Amplitude Analysis at JPAC

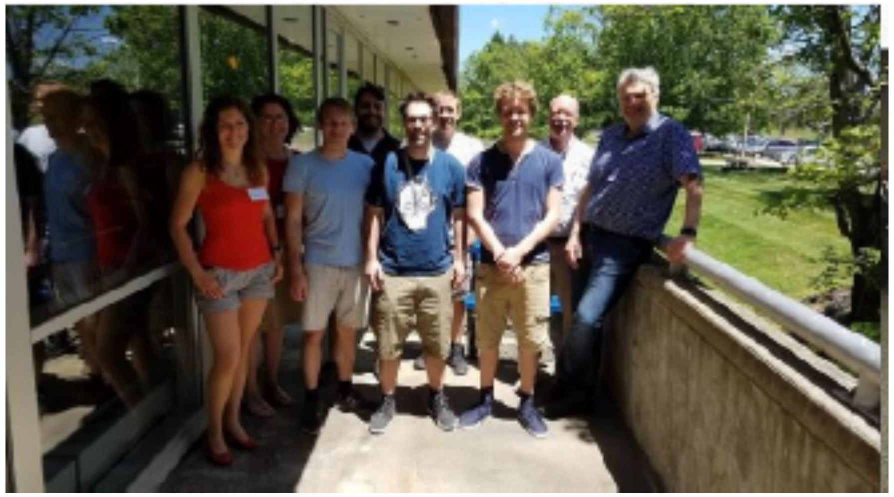
Adam Szczepaniak, Indiana University/Jefferson Lab

Joint Physics Analysis Center

Joint Physics Analysis Center

JPAC

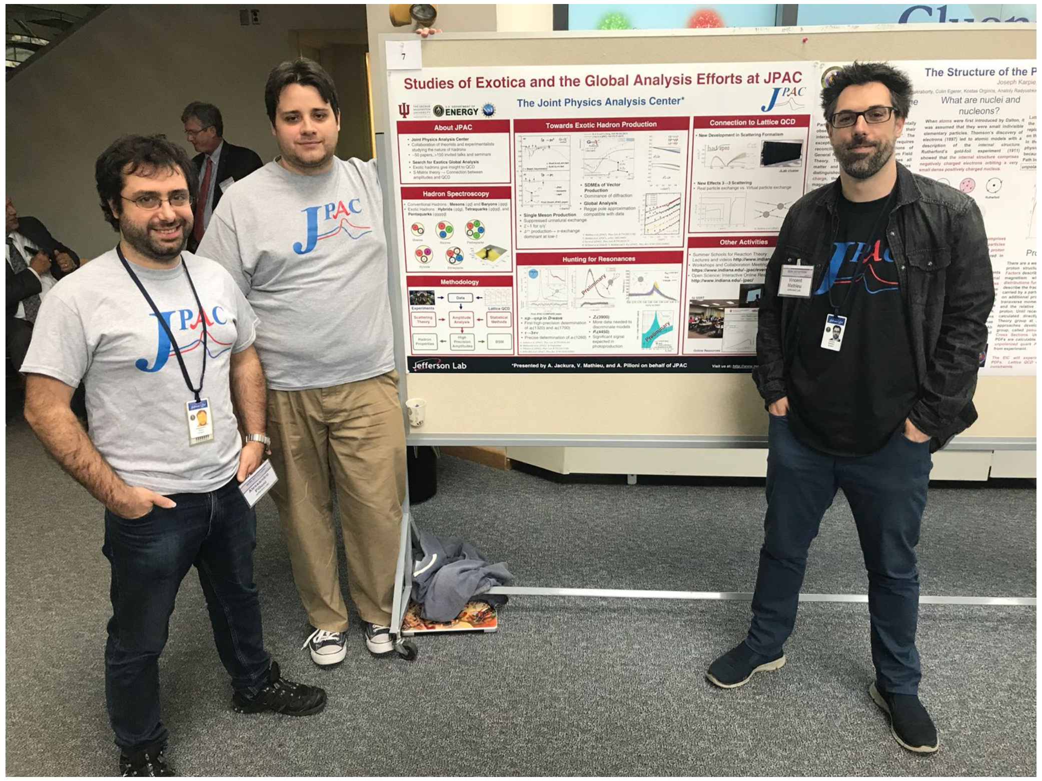
- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other accelerator laboratories



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

https://jpac.jlab.org

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



Why spectroscopy : Stranger Things of Hadrons

small world (10^{-15}m)
of fast (v~c) particles
exerting ~1T forces !!!

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

The dual role of gluons

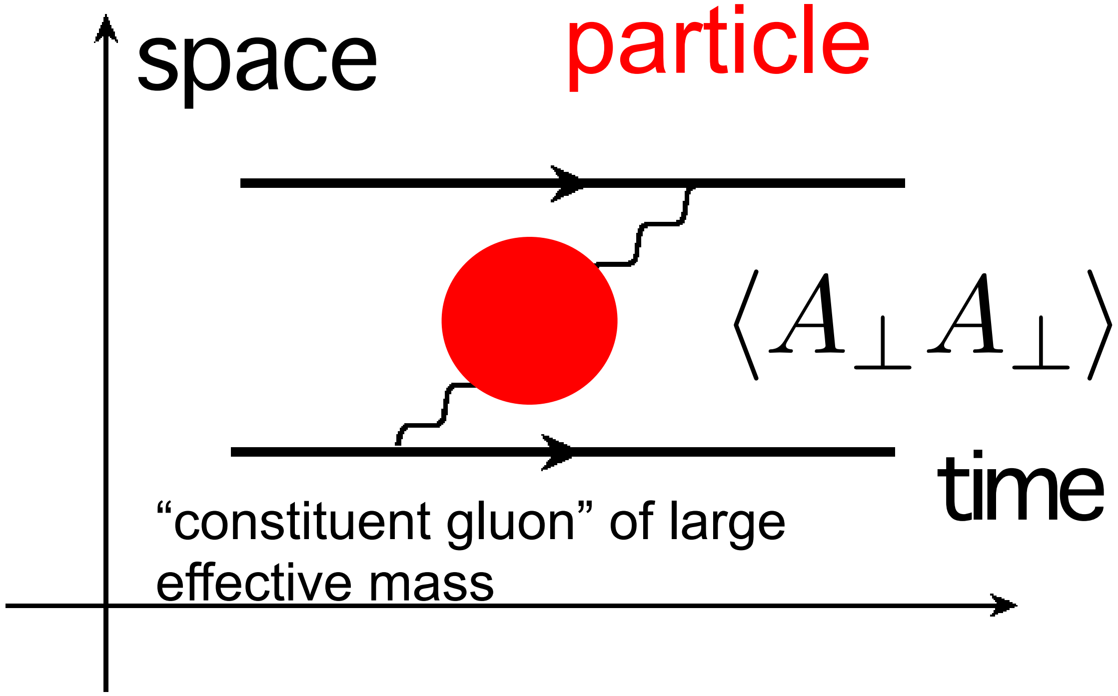
provide confinement → color flux tubes

are confined → constituent gluons

Hybrid mesons,: evidence for constituent gluons ?

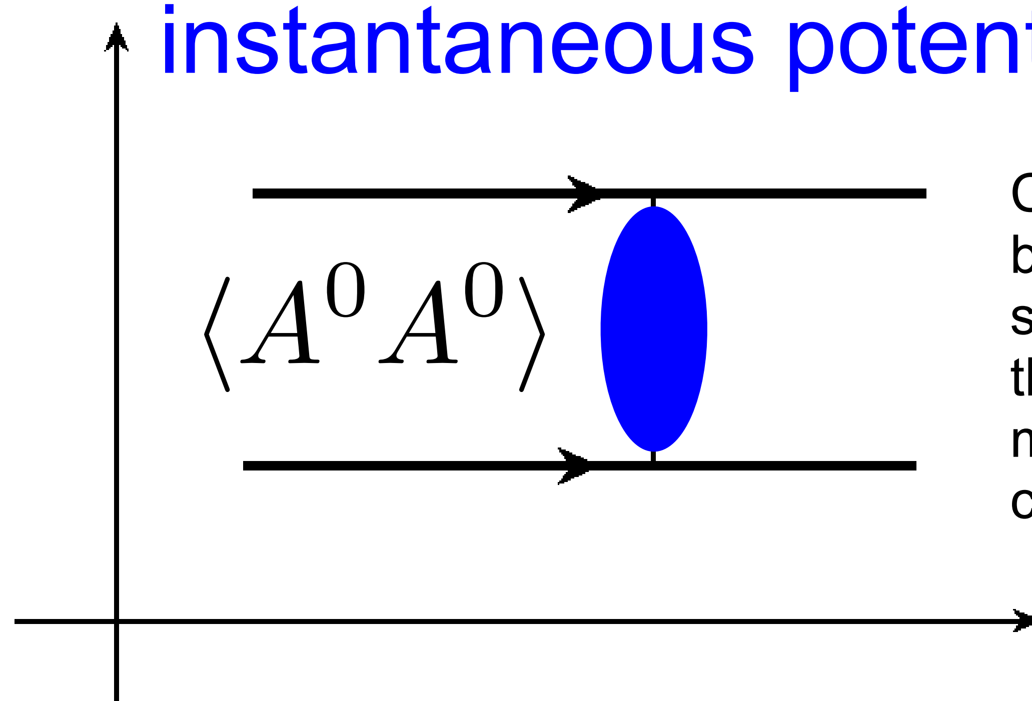
It is necessary to fix physical gauge (e.g. Coulomb)

massive, effective particle



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

long range instantaneous potential



Color interactions between external sources emerges through chromo-magnetic condensate

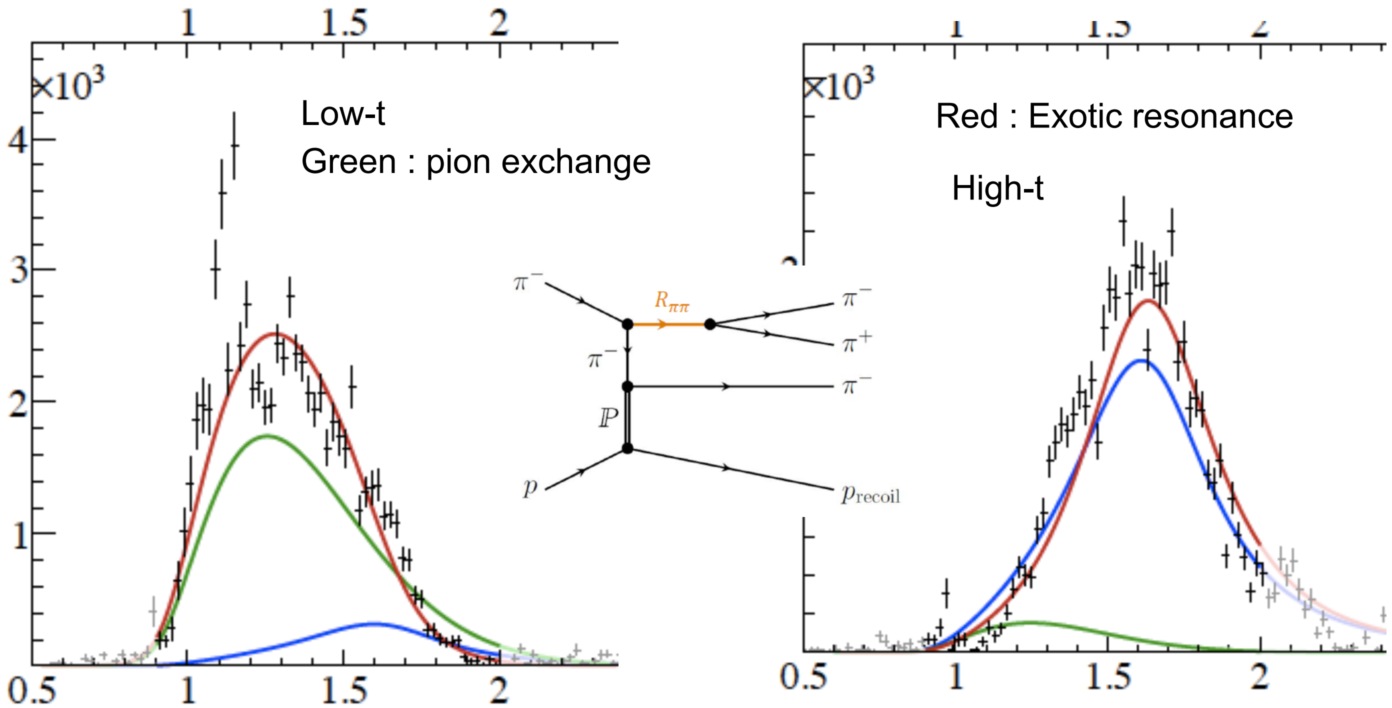
0-+ 1-+ 2-+ 1--

lowest-mass hybrid multiplet

Plenty of signatures: hybrids

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

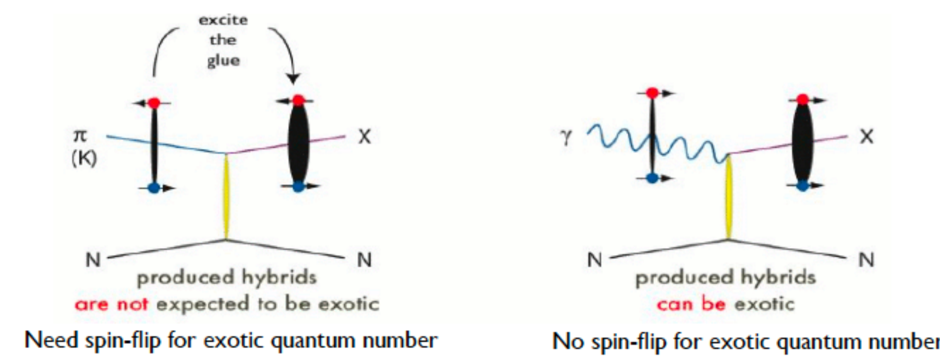
- In low-t pion diffraction (COMPASS) exotic wave production compatible with one pion exchange (but not at high-t)

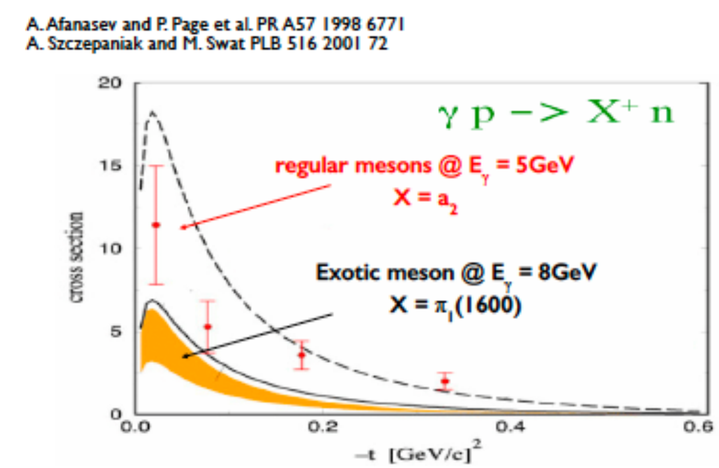


COMPASS (2018)

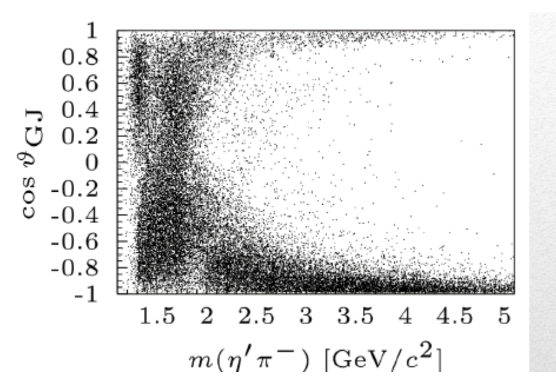
$\pi^- p \rightarrow \eta^{(\prime)} \pi^- p$

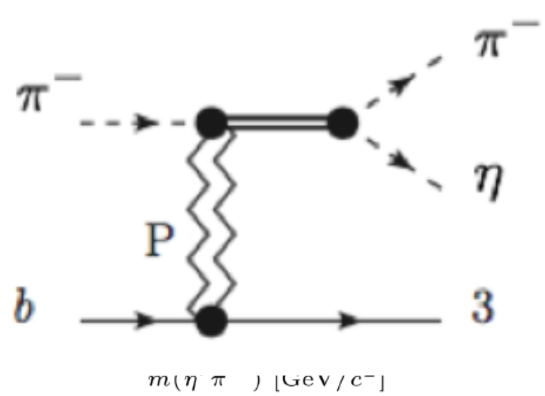
- In photoproduction (GlueX,CLAS12) exotic mesons produced via pion exchange (both good and bad)

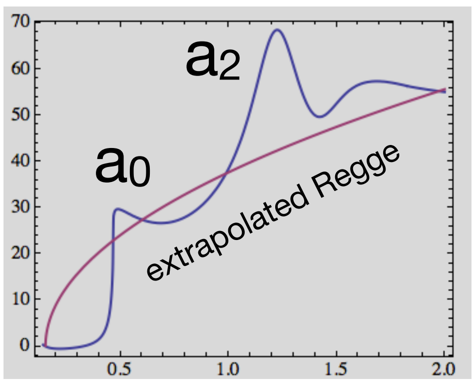




- Large exotic wave seen in $\eta^{(\prime)}\pi$ production : Golden Channel







Glueball candidates on the horizon

BESIII

J/ψ annihilates into gluons

Experimental results from J/ψ radiative decays to scalars or tensors:

- $B(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9}) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma \pi\pi) = (4.0 \pm 1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma \omega\omega) = (3.1 \pm 1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma \eta\eta) = (2.35^{+0.13}_{-0.11}{}^{+1.24}_{-0.74}) \times 10^{-4}$

$\Rightarrow$ $B(J/\psi \to \gamma f_0(1710)) > 1.7 \times 10^{-3}$

- $B(J/\psi \to \gamma f_2(2340) \to \gamma \eta\eta) = (5.60^{+0.62}_{-0.65}{}^{+2.37}_{-2.07}) \times 10^{-5}$
- $B(J/\psi \to \gamma f_2(2340) \to \gamma \phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$
- $B(J/\psi \to \gamma f_2(2340) \to \gamma K_S^0 K_S^0) = (5.54^{+0.34}_{-0.40}{}^{+3.28}_{-1.49}) \times 10^{-5}$

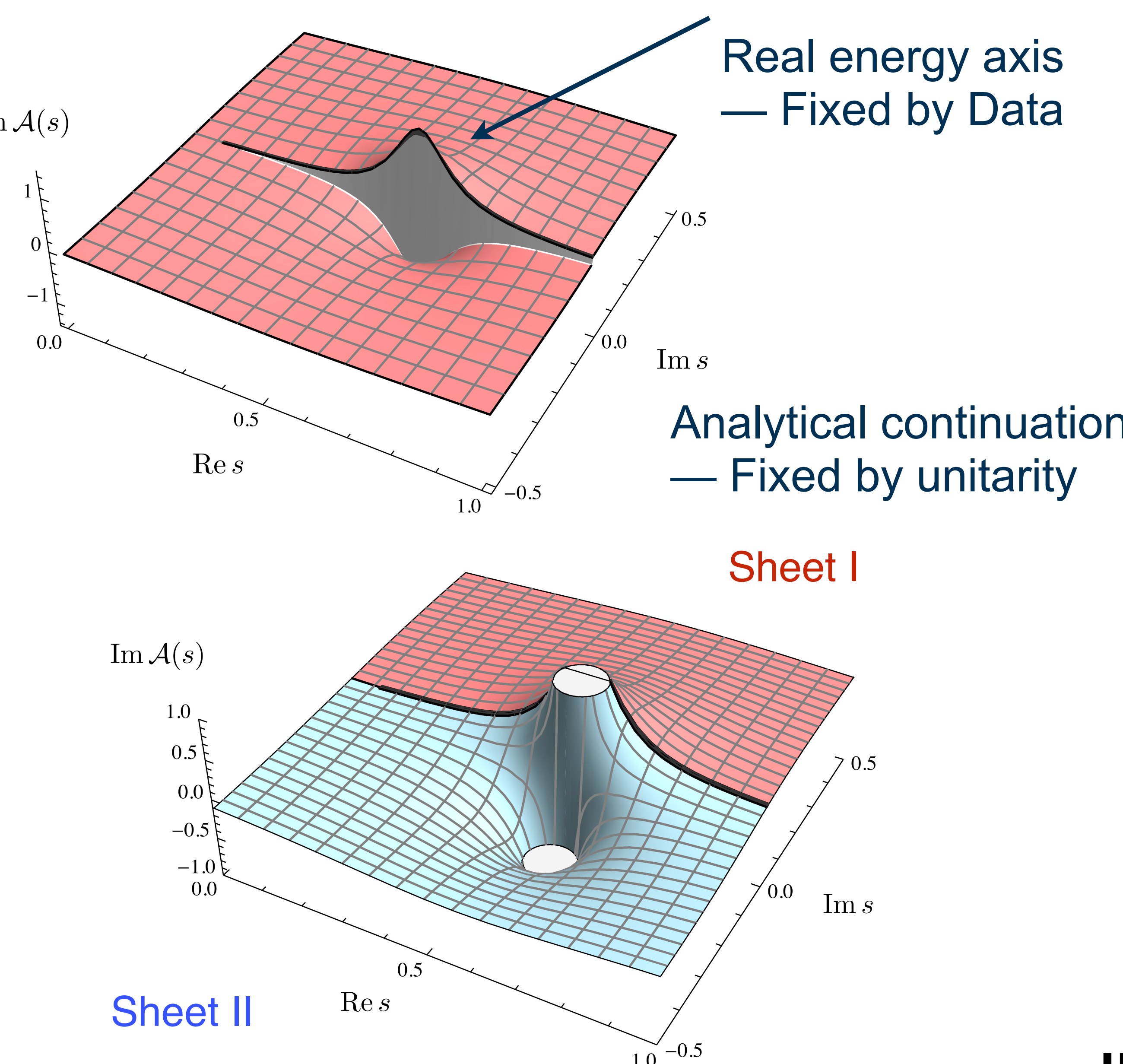
$f_0(1710)$ / $f_2(2340)$: candidates of the scalar/ tensor glueballs ?

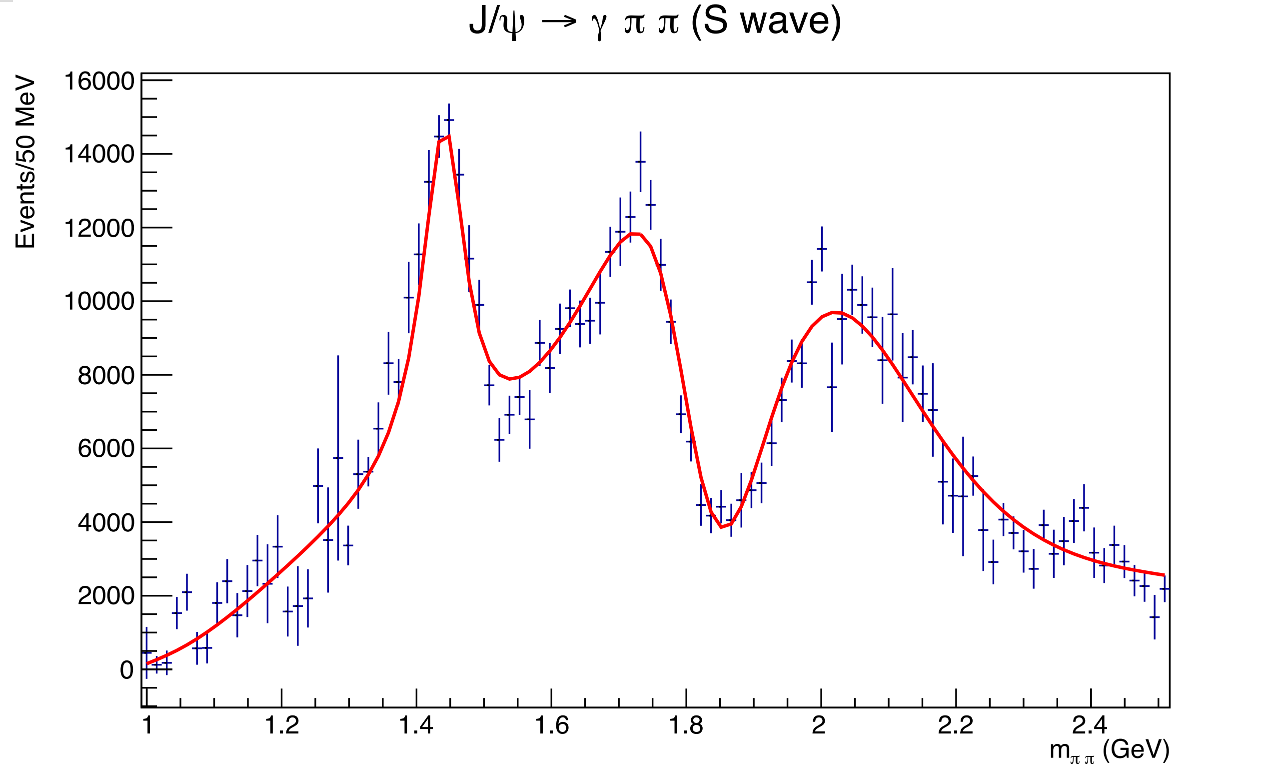
Chang-Zheng Yuan (from Lattice 2019), Beijiang Liu (HADRON 2019)

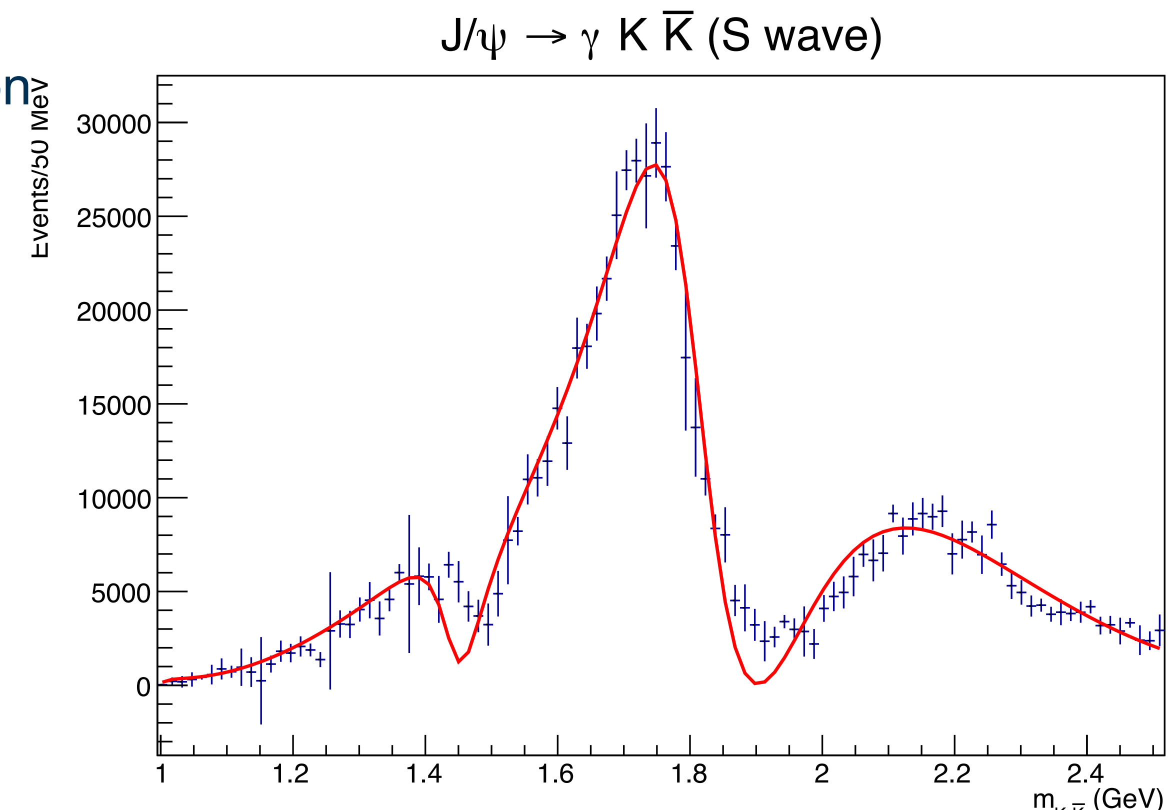
Its all complex calculus : amplitudes vs data

$$e^+e^- \to J/\psi \to \gamma\pi\pi, K\bar{K}$$

Extraction of resonance properties requires analysts of analytical reaction amplitudes

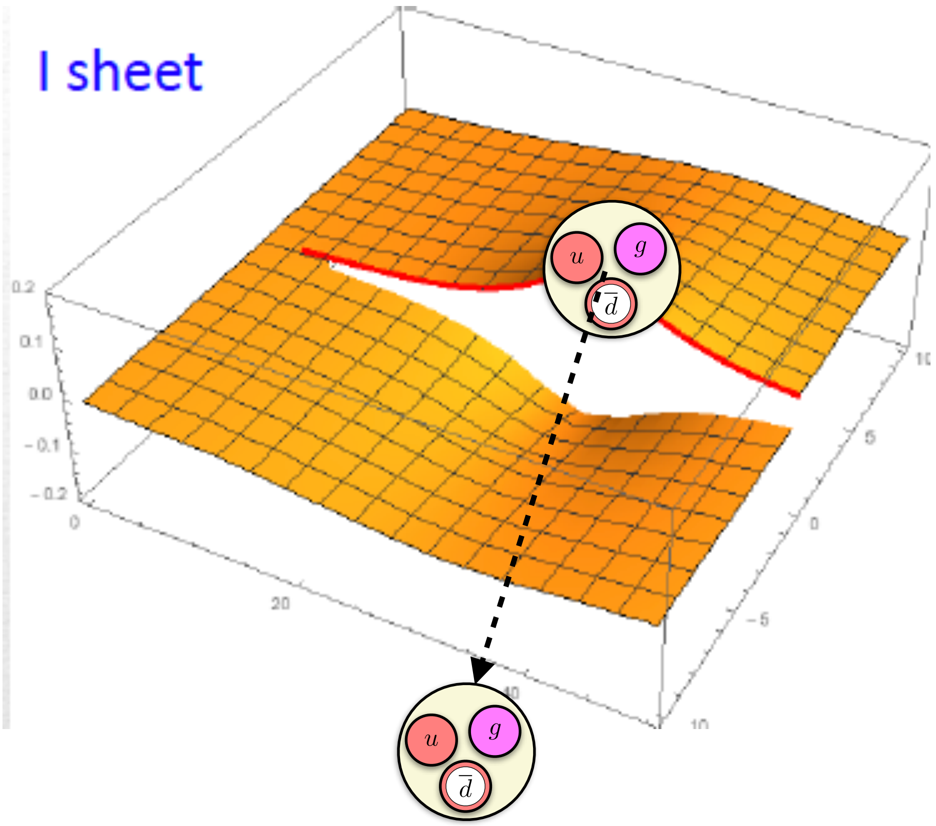


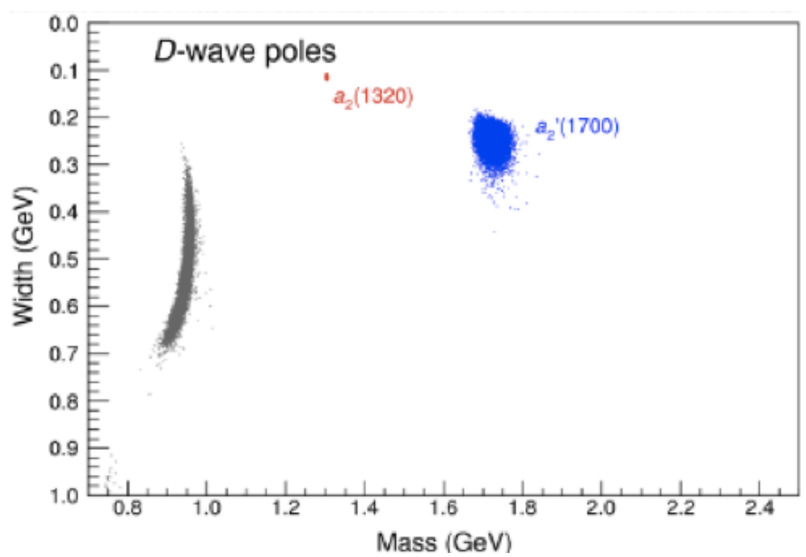




JPAC (A.Rodas in progress)

In practice: bottom - top approach

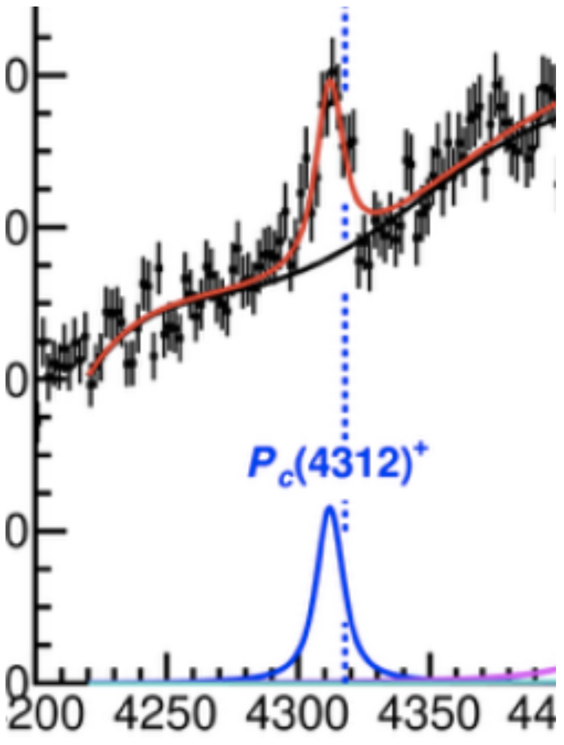


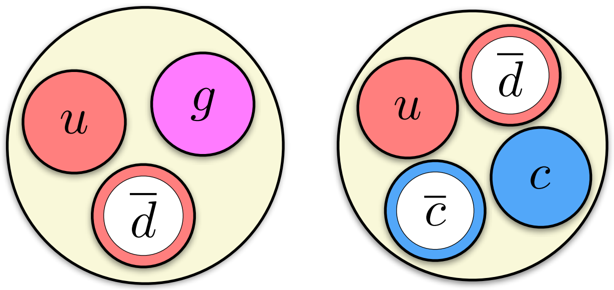


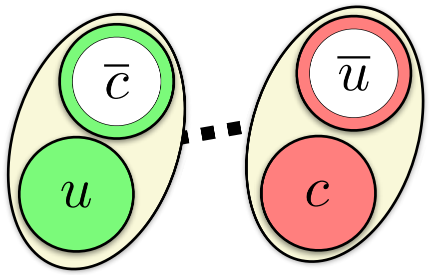
- Reconstruct amplitudes from its singularities (poles, cuts) Recall that each singularity has its own physical interpretation (open channels, aka particle loops do NOT generate resonances, they generate widths)

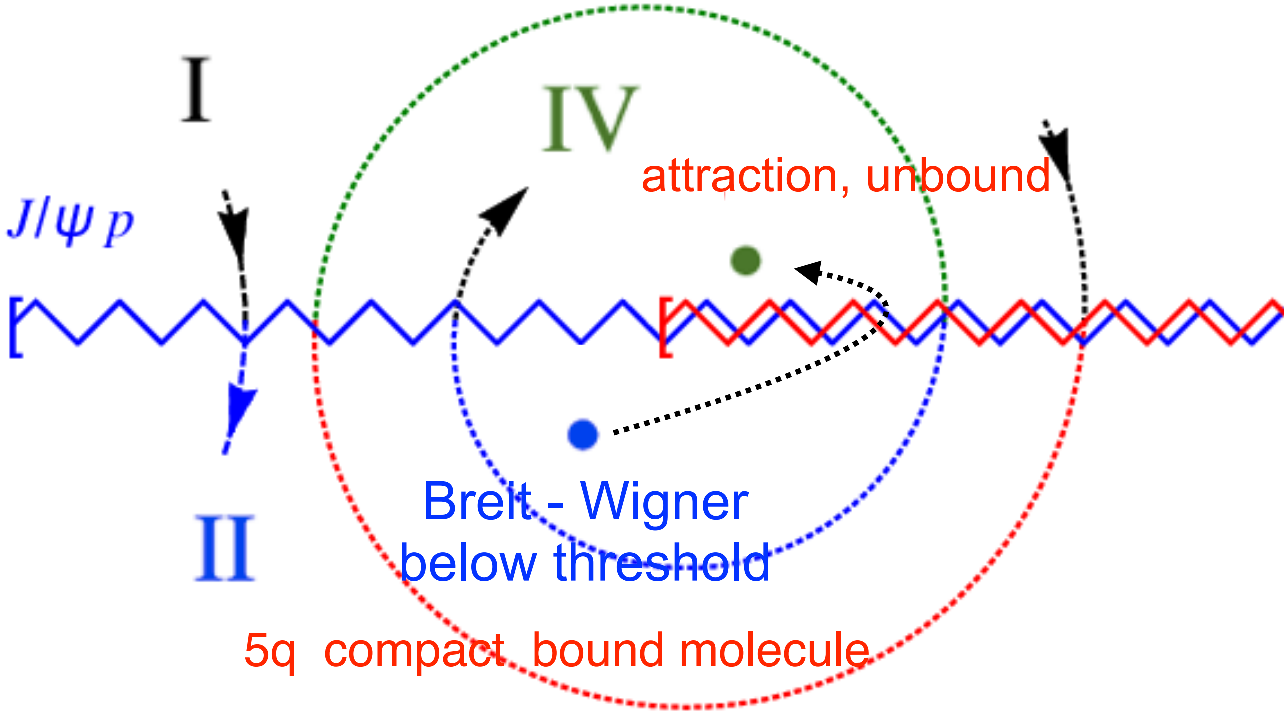
- Use data to determine best hypothesis

- Test how singularities depend on parameters (channel couplings, thresholds, etc.) to infer their microscopic origins.

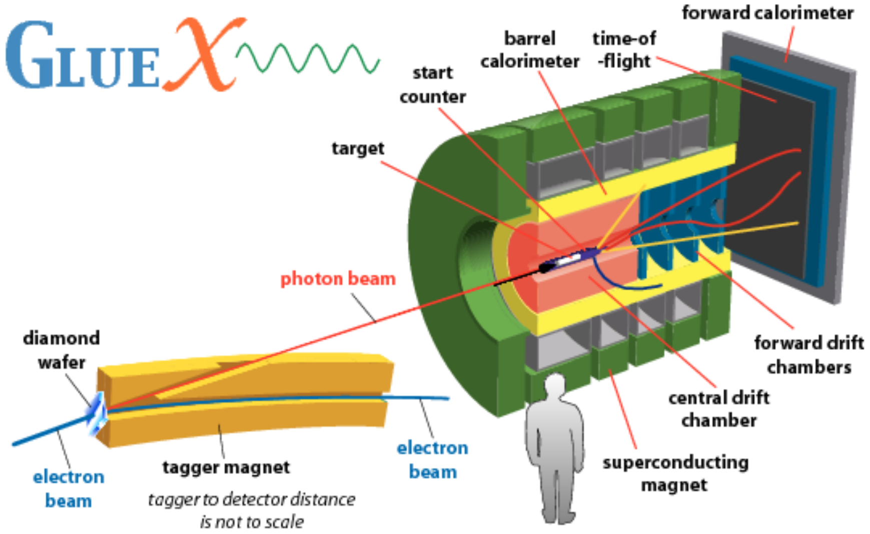


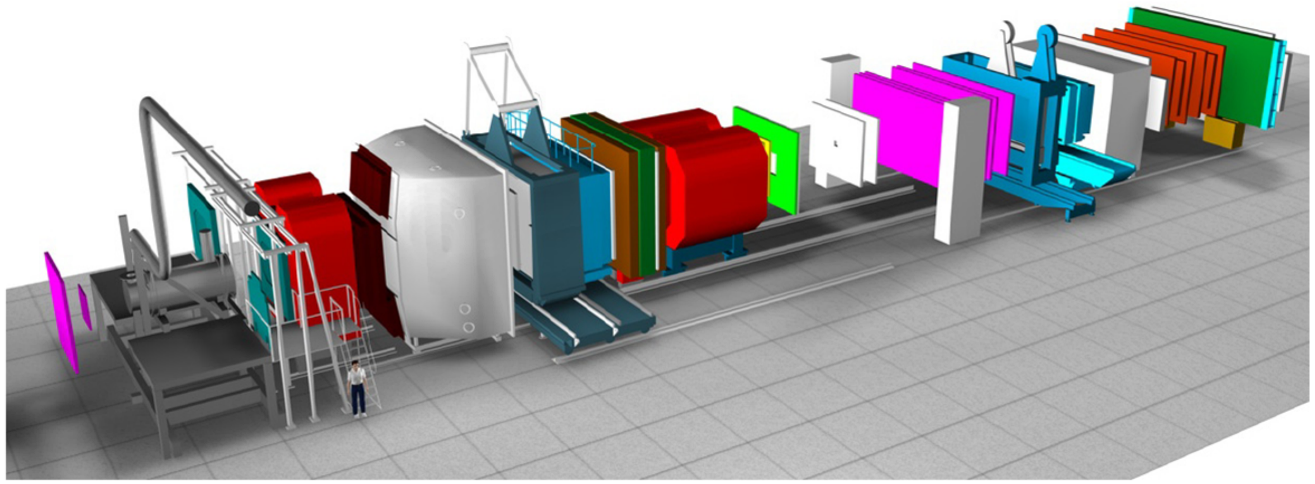


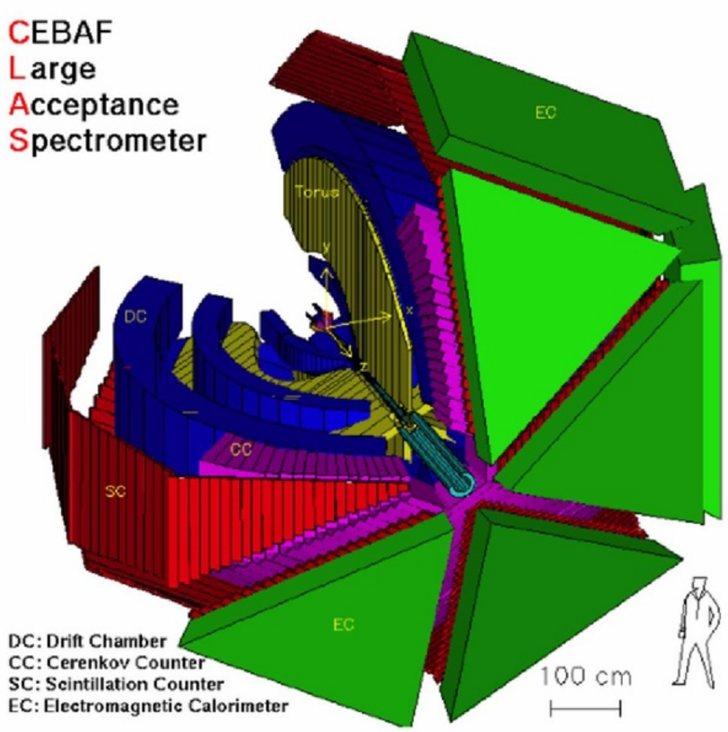




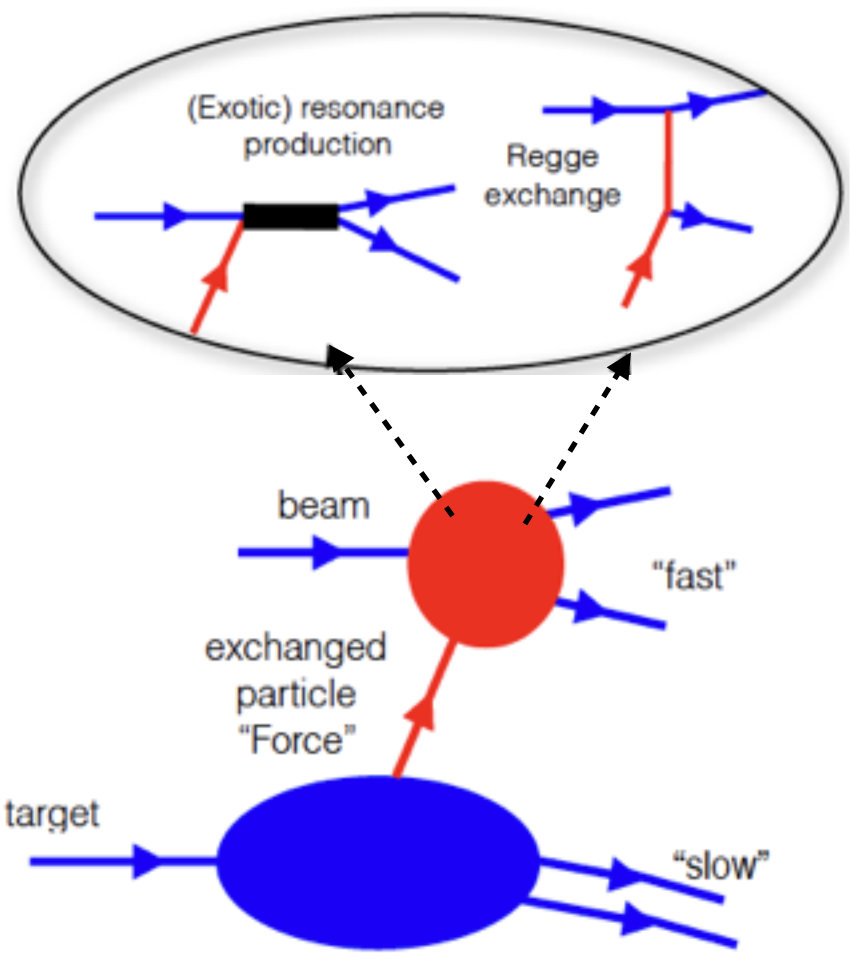
Spectroscopy from peripheral production





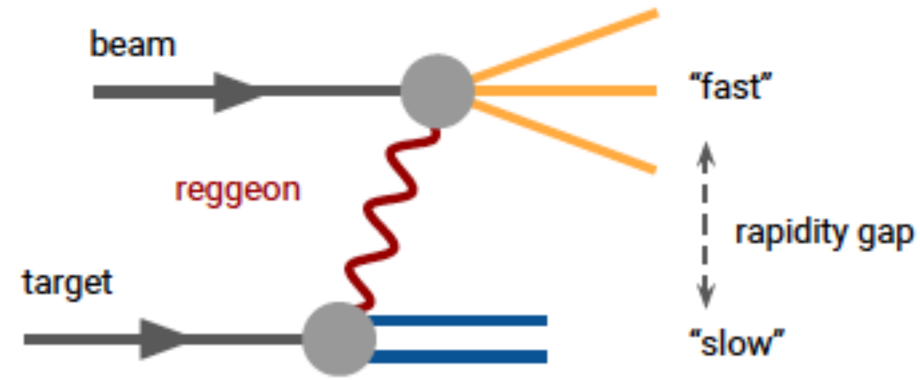


- Need to establish factorization between beam and target fragmentation (Regge factorization)
- Single Regge pole exchange dominate over cut other singularities (cuts, daughters)



Global Regge analysis

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



- Factorizable Regge pole exchange

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

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

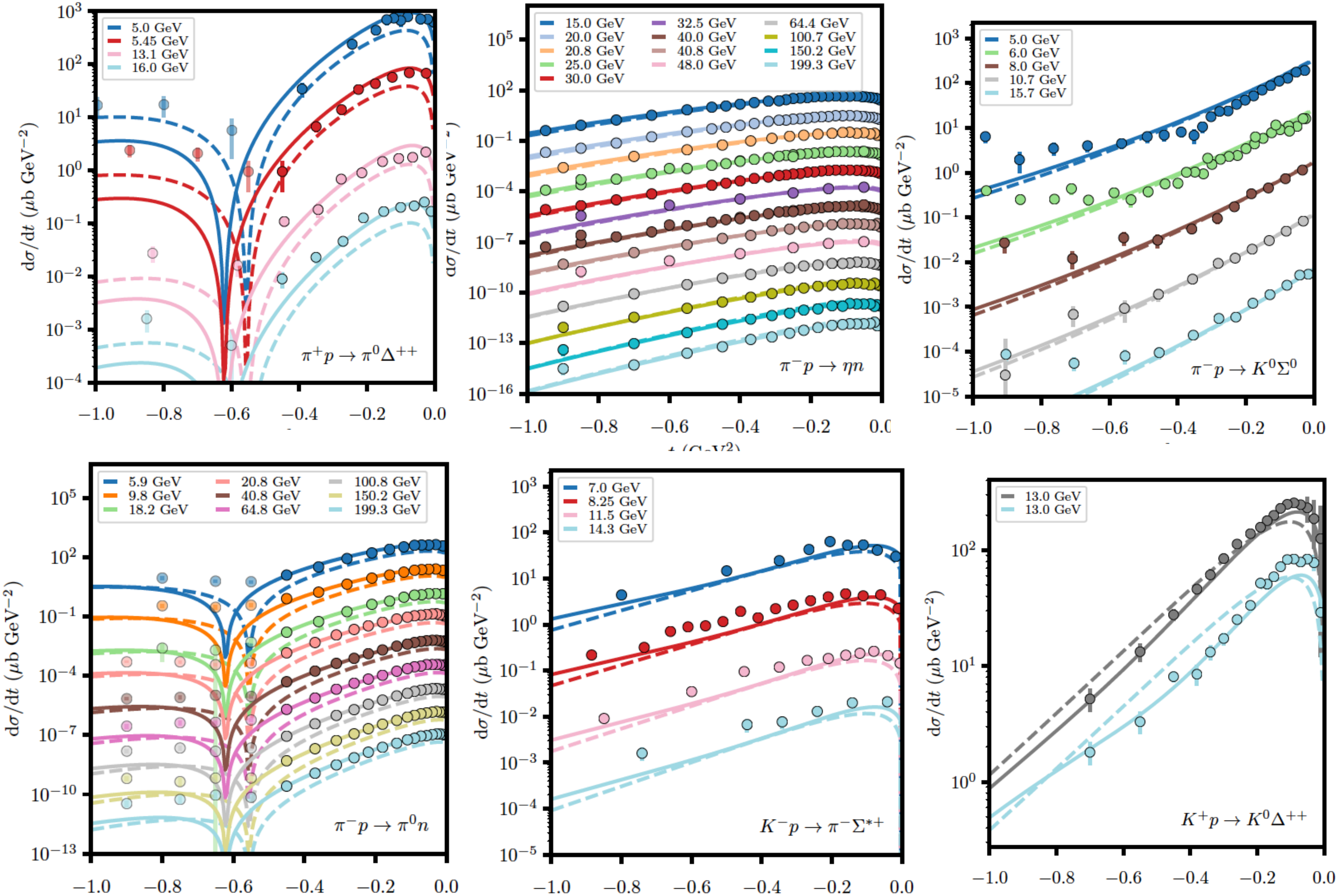
$$\mathcal{F}_e(s,t) = -\frac{\zeta_e \pi \alpha_e^1}{\Gamma(\alpha_e(t)-l_e+1)}\frac{1+\zeta_e e^{-i\pi\alpha_e(t)}}{2\sin\pi\alpha_e(t)}\left(\frac{s}{s_0}\right)^{\alpha_e(t)}$$

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

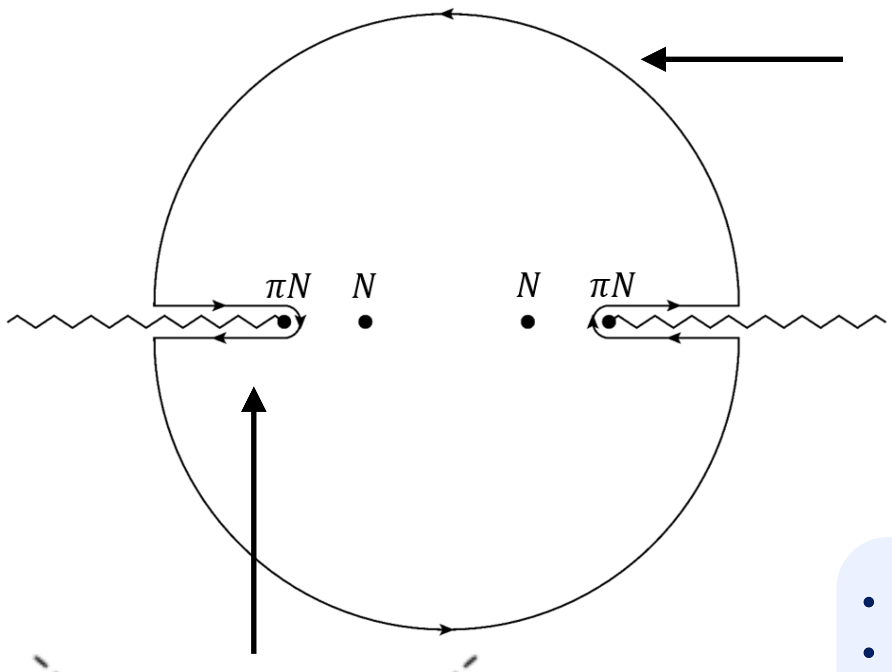
$$\mathcal{F}_e(s,t) \xrightarrow[t\to m_e^2]{} \frac{(s/s_0)^{J_e}}{m_e^2-t}.$$

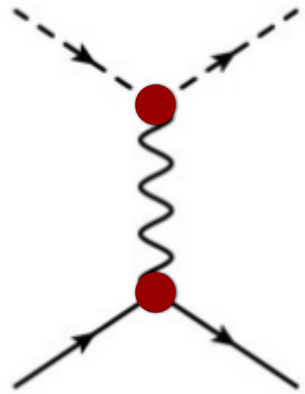
(6 SU(3) couplings, 1 mixing angle, 2 exp. slopes)

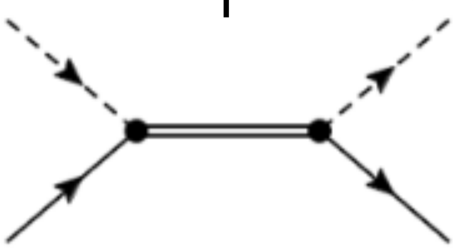
Global Regge pole analysis



Finite Energy Sum Rules





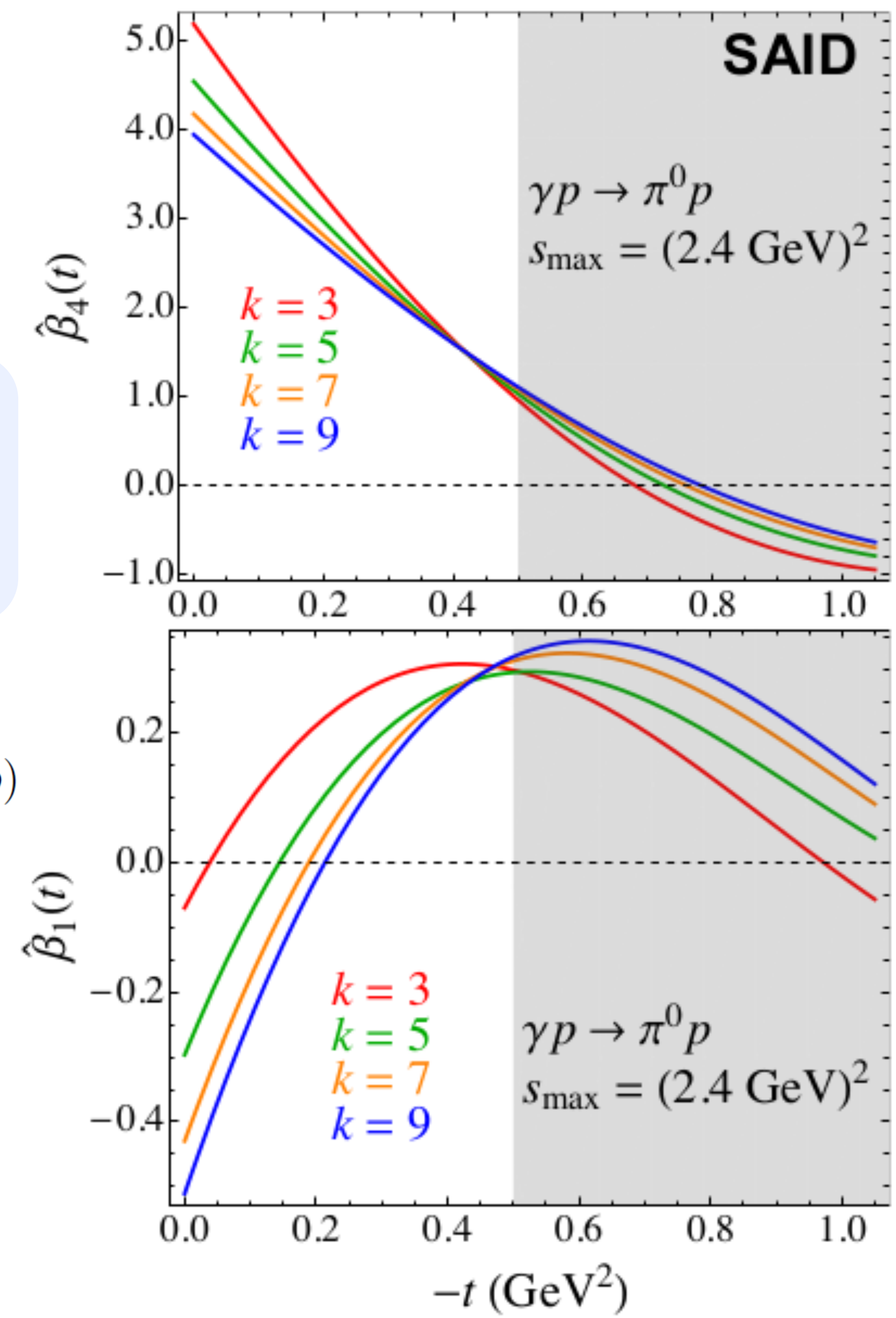


- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

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

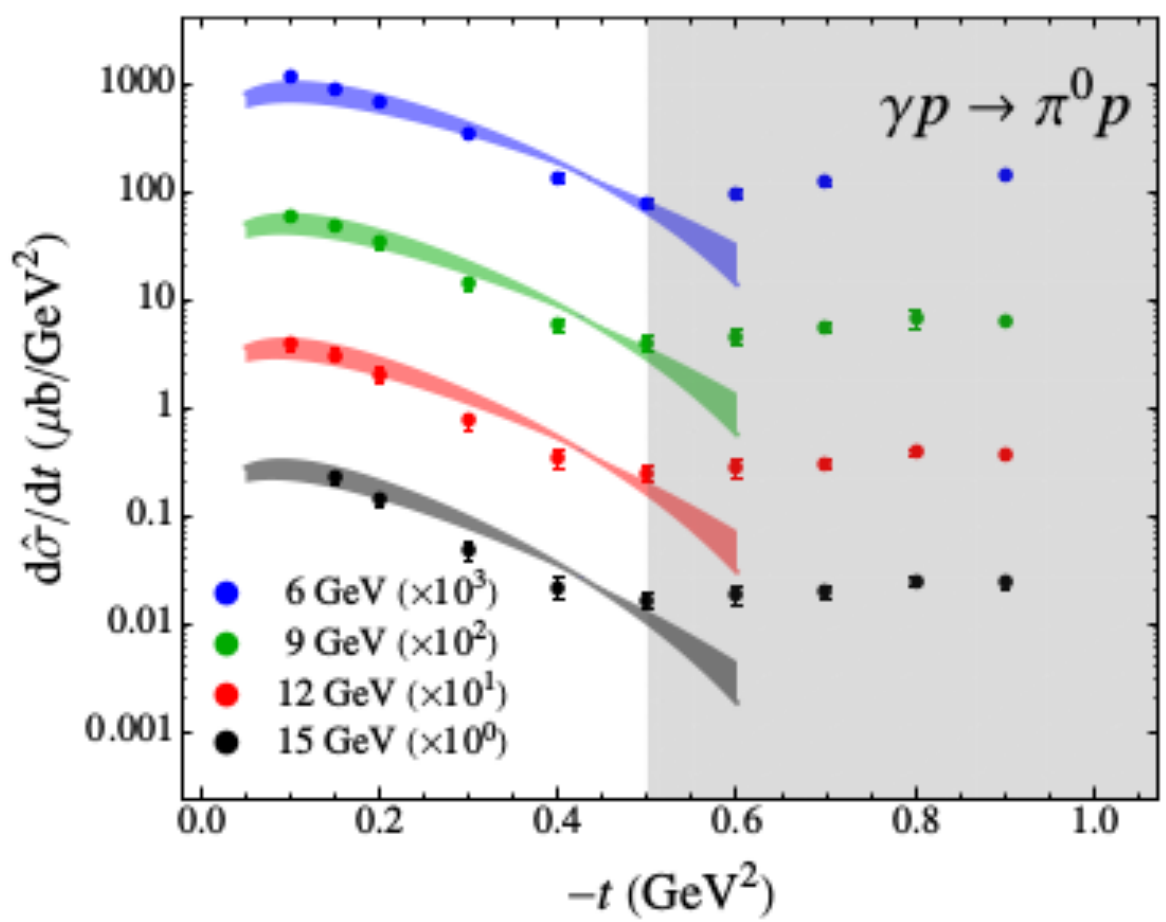
$$\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu = \beta_i(t)\frac{\Lambda^{\alpha(t)+k}}{\alpha(t)+k}$$

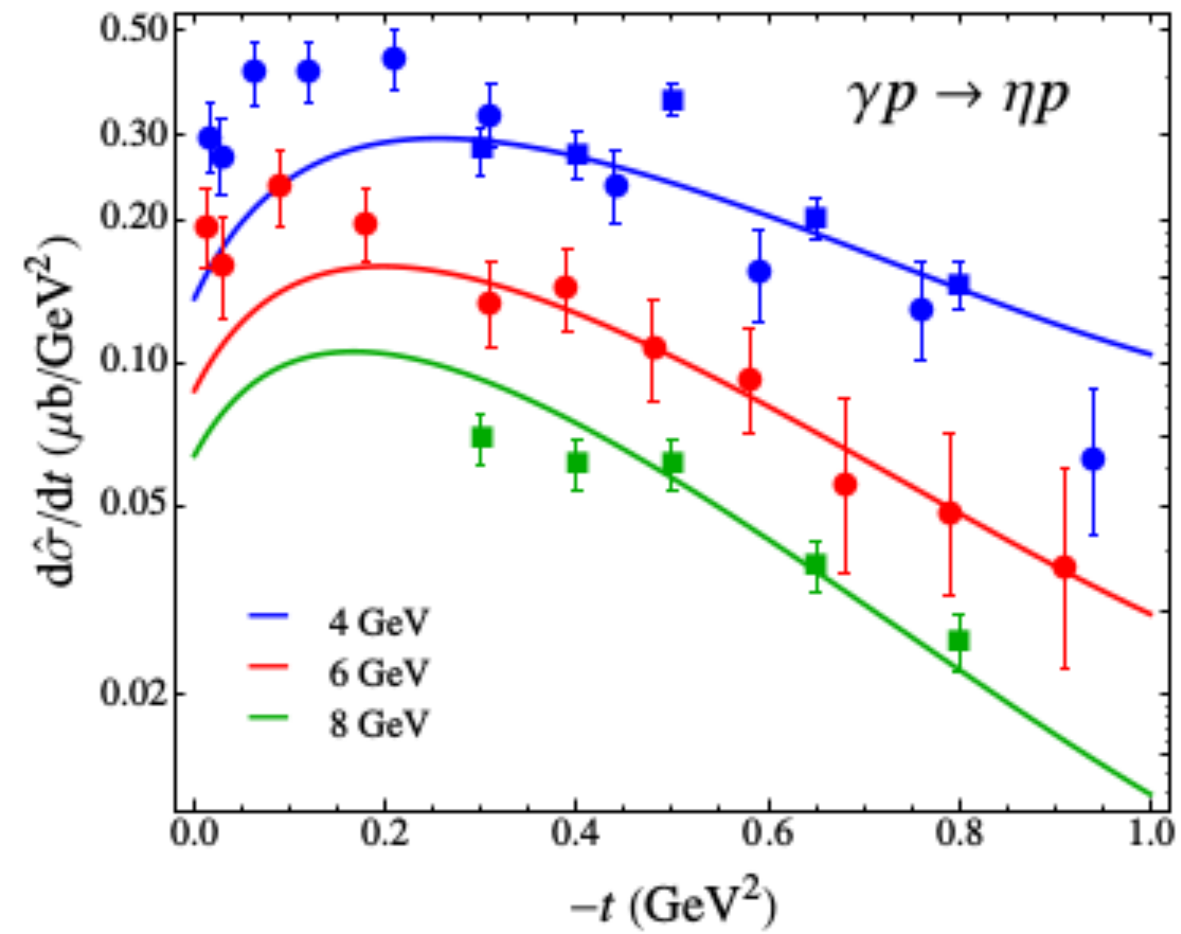
$$\boxed{\beta_i(t) = \frac{\alpha(t)+k}{\Lambda^{\alpha(t)+k}}\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu}$$



Finite Energy Sum Rules

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



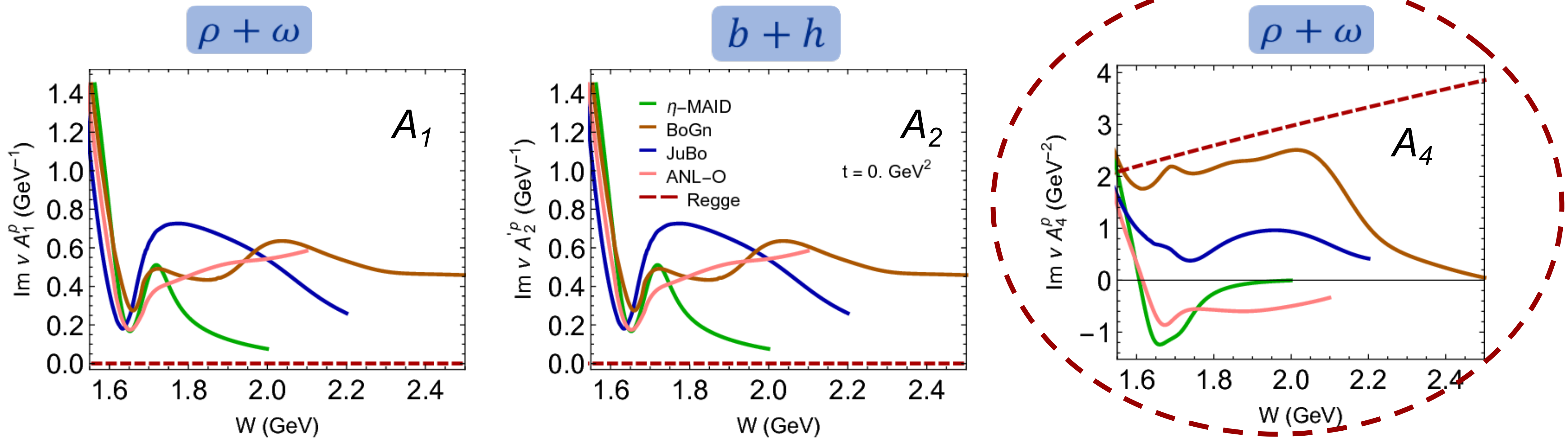


Combine energy regimes
- Low-energy model ((SAID, MAID, Bonn-Gatchina, Julich-Bonn,…)
- Predict high-energy observables

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

Constraining the resonance spectrum

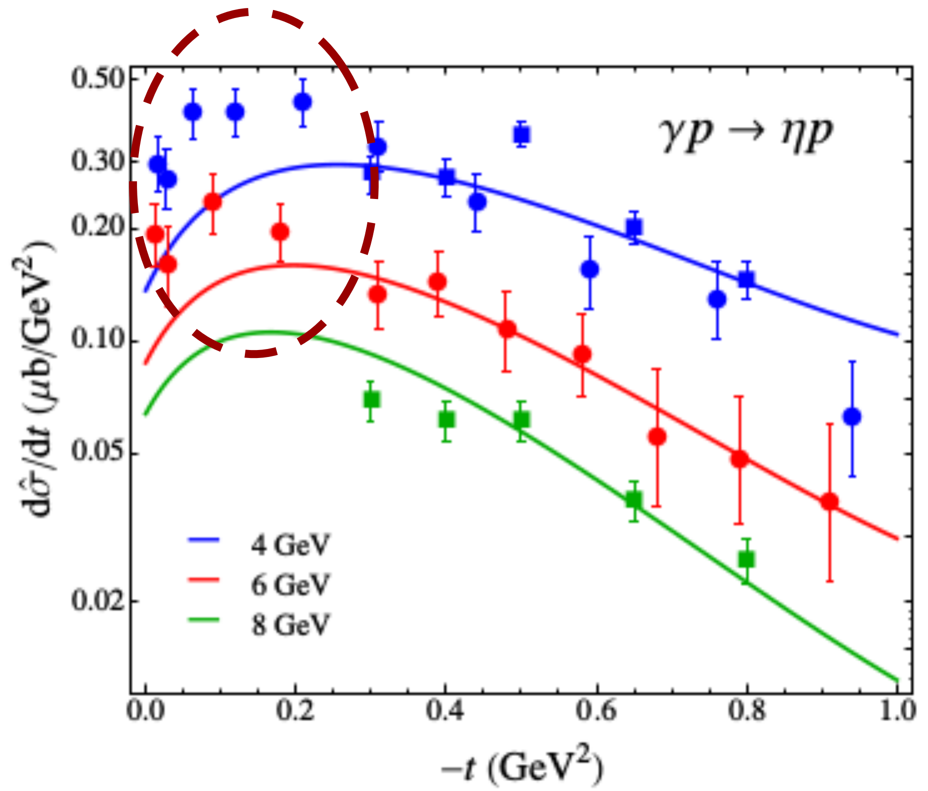
[J.Nys *et al.*, PRD95 (2017) 034014]



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

Possibilities

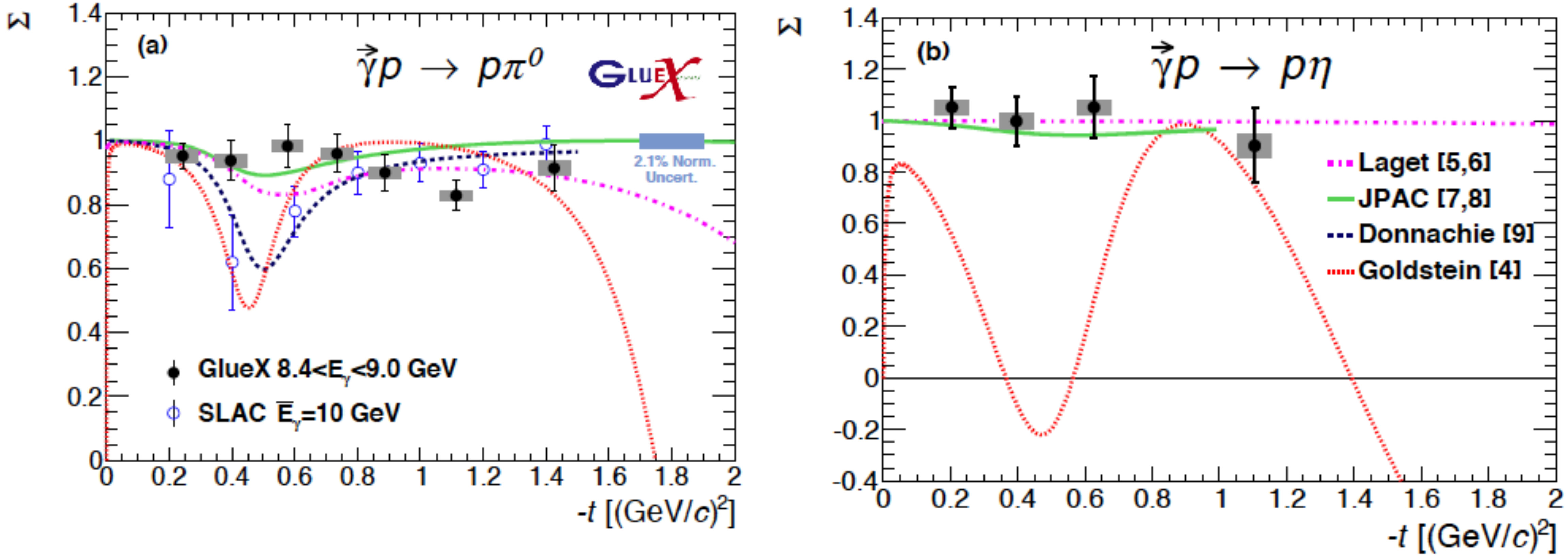
- Low-energy model inconsistent
- Cut-off not high enough
  - High mass resonances!

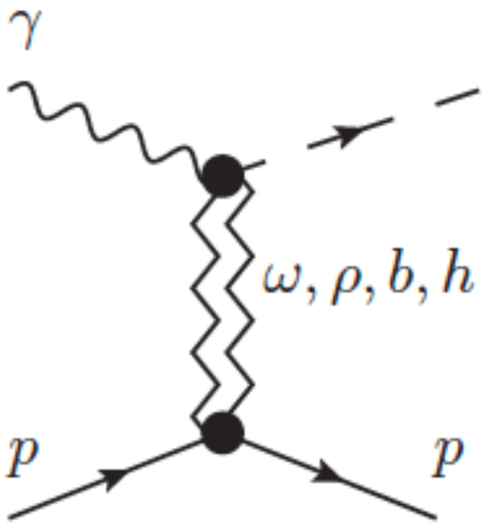


Beam asymmetry: measurement of the exchange process

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

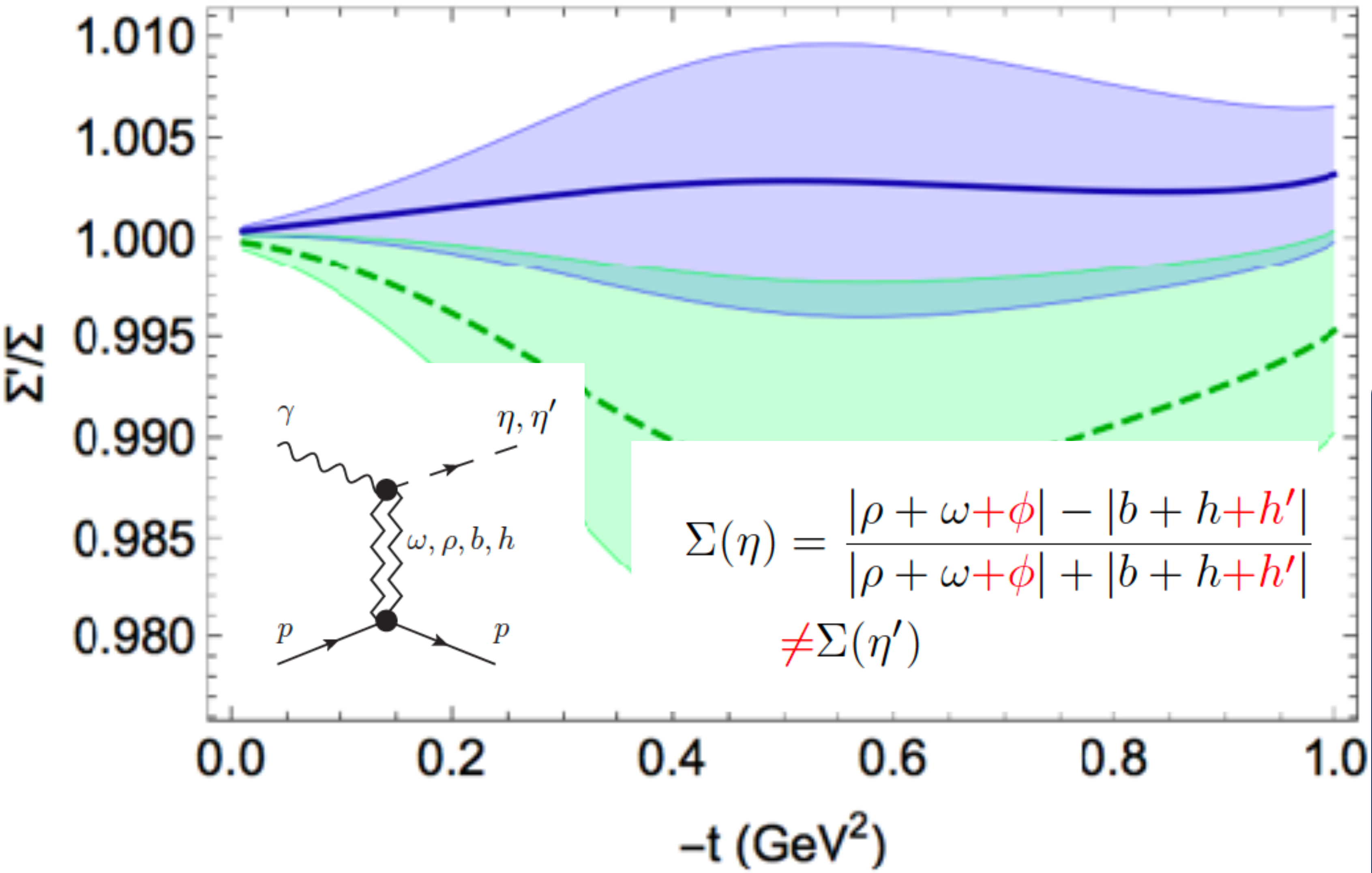
H. Al Ghoul et al. [GlueX]
Phys. Rev. C95 (2017) no.4, 042201
+V. Mathieu, J. Nys [JPAC]





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

η/η' asymmetry probes coupling to strangeness



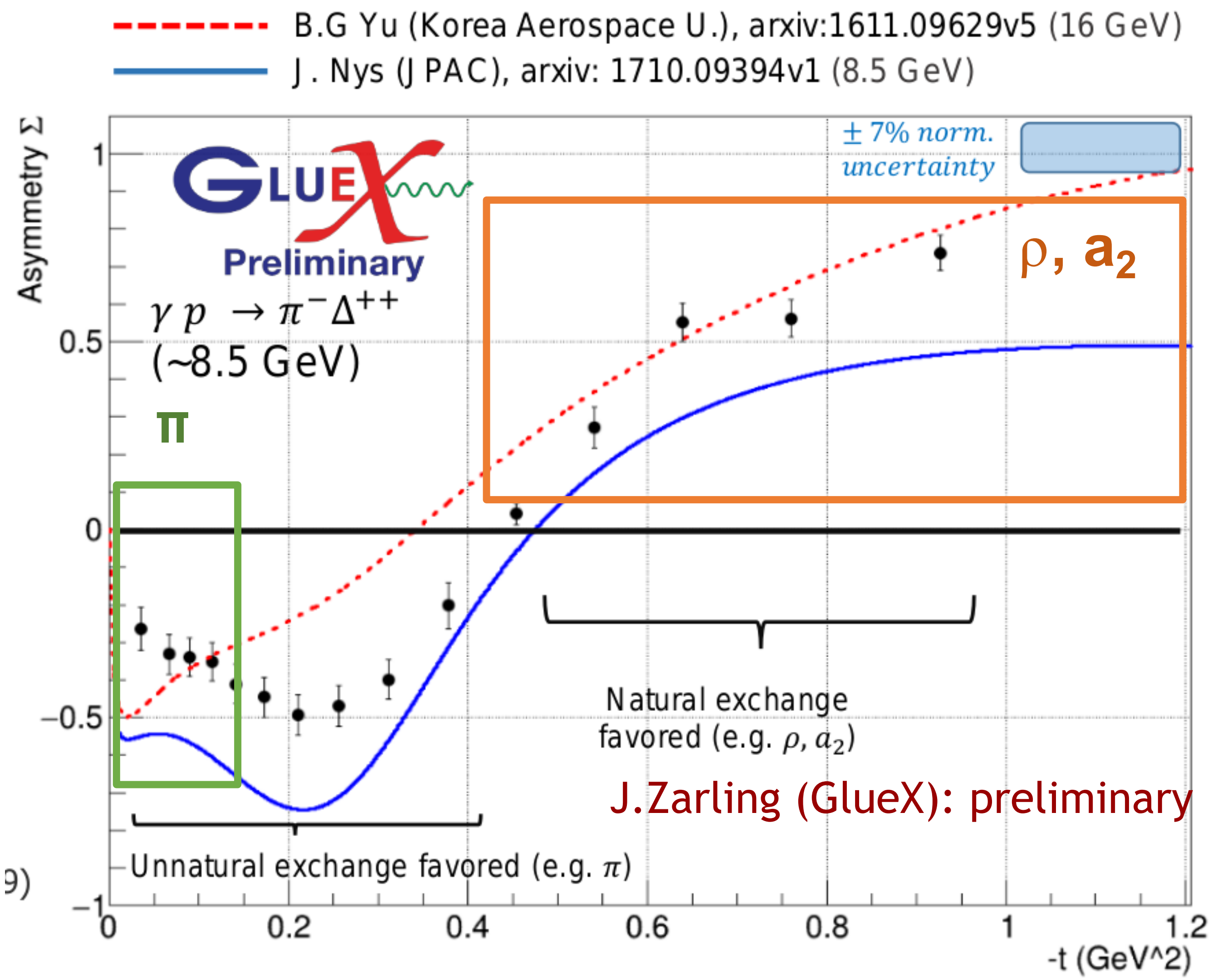
Based on the FESR for η:
predict beam asymmetry for η'

- 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)

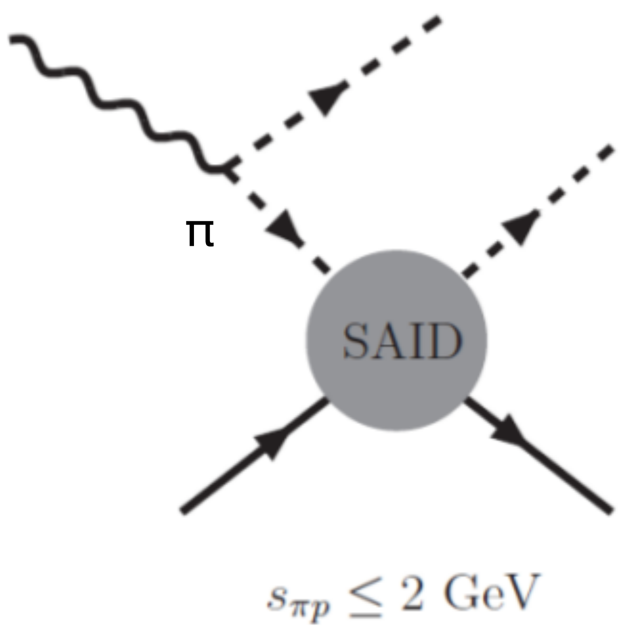
πΔ photoproduction



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

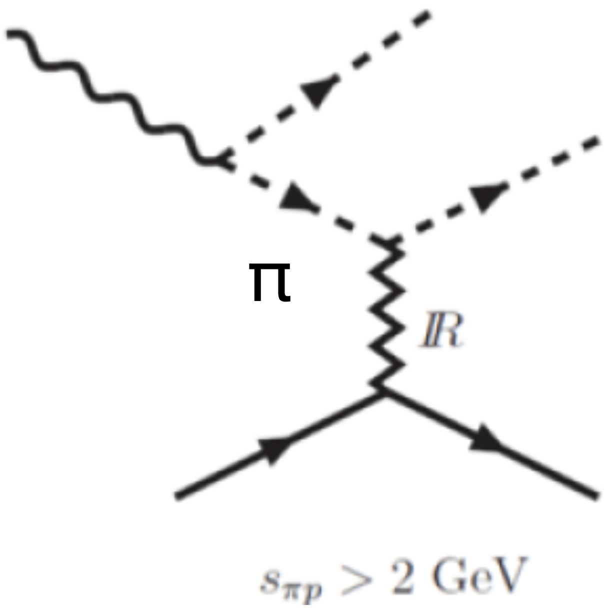
J.Nys et al. (JPAC) Phys.Lett. B779, 77 (2018)

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

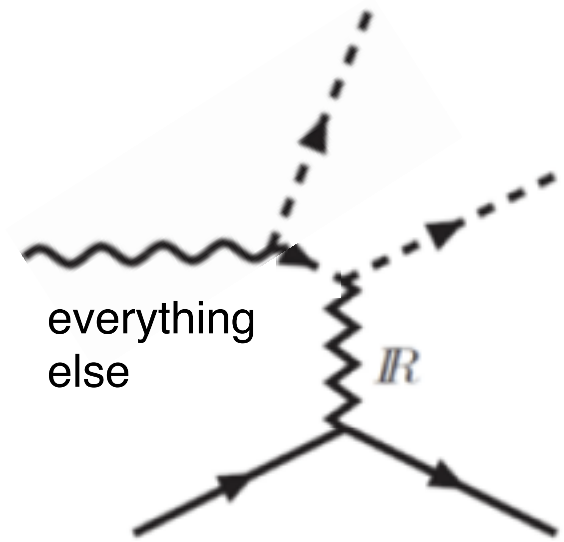


Łukasz Bibrzycki et al. (Cracow,JPAC)

OPE vs other exchanges

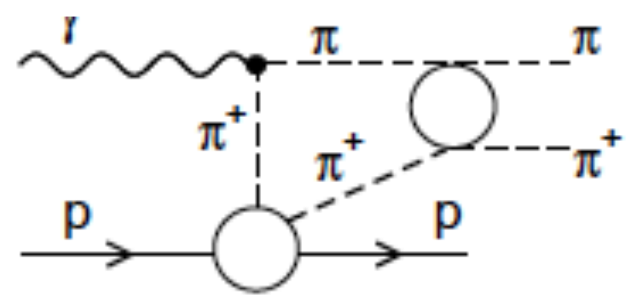


- Long range exchange

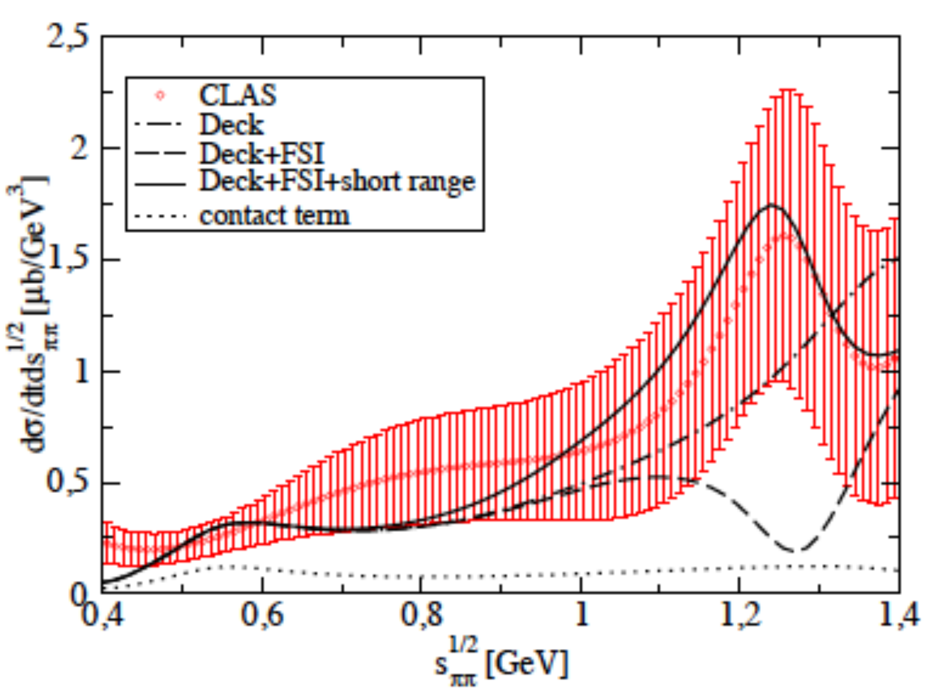


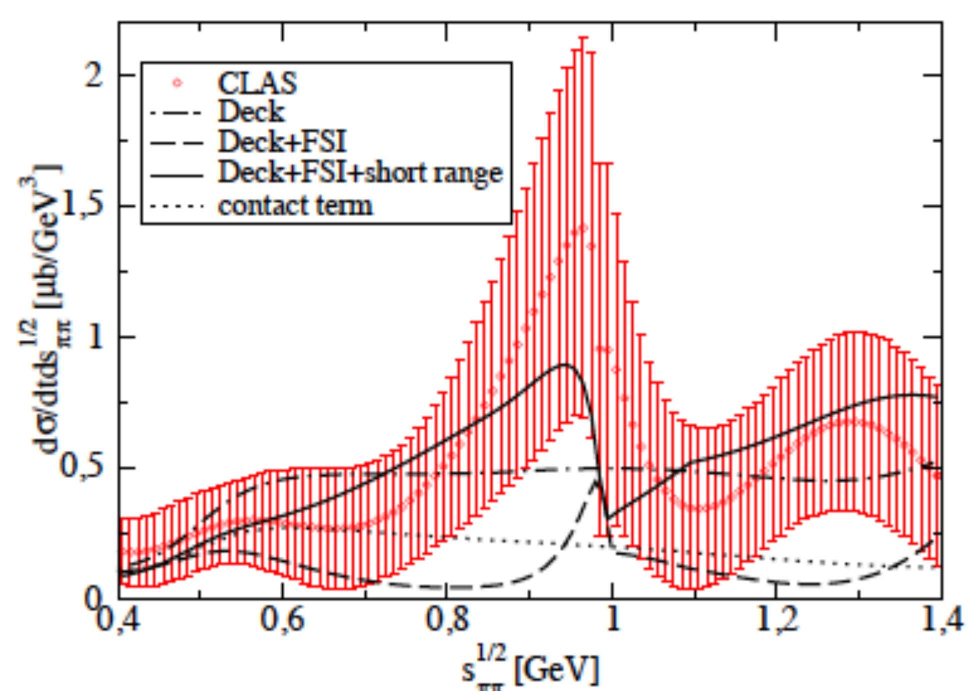
- Short range exchange

- When Final State Interactions are taken into account one produces a dip the other a pick at a resonance mass



Bibrzycki,Bydzovsky,Kaminski,AS (2018)





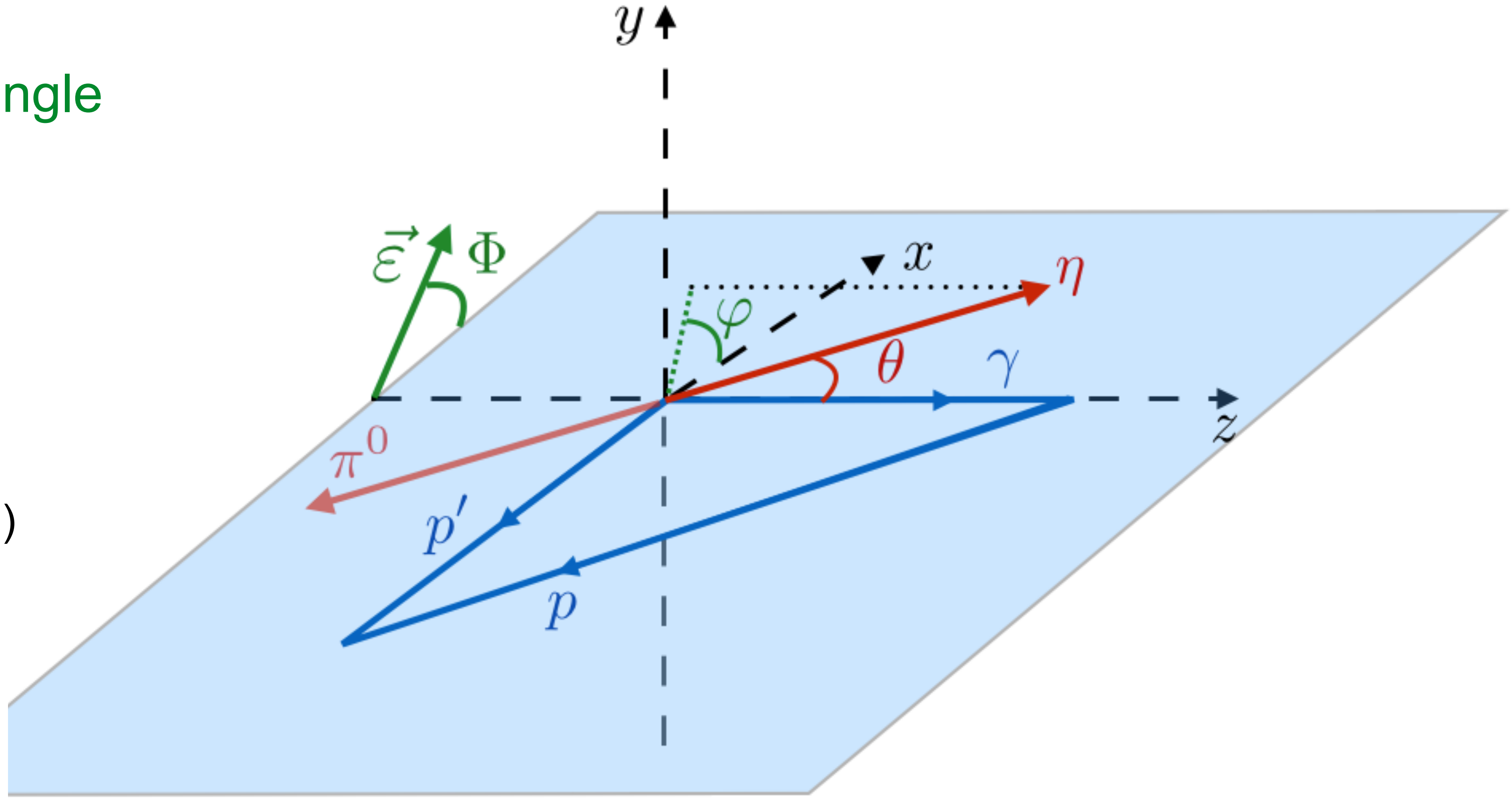
Moment analysis

$$I(\Omega, \Phi) = I^0(\Omega) - P_\gamma I^1(\Omega)\cos 2\Phi - P_\gamma I^2(\Omega)\sin 2\Phi$$

polarization angle

η decay angles

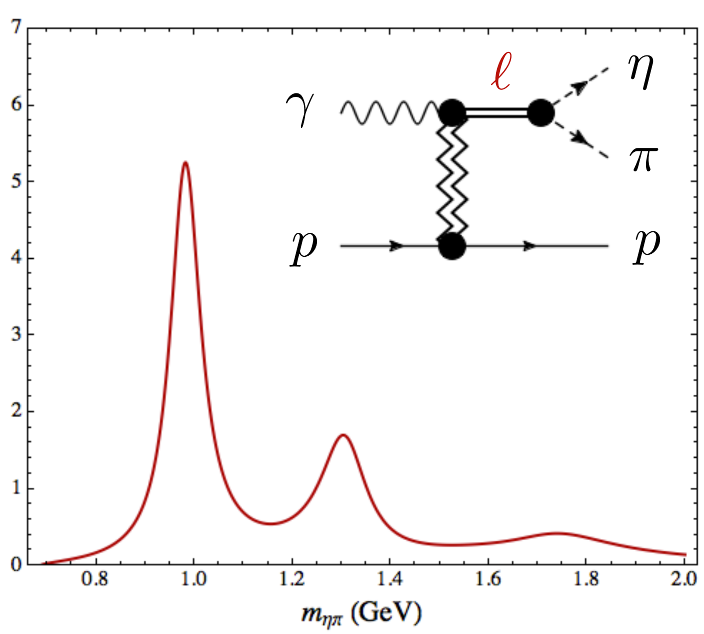
$\Omega = (\theta, \phi)$



Beam energy (fixed)

momentum transfer (integrated)

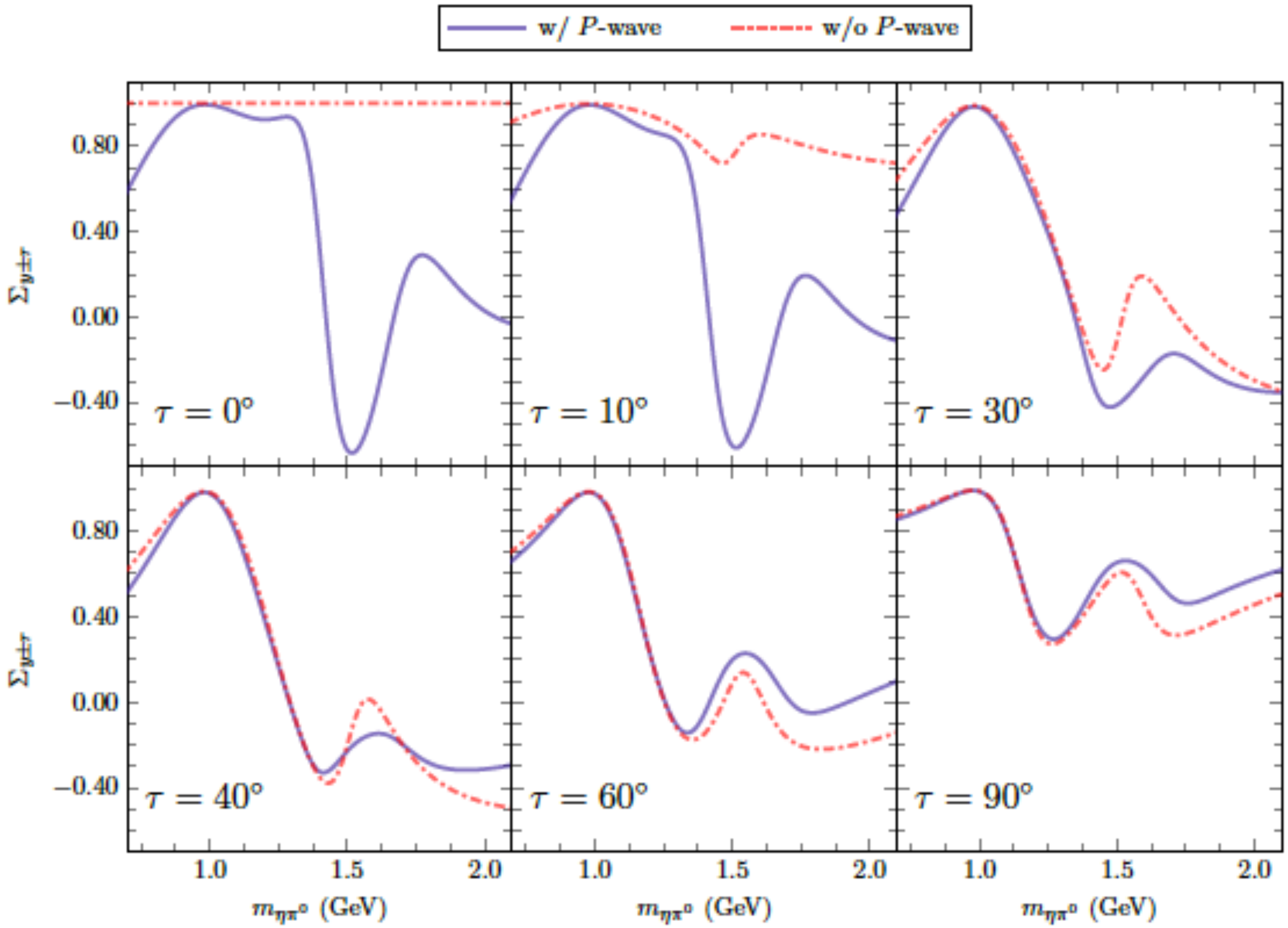
$\eta\pi$ invariant mass (binned)

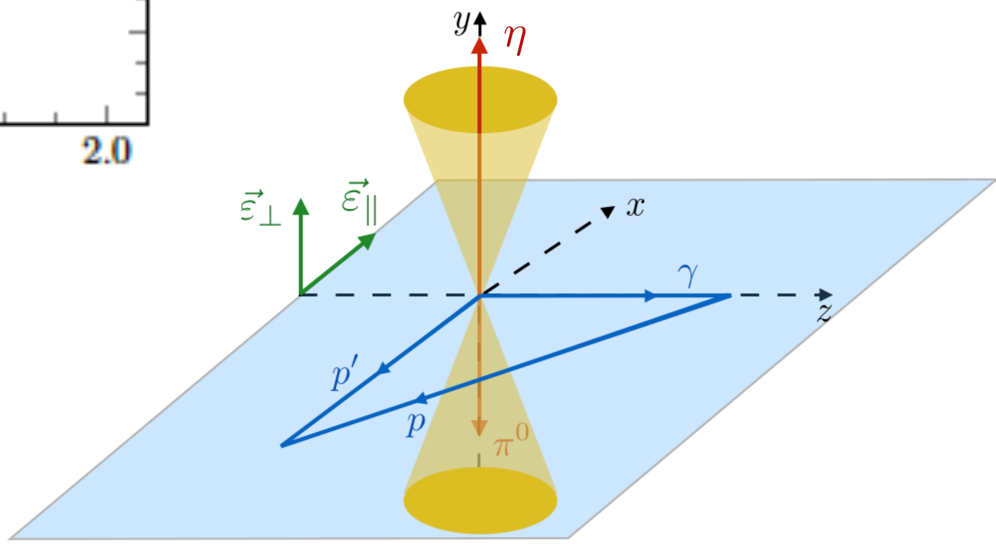


$$R = \{\underbrace{a_0(980)}_{S_0^{(+)}}, \underbrace{\pi_1(1600)}_{P_{0,1}^{(+)}}, \underbrace{a_2(1320), a_2(1700)}_{D_{0,1,2}^{(+)}}\}$$

V.Mathieu et al (JPAC), arXiv:1906.04841

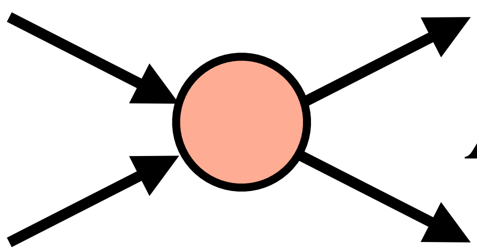
Beam asymmetry





3-to-3 particle scattering

Amplitudes can be reconstructed from unitarily (analyticity)
The problem is how to implement unitary in mupltipartilce reactions



$$A(s, t) \to A_l(t)$$

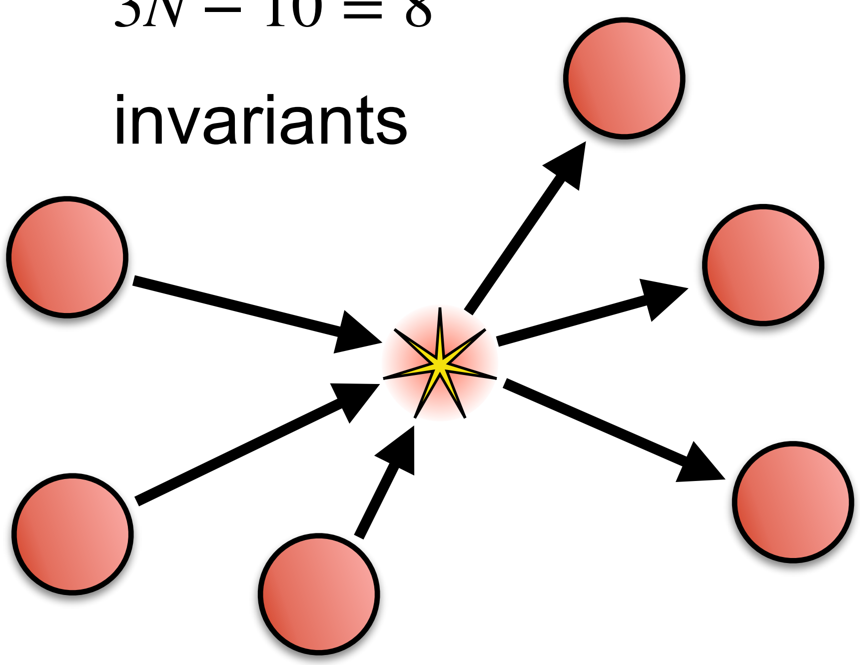
- 2-to-2 partial waves diagonalize unitarity

$$A_l(s) = K^{-1}(s) - i\rho(s)$$

- K-matrix = infinite volume solution to unitarity
- Luscher (quantization condition) = finite volume solution to unitarity

$3N - 10 = 8$

invariants



$$A(s, s_{12}, t_{12'}, \cdots) \to A^J_{\Lambda,\Lambda'}(s_{12}, s, s_{1'2'})$$

- Helicity partial waves represent (quasi) two-body isobar/dimer spectator
- Difference in various approaches has to do with how the K-matrix is introduced (symmetrization)
- JPAC : Proof of equivalence (on the real axis)

A.Jackura et al., Phys.Rev. D100 (2019), 034508

Resonance parameter determination

JPAC

$a_2(1700)$ $\quad I^G(J^{PC}) = 1^-(2^{++})$

$a_2(1700)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1705±40 OUR AVERAGE				
1722±15±67		[1] RODAS	19 JPAC	191 $\pi^- p \to \eta^{(\prime)}\pi^- p$
1698±44		[2] AMSLER	02 CBAR	0.9 $\bar{p}p \to \pi^0\eta\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1681^{+22}_{-35}	46M	[3,4] AGHASYAN	18B COMP	190 $\pi^- p \to \pi^-\pi^+\pi^- p$
1720±10±60		[5] JACKURA	18 JPAC	$\pi^- p \to \eta\pi^- p$
1726±12±25		[4] ABLIKIM	17K BES3	$\psi(2S) \to \gamma\eta\pi^+\pi^-$

$\pi_1(1600)$ $\quad I^G(J^{PC}) = 1^-(1^{-+})$

$\pi_1(1600)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1660^{+15}_{-11} OUR AVERAGE Error includes scale factor of 1.2.				
1564± 24±86		[1] RODAS	19 JPAC	191 $\pi^- p \to \eta^{(\prime)}\pi^- p$
1600^{+110}_{-60}	46M	[2] AGHASYAN	18B COMP	190 $\pi^- p \to \pi^-\pi^+\pi^- p$

$a_2(1320)$ $\quad I^G(J^{PC}) = 1^-(2^{++})$

$a_2(1320)$ MASS

VALUE (MeV)	DOCUMENT ID
1316.9±0.9 OUR AVERAGE Includes data from the 4 datablocks that follow this one. Error includes scale factor of 1.9. See the ideogram below.	

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1312.2± 2.8 OUR AVERAGE Error includes scale factor of 2.6. See the ideogram below.					
1306.0± 0.8±1.3		[1] RODAS	19 JPAC		191 $\pi^- p \to \eta^{(\prime)}\pi^- p$
1308 ± 9		BARBERIS	00H		450 $pp \to p_f\eta\pi^0 p_s$

$a_1(1260)$ $\quad I^G(J^{PC}) = 1^-(1^{++})$

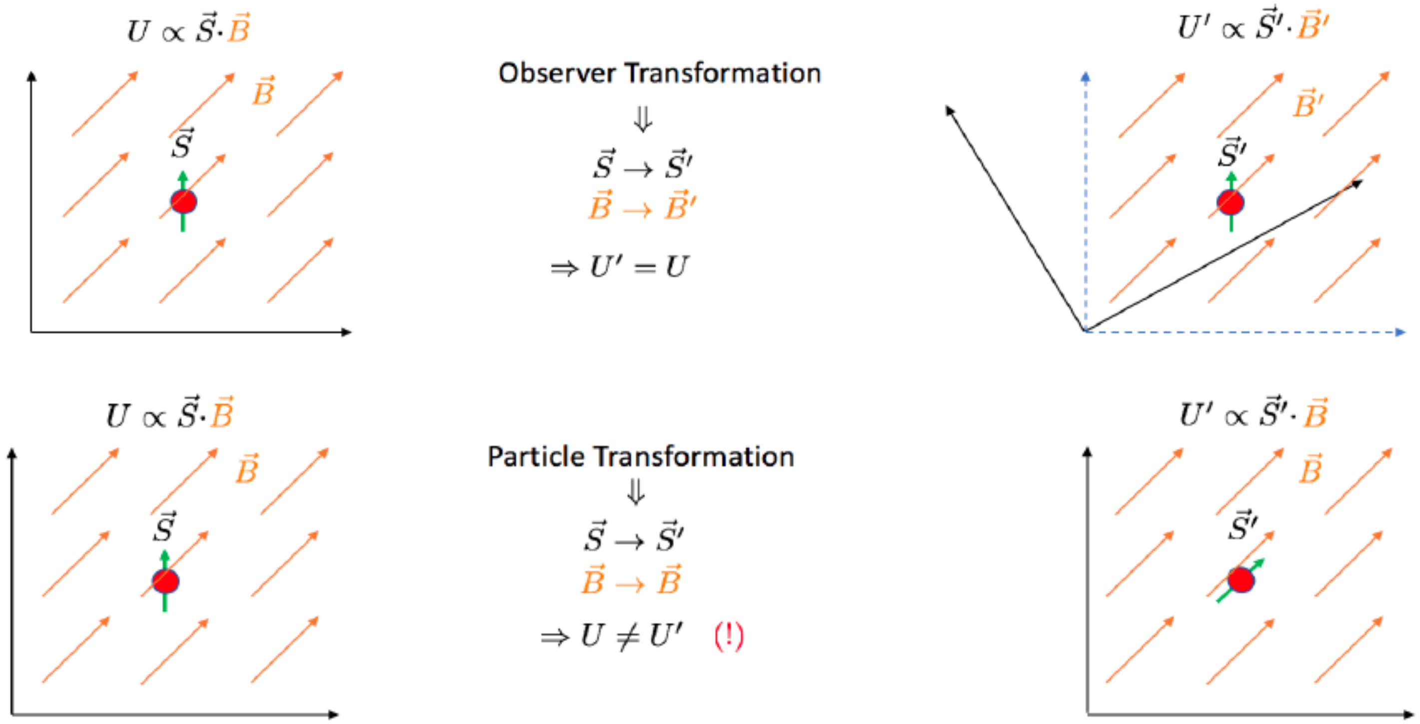
See also our review under the $a_1(1260)$ in PDG 06, Journal of Physics **G33** 1 (2006).

$a_1(1260)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1230 ±40 OUR ESTIMATE				
1299 $^{+12}_{-28}$	46M	[1] AGHASYAN	18B COMP	190 $\pi^- p \to \pi^-\pi^+\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1195.05± 1.05± 6.33	894k	AAIJ	18AI LHCB	$D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$
1209 ± 4 $^{+12}_{-9}$		[2] MIKHASENKO	18 RVUE	$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
1225 ± 9 ±20	7k	[3] DARGENT	17 RVUE	$D^0 \to \pi^-\pi^+\pi^-\pi^+$

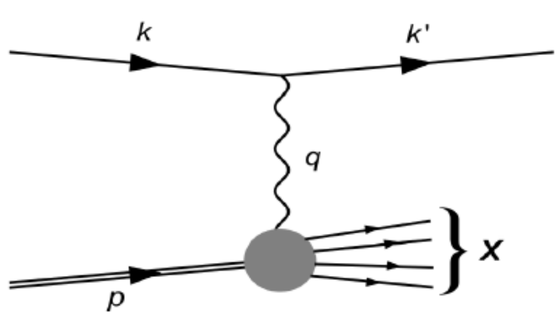
The Review of Particle Physics
M. Tanabashi et al. [Particle Data Group],
Phys. Rev. **D98**, 030001 (2018) and 2019 update

(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, …



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

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

- 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.

JPAC 2019

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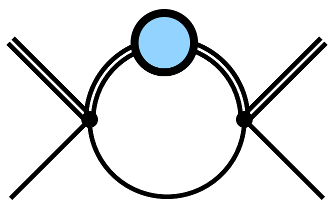
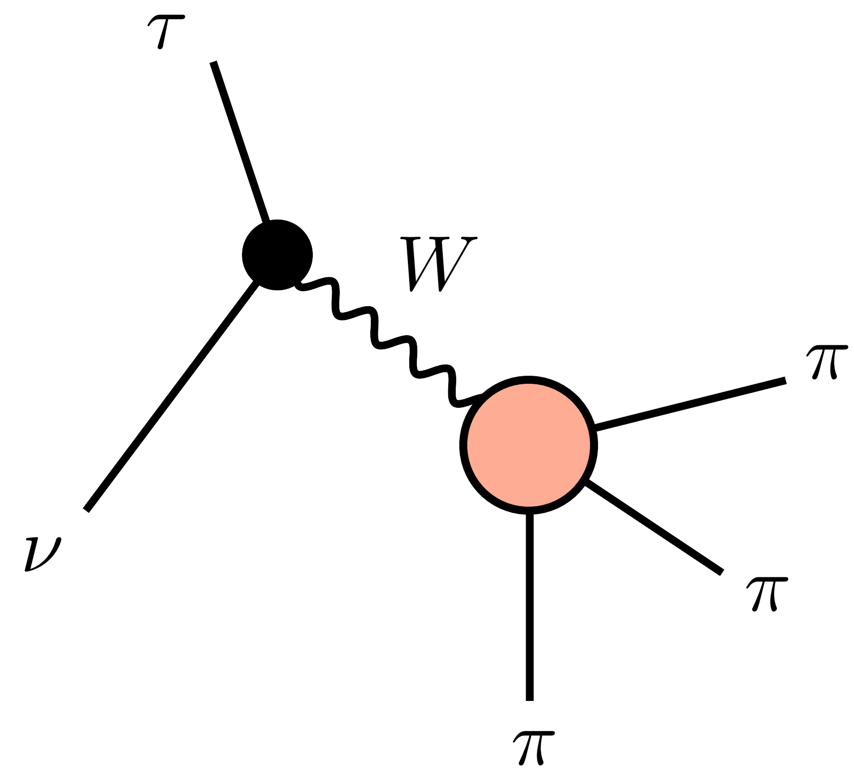
[2]JLab/IU funded

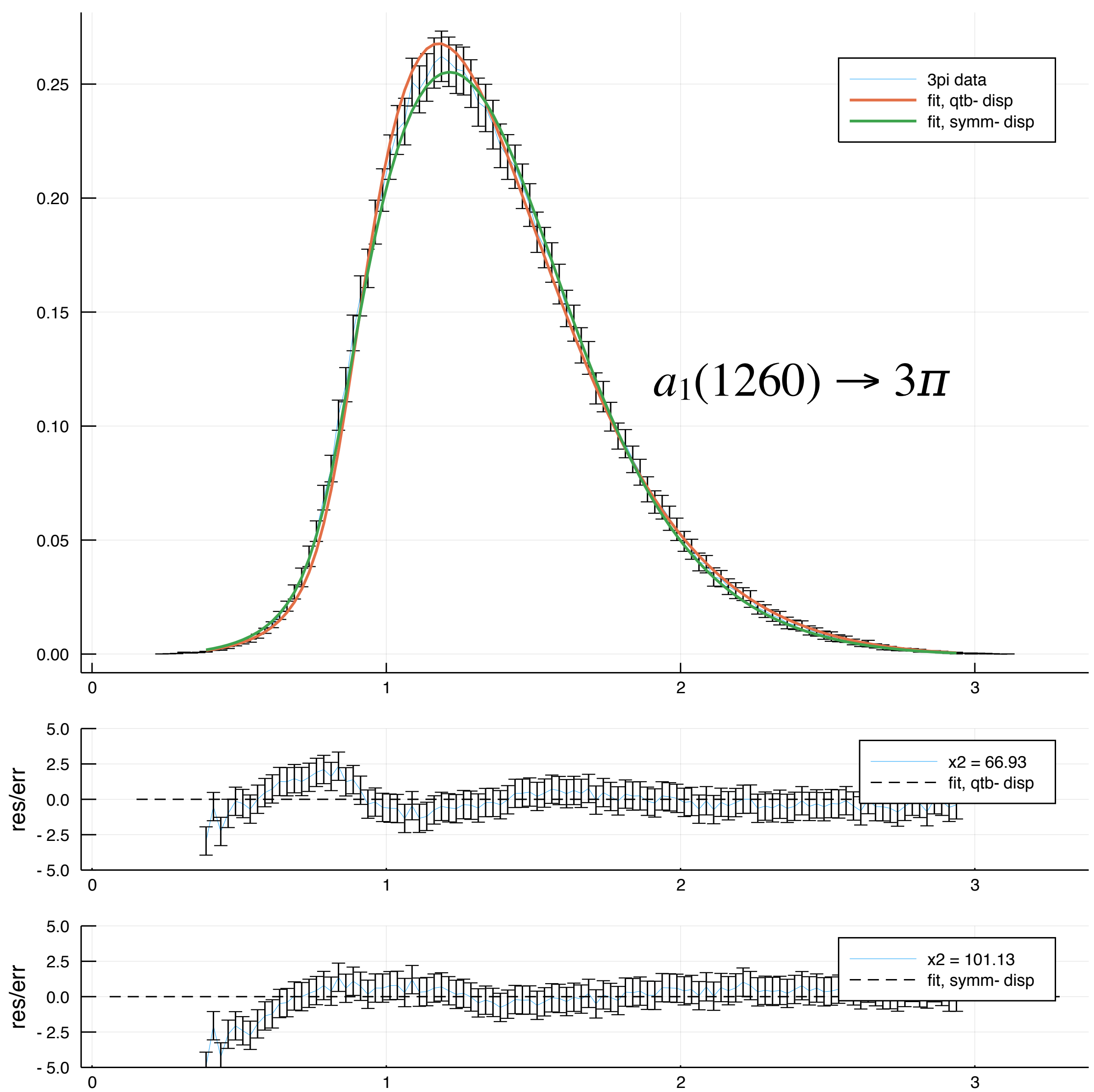
Experimental collaborations: GlueX, CLAS12, COMPASS, MAMI, BaBar, Belle, BES, KLOE, LHCb

$a_1(1260)$

- Quasi-two-body approximation







M. Mikhasenko et al. [JPAC], Phys. Rev. **D98**, 096021 (2018)