Amplitude Analyses of Meson Photo and Electroproduction

Results from JPAC

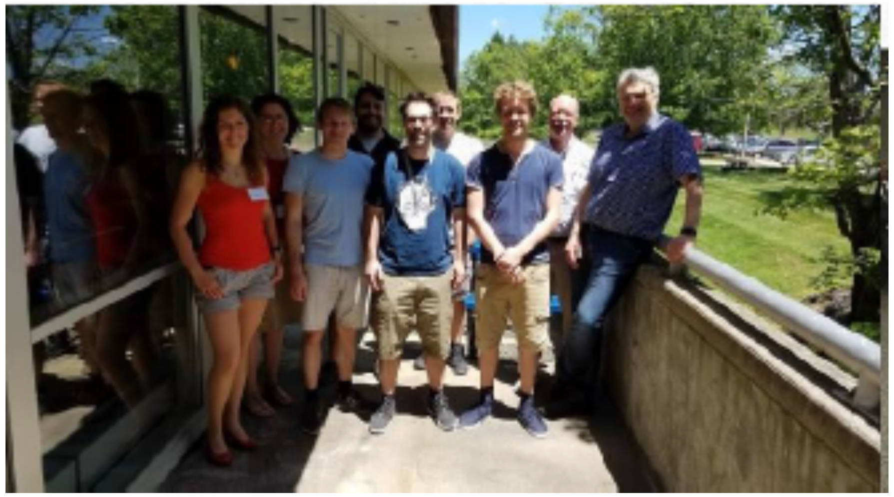
Adam Szczepaniak, Indiana University/Jefferson Lab

Join Physics Analysis Center

Joint Physics Analysis Center

JPAC

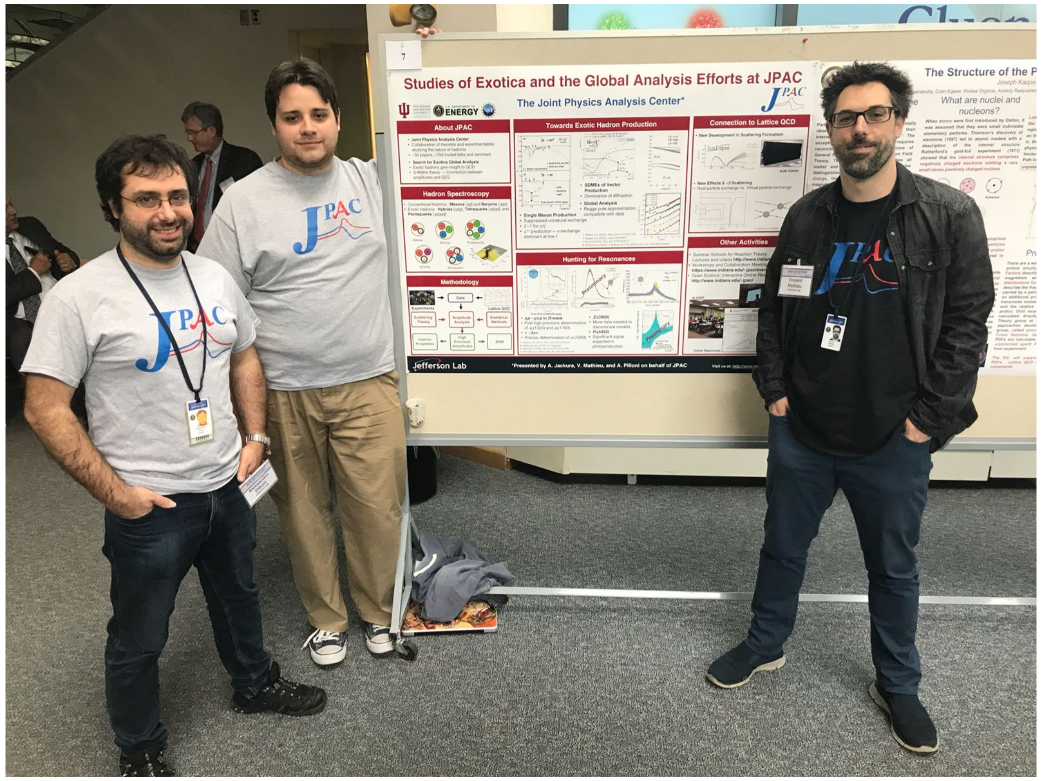
- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other accelerator laboratories



- Contribute to education of new generation of practitioners in physics of strong interactions : Graduate course on reaction theory

https://jpac.jlab.org

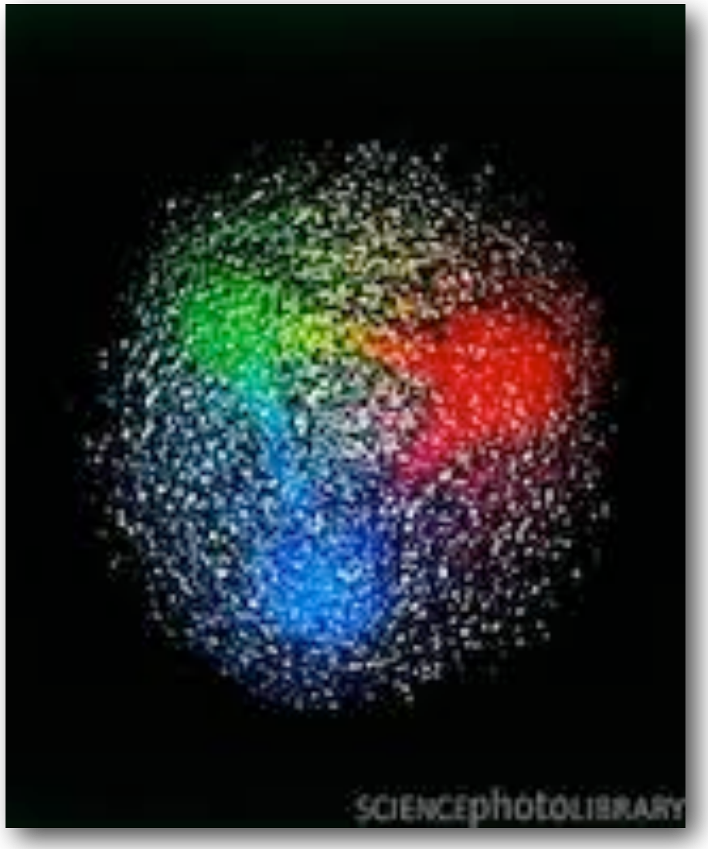
http://ceem.indiana.edu/jpac



Outline:

- Why ? Aspects of QCD and Confinement
- High precision data calls for precision in theoretical analysis — Amplitude analysis
- Sample of JPAC recent results

Why spectroscopy

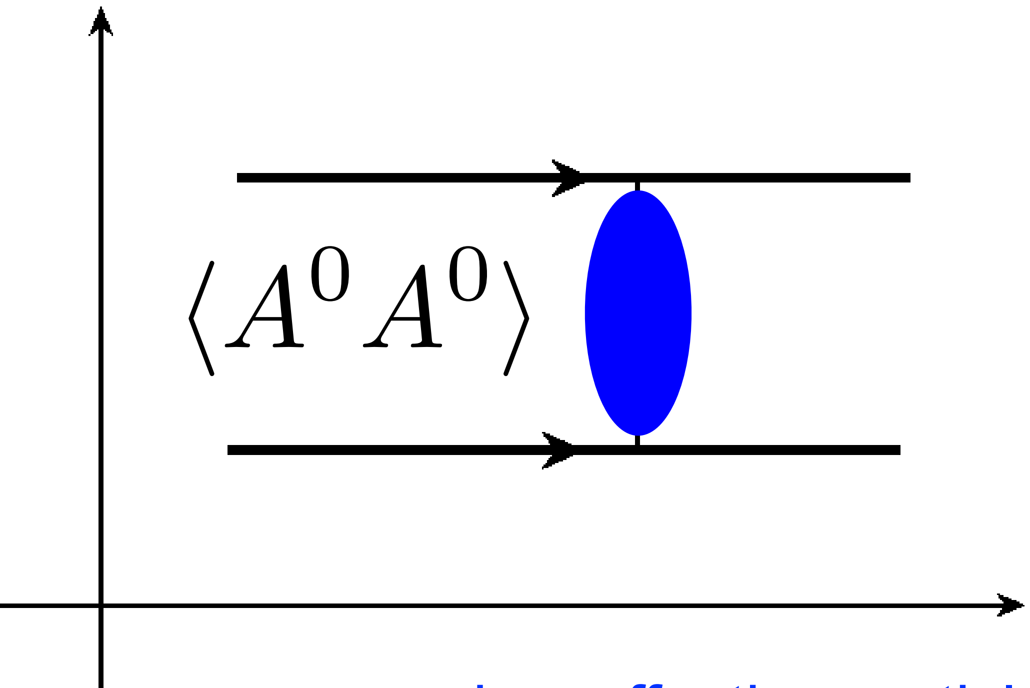


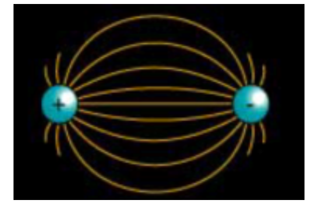
(Most) Hadrons are composed from valence quarks
What does it mean ?

Are constituent quarks (gluons?) real ?
→ How is mass generated
What about gluons ?
→ confinement vs Higgs behavior

The dual role of gluons

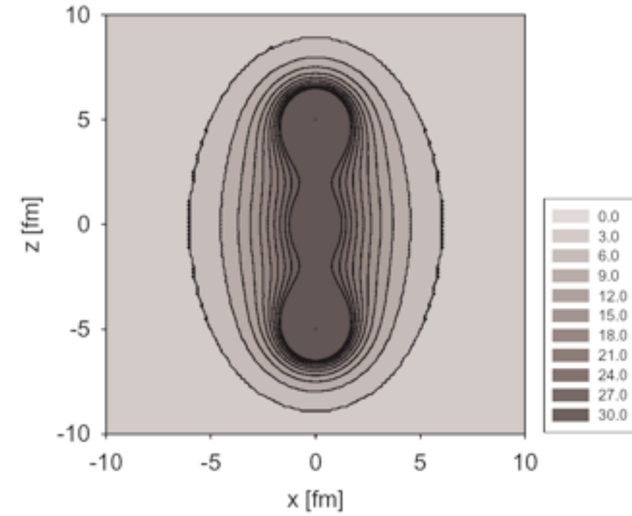
long range instantaneous potential

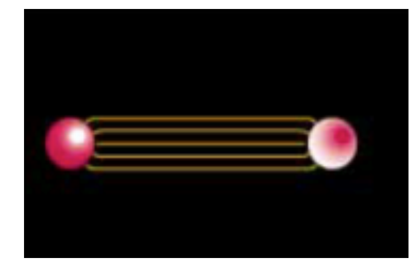




Possible scenario : Color interactions between external sources emerges through chromo-magnetic condensate

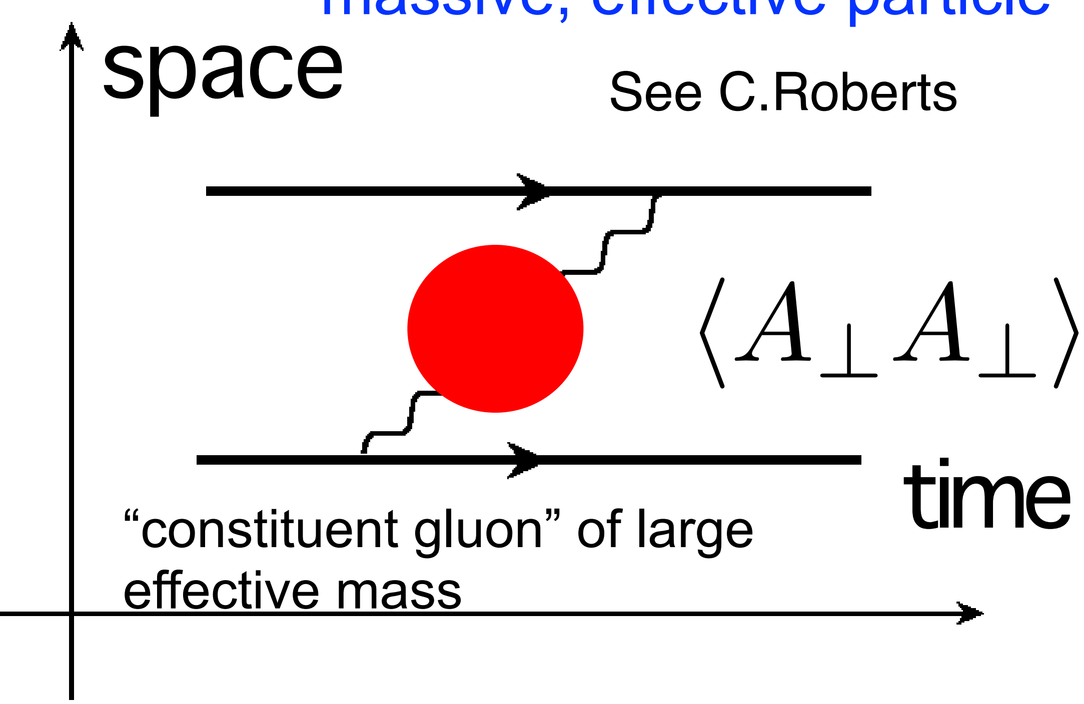
$$\vec{E}_L^2(x/R \to \infty) \sim \frac{R^2}{x^4}$$



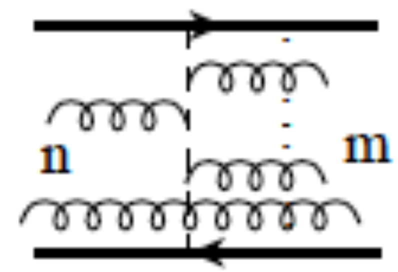


massive, effective particle

See C.Roberts

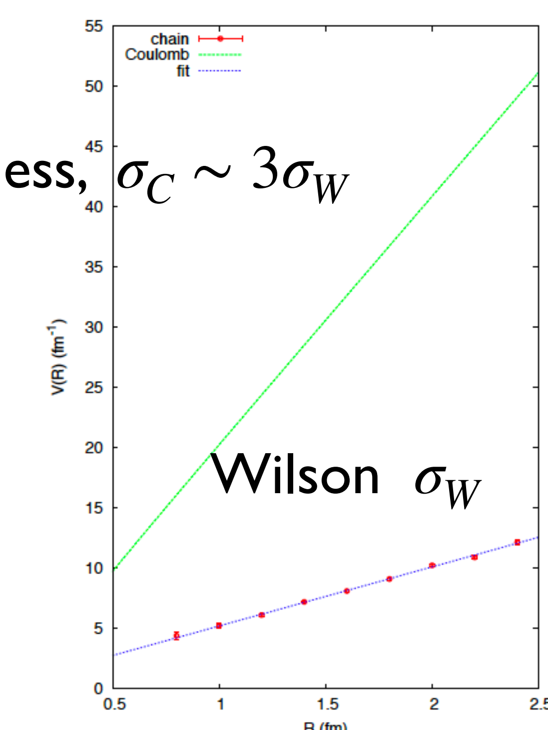


"stringless states": How collimated fluxes emerge (how power-law becomes an exponentials) ?



$$J^{PC}_{gluon} = 1^{+-}$$

Stringless, $\sigma_C \sim 3\sigma_W$

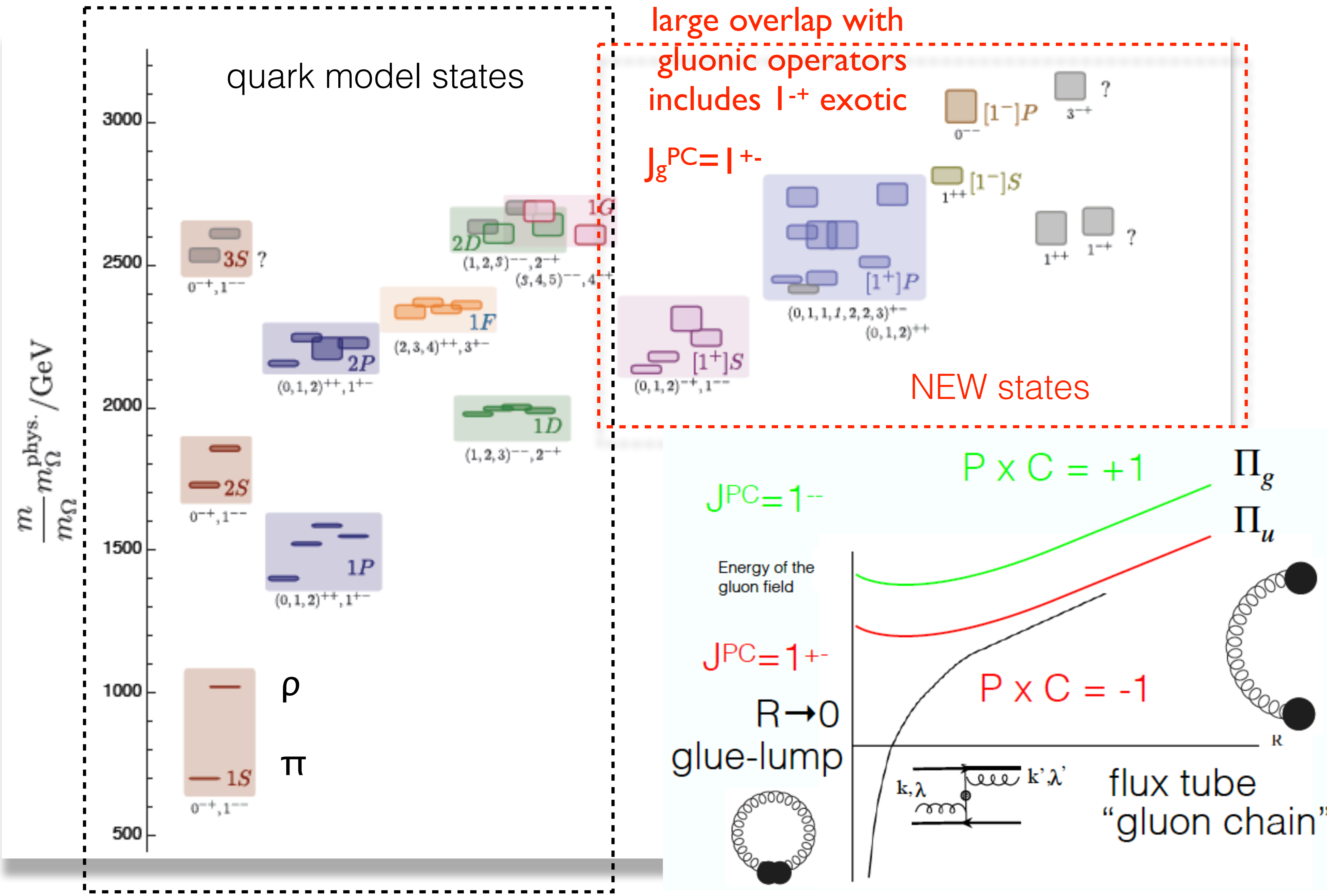


"stringy states" from constituent gluon chains

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

lowest-mass hybrid multiplet

Quark Model with Gluons : Hybrid States



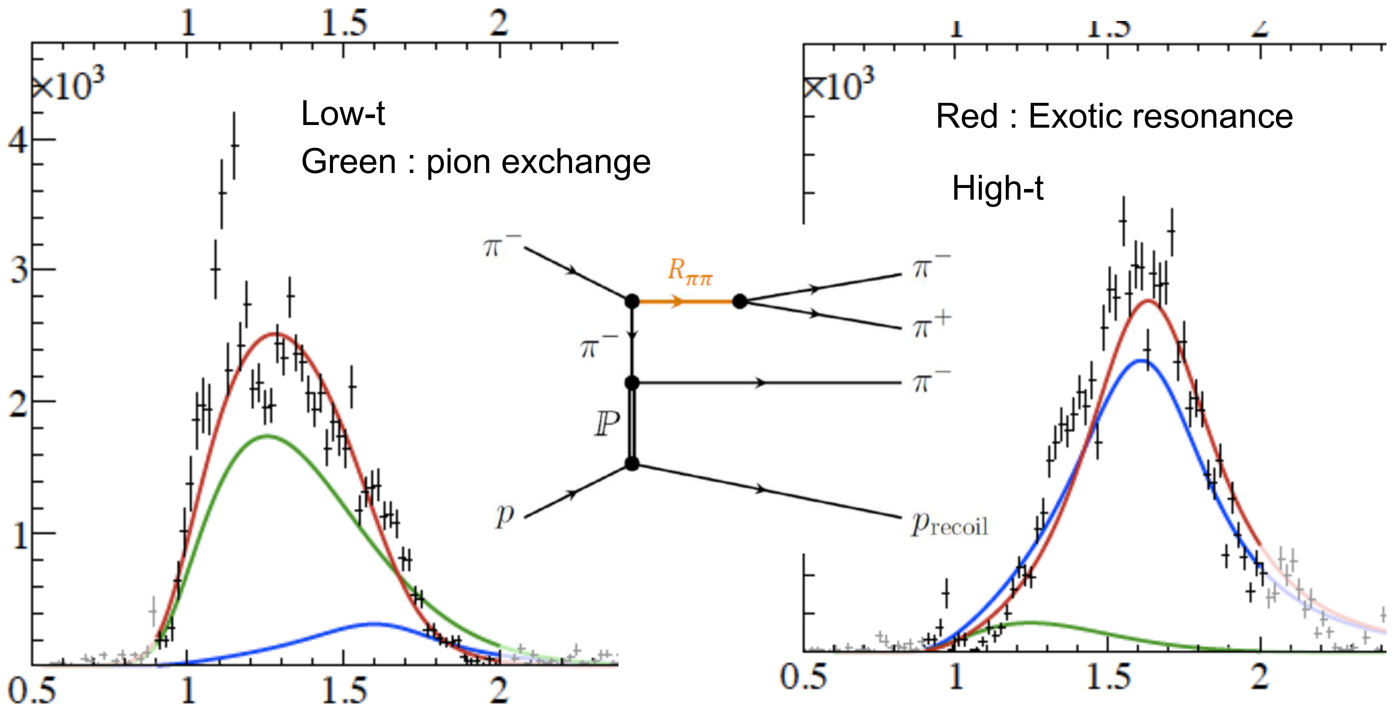
HASPEC@JLab : Isovector states ~700MeV pion

$$|hybrid\rangle = |J J_g L_{Q\bar{Q}} S\rangle$$

Plenty of signatures: hybrids

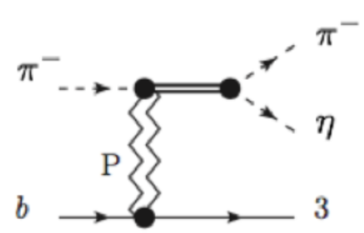
- Exotic $J^{PC}=1^{-+}$ (hybrid) mesons expected (VES, GAMS,E852, COMPASS, and theory)

- In low-t pion diffraction (COMPASS) exotic wave production compatible with one pion exchange (but not at high-t)

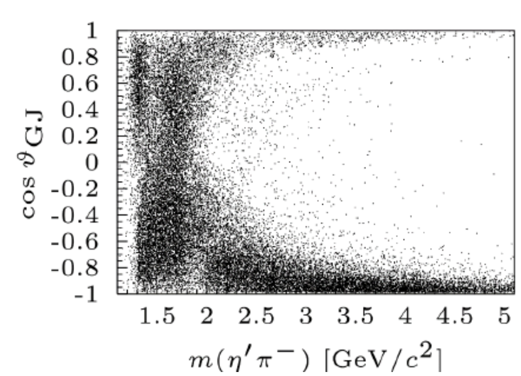


COMPASS (2018)

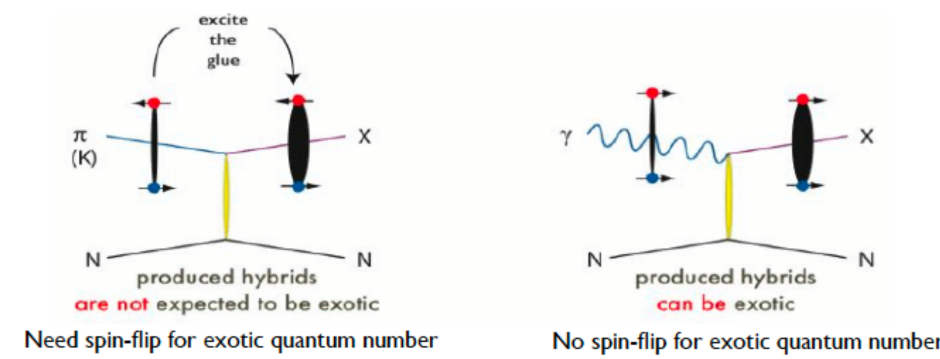
$\pi^- p \rightarrow \eta^{(')} \pi^- p$

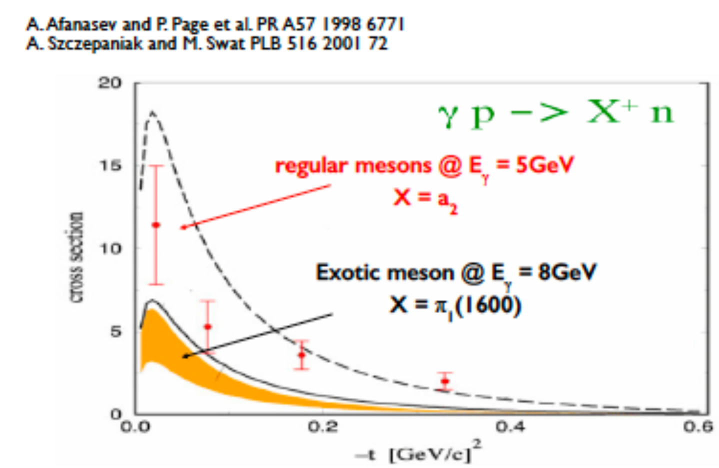


- Large exotic wave seen in $\eta^{(')} \pi$ production : Golden Channel



- In photoproduction (GlueX,CLAS12) exotic mesons produced via pion exchange (both good and bad)





- Dualities : “reggeons”-resonances”, “pomerons/ gluons”, “quarks-hadrons”, ect — analytical amplitudes

Amplitude analysis : connecting data to QCD

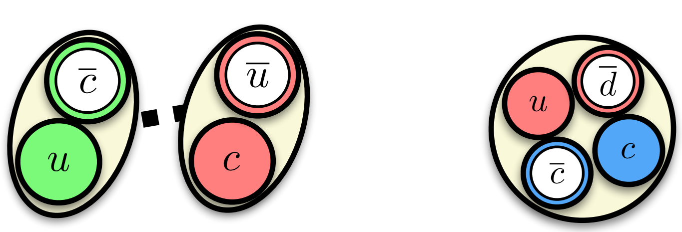
Bottom → Up

Amplitudes

Rules (bubbles, regularization, renormalization, etc.)

↑ Data

Microscopic model



Mesonic-Molecules   Tetraquarks

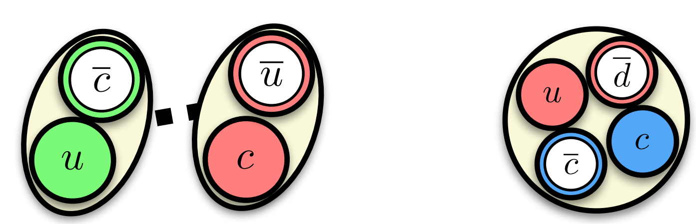
Top → Bottom

Amplitudes

Data ↓

Physical interpretation of poles, cuts,

Microscopic model



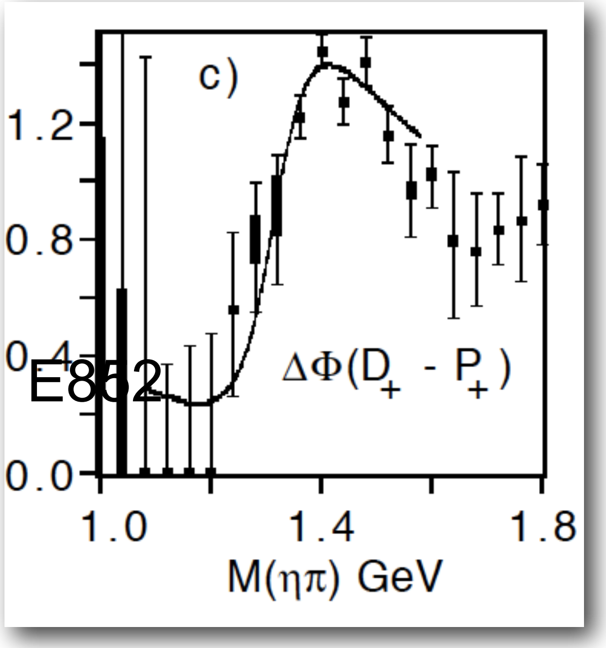
Mesonic-Molecules   Tetraquarks

The π_1 (exotic) meson candidate

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

$$M = 1370 \pm 16^{+50}_{-30} \ \mathrm{MeV}/c^2$$
$$\Gamma = 385 \pm 40^{+65}_{-105} \ \mathrm{MeV}/c^2$$

π_1 (1400) E852, also GAMS, VES, Crystal Barrel



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

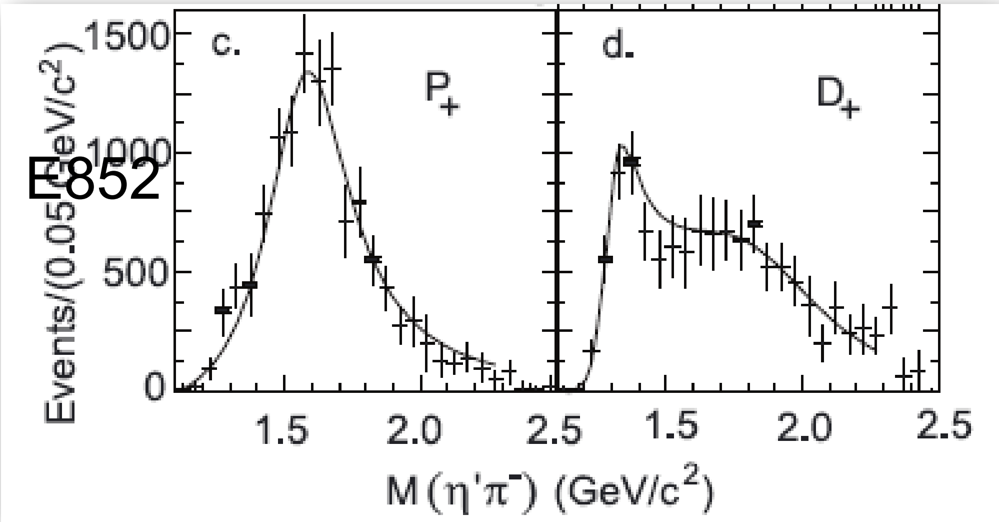
$$M = 1597 \pm 10^{+45}_{-10} \ \mathrm{MeV}/c^2$$
$$\Gamma = 340 \pm 40^{+50}_{-50} \ \mathrm{MeV}/c^2$$

π_1 (1600)

E852, also COMPASS,CLEO

Is it 1400 or 1600 ?

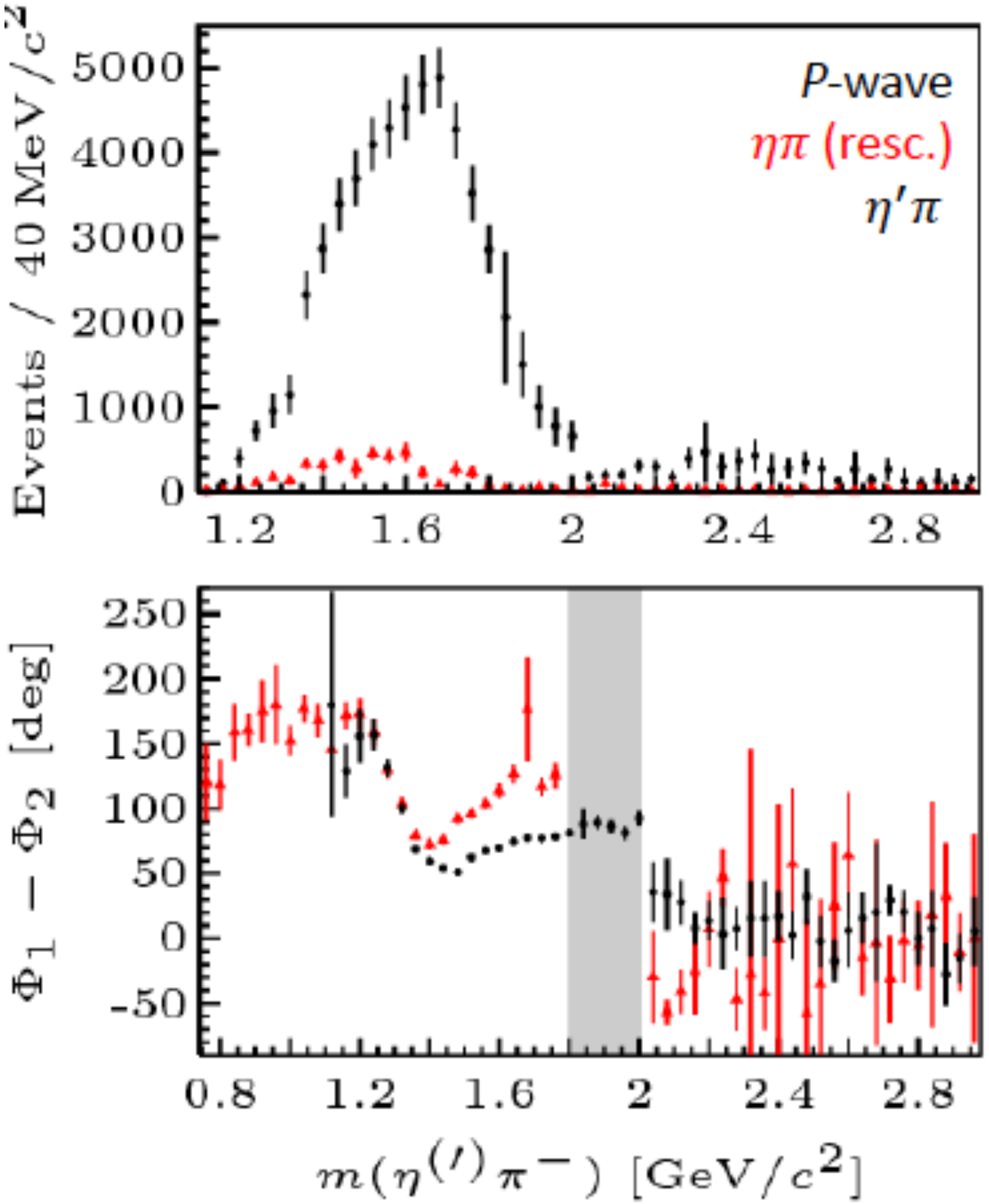
COMPASS consistent with both



COMAPSS data, JLab data coming soon !

Data

COMPASS, PLB740, 303-311



A sharp drop appears at 2 GeV in *P*-wave intensity and phase

No convincing physical motivation for it

It affects the position of the $a_2'(1700)$

We decided to fit up to 2 GeV only

Coupled channel: the model

A. Rodas, AP *et al.* (JPAC), to appear

Two channels, $i, k = \eta\pi, \eta'\pi$ Two waves, $J = P, D$ 37 fit parameters

$$D^J_{ki}(s) = \left[K^J(s)^{-1}\right]_{ki} - \frac{s}{\pi}\int_{s_k}^{\infty} ds' \frac{\rho N^J_{ki}(s')}{s'(s'-s-i\epsilon)}$$

$$K^J_{ki}(s) = \sum_R \frac{g_k^{(R)} g_i^{(R)}}{m_R^2 - s} + c^J_{ki} + d^J_{ki}\, s$$

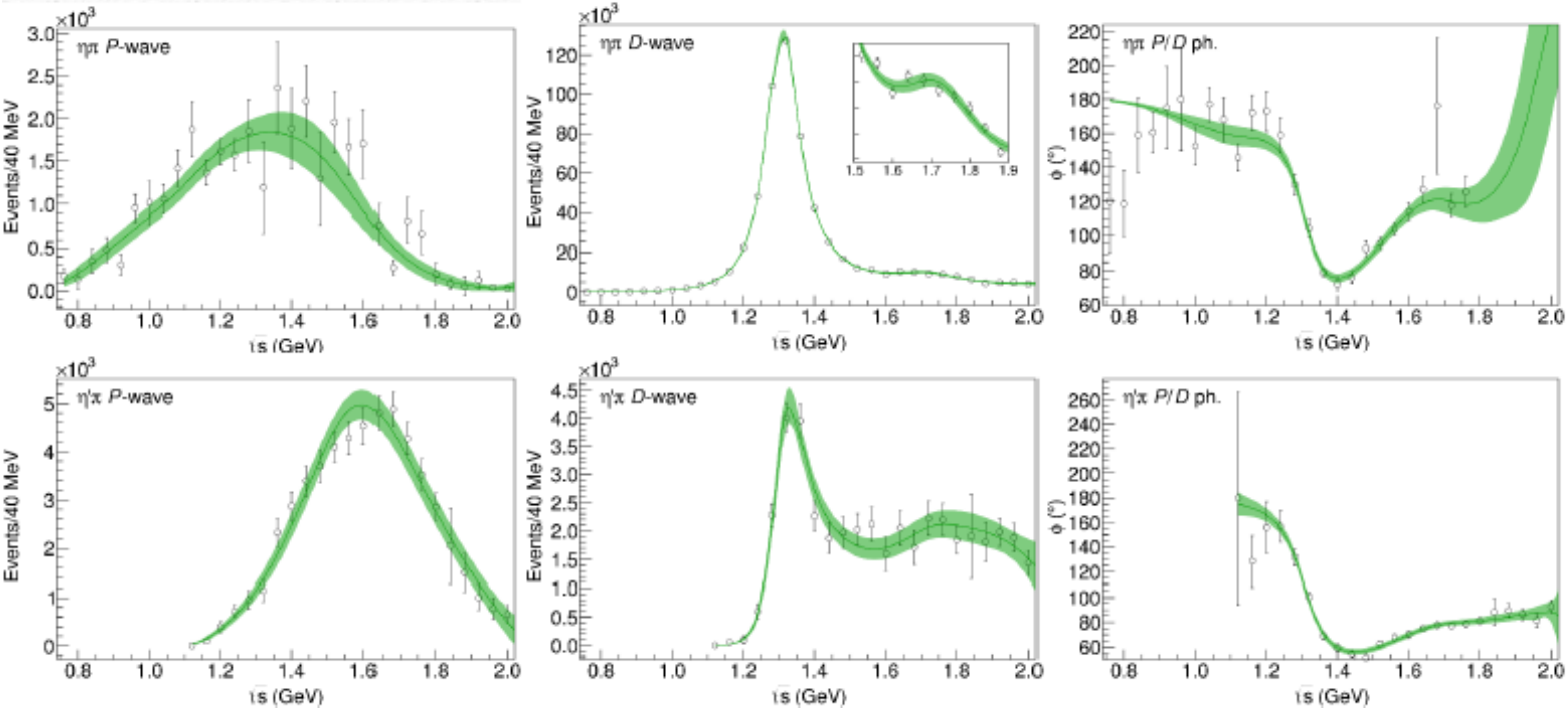
1 K-matrix pole for the P-wave
2 K-matrix poles for the D-wave

$$\rho N^J_{ki}(s') = g\,\delta_{ki}\,\frac{\lambda^{J+1/2}\left(s', m^2_{\eta^{(\prime)}}, m^2_\pi\right)}{(s'+s_R)^{2J+1+\alpha}}$$

$$n^J_k(s) = \sum_{n=0}^{3} a_n^{J,k}\, T_n\!\left(\frac{s}{s+s_0}\right)$$

Left-hand scale (Blatt-Weisskopf radius) $s_R = s_0 = 1\ \mathrm{GeV}^2$
$\alpha = 2$ as in the single channel, 3rd order polynomial for $n^J_k(s)$

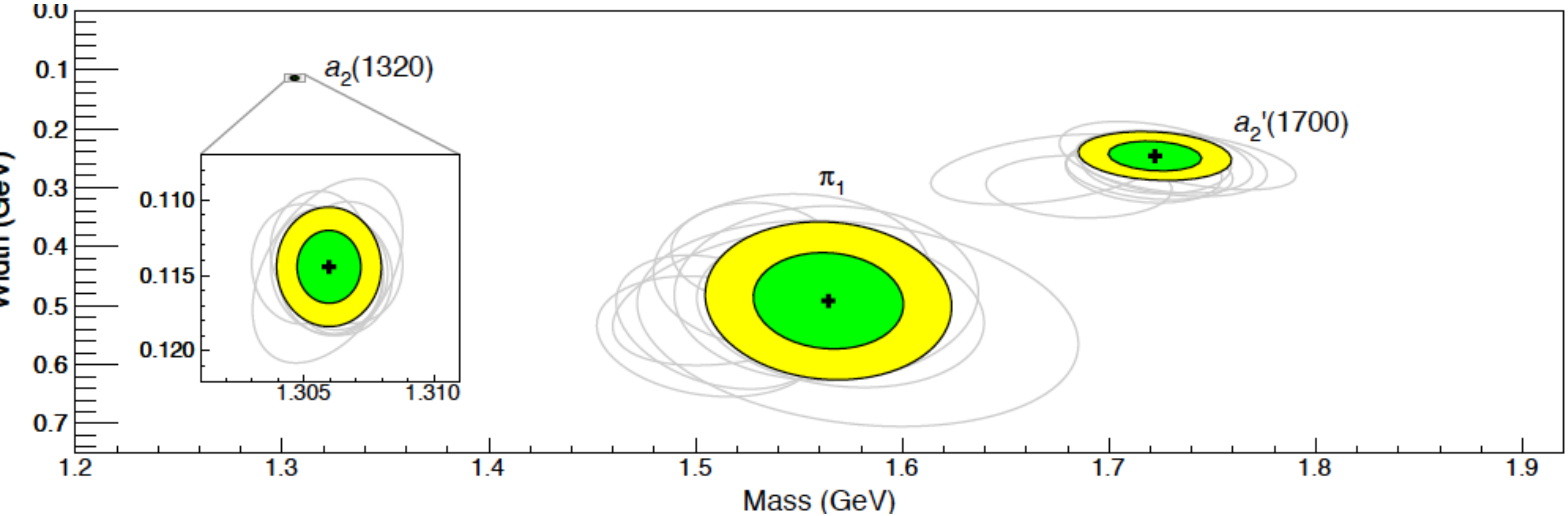
Fit



$\chi^2/\text{dof} = 162/122 \sim 1.3$, statistical error estimated via 50k bootstraps

Bands show the 2σ error

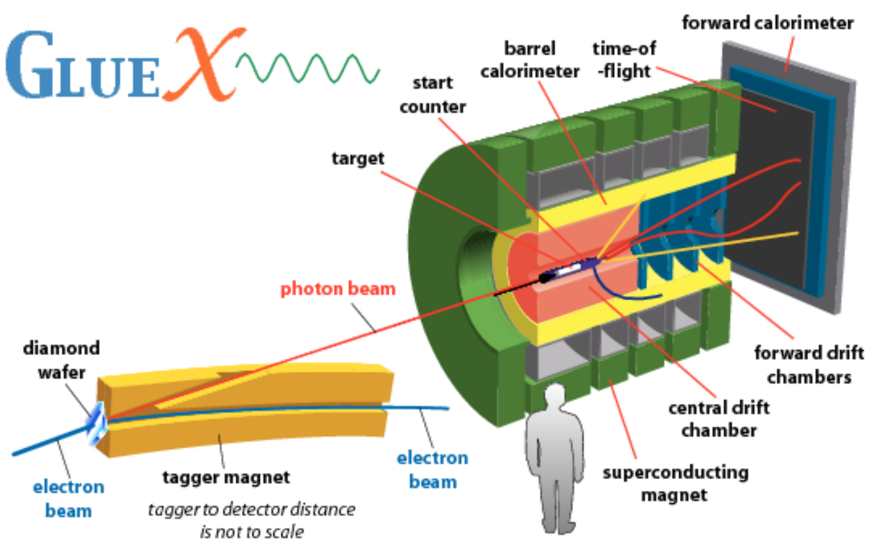
Bootstrap + model variations

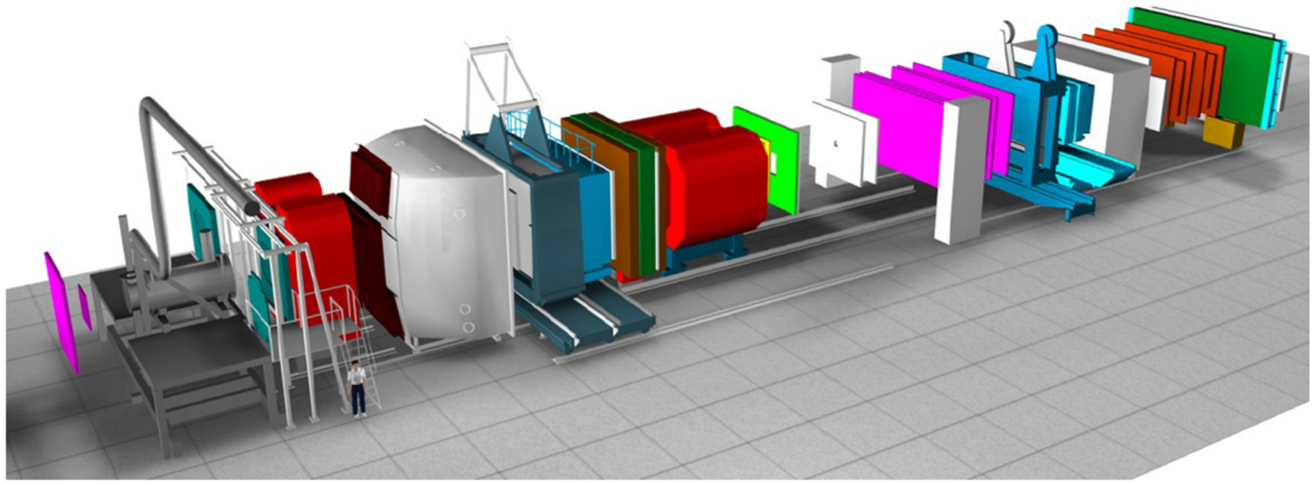


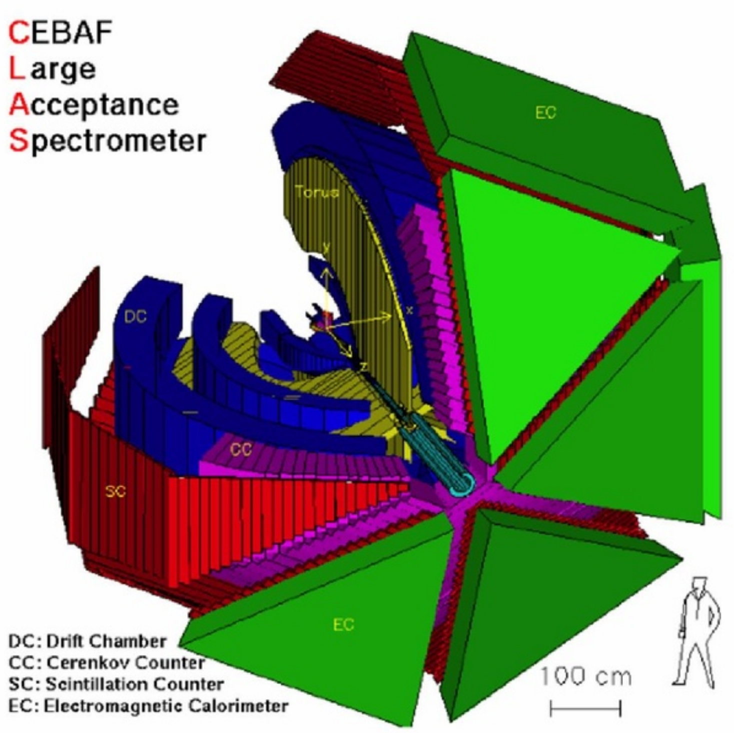
The variance of the bootstrapped poles gives the statistical error

Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	1306.0 ± 0.8	114.4 ± 1.6
$a_2'(1700)$	1722 ± 15	247 ± 17
π_1	1564 ± 24	492 ± 54

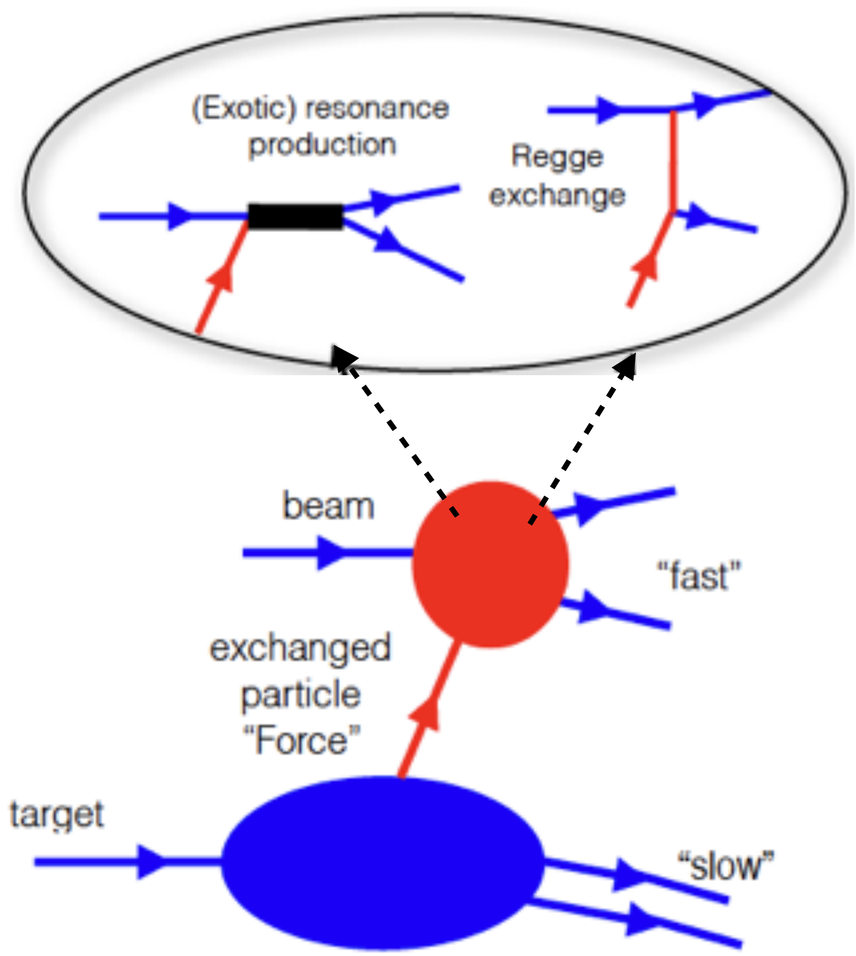
Regge factorization





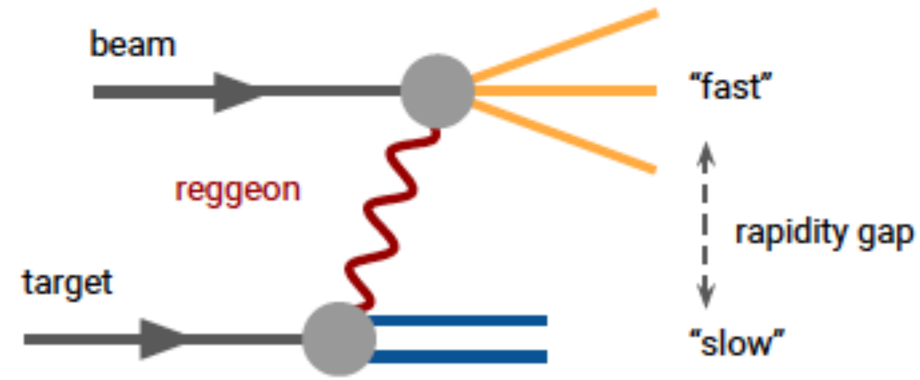


- Need to establish factorization between beam and target fragmentation (Regge factorization)
- Single Regge pole exchange dominate over cut other singularities (cuts, daughters)



Global analysis of single Regge factorization

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



- Factorizable Regge pole exchange

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

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

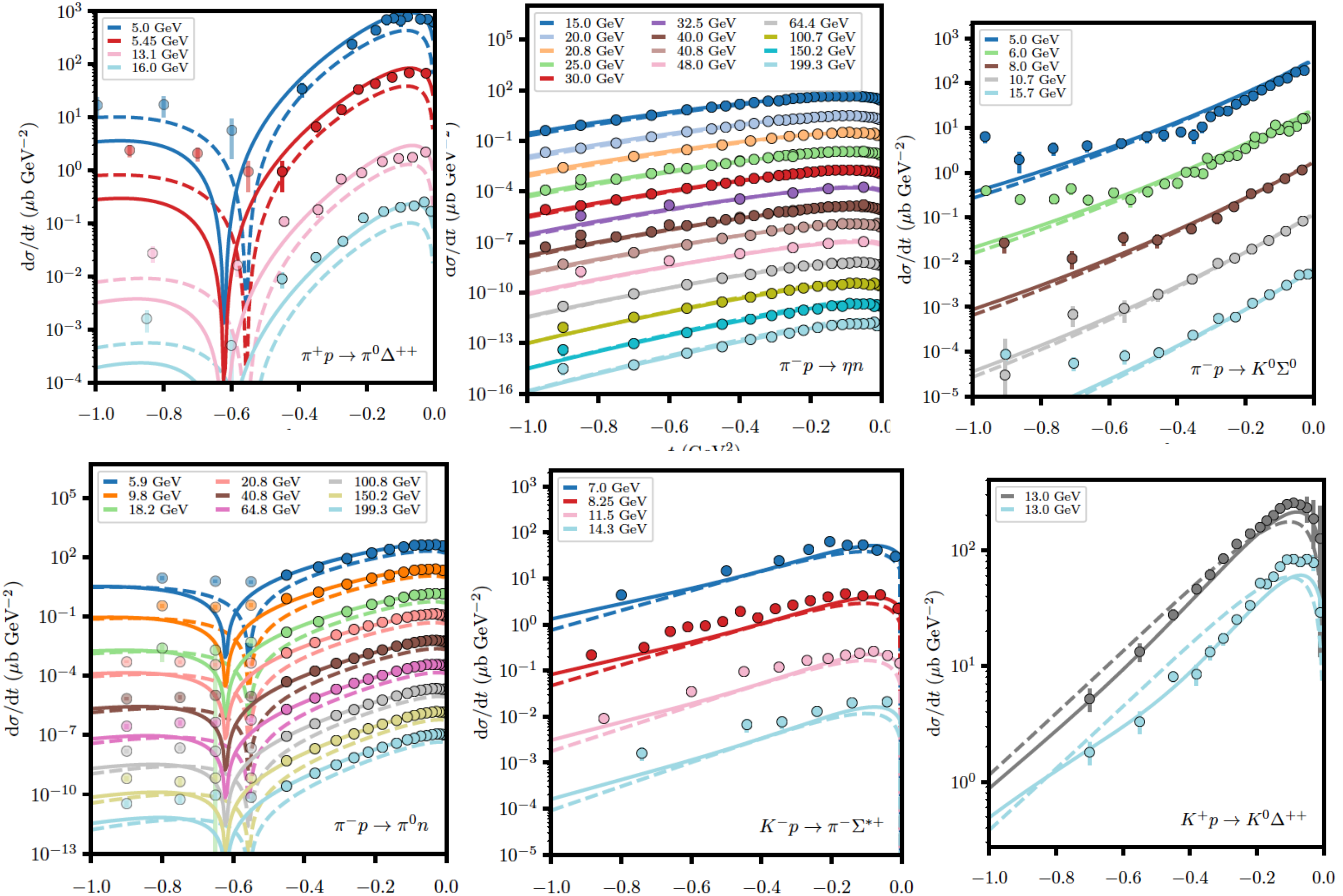
$$\mathcal{F}_e(s,t) = -\frac{\zeta_e \pi \alpha_e^1}{\Gamma(\alpha_e(t)-l_e+1)}\frac{1+\zeta_e e^{-i\pi\alpha_e(t)}}{2\sin\pi\alpha_e(t)}\left(\frac{s}{s_0}\right)^{\alpha_e(t)}$$

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

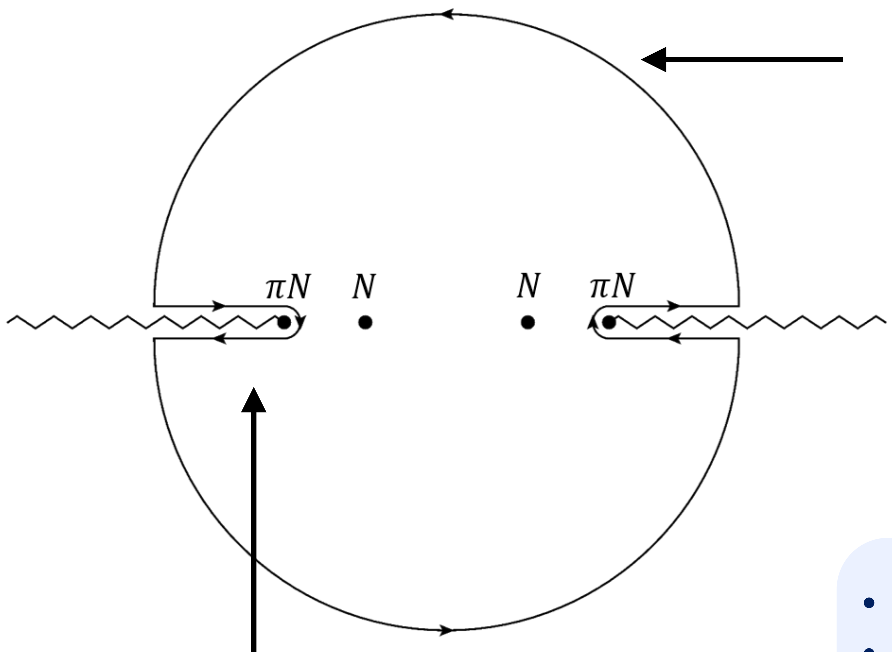
$$\mathcal{F}_e(s,t) \underset{t\to m_e^2}{\longrightarrow} \frac{(s/s_0)^{J_e}}{m_e^2-t}.$$

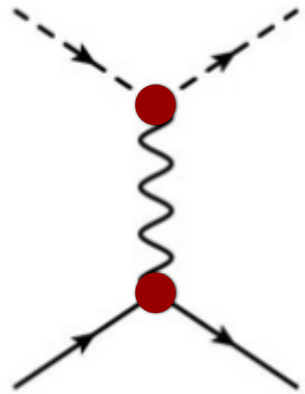
(6 SU(3) couplings, 1 mixing angle, 2 exp. slopes)

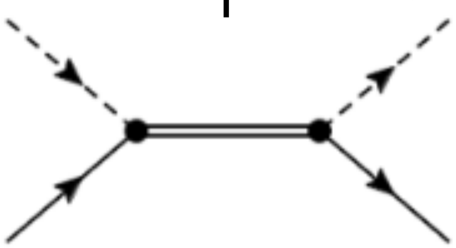
Global Regge pole analysis



Finite Energy Sum Rules





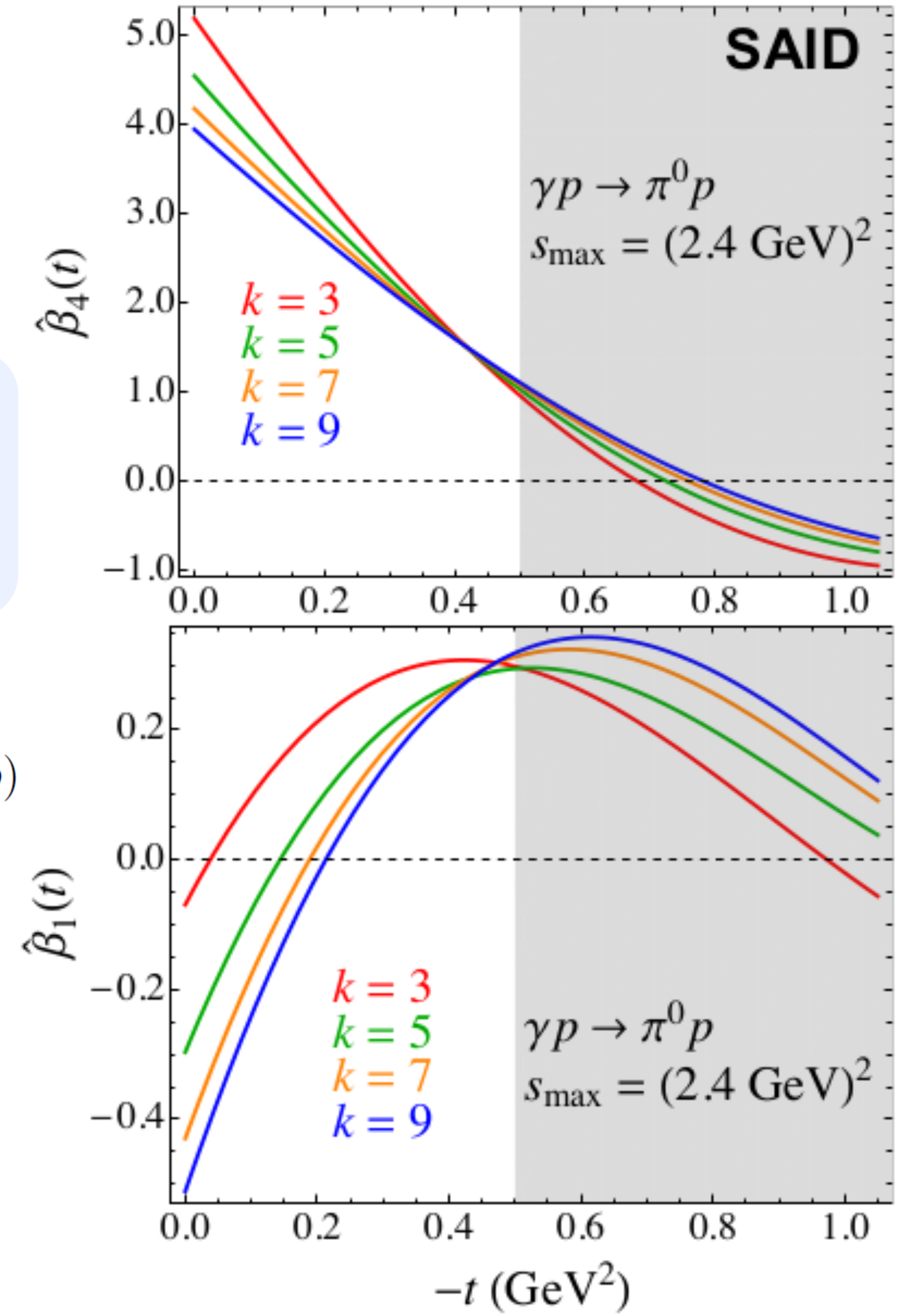


- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

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

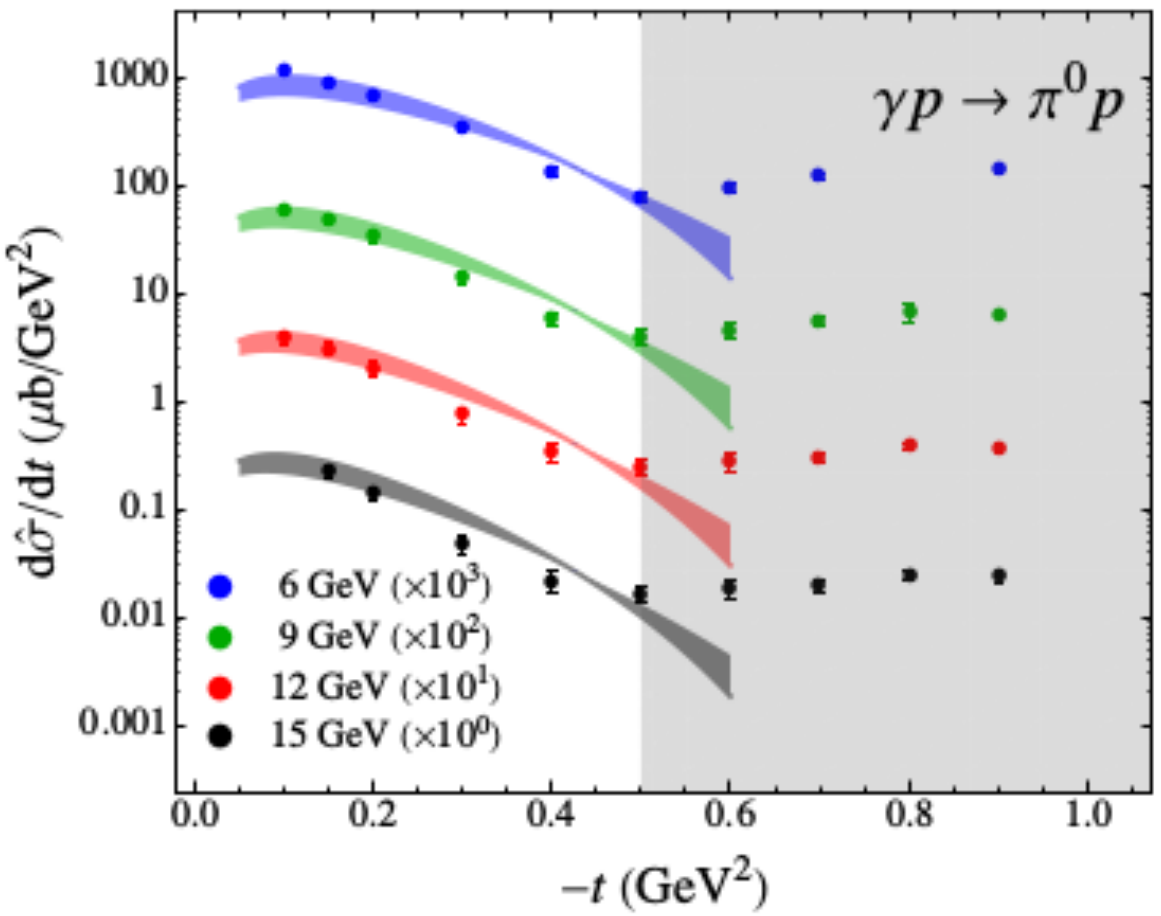
$$\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu = \beta_i(t)\frac{\Lambda^{\alpha(t)+k}}{\alpha(t)+k}$$

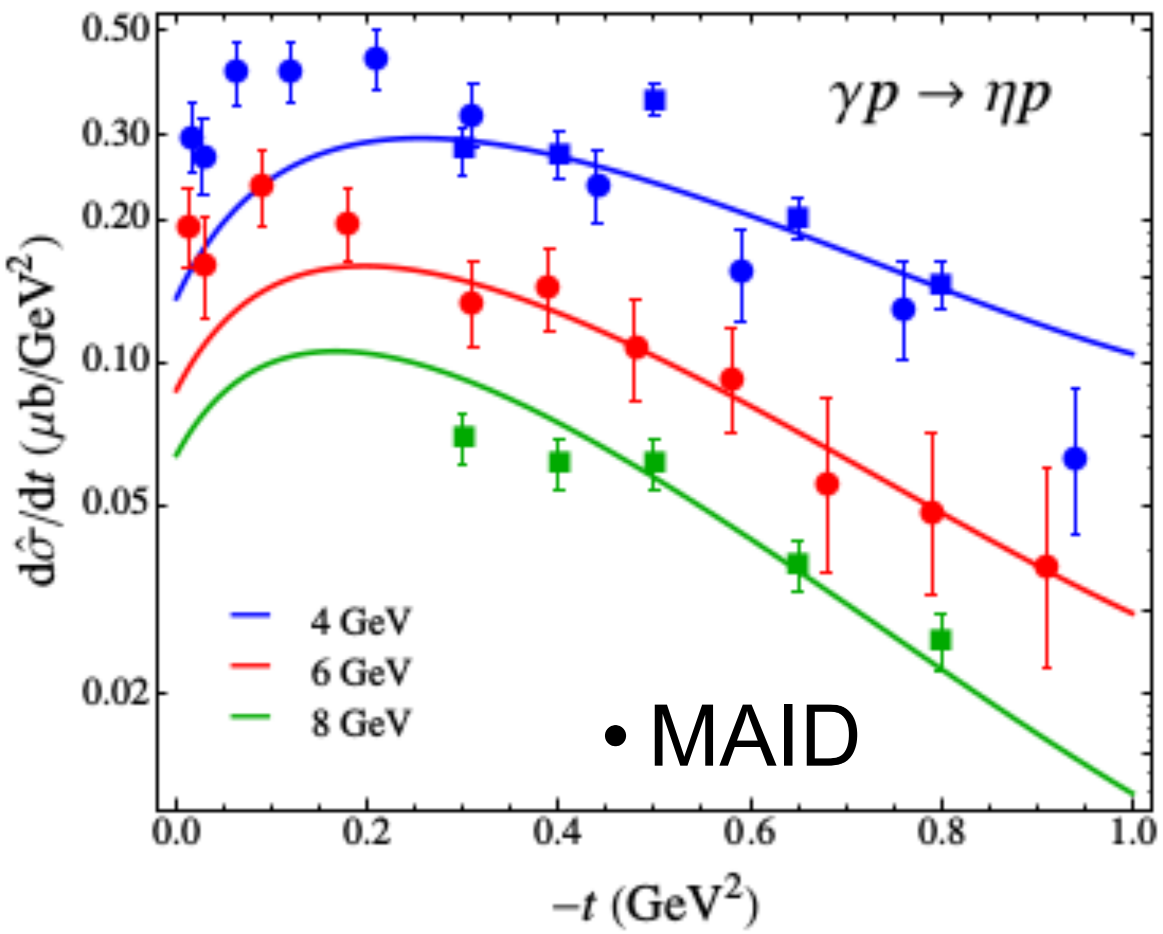
$$\beta_i(t) = \frac{\alpha(t)+k}{\Lambda^{\alpha(t)+k}}\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu$$



Finite Energy Sum Rules

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





Combine energy regimes

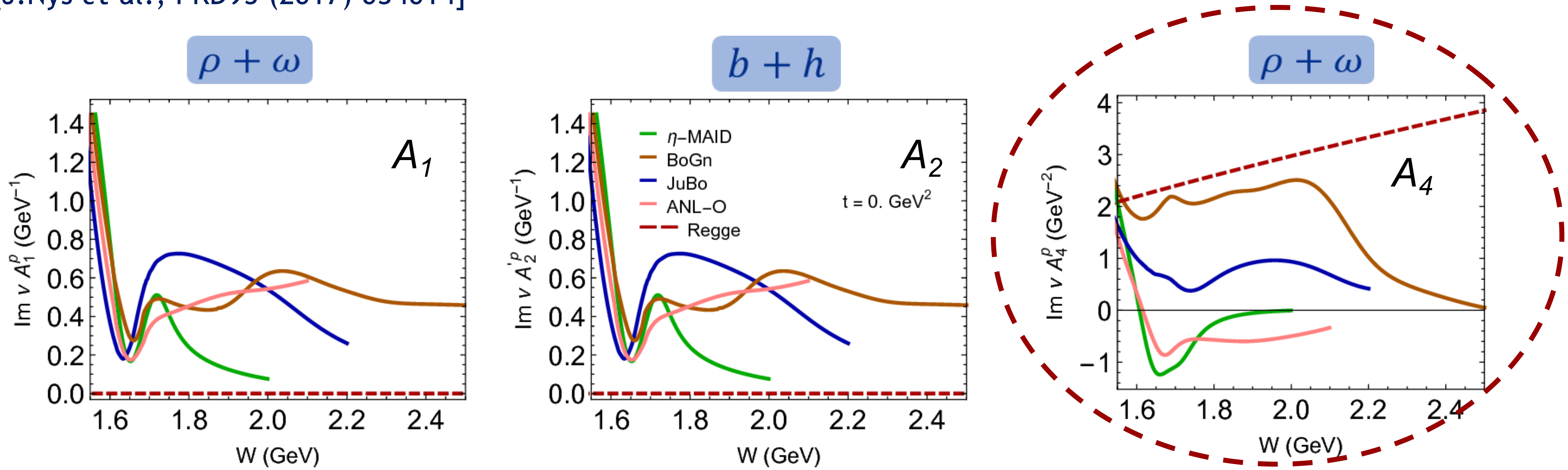
- Low-energy model ((SAID, MAID, Bonn-Gatchina, Julich-Bonn,…)
- Predict high-energy observables

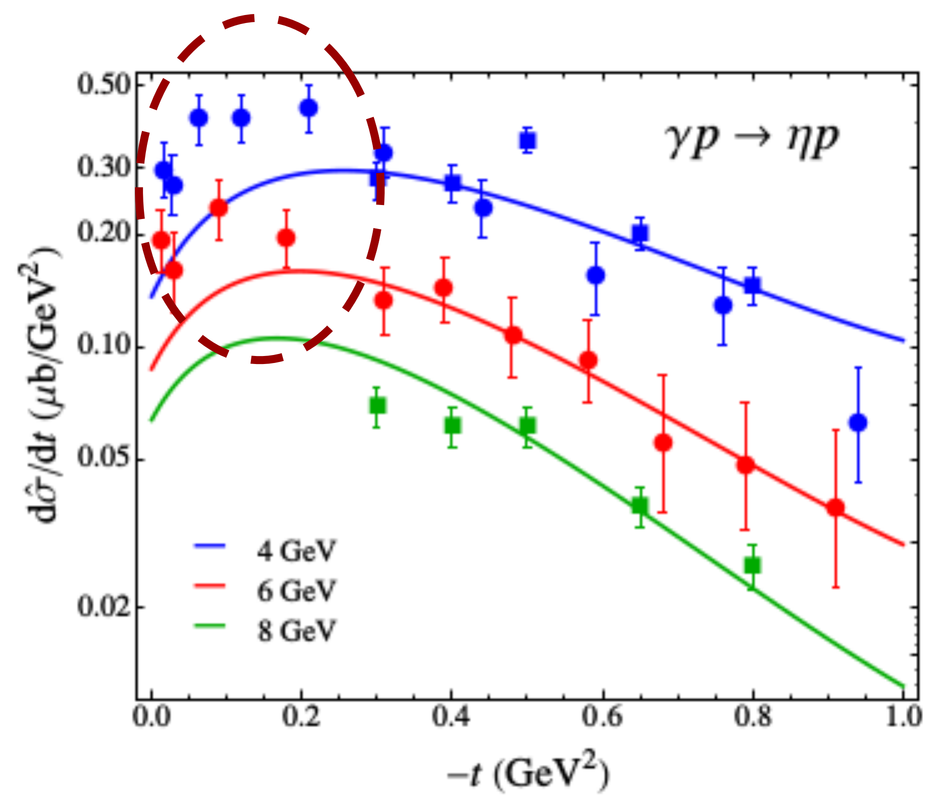
Two applications

- 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

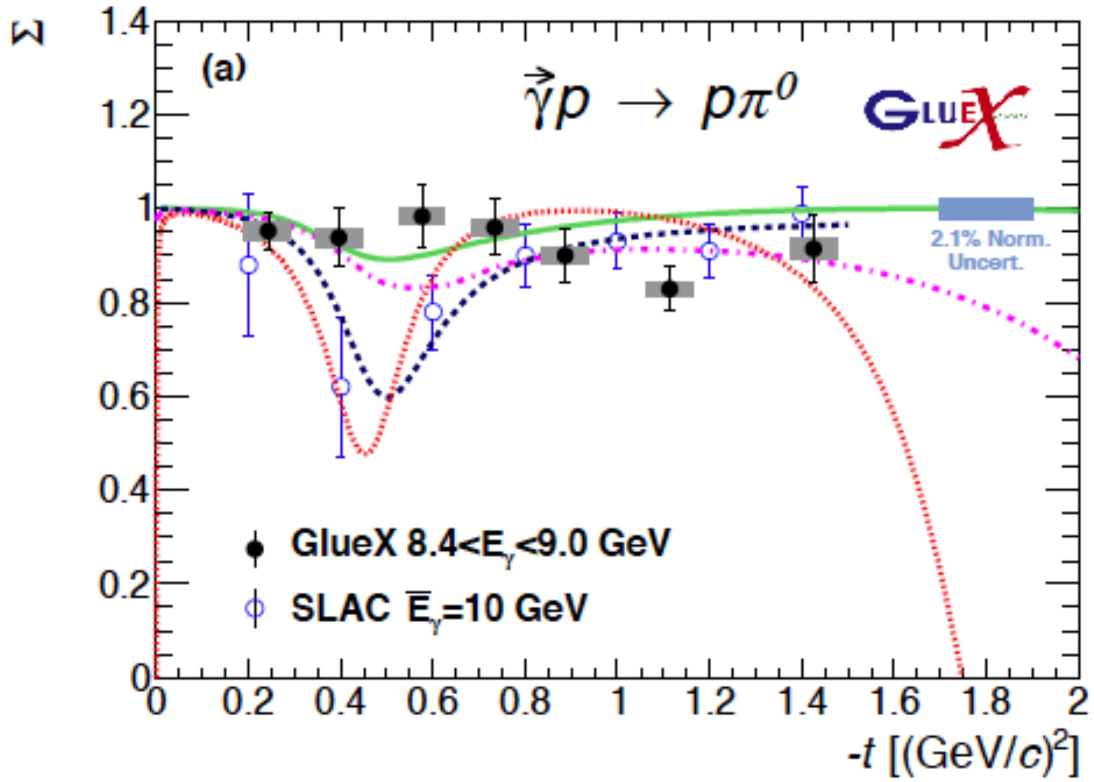
Possibilities

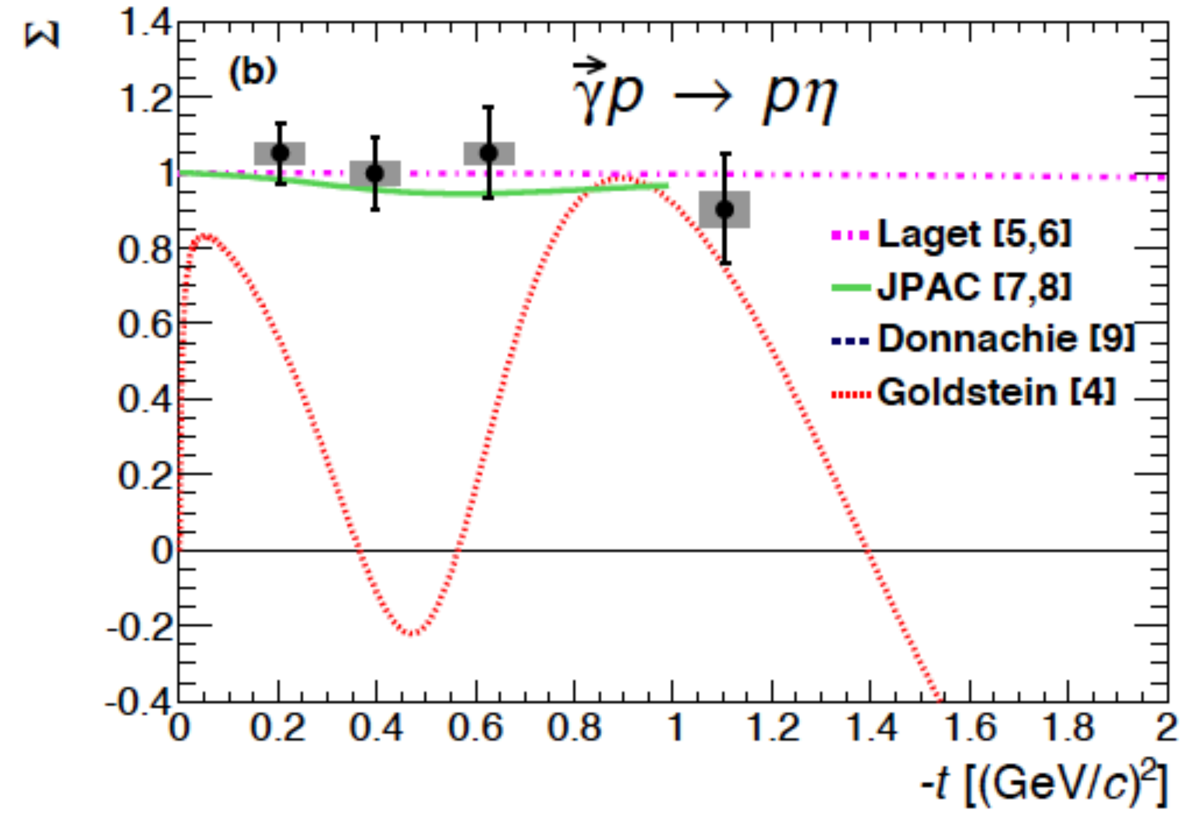
- Low-energy model inconsistent
- Cut-off not high enough
  - High mass resonances!

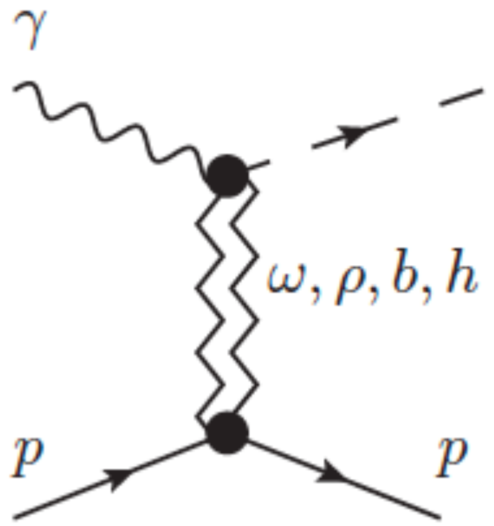
Beam asymmetry: measurement of the exchange process

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

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

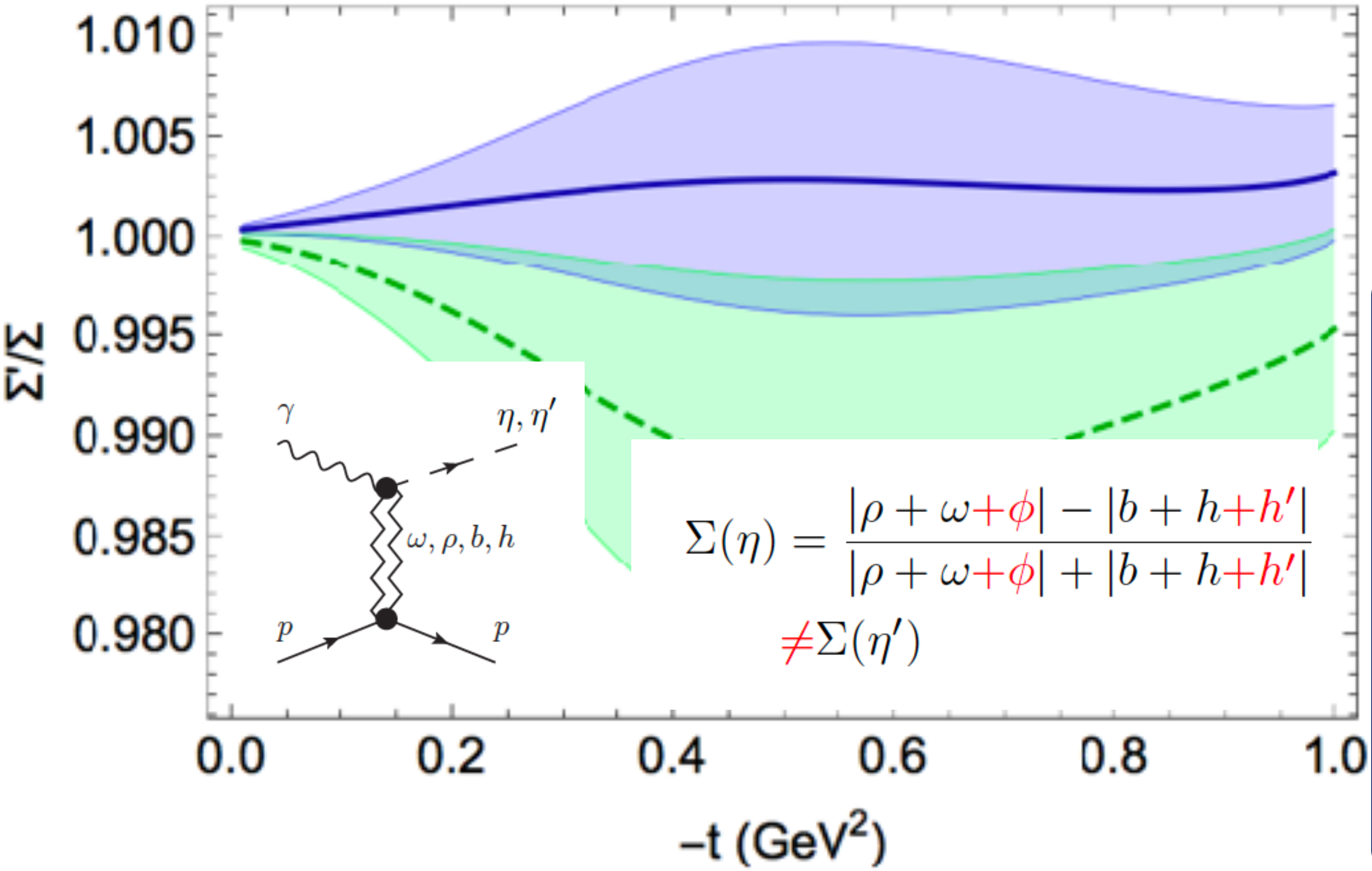






- Global fits indicate weak unnatural exchanges
- Possible tension between GlueX and SLAC data ?

η/η' asymmetry probes coupling to strangeness



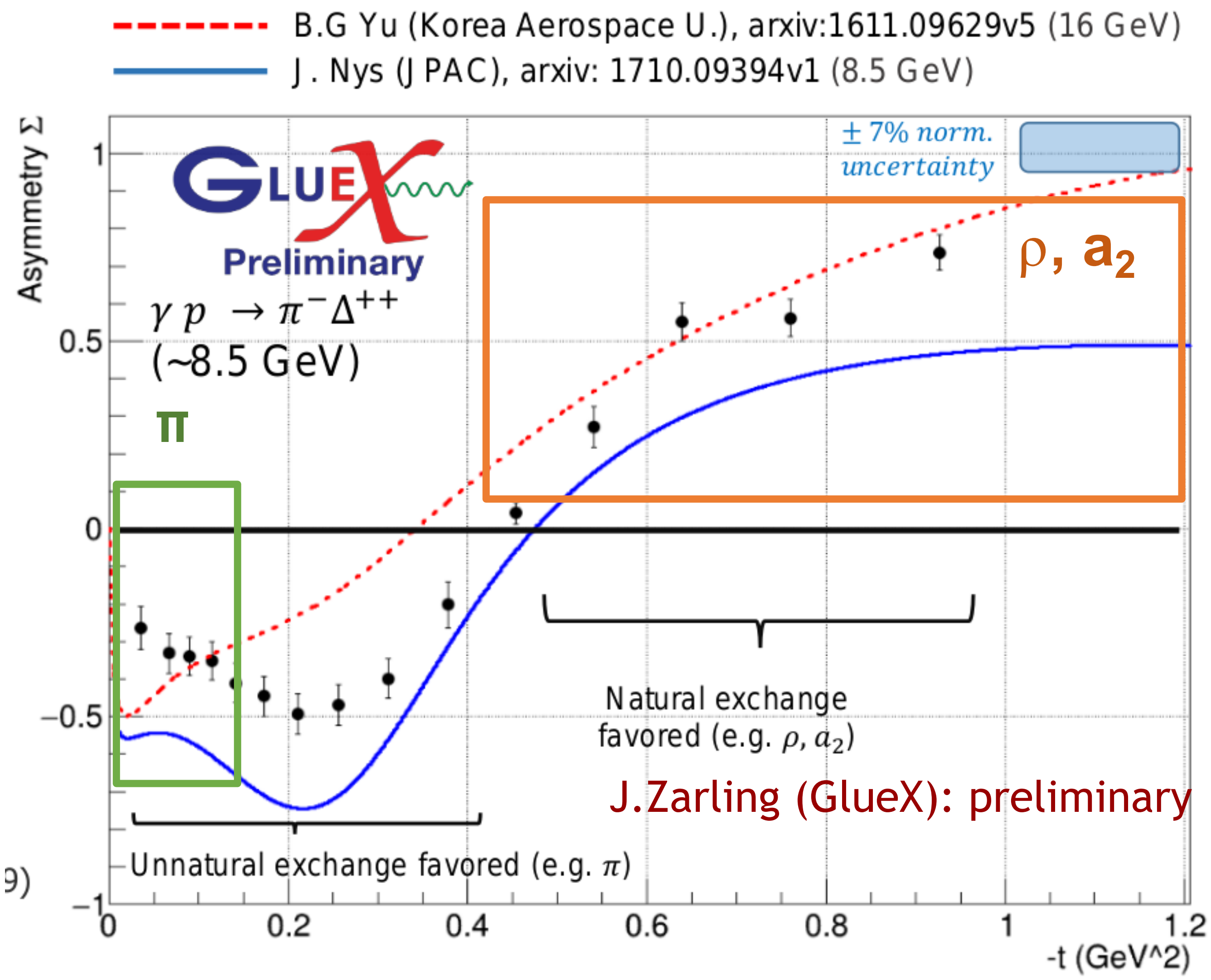
Based on the FESR for η:
predict beam asymmetry for η'

- 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**

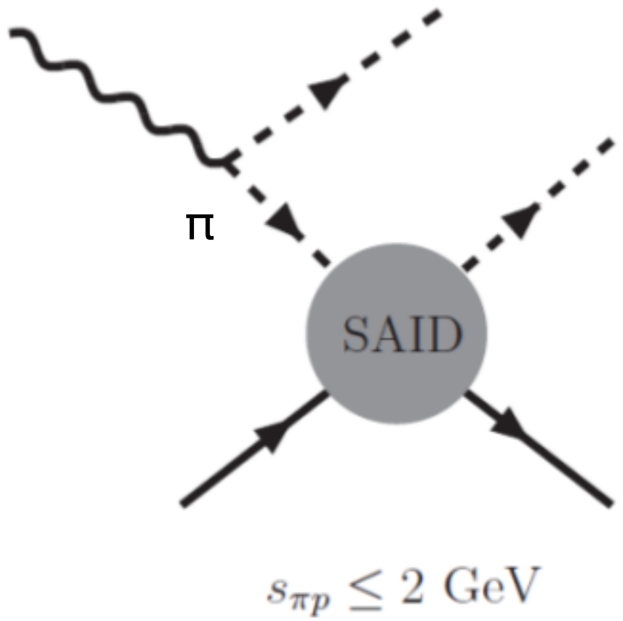
V.Mathieu et al. (JPAC) Phys. Lett. B774, 362 (2017)

πΔ photoproduction



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

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



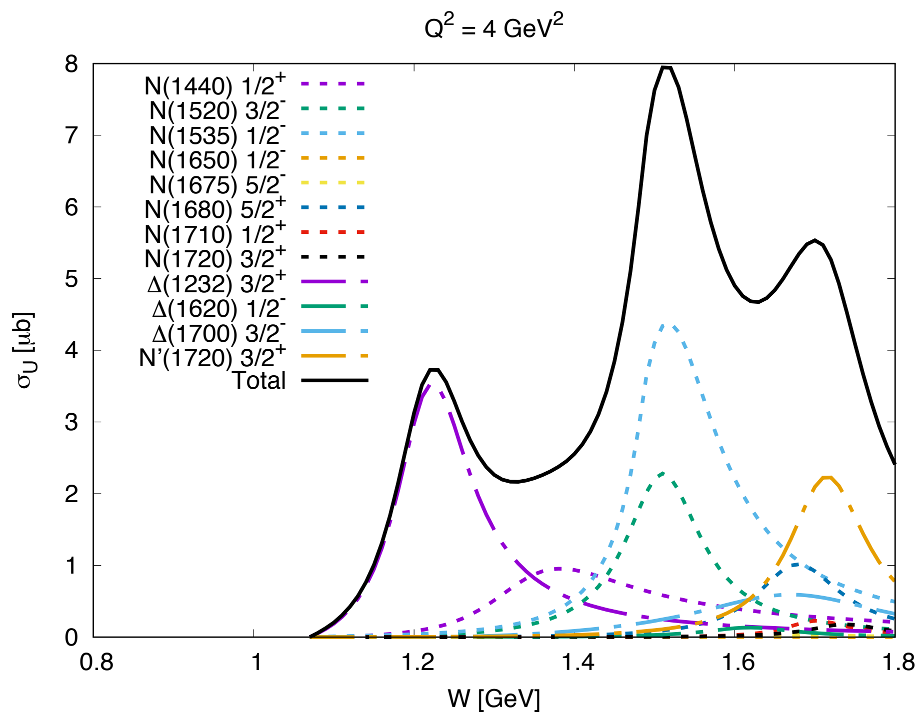
Łukasz Bibrzycki et al. (Cracow,JPAC)

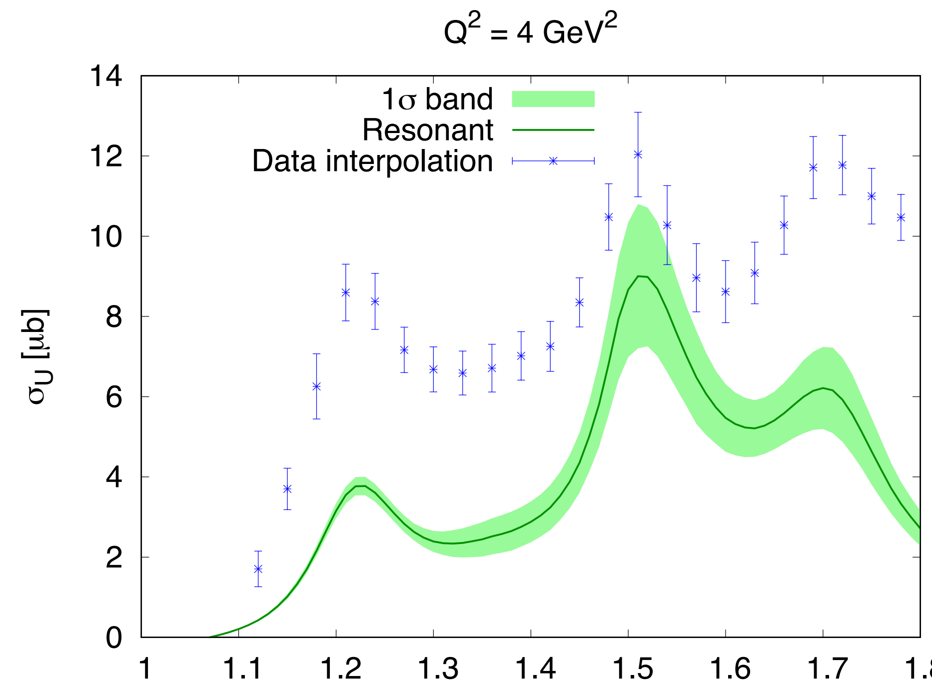
Comparison to GlueX data
- Confirmation of interference pattern
- High -t: natural, low -t: unnatural
- Mismatch: oddly behaved π exchange
  - Ongoing analysis
  - Experimental or theoretical?

N* in inclusive electron scattering

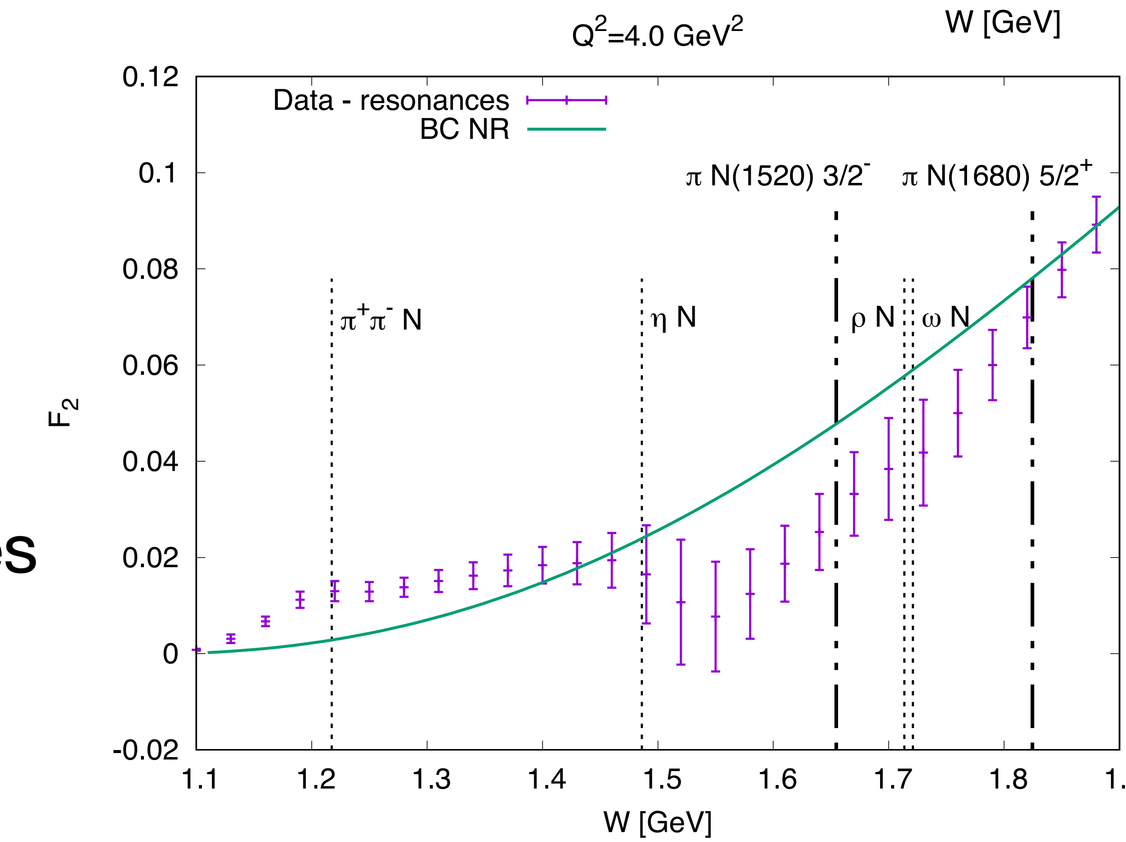
A. N. Hiller Blin et al., PRC 100 (2019) 035201

Exclusive CLAS data for computation of N* contribution to inclusive observables: non-trivial Q^2 dependence and interplay between resonance tails





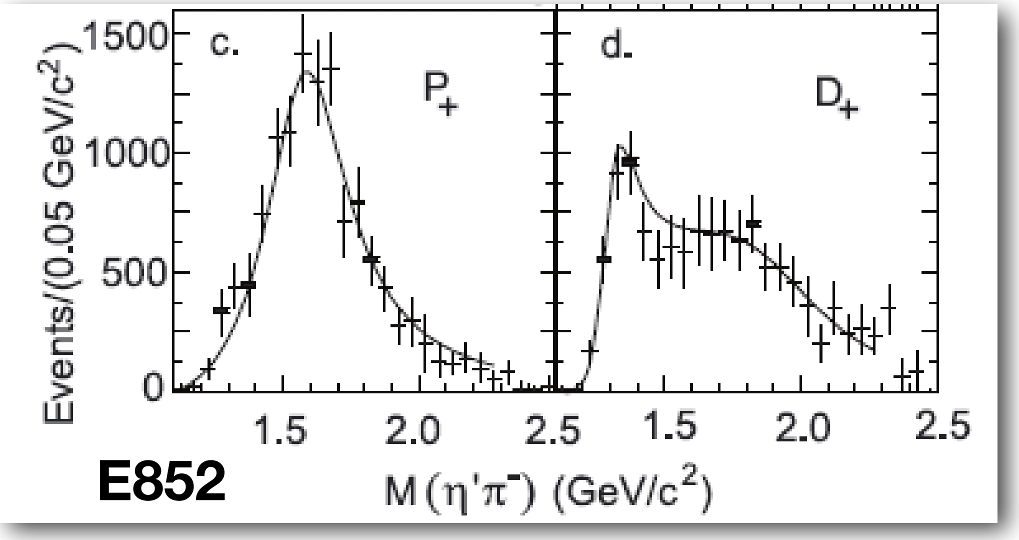
Useful tool for CLAS12 and understanding of non-resonant background: quark-hadron duality studies



Other exotics

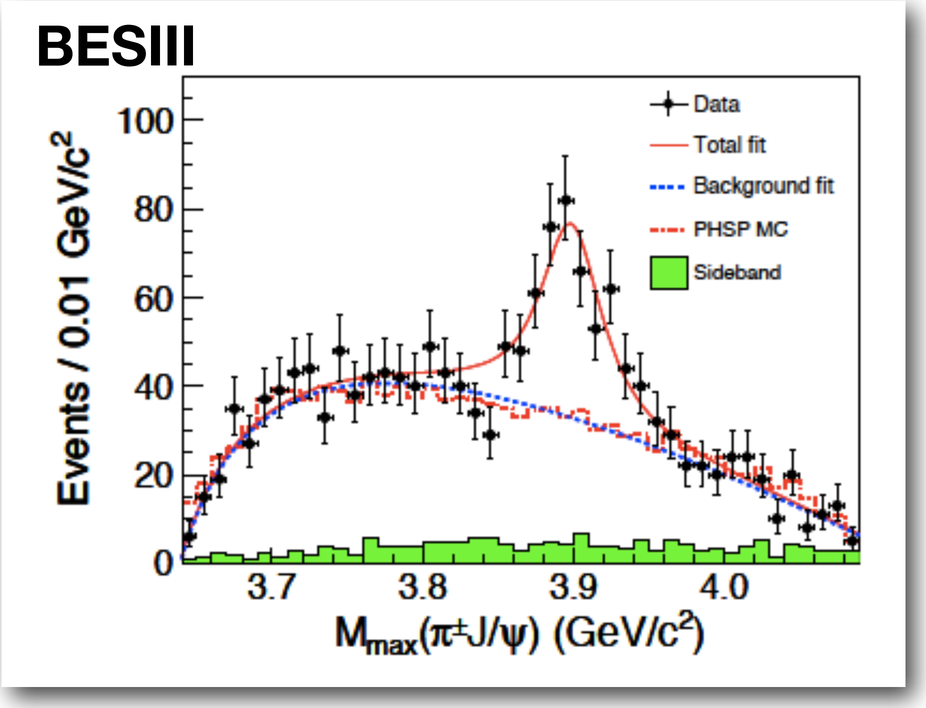
- $J^{PC}=1^{-+}$ I=1, light exotic hybrid ?

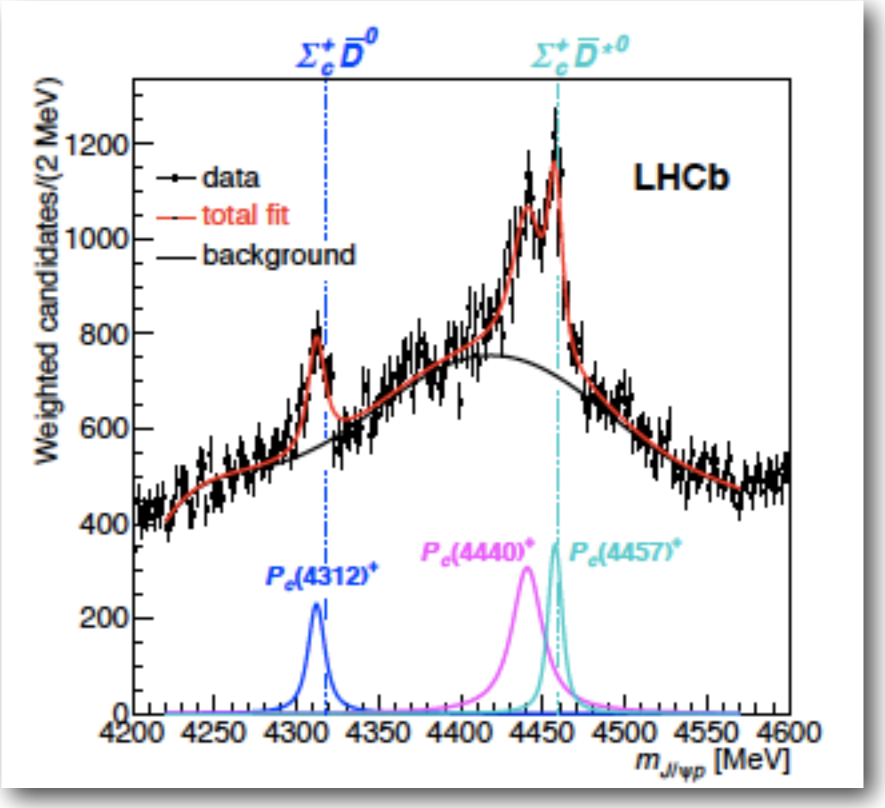
  Yes : "Normal resonance"



- $Z_c(3900)$ in $J/\psi\ \pi\ \pi$, $\bar{D}D^*$?

  Inconclusive

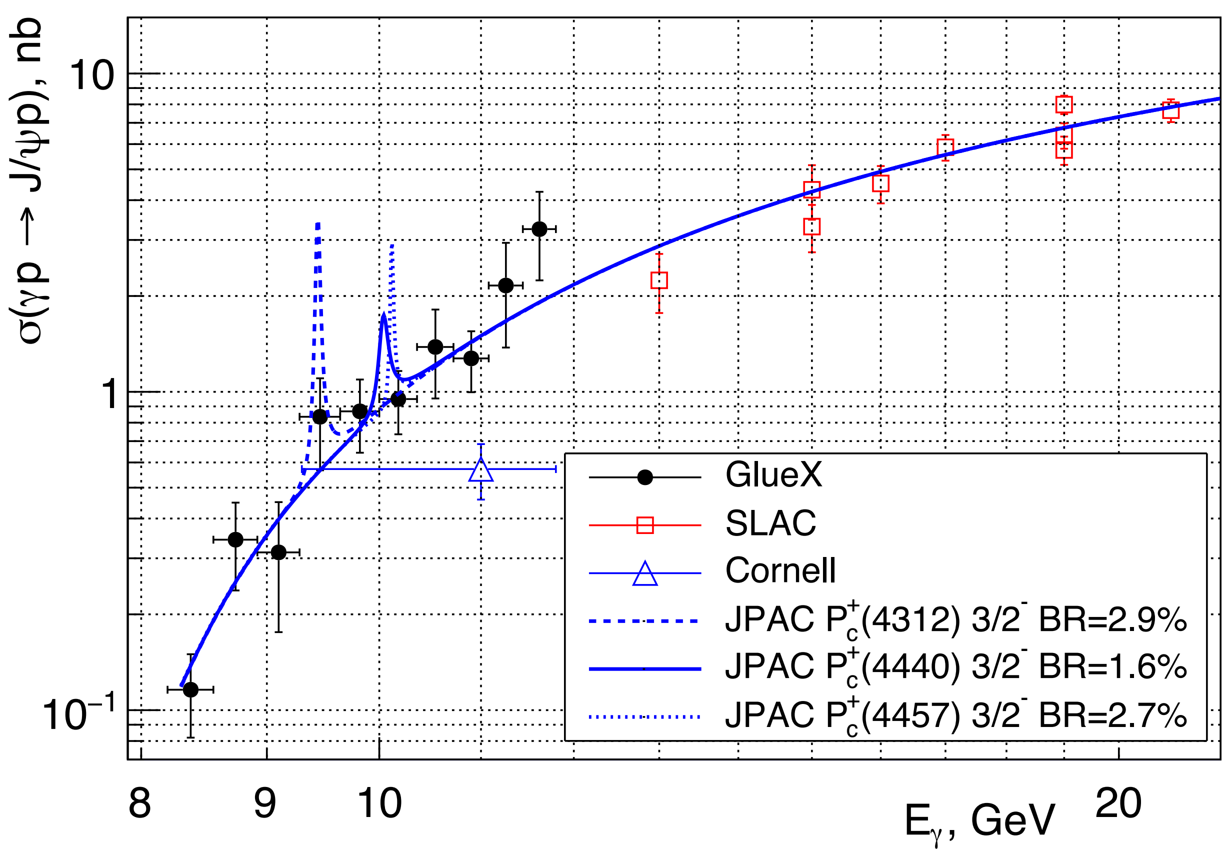


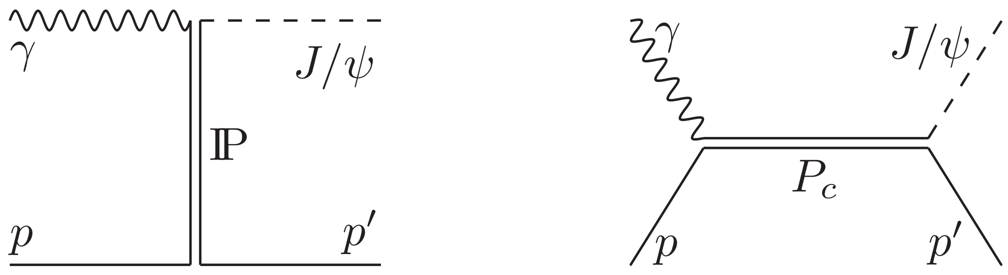


- $P_c(4312)$ in $\Lambda_b \rightarrow J/\psi$ p K

  No : Unbound

Pentaquarks (or not)





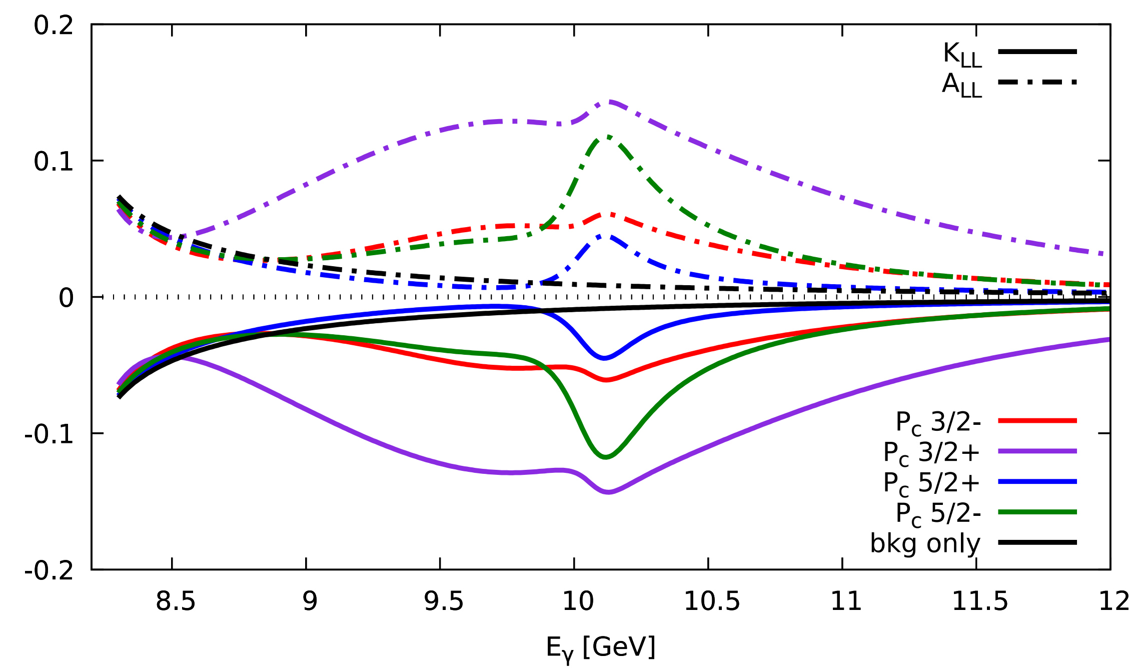
- Pomeron exchange + P_c excitation
- Vector meson dominance assumed

A.N.Hiller Blin et al., PRD 94 (2016) 034002

Signals in polarization observables: two resonances assumed

Polarization observables expected to have higher sensitivity to signals

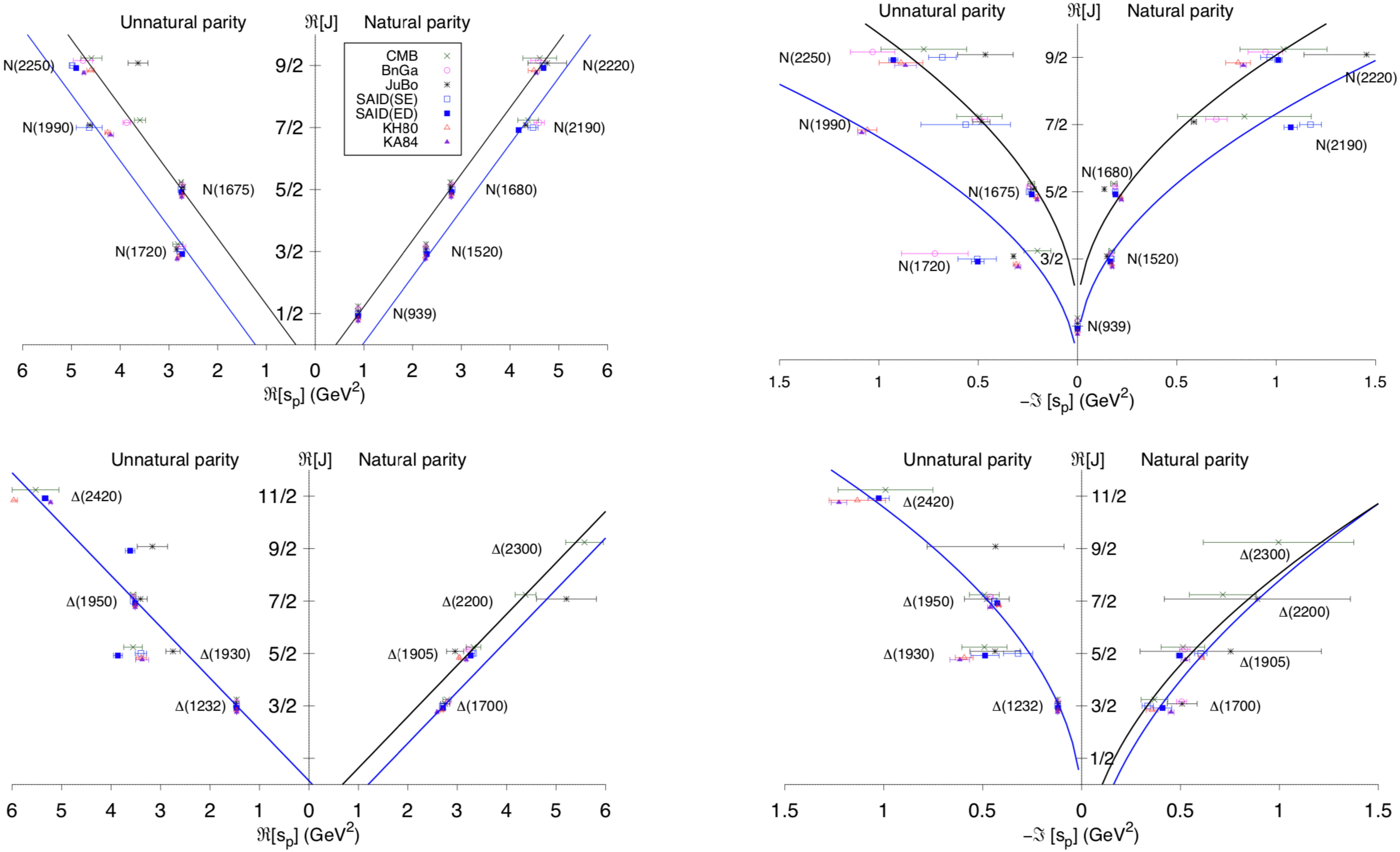
$$A(K)_{LL} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)}$$



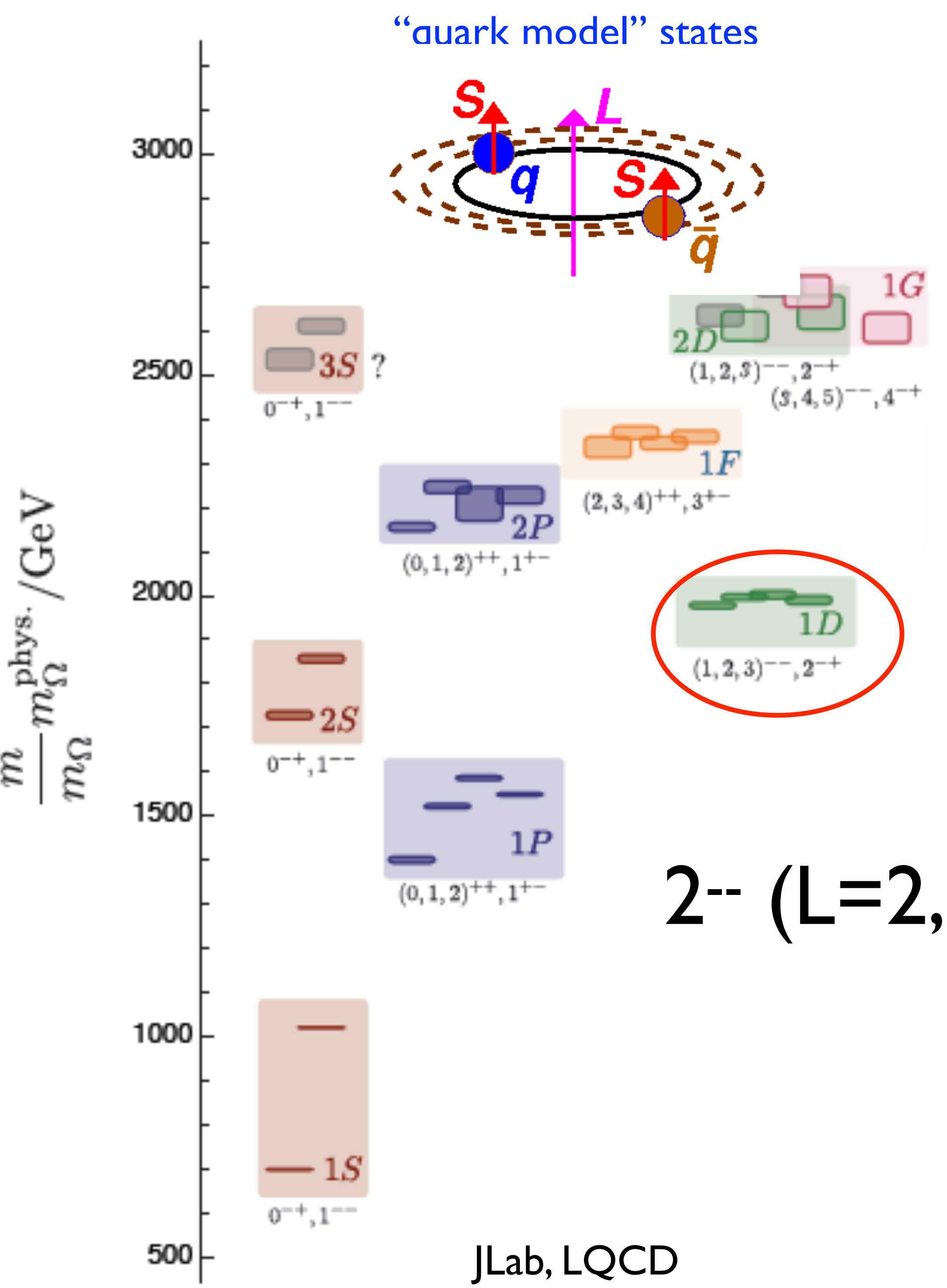
D. Winney et al., PRD 100 (2019) 034019

Regge trajectories

J. A. Silva-Castro et al. [JPAC]
Phys. Rev. **D99**, 034003 (2019)



More hints from Regge



2^{--} (L=2,S=1)

I^G	naturality $=P(-1)^J$	twist =+1 if J=0,2,.. =-1 if J=1,3...	name
0^+	+1	+1	f_0, f_2,...
0^+	+1	-1	$\eta/\eta'_1, \eta/\eta'_3$,... ($1^{-+}, 3^{-+}$,..)
0^+	-1	+1	$\eta/\eta'_0, \eta/\eta'_2$,...
0^+	-1	-1	f_1, f_3,...
0^-	+1	+1	h_0, h_2,.. ($0^{+-}, 2^{+-}$,..)
0^-	+1	-1	$\omega/\phi_1, \omega/\phi_3$,..
0^-	-1	+1	$\omega/\phi_0, \omega/\phi_2$,...($0^{--}, 2^{--}$,... :not seen)
0^-	-1	-1	h_1, h_3,...
1^+	+1	+1	b_0, b_2,.. ($0^{+-}, 2^{+-}$,..)
1^+	+1	-1	ρ_1, ρ_3,..
1^+	-1	+1	ρ_0, ρ_2,... ($0^{--}, 2^{--}$,.. :not seen)
1^+	-1	-1	b_1, b_3,..
1^-	+1	+1	a_0, a_2,...
1^-	+1	-1	π_1, π_3,... ($1^{-+}, 3^{-+}$,..)
1^-	-1	+1	π, π_2,...
1^-	-1	-1	a_1, a_3,...

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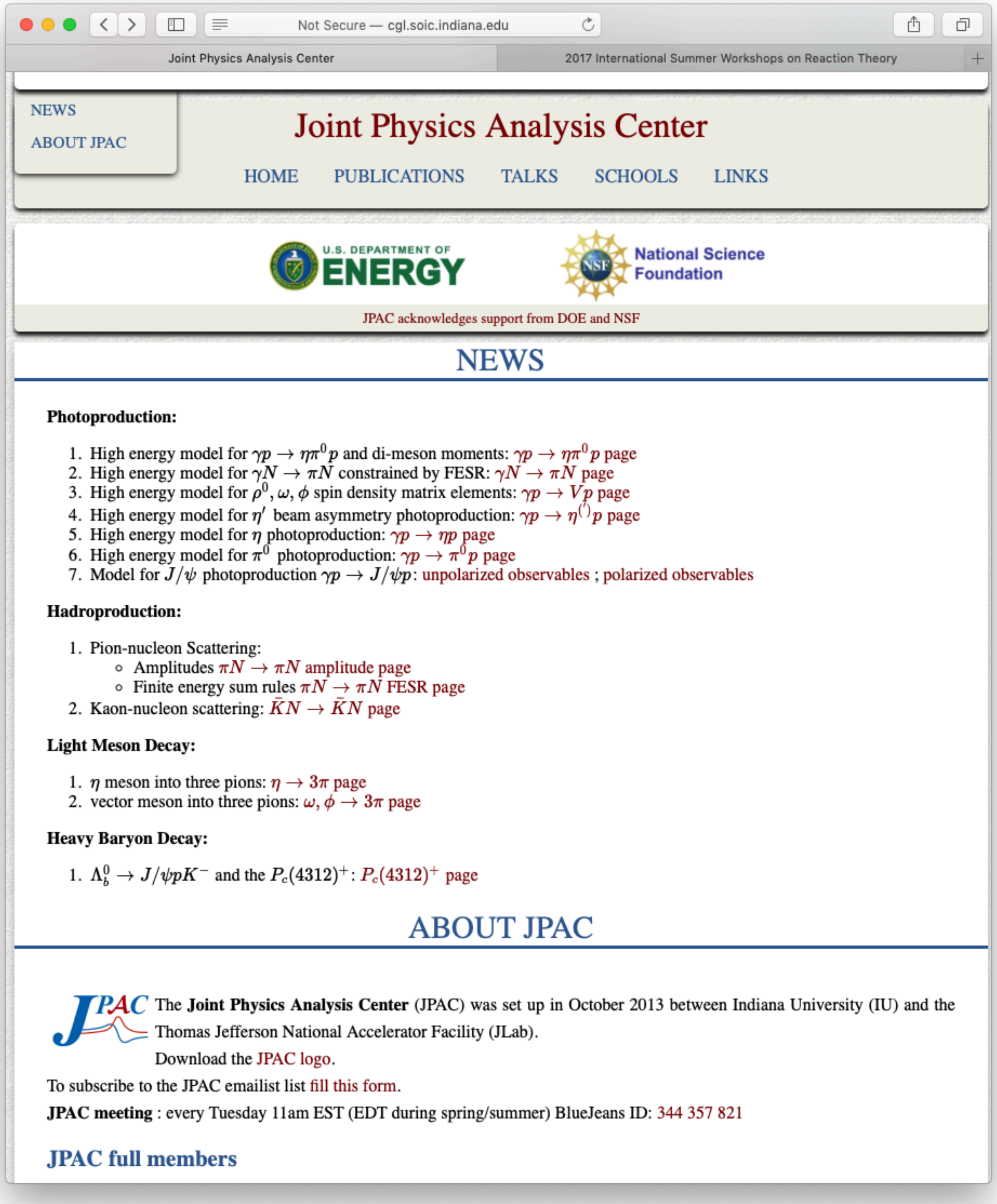

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JPAC acknowledges support from DOE and NSF

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2. High energy model for $\gamma N \to \pi N$ constrained by FESR: $\gamma N \to \pi N$ page
3. High energy model for ρ^0, ω, ϕ spin density matrix elements: $\gamma p \to V p$ page
4. High energy model for η' beam asymmetry photoproduction: $\gamma p \to \eta^{(\prime)} p$ page
5. High energy model for η photoproduction: $\gamma p \to \eta p$ page
6. High energy model for π^0 photoproduction: $\gamma p \to \pi^0 p$ page
7. Model for J/ψ photoproduction $\gamma p \to J/\psi p$: unpolarized observables ; polarized observables

Hadroproduction:

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   - Amplitudes $\pi N \to \pi N$ amplitude page
   - Finite energy sum rules $\pi N \to \pi N$ FESR page
2. Kaon-nucleon scattering: $\bar{K}N \to \bar{K}N$ page

Light Meson Decay:

1. η meson into three pions: $\eta \to 3\pi$ page
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1. $\Lambda_b^0 \to J/\psi p K^-$ and the $P_c(4312)^+$: $P_c(4312)^+$ page

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The **Joint Physics Analysis Center** (JPAC) was set up in October 2013 between Indiana University (IU) and the Thomas Jefferson National Accelerator Facility (JLab).
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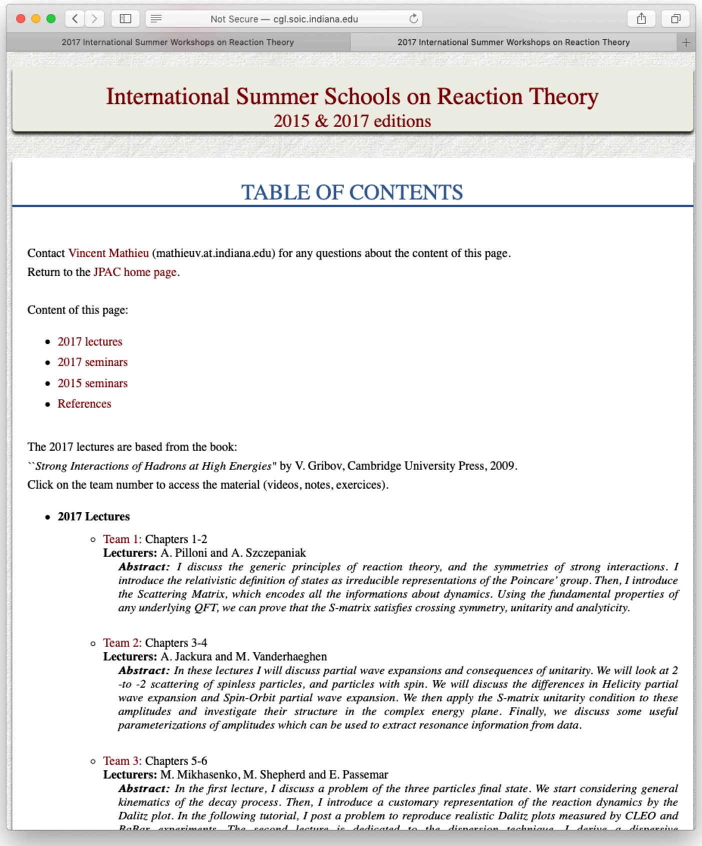

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The 2017 lectures are based from the book:
``*Strong Interactions of Hadrons at High Energies*" by V. Gribov, Cambridge University Press, 2009.
Click on the team number to access the material (videos, notes, exercices).

- **2017 Lectures**
  - Team 1: Chapters 1-2
    Lectures: A. Pilloni and A. Szczepaniak
    Abstract: *I discuss the generic principles of reaction theory, and the symmetries of strong interactions. I introduce the relativistic definition of states as irreducible representations of the Poincare' group. Then, I introduce the Scattering Matrix, which encodes all the informations about dynamics. Using the fundamental properties of any underlying QFT, we can prove that the S-matrix satisfies crossing symmetry, unitarity and analyticity.*
  - Team 2: Chapters 3-4
    Lecturers: A. Jackura and M. Vanderhaeghen
    Abstract: *In these lectures I will discuss partial wave expansions and consequences of unitarity. We will look at 2 -to -2 scattering of spinless particles, and particles with spin. We will discuss the differences in Helicity partial wave expansion and Spin-Orbit partial wave expansion. We then apply the S-matrix unitarity condition to these amplitudes and investigate their structure in the complex energy plane. Finally, we discuss some useful parameterizations of amplitudes which can be used to extract resonance information from data.*
  - Team 3: Chapters 5-6
    Lecturers: M. Mikhasenko, M. Shepherd and E. Passemar
    Abstract: *In the first lecture, I discuss a problem of the three particles final state. We start considering general kinematics of the decay process. Then, I introduce a customary representation of the reaction dynamics by the Dalitz plot. In the following tutorial, I post a problem to reproduce realistic Dalitz plots measured by CLEO and*

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2019 PUBLICATIONS

...lloni, Hiller Blin, Fernandez-Ramirez, Albaladejo, Mathieu, Mokeev and Szczepaniak
...ion observables in pentaquark photoproduction,''
....09393 [hep-ph] ; Journal: Phys. Rev. D **100**, 034019 (2019)

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``Moments of angular distribution and beam asymmetries in $\eta\pi^0$ photoproduction at GlueX,''
e-Print: arXiv:1906.04841 [hep-ph] ; Journal: Phys. Rev. D **100**, 054017 (2019)

Jackura, Dawid, Fernandez-Ramirez, Mathieu, Mikhasenko, Pilloni, Sharpe and Szczepaniak
``On the Equivalence of Three-Particle Scattering Formalisms,''
e-Print: arXiv:1905.12007 [hep-ph] ; Journal: Phys. Rev. D **100**, 034508 (2019)

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``Three-body scattering: Ladders and Resonances,''
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``Interpretation of the LHCb $P_c(4312)^+$ Signal,''
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``Nucleon resonance contributions to unpolarised inclusive electron scattering ,''
e-Print: arXiv:1904.08016 [hep-ph] ; Journal: Phys. Rev. C **100**, 035201 (2019)

2018 PUBLICATIONS

Rodas, Pilloni, Albaladejo, Fernandez-Ramirez, Jackura, Mathieu, Mikhasenko, Nys, Pauk, Ketzer and Szczepaniak
``Determination of the pole position of the lightest hybrid meson candidate,''
e-Print: arXiv:1810.04171 [hep-ph] ; Journal: Phys. Rev. Lett. **102** 042002 (2019)

Mikhasenko, Pilloni, Albaladejo, Fernandez-Ramirez, Jackura, Mathieu, Nys, Rodas, Ketzer and Szczepaniak
``Pole position of the $a_1(1260)$ from τ-decay,''
e-Print: arXiv:1810.00016 [hep-ph] ; Journal: Phys. Rev. D**98** 096021 (2018)

Jackura, Fernandez-Ramirez, Mathieu, Mikhasenko, Nys, Pilloni, Saldana, Sherrill and Szczepaniak
``Phenomenology of Relativistic $3 \to 3$ Reaction Amplitudes within the Isobar Approximation,''
e-Print: arXiv:1809.10523 [hep-ph] ; Journal: Eur. Phys. J. C**79** 56 (2019)

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``Regge phenomenology of the N^* and Δ^* poles,''

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Jefferson Lab 🇺🇸

Michael Döring[1]

Victor Mokeev

Emilie Passemar[2]

Adam Szczepaniak[2]

Miguel Albaladejo

California State U 🇺🇸

Peng Guo

Pedagogical U Kraków 🇵🇱

Lukasz Bibrzycki

INP Kraków 🇵🇱

Robert Kaminski

U of Adelaide 🇦🇺

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Geoffrey Fox

Tim Londergan

Nathan Sherrill

Daniel Winney

Sebastian Dawid

CERN 🇪🇺 🇨🇭

Misha Mikhasenko

UCM 🇪🇸

Vincent Mathieu

Arkaitz Rodas

ECT* 🇮🇹

Alessandro Pilloni

George Washington U 🇺🇸

Ron Workman

Old Dominion U 🇺🇸

Andrew Jackura

UNAM 🇲🇽

Cesar Fernández-Ramírez

Jorge Silva Castro

INFN Genoa 🇮🇹

Andrea Celentano

JGU-Mainz U 🇩🇪

Astrid Hiller-Blin

Igor Danilkin

Experimental collaborations: GlueX, CLAS12, COMPASS, MAMI, BaBar, Belle, BES, KLOE, LHCb

Faculty / Staff

Postdoc

PhD student

[1]JLab/GWU funded

[2]JLab/IU funded