

EXOTICA IN HADRON SPECTROSCOPY

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4TH PIKIO MEETING

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Joint Physics Analysis Center

JPAC is a collaboration between theorists, phenomenologists, and experimentalists to provide phenomenological and data analysis tools for hadron physics

~ 20 active members

> 40 Research Papers (Phys.Rev., Phys.Lett, Eur.J. Phys.) O(10)

ongoing analyses

Regular lecture series on relativistic reaction theory

Summer Workshop on Reaction Theory (2015 & 2017)

<http://www.indiana.edu/~ssrt/>

The screenshot shows the website for the Joint Physics Analysis Center (JPAC) project. At the top, logos for Indiana University Bloomington, Jefferson Lab (Thomas Jefferson National Accelerator Facility), and The George Washington University are displayed. Below the logos, the text "Joint Physics Analysis Center" is centered, with navigation links for HOME, PROJECTS, PUBLICATIONS, and LINKS. A National Science Foundation (NSF) logo is also present, with the text "This project is supported by NSF". The main title of the page is $\gamma p \rightarrow \eta p$. The content includes a paragraph stating: "We present the model published in [Nys16]. The differential cross section for $\gamma p \rightarrow \eta p$ is computed with Regge amplitudes in the domain $E_\gamma \geq 4$ GeV and $0 \leq -t \leq 1$ (in GeV^2). We use the CGLN invariant amplitudes A_i defined in [Chew57a]. See the section Formalism for the definition of the variables. The model and its context is detailed in [Nys16]. We report here only the main features of the model." To the right of this text is a Feynman diagram showing a photon (γ) with momentum k and a proton (p) with momentum p_2 interacting at a vertex to produce an eta meson (η) with momentum q and a proton (p) with momentum p_4 . The interaction is mediated by a Reggeon with momentum ω and parameters ρ, b, h . Below the text is a section titled "Formalism" which states: "The differential cross section is a function of 2 kinematic variables. The first is the beam energy in the laboratory frame E_γ (in GeV) or the total energy squared s (in GeV^2). The second is the cosine of the scattering angle in the rest frame $\cos \theta$ or the" and provides instructions to download an output file and lists the columns: t (GeV^2), \cos (θ), $D\text{sig}/D\text{t}$ (micro barn/ GeV^2), $D\text{sig}/D\Omega$ (micro barn), and Sigma (θ). Below this is a section titled "Observable: differential cross section" with instructions to download plots for $O_x=t$ and $O_x=\cos$. Two plots are shown: the left plot shows $D\text{sigma}/D\text{t}$ (micro b/ GeV^2) vs t (GeV^2) with a blue curve peaking at $t \approx -0.1$; the right plot shows $D\text{sig}/D\Omega$ (micro b) vs $\cos \theta$ with a red curve peaking at $\cos \theta \approx 0.98$.

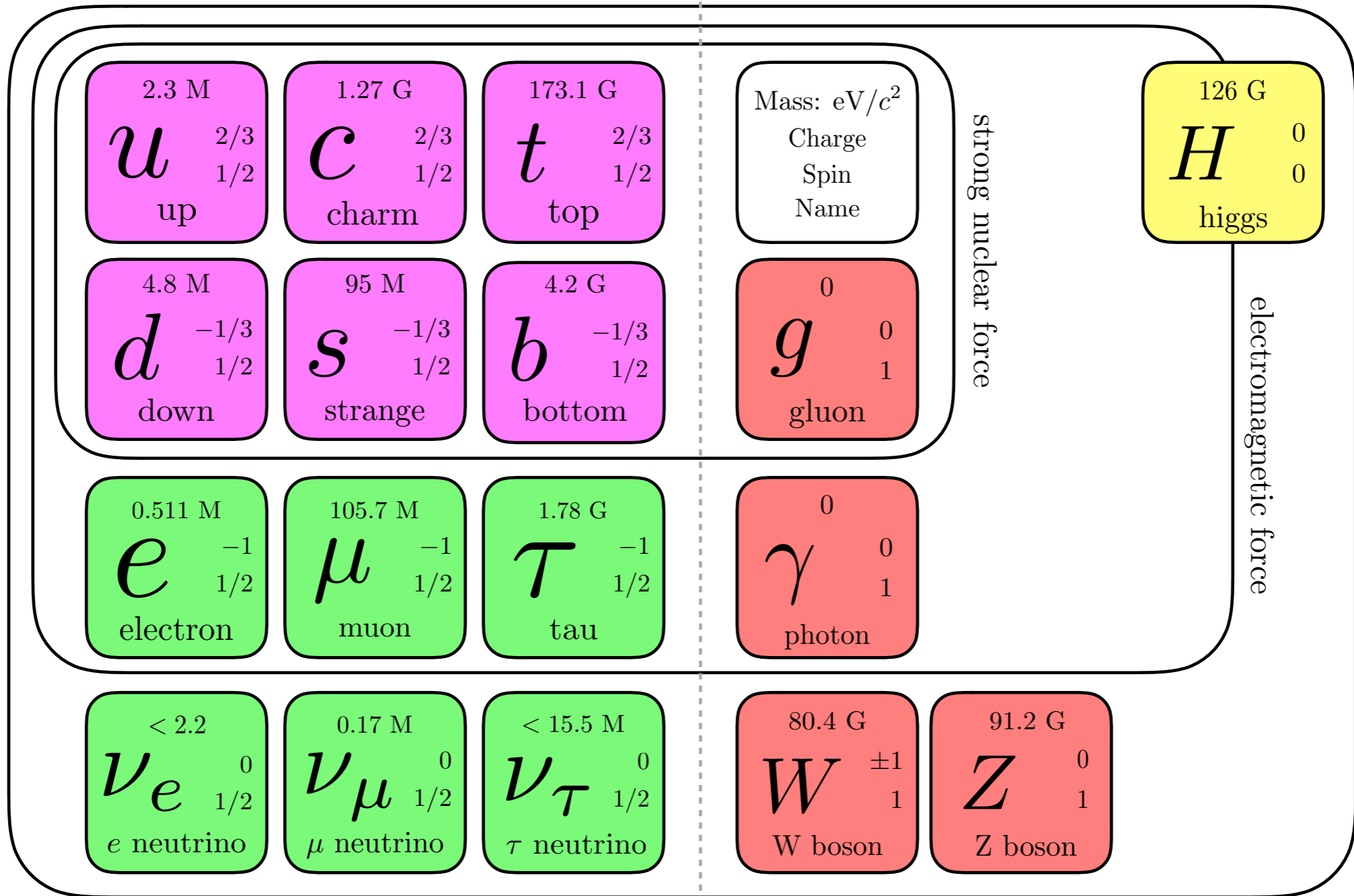
QUARKS

LEPTONS

1st

2nd

3rd



FERMIONS

GAUGE BOSONS

strong nuclear force

electromagnetic force

weak nuclear force

QCD and Hadrons

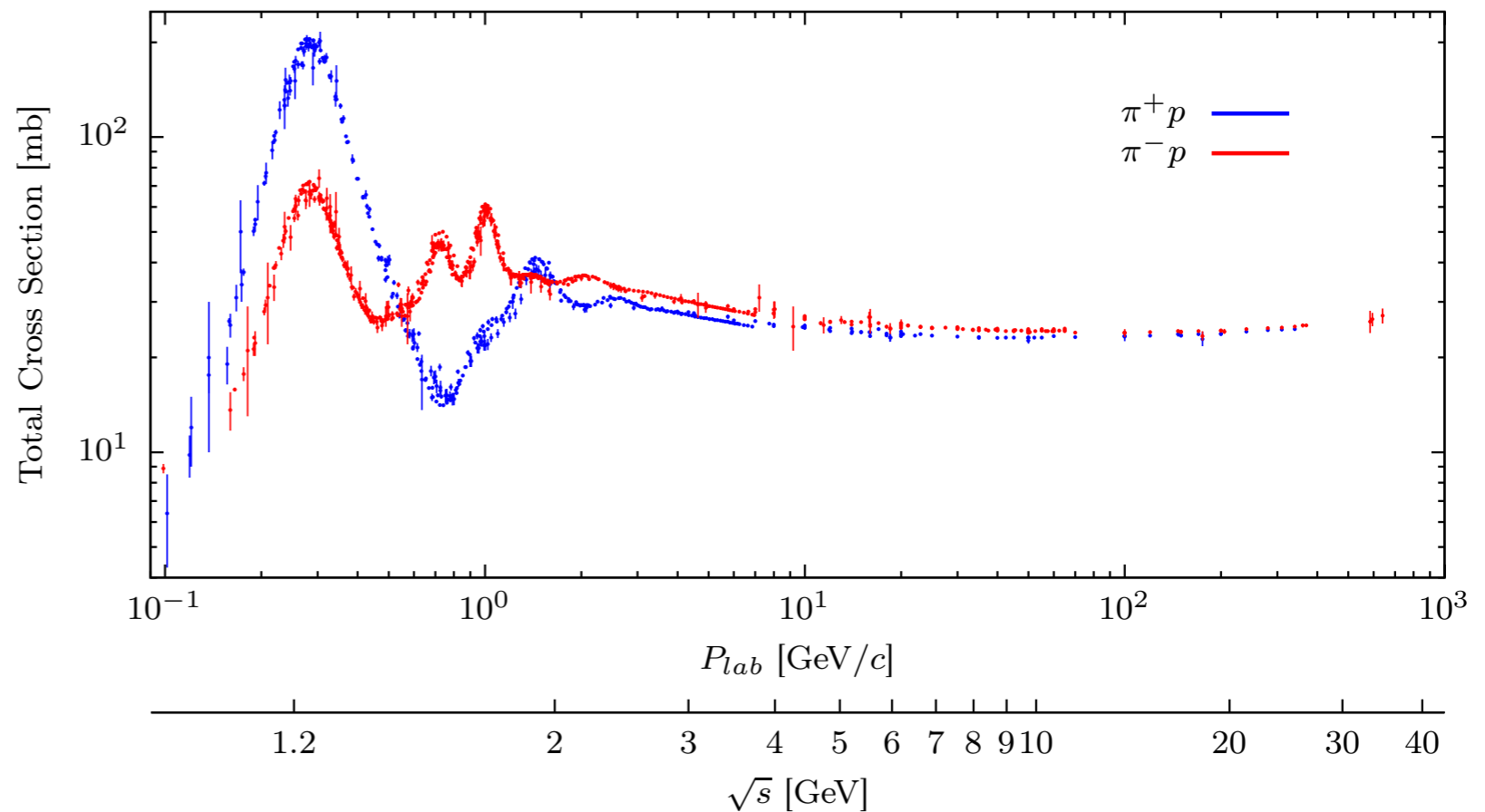
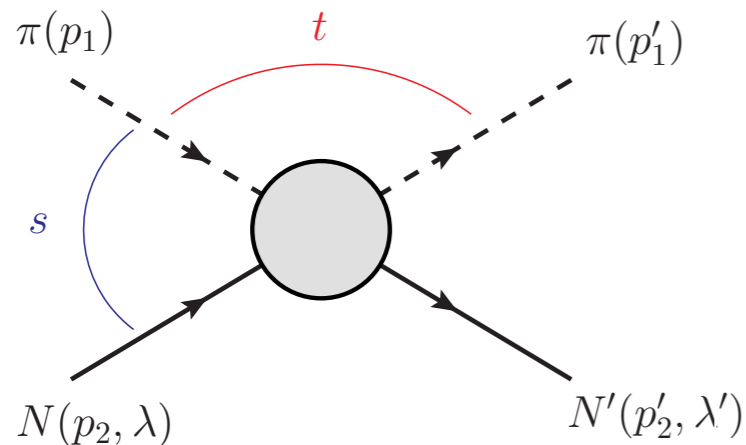
2.3 M u up 2/3 1/2	1.27 G c charm 2/3 1/2	173.1 G t top 2/3 1/2	
4.8 M d down -1/3 1/2	95 M s strange -1/3 1/2	4.2 G b bottom -1/3 1/2	0 g gluon 0 1

Theory of quarks and gluons - Quantum Chromodynamics (QCD)

$$\mathcal{L} = \sum_j \frac{1}{2} \bar{\psi}_{q,j} (i \overleftrightarrow{D} - m_j) \psi_{q,j} - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a$$

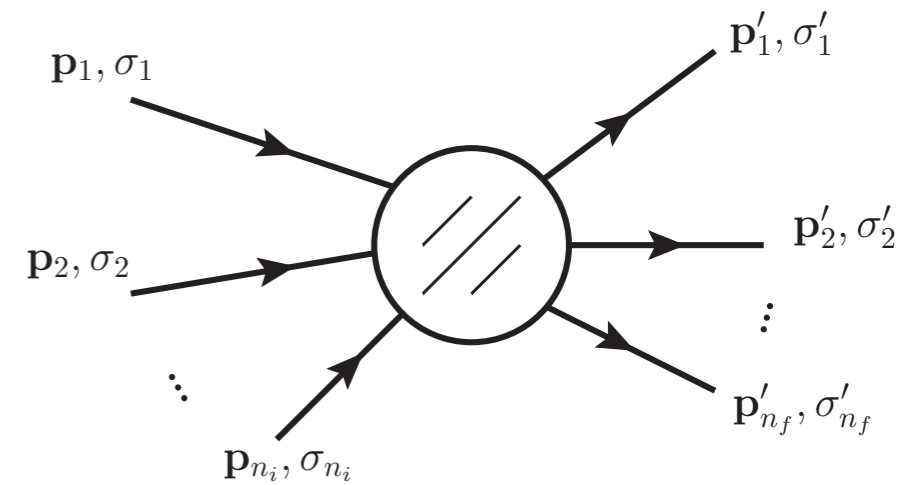
How can such a ‘simple’ theory give rise to the rich structures of hadrons?

$$\pi N \rightarrow \pi N$$



Reaction Theory

Use fundamental physics from relativistic reaction theory (unitarity, analyticity, etc.) to constrain hadronic reaction amplitudes



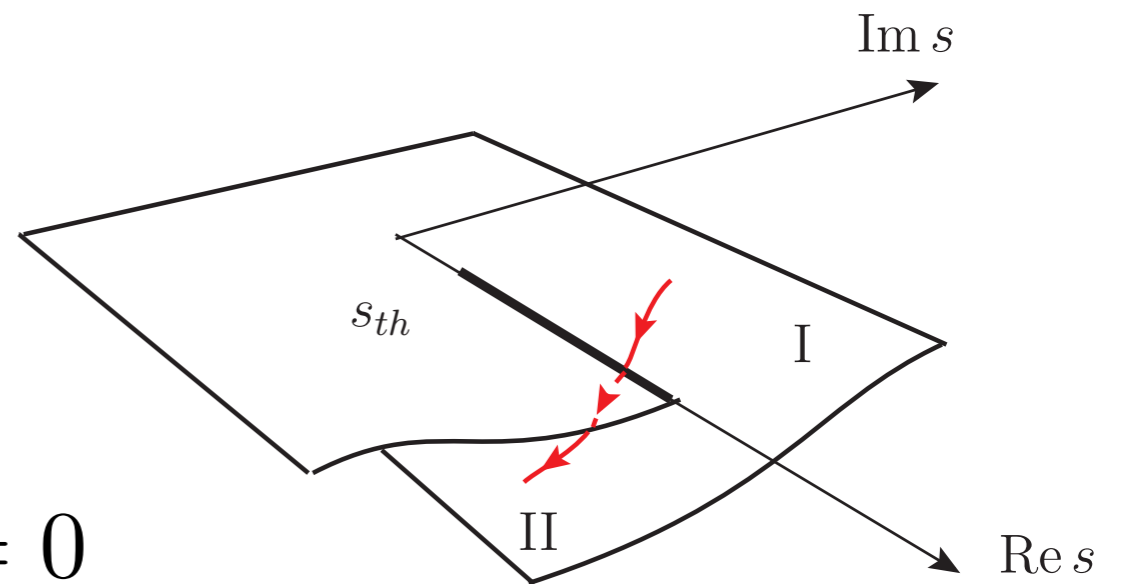
$$\langle \{\mathbf{p}'\sigma'\} | T | \{\mathbf{p}\sigma\} \rangle = (2\pi)^4 \delta^4(P' - P) \mathcal{A}_{\{\sigma',\sigma\}}(\{\mathbf{p}', \mathbf{p}\})$$

Probability conservation S -matrix is unitary operator $\implies S^\dagger S = S S^\dagger = \mathbb{1}$

$$S = \mathbb{1} + iT$$

$$\implies T - T^\dagger = iT^\dagger T$$

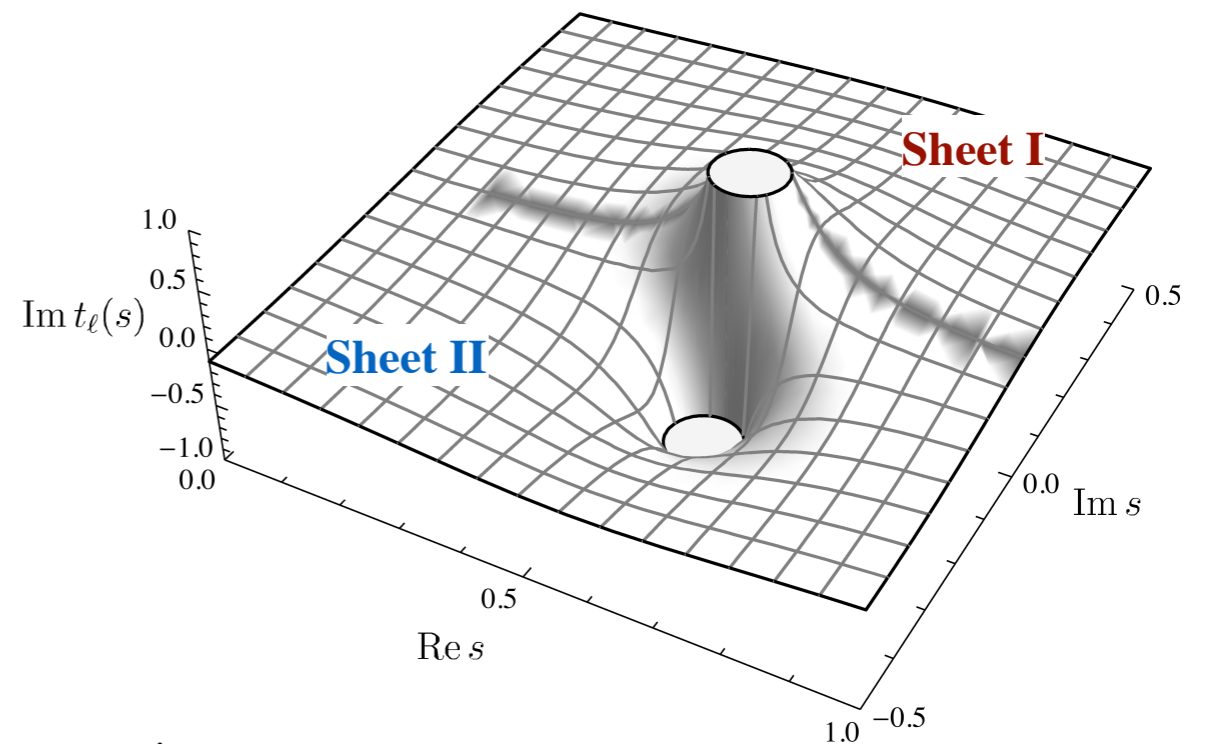
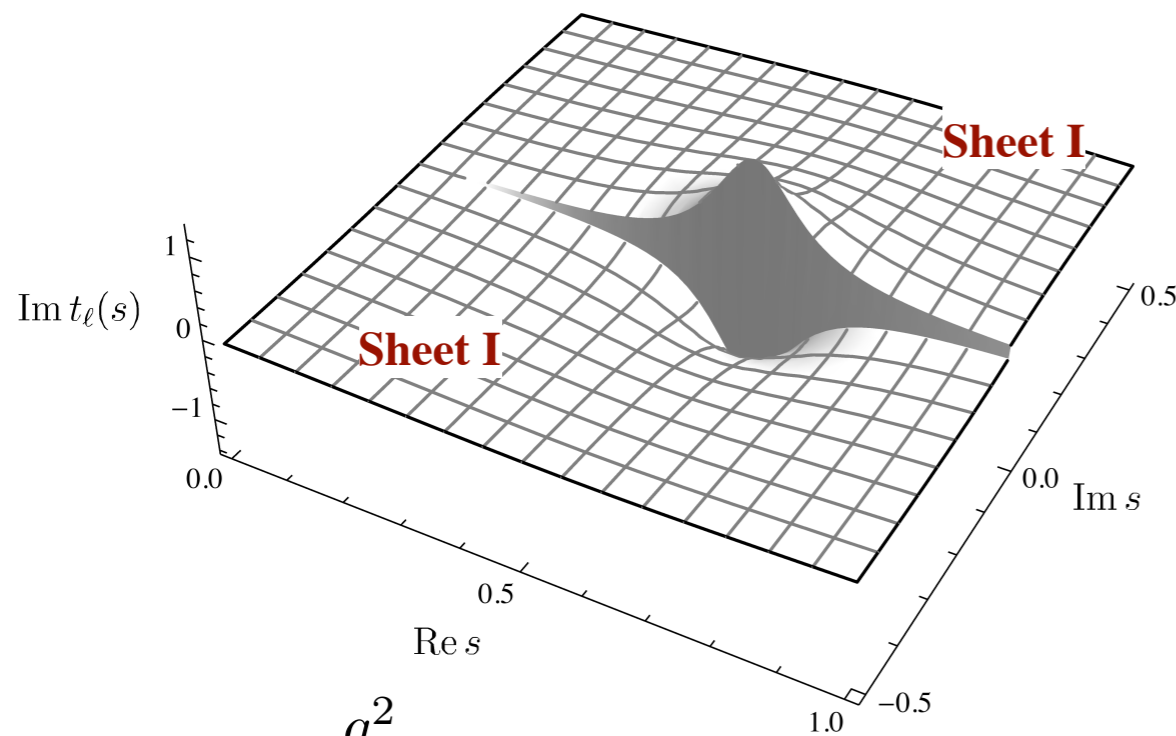
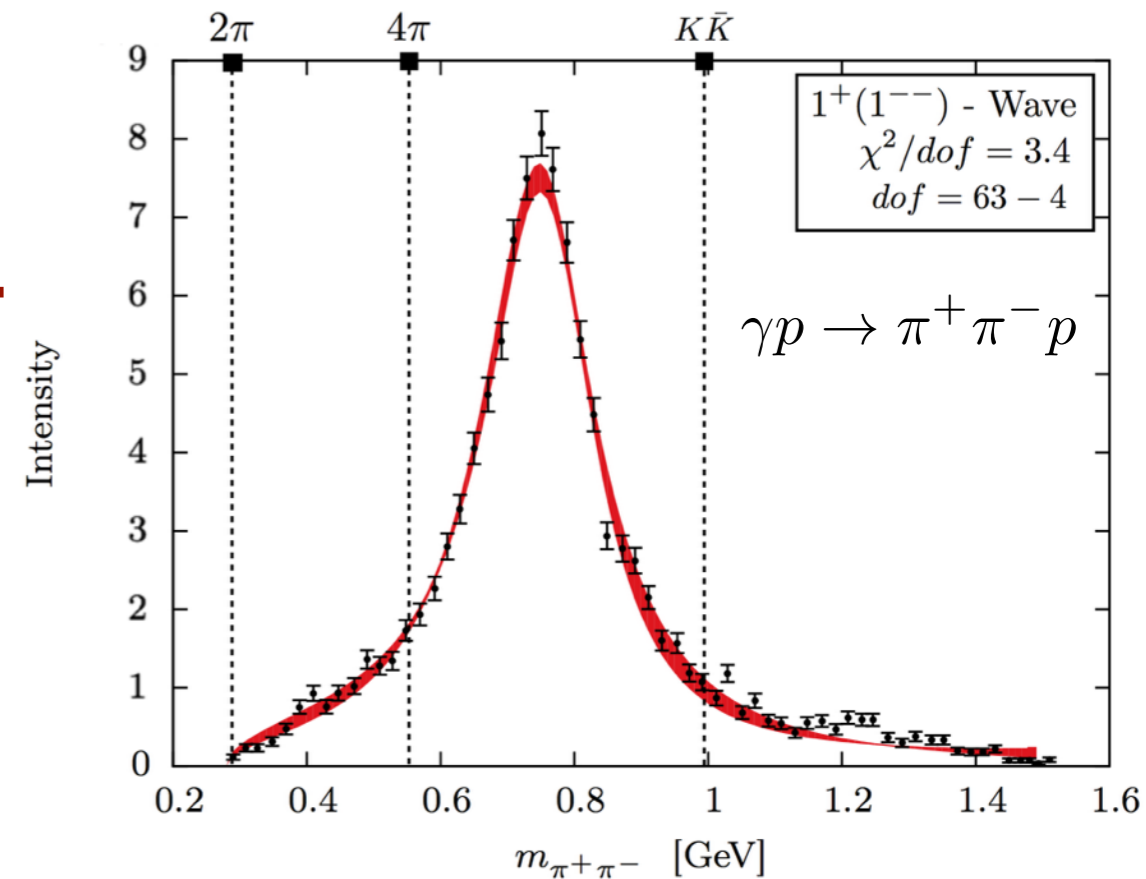
$$\implies \mathcal{A}(s + i\epsilon, t) - \mathcal{A}(s - i\epsilon, t) \neq 0$$



Reaction Theory

Causality implies amplitudes are analytic functions of kinematic variables (energy)

Resonance poles lie underneath unitarity cuts on unphysical Riemann sheets



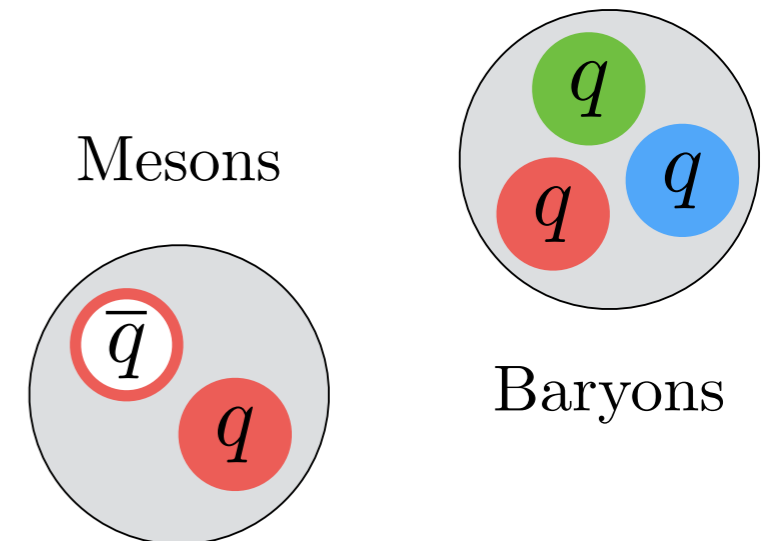
$$t(s) = \frac{g^2}{m^2 - s - i\sqrt{s}\Gamma(s)}$$



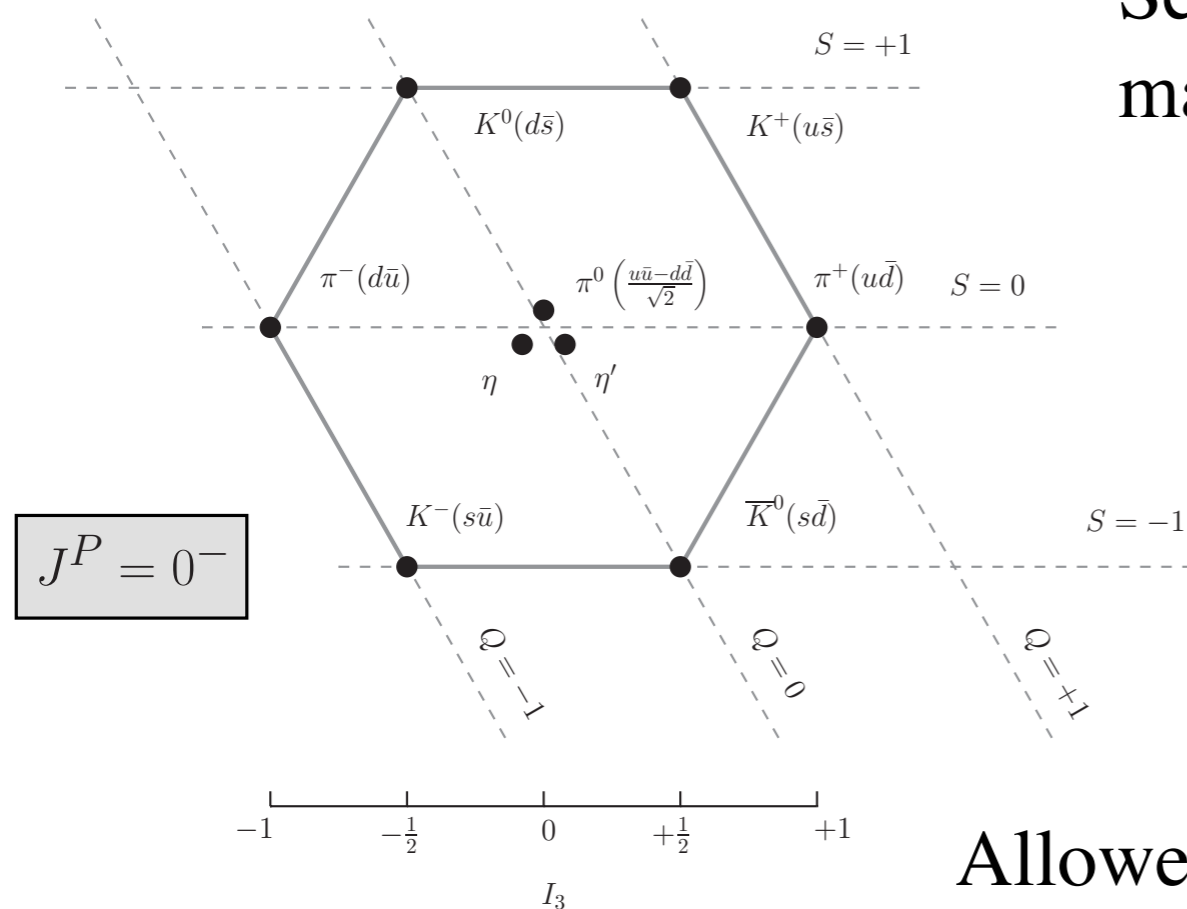
Spectroscopy

The constituent quark model provides a classification scheme for hadrons

Some quantum numbers are not included



Search for exotic quantum numbers is goal of many experiments (GlueX, COMPASS, etc.)



$$S = 0, 1$$

$$L = 0, 1, 2, \dots$$

$$|L - S| \leq J \leq |L + S|$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

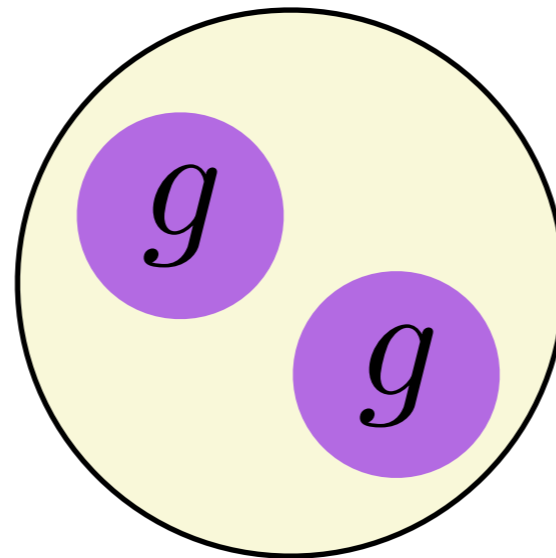
Allowed : $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \dots$

Forbidden : $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \dots$

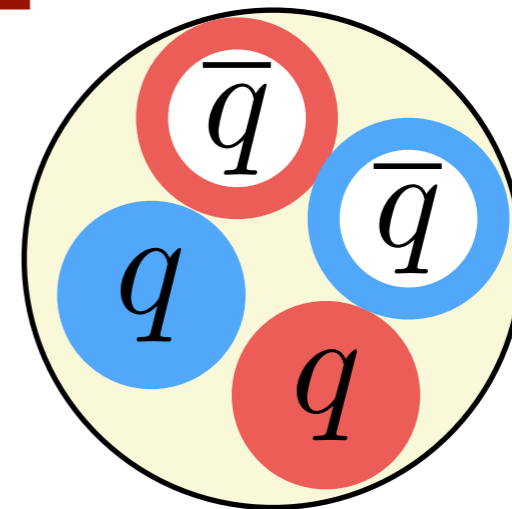
Exotic Hadrons

Not forbidden by QCD

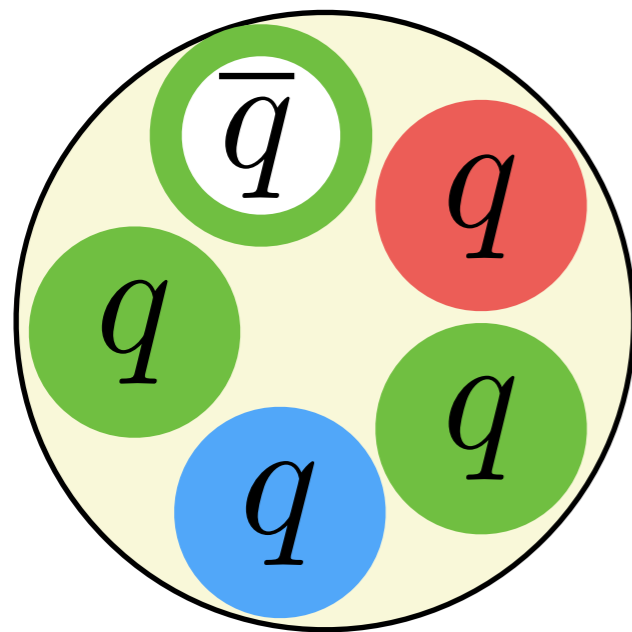
Do these states exist?
Have we seen them?



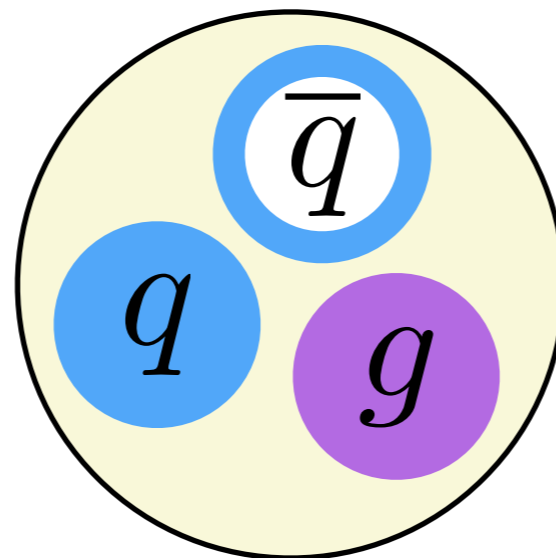
Glueballs



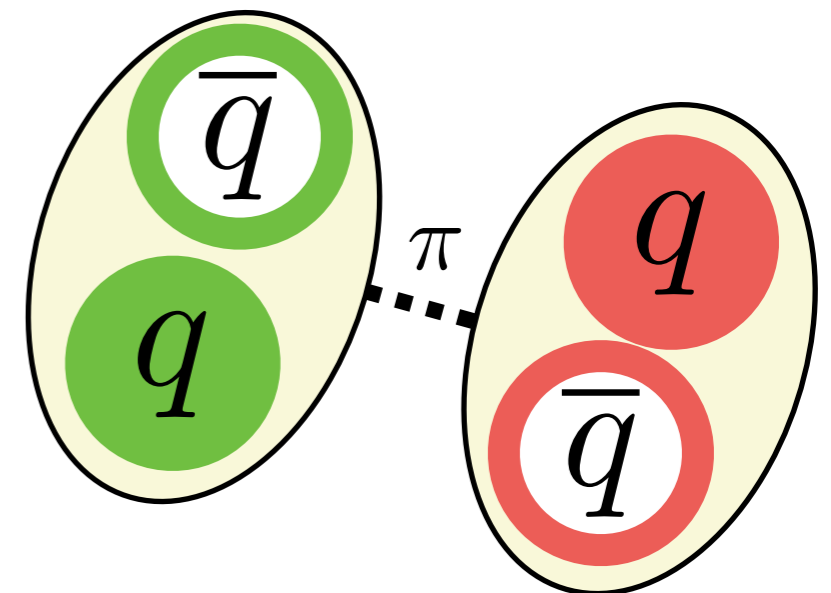
Tetraquarks



Pentaquarks



Hybrids

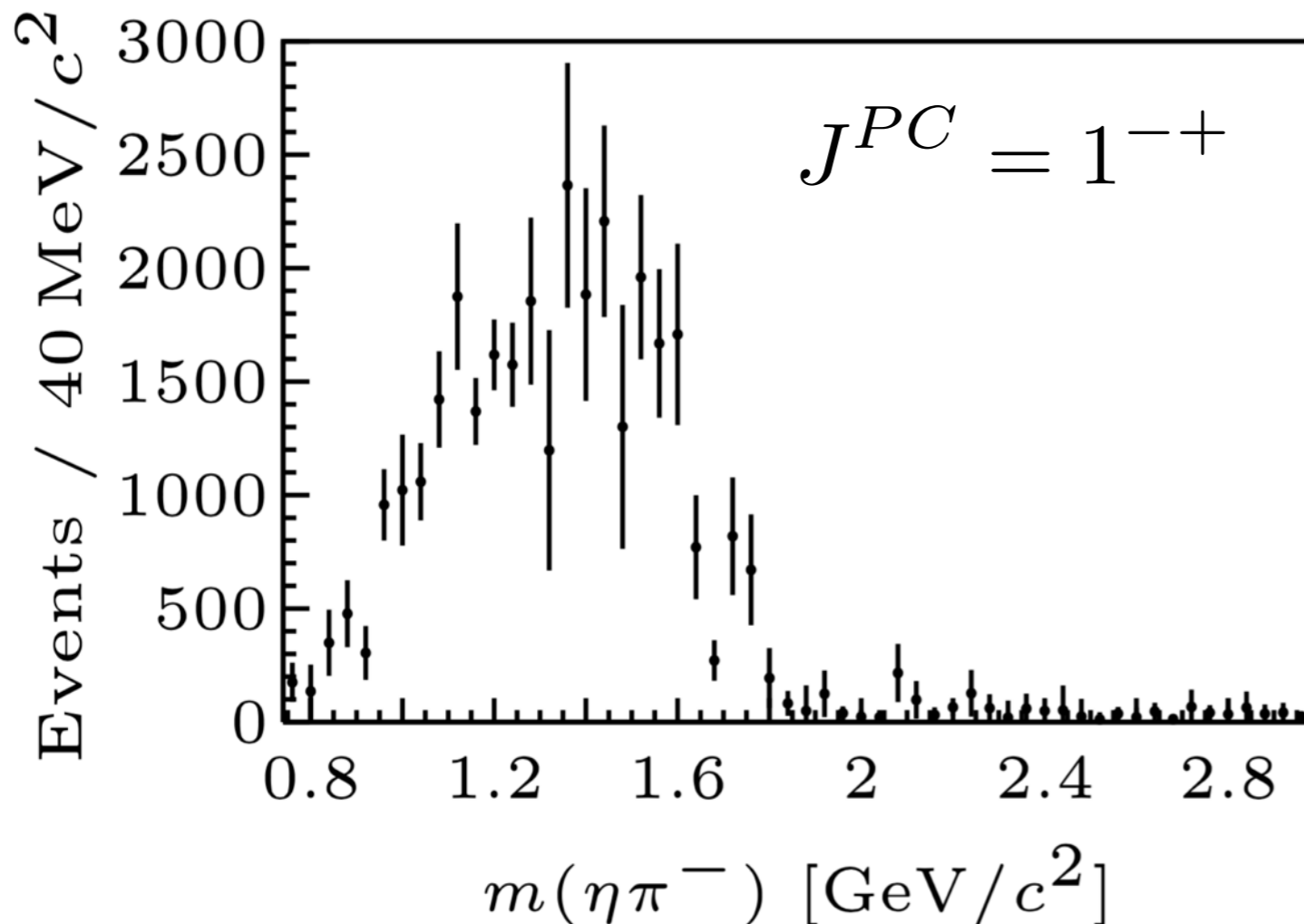
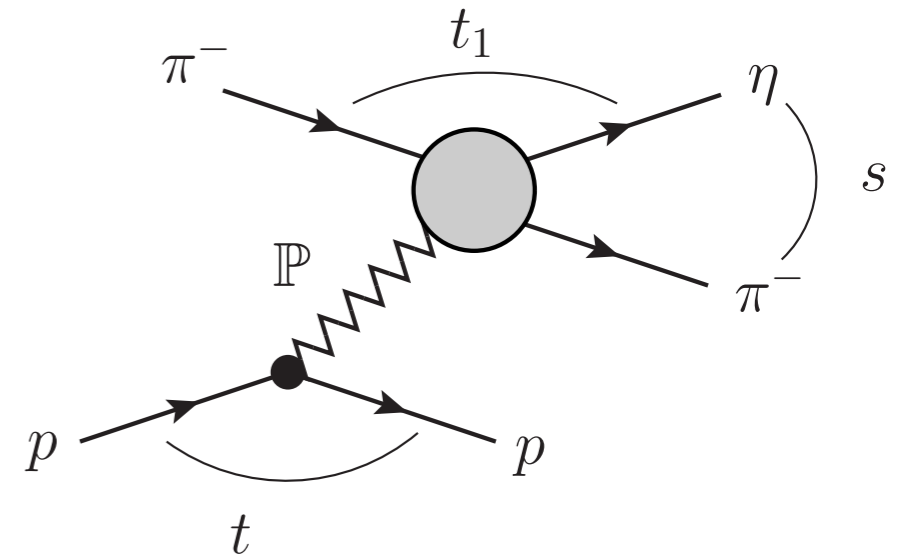


Mesonic-Molecules

Exotics at COMPASS

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

JPAC working with COMPASS
to analyze this data



JPAC developed relativistic
reaction model to compare
with data

Before analyzing this data,
apply reaction model to
simpler system

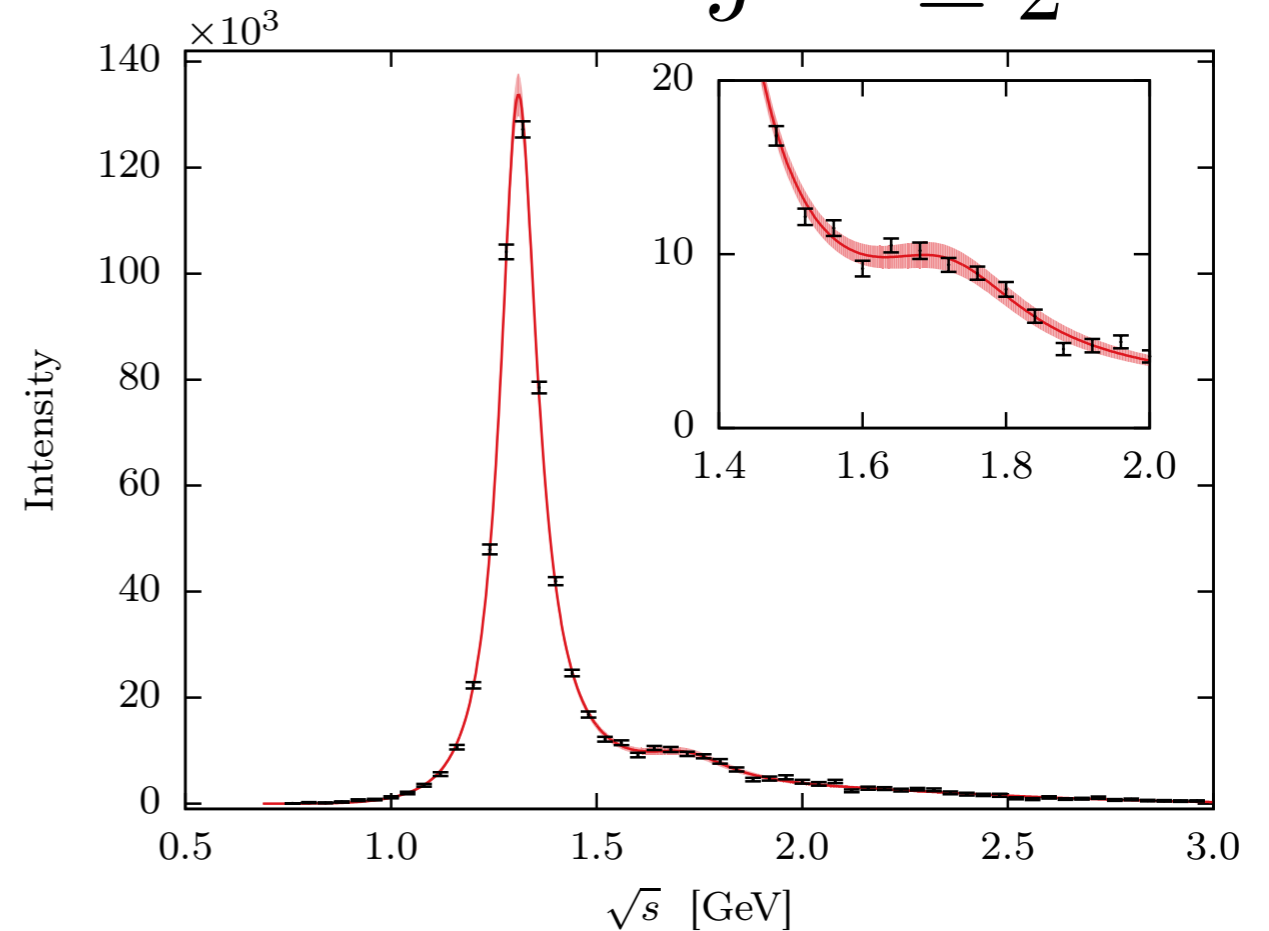
[C. Adolph [COMPASS], Phys. Lett. B 740, 303 (2015)]

Exotics at COMPASS

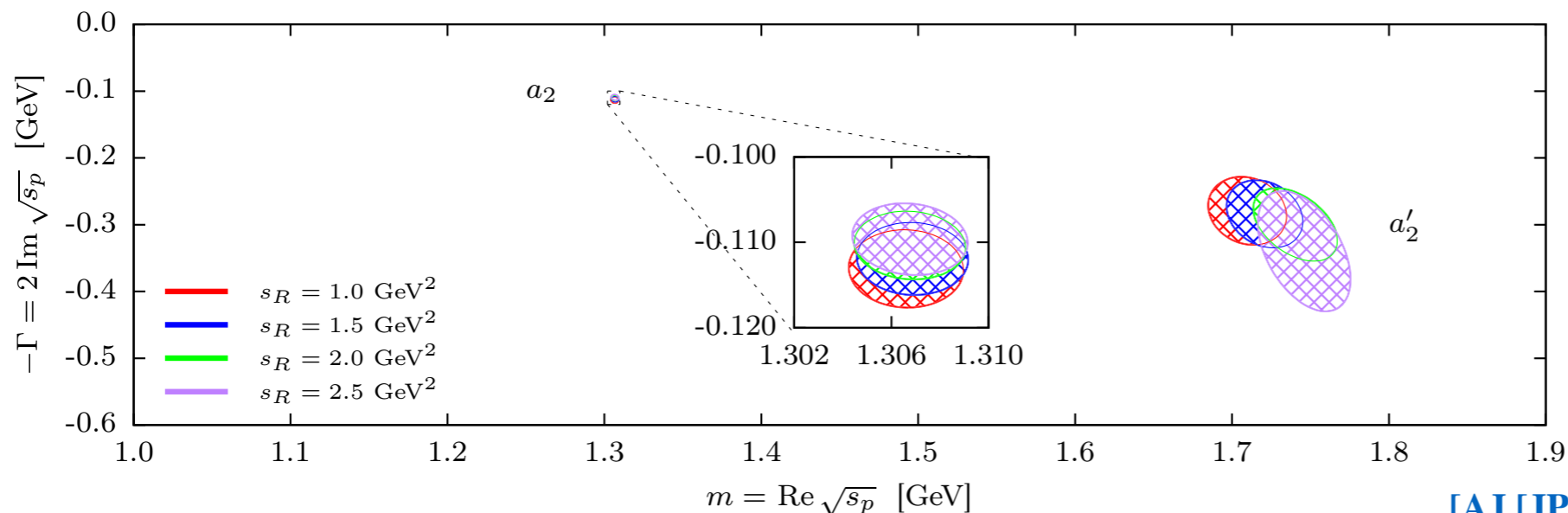
$$\pi p \rightarrow \eta^{(\prime)} \pi p$$

First joint publication between JPAC and COMPASS out, laying the ground work of this analysis

$$J^{PC} = 2^{++}$$

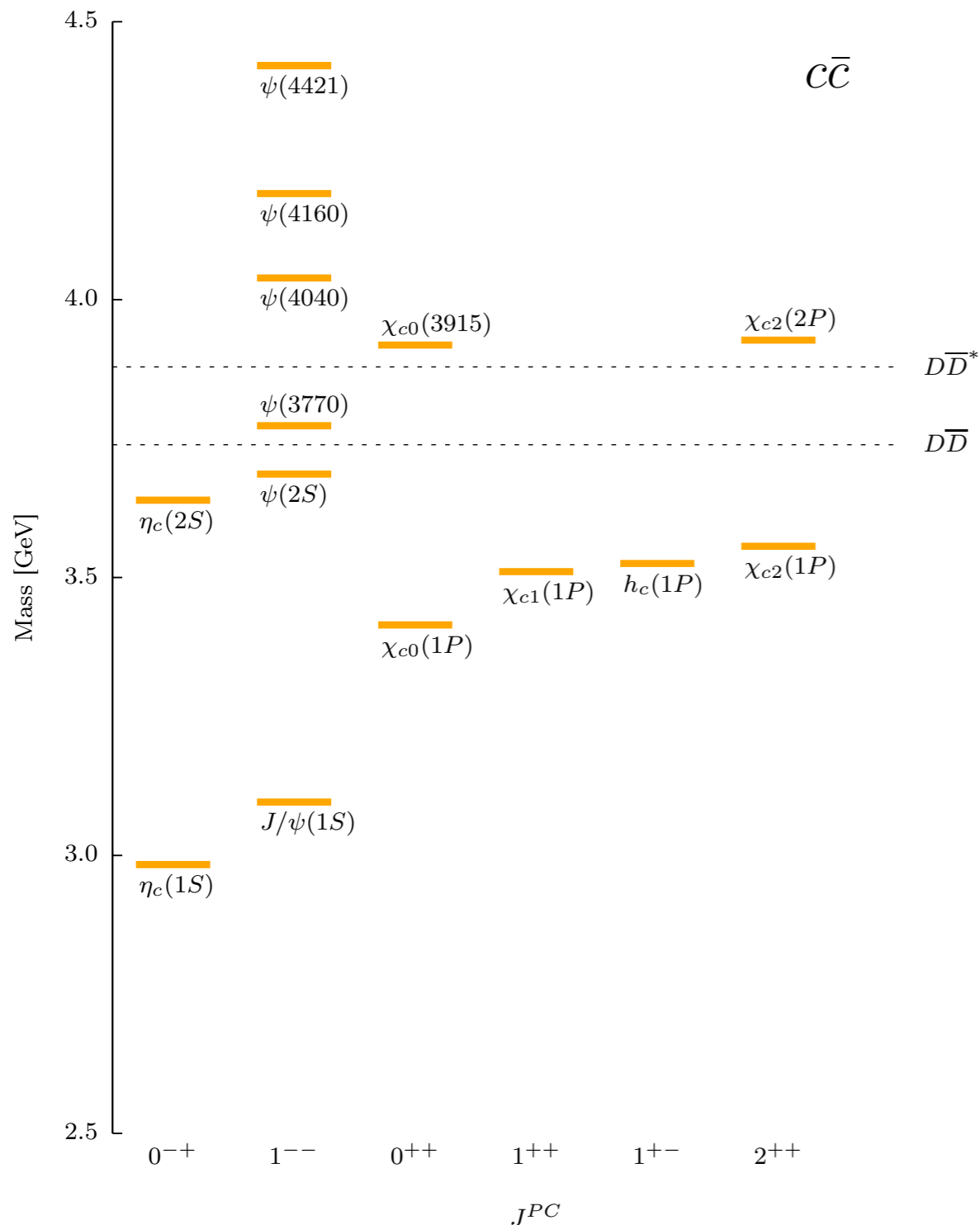
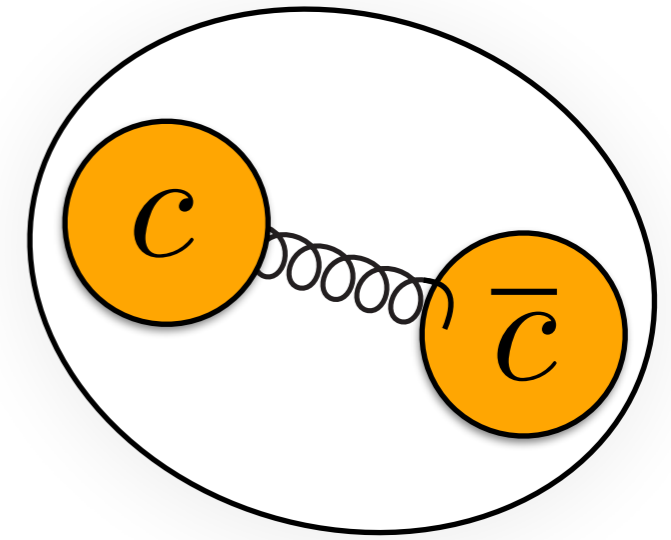


Extract pole positions of a_2, a'_2



[AJ [JPAC & COMPASS], arXiv:1707.02848]

Charmonium



Quark models give qualitative features of heavy quarkonia ($c\bar{c}$, $b\bar{b}$)

All seemed to be generally understood until 2003

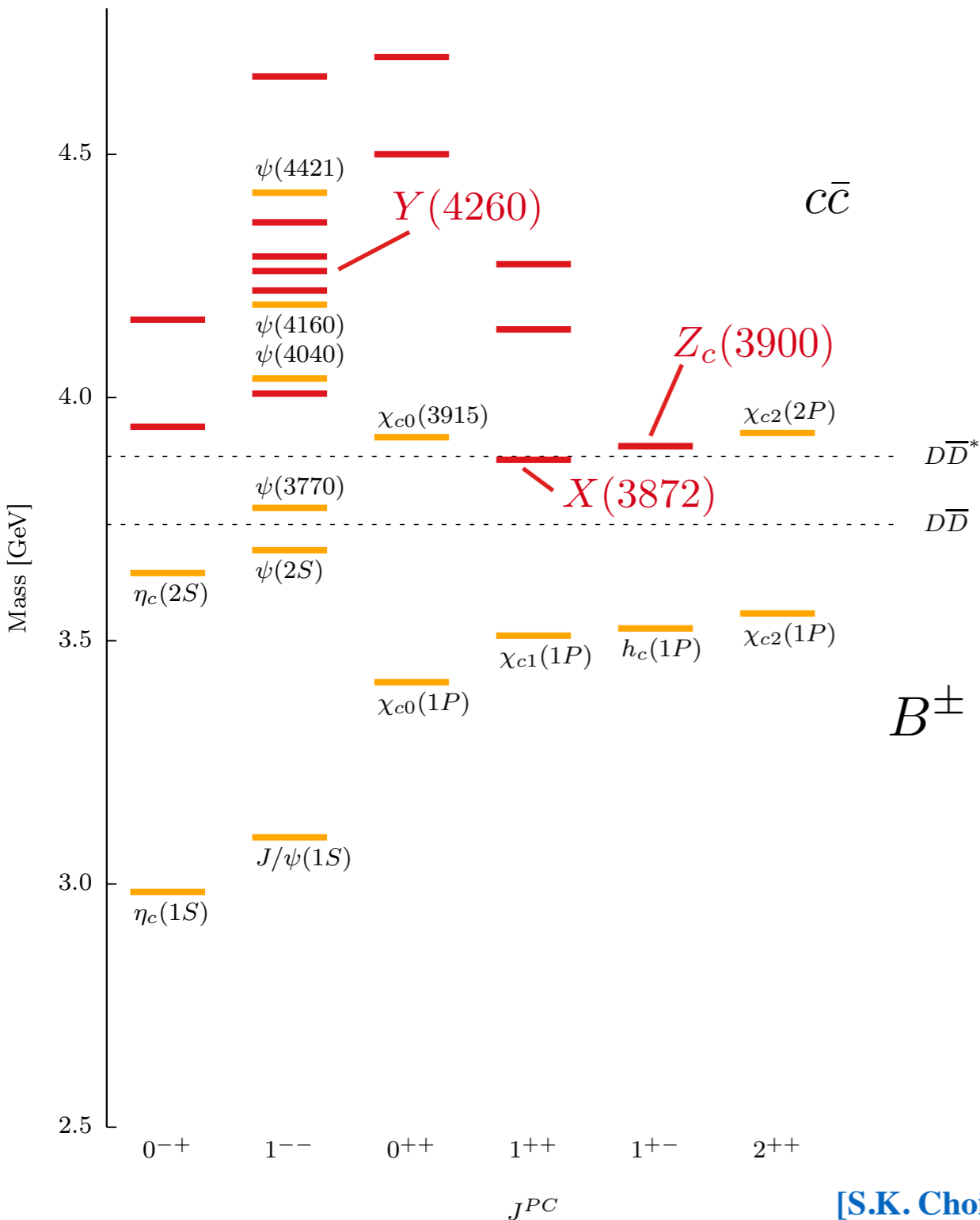
one-gluon exchange

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

linear confinement

$$\alpha_s(M_Q) \sim 0.3$$

Exotics in Charmonium

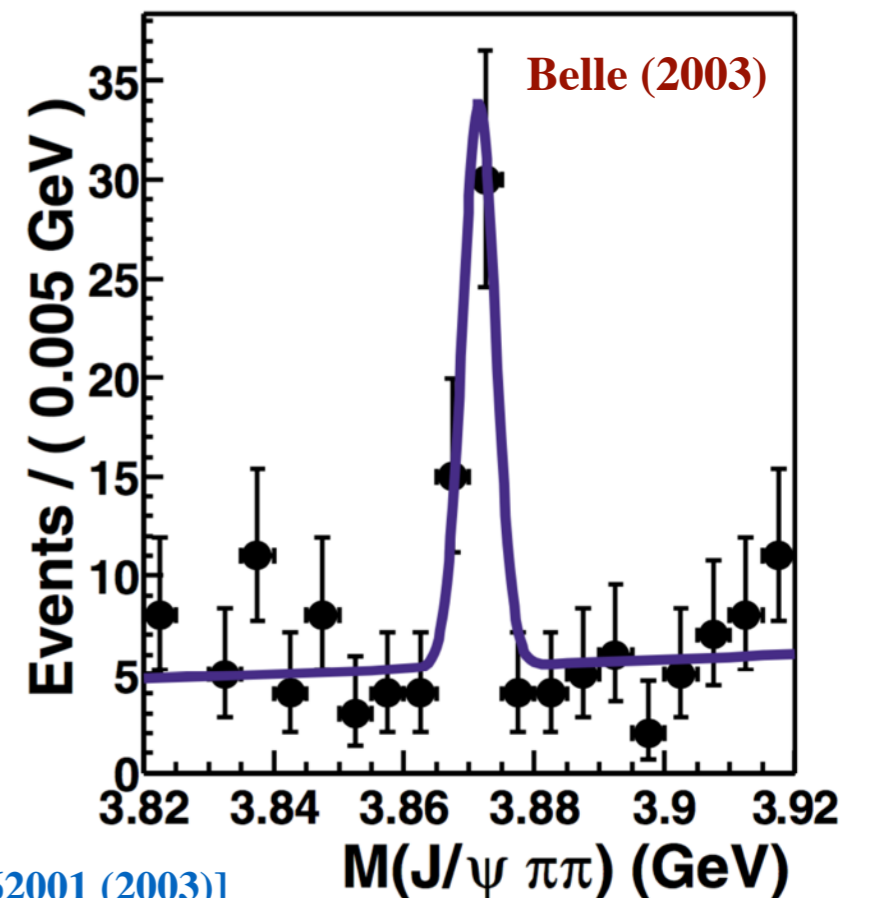
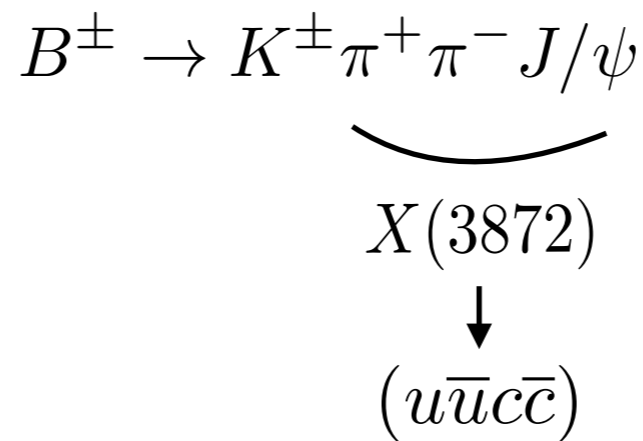


In 2003, the state $X(3872)$ was discovered by Belle

Began the XYZ era of hadron spectroscopy

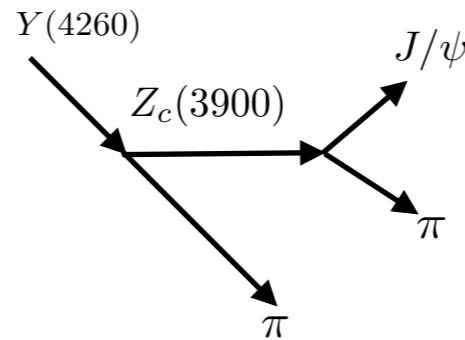
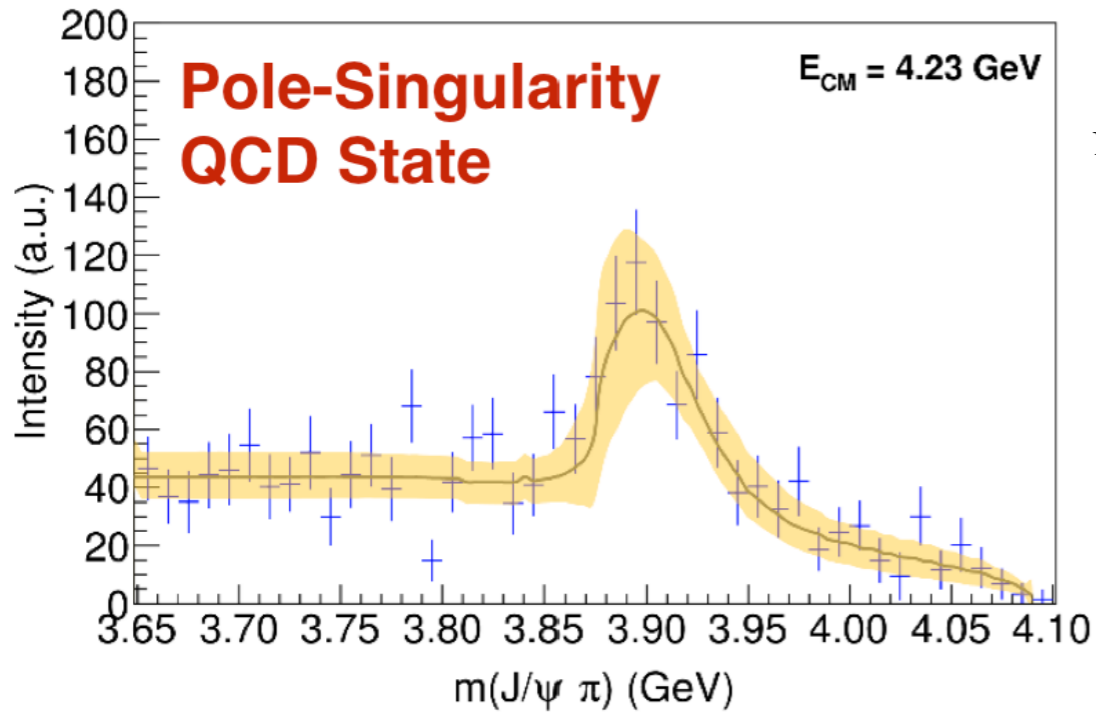
Unconventional quark assignments (tetraquark-like)

What is the nature of these states?



[S.K. Choi [Belle], Phys. Rev. Lett. 91, 262001 (2003)]

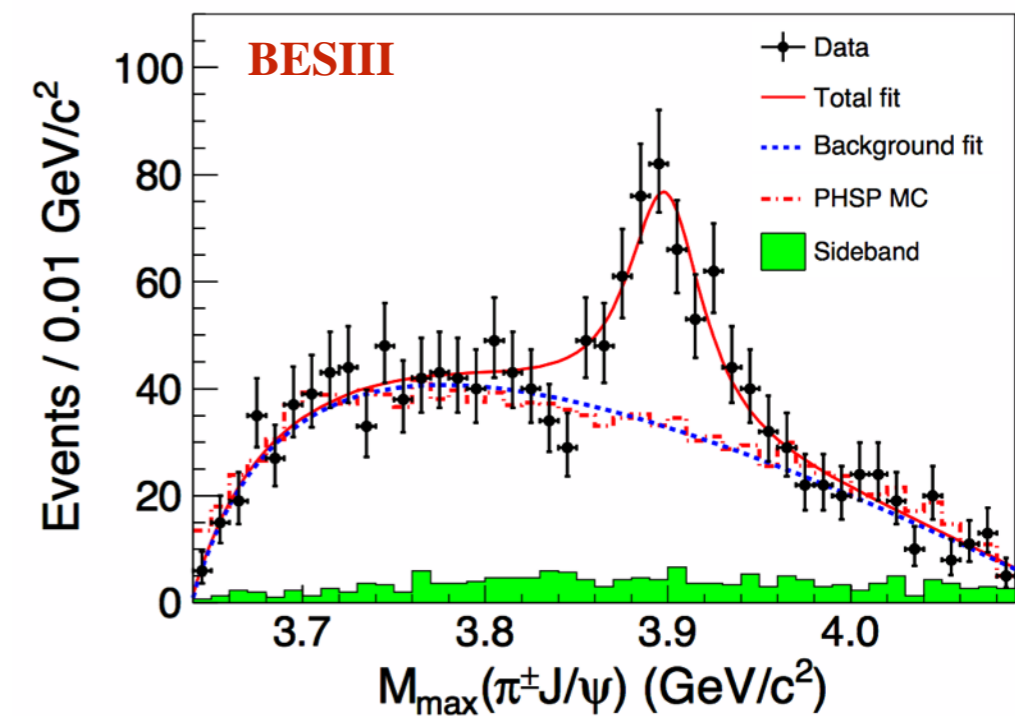
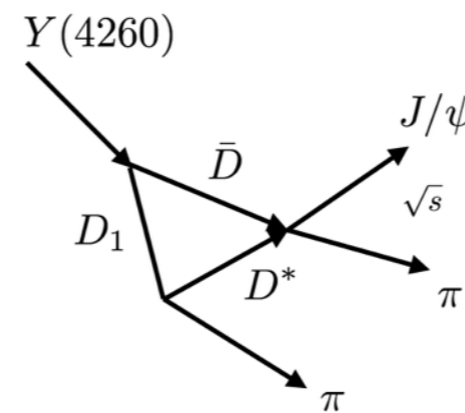
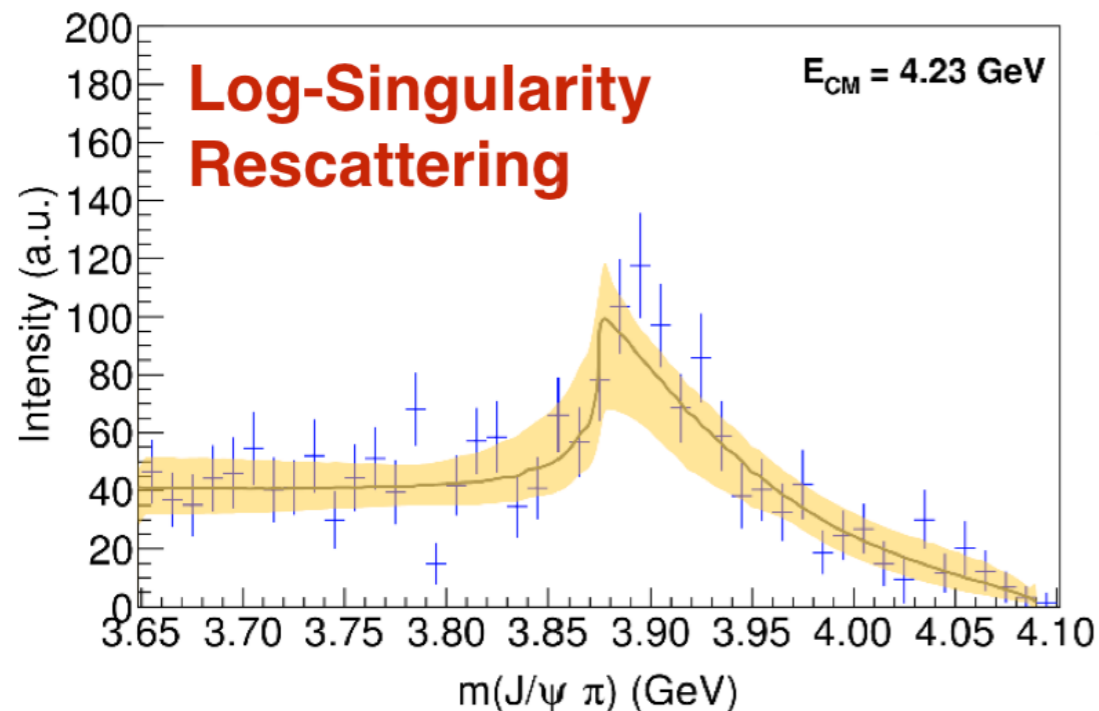
$Z_c(3900)$



Found in decay of

$$Y(4260) \rightarrow J/\psi \pi \pi$$

Test QCD-pole models and non-QCD pole models



[A.Pilloni, [JPAC] Phys. Lett. B 772, 200 (2017)]

[Liu, BESIII & Belle Collaboration, arXiv:1311.0762v1]

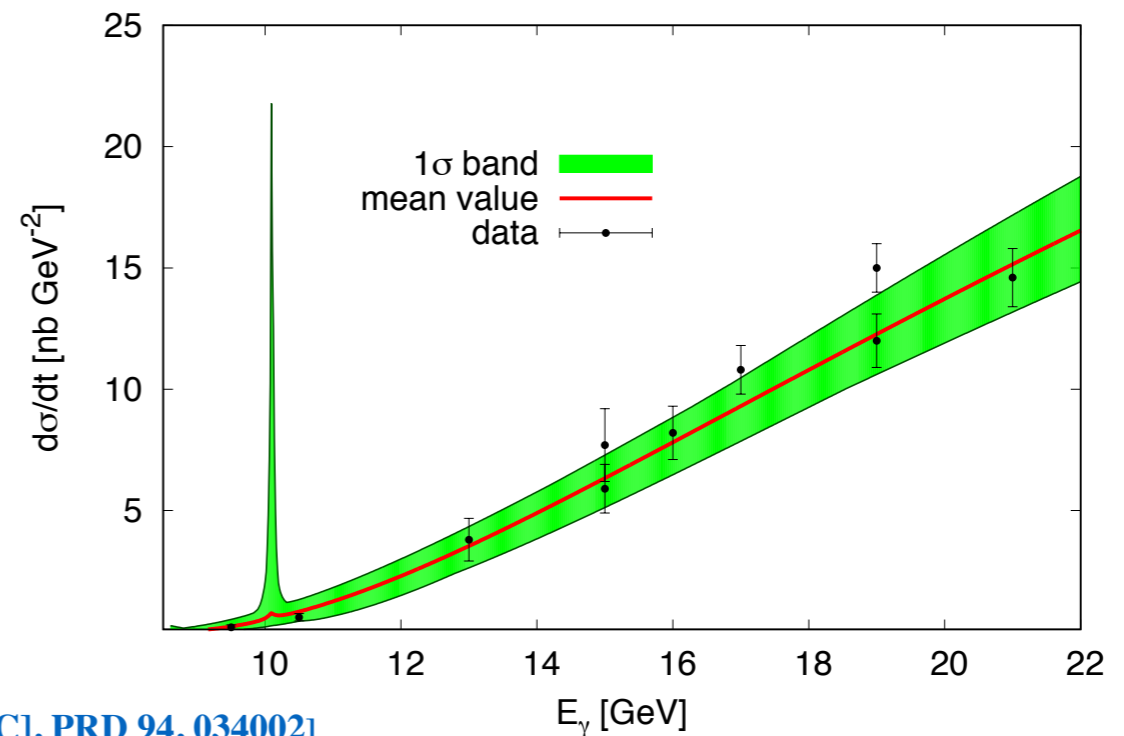
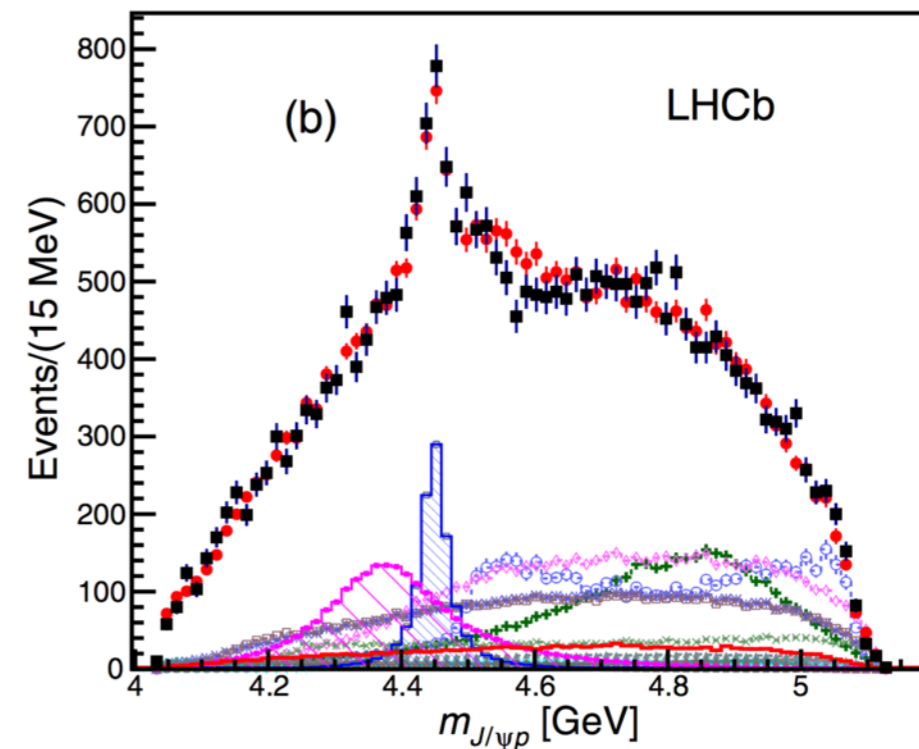
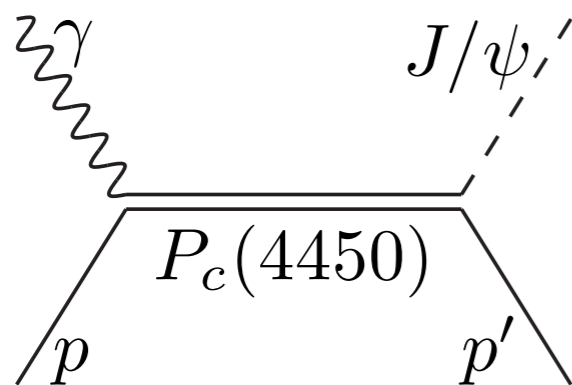
LHCb Pentaquark

[R. AAIJ [LHCb], PRL 115, 072001]

LHCb claim discovery of pentaquarks $P_c(4450)$ and $P_c(4380)$ in $\Lambda_b \rightarrow KJ/\psi p$

Proposal to search for $P_c(4450)$ in photoproduction at JLab

Combined JPAC-LHCb analysis on Λ_b decay using JPAC hyperon spectrum



[A.H. BLIN [JPAC], PRD 94, 034002]

Conclusion

Hadron Spectroscopy is an increasingly active field

Many states with unknown origin have been discovered, with more discovered yearly — Exotica breed new life into low-energy QCD

Active work between theorist and experimentalist to construct reliable models to extract physics — JPAC is leader in this effort

General principles of reaction theory can be used to constrain models for experimental analysis — and can be used to discriminate interpretations

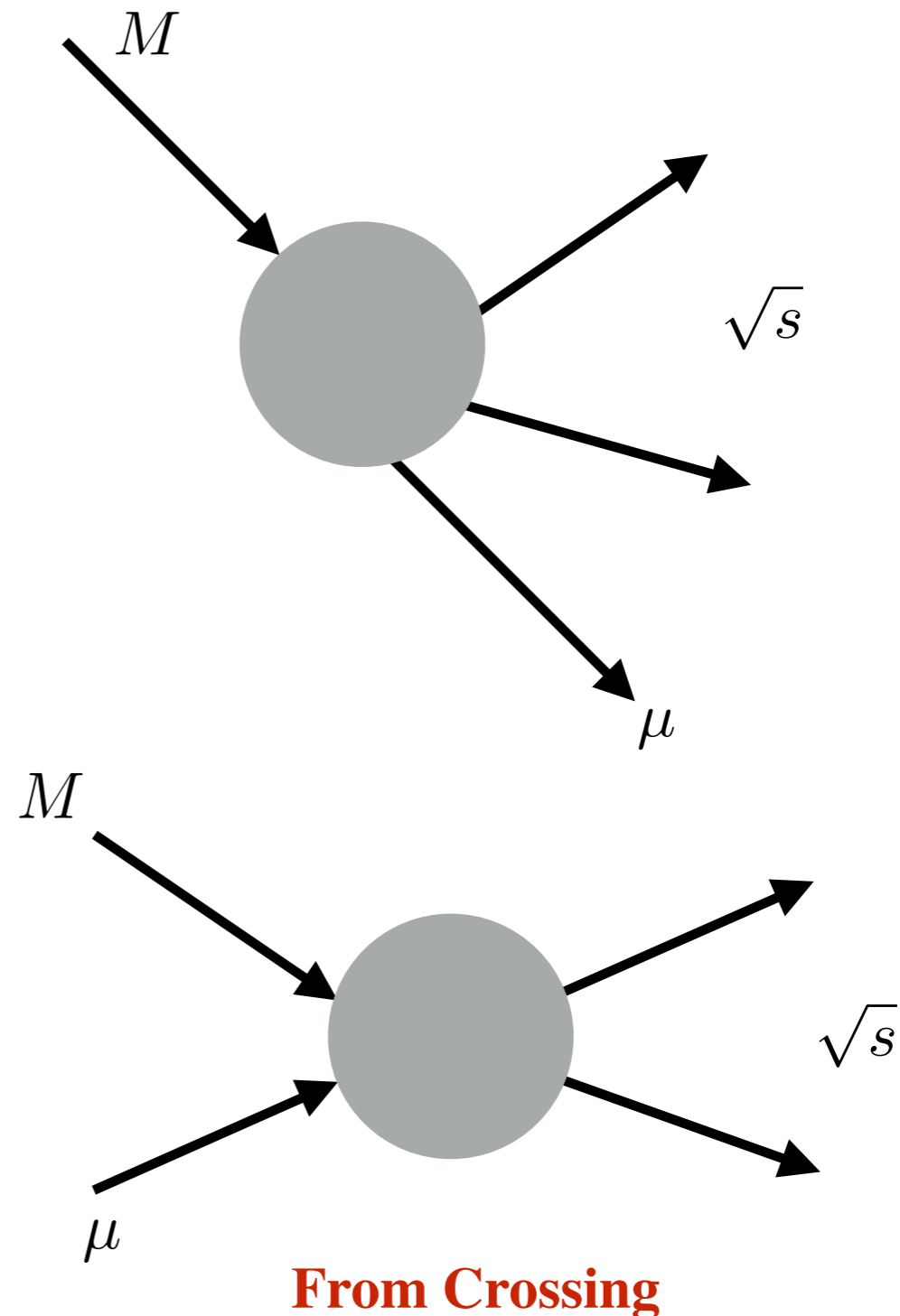
Back-Up

Triangle Mechanism

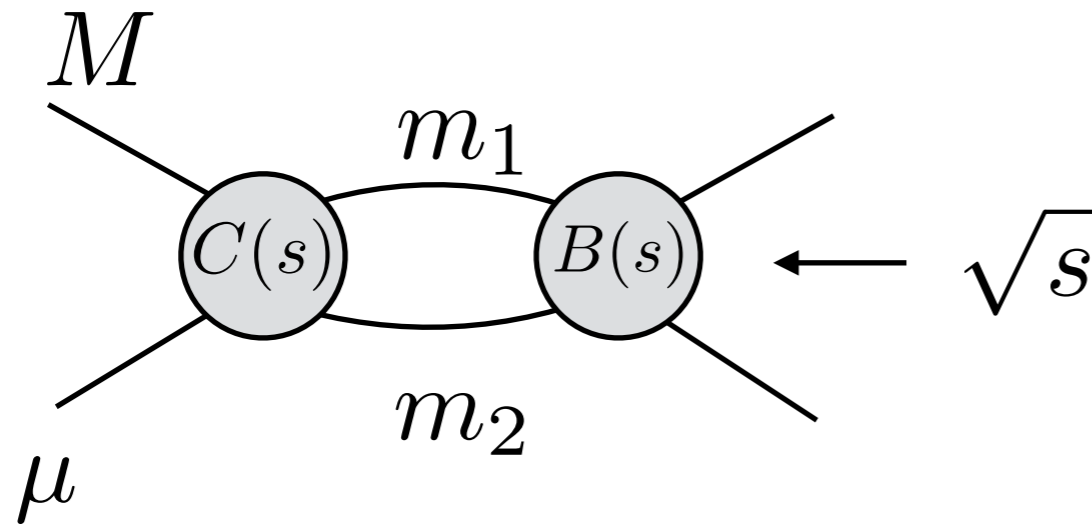
Look at 3-Body decay of particle M

Masses can be such that non-resonant peaks appear in invariant mass

For these examples, assumption that all particles are scalar



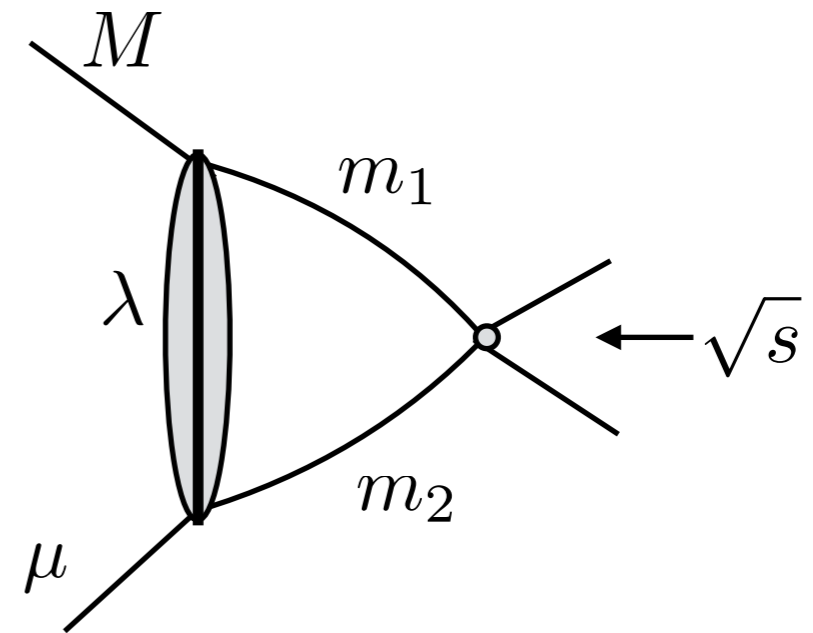
Triangle Mechanism



$$\text{Im } T(s) = B^*(s)\rho(s)C(s)\Theta(s - s_t)$$

$$T(s) = \frac{1}{\pi} \int ds' \frac{B^*(s')\rho(s')C(s')}{s' - s}$$

2-Body intermediate phase space $\rho(s)$



For simplicity, B(s)=CONST

After partial wave projection

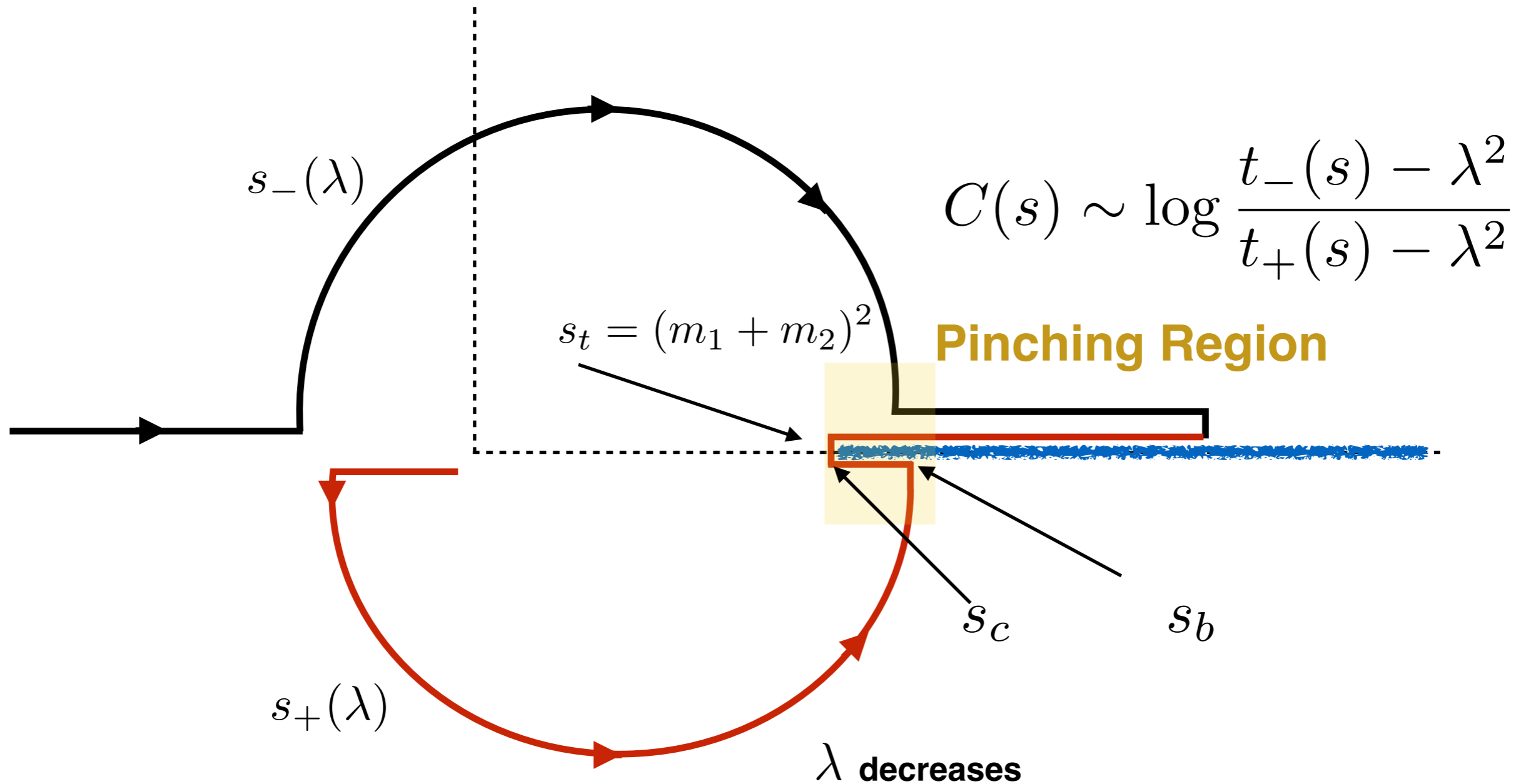
$$C(s) \sim \log \frac{t_-(s) - \lambda^2}{t_+(s) - \lambda^2}$$

Look for singularities of C(s)

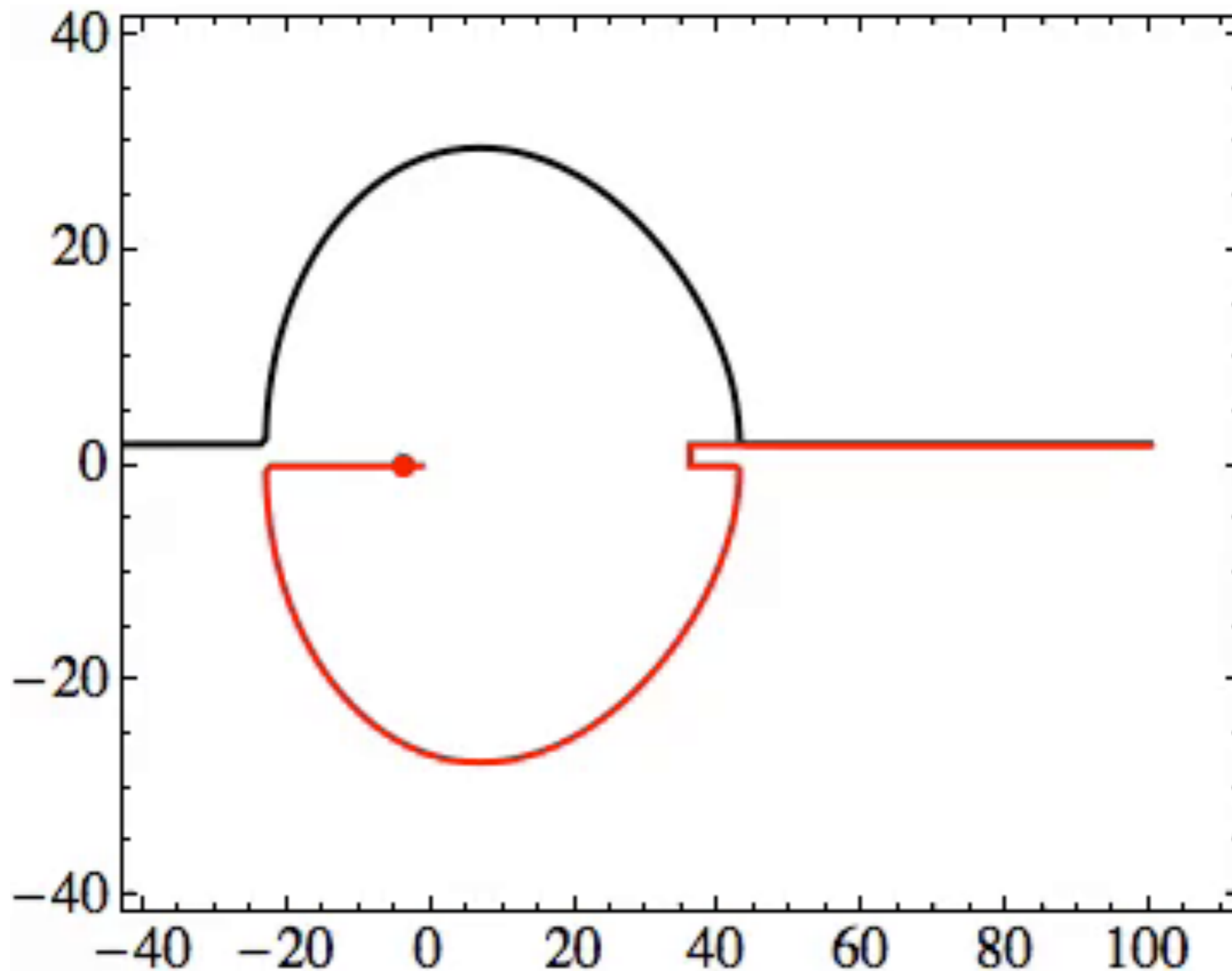
[A. Szczepaniak, arXiv:1501.01691v3]

Triangle Branching Points

- Find 2 solutions $s_{+,-}$ as a function of λ for singular $C(s)$



Branch Cut Movement



Credit: I. Danilkin

Triangle Mechanism

- Peaks appear in physical region when

$$\lambda_c < \lambda < \lambda_b$$

$$s_c < s_{peak} < s_b$$

- These are associated with the pinching effect, not poles, in the amplitude
- Two examples: Z(3900) & Pc(4450)

