EXOTICA IN HADRON SPECTROSCOPY

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4TH PIKIO MEETING

09/16/2017

Joint Physics Analysis Center

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

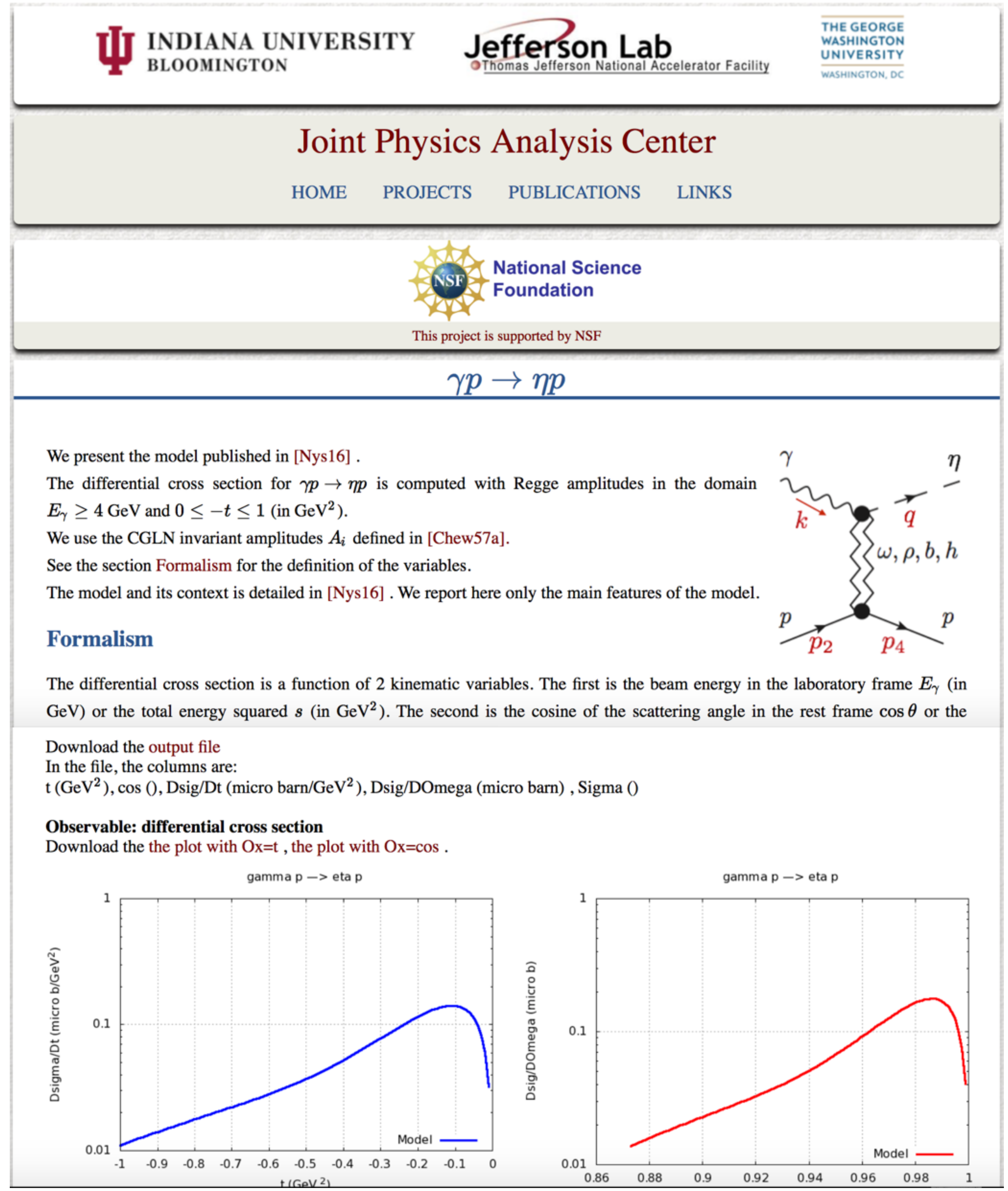
~ 20 active members

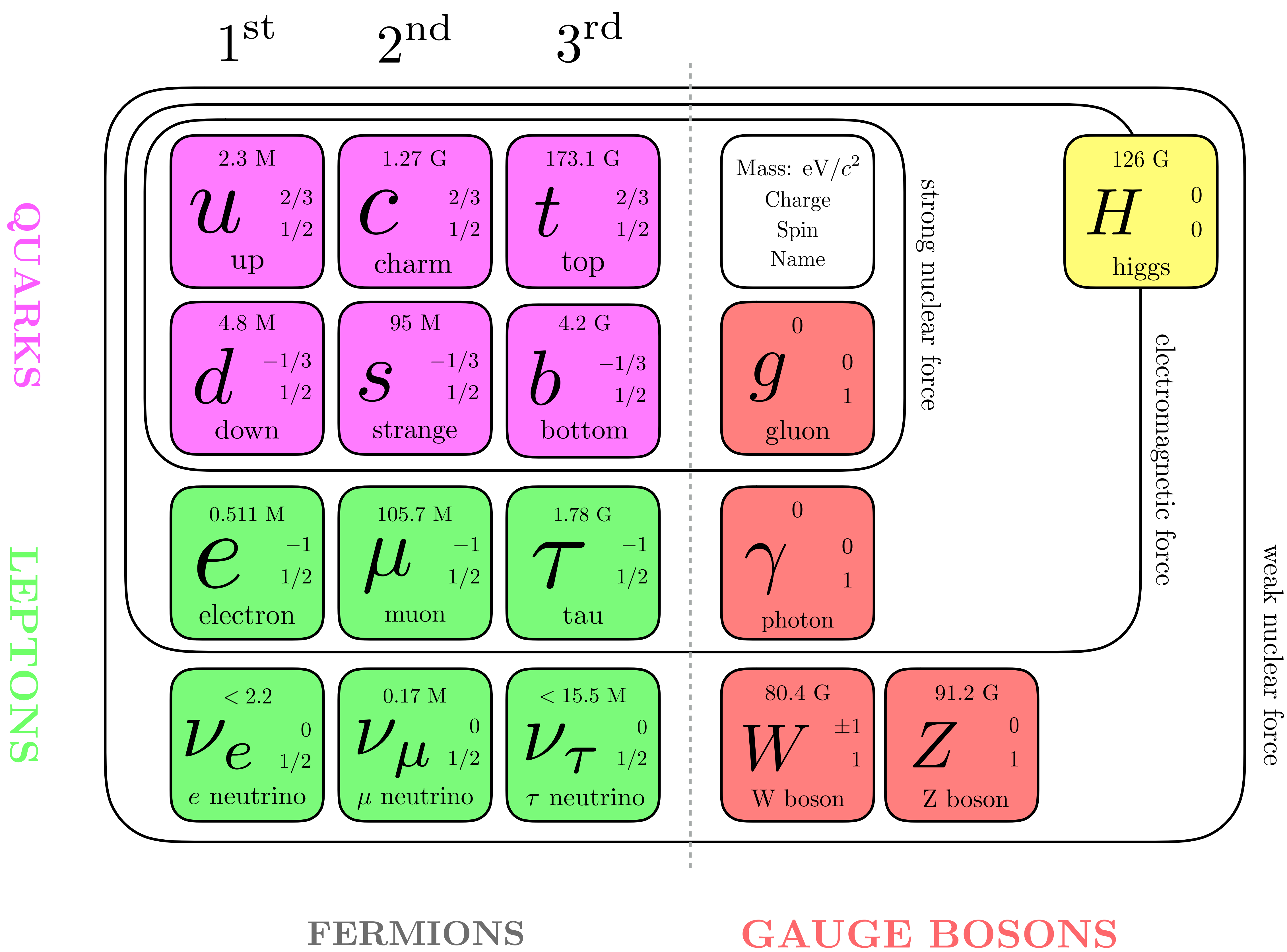
> 40 Research Papers (Phys.Rev., Phys.Lett, Eur.J. Phys.) O(10) ongoing analyses

Regular lecture series on relativistic reaction theory

Summer Workshop on Reaction Theory (2015 & 2017)

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




1st
2nd
3rd
QUARKS
LEPTONS
2.3 M
u
2/3
1/2
up
1.27 G
c
2/3
1/2
charm
173.1 G
t
2/3
1/2
top
Mass: eV/c^2
Charge
Spin
Name
126 G
H
0
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higgs
4.8 M
d
−1/3
1/2
down
95 M
s
−1/3
1/2
strange
4.2 G
b
−1/3
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bottom
0
g
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1
gluon
0.511 M
e
−1
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electron
105.7 M
μ
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muon
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τ
−1
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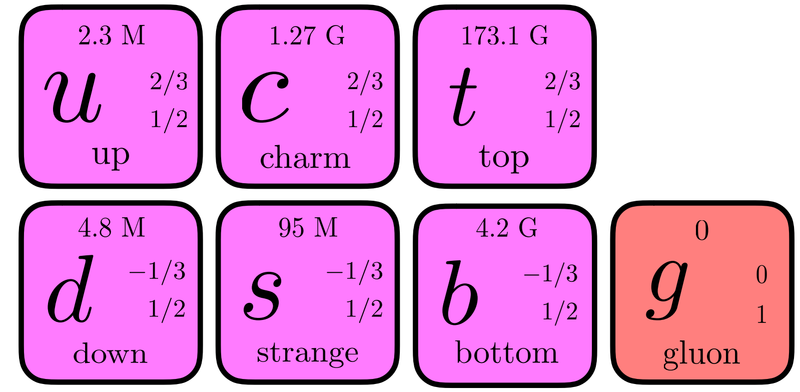
photon
< 2.2
ν_e
0
1/2
e neutrino
0.17 M
ν_μ
0
1/2
μ neutrino
< 15.5 M
ν_τ
0
1/2
τ neutrino
80.4 G
W
±1
1
W boson
91.2 G
Z
0
1
Z boson
strong nuclear force
electromagnetic force
weak nuclear force
FERMIONS
GAUGE BOSONS

QCD and Hadrons

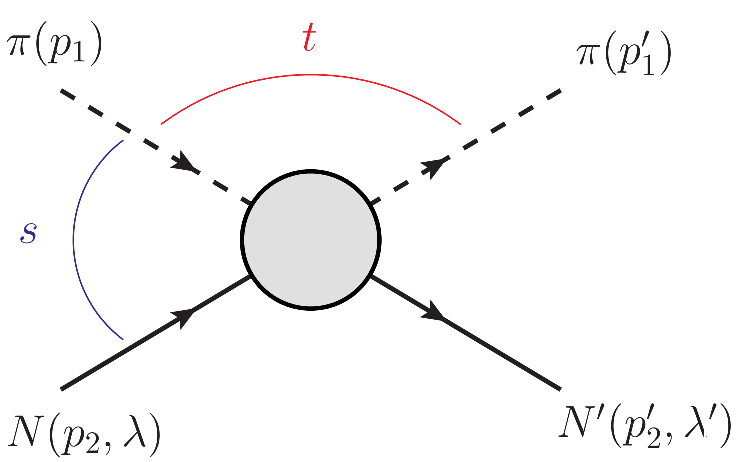


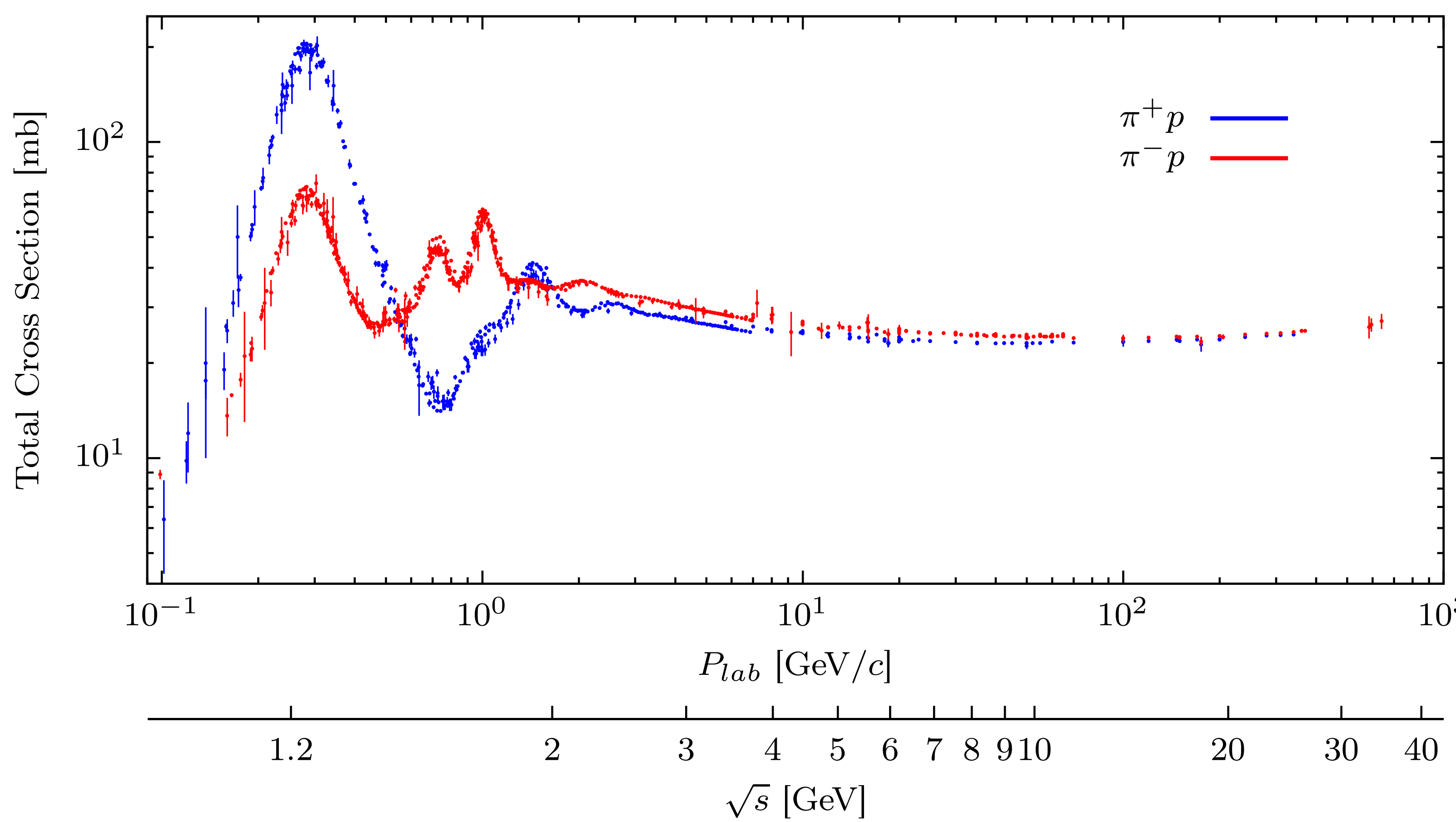
Theory of quarks and gluons - Quantum Chromodynamics (QCD)

$$\mathcal{L} = \sum_j \frac{1}{2}\overline{\psi}_{q,j}(i\overleftrightarrow{\not{D}} - m_j)\psi_{q,j} - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu}$$

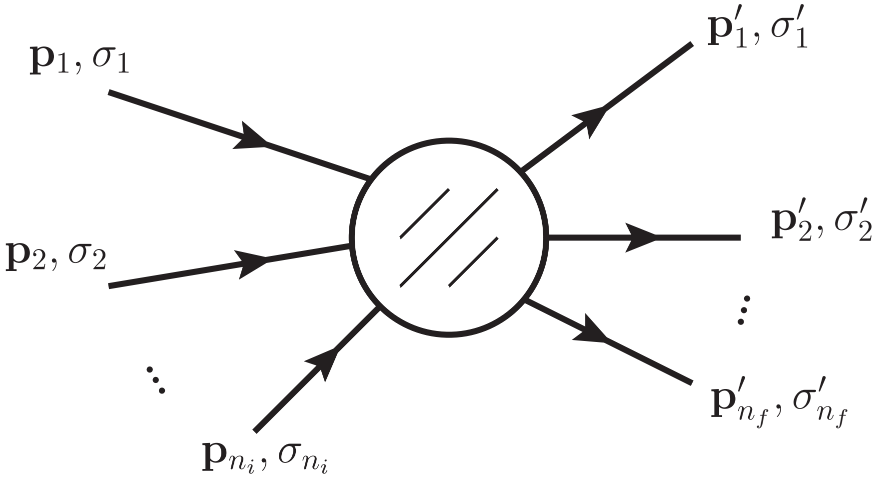
How can such a ‘simple’ theory give rise to the rich structures of hadrons?

$$\pi N \to \pi N$$





Reaction Theory



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

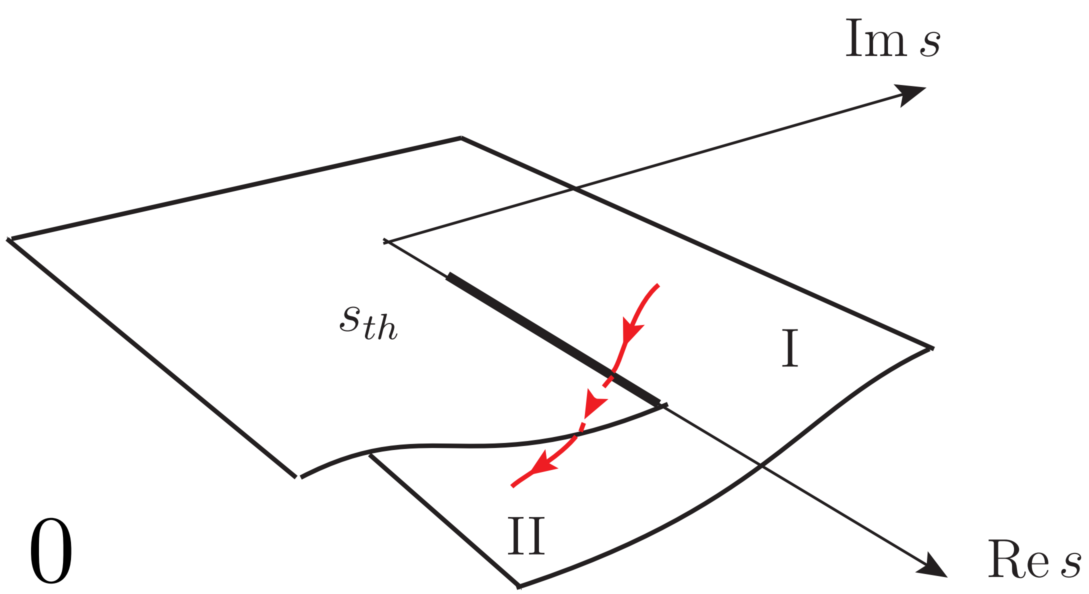
$$\langle\{\mathbf{p}'\sigma'\}|\,T\,|\{\mathbf{p}\sigma\}\rangle = (2\pi)^4\delta^4(P'-P)\mathcal{A}_{\{\sigma',\sigma\}}(\{\mathbf{p}',\mathbf{p}\})$$

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

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

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

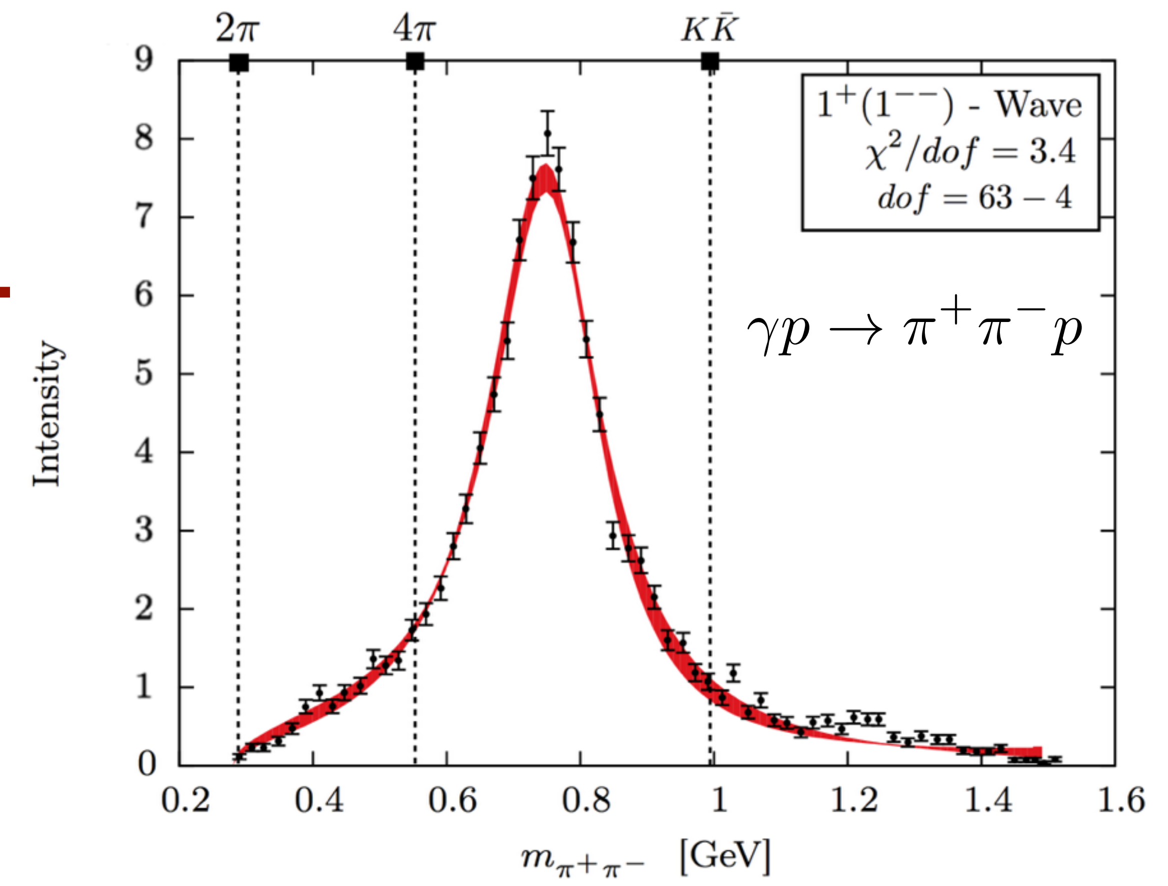
$$\implies \quad \mathcal{A}(s+i\epsilon,t) - \mathcal{A}(s-i\epsilon,t) \neq 0$$

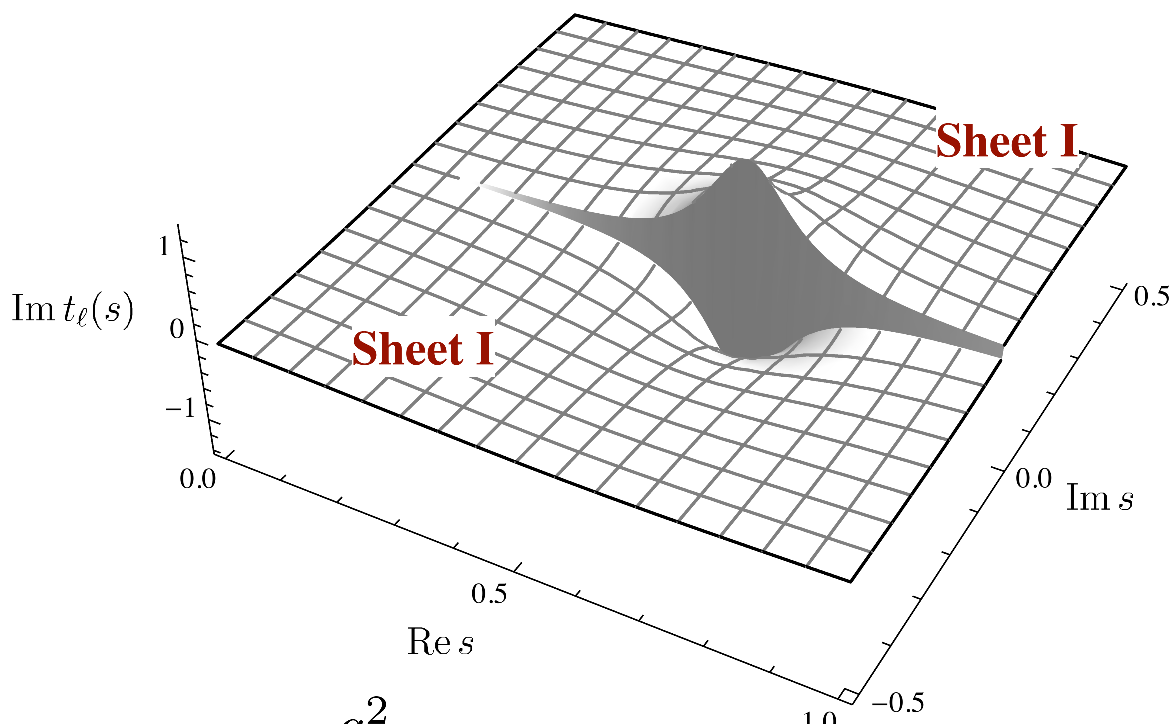


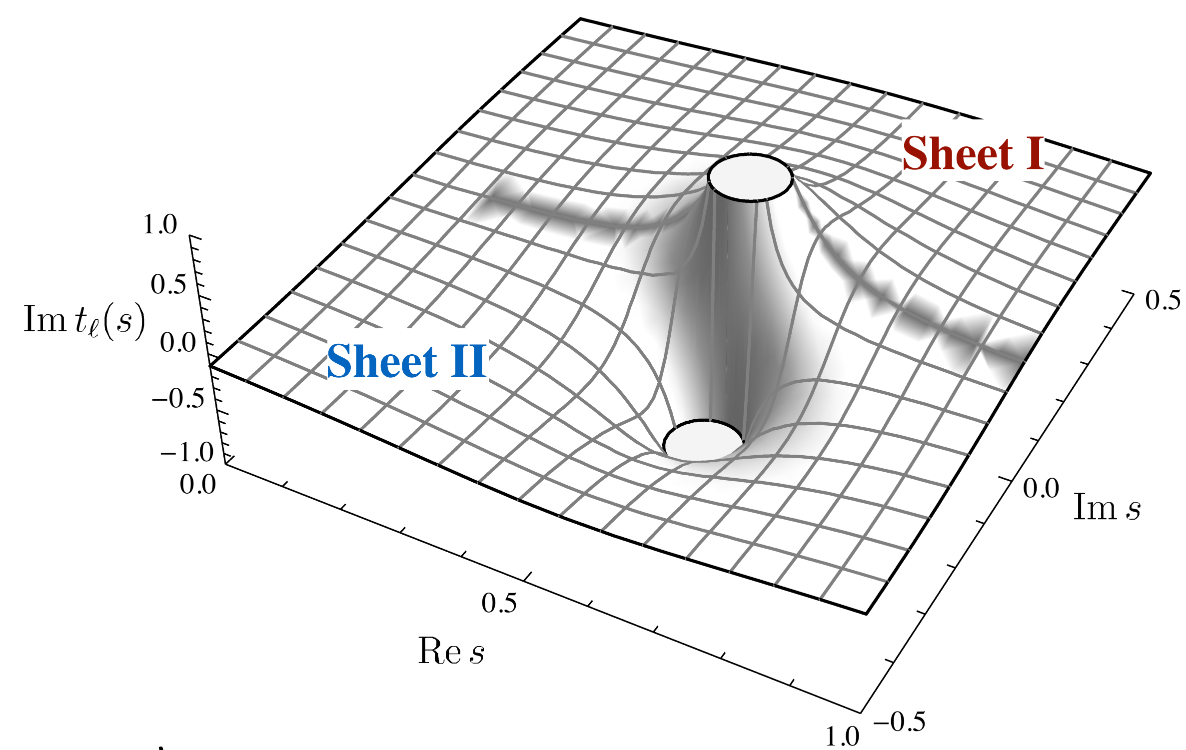
Reaction Theory

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

Resonance poles lie underneath unitarity cuts on unphysical Riemann sheets





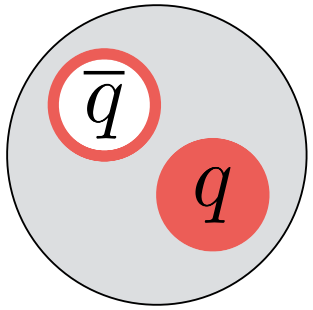


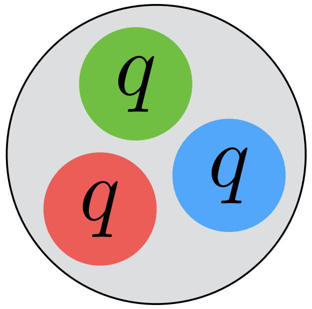
$$t(s) = \frac{g^2}{m^2 - s - i\sqrt{s}\,\Gamma(s)}$$

$$\pi\pi \to \rho \to \pi\pi$$

Spectroscopy

Mesons

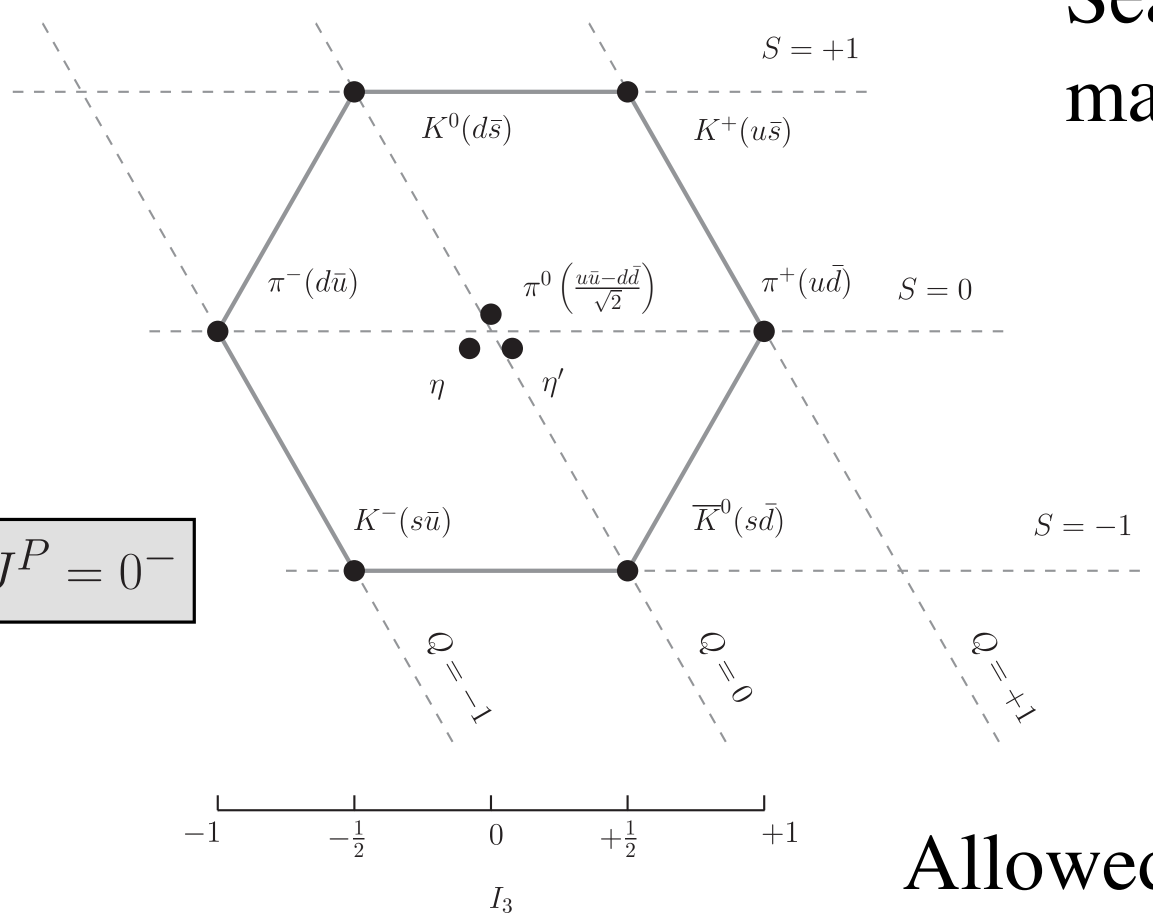




Baryons

The constituent quark model provides a classification scheme for hadrons

Some quantum numbers are not included



$J^P = 0^-$

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

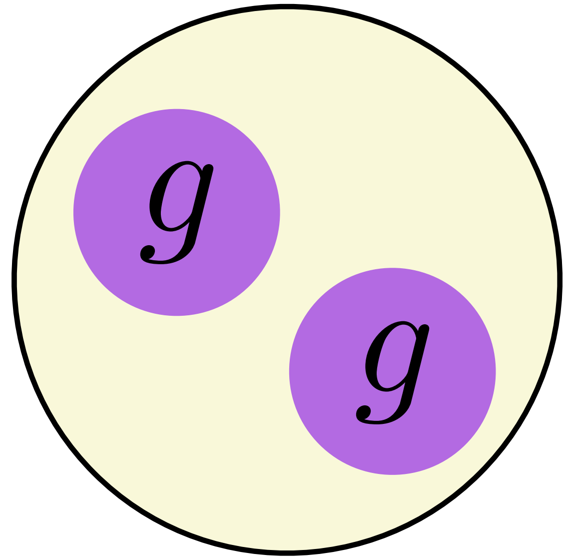
$$S = 0, 1$$
$$L = 0, 1, 2, \ldots$$
$$|L - S| \leq J \leq |L + S|$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

$$\text{Allowed}: \quad 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$$
$$\text{Forbidden}: \quad 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$$

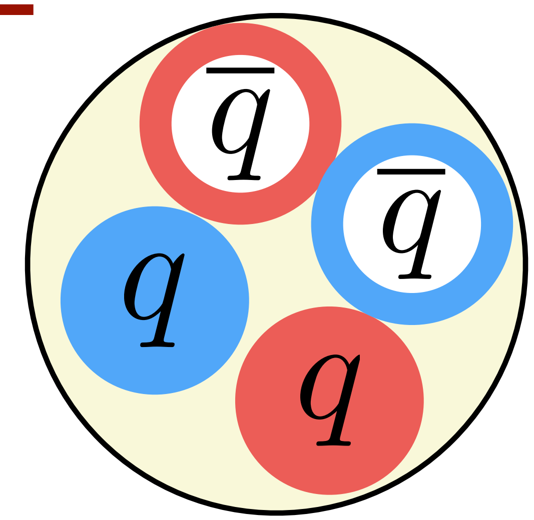
Exotic Hadrons

Not forbidden by QCD

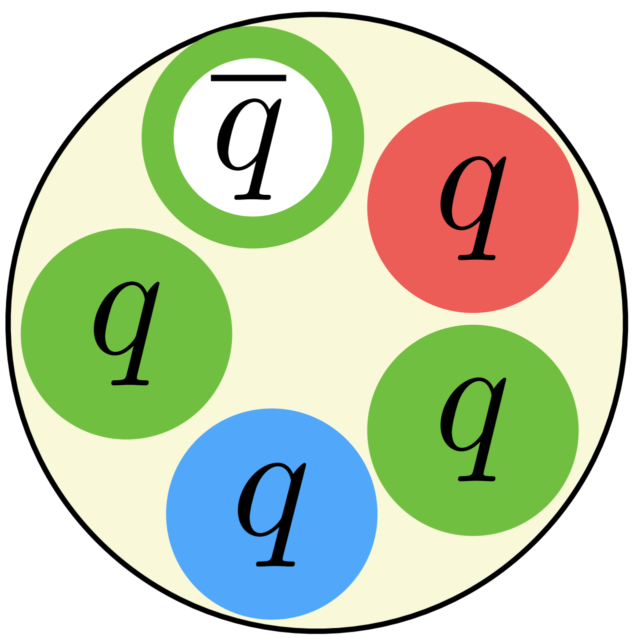
Do these states exist?
Have we seen them?



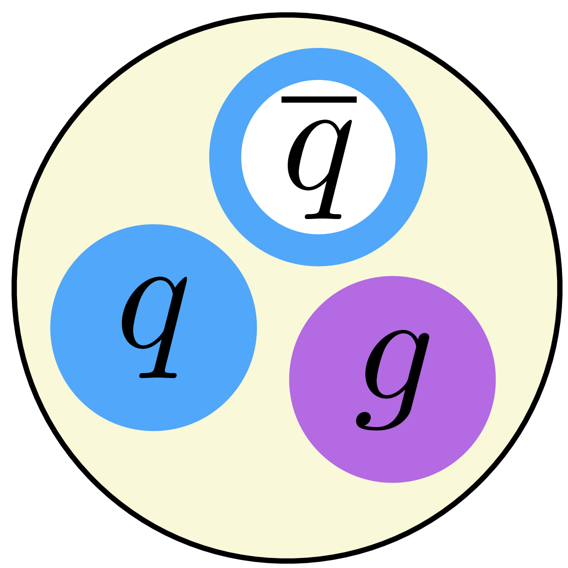
Glueballs



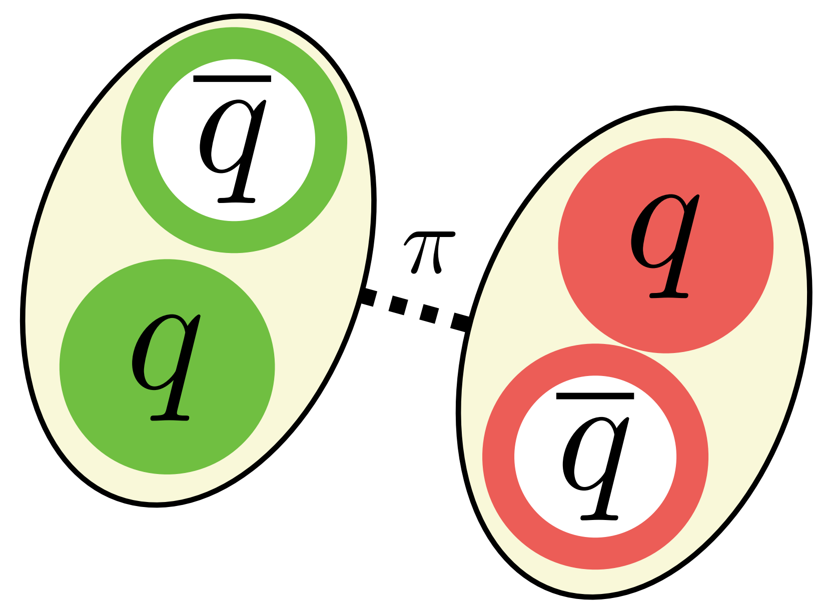
Tetraquarks



Pentaquarks

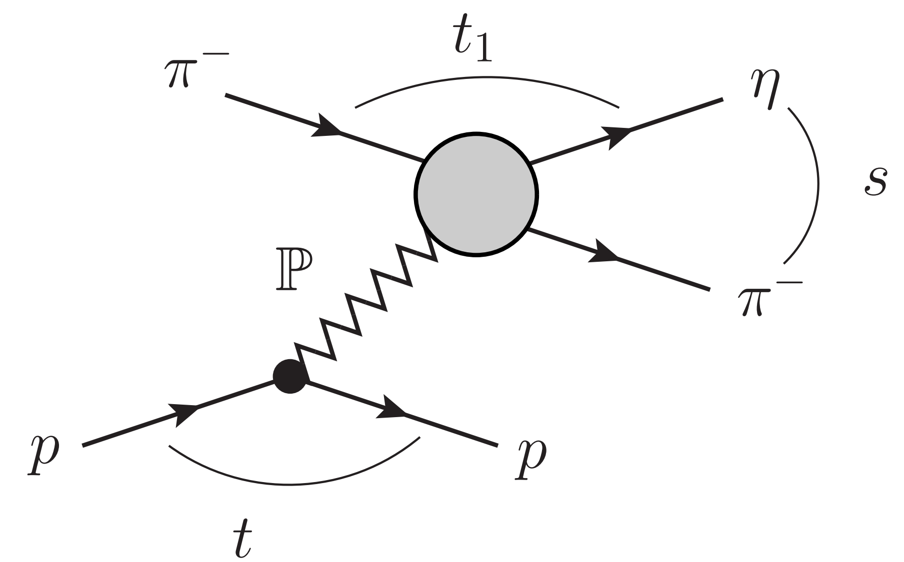


Hybrids



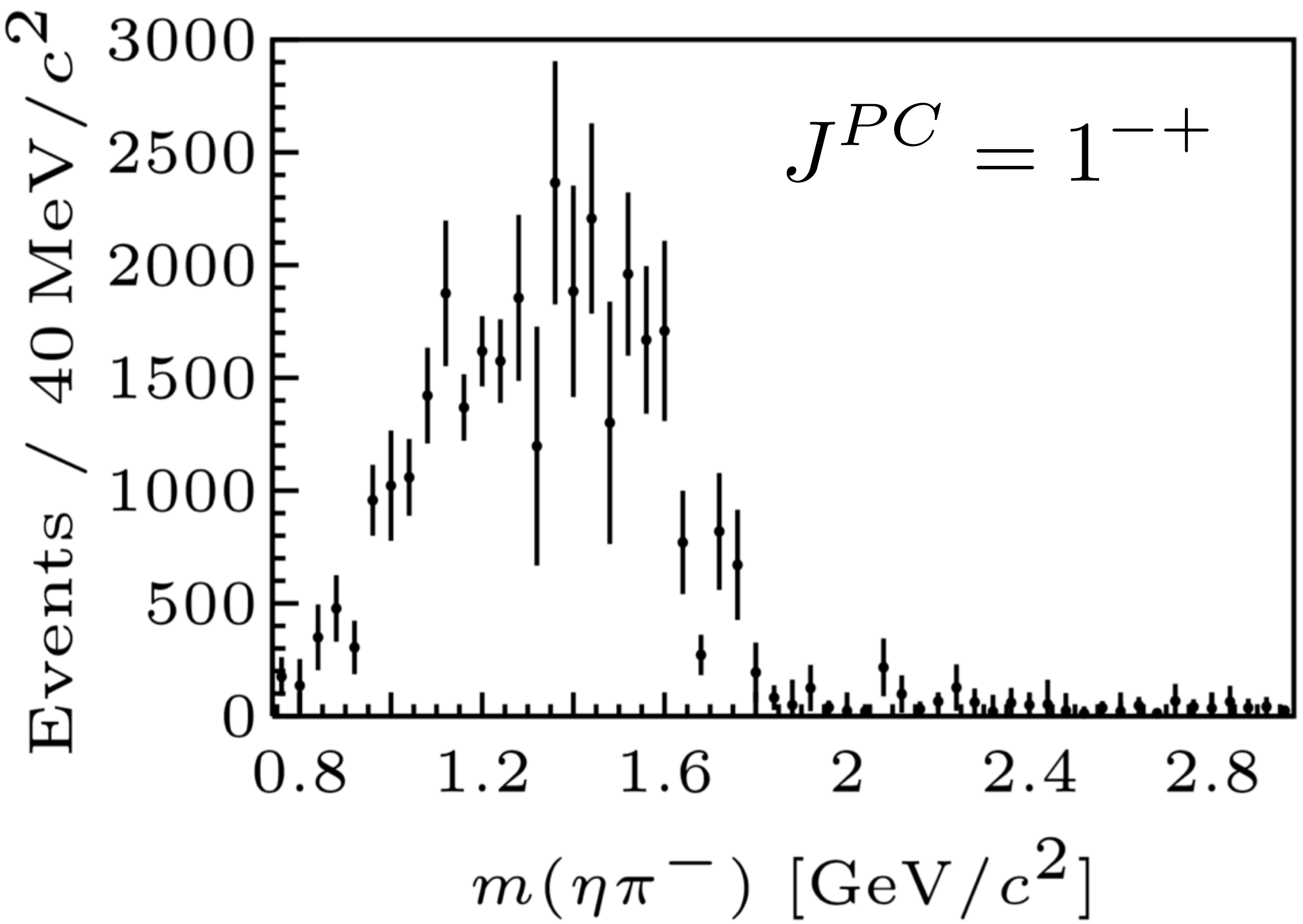
Mesonic-Molecules

Exotics at COMPASS



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

JPAC working with COMPASS to analyze this data



JPAC developed relativistic reaction model to compare with data

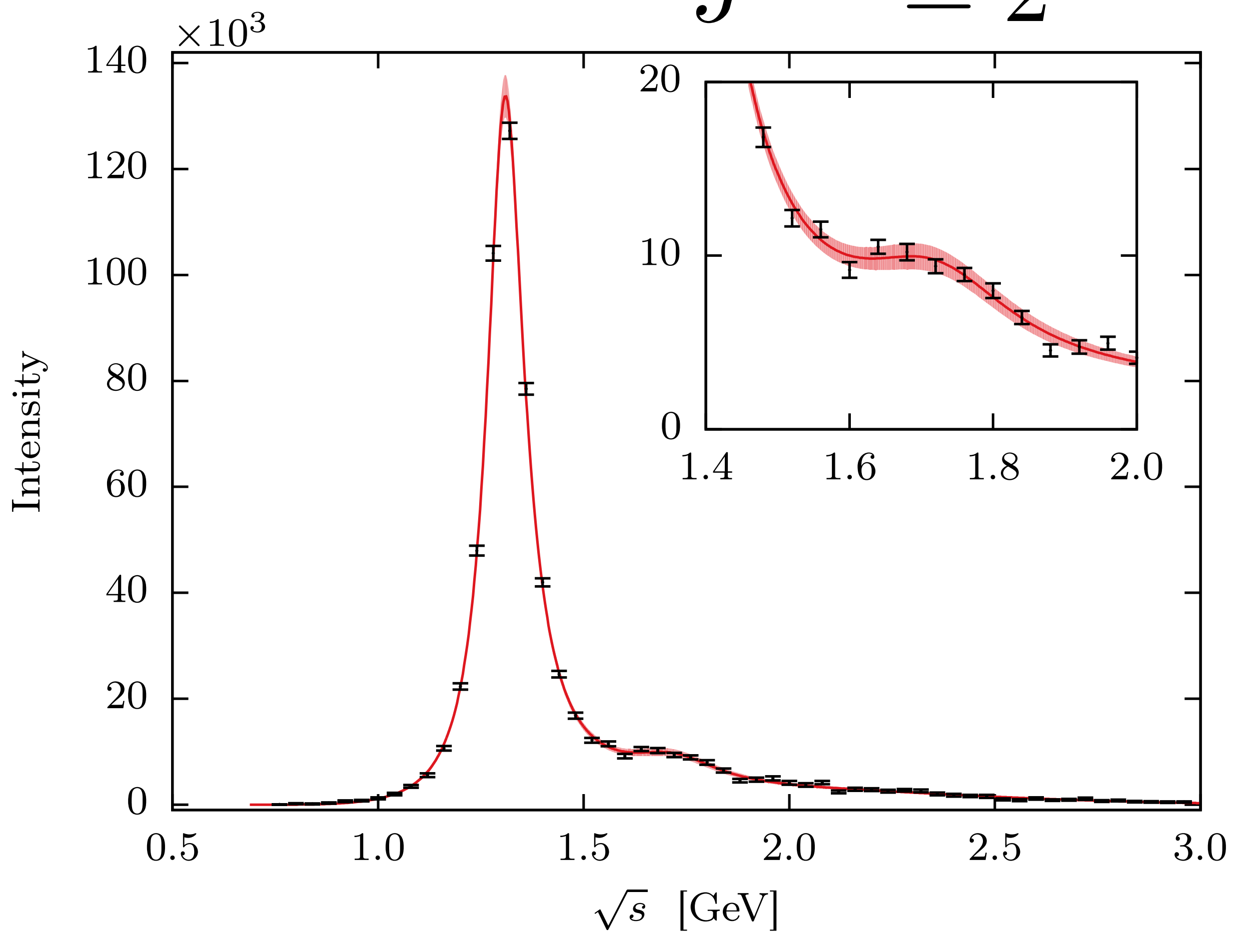
Before analyzing this data, apply reaction model to simpler system

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

Exotics at COMPASS

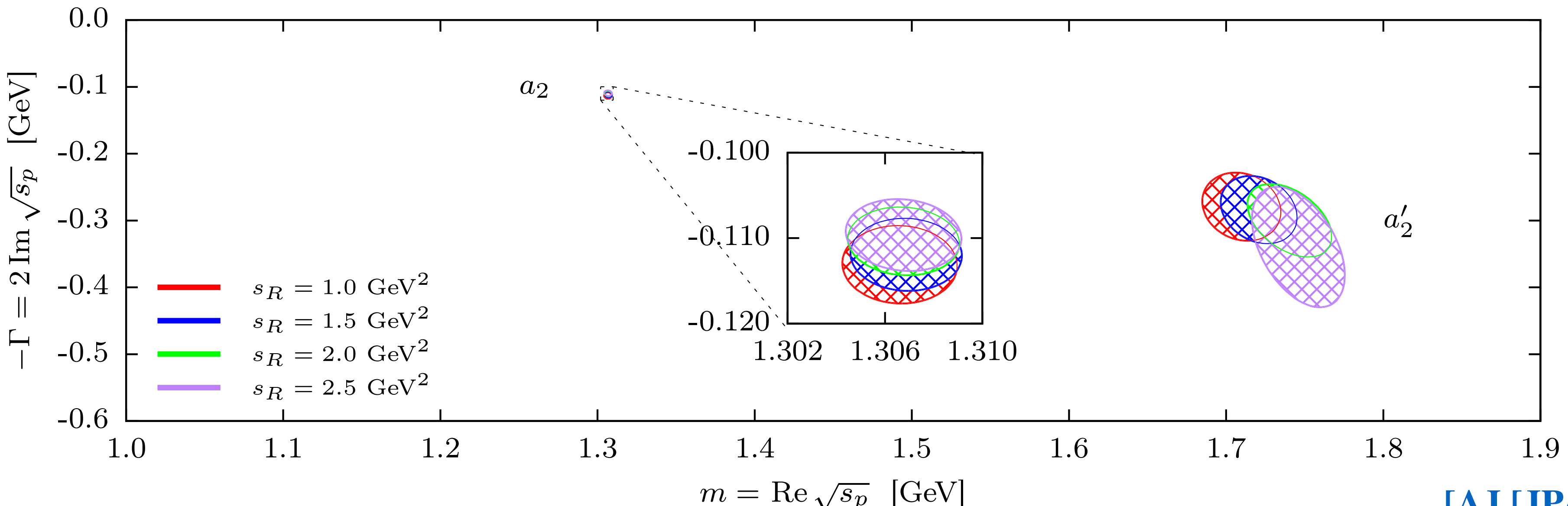
$$\pi p \to \eta^{(\prime)} \pi p$$

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



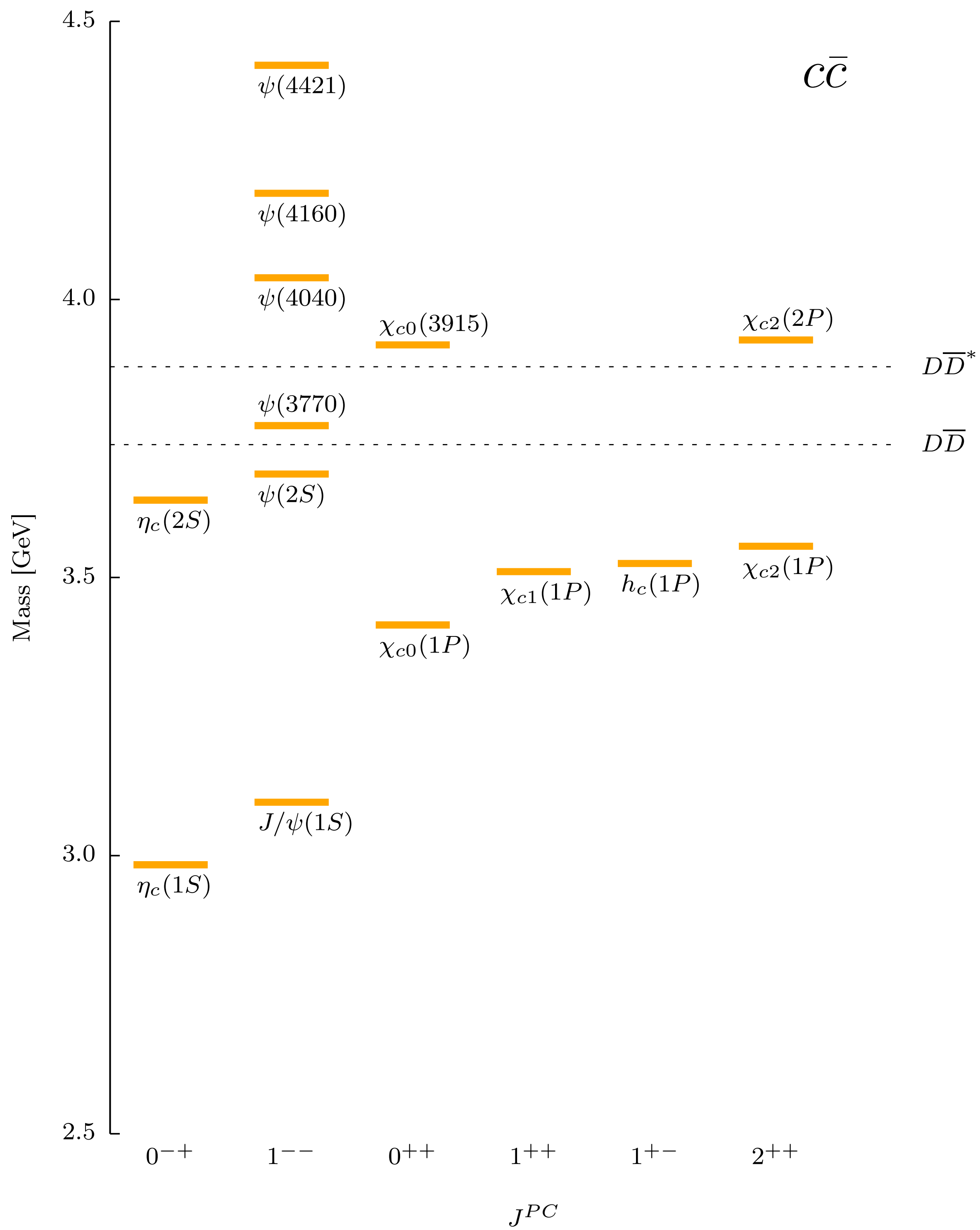
First joint publication between JPAC and COMPASS out, laying the ground work of this analysis

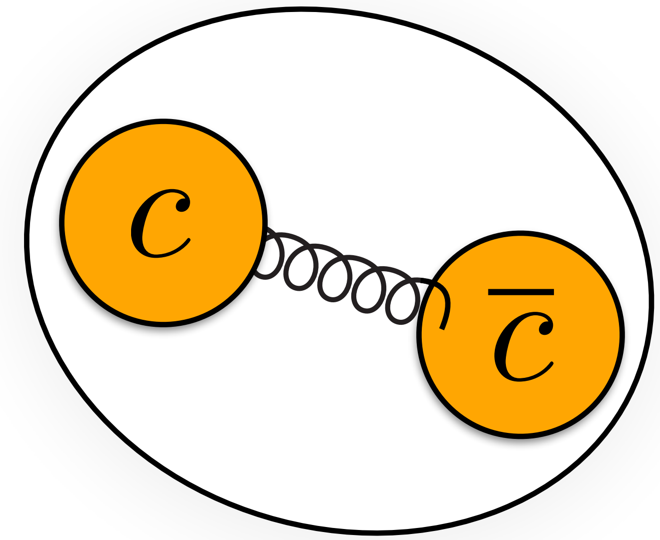
Extract pole positions of a_2, a_2'



[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

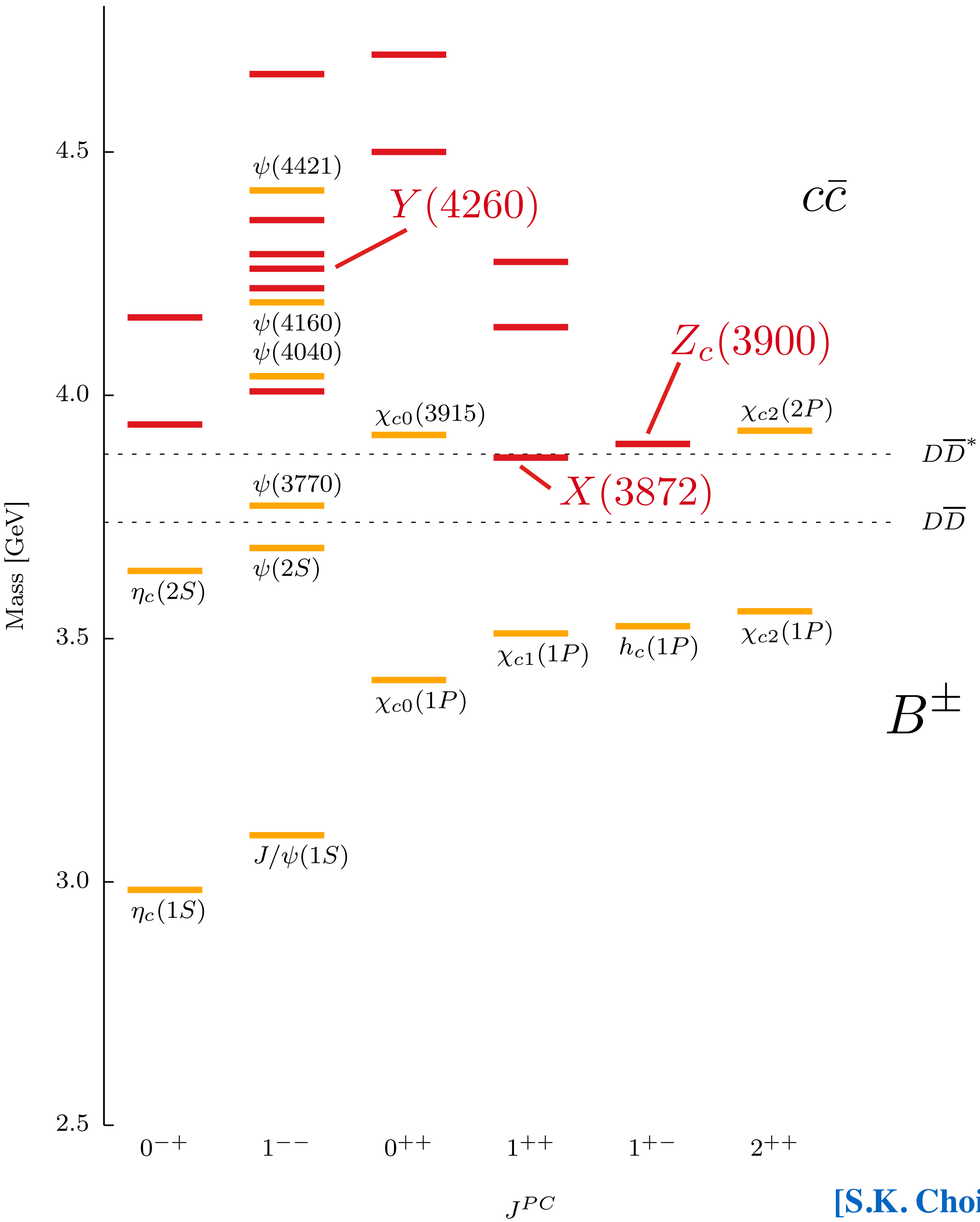
one-gluon exchange

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

linear confinement

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

Exotics in Charmonium



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

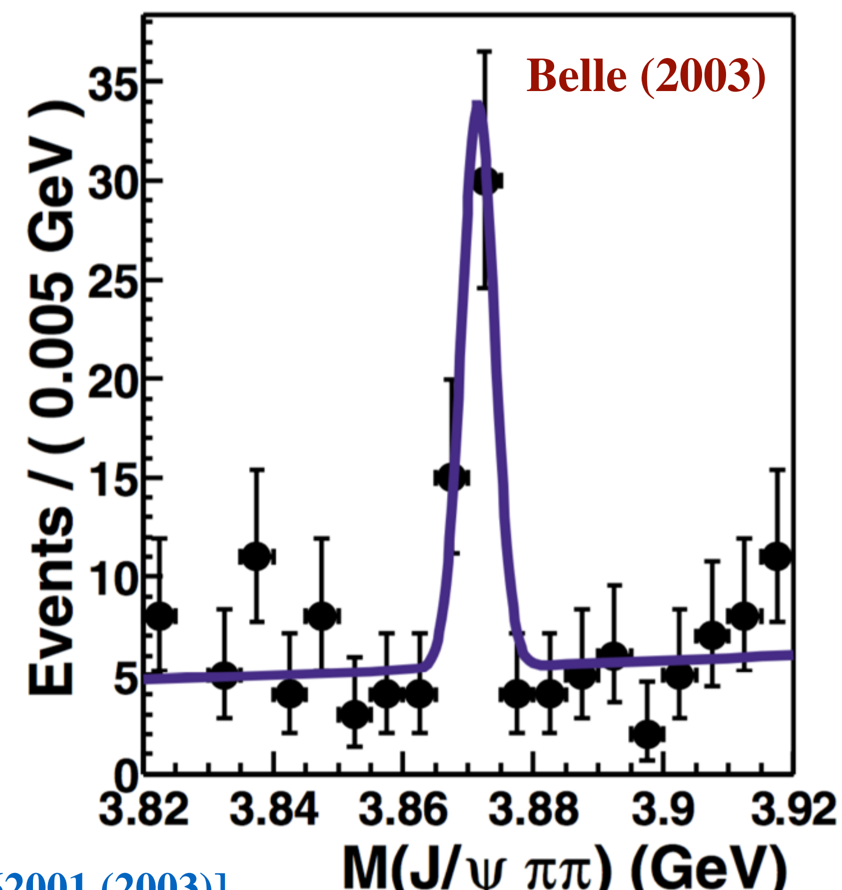
Began the XYZ era of hadron spectroscopy

Unconventional quark assignments (tetraquark-like)

What is the nature of these states?

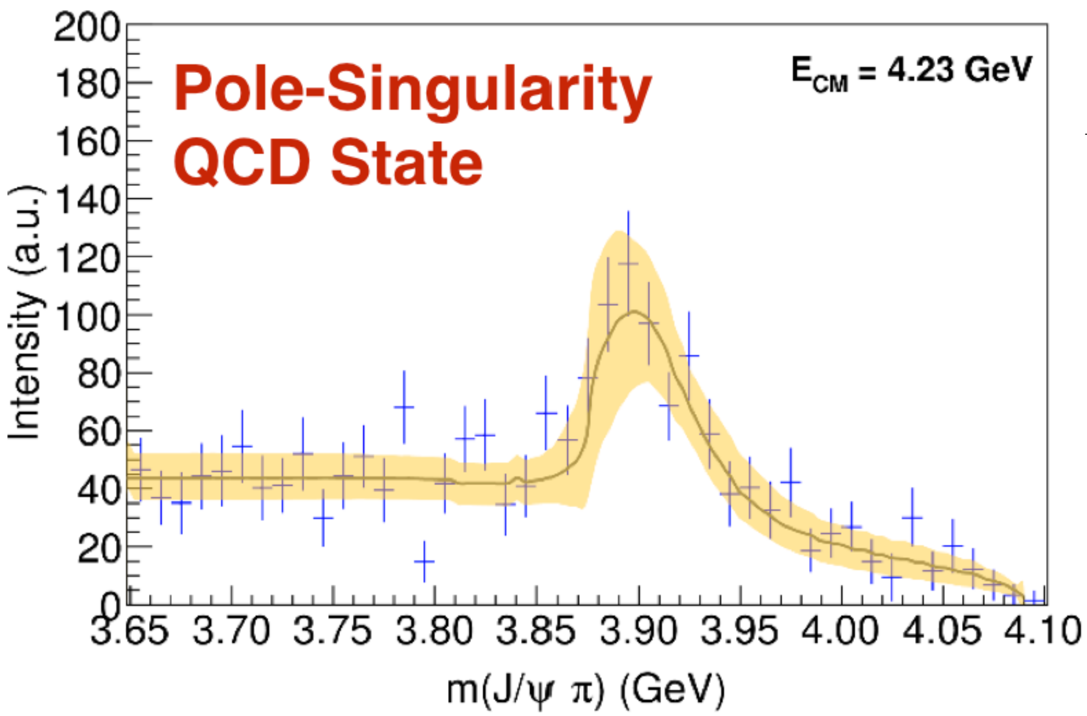
$$B^{\pm} \to K^{\pm} \underbrace{\pi^{+}\pi^{-} J/\psi}_{X(3872)}$$

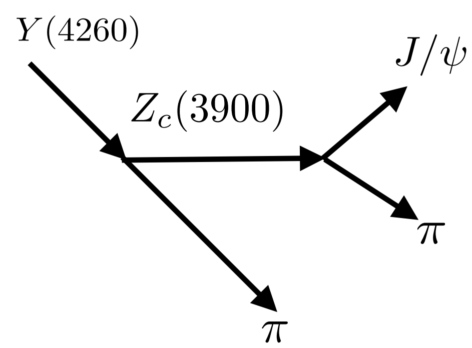
$$X(3872) \downarrow (u\bar{u}c\bar{c})$$



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

$Z_c(3900)$

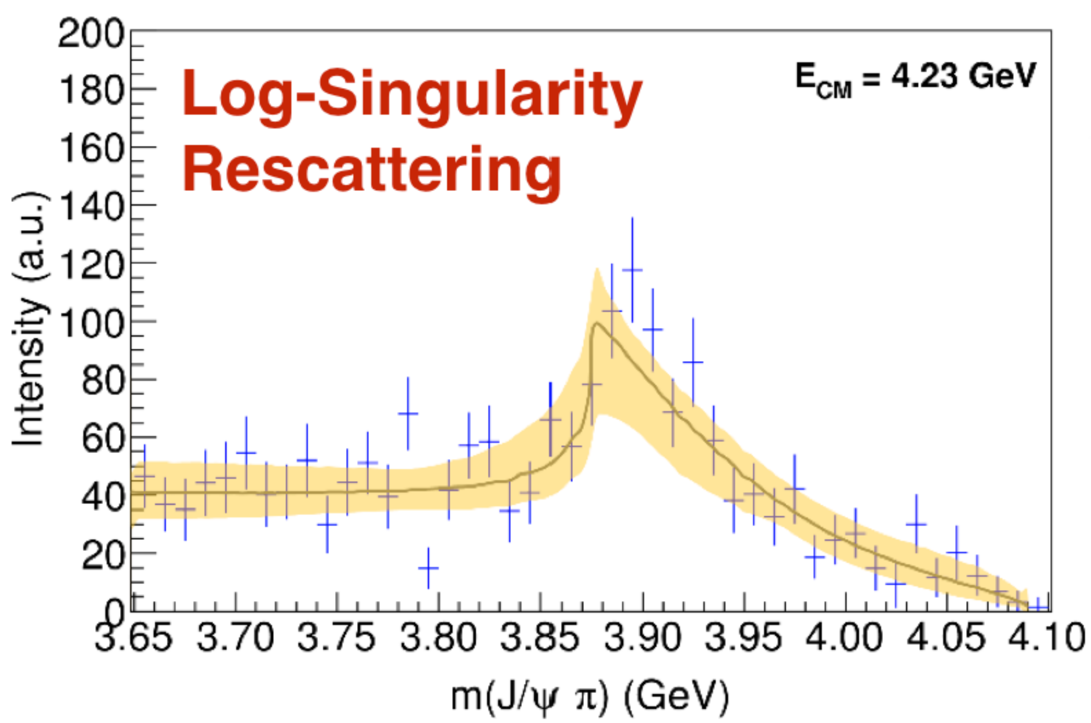


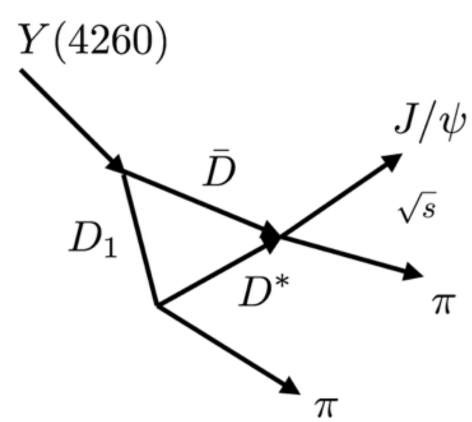


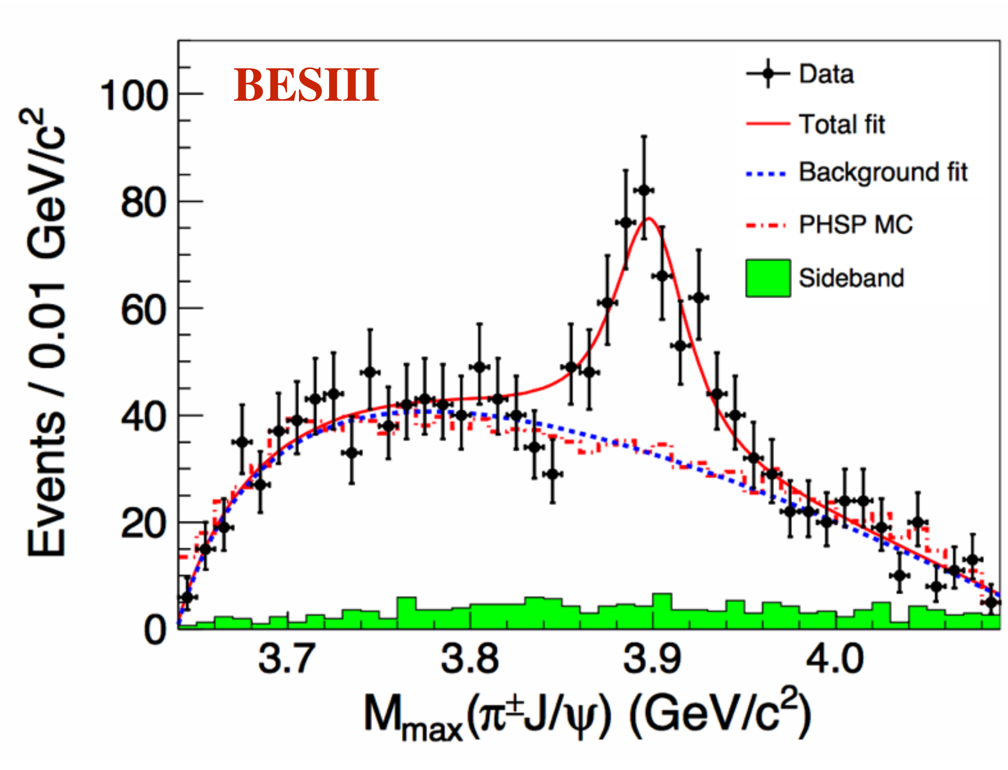
Found in decay of

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

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]

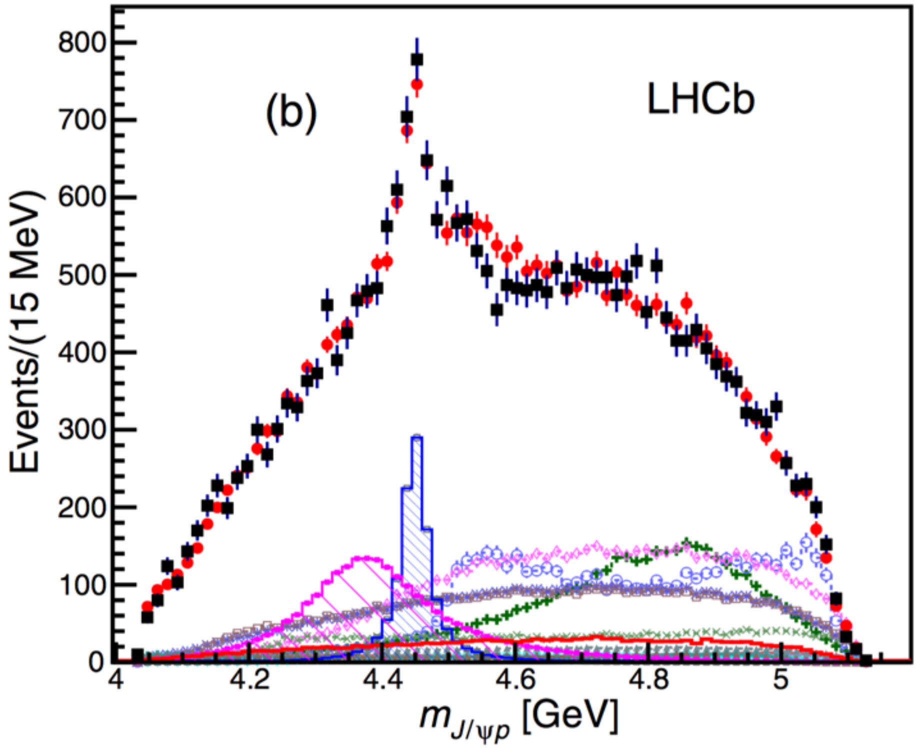
LHCb Pentaquark

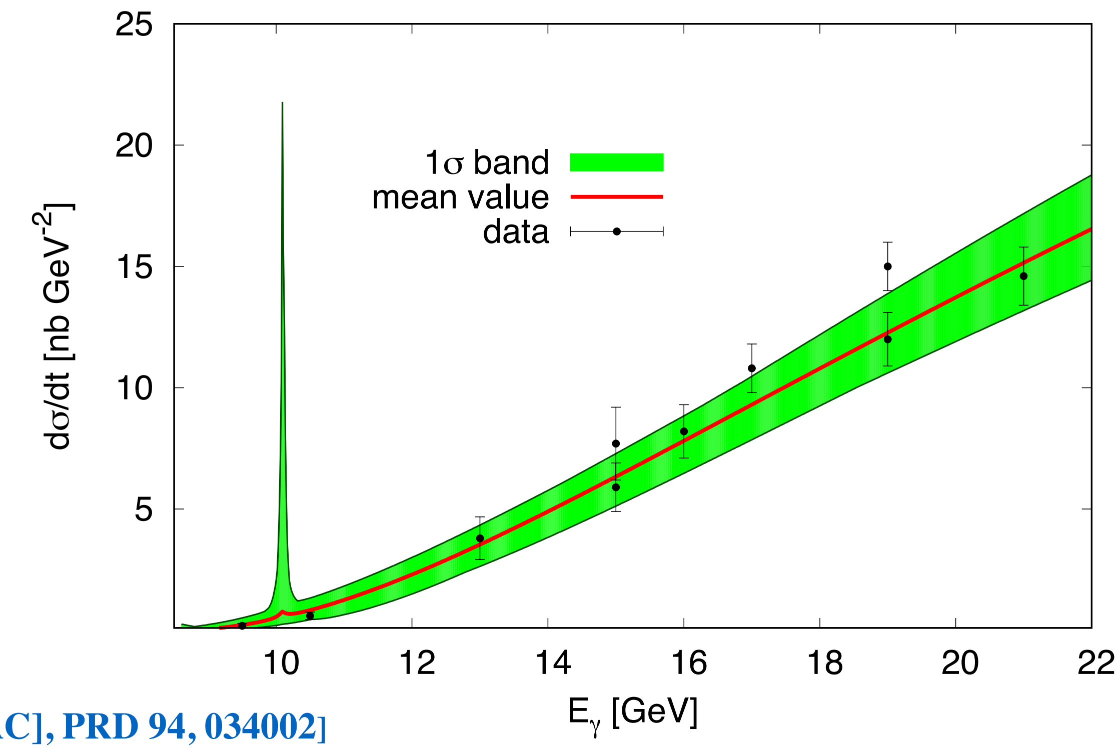
[R. AAIJ [LHCB]., PRL 115, 072001]

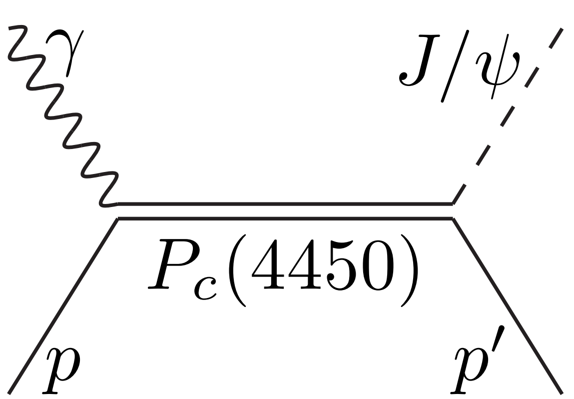
LHCb claim discovery of pentaquarks $P_c(4450)$ and $P_c(4380)$ in $\Lambda_b \to KJ/\psi p$

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

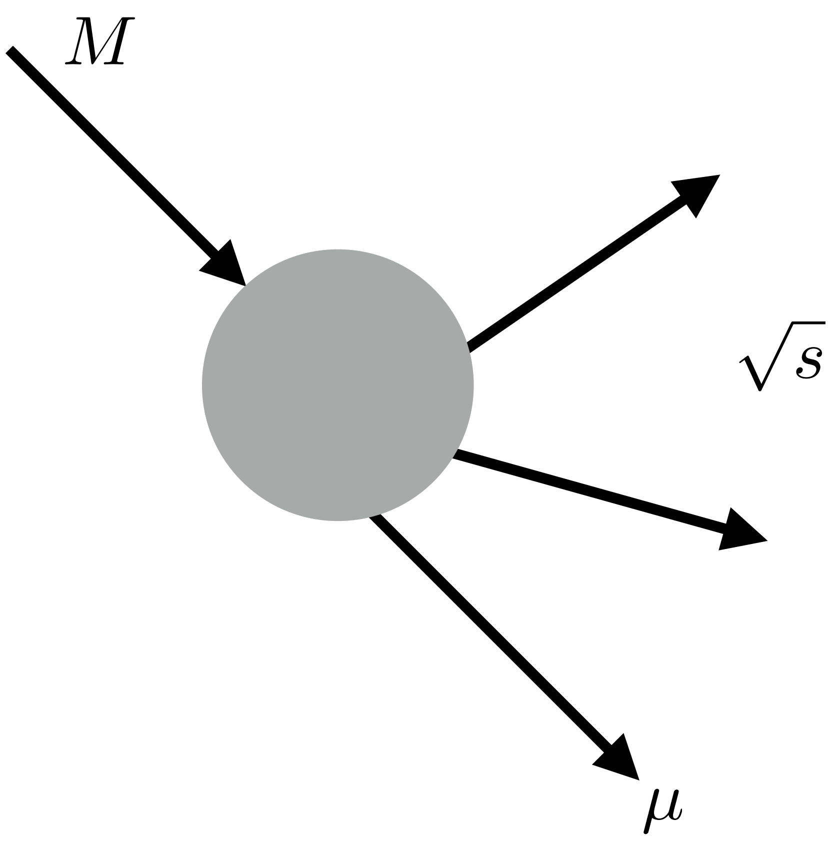
Back-Up

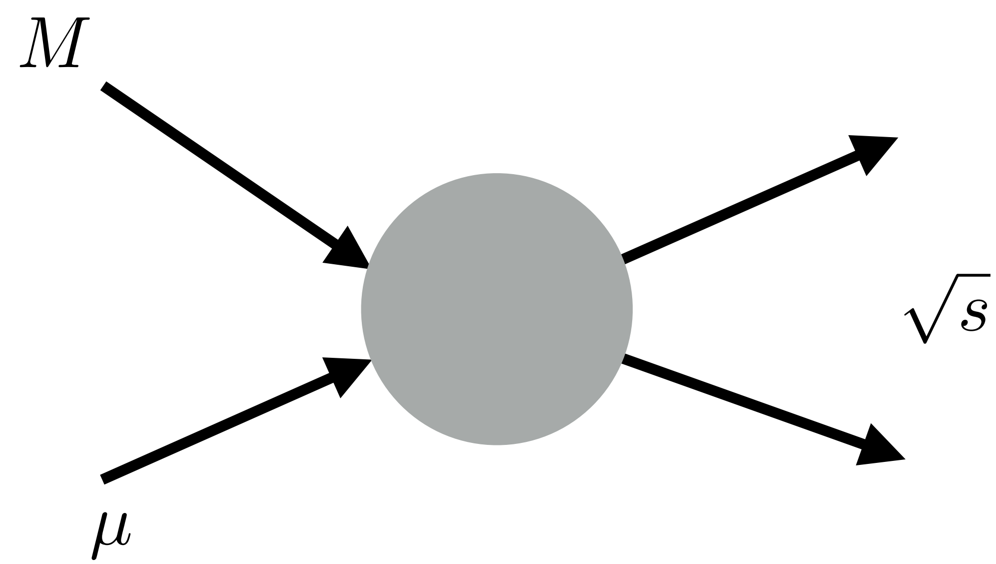
Triangle Mechanism

Look at 3-Body decay of particle M

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

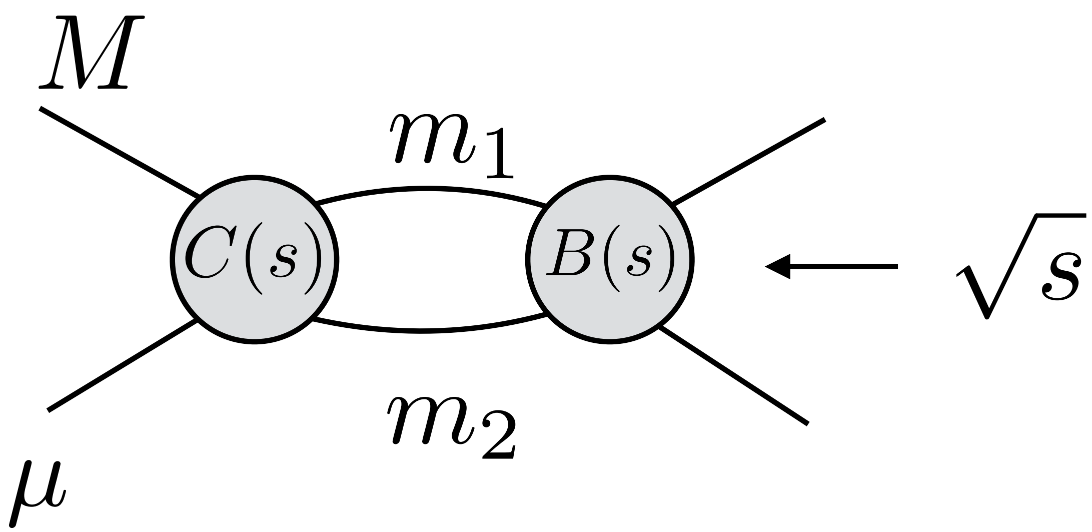
For these examples, assumption that all particles are scalar

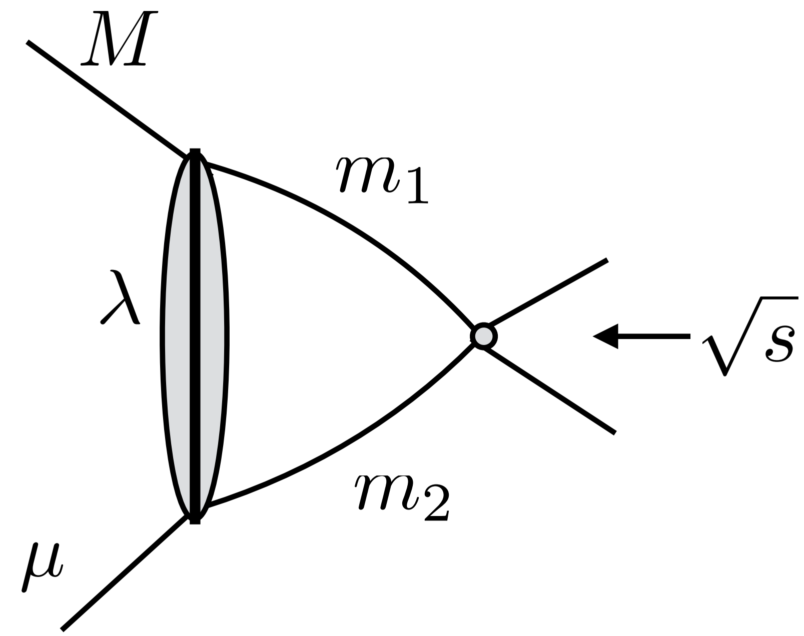




From Crossing

Triangle Mechanism





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

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

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

For simplicity, B(s)=CONST

After partial wave projection

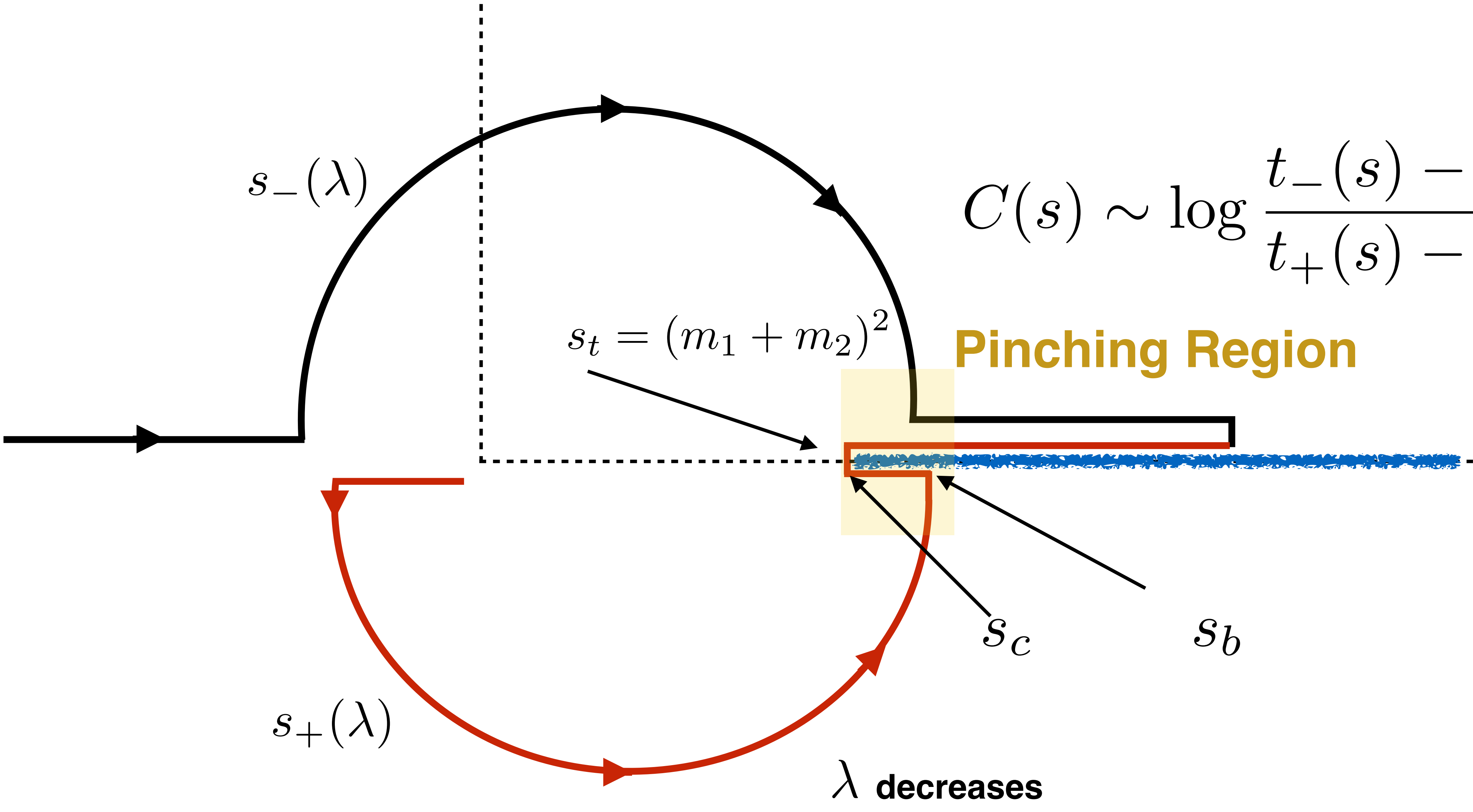
$$C(s) \sim \log \frac{t_-(s) - \lambda^2}{t_+(s) - \lambda^2}$$

Look for singularities of C(s)

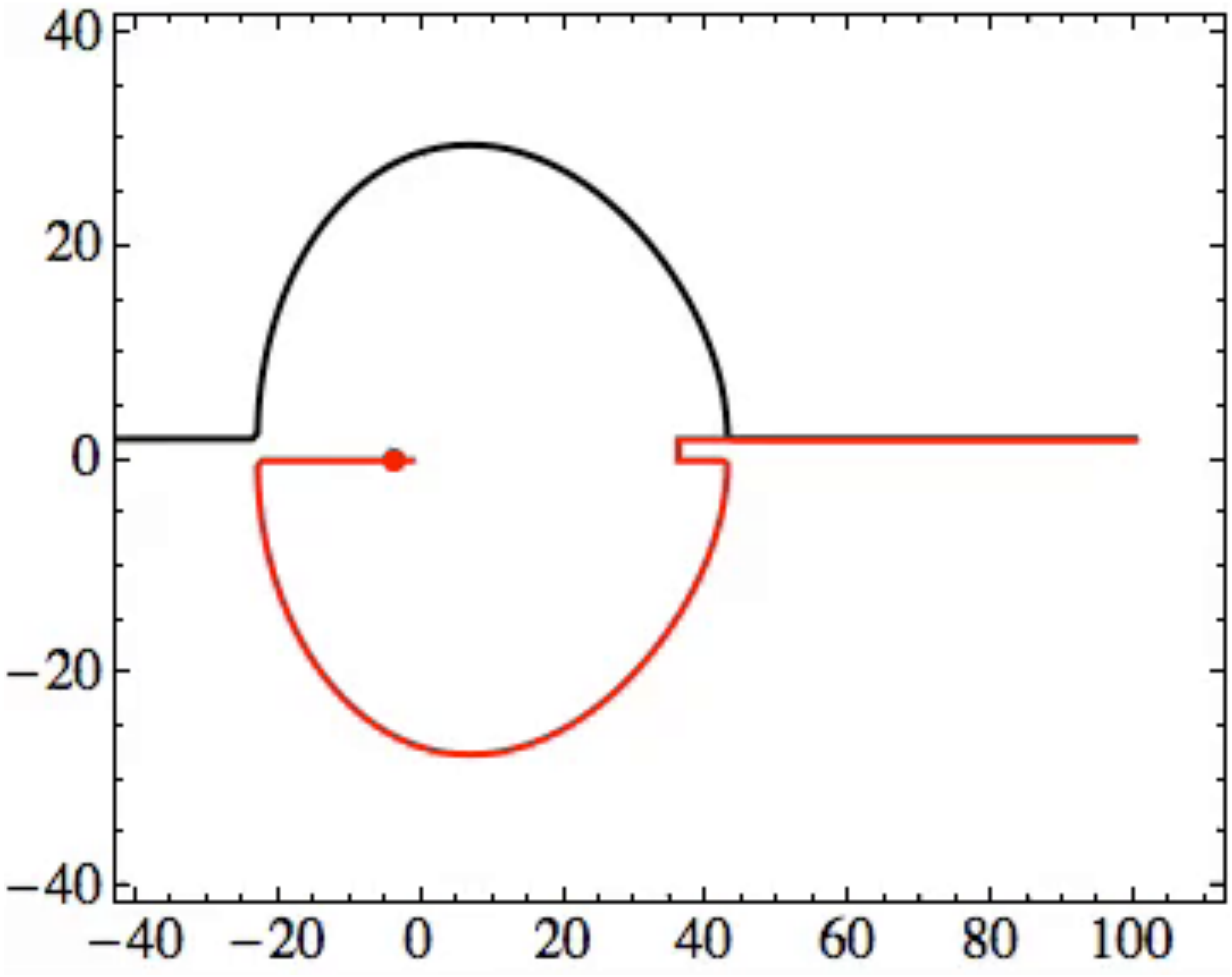
[A. Szczepaniak, arXiv:1501.01691v3]

Triangle Branching Points

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



Branch Cut Movement



λ **decreases**

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)