Amplitude Analyses for Hadron Spectroscopy

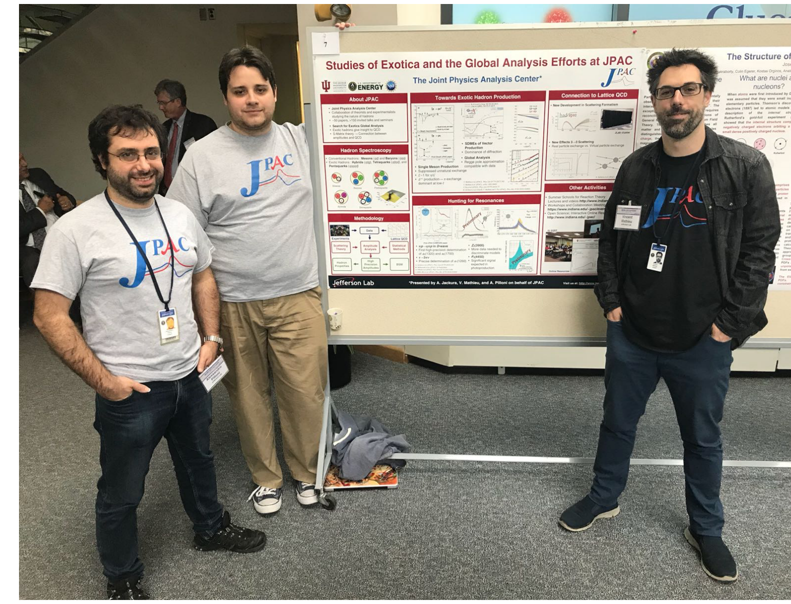
(Sample) of results from JPAC

Adam Szczepaniak, Indiana University/Jefferson Lab

Join Physics Analysis Center

Joint Physics Analysis Center

JPAC

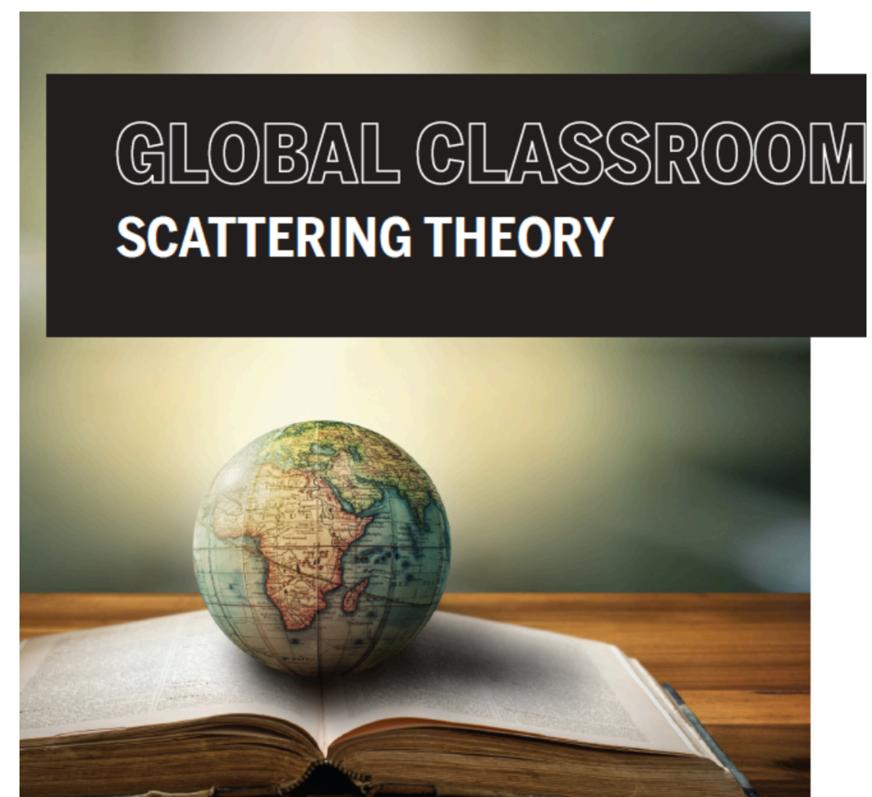


- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other experiments

- 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



Why spectroscopy

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

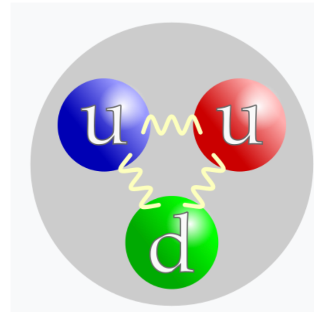
Are constituent quarks (gluons?) real ?
→ How is mass generated
What about gluons ?

- The first step How many hadrons are there
— Amplitude analysis

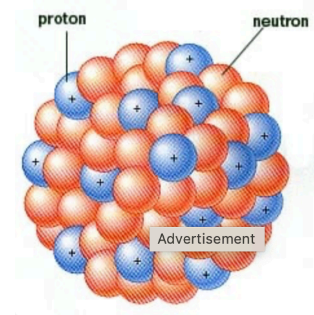
André Petermann *Murray Gell-Mann* *George Zweig*

Petrov, V,A. "Half a Century with Quarks". arXiv:1412.8681

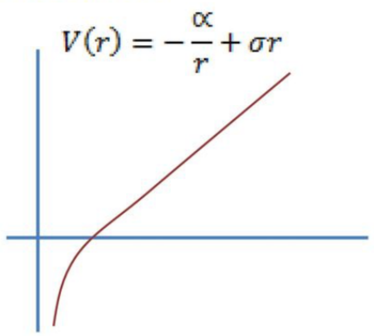
Hadrons



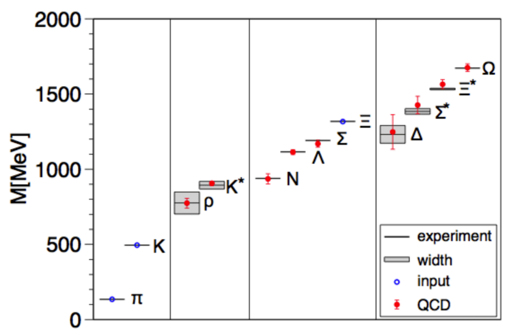
Nuclei



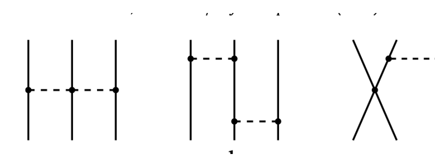
he Nobel Prize in Physics 1963. NobelPrize.org. Nobel Prize Outreach AB 2022. Sat. 17 Sep 2022.



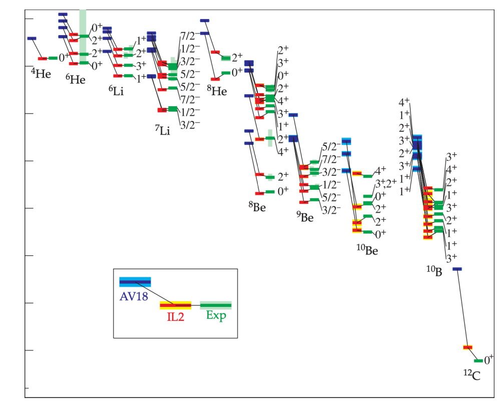
E.Echten et al. Phys. Rev. Lett. 34, 369 (1978)



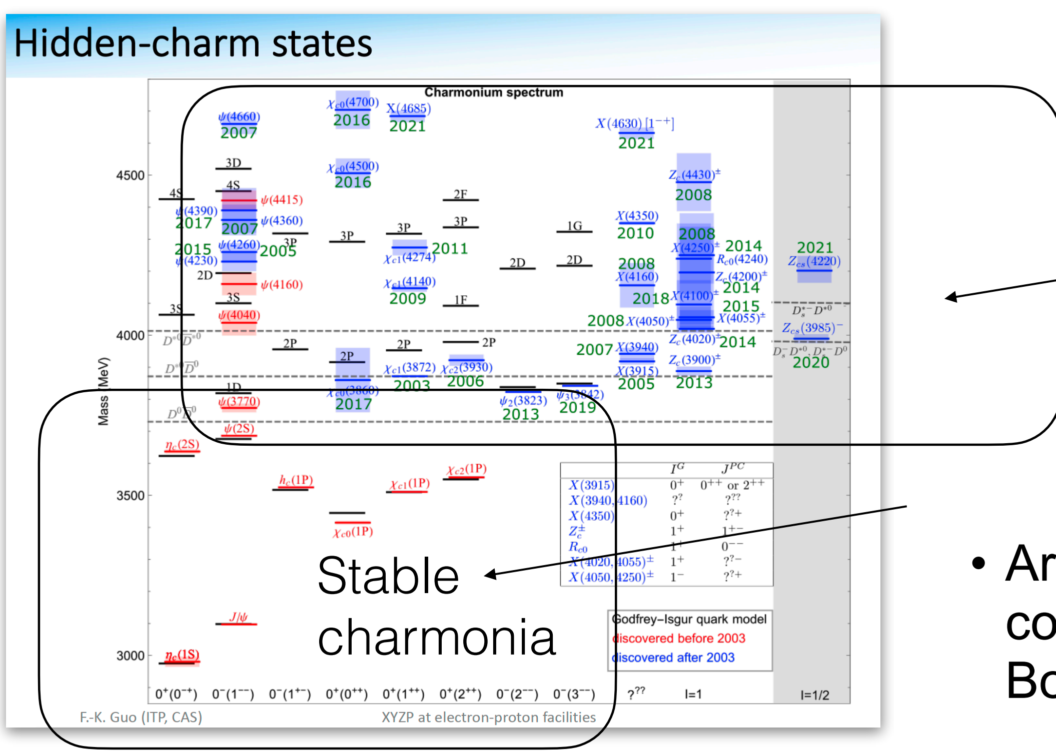
S. Durr et al., Science 322, 1224 (2008)



R. Machleidt,D.R. Entem, PhysRep, 503,1 (2011)



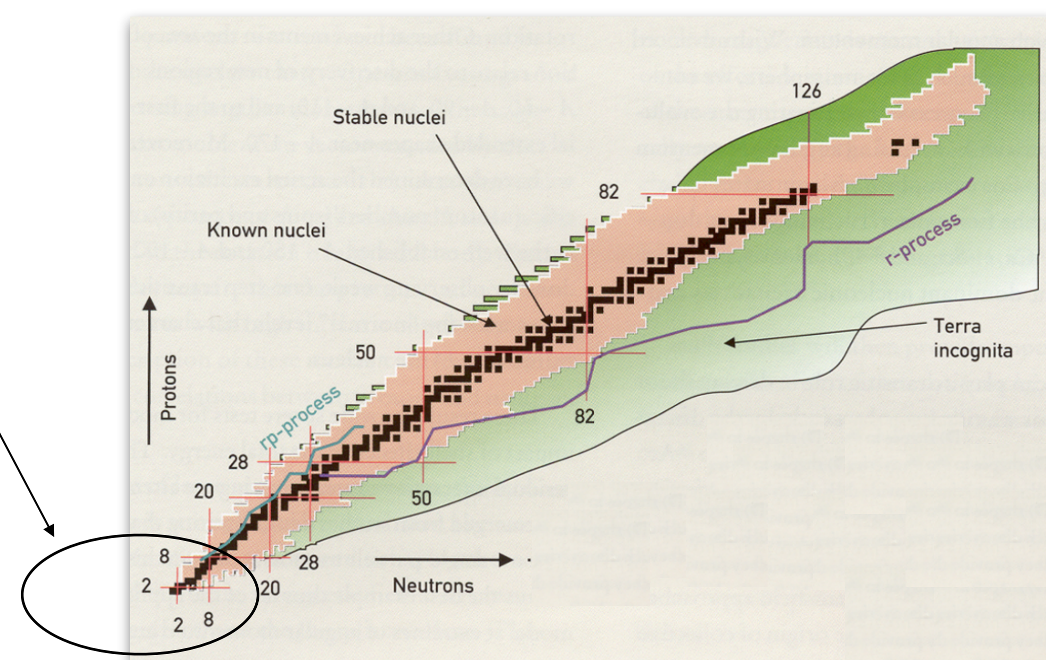
D.Dean, Physics Today 60, 11, 48 (2007)



Terra incognita

Stable charmonia

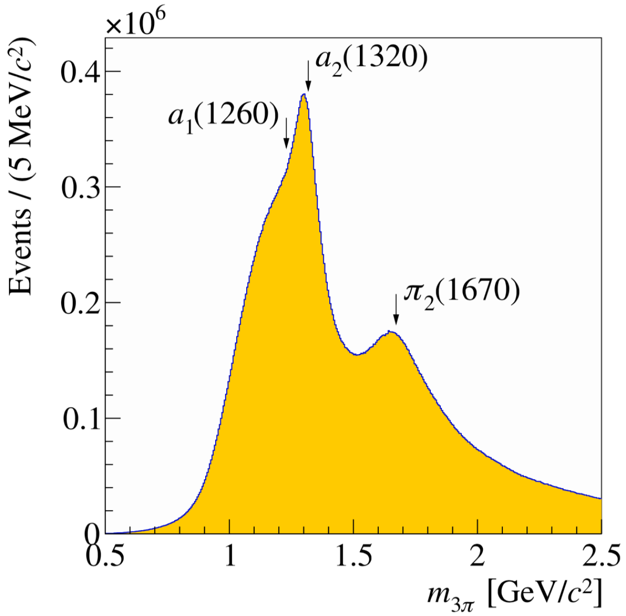
- Are these analogs of compact, halo, Borromean, etc.



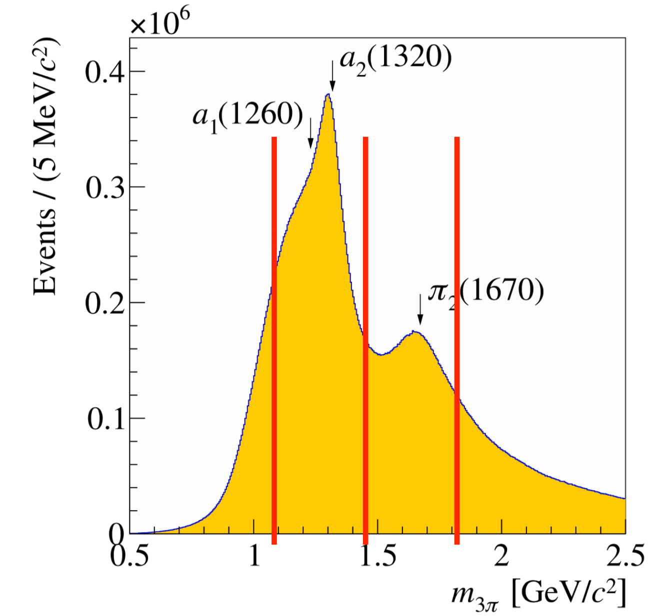
F-K.Guo

JPAC's role

Experiment

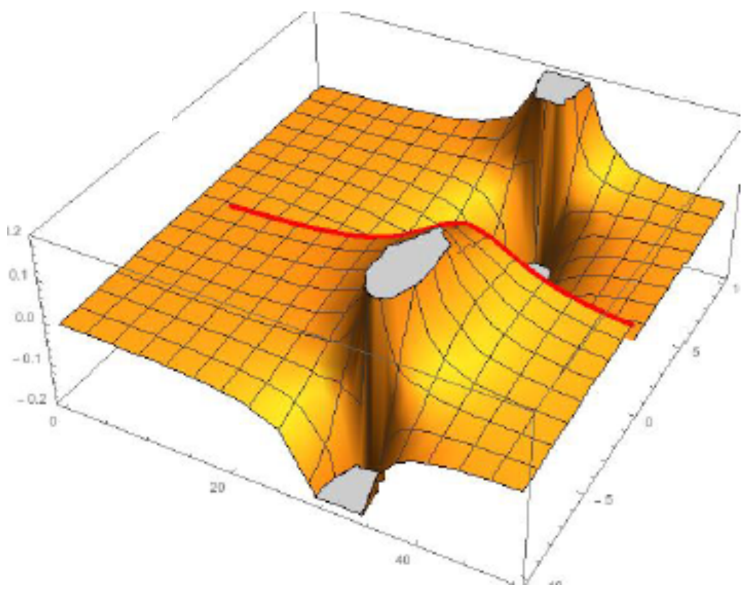


QCD (lattice)



Reaction Amplitudes

- Causality protects the energy plane
- All interesting phenomena (e.g. hadrons) reside in unphysical sheets and need be fitted to the data

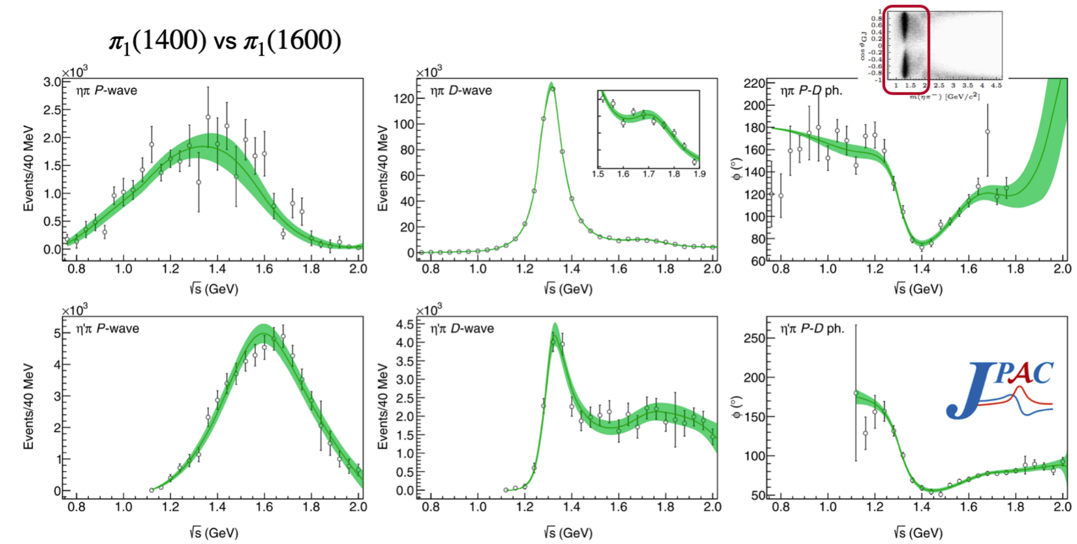


Beyond "static mass generation" Exotic hybrid

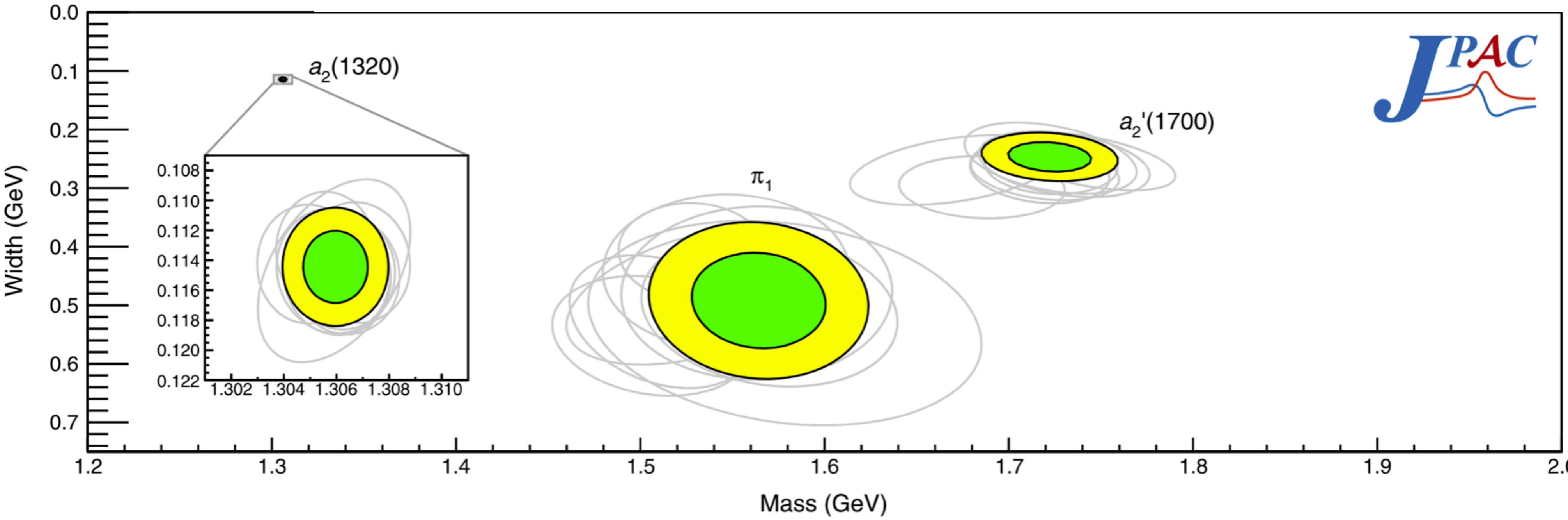
$J^{PC} = 1^{-+}$ Outside valance quark model

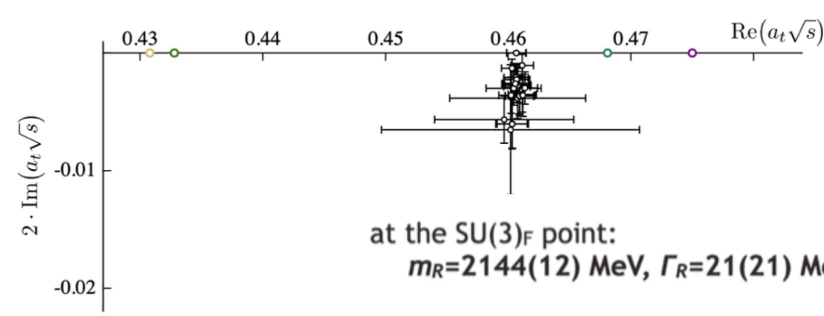
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

[A.Rodas, et al (JAPC) PRL (2019)]



[C.Adolph, et all COMPASS, Phys.Lett.B 740 (2015) 303]





at the SU(3)F point:
m_R=2144(12) MeV, Γ_R=21(21) MeV

A.Woss et al. PRD 103 (2021) 5, 054502

generates for a π_1 at 1564 MeV:

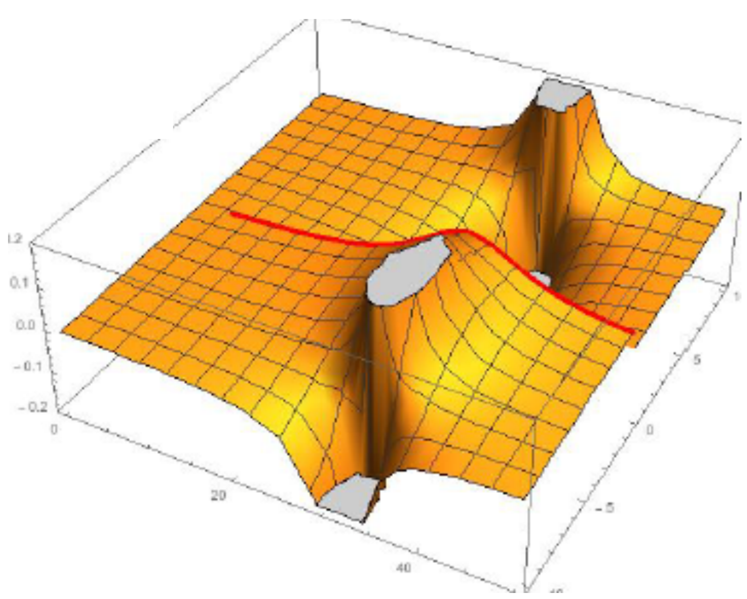
Γ_{TOT} ~ 140-600 MeV

$\Gamma(\pi\eta) \lesssim 1$ MeV
$\Gamma(\pi\eta') \lesssim 20$ MeV
$\Gamma(\pi\rho) \lesssim 12$ MeV
$\Gamma(\pi b_1)$ ~ 140-530 MeV

Non relativistic theory : potentials

QFT : crossing symmetry (not enough)

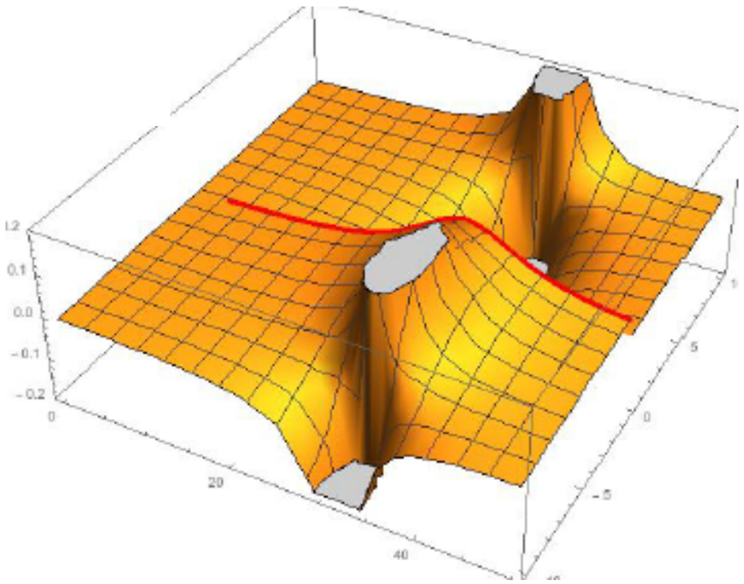
Analyticity : unitarity



Regge theory

$$f(E_{cm}, \theta) = A(s,t) = \sum_{l=0} (2l+1)\, f_l(s)\, P_l(\cos\theta_s)$$

Analytical in s $f_1(s)$

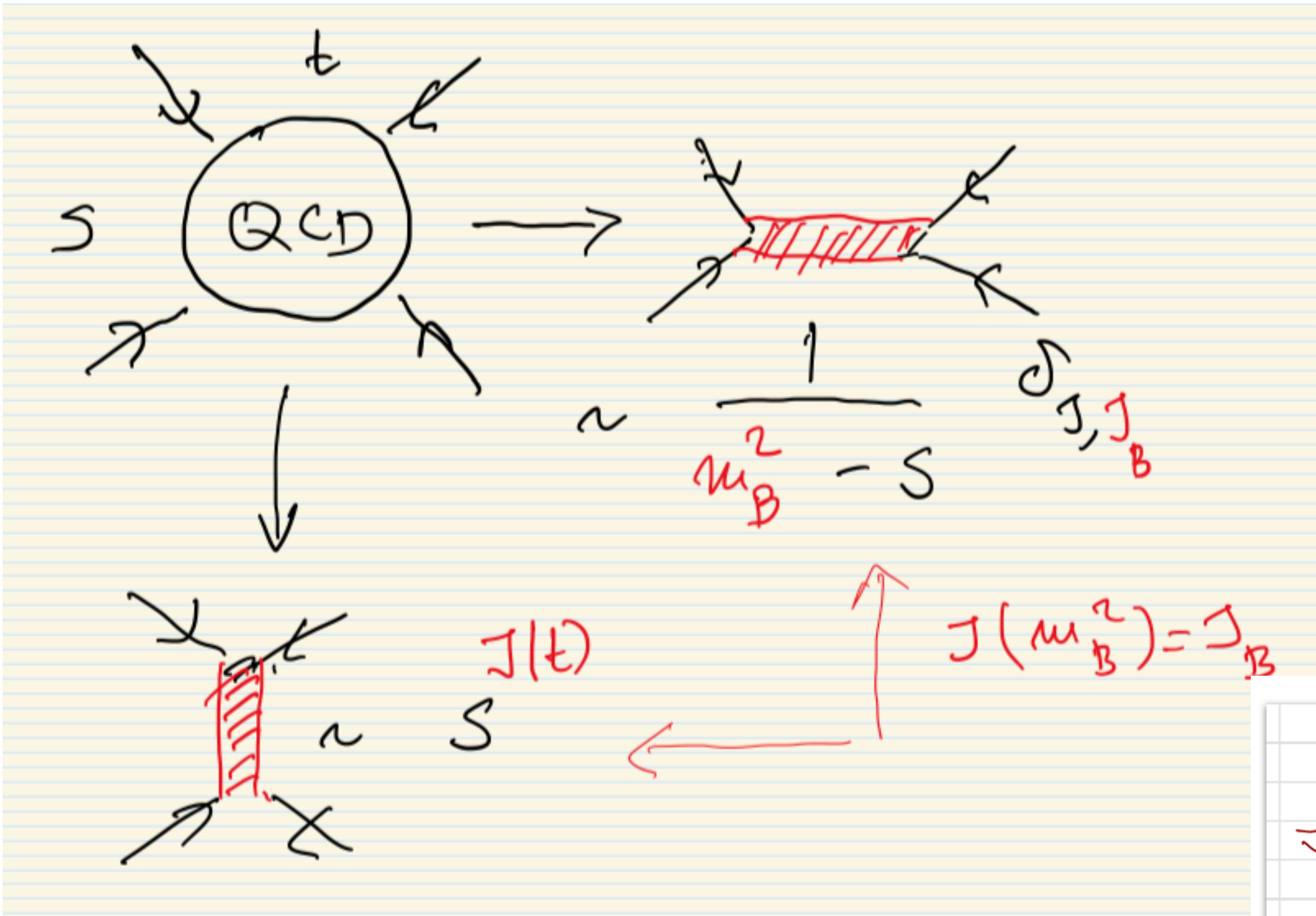


$$f_l(s)$$

Partial waves are analytical functions of l with poles (Regge poles) representing spin

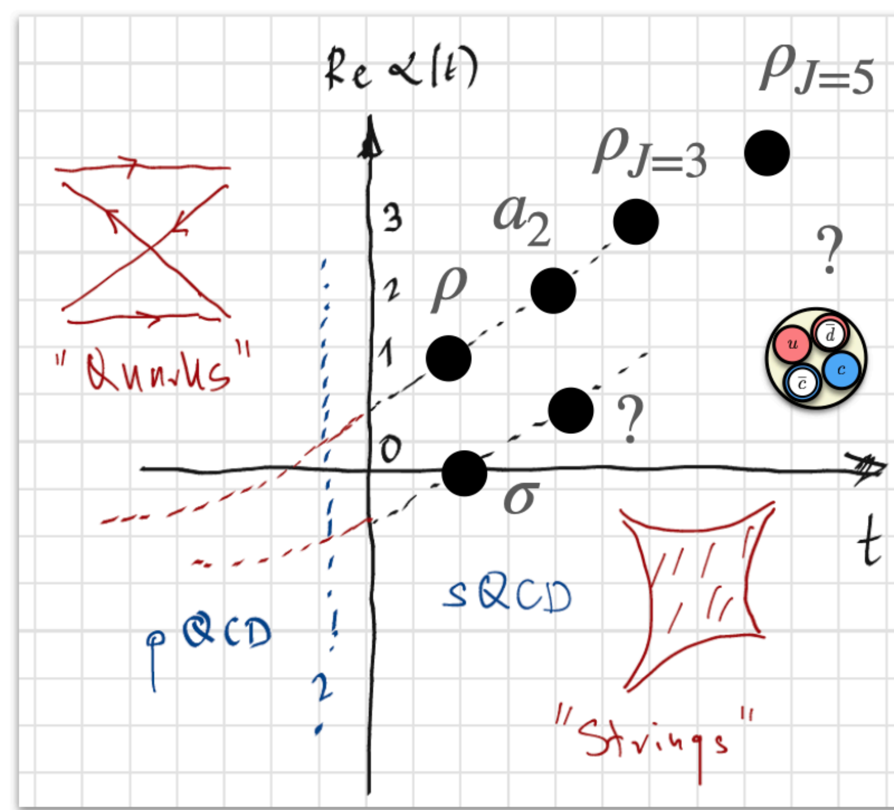
$$l = \alpha(s)$$

Regge theory is useful



- Spin off all particles (the electron, quark, deuteron, XYZ,…) evolves $J = J(t)$ possibly through the same mechanisms that generate its mass $t = m_B^2$.

- Most hadrons have a "long" J~1-10 linear section, consistent with confinement of chromo-electric fluxes (dual Meisner superconductor)



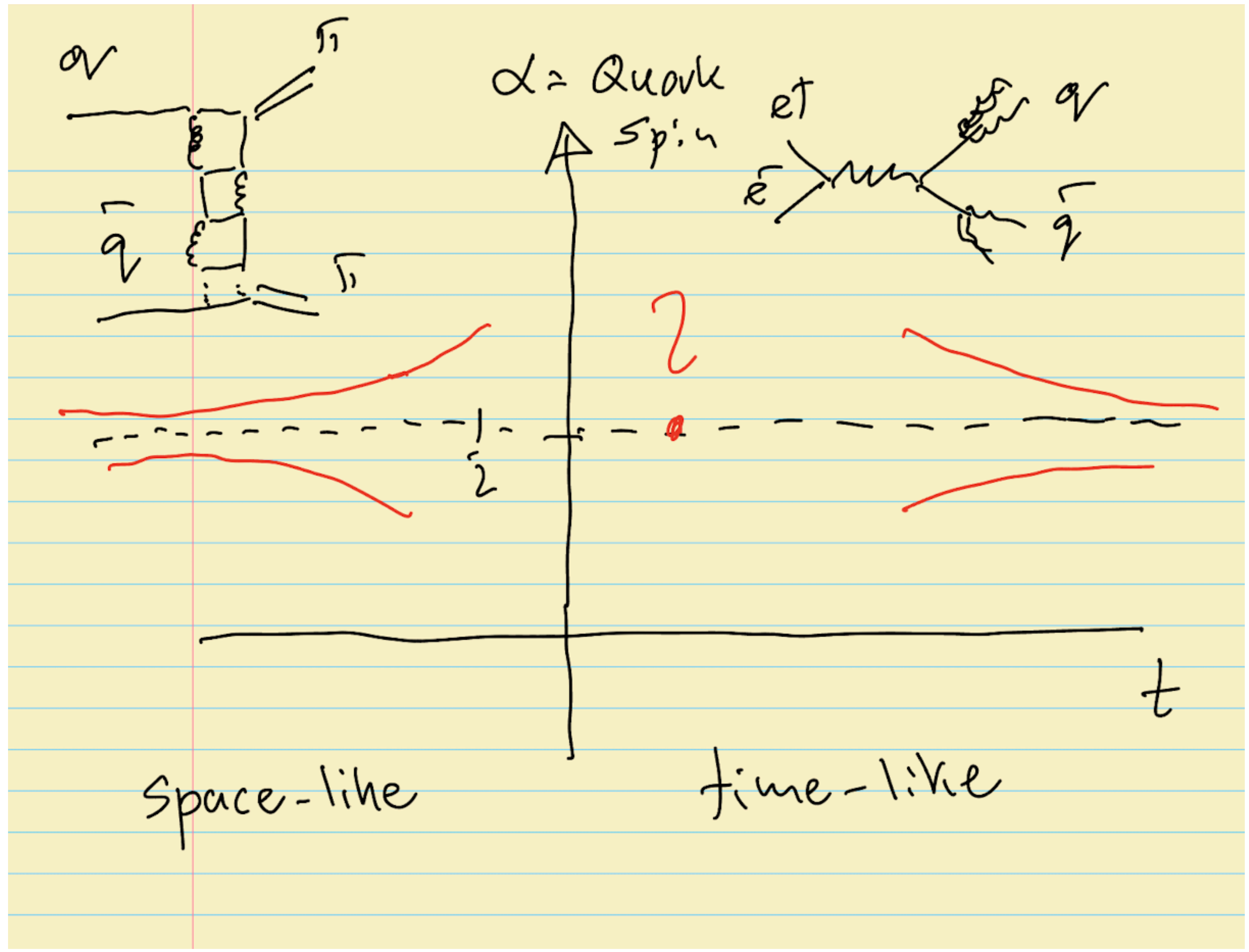
Quarks as a reggeion

- Can constituent quark be characterized by ?

$$J(\sim 300\ \text{MeV}) = \frac{1}{2}$$

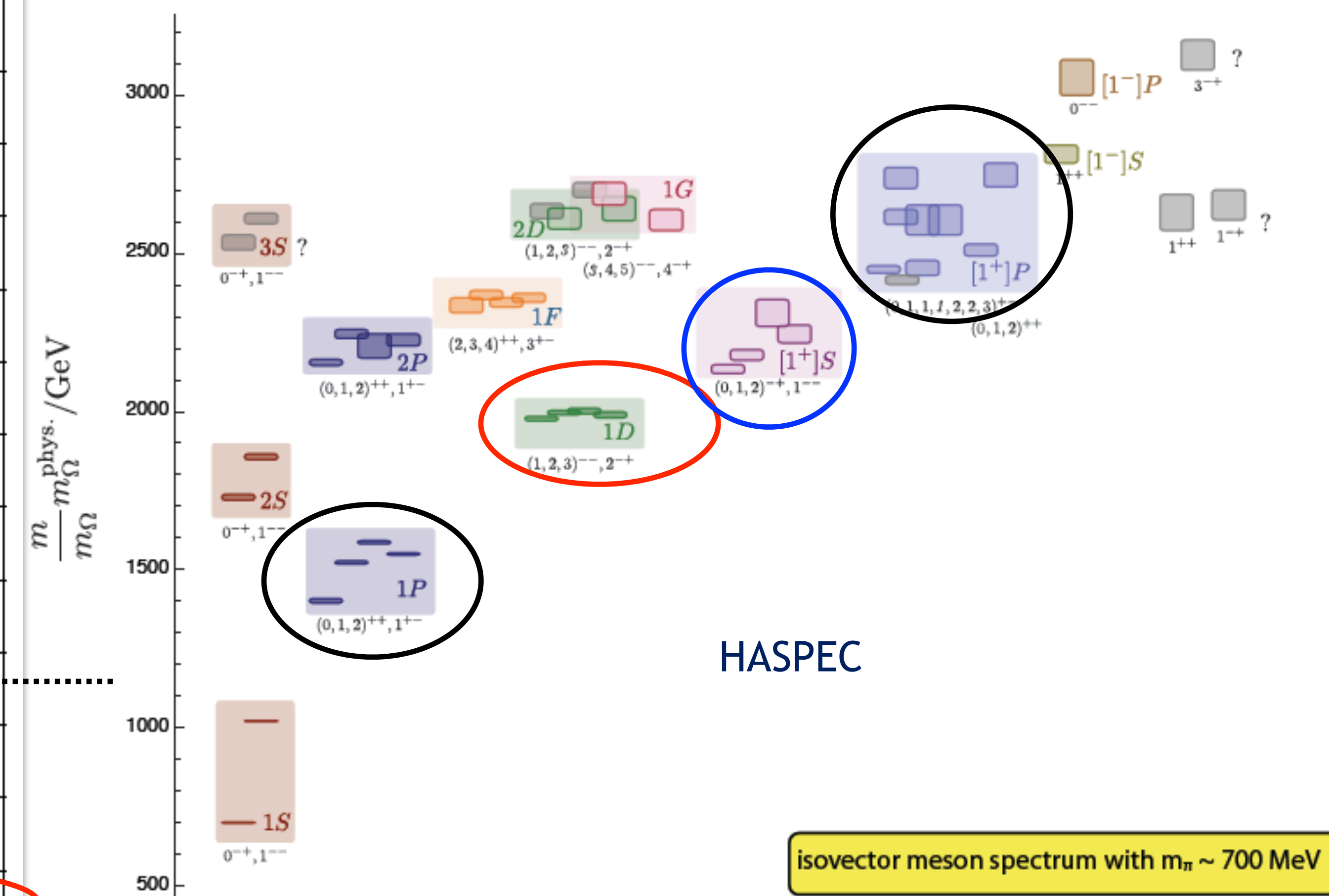
- How is quark confinement manifested through J(t) ?

$$J(t < \infty) < \frac{1}{2}$$

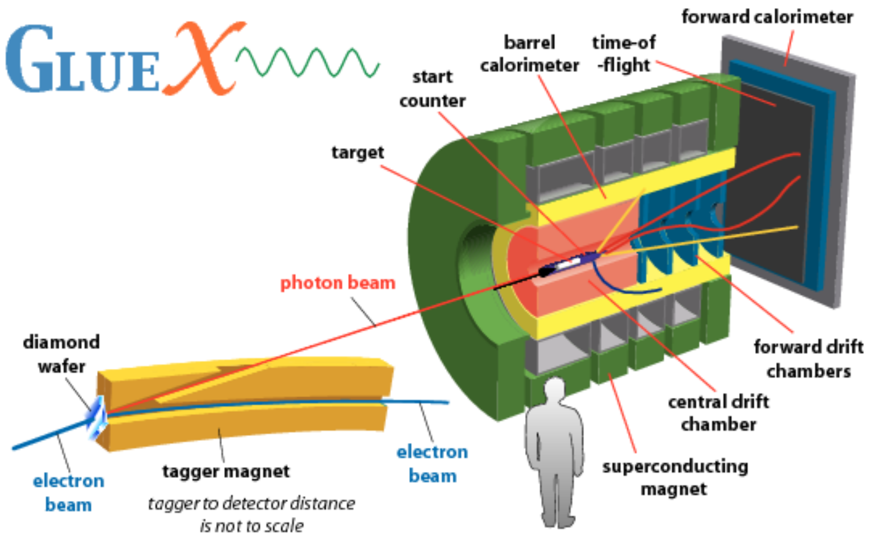


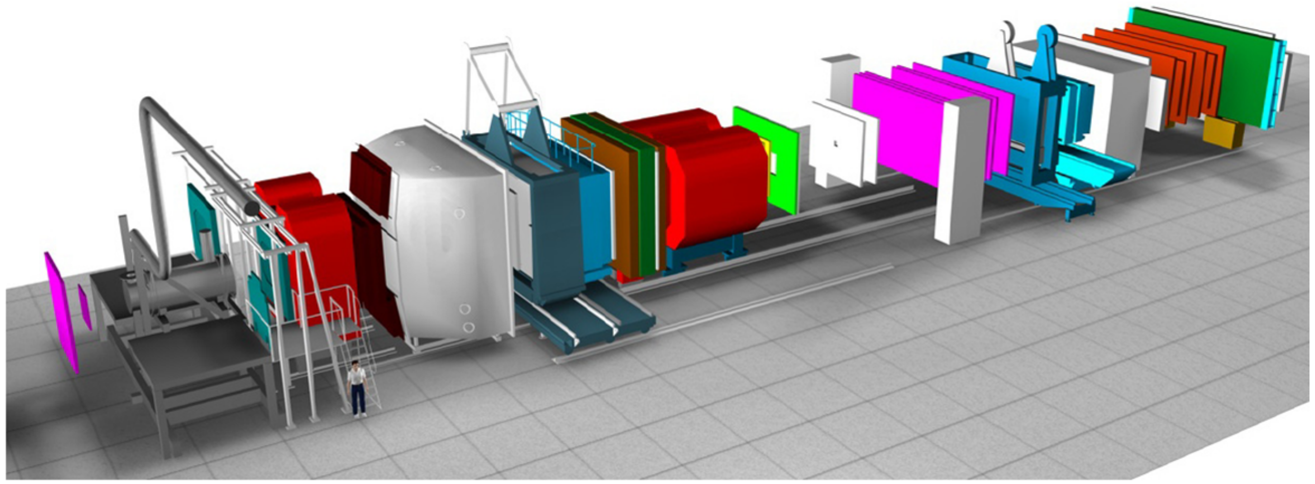
More hints from Regge

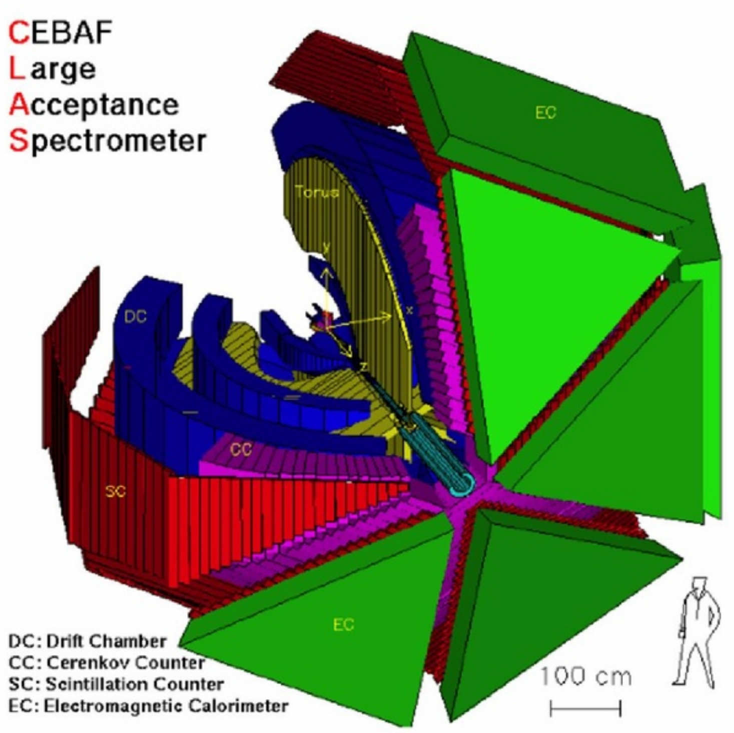
I^G	naturality $=P(-1)^J$	twist =+1 if J=0,2,.. =-1 if J=1,3...	name
0^+	+1	+1	f_0, f_2,...
0^+	+1	-1	$\eta/\eta'_1, \eta/\eta'_3$,... ($1^{-+}, 3^{-+}$,..)
0^+	-1	+1	$\eta/\eta'_0, \eta/\eta'_2$,...
0^+	-1	-1	f_1, f_3,...
0^-	+1	+1	h_0, h_2,.. ($0^{+-}, 2^{+-}$,..)
0^-	+1	-1	$\omega/\phi_1, \omega/\phi_3$,..
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,...



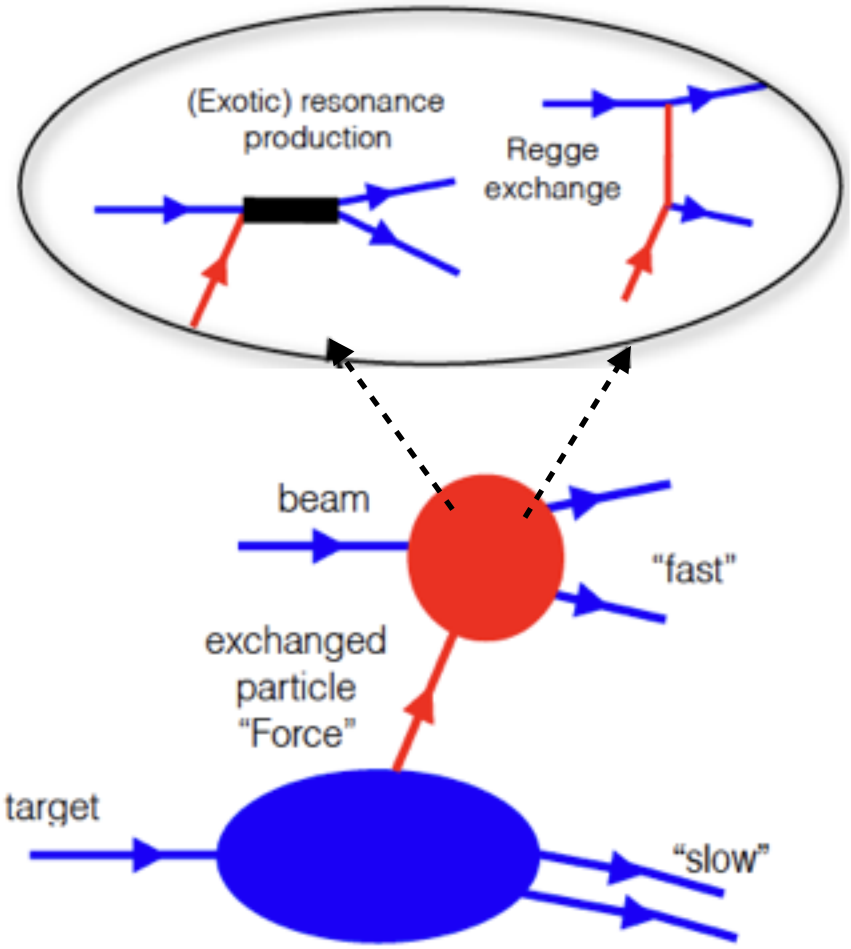
Regge factorization





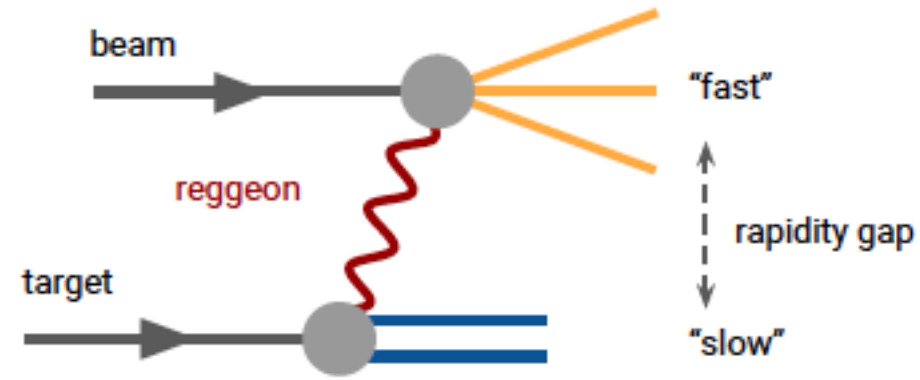


- Need to establish factorization between beam and target fragmentation (Regge factorization)
- Single Regge pole exchange dominate over cut other singularities (cuts, daughters)



Global analysis of single Regge factorization

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



- Factorizable Regge pole exchange

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

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

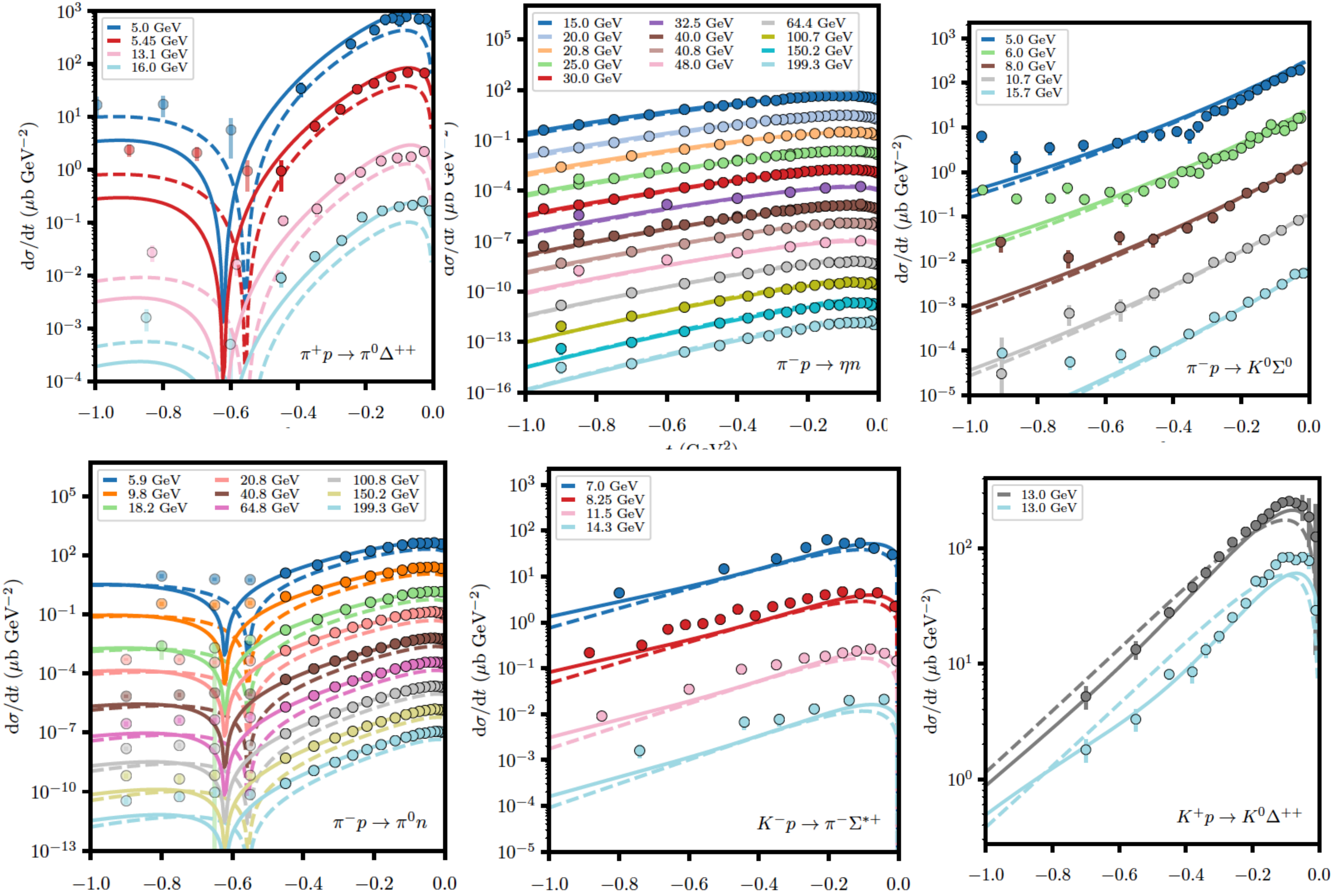
$$\mathcal{F}_e(s,t) = -\frac{\zeta_e \pi \alpha_e^1}{\Gamma(\alpha_e(t)-l_e+1)}\frac{1+\zeta_e e^{-i\pi\alpha_e(t)}}{2\sin\pi\alpha_e(t)}\left(\frac{s}{s_0}\right)^{\alpha_e(t)}$$

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

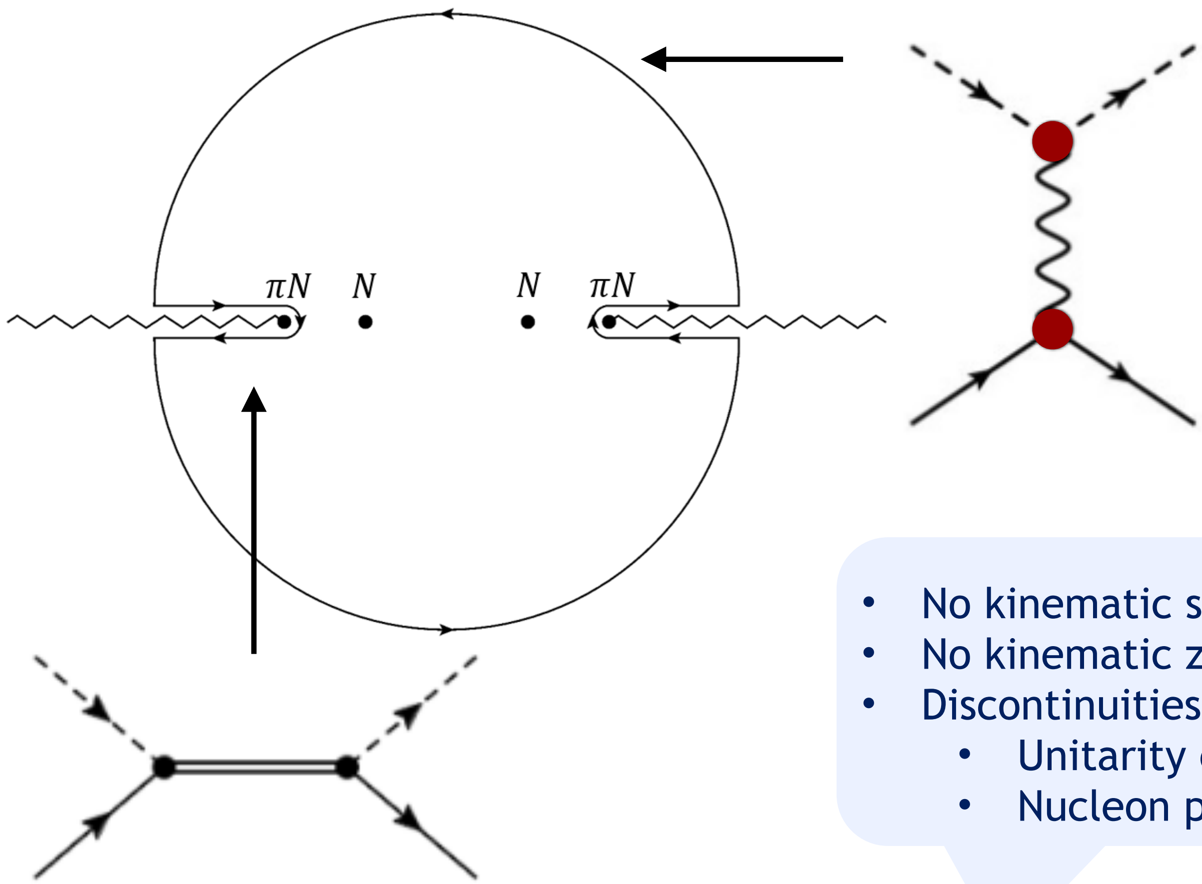
$$\mathcal{F}_e(s,t) \underset{t\to m_e^2}{\longrightarrow} \frac{(s/s_0)^{J_e}}{m_e^2 - t}.$$

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

Global Regge pole analysis



Finite Energy Sum Rules

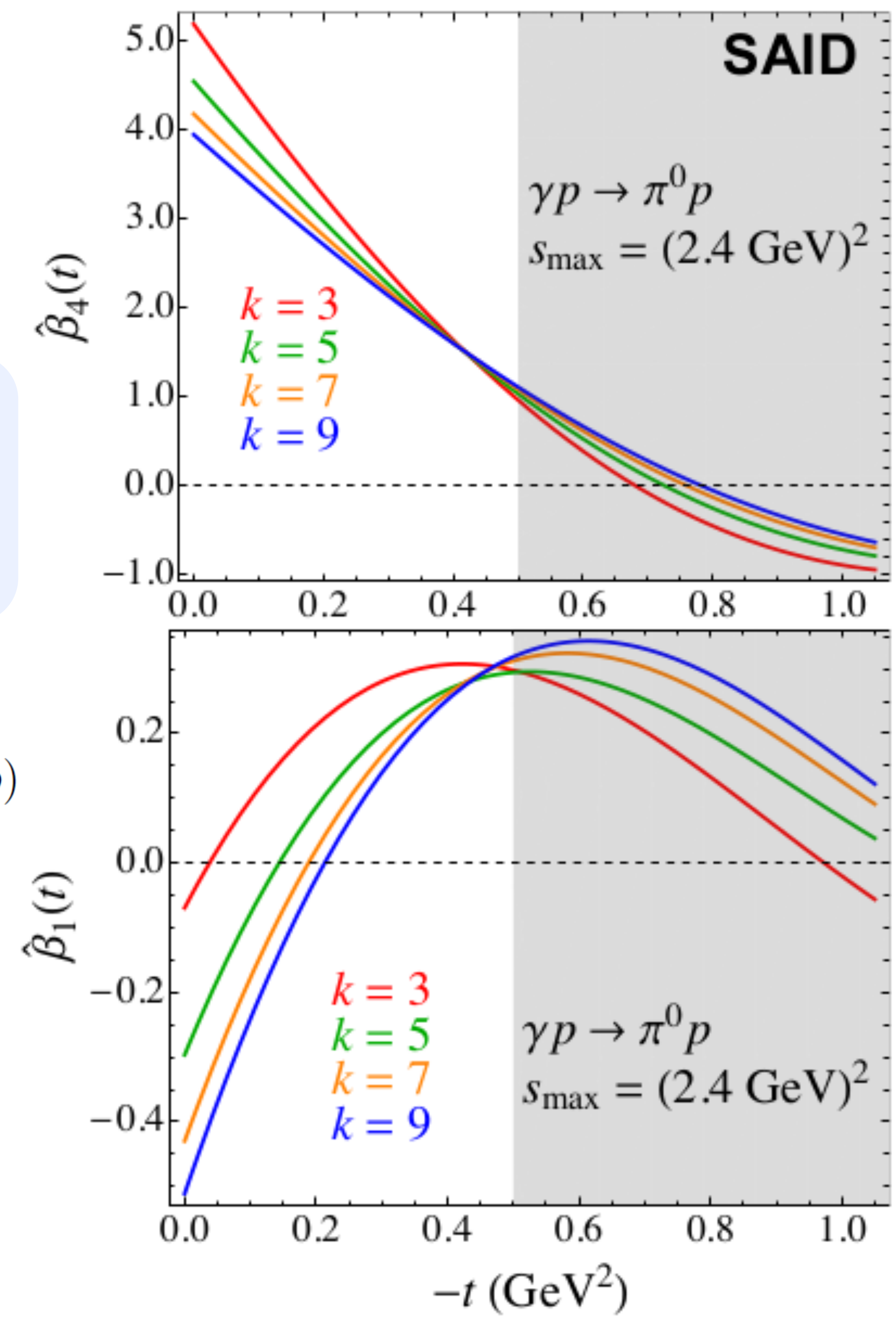


- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

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

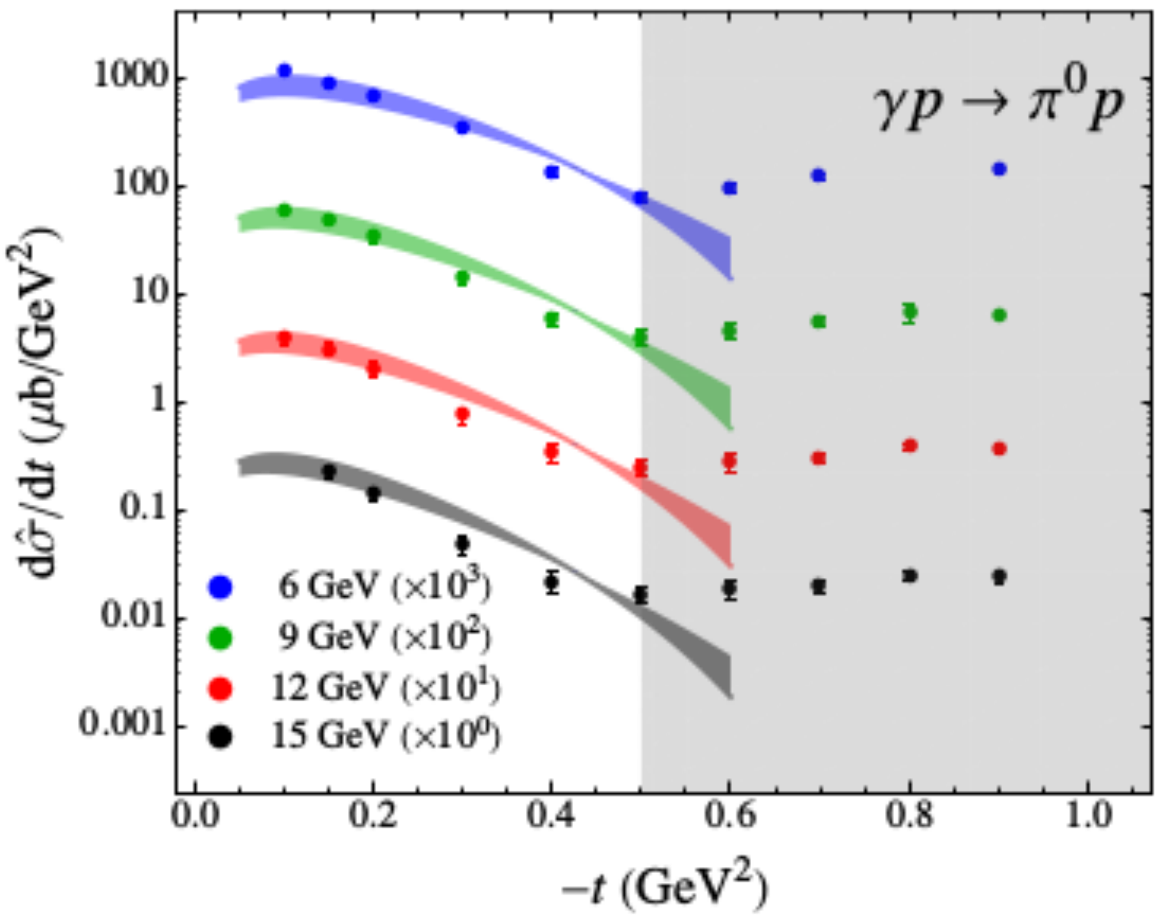
$$\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu = \beta_i(t)\frac{\Lambda^{\alpha(t)+k}}{\alpha(t)+k}$$

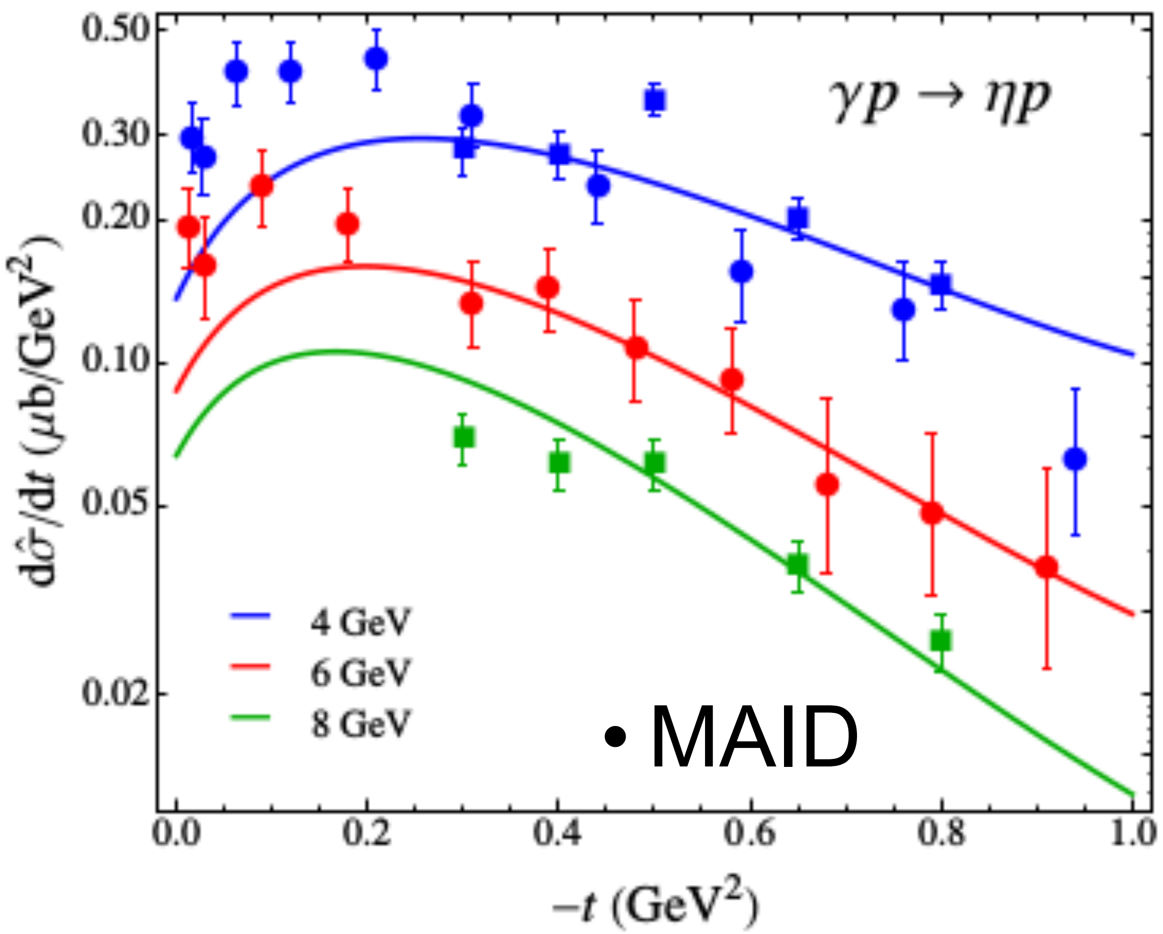
$$\beta_i(t) = \frac{\alpha(t)+k}{\Lambda^{\alpha(t)+k}}\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu$$



Finite Energy Sum Rules

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



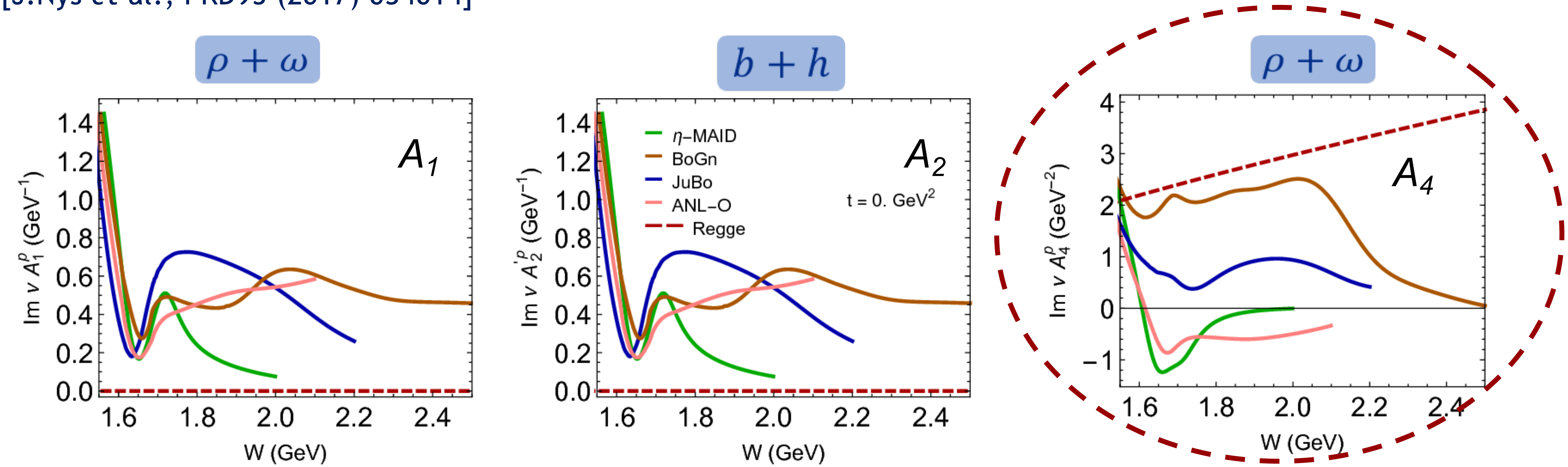


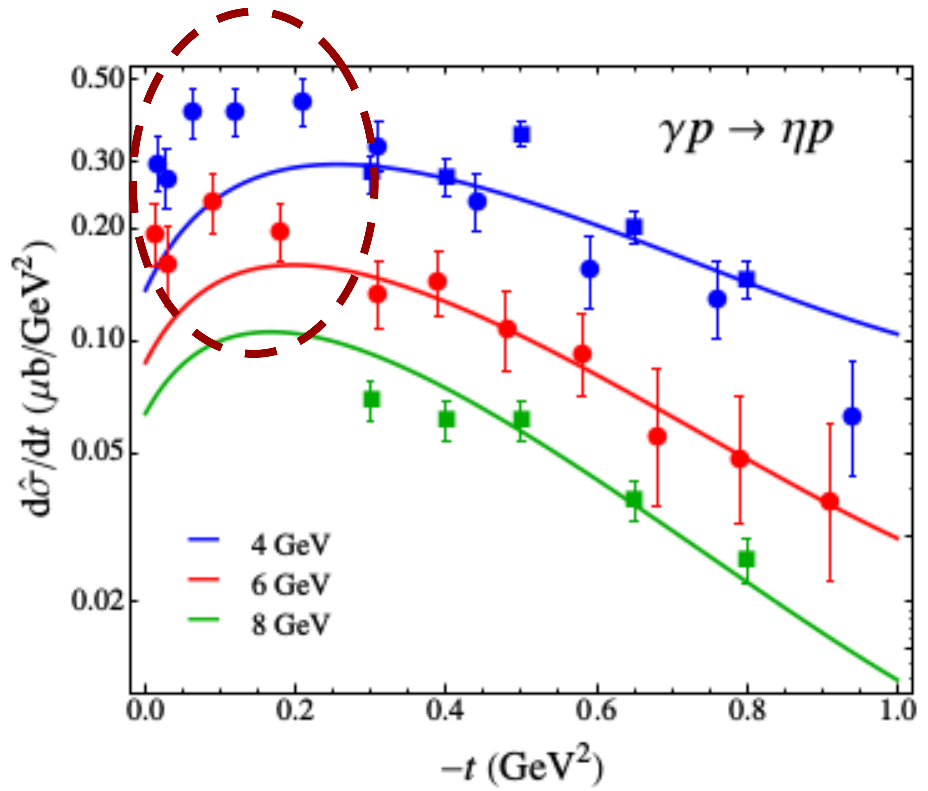
Combine energy regimes
- Low-energy model ((SAID, MAID, Bonn-Gatchina, Julich-Bonn,…)
- Predict high-energy observables

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

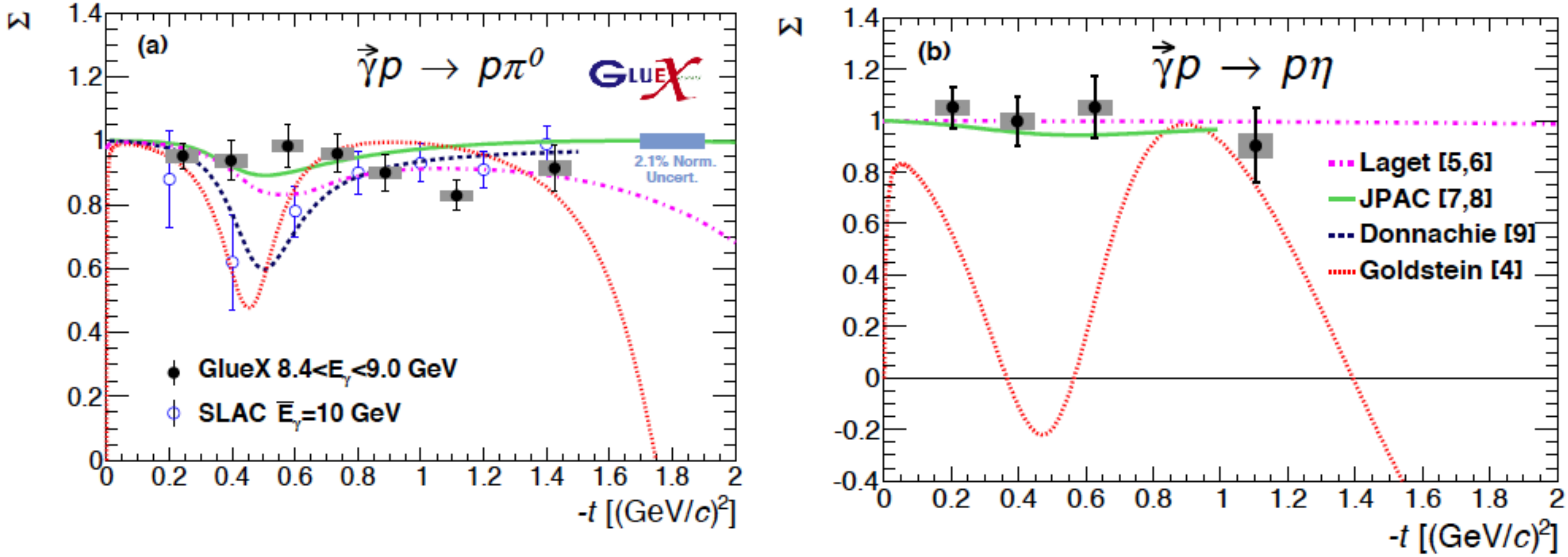
Possibilities

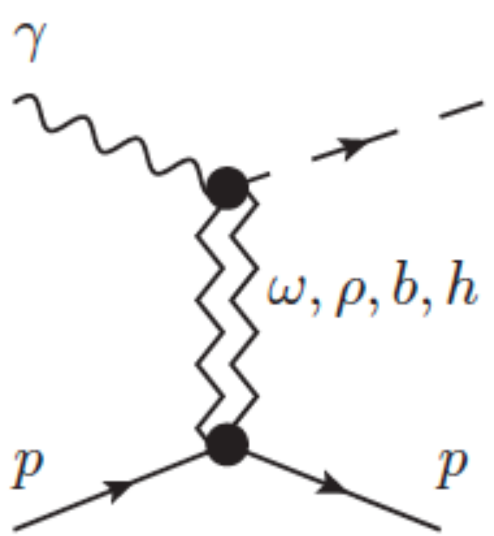
- Low-energy model inconsistent
- Cut-off not high enough
  - High mass resonances!

Beam asymmetry: measurement of the exchange process

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

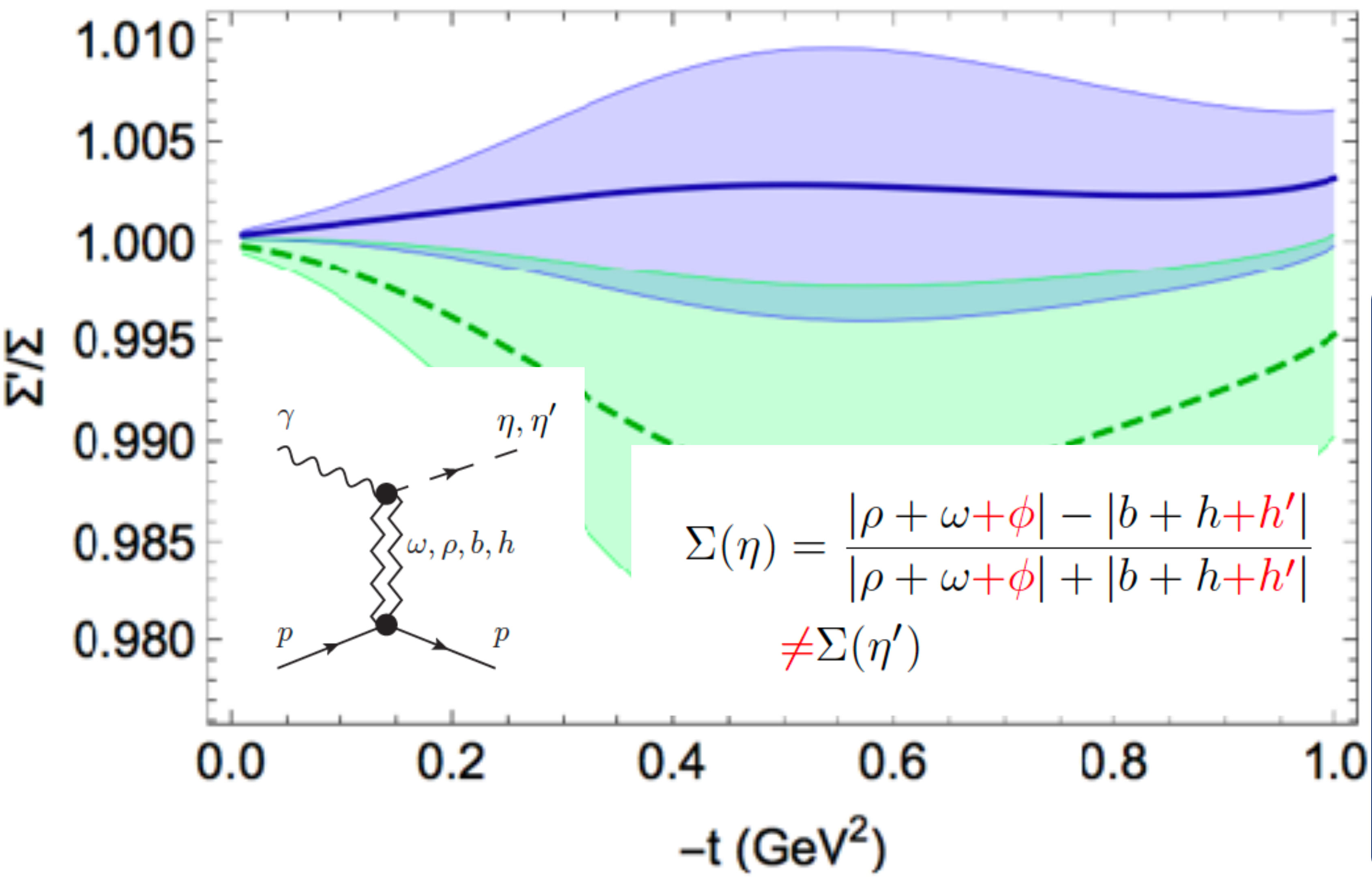
H. Al Ghoul et al. [GlueX]
Phys. Rev. C95 (2017) no.4, 042201
+V. Mathieu, J. Nys [JPAC]





- 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’

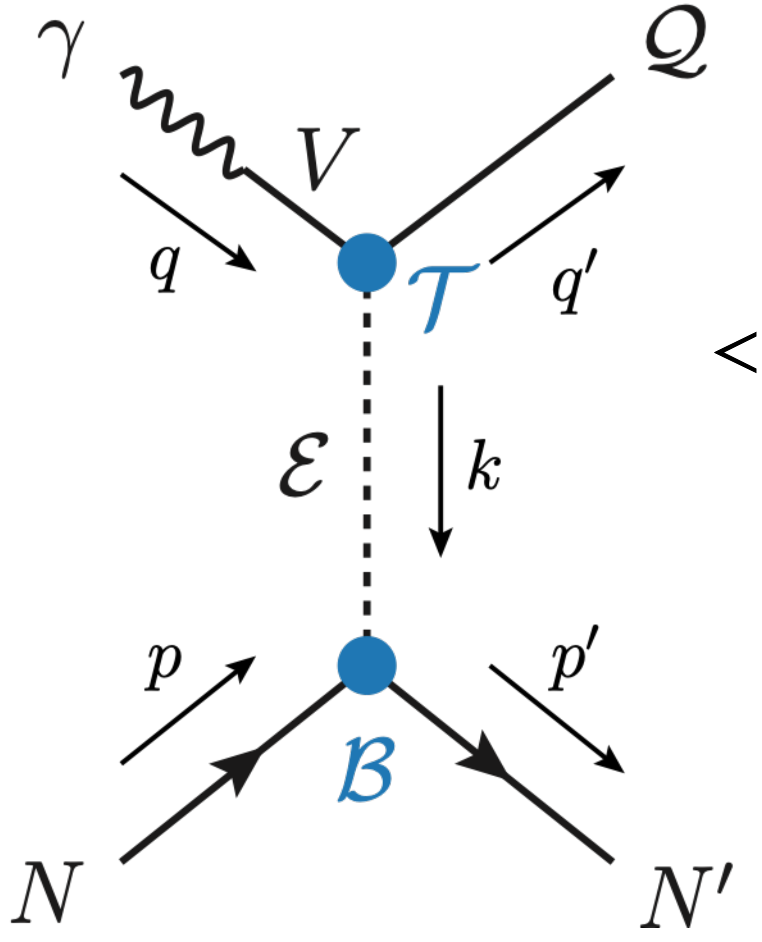
- Same exchanges
- Natural exchanges (ρ,ω) dominant
  - Couplings from radiative decays
  - Mixing angle cancels in ratio
- Unknown behavior of
  - ϕ exchange
  - unnatural exchanges (b,h)

Prediction: **≈ same beam asymmetry**

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

Exclusive photo-/electro-production of XYZ'd

- Couplings from data as much as possible, not relying on the nature of XYZ
- VMD is used to couple the incoming photon to a vector quarkonium V
- Bottom vertex from standard photoproduction phenomenology
- Top vertex from measured $\mathcal{Q} \to V \mathcal{E}$ decay width

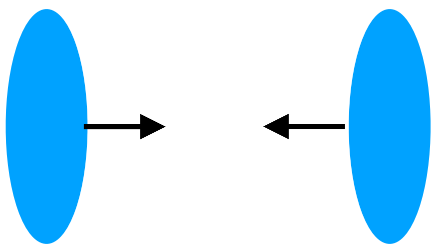


M. Albaladejo et al. [JPAC], PRD (2020)

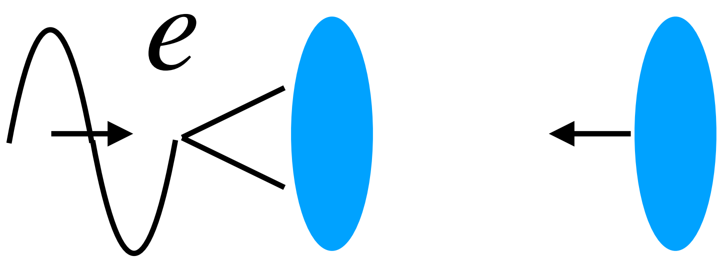
$$< \lambda_{\mathcal{Q}} \lambda'_N | T | \lambda_\gamma \lambda_N > = \sum_{V,\mathcal{E}} \frac{e f_V}{m_V} \mathcal{T}^{\alpha_1 \cdots \alpha_j}_{\lambda_V = \lambda_\gamma, \lambda_{\mathcal{Q}}} \mathcal{P}_{\alpha_1 \cdots \alpha_j; \beta_1 \cdots \beta_j} \mathcal{B}^{\beta_1 \cdots \beta_j}_{\lambda_N \lambda'_N}$$

Simple remarks about cross sections

$$\sigma_{a+b\to c+b} \sim \pi R_{eff}^2$$



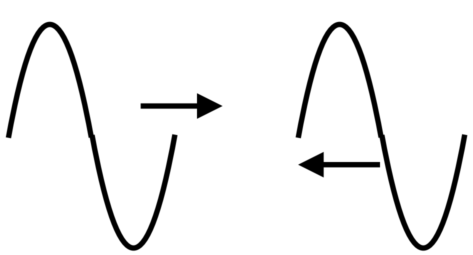
$(1-100)\ mb$



$(0.1-10)\ mb$

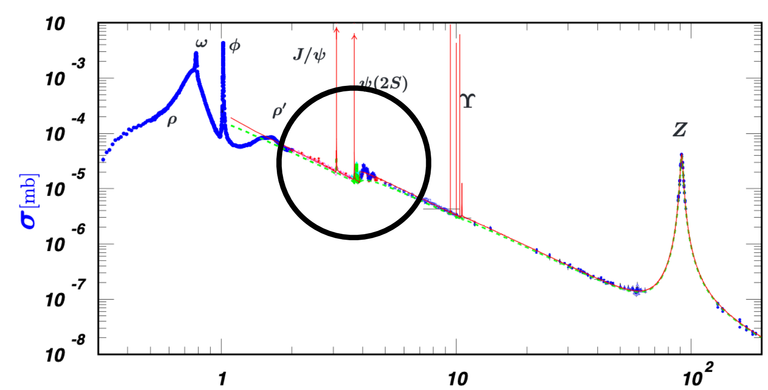
e/γ

- XYZ production cross section ~ 1 mb
- XYZ detection = production x branching ratio



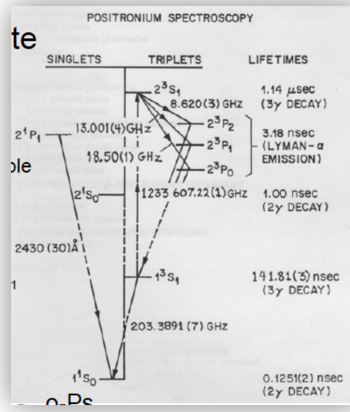
$R_{eff} \sim \frac{1}{\sqrt{s}}$

$$\sim 0.1mb \times [Br(R \to e^+e^-)Br(R \to f)]$$

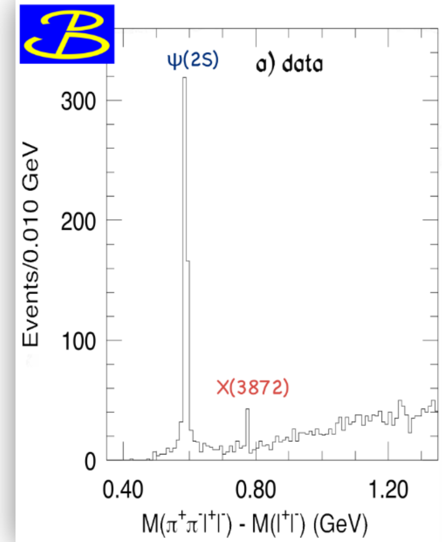


- For J/ψ $B(R \to l^+l^-) \sim 0.1$
- For other resonances $B(R \to l^+l^-) \sim 10^{-5} - 10^{-4}$

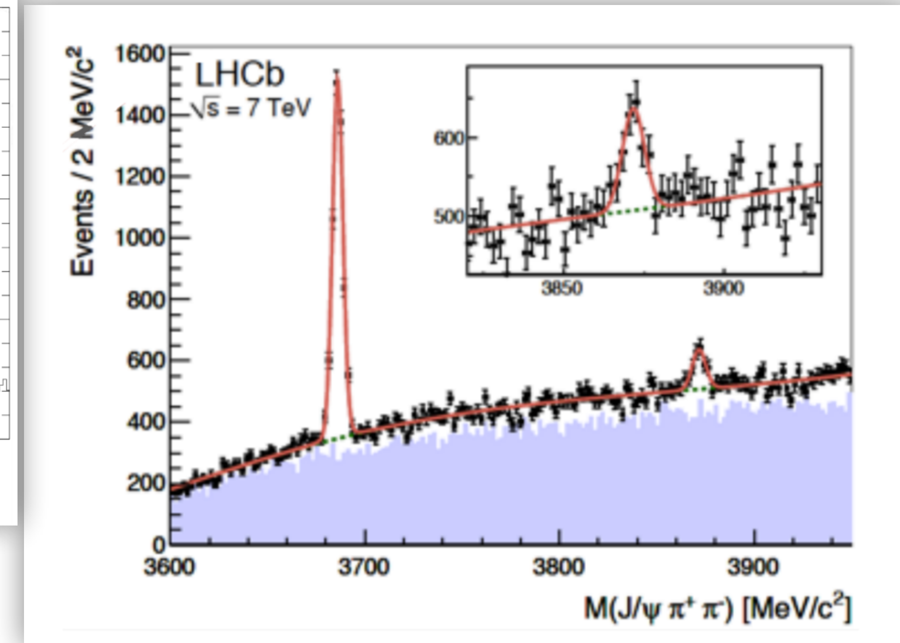
- The J/ψ and other $c\bar{c}'$ were expected to follow the positronium-like spectrum

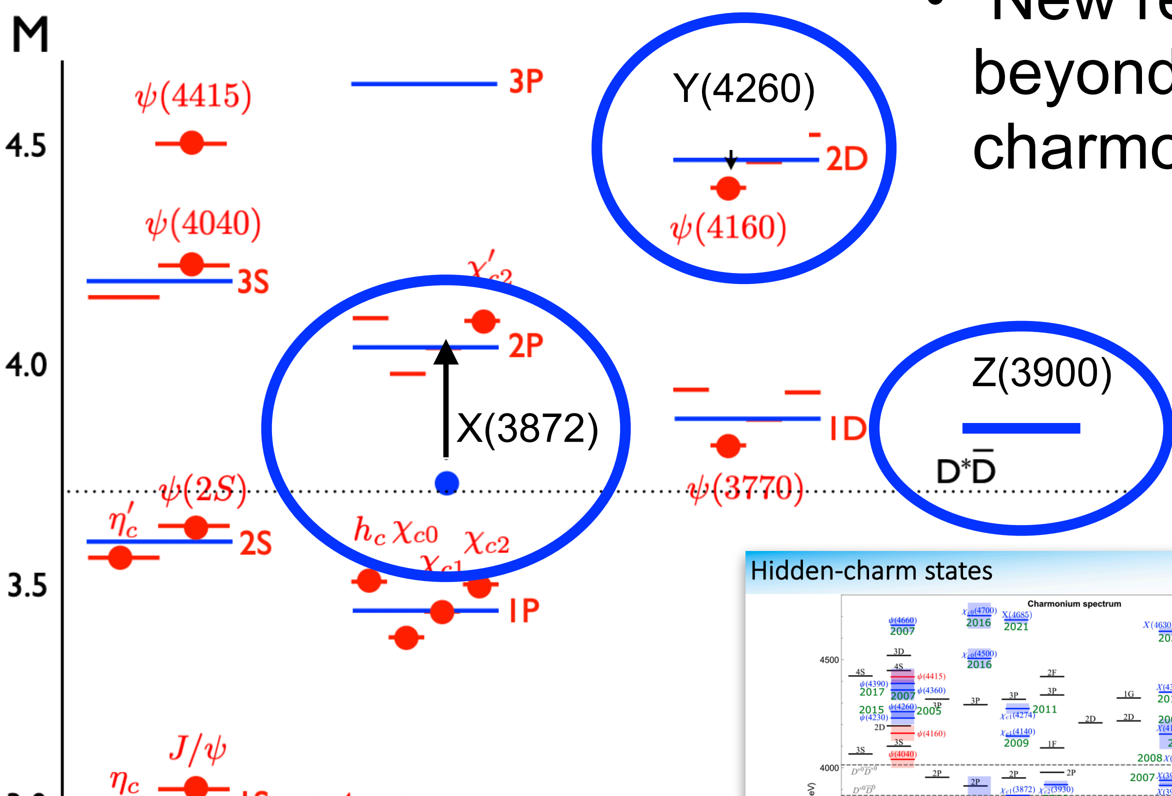


$$V(r) = -\frac{C_F \alpha_s}{r} + \sigma r$$



$X(3872)$ ($\chi_{c1}(3872)$)

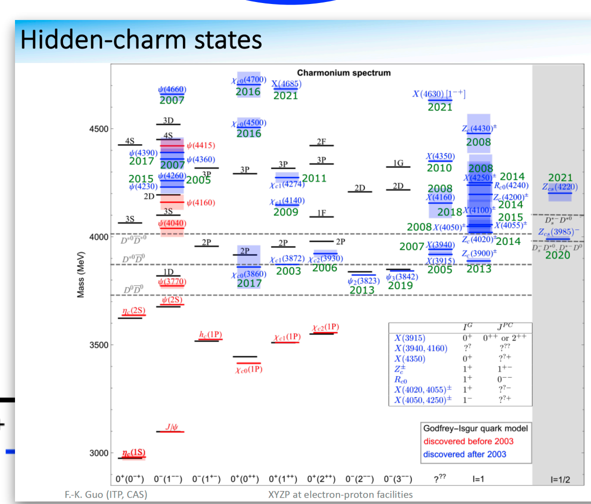




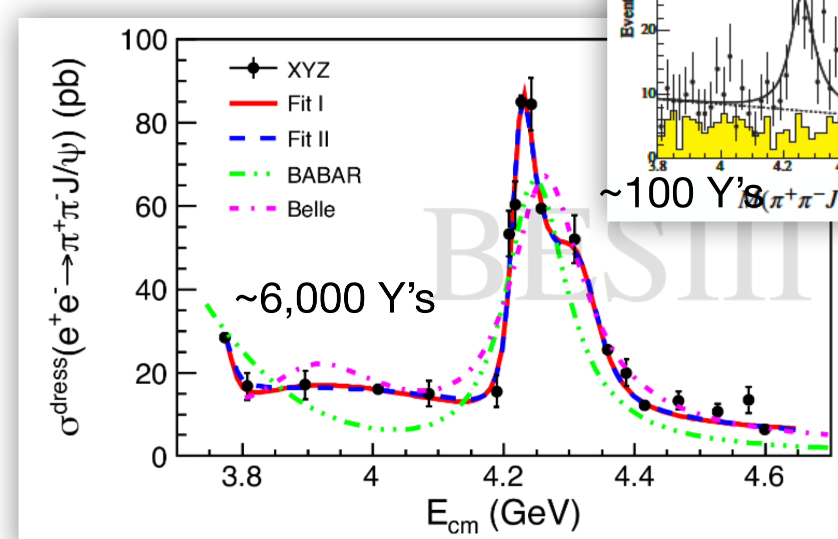
- New resonances (?) are beyond the usual charmonium interpretation

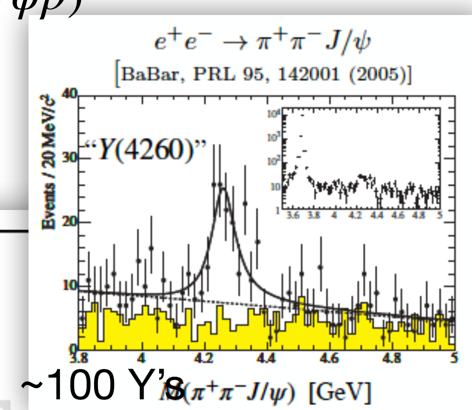
Very close to $D\bar{D}^*$ threshold
Isospin violation too big

$$\frac{\Gamma(X \to J/\psi\omega)}{\Gamma(X \to J/\psi\rho)} \sim 0.8 \pm 0.3$$



$Y(4260)$

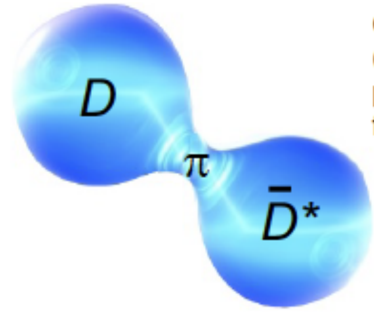


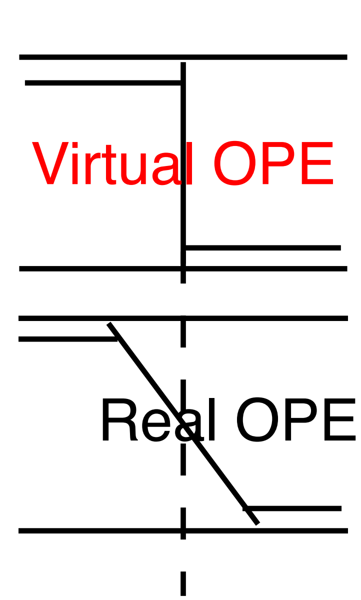


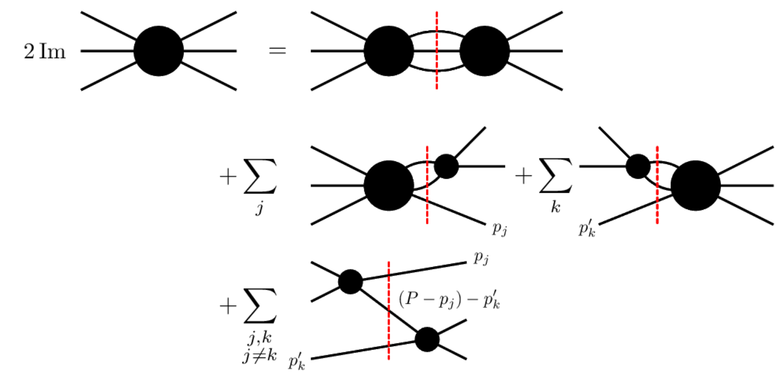
~100 Y's

- Not seen decaying into OZI-favored open charm pairs, but seen $J/\psi\ \pi\pi$

Interpretations







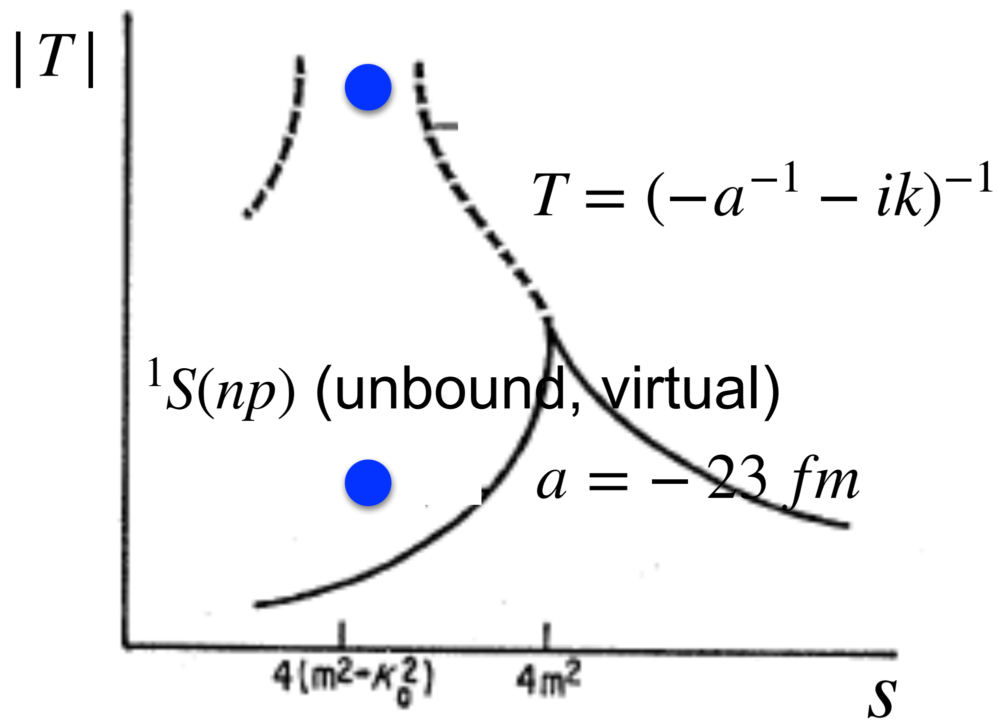
S-matrix meets lattice

Is X(3872) a molecule ?

$$M_{X(3872)} - M_{D^0} - M_{\bar{D}^{*0}}$$
$$= -0.01 \pm 0.14 MeV$$

$^3S(np)$ (bound deuteron)

$$a = +5\ fm$$

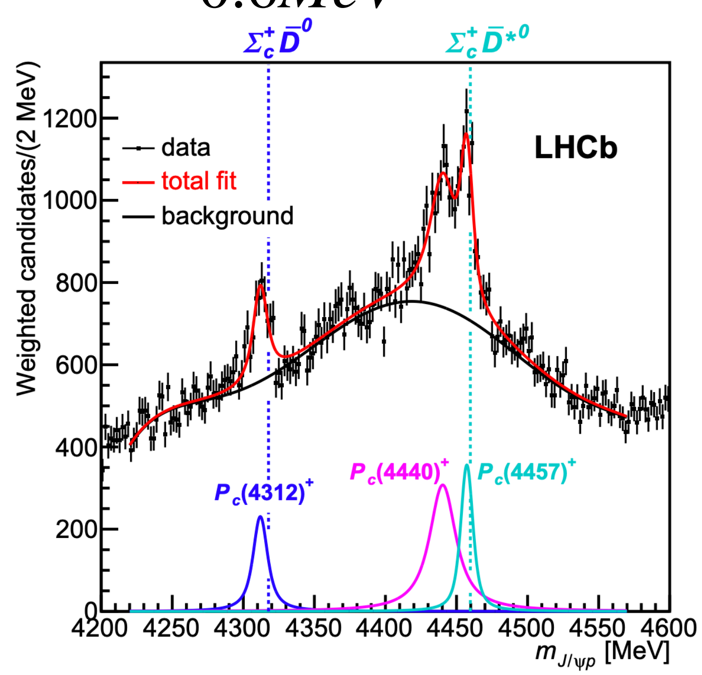


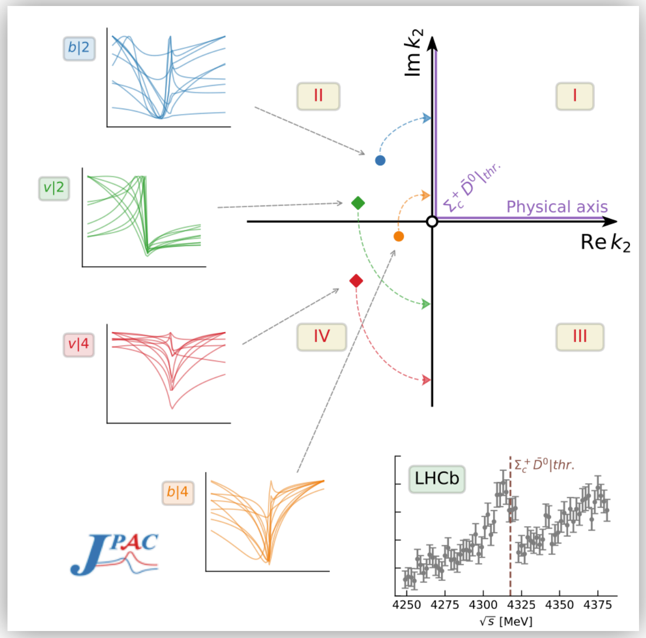
$^1S(np)$ (unbound, virtual)

$$a = -23\ fm$$

Is Pentaquark a molecule ?

$$-0.6 MeV$$

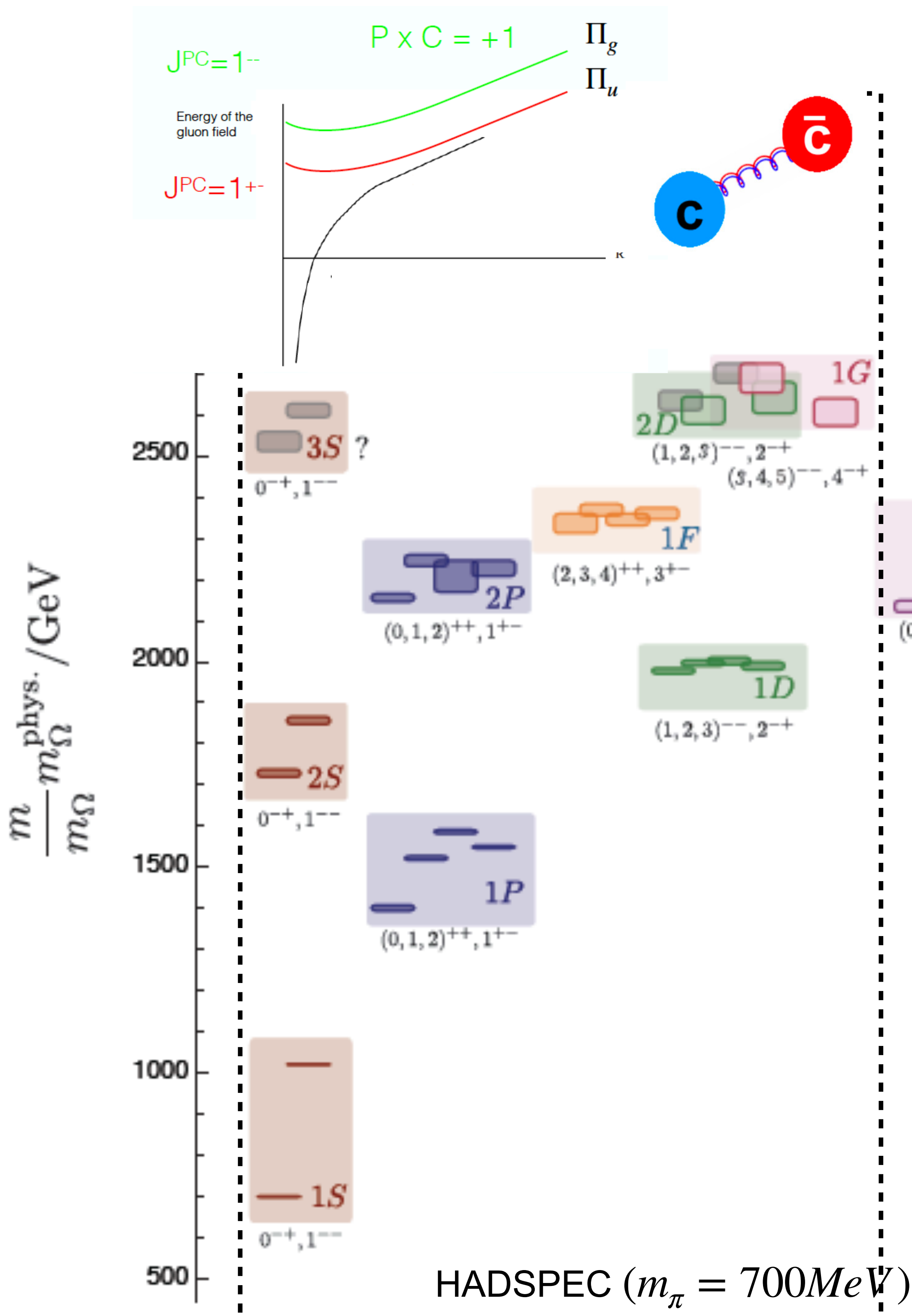




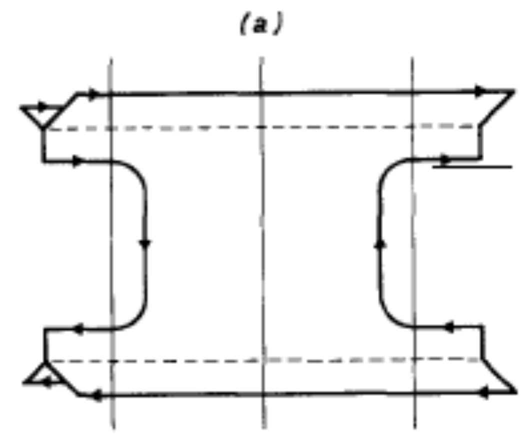
Hadron spectroscopy meets AL/ML

Interpretations

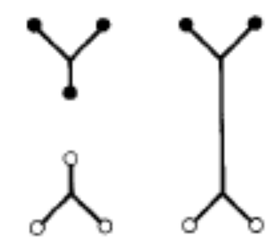
Multiquarks : QCD string and its excitations could result in hybrids, tetra-quarks, penta-quarks



Is Y(4260) one of the 4 lowest hybrids



tetraquark - (anti)baryon duality

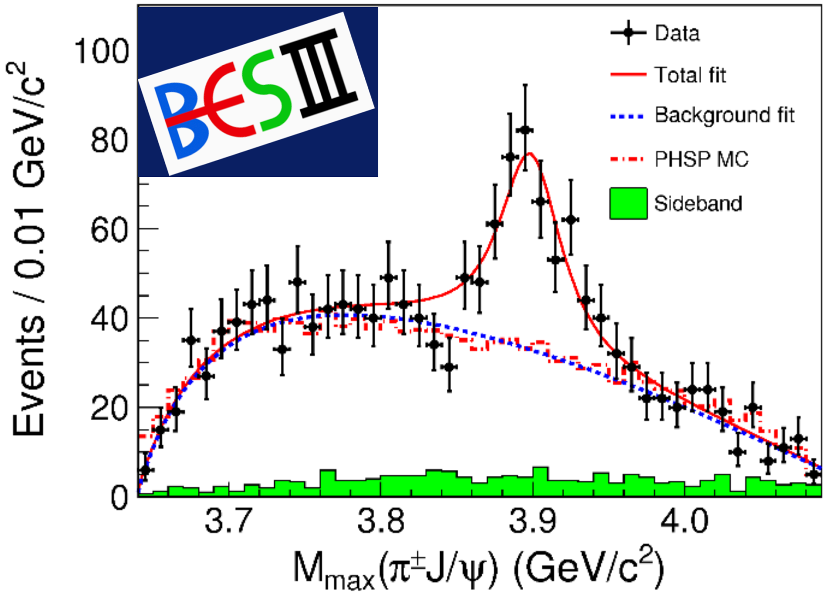


Muti quark states and duality (large-N_c, QCD strings)

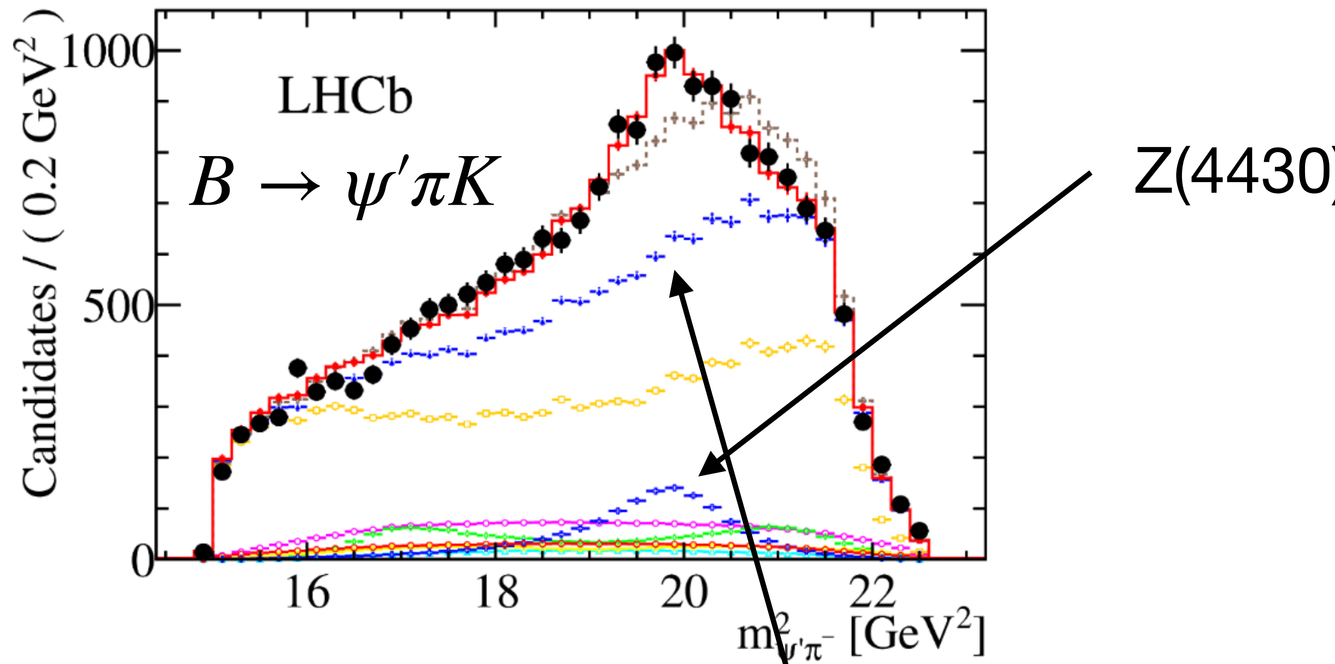
G.Rossi G. Veneziano
Phys. Rep.1982

Interpretations

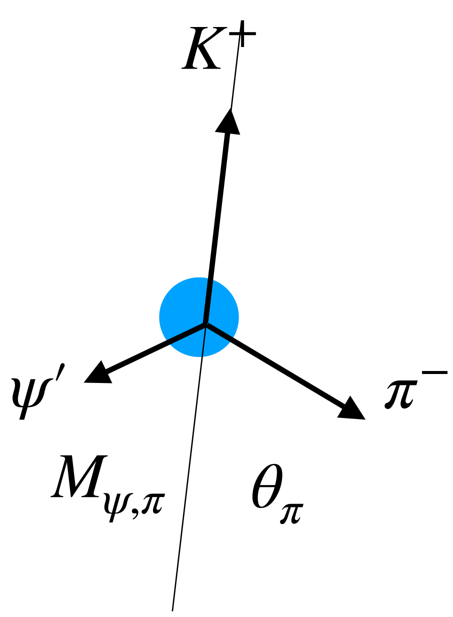
Are the Z's true resonances or kinematic effects



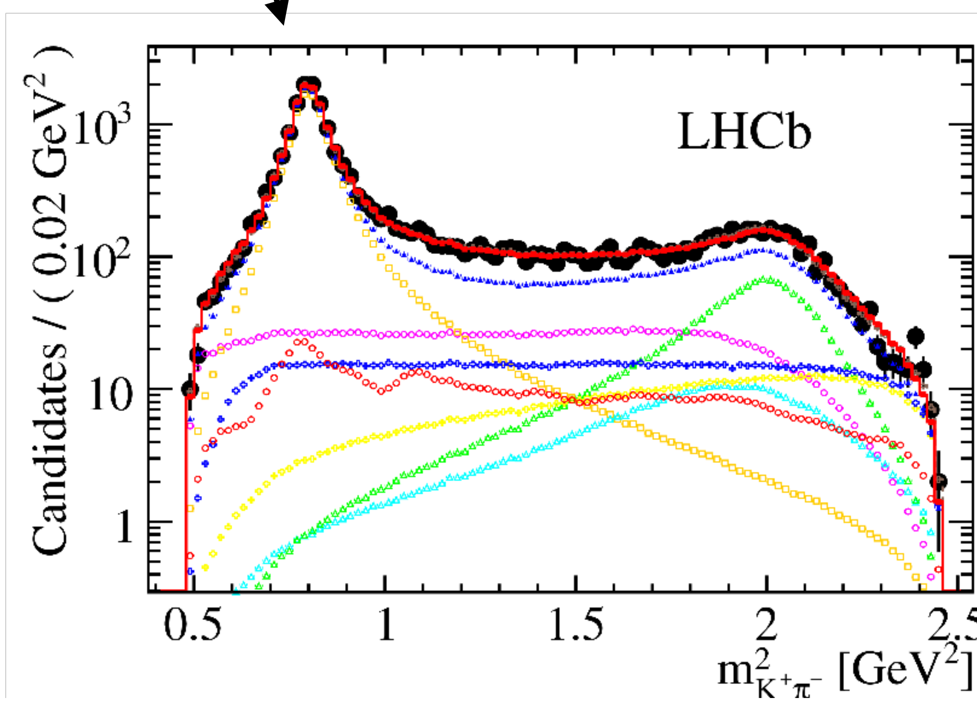
$e^+e^- \to Y \to J/\psi\pi^+\pi^-$



Kinematic effects from K* decays ?



$$B \to \psi'\pi^-K^+ \begin{cases} \nearrow K^{*0}\psi' \to \pi^-K^+\psi' \\ \searrow Z^-K^+ \to \psi'\pi^-K^+ \end{cases}$$



Need for complete amplitude analysis

XYZP phot-electro/production (reviews)

$XYZP$ spectroscopy at a charm photoproduction factory

M. Albaladejo,[1] M. Battaglieri,[2,3] A. Esposito,[4] C. Fernández-Ramírez,[5]
A. N. Hiller Blin,[1] V. Mathieu,[6] W. Melnitchouk,[1] M. Mikhasenko,[7] V. I. Mokeev,[2]
A. Pilloni,[3,8,*] A. D. Polosa,[9] J.-W. Qiu,[1] A. P. Szczepaniak,[1,10,11] and D. Winney[10,11]

LoI RF7_RF0_120

arXiv:2203.08290

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

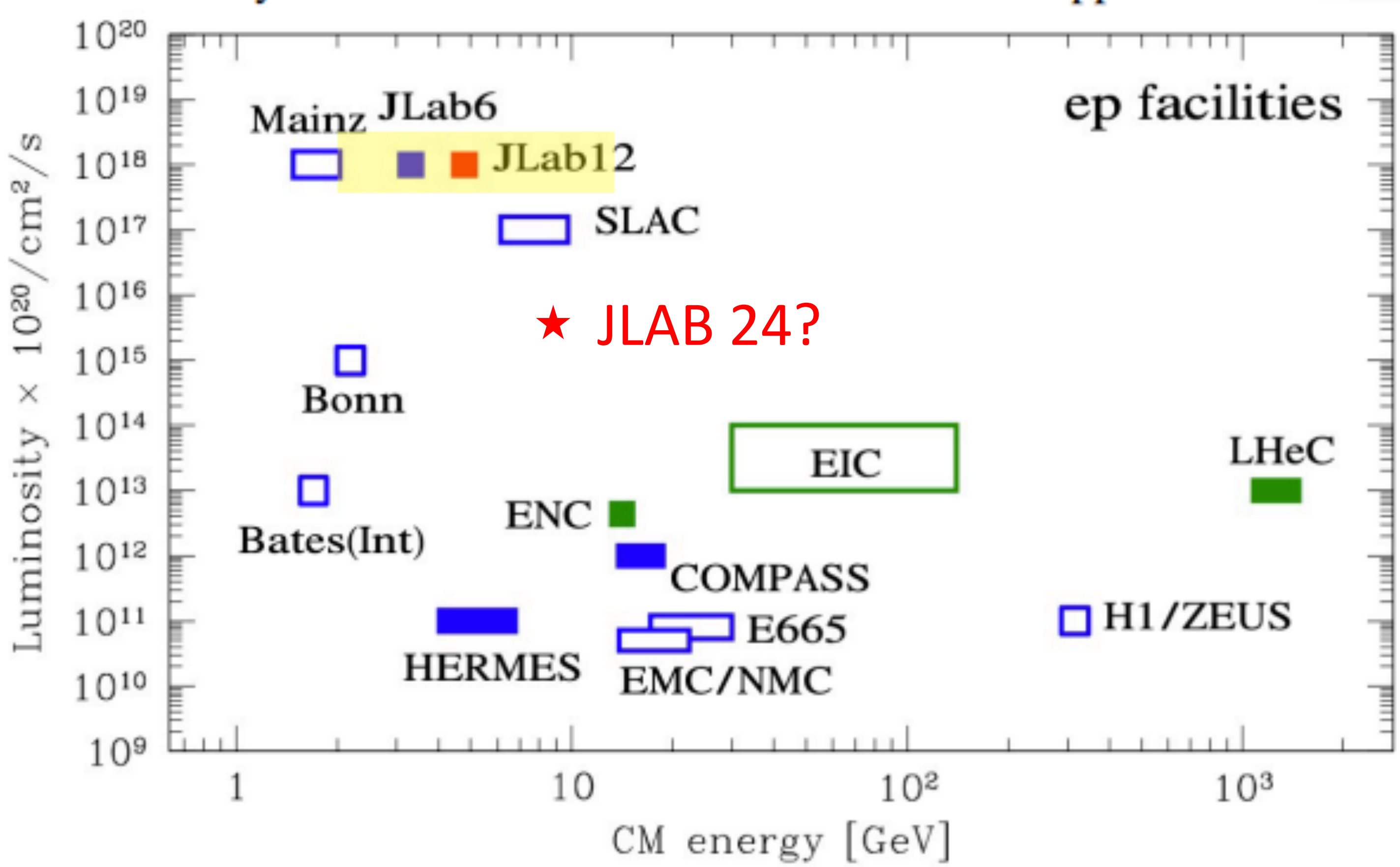
Hadron Spectroscopy in Photoproduction

Miguel Albaladejo[1], Lukasz Bibrzycki[2], Sean Dobbs[3], César Fernández-Ramírez[4,5],
Astrid N. Hiller Blin[6], Vincent Mathieu[7,8], Alessandro Pilloni[9,10], Justin Stevens[11],
Adam P. Szczepaniak[12,13,14], and Daniel Winney[13,14,15,16]

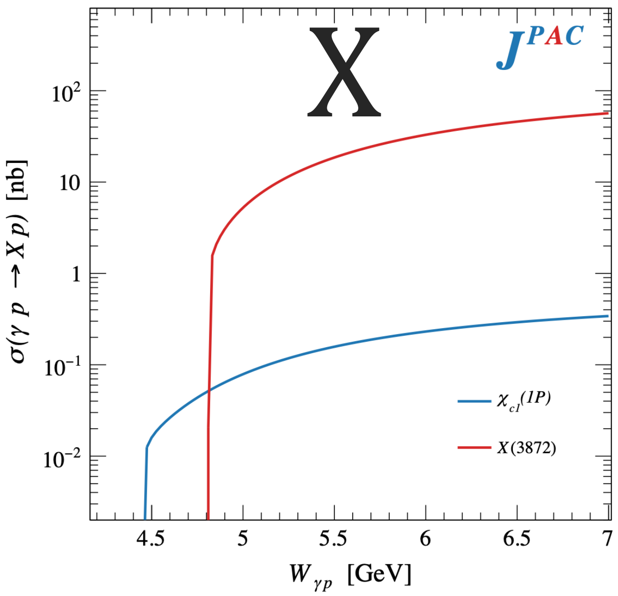
arXiv:2112.00060

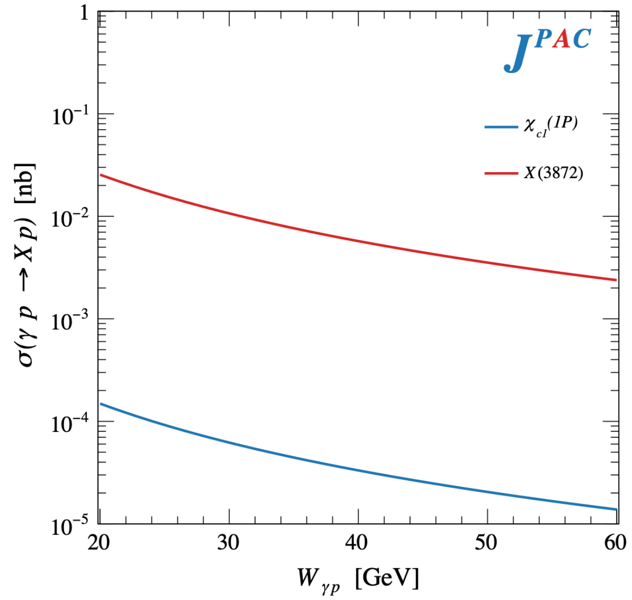
Physics with CEBAF at 12 GeV and Future Opportunities

Ent[2], Qiu[2,8],

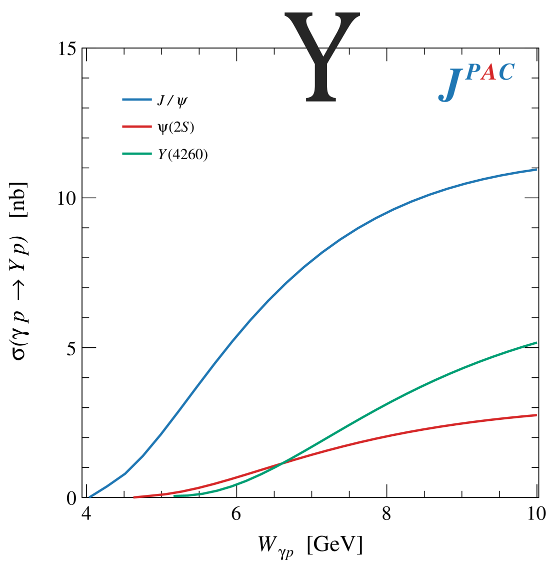


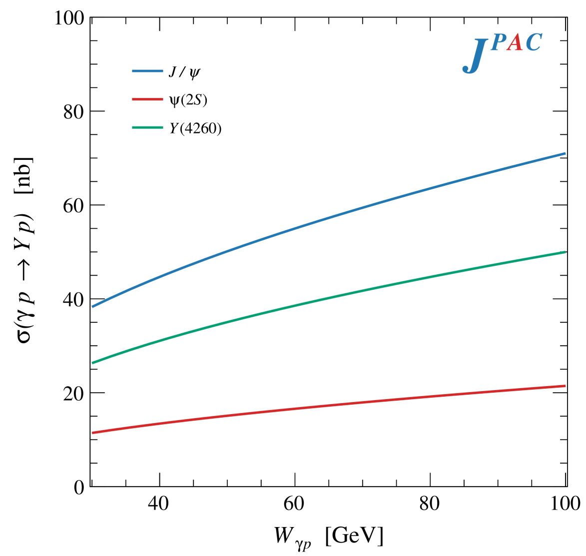
EIC/JLab++ explore the complementarity of diffraction, peripheral and/or direct production



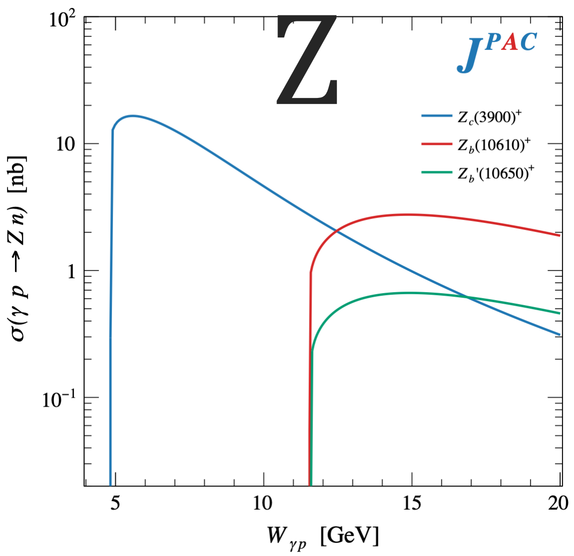


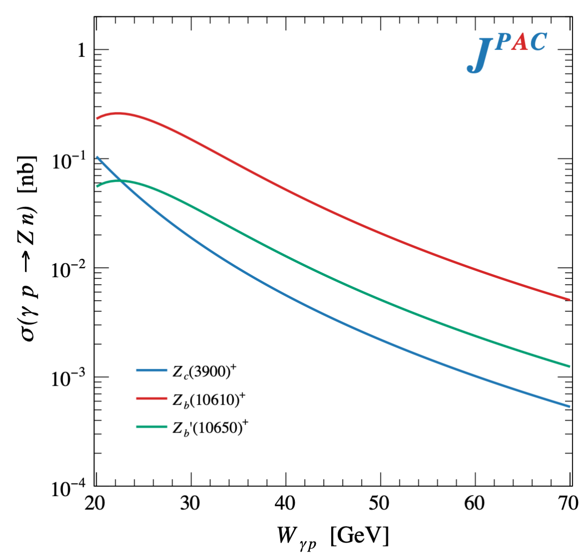
- **ω** and **ρ** exchanges give main contributions:





- Diffractive production, dominated by Pomeron (2-gluon) exchange. Benefits from higher energies at the EIC

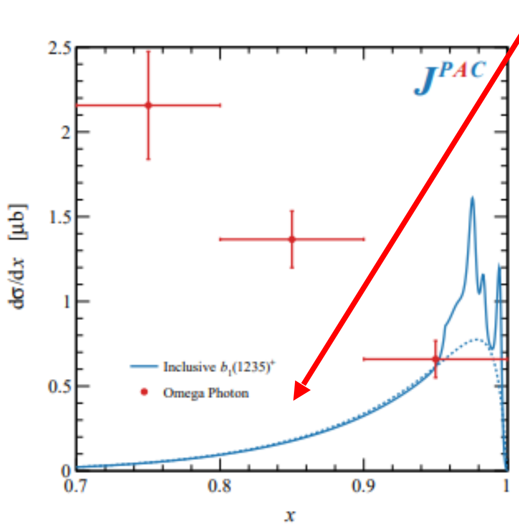




- Focus $Z_c(3900) \to J/\psi\pi$, $Z_b(10610) \to \Upsilon(nS)\pi$, pion is exchange

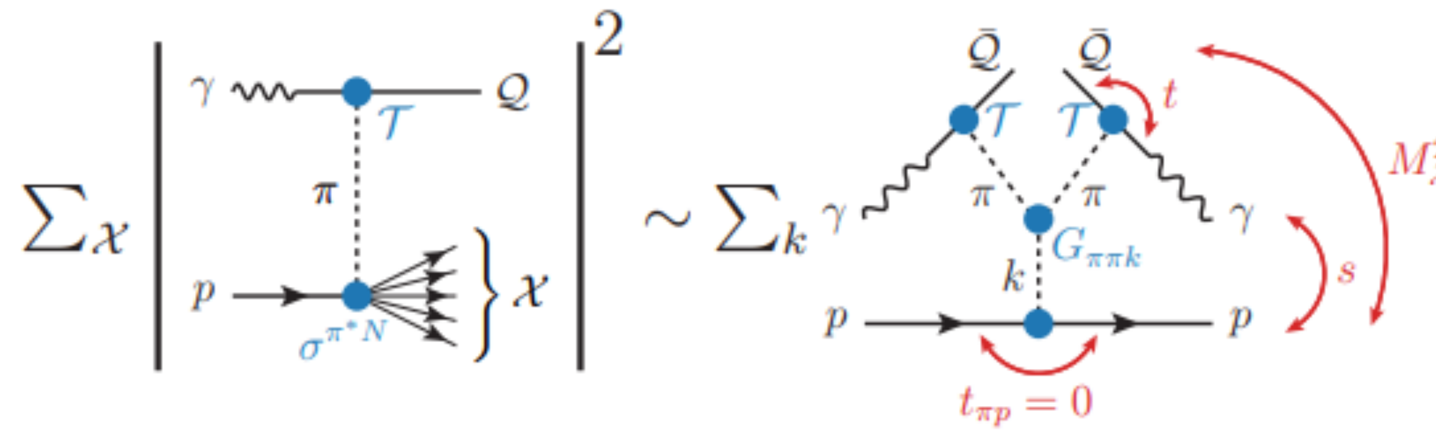
Semi-inclusive production of the Z's

- Semi-inclusive cross sections are typically larger
- For small t and large x, one can assume the process to be dominated by pion exchange
- The bottom vertex depends on the (known) pion-proton total cross section
- The pion is exchanged in the t-channel
- Model benchmarked on b_1 production

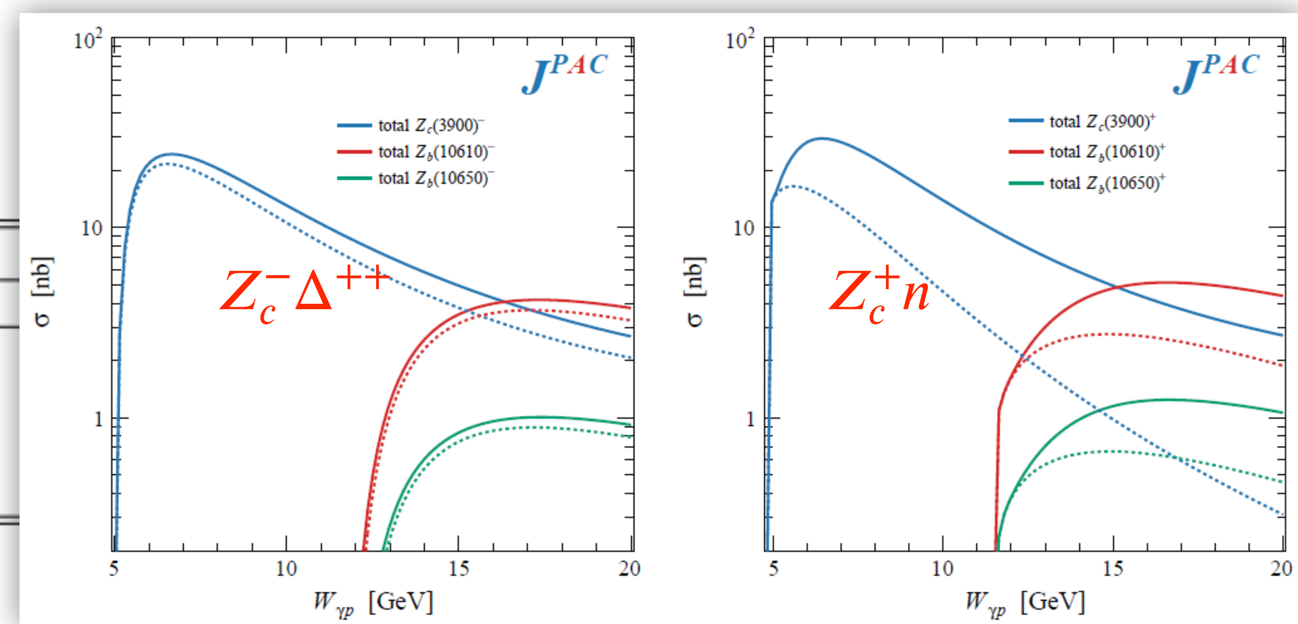


Model underestimates lower bins, conservativ estimates

The model is expected to hold in the highest bin

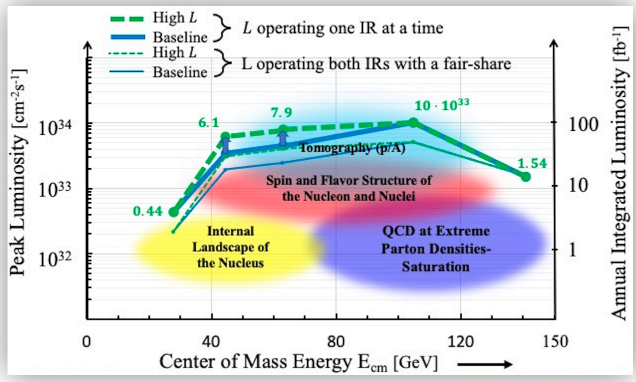


$\mathcal{Q}$	$\sigma(\gamma p \to \mathcal{Q}^\pm \mathcal{X})$ [pb] 30 GeV	60 GeV	90 GeV	$\sigma(\gamma p \to \mathcal{Q}^+ n)$ [pb] 30 GeV	60 GeV
$b_1(1235)$	$60 \cdot 10^3$	$60 \cdot 10^3$	$61 \cdot 10^3$	43	2.3
$Z_c(3900)$	187	146	140	19	1.0
$Z_b(10610)$	163	15	5	150	10
$Z_b(10650)$	40	4	1	37	2.4



XYZ yields

- X,Z production benefits form low CM energies
- Luminosity too low at 28 GeV
- Current simulations for 41 GeV configuration
- Luminosity assumed $6.1 \times 10^{33} cm^{-2} s^{-1}$



D. Glazier @ EIC Workshop

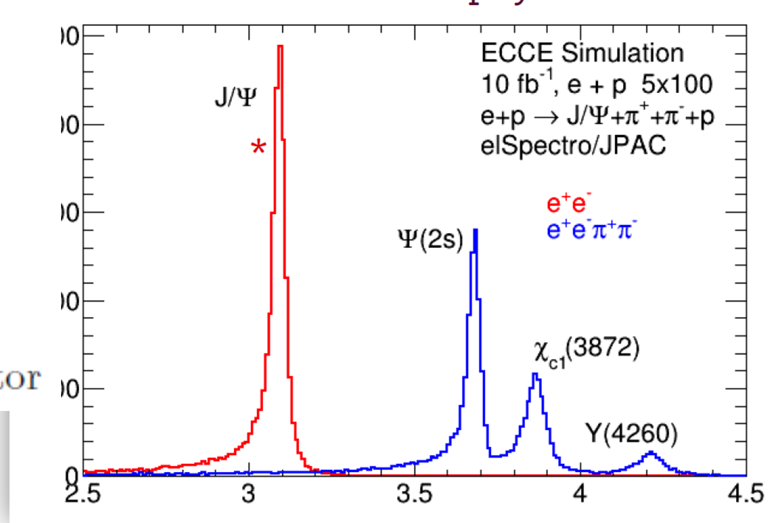
TABLE II. Summary of results for production of some states of interest at the EIC electron and proton beam momentum $5 \times 100 (GeV/c)$ (for electron x proton). Columns show : the meson name; our estimate of the total cross section; production rate per day, assuming a luminosity of 6.1×10^{33} cm^{-2}s^{-1}; the decay branch to a particular measurable final state; its ratio; the rate per day of the meson decaying to the given final state.

Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\ \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\ J/\Psi$	100	46
$Z_{cs}(4000)$	0.23	0.20 M	$J/\Psi\ K^+$	10	1.2 k
$Z_b(10610)$	0.04	0.034 M	$\Upsilon(2S)\ \pi^+$	3.6	24

	17 GeV		24 GeV	
	produced	detected	produced	detected
$Z_c(3900)^+$	2.2 k	371	4.2 k	588
$X(3872)$	1.1 k	32	4.2 k	63

TABLE I. Estimates of yields for day of data taking at CLAS24 assuming a zero-angle electron detector

ecce-note-phys-2021-12



Comparable yields at the EIC or at a possible upgraded CLAS24

JPAC members 2022