High Energy Photoproduction at JPAC

Alessandro Pilloni

on behalf of JPAC

Exploring Hadrons with Electromagnetic Probes:
Structure, Excitations, Interactions
JLab, November 3rd, 2017

Jefferson Lab

Outline

- π^0 photoproduction
  Mathieu, Fox, Szczepaniak (JPAC), PRD92, 074013

  Mathieu, Nys, AP, Fernández-Ramírez, Jackura,
  Mikhasenko, Pauk, Szczepaniak, Fox, (JPAC), arXiv:1708.07779

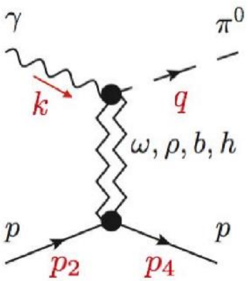
- η photoproduction
  Nys, Mathieu, Fernández-Ramírez, Hiller Blin, Jackura,
  Mikhasenko, AP, Szczepaniak, Fox, Ryckebusch (JPAC), PRD95, 034014

- η' photoproduction
  Nys, Mathieu, Fernández-Ramírez, Jackura, Mikhasenko,
  AP, Szczepaniak, Fox (JPAC), PLB774, 362-367

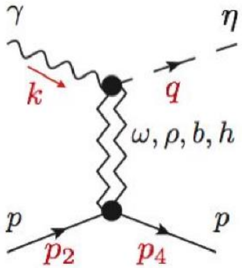
- $\pi\Delta$ photoproduction
  Nys, Mathieu, Fernández-Ramírez, Jackura, Mikhasenko,
  AP, Sherrill, Ryckebusch, Szczepaniak, Fox (JPAC), arXiv:1710.09394

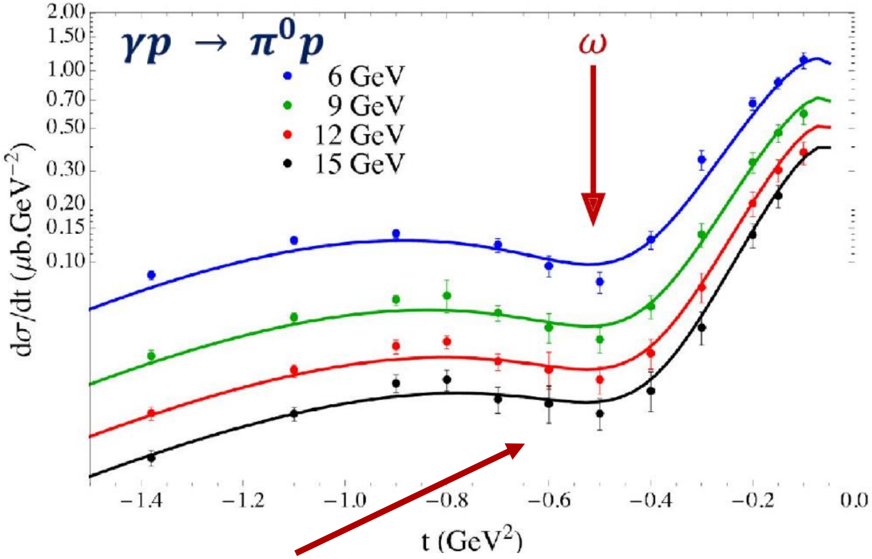
Slides stolen from J. Nys and V. Mathieu

π^0, η photoproduction

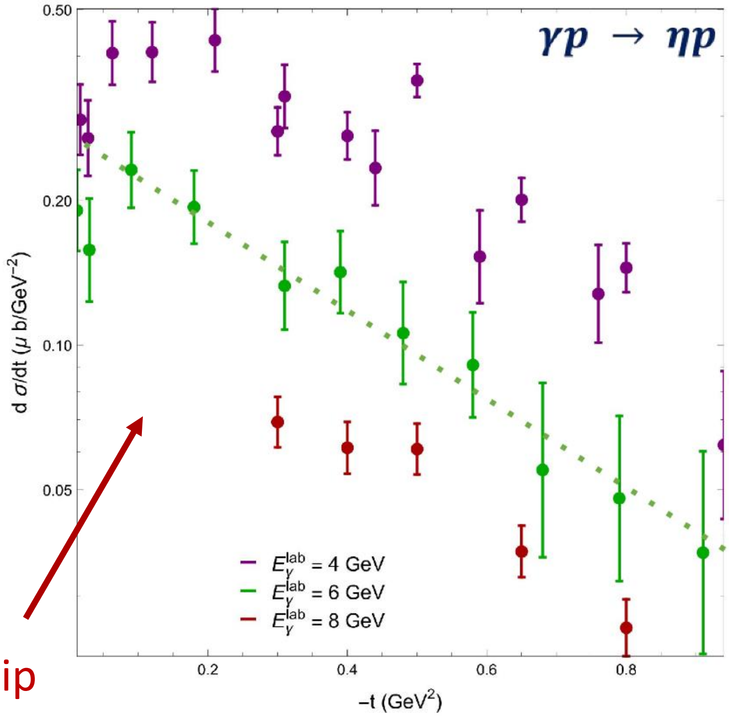


$$A(\eta) = \sqrt{3}\mathcal{A}\left[A_\rho(\pi^0) + A_b(\pi^0) + \frac{1}{9}(A_\omega(\pi^0) + A_h(\pi^0))\right]$$





Dominant contribution from ω
dip because of NWSZ



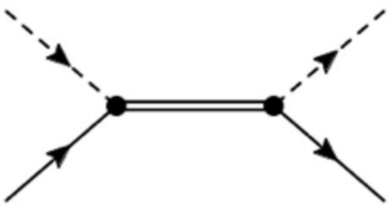
ω suppressed, no dip

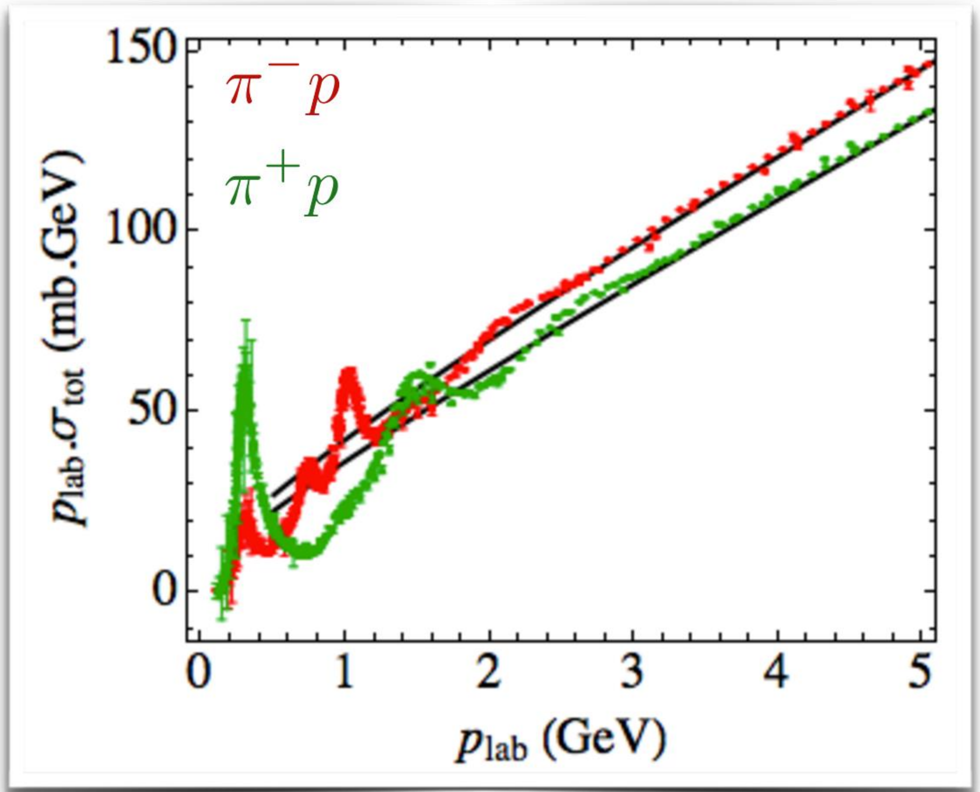
[Data: Dewire 1971, Braunschweig 1970]

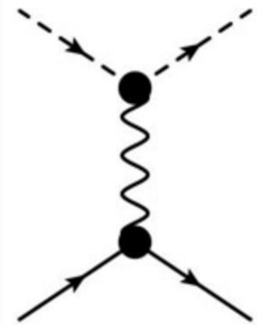
Duality

Low energy: **baryon resonances**

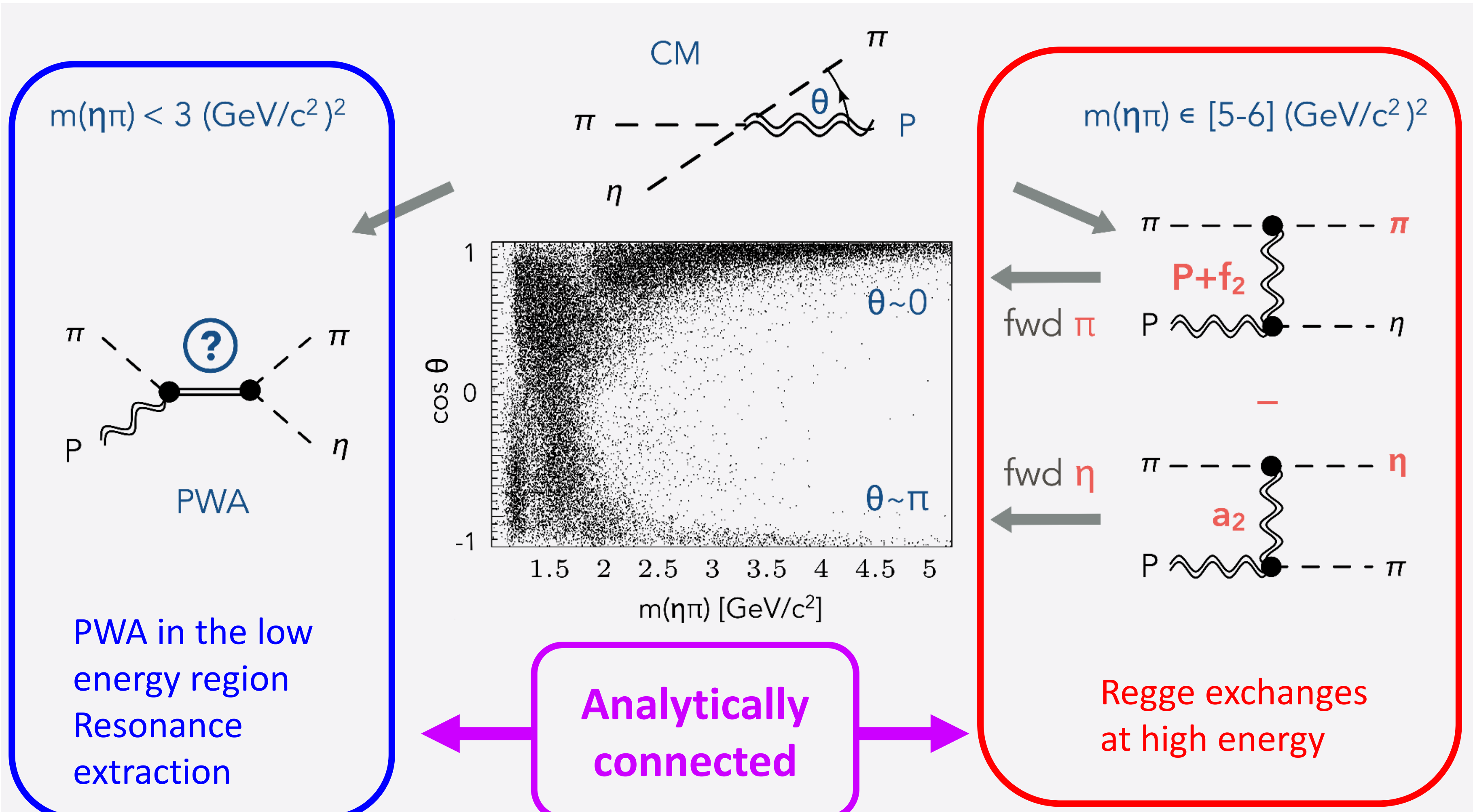
High energy: **Regge exchange**





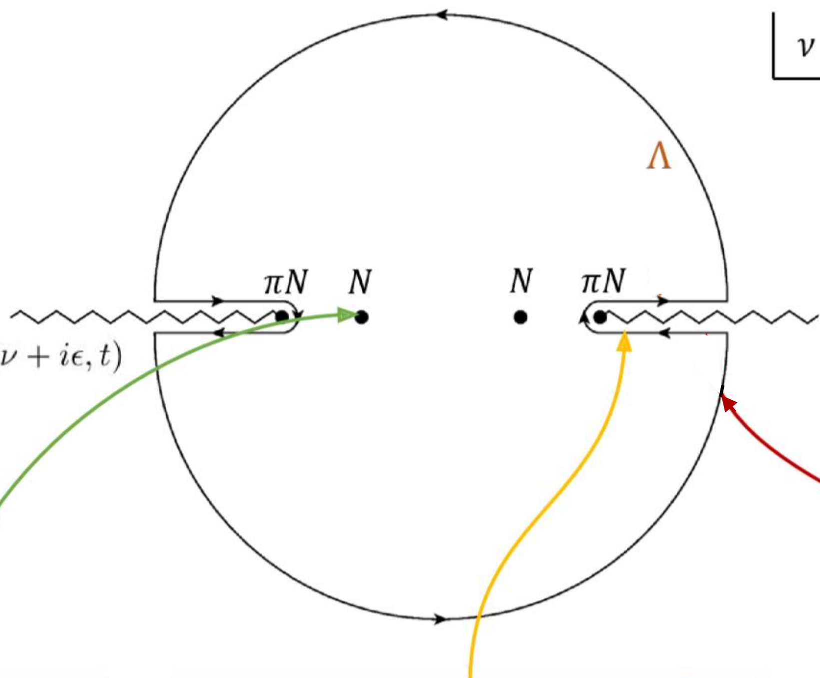


Finite energy sum rules



Finite energy sum rules

$A_i(\nu, t)\nu^k$



$A_i^\sigma(-\nu - i\epsilon, t) = \xi_i A_i^\sigma(\nu + i\epsilon, t)$

$-\beta_i(t)\dfrac{\tau + e^{-i\pi\alpha(t)}}{\sin \pi\alpha(t)}(r_i\nu)^{\alpha(t)-1}$

ν

Fixed t

Crossing variable: $\nu = \frac{s-u}{4\,M}$

s-channel: + ν

u-channel: - ν

$$\pi B_i^\sigma(t)\left(\frac{\nu_M}{\Lambda}\right)^k + \int_{\nu_\pi}^{\Lambda} \text{Im } A_i^\sigma(\nu', t)\left(\frac{\nu'}{\Lambda}\right)^k d\nu' = \beta_i^\sigma(t)\frac{(\Lambda/\nu_0)^{\alpha(t)}}{\alpha(t)+k}\nu_0$$

Nucleon pole — Low-energy model — Regge pole

Analyticity results in Finite-Energy Sum Rules.

CGLN basis and scalar amplitudes

$$A_{\lambda';\lambda\,\lambda_\gamma}(s,t) = \overline{u}_{\lambda'}(p')\left(\sum_{k=1}^{4} A_k(s,t) M_k\right) u_\lambda(p)$$

- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

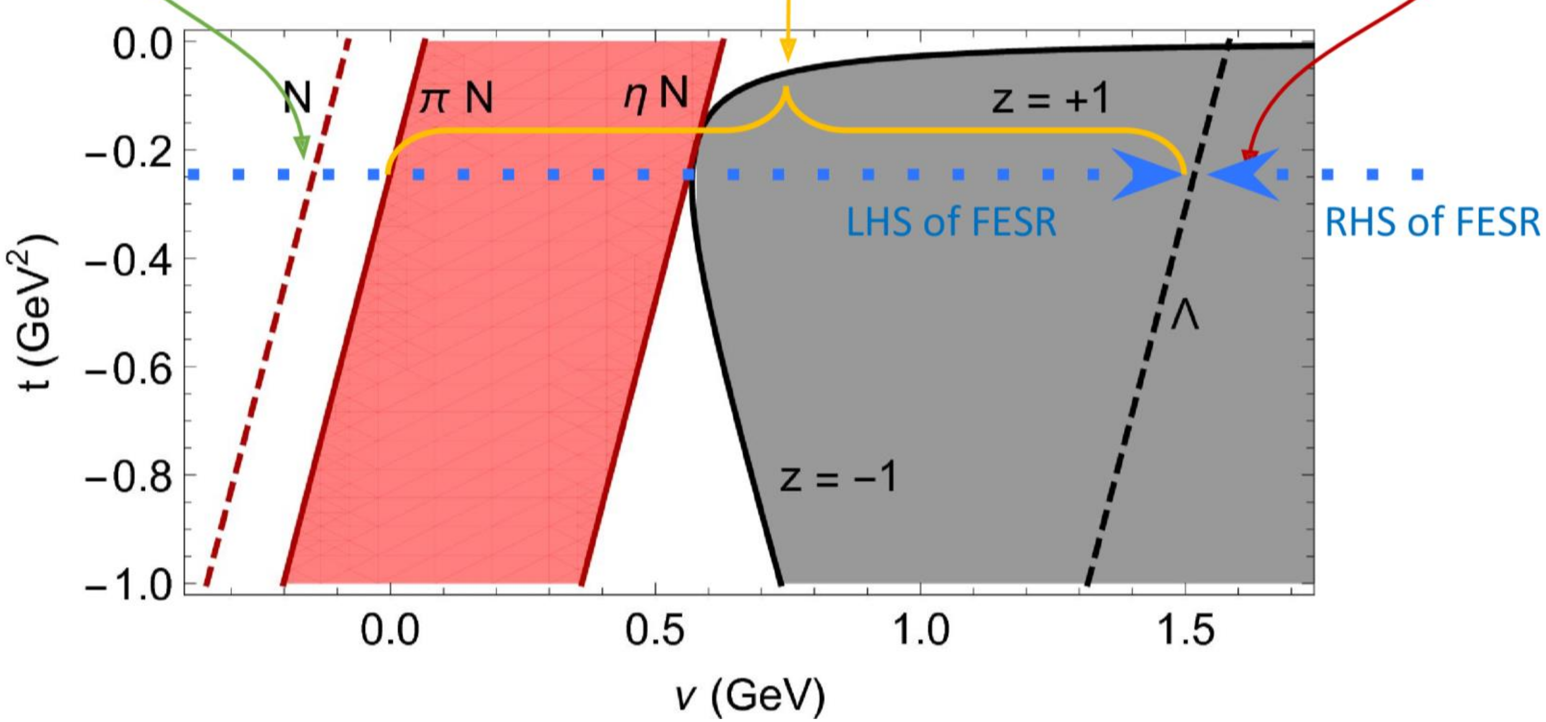
$$M_k \equiv M_k(s,t,\lambda_\gamma)$$

$$M_1 = \frac{1}{2}\gamma_5\gamma_\mu\gamma_\nu F^{\mu\nu}\,,$$
$$M_2 = 2\gamma_5 q_\mu P_\nu F^{\mu\nu}\,,$$
$$M_3 = \gamma_5\gamma_\mu q_\nu F^{\mu\nu}\,,$$
$$M_4 = \frac{i}{2}\epsilon_{\alpha\beta\mu\nu}\gamma^\alpha q^\beta F^{\mu\nu}\,.$$

$\gamma p \to \eta p$, Dispersive integral

$$\pi B_i^\sigma(t)\left(\frac{\nu_M}{\Lambda}\right)^k + \int_{\nu_\pi}^{\Lambda} \mathrm{Im}\, A_i^\sigma(\nu',t)\left(\frac{\nu'}{\Lambda}\right)^k d\nu' = \beta_i^\sigma(t)\frac{(\Lambda/\nu_0)^{\alpha(t)}}{\alpha(t)+k}\nu_0$$

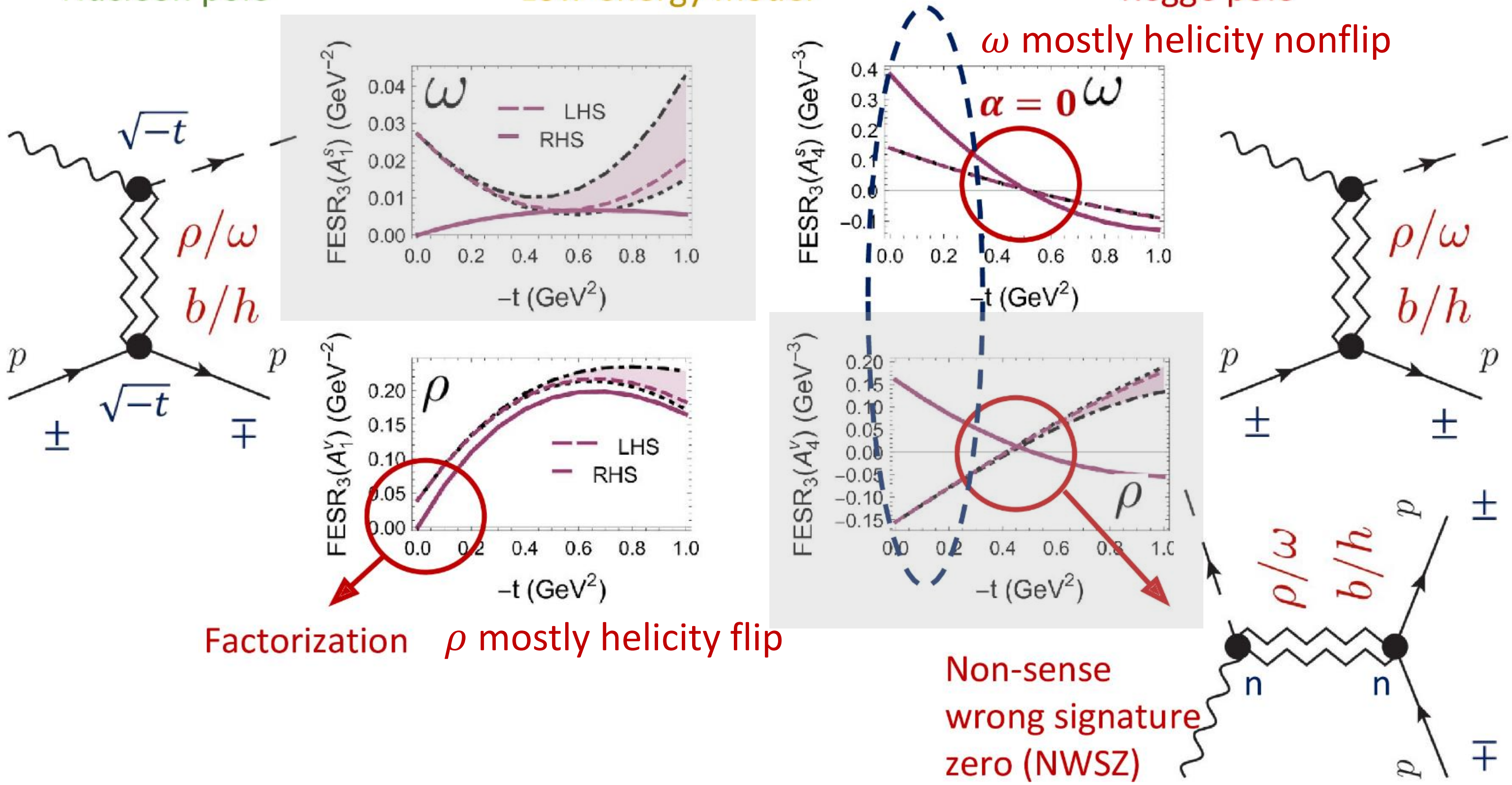
Nucleon pole   Low-energy model   Regge pole



Natural contributions

$$\pi B_i^\sigma(t)\left(\frac{\nu_M}{\Lambda}\right)^k + \int_{\nu_\pi}^{\Lambda} \text{Im } A_i^\sigma(\nu',t)\left(\frac{\nu'}{\Lambda}\right)^k d\nu' = \beta_i^\sigma(t)\frac{(\Lambda/\nu_0)^{\alpha(t)}}{\alpha(t)+k}\nu_0$$

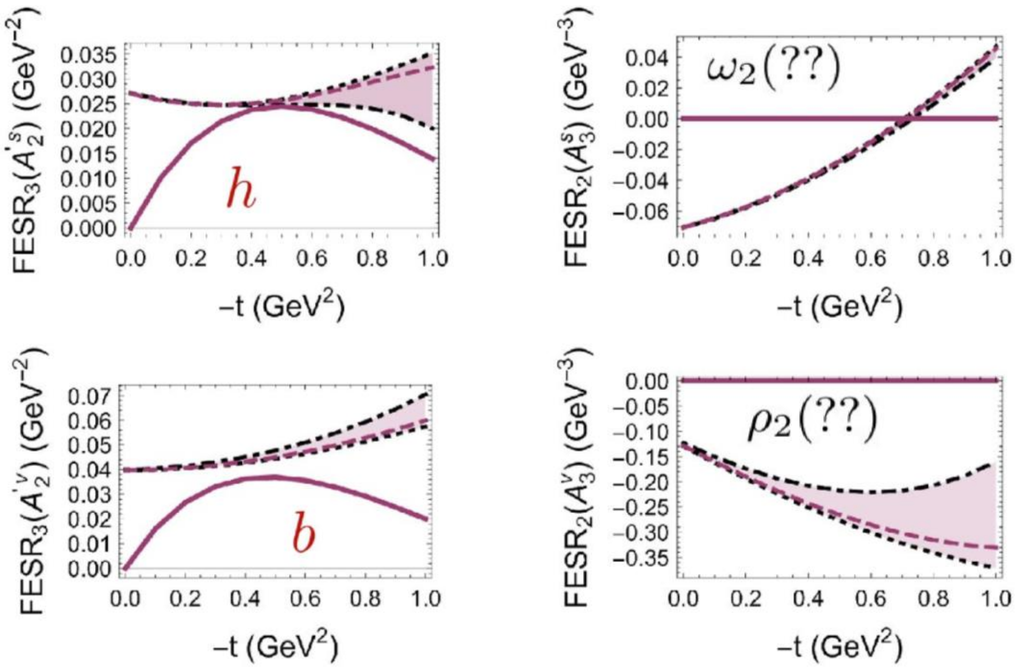
Nucleon pole — Low-energy model — Regge pole



$\gamma p \to \eta p$, Unnatural contributions

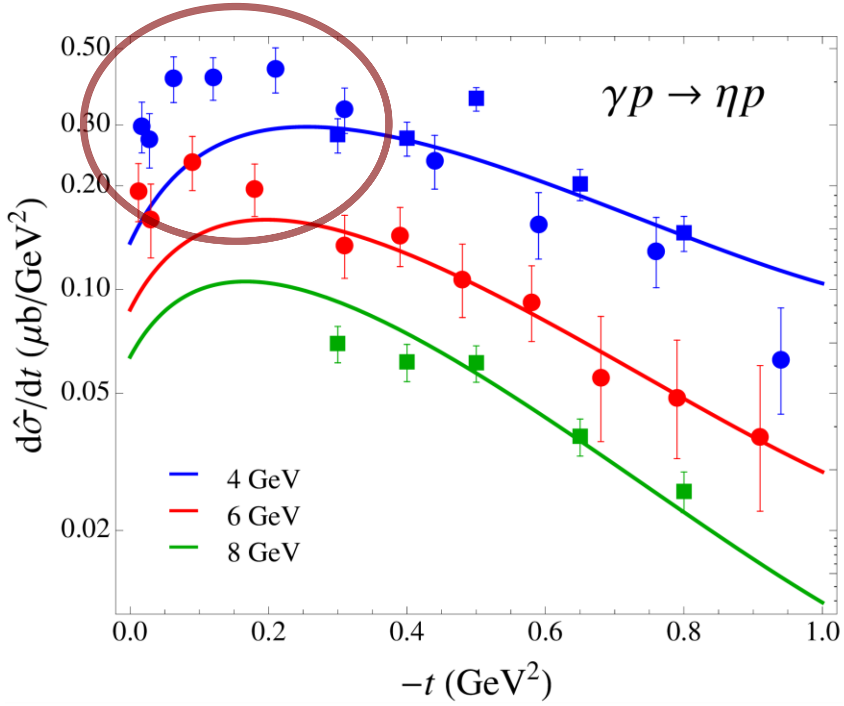
$$\pi B_i^\sigma(t)\left(\frac{\nu_M}{\Lambda}\right)^k + \int_{\nu_\pi}^{\Lambda} \mathrm{Im}\, A_i^\sigma(\nu',t)\left(\frac{\nu'}{\Lambda}\right)^k d\nu' = \beta_i^\sigma(t)\frac{(\Lambda/\nu_0)^{\alpha(t)}}{\alpha(t)+k}\nu_0$$

Nucleon pole — Low-energy model — Regge pole



Look for unnatural contributions in the beam asymmetry

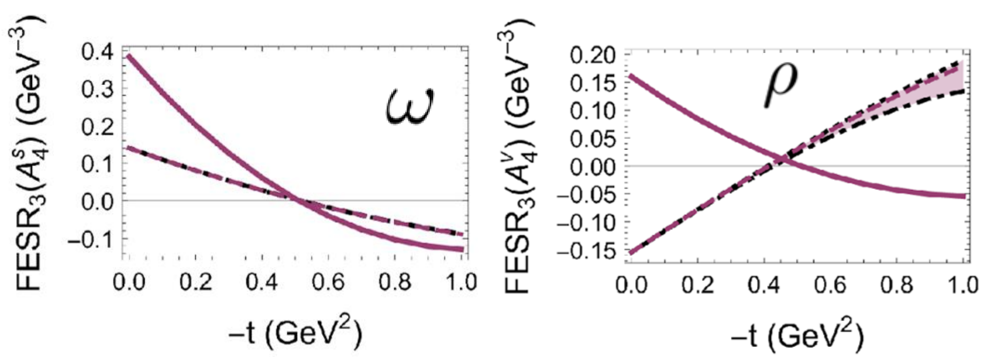
$\gamma p \to \eta p$, Results



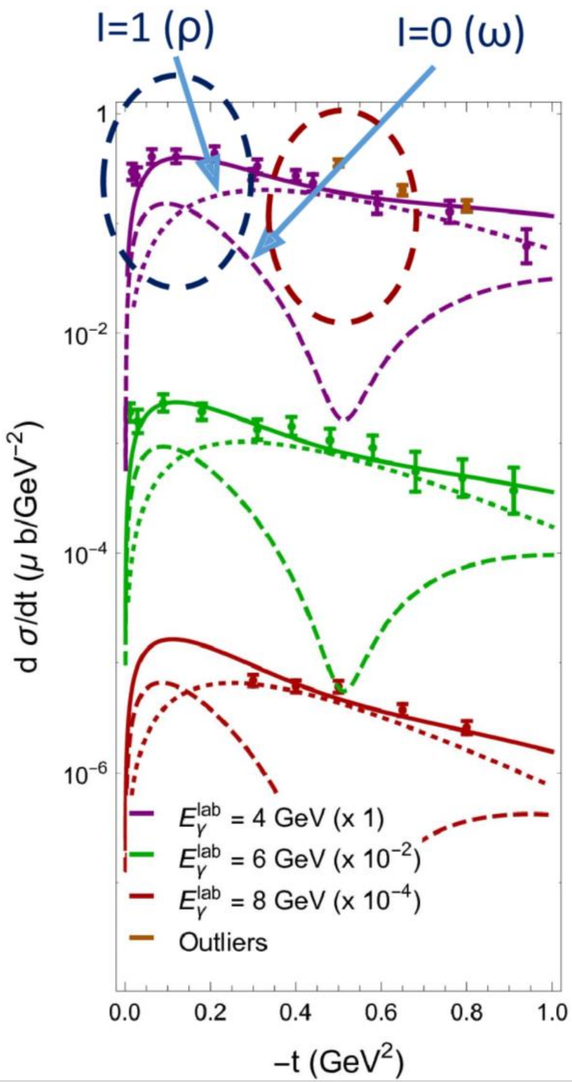
Some strength is missing at forward t
Likely because of the cancellation between the ρ and ω in η-MAID

A flipped sign for ρ is suggested by FESR, and by other low-energy models:

We flip the sign of ρ

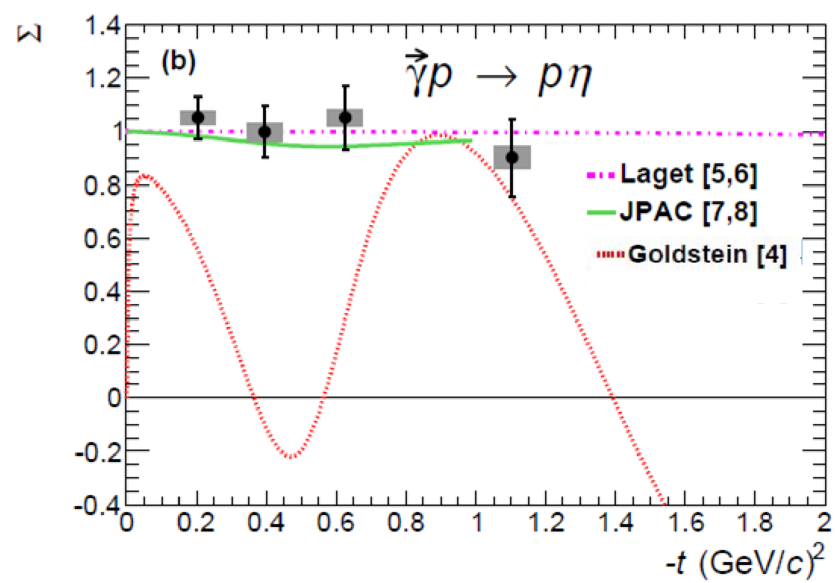


$\gamma p \to \eta p$, Results



Natural dominant: $\Sigma = +1$

Unnatural dominant: $\Sigma = -1$



GlueX + Mathieu & Nys, PRC95, 042201

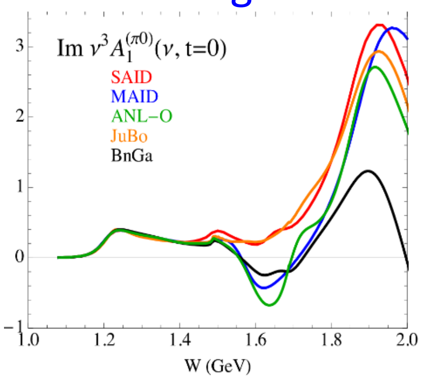
Fill up the dip with natural contribution: ρ

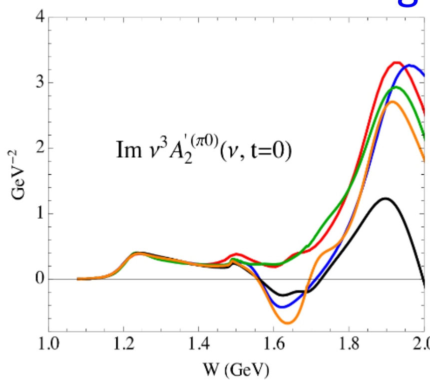
$\gamma p \to \pi^0 p$, Results

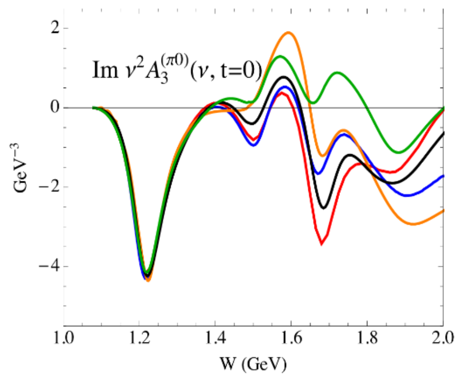
A_1 A_2' A_3 A_4

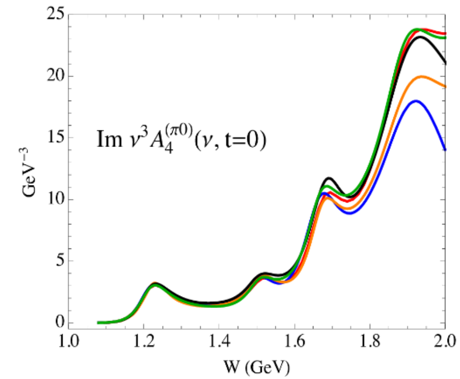
SAID
MAID
ANL−O
JuBo
BnGa

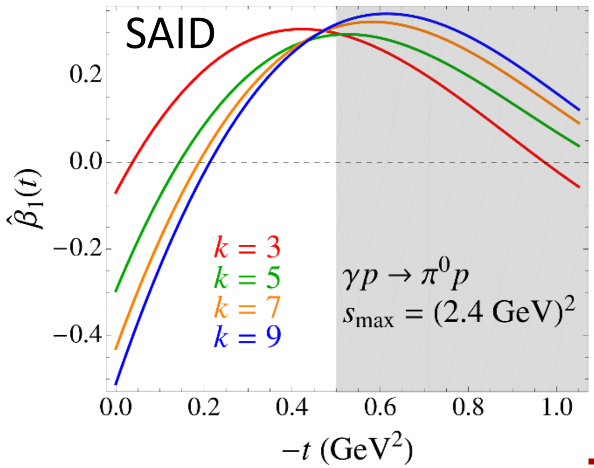
Disagreement between models at high W

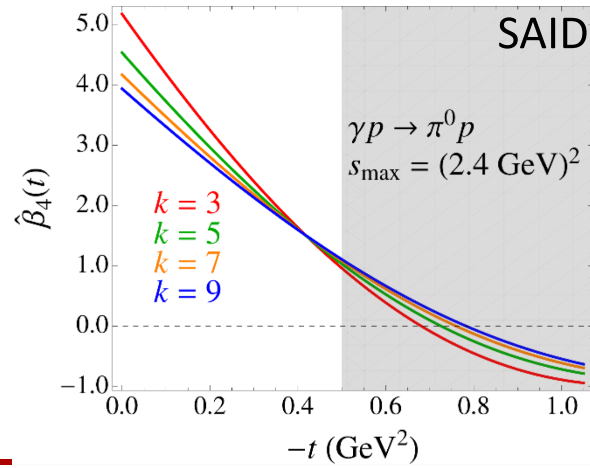






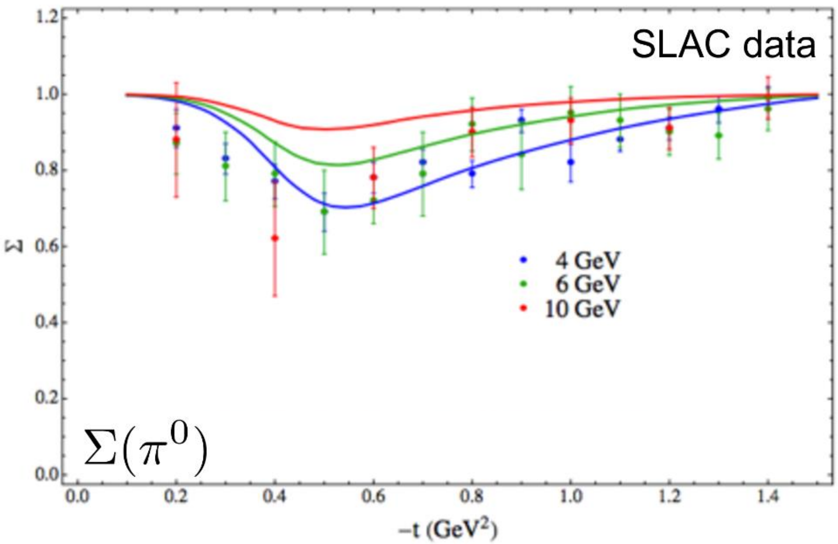


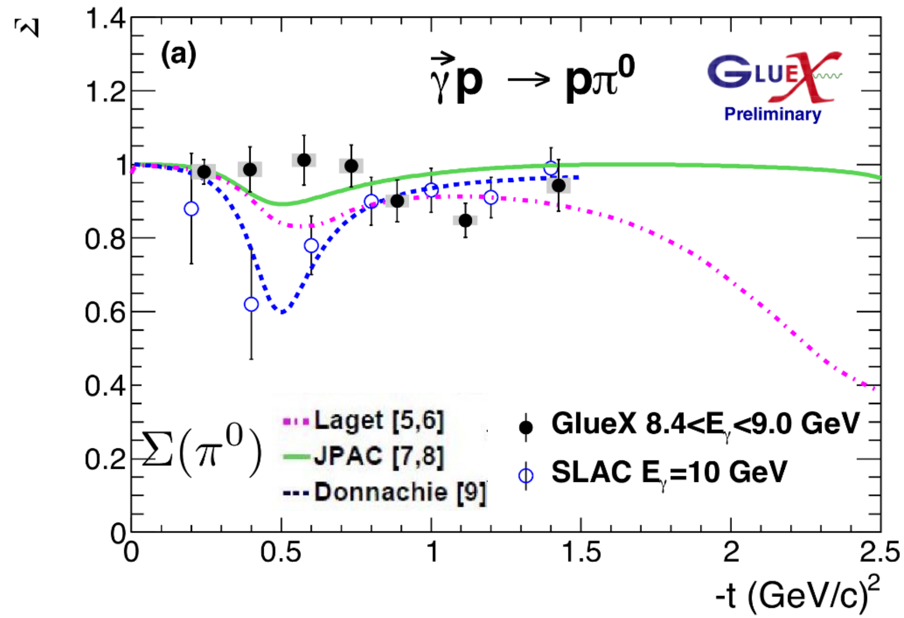




Dividing out the known dependence of k,
the residues are indeed fairly indipendent

$\gamma p \to \pi^0 p$ beam asymmetry





GlueX + Mathieu & Nys, PRC95, 042201

$$\Sigma = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

decreases with E_γ drops with E_γ

$\Sigma \to 1$ as E_γ increases

The beam asymmetry confirms a small contribution of unnatural exchanges, suggesting the dip at $t = -0.5\ \text{GeV}^2$ to be filled by some rescattering (cut)

η vs. η' beam asymmetries

$$\Sigma^{(\prime)} = \frac{d\sigma_\perp^{(\prime)} - d\sigma_\parallel^{(\prime)}}{d\sigma_\perp^{(\prime)} + d\sigma_\parallel^{(\prime)}}$$

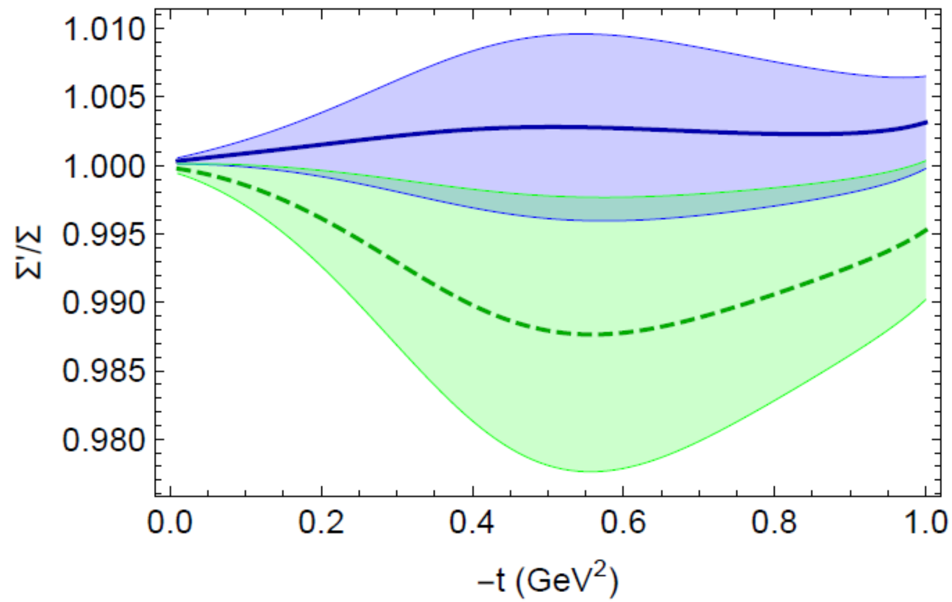
$$\frac{\Sigma'}{\Sigma} = 1 + \frac{1-\Sigma^2}{\Sigma} \cdot \frac{k_V - k_A}{(1+\Sigma)k_V + (1-\Sigma)k_A}$$

$$k_V = \frac{d\sigma'_\perp}{d\sigma_\perp}, \qquad k_A = \frac{d\sigma'_\parallel}{d\sigma_\parallel}.$$

Quark model predictions:

$$k_V = k_A = \tan^2\varphi$$

Mathieu, Nys *et al.* (JPAC), PLB774, 362-367

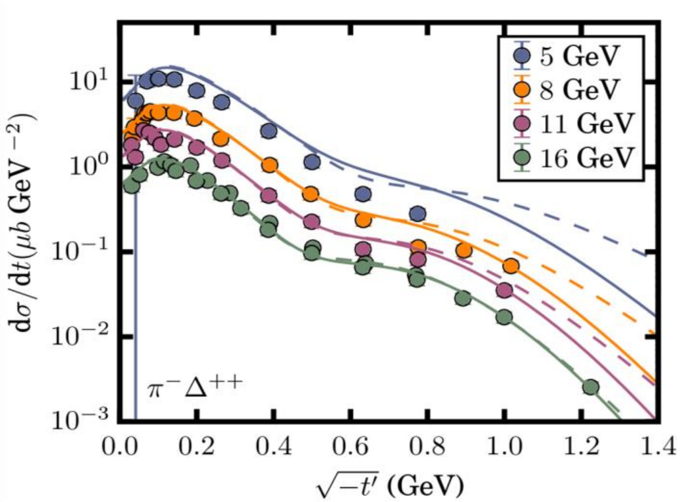


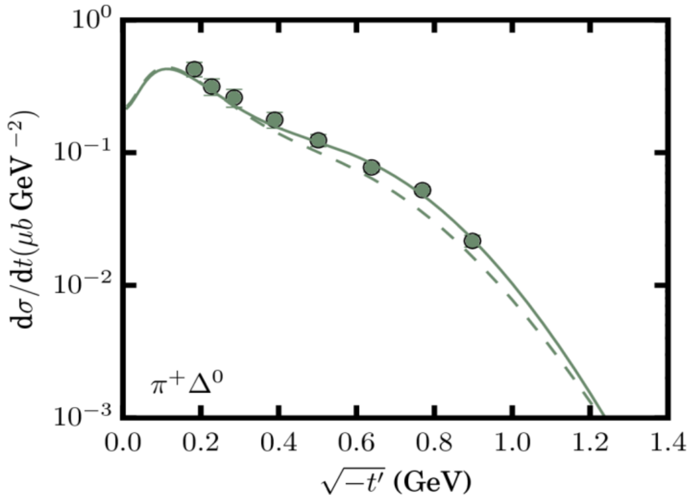
Dominant exchanges: ρ, ω
Variations: b, h radiative decays

Sizable deviation from 1:

- Non-negligible contributions from **hidden strangeness**
- Signicant deviation from the quark model description

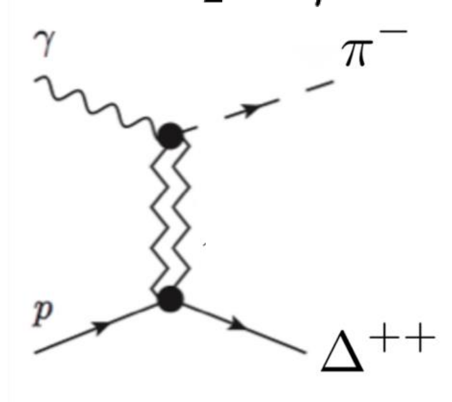
$\pi\Delta$ photoproduction



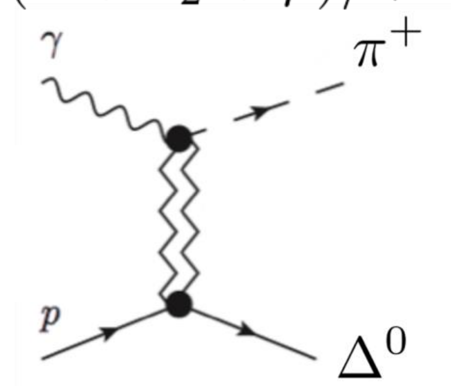


- Regge poles and cuts included
- Poor man absorption for π exchange
- Photocouplings extracted from radiative decays, $\beta_{+,1}^{a_2,\gamma\pi} \sim 1.8 \times \beta_{+,1}^{\rho,\gamma\pi}$ and $\beta_{+,1}^{\pi,\gamma\pi} \sim 4.4 \times \beta_{+,1}^{b,\gamma\pi}$ instead of the factor of 3 suggested by VMD
- Bottom vertices $g_{\rho p\Delta}$, $g_{a_2 p\Delta}$ degenerate
- $\alpha_\rho = \alpha_{a_2}$ (weak degeneracy)

$\pi + a_2 - \rho$

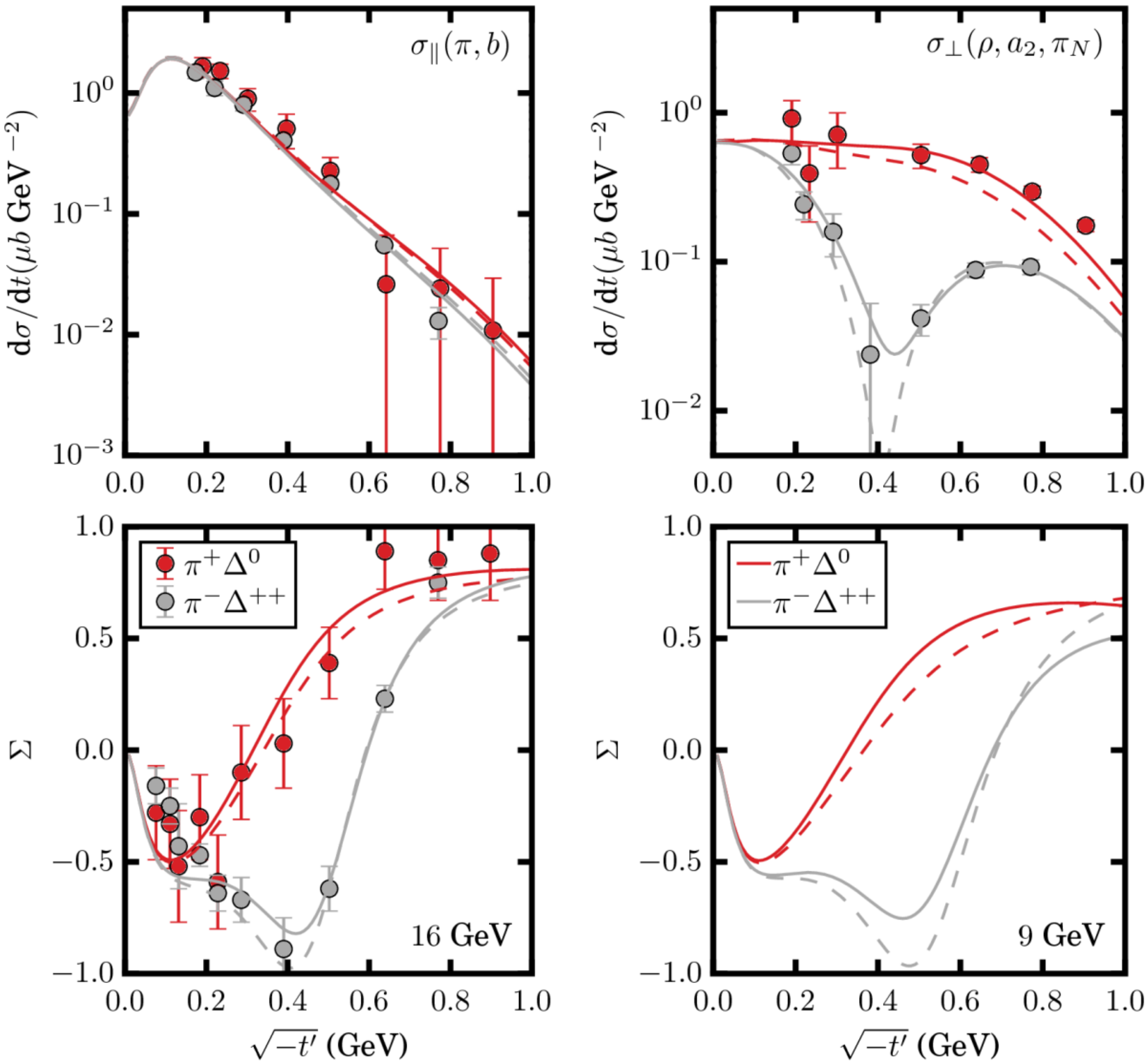


$(\pi + a_2 + \rho)/\sqrt{3}$



Data: Boyarski (1968), Quinn (1979)

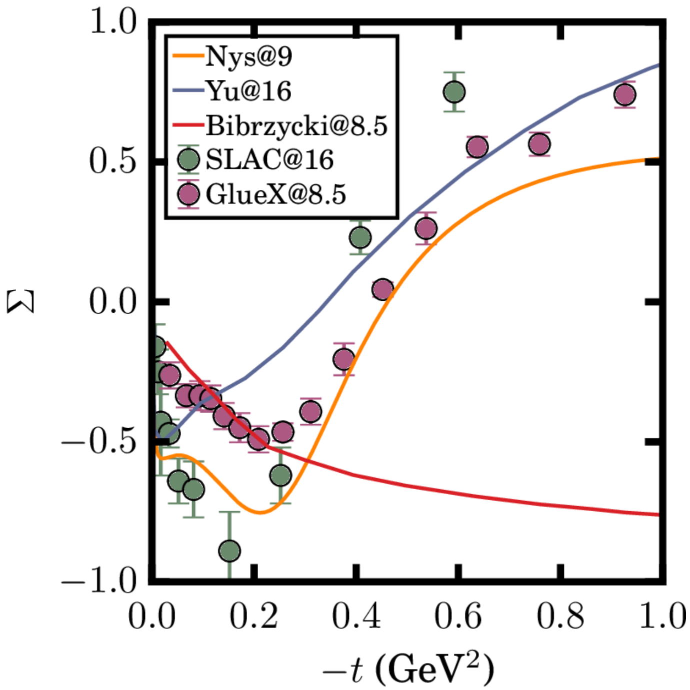
Polarized σ and beam asymmetry

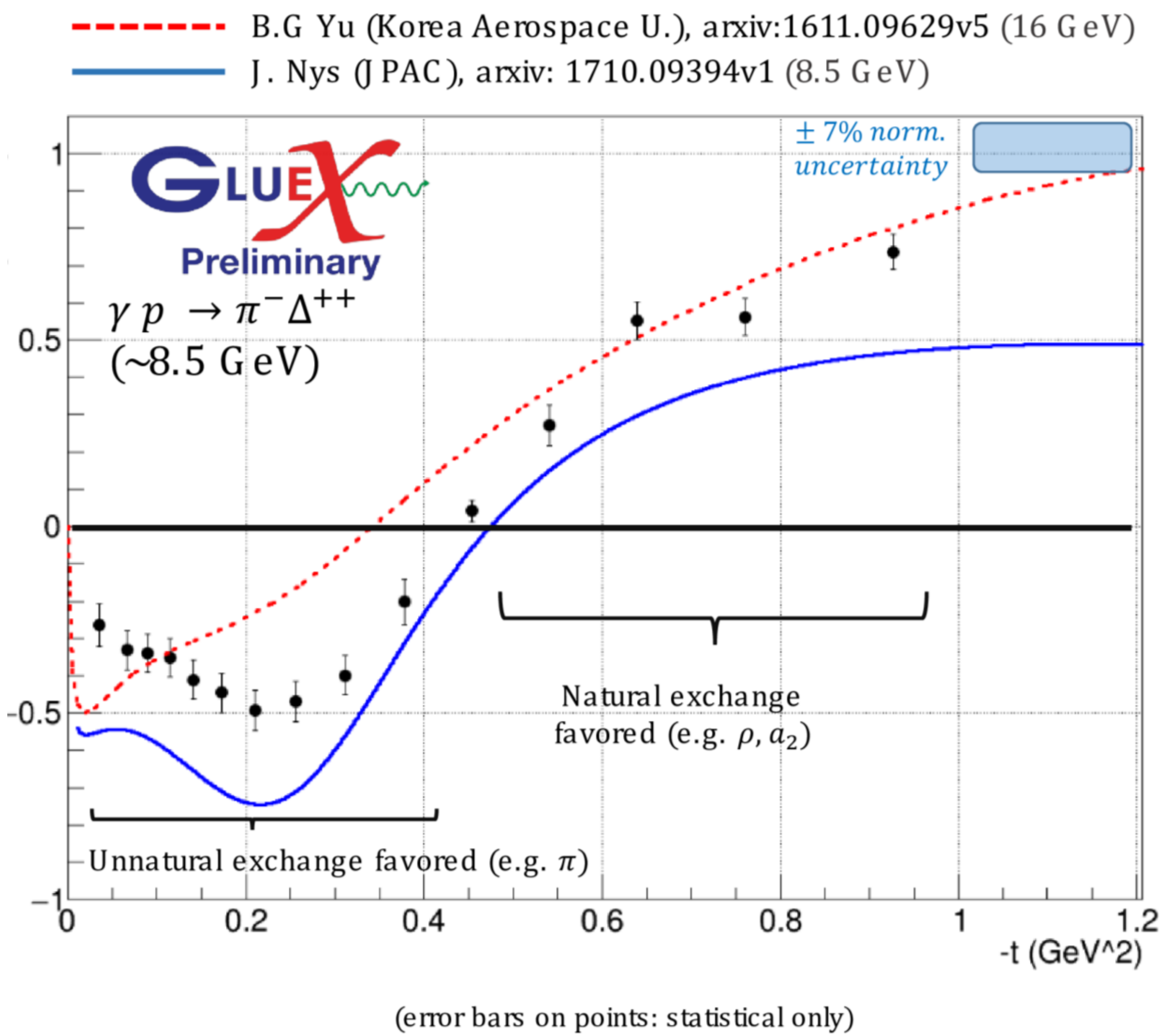


$\Sigma = +1 : \rho, a_2$

$\Sigma = -1 : \pi, b$

Beam asymmetry at GlueX

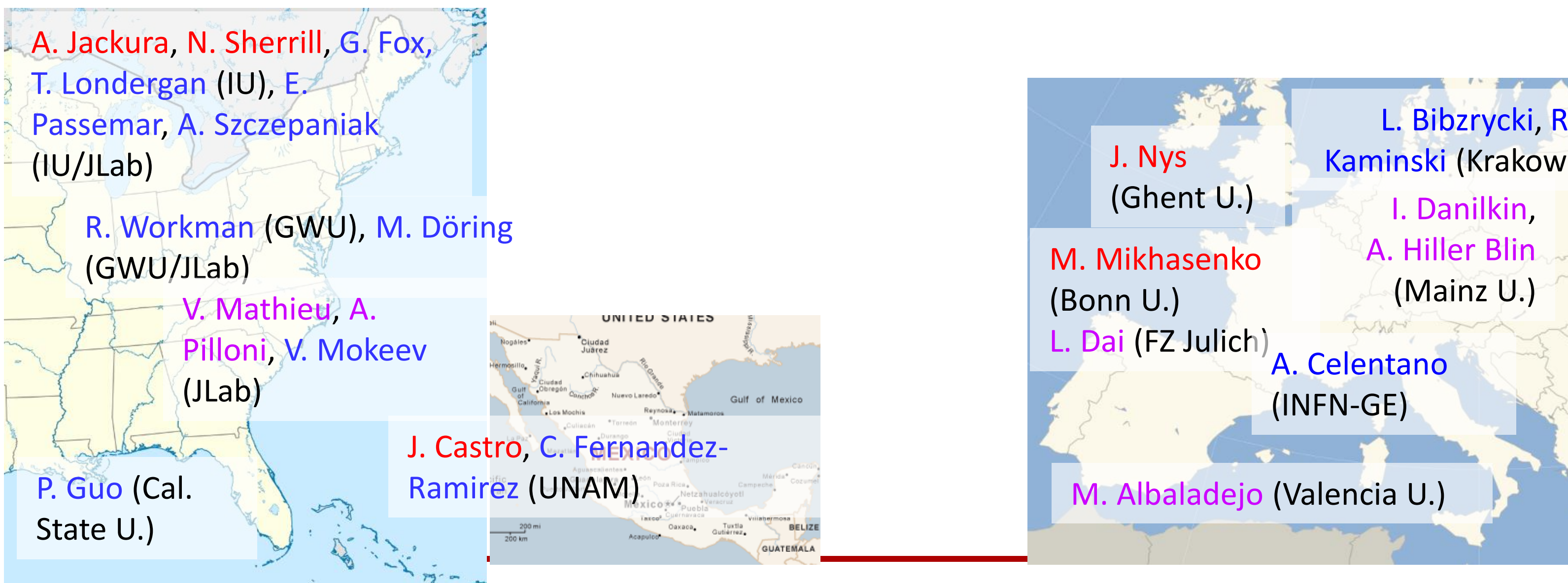




J. Zarling, APS-DNP2017

Conclusions

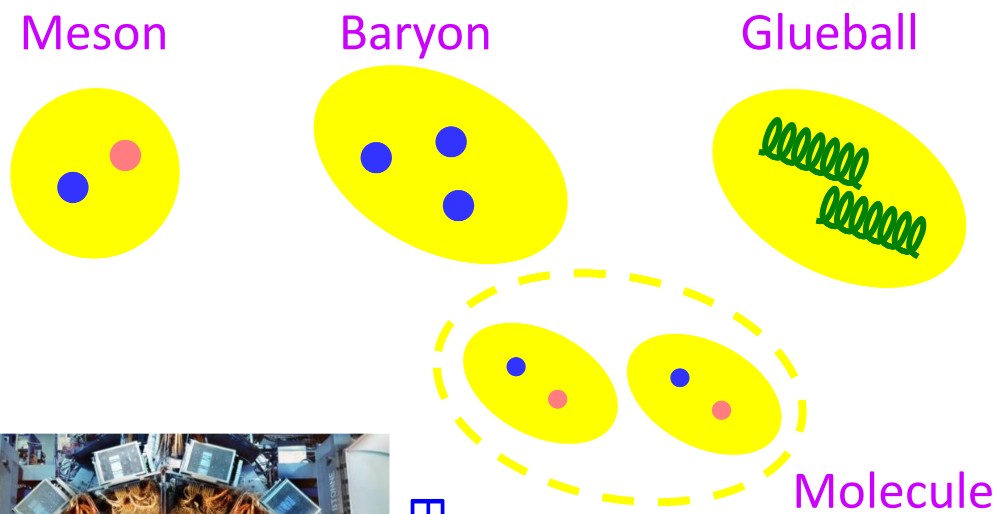
- Joint Physics Analysis Center is a joint effort between theorists and experimentalists to work together to make the best use of the next generation of very precise data taken at JLab and in the world
- Codes are public and available on http://www.indiana.edu/~jpac/
- Many other ongoing projects (both for meson and baryon spectroscopy, and for high energy observables), with a particular attention to producing complete reaction models for the golden channels in exotic meson searches

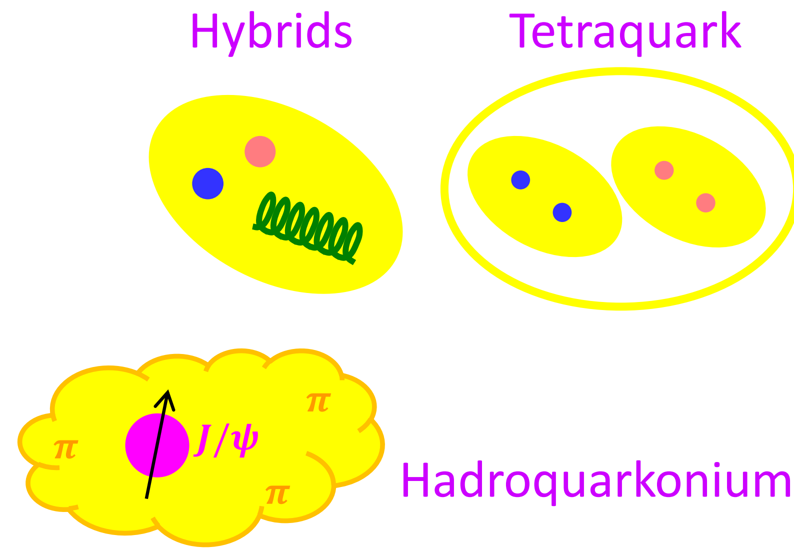


Students, Postdocs, Faculties

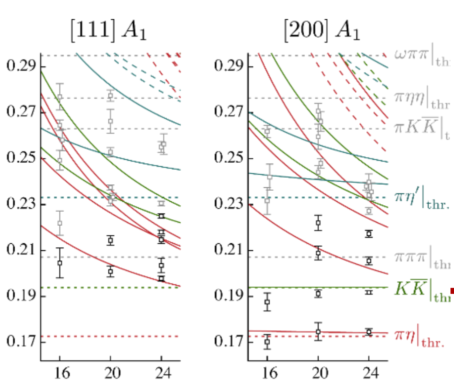
BACKUP

Hadron Spectroscopy





Experiment



Lattice QCD

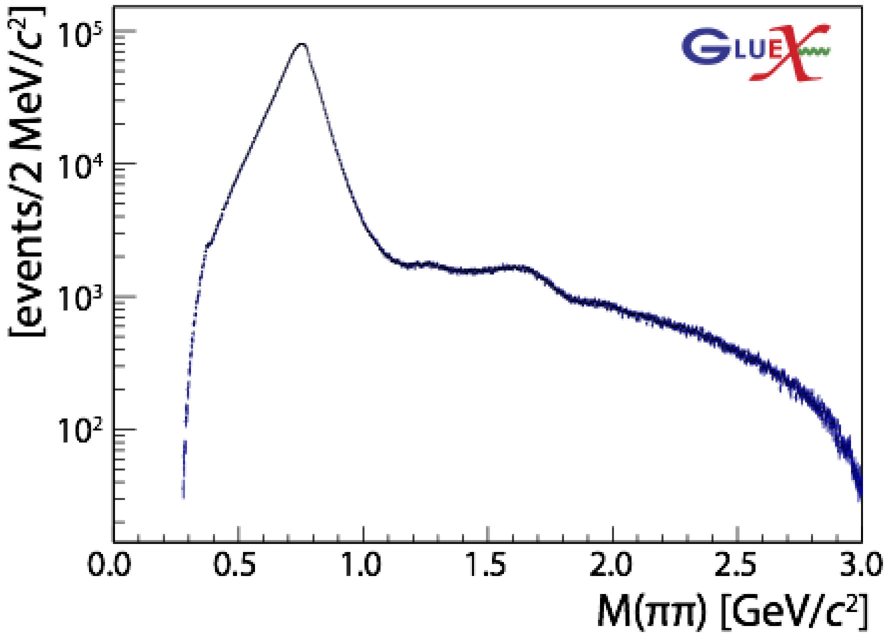
Data

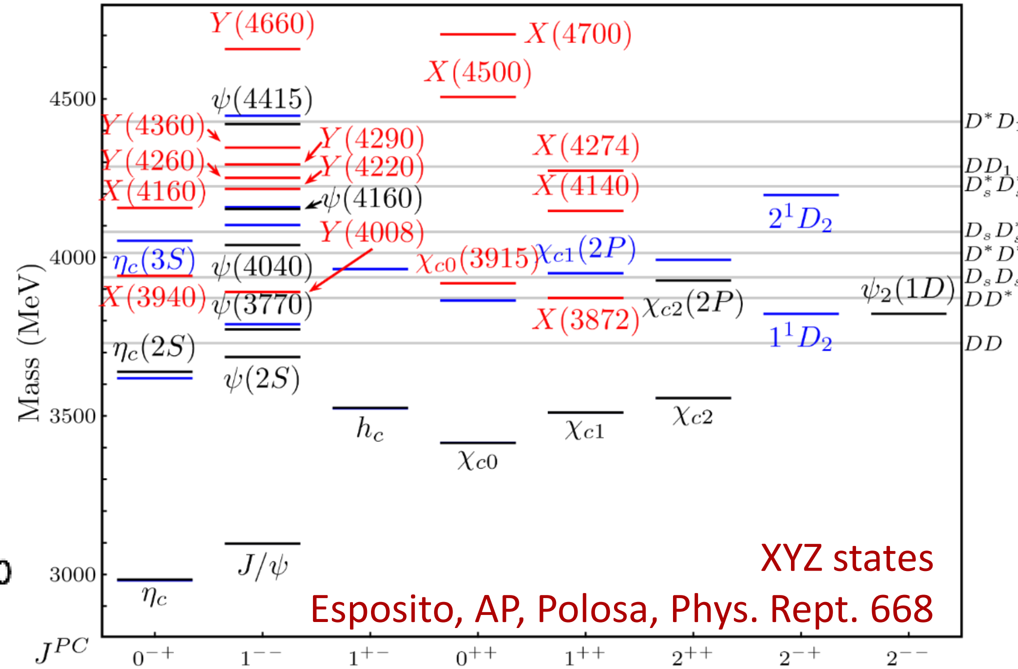
?

Fundamental properties, Model building

Interpretations on the spectrum leads to understanding fundamental laws of nature

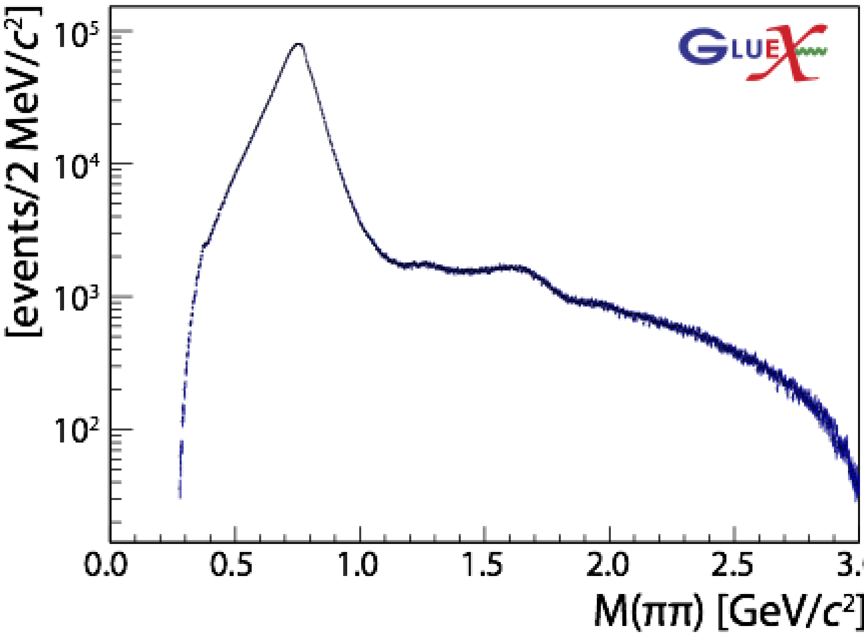
Hadron Spectroscopy

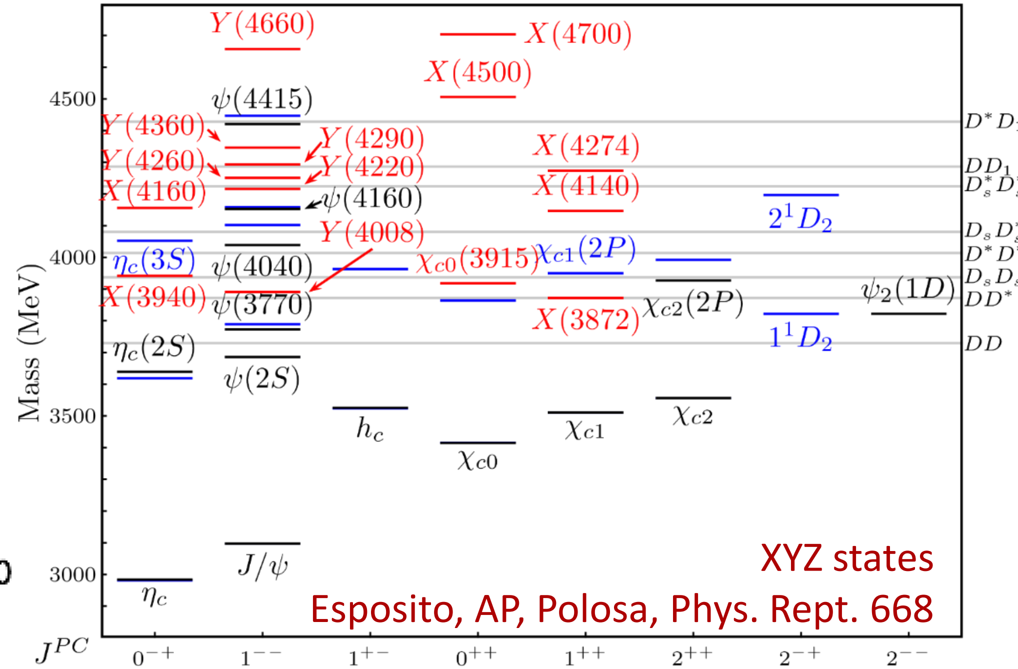




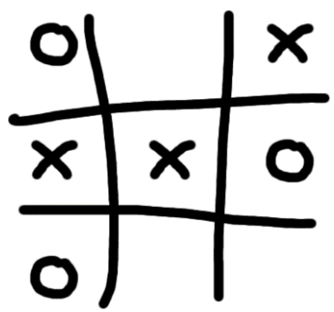
Data → ? → Fundamental properties, Model building

Hadron Spectroscopy



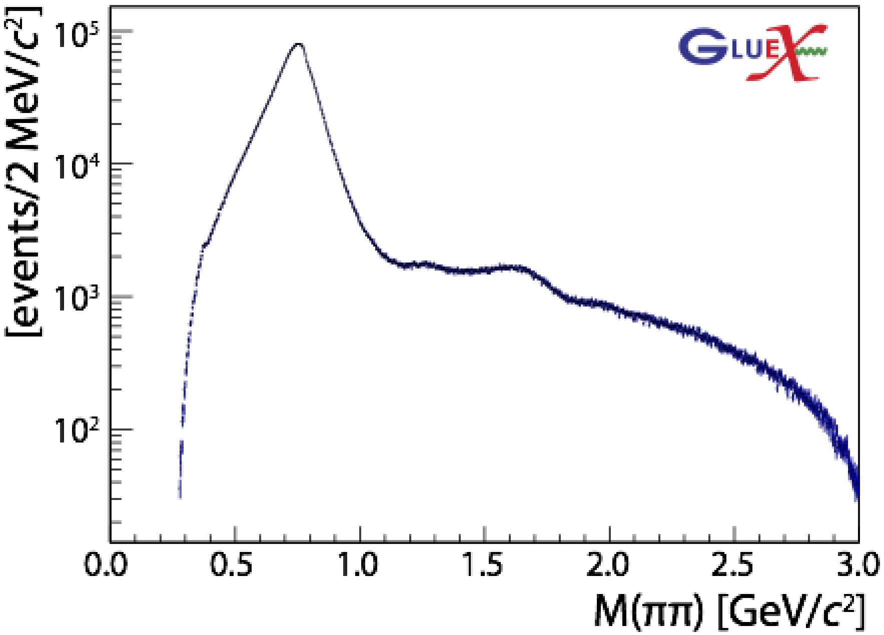


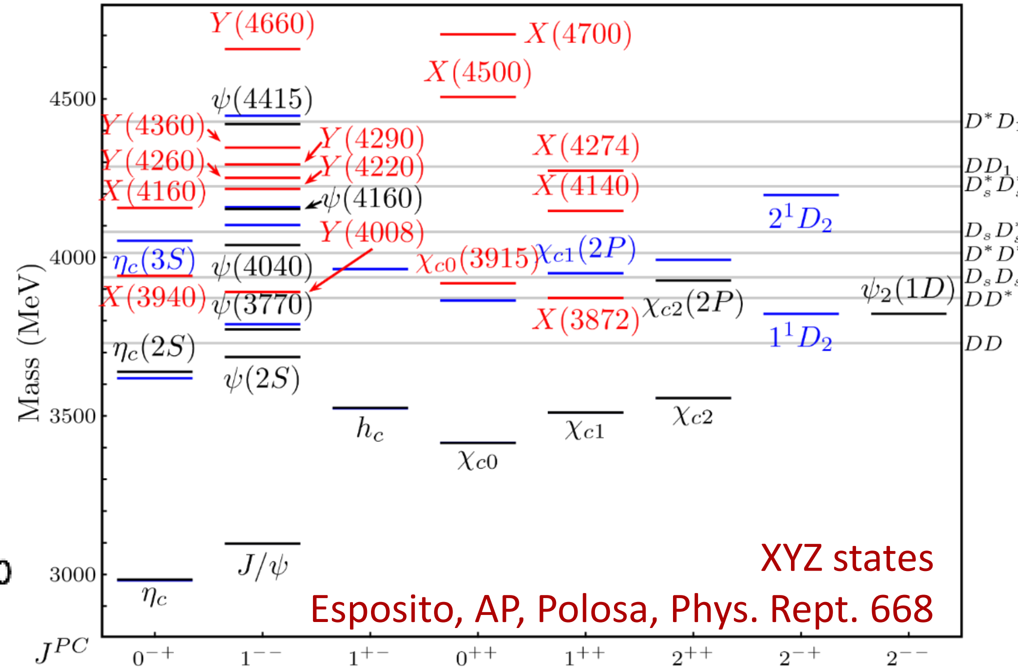
Data

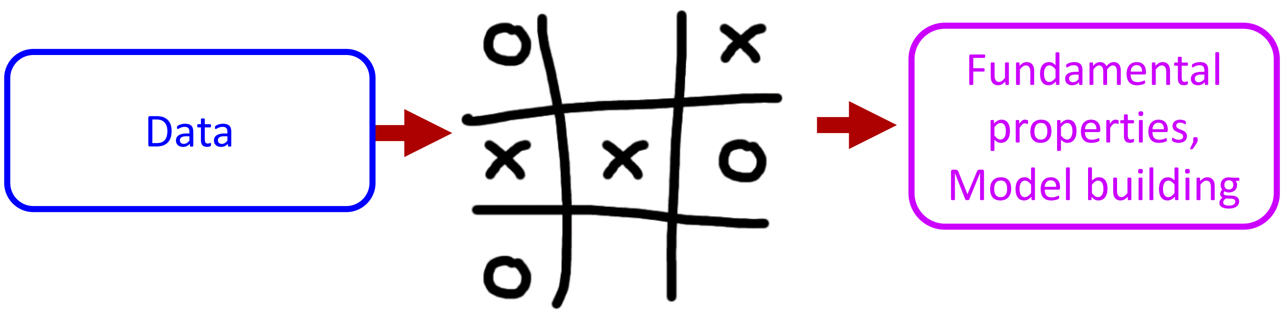


Fundamental properties, Model building

Hadron Spectroscopy



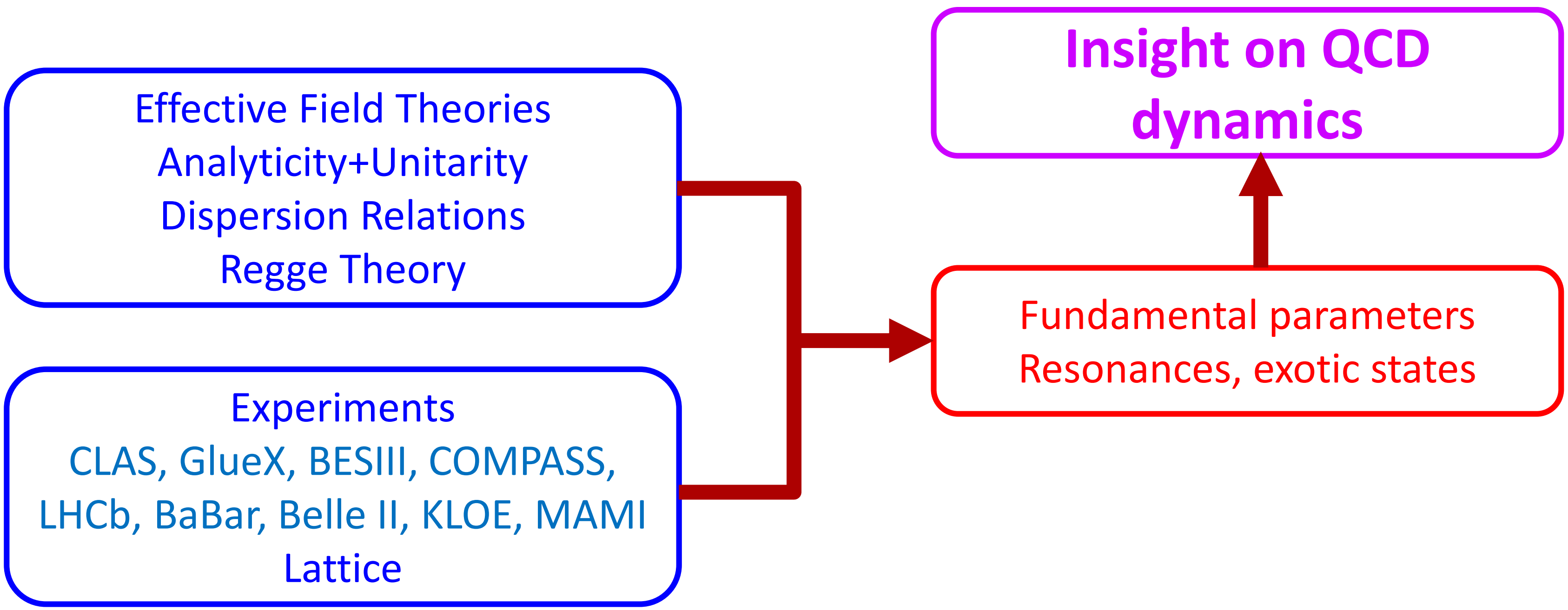




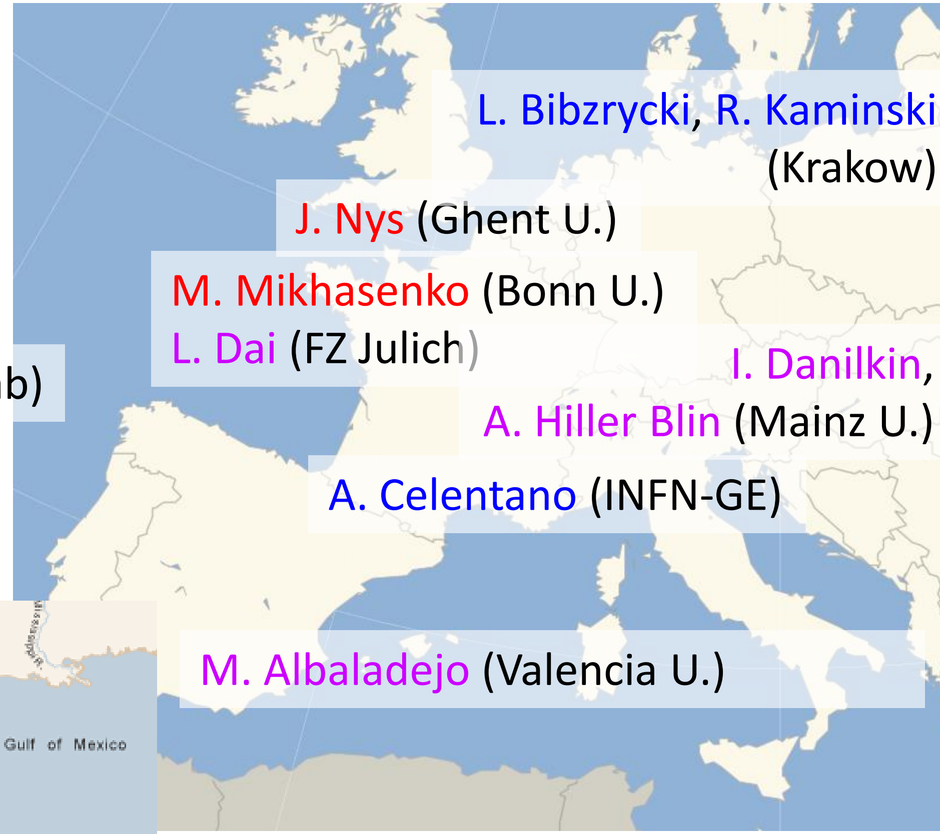
Improvement needed! With great statistics comes great responsibility!

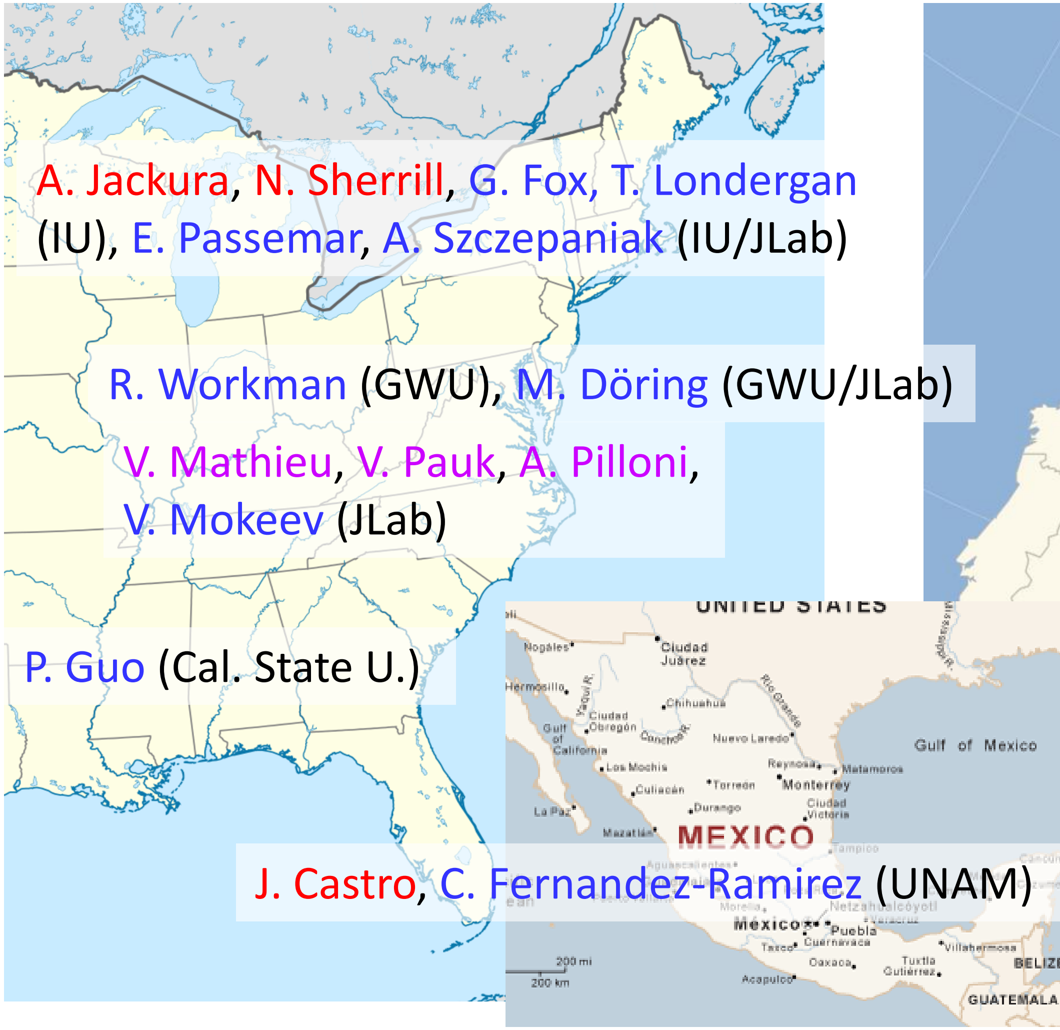
Joint Physics Analysis Center

- Joint effort between theorists and experimentalists to work together to make the best use of the next generation of very precise data taken at JLab and in the world
- Created in 2013 by JLab & IU agreement
- It is engaged in education of further generations of hadron physics practitioners



Joint Physics Analysis Center





A. Jackura, N. Sherrill, G. Fox, T. Londergan (IU), E. Passemar, A. Szczepaniak (IU/JLab)

R. Workman (GWU), M. Döring (GWU/JLab)

V. Mathieu, V. Pauk, A. Pilloni, V. Mokeev (JLab)

P. Guo (Cal. State U.)

J. Castro, C. Fernandez-Ramirez (UNAM)

L. Bibzrycki, R. Kaminski (Krakow)

J. Nys (Ghent U.)

M. Mikhasenko (Bonn U.)

L. Dai (FZ Julich)

I. Danilkin, A. Hiller Blin (Mainz U.)

A. Celentano (INFN-GE)

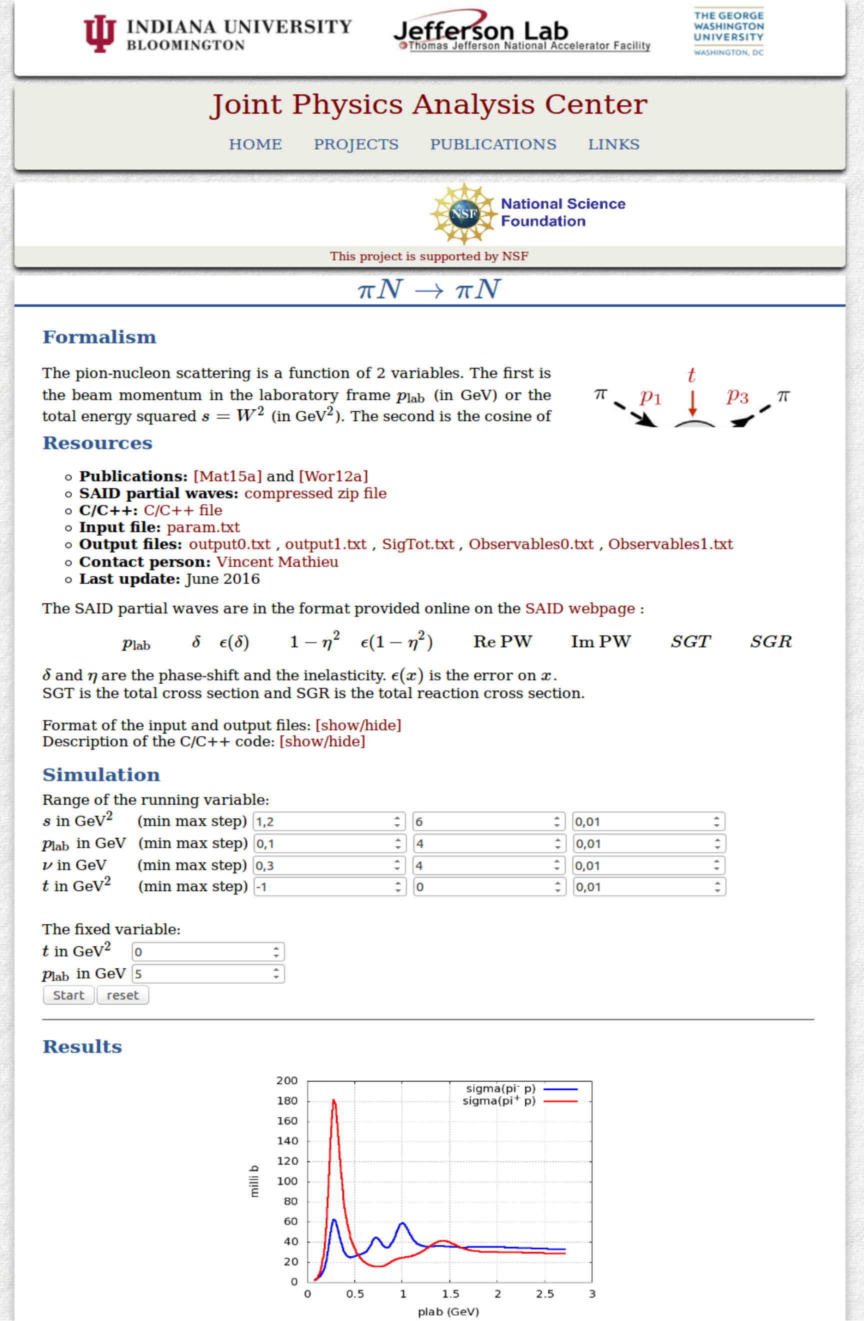
M. Albaladejo (Valencia U.)

Students, Postdocs, Faculties

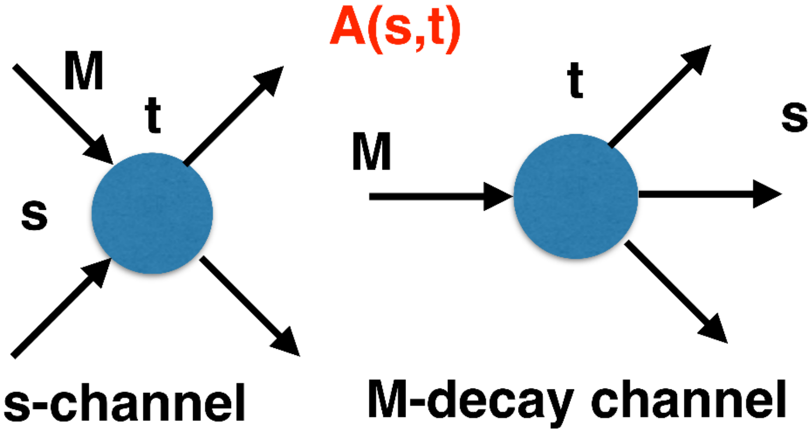
Interactive tools

- Completed projects are fully documented on interactive portals
- These include description on physics, conventions, formalism, etc.
- The web pages contain source codes with detailed explanation how to use them. Users can run codes online, change parameters, display results.

http://www.indiana.edu/~jpac/



S-Matrix principles



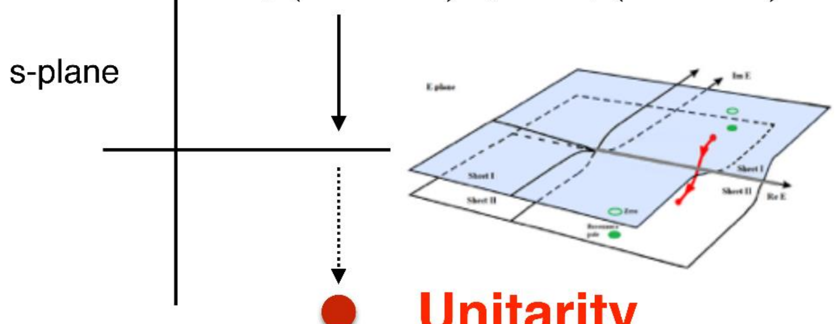
Crossing

$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

Analyticity

$$A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)$$

$$A_l(s+i\epsilon) \neq A_l(s-i\epsilon)$$



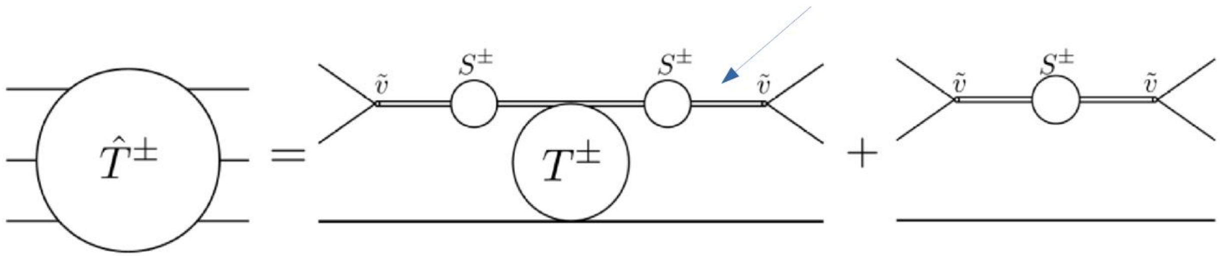
Unitarity

These are constraints the amplitudes have to satisfy, but do not fix the dynamics

Resonances (QCD states) are poles in the unphysical Riemann sheets

Three-Body Unitarity

Hu, Mai, Doring, AP, Szczepaniak, EPJA, arXiv:1707.06118



The full implementation of three-body unitarity is a major step for understanding the states appearing in such final states

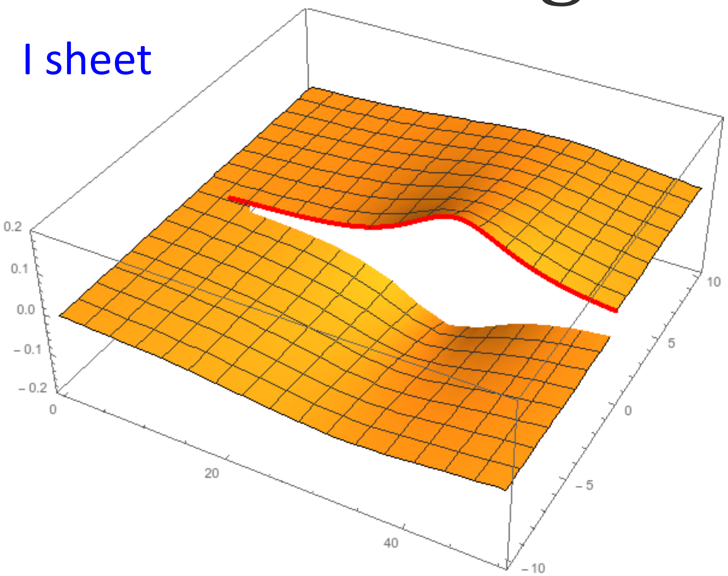
e.g. $a_1(1260)^+ \to \pi^+\pi^-\pi^+, \pi_1(1400)^+ \to \pi^+\pi^-\pi^+, X(3872) \to D^0\overline{D^0}\pi^0$

We completed the proof of the Amado model,
based on the isobar approximation
and a Bethe-Salpeter ansatz for the amplitude

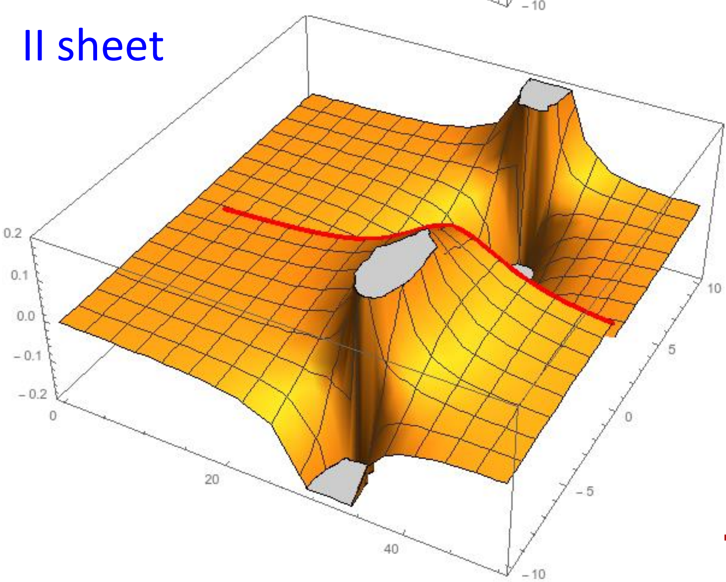
See M. Doring's talk at 11:30am

Pole hunting

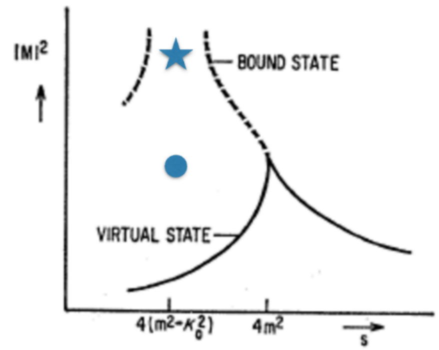
I sheet

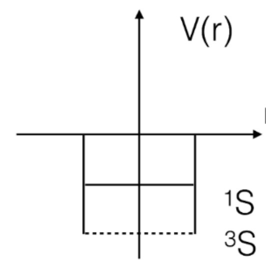


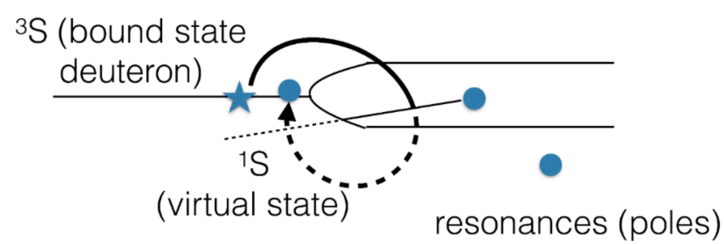
II sheet



Bound states on the real axis 1st sheet
Not-so-bound (virtual) states on the real axis 2nd sheet

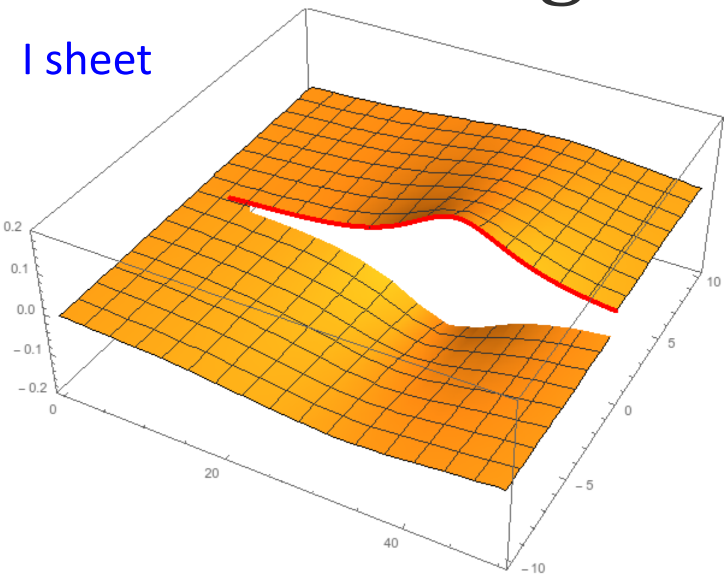




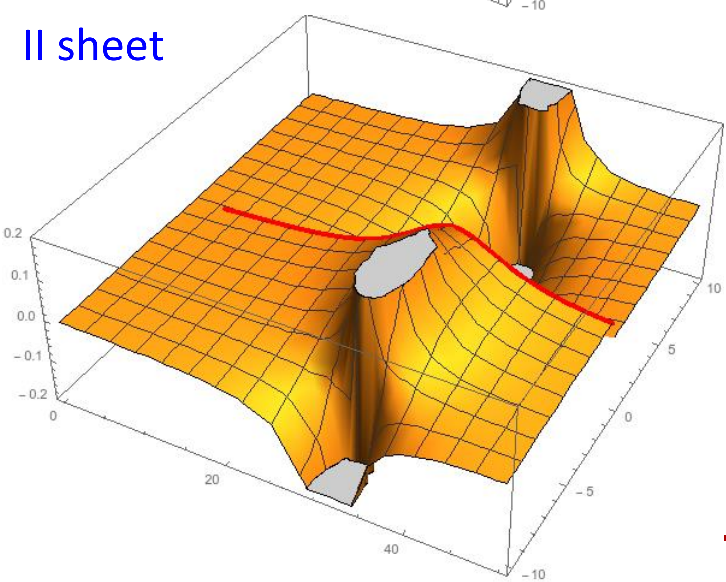


Pole hunting

I sheet



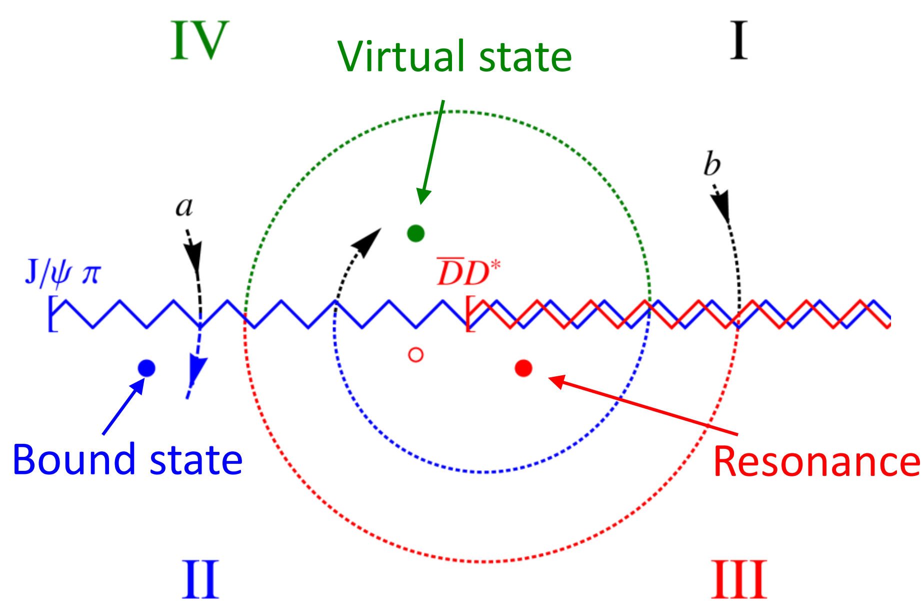
II sheet



More complicated structure when
more thresholds arise:
two sheets for each new threshold

III sheet: usual resonances

IV sheet: cusps (virtual states)

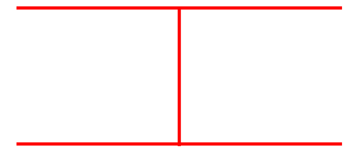


Higher energies: Regge exchange

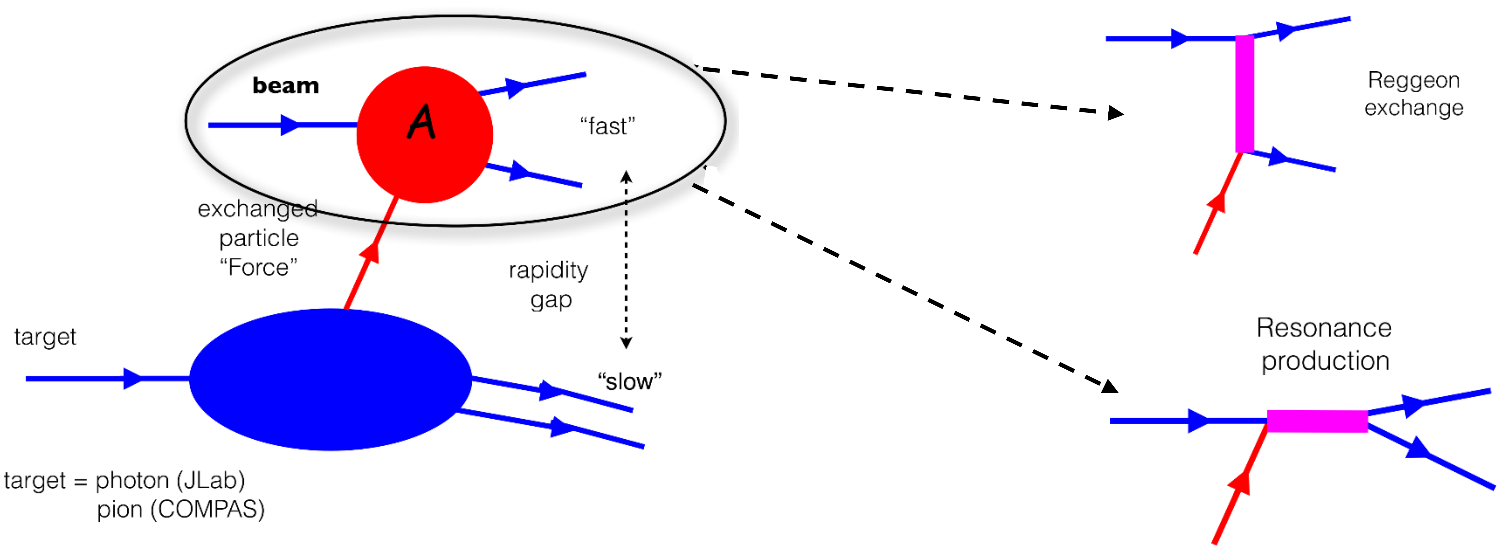
Resonances are poles in s for fixed l
dominate low energy region

$$A_l \sim \frac{g_1 g_2}{s_p - s}$$

Reggeons are poles in l for fixed s
dominate high energy region



$$A \sim \sum s^l \sim \beta(t)\, s^{\alpha(t)}$$



Production

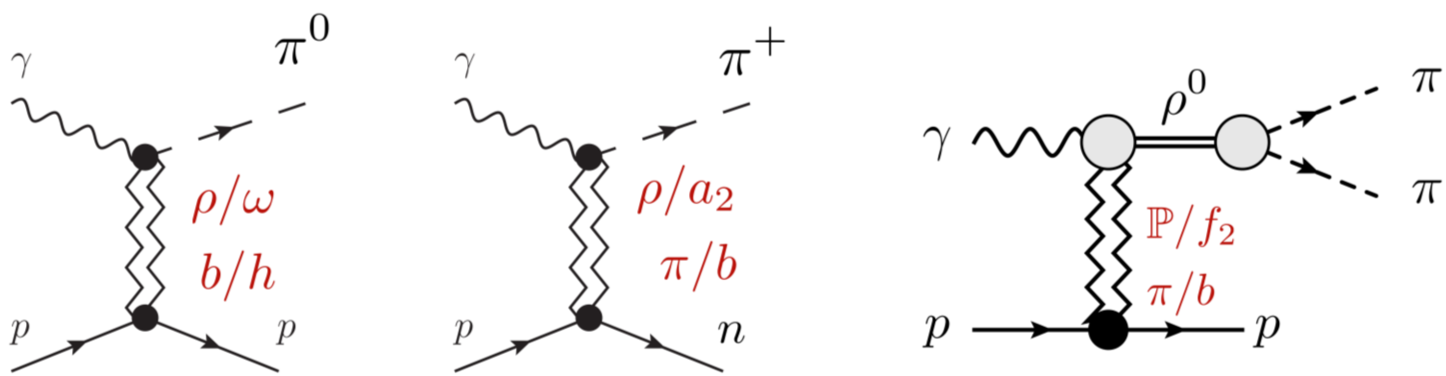
- $>$ 40 Research Papers (Phys.Rev., Phys.Lett, Eur.J. Phys.)
- $\sim$120 Invited Talks and Seminars
- $O(10)$ ongoing analyses
- Summer Schools on Reaction Theory (IU, 2015 and 2017)
- Workshop "Future Directions in Hadron Spectroscopy" (JLab, 2014 and UNAM 2017)

FESR	V. Mathieu *et al.*,	arXiv:1708.07779
$\pi\, N \to \eta\, \pi\, N$	A. Jackura *et al.*,	arXiv:1707.02848
$\gamma\, N \to \eta\, N$ vs. $\to \eta'\, N$	V. Mathieu *et al.*,	arXiv:1704.07684
$Z_c(3900)$	A. Pilloni *et al.*,	PLB772, 200
$\gamma\, N \to \eta\, N$	J. Nys *et al.*,	PRD95, 034014
$\gamma\, p \to J/\psi\, p$	A. Blin *et al.*,	PRD94, 034002
$K\, N \to K\, N$	C. Fernandez-Ramirez *et al.*,	PRD93, 034029; PRD93, 074015
$\gamma\, p \to \pi^0\, p$	V. Mathieu *et al.*,	PRD92, 074013
$\pi\, N \to \pi\, N$	V. Mathieu *et al.*,	PRD92, 074004
$\eta \to \pi^+\, \pi^-\, \pi^0$	P. Guo *et al.*,	PRD92, 054016; PLB771, 497
$\omega, \phi \to \pi^+\, \pi^-\, \pi^0$	I. Danilkin *et al.*,	PRD91, 094029
$\gamma\, p \to K^+\, K^-\, p$	M. Shi *et al.*,	PRD91, 034007

π, ρ photoproduction

Test factorization on the simplest cases

1. Neutral pion photoproduction
2. Charged pion photoproduction
3. Rho meson photoproduction



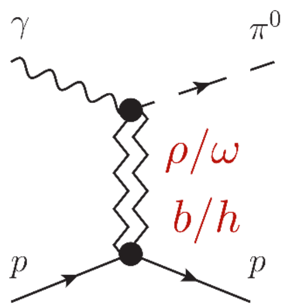
natural exchanges: $\rho/\omega/f_2/a_2/\mathbb{P}$ $\quad P = (-)^J$

unnatural exchanges: $\pi/b/h$ $\quad P = -(-)^J$

special ?

$\gamma\, p \rightarrow \pi^0\, p$

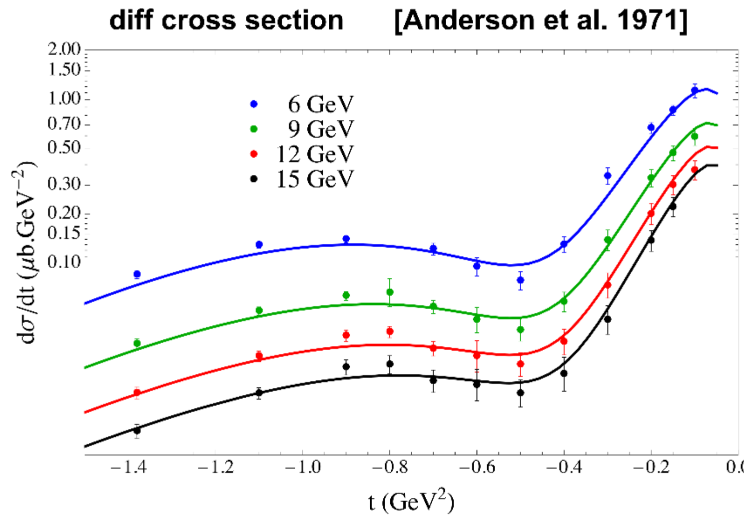
Model based on factorization with parameters fitted

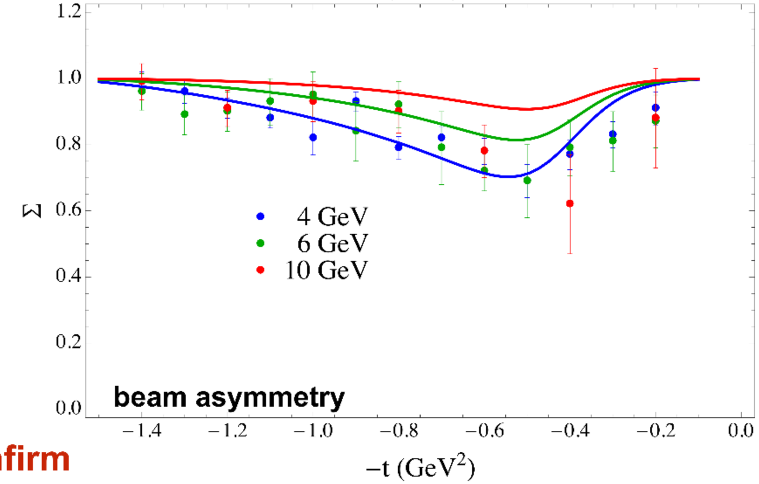


$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

axial-vector exchanges strength decreases with energy

More precise data@JLAB could confirm

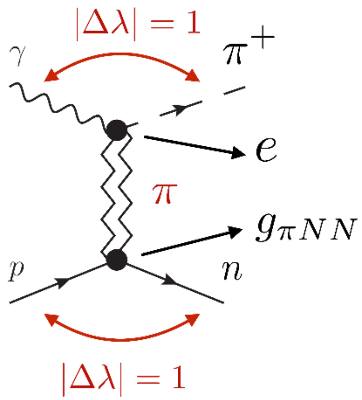




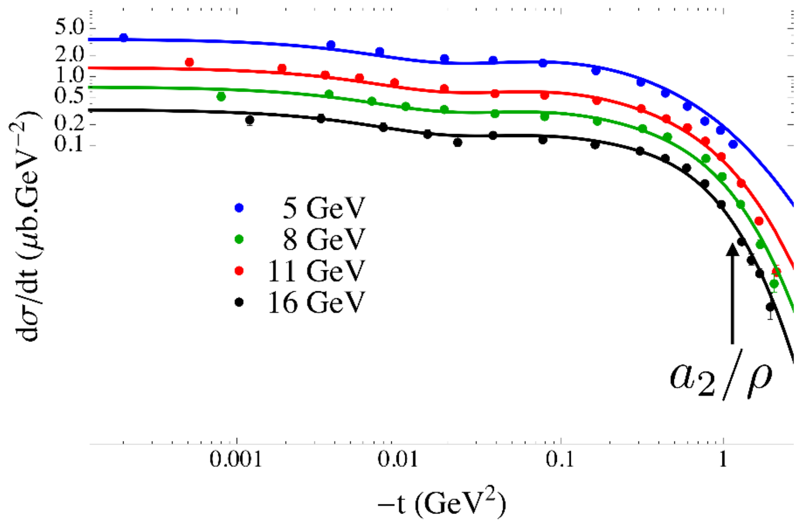
Mathieu *et al.* (JPAC), PRD92, 074013

$\gamma\, p \to \pi^+\, n$

Pion dominate very small |t| :



[Boyarski et al. 1968]



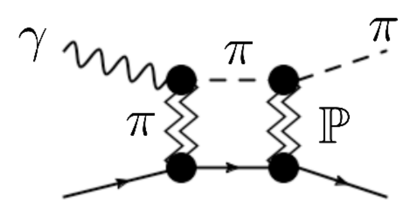
Factorization of Regge residues:
$(\lambda_\gamma, \lambda_\pi) = (1, 0)$ **and**

$$(\lambda_p, \lambda_n) = \left(-\frac{1}{2}, +\frac{1}{2}\right) \qquad A^{10}_{-\frac{1}{2}\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

$$(\lambda_p, \lambda_n) = \left(+\frac{1}{2}, -\frac{1}{2}\right) \qquad A^{10}_{\frac{1}{2}-\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

$$|(\lambda_\gamma - \lambda_p) - (\lambda_\pi - \lambda_{p'})| = 0$$

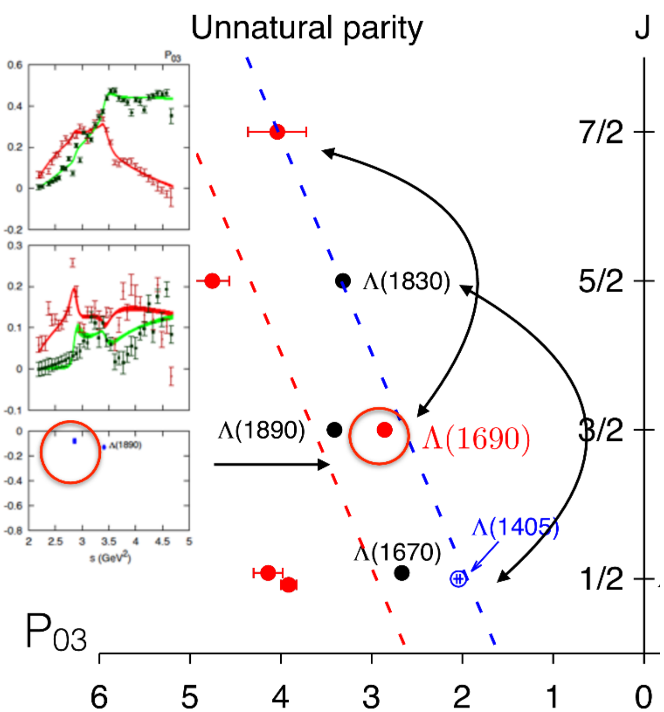
William's Poor man absorption: $\rightarrow \dfrac{-m_\pi^2}{m_\pi^2 - t}$

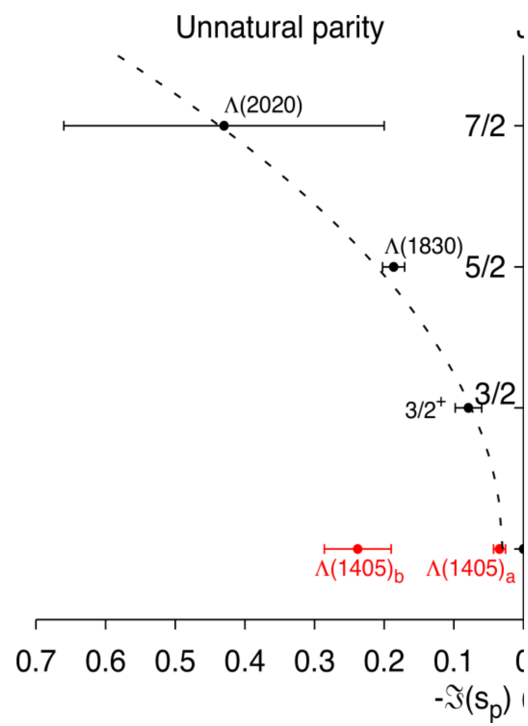


Mathieu (JPAC), in progress

KN scattering and the $\Lambda(1405)$

Coupled-channel K matrix model (up to 13 channels per partial wave), analyticity in angular momentum enforced, fit to KSU partial waves

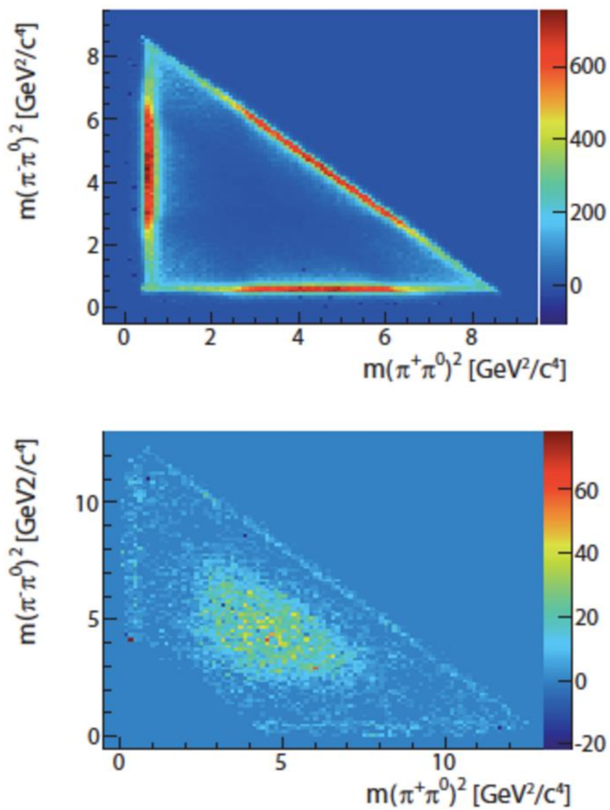




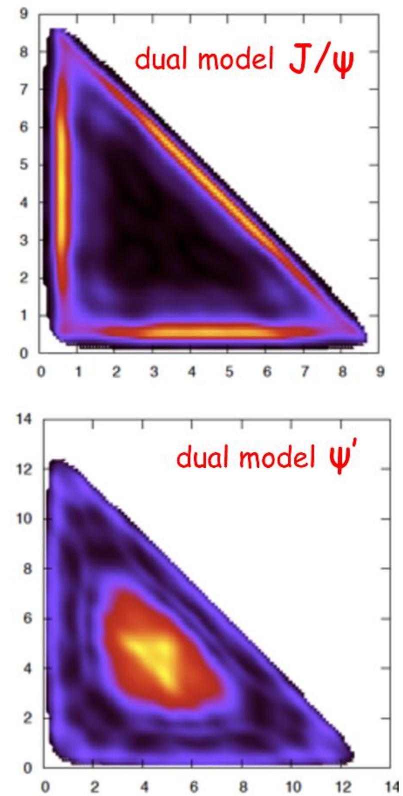
One of the $\Lambda(1405)$ poles is out of the trajectory
→ non 3-q state

Fernandez-Ramirez *et al*. (JPAC), PRD93, 034029
Fernandez-Ramirez *et al*. (JPAC), PRD93, 074015

$\psi^{(\prime)} \to \pi^+\pi^-\pi^0$ within dual models



BESIII, Phys.Lett. B710 (2012) 594-599



$$A(s,t) = \frac{\Gamma(-J(s))\Gamma(-J(t))}{\Gamma(-J(s)-J(t))}$$

Szczepaniak and Pennington, PLB737, 283