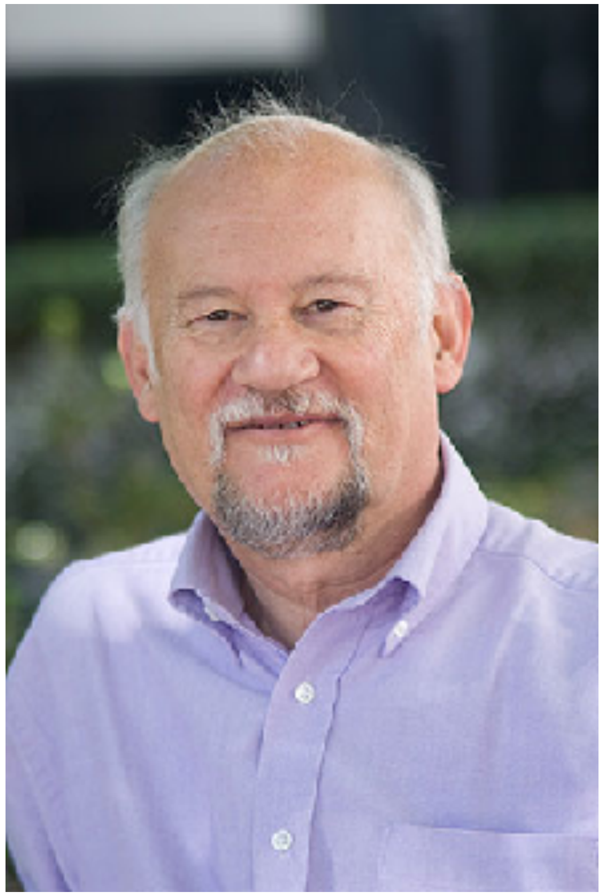
New results on hadron spectroscopy from JPAC

Adam Szczepaniak, Indiana University/Jefferson Lab

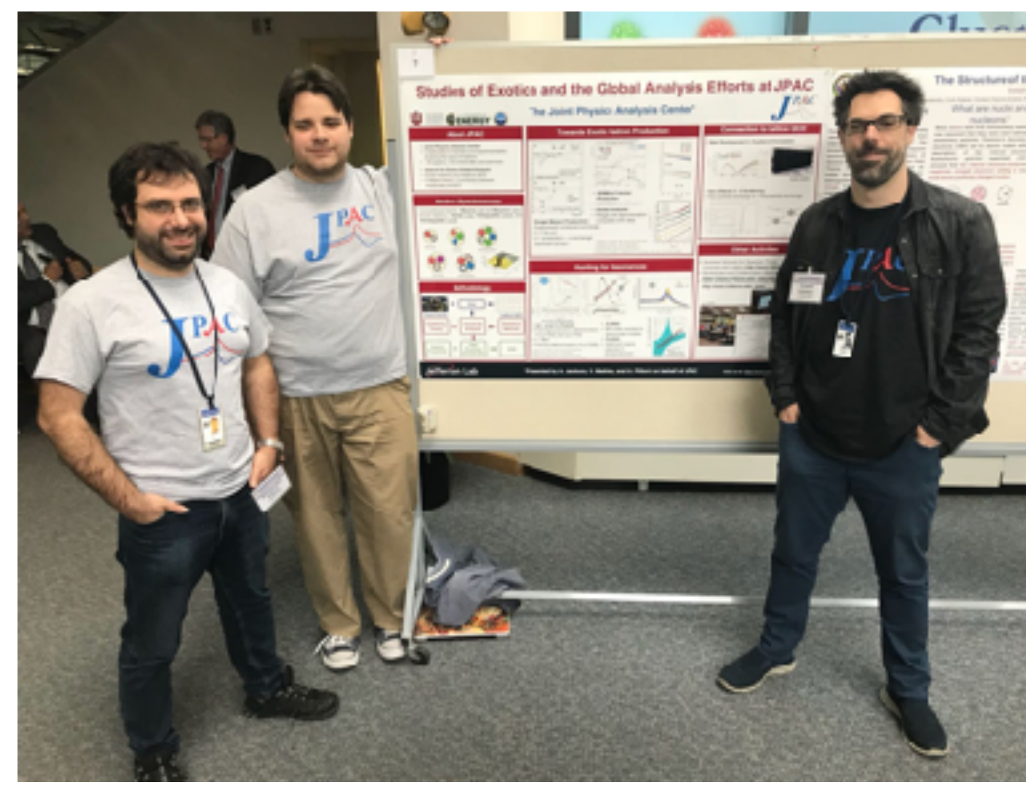
In Memory



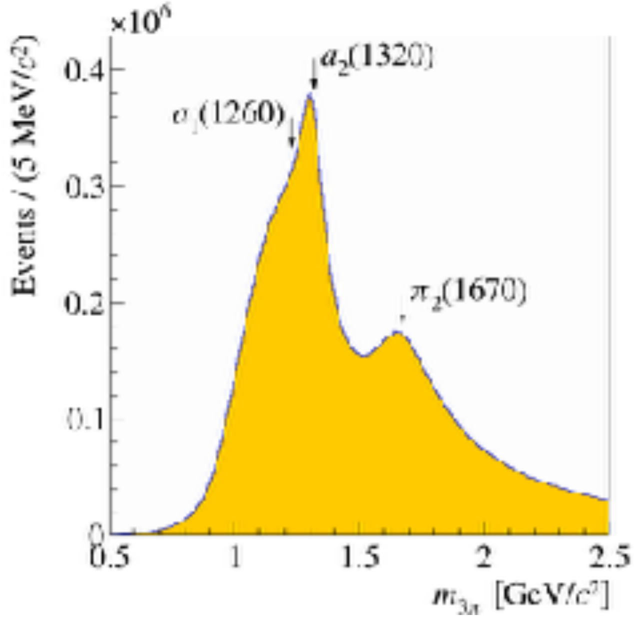
Mike Pennington (1946-2018)

Joint Physics Analysis Center

- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other accelerator laboratories.
- Contribute to education of new generation of practitioners in physics of strong interactions.
- In this talk : JPAC's role in spectroscopy analysis and some "exotic" physics

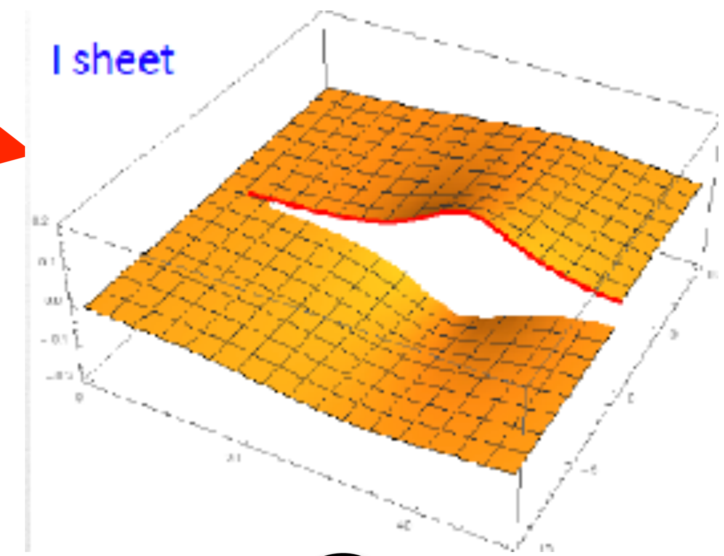


Identifying resonances



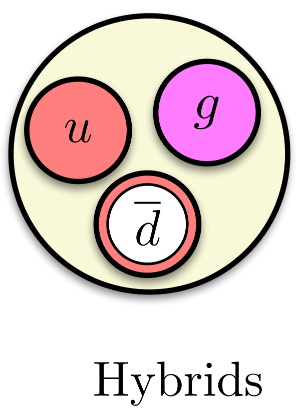
- Experimental or lattice signatures (real axis data: cross section bump and dips, energy levels)

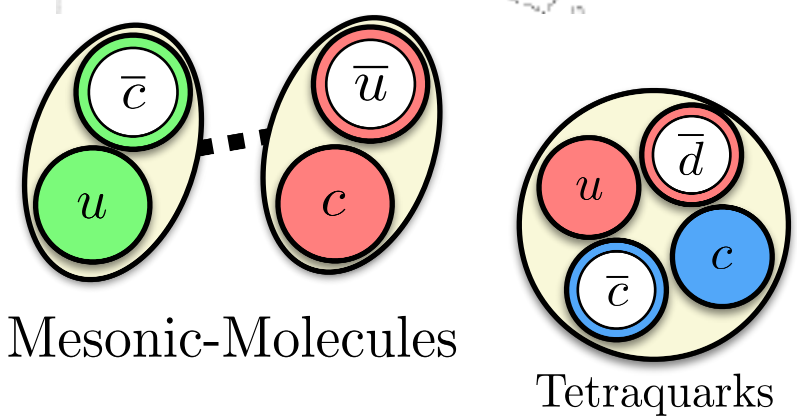
Reaction amplitudes



- Theoretical signatures (complex plane singularities: poles, cusps)

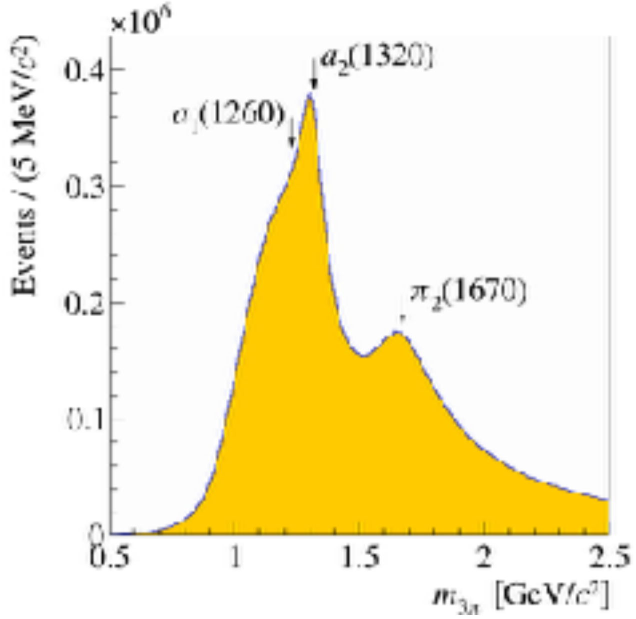
Microscopic Models

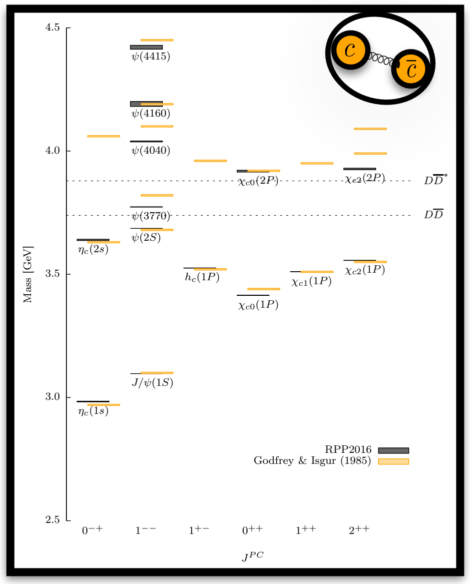




- What is the interpretation (constituent quarks, molecules, …) ?

Identifying resonances





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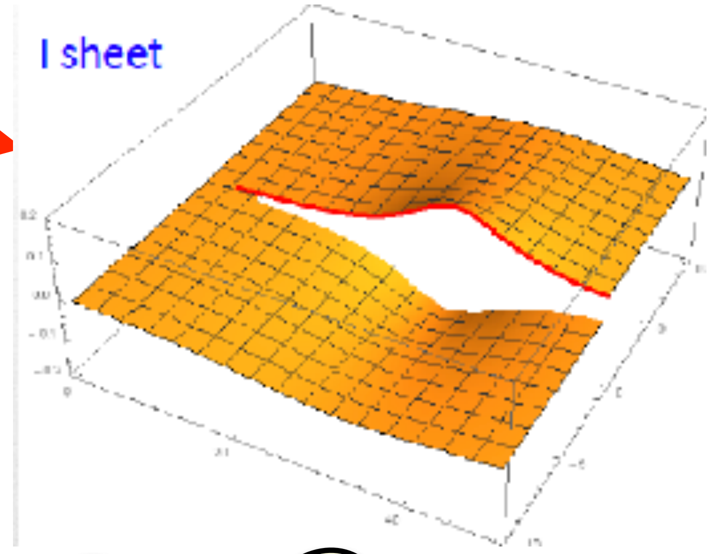
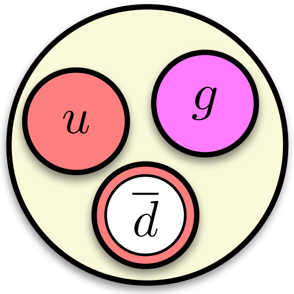
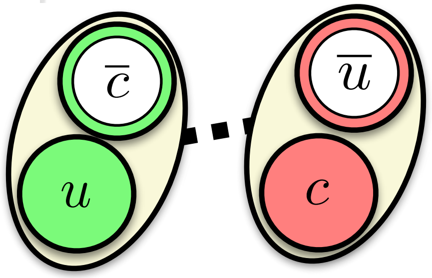


- Theoretical signatures (complex plane singularities: poles, cusps)

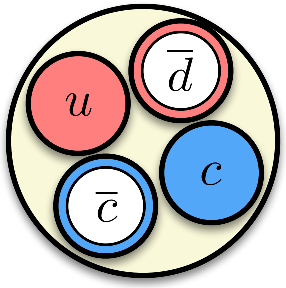
Microscopic Models



Hybrids



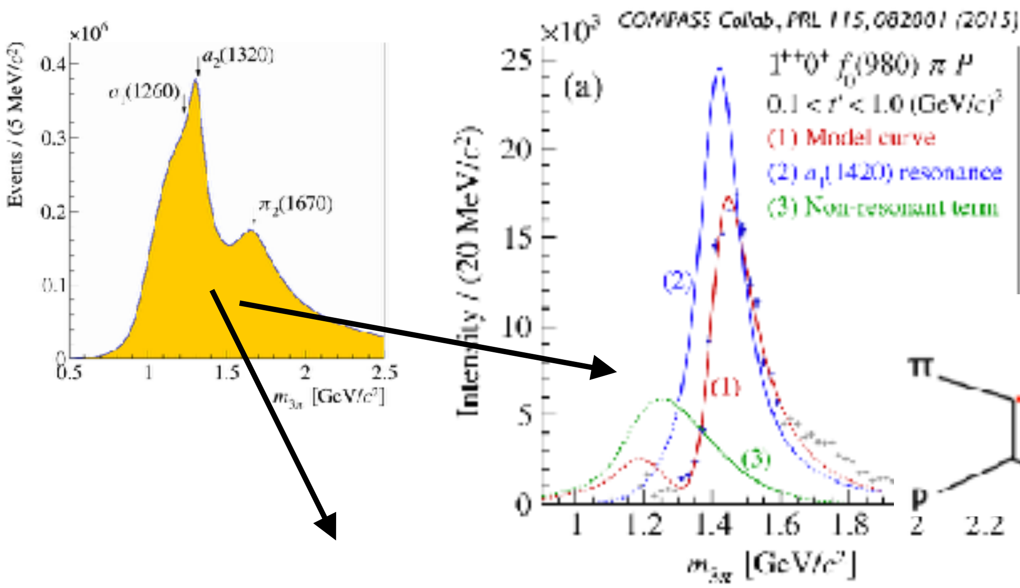
Mesonic-Molecules



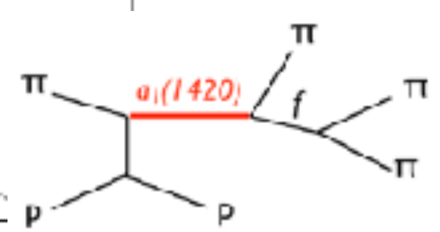
Tetraquarks

- What is the interpretation (constituent quarks, molecules, …) ?

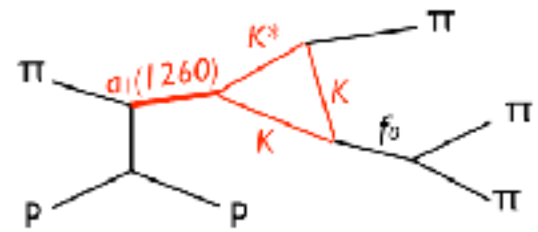
Signatures of new, unusual light resonances



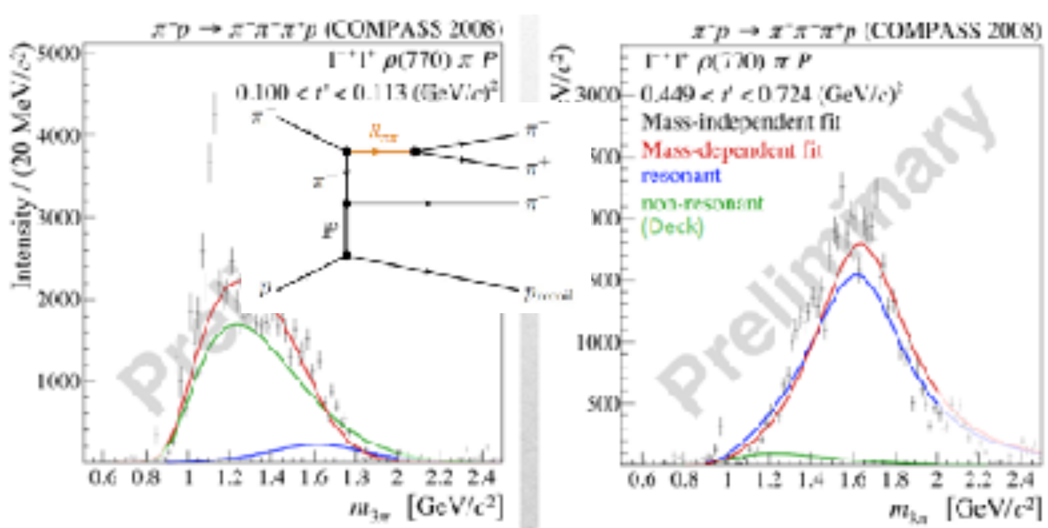
- High precision PWA of 3pi diffractive association yields a new $a_1(1420)$ incompatible with the quark model/Regge expectations.



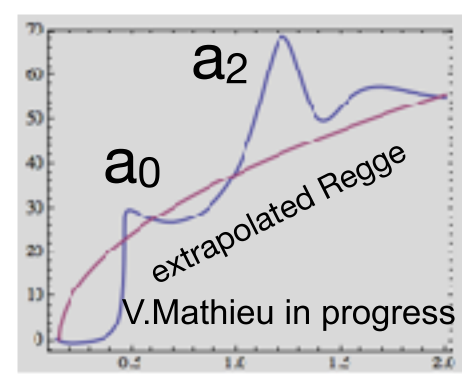
Or ?

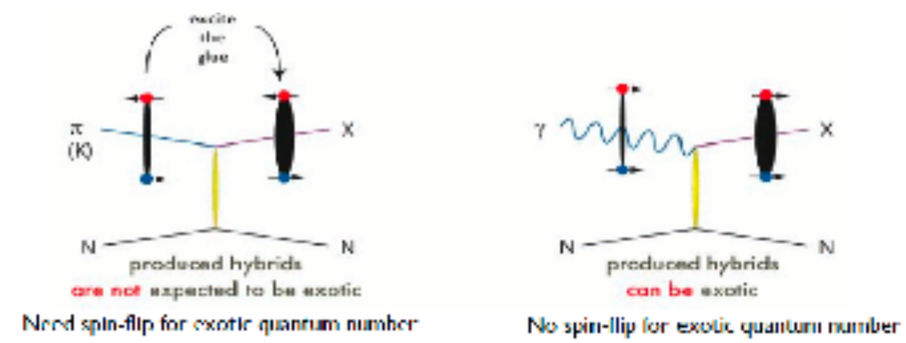


- At low-t exotic wave production compatible with one pion exchange

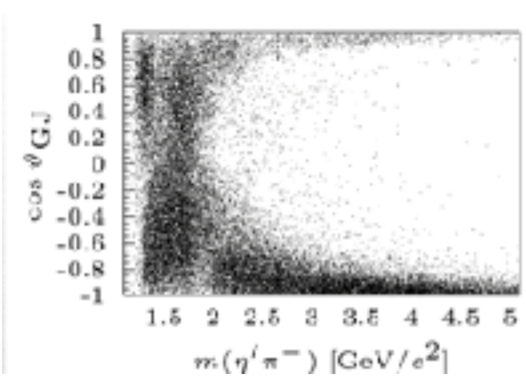


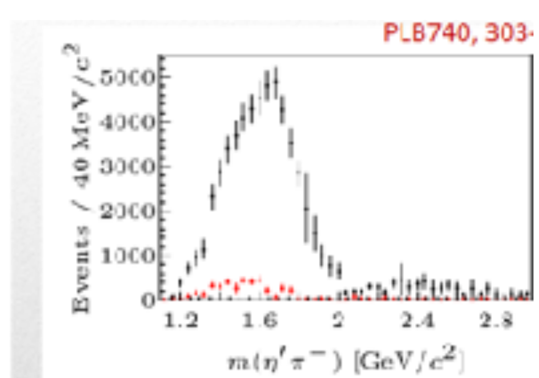
- In photoproduction exotic mesons be produced via pion exchange

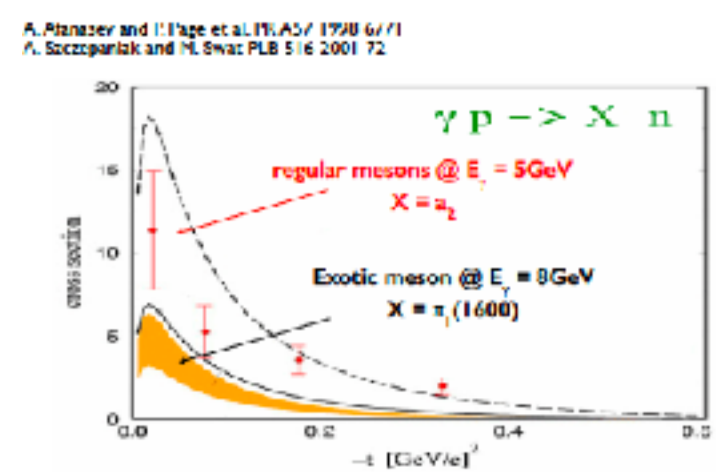




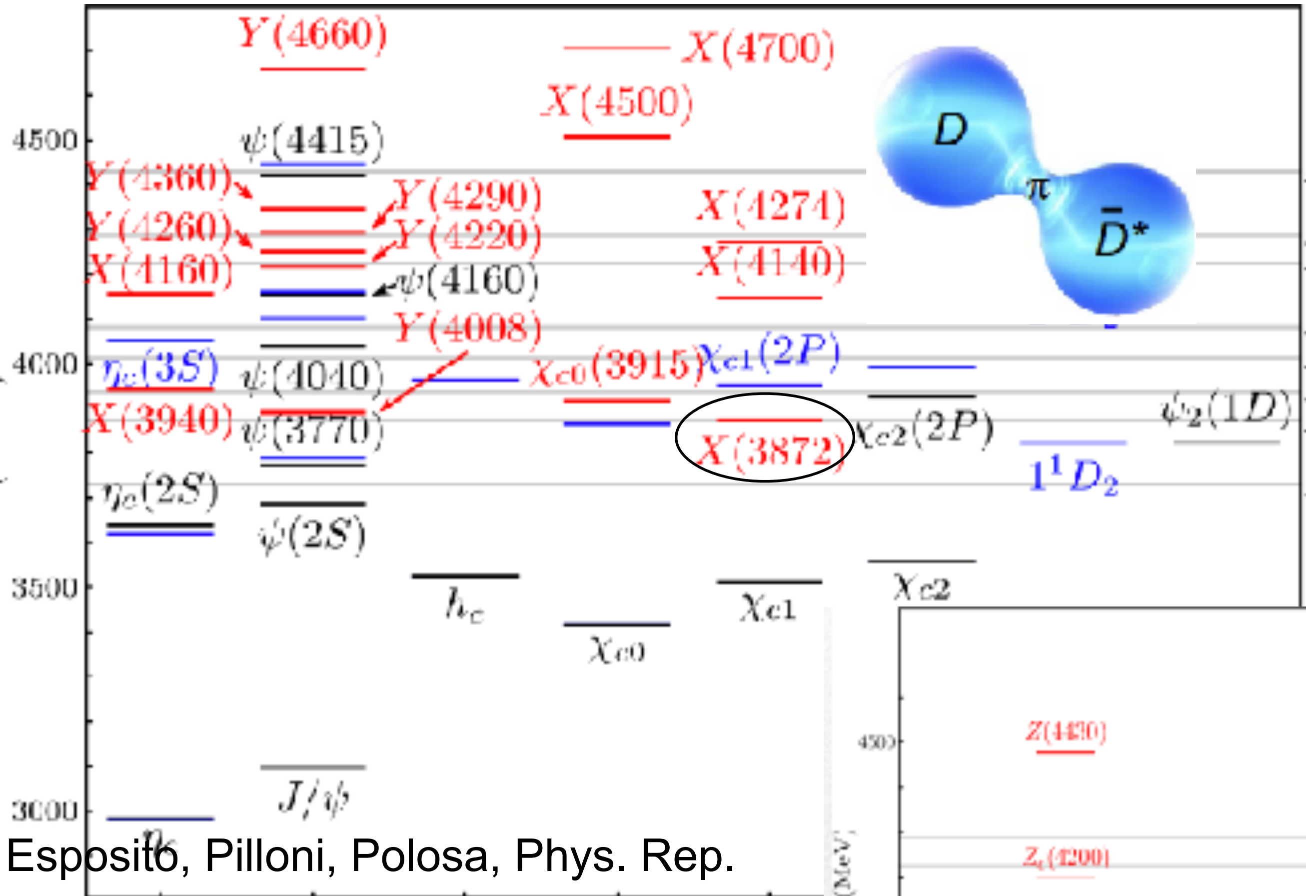
- Large exotic wave seen in $\eta^{(\prime)}\pi$ production : FESR's to constrain P-wave



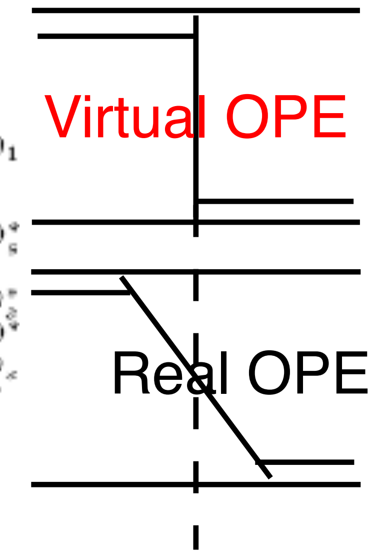


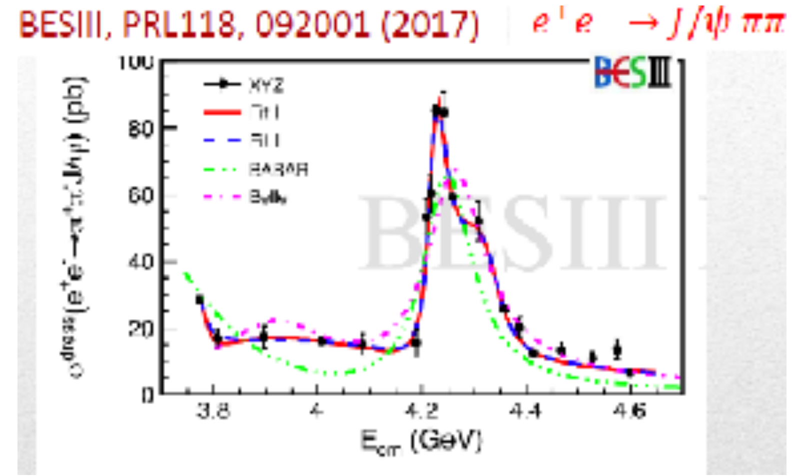


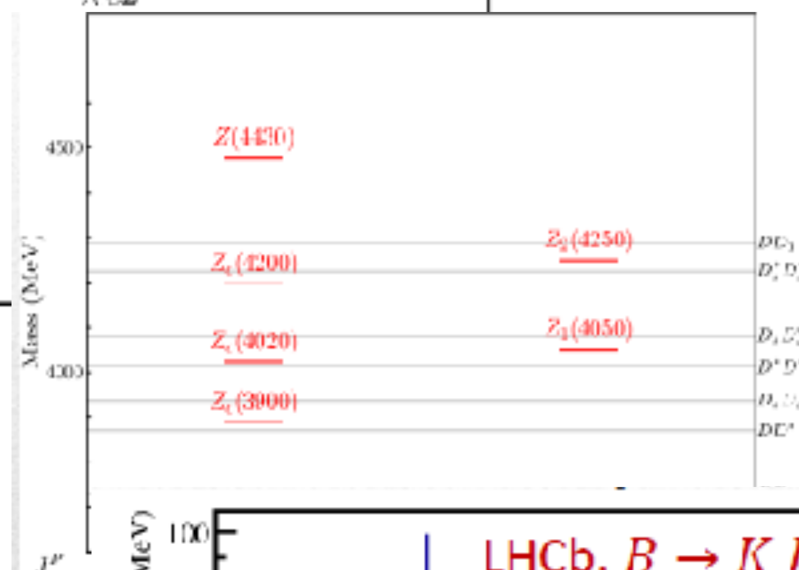
Signatures of unusual heavy quark resonances



Esposito, Pilloni, Polosa, Phys. Rep.





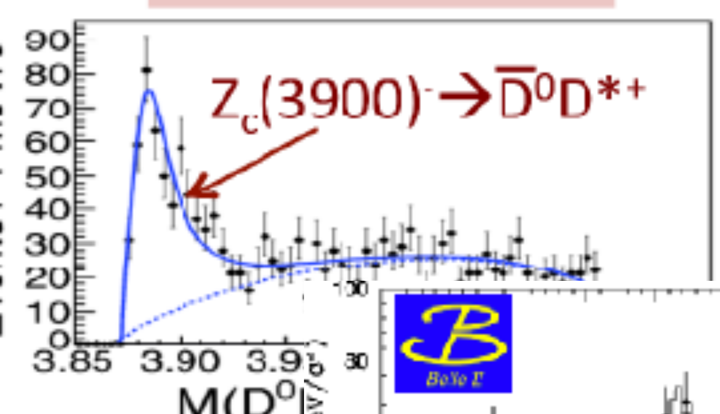


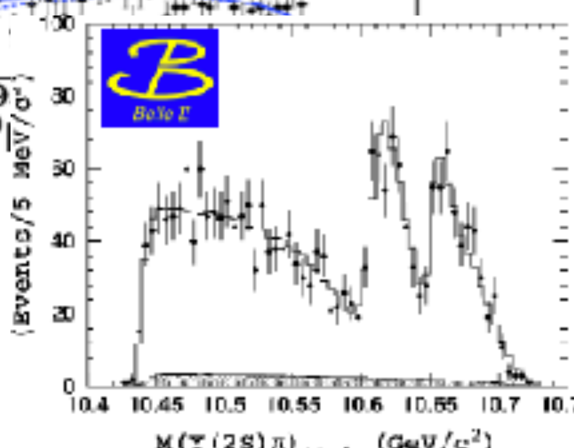
REMARK ON ENERGY PEAKS IN MESON SYSTEMS

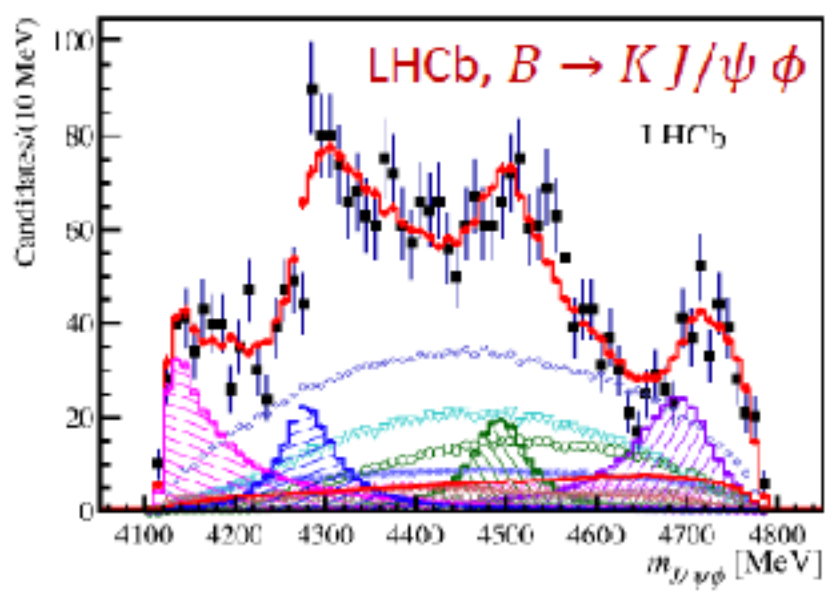
M. Nauenberg A. Pais

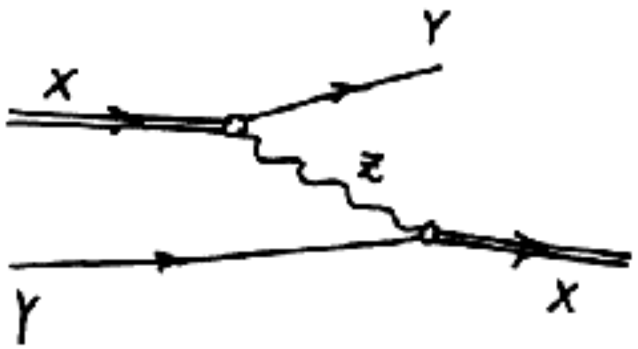
If the width of particle X is not very large we will stay close to the physical region. This almost singular behavior of $A(s)$ for certain physical s causes the peaking effect to which we refer as an (X, Y, Z) peak.

BESIII PRL 112, 022001

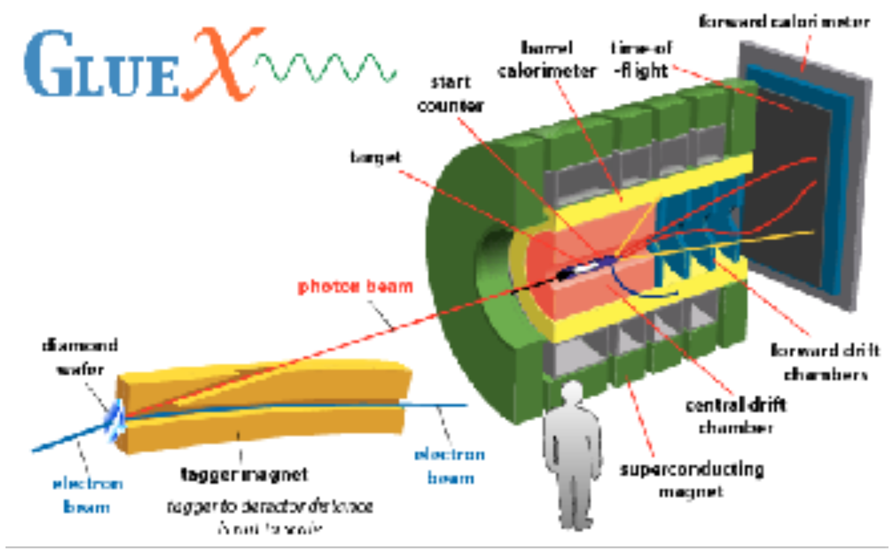


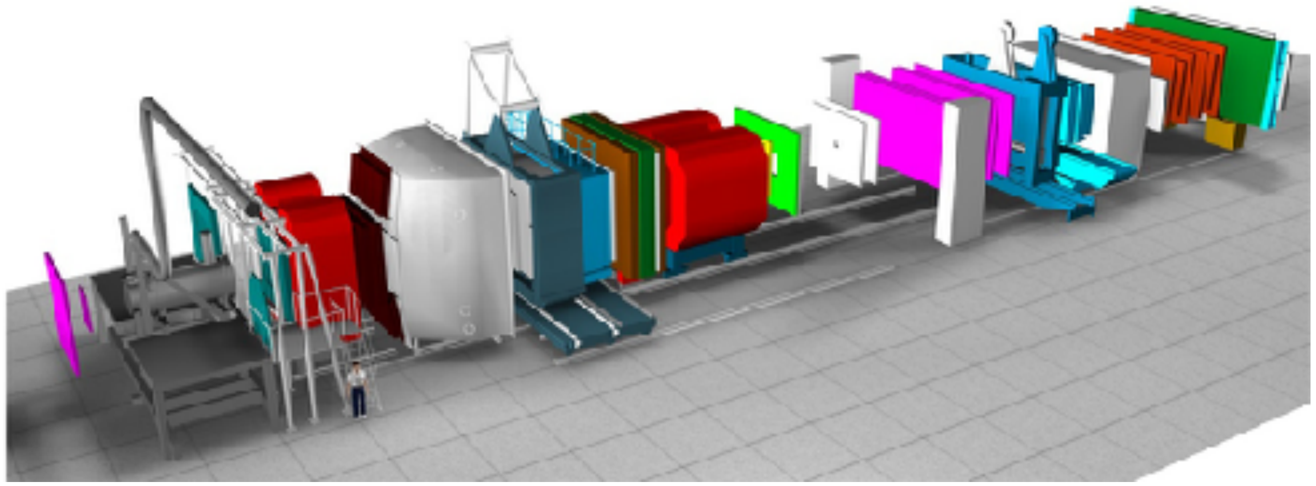


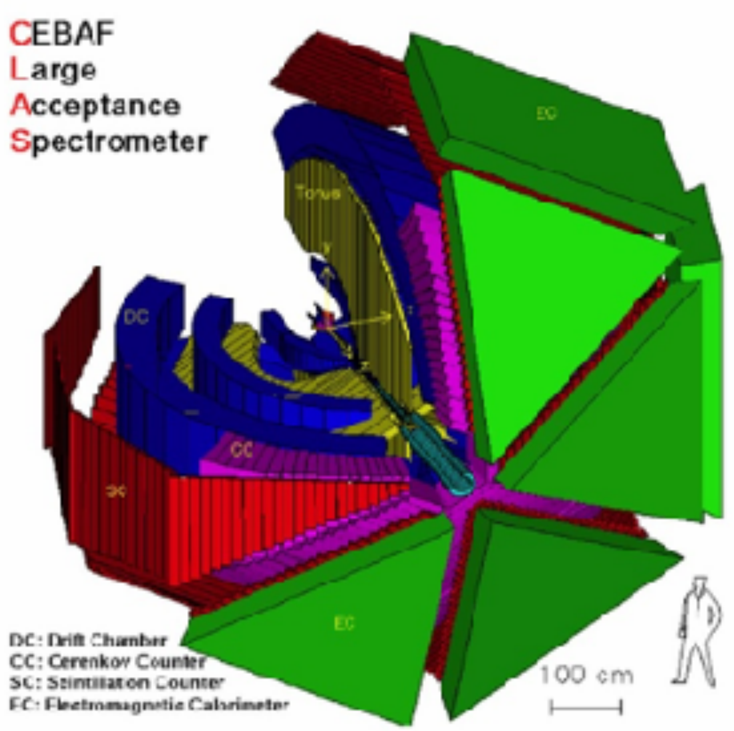




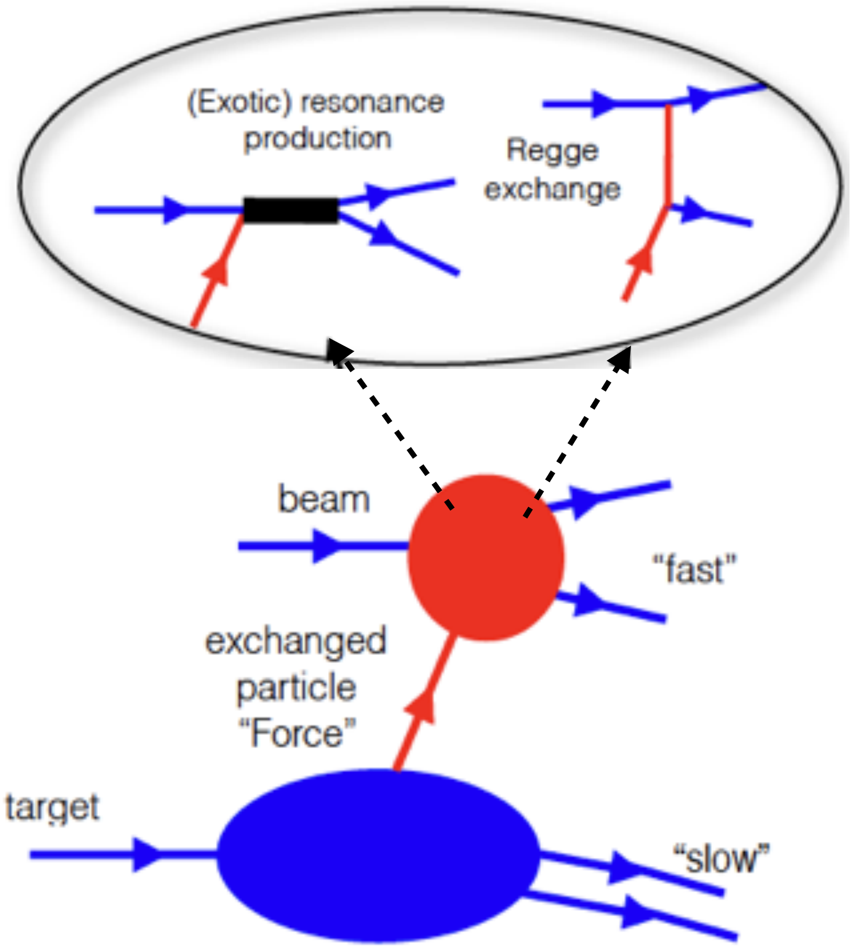
Spectroscopy from peripheral production





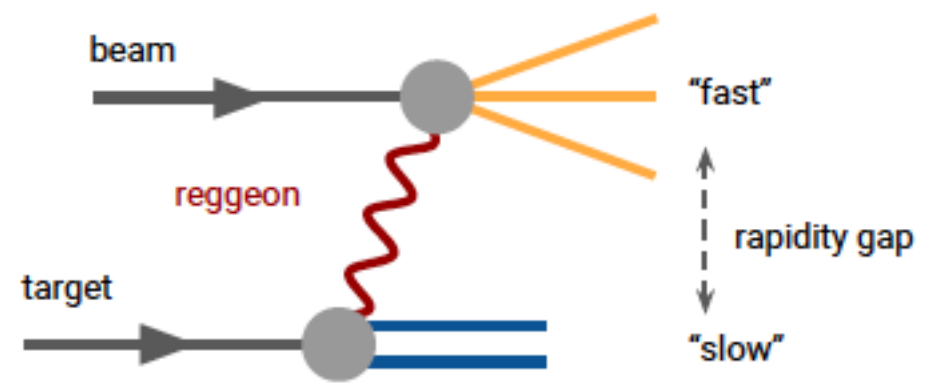


- Need to establish factorization between beam and target fragmentation (Regge factorization)
- Single Regge pole exchange dominate over cut other singularities (cuts, daughters)



Global Regge analysis

- Test Regge pole hypothesis and estimate corrections (daughters, cuts)



- Factorizable Regge pole exchange

$$\mathcal{R}(s,t) \equiv \left(\frac{1-z_s}{2}\frac{\nu}{-t}\right)^{\frac{1}{2}|\mu-\mu'|}\left(\frac{1+z_s}{2}\right)^{\frac{1}{2}|\mu+\mu'|}$$

$$A_{\mu_4\mu_3\mu_2\mu_1} = \mathcal{R}(s,t)\sqrt{-t}^{|\mu_1-\mu_3|}\sqrt{-t}^{|\mu_2-\mu_4|}\hat{\beta}^{e13}_{\mu_1\mu_3}(t)\hat{\beta}^{e24}_{\mu_2\mu_4}(t)\mathcal{F}_e(s,t)$$

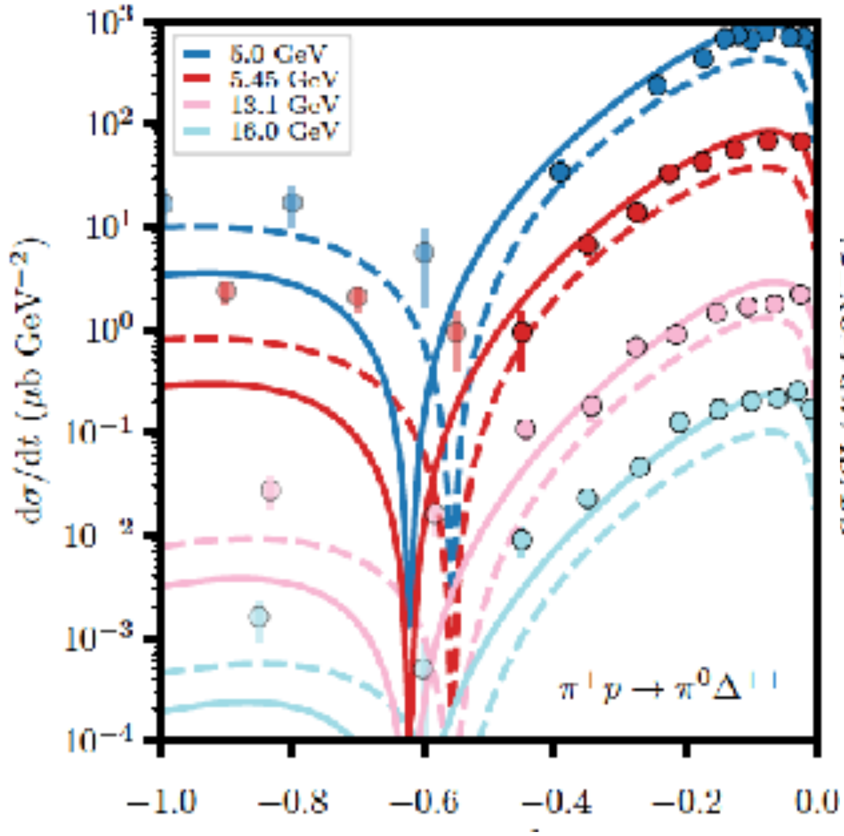
$$\mathcal{F}_e(s,t) = -\frac{\zeta_e\pi\alpha_e^1}{\Gamma(\alpha_e(t)-l_e+1)}\frac{1+\zeta_e e^{-i\pi\alpha_e(t)}}{2\sin\pi\alpha_e(t)}\left(\frac{s}{s_0}\right)^{\alpha_e(t)}$$

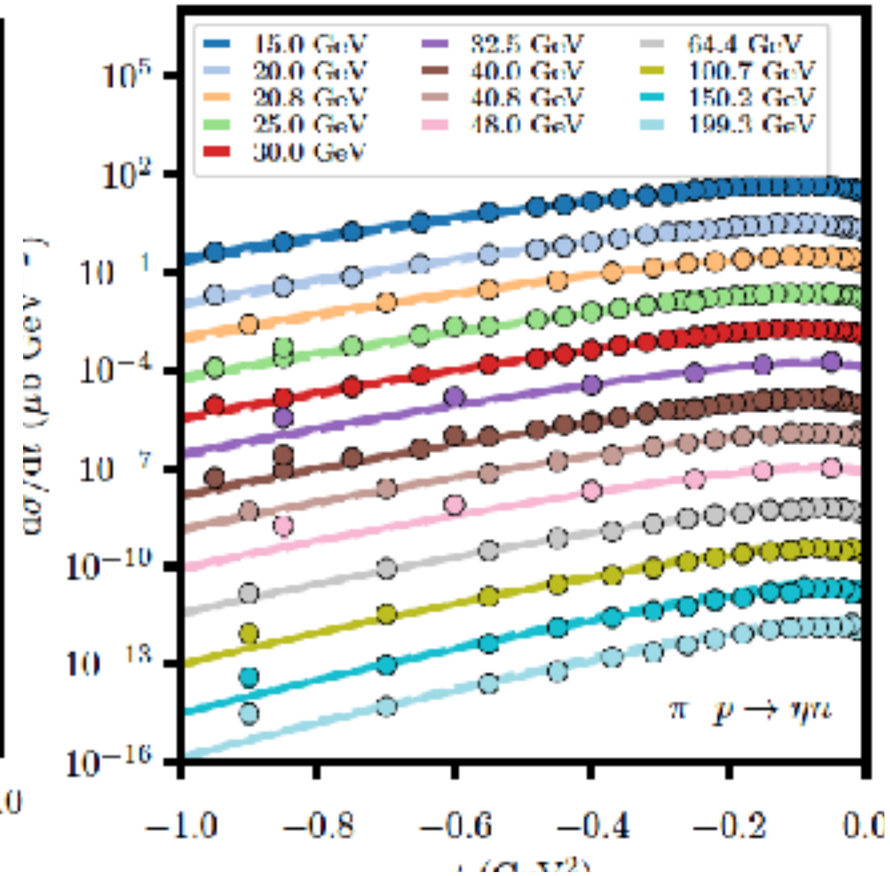
- N_{Data}=1271, N_{par}=9

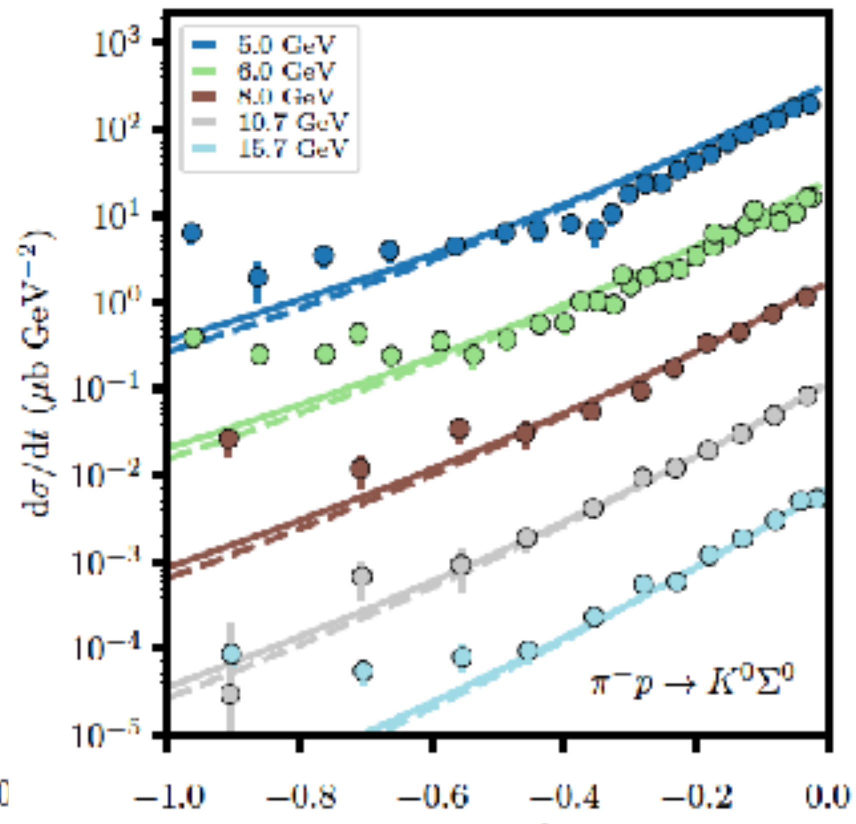
$$\mathcal{F}_e(s,t) \underset{t\to m_e^2}{\longrightarrow} \frac{(s/s_0)^{J_e}}{m_e^2-t}.$$

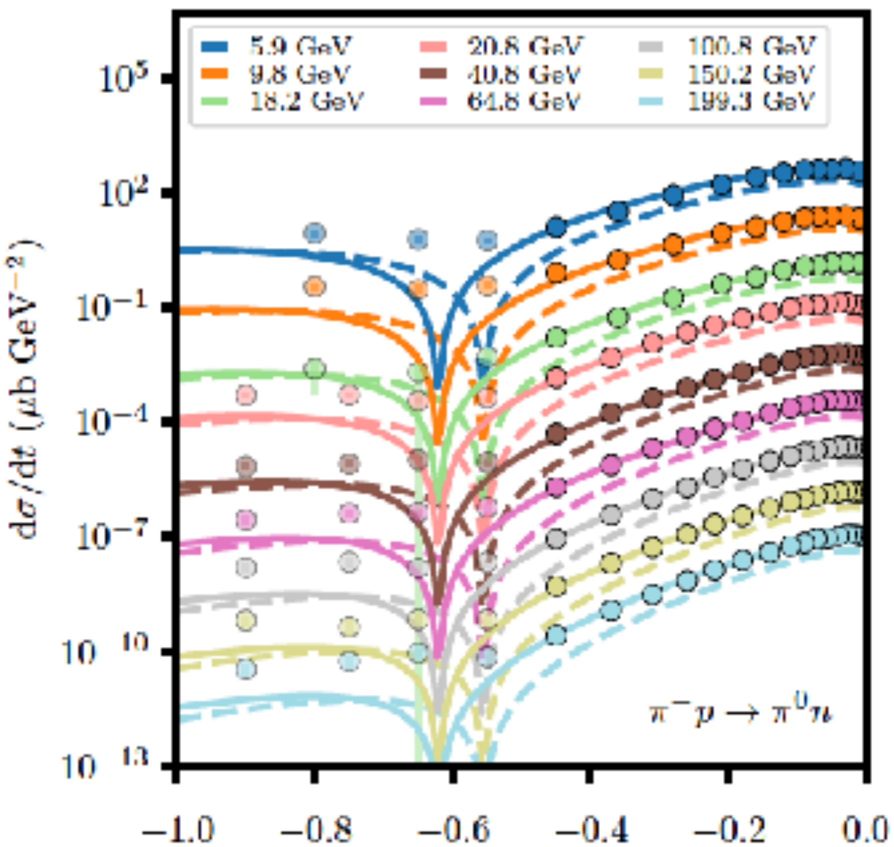
(6 SU(3) couplings, 1 mixing angle, 2 exp. slopes)

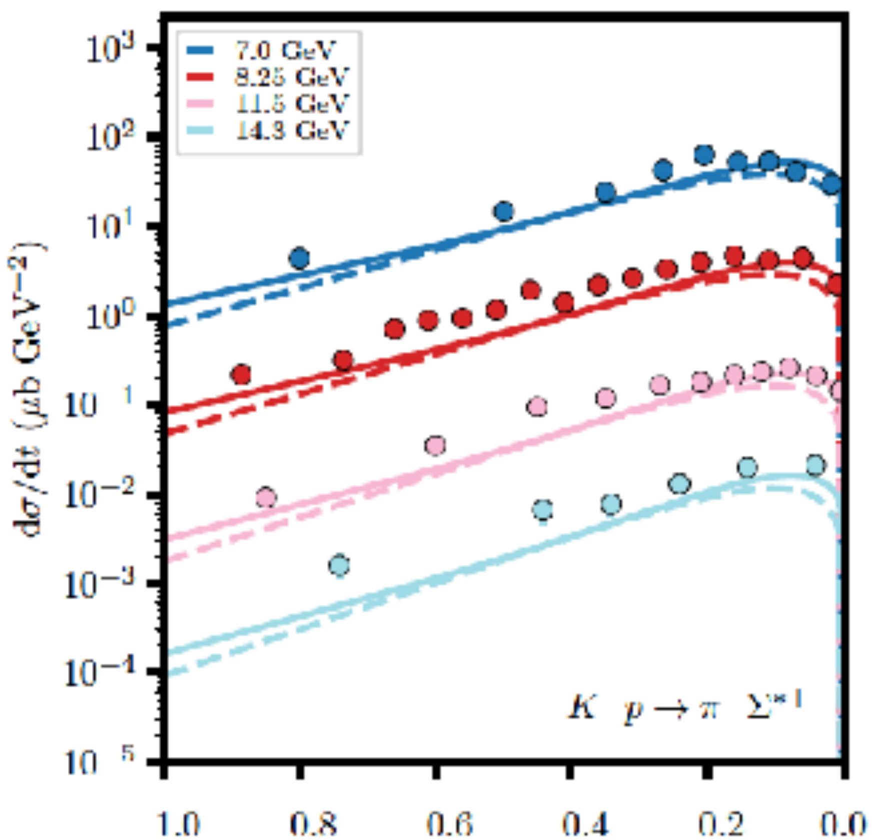
Global Regge pole analysis

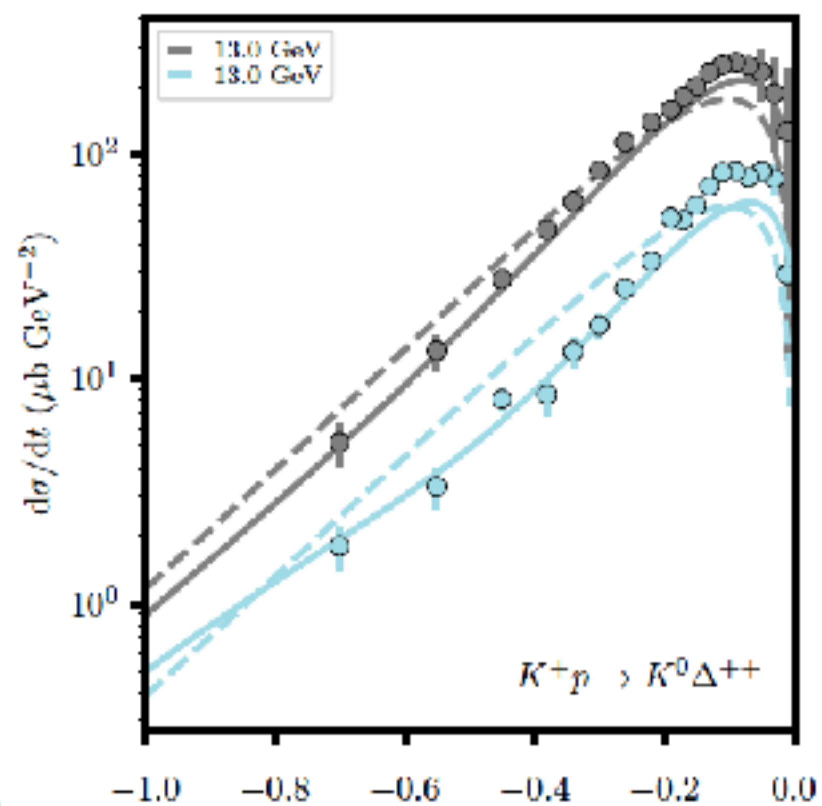








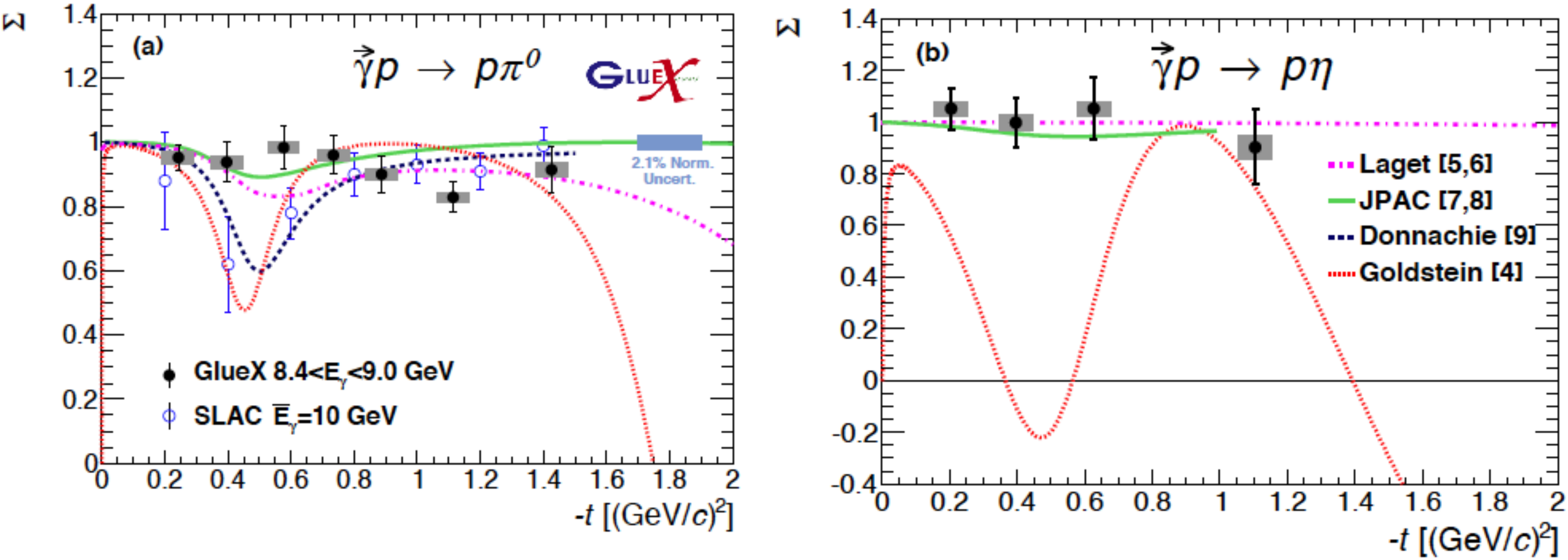




Beam asymmetry: measurement of the exchange process

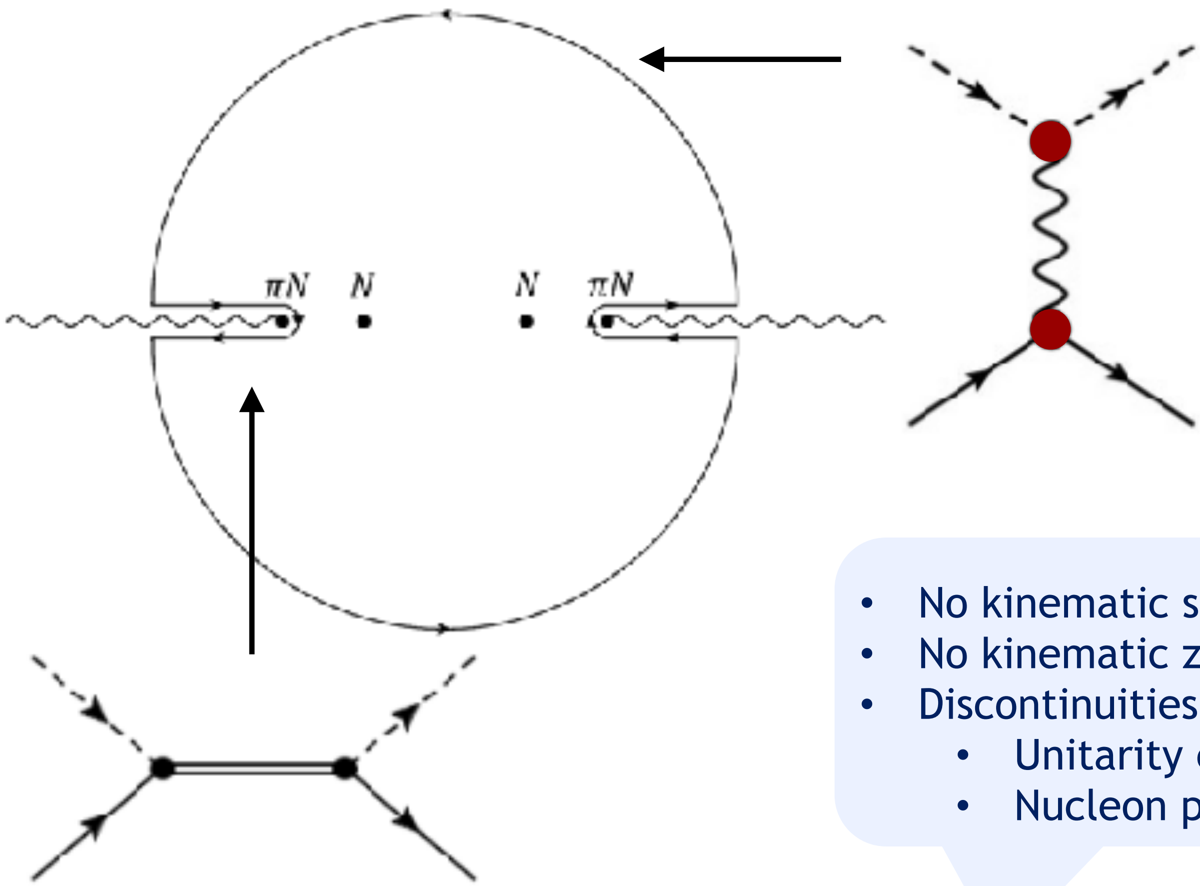
$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

H. Al Ghoul et al. [GlueX]
Phys. Rev. C95 (2017) no.4, 042201
+V. Mathieu, J. Nys [JPAC]



- Possible tension between GlueX and SLAC data ?

Finite Energy Sum Rules

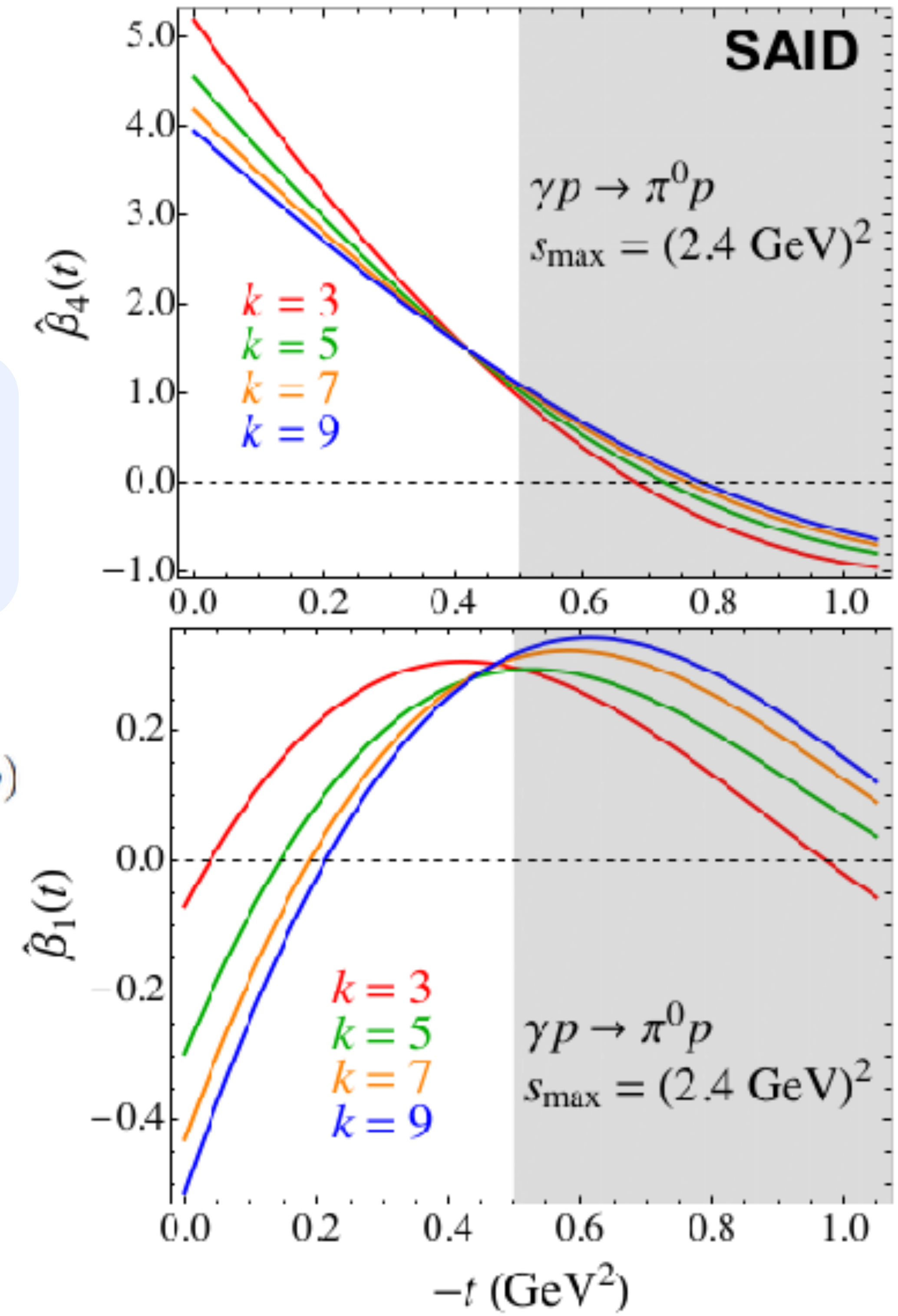


- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

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

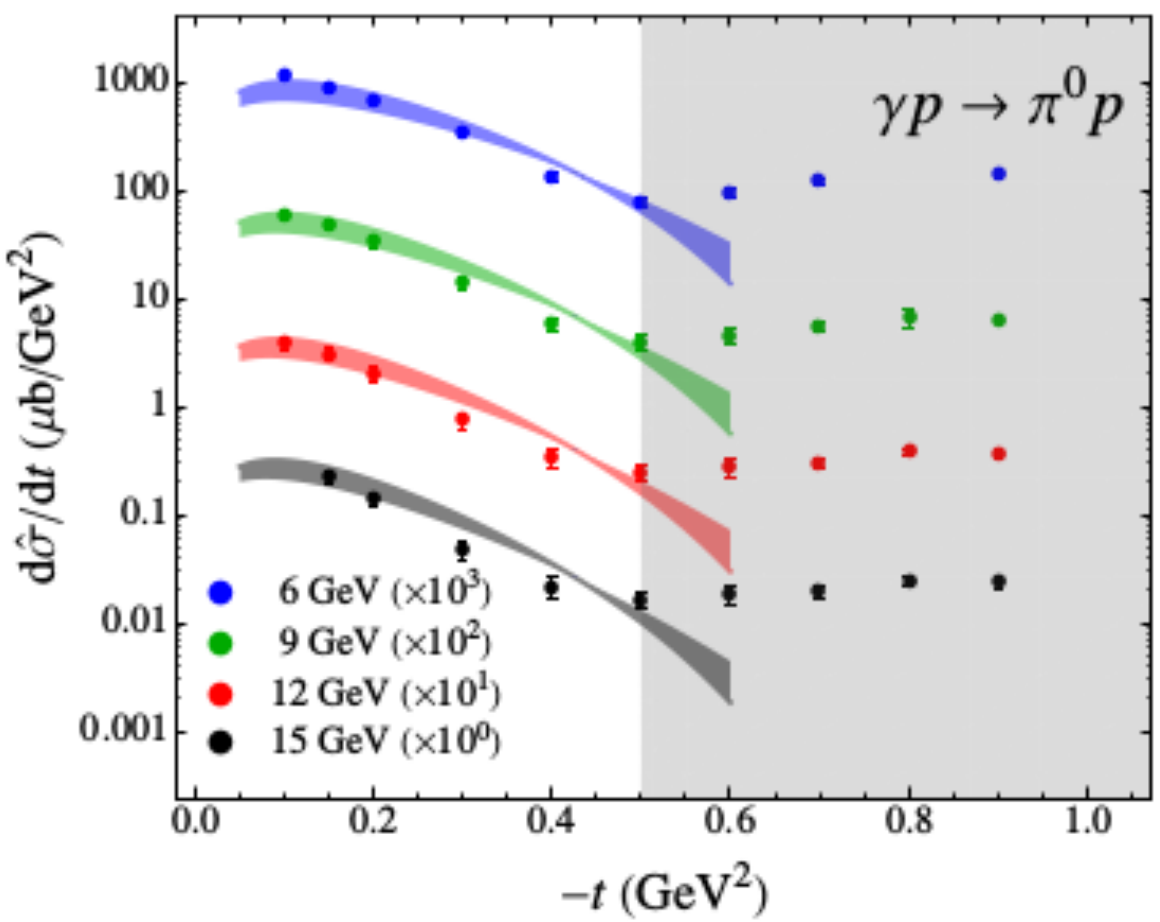
$$\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu = \beta_i(t)\frac{\Lambda^{\alpha(t)+k}}{\alpha(t)+k}$$

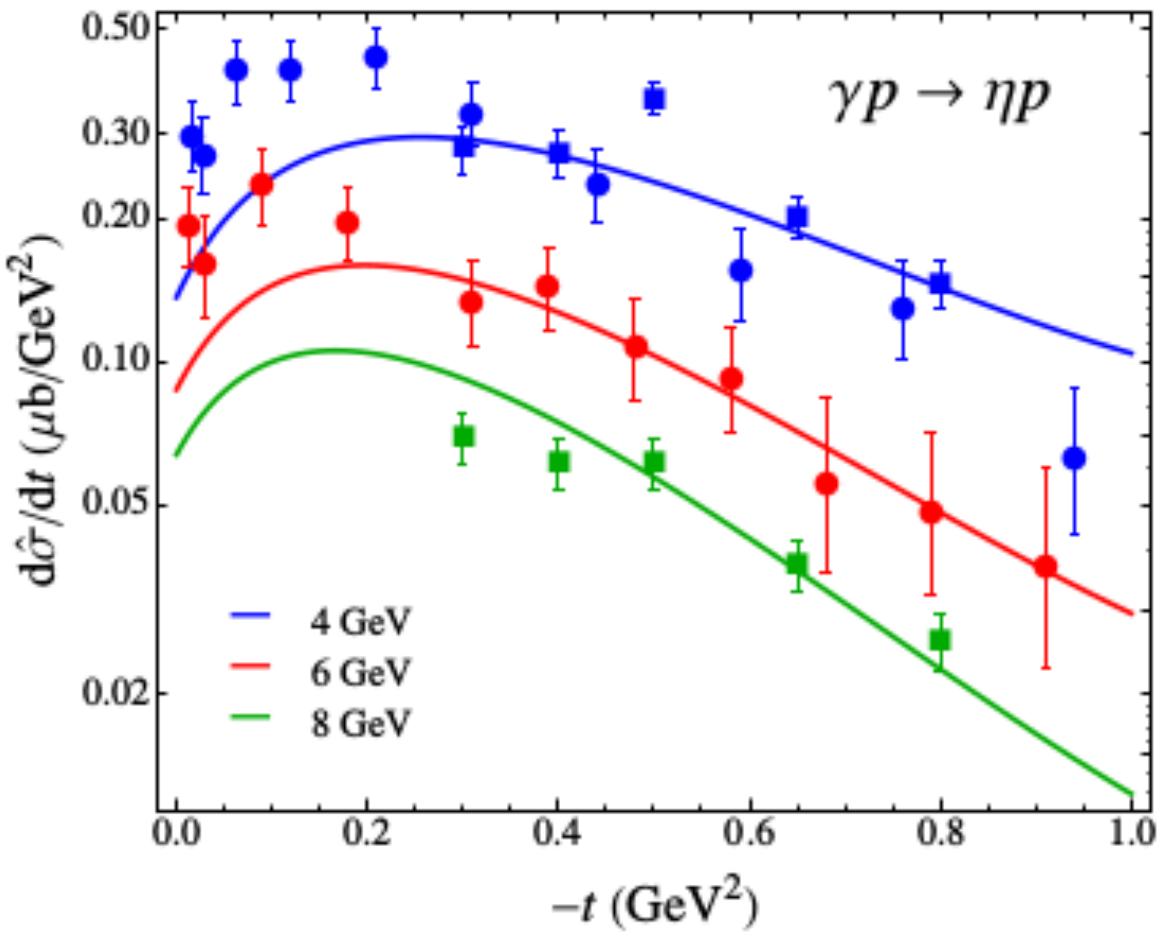
$$\beta_i(t) = \frac{\alpha(t)+k}{\Lambda^{\alpha(t)+k}}\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu$$



Finite Energy Sum Rules

[V. Mathieu, J.Nys. *et al*. (JPAC) 1708.07779 (2017)]





Combine energy regimes

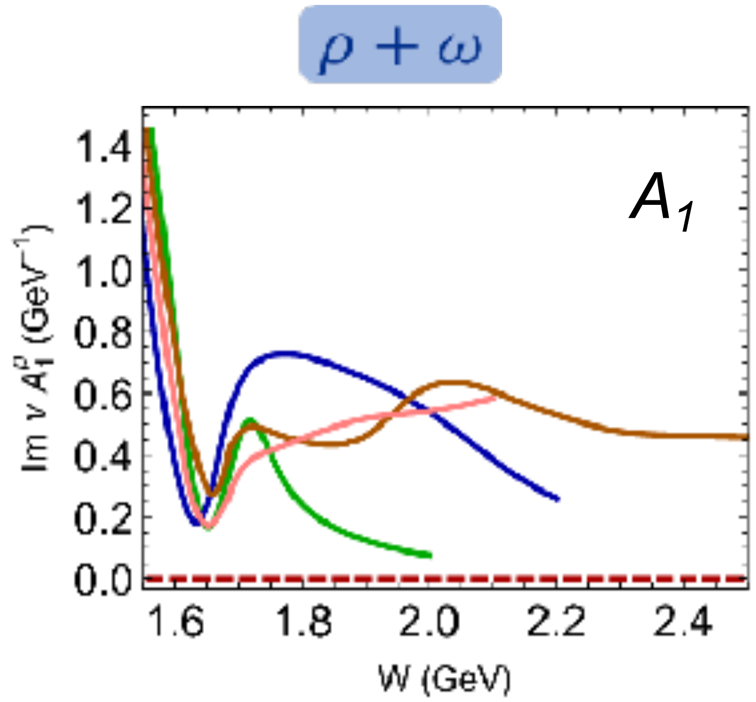
- Low-energy model ((SAID, MAID, Bonn-Gatchina, Julich-Bonn,…)
- Predict high-energy observables

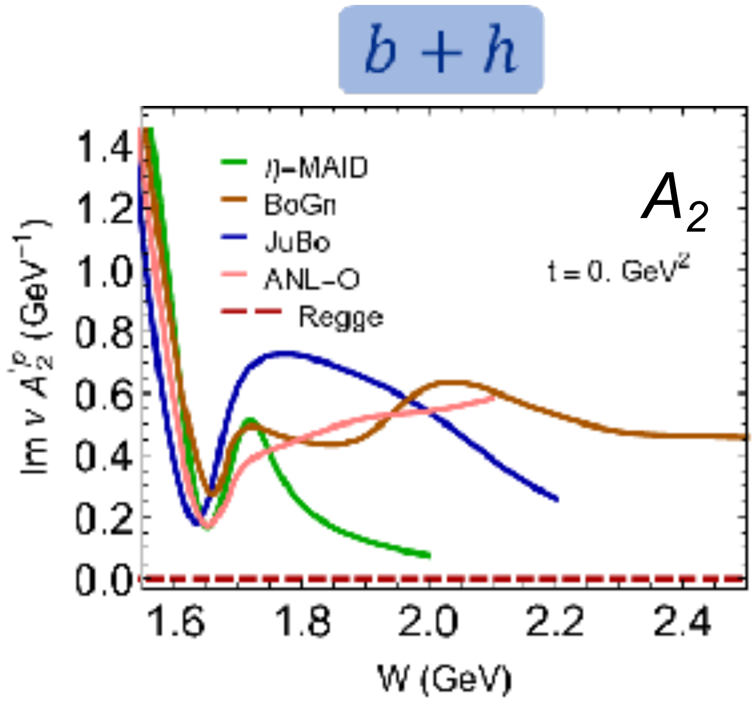
Two applications

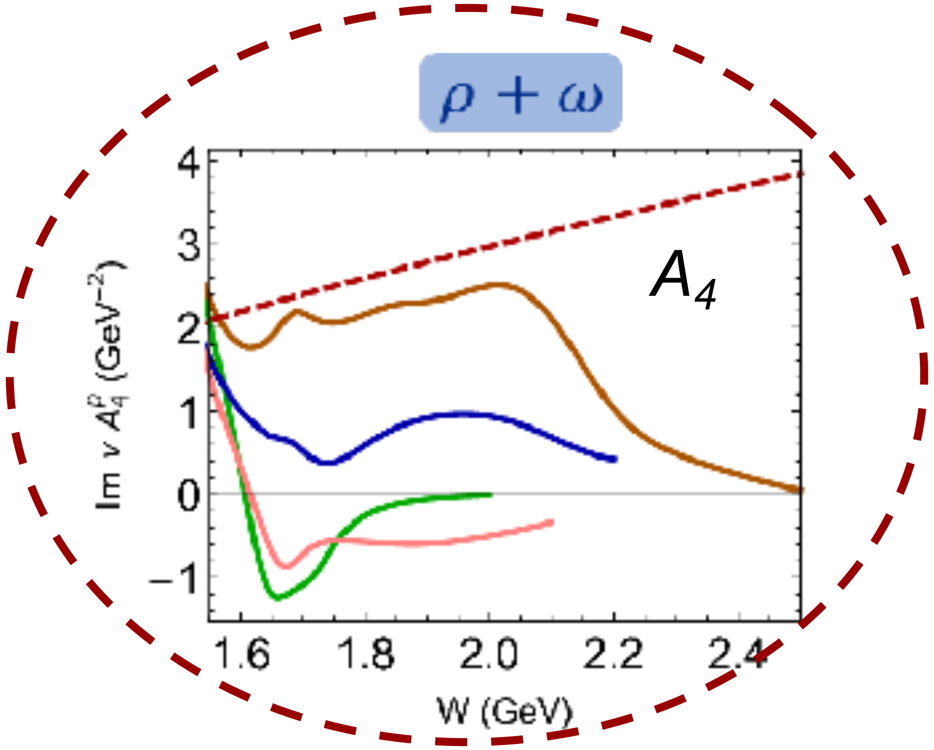
- Understand high-energy dynamics
- Constraining low-energy models

Constraining the resonance spectrum

[J.Nys *et al.*, PRD95 (2017) 034014]



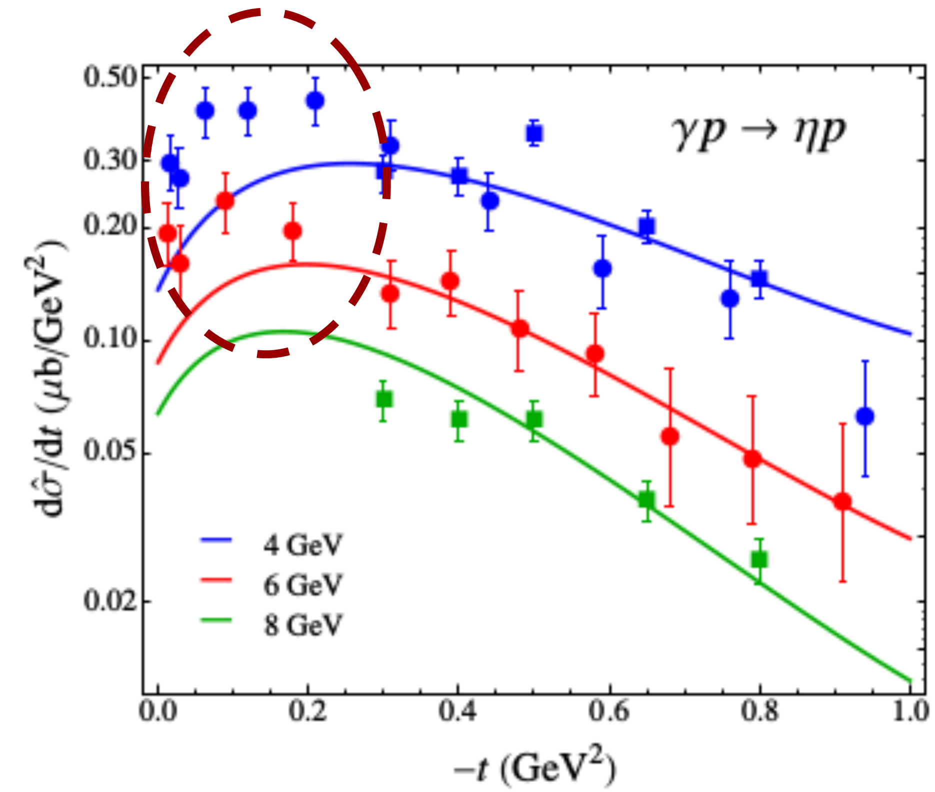




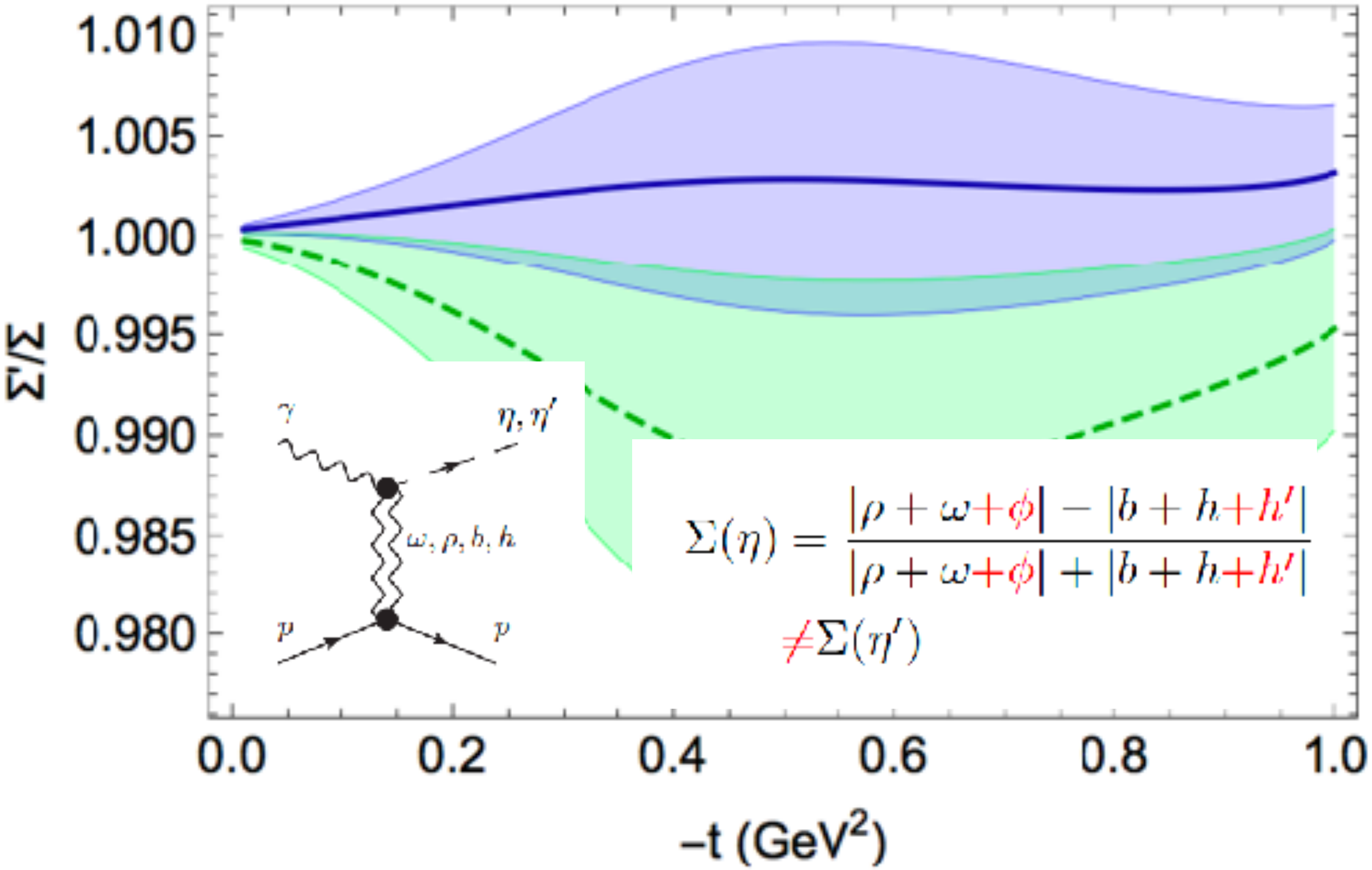
Ambiguities in the low-energy model (η-MAID)
→ Mismatch with high-energy data

Possibilities

- Low-energy model inconsistent
- Cut-off not high enough
  - High mass resonances!



η/η' asymmetry probes coupling to strangeness



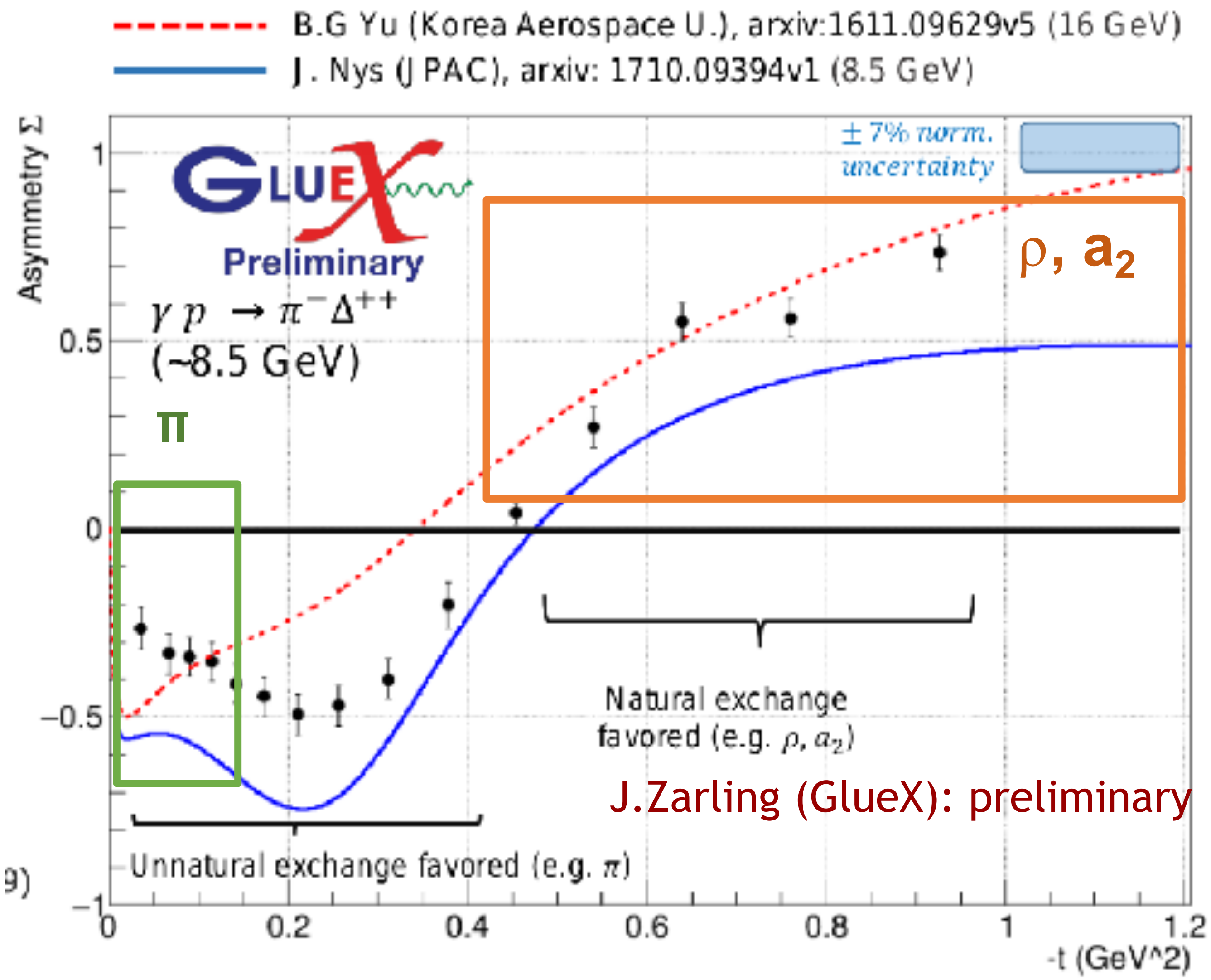
Based on the FESR for η:
predict beam asymmetry for η'

- Same exchanges
- Natural exchanges (ρ,ω) dominant
  - Couplings from radiative decays
  - Mixing angle cancels in ratio
- Unknown behavior of
  - ϕ exchange
  - unnatural exchanges (b,h)

Prediction: ≈ **same beam asymmetry**

V.Mathieu et al. (JPAC) Phys. Lett. B774, 362 (2017)

πΔ photoproduction

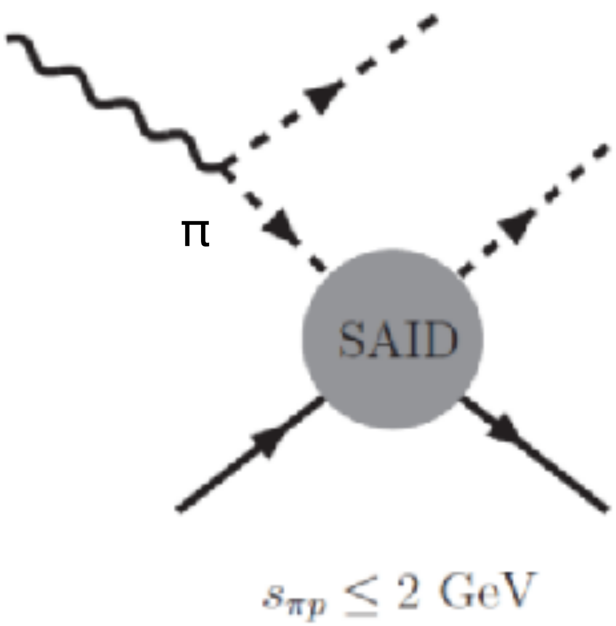


Comparison to GlueX data

- Confirmation of interference pattern
- High -t: natural, low -t: unnatural
- Mismatch: oddly behaved π exchange
  - Ongoing analysis
  - Experimental or theoretical?

- Stringent test of one-pion-exchange production
- Possible to make parameter-free predictions

J.Nys et al. (JPAC) Phys.Lett. B779, 77 (2018)



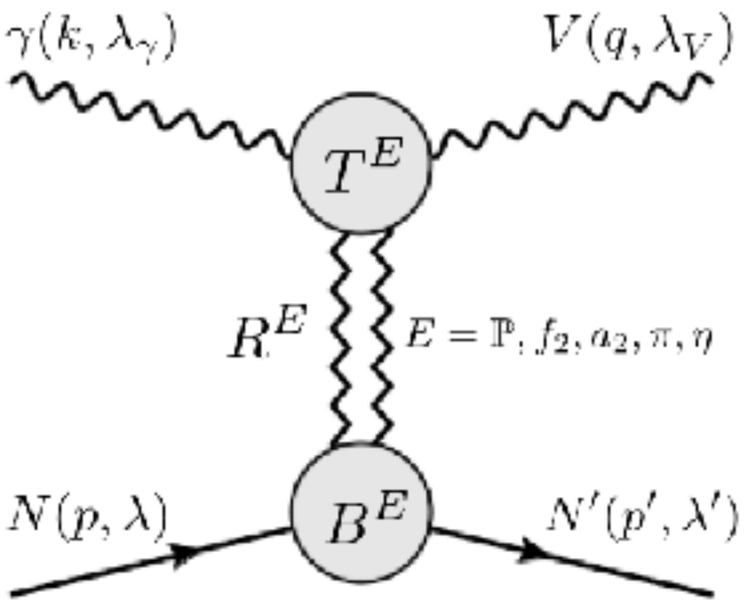
Łukasz Bibrzycki et al. (Cracow,JPAC)

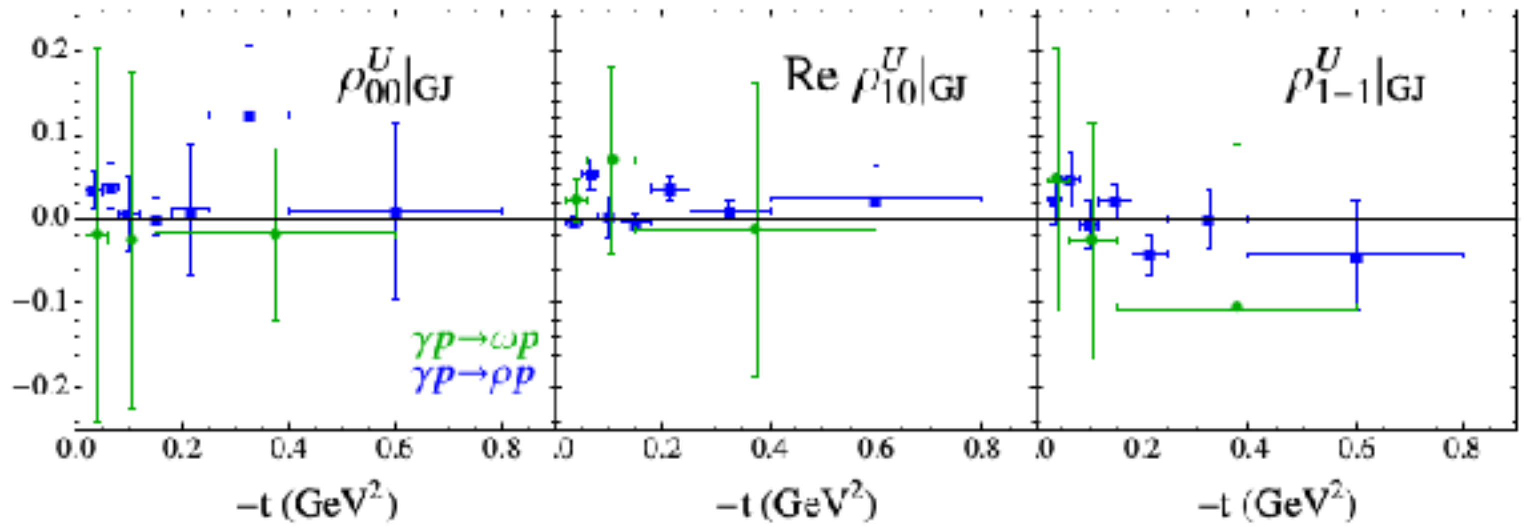
Vector meson production

- Pomeron dominates at high energies
- Isoscalar exchanges dominantly helicity non-flip ($\lambda=\lambda'$)
- Unnatural exchanges: only helicity flip ($|\lambda-\lambda'|=1$)

$$\mathcal{M}_{\substack{\lambda_V,\lambda_\gamma \\ \lambda',\lambda}}(s,t) = \sum_{E=\pi,\eta,\mathbb{P},f_2,a_2} \mathcal{M}^E_{\substack{\lambda_V,\lambda_\gamma \\ \lambda',\lambda}}(s,t)$$

$$\mathcal{M}^{\substack{N \\ U}}_{\substack{-\lambda_\gamma,-\lambda_V \\ \lambda,\lambda'}} = \pm(-1)^{\lambda_\gamma-\lambda_V}\mathcal{M}^{\substack{N \\ U}}_{\substack{\lambda_\gamma,\lambda_V \\ \lambda,\lambda'}}$$





$$\rho^{\substack{N \\ U}}_{00} = \frac{1}{2}\left(\rho^0_{00} \mp \rho^1_{00}\right),$$

$$\text{Re}\,\rho^{\substack{N \\ U}}_{10} = \frac{1}{2}\left(\text{Re}\,\rho^0_{10} \mp \text{Re}\,\rho^1_{10}\right),$$

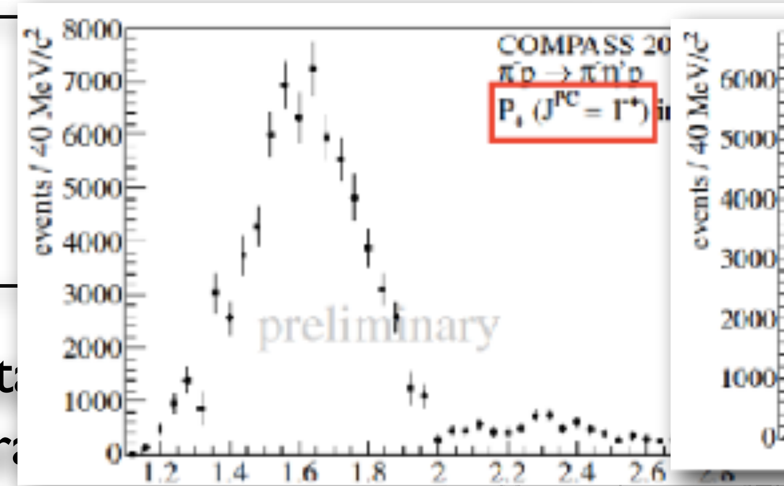
$$\rho^{\substack{N \\ U}}_{1-1} = \frac{1}{2}\left(\rho^1_{1-1} \pm \rho^1_{11}\right).$$

V.Mathieu, et al. (JPAC) Phys.Rev. D97, 094003 (2018)

$\pi^- p \to \eta\pi^- p$

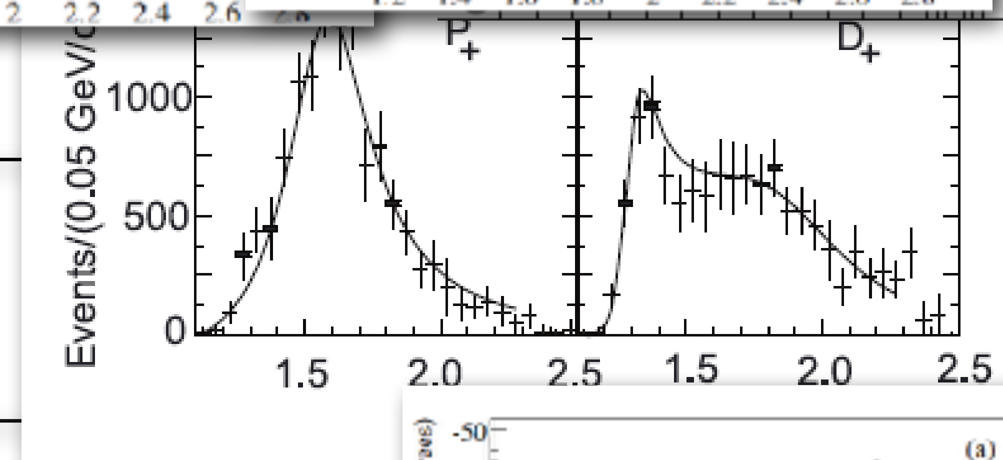
$M = 1370 \pm 16^{+50}_{-30}\ \mathrm{MeV}/c^2$

$\Gamma = 385 \pm 40^{+65}_{-105}\ \mathrm{MeV}/c^2$



$\pi^- p \to \eta\pi^0 n$

No consistent B-W interpret… possible but a weak $\eta\pi$ inter… exists and can reproduce the exotic wave



$\pi^- p \to \eta'\pi^- p$

$M = 1597 \pm 10^{+45}_{-10}\ \mathrm{MeV}/c^2$

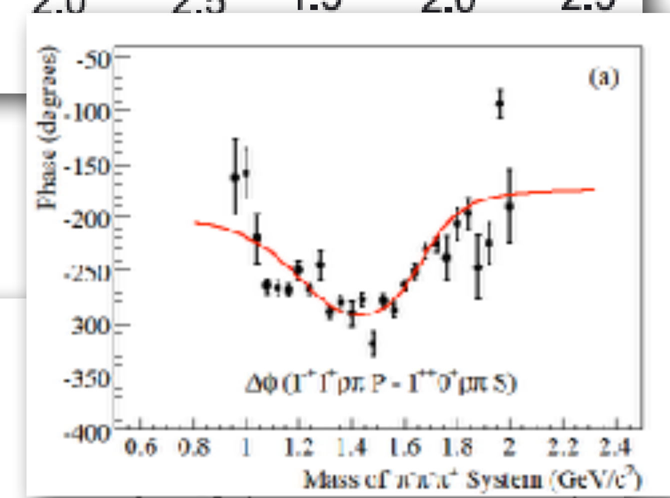
$\Gamma = 340 \pm 40^{+50}_{-50}\ \mathrm{MeV}/c^2$

$\pi^- p \to \rho^0\pi^- p$

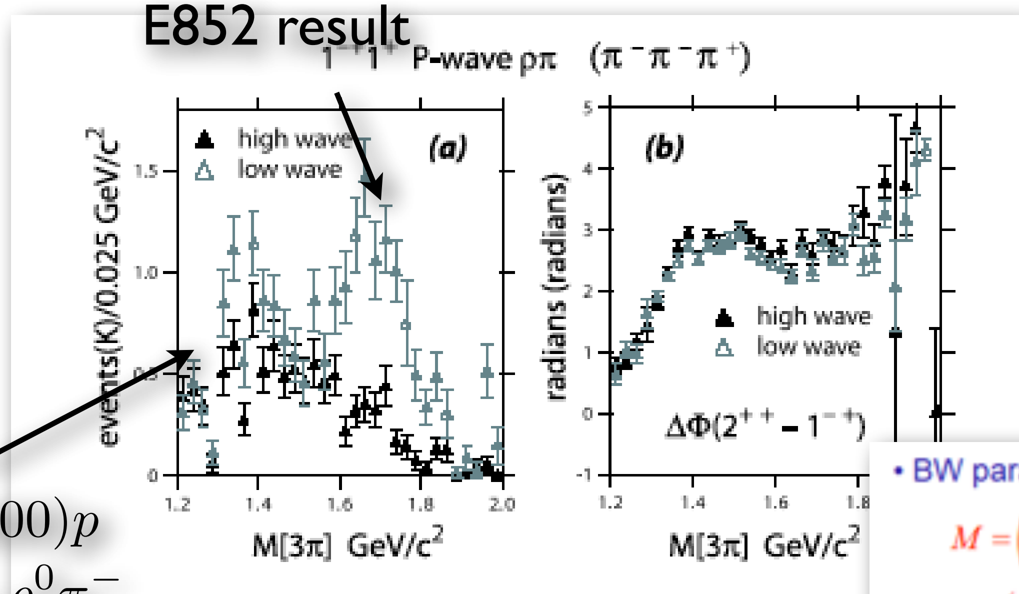
$M = 1593 \pm 8^{+29}_{-47}\ \mathrm{MeV}/c^2$

$\Gamma = 168 \pm 20^{+150}_{-12}\ \mathrm{MeV}/c^2$

BNL (E852) yes/no
COMPASS yes



E852 result



$\pi^- p \to \pi_2^-(1600)p$

$\pi_2^- \to \rho^0\pi^-$

$\rho^0 \to \pi\pi$

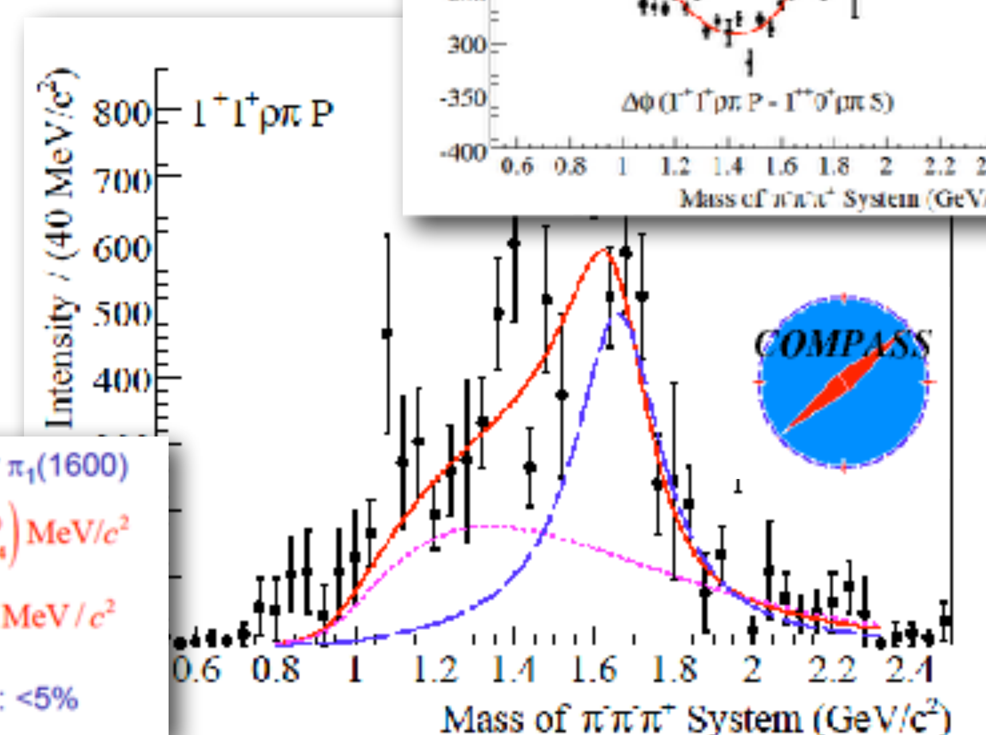
FIG. 25: (a) The $1^{-+}1^{+}$ P-wave $\rho\pi$ partial wave … charged mode ($\pi^-\pi^-\pi^+$) for the high-wave set PWA … low-wave set PWA and (b) the phase difference $\Delta\Phi$ b… the 2^{++} and 1^{-+} for the two wave sets.

- BW parameters for $\pi_1(1600)$

$M = \left(1660 \pm 10^{+0}_{-64}\right)\ \mathrm{MeV}/c^2$

$\Gamma = \left(269 \pm 21^{+42}_{-64}\right)\ \mathrm{MeV}/c^2$

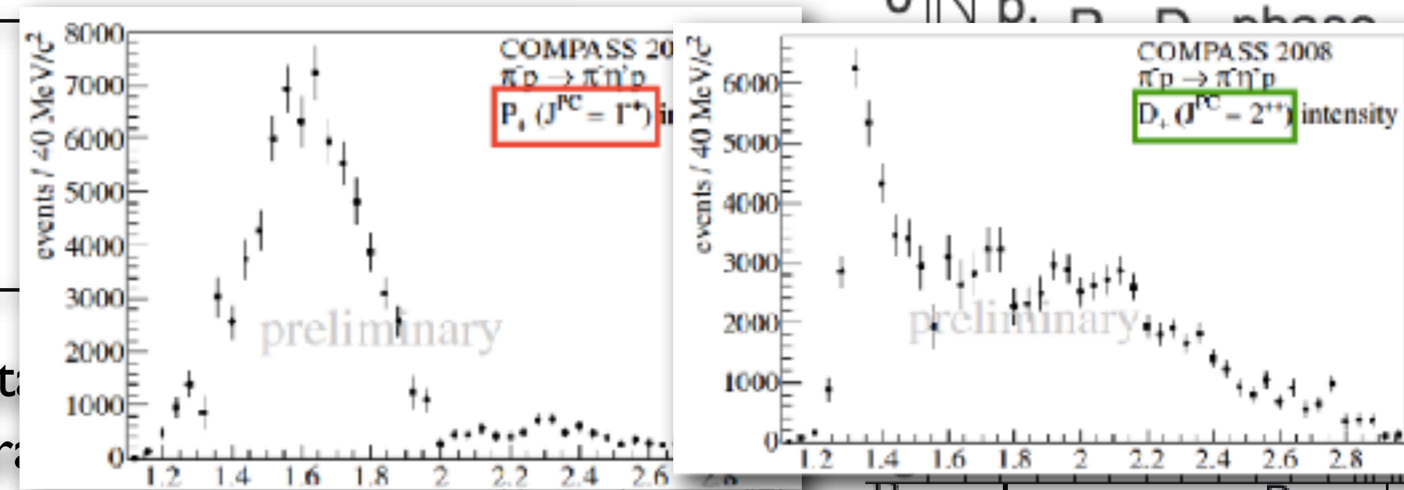
- Leakage negligible: <5%



$\pi^- p \to \eta \pi^- p$

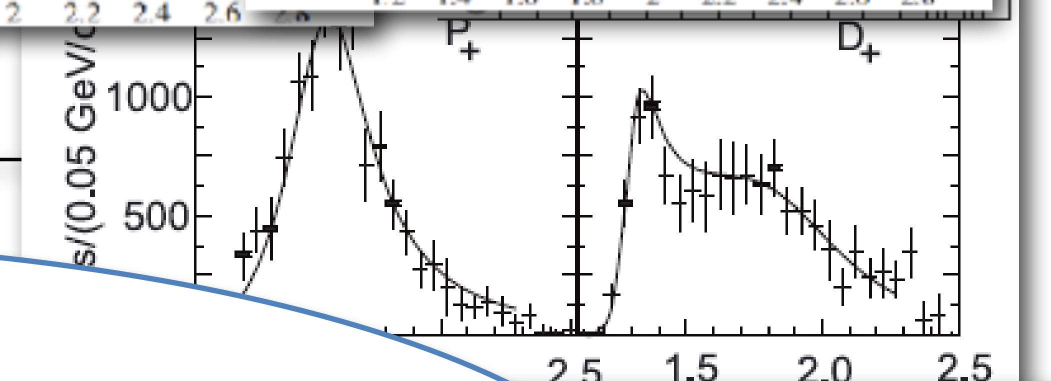
$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2



$\pi^- p \to \eta \pi^0 n$

No consistent B-W interpret
possible but a weak ηπ inter
exists and can reproduce the exotic wave



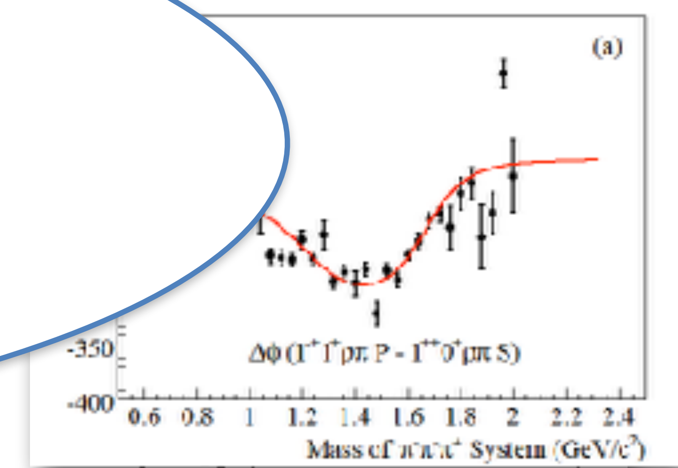
$\pi^- p \to \eta' \pi^- p$

$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

Γ = 34

$\pi^- p \to \rho^0$

Need to be confirmed



$\pi^- p \to \pi_2^-(1600) p$

$\pi_2^- \to \rho^0 \pi^-$

$\rho^0 \to \pi^- \pi^+$

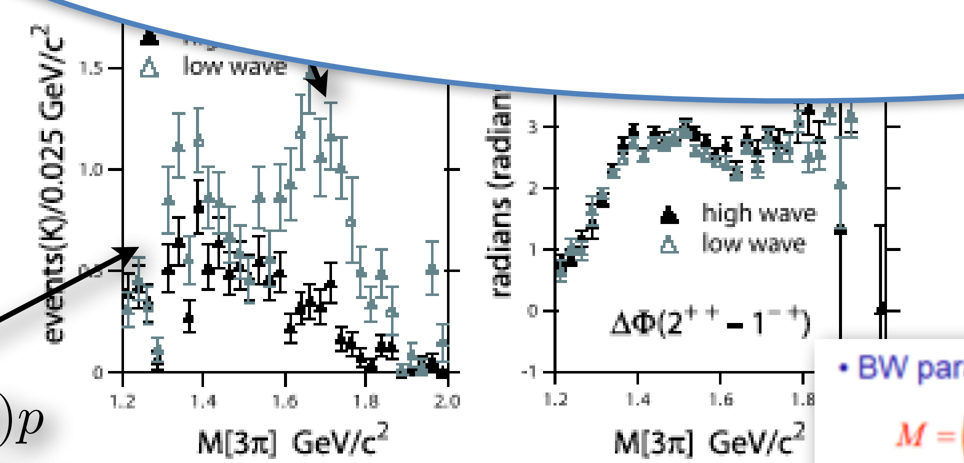


FIG. 25: (a) The $1^{-+}1^+$ P-wave $\rho\pi$ partial wave charged mode ($\pi^-\pi^-\pi^+$) for the high-wave set PWA a low-wave set PWA and (b) the phase difference $\Delta\Phi$ b the 2^{++} and 1^{-+} for the two wave sets.

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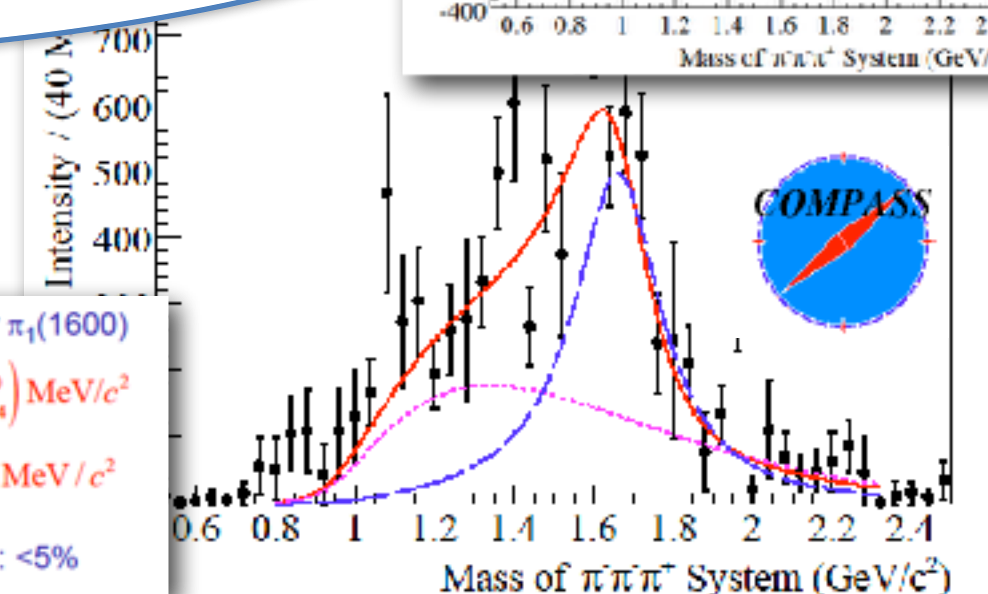
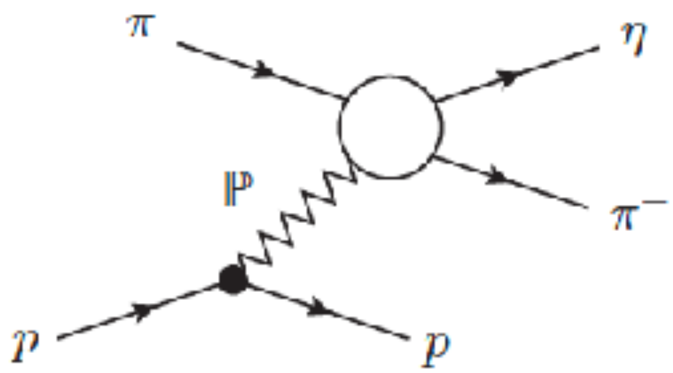
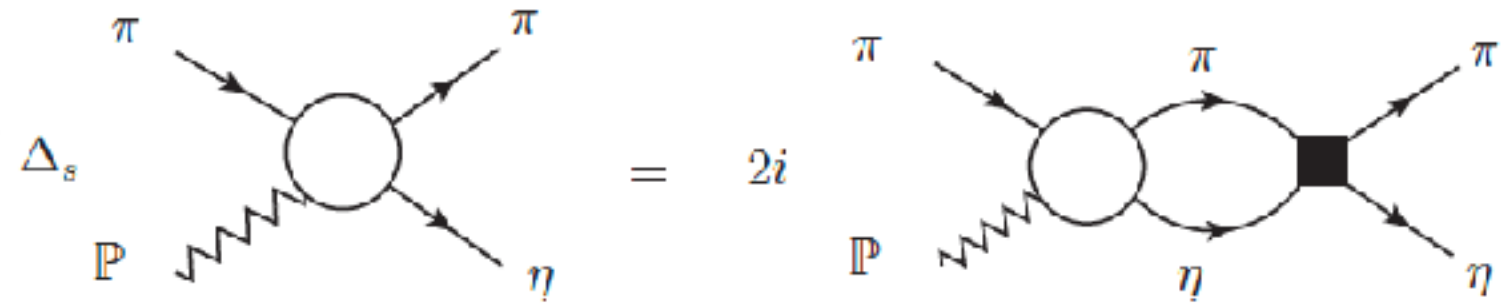


A.Jackura et al. (JPAC/COMPASS) Phys.Lett. B779, 464 (2018)

$$\Delta_s\, a_{\ell m_\ell}(s) = 2i\,\rho_\ell(s) t_\ell^*(s) a_{\ell m_\ell}(s)$$





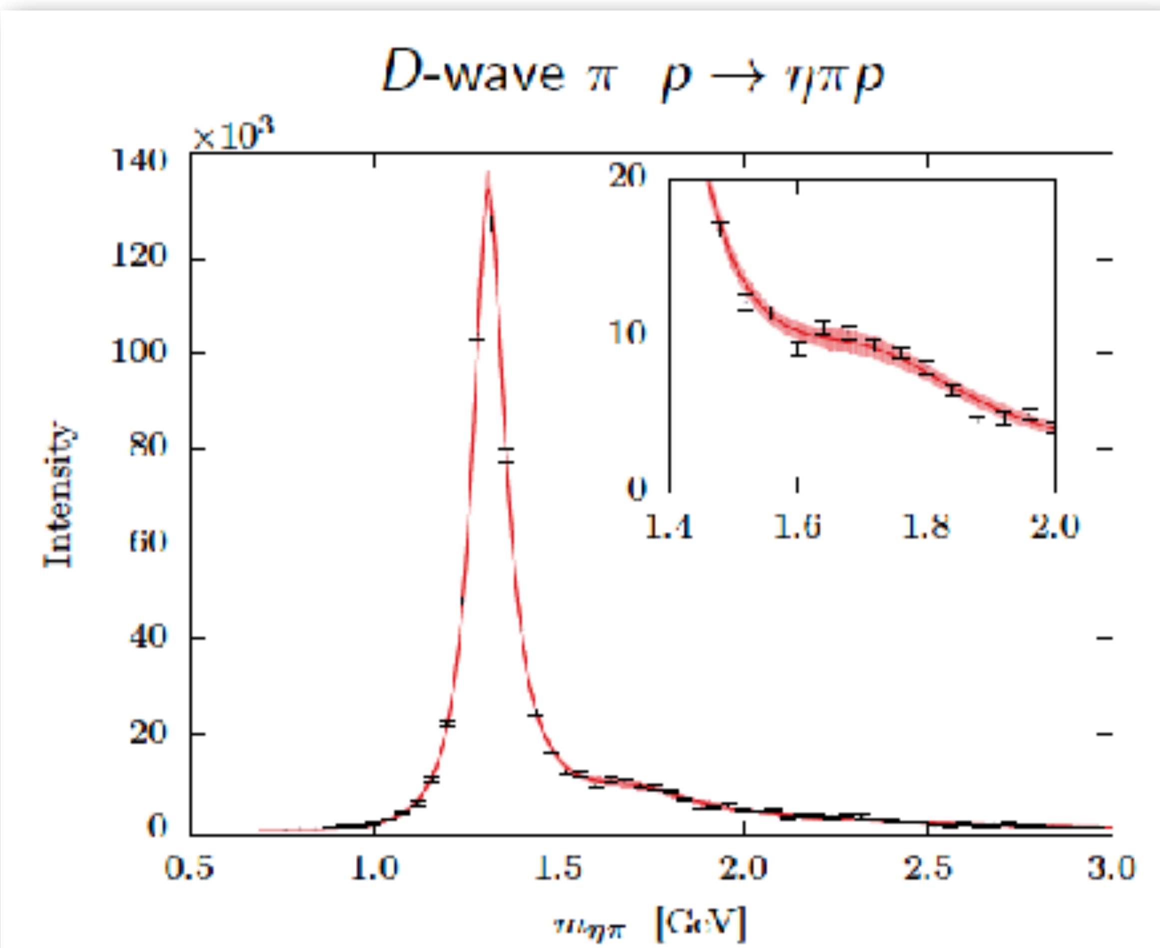
Production($s_{\pi\pi}$) x Interactions in ηπ ($s_{\pi\pi}$)

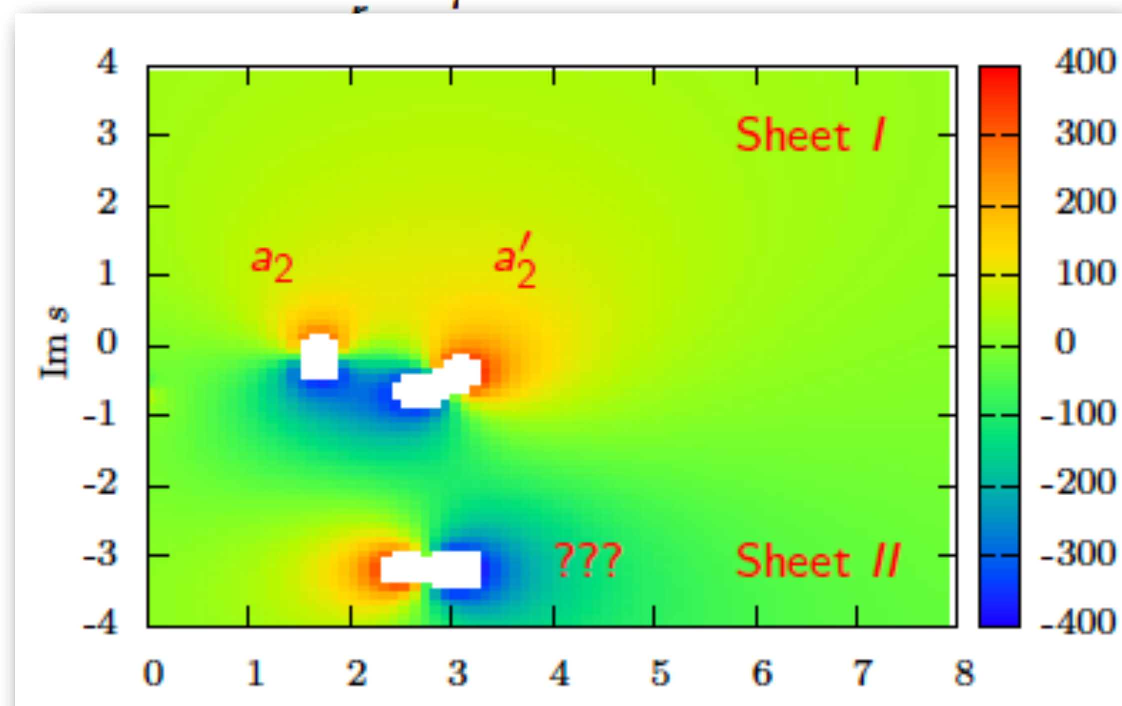
Constrained by unitary

$$a_{\ell m_\ell} = f_{\ell m_\ell}(s) t_\ell(s)$$

$$f_{\ell m_\ell}(s) = \sum_{n=0} \alpha_n\, T_n(\omega(s)) \quad t_\ell(s) = N(s)/D(s) \quad D(s) = D^0(s) - \frac{s}{\pi}\int_{s_{th}}^{\infty} ds' \frac{\rho(s')N(s')}{s'(s'-s)}$$

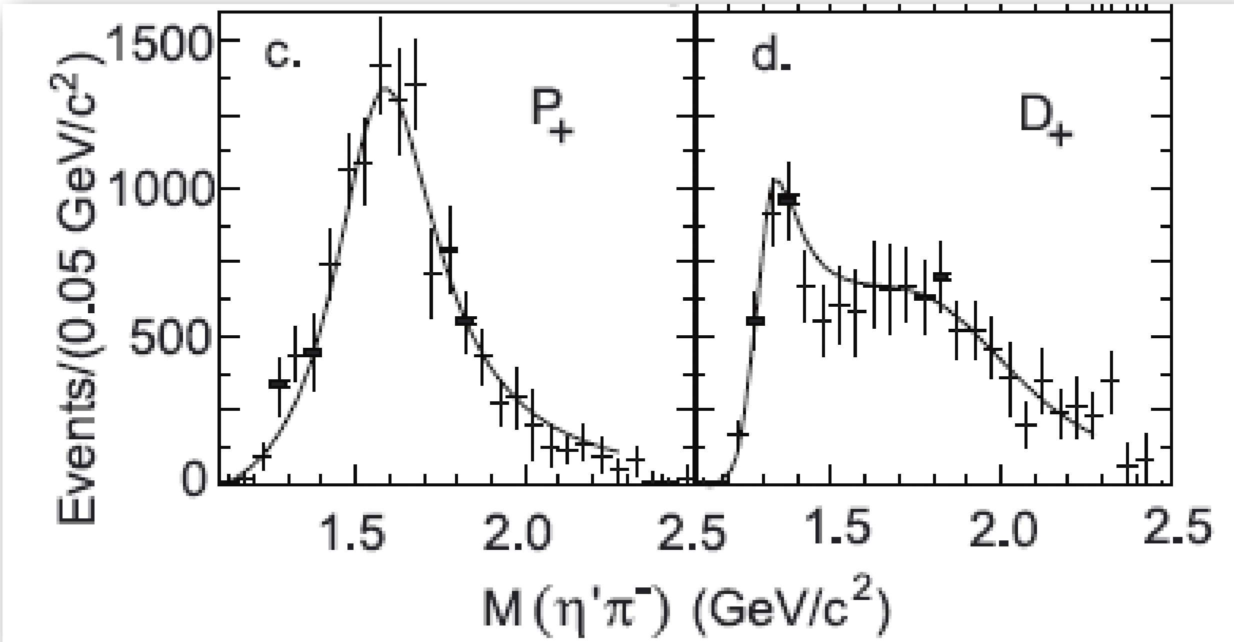
$$D^0(s) = a - bs - \sum_r \frac{c_r}{s_r - s}$$



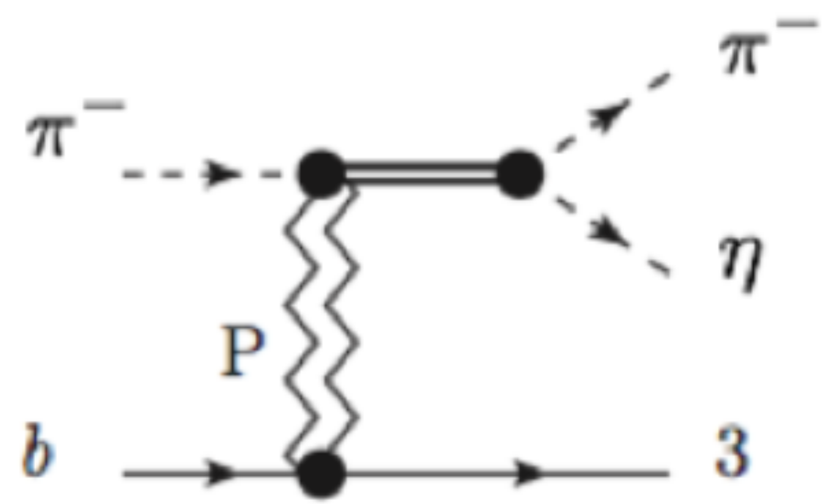


$M(1320) = 1.308(2)$ GeV, $\Gamma(1320) = 0.113(1)$ GeV
$M(1700) = 1.71(6)$ GeV, $\Gamma(1700) = 0.30(6)$ GeV

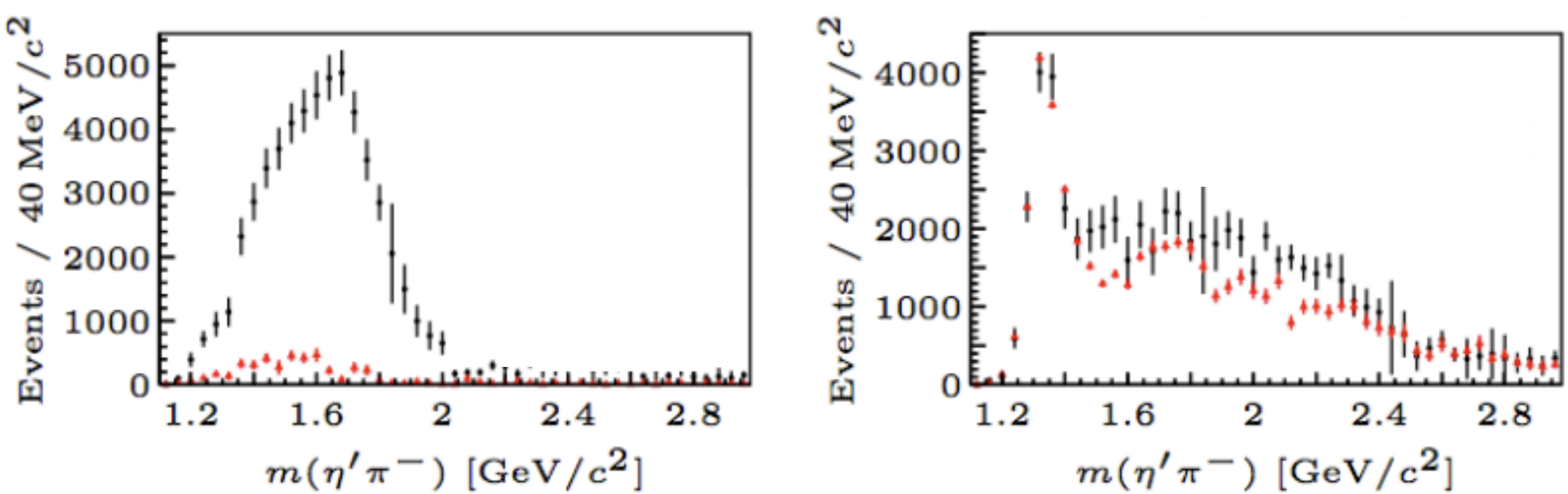
$$\pi^- p \to \eta' \pi^- p$$



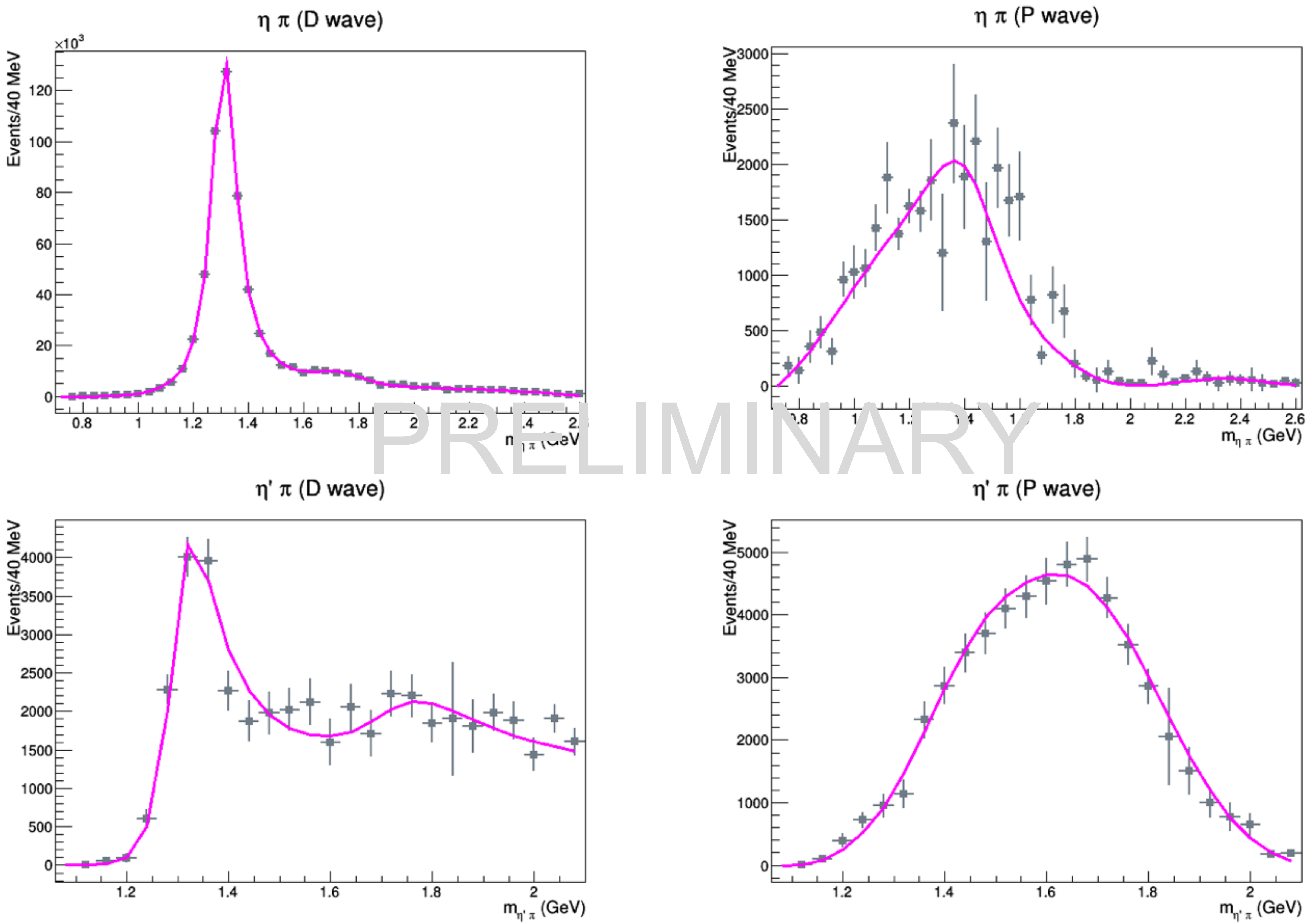
E852



COMPASS

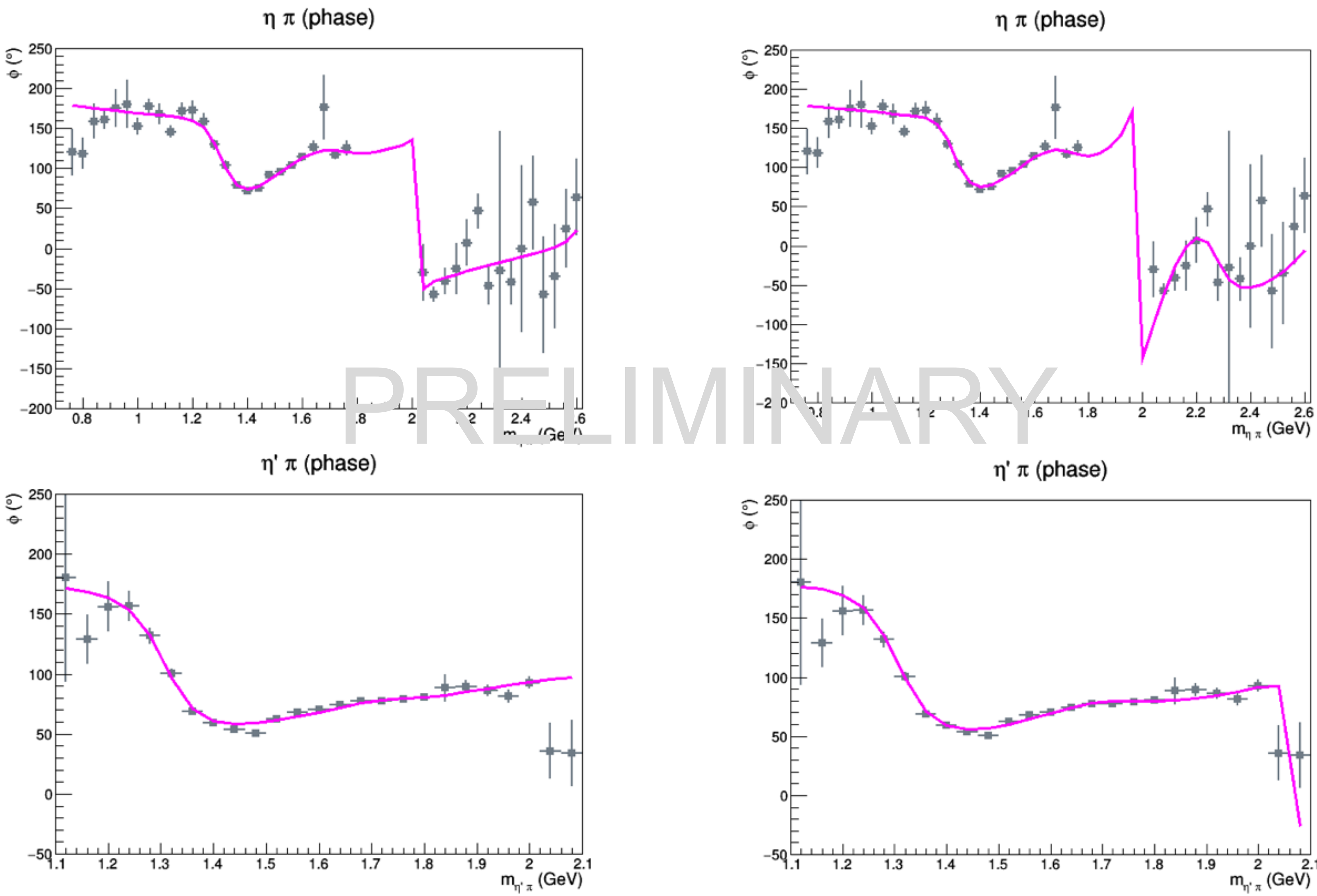


Fits to COMPASS data (preliminary)



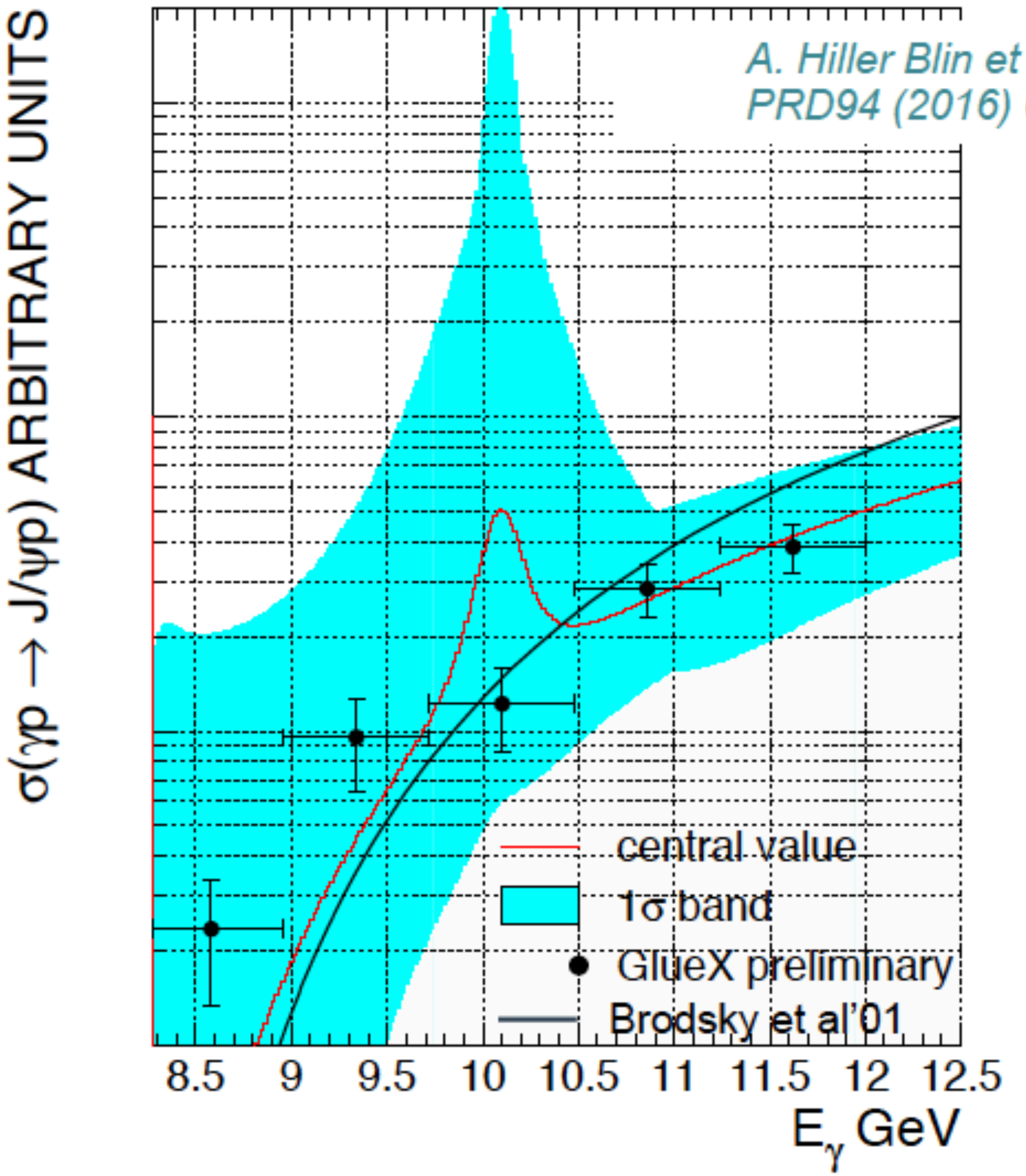
Fits to COMPASS data (preliminary)

2 poles | *1 pole*



Exotic physics: P_c at JLAB

Confirmation possible thorough photoproduction

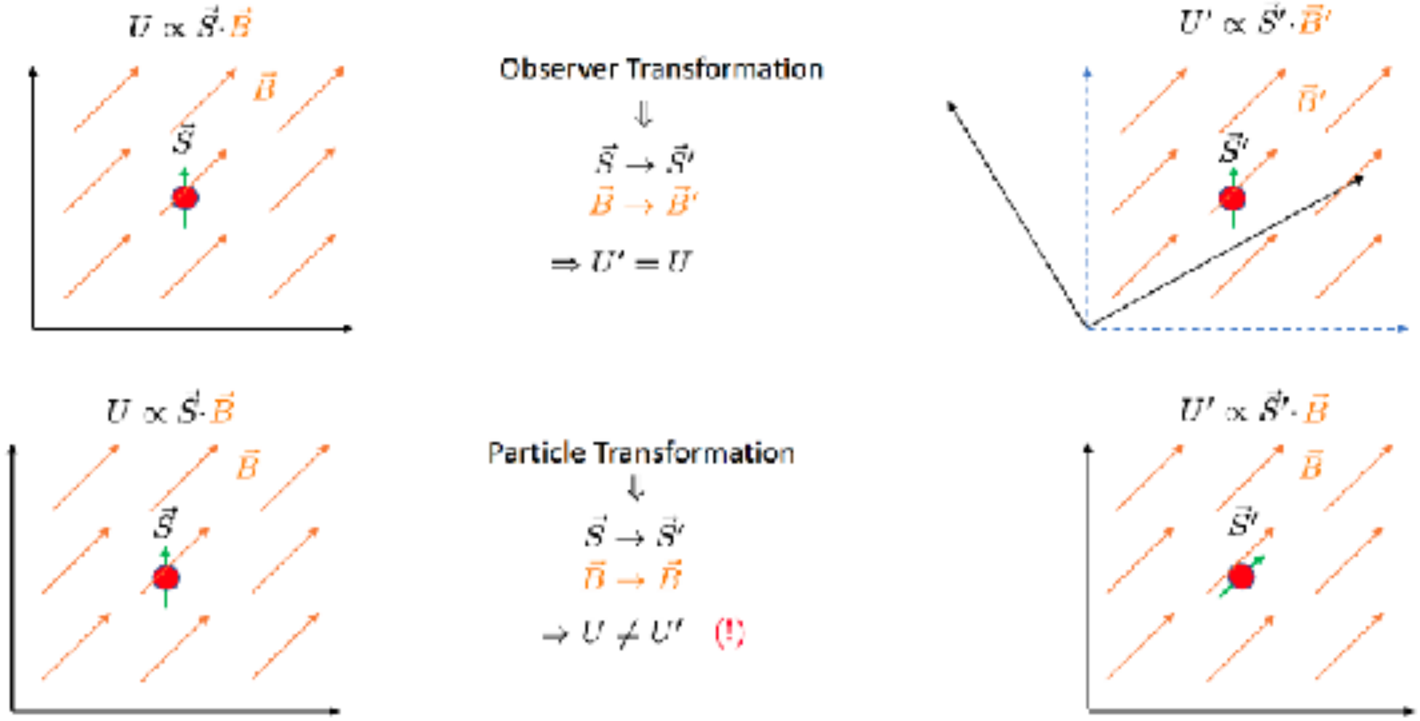


If P_c is confirmed, need to:

- Study the electromagnetic properties
- Look for the other members of the P_c multiplet
- Investigate its nature on the model of *A. Pilloni et al., Phys.Lett. B772 (2017) 200*
- NB: Arbitrary normalization for data

S.J. Brodsky, E. Chudakov , P. Hoyer, J.M. Laget Phys.Lett. B498 (2001) 23-28

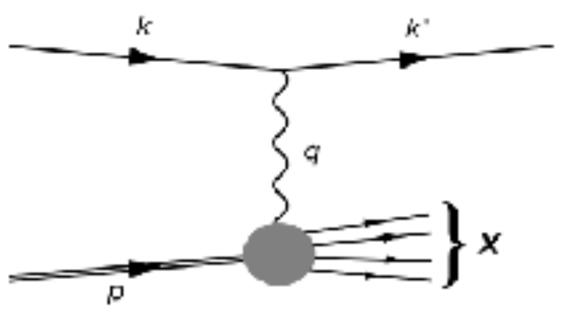
(Very) exotic physics: constraining Lorentz symmetry violation



- Observer transformations do not affect results.
- Particle transformation, e.g. rotation of the experiment in the background filed produces a physical effect.

- There is a well defined SME $\mathcal{L}_{SME} = \mathcal{L}_{Gravity} + \mathcal{L}_{SM} + \mathcal{L}_{LV}$ e.g $a_\mu \bar{\psi}\gamma^\mu\psi,\ c_{\mu\nu}\bar{\psi}\gamma^\mu \overleftrightarrow{D}^\nu\psi$
  (D.Colladay & V.A. Kostelecky, PRD55, 6760 (1997); PRD58, 1166002 (1998); PRD69, 105009 (2004))

- Only a few constraints in the quark sector : use DIS, SDIS, Drell-Yan, …



$$W^{\mu\nu} \simeq i \int d^4x e^{iq\cdot x} \int_0^1 d\xi \sum_{f=u,d} \frac{f_f(\xi)}{\xi} \langle \xi P | T\{J^\mu(x) J^\nu(0)\} | \xi P \rangle$$

$$\Gamma^\mu_f = \gamma^\mu + c_f^{\mu\nu}\gamma_\nu$$

- The first estimate on the sidereal time dependent coefficients c_f were obtained using HERA data: $O(10^{-5})$
  (V.A.Kostelecky, E.Lunghi, A.Vieira, PLB729, 272 (2017))

- Sensitivity studies for EIC are under way: N.Sherrill, A.Accardi, E.Lunghi.

Impact

- > 40 Research Papers (Phys. Rev. Lett., Phys.Rev., Phys.Lett., Eur.J. Phys.)
- ~120 Invited Talks and Seminars
- $\mathcal{O}(10)$ on going analyses
- Many projects, e.g.,
  - $\pi N \to \eta\pi N$ *A. Jackura et al.,* arXiv:1707.02848
  - η, η' beam asymmetry *V. Mathieu et al.,* arXiv:1704.07684
  - $Z_c(3900)$ *A. Pilloni et al.,* PLB772 (2017) 200
  - $\gamma p \to \eta p$ *J. Nys et al.,* PRD95 (2017) 034014
  - $P_c(4450)$ *A. Hiller Blin et al.,* PRD94 (2016) 034002
  - $\eta \to \pi^+\pi^-\pi^0$ *P. Guo et al.,* PRD92 (2015) 054016, PLB (2017) 497
  - $\Lambda(1405)$ *C. Fernández-Ramírez et al.,* PRD93 (2016) 074015
  - $KN \to KN$ *C. Fernández-Ramírez et al.,* PRD93 (2016) 034029
  - $\pi N \to \pi N$ *V. Mathieu et al.,* PRD92 (2015) 074004
  - $\gamma p \to \pi^0 p$ *V. Mathieu et al.,* PRD92 (2015) 074013
  - $\omega,\phi \to \pi^+\pi^-\pi^0$ *I. Danilkin et al.,* PRD91 (2015) 094029
  - $\gamma p \to K^+K^-p$ *M. Shi et al.,* PRD91 (2015) 034007
  - …
- Collaboration between JPAC and experimental collaborations: co-authoring papers
  - GlueX, CLAS12, COMPASS, BaBar, Belle, BES
  - KLOE, LHCb *in preparation*

JPAC 2018

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[1]JLab/GWU funded
[2]JLab/IU funded

Collaborating with: CLAS12 & GlueX (JLab 🇺🇸), COMPASS & LHCb (CERN 🇪🇺🇨🇭), MAMI (Mainz 🇩🇪), BESIII (Beijing 🇨🇳), KLOE (Frascati 🇮🇹), BELLE II (KEK 🇯🇵), BABAR (SLAC 🇺🇸)