Practically implementable advances in PWA theory for meson decays

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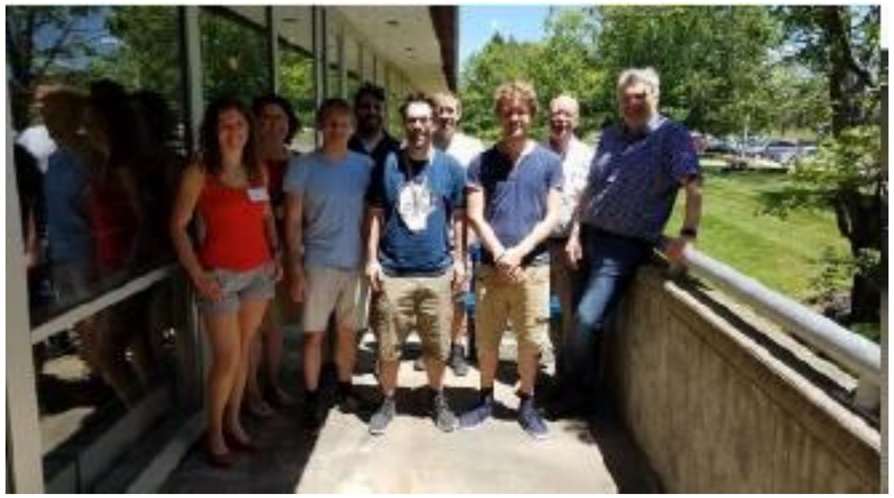
JPAC

Joint Physics Analysis Center

Joint Physics Analysis Center

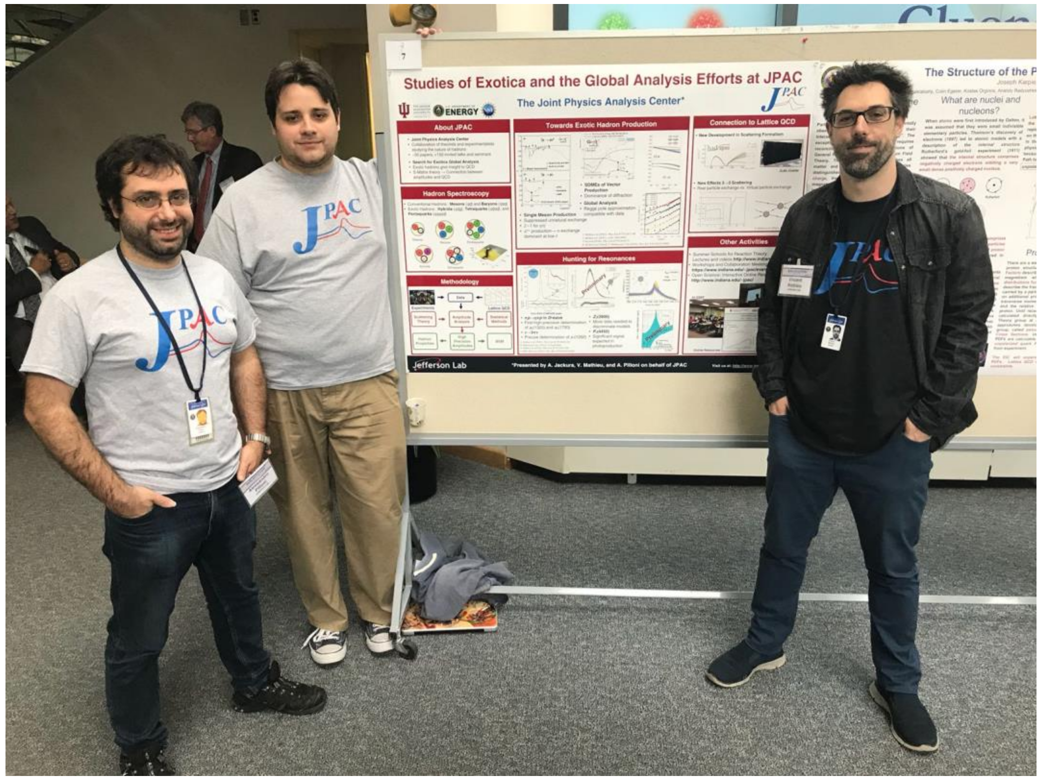
- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other accelerator laboratories

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



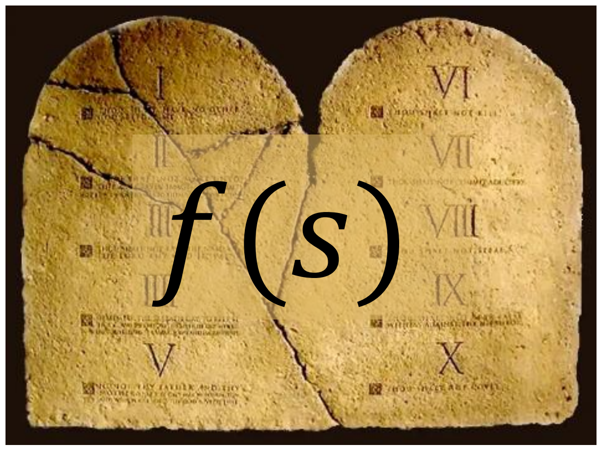
https://jpac.jlab.org

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

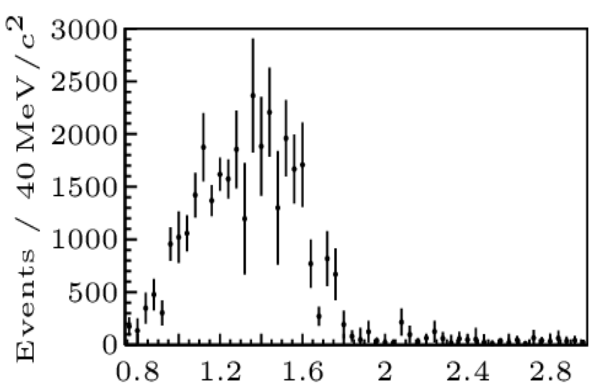


The flowchart(s)

1) You are given a model/theory



2) You calculate the amplitude

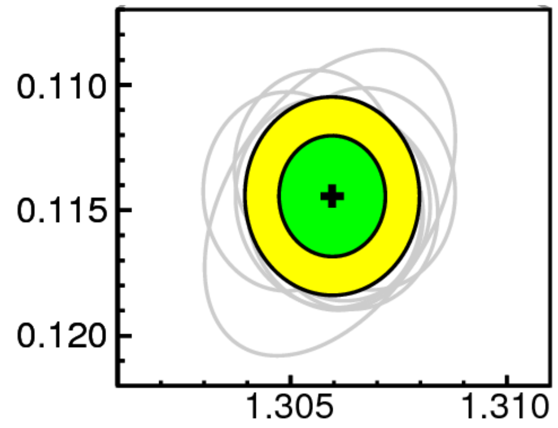


3) You compare with data.
Or you don't.

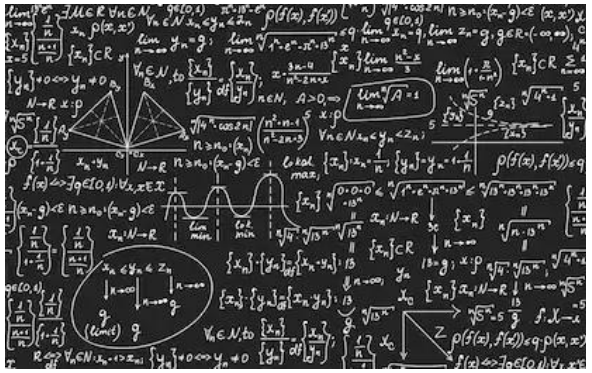
Predictive power ✓
Physical interpretation ✓
(within the model! ✗)
Biased by the input ✗

The flowchart(s)

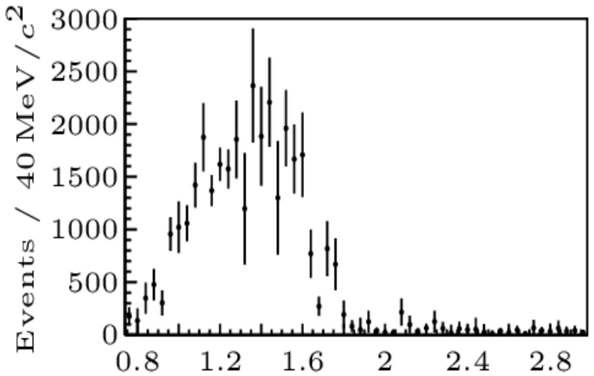
Less predictive power ✗
Some physical interpretation ✗
Minimally biased ✓



3) You extract physics

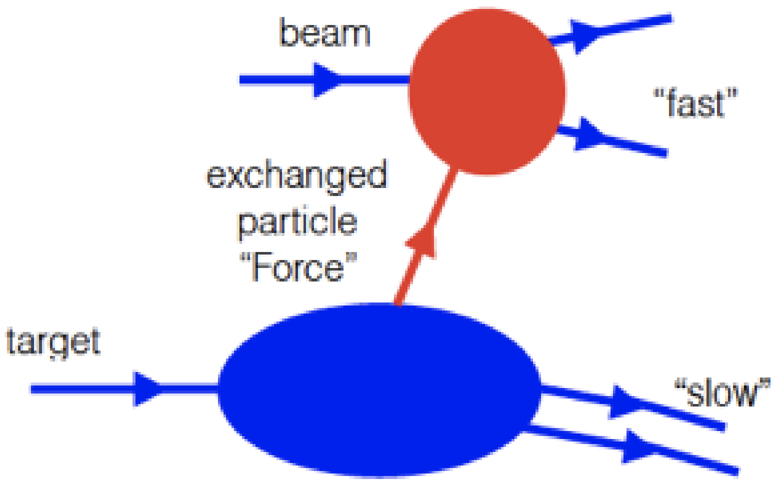


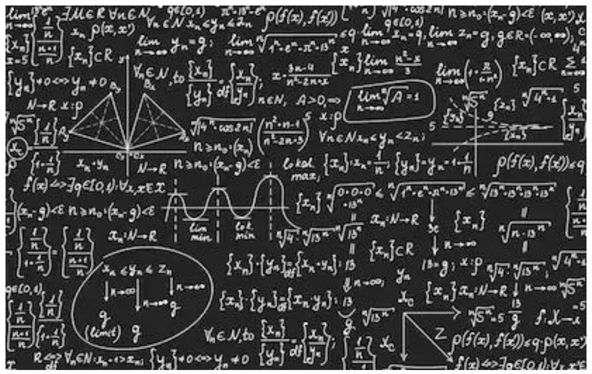
2) You choose a set of generic amplitudes



1) You start with data

Semantic areas

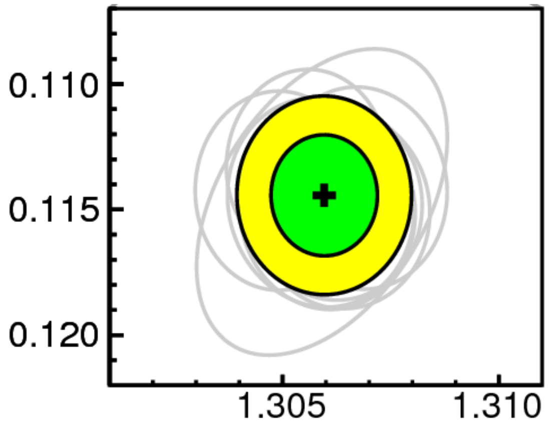




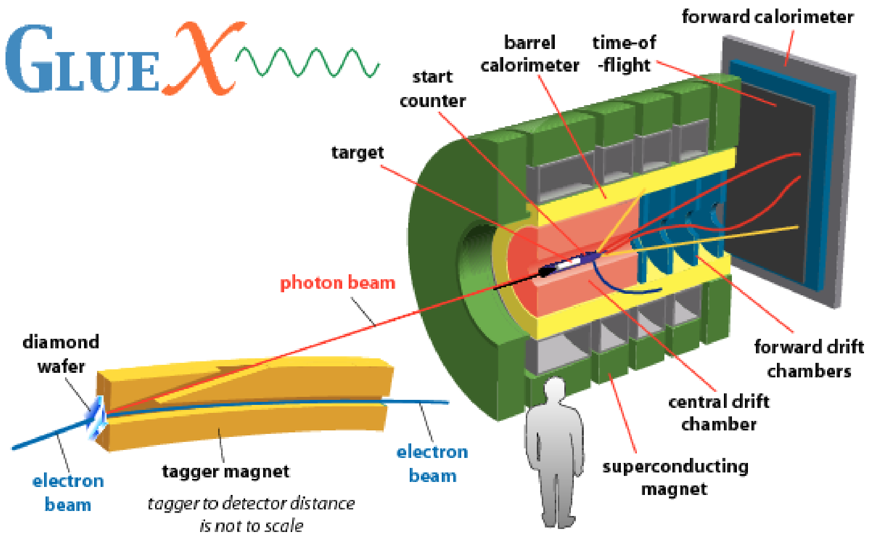
Formalism

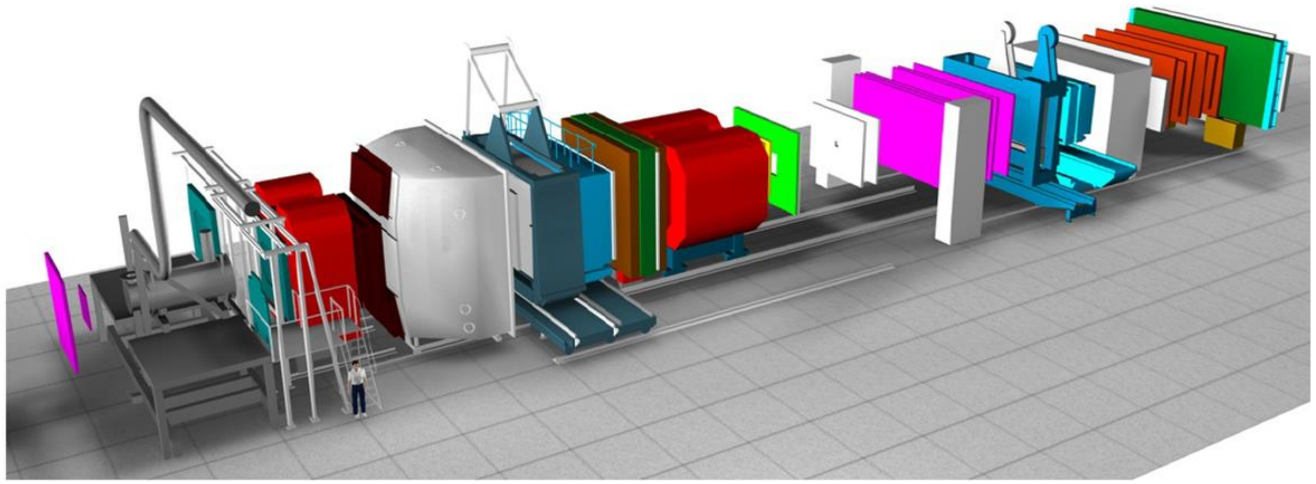
Production mechanisms

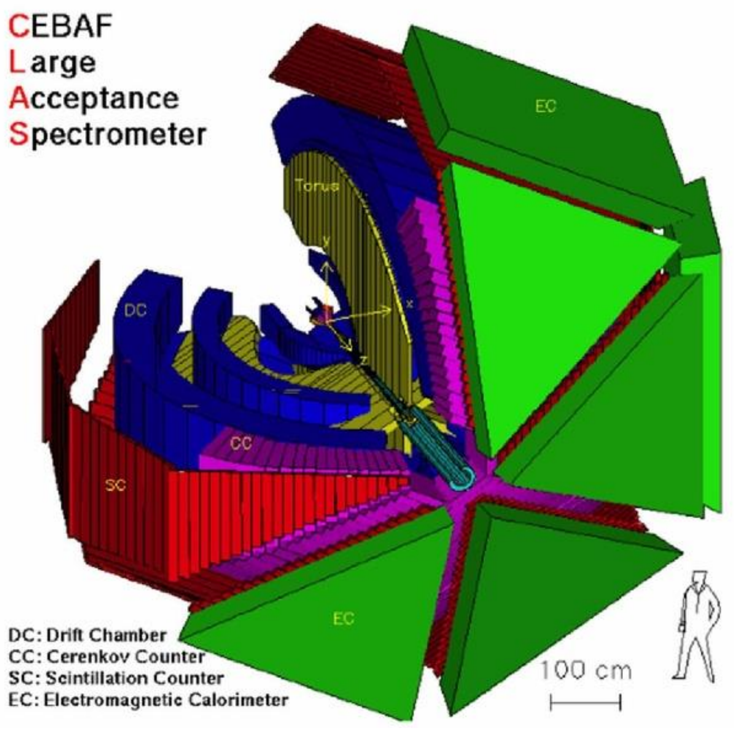
Resonance extraction



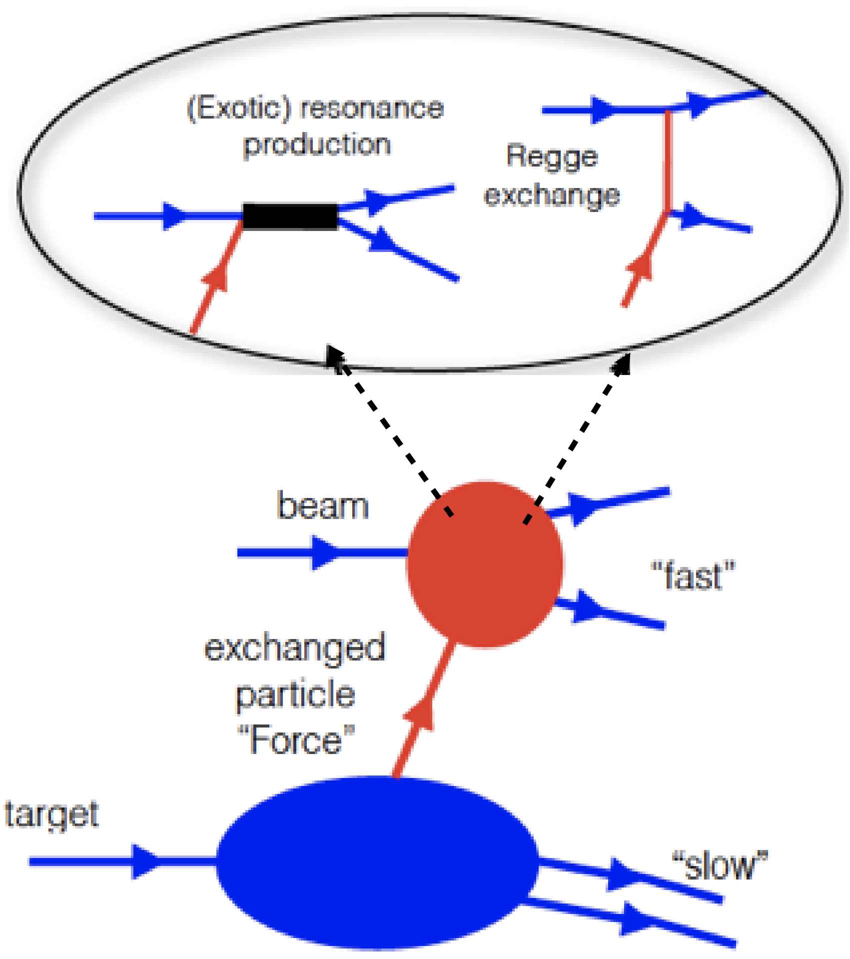
Spectroscopy from peripheral production





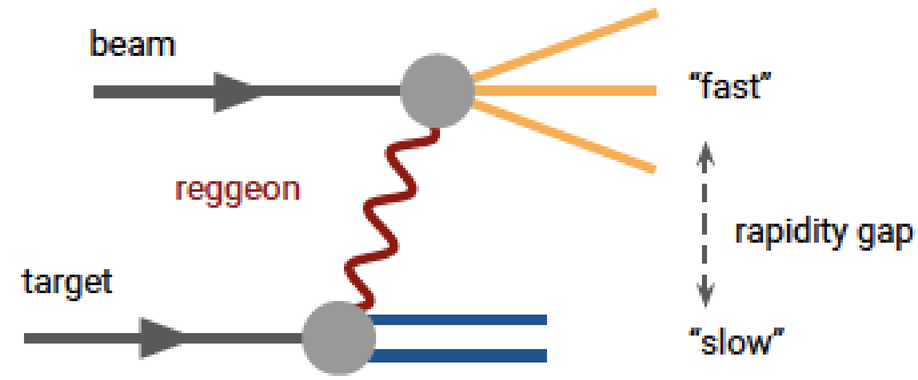


- Need to establish factorization between beam and target fragmentation (Regge factorization)
- Single Regge pole exchange dominate over cut other singularities (cuts, daughters)



Global Regge analysis

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



- Factorizable Regge pole exchange

J.Nys et al. (JPAC) Phys.Rev. D98 (2018) 034020

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

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

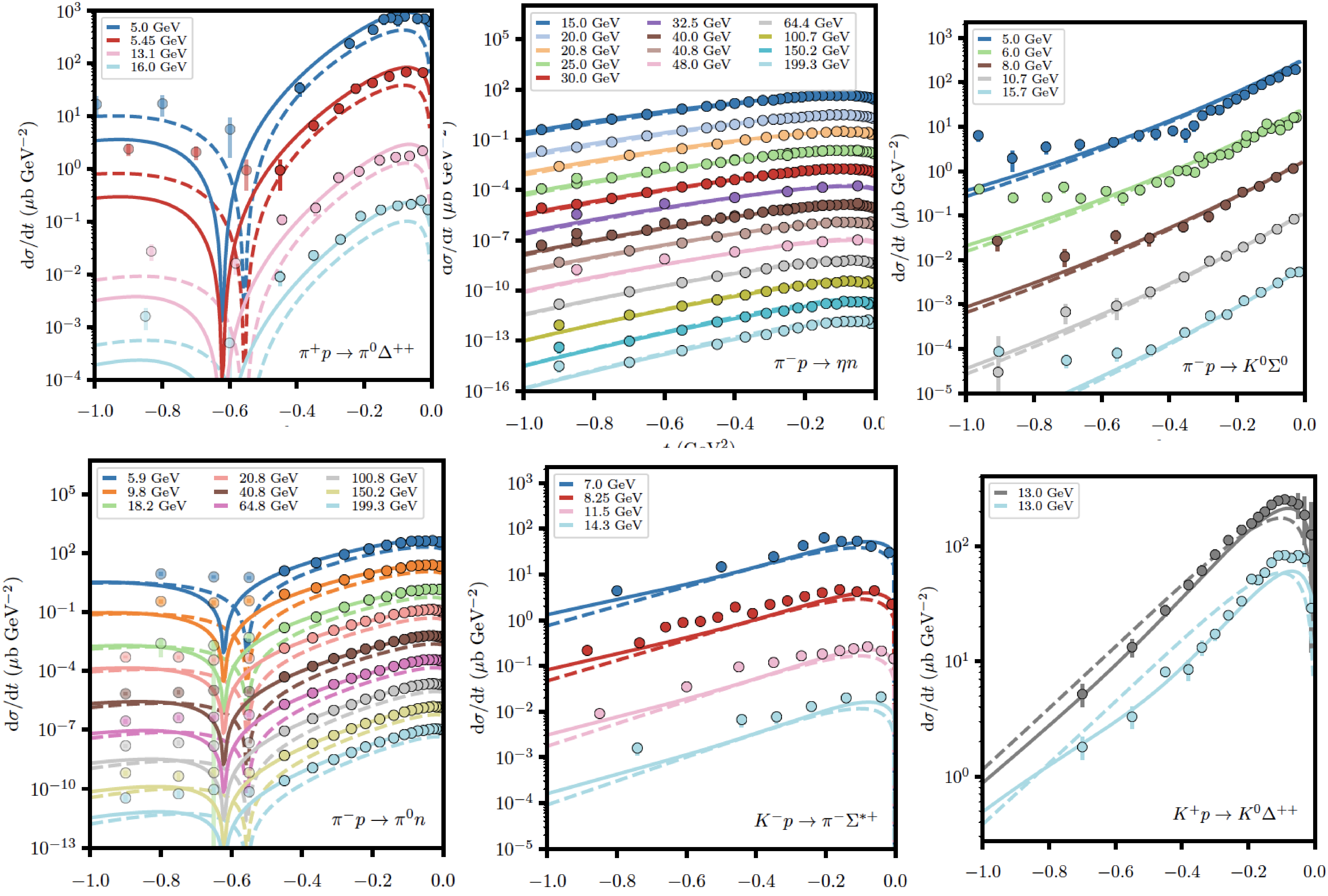
$$\mathcal{F}_e(s,t) = -\frac{\zeta_e \pi \alpha_e^1}{\Gamma(\alpha_e(t)-l_e+1)}\frac{1+\zeta_e e^{-i\pi\alpha_e(t)}}{2\sin\pi\alpha_e(t)}\left(\frac{s}{s_0}\right)^{\alpha_e(t)}$$

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

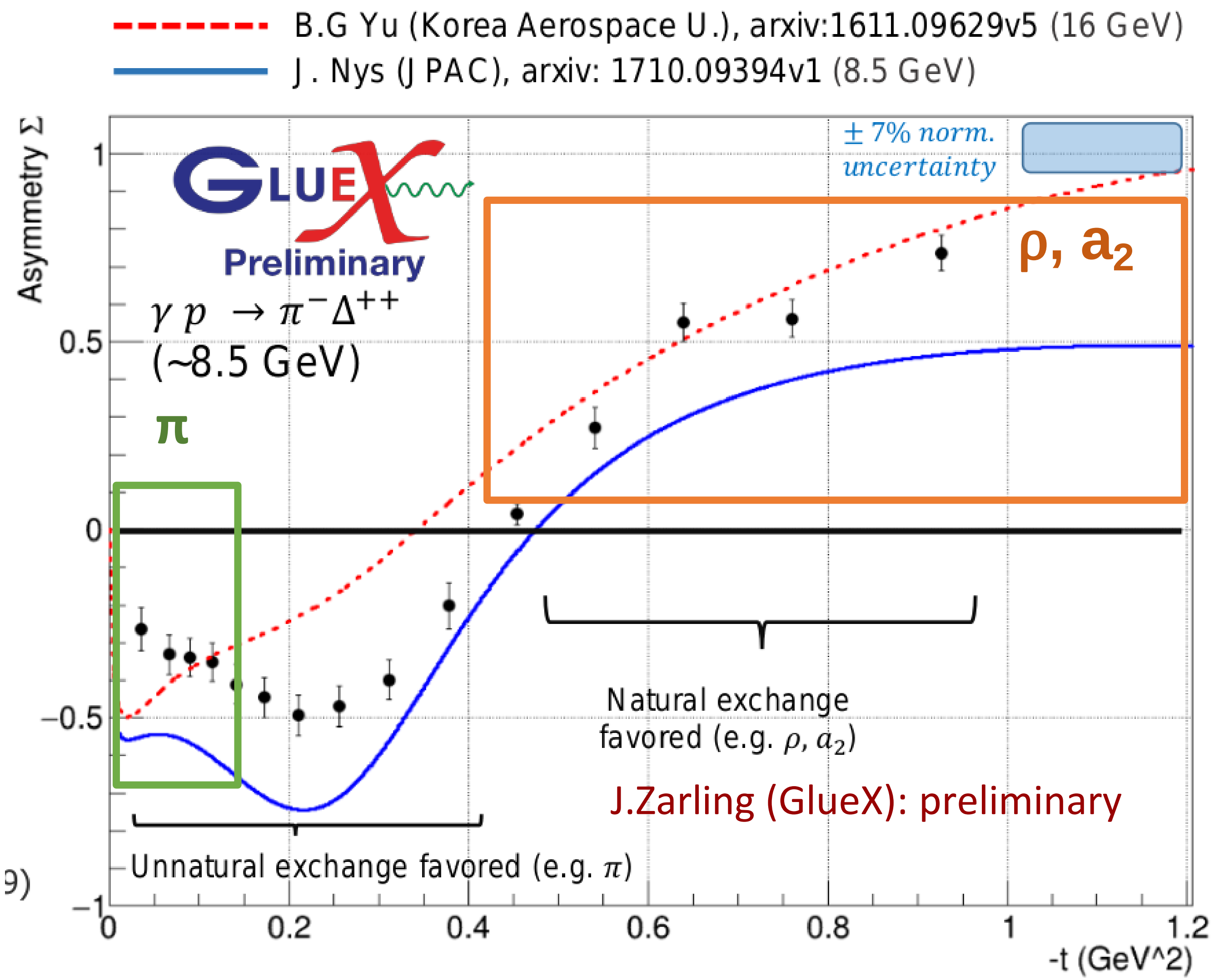
$$\mathcal{F}_e(s,t) \underset{t\to m_e^2}{\longrightarrow} \frac{(s/s_0)^{J_e}}{m_e^2-t}.$$

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

Global Regge pole analysis

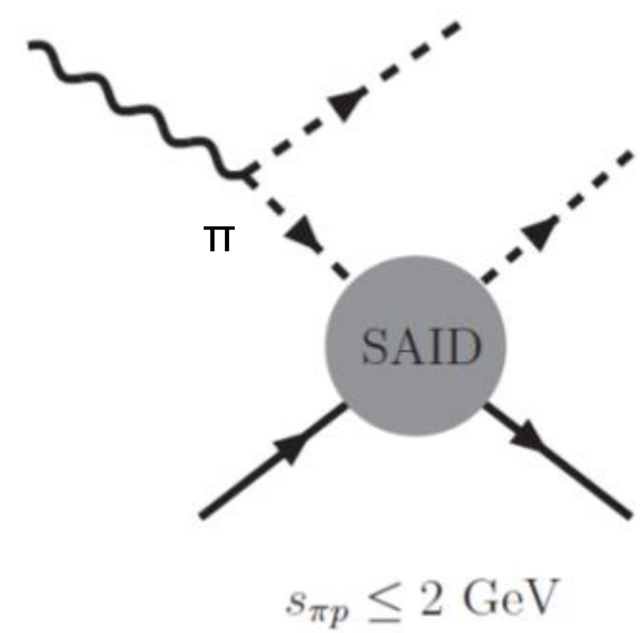


πΔ photoproduction



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

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

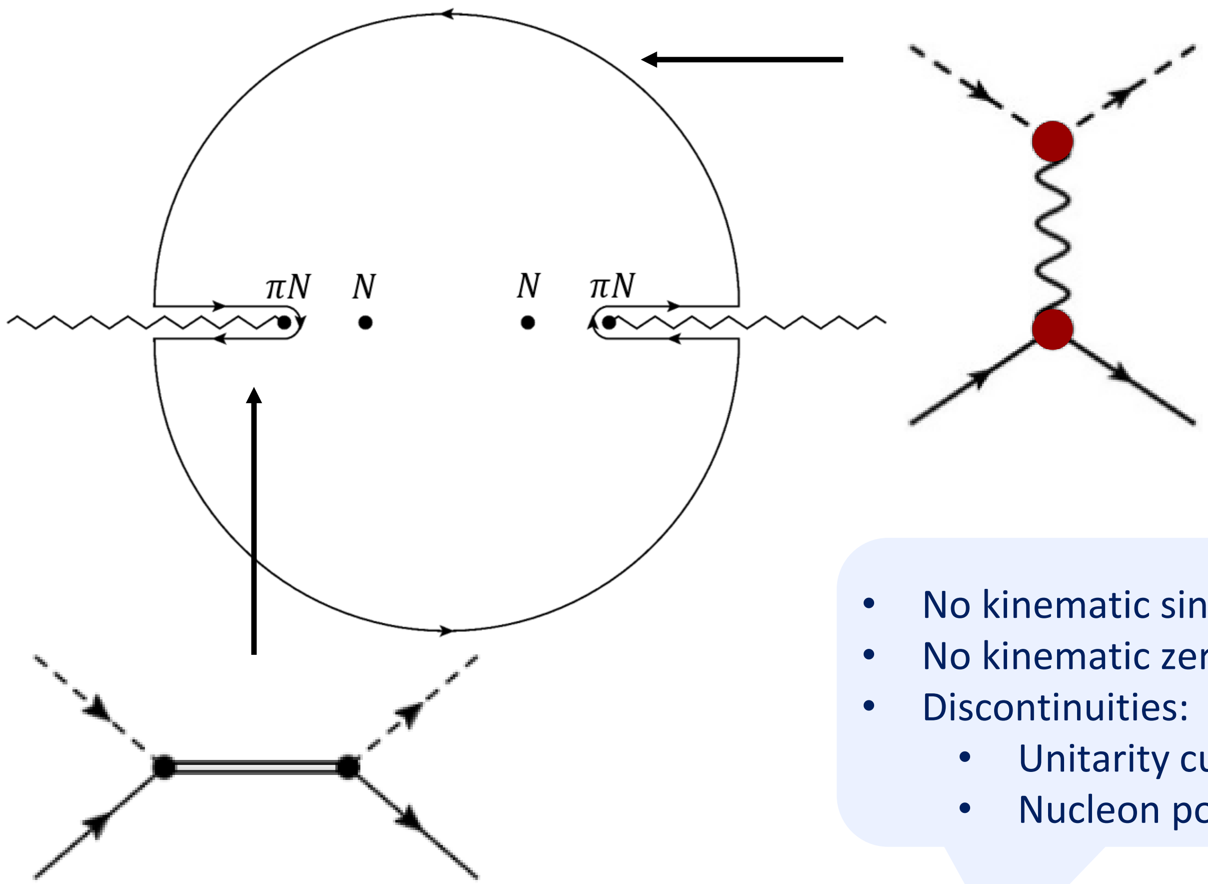


Łukasz Bibrzycki et al. (Cracow,JPAC)

Comparison to GlueX data

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

Finite Energy Sum Rules

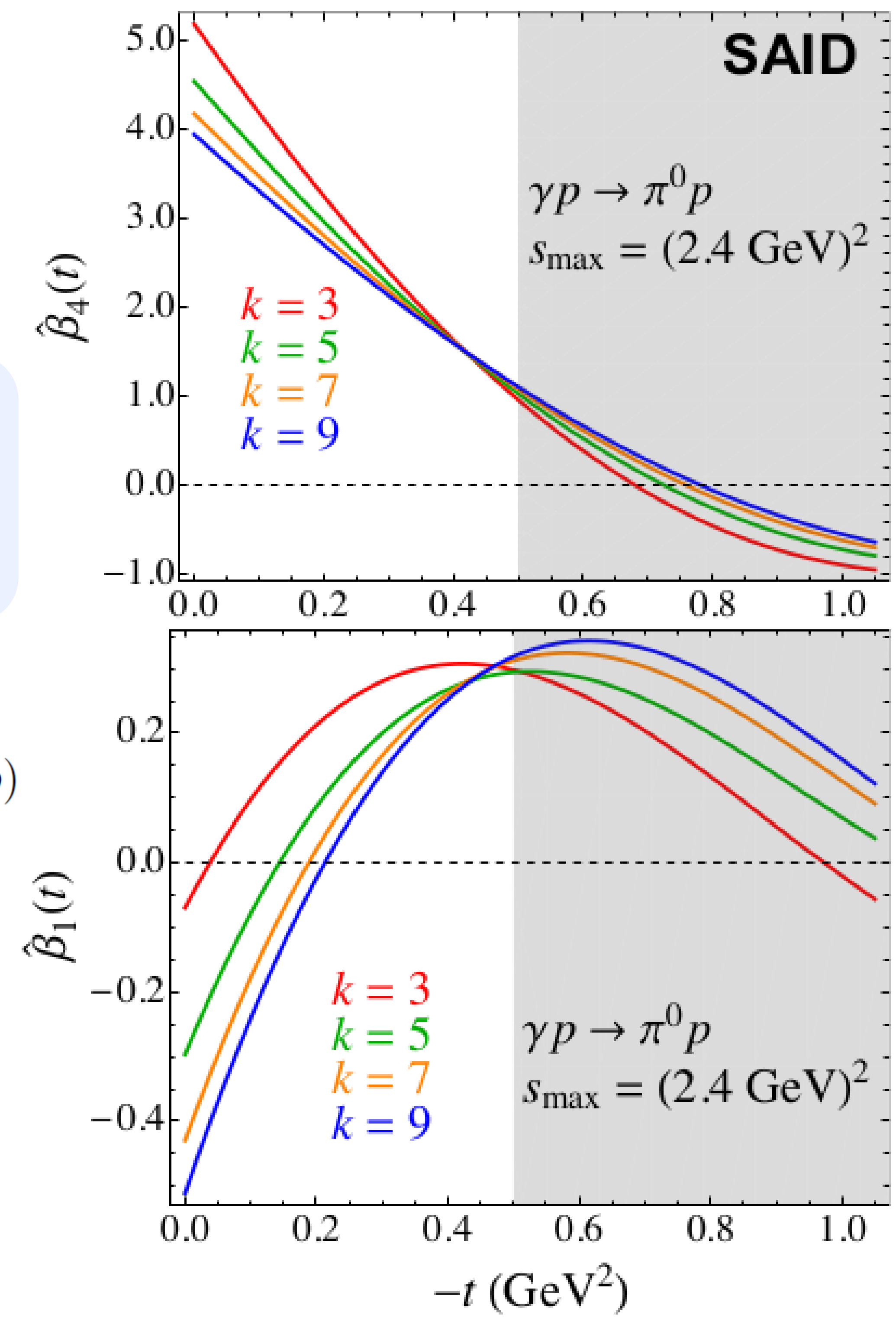


- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

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

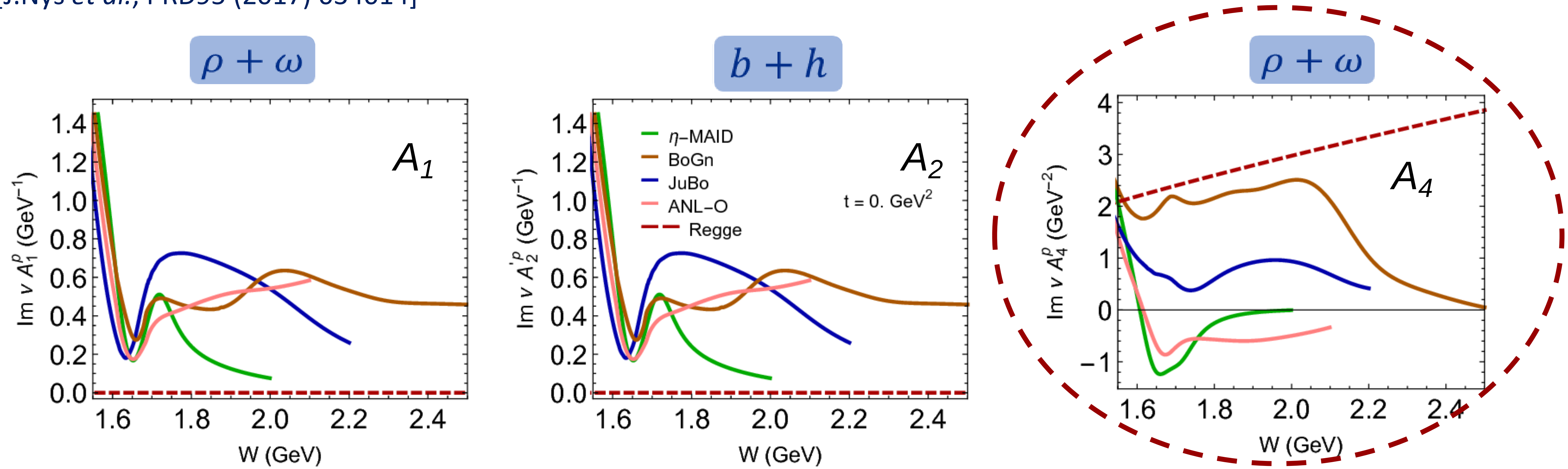
$$\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu = \beta_i(t)\frac{\Lambda^{\alpha(t)+k}}{\alpha(t)+k}$$

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



Constraining the resonance spectrum

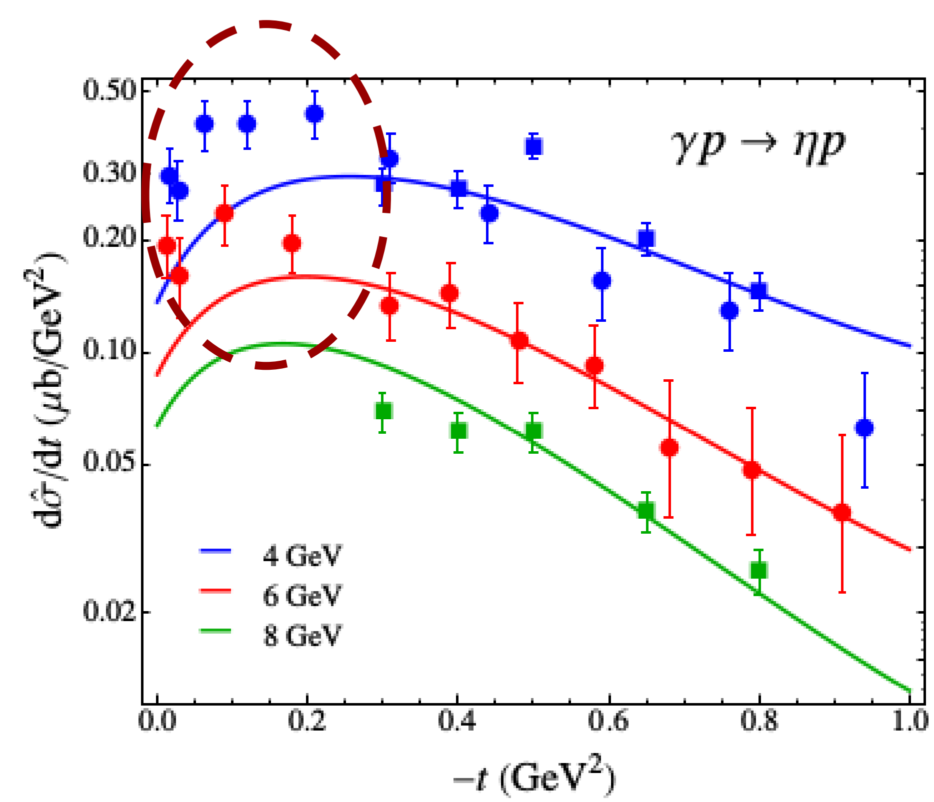
[J.Nys *et al.*, PRD95 (2017) 034014]



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!



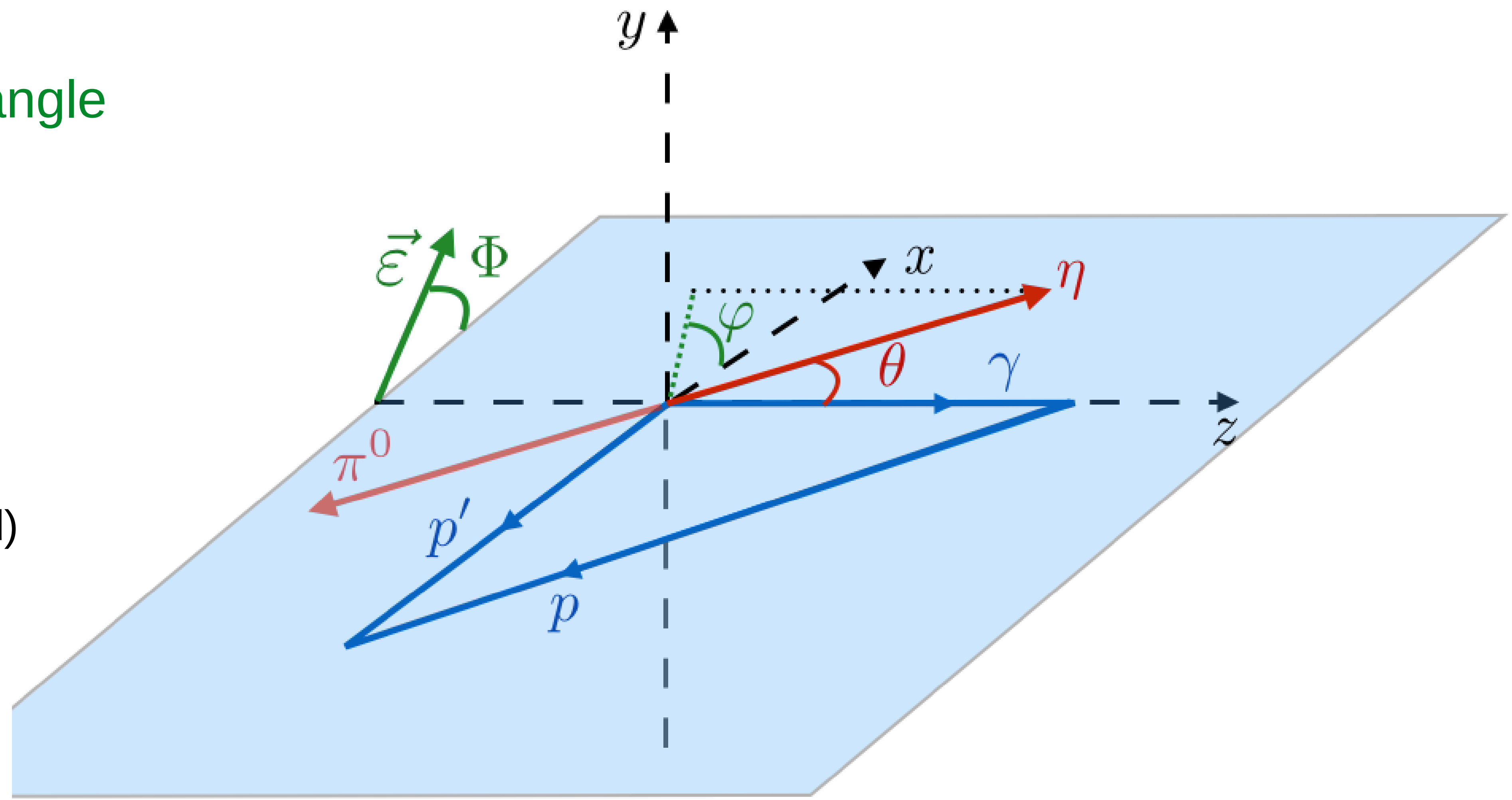
Moment analysis

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

polarization angle

η decay angles

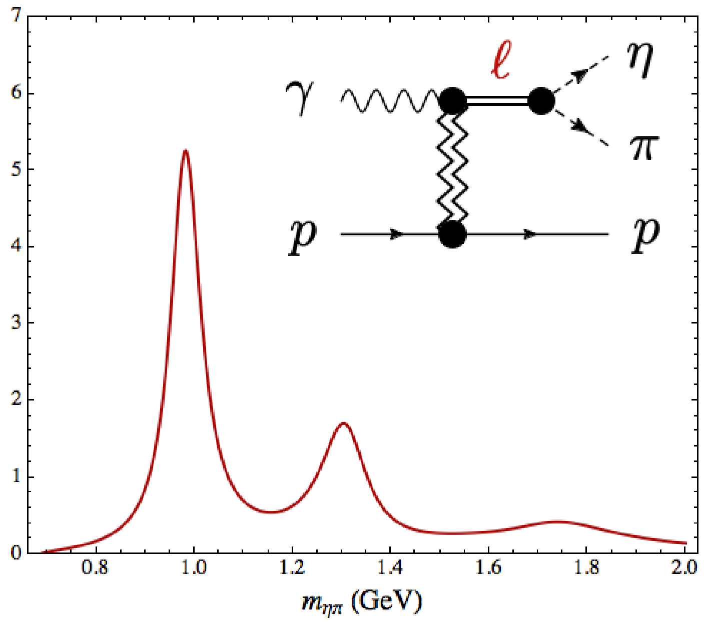
$\Omega = (\theta, \phi)$



Beam energy (fixed)

momentum transfer (integrated)

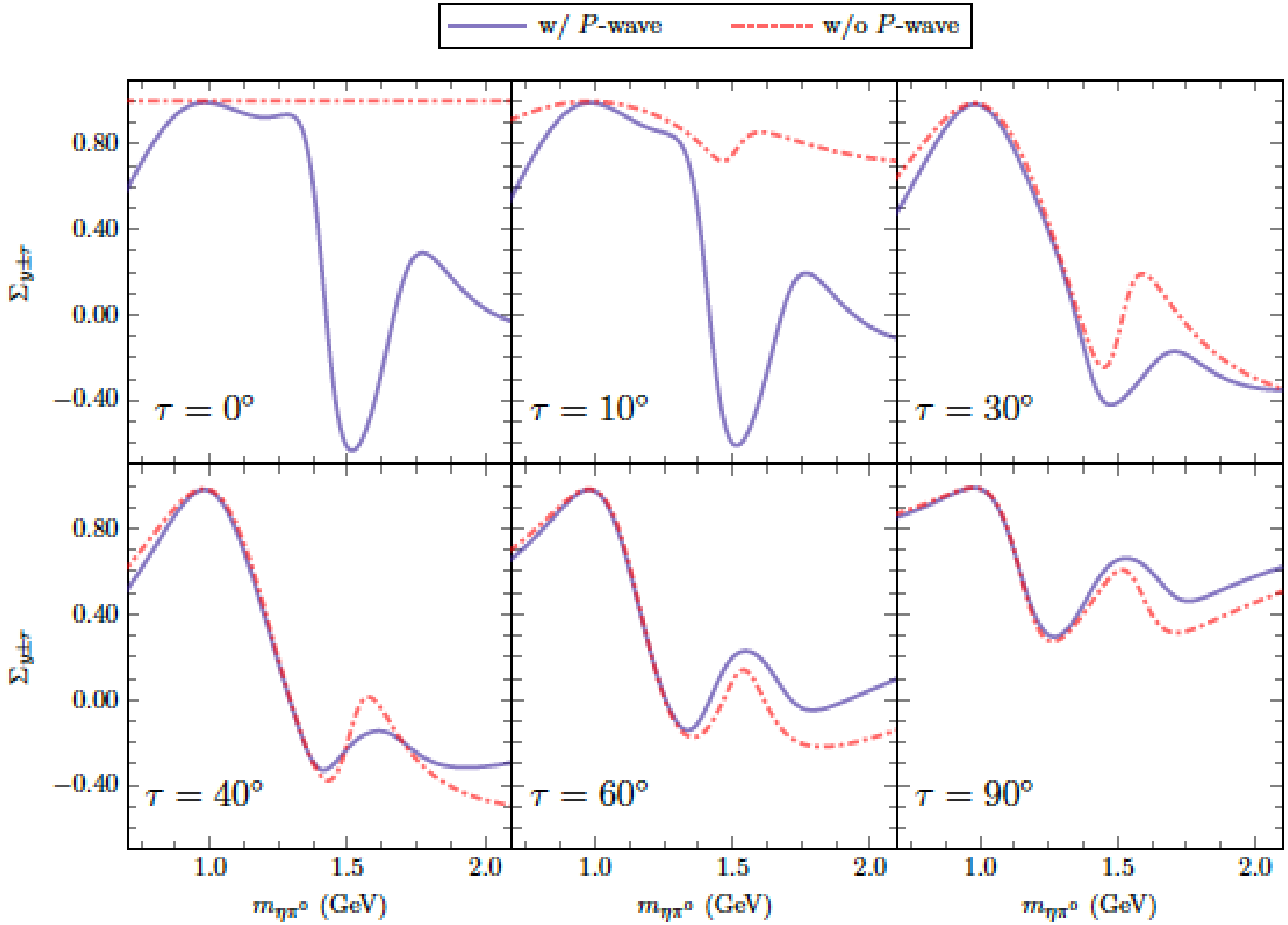
$\eta\pi$ invariant mass (binned)

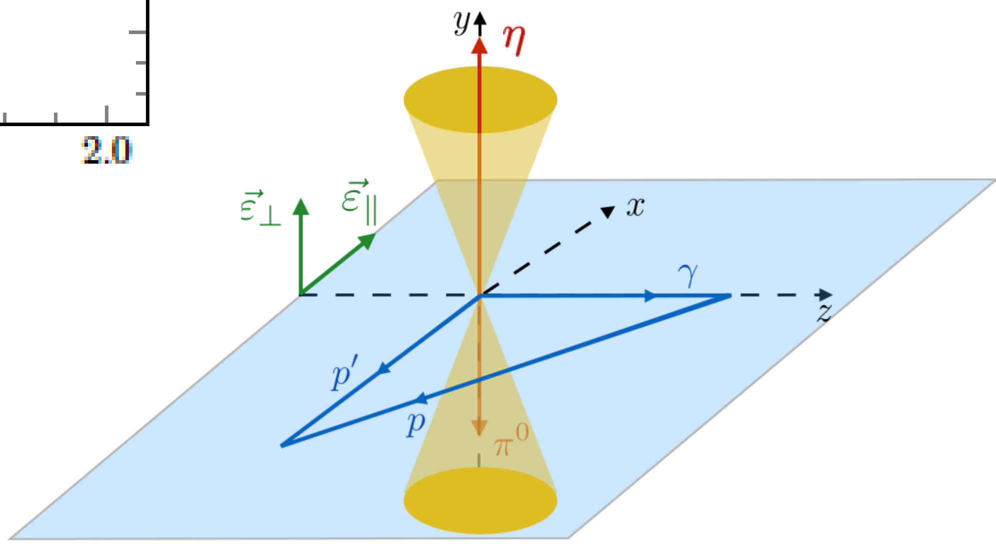


$$R = \{\underbrace{a_0(980)}_{S_0^{(+)}}, \underbrace{\pi_1(1600)}_{P_{0,1}^{(+)}}, \underbrace{a_2(1320), a_2(1700)}_{D_{0,1,2}^{(+)}}\}$$

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

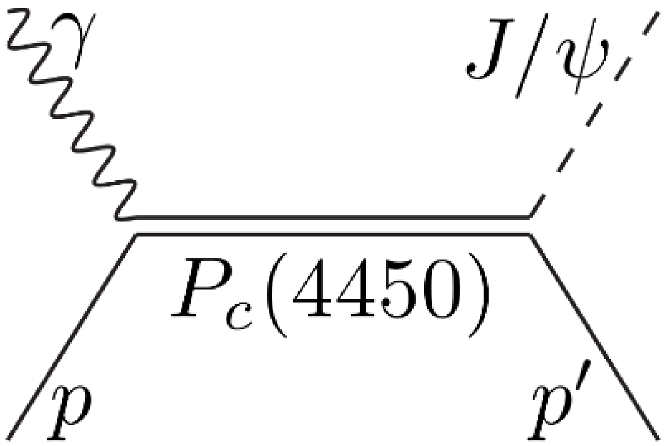
Beam asymmetry





Pentaquark photoproduction

To exclude any rescattering mechanism, we propose to search the $P_c(4450)$ state in photoproduction.



Hadronic vertex EM vertex

$$\langle \lambda_\psi \lambda_{p'} | T_r | \lambda_\gamma \lambda_p \rangle = \frac{\langle \lambda_\psi \lambda_{p'} | T_{\text{dec}} | \lambda_R \rangle \langle \lambda_R | T_{\text{em}}^\dagger | \lambda_\gamma \lambda_p \rangle}{M_r^2 - W^2 - i\Gamma_r M_r}$$

Hadronic part

- 3 independent helicity couplings, $\rightarrow$ approx. equal, $g_{\lambda_\psi, \lambda_{p'}} \sim g$
- g extracted from total width and (unknown) branching ratio

Vector meson dominance relates the radiative width to the hadronic width

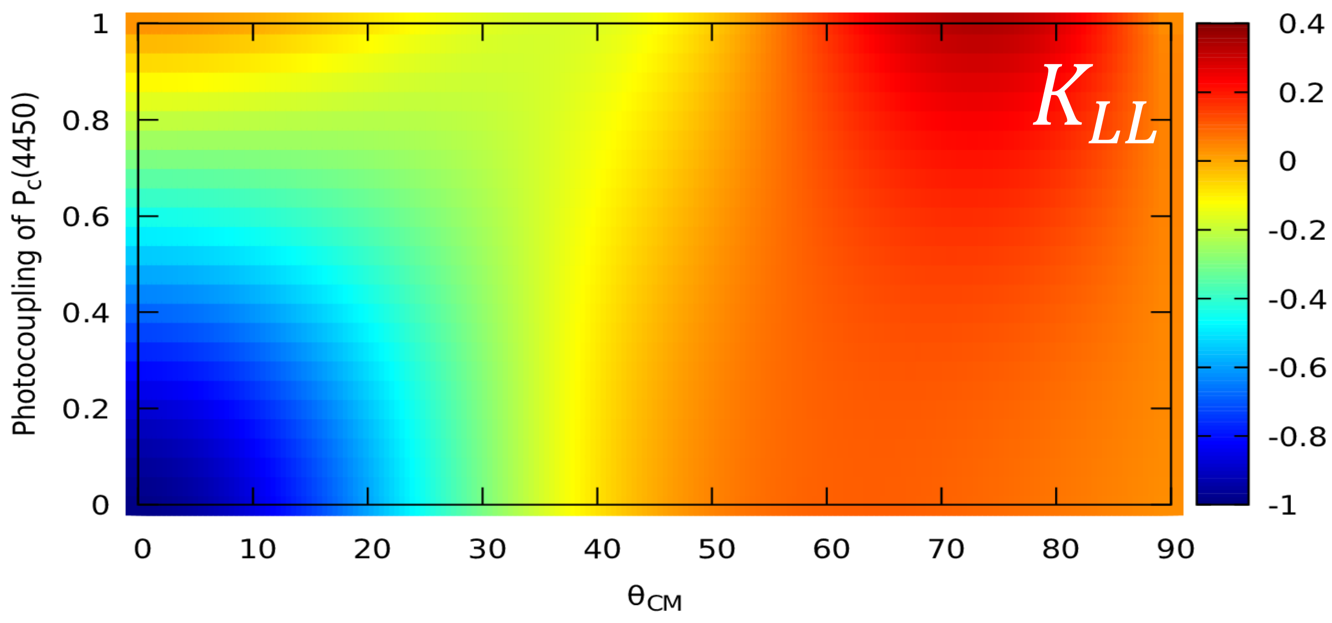
$$\Gamma_\gamma = 4\pi\alpha \, \Gamma_{\psi p} \left(\frac{f_\psi}{M_\psi} \right)^2 \left(\frac{\bar{p}_i}{\bar{p}_f} \right)^{2\ell+1} \times \frac{4}{6}$$

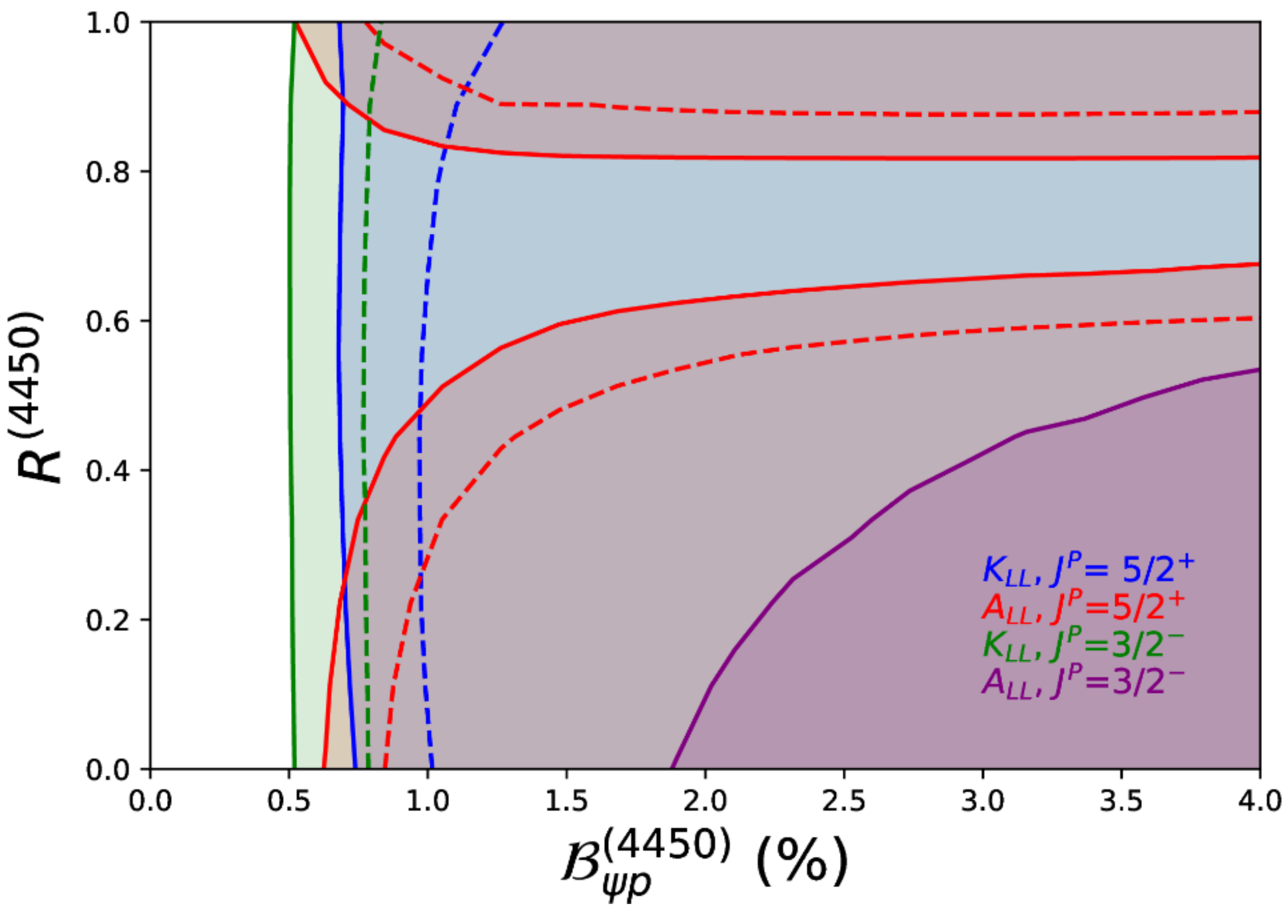
Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Pentaquark photoproduction

One can take advantage of the polarized beam at JLab
High intensity beam in SBS (Hall A) looks promising
Need polarized target (A_{LL}) or polarization of recoiling proton (K_{LL})

$$\mathrm{A(K)_{LL}} = \frac{1}{2}\left[\frac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)} - \frac{d\sigma(-+) - d\sigma(--)}{d\sigma(-+) + d\sigma(--)}\right]$$



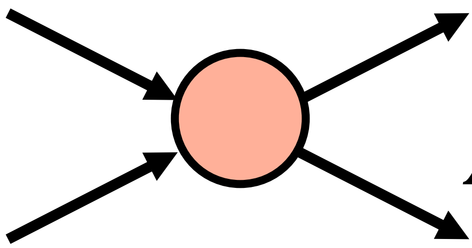


Sensitivity of Polarization observables
to 5q parameters at SBS

Fanelli, Pentchev, Wojtsekhowski, LoI12-18-001
D. Winney, *et al.* (JPAC), Phys.Rev. D100 (2019) 034019

3-to-3 particle scattering

Amplitudes can be reconstructed from unitarity (analyticity)
The problem is how to implement unitarity in multiparticle reactions



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

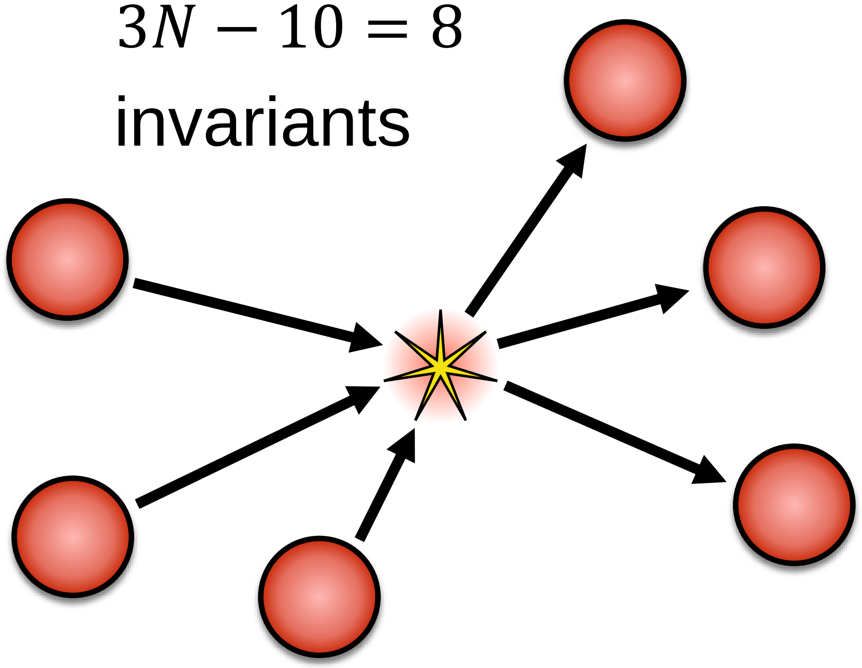
- 2-to-2 partial waves diagonalize unitarity

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

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

$3N - 10 = 8$

invariants

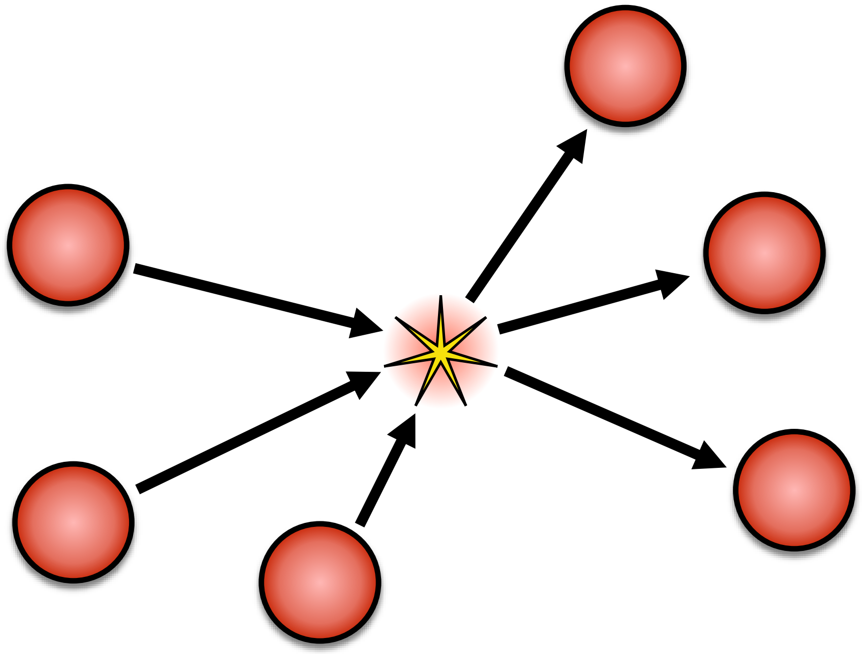


$$A(s, s_{12}, t_{12'}, \cdots) \rightarrow A^{J}_{\Lambda,\Lambda'}(s_{12}, s, s_{1'2'})$$

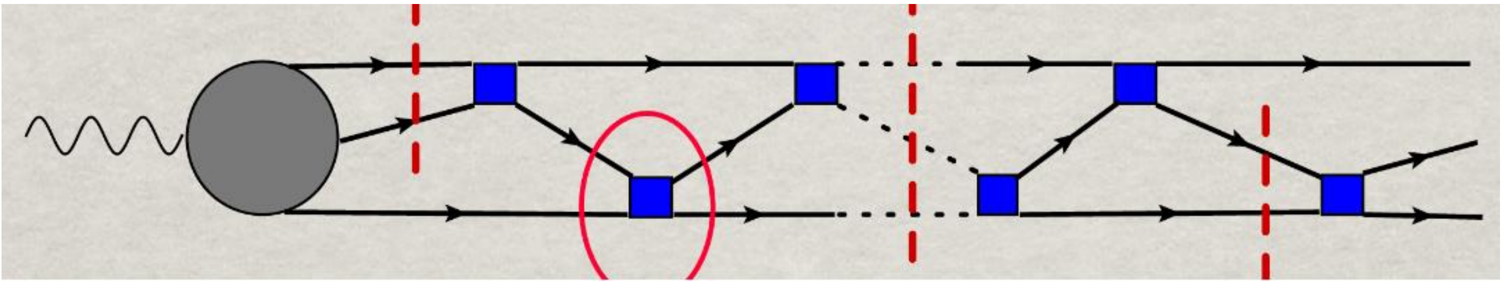
- Helicity partial waves represent (quasi) two-body isobar/dimer spectator
- Difference in various approaches has to do with how the K-matrix is introduced (symmetrization)
- JPAC : Proof of equivalence (on the real axis)

A.Jackura et al., Eur.Phys.J. C79 (2019) no.1, 56
A.Jackura et al., Phys.Rev. D100 (2019), 034508

3-to-3 particle scattering



Divide et impera!



- Solve Khuri-Treiman once and for all to describe the isobar lineshape deformed by 3-body rescattering
- Factorization ansatz: 3-body unitarity simplifies to an algebraic equation as in 2-body scattering

$$\widehat{\mathcal{R}}(s) - \widehat{\mathcal{R}}^\dagger(s) = i\,\widehat{\mathcal{R}}^\dagger(s)\Sigma(s)\,\widehat{\mathcal{R}}(s),$$

M. Mikhasenko et al., JHEP 1908 (2019), 080

Resonance parameter determination

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

$a_2(1700)$ 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).

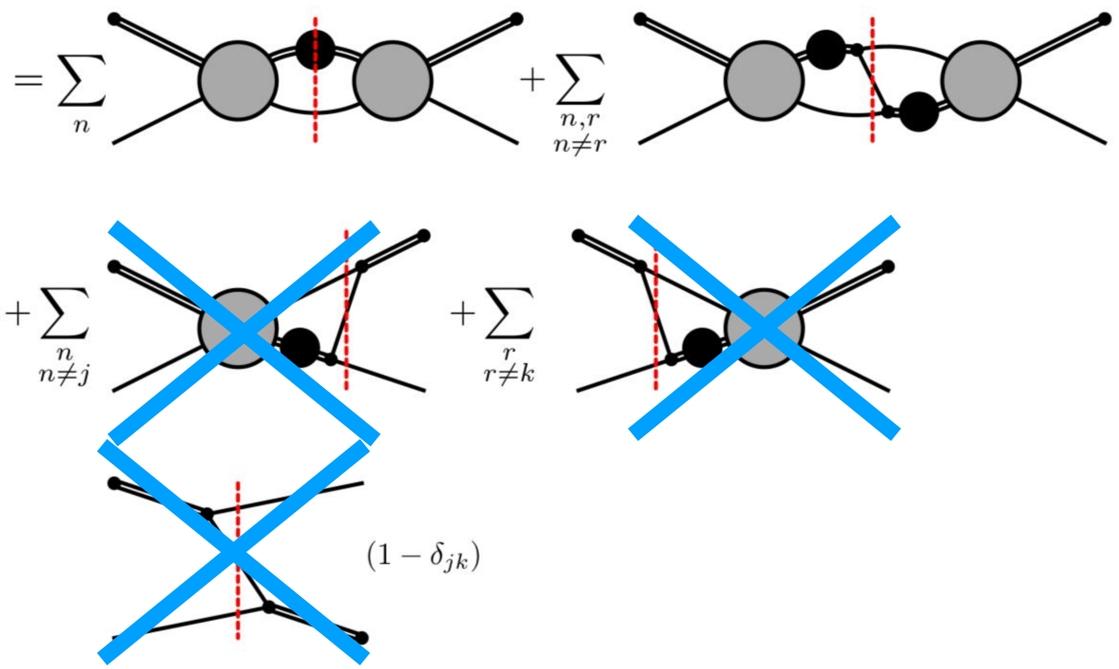
$a_1(1260)$ MASS

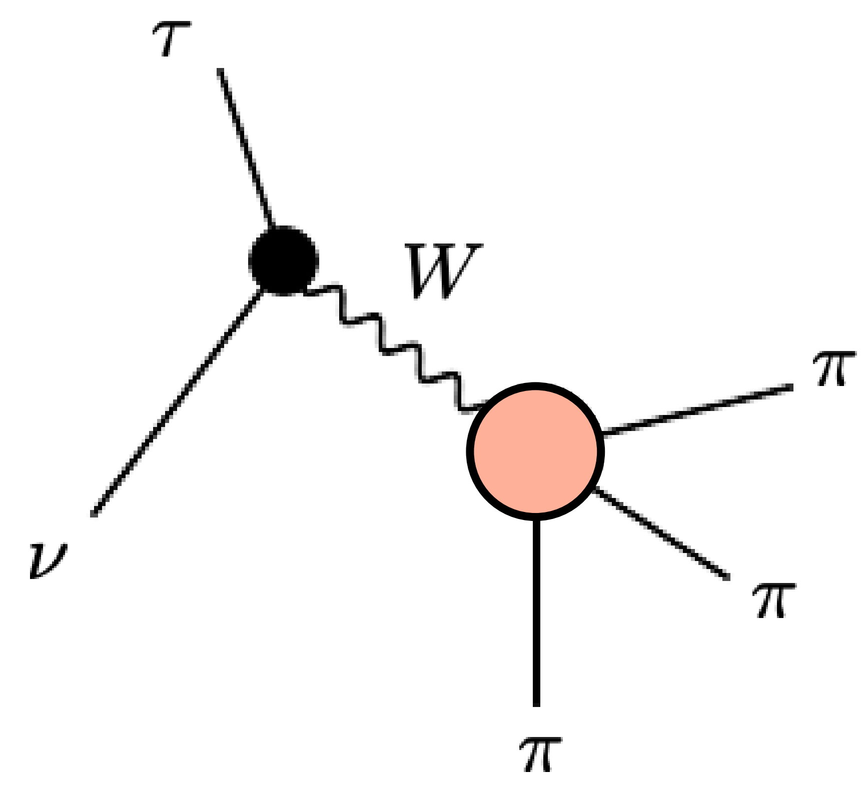
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1230 ±40 OUR ESTIMATE					
1209^{+12}_{-28}	46M	[1] AGHASYAN	18B	COMP	190 $\pi^- p \to \pi^-\pi^+\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1195.05± 1.05± 6.33	894k	AAIJ	18AI	LHCB	$D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$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

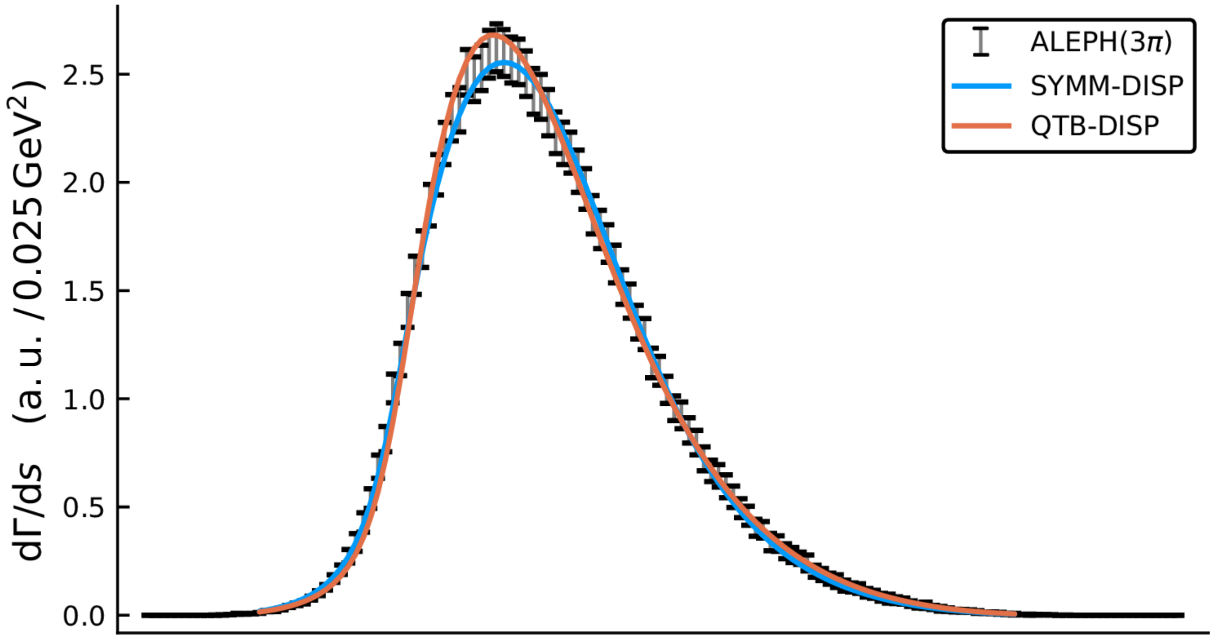
$a_1(1260)$

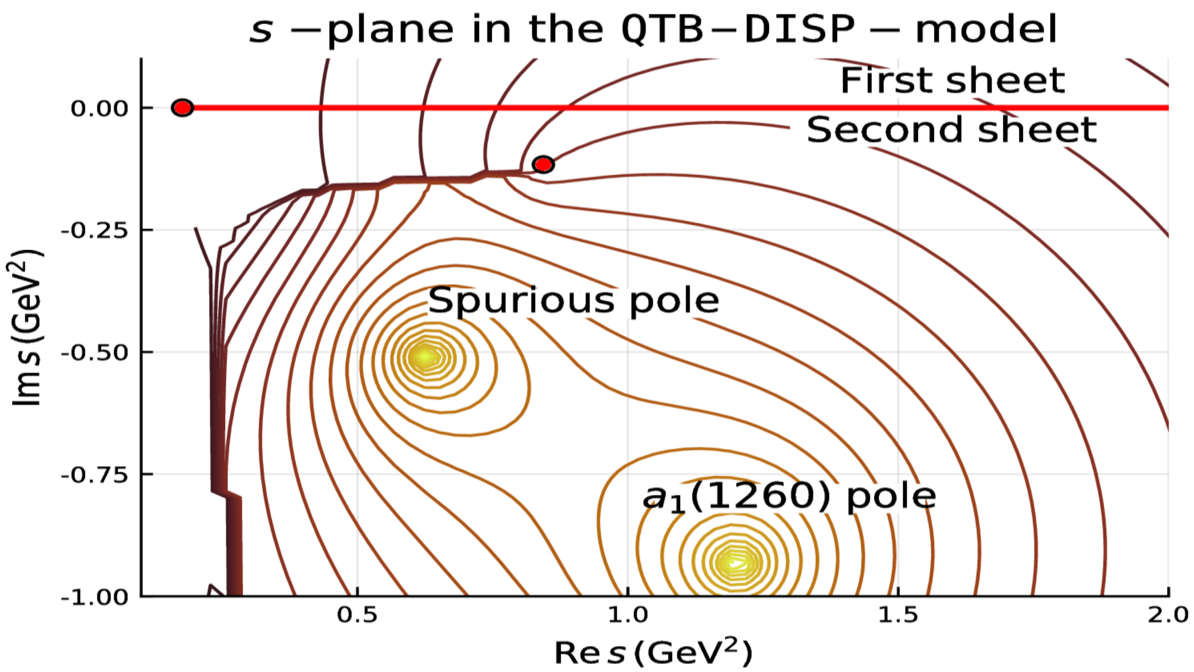
- Quasi-two-body approximation





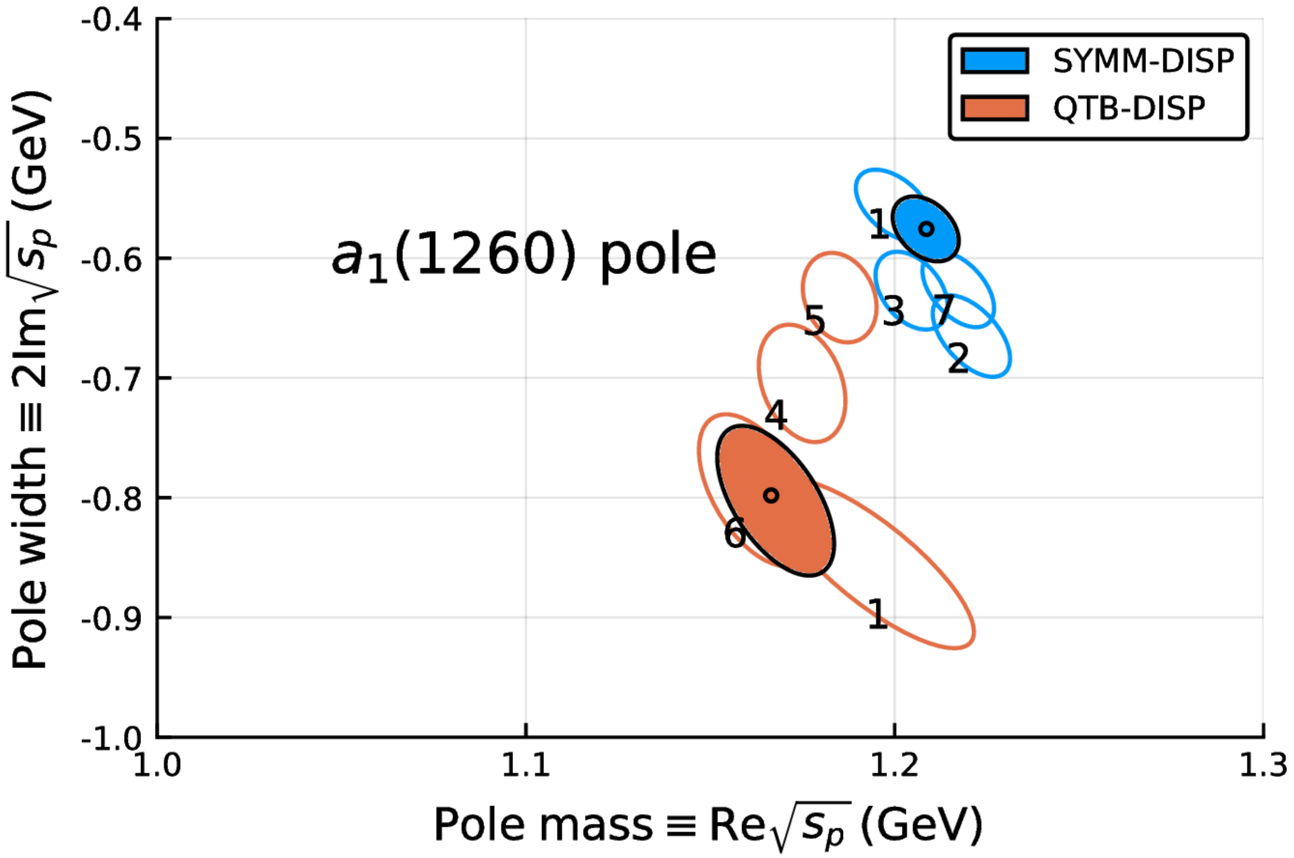
M. Mikhasenko et al. [JPAC],
Phys. Rev. **D98**, 096021 (2018)





$a_1(1260)$

#	Fit studies	QTB-DISP $\chi^2/\text{n.d.f.}$	SYMM-DISP $\chi^2/\text{n.d.f.}$
1	$s < 2\ \text{GeV}^2$	53/62	81/62
2	$R' = 3\ \text{GeV}^{-1}$		18/100
3	$m'_\rho = m_\rho + 10\ \text{MeV}$		83/100
4	$m'_\rho = m_\rho - 10\ \text{MeV}$	37/100	
5	$m'_\rho = m_\rho - 20\ \text{MeV}$	30/100	
6	$\Gamma'_\rho = \Gamma_\rho + 5\ \text{MeV}$	66/100	
7	$\Gamma'_\rho = \Gamma_\rho - 30\ \text{MeV}$		36/100



$$m_p^{(a_1(1260))} = (1209 \pm 4^{+12}_{-9})\ \text{MeV}, \quad \Gamma_p^{(a_1(1260))} = (576 \pm 11^{+80}_{-20})\ \text{MeV}$$

Glueball candidates on the horizon

BESIII

J/ψ annihilates into gluons

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

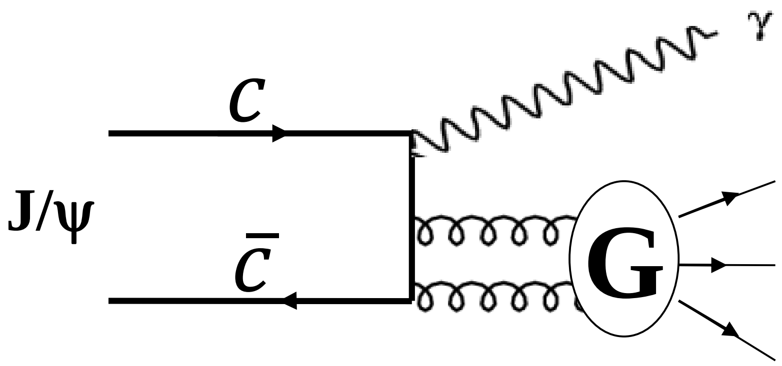
- $B(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9}) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.0 \pm 1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega) = (3.1 \pm 1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to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

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

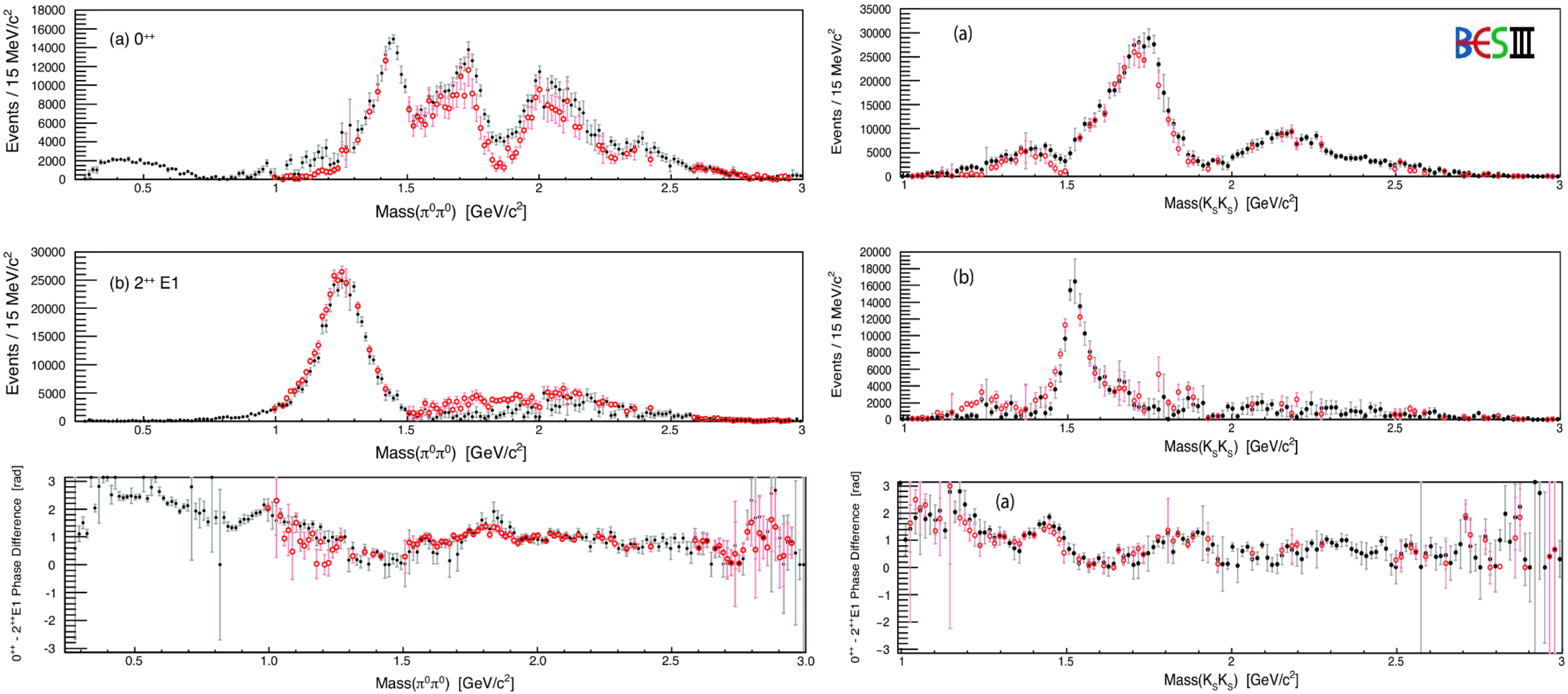
- $B(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (5.60^{+0.62}_{-0.65}{}^{+2.37}_{-2.07}) \times 10^{-5}$
- $B(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$
- $B(J/\psi \to \gamma f_2(2340) \to \gamma K_S^0 K_S^0) = (5.54^{+0.34}_{-0.40}{}^{+3.28}_{-1.49})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

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

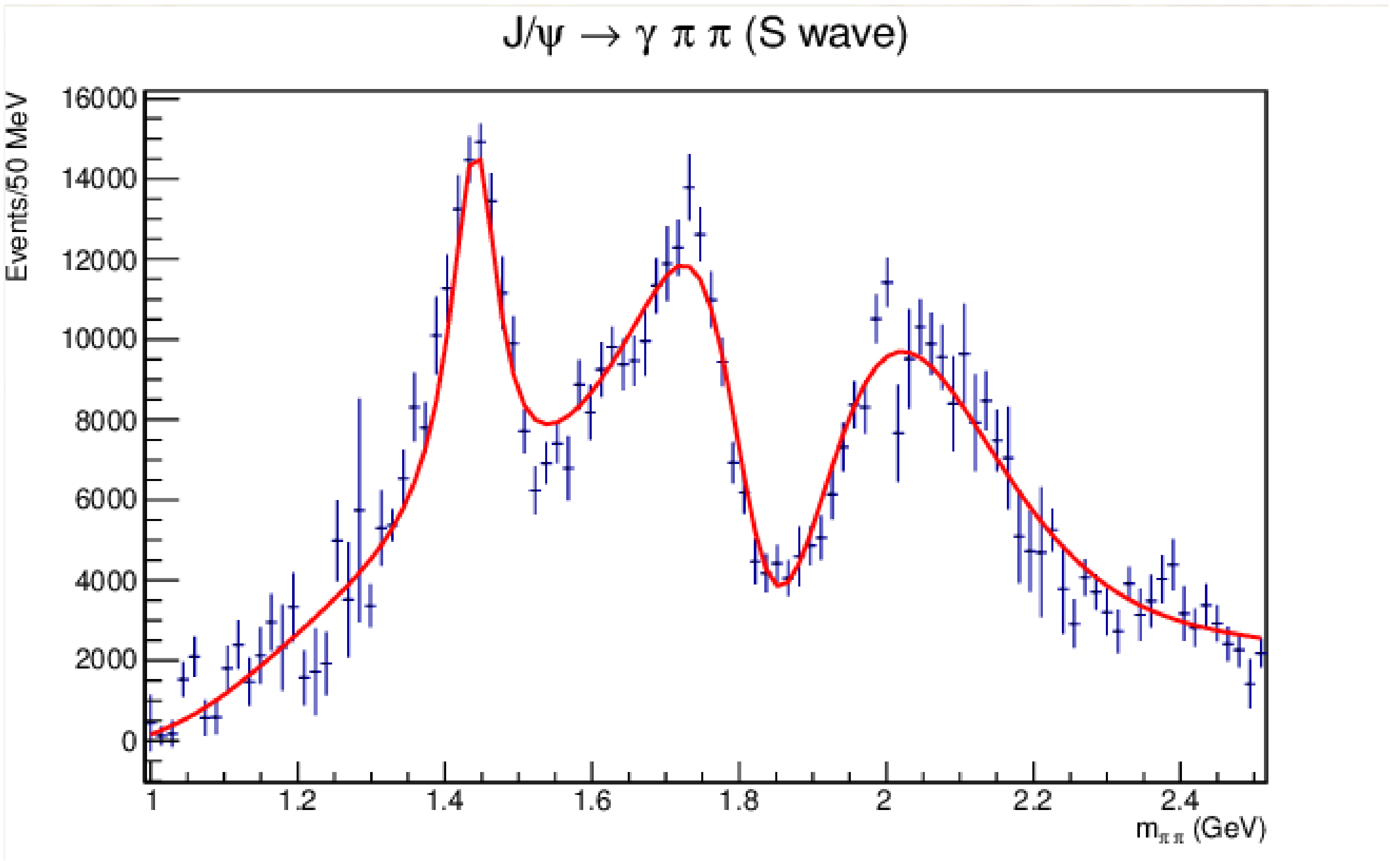
$J/\psi \to \gamma\, \pi^0\pi^0$ and $\to \gamma\, K_S^0 K_S^0$

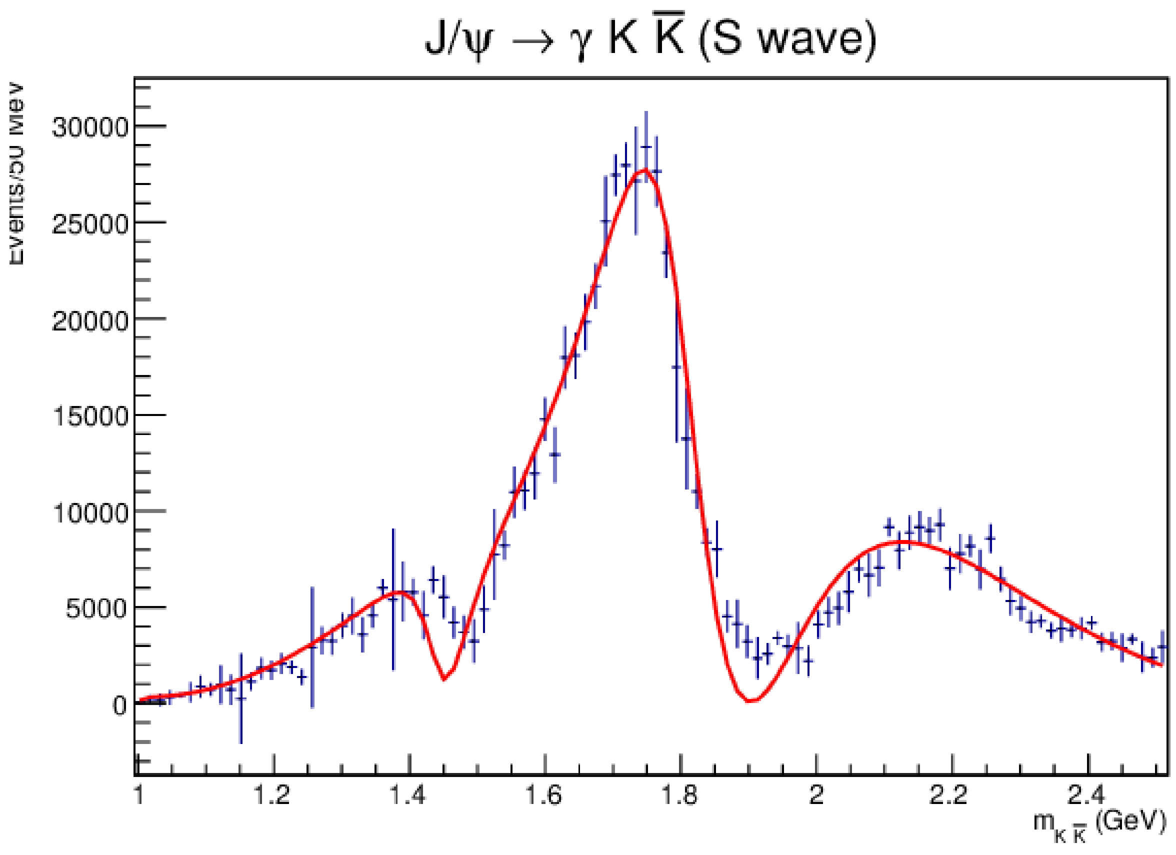


This is a gluon-rich process, expected to be one of th
golden channels for the search of the scalar glueball

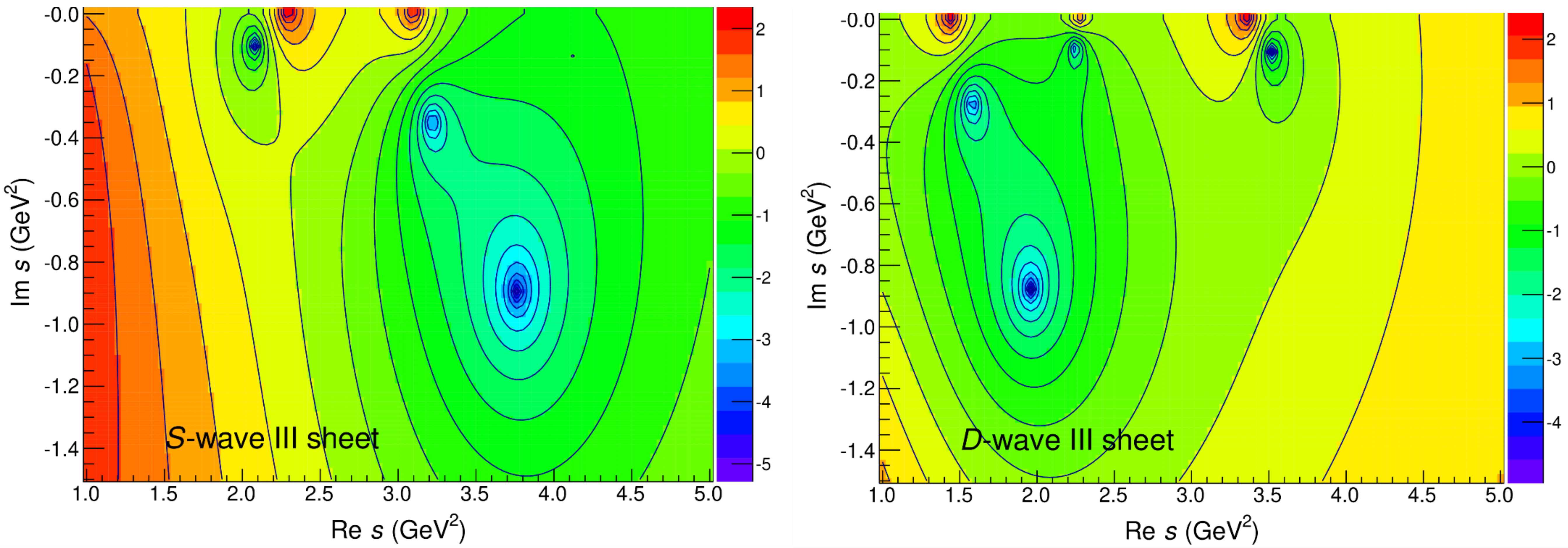


Fit results (preliminary)





Pole positions (preliminary)



$$M(f_0(1500)) = 1460\ \text{MeV}$$
$$M(f_0(1710)) = 1800\ \text{MeV}$$
$$M(f_0(2020)) = 1970\ \text{MeV}$$

$$\Gamma(f_0(1500)) = 85\ \text{MeV}$$
$$\Gamma(f_0(1710)) = 190\ \text{MeV}$$
$$\Gamma(f_0(2020)) = 490\ \text{MeV}$$

JPAC 2019

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Faculty / Staff

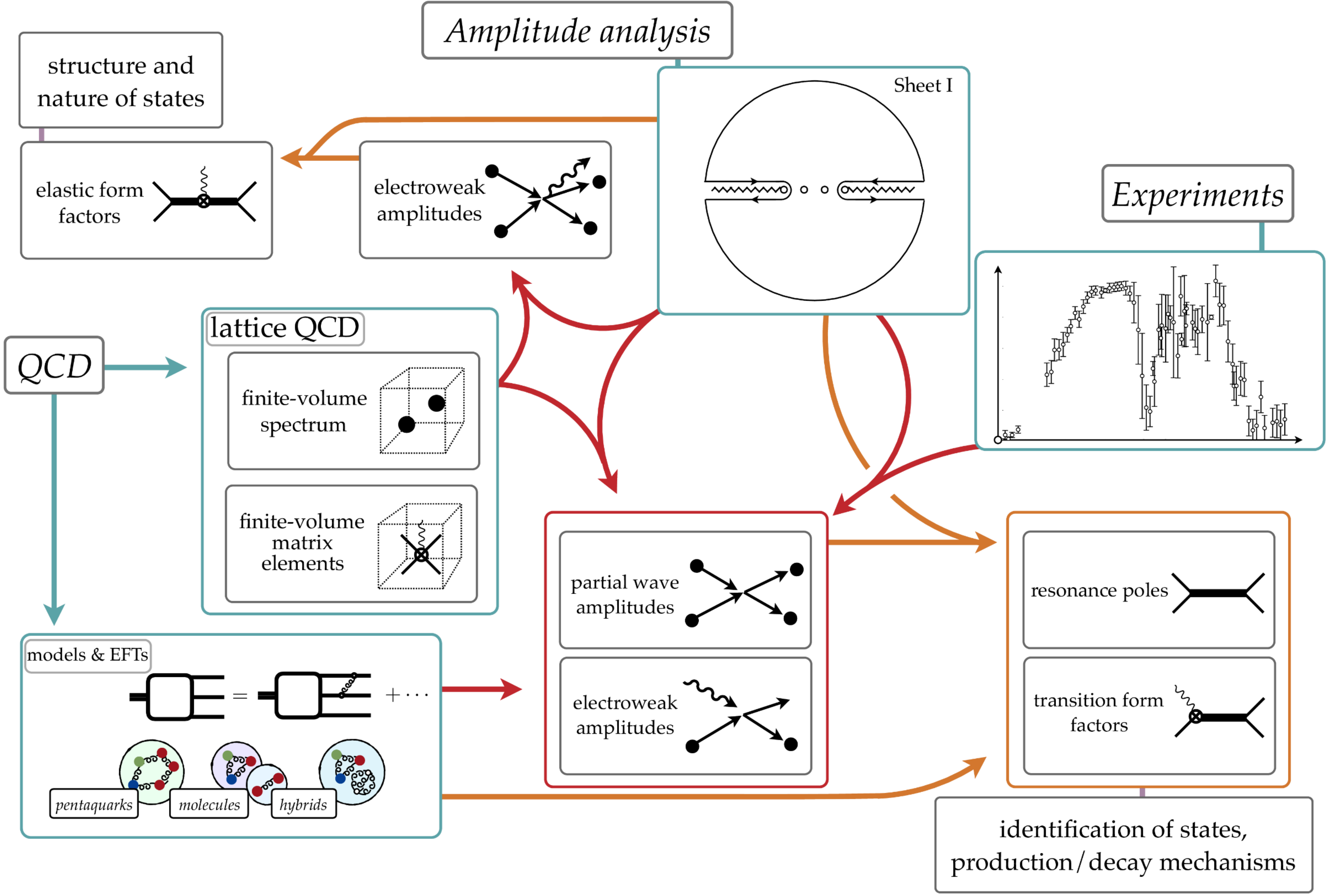
Postdoc

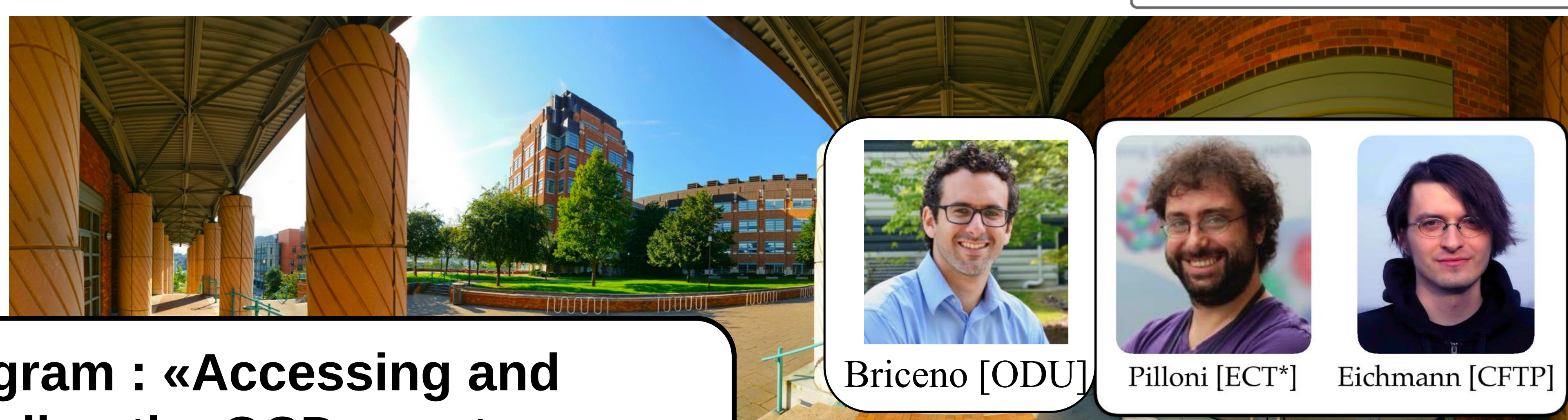
PhD student

[1]JLab/GWU funded

[2]JLab/IU funded

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





INT Program : «Accessing and Understanding the QCD spectrum»
August 17-September 18, 2020

BACKUP

The dual role of gluons

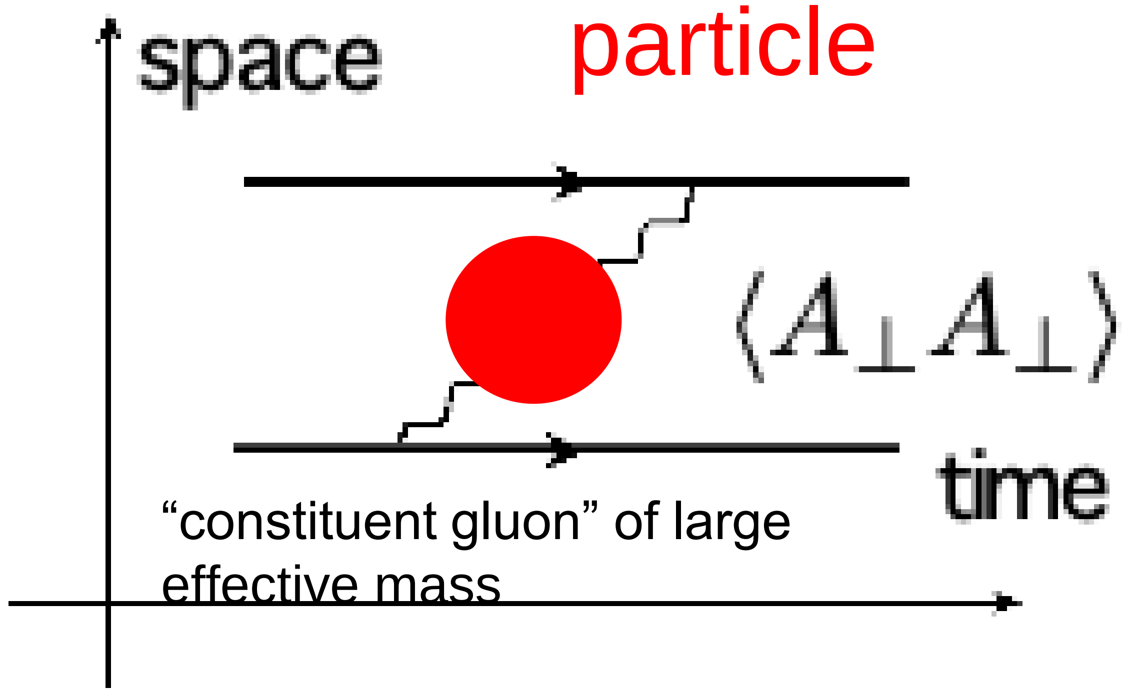
provide confinement → color flux tubes

are confined → constituent gluons

Hybrid mesons,: evidence for constituent gluons ?

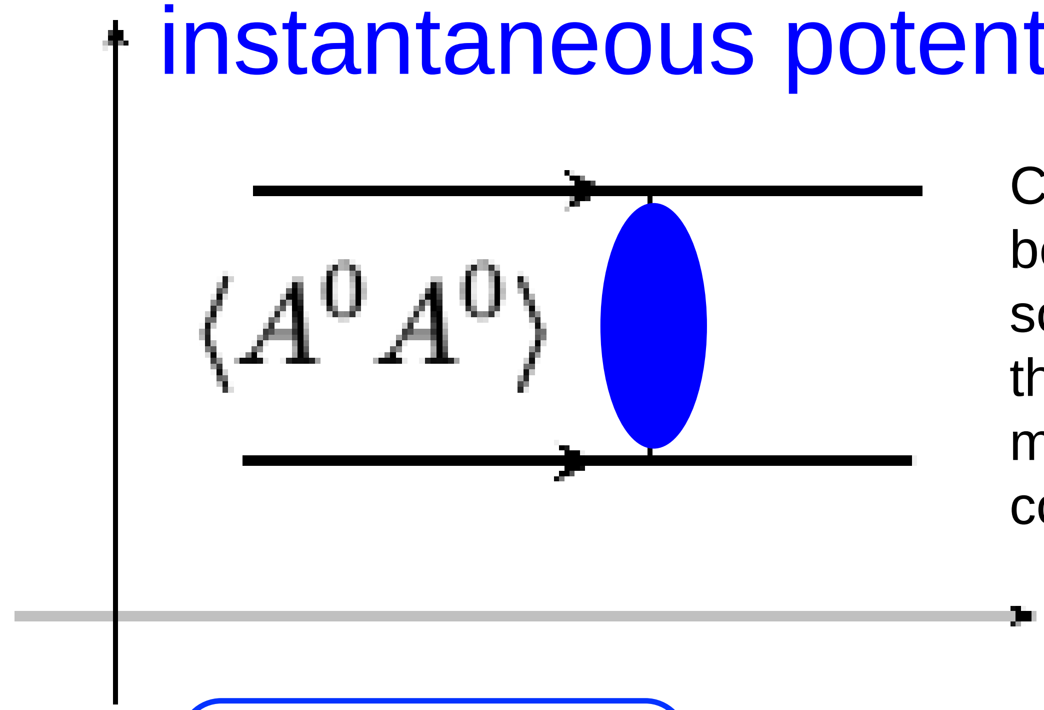
It is necessary to fix physical gauge (e.g. Coulomb)

massive, effective particle



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

long range instantaneous potential



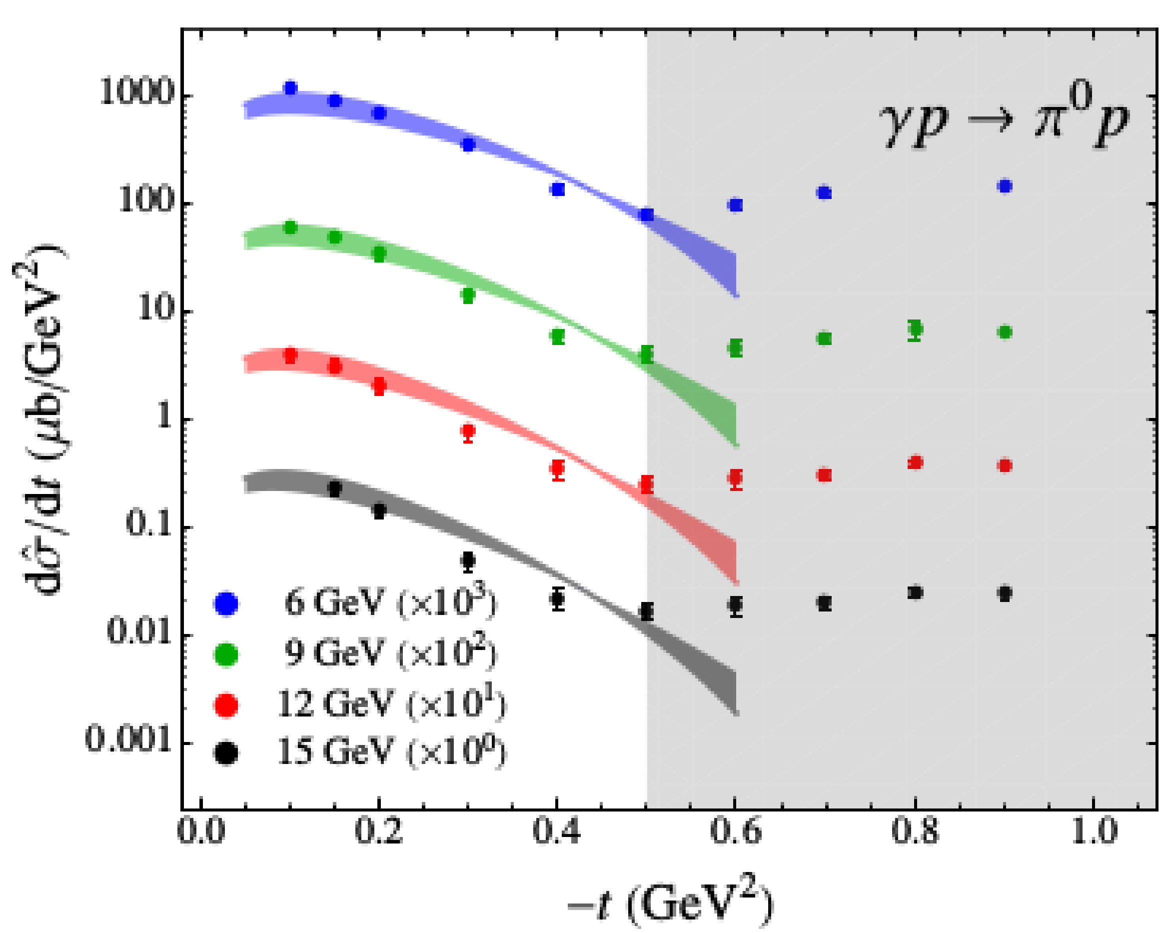
Color interactions between external sources emerges through chromo-magnetic condensate

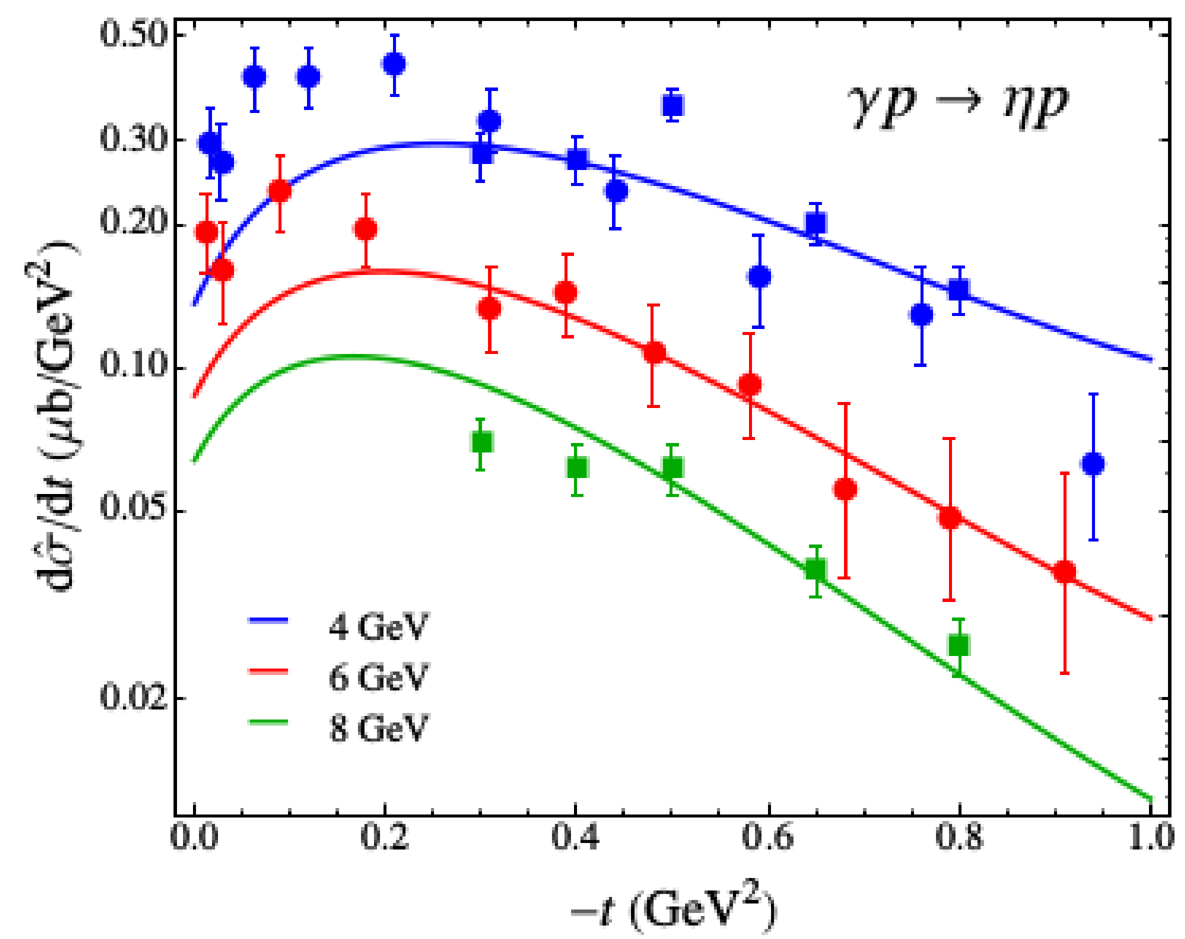
0^{-+} 1^{-+} 2^{-+} 1^{--}

lowest-mass hybrid multiplet

Finite Energy Sum Rules

[V. Mathieu, J.Nys. *et al.* (JPAC) EPL 122, 41001 (2017)]





Combine energy regimes

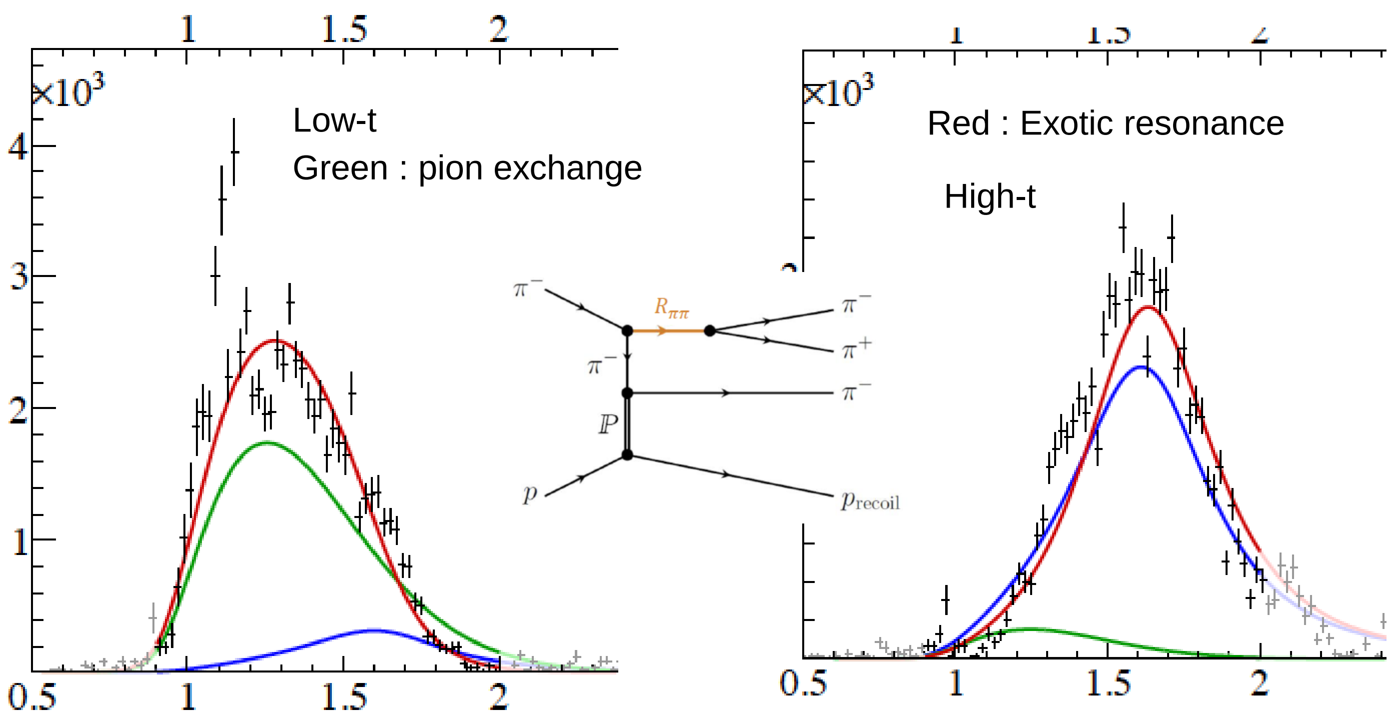
- Low-energy model ((SAID, MAID, Bonn-Gatchina, Julich-Bonn,…)
- Predict high-energy observables

Two applications

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

Plenty of signatures: hybrids

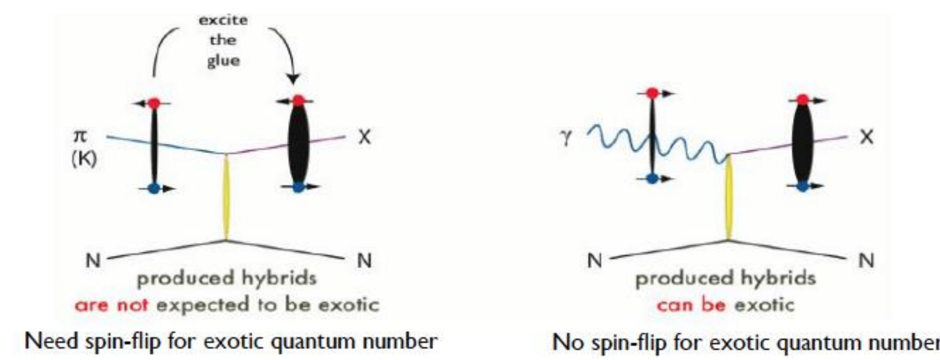
- Exotic $J^{PC}=1^{-+}$ (hybrid) mesons expected (VES, GAMS,E852, COMPASS, and theory)
- In low-t pion diffraction (COMPASS) exotic wave production compatible with one pion exchange (but not at high-t)

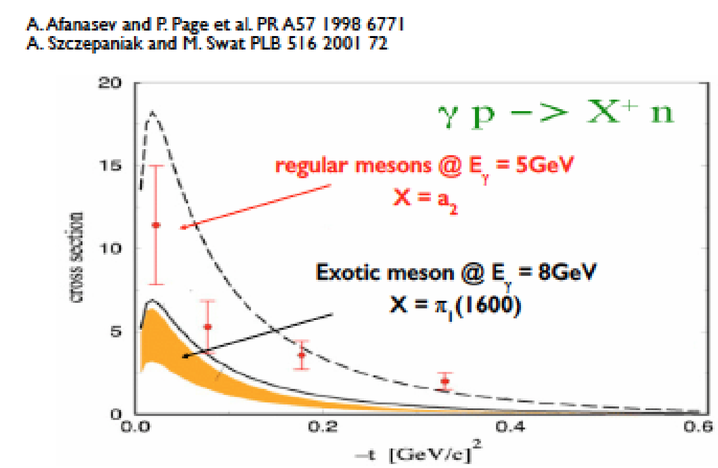


COMPASS (2018)

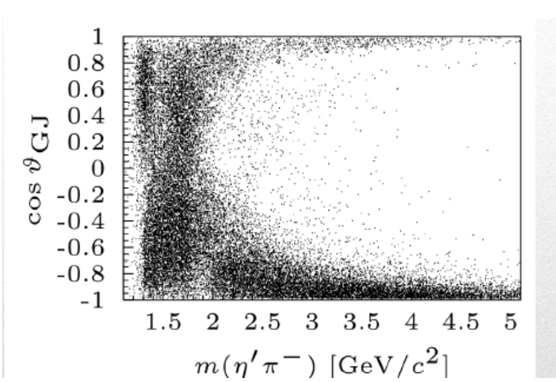
$\pi^- p \rightarrow \eta^{(\prime)} \pi^- p$

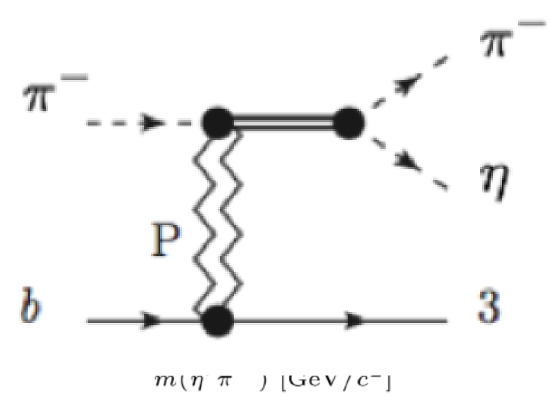
- In photoproduction (GlueX,CLAS12) exotic mesons produced via pion exchange (both good and bad)

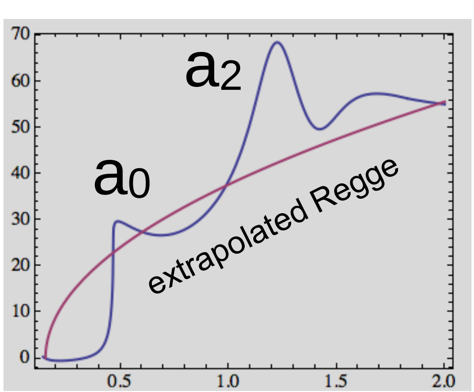




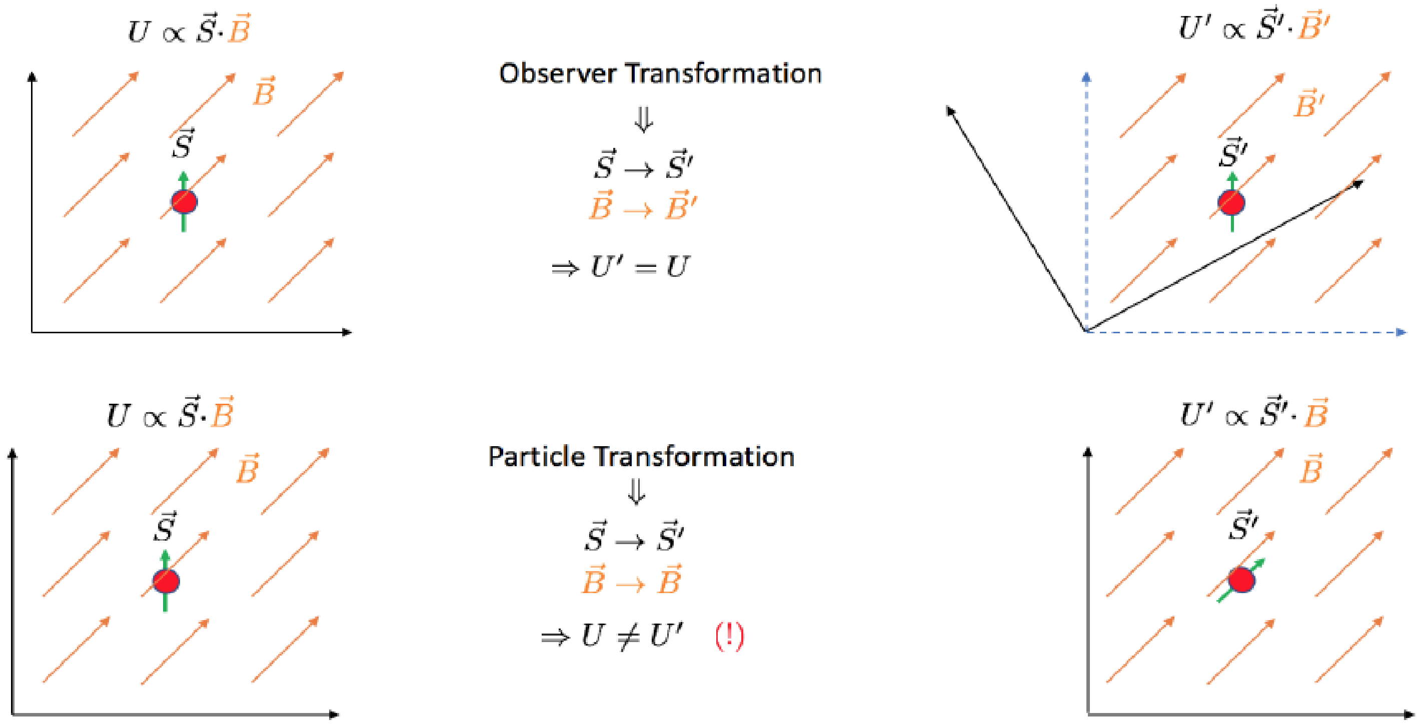
- Large exotic wave seen in $\eta^{(\prime)}\pi$ production : Golden Channel







(Very) exotic physics: constraining Lorentz symmetry violation

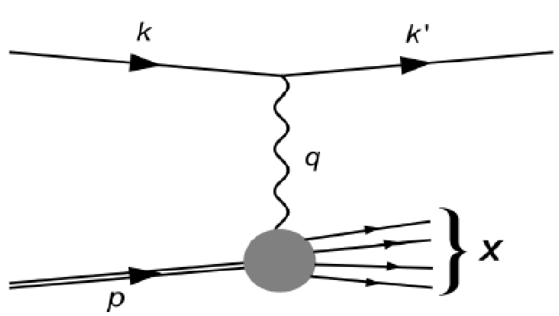


- Observer transformations do not affect results.
- Particle transformation, e.g. rotation of the experiment in the background filed produces a physical effect.

- 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, …



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

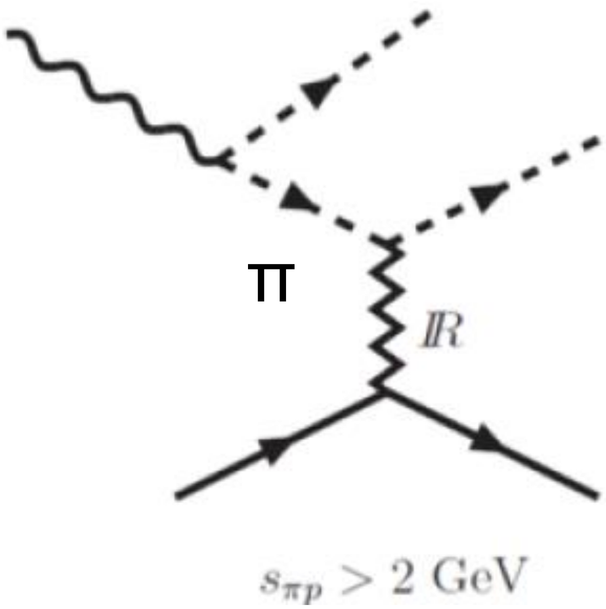
$$\Gamma_f^\mu = \gamma^\mu + c_f^{\mu\nu}\gamma_\nu$$

- The first estimate on the sidereal time dependent coefficients c_f were obtained using HERA data: $O(10^{-5})$

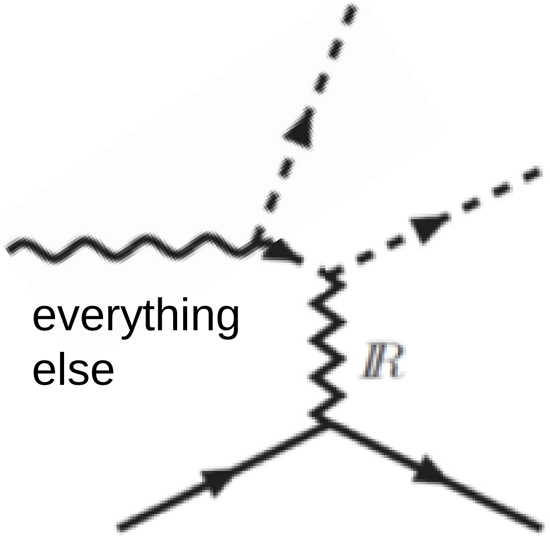
(V.A.Kostelecky, E.Lunghi, A.Vieira, PLB729, 272 (2017))

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

OPE vs other exchanges

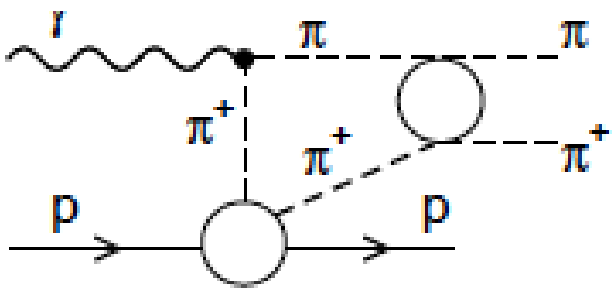


- Long range exchange



- 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)