Novel Approaches in Hadron Spectroscopy

Misha Mikhasenko
on behalf of JPAC

ORIGINS Excellence Cluster, Germany

August 1st, 2022
Quark Confinement 2022

Joint Physics Analysis Center

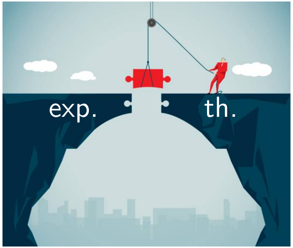
Joint effort of theorists and experimentalists to foster studies of strong interaction

Collaboration with several experimental groups

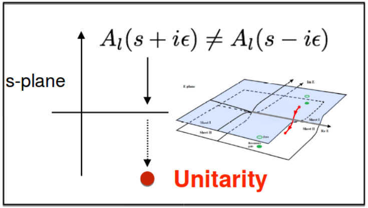
Involved in ongoing projects with LHCb, COMPASS, GlueX, BESIII, and EIC.

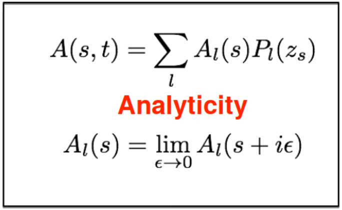
Tools in hadron spectroscopy

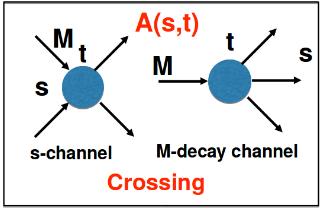
General principles of the scattering theory



- Lorentz invariance = independence of the reference frame, known behavior under boosts and rotations
- Unitarity = constraint to imaginary part of scattering amplitude
- Analyticity = implementation of relevant, closest singularities
- Crossing = decay and scattering regions are analytically connected





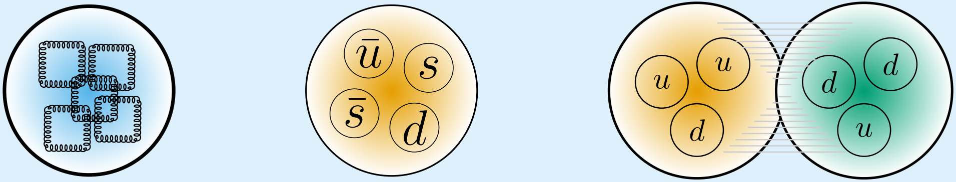


Selected results for the talk

1. Reaction theory and lineshape
   - Resonances in J/ψ radiative decays
2. Three-body problem
   - Dalitz-plot decomposition
   - Three-body unitarity
3. Production mechanism
   - Double-Regge production

The report is based on the recent review [JPAC, PPNP (2022) 103981, arXiv:2112.13436]

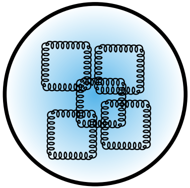
Most recent studies of on hadronic states



- Deep Learning Exotic Hadrons [PRD 105 (2022) L091501]
- Scalar and tensor resonances in J/ψ radiative decays (*) [EPJC 82 (2022) 1, 80]

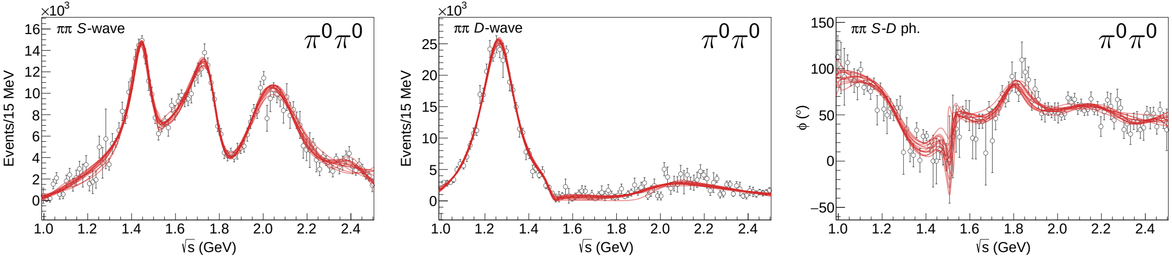
$J/\psi \to \gamma\pi^0\pi^0$ and $\to \gamma K_S^0 K_S^0$

[JPAC, EPJC 82 (2022) 1, 80]



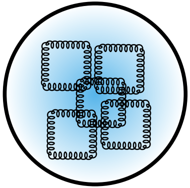
$f_0(1710)$?

- A gluon-rich process, expected to be the golden channel for the search of the scalar glueball
- BESIII data [PRD98 (7) (2018) 072003; PRD92 (5) (2015) 052003]
- Three-channel $(\pi\pi/KK/\rho\rho)$ K-matrix with the CDD poles



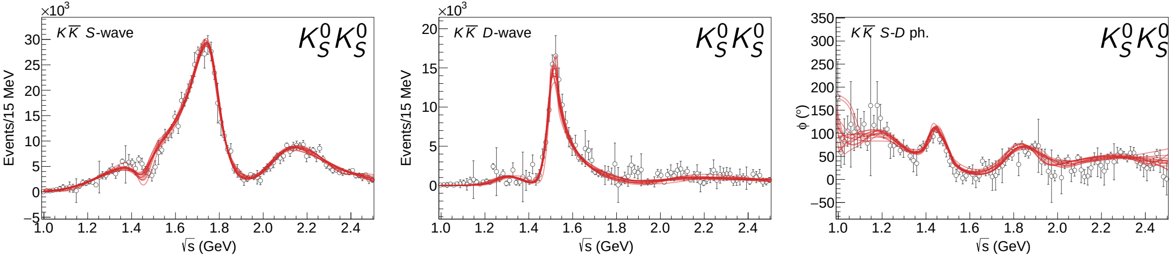
$J/\psi \to \gamma\pi^0\pi^0$ and $\to \gamma K_S^0 K_S^0$

[JPAC, EPJC 82 (2022) 1, 80]



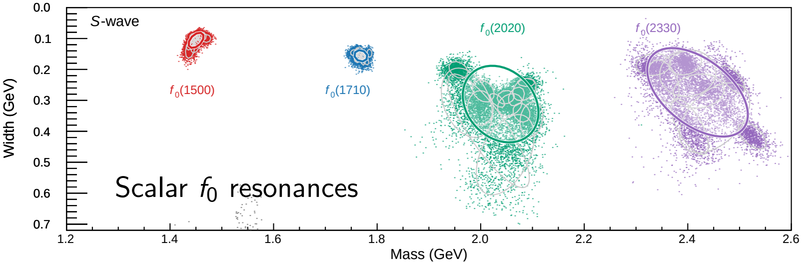
$\boxed{f_0(1710)\,?}$

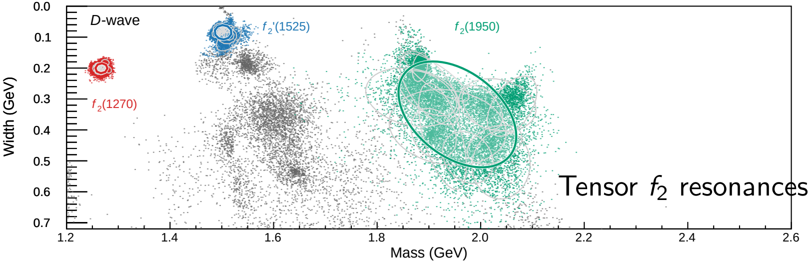
- A gluon-rich process, expected to be the golden channel for the search of the scalar glueball
- BESIII data [PRD98 (7) (2018) 072003; PRD92 (5) (2015) 052003]
- Three-channel $(\pi\pi/KK/\rho\rho)$ K-matrix with the CDD poles



Parameters of the resonances

- Here, 14 best fits with bootstrap analysis
- 4 scalar resonances, 3 tensor resonance reliably established
- More states might be present, but require more data / channels
- Large model uncertainty related to additional/spurious poles

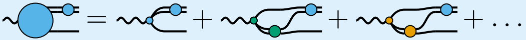




Large production coupling of $f_0(1710)$ suggests it to have sizable glueball components

Recent progress on three-body interaction

(*) will be shown today



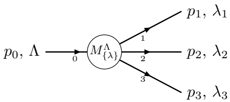
- BESIII puzzle on the $\omega \to 3\pi$ KT and $\omega \to \gamma\pi$ [JPAC, EPJC 80 (2020) 12, 1107]
- Quantization for $3 \to 3$ scattering on lattice [JPAC, PRD 100 (2019) 3, 034508]
- Application of Dalitz-plot decomposition (*) [JPAC, PRD 101 (2020) 3, 034033]
  - $\Xi_b^- \to pK^-K^-$ [LHCb, PRD 104 (2021) 5, 052010]
  - $B_s \to J/\psi p\bar{p}$ [LHCb, PRL 128 (2022) 6, 062001]
  - $B^- \to J/\psi \Lambda \bar{p}$ [LHCb, (in preparation)]
- Application of three-body unitarity to resonance physics [JPAC, JHEP 08 (2019) 080]
  - Study of the π_2 resonances for COMPASS (*) [JPAC, PPNP (2022) 103981]
  - $\Lambda_b^{**0} \to \Lambda_b^0 \pi^+\pi^-$ [LHCb, JHEP 06 (2020) 136]
  - Study of $T_{cc}^+ \to D^0 D^0 \pi^+$ [LHCb, Nature Commun. 13 (2022) 1, 3351]

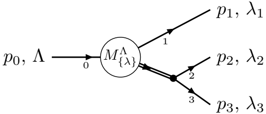
Conventional helicity approach

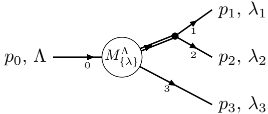
Complicated cases: particles with spin in isobar model [Hansen (1974)], [Herndon(1975)]

$$M^{\Lambda}_{\{\lambda\}} = M^{\Lambda}_{1,\{\lambda\}} + M^{\Lambda}_{2,\{\lambda\}} + M^{\Lambda}_{3,\{\lambda\}}$$

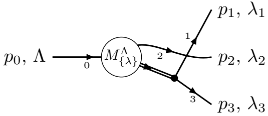
$$\underbrace{M^{\Lambda}_{\{\lambda\}}} \quad = \underbrace{H_1 D(\phi_1,\theta_1,0)\, D(\phi_{23},\theta_{23},0)\, W_1(\dots)} + \underbrace{H_3 D(\phi_3,\theta_3,0)\, D(\phi_{12},\theta_{12},0)\, W_3(\dots)}$$







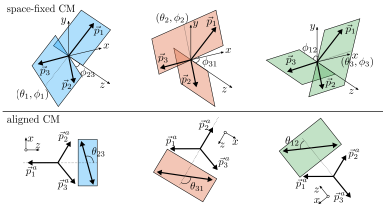
$$+ \underbrace{H_2 D(\phi_2,\theta_2,0)\, D(\phi_{31},\theta_{31},0)\, W_2(\dots)}$$



- A special set of angles for every decay chain
- Consistently of quantization direction – **Wigner rotations**

$$W_i(\dots) = D^{j_1}(\tilde{\phi}^i_1, \tilde{\theta}^i_1, 0)\, D^{j_2}(\tilde{\phi}^i_2, \tilde{\theta}^i_2, 0)\, D^{j_3}(\tilde{\phi}^i_3, \tilde{\theta}^i_3, 0)$$

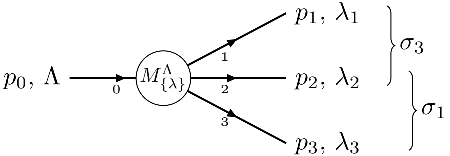
- Fails for non-integer spin



The Dalitz-Plot decomposition

[JPAC, PRD 101, 034033 (2020)]

Reformulation of the helicity approach



$$= \sum_{\nu} \underbrace{D^{J*}_{\Lambda\nu}(\phi_1, \theta_1, \phi_{23})}_{\text{Decay-plane orientation}} \times \underbrace{O^{\nu}_{\{\lambda\}}(m_{12}^2, m_{23}^2)}_{\text{Dalitz-plot function}}$$

Model-independent factorization of the overall rotation:

- Exploits properties of the Lorentz group (orientation – just three Euler angles)
- Dalitz-plot function depends entirely on 2 variables, m_{23}^2, and m_{12}^2.
- (!!!) No azimuthal angles in dynamic function.
- Generalizes for n-body decay: 3 rotation $\oplus$ $3n-7$ dynamic variables
- Fixes problem of 4π symmetry of half-integer spin decays

Decay amplitude in the aligned configuration [JPAC, PRD 101 (2020) 3, 034033]]

is a function of Mandelstam variables

Master formula $0 \to 1\,2\,3$ decay with arbitrary spins

$$O^{\nu}_{\{\lambda\}}(m_{12}^2, m_{23}^2) = \sum_{k=1}^{3} \sum_{s}^{(ij)\to i,j} \sum_{\tau} \sum_{\{\lambda'\}} \delta_{\lambda_0',\tau-\lambda_k'} H^{s}_{\tau,\lambda_k'} \mathrm{BW}(\sigma) H^{s}_{\lambda_i',\lambda_j'} d^{s}_{\tau,\lambda_i'-\lambda_j'}(\theta_{ij})$$
$$\times\, d^{j_0}_{\lambda_0,\lambda_0'}(\zeta^0_{k(\cdot)}) d^{j_1}_{\lambda_1',\lambda_1}(\zeta^1_{k(\cdot)})\, d^{j_2}_{\lambda_2',\lambda_2}(\zeta^2_{k(\cdot)})\, d^{j_3}_{\lambda_3',\lambda_3}(\zeta^3_{k(\cdot)}),$$

- $H^{s}_{\tau,\lambda_k'}$ and $H^{s}_{\lambda_i',\lambda_j'}$ are helicity couplings
- The angles are standard functions of (m_{12}^2, m_{23}^2):
  - $\theta_{ij}(m_{12}^2, m_{23}^2)$ is an isobar decay angle
  - $\zeta^{i}_{k(\cdot)}(m_{12}^2, m_{23}^2)$ is the particle-i Wigner angle

- widely used in LHCb
- implemented in frameworks

Amplitude for resonance process

[JPAC, JHEP 08 (2019) 080]

Two-body resonance

$$\hat{\mathcal{T}}_2(s) = \frac{g^2}{m^2 - s - ig^2\Phi_2(s)} \to \frac{1}{(m^2 - s)/g^2 - \Sigma_2(s)}$$

- Self-energy: $ig^2\Phi_2(s) \to \Sigma_2(s)$, Chew-Mandelstam to ensure analyticity.

Amplitude for resonance process

[JPAC, JHEP 08 (2019) 080]

Two-body resonance

$$\hat{\mathcal{T}}_2(s) = \frac{g^2}{m^2 - s - ig^2\Phi_2(s)} \to \frac{1}{(m^2 - s)/g^2 - \Sigma_2(s)}$$

- Self-energy: $ig^2\Phi_2(s) \to \Sigma_2(s)$, Chew-Mandelstam to ensure analyticity.

Three-body resonance

$$\hat{\mathcal{T}}_R(s) = \frac{1}{(m^2 - s)/g^2 - \Sigma(s)} = \frac{1}{\mathcal{K}_1^{-1}(s) - \Sigma(s)}$$

- Dispersion relation for the self-energy:

$$\Sigma(s) = \frac{s}{2\pi} \int_{s_{\text{th}}}^{\infty} \frac{\mathrm{d}s'}{s'(s' - s)} \int_{\text{Dalitz}(s')} \left| \hat{\mathcal{A}}_{R\to 1,2,3}(s', \sigma_1', \sigma_2') \right|^2 \mathrm{d}\Phi_3'$$

- The $\left| \hat{\mathcal{A}}_{R\to 1,2,3}(s, \sigma_1, \sigma_2) \right|^2$ is observable (+FSI)

Amplitude for resonance process

[JPAC, JHEP 08 (2019) 080]

Two-body resonance

$$\hat{\mathcal{T}}_2(s) = \frac{g^2}{m^2 - s - ig^2\Phi_2(s)} \to \frac{1}{(m^2-s)/g^2 - \Sigma_2(s)}$$

- Self-energy: $ig^2\Phi_2(s) \to \Sigma_2(s)$, Chew-Mandelstam to ensure analyticity.

Three-body resonance

$$\hat{\mathcal{T}}_R(s) = \frac{1}{(m^2-s)/g^2 - \Sigma(s)} = \frac{1}{\mathcal{K}_1^{-1}(s) - \Sigma(s)}$$

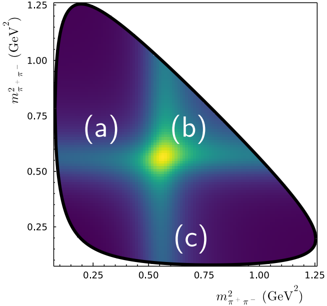
- Dispersion relation for the self-energy:

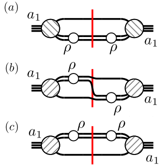
$$\Sigma(s) = \frac{s}{2\pi}\int_{s_{\text{th}}}^{\infty} \frac{\mathrm{d}s'}{s'(s'-s)} \int_{\text{Dalitz}(s')} \left|\hat{\mathcal{A}}_{R\to1,2,3}(s',\sigma_1',\sigma_2')\right|^2 \mathrm{d}\Phi_3'$$

- The $\left|\hat{\mathcal{A}}_{R\to1,2,3}(s,\sigma_1,\sigma_2)\right|^2$ is observable (+FSI)

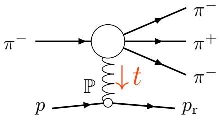
Example:

$\boxed{a_1 \to \rho(\to \pi\pi)\pi}$



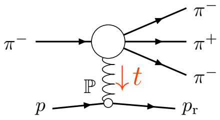


The π_2 resonances with COMPASS data [JPAC, PPNP (2022) 103981; MM, PhD thesis]



- COMPASS experiment at CERN
  - Diffractive production of 3π system
  - pion beam scattered off proton target,
- PWA to separate J^P for every $m_{3\pi}$ bin
- 11 data sets with different $t = p_{\mathbb{P}}^2$.

The π_2 resonances with COMPASS data [JPAC, PPNP (2022) 103981; MM, PhD thesis]

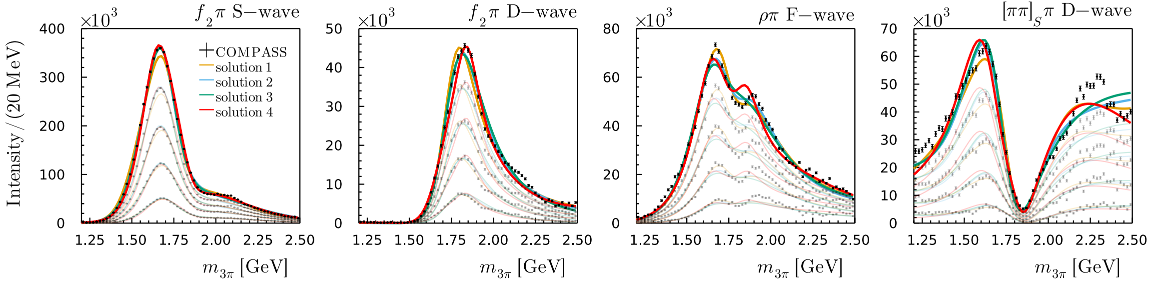


- COMPASS experiment at CERN
  - Diffractive production of 3π system
  - pion beam scattered off proton target,
- PWA to separate J^P for every $m_{3\pi}$ bin
- 11 data sets with different $t = p_{\mathbb{P}}^2$.

Resonance analysis of $J^P = 2^+$:

- coupled-channel K-matrix
- large model uncertainty

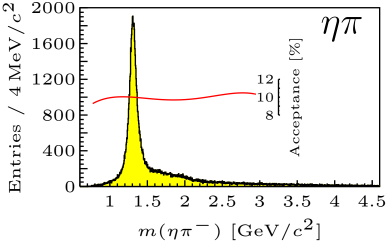
	m_p (MeV)	Γ_p (MeV)
$\pi_2(1670)$	1650–1750	280–380
$\pi_2(1880)$	1770–1870	200–450
$\pi_2(2005)$	1890–2190	590–1340

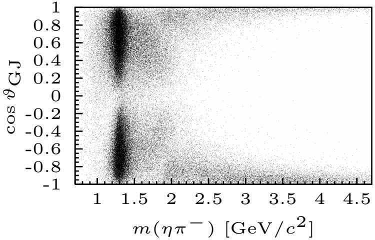


Recent studies of the hadron production mechanism

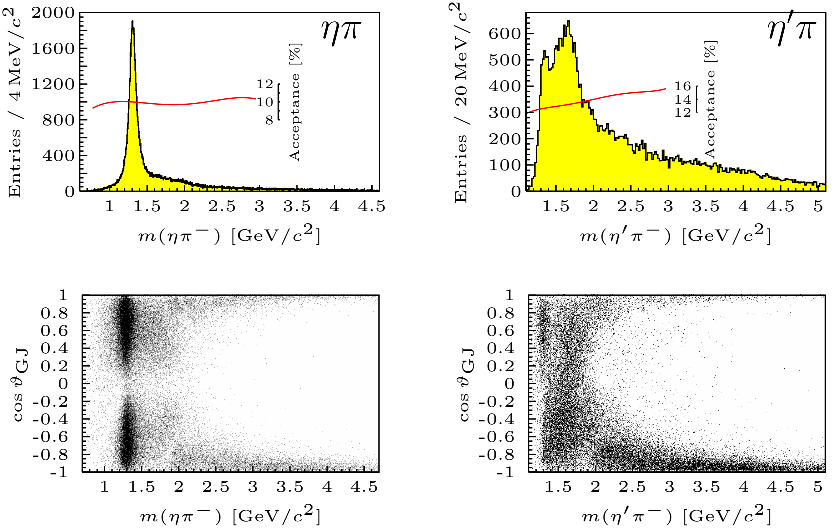
- Nucleon resonances in inclusive electron scattering [JPAC, PRC104 (2021) 025201]
- XYZ production in electron-proton collisions [JPAC, PRD102 (2020) 114010]
- Two-meson production in the double-Regge region (*) [JPAC, EPJC 81 (2021) 647]
- Finite energy sum rules [JPAC, (in progress)]

Features of $\eta\pi$ vs $\eta'\pi$ production at high energy [(COMPASS) PLB 740 (2015) 303]

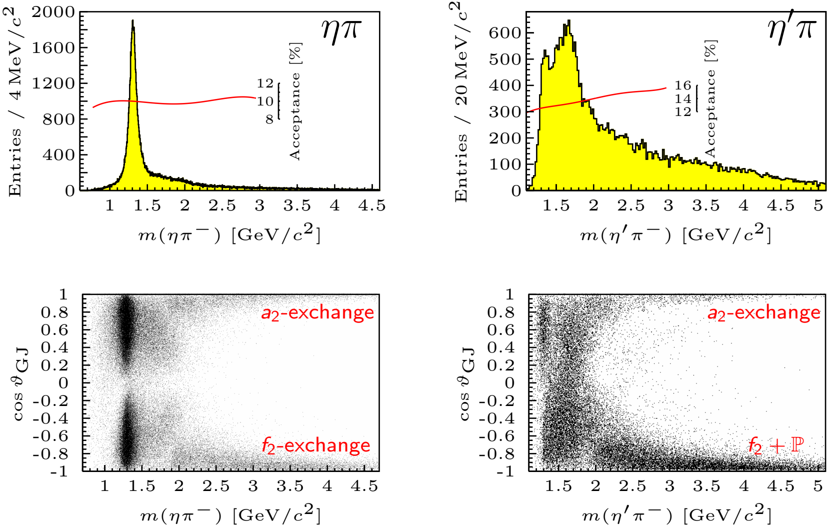




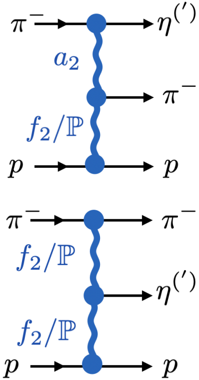
Features of $\eta\pi$ vs $\eta'\pi$ production at high energy [(COMPASS) PLB 740 (2015) 303]



Features of $\eta\pi$ vs $\eta'\pi$ production at high energy [(COMPASS) PLB 740 (2015) 303]



High-energy dynamics:

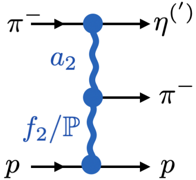


Double-Regge model

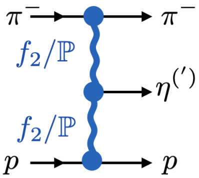
[JPAC, Eur.Phys.J.C 81 (2021) 647]

inspired by [Shimada et al. (1978)]

$$T_{\alpha_1/\alpha_2}(s_1,s_2) = K\Gamma(1-\alpha_1)\Gamma(1-\alpha_2)(\alpha' s)^{-1}(\alpha' s_1)^{\alpha_1}(\alpha' s_2)^{\alpha_2}$$
$$\times\left[\eta^{\alpha_1}\xi_1\xi_{21}V(\alpha_1,\alpha_2,\eta)+\eta^{\alpha_2}\xi_2\xi_{12}V(\alpha_2,\alpha_1,\eta)\right]$$



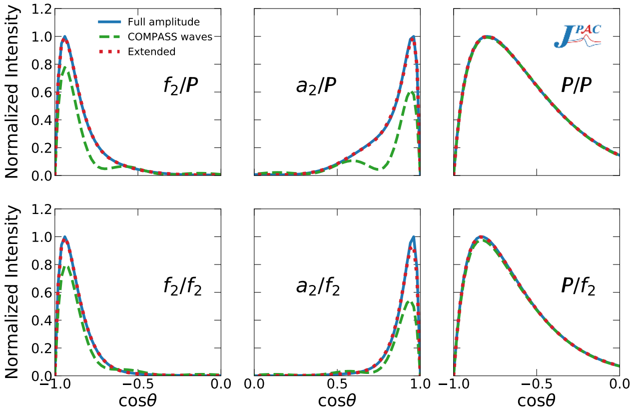
- K kinematic function $\sim \sin\theta_{\mathrm{GJ}}\sin\phi_{\mathrm{TY}}$.
- $s_i^{\alpha_i(t_i)}$ for both reggeons
- ξ_i and ξ_{ij} are the signature factors
- $\eta = s/(\alpha' s_1 s_2)$ is finite in the Double Regge limit
- $V(\alpha_1,\alpha_2,\eta)$ is the reggeon-reggeon vertex.
  Minimal model: all residuals in the vertex function are the same.



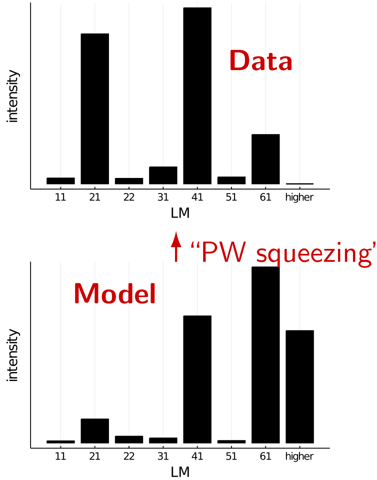
$$A = \underbrace{c_1\,T_{a_2/\mathbb{P}(f_2)}}_{\eta\text{ forward}} + \underbrace{c_2\,T_{f_2/\mathbb{P}(f_2)}}_{\pi\text{ forward}} + \underbrace{c_3\,T_{\mathbb{P}/\mathbb{P}(f_2)}}_{\pi\text{ forward}}.$$

Effect of PW-set trunction

- Data is analyzed in **truncated** PW set: $L \leq 6,\ M \leq 2$
- Extended likelihood fit $\Rightarrow$ force intensity redistribution
- “Squeezing” the full series to the truncated set



PW expansion:



summed $2.4 < m_{\eta\pi} < 3.0\,\mathrm{GeV}$.

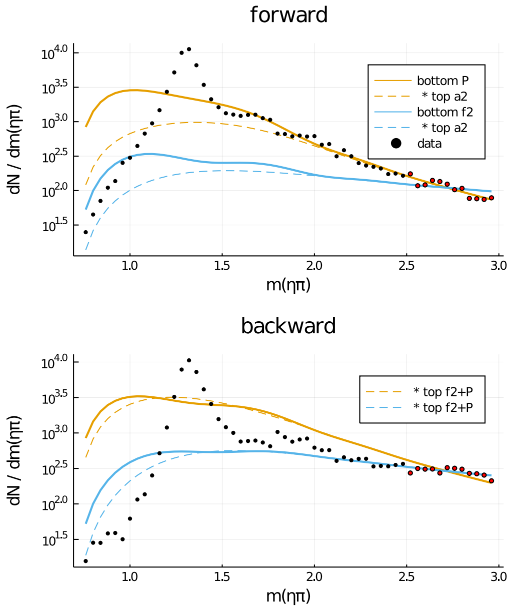
Bottom exchange: f_2 vs $\mathbb{P}$

Representative: forward, backward intensity

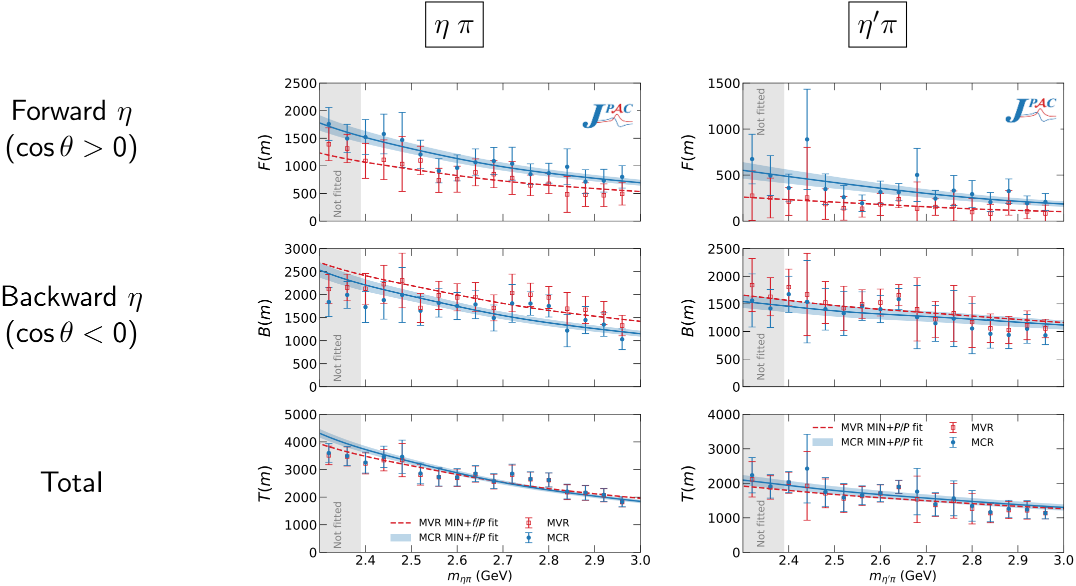
$$F^{(m_{\eta\pi})} = \int_{\cos\theta>0} I(\Omega)\,\mathrm{d}\Omega,$$
$$B^{(m_{\eta\pi})} = \int_{\cos\theta<0} I(\Omega)\,\mathrm{d}\Omega.$$

Can be computed for the model, and from the "data" partial waves.

- The slope $\mathrm{d}I/\mathrm{d}m_{\eta\pi}$ is sensitive to the bottom exchange
- The slope is different in the forward and the backward regions



Integral intensities



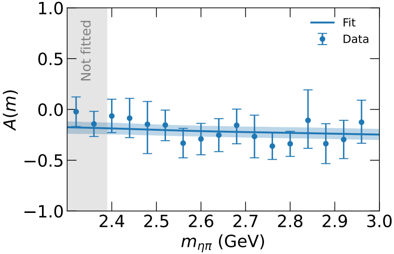
Conclusions on contributing processes

FB Asymmetry

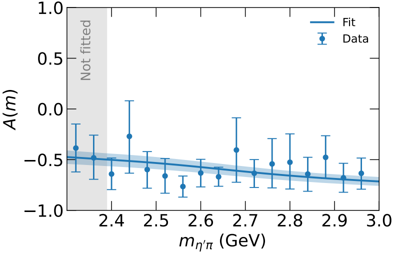
$$\frac{(\cos\theta>0)-(\cos\theta>0)}{(\cos\theta>0)+(\cos\theta>0)}$$

- $a_2 - f_2$ coupling degeneracy lead to nearly no asymmetry for $\eta\pi$
- Three effects of large asymmetry in $\eta'\pi$:
  - no $a_2 - f_2$ symmetry
  - significant $\mathbb{P}/\mathbb{P}$ process
  - mass difference

$\boxed{\eta\,\pi}$



$\boxed{\eta'\pi}$



	$\eta\pi$	$\eta'\pi$
$(a_2/\mathbb{P})$	0.4 ± 0.04	0.35 ± 0.05
$(f_2/\mathbb{P})$	0.3 ± 0.05	not needed
(a_2/f_2)	3.4 ± 0.4	0.6 ± 0.5
(f_2/f_2)	6.6 ± 0.7	7.6 ± 0.7
$(\mathbb{P}/\mathbb{P})$	not needed	$(18 \pm 2) \times 10^{-3}$

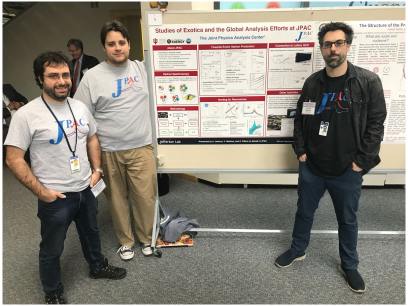
Summary

- JPAC started in 2013 as project between Indiana university and JLab
- Much expanded and matured since then
- The driving force is enthusiasm and curiosity
- **The main focus is on development the tools to tackle challenges in hadron spectroscopy**
- Also, we organize lecture courses and various school
- Close cooperation with experimental groups is essential

Everyone sharing the interest in hadron physics is WELCOME TO JOIN!!

Activities on JPAC

- Over 120 research articles
- Over 200 invited talks
- Summer schools (2015, 2017)
- Many workshop, conferences, programs
- Scattering courses (2021, 2022)
- Affiliated membership in many experiments
- Recent PhDs: D.Winney (2021), N.Sherrill (2021), A.Jackura (2019), A.Rodas (2019), M.Mikhasenko (2019), J.Nys (2018), A.Hiller-Blin (2018)
- Recent faculty position: C.Fernandez, M.Albaladejo, V.Mathieu, A.Pilloni



Thank you for the attention!