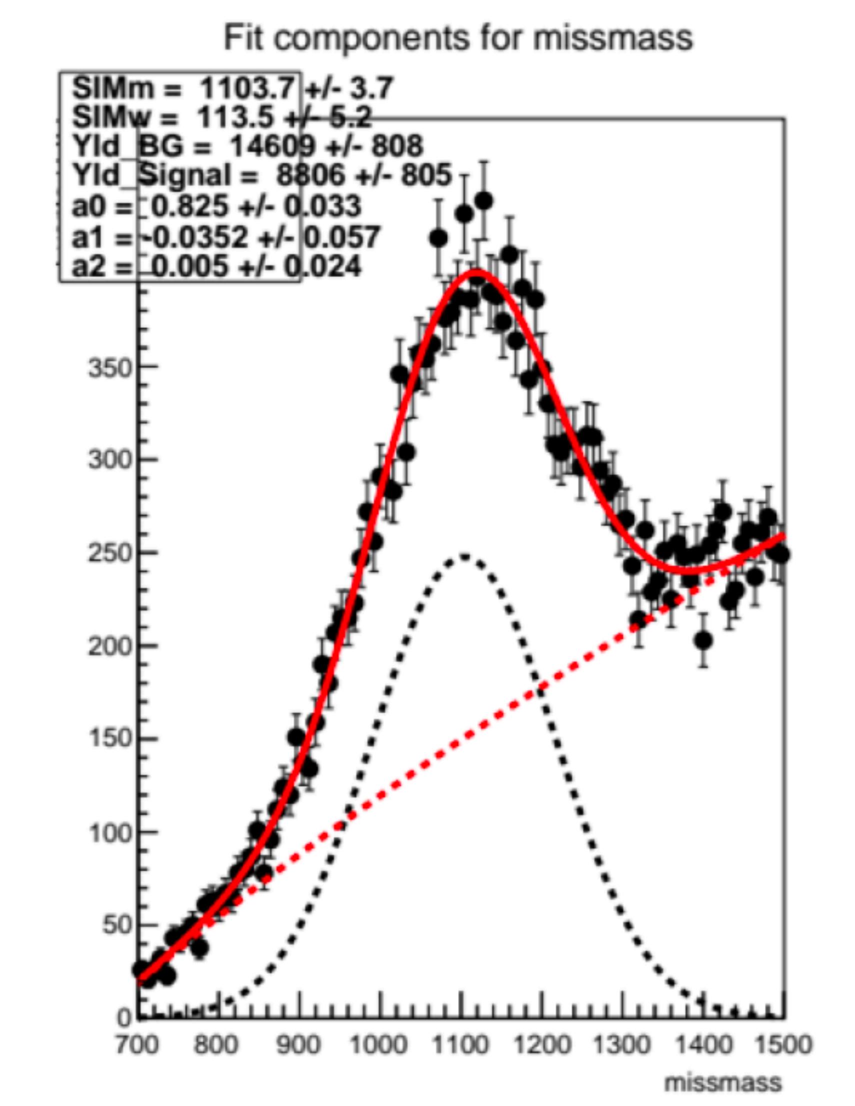
MesonEx data
$\gamma\, p \rightarrow (p)\, \pi^0$

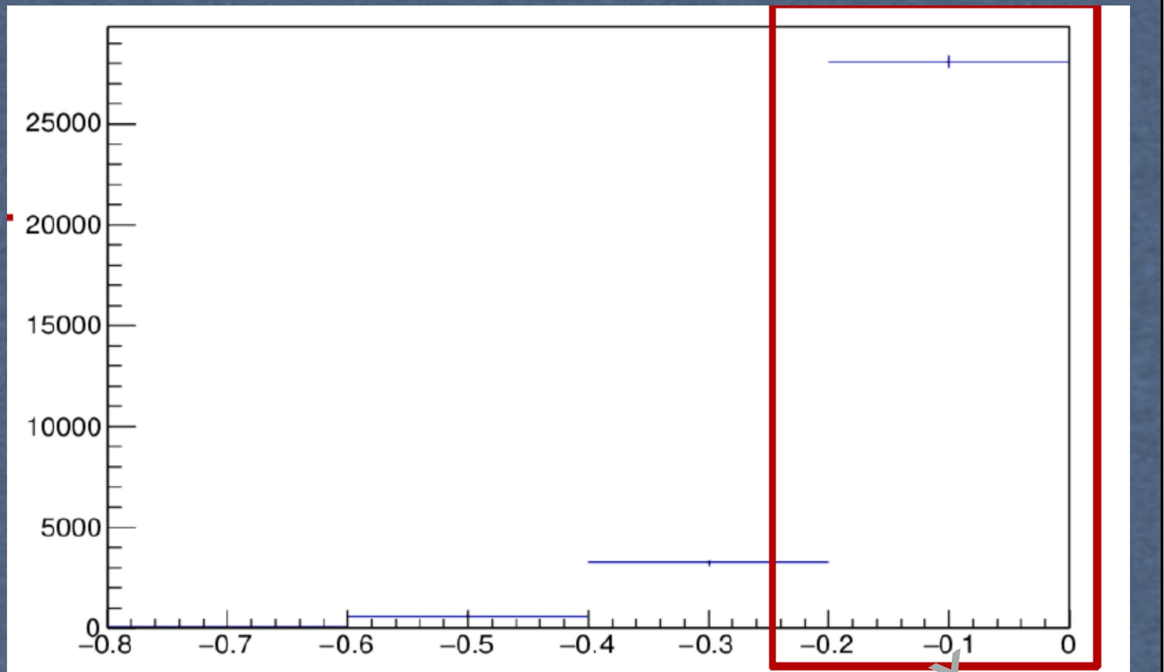
- Fall2018 RGA dataset
- 2 photons & 1electrons in FT
- 2ns time difference between detected particle
- Sum of photons momentum between 5.5 and 10.5 GeV
- Virtual photon energy between 3 and 9 GeV
- Q^2 between 0 and -0.5 GeV

L.Biondo



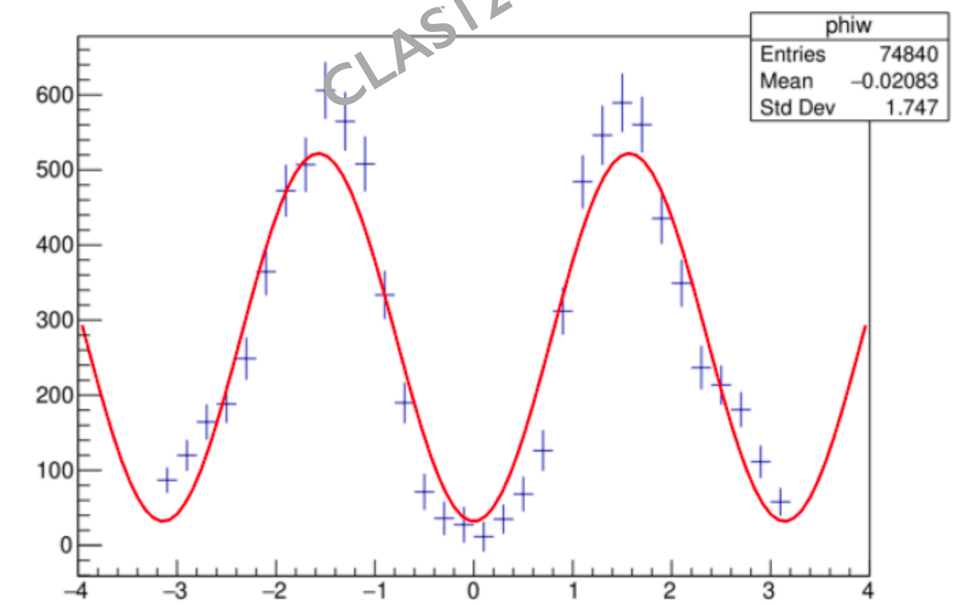
- SLAC and GlueX comparison





- t (Fall2018 - skim2)
The boxed sector highlights the SLAC/GlueX correspondent region.

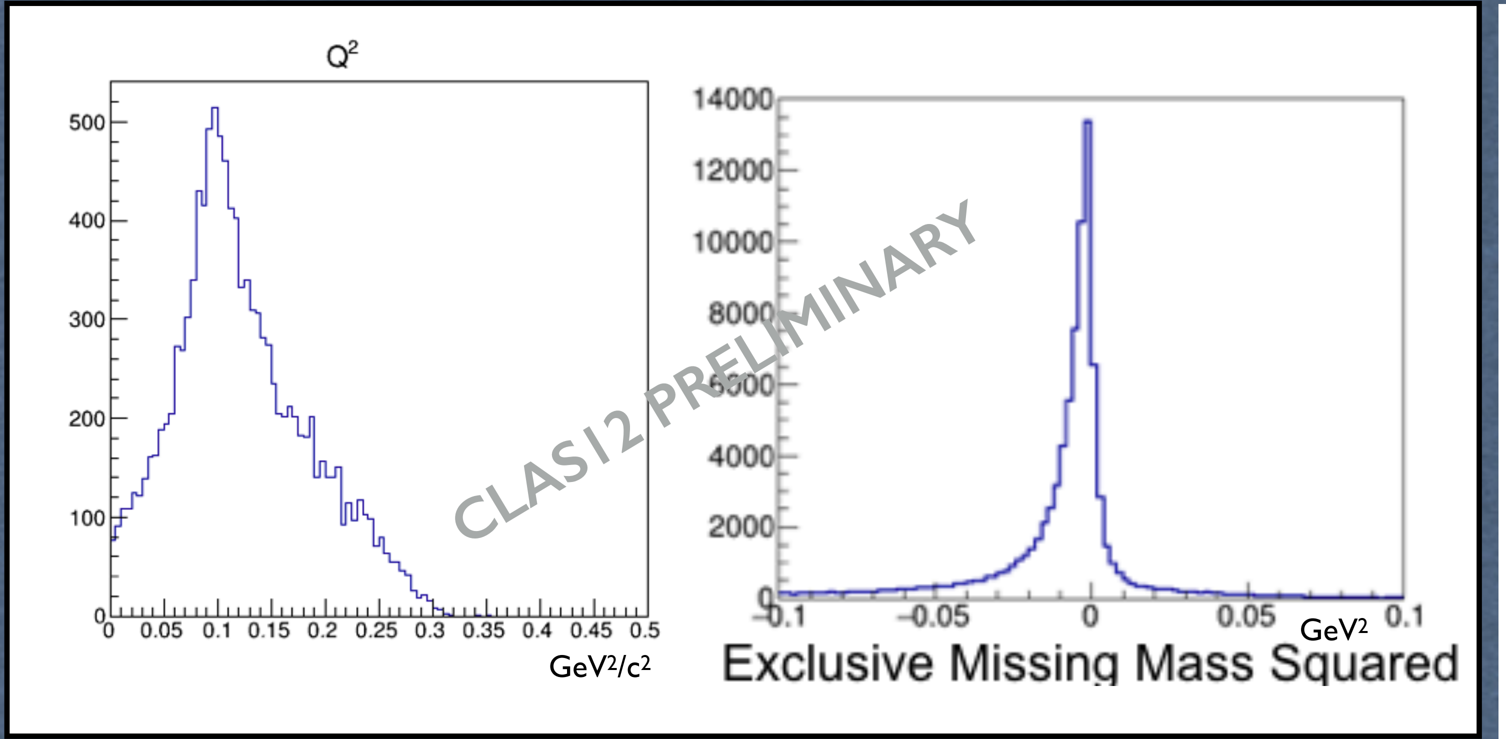
CLAS12 PRELIMINARY

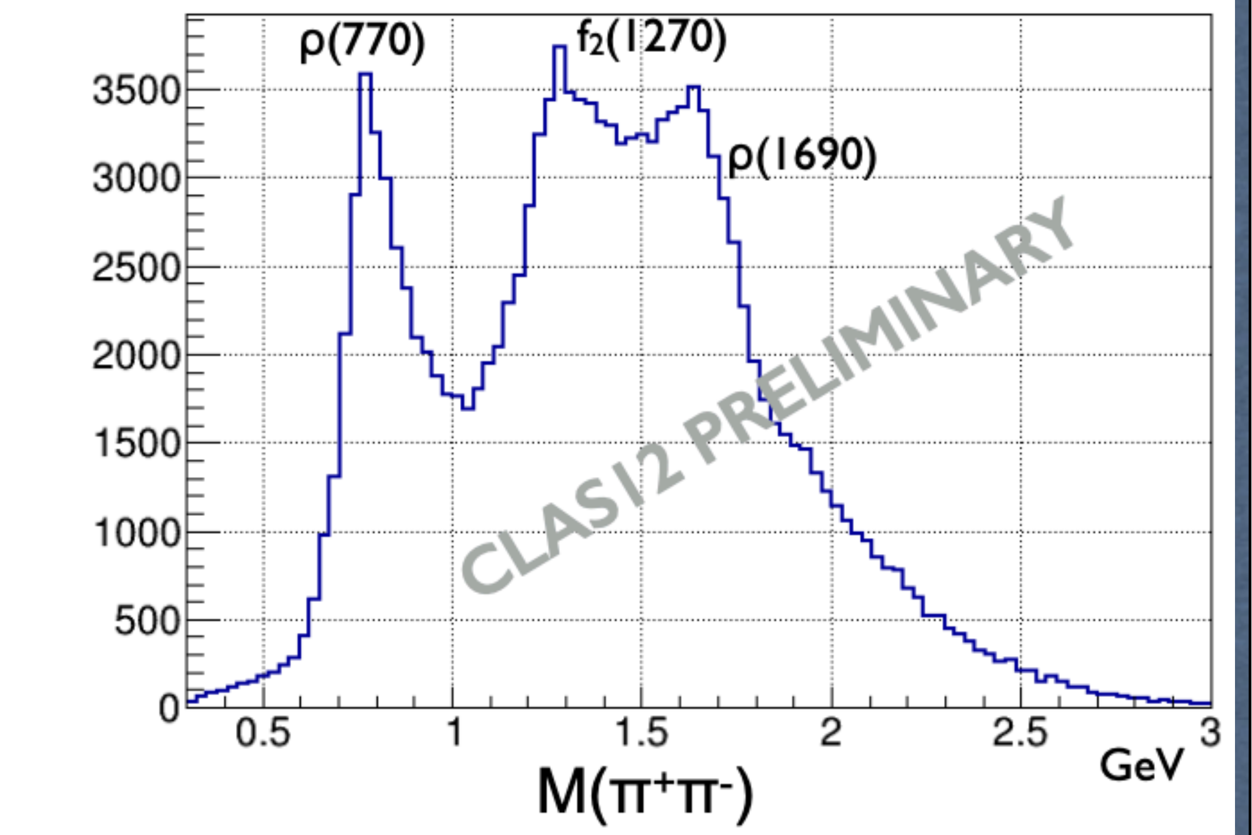


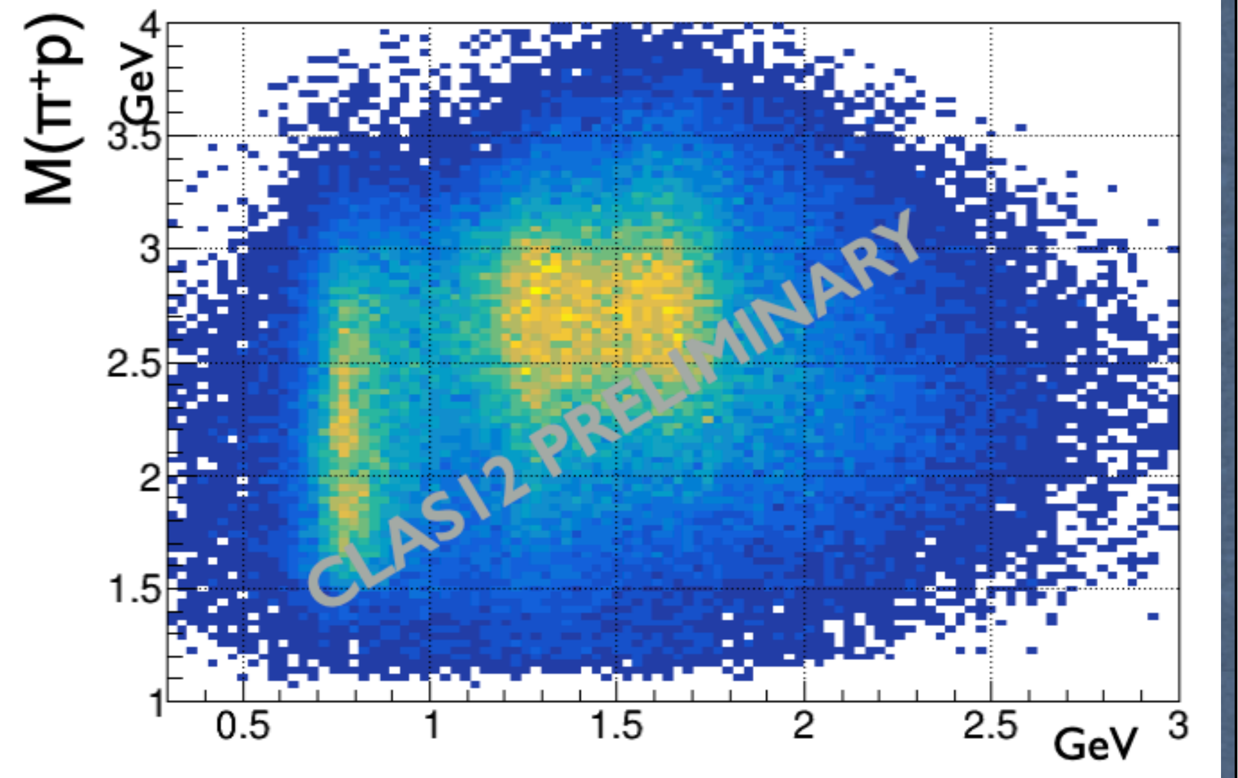
- Test Beam Asymmetry can be extracted from phi, here plotted for all the weighted events. More analysis are needed for the extraction of the physical quantity.

MesonEx data

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







- Use standard CLAS12 PID (FT based start time)
- $p\pi^+\pi^-$ exclusive reaction
- All *-t*
- $\langle Q^2 \rangle = 0.07$ GeV^2/c^2
- E_{Beam} = 10.6 GeV $\rightarrow$ $6 < E_\gamma < 10$ GeV

- Trigger/Torus Field/Detector $\rightarrow$ Low acceptance for $M_{\pi\pi} < 1.1$GeV

- Need to account for N*/Δ in Moments Fits, but contributions do not look too strong
- Complementary cuts select baryons for further studies

D.Glazier

D.Glazier

MesonEx data

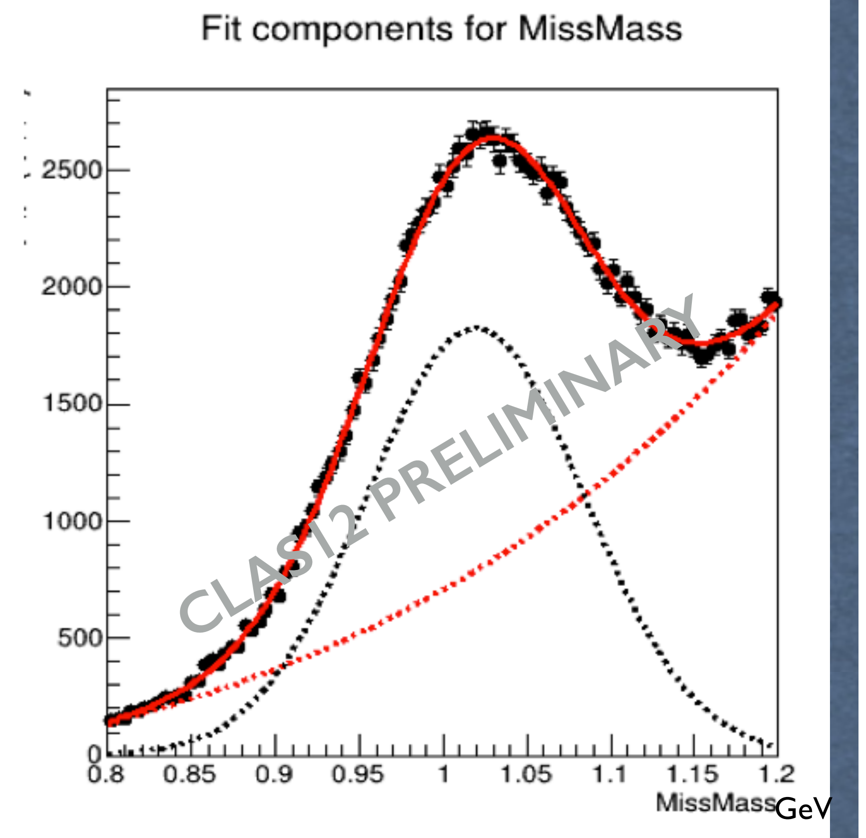
$\gamma\, p \rightarrow (n)\, \pi^+\, \pi^+\, \pi^-$

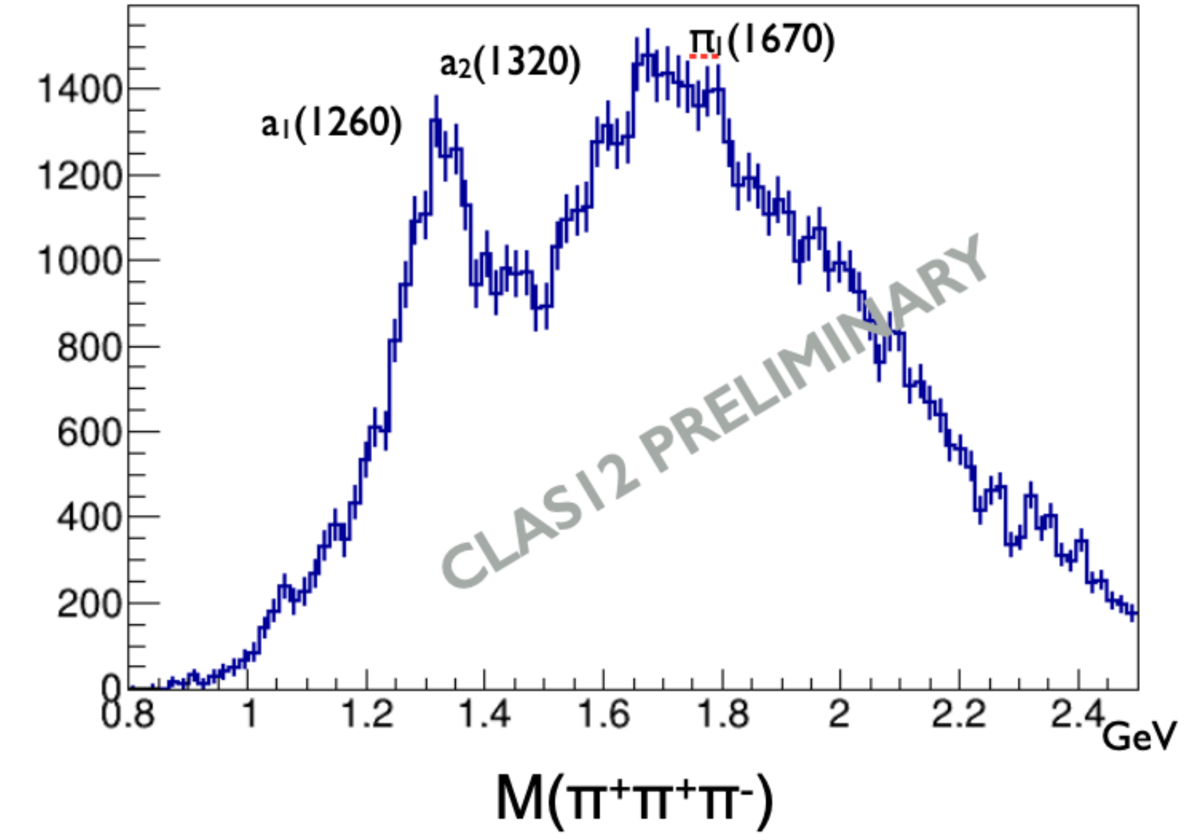
- Use standard CLAS12 PID (FT based start time)
- $p\pi^+\pi^-$ exclusive reaction
- $-t < -2$ *GeV*
- $6<E_\gamma<10$ GeV

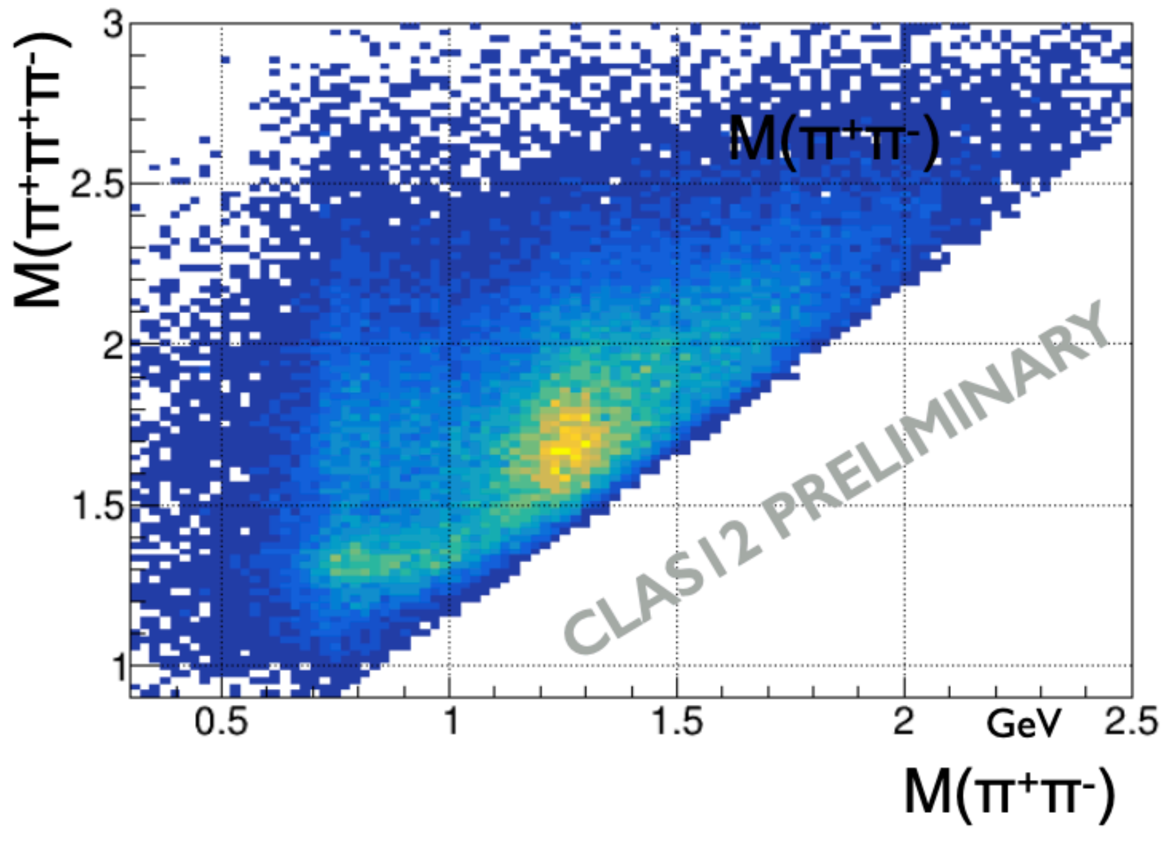
- Trigger/Torus Field/Detector → Low acceptance for M < 1.3GeV

- Need to include N*/Δ + 2π contributions in the analysis

Fit MissingMass to identify neutron

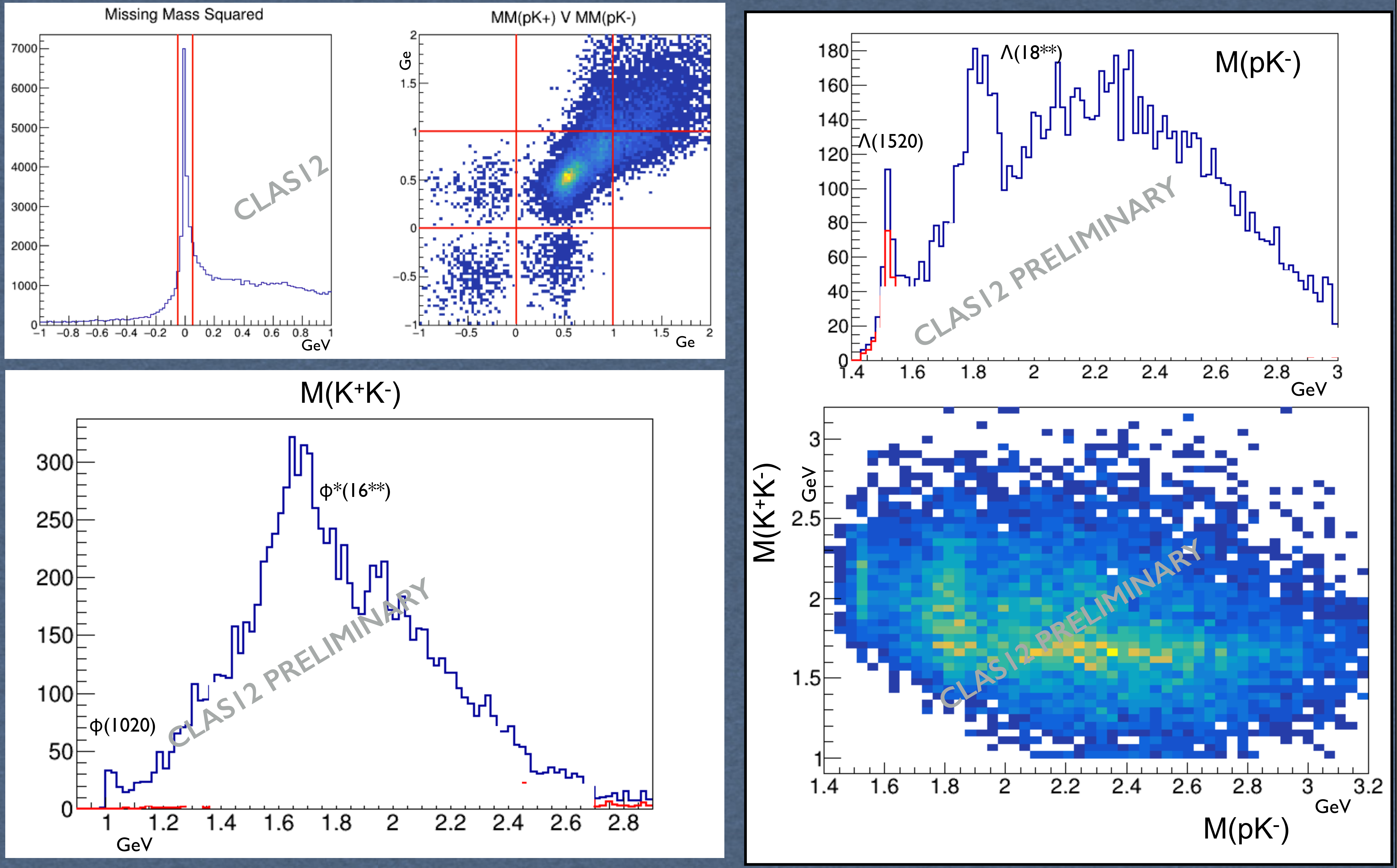






MesonEx data

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



- Need to account for hyperons in Moments Fits

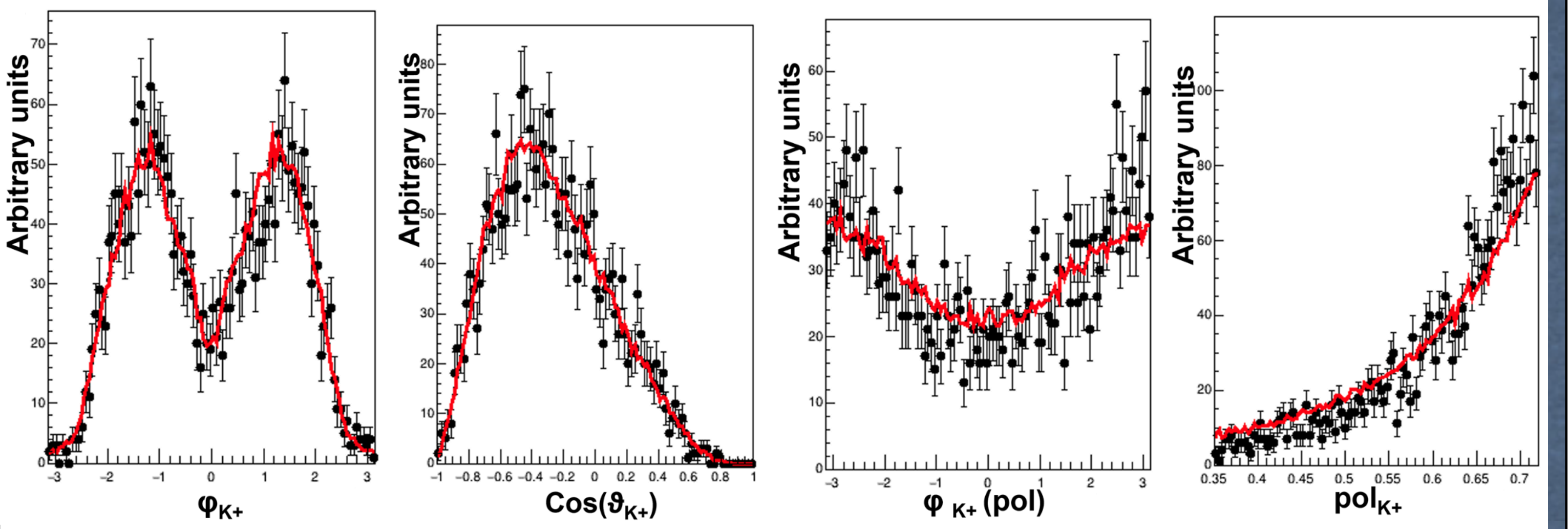
D.Glazier

K^+K^- Moments of Angular Distribution

Matthew Nicol

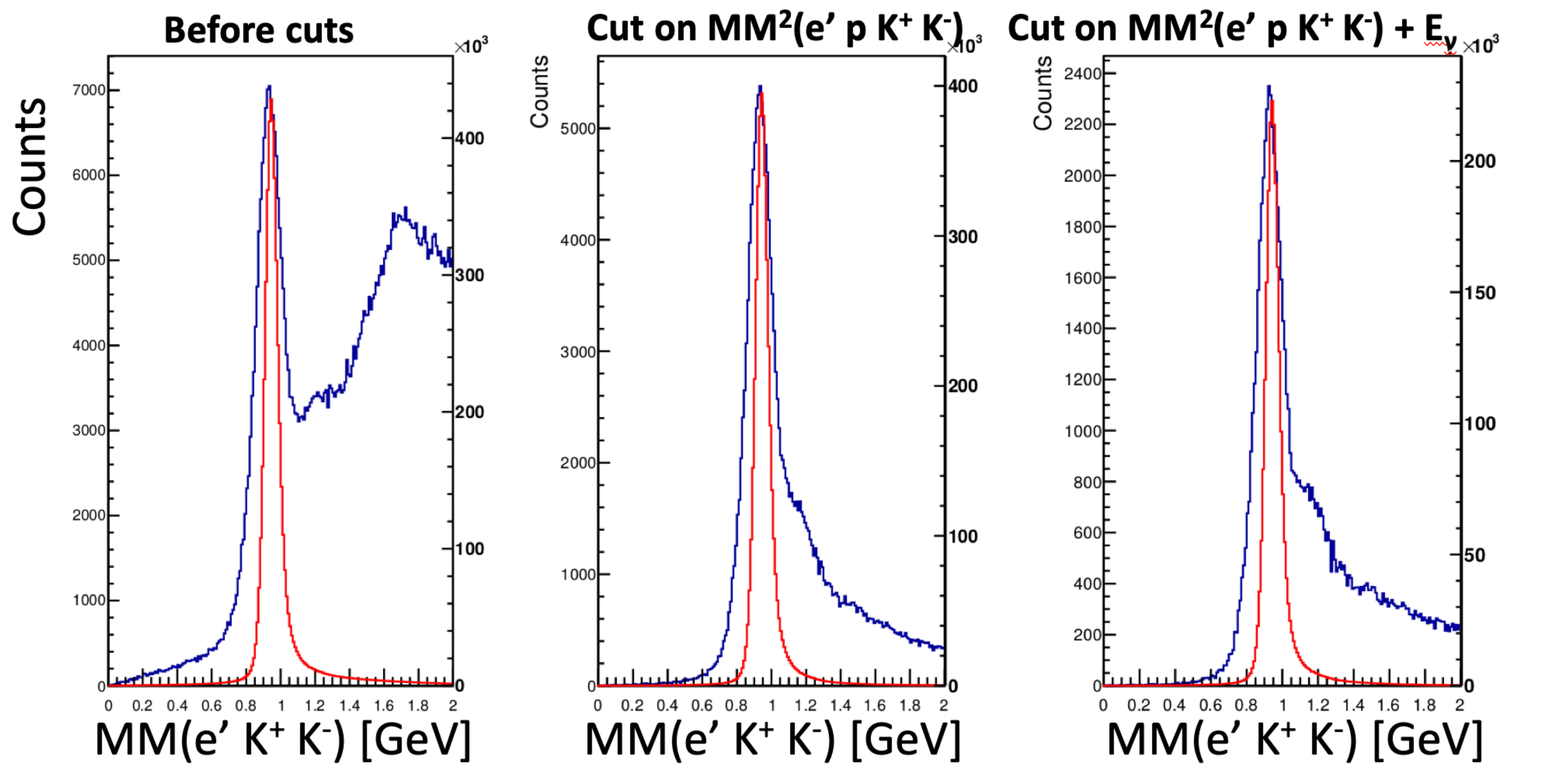
Decay Angles

Black - Experiment
Red - Simulation



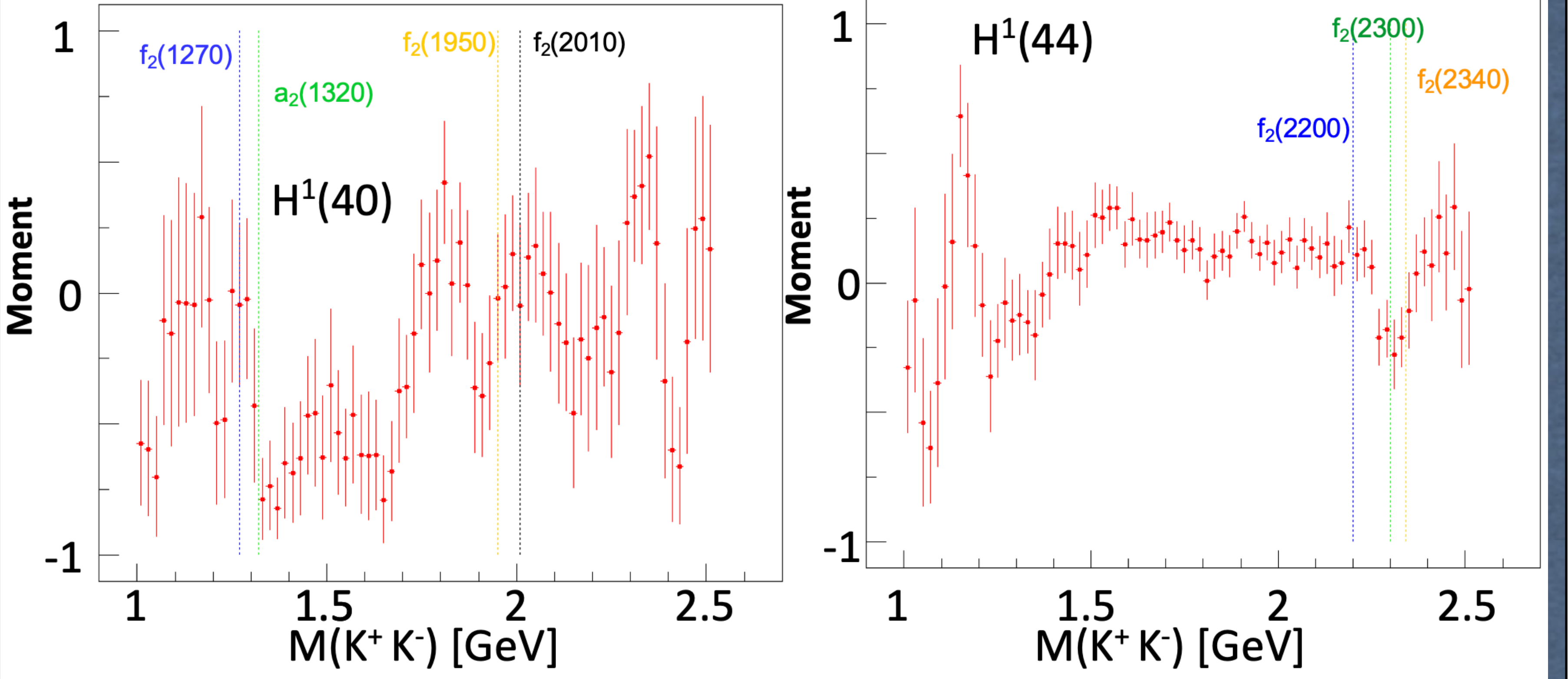
Proton Recons.

Blue - Experiment
Red - Simulation



Angular Distribution Moments

- Known Mesons at points of interest highlighted

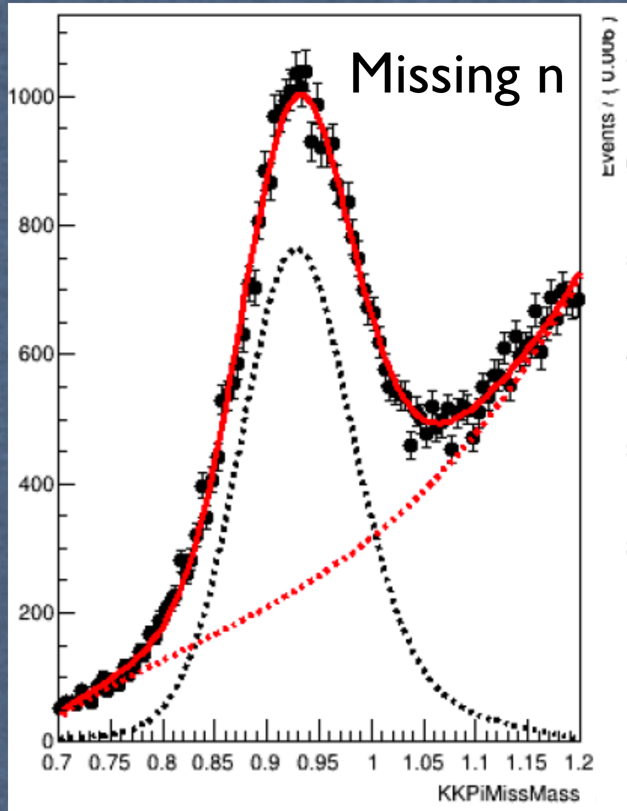


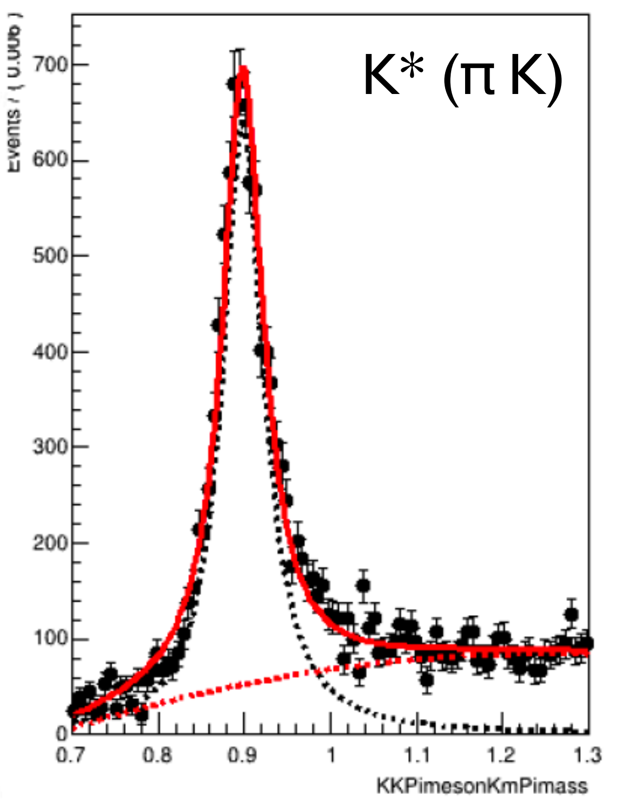
R.Wishart

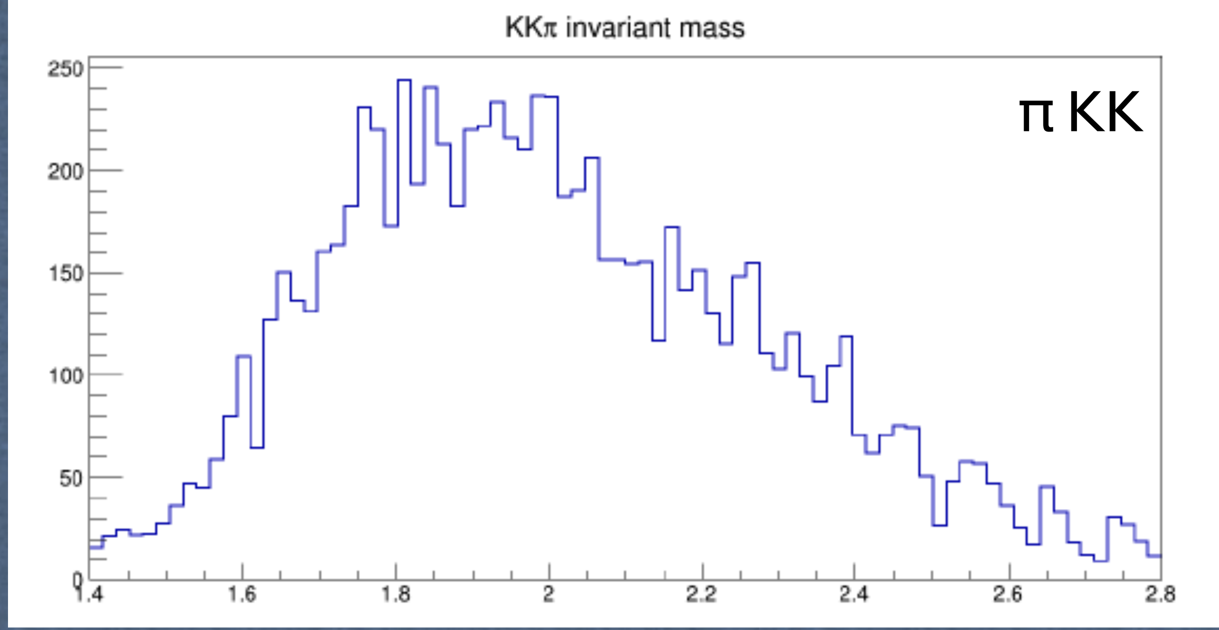
MesonEx data

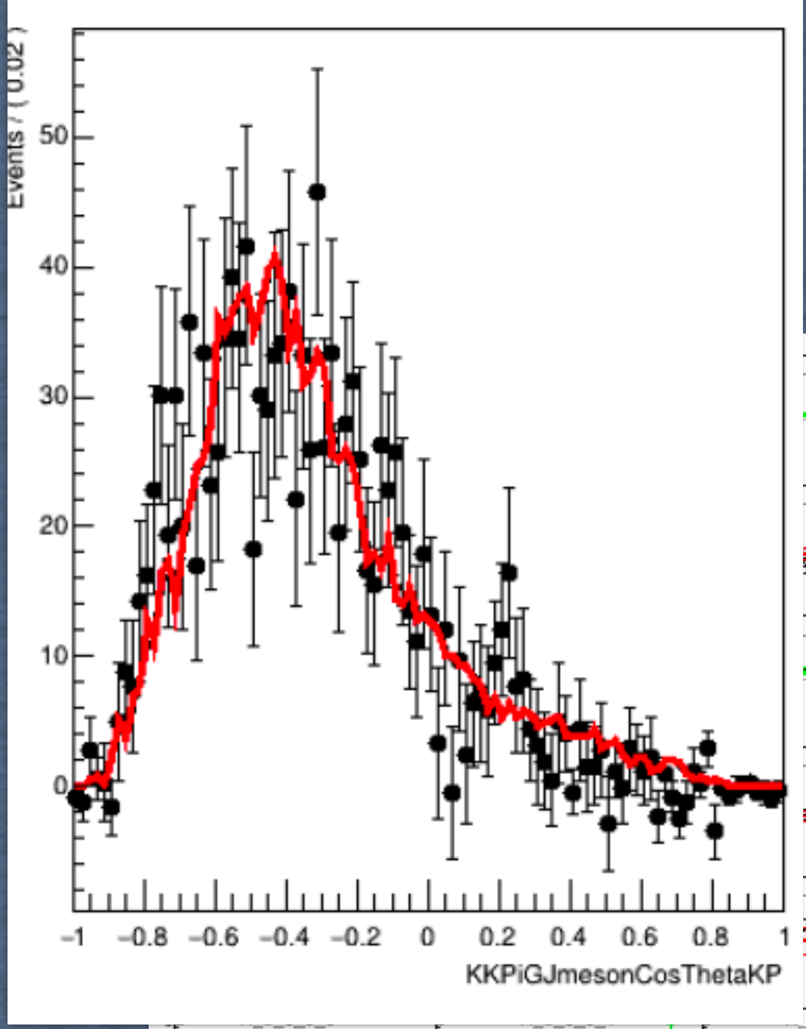
$\gamma\, p \rightarrow (n)\, K^+ K^- \pi^+$

- Fall 2018 RGA dataset (inbending and outbending)
- Q^2 between 0.07 and 0.3 GeV
- e- in FT, hadrons in FD



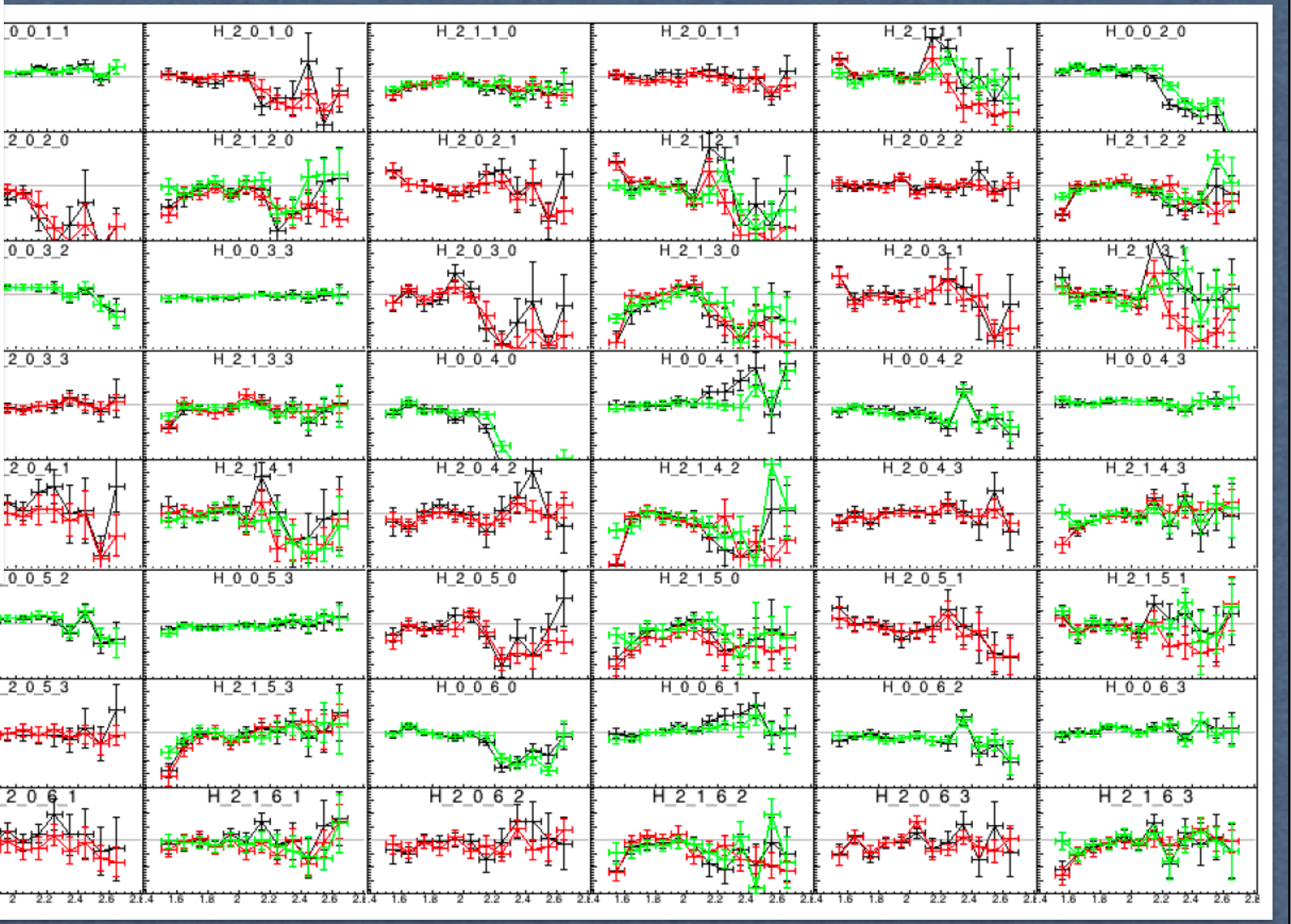






- We want to extract the moments are calculated as fit parameters of the intensity:

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



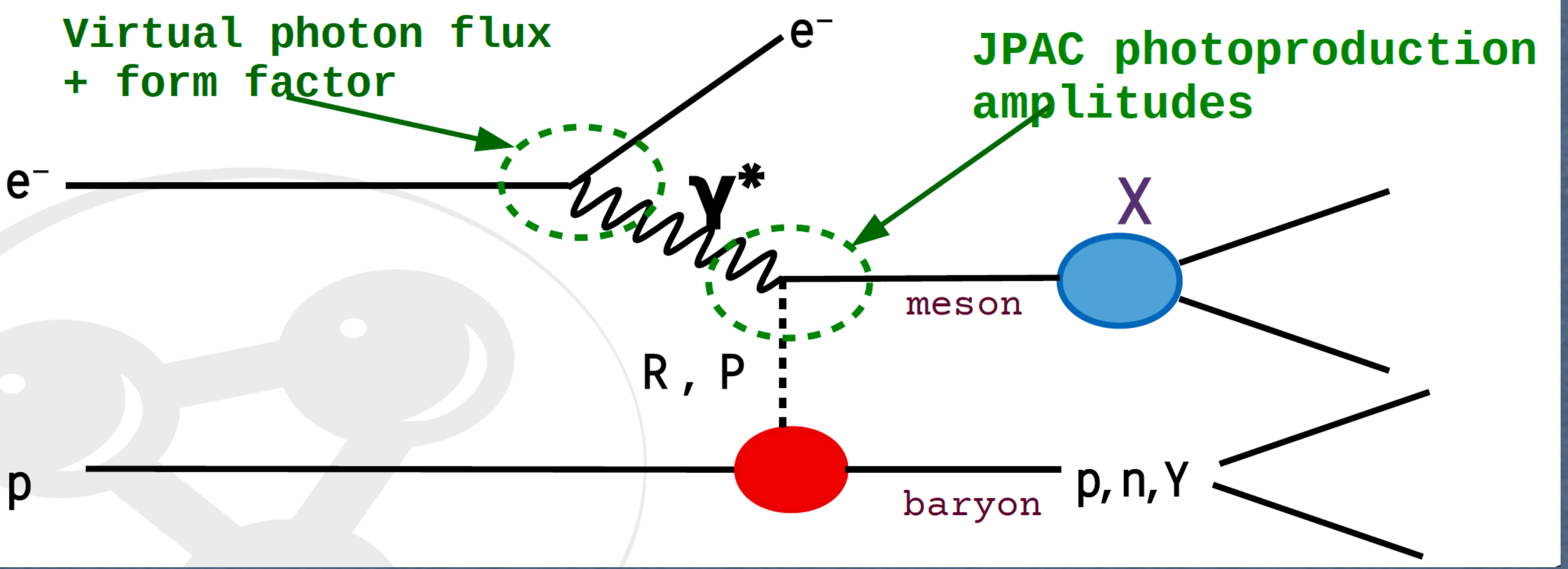
MesonEx tools
elSpectro

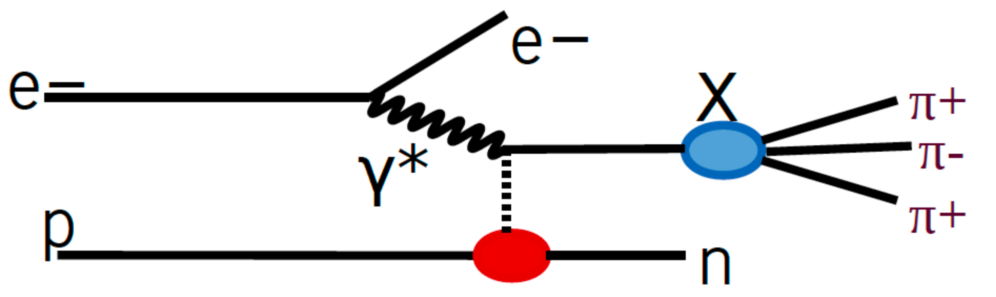
clas12-elSpectro

Factorise 2 photon vertices

Virtual photon flux
+ form factor

JPAC photoproduction
amplitudes



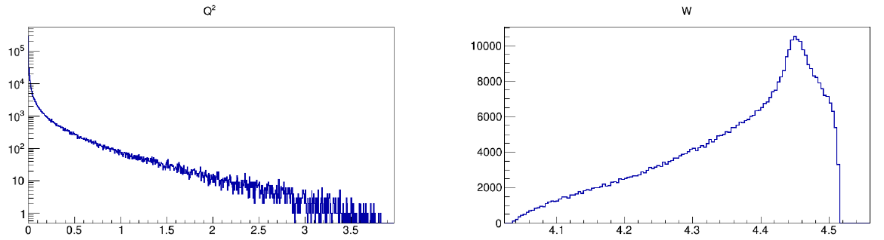


D.Glazier

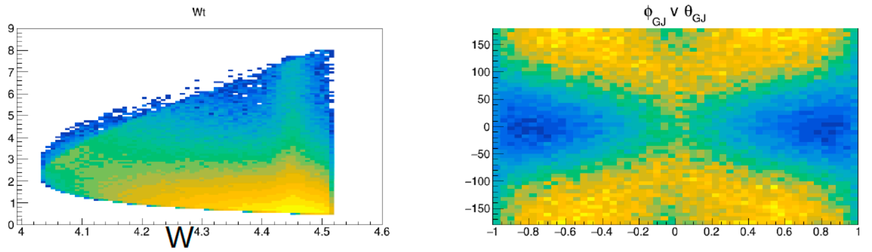
Example J/ψ production with Pentaquark

γ*+p → J/ψ + p
J/ψ → e+e-

JpacPhoto:
With s-channel P(4450)
And pomeron exchange

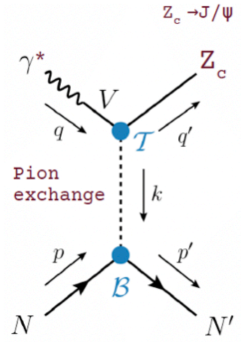



```
reaction_kinematics * ptr = new reaction_kinematics(3.0969160);//Jpsi mass
// ---------------------------------------------------------------------------
// S - CHANNEL

// Two different pentaquarks
// masses and widths from 2015 LHCb paper [2]
auto P_c4450 =new baryon_resonance(ptr, 3, -1, 4.45, 0.040, "P_{c}(4450)");
P_c4450->set_params({0.01, .7071}); // 2% branching fraction

auto P_c4380 = new baryon_resonance(ptr, 5, +1, 4.38, 0.205, "P_{c}(4380)");
P_c4380->set_params({0.01, .7071}); // 2% branching fraction

// ---------------------------------------------------------------------------
// T - CHANNEL

// Set up pomeron trajectory
// Best fit values from [1]
 auto alpha =new linear_trajectory(+1, 0.941, 0.364, "pomeron");

// Create amplitude with kinematics and trajectory
auto  background = new pomeron_exchange(ptr, alpha, false, "Background");

// normalization and t-slope
background->set_params({0.379, 0.12});
// SUM
amplitude_sum sum5q(ptr, {background, P_c4450}, "5q Sum");
```

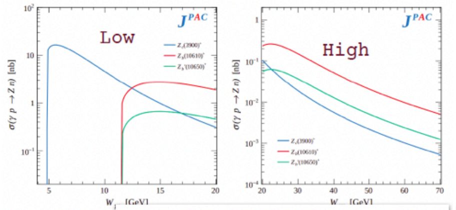


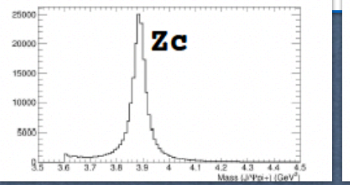

```
auto jpsi=particle(443,model(new VectorSDMEDecay({},{11,-11})));
auto jpac_amp = Amplitude();
auto pGammaStarDecay = new JpacModelst{&jpac_amp, {jpsi},{2212} };
auto prod = new DecayModelQ2W{
  0,pGammaStarDecay,new TwoBody_stu{0.1, 0.9, 0.5,0,0}};

//fixed target experiment
mesonex( ebeamE ,  prod);

writer(new LundWriter{Form("ep_Jpsi.dat",(int)ebeamE)});

initGenerator();

for(int i=0;i<nEvents;i++)
  nextEvent();
```

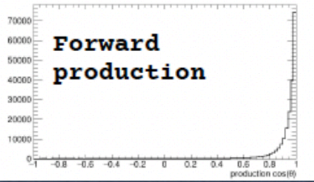
Z_c(3900) in CLAS24



In 50 days:
210k events

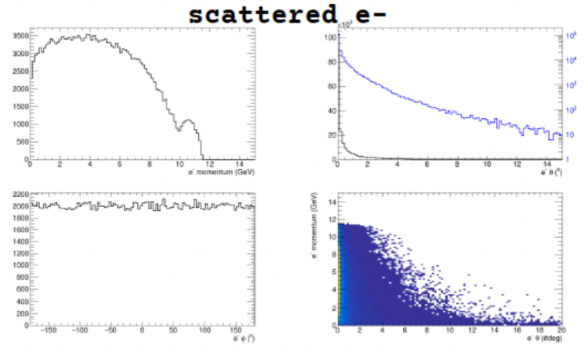






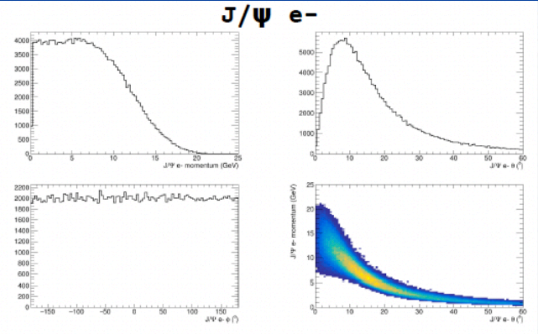
D.Glazier

scattered e-



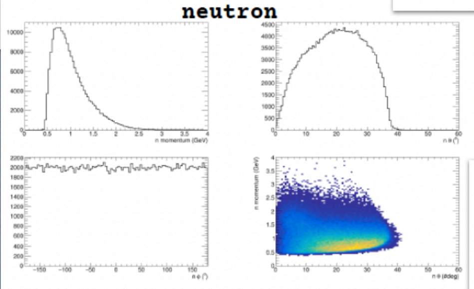
Most e- < 1deg
And < 12 GeV

J/ψ e-



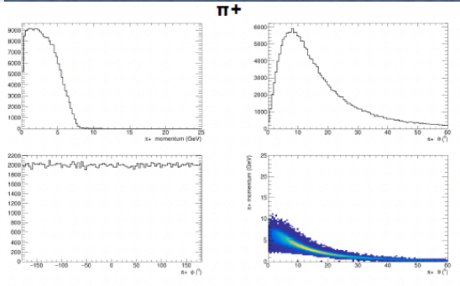
Leptons up to 20 GeV

neutron



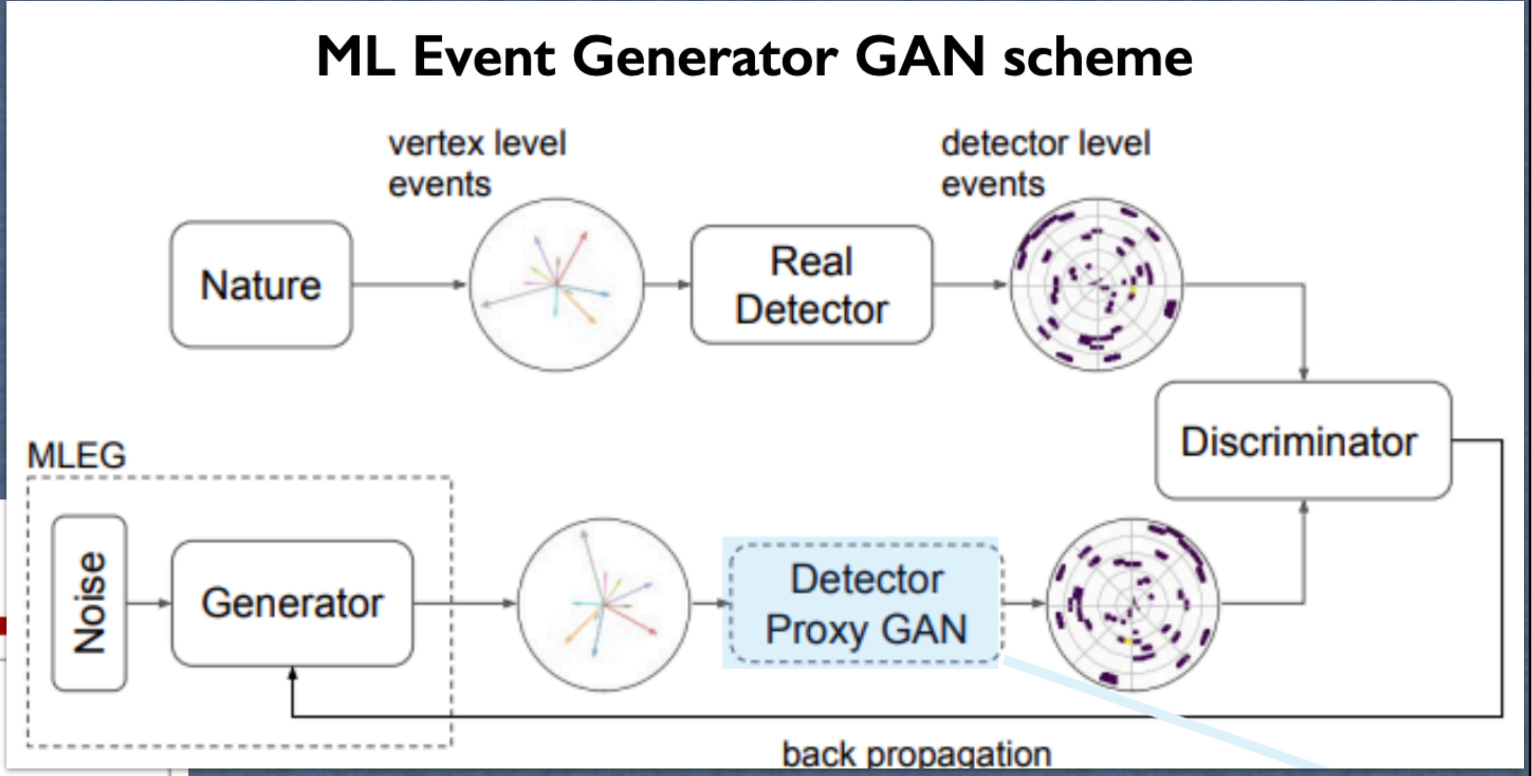
Neutron detection from 0.5 GeV

π+

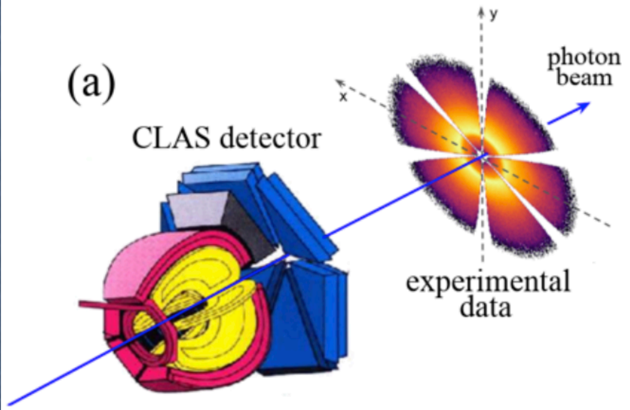


Decay pions have lower momentum
Similar angular range

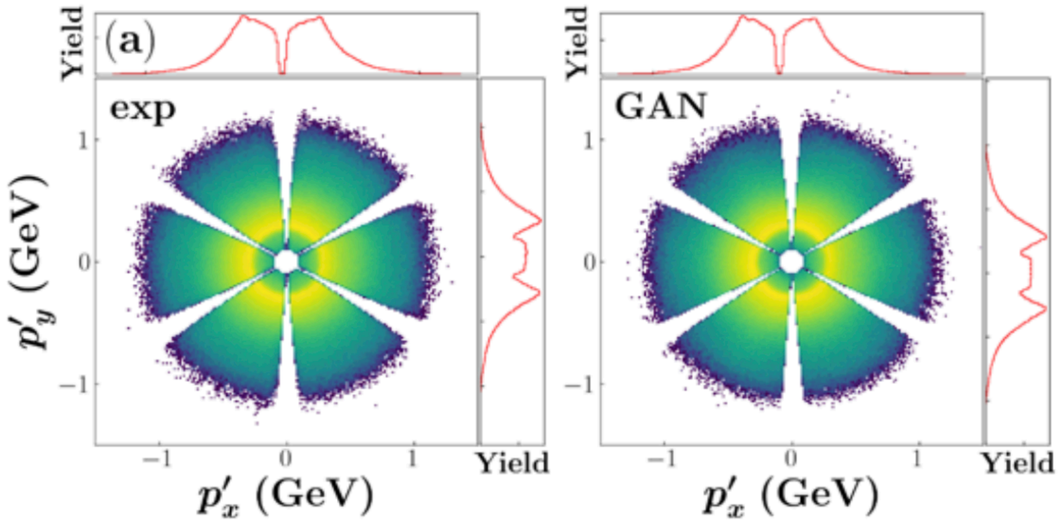
MesonEx tools
A(i)DAPT

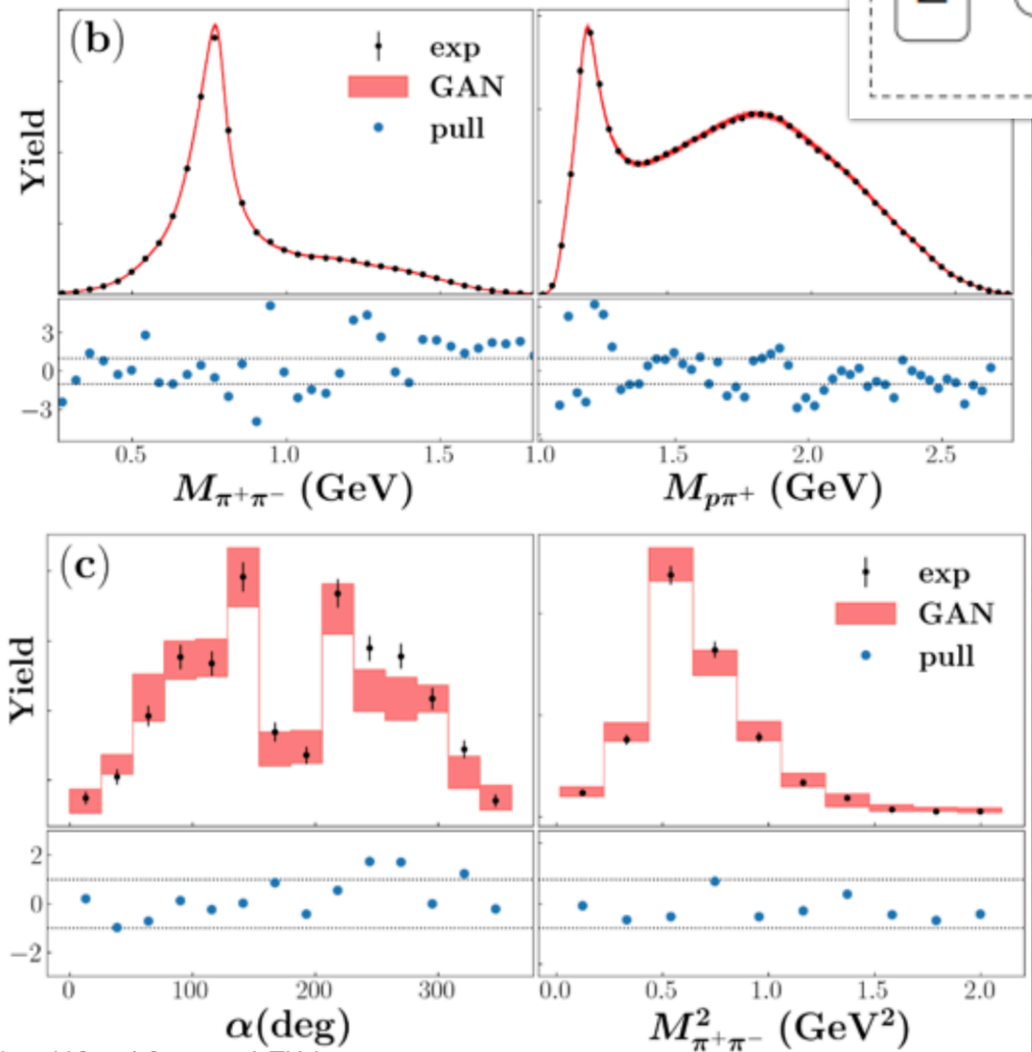


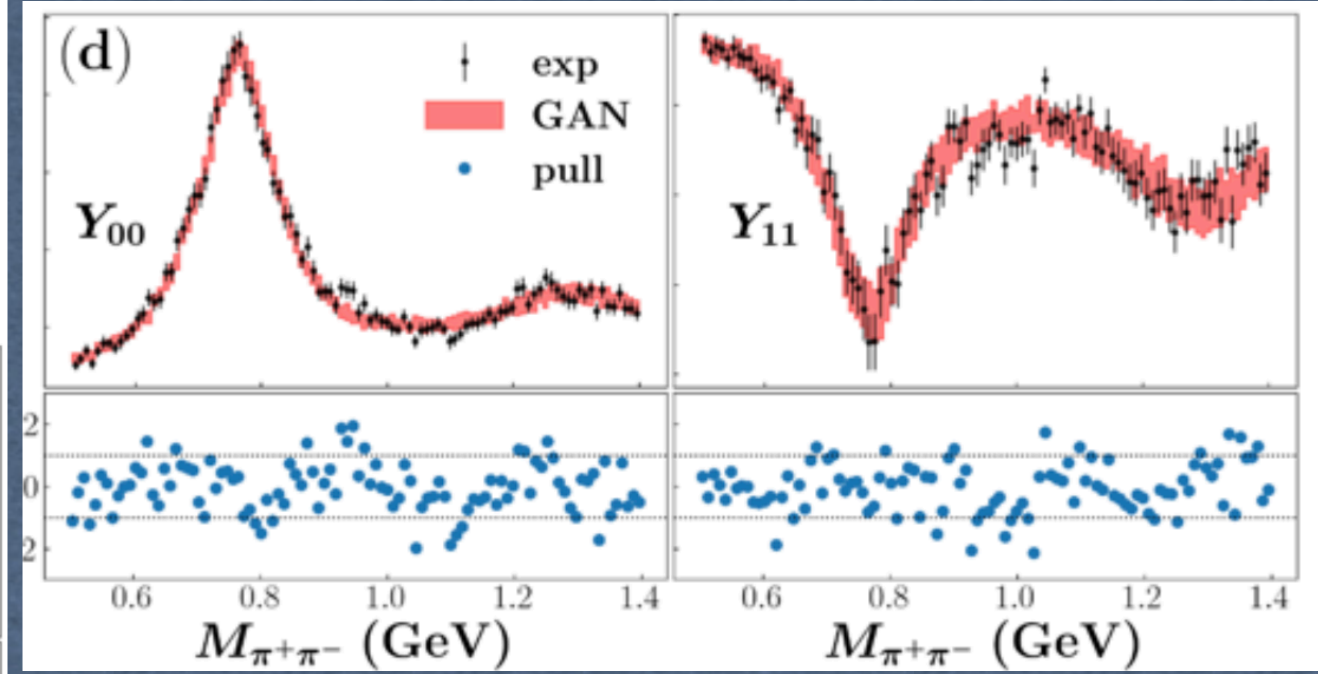
Synthetic vs data (no detector unfolding)



- These results did not correct for detector effects (no unfolding)
- Despite CLAS distortions (mainly acceptance), GAN is able to mimic the data set







Credit: Y.Alanazi Awadh, , P.Ambrozewicz, G. Costantini A.Hiller Blin, E. Isupov, T. Jeske, Y.Li, L.Marsicano W. Menlnitchouk, V.Mokeev, N.Sato, A.Szczepaniak, T.Viducic

Summary and outlook

✳ MesonEx is a comprehensive meson spectroscopy program running in Hall-B at JLab complementary to GLUEX

✳ Exotics and strangeness-rich mesons search with CLAS12 detector exploiting excellent resolution and particle ID

✳ Low Q^2 electron scattering to produce a high intensity, linear polarized, quasi-real photon beam

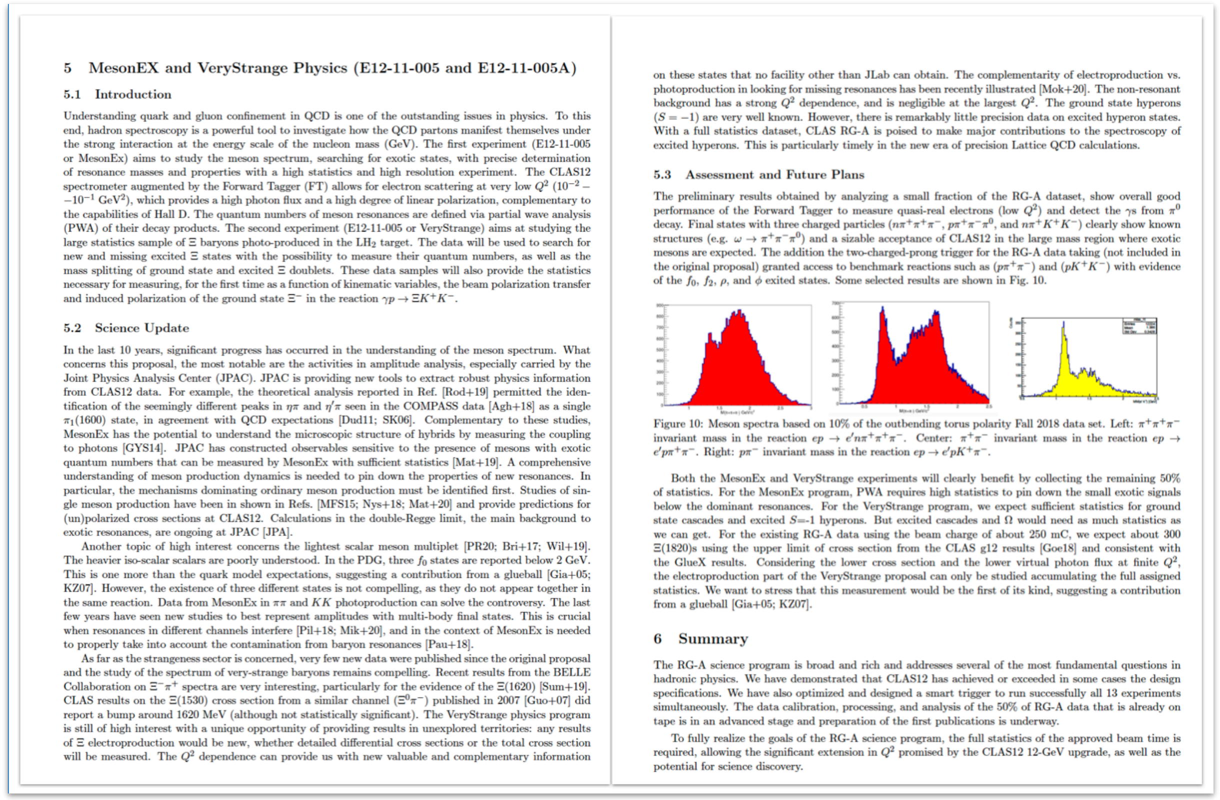
✳ Experience in PWA gained with CLAS6 (angular moments analysis, ML/AI approach) will be valuable for CLAS12 data analysis

✳ MesonEx analysis tools developed and tested on available data (Pass1 RGA-), supported by JPAC

✳ Current PASS1 data suffer from reduced tracking efficiency (multi-particle final states) and missing CD information

✳ Waiting for PASS2 (baryons in CD and increased statistics) to extract MesonEx physics out of data

Presented to PAC48 in the RG-A jeopardy review



5 MesonEX and VeryStrange Physics (E12-11-005 and E12-11-005A)

5.1 Introduction

Understanding quark and gluon confinement in QCD is one of the outstanding issues in physics. To this end, hadron spectroscopy is a powerful tool to investigate how the QCD partons manifest themselves under the strong interaction at the energy scale of the nucleon mass (GeV). The first experiment (E12-11-005 or MesonEx) aims to study the meson spectrum, searching for exotic states, with precise determination of resonance masses and properties with a high statistics and high resolution experiment. The CLAS12 spectrometer augmented by the Forward Tagger (FT) allows for electron scattering at very low Q^2 (10^{-2} – -10^{-1} GeV^2), which provides a high photon flux and a high degree of linear polarization, complementary to the capabilities of Hall D. The quantum numbers of meson resonances are defined via partial wave analysis (PWA) of their decay products. The second experiment (E12-11-005 or VeryStrange) aims at studying the large statistics sample of Ξ baryons photo-produced in the LH_2 target. The data will be used to search for new and missing excited Ξ states with the possibility to measure their quantum numbers, as well as the mass splitting of ground state and excited Ξ doublets. These data samples will also provide the statistics necessary for measuring, for the first time as a function of kinematic variables, the beam polarization transfer and induced polarization of the ground state Ξ^- in the reaction $\gamma p \to \Xi K^+ K^-$.

5.2 Science Update

In the last 10 years, significant progress has occurred in the understanding of the meson spectrum. What concerns this proposal, the most notable are the activities in amplitude analysis, especially carried by the Joint Physics Analysis Center (JPAC). JPAC is providing new tools to extract robust physics information from CLAS12 data. For example, the theoretical analysis reported in Ref. [Rod+19] permitted the identification of the seemingly different peaks in $\eta\pi$ and $\eta'\pi$ seen in the COMPASS data [Agh+18] as a single $\pi_1(1600)$ state, in agreement with QCD expectations [Dud11; SK06]. Complementary to these studies, MesonEx has the potential to understand the microscopic structure of hybrids by measuring the coupling to photons [GYS14]. JPAC has constructed observables sensitive to the presence of mesons with exotic quantum numbers that can be measured by MesonEx with sufficient statistics [Mat+19]. A comprehensive understanding of meson production dynamics is needed to pin down the properties of new resonances. In particular, the mechanisms dominating ordinary meson production must be identified first. Studies of single meson production have been in shown in Refs. [MFS15; Nys+18; Mat+20] and provide predictions for (un)polarized cross sections at CLAS12. Calculations in the double-Regge limit, the main background to exotic resonances, are ongoing at JPAC [JPA].

Another topic of high interest concerns the lightest scalar meson multiplet [PR20; Bri+17; Wil+19]. The heavier iso-scalar scalars are poorly understood. In the PDG, three f_0 states are reported below 2 GeV. This is one more than the quark model expectations, suggesting a contribution from a glueball [Gia+05; KZ07]. However, the existence of three different states is not compelling, as they do not appear together in the same reaction. Data from MesonEx in $\pi\pi$ and KK photoproduction can solve the controversy. The last few years have seen new studies to best represent amplitudes with multi-body final states. This is crucial when resonances in different channels interfere [Pil+18; Mik+20], and in the context of MesonEx is needed to properly take into account the contamination from baryon resonances [Pau+18].

As far as the strangeness sector is concerned, very few new data were published since the original proposal and the study of the spectrum of very-strange baryons remains compelling. Recent results from the BELLE Collaboration on $\Xi^-\pi^+$ spectra are very interesting, particularly for the evidence of the $\Xi(1620)$ [Sum+19]. CLAS results on the $\Xi(1530)$ cross section from a similar channel ($\Xi^0\pi^-$) published in 2007 [Guo+07] did report a bump around 1620 MeV (although not statistically significant). The VeryStrange physics program is still of high interest with a unique opportunity of providing results in unexplored territories: any results of Ξ electroproduction would be new, whether detailed differential cross sections or the total cross section will be measured. The Q^2 dependence can provide us with new valuable and complementary information on these states that no facility other than JLab can obtain. The complementarity of electroproduction vs. photoproduction in looking for missing resonances has been recently illustrated [Mok+20]. The non-resonant background has a strong Q^2 dependence, and is negligible at the largest Q^2. The ground state hyperons ($S = -1$) are very well known. However, there is remarkably little precision data on excited hyperon states. With a full statistics dataset, CLAS RG-A is poised to make major contributions to the spectroscopy of excited hyperons. This is particularly timely in the new era of precision Lattice QCD calculations.

5.3 Assessment and Future Plans

The preliminary results obtained by analyzing a small fraction of the RG-A dataset, show overall good performance of the Forward Tagger to measure quasi-real electrons (low Q^2) and detect the γs from π^0 decay. Final states with three charged particles ($n\pi^+\pi^+\pi^-$, $p\pi^+\pi^-\pi^0$, and $n\pi^+K^+K^-$) clearly show known structures (e.g. $\omega \to \pi^+\pi^-\pi^0$) and a sizable acceptance of CLAS12 in the large mass region where exotic mesons are expected. The addition the two-charged-prong trigger for the RG-A data taking (not included in the original proposal) granted access to benchmark reactions such as ($p\pi^+\pi^-$) and (pK^+K^-) with evidence of the f_0, f_2, ρ, and ϕ exited states. Some selected results are shown in Fig. 10.

Figure 10: Meson spectra based on 10% of the outbending torus polarity Fall 2018 data set. Left: $\pi^+\pi^+\pi^-$ invariant mass in the reaction $ep \to e'n\pi^+\pi^+\pi^-$. Center: $\pi^+\pi^-$ invariant mass in the reaction $ep \to e'p\pi^+\pi^-$. Right: $p\pi^-$ invariant mass in the reaction $ep \to e'pK^+\pi^-$.

Both the MesonEx and VeryStrange experiments will clearly benefit by collecting the remaining 50% of statistics. For the MesonEx program, PWA requires high statistics to pin down the small exotic signals below the dominant resonances. For the VeryStrange program, we expect sufficient statistics for ground state cascades and excited S=-1 hyperons. But excited cascades and Ω would need as much statistics as we can get. For the existing RG-A data using the beam charge of about 250 mC, we expect about 300 $\Xi(1820)$s using the upper limit of cross section from the CLAS g12 results [Goe18] and consistent with the GlueX results. Considering the lower cross section and the lower virtual photon flux at finite Q^2, the electroproduction part of the VeryStrange proposal can only be studied accumulating the full assigned statistics. We want to stress that this measurement would be the first of its kind, suggesting a contribution from a glueball [Gia+05; KZ07].

6 Summary

The RG-A science program is broad and rich and addresses several of the most fundamental questions in hadronic physics. We have demonstrated that CLAS12 has achieved or exceeded in some cases the design specifications. We have also optimized and designed a smart trigger to run successfully all 13 experiments simultaneously. The data calibration, processing, and analysis of the 50% of RG-A data that is already on tape is in an advanced stage and preparation of the first publications is underway.

To fully realize the goals of the RG-A science program, the full statistics of the approved beam time is required, allowing the significant extension in Q^2 promised by the CLAS12 12-GeV upgrade, as well as the potential for science discovery.

✳ MesonEx and jeopardy process in PAC48

✳~50% of RG-A still to go will take advantage of L3 trigger, meson-spectroscopy optimisation, and hopefully hi-lumy ops

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