
# The HASPECT network


*M.Battaglieri*
*INFN -GE*
*Italy*

# Hadron spectroscopy ingredients

* Experiment
* Theory
* Analysis strategy
* Analysis tools

# Hadron spectroscopy ingredients

✳ Experiment

- High statistics, high quality data
- Use different probes (hadron/em)
- Loose trigger to record multiple final states
- Thorough investigation of badly known sectors (eg. strangness-rich mesons, quarkonia, …)
- Access a large kinematic

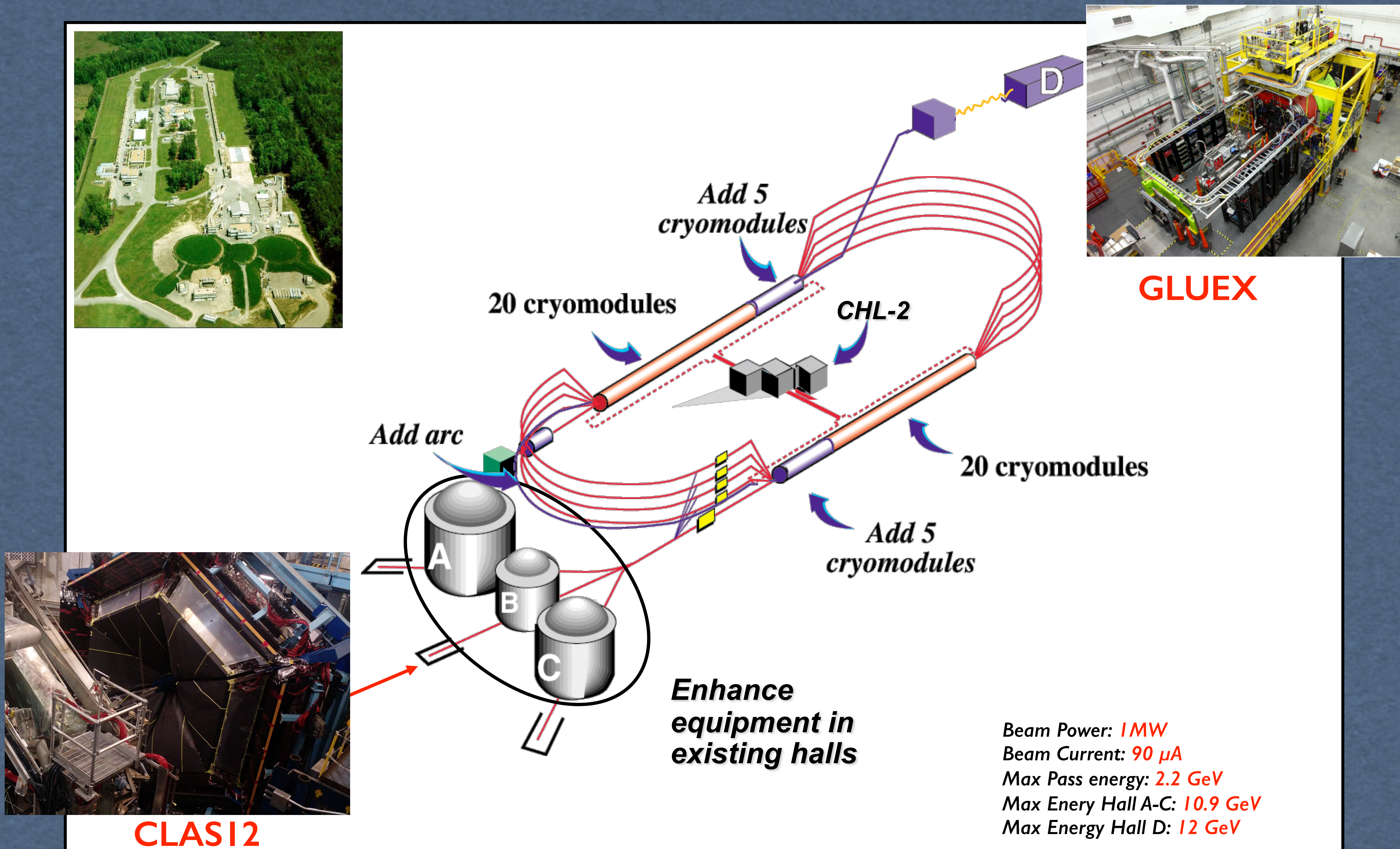
MesonEx program with CLAS12 at JLab
GLUEX in Hall-D at JLab
COMPASS @ CERN
BES-III, LHCb, BelleII

✳ Theory

✳ Analysis strategy

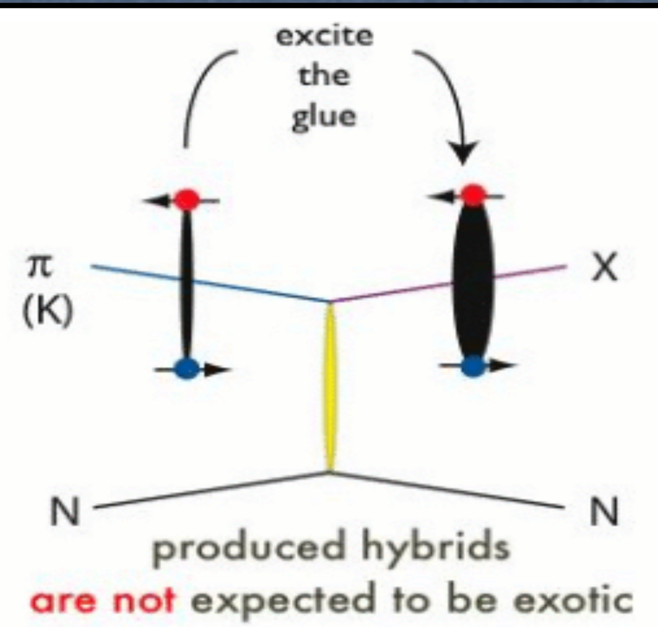
✳ Analysis tools

# Jefferson Lab at 12 GeV



# Why photoproduction

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



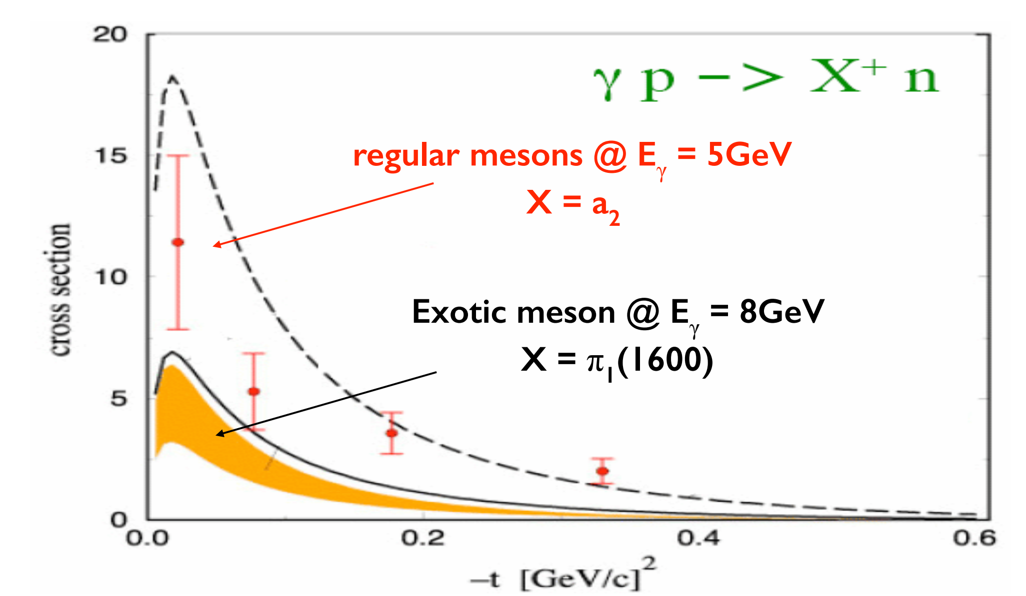

Need spin-flip for exotic quantum number

No spin-flip for exotic quantum number

★ 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

A. Afanasev and P. Page et al. PR A57 1998 6771
A. Szczepaniak and M. Swat PLB 516 2001 72



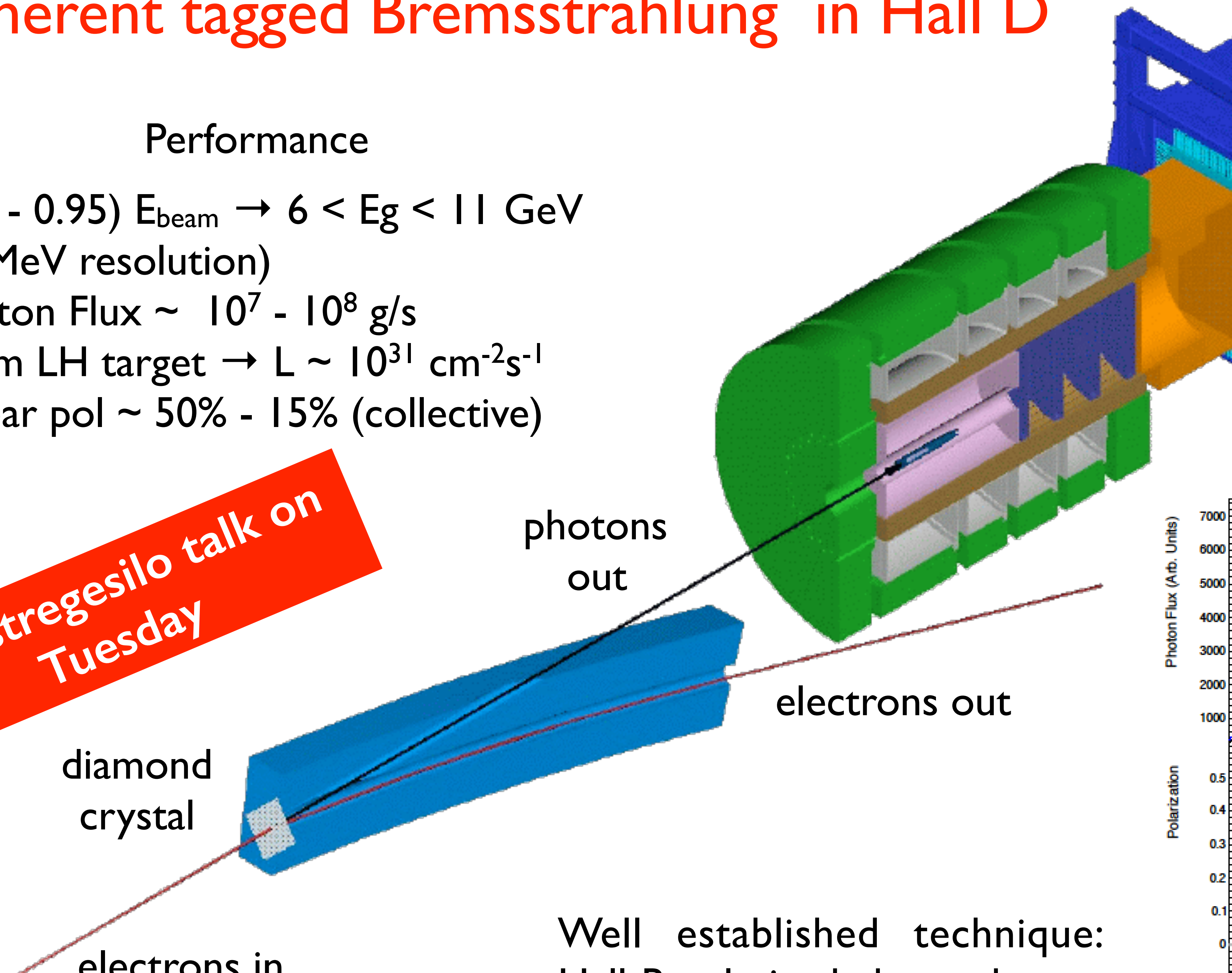
# Meson spectroscopy with photons at JLab-12GeV

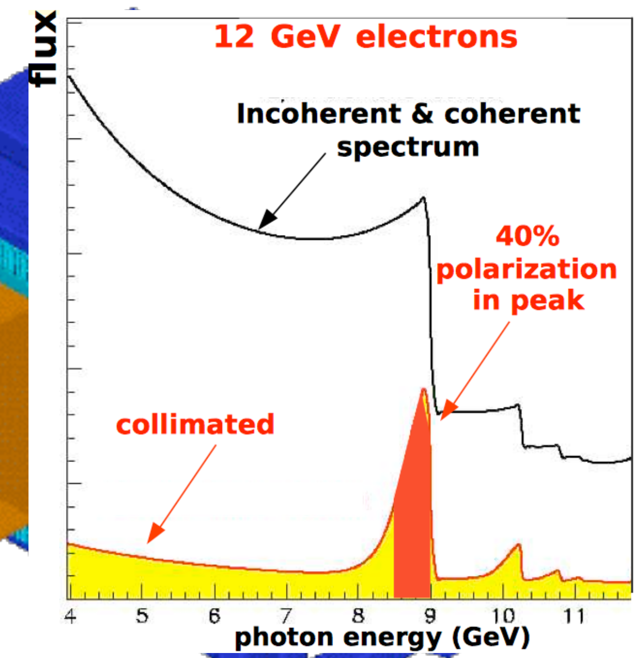
## Coherent tagged Bremsstrahlung in Hall D

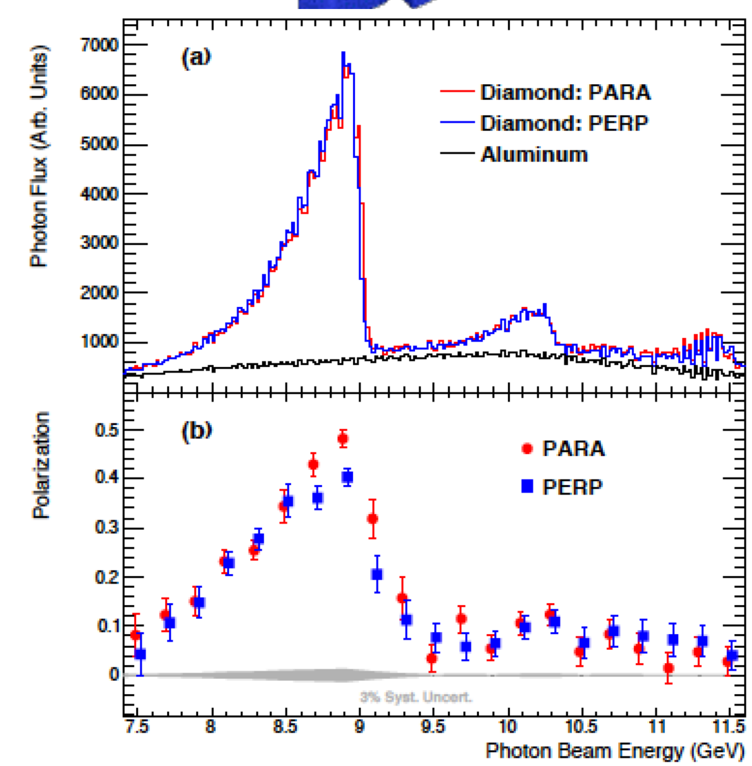
Performance

(0.5 - 0.95) $E_{beam}$ → 6 < Eg < 11 GeV
(10MeV resolution)
Photon Flux ~ $10^7$ - $10^8$ g/s
30cm LH target → L ~ $10^{31}$ $cm^{-2}s^{-1}$
Linear pol ~ 50% - 15% (collective)

A.Austregesilo talk on Tuesday

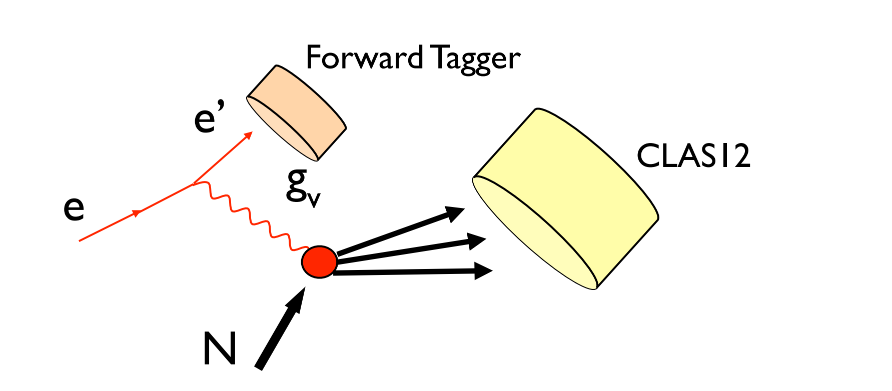


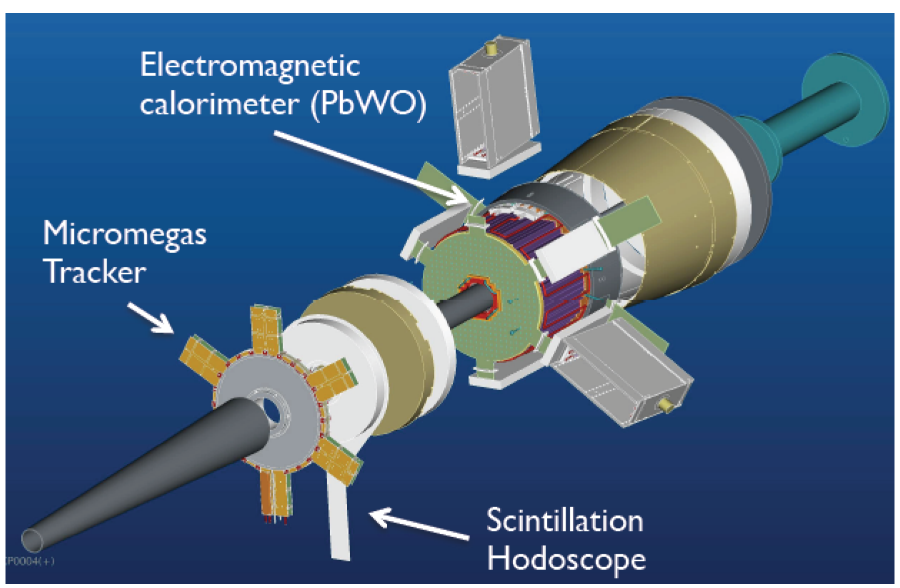




Well established technique:
Hall-B polarized photon beam

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



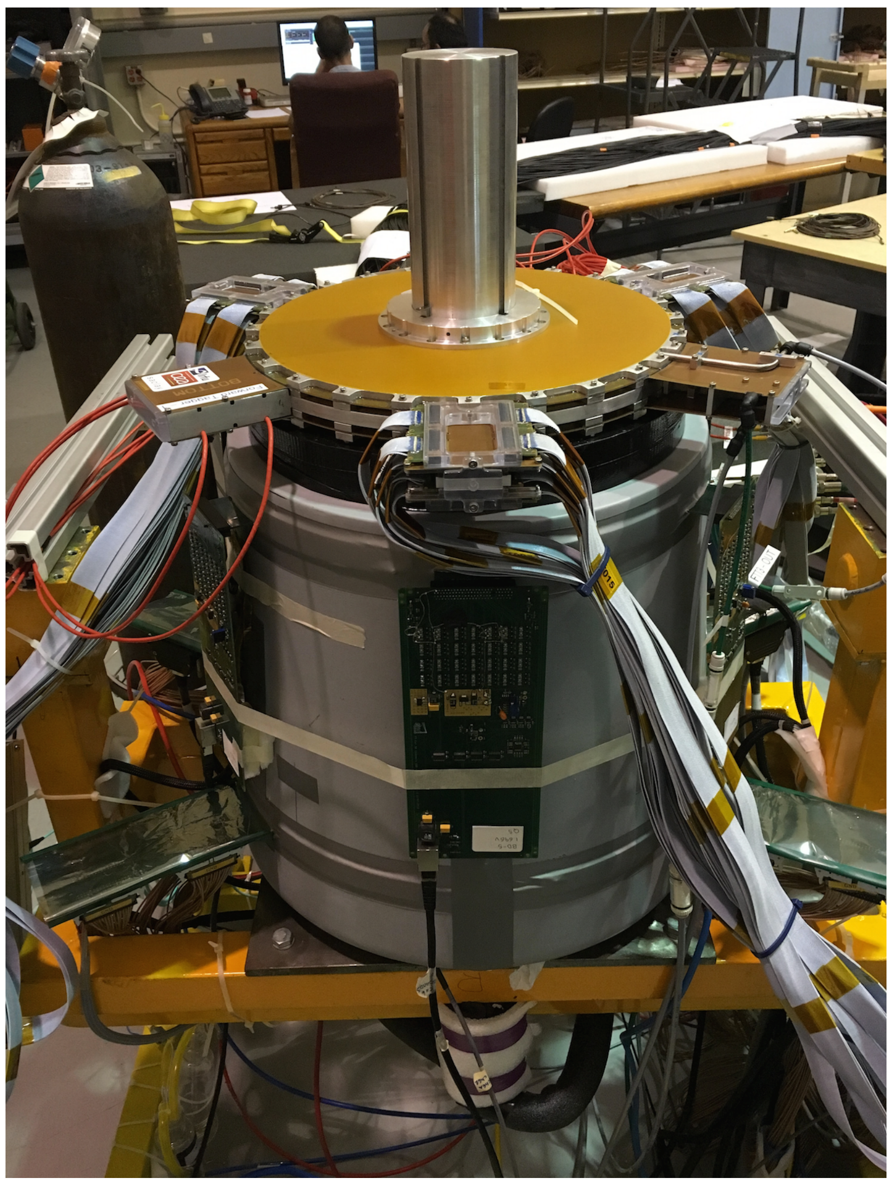

| | |
|---|---|
| $E_{scattered}$ | 0.5 - 4.5 GeV |
| $\theta$ | $2.5^o$ - $4.5^o$ |
| $\phi$ | $0^o$ - $360^o$ |
| $\nu$ | 6.5 - 10.5 GeV |
| $Q^2$ | 0.01 - 0.3 GeV$^2$ ($< Q^2 >$ 0.1 GeV$^2$) |
| W | 3.6 - 4.5 GeV |




- ★ Electron scattering at "0" degrees ($2.5^O$ - $4.5^O$)
  - ➤ 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)**

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



★ Electron scattering at "0" degrees (2.5° - 4.5°)
  ➤ low $Q^2$ virtual photon ⇔ real photon

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

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  ➤ High resolution and excellent PID (kaon identification)

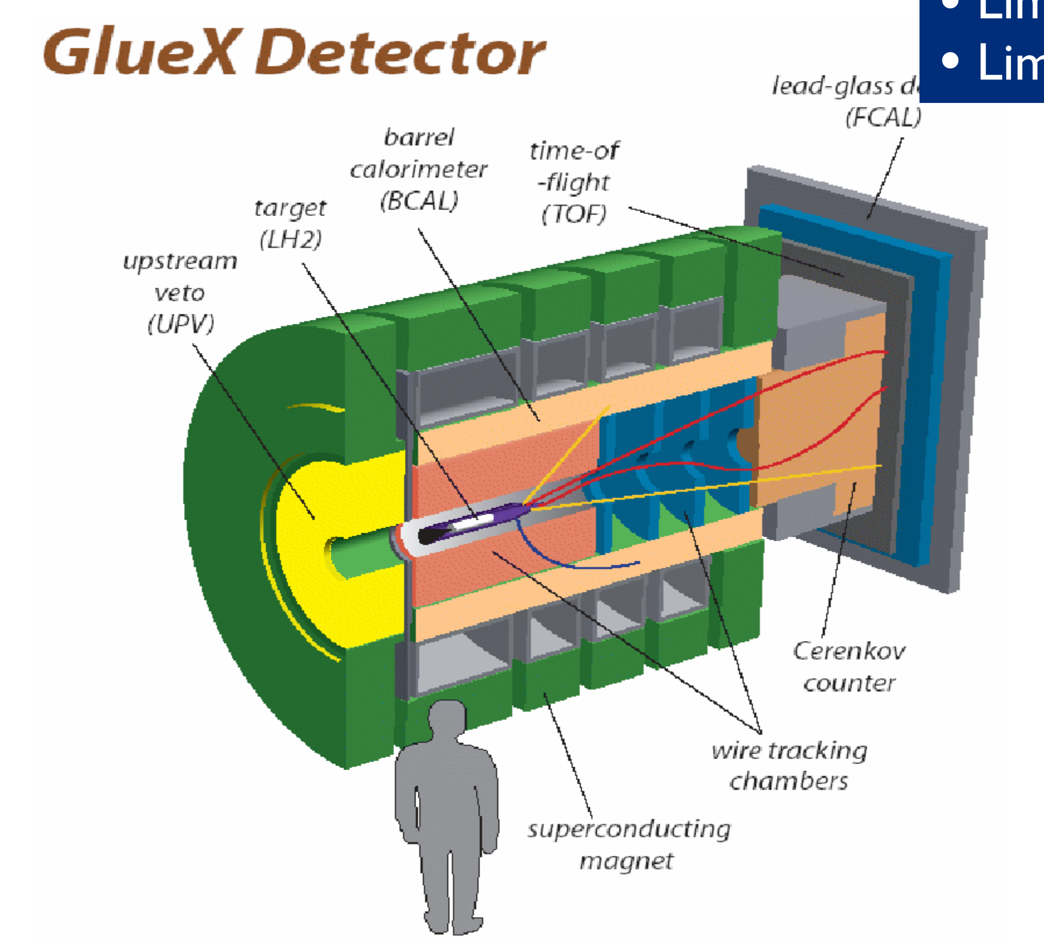
**CLAS12 ForwardTagger detector ready for installation!**

# Meson spectroscopy with photons at JLab-12 GeV

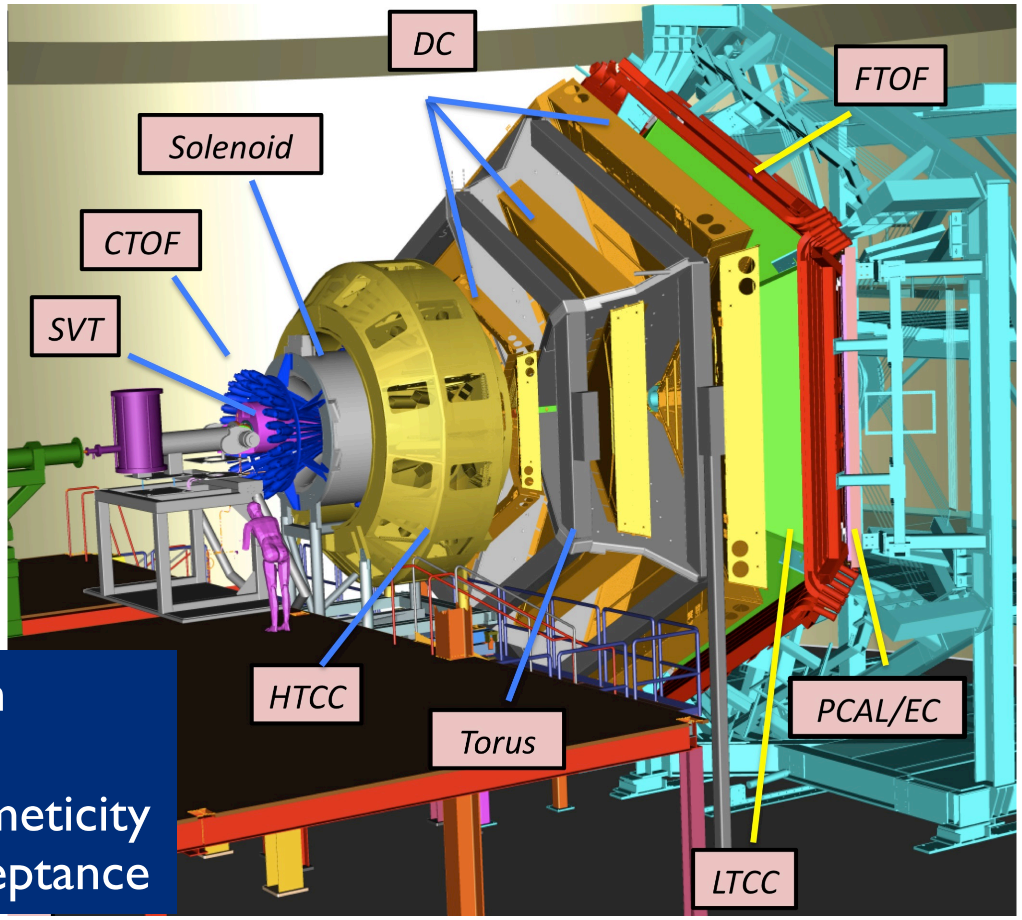
- Determination of JPC of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

## 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

# Hadron spectroscopy ingredients

✳ Experiment

✳ Theory

- LQCD: the final word (?)
- Effective Models: to interpret the physics meaning of LQCD
- Phenomenological models: to extract information from the data (Regge, Veneziano, duality)
- Theory helps experiments: decay widths, golden channel, …

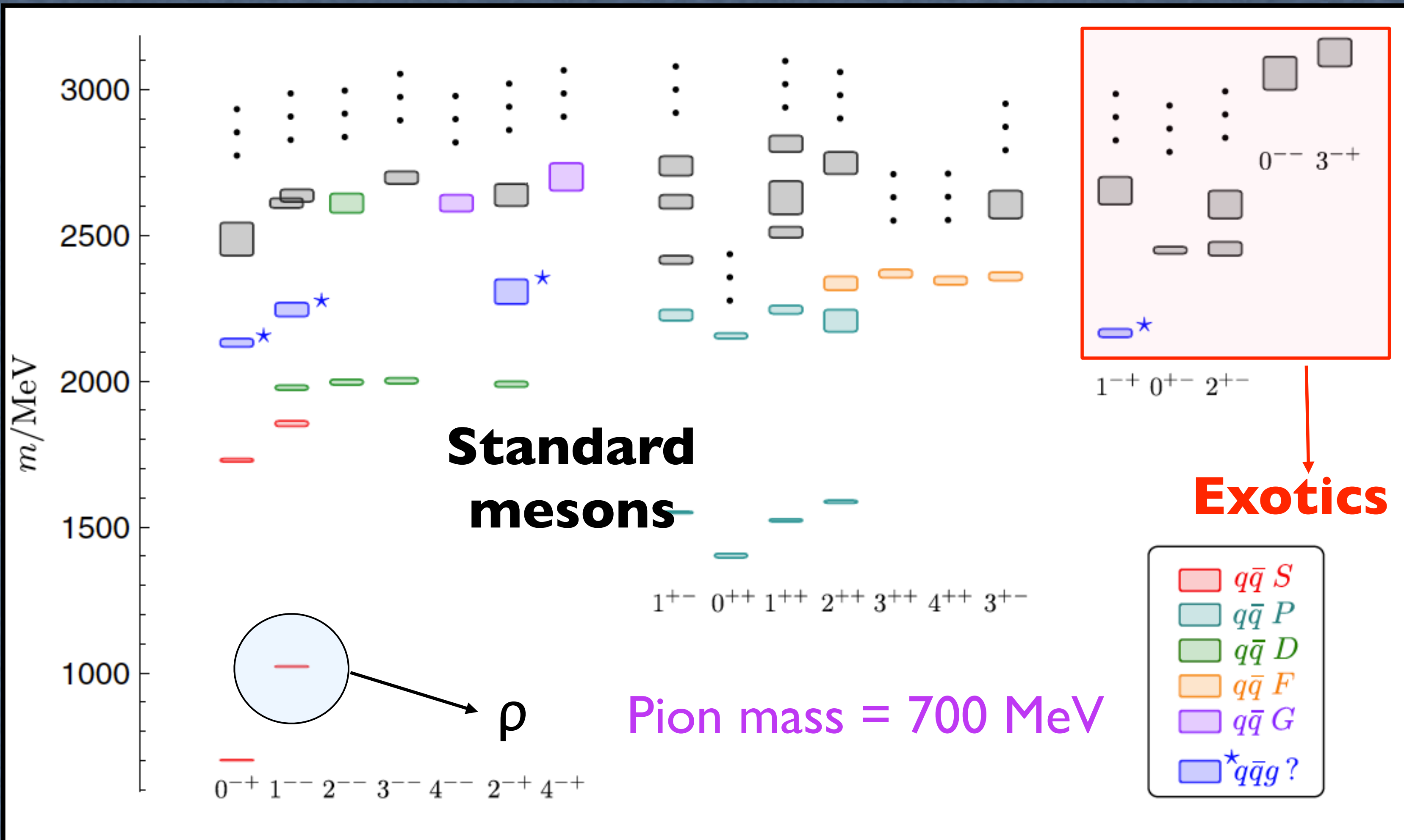
JPAC (and twin centers) progresses

A.Szczepaniak,
V.Mathieu, A.Pilloni

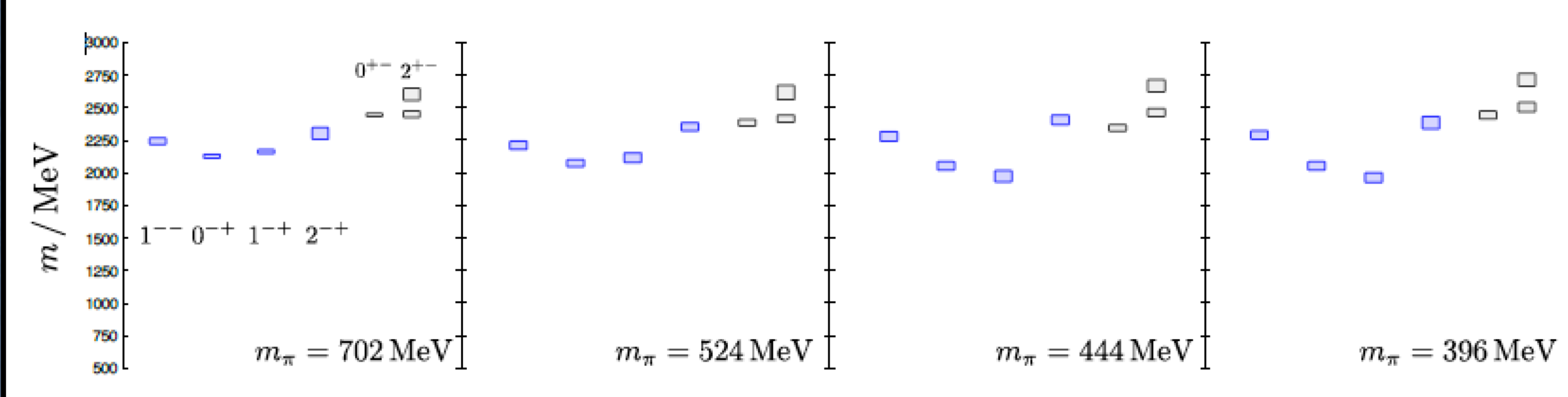
✳ Analysis strategy

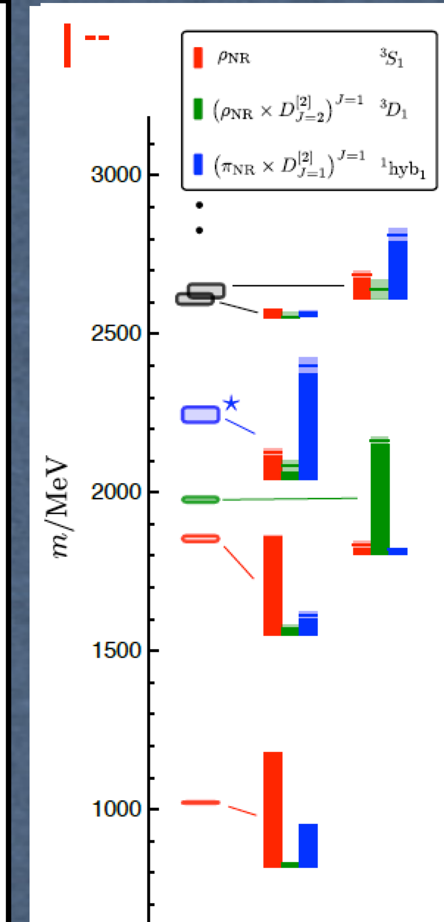
✳ Analysis tools

# Lattice QCD calculations



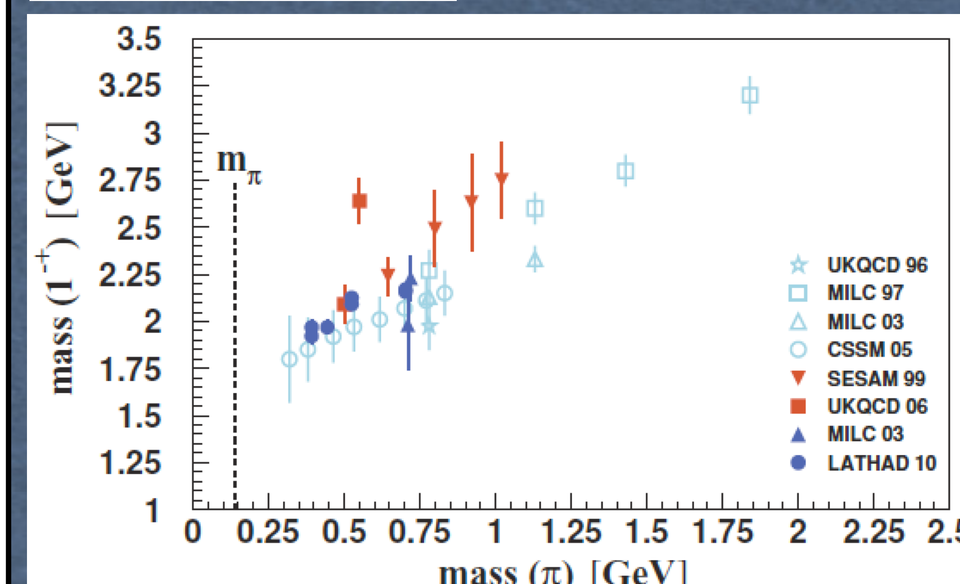

J.Dudek et al Phys.Rev.D82 (2010) 034508   J.Dudek et al., Phys. Rev. D84, 074023 (2011)




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

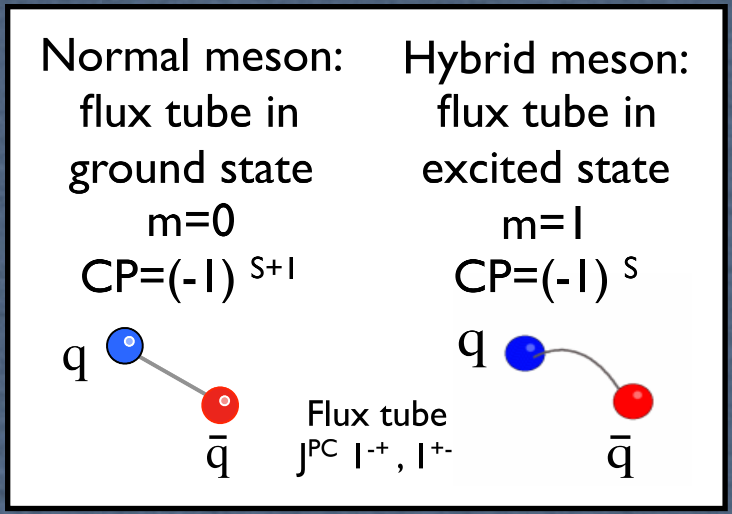
- Interpretation in term of CQM + Gluon field
- Dependence on Lattice size
- Dependence on pion mass



# Gluonic excitation models

## Flux tube model

- Gluonic field confined in a tube between q and anti-q
- Linear Regge trajectories
- Hybrid mesons as transverse oscillation of the tube
- Flux-tube breaking give rise to meson decay




Lightest multiplet
$(0,1,2)^{-+},(0,1,2)^{+-}, 1^{--}, 1^{++}$

## Bag model

- Quarks confined inside a cavity
- Full relativistic
- Gluonic excitation: gluonic field modes by boundary conditions

Lightest multiplet
$(0,1,2)^{-+},1^{--}$

## CQM + constituent gluon

- qq + massive transverse quasi-gluon ($J_g^{P_gC_g}$)
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave

qq in S-wave + $J_g^{P_gC_g}=1^{--}$ in S-wave

Lightest multiplet
$(0,1,2)^{++},1^{+-}$

qq in P-wave + $J_g^{P_gC_g}=1^{--}$ in S-wave

Lightest multiplet
$0^{--},(1^{--})^3,(2^{--})^2,3^{--},0^{-+},0^{-+},1^{-+}, 2^{-+}$

- Repulsive 3-body force selects $J_g^{P_gC_g}=1^{+-}$ in relative P-wave added to a qq pair is S-wave or P-wave

qq in S-wave + $J_g^{P_gC_g}=1^{+-}$ in P-wave

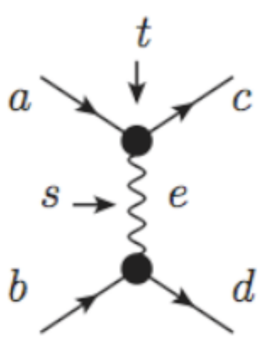
Lightest multiplet
$(0,1,2)^{-+},1^{--}$

qq in P-wave + $J_g^{P_gC_g}=1^{+-}$ in P-wave

Lightest multiplet
$0^{+-},(1^{+-})^3,(2^{+-})^2,3^{+-}, (0,1,2)^{++}$

# Regge phenomenology in a nut-shell

- Exploit the analytical structure of the amplitude

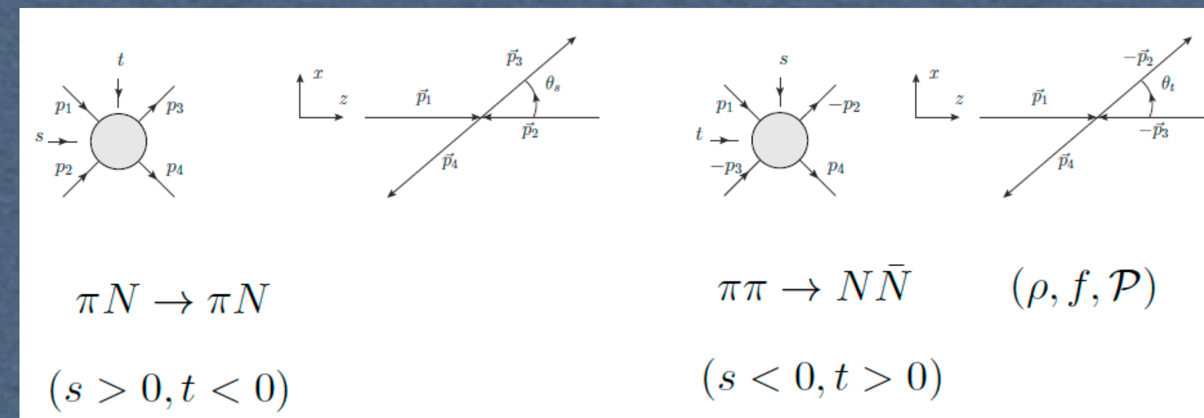



$$A(s,t) = 16\pi \sum_{\ell} (2\ell + 1) A_\ell(t) P_\ell(z_t)$$

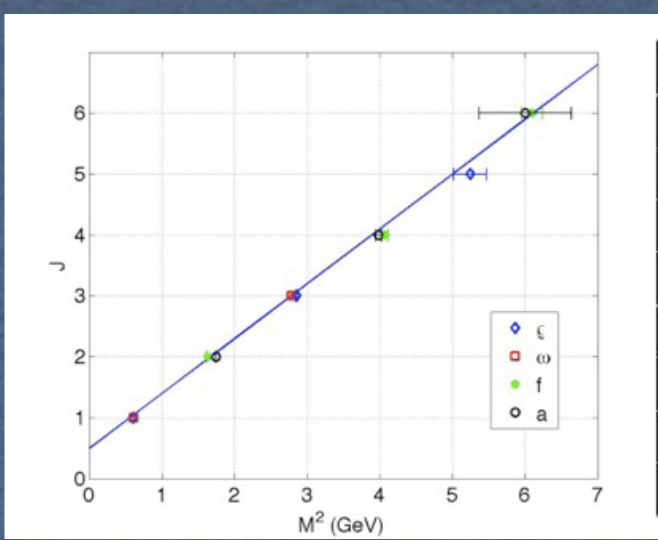
$$A(s,t) \propto \sum_{e} \beta_e(t) \frac{s^{\alpha_e(t)}}{\sin \pi \alpha_e(t)}$$

17

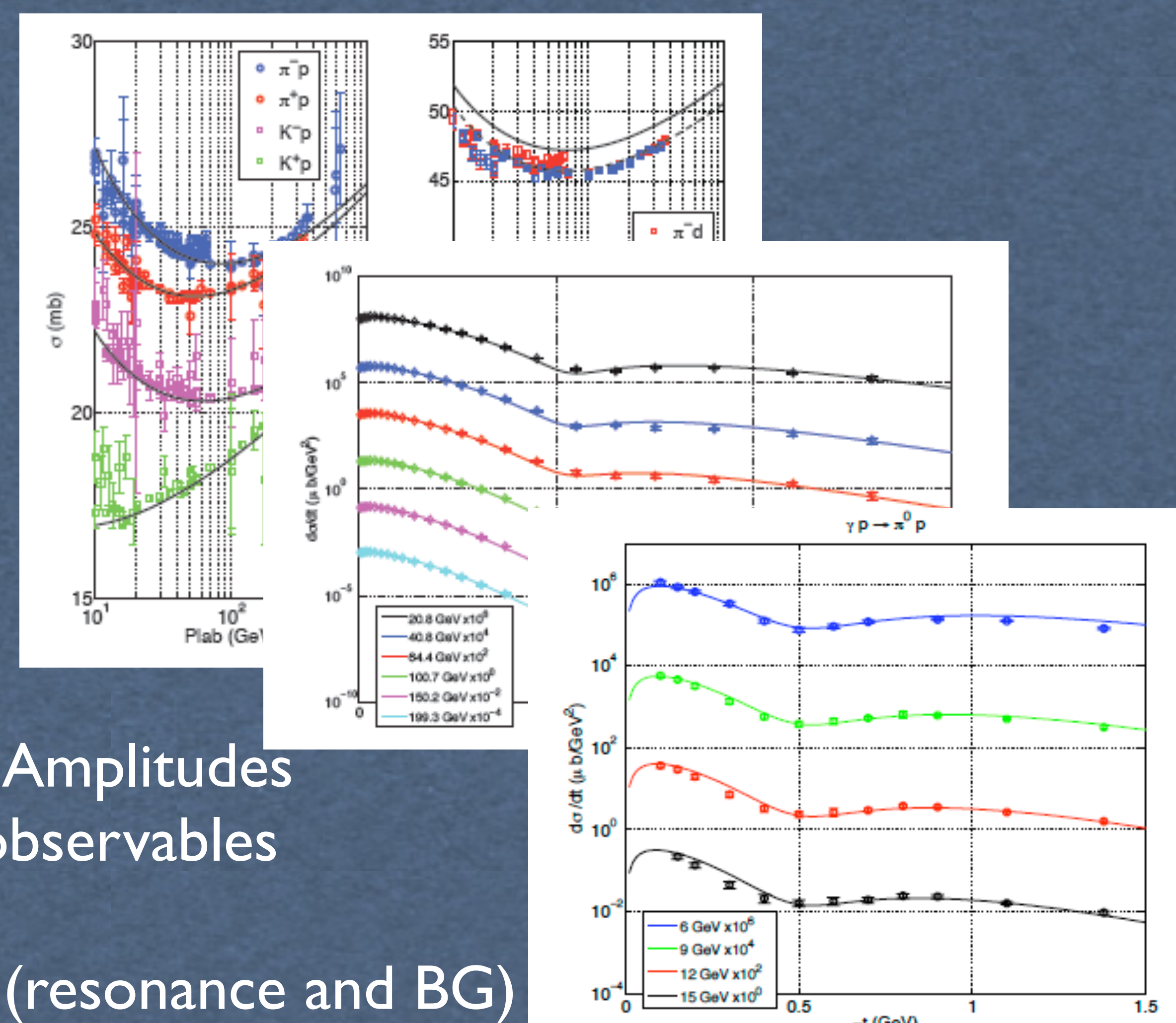
- Implement crossing symmetry




- Regge trajectories

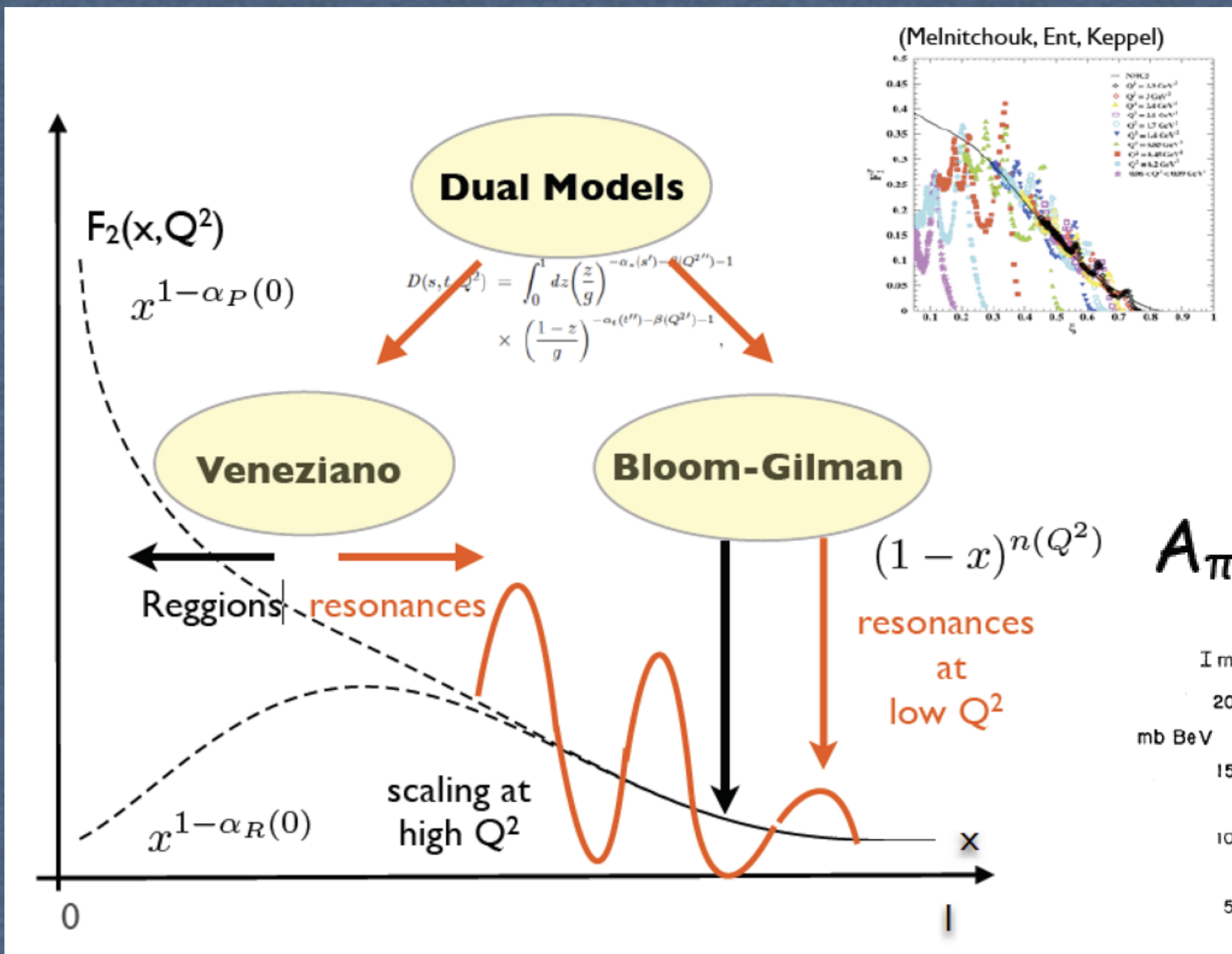


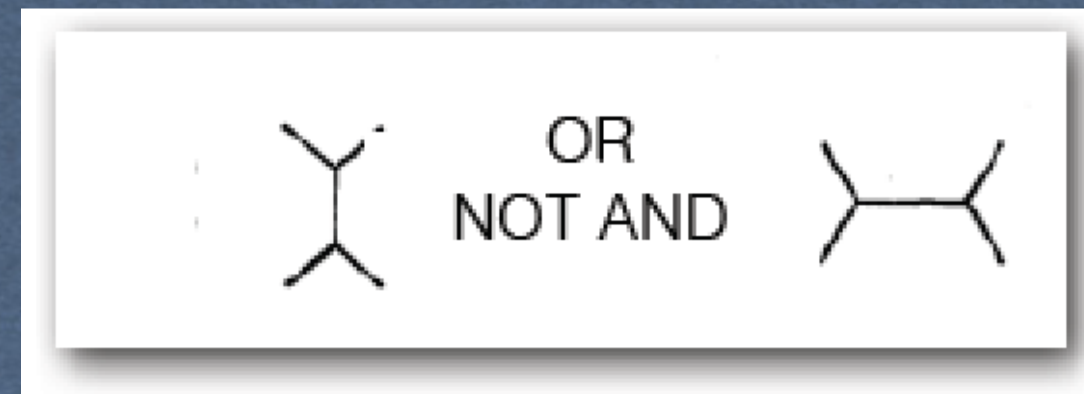

| $I^{G\tau\eta}$ | | | $I^{G\tau\eta}$ | |
|---|---|---|---|---|
| $0^{+++}$ | $f$ | $0.5 + 0.9t$ | $0^{+--}$ | $\bar{f}$ |
| $0^{--+}$ | $\omega$ | $0.5 + 0.9t$ | $0^{-+-}$ | $\bar{\omega}$ |
| $1^{-++}$ | $a$ | $0.4 + 0.9t$ | $1^{---}$ | $\bar{a}$ |
| $1^{+-+}$ | $\rho$ | $0.5 + 0.9t$ | $1^{++-}$ | $\bar{\rho}$ |
| $0^{++-}$ | $\eta$ | $0.7(t - m_\pi^2)$ | $0^{+-+}$ | $\bar{\eta}$ |
| $0^{---}$ | $h$ | $0.7(t - m_\pi^2)$ | $0^{-++}$ | $\bar{h}$ |
| $1^{-+-}$ | $\pi$ | $0.7(t - m_\pi^2)$ | $1^{--+}$ | $\bar{\pi}$ |
| $1^{+--}$ | $b$ | $0.7(t - m_\pi^2)$ | $1^{+++}$ | $\bar{b}$ |




- Efficient and theoretically correct way to parametrize Amplitudes
- Good agreement to total xsec, differential xsec, spin observables
- Many different reactions (probes) and channels
- Regge theory can be used to parametrize Amplitudes (resonance and BG)

# Duality at work




$$A_{\pi N \to \pi N}(s,t) = A(s,t) + \tfrac{1}{2} i\,\gamma(k+k')B(s,t)$$

$\langle A_{Backgrond} \rangle \sim \langle A_{Pomeron} \rangle$

$\langle A_{Resonance} \rangle \sim \langle A_{Regge} \rangle$

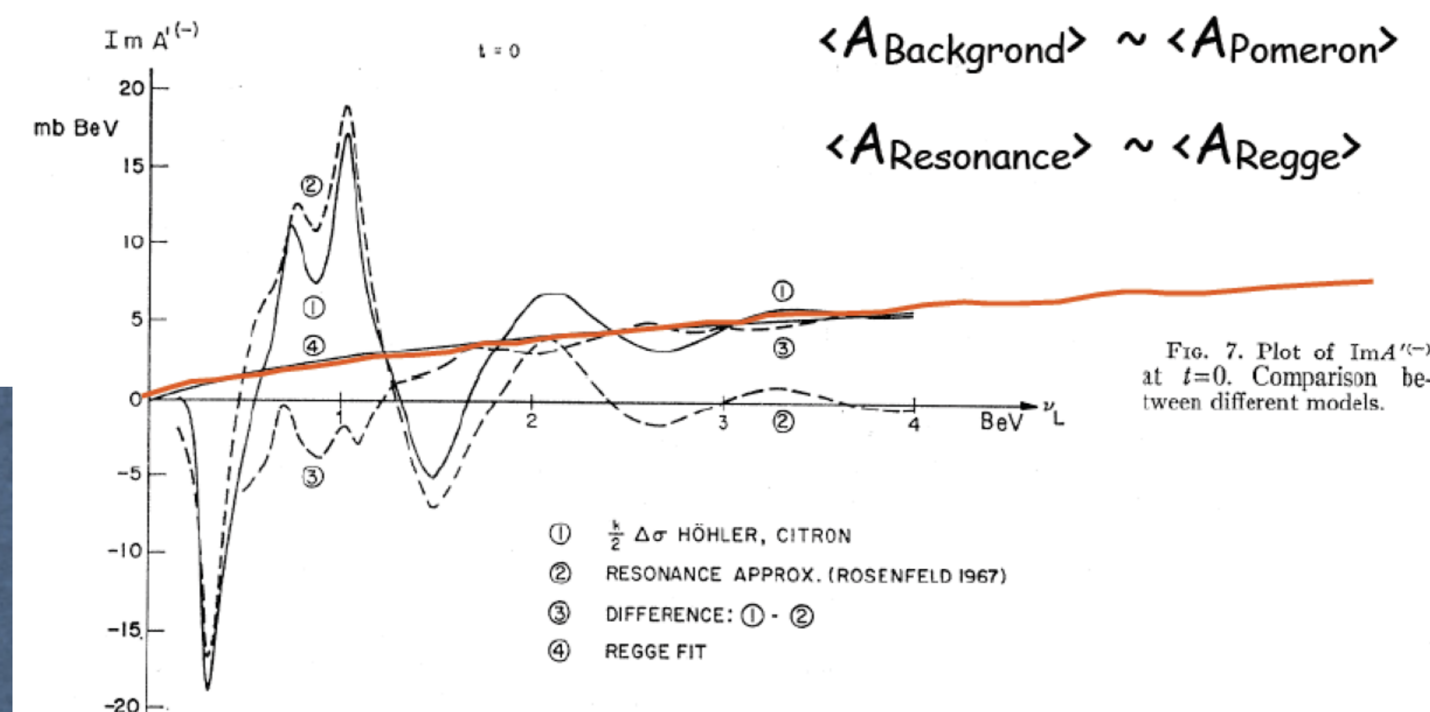



FIG. 7. Plot of $\mathrm{Im}A'^{(-)}$ at $t=0$. Comparison between different models.

$A \neq A_{Resonance} + A_{Regge}$

- ✳Resonance dual to leading reggeons
- ✳Background due to Pomeron

# Hadron spectroscopy ingredients

✳ Experiment

✳ Theory

✳ Analysis strategy

- PWA: Isobar Model, ad-hoc solutions for limited kinematic domain
- PWA: how far can go a model-independent PWA in the real world?
- Multiple channels approach (Q2 as a filter?)
- Spot vs systematic studies
- Could meson decay's studies simplify the analysis?
- Data: CLAS6 (g11, g12, eXX), CLAS12

JLab Working Groups activity:
HASPECT, LMD, CLAS/PANDA, JPAC, …

✳ Analysis tools

# JLab Working Groups activity

★ HASPECT (HAdron SPEctroscopy CenTer) WG

- Stable working group in Genova + satellites
- Weekly skype meetings and HASPECT weeks
- Analysis of CLAS data and projection on CLAS12

★ LMD (Light Mesons Decay) WG

- Stable working group at JLab
- Involvement of Julich Group
- Interest for a wide community (e+e- colliders)

★ CLAS/PANDA Joint Activity Board

- Mixed committee to explore overlaps and synergies
- light and heavy quark spectroscopy
- complementarity of production/annihilation

★ JPAC (Joint Physics Analysis Center)

- Develop the analysis framework
- Analysis of JLab and world-data
- Progress in amplitude analysis

★ PyPWA project

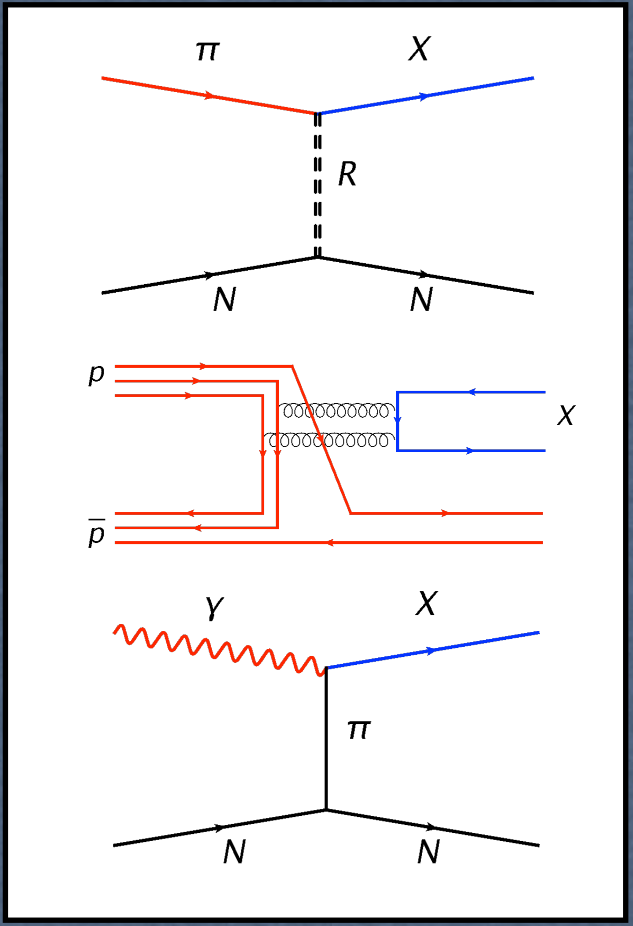
C.Salgado

Present:

- e+e-: BESIII and KLOE
- B decay: LHCb
- Belle, CLEO, BABAR

Future:

- Photoproduction at JLab:
- p p-bar at GSI: PANDA



# A first attempt ...

*MB, R.DeVita A. Szczpaniak et al Phys.Rev.Lett. 102:102001,2009*
*MB, R.DeVita A. Szczpaniak et al Phys.Rev. D80:072005,2009*

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

**Amplitude parametrization (Dispersion relation)**

**Related to $\pi\pi$ scattering matrix: phase-shift, inelasticity, S-P-D-F amplitude in 0.4 GeV < $M_{\pi\pi}$ < 1.4 GeV**

$$a_{lm,I}(s) = \frac{1}{2}[I + S_{lm,I}(s)]\boxed{\tilde{a}_{lm,I}(s)} - \frac{1}{\pi}D^{-1}_{lm,I}(s)PV\int_{s_{th}} ds' \frac{N_{lm,I}(s')\rho(s')\boxed{\tilde{a}_{lm,I}(s')}}{s'-s}$$

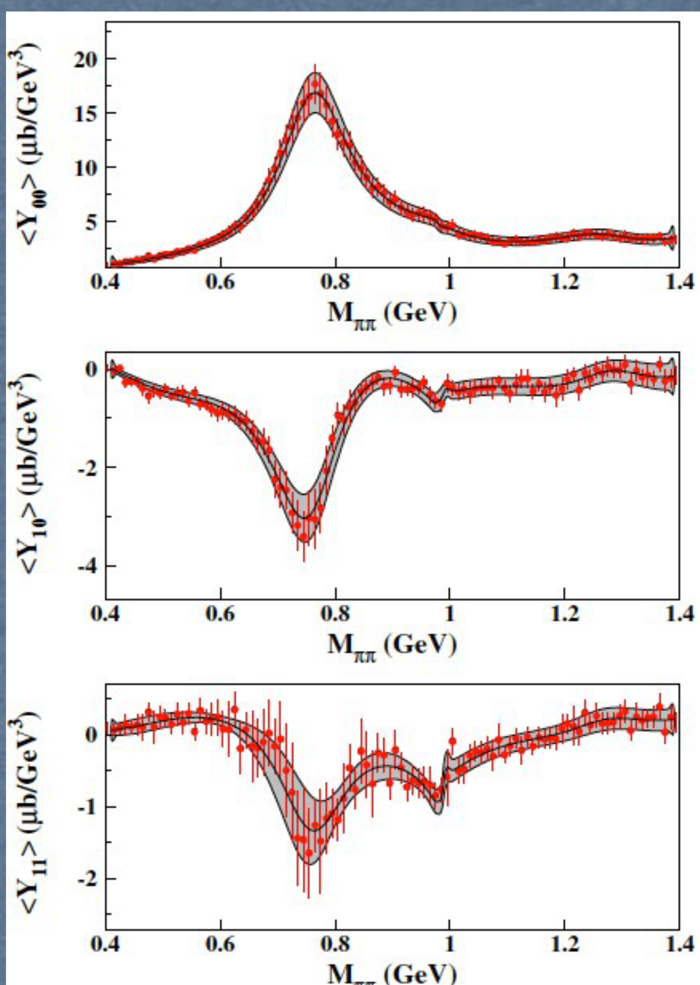
$$\tilde{a}_{lm,I} = [\mathcal{A} + \mathcal{B}s + \mathcal{C}s^2 + \cdots][k]$$

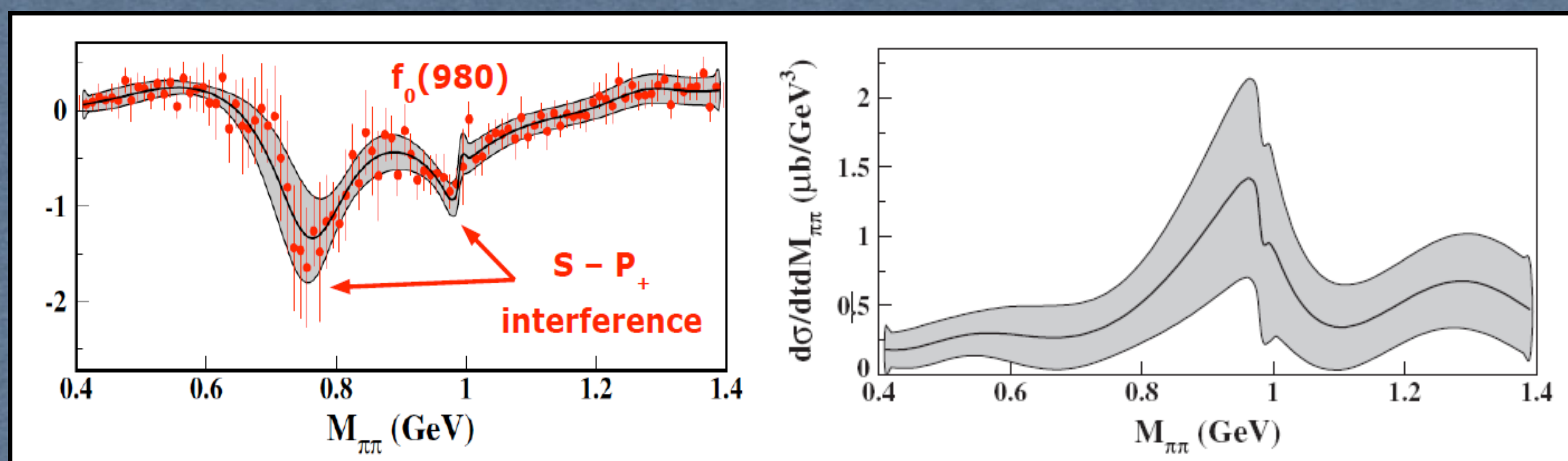
**Expanded in a Taylor series: coefficient fit to the experimental moment**

## $\gamma\, p \rightarrow p\, \pi\, \pi$

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

- P-wave: $\rho$ meson
- D-wave: $f_2(1270)$
- S-wave: $\sigma$, $f_0(980)$ and $f_0(1320)$




First observation of the $f_0(980)$ in a photoproduction experiment

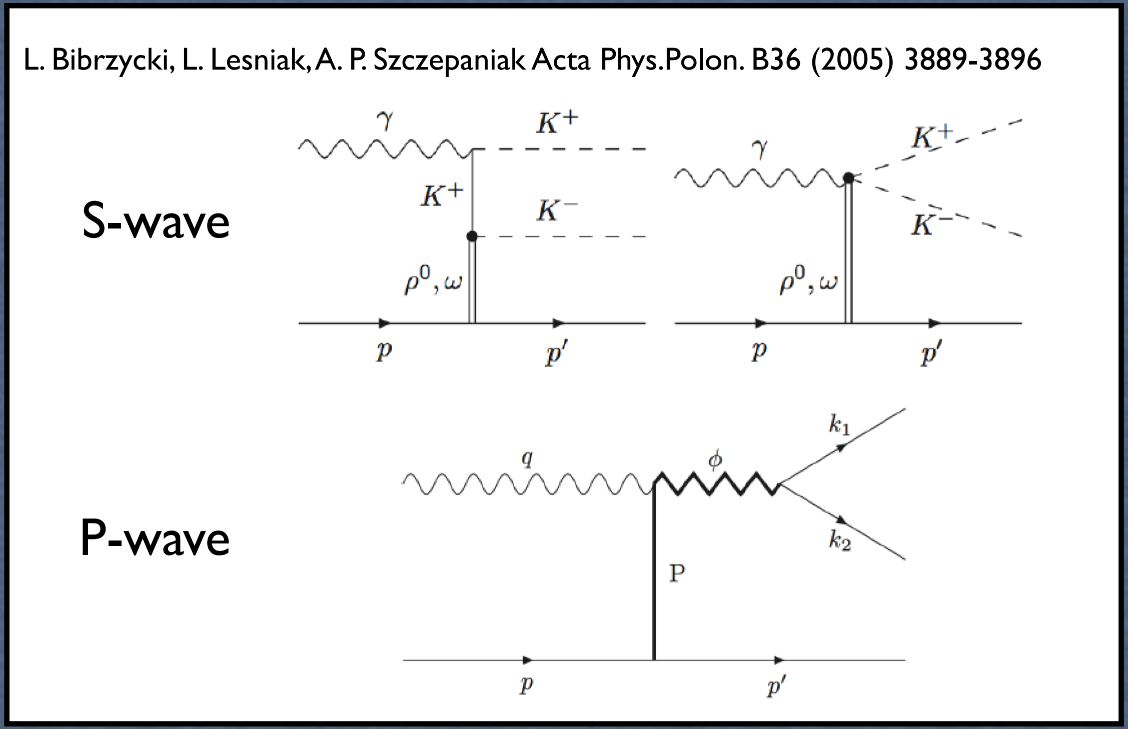
# the follow-up ...

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

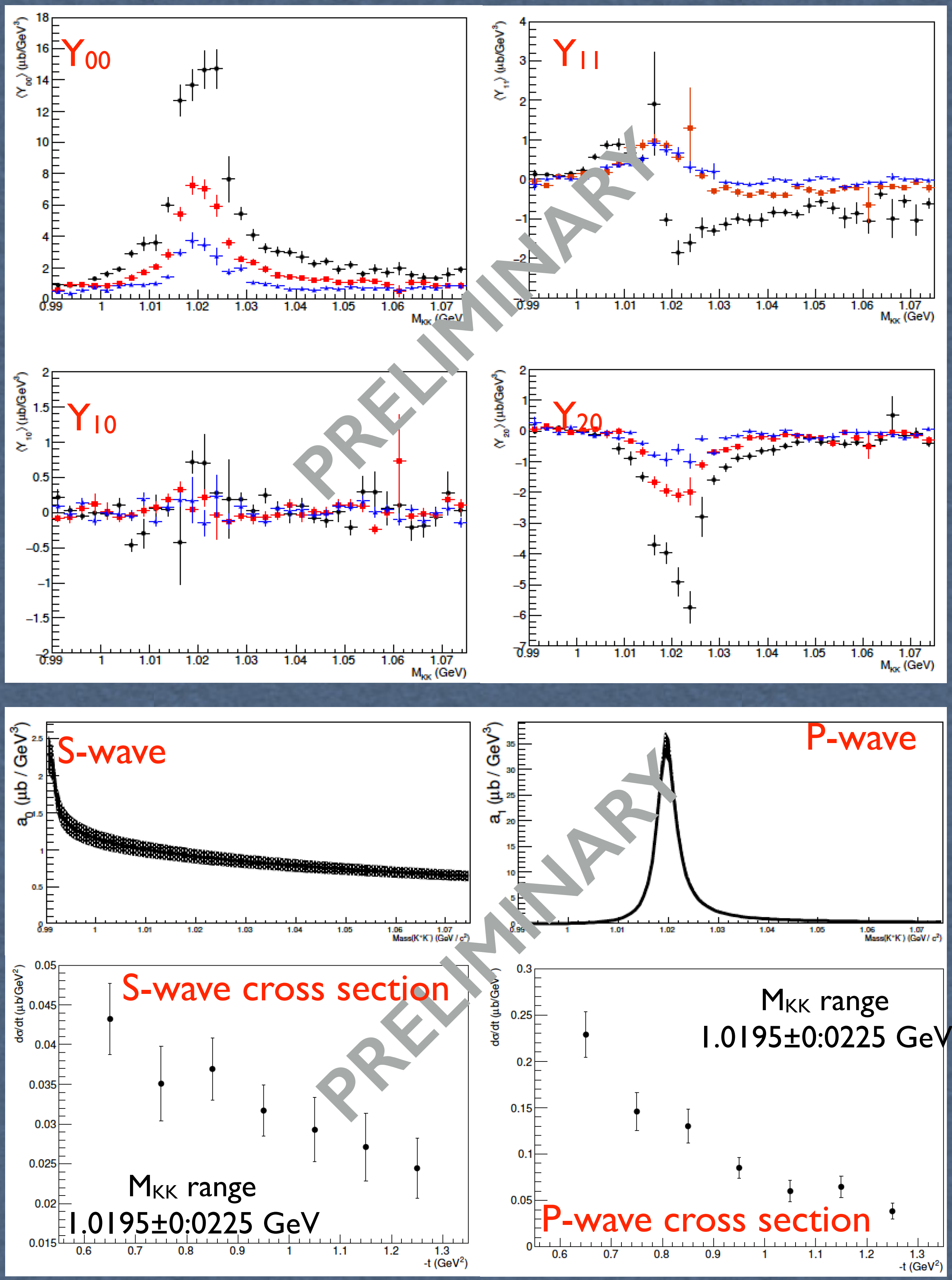
- S.Lombardo (IU/Cornell)
- Full analysis from g11 CLAS6 data set
- S-P interference in 2k system

**Method:**

- Extract moments from data
- Parametrise amplitudes with a model: P-wave: pomeron, s-wave: rho, omg t-exch
- Fit moments to obtain PW cross sections




2k amplitudes provided by JPAC



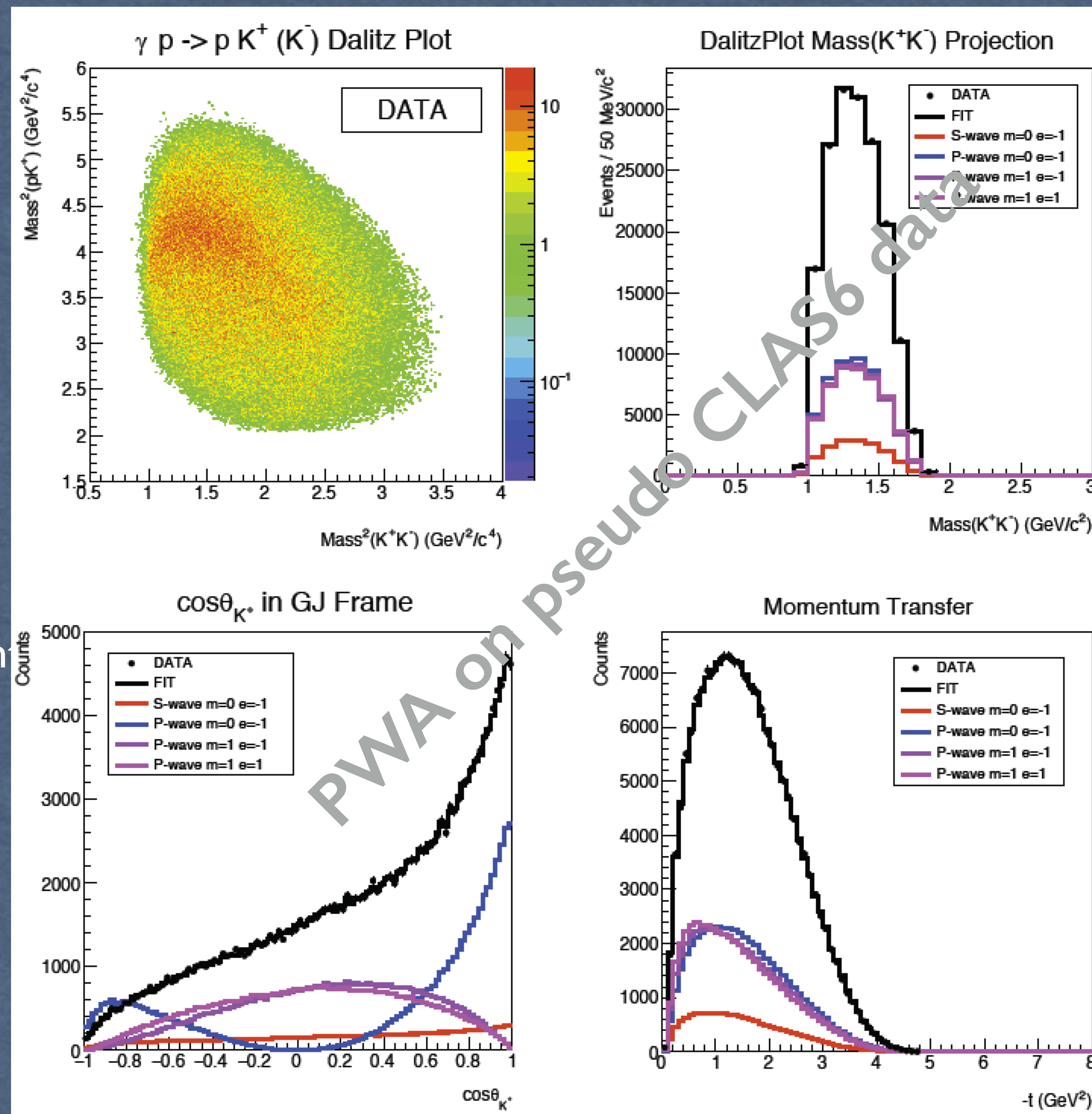
# towards a full PWA

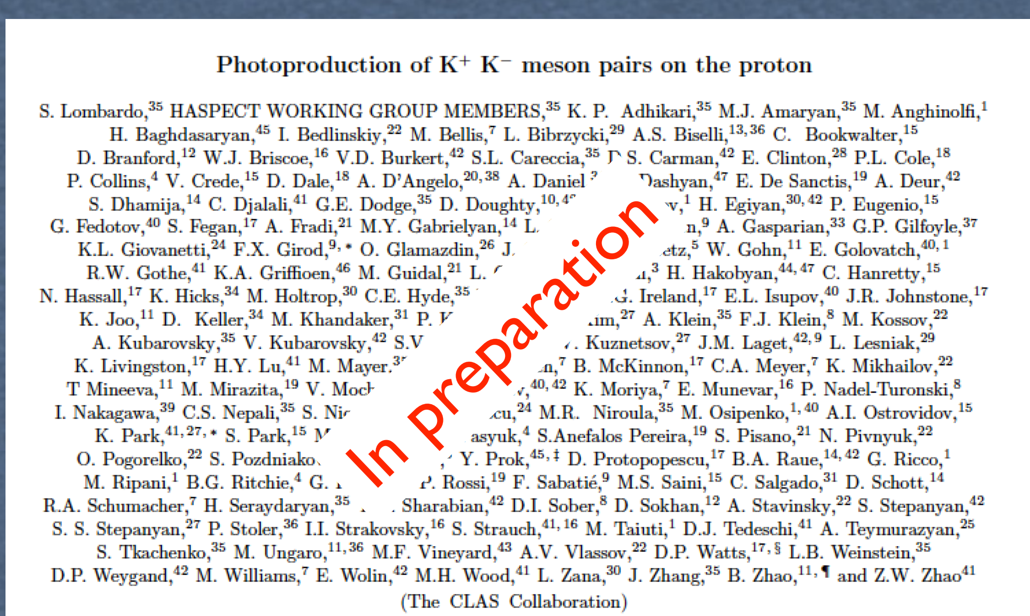
**γ p → p k k**

- I.Stankovic (U Edinburgh)
- Full PWA using the same CLAS6 - g11 data set

**Procedure:**

- Extract moments from data in a model independent way and compare to the previous CLAS6 analysis
- Test the fit procedure on pseudo data
- Run the full PWA to extract the dominant and sub-leading waves



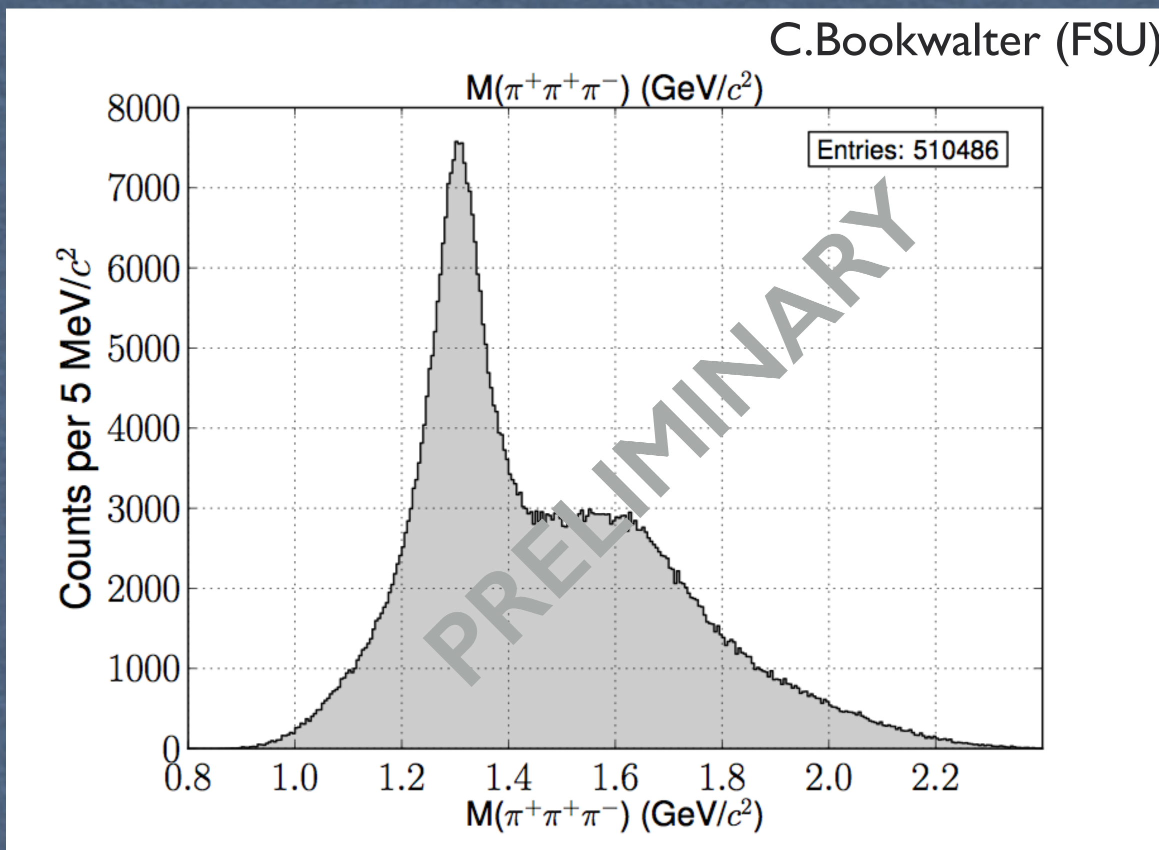
Photoproduction of $K^+ K^-$ meson pairs on the proton

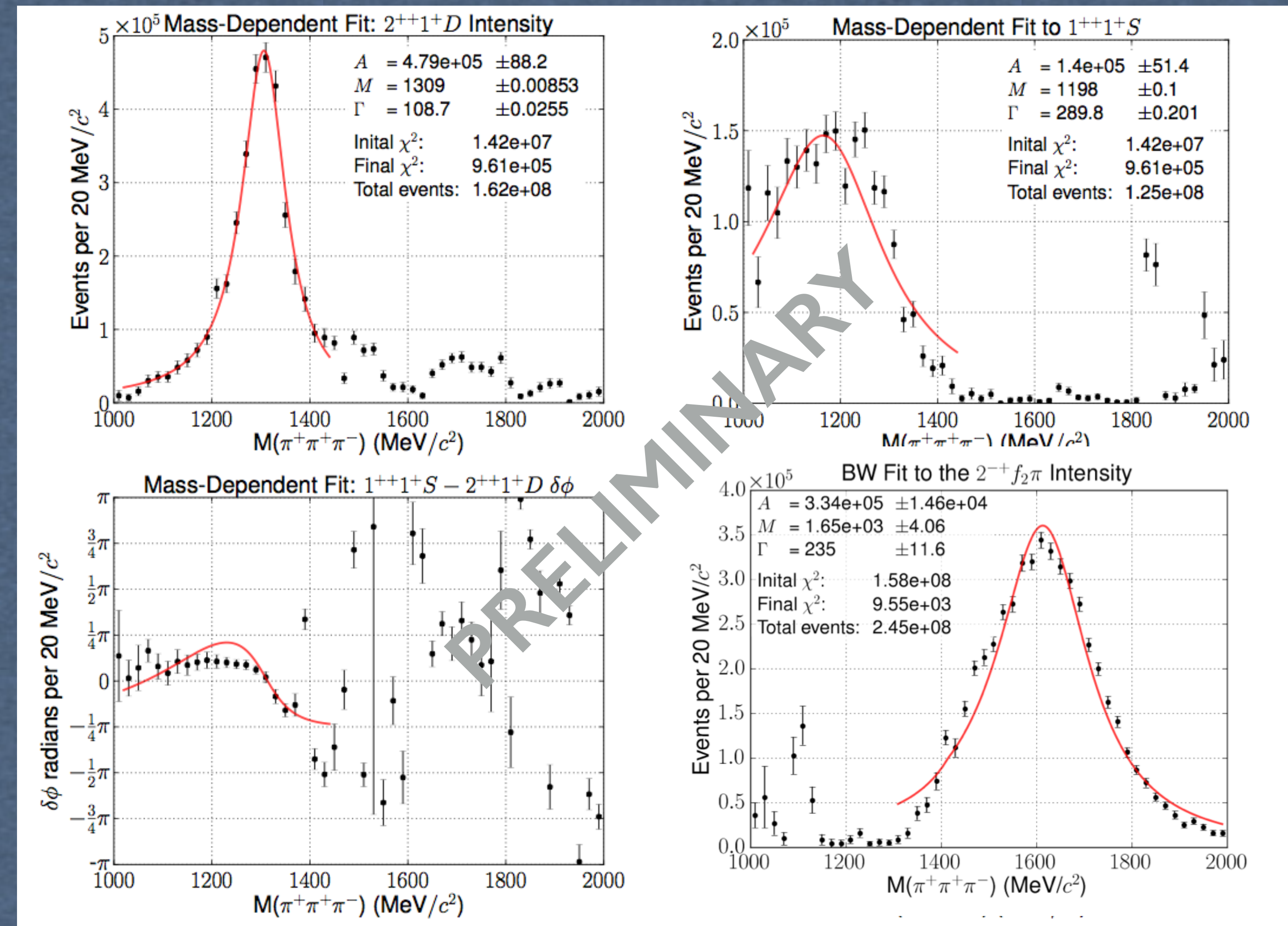
S. Lombardo,[35] HASPECT WORKING GROUP MEMBERS,[35] K. P. Adhikari,[35] M.J. Amaryan,[35] M. Anghinolfi,[1] H. Baghdasaryan,[45] I. Bedlinskiy,[22] M. Bellis,[7] L. Bibrzycki,[29] A.S. Biselli,[13,36] C. Bookwalter,[15] D. Branford,[12] W.J. Briscoe,[16] V.D. Burkert,[42] S.L. Careccia,[35] [illegible] S. Carman,[42] E. Clinton,[28] P.L. Cole,[18] P. Collins,[4] V. Crede,[15] D. Dale,[18] A. D'Angelo,[20,38] A. Daniel [illegible] Dashyan,[47] E. De Sanctis,[19] A. Deur,[42] S. Dhamija,[14] C. Djalali,[41] G.E. Dodge,[35] D. Doughty,[10,4] [illegible] H. Egiyan,[30,42] P. Eugenio,[15] G. Fedotov,[40] S. Fegan,[17] A. Fradi,[21] M.Y. Gabrielyan,[14] L. [illegible] A. Gasparian,[33] G.P. Gilfoyle,[37] K.L. Giovanetti,[24] F.X. Girod,[9,*] O. Glamazdin,[26] J. [illegible] W. Gohn,[11] E. Golovatch,[40,1] R.W. Gothe,[41] K.A. Griffioen,[46] M. Guidal,[21] L. [illegible] H. Hakobyan,[44,47] C. Hanretty,[15] N. Hassall,[17] K. Hicks,[34] M. Holtrop,[30] C.E. Hyde,[35] [illegible] Ireland,[17] E.L. Isupov,[40] J.R. Johnstone,[17] K. Joo,[11] D. Keller,[34] M. Khandaker,[31] P. [illegible] A. Klein,[35] F.J. Klein,[8] M. Kossov,[22] A. Kubarovsky,[35] V. Kubarovsky,[42] S.V [illegible] Kuznetsov,[27] J.M. Laget,[42,9] L. Lesniak,[29] K. Livingston,[17] H.Y. Lu,[41] M. Mayer,[3] [illegible] B. McKinnon,[17] C.A. Meyer,[7] K. Mikhailov,[22] T Mineeva,[11] M. Mirazita,[19] V. Moc [illegible] K. Moriya,[7] E. Munevar,[16] P. Nadel-Turonski,[8] I. Nakagawa,[39] C.S. Nepali,[35] S. Ni [illegible] M.R. Niroula,[35] M. Osipenko,[1,40] A.I. Ostrovidov,[15] K. Park,[41,27,*] S. Park,[15] M [illegible] S.Anefalos Pereira,[19] S. Pisano,[21] N. Pivnyuk,[22] O. Pogorelko,[22] S. Pozdniako [illegible] Y. Prok,[45,‡] D. Protopopescu,[17] B.A. Raue,[14,42] G. Ricco,[1] M. Ripani,[1] B.G. Ritchie,[4] G. [illegible] Rossi,[19] F. Sabatié,[9] M.S. Saini,[15] C. Salgado,[31] D. Schott,[14] R.A. Schumacher,[7] H. Seraydaryan,[35] [illegible] Sharabian,[42] D.I. Sober,[8] D. Sokhan,[12] A. Stavinsky,[22] S. Stepanyan,[42] S. S. Stepanyan,[27] P. Stoler,[36] I.I. Strakovsky,[16] S. Strauch,[41,16] M. Taiuti,[1] D.J. Tedeschi,[41] A. Teymurazyan,[25] S. Tkachenko,[35] M. Ungaro,[11,36] M.F. Vineyard,[43] A.V. Vlassov,[22] D.P. Watts,[17,§] L.B. Weinstein,[35] D.P. Weygand,[42] M. Williams,[7] E. Wolin,[42] M.H. Wood,[41] L. Zana,[30] J. Zhang,[35] B. Zhao,[11,¶] and Z.W. Zhao[41]

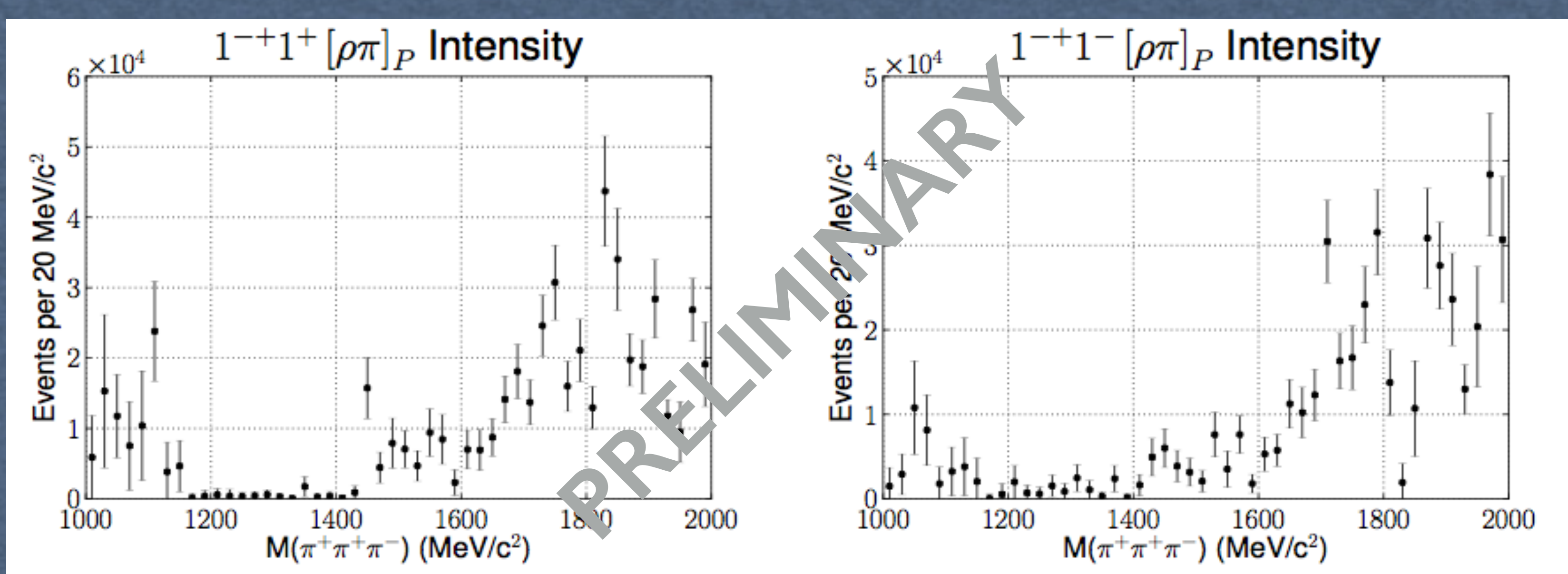
(The CLAS Collaboration)

In preparation

# The 3π system from CLAS-g12 data set




Evidence of dominant resonances
No evidence of exotic state
(confirmed by a new analysis of A.Tsaris (FSU))

**PWA in CLAS is feasible!**

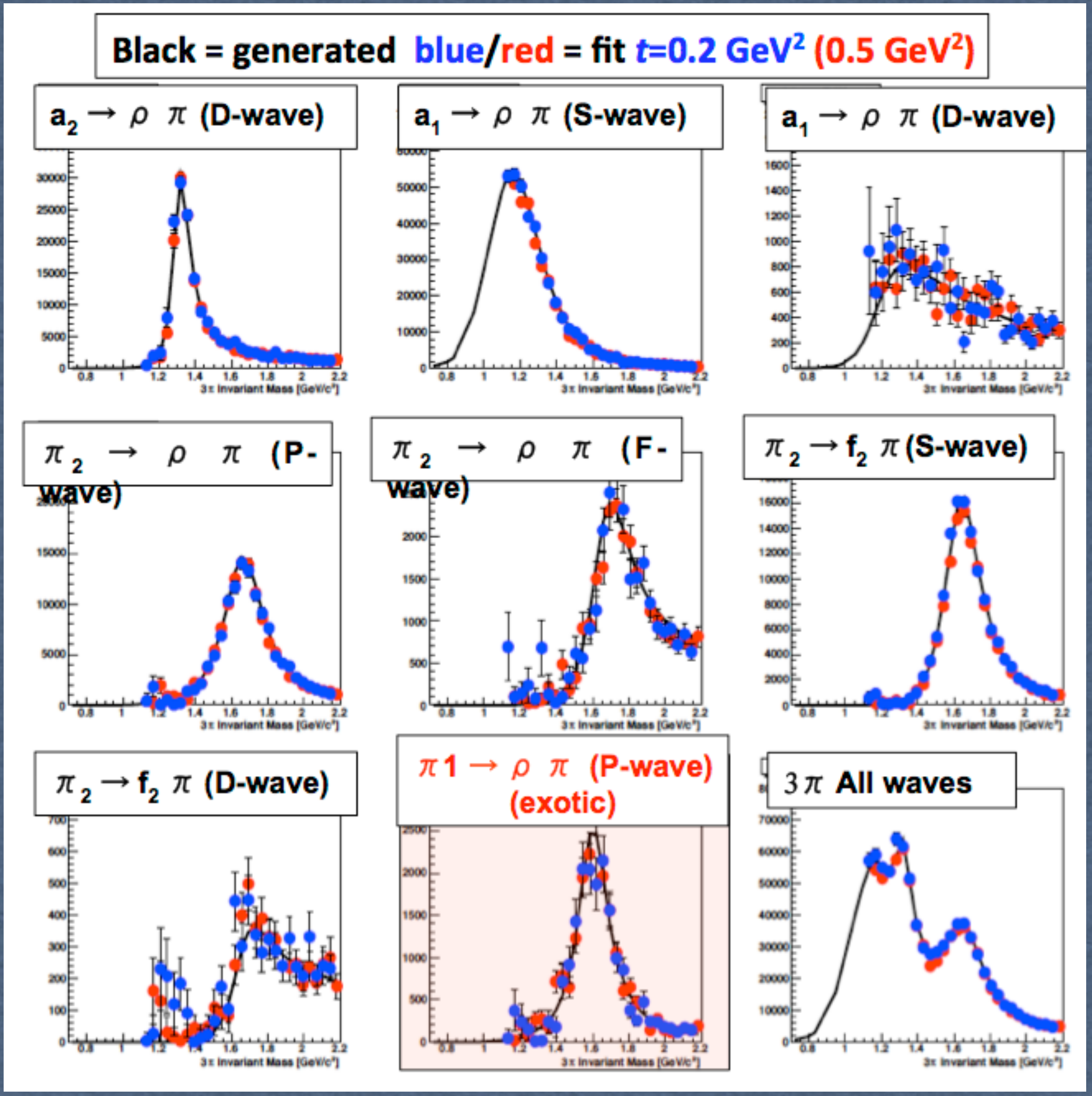
**Needs to have higher energy and statistics and test other final states**
**→ CLAS12**

# PWA with CLAS12 (fastMC)

D.Glazier (U of Glasgow)

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

- 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)
  - $\pi 1 \rightarrow \rho\, \pi$ (P-wave) (exotic)
- Amplitudes calculated by A.Szczepaniak and P.Guo
- CLAS12 acceptance projected and fitted
- PWA is stable against CLAS12 acceptance/ resolution distortion

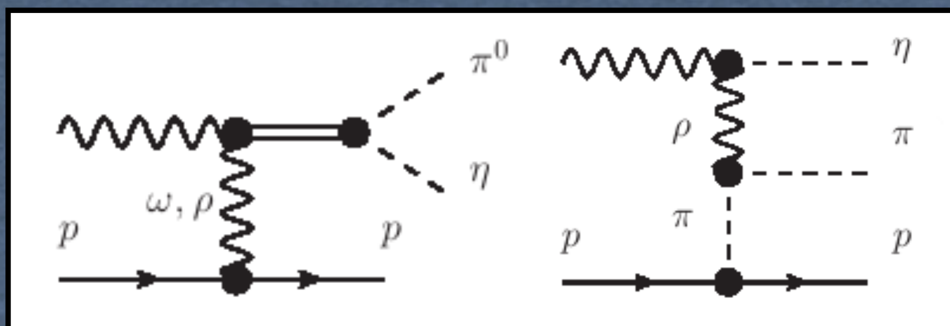



**PWA in CLAS12 is feasible!**

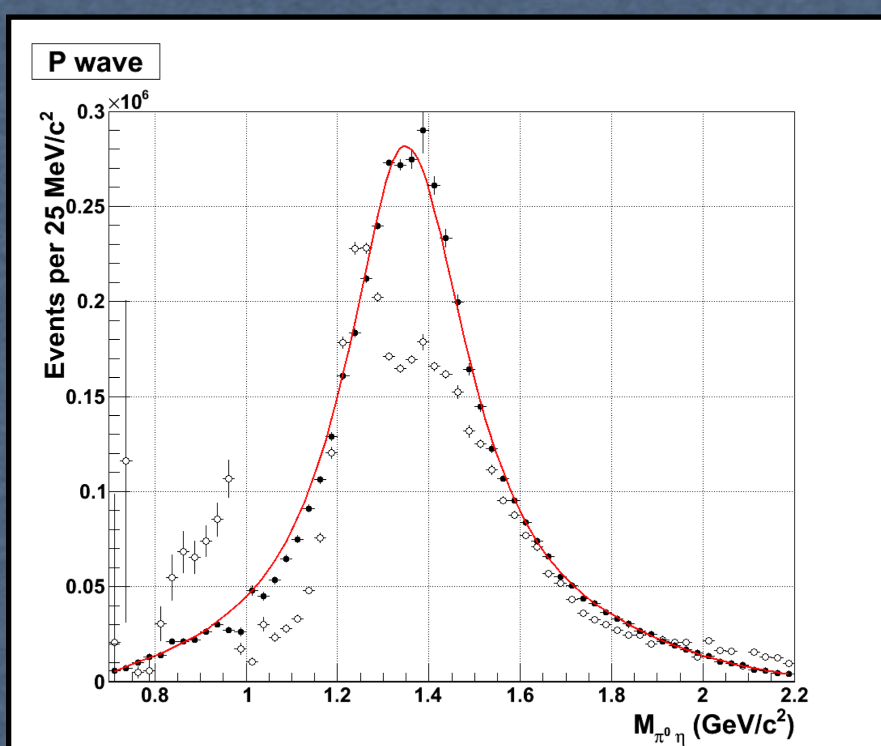
# The ηπ in CLAS-g12

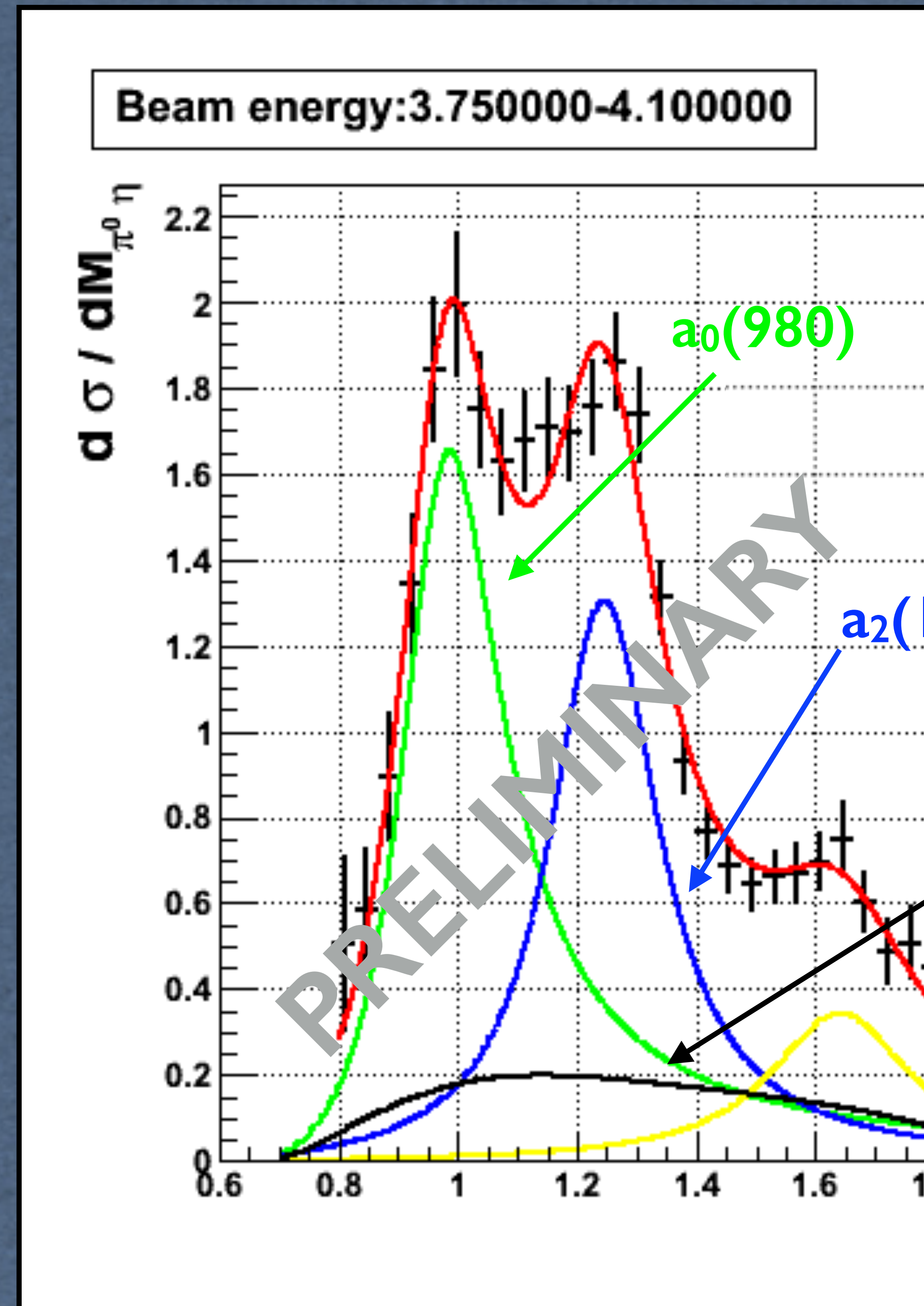
$\gamma p \to p \eta \pi$

- A.Celentano (INFN-GE) PhD Thesis




- Amplitudes provided by V.Mathieu (ECT*) and A.Szczepaniak (IU&JLab)
- Preliminary analysis on CLAS6 data to fix parameters




| Resonance | $J^{PC}$ |
|---|---|
| $a_0\,(980)$ | $0^{++}$ |
| $a_2\,(1320)$ | $2^{++}$ |
| $a_2\,(1700)$ | $2^{++}$ |
| $\pi_1\,(1400)$ | $1^{-+}$ |

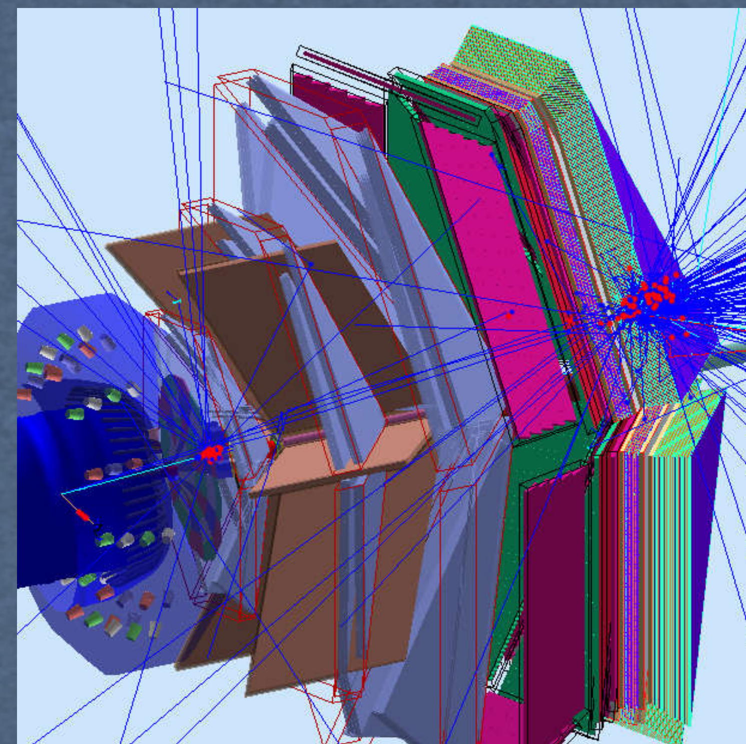
- Full projection on CLAS12 and PWA
- Sensitivity for P-wave > 5% $a_2(1320)$

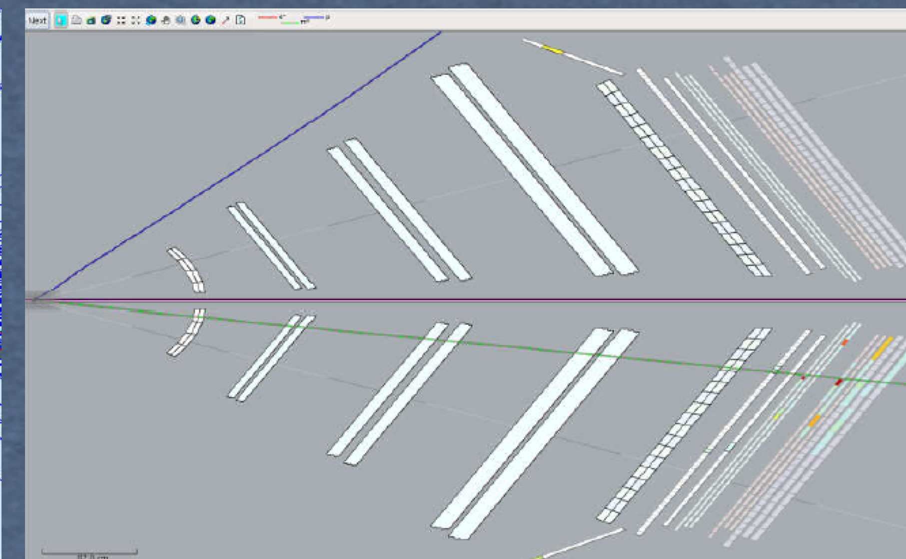
**Needs higher energy, higher statistics → CLAS12**

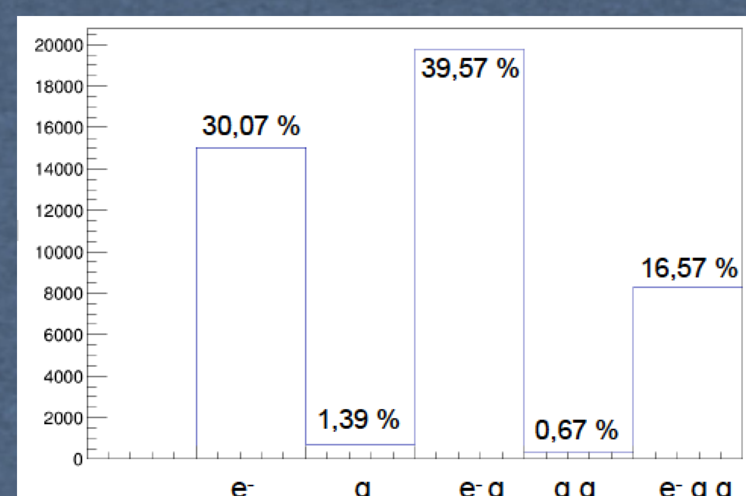
# PWA with (realistic simulation of) CLAS12

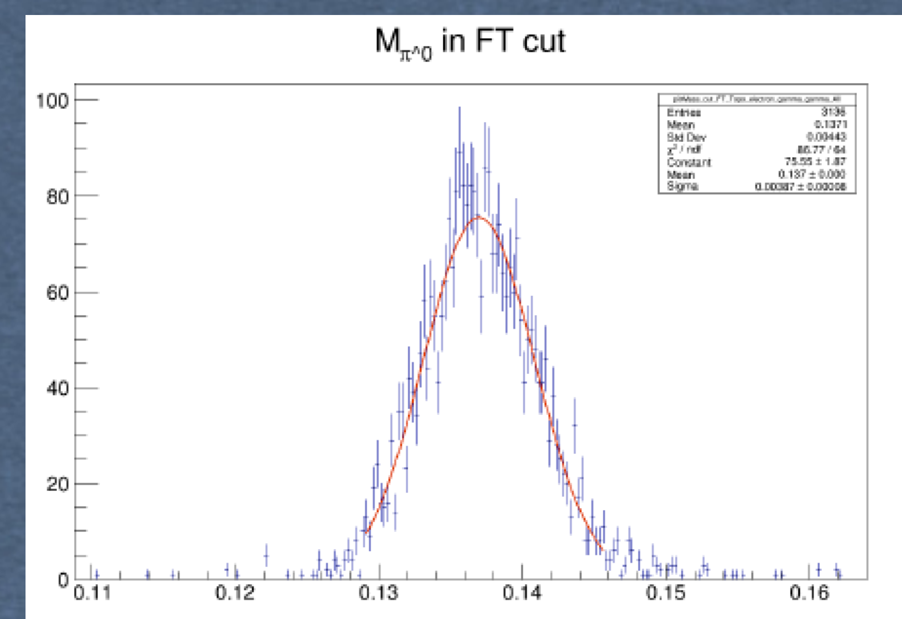
**$e\,p \to e'\,p\,\pi0$ ($\gamma\,p \to p\,\pi0$)**

- S.Dihel (U Giessen)
- Full CLAS12 GEANT4 simulation
- Full reconstruction
- Electroproduction amplitudes provided by JPAC (V.Mathieu)
- AMPTOOLS
- Electron detected at small angles in the CLAS12-FT

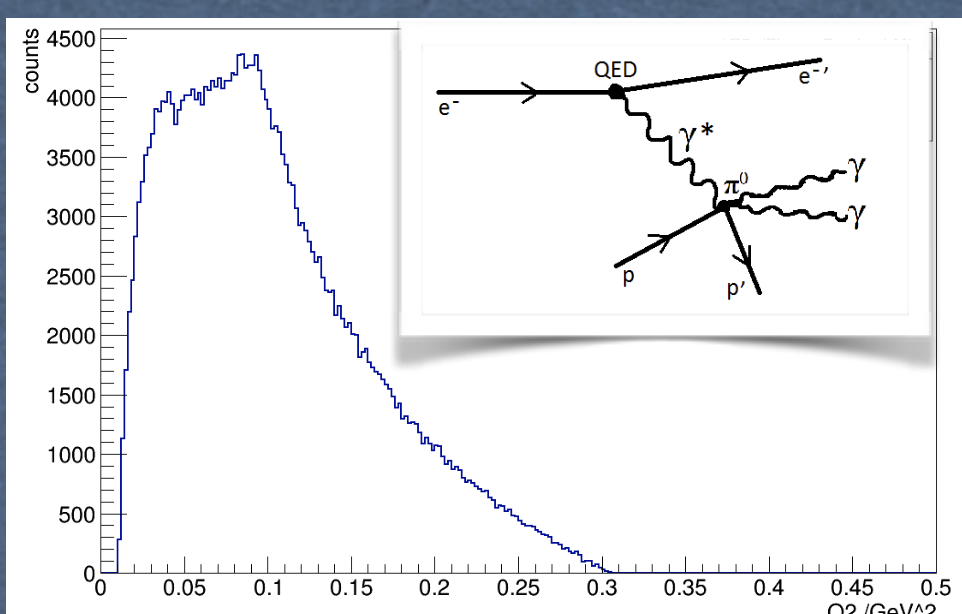







137 MeV/c² reconstrcuted (lit.: 134,98 MeV/c²)




**High level physics analysis is starting soon!**

- $\gamma_v$ Linear polarisation: $\sigma'_{TT}$ ($\Sigma$)
- Xsection
- Large-t behaviour - $d\sigma/dt(90^O)$
- e- polarisation: $\sigma_{TL}$ (no available in photoproduction!)
- Full PWA

# A new (old?) approach: Veneziano amplitudes

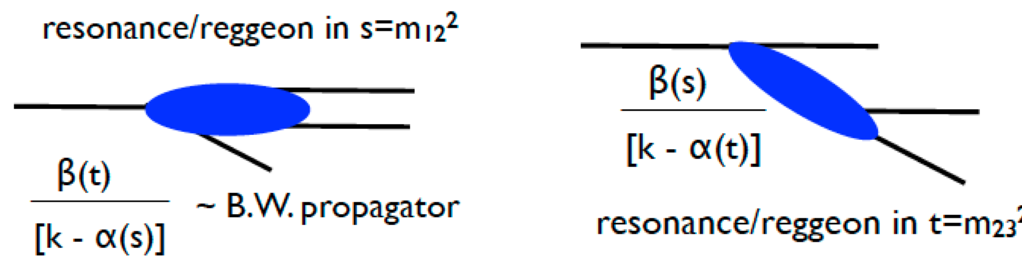
$B_4$ amplitude

A.Szczepaniak & M.Pennington extension of Veneziano amplitude (arXiv:1403.5782)

$$A(s,t) = \frac{\Gamma(-\alpha(s))\Gamma(-\alpha(t))}{\Gamma(-\alpha(s)-\alpha(t))} \qquad \alpha(s) = a + bs$$

Resonances couplings, β, should depend on final state particles: a linear superposition of Veneziano amplitudes can be used to suppress or enhance individual resonances or trajectories

- Correct analytic structure (poles)
- Proper asymptotic behaviour (Regge)

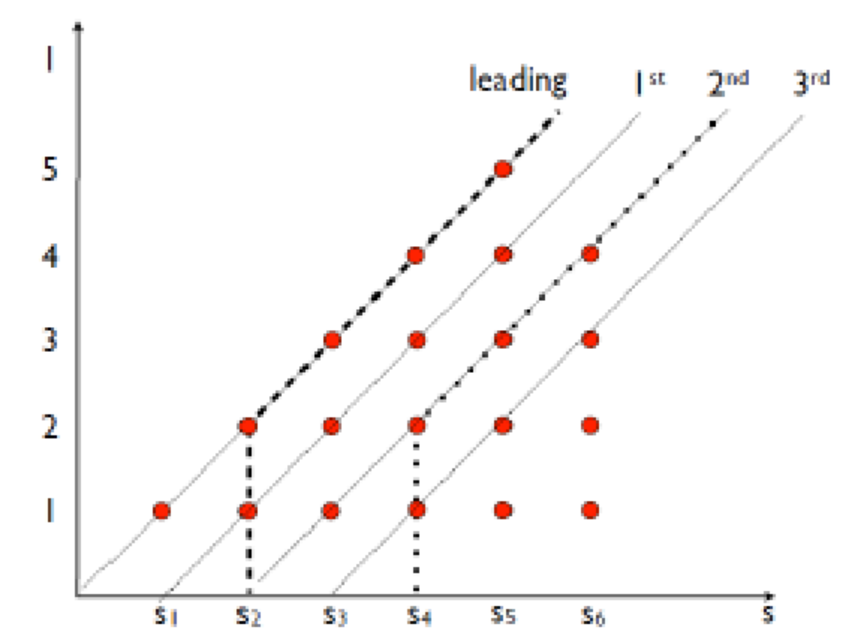



Combinations of $A_{n,m}$ that result in an amplitude containing only a finite number of poles

$$A_{n,m}(s,t) = \frac{\Gamma(n-\alpha_s)\Gamma(n-\alpha_t)}{\Gamma(n+m-\alpha_s-\alpha_t)}$$

e.g. keeping only the pole at $\alpha_S$=1 $\qquad A_1(s,t) = c_{1,1}\frac{2-\alpha_s-\alpha_t}{(1-\alpha_s)(1-\alpha_t)}$

e.g. $\omega \rightarrow 3\pi$: Bose statistics and isospin conservation require no spin-even resonances allowed



# A new (old?) approach: Veneziano amplitudes

## $\gamma\, p \to p\, \omega \to p\, \pi\pi\pi$

- A. Celentano (INFN-GE)
- Decay decouples production from genuine meson-meson interaction
- $\omega$ decay $M(\pi^+\pi^-) < 0.45$ GeV
- 3-body effects

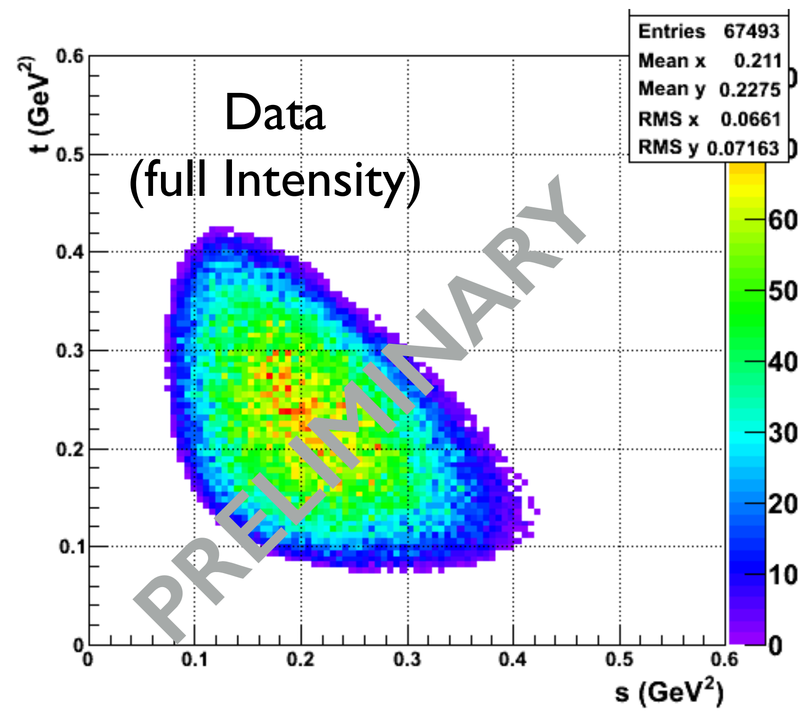
## Analysis in collaboration with JPAC

$$A_\lambda = \varepsilon_{\mu\nu\alpha\beta}\, p_+^\nu p_-^\alpha p_0^\beta \varepsilon_\lambda^\mu\, A(s,t,u)$$

$$I = \sum_{\lambda,\lambda'} A^*_\lambda \rho^\lambda_{\lambda'} A_{\lambda'} = K^2 W_\rho(\theta,\phi)|A|^2$$

$$K^2 = s\,t\,u - m^2(M^2-m^2)^2 = |\vec{p_a}\times\vec{p_b}|^2$$

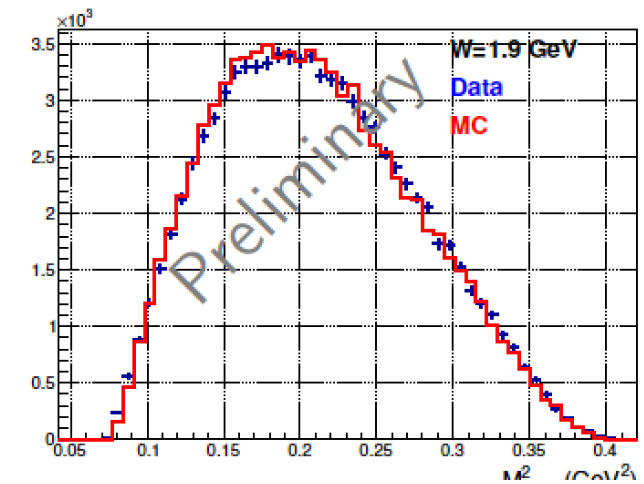
$W_\rho(\theta,\phi)$ : Spin density matrix




- A= $A_1$ ($\rho$ only)

$$\alpha_s = 0.47 + 0.9s + 0.12\,i\,\sqrt{s-4m_\pi^2}$$

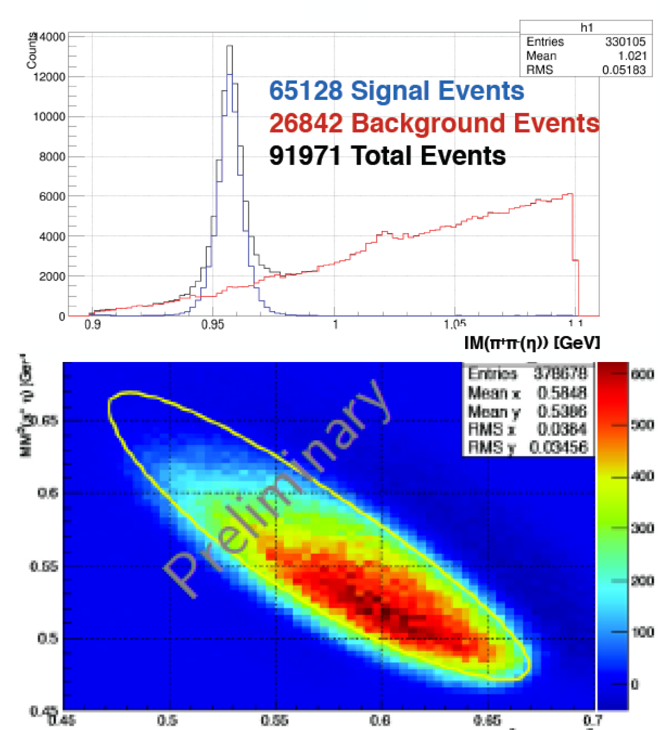
$$s_\rho = 0.58 - 0.095\,i\,(M = 0.76\text{ GeV},\ \Gamma = 0.124\text{ GeV})$$



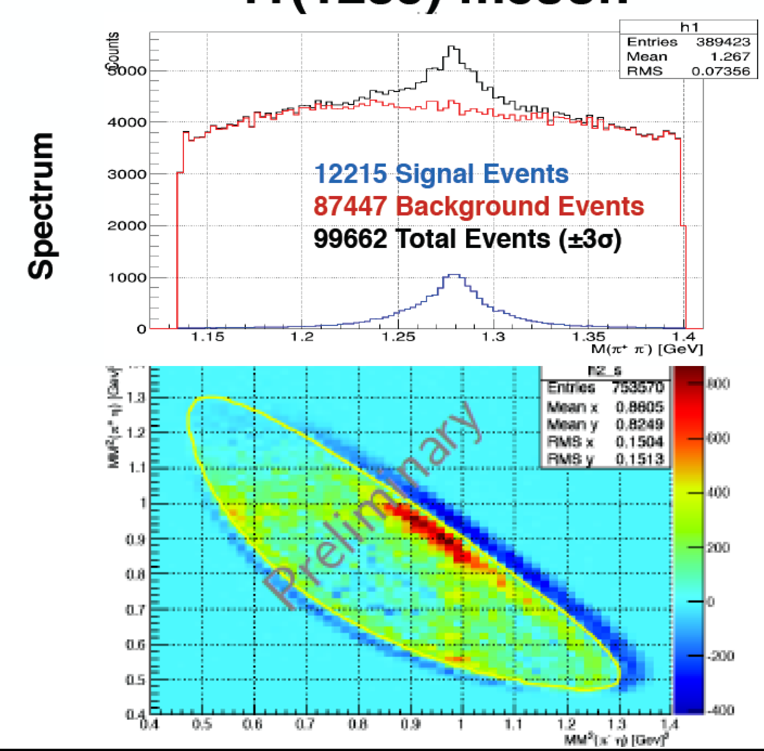

## $\gamma\, p \to p\, \eta' \to p\, \pi\, \pi\, \eta$
## $\to p\, f_1(1285)\, \eta$

- A. Rizzo (INFN-RM2)
- $(\pi\eta)$ invariant mass spectrum
- $\eta'$ decay $M(\pi\eta) < 0.8$ GeV

η' meson




f1(1285) meson

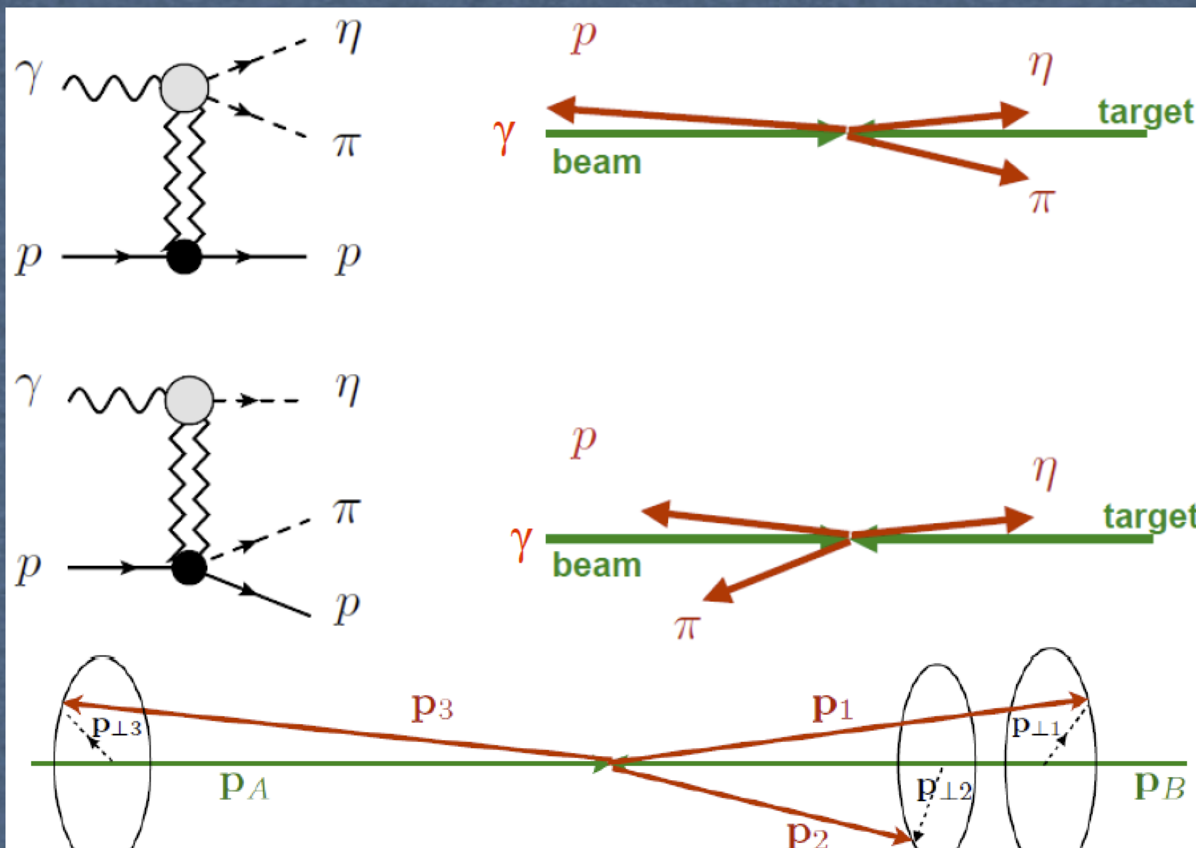



## amplitudes provided by JPAC

# Longitudinal analysis

## Separation between beam and target fragmentations

D.Glazier (U of Glasgow)

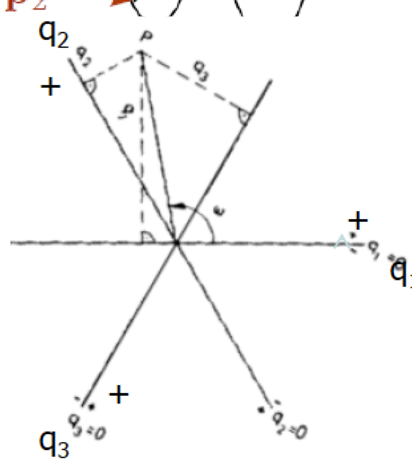


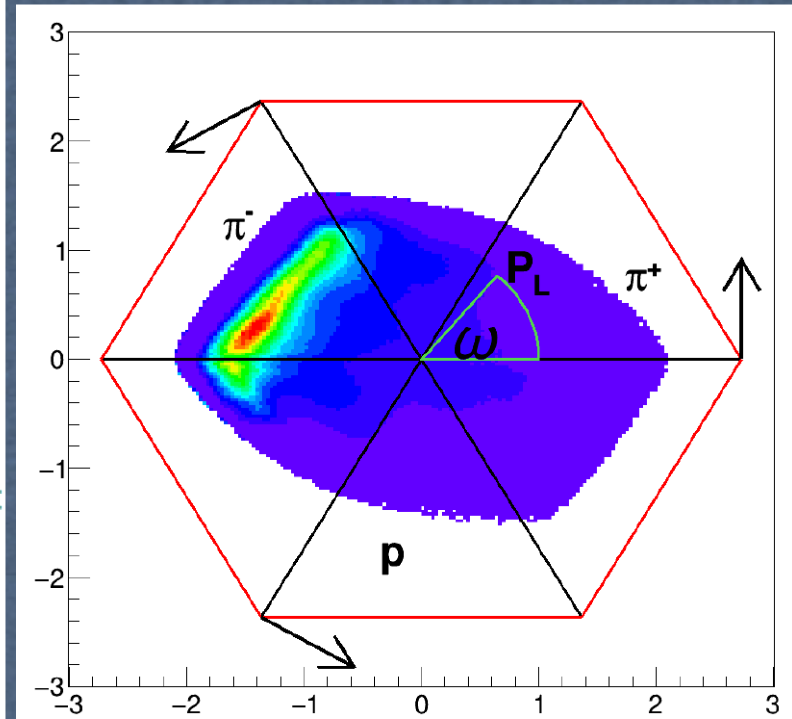

$$p_i = q_i + p_{\perp i} \,, \quad \sum_{i=1}^{N} q_i = 0 \,, \quad \sum_{i=1}^{N} |q_i| \leq W$$

$$q_1 = r \sin\omega \,,$$

$$q_2 = r \sin(\omega - \frac{2\pi}{3}) \,,$$

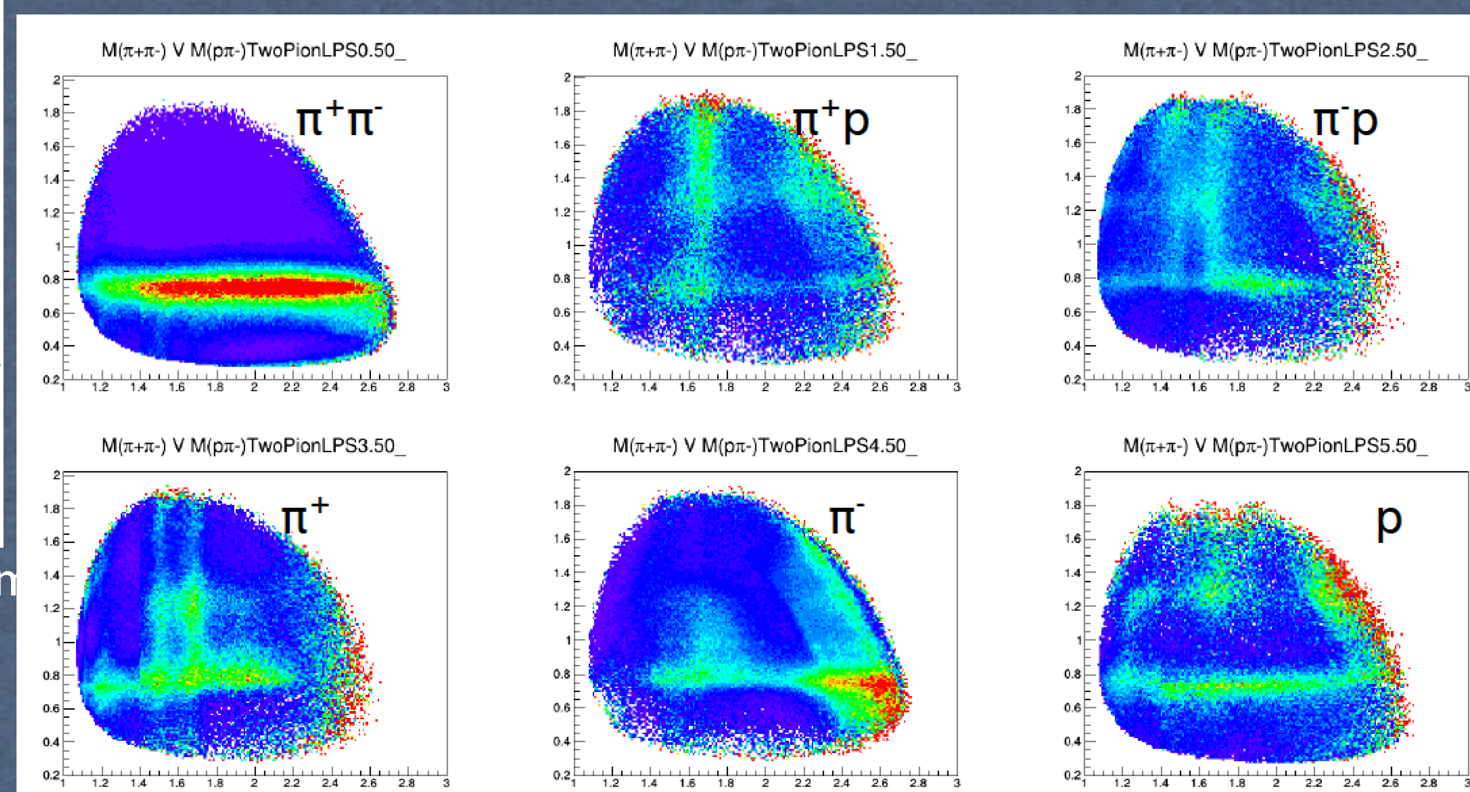
$$q_3 = r \sin(\omega - \frac{4\pi}{3})$$




van Hove plots
for γ p → p π π

- Sum Topologies, Split into LP Sector
- Baryon/Meson Masses : M(π+π-) v M(π-p)
- Named particles are travelling forward



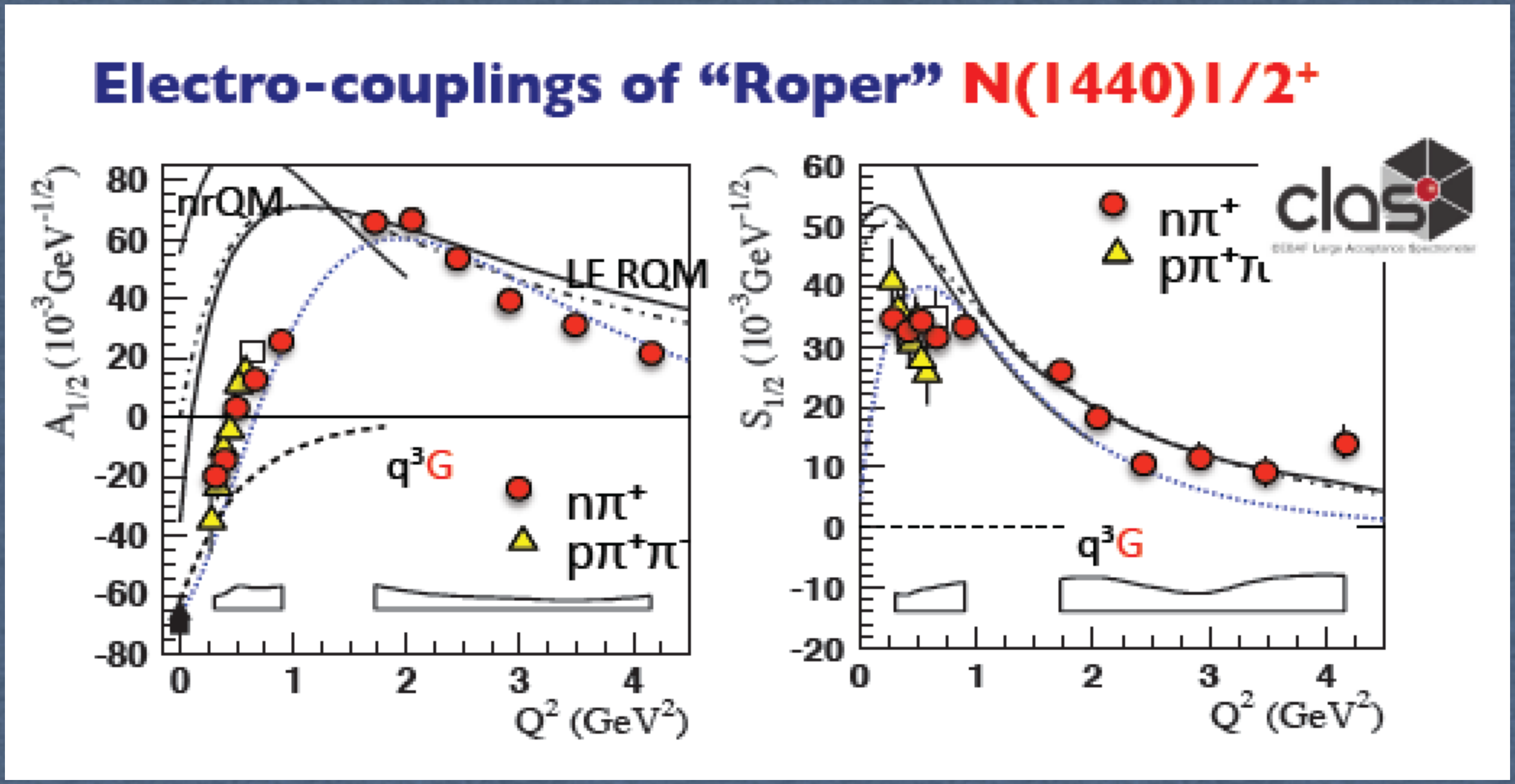

3-body final state has 2 independent degrees of freedon
Define these as radius r and angle ω
Define "positive, negative" for each $q_i$

E conservation: allowed region is bounded

# 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 $A_{1/2}(Q_2)$ faster than for ordinary three quark states, because of extra glue-component in valence structure




A suppressed longitudinal amplitude $S_{1/2}(Q_2)$ in comparison with transverse electro-excitation amplitude $Q_3G$ $Q_3G$

- $N\pi$ and $N\pi\pi$ 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

# Hadron spectroscopy ingredients

✳ Experiment

✳ Theory

✳ Analysis strategy

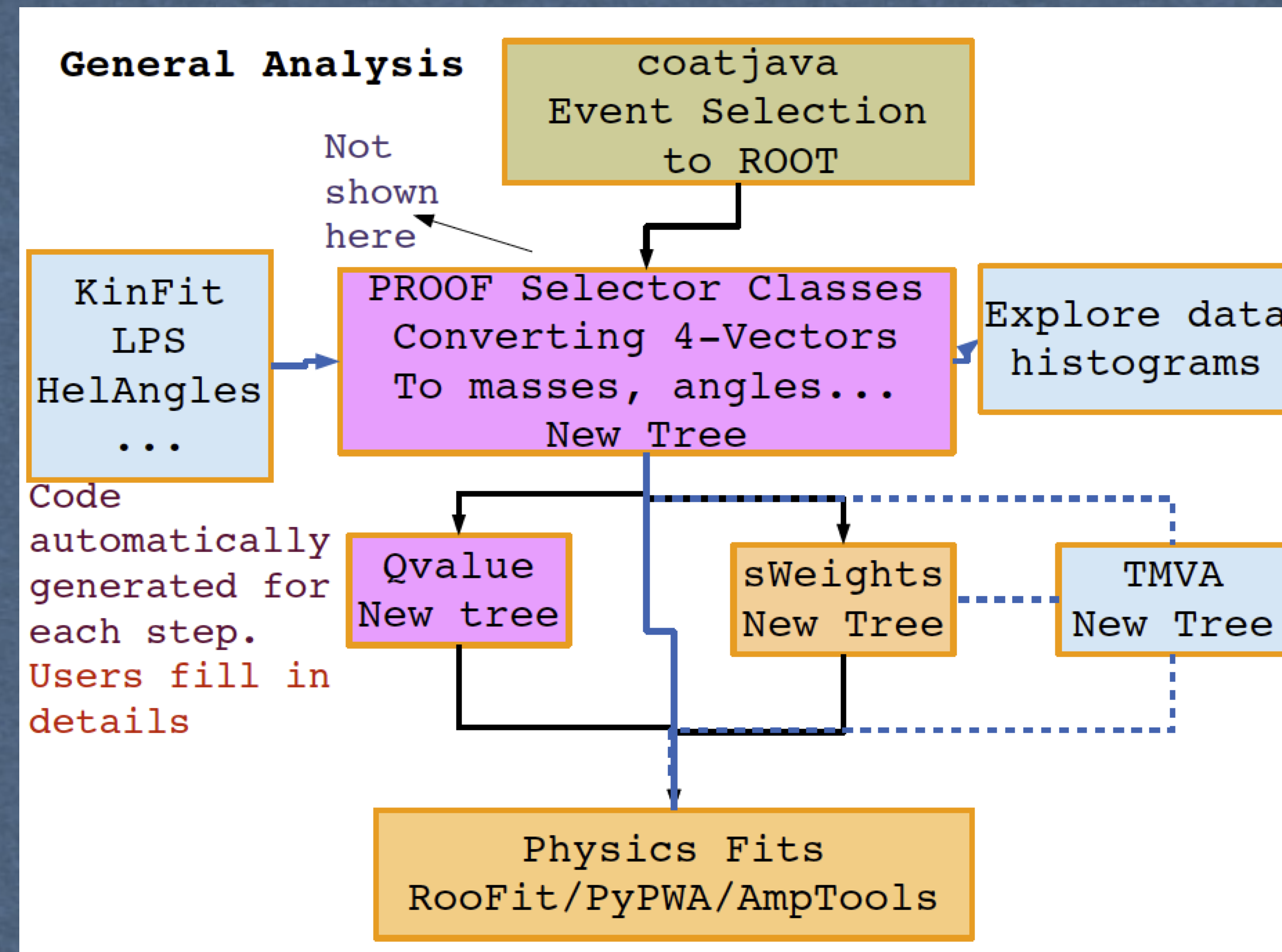
## ✳ Analysis tools

- HASPECT analysis framework
- HASPECT tools: AmpTools, EDGen
- CLAS6: data mining and data preservation
- CLAS12 simulations and full reconstruction framework

The HASPECT tools for MesonEx

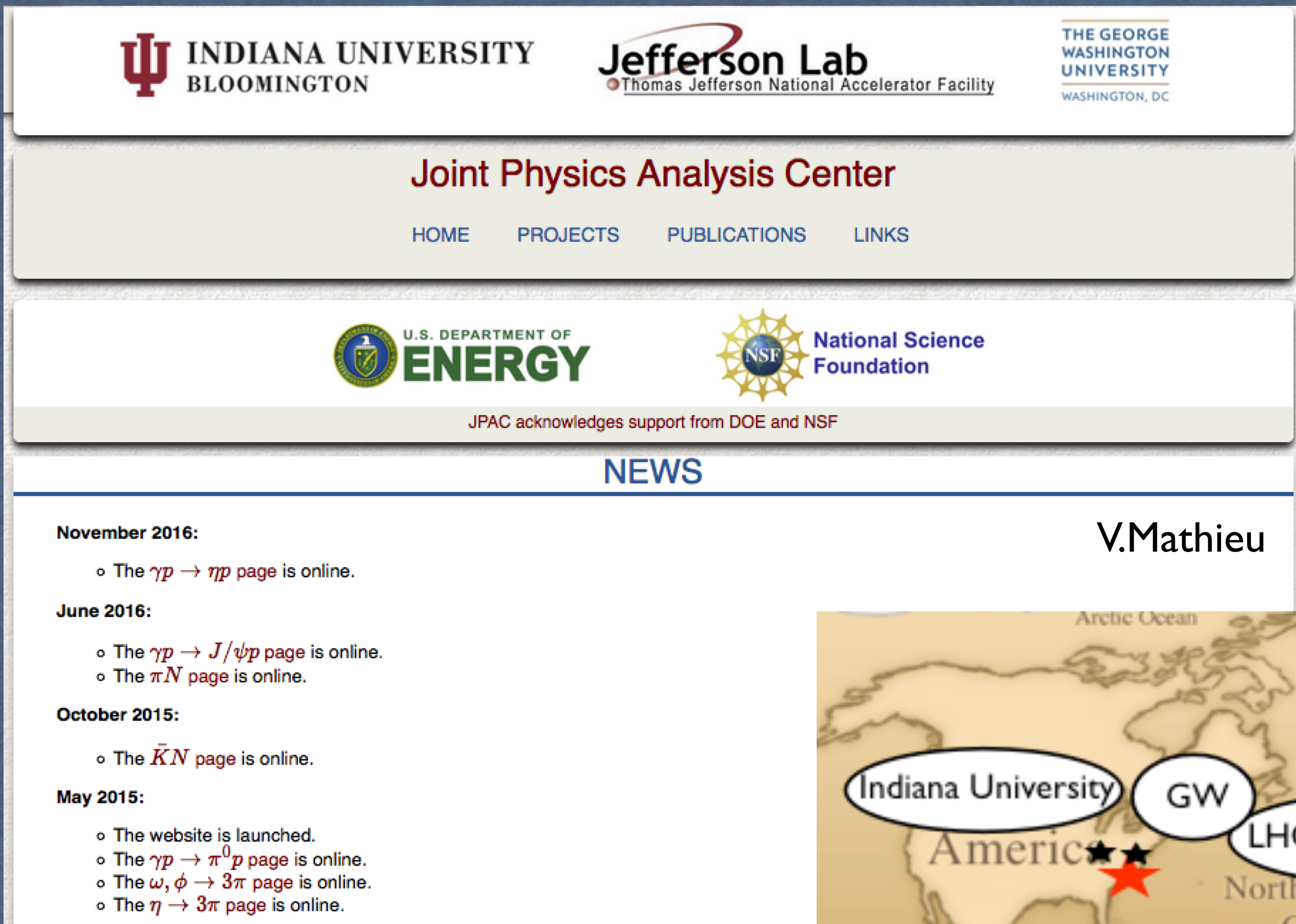
# Getting ready for the challenge: HASPECT tools

- ★ Set up a common analysis framework
- ★ Grab theoretical amplitude from JPAC
- ★ Define a list of *benchmark* and *golden channels* accessible at limited (6 GeV) energy:
  - $\gamma p \to N \pi \pi$
  - $\gamma p \to N K K$
  - $\gamma p \to N \eta \pi$
  - $\gamma p \to N \omega$
  - $\gamma p \to N \pi \pi \pi$
  - $\gamma p \to N \eta \pi \pi$
  - $\gamma p \to N \pi^+ \pi^- \pi^- K^+$
  - $\gamma p \to N \varphi \pi$
  - $\gamma p \to N \varphi \eta$
  - $\gamma p \to N \omega \pi^+ \pi^-$
- ★ test the analysis machinery on CLAS6 data
- ★ project to CLAS12




- Theoretical support:
  JPAC (US), L.Bibrzycki (Krakow), R.Kaminski (Krakow), E.Santopinto (INFN-GE)
- Experimental Analysis:
  A.Celentano, (INFN-GE), S.Dihel (Giessen), S.Fegan (Mainz), A. Filippi (INFN-TO), D.Glazier (Glasgow), S.Hughes (Edinburgh), K.Hicks (OhioU), S.Lombardo (Cornell), A.Rizzo (RomaTV), I Stankovic (Edinburgh), L.Zana (Edinburgh)

# Act locally but think globally!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JPAC acknowledges support from DOE and NSF

NEWS

**November 2016:**

- The $\gamma p \to \eta p$ page is online.

**June 2016:**

- The $\gamma p \to J/\psi p$ page is online.
- The $\pi N$ page is online.

**October 2015:**

- The $\bar{K}N$ page is online.

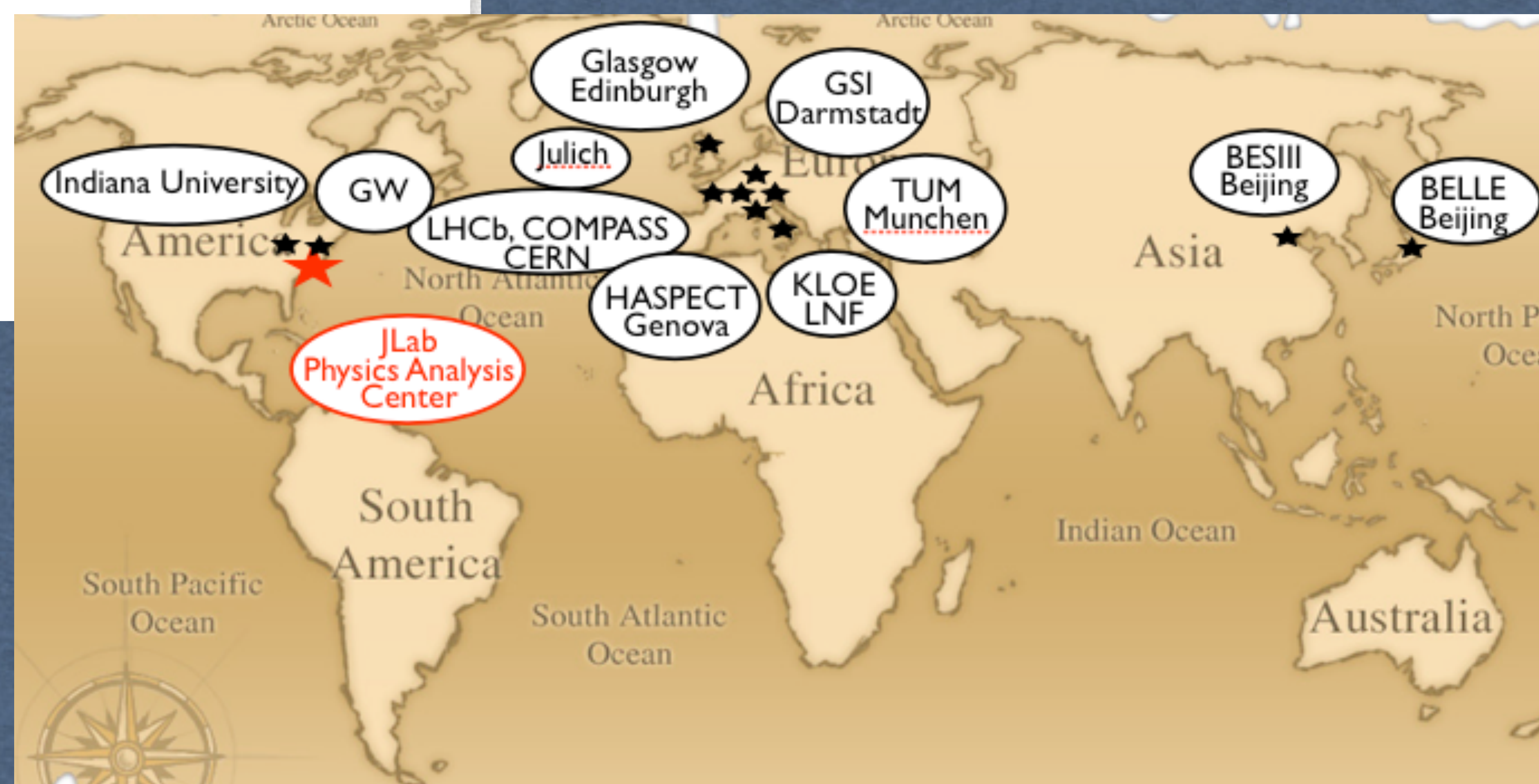
**May 2015:**

- The website is launched.
- The $\gamma p \to \pi^0 p$ page is online.
- The $\omega, \phi \to 3\pi$ page is online.
- The $\eta \to 3\pi$ page is online.

V.Mathieu

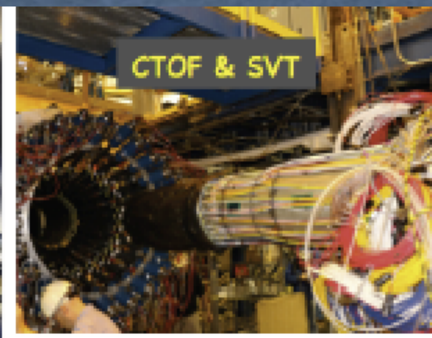
## Global strategy:

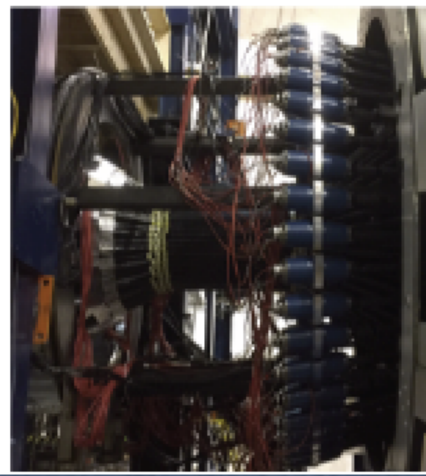
✳Creation of twin and parallel centers for both analysis and theory development
✳Collaboration and exchanges: personnel, short visits, ...
✳Coordination via Joint Physics Analysis Center
✳Creation of a "Hadron spectrum" working group




## Common funding plans:

- European-FP7 (EU calls and local): HadronS-HPH, Synergy grants
- DOE-Topical -collaboration proposals
- Canaletto/LiQuHas (Italy/Polland)



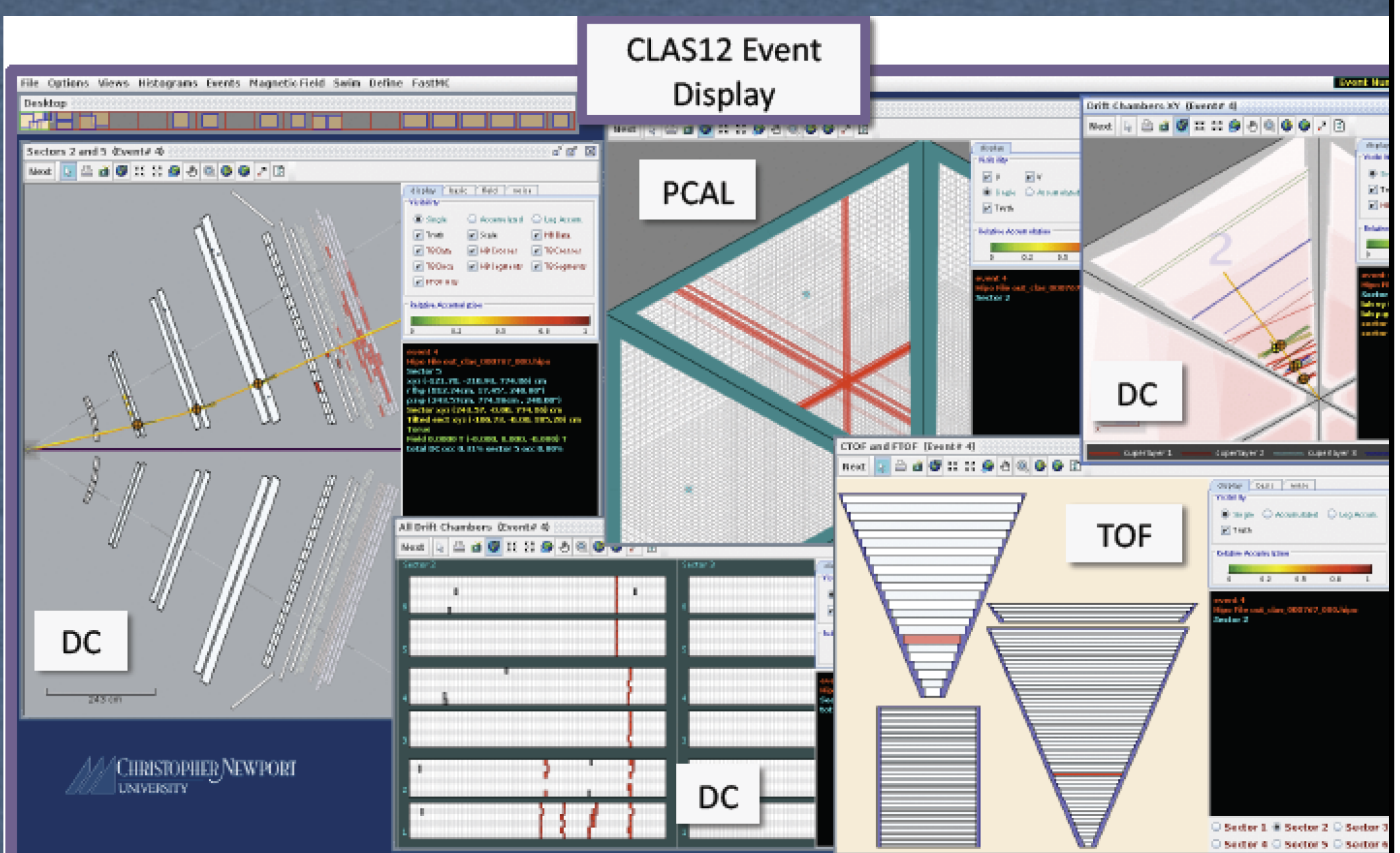



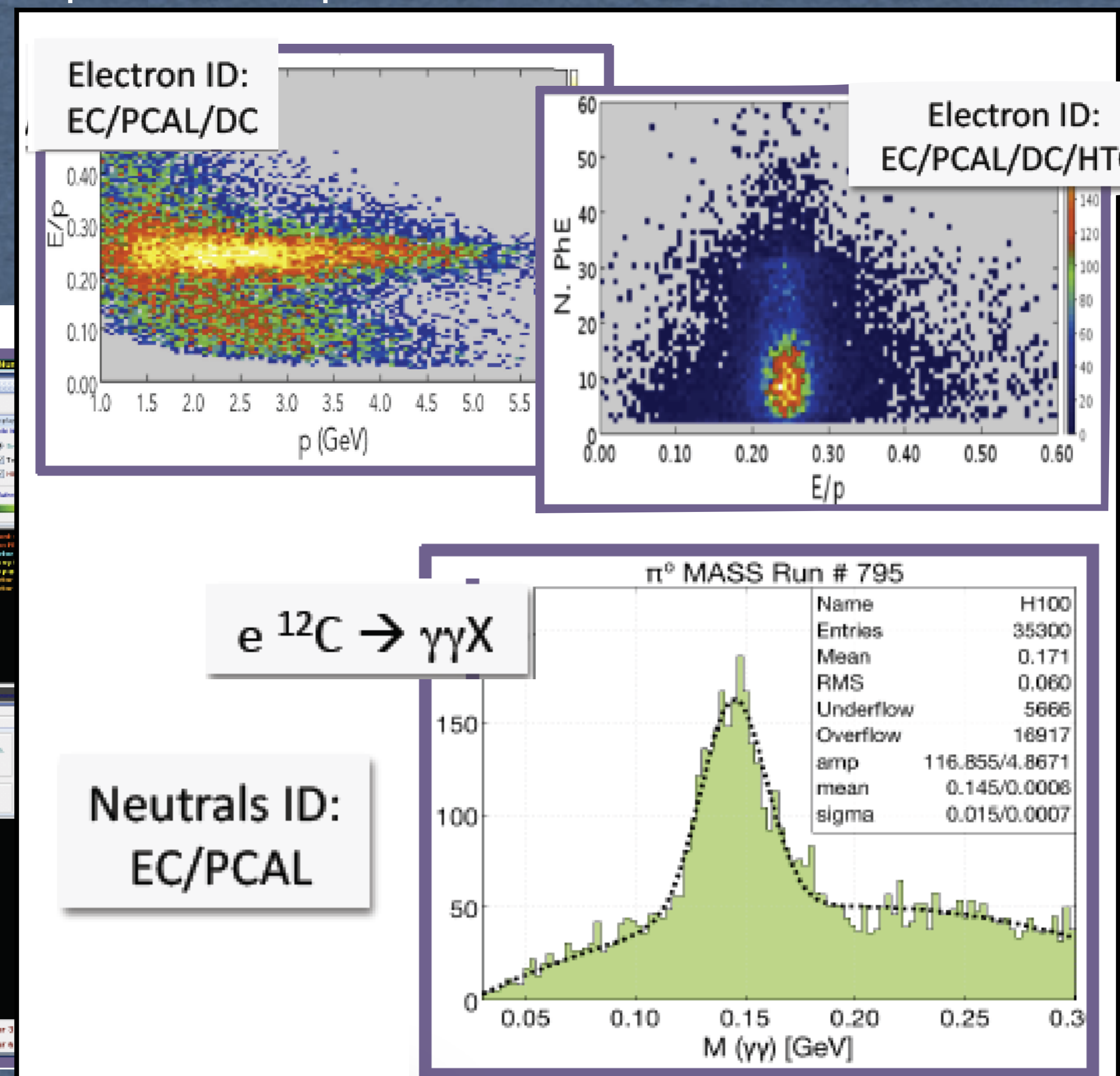
# First data tacking with CLAS12

★ Short test run in February at E=6.5 GeV

★ All base equipment installed and operational (CTOF,DC, EC, FTOF, HTCC, LTCC, PCAL, SVT)

★ The run successfully proved the CLAS12 key performance parameters



# Conclusions

✳ Comprehensive meson spectroscopy program at JLab (Gluex & MesonEx)

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

✳Bremsstrahlung and Low $Q^2$ electron scattering to produce a high intensity, linear polarized, real (Hall-D) and quasi-real (Hall-B) photon beam

✳ Expected abundant and precise data requires a solid PWA analysis framework

✳ The strategy: build the analysis framework in advance, test it on CLAS6 data and project on CLAS12 to be ready on day-1

✳ Continuous interaction between JLab WGs (HASPECT, LMD, JPAC) and the other centers (BES, GSI, Julich) to meet the challenge

**High-performance detector, high intensity e/γ beams, strong analysis framework are the ingredients to make CLAS12 a leading facility in modern hadron spectroscopy**

# Backup slides