Exotic Mesons Spectroscopy: Challenges and Prospects

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Jefferson Lab
Joint Physics Analysis Center

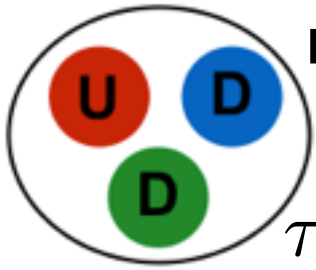
Light Cone Conference
JLab, May 2018

Jefferson Lab
Thomas Jefferson National Accelerator Facility

JPAC Joint Physics Analysis Center

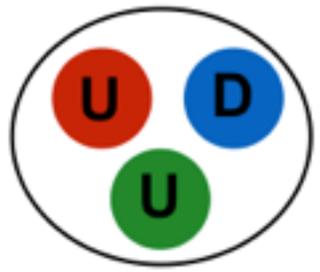
Ordinary and Exotic Hadrons

Ordinary baryons:



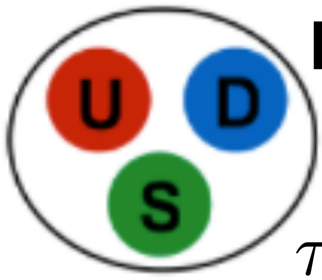
neutron

$\tau \sim 10^3 s$



proton

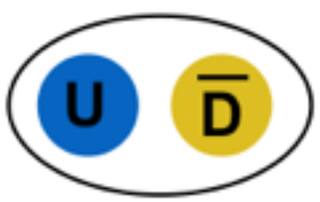
stable



baryon Λ

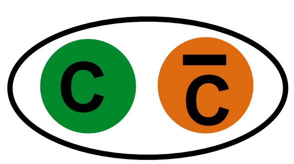
$\tau \sim 10^{-10} s$

Ordinary mesons



pion

$\tau \sim 10^{-8} s$



J/ψ

$\tau \sim 10^{-20} s$

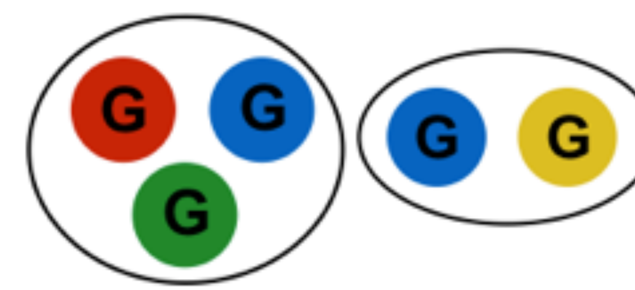
kaon

$\tau \sim 10^{-8} s$

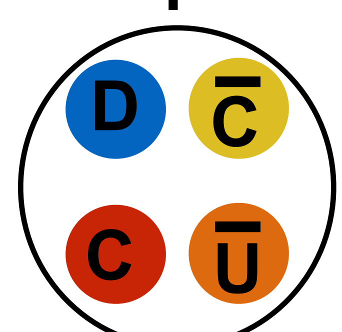
Exotic matter

hybrid mesons

glueballs



tetraquarks



pentaquarks

Ordinary and Exotic Hadrons

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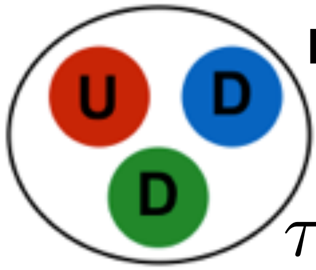

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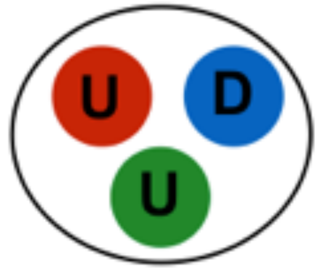
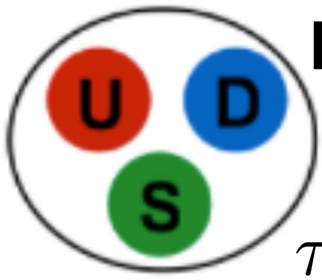
$\tau \sim 10^3 s$



proton

stable



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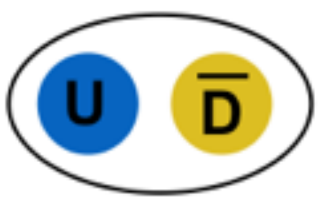

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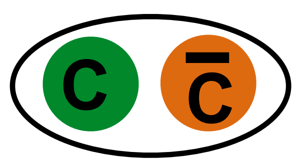

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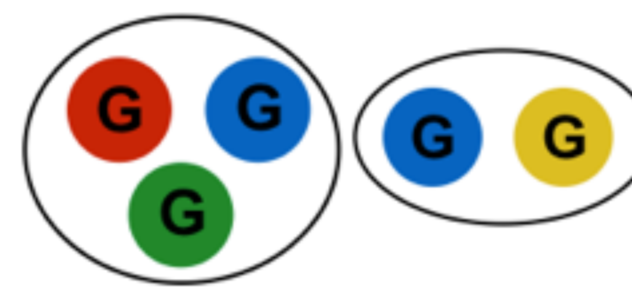
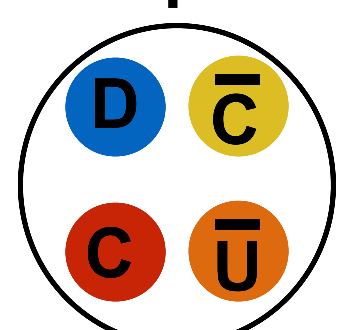
glueballs



tetraquarks



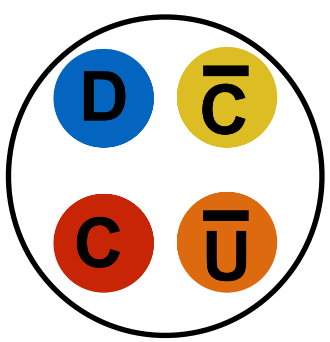
pentaquarks

Outline

- **Exotic light meson spectroscopy**
  in exclusive diffraction reactions:

$$\gamma p \to \pi^0 \eta^{(\prime)} p$$

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



- **Exotic heavy meson spectroscopy**
  in three, four particle decays:

$$B^\pm \to K^\pm \pi^+ \pi^- J/\psi$$

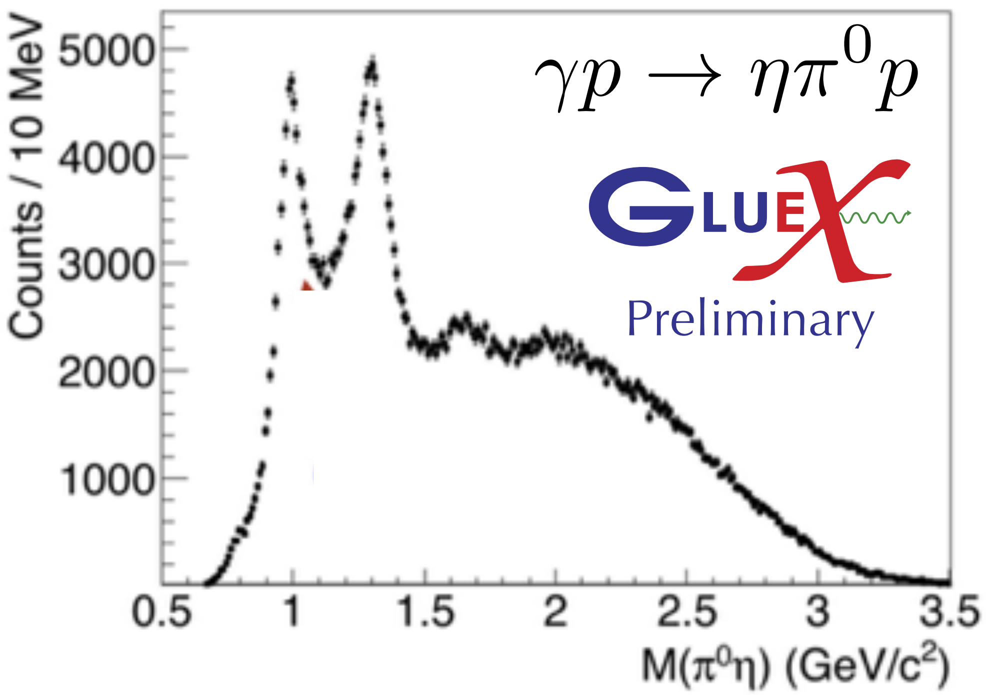
$$e^+ e^- \to \pi^+ \pi^- J/\psi$$

Light Meson Spectroscopy

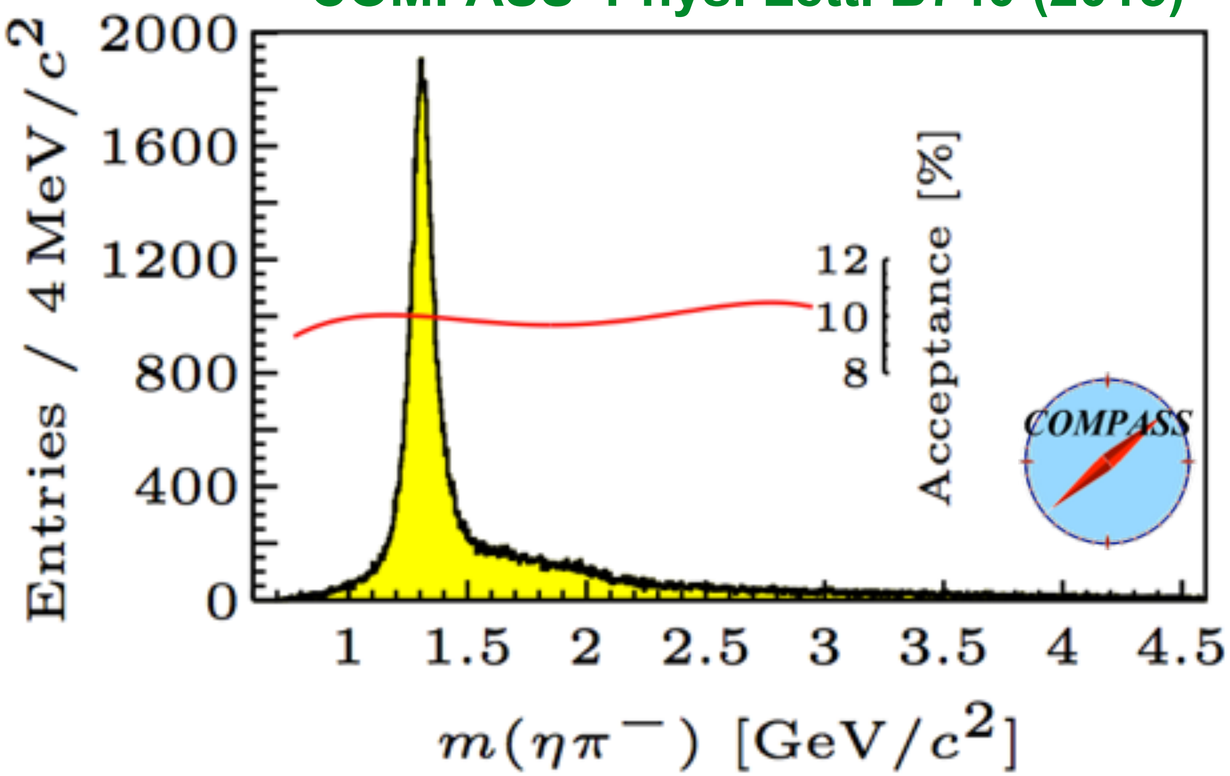
$$E_{\text{beam}} = 9 \text{ GeV}$$

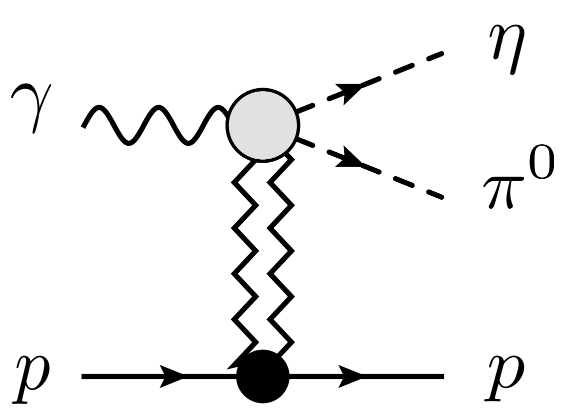
$$E_{\text{beam}} = 190 \text{ GeV}$$

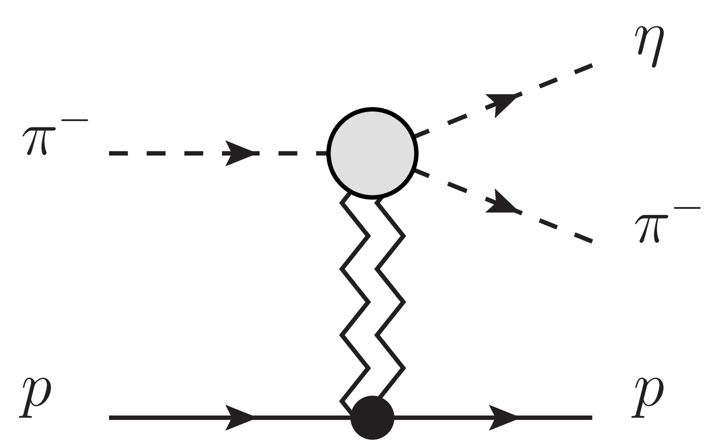
GlueX



COMPASS Phys. Lett. B740 (2015)

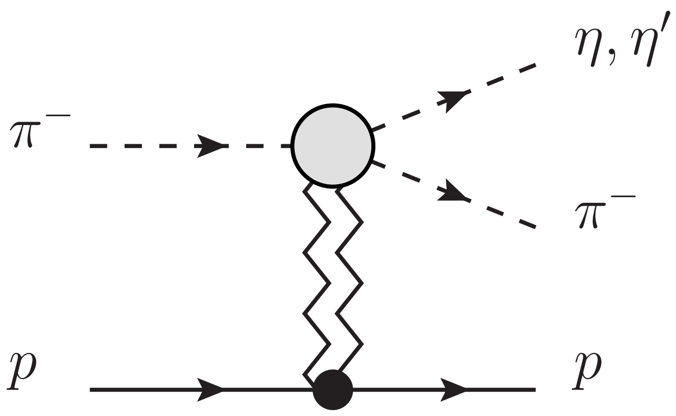


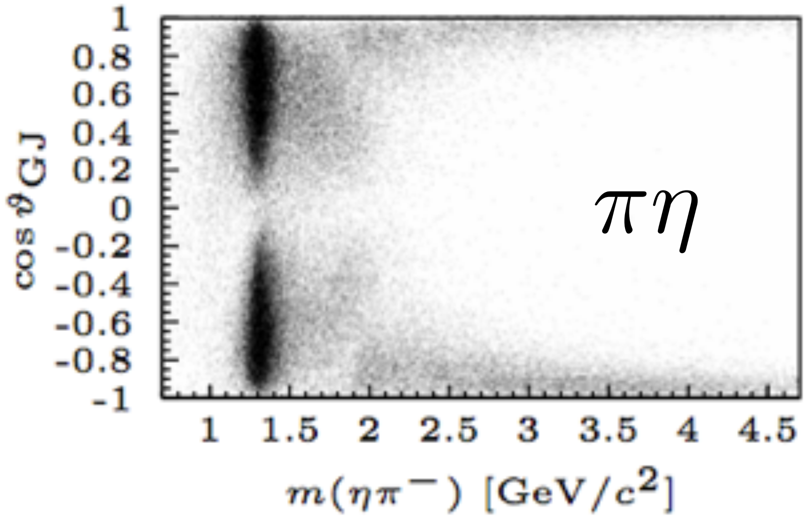


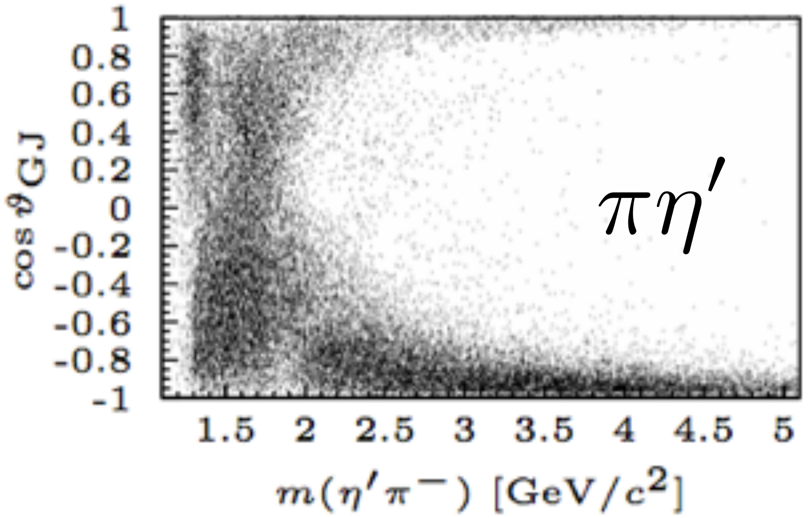


Eta-Pi @COMPASS

COMPASS Phys. Lett. B740 (2015)







Eta-Pi @COMPASS

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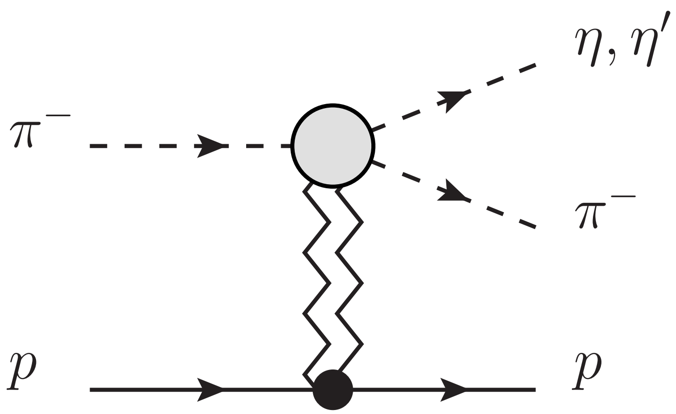
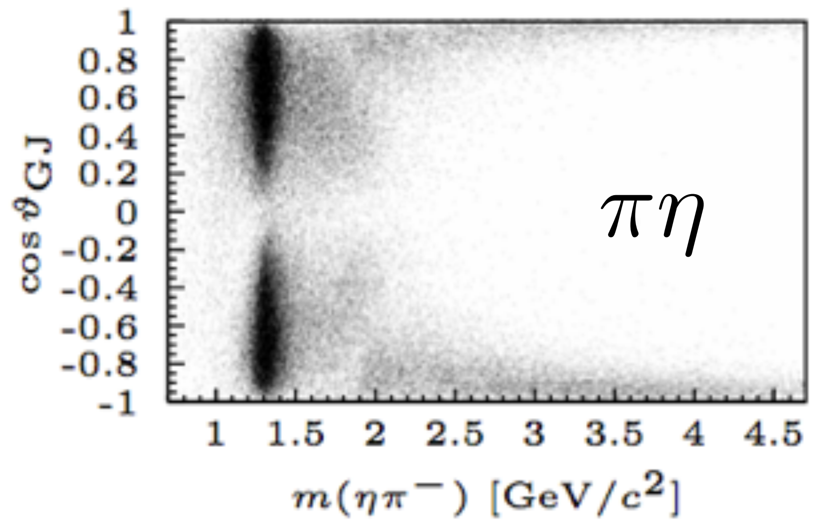
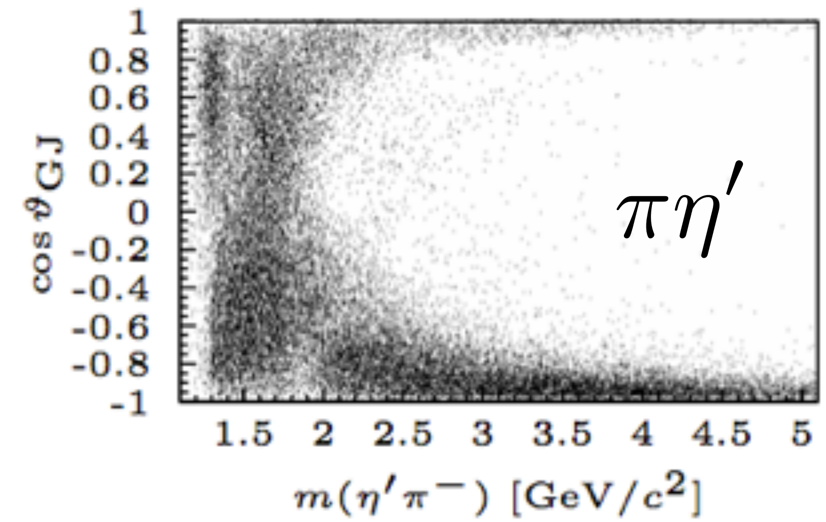
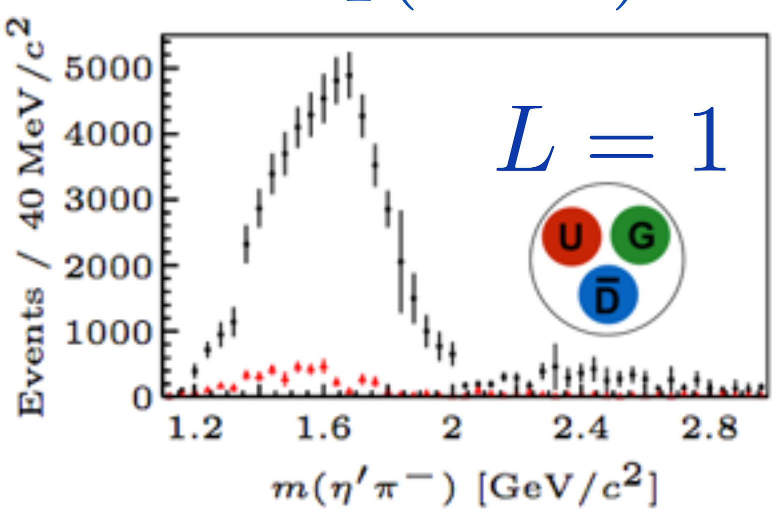


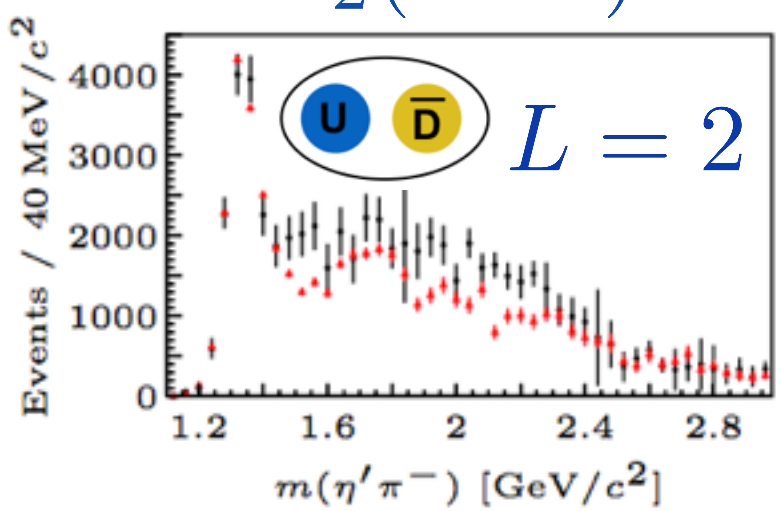




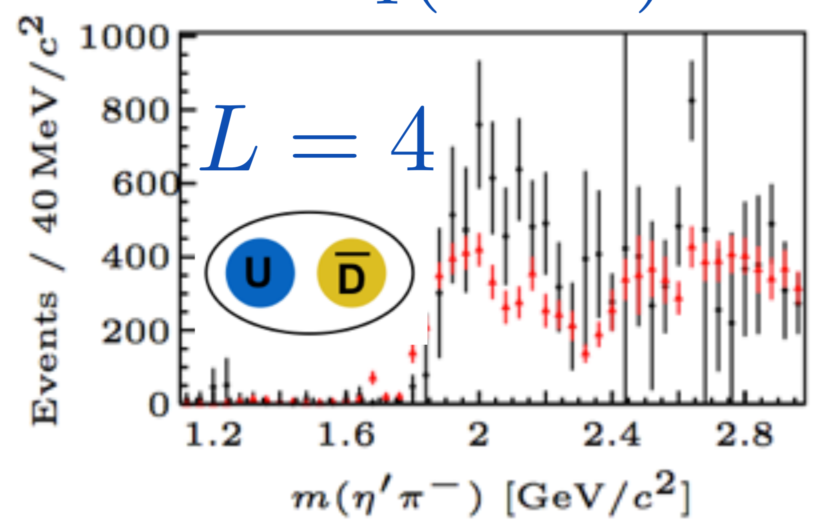
$\pi_1(1600)$?

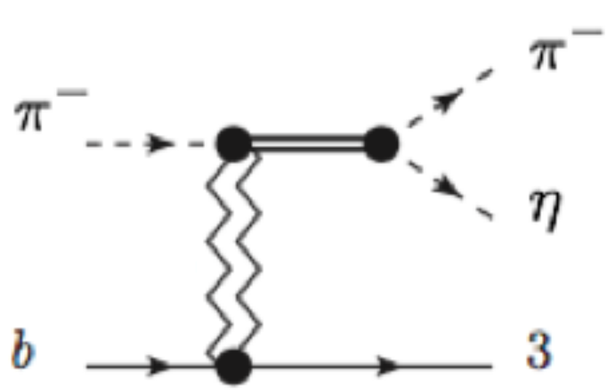


$a_2(1320)$



$a_4(2040)$



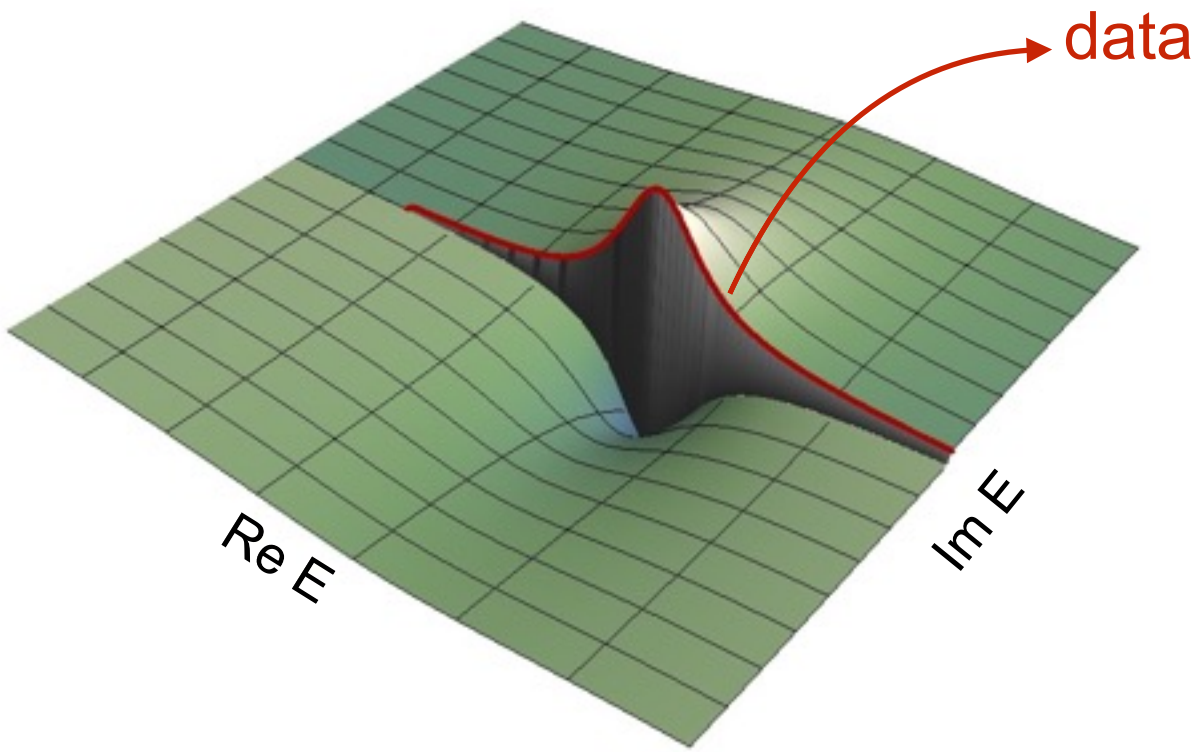


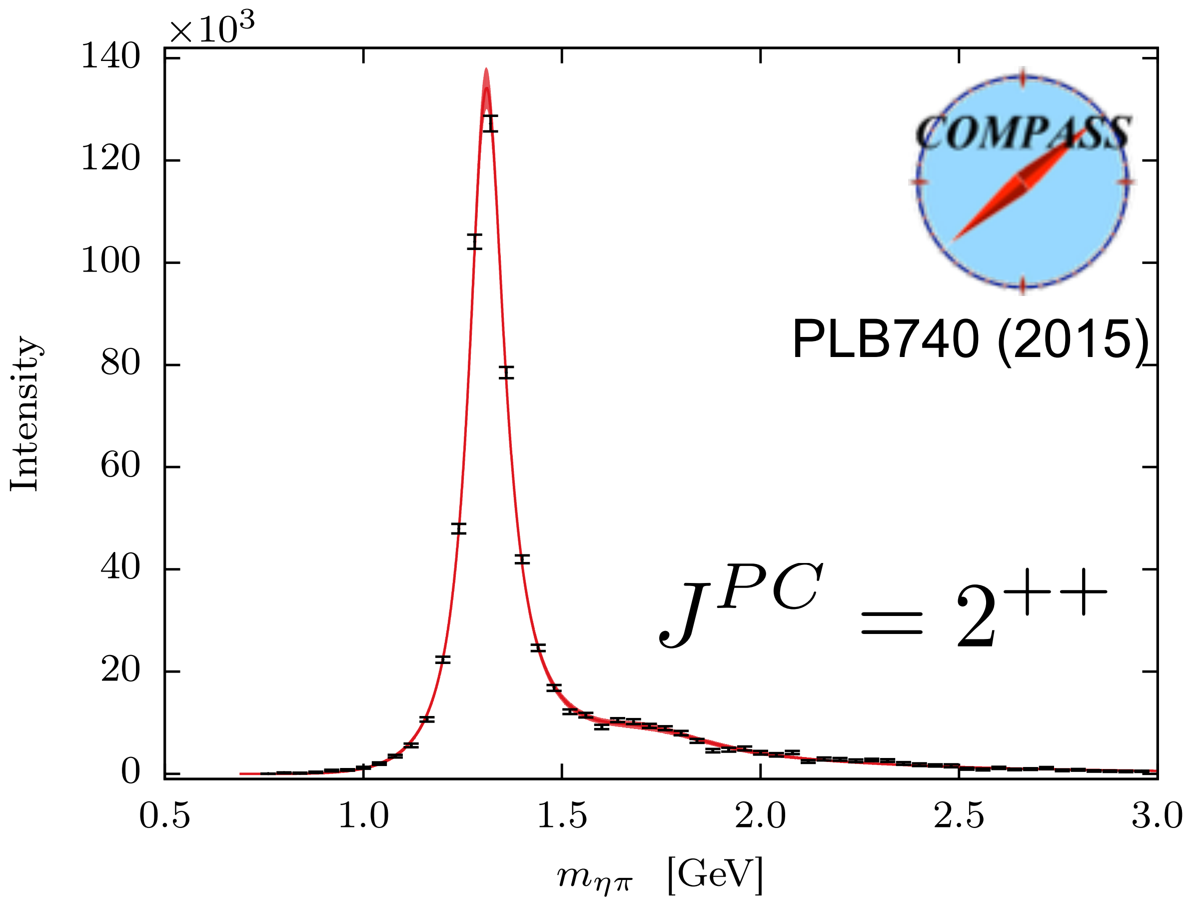
black: $\pi\eta'$

red: $\pi\eta$ **(scaled)**

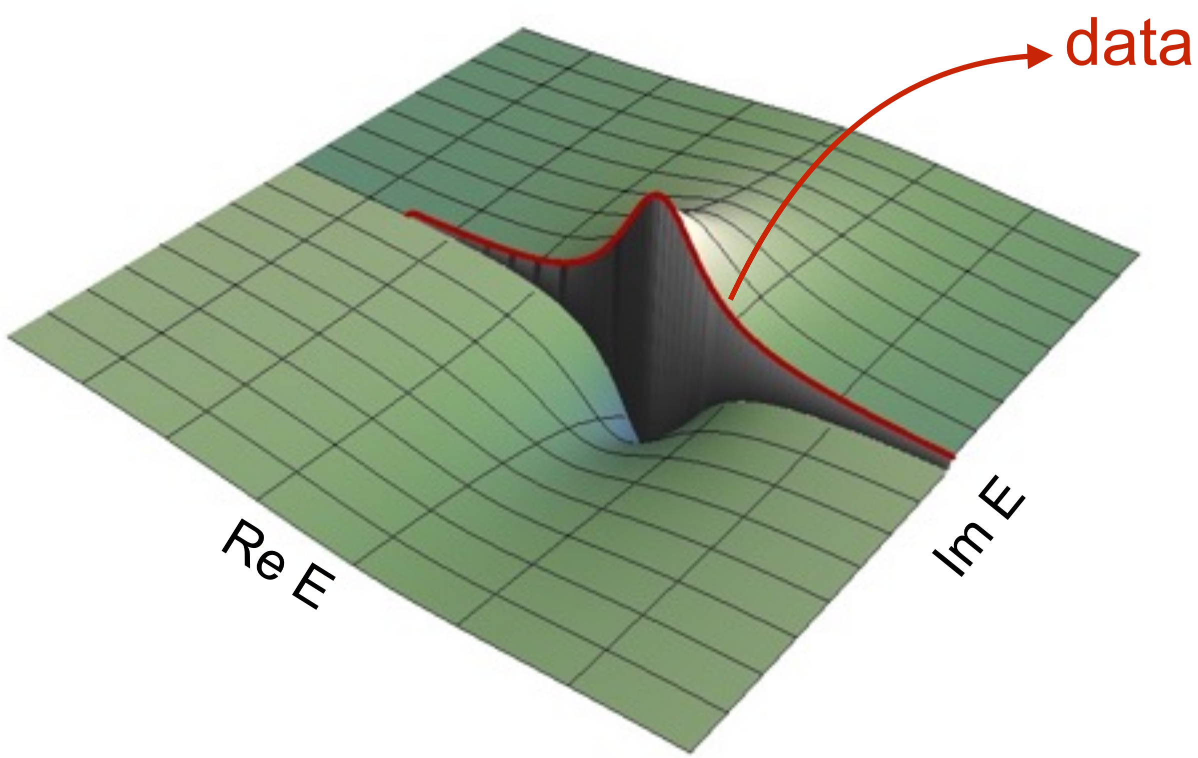
Resonance in angular mom. L = 1 ?

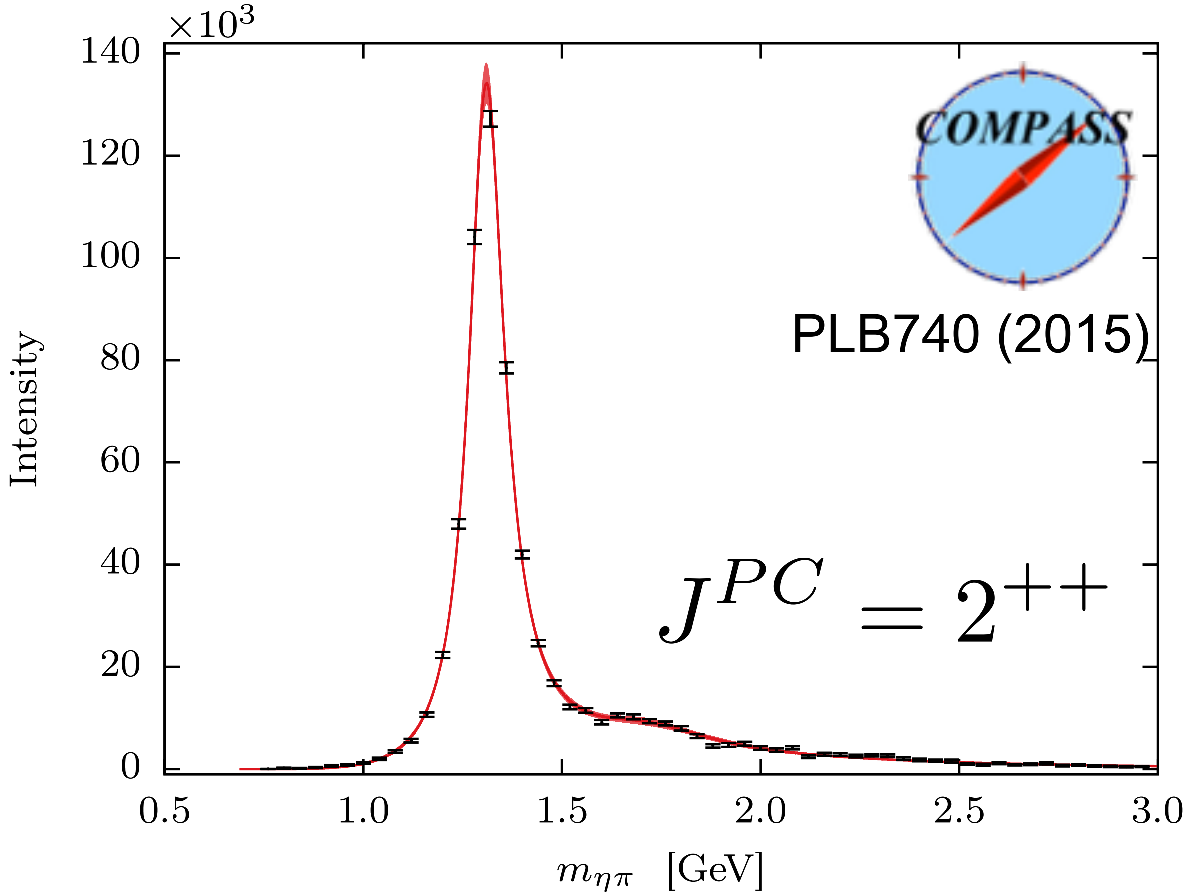
Resonances as poles

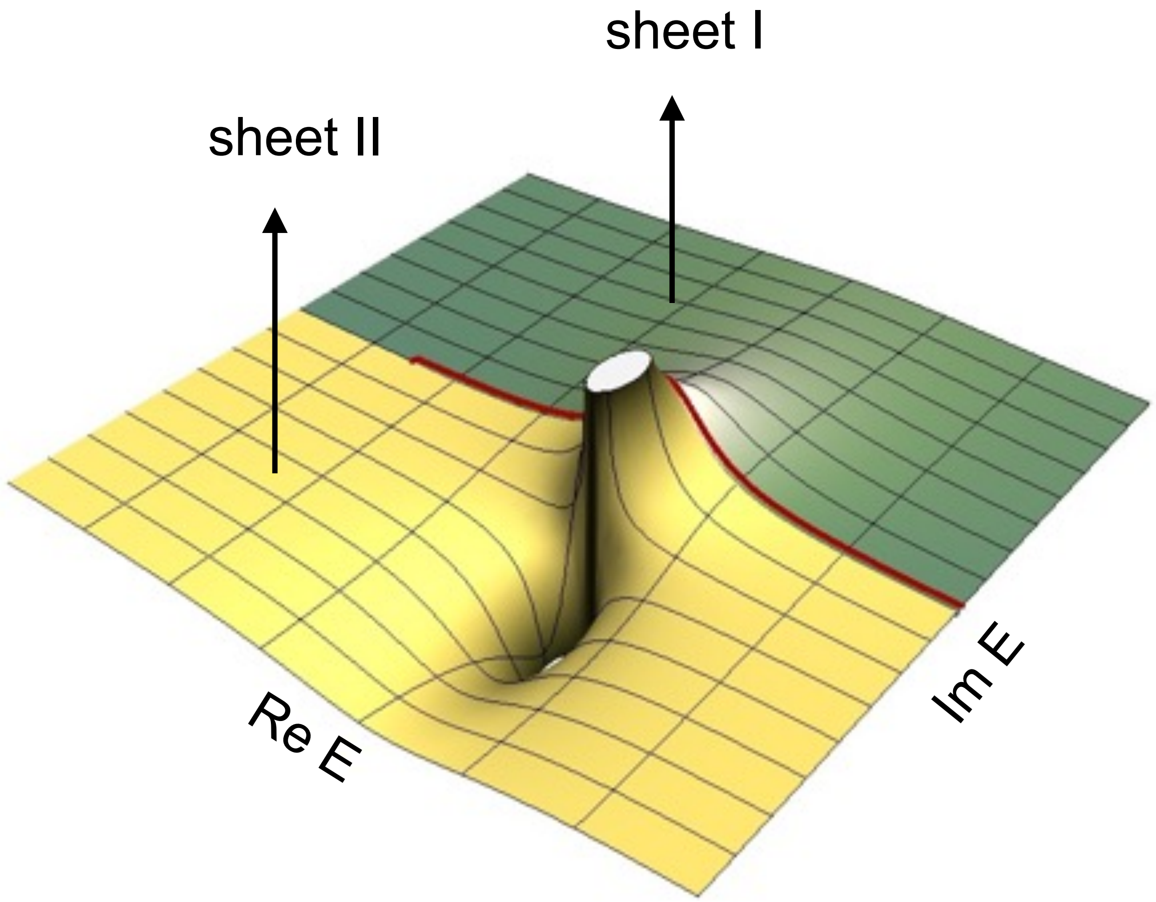




Resonances as poles





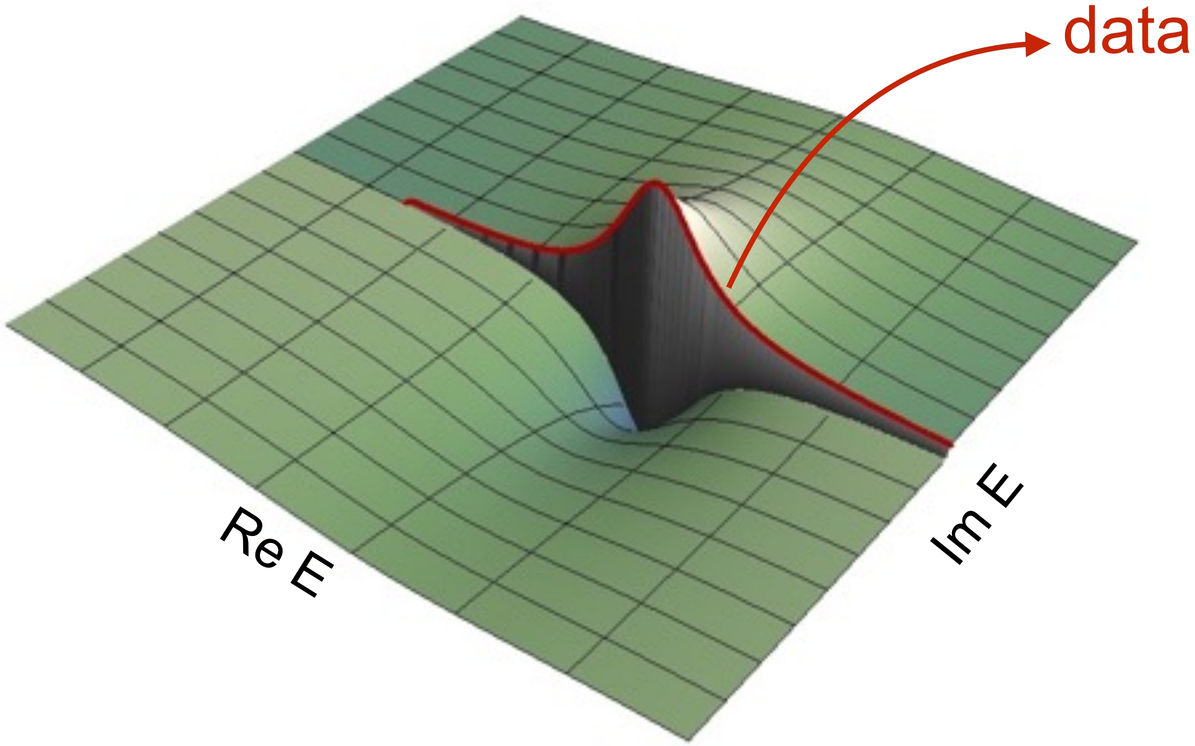


Poles in the complex energy plane:

- **Real part ~ mass**
- **Imaginary part ~ width**
- **Residue ~ coupling**

Poles or resonances are the universal building blocks of reactions

Two-body unitarity

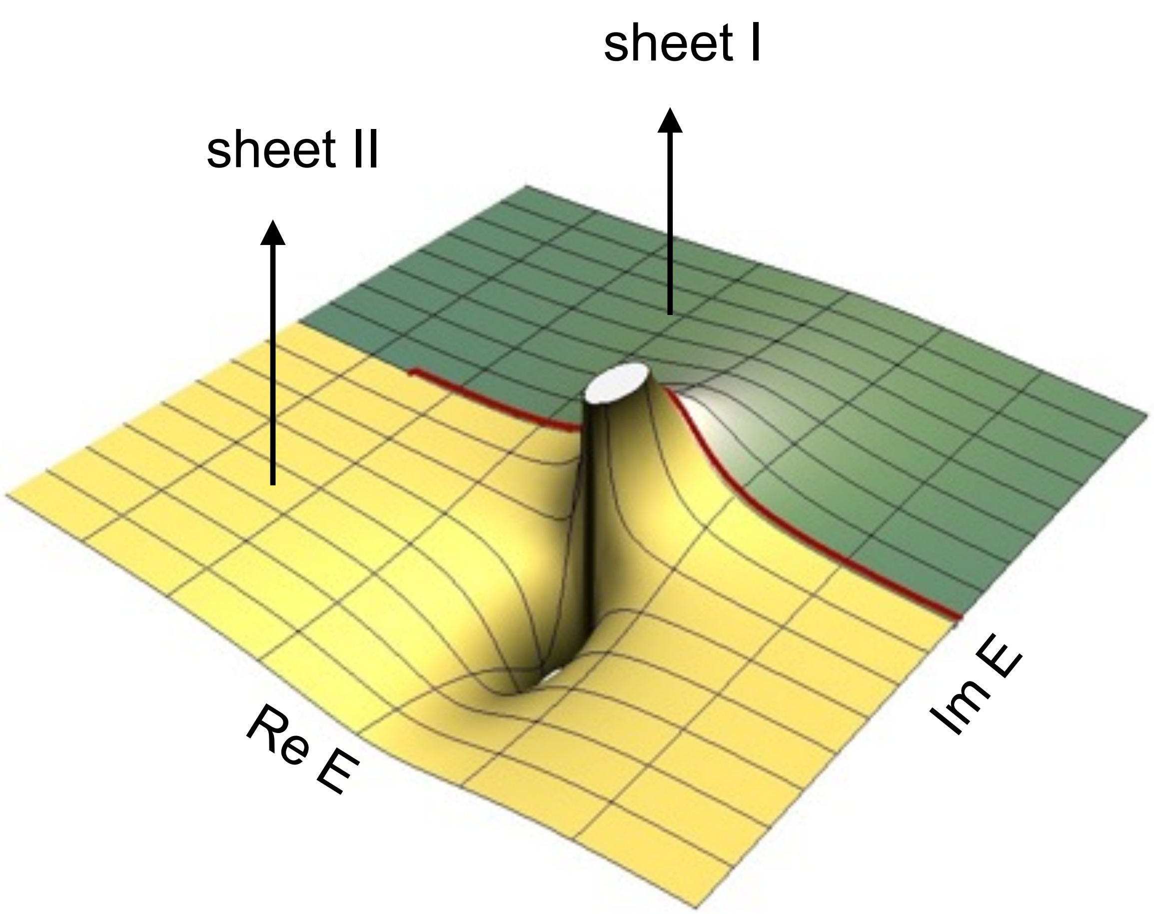


partial wave phase space

$$\mathrm{Im}\ t_\ell^{-1}(s) = -\rho(s)$$

$$t_\ell(s \pm i\epsilon) = \frac{1}{K(s) \mp i\rho(s)}$$

satisfies causality
(regular outside the real axis)

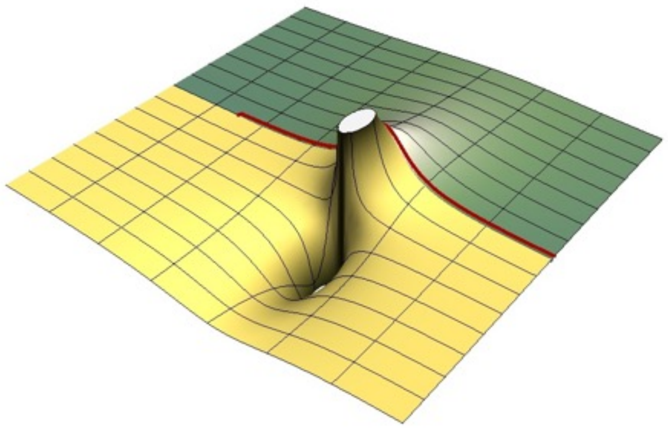


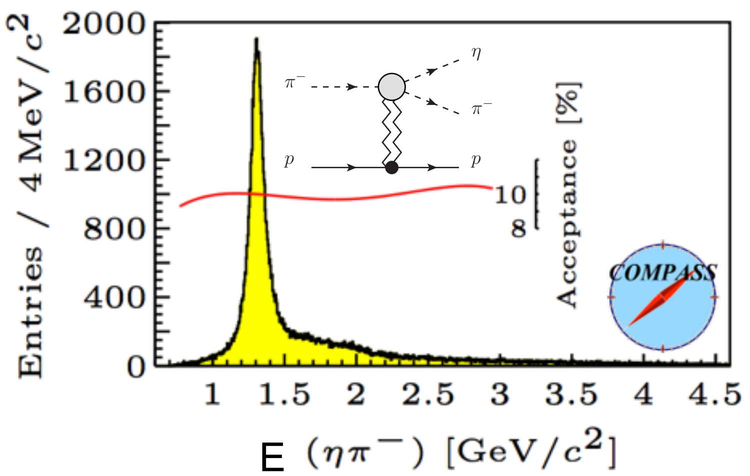
define function on sheet II
on the lower half plane

$$t_\ell^{II}(s) = \frac{1}{K(s) - i\rho(s)}$$

example $= \dfrac{m\Gamma}{m^2 - s - i\rho(s)m\Gamma}$

Matching Theory and Experiments





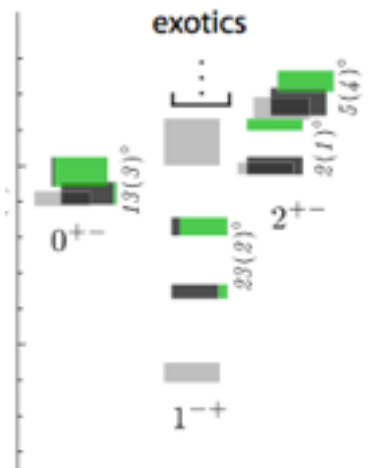
Resonances properties

Experiments: JLab, CERN,…

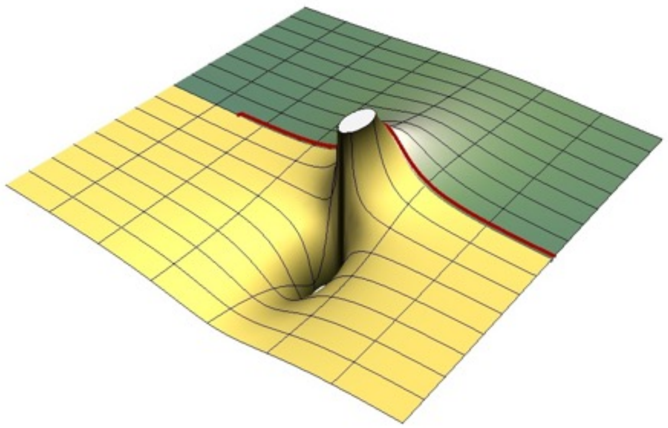
amplitude analysis

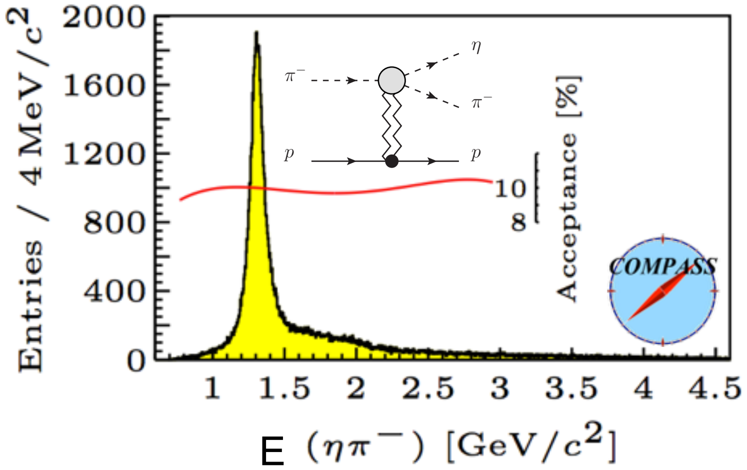
implementation of S-matrix constraints

Matching Theory and Experiments



Dudek PRD84





Theory:
Quantum Chromodynamics

quark models, lattice QCD, light-front quantization…

Resonances properties

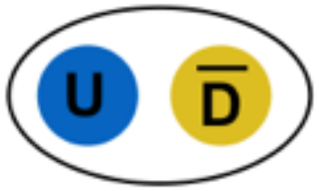
Experiments: JLab, CERN,…

amplitude analysis

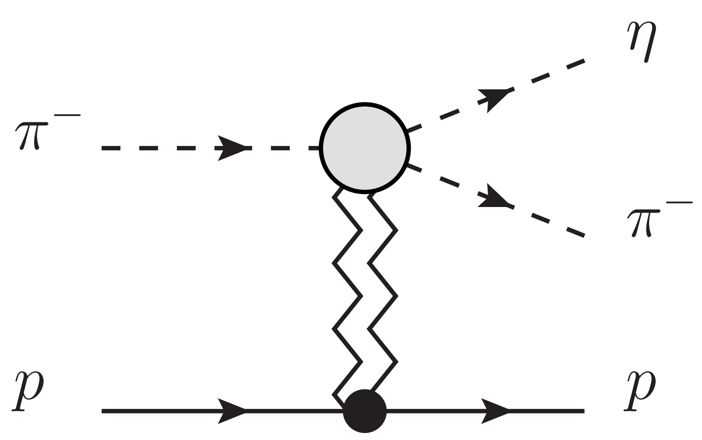
implementation of S-matrix constraints

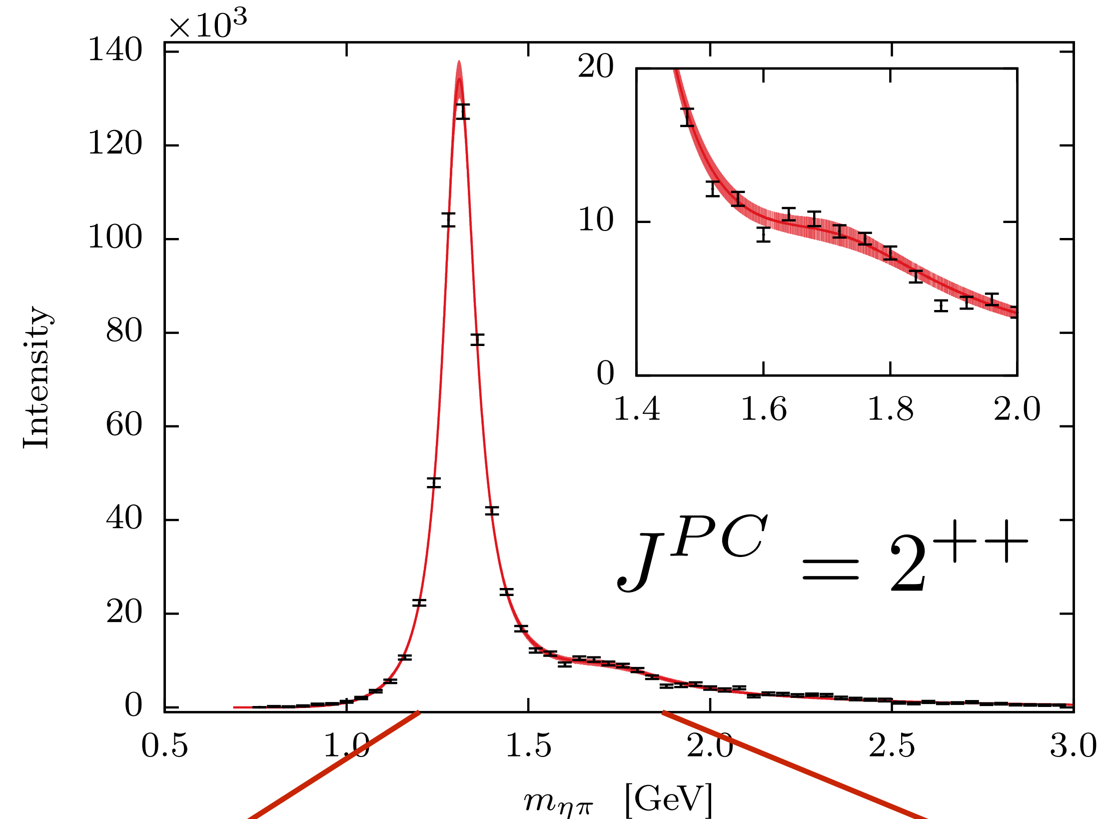
Interpretation

Ordinary matter



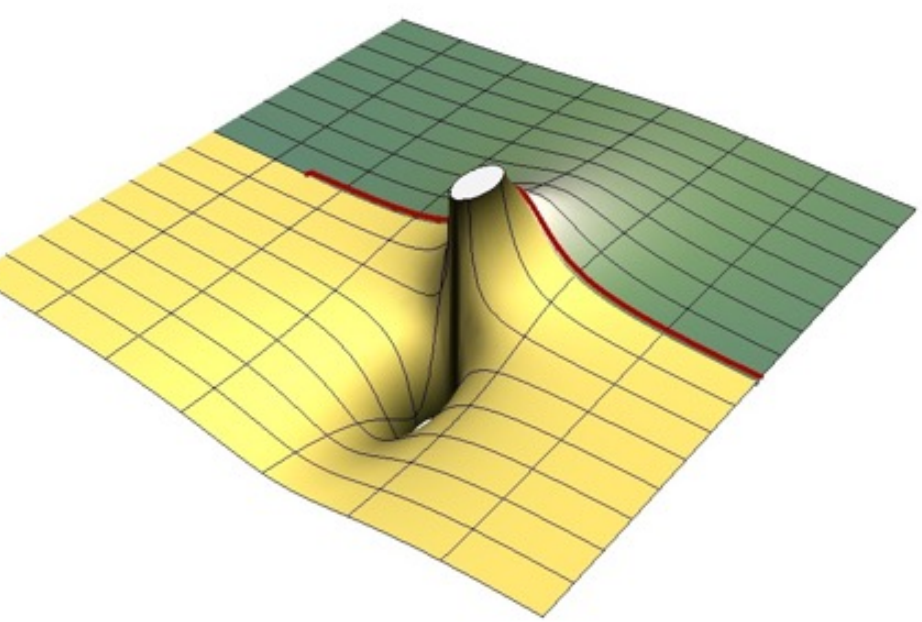
Exotic matter

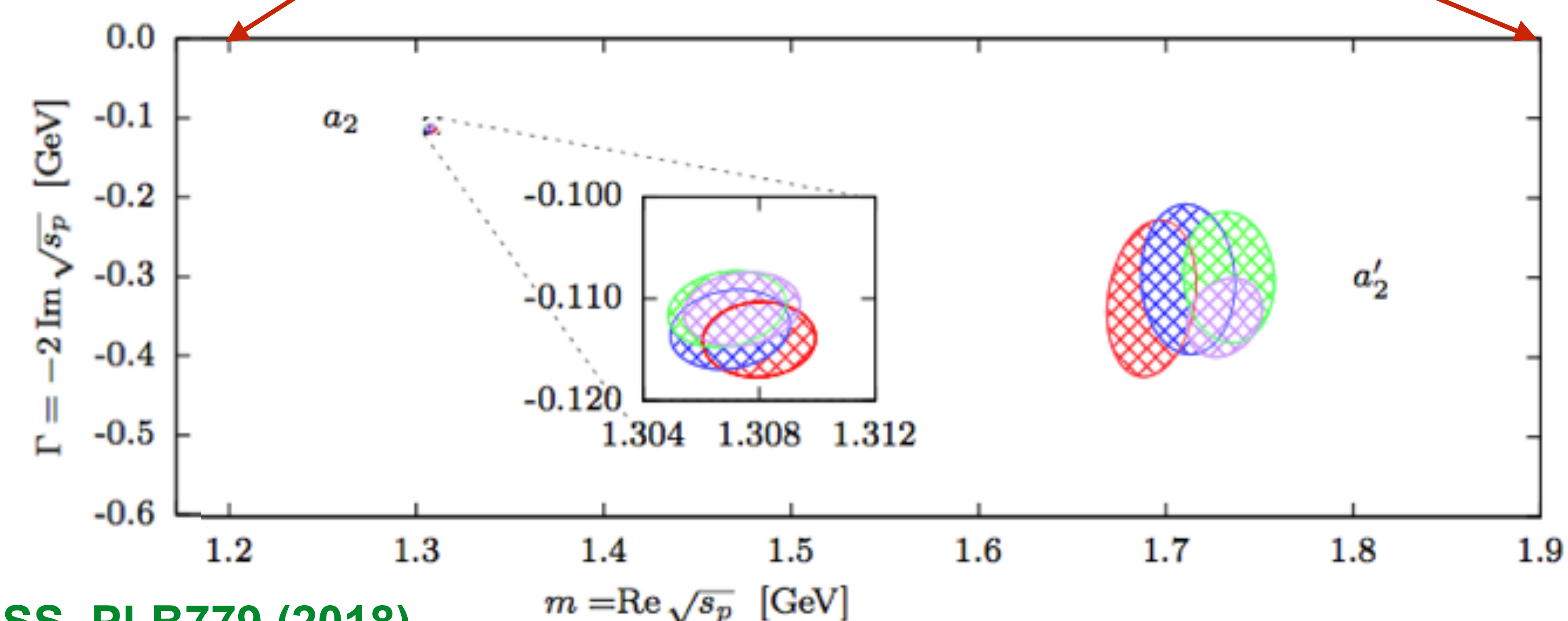




first precise determination of

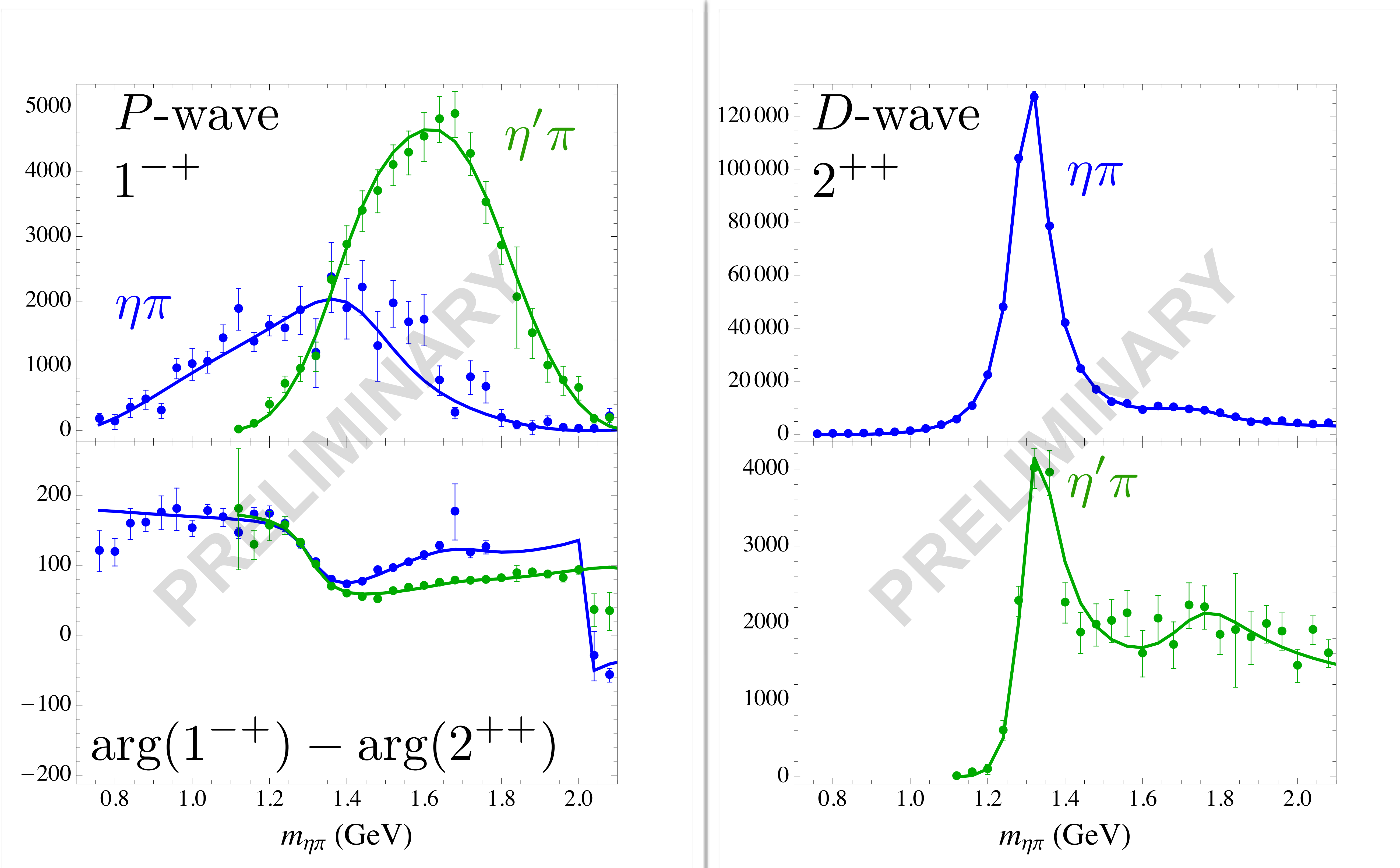
$a_2(1700)$ **pole location**





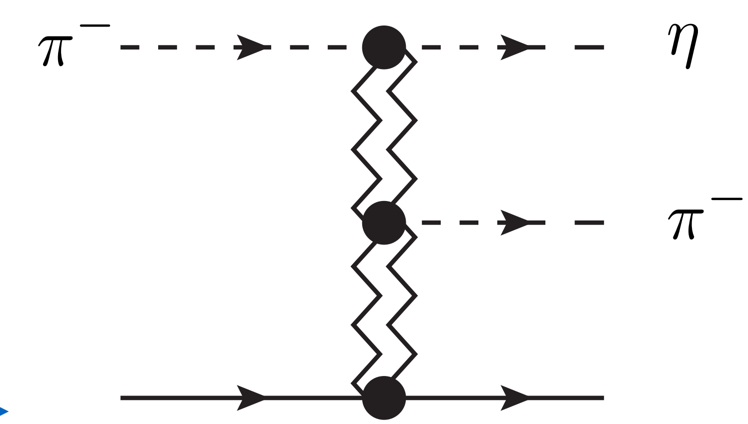
A. Jackura et al (JPAC) and COMPASS, PLB779 (2018)

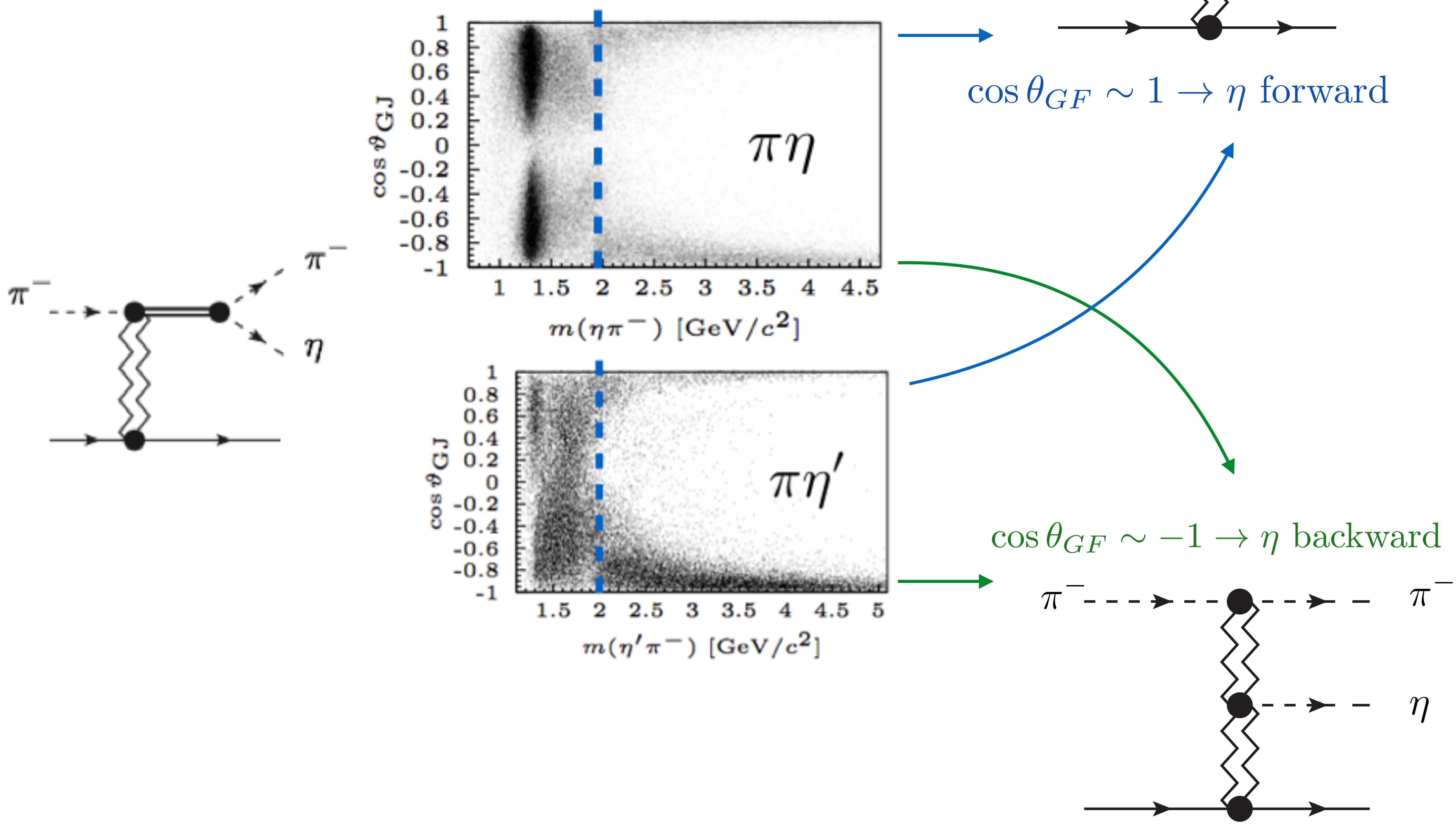
Exotic wave @COMPASS



On-going analysis: Systematic studies and exploration of the complex plane

Dispersion relation relates the high (exchanges) and the low (resonances) regions





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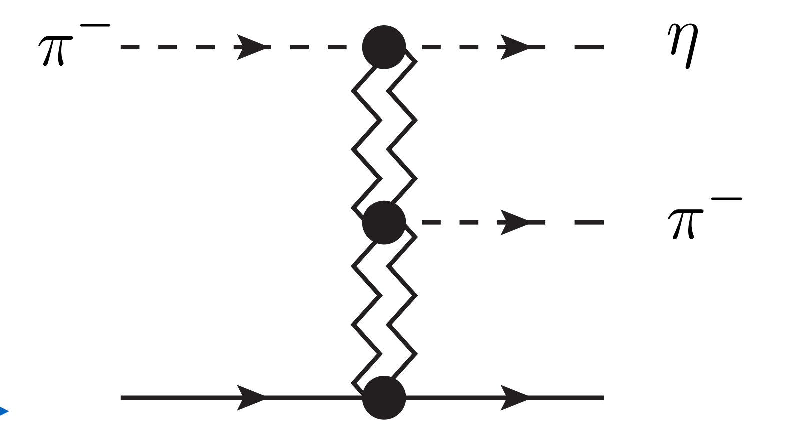

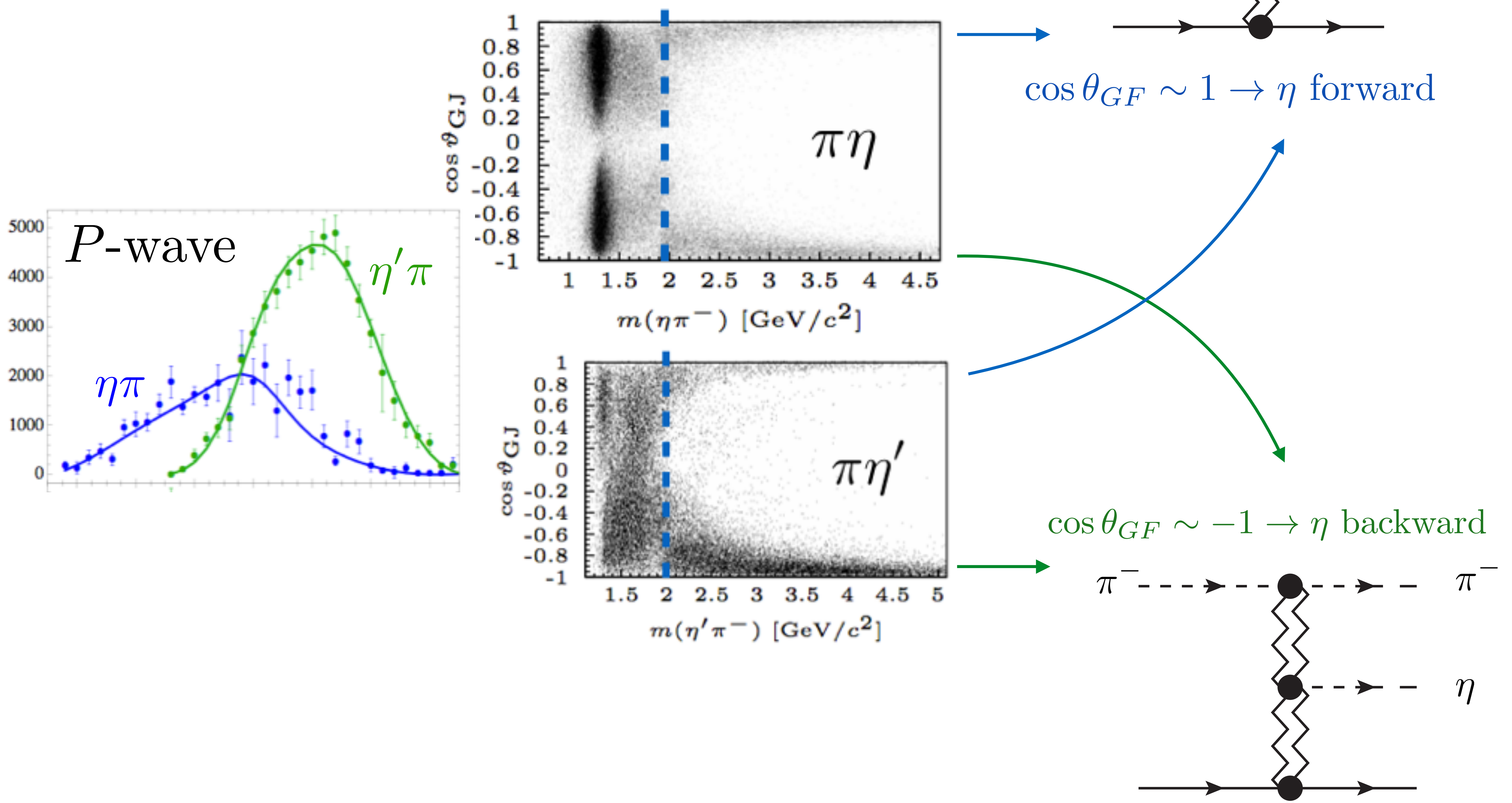

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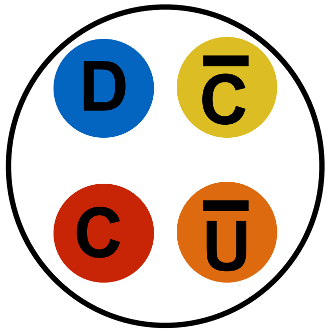
  in exclusive diffraction reactions:

$$\gamma p \to \pi^0 \eta^{(\prime)} p$$

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

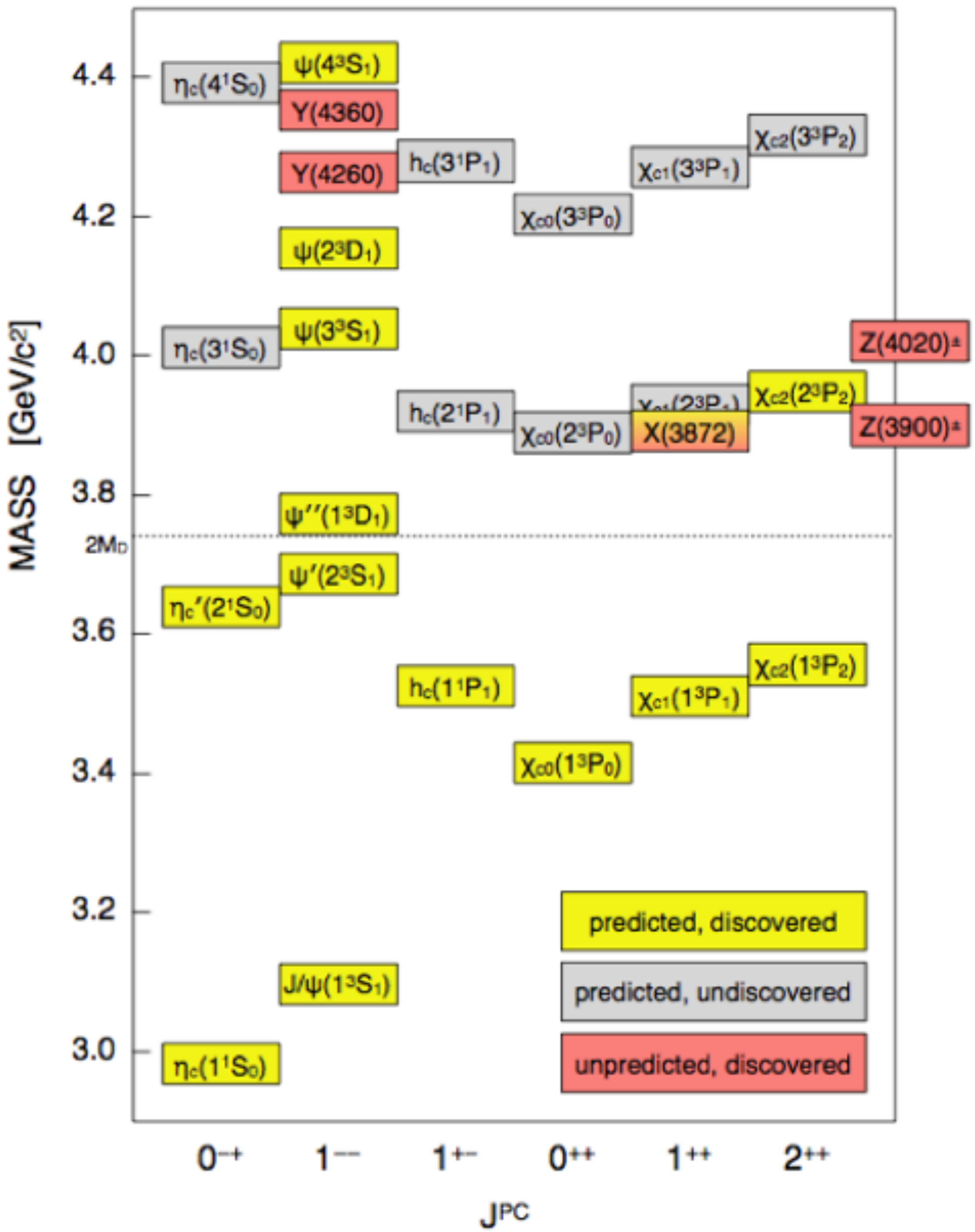


- **Exotic heavy meson spectroscopy**
  in three, four particle decays:

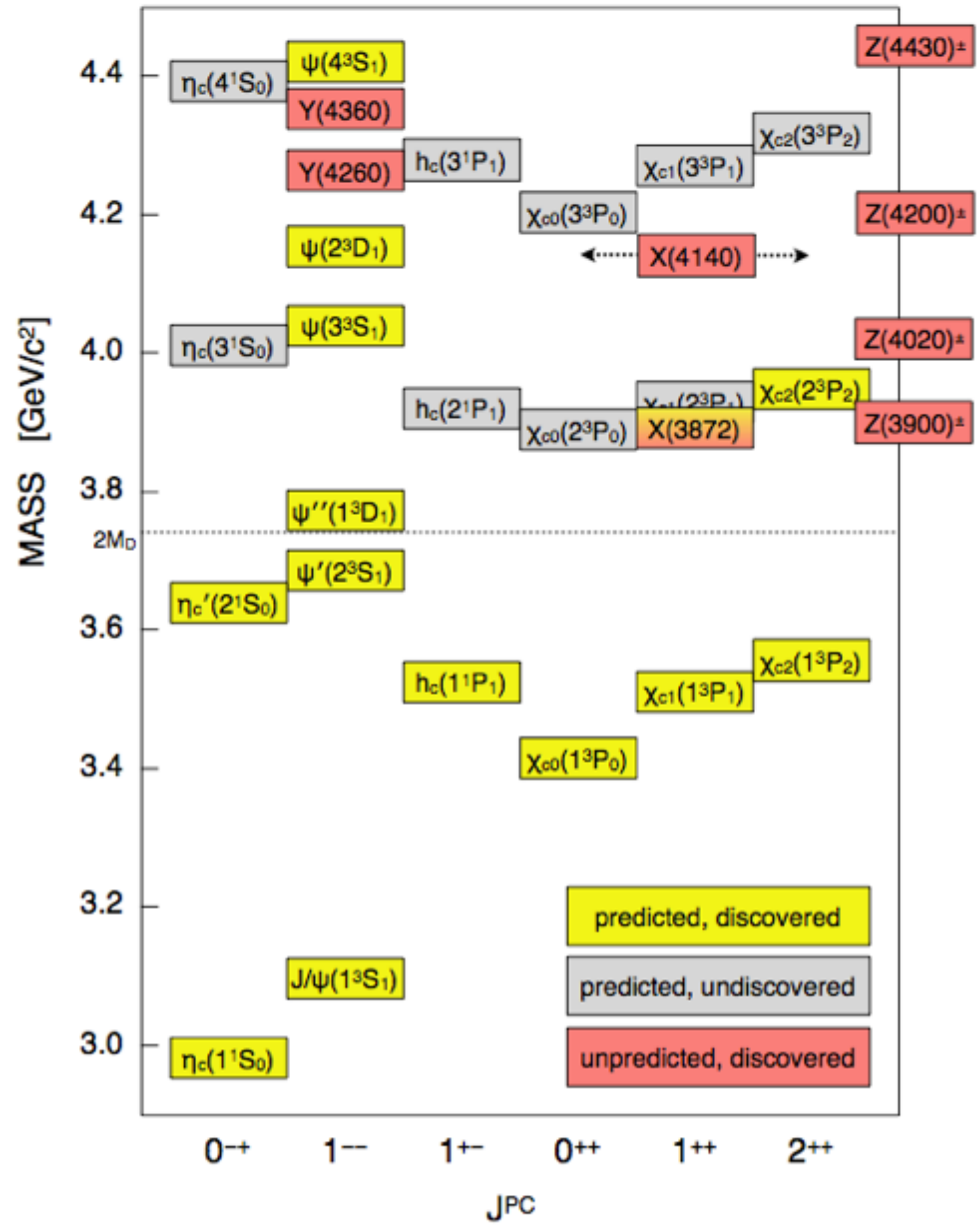
$$B^\pm \to K^\pm \pi^+ \pi^- J/\psi$$

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

e^+e^- Collisions



in *B* Decay

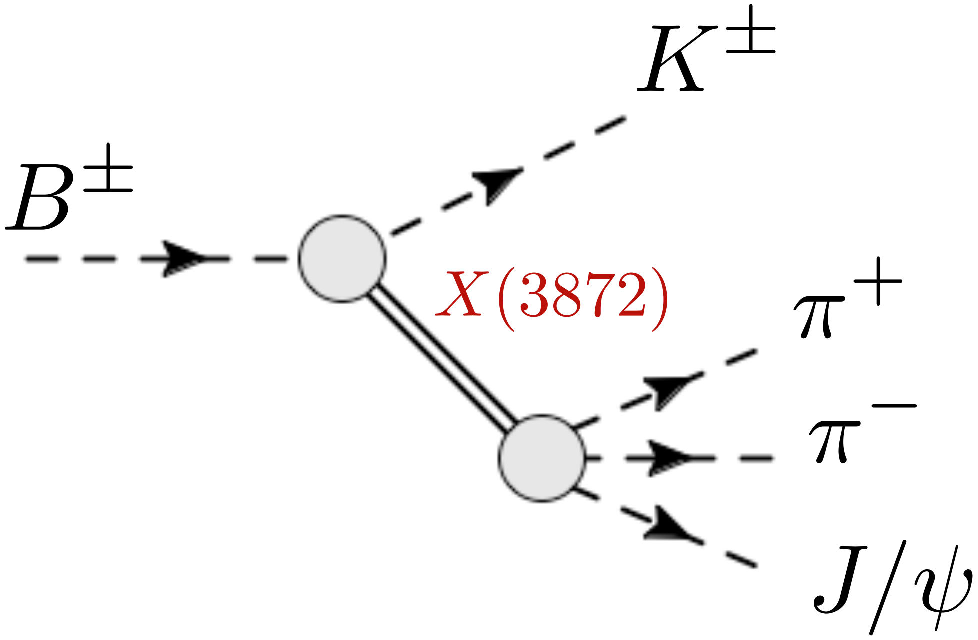


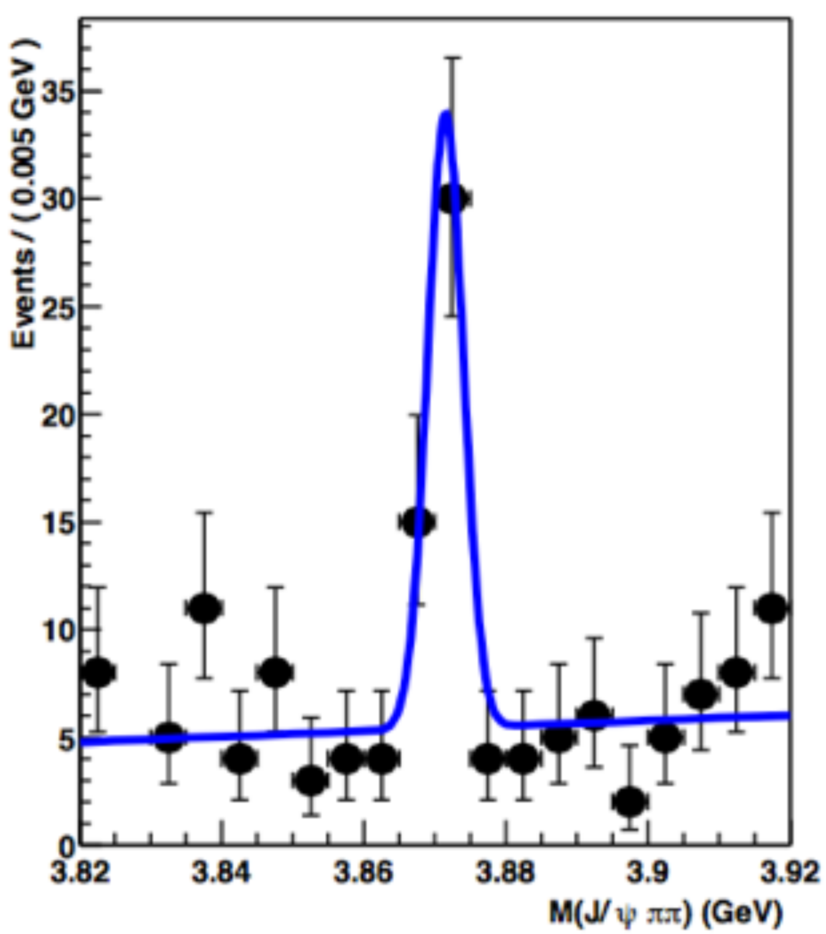
reviews on the theory side:

Esposito et al Phys. Rep. 668 (2017)

Guo et al Rev. Mod. Phys. 90 (2018)

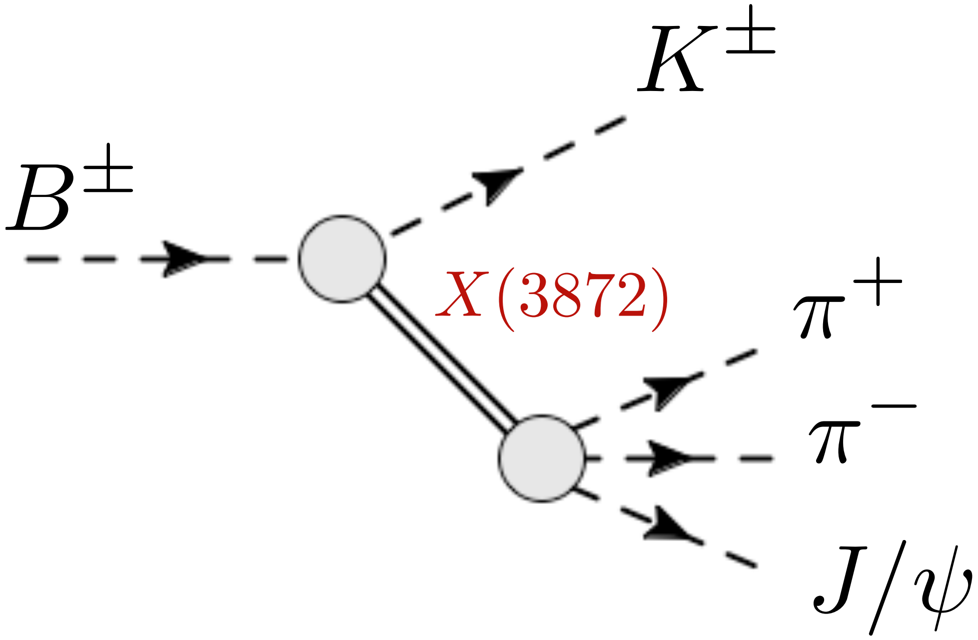
X(3872)

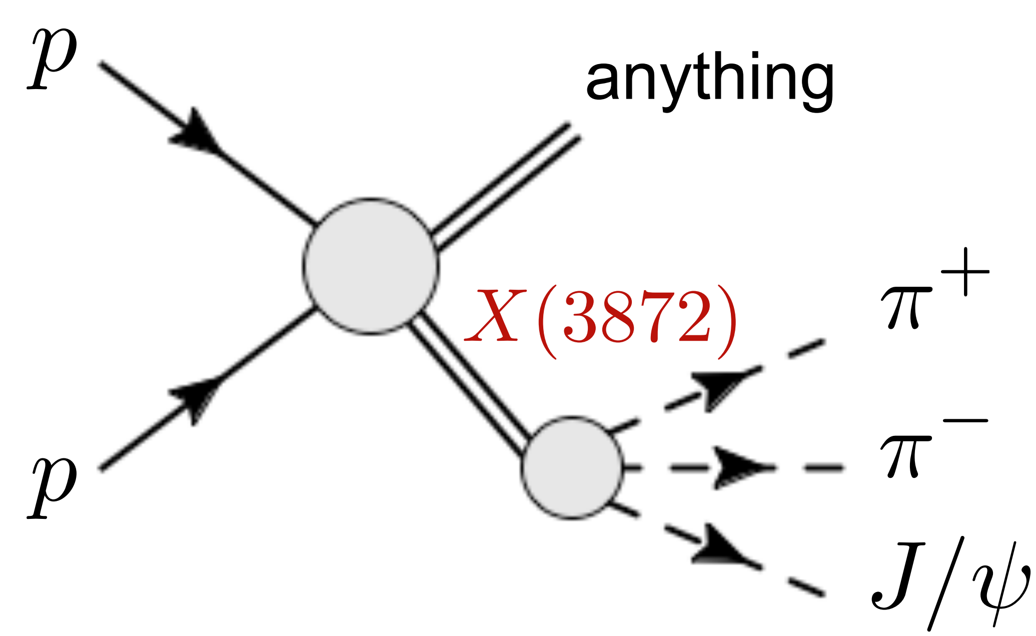


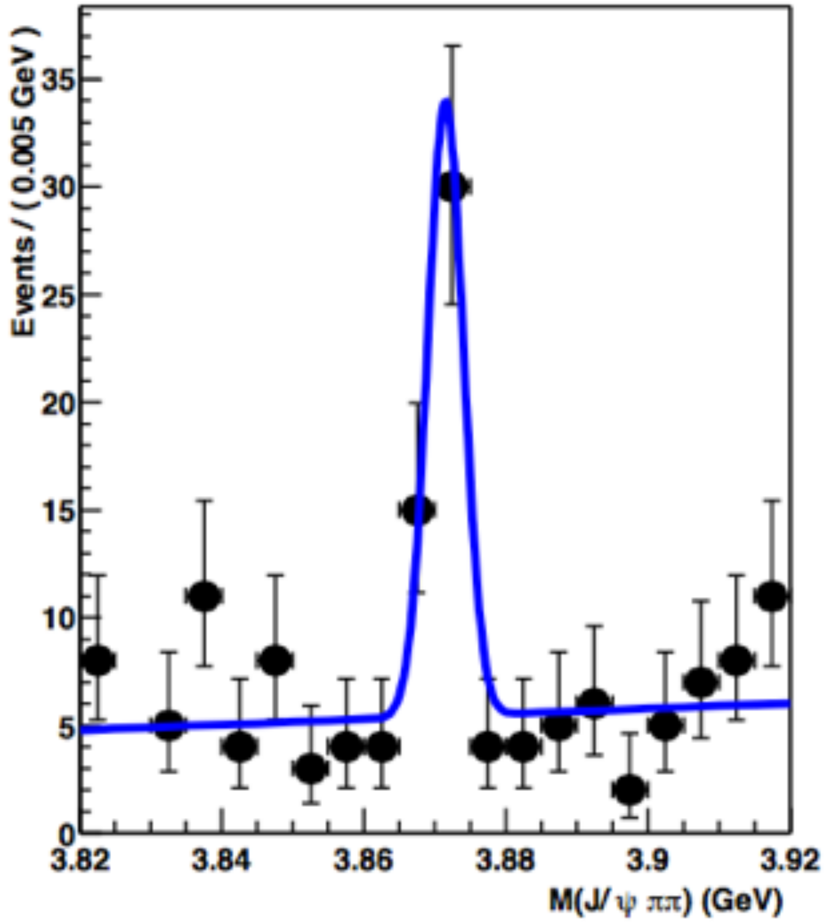


Belle PRL91 (2003)

X(3872)







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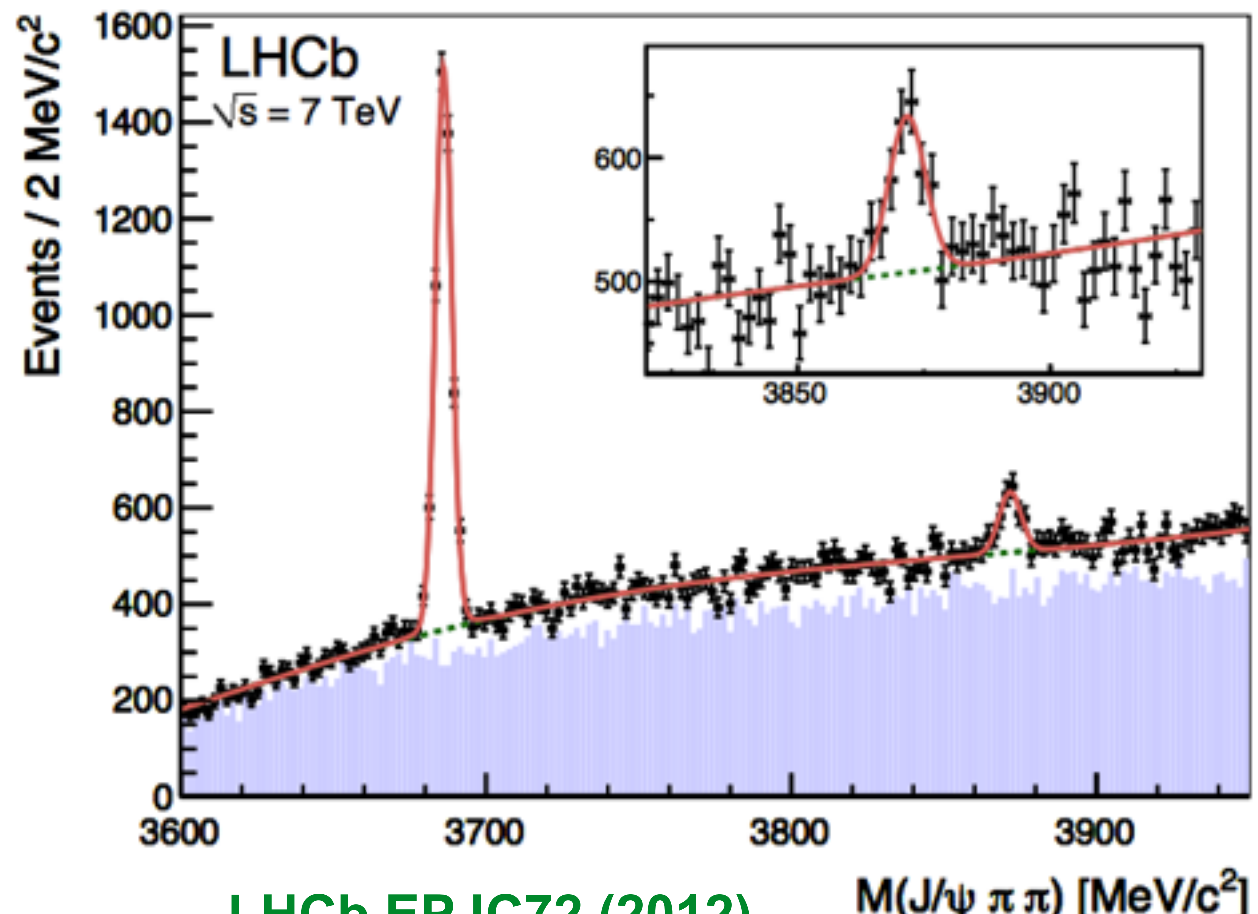
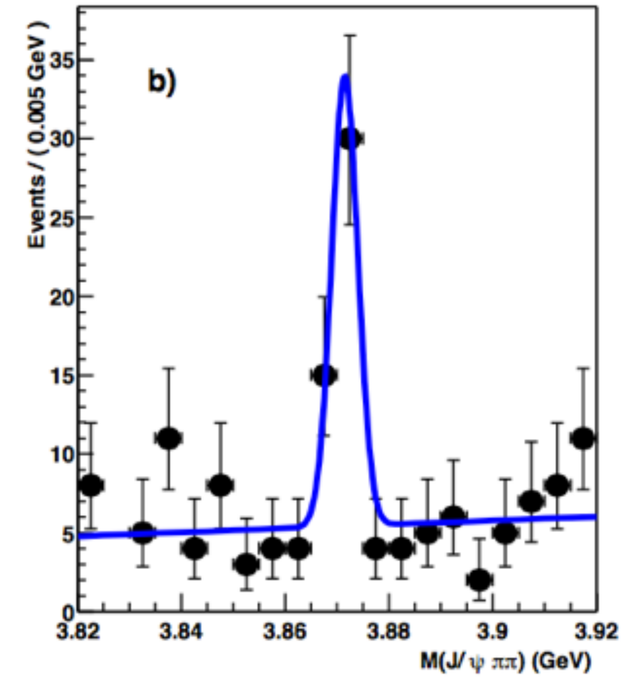


LHCb EPJC72 (2012)

X(3872)

narrow structure around 3872 MeV

very close to $D\bar{D}^*$ **threshold**



Theory:
Quantum Chromodynamics

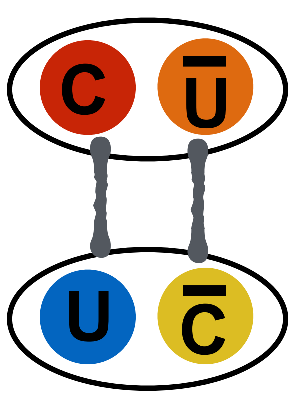
quark models

X(3872)
properties, interpretation

Experiments:
Belle, Babar, BESIII, LHCb

$D\bar{D}^*$

molecule?



Törnqvist Z. Phys. C 61 (1994)

X(3872)

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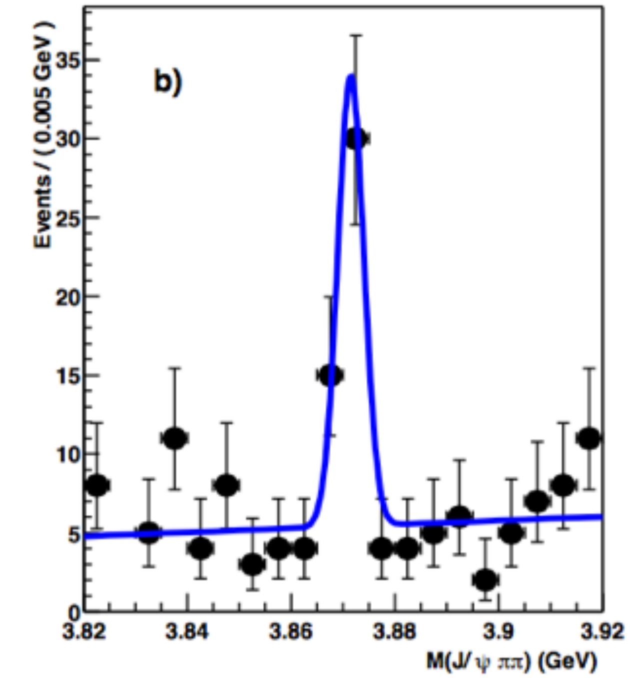

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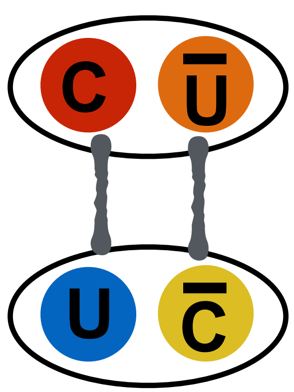
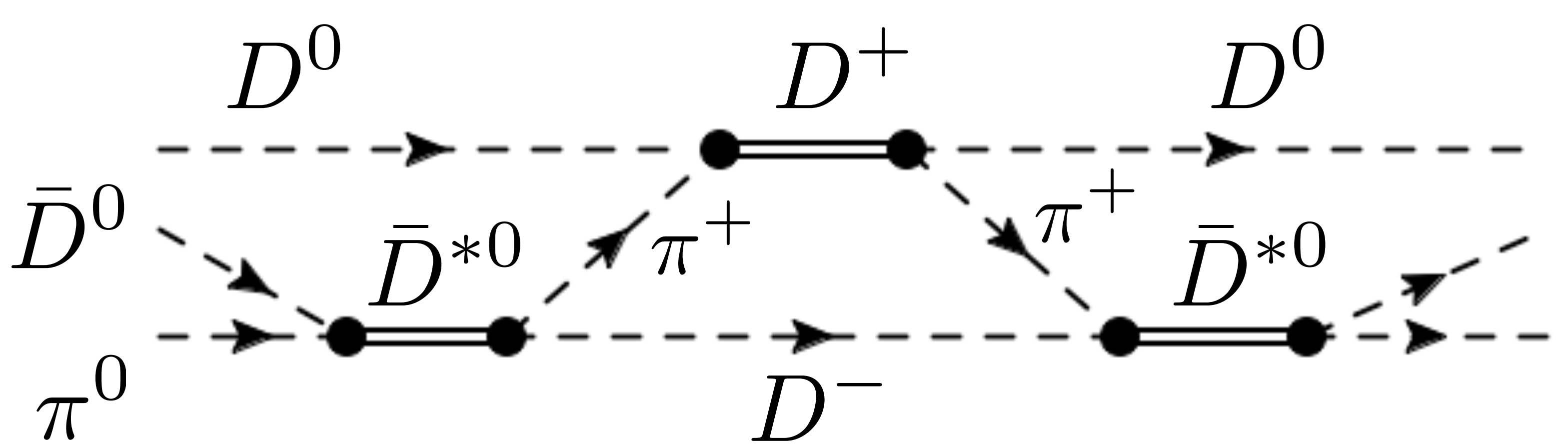
molecule?



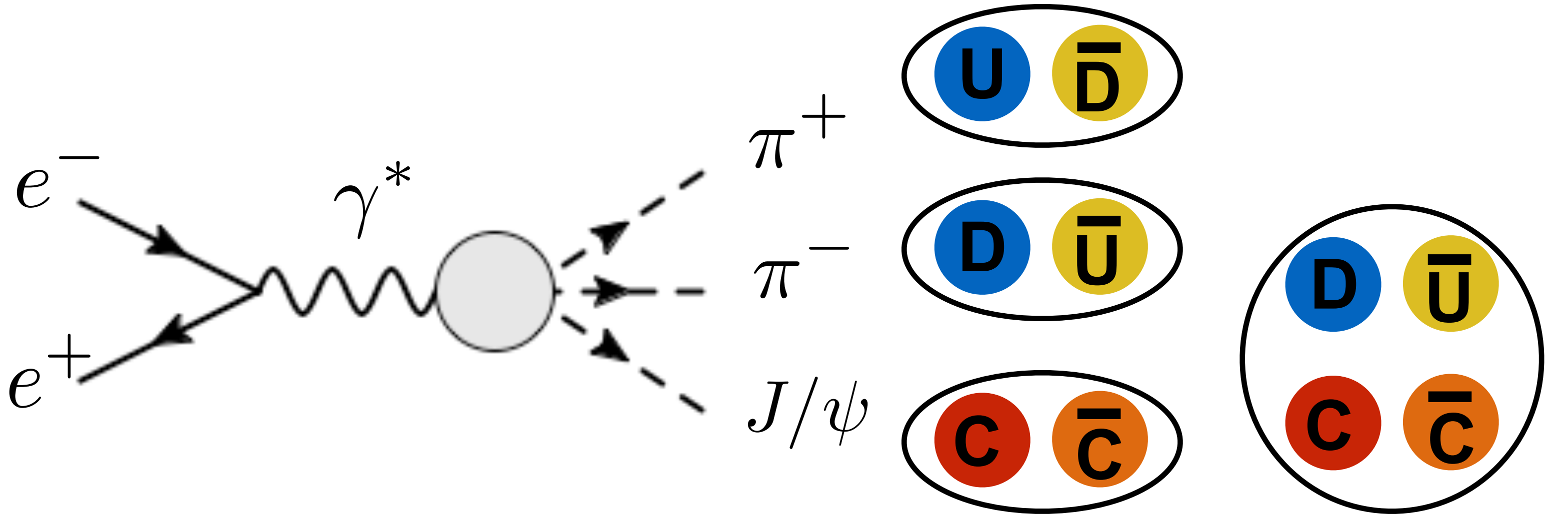


Törnqvist Z. Phys. C 61 (1994)

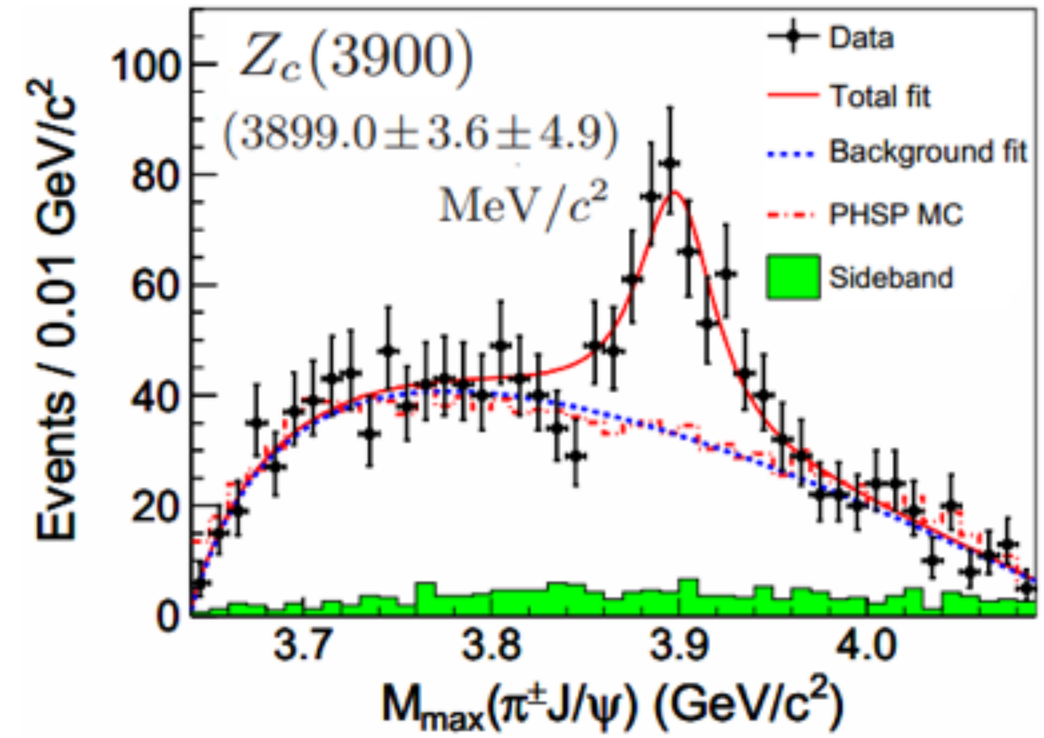
Mai, Döring, Pilloni and Szczepaniak EPJA53 (2017)

Briceno, Hansen and Sharpe PRD95 (2017)

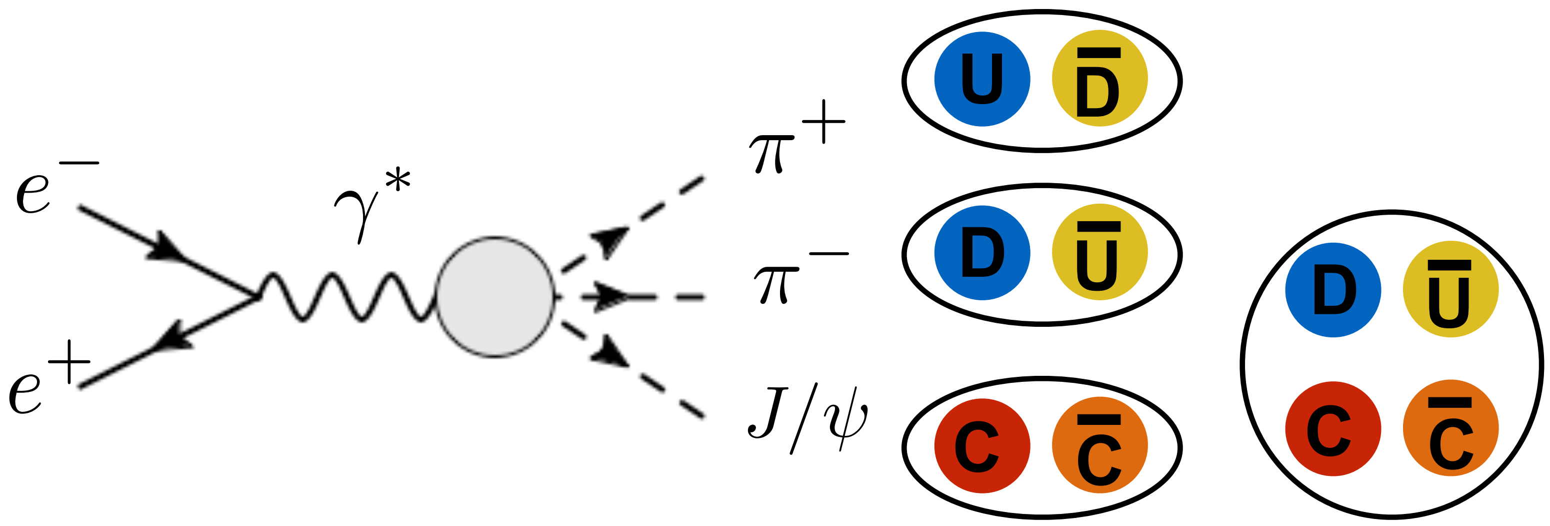
Z(3900)@BESIII



BESIII PRL 110 (2013)



Z(3900)@BESIII



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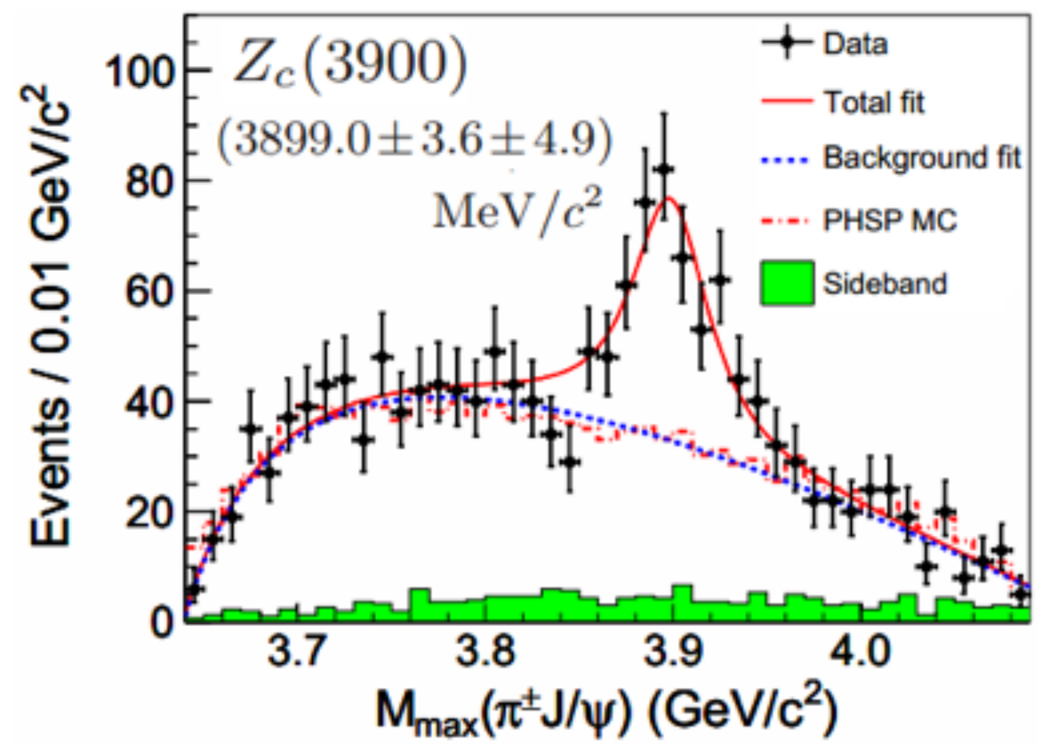
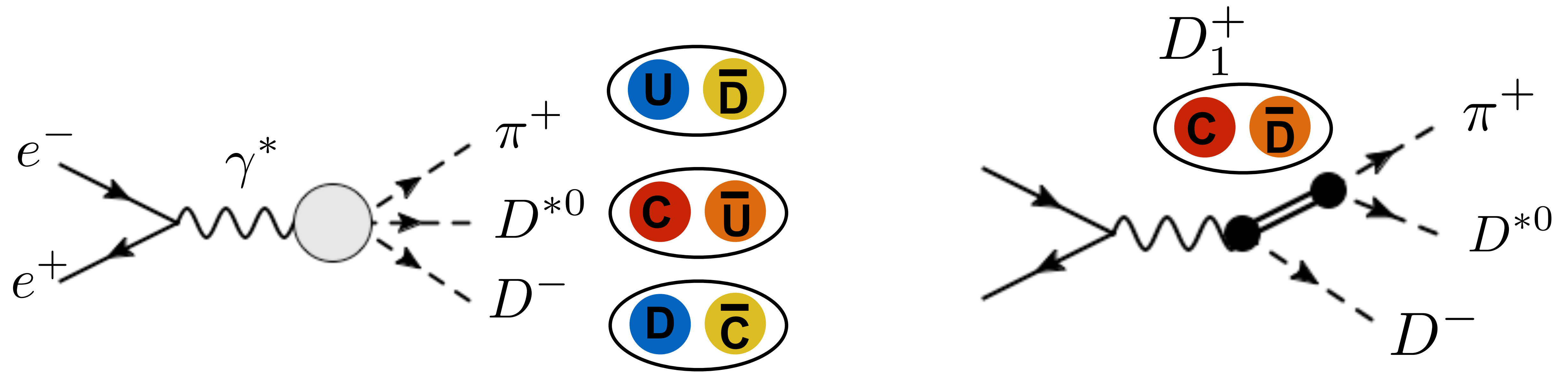
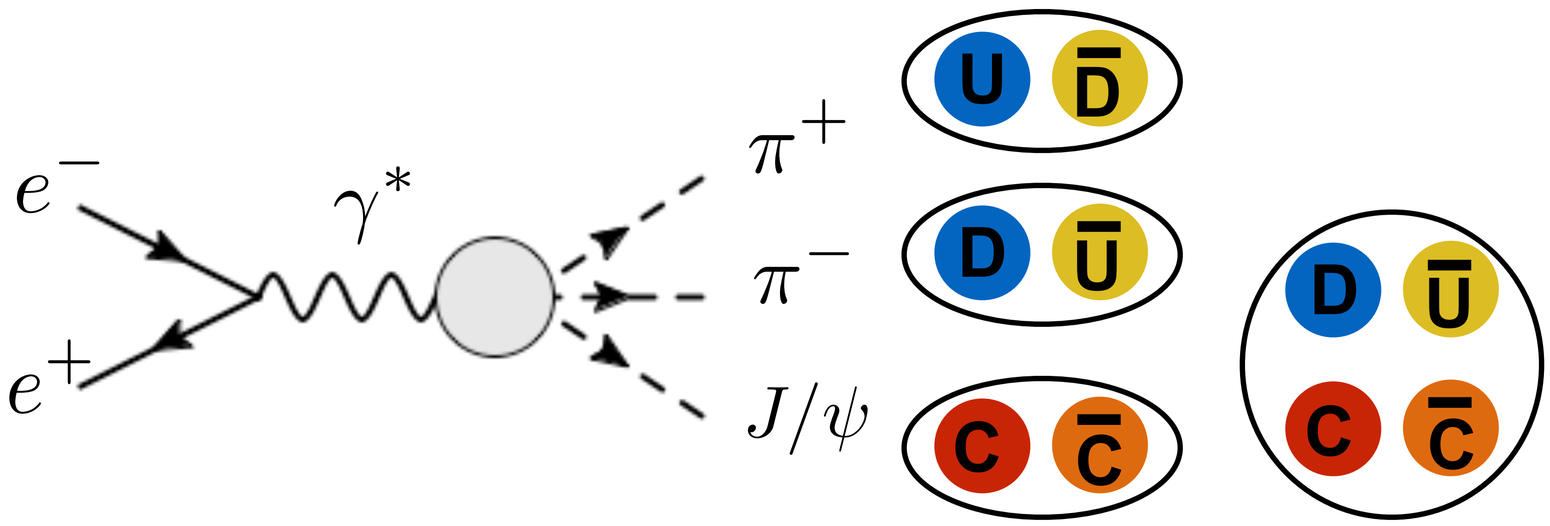


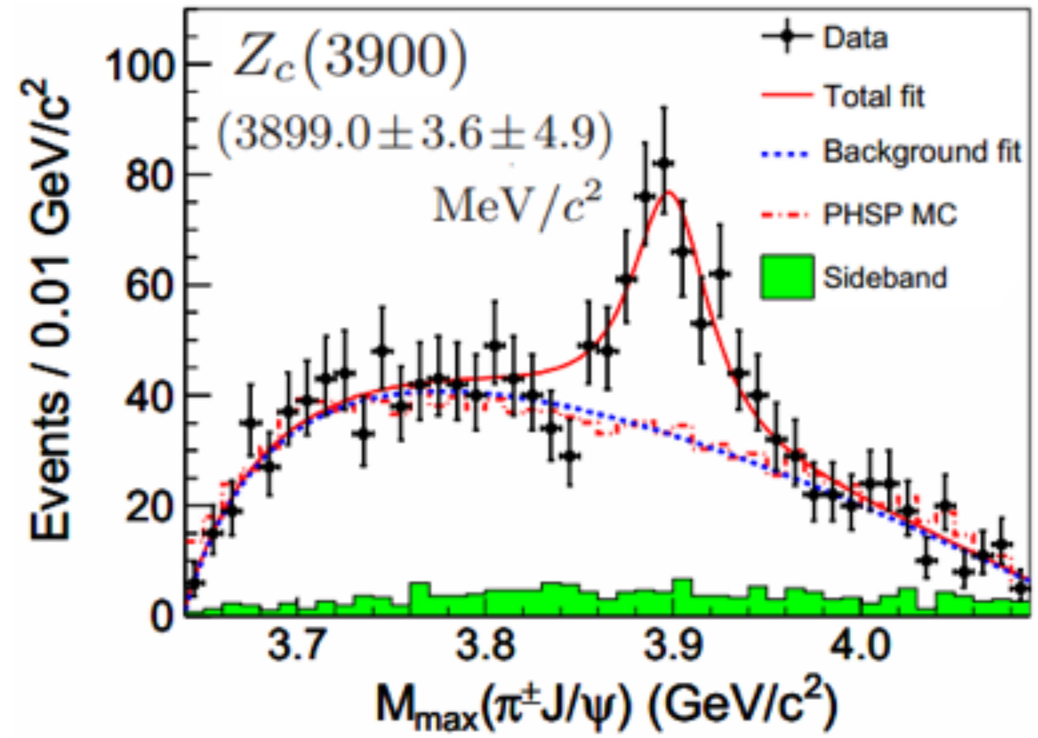
Cross channel resonance might introduce kinematical effects



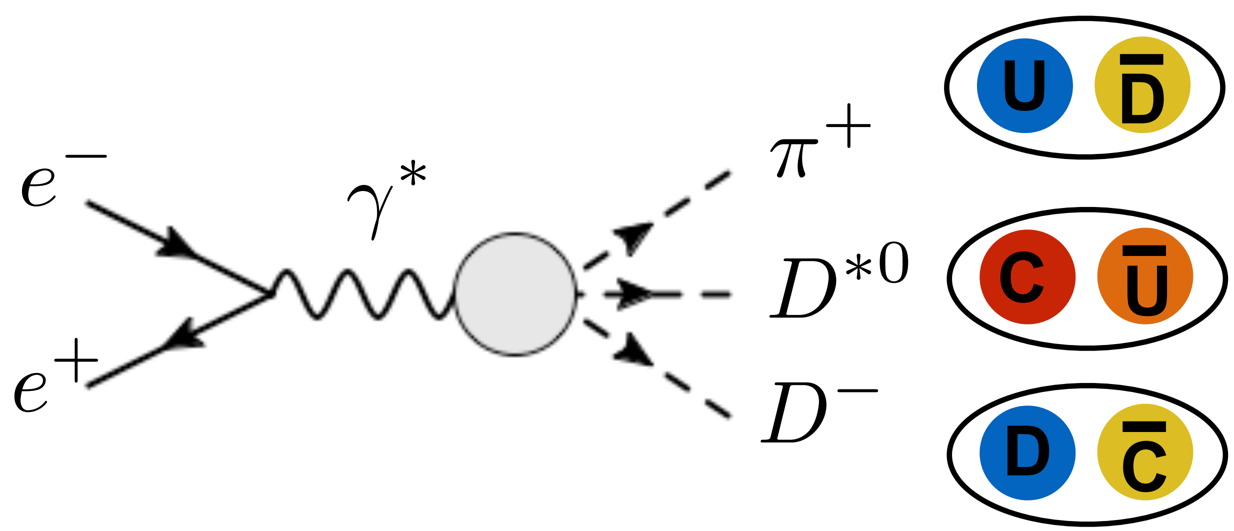
Z(3900)@BESIII

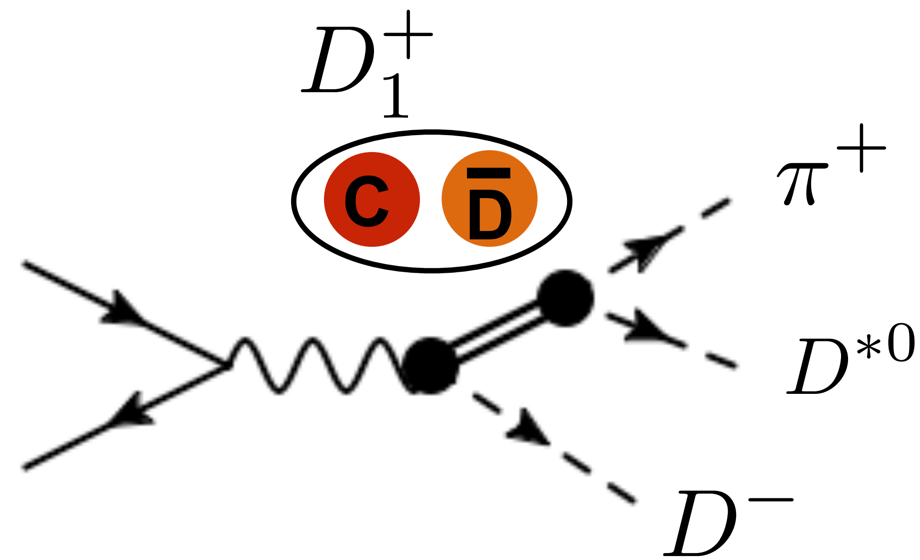


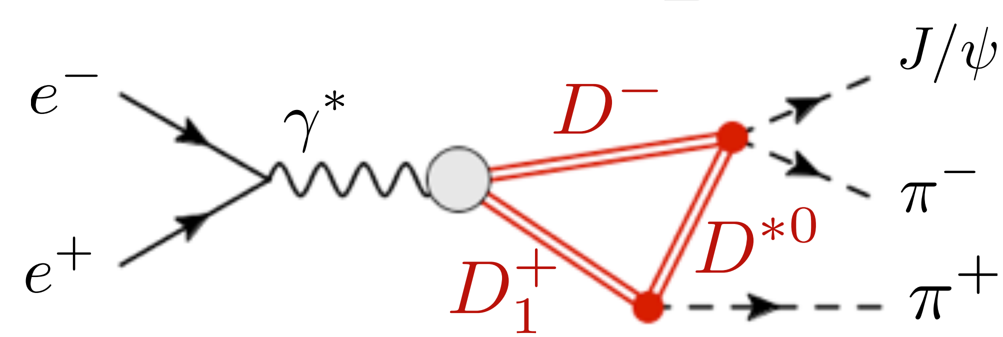
BESIII PRL 110 (2013)



Cross channel resonance might introduce kinematical effects



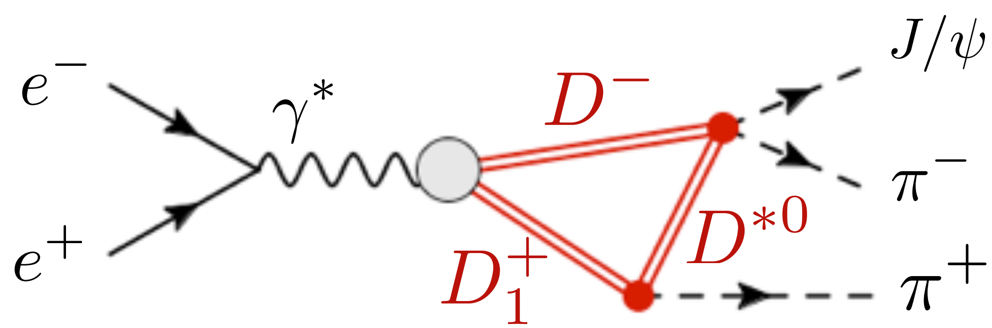


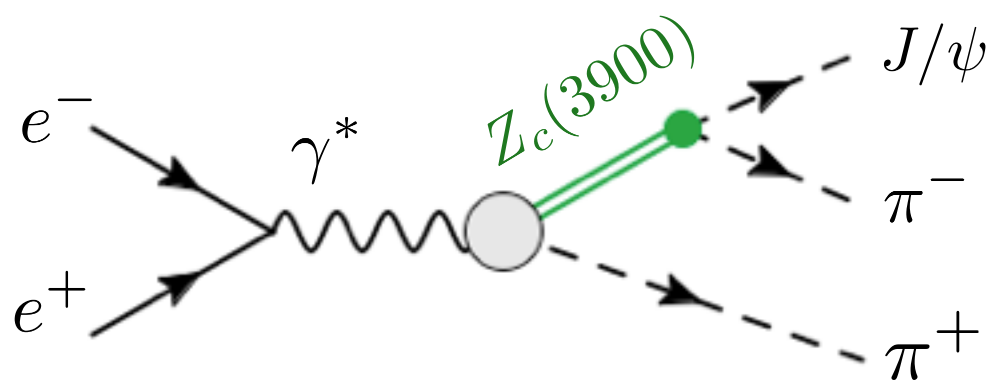


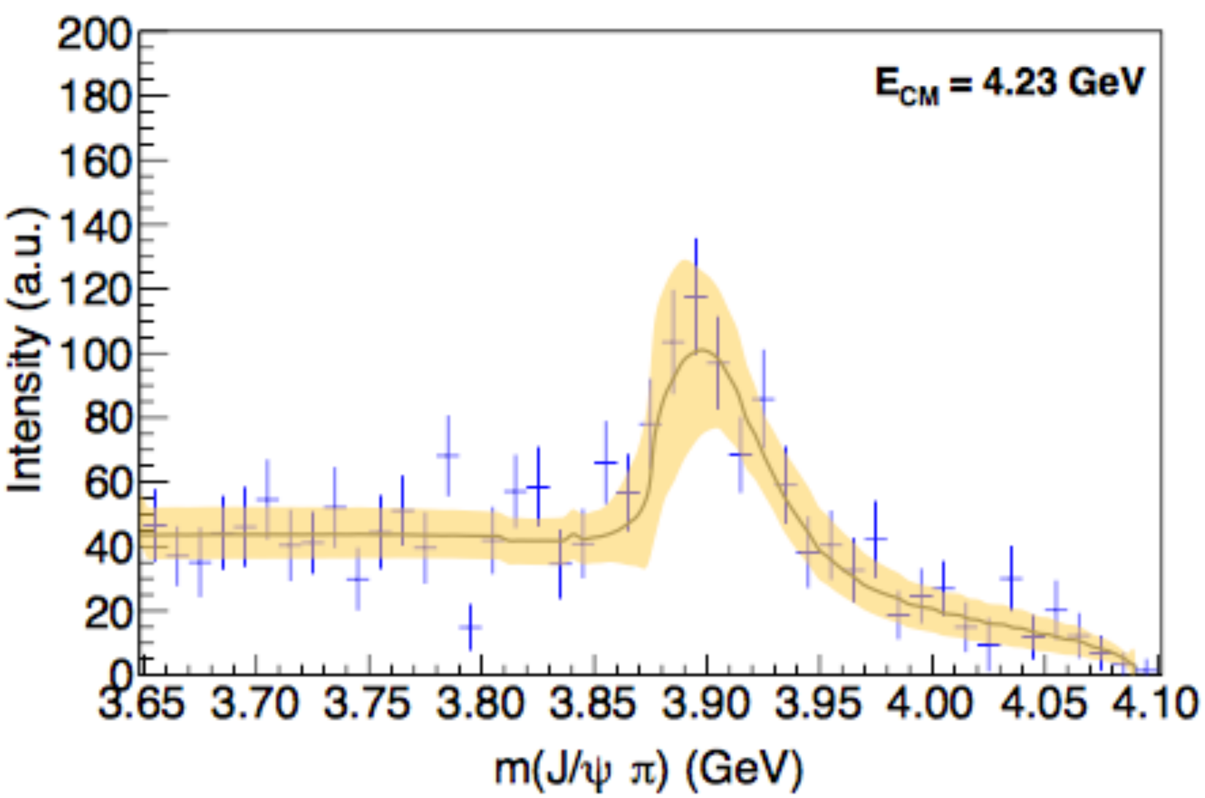
Z(3900)@BESIII

Pilloni et al (JPAC) PLB 772 (2017)

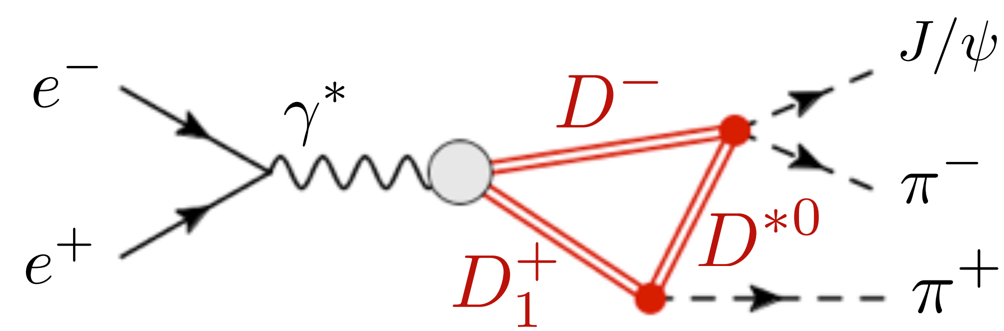
with tetraquark

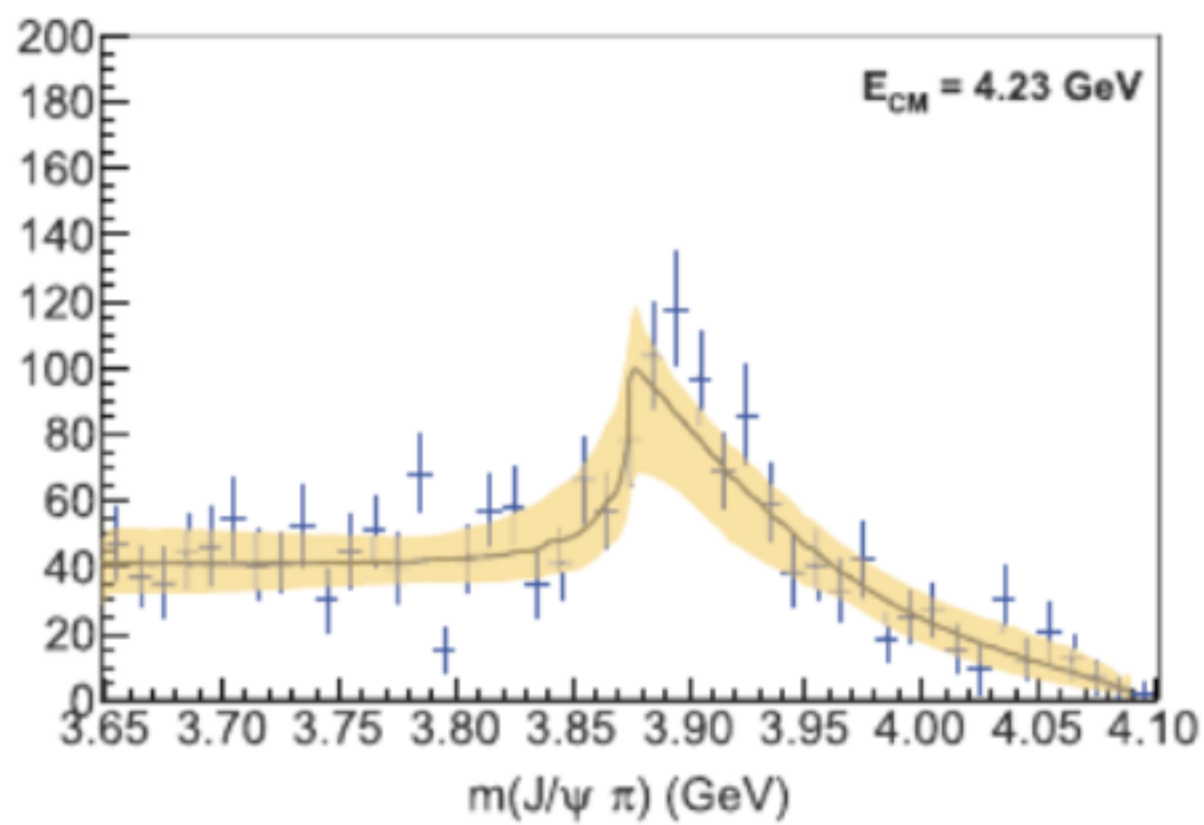






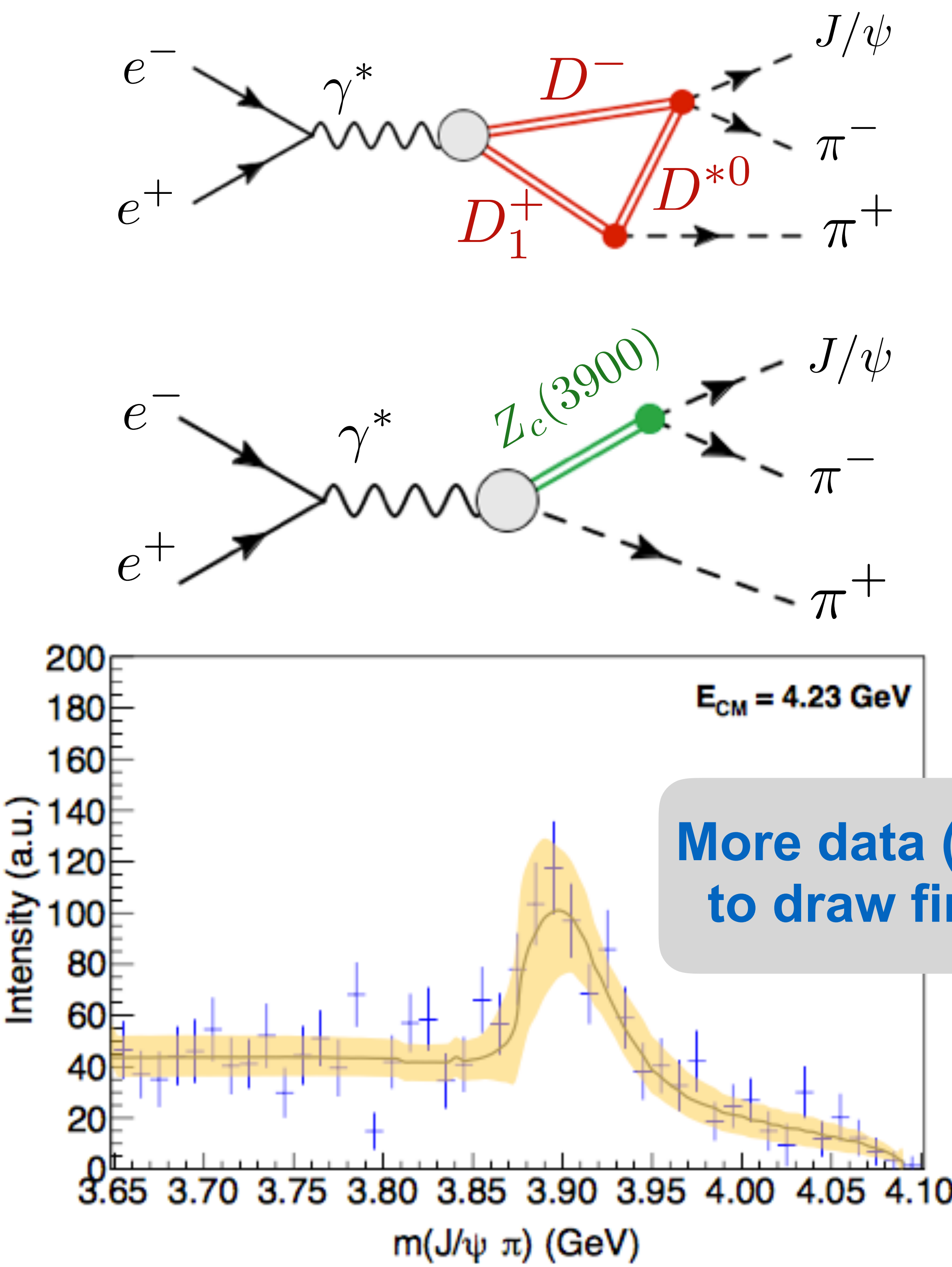
without tetraquark



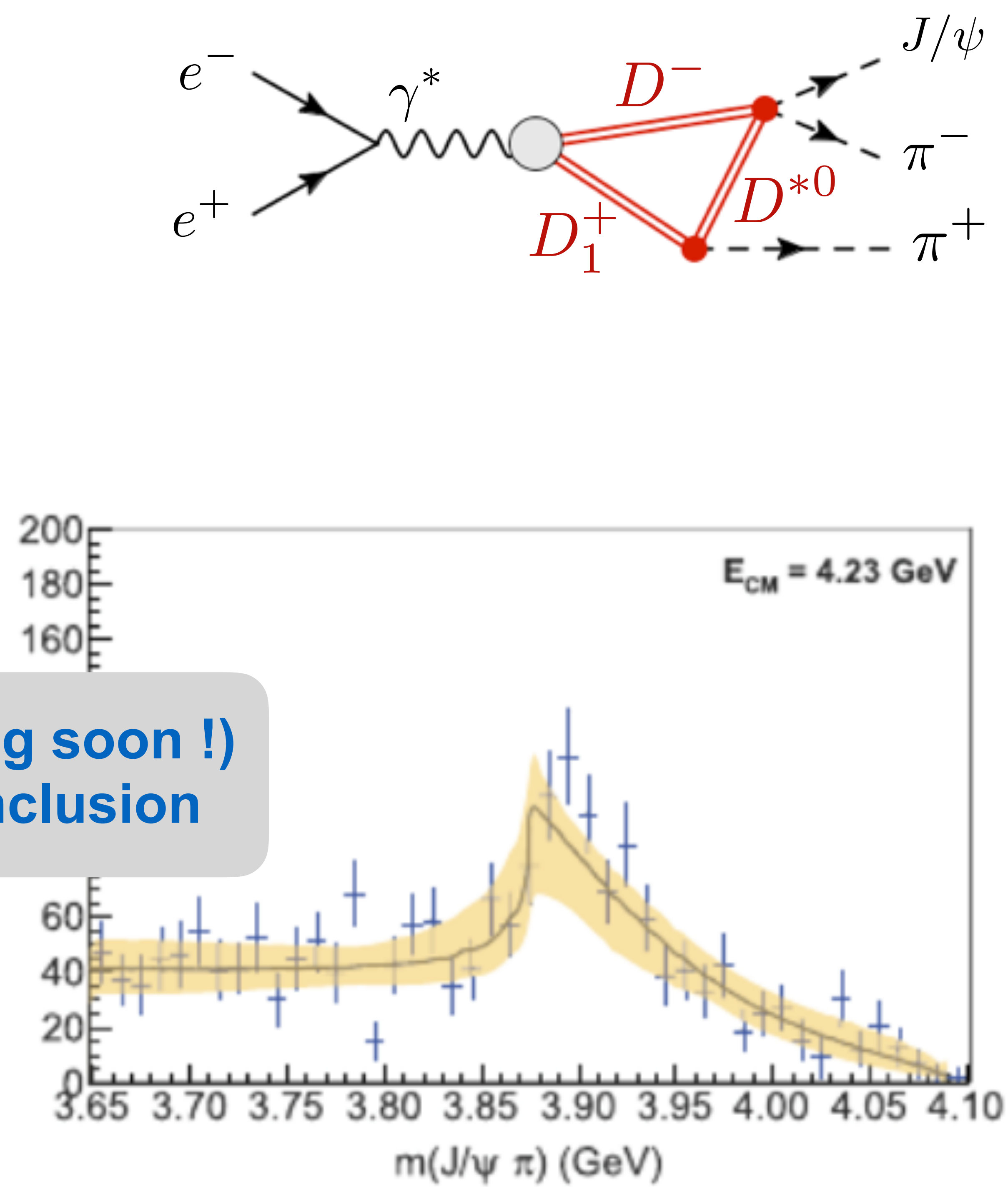


Pilloni et al (JPAC) PLB 772 (2017)

with tetraquark



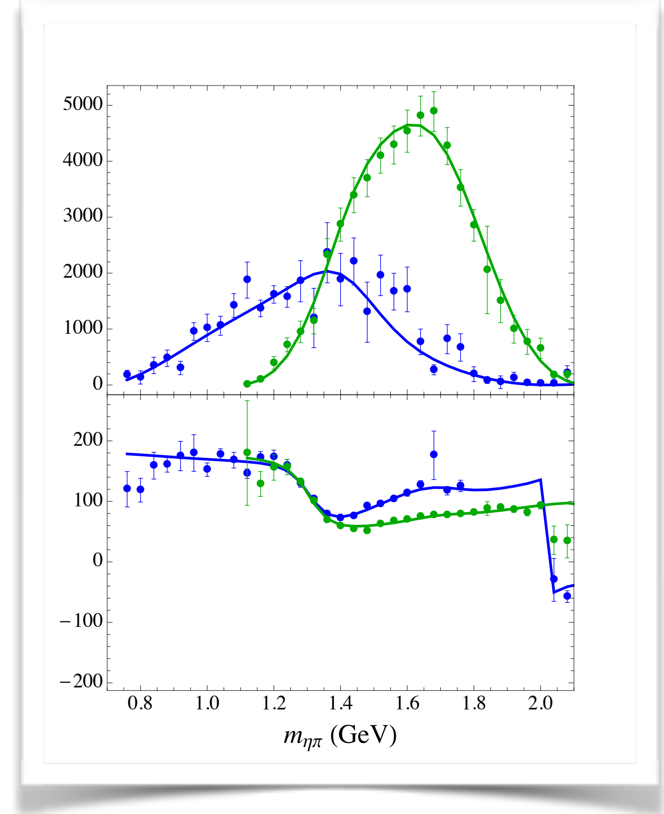
without tetraquark



More data (coming soon !) to draw firm conclusion

Summary

- **Hybrid meson @**



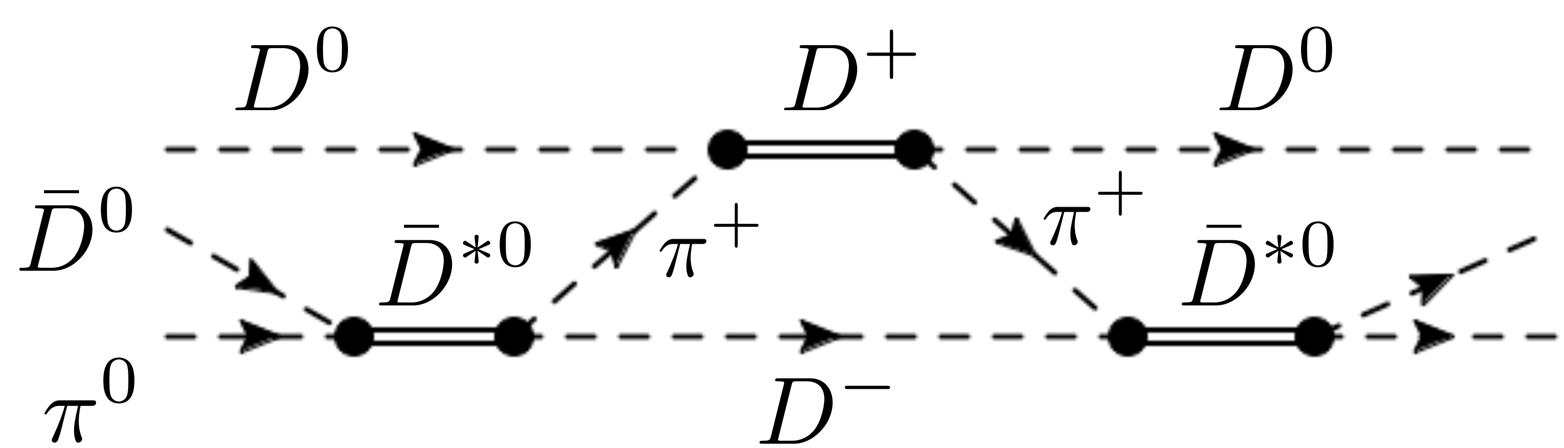
main channels:

$$\gamma p \to \pi^0 \eta^{(\prime)} p$$
$$\pi^- p \to \pi^- \eta^{(\prime)} p$$

main physics: 2-body unitarity in coupled channels

- **Tetraquarks @**

main physics:
3-body unitarity



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

INDIANA UNIVERSITY BLOOMINGTON

Jefferson Lab
Thomas Jefferson National Accelerator Facility

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

Resources

- **Publication:** [Mat15a]
- **Fortran:** Fortran file, Input file, Output file
- **C/C++:** AmpTools class, C/C++ file, AmpTools class header
- **Mathematica:** notebook , converted in text
- **Data:** Anderson, All data
- **Contact person:** Vincent Mathieu
- **Last update:** November 2015

Description of the Fortran code: [show/hide]
Description of the C/C++ code: [show/hide]

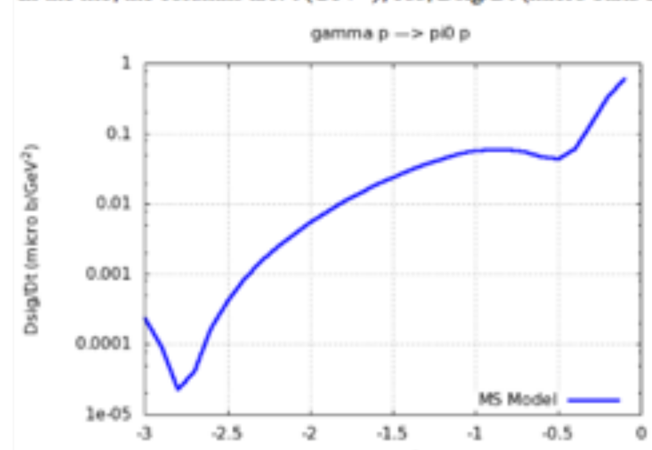
Run the code

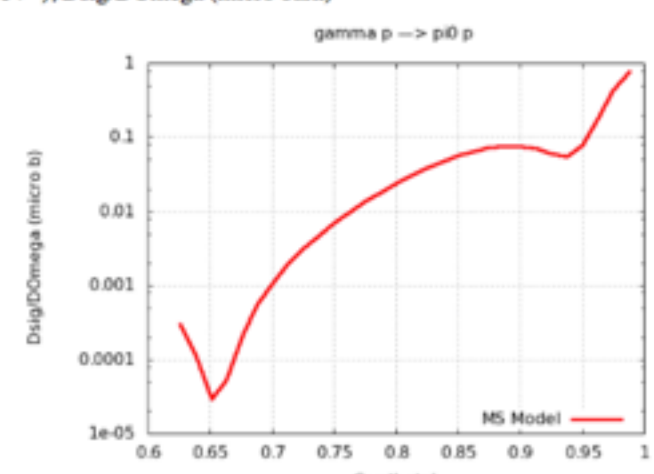
Choose the beam energy in the lab frame E_γ , the other variable (t or $\cos\theta$) and its minimal, maximal, and increment values.
If you choose t (cos) only the min, max and step values of t ($\cos\theta$) are read.

E_γ in GeV 9
t cos
t in GeV² (min max step) -3 -0.1 0.1
$\cos\theta$ (min max step) 0.5 0.95 0.01
Start reset

beam energy: 9 GeV
Observable: differential cross section
X variable: t with interval -3:0.1:-0.1

Download the output file, the plot with Ox=t , the plot with Ox=cos .
In the file, the columns are: t (GeV²), cos, Dsig/Dt (micro barn/GeV²), Dsig/DOmega (micro barn)



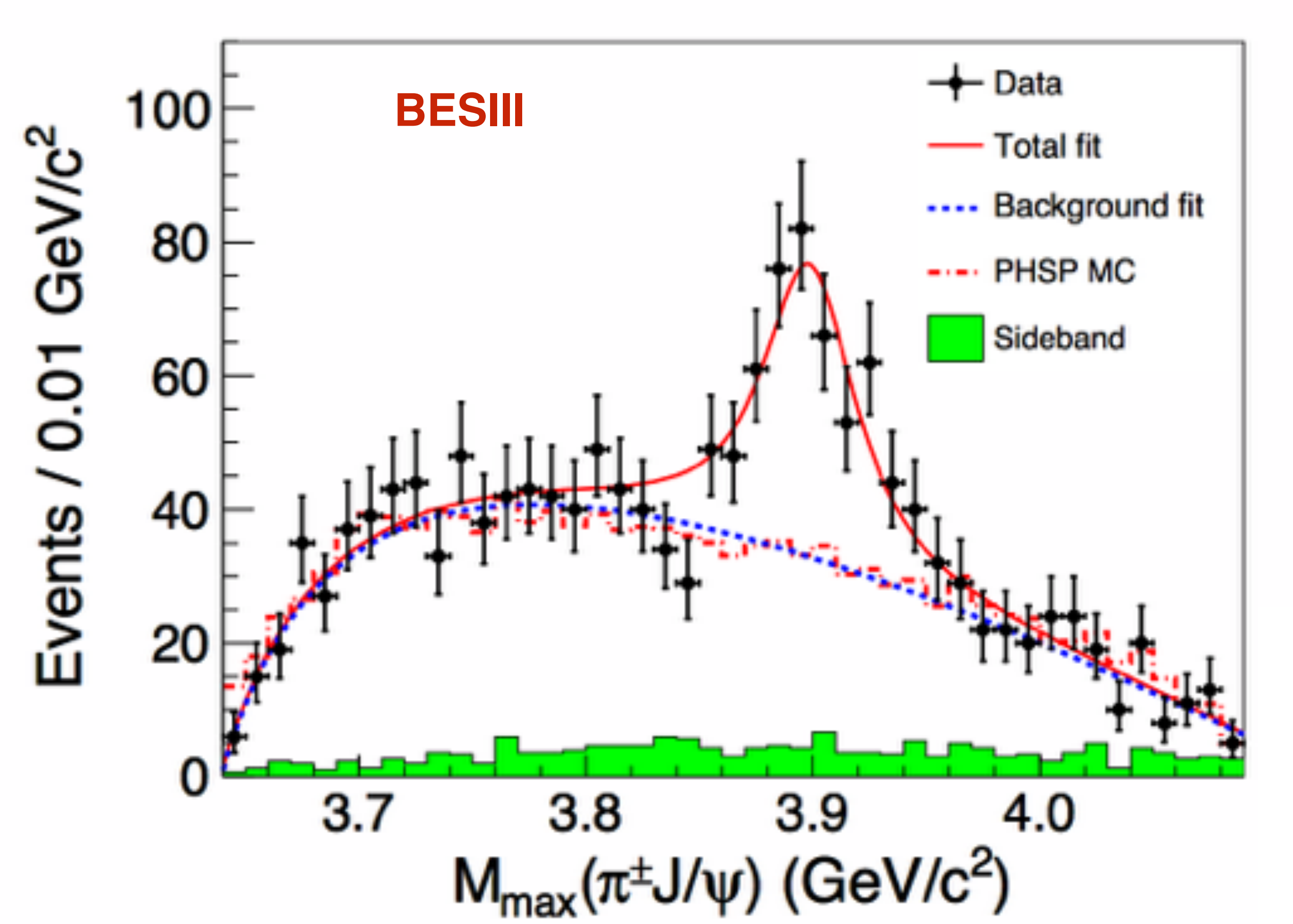


Interactive webpage: http://www.indiana.edu/~jpac/

1.	United States	493	(32.18%)
2.	Germany	169	(11.03%)
3.	United Kingdom	150	(9.79%)
4.	Mexico	103	(6.72%)
5.	Italy	57	(3.72%)
6.	Spain	52	(3.39%)
7.	Belgium	38	(2.48%)
8.	China	37	(2.42%)
9.	(not set)	37	(2.42%)
10.	Brazil	35	(2.28%)
11.	Poland	31	(2.02%)
12.	Austria	30	(1.96%)
13.	Japan	26	(1.70%)
14.	Switzerland	25	(1.63%)
15.	Russia	20	(1.31%)
16.	Saudi Arabia	20	(1.31%)
17.	Iraq	17	(1.11%)
18.	India	16	(1.04%)
19.	Canada	15	(0.98%)
20.	Netherlands	15	(0.98%)
21.	France	12	(0.78%)
22.	Bosnia & Herzegovina	10	(0.65%)
23.	Greece	10	(0.65%)
24.	Portugal	9	(0.59%)
25.	South Korea	7	(0.46%)

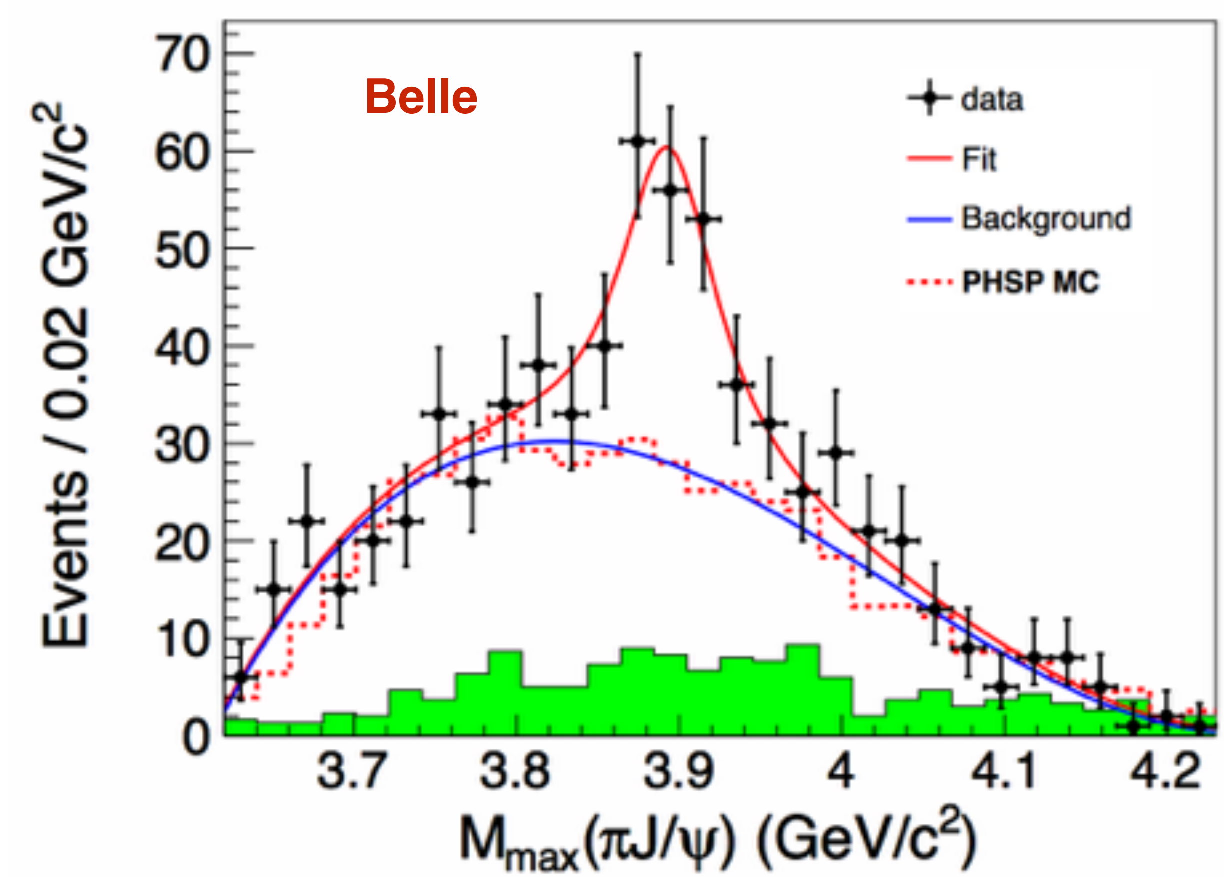
Backup Slides

Z(3900)



- Discovered by Belle & BESIII 2013

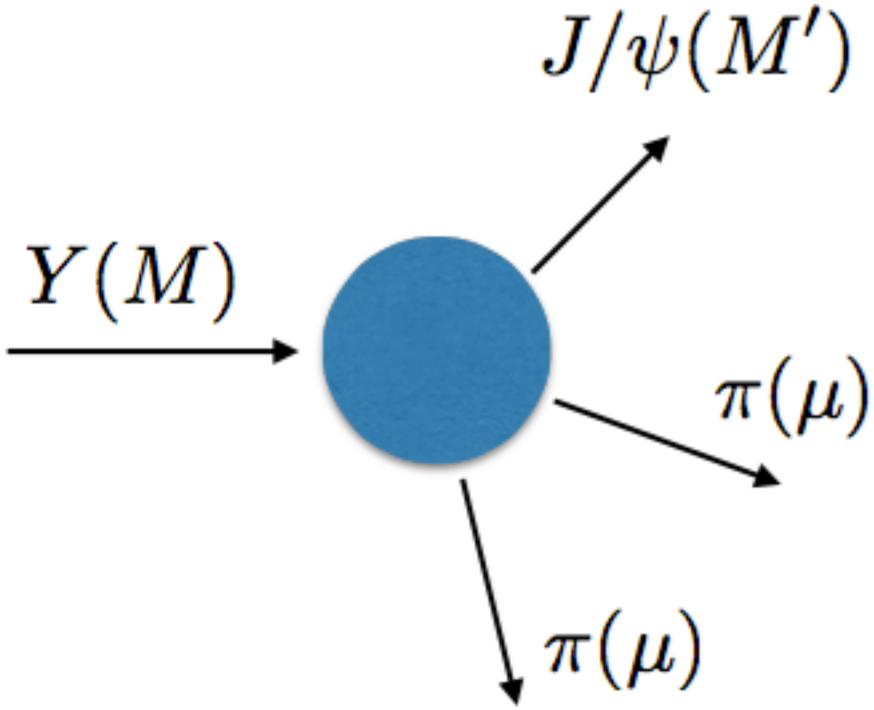
- Seen in decay $Y(4260) \to J/\psi\pi\pi$



Liu, BESIII & Belle Collaboration, arXiv:1311.0762v1

Close to $\bar{D}D^*$ threshold

Special case: Szczepaniak arXiv:1501.01691
Real case: JPAC, in preparation



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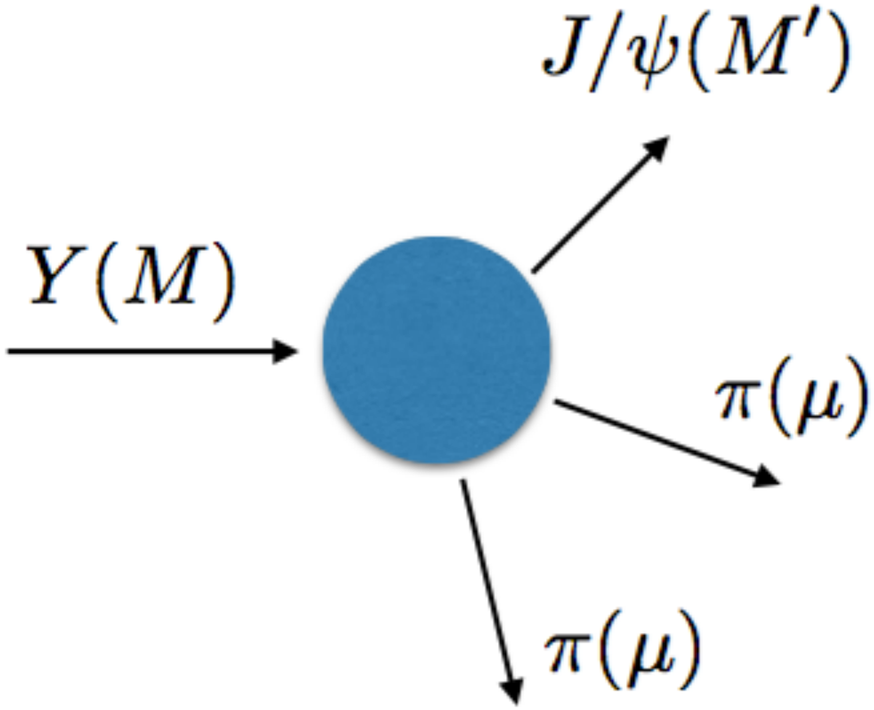

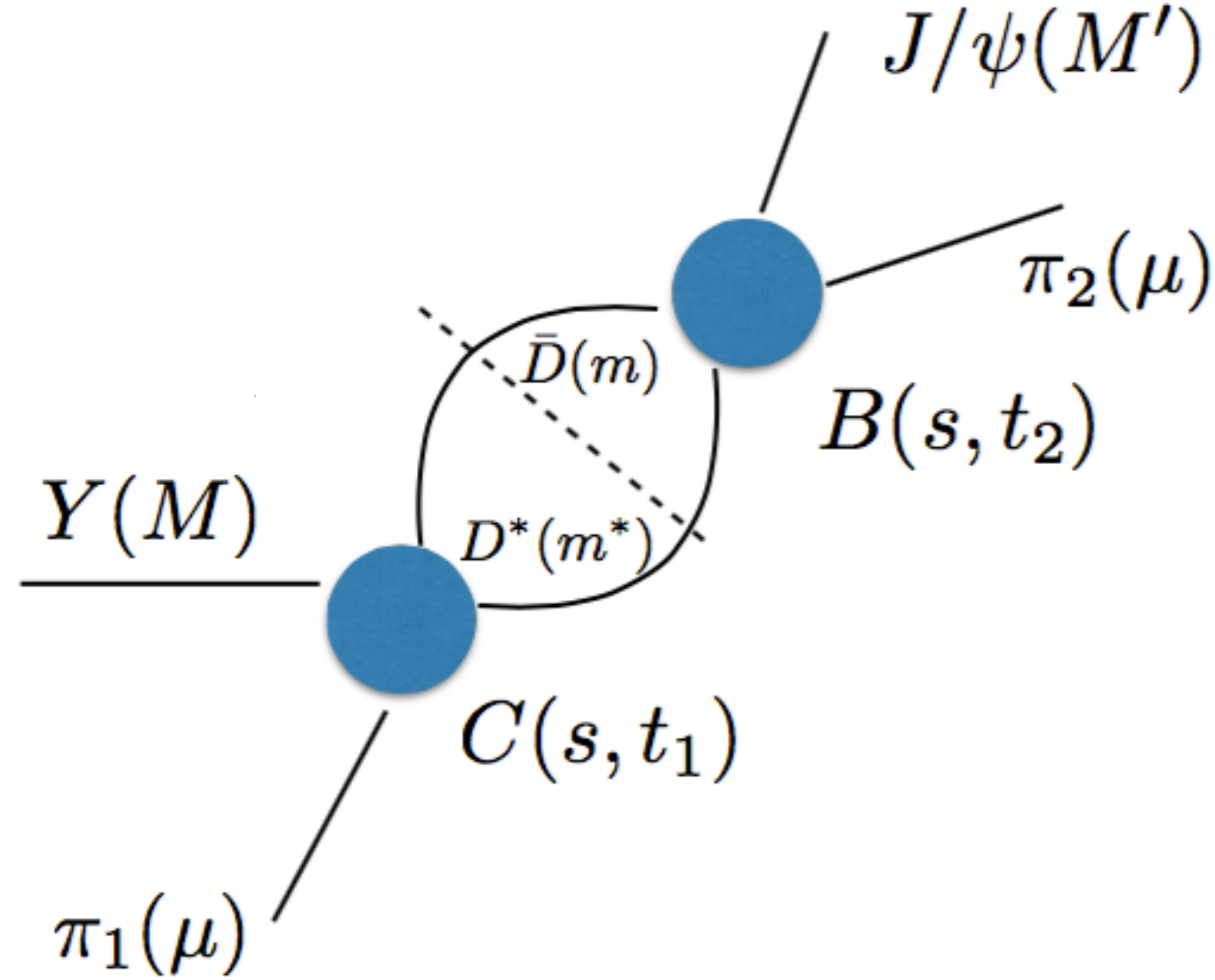

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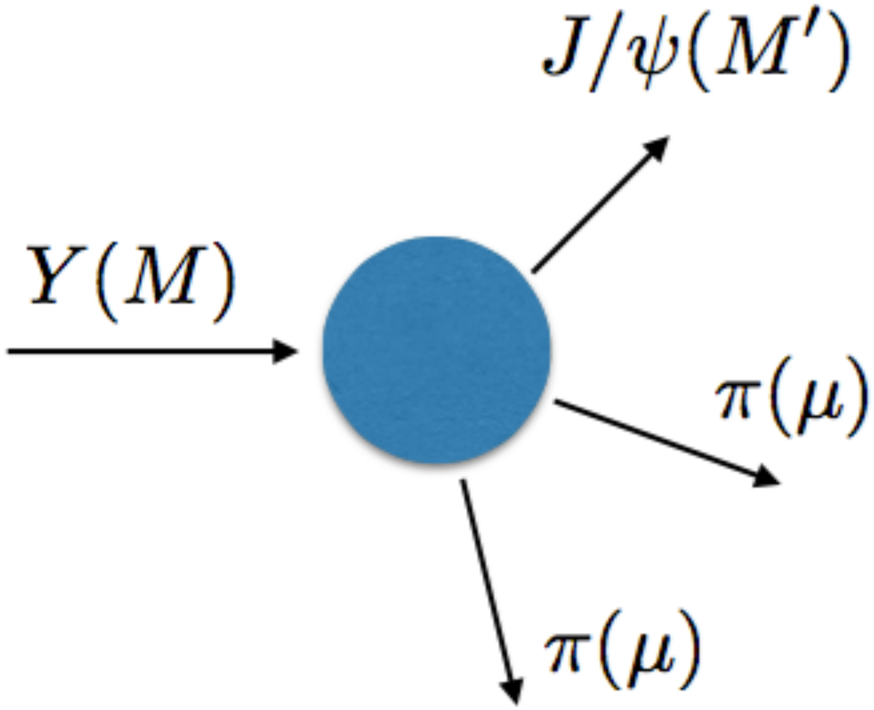
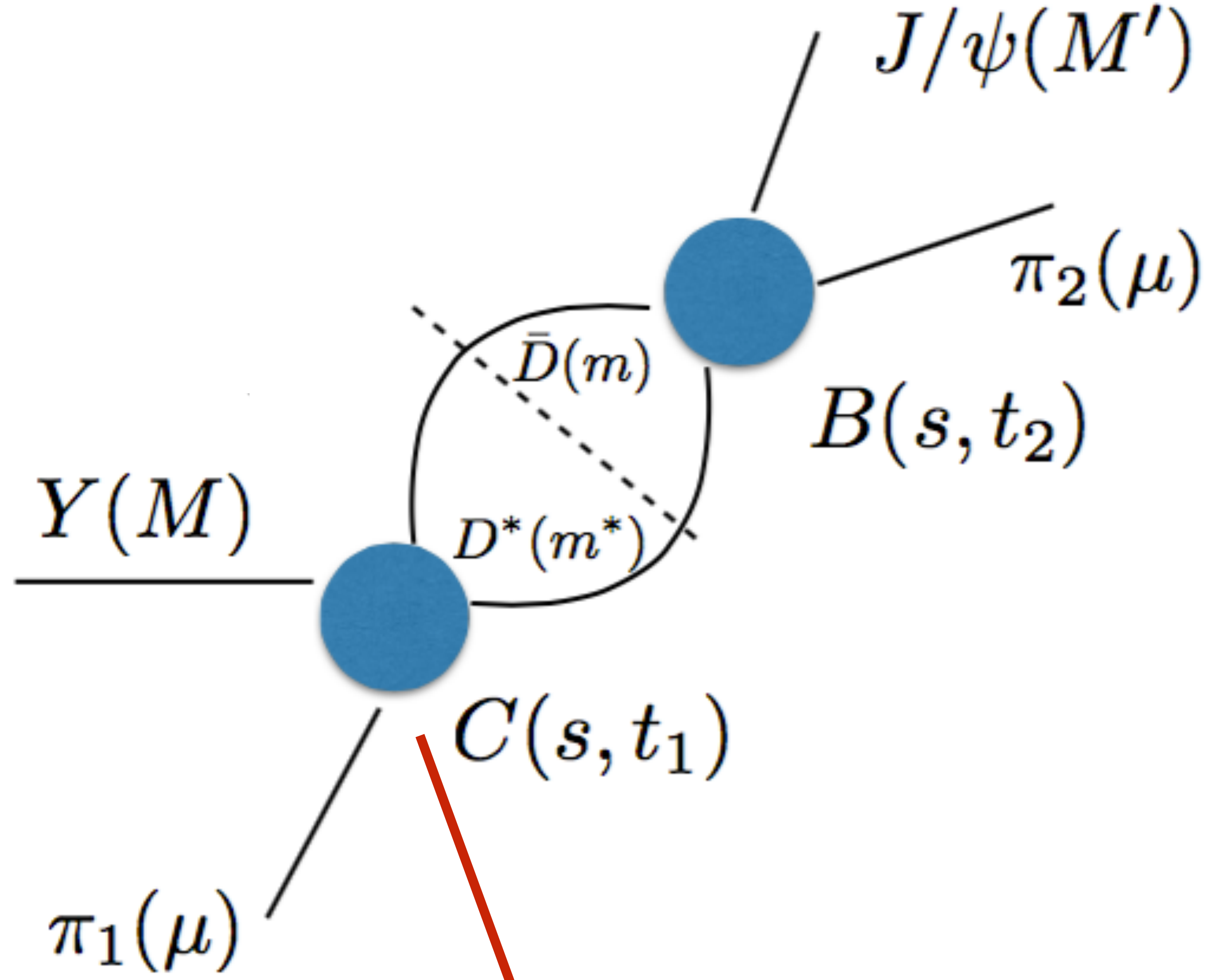
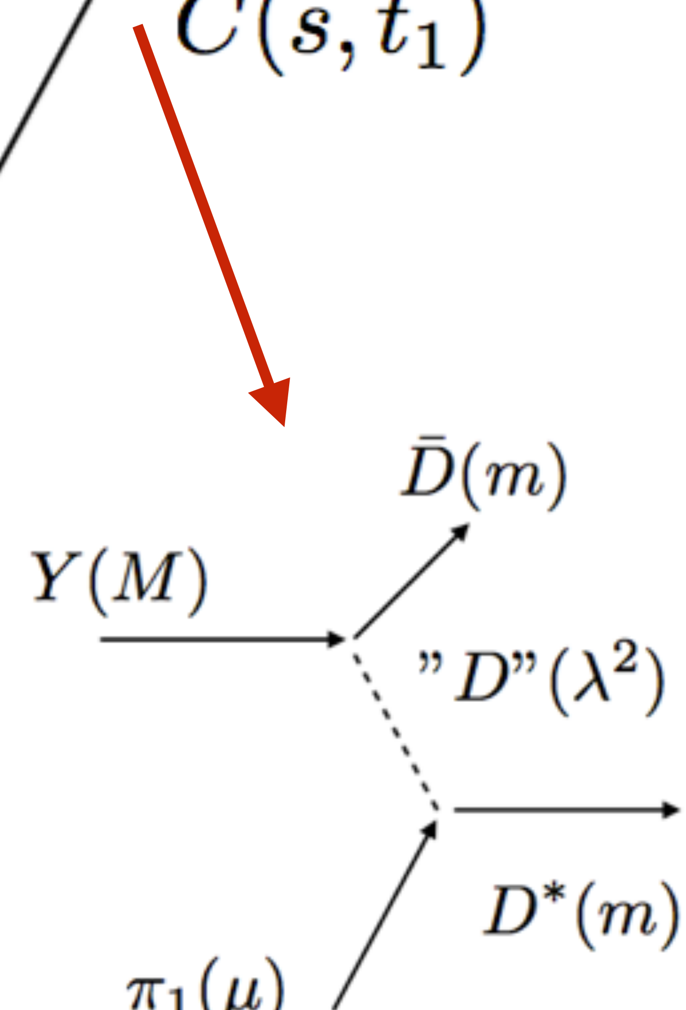


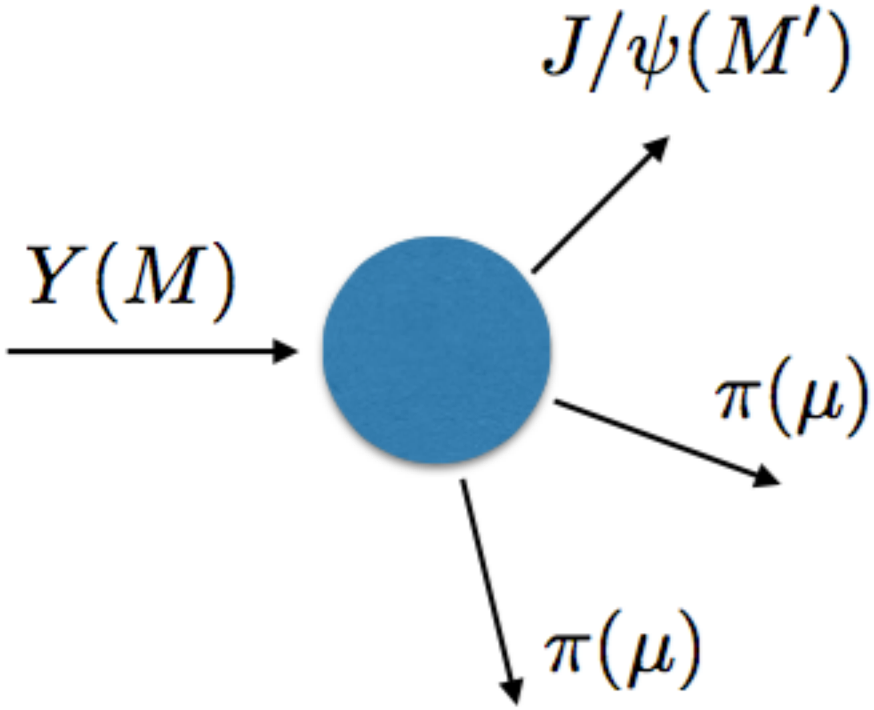


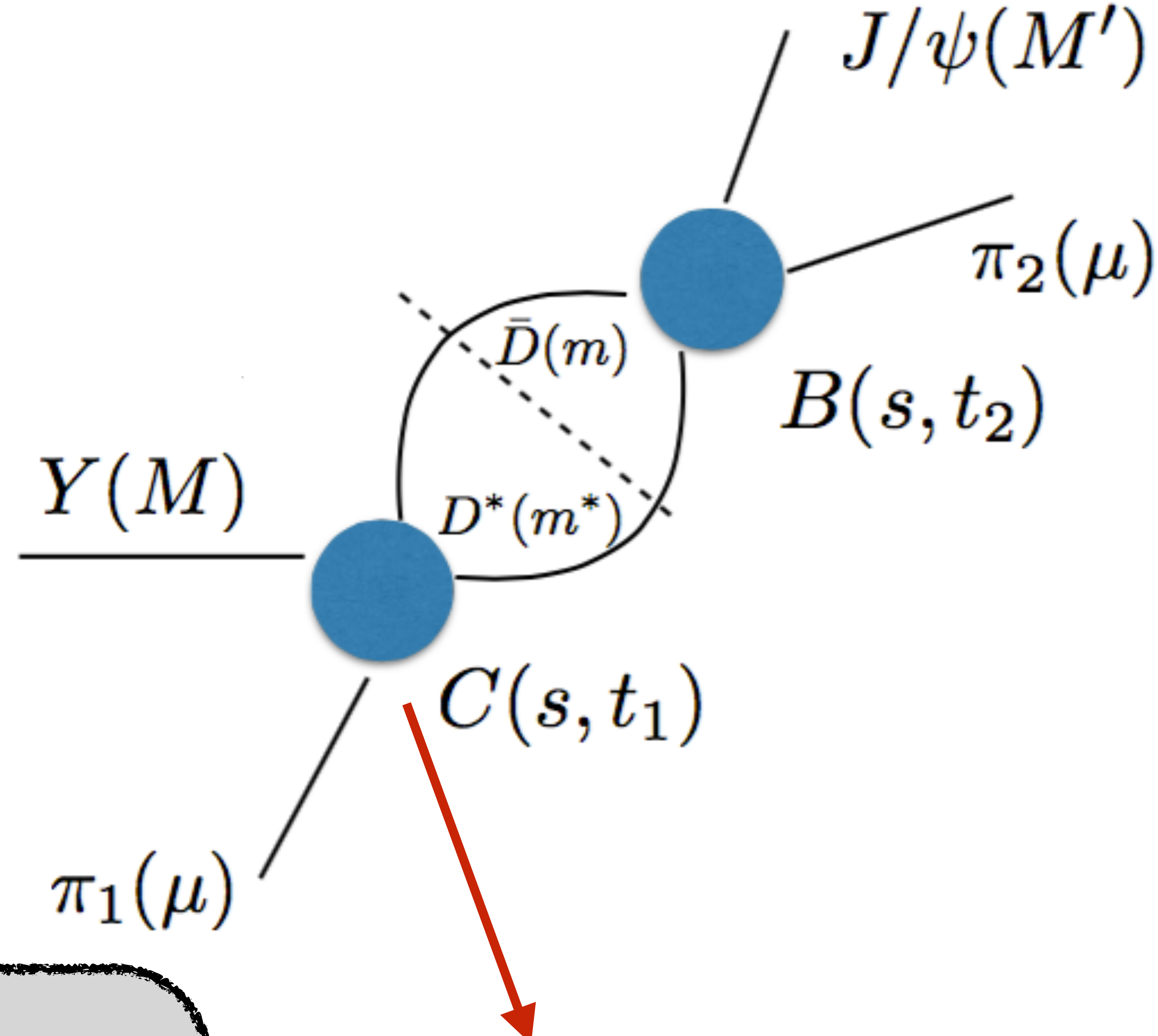


$\mu = 0$

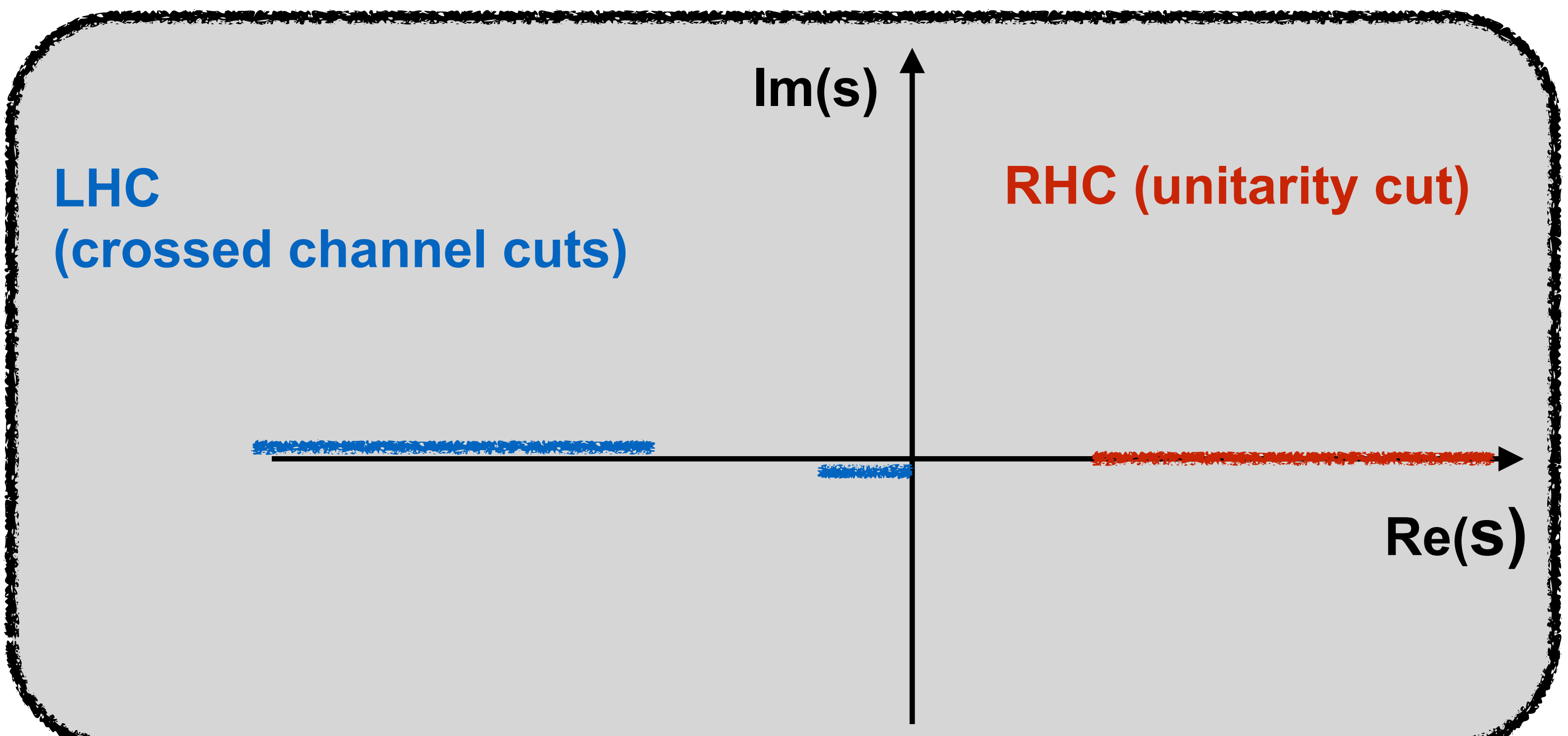
$m = m^*$

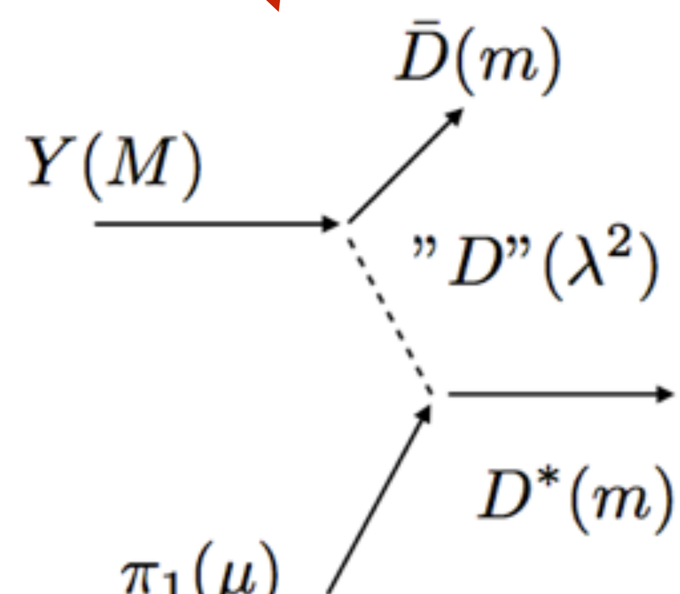
Special case: Szczepaniak arXiv:1501.01691
Real case: JPAC, in preparation





Analytic structure of C(s) S-wave





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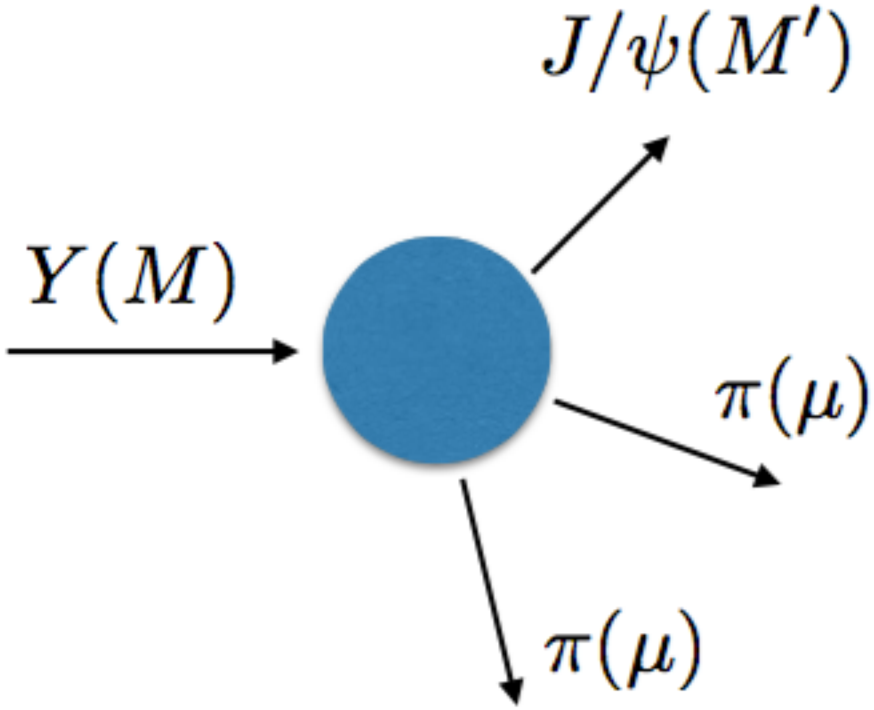
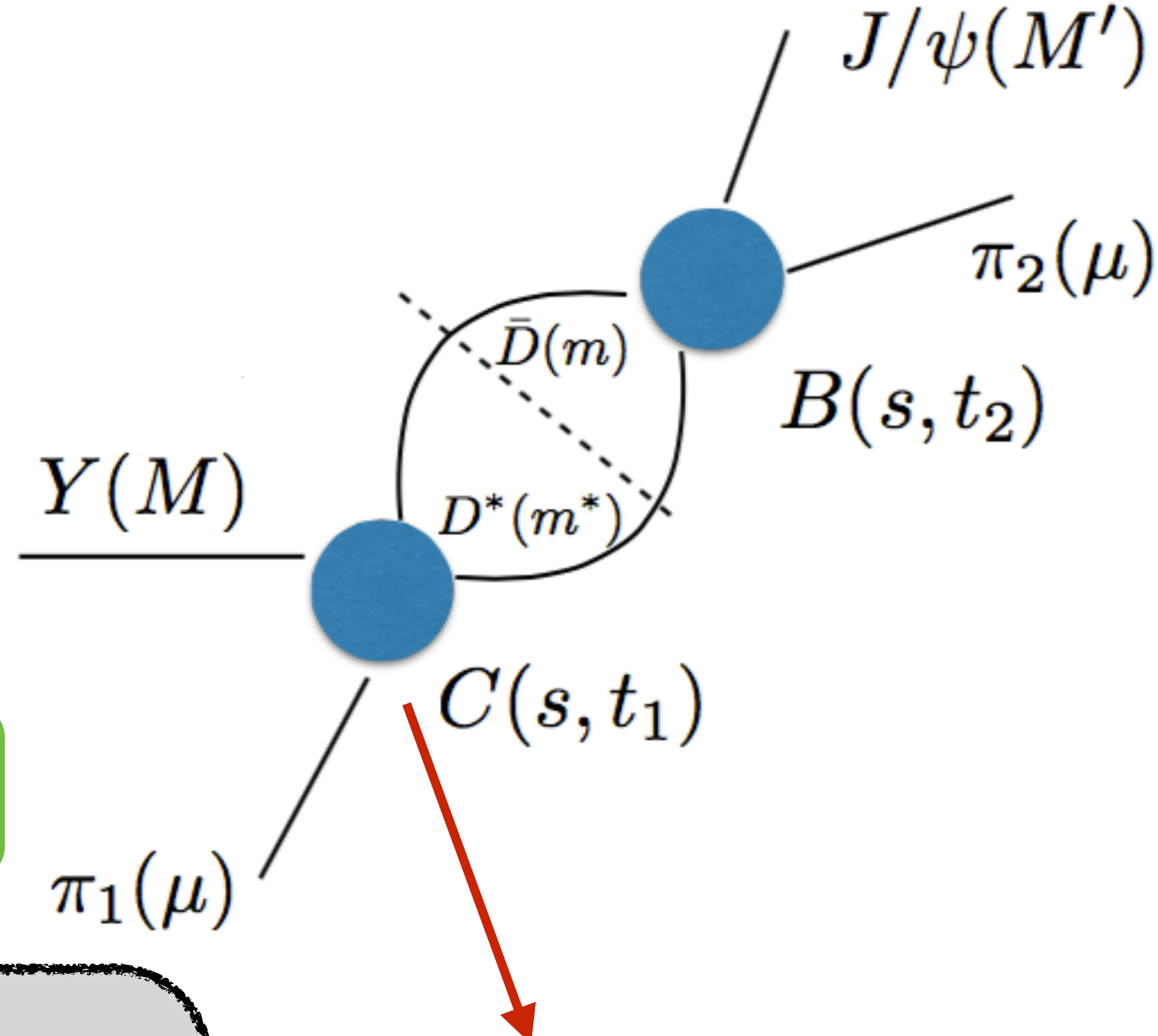
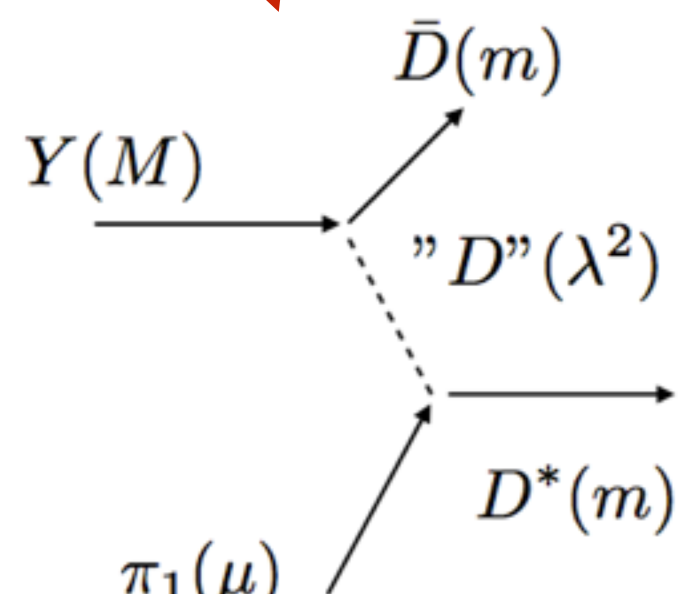




$$(M-m)^2 > \lambda^2 > M^2/2 - m^2$$



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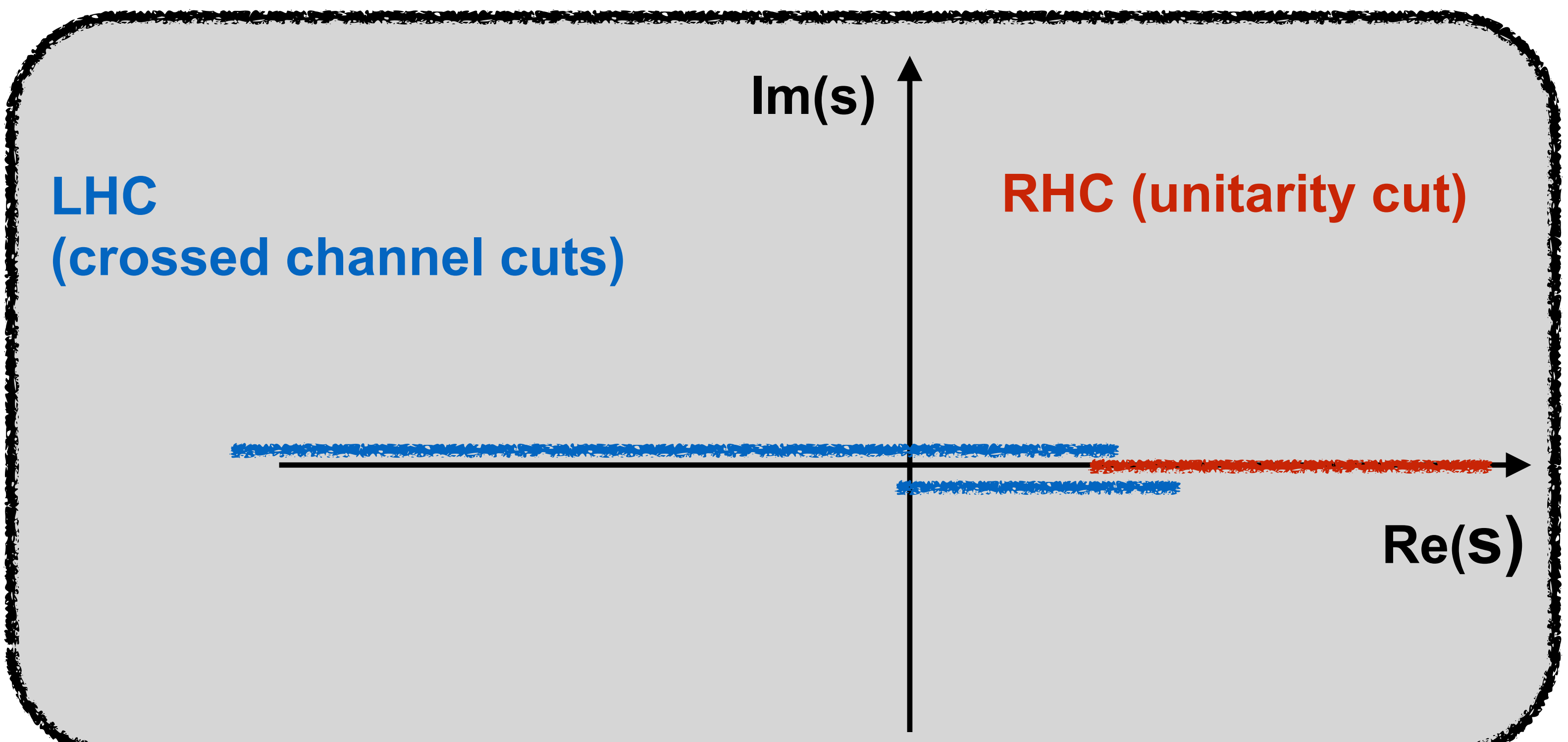

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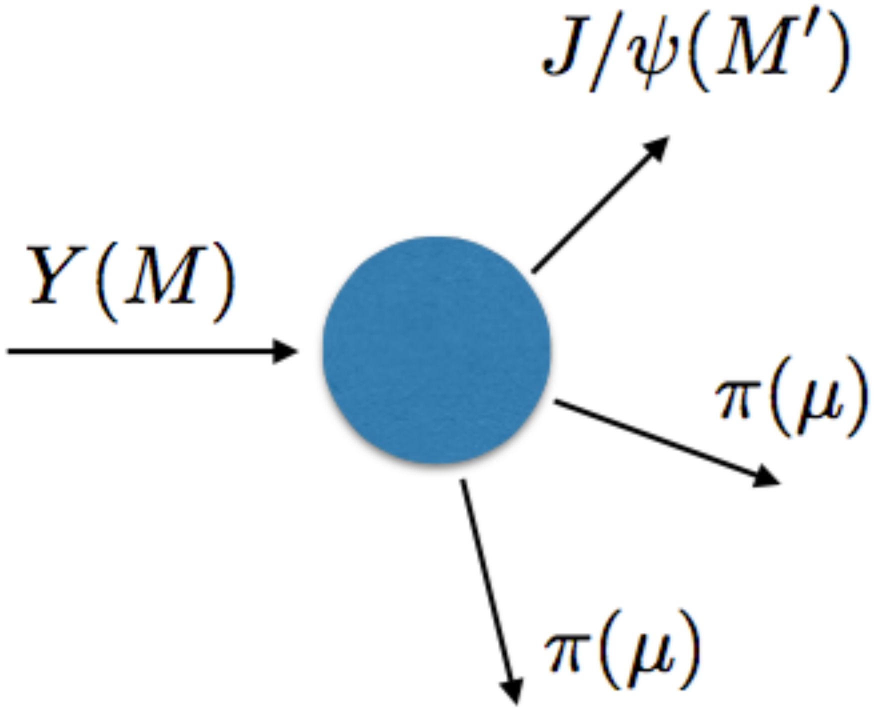

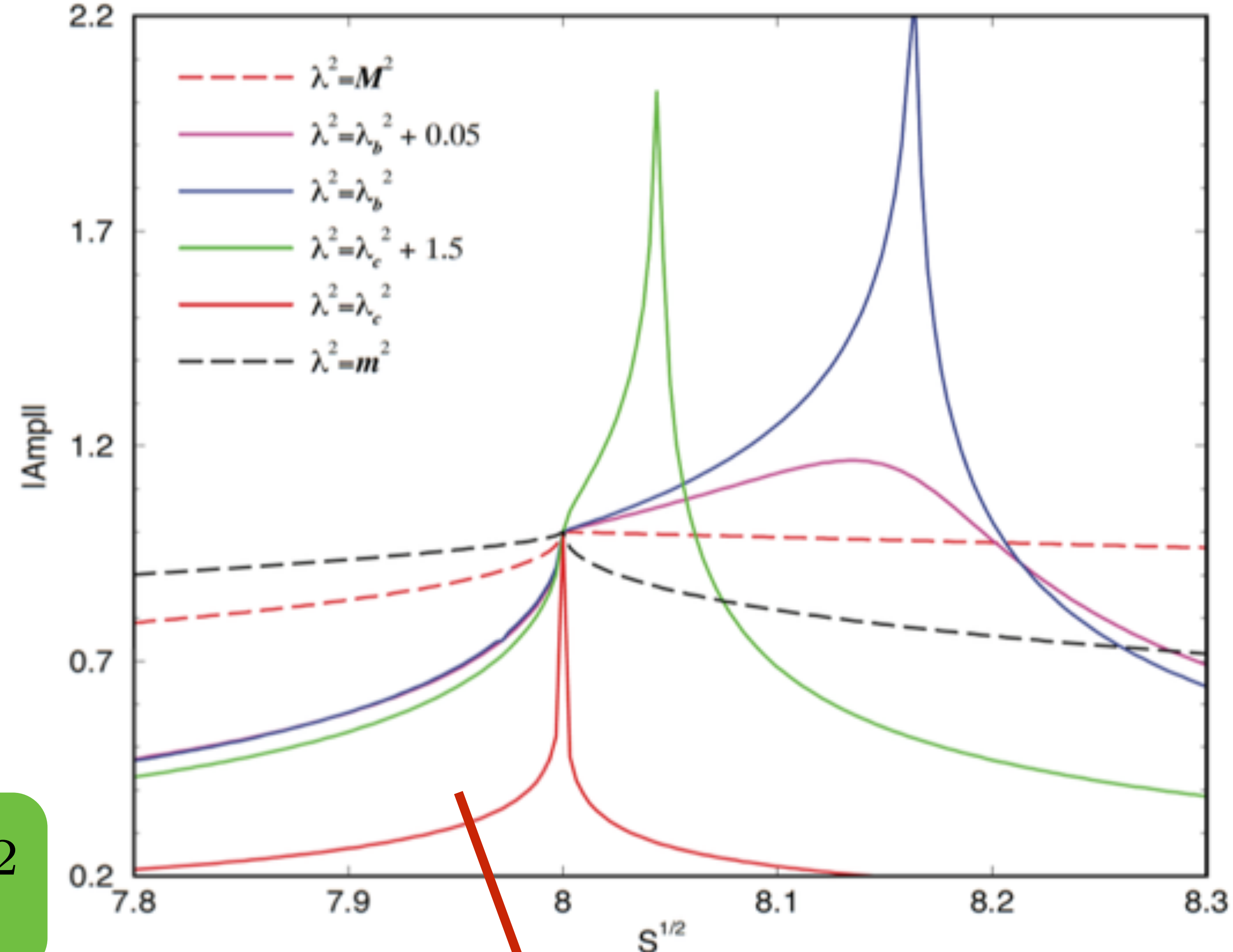

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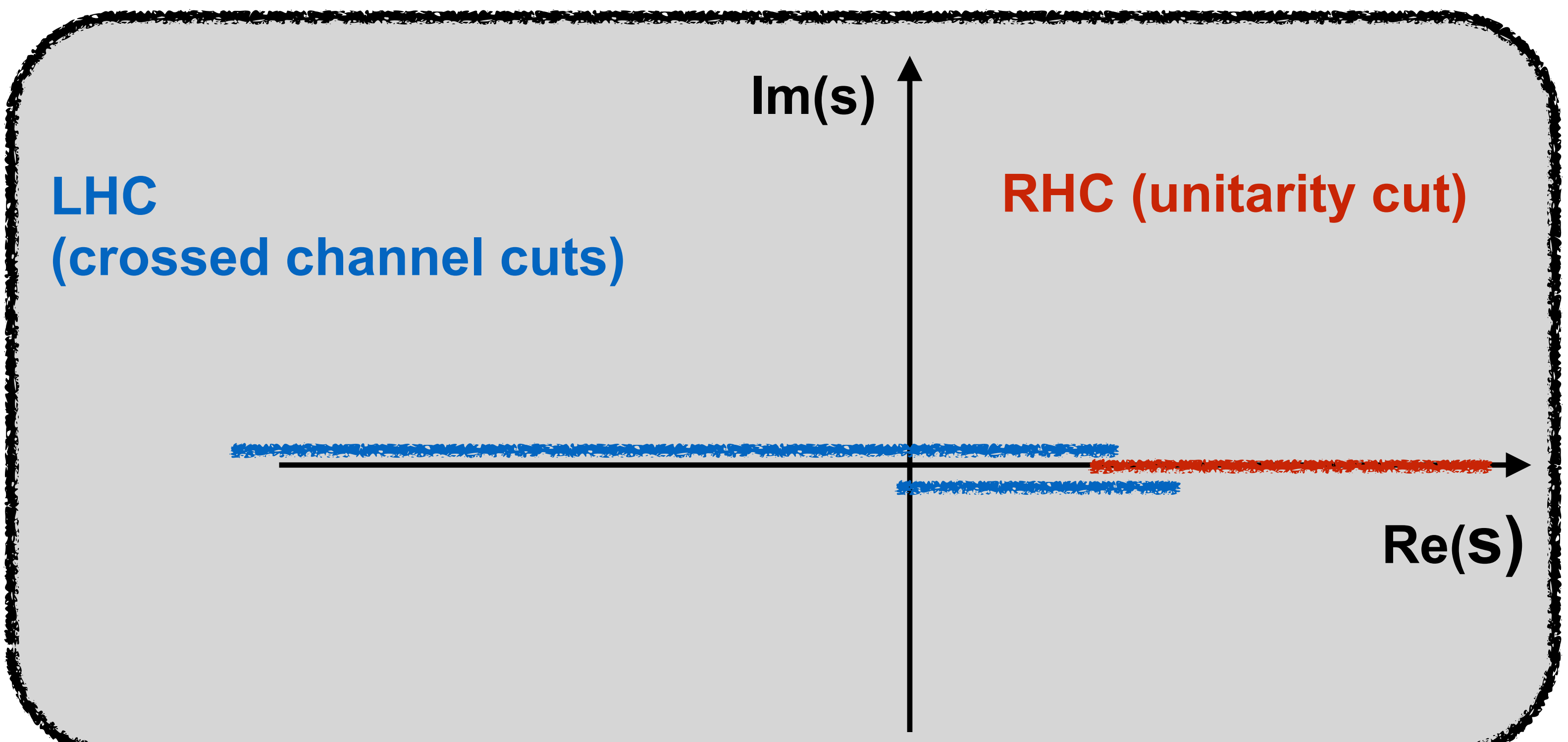

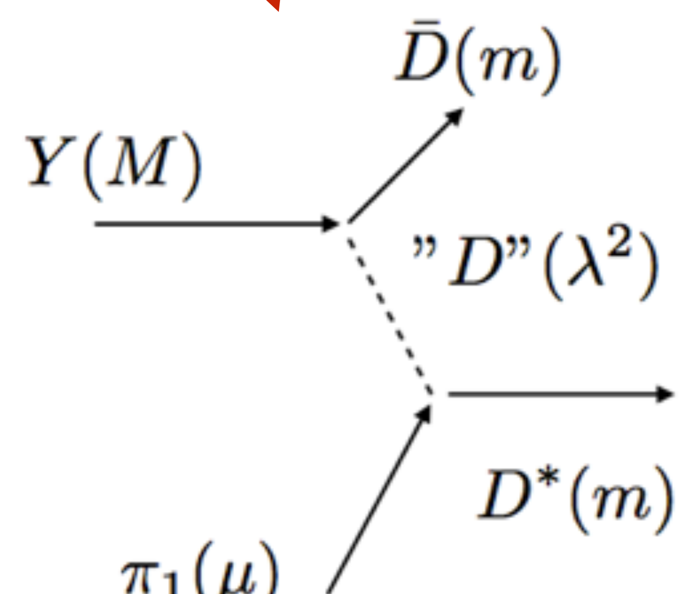

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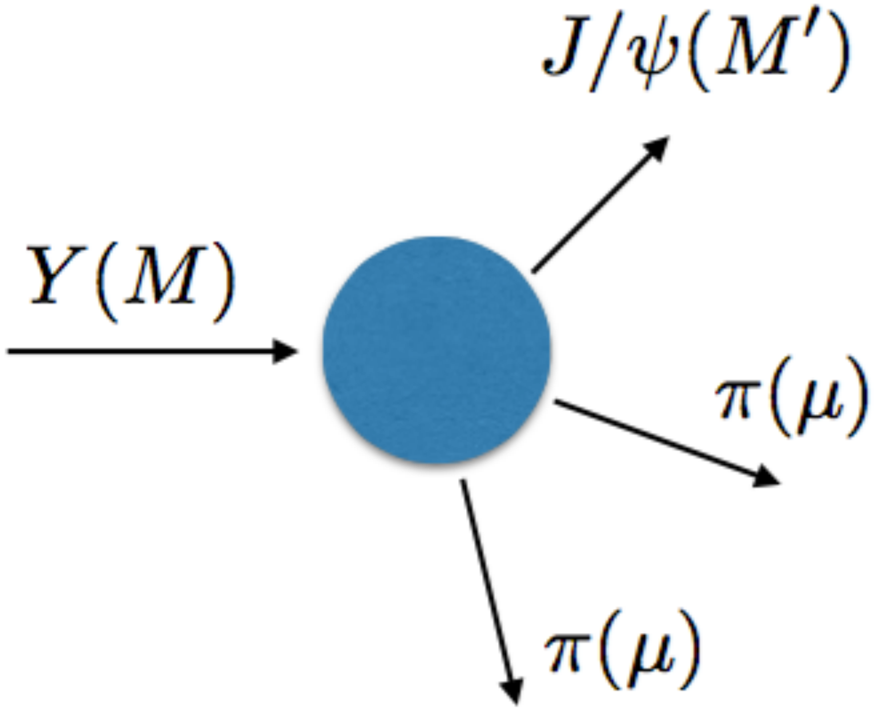

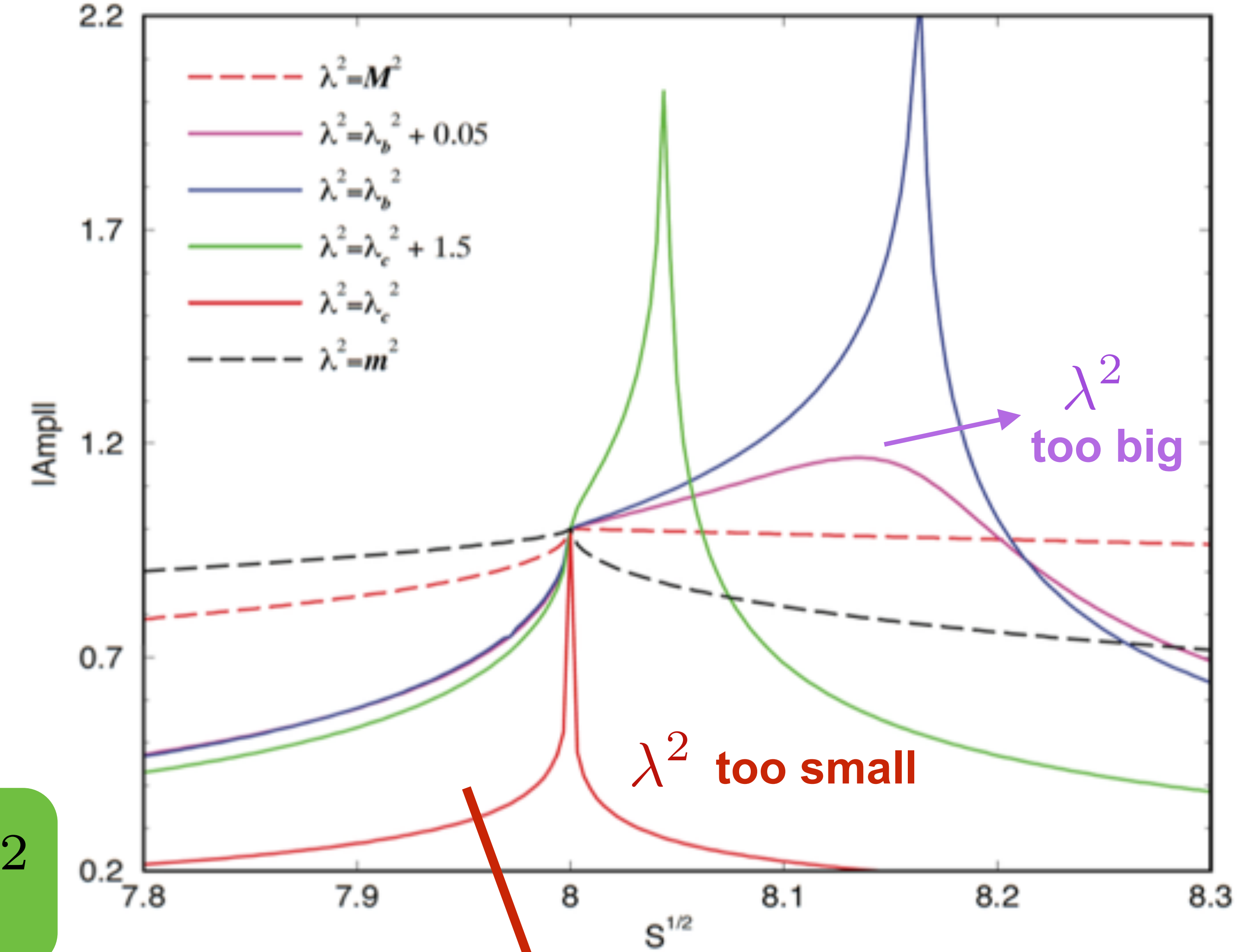

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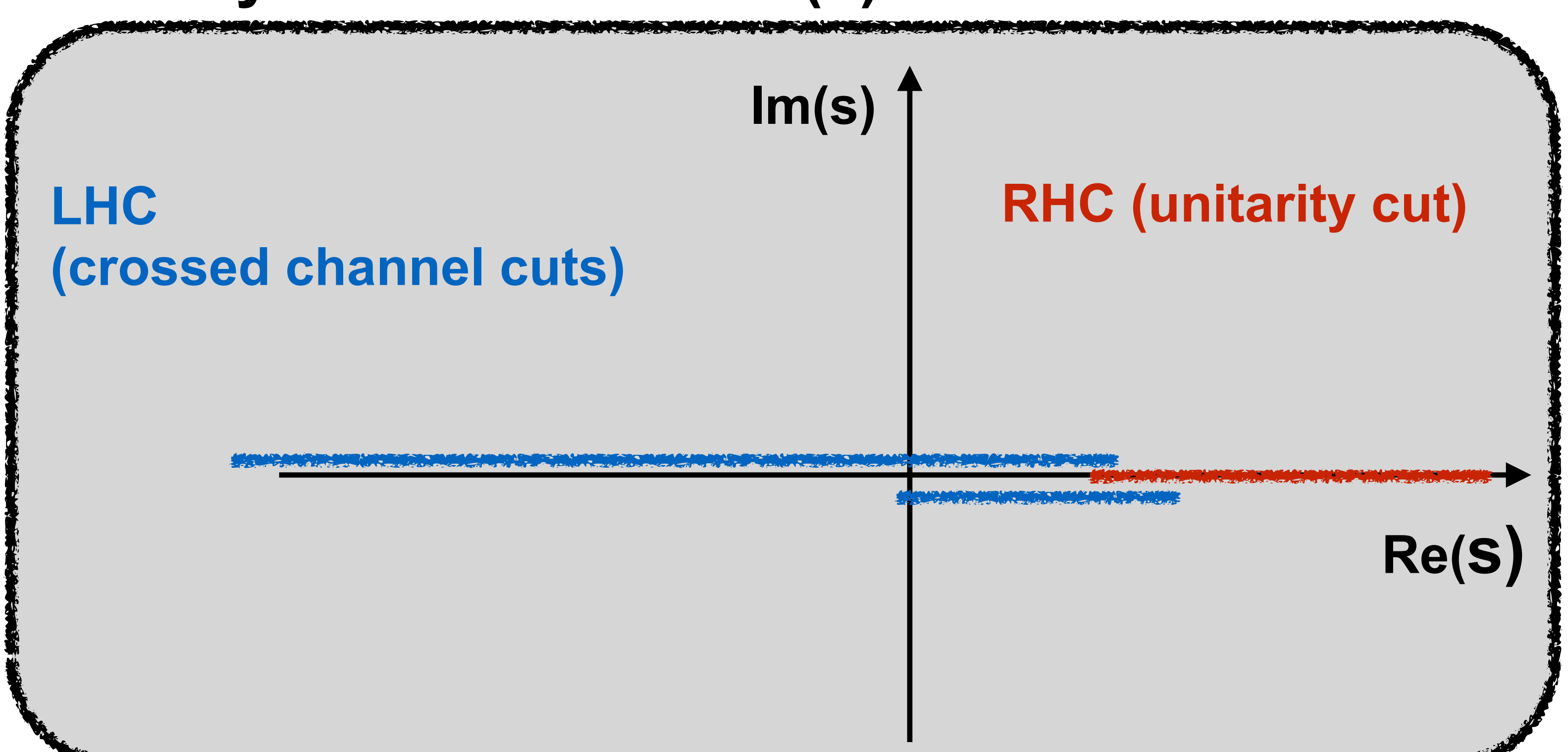

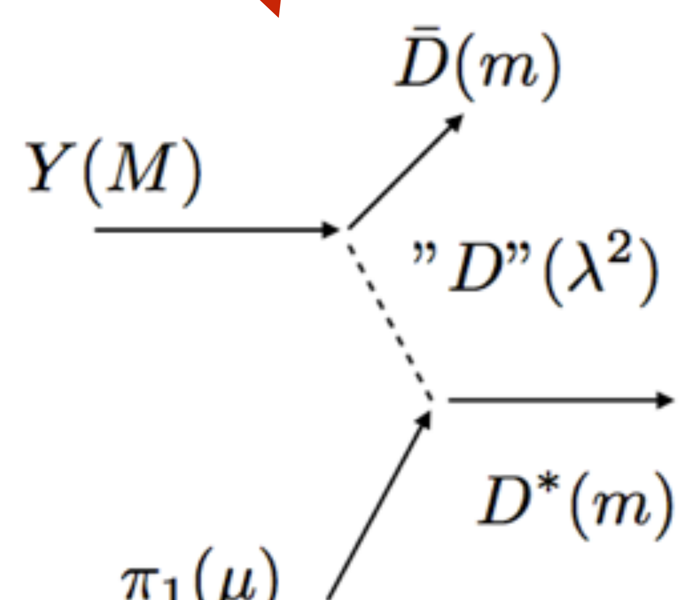

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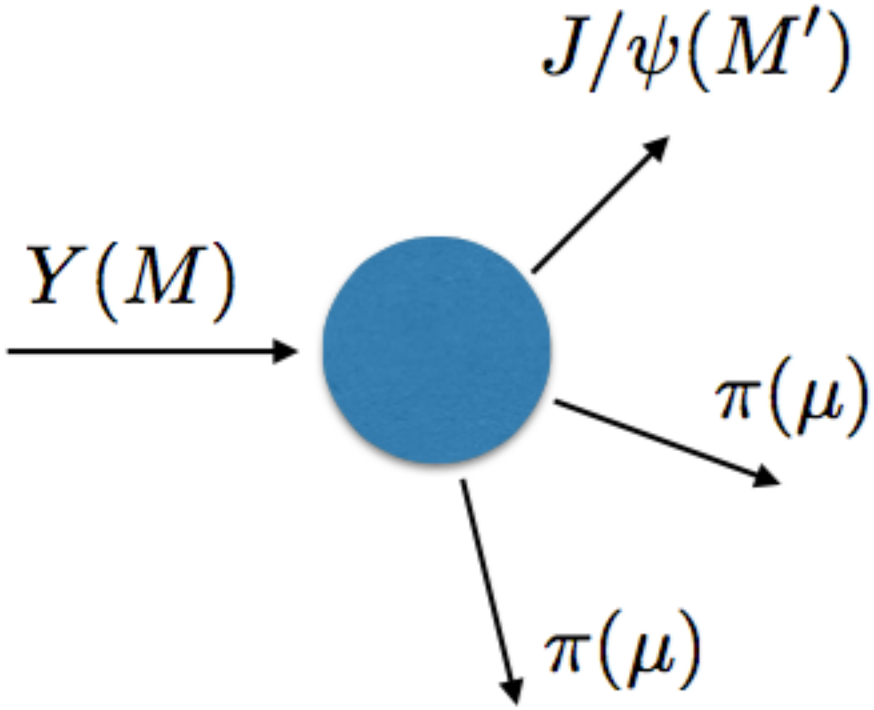

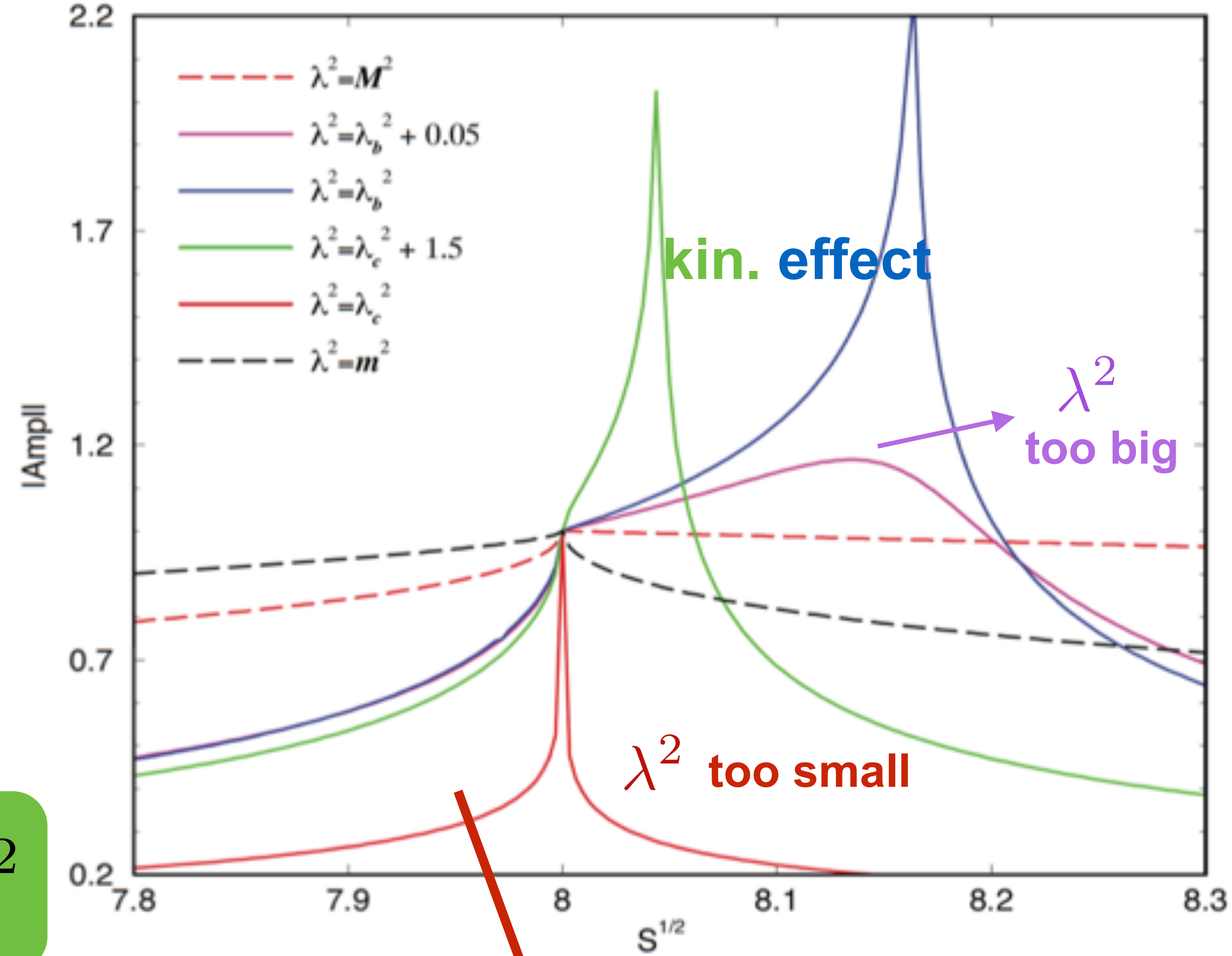

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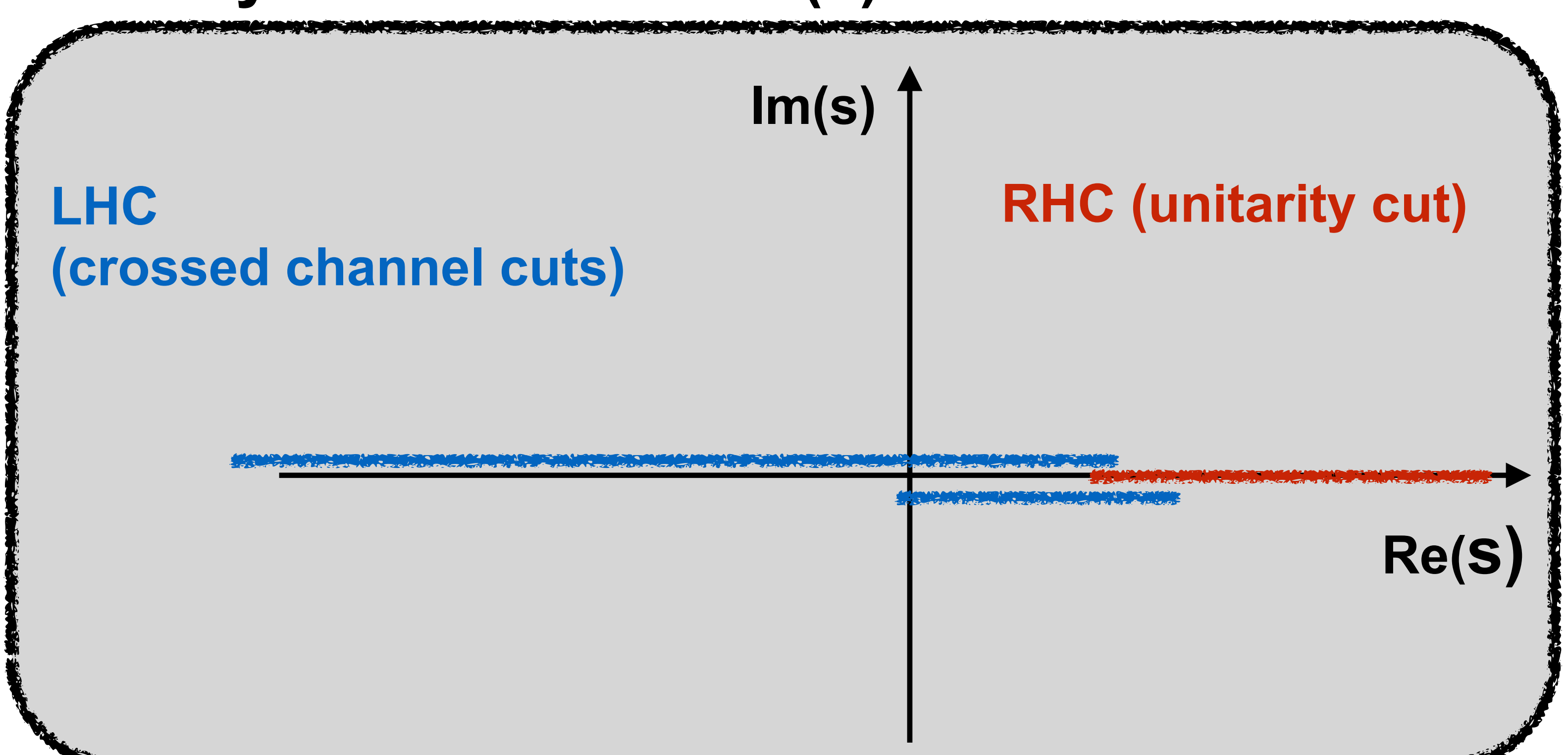

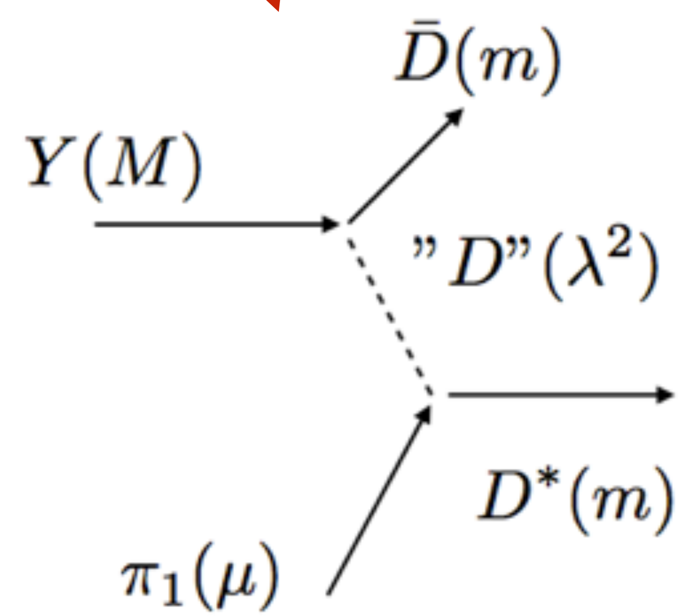

$$\mu = 0$$
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LHC produced by exchanges

$$f_L(s) = \frac{2\sqrt{s}}{(M^2 - s)\sqrt{4m^2 - s}} \log \frac{\lambda^2 - t_-(s)}{\lambda^2 - t_+(s)}$$

$$t_\pm(s) \equiv t(s, \pm 1)$$

$$t_\pm(s_\pm(\lambda^2)) = \lambda^2$$

This function has indeed LHC's

between the four branching points: $s = -\infty, 0, s_\pm(\lambda^2)$

F_L integrated over RHC: $F(s) = F_L(s) + t(s)\frac{1}{\pi}\int_{s_0}^{\infty} \frac{\rho(s')F_L(s')}{s' - s} ds'$

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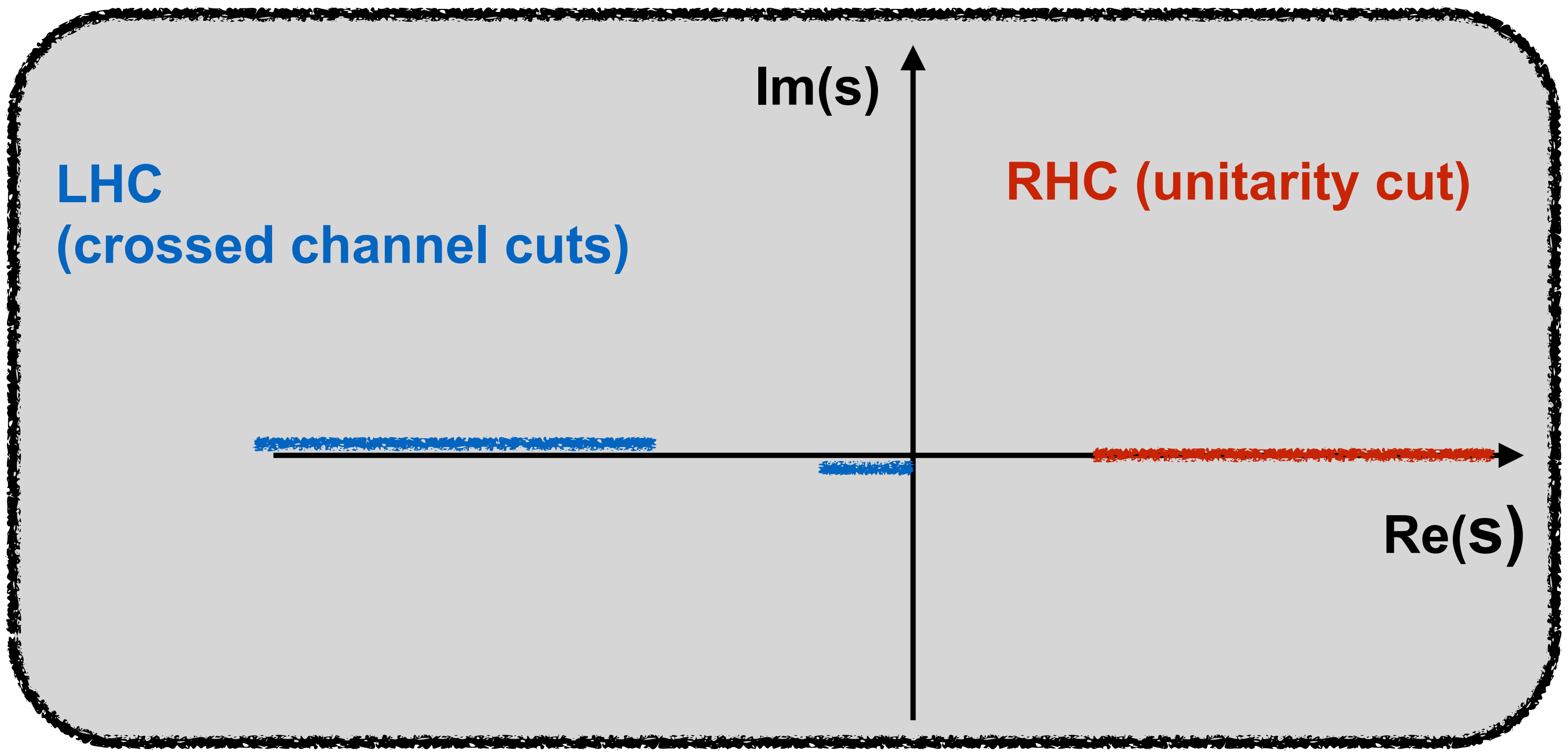
λ^2 **big**



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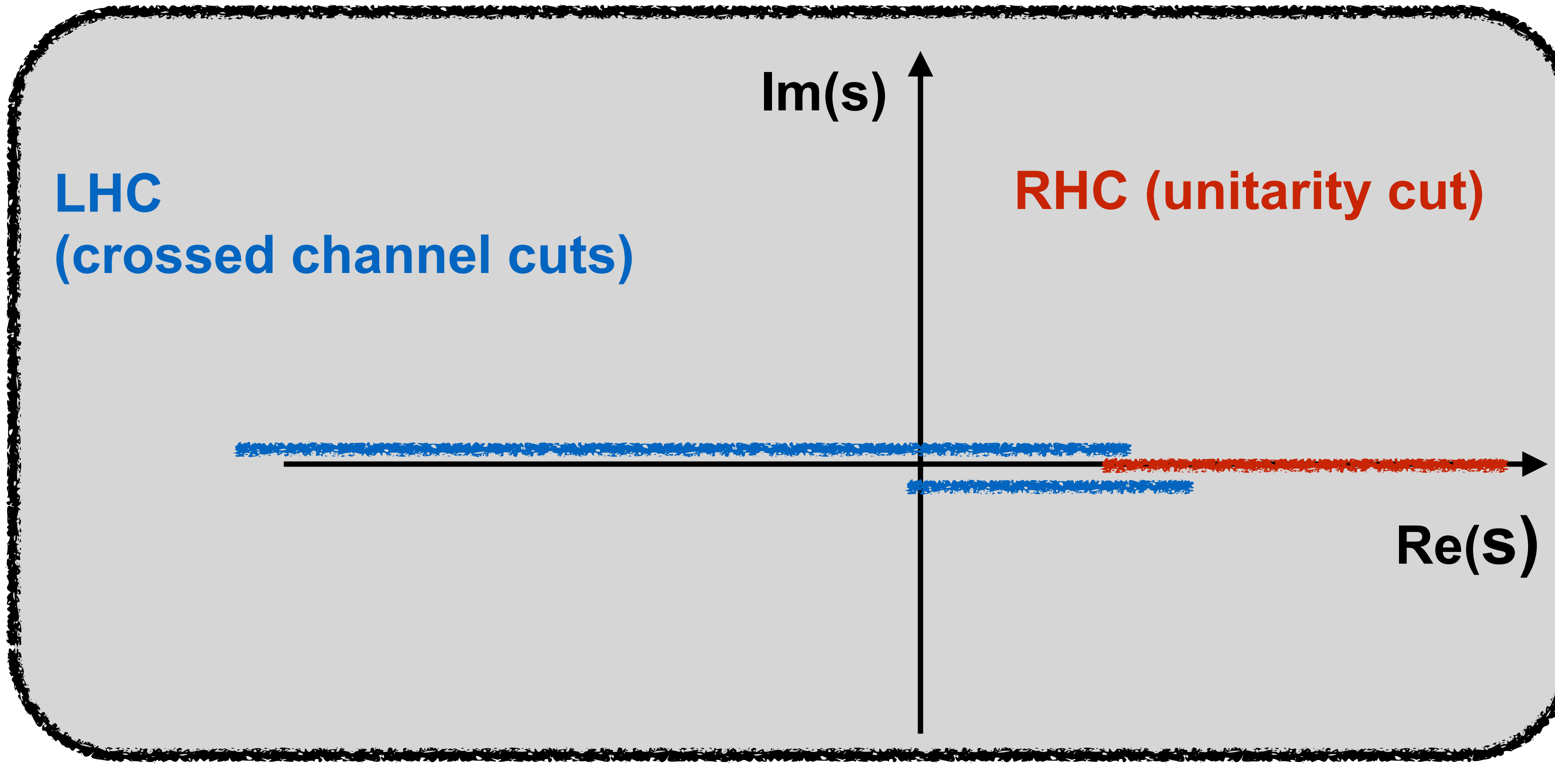
λ^2 **small**



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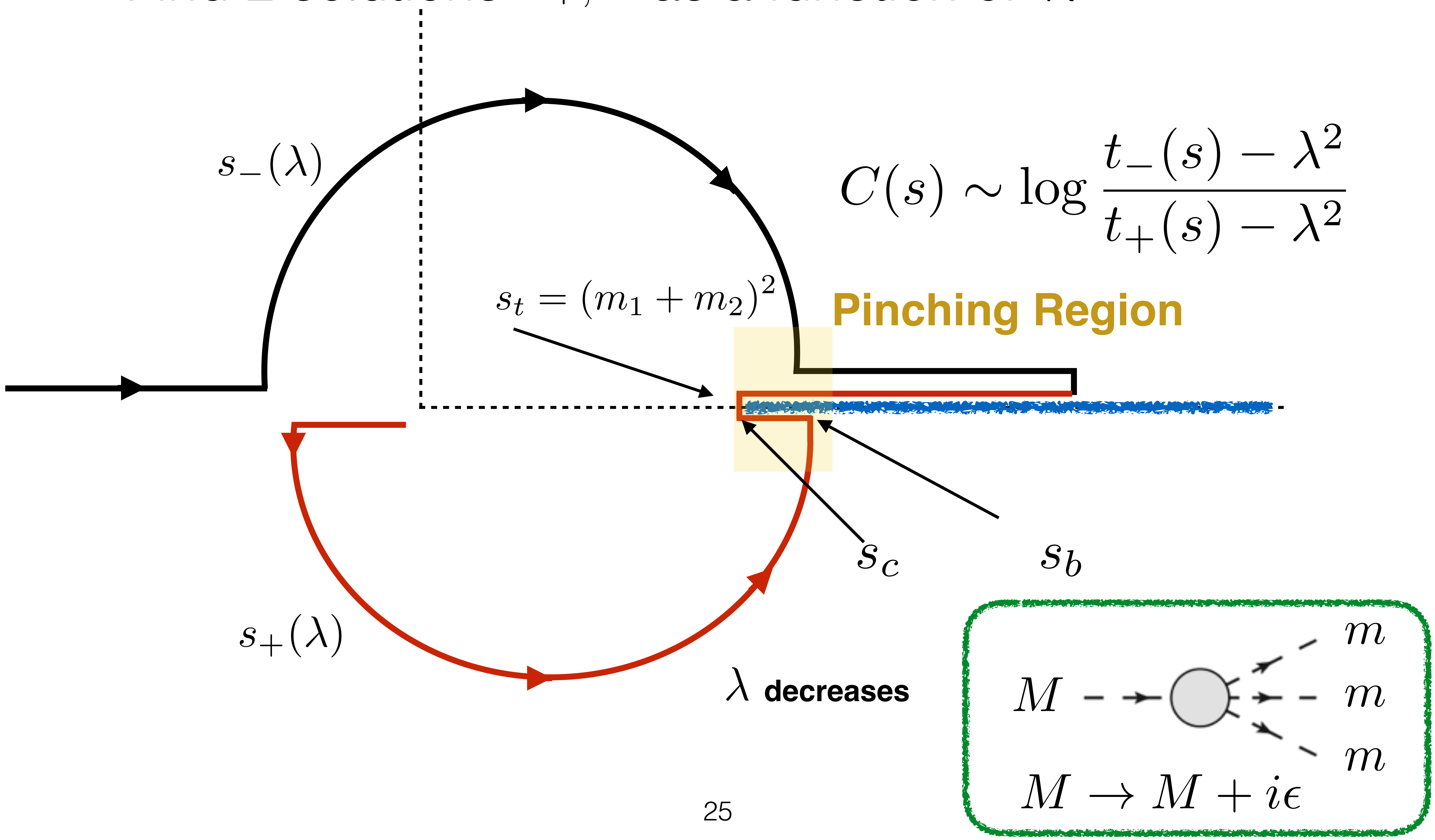
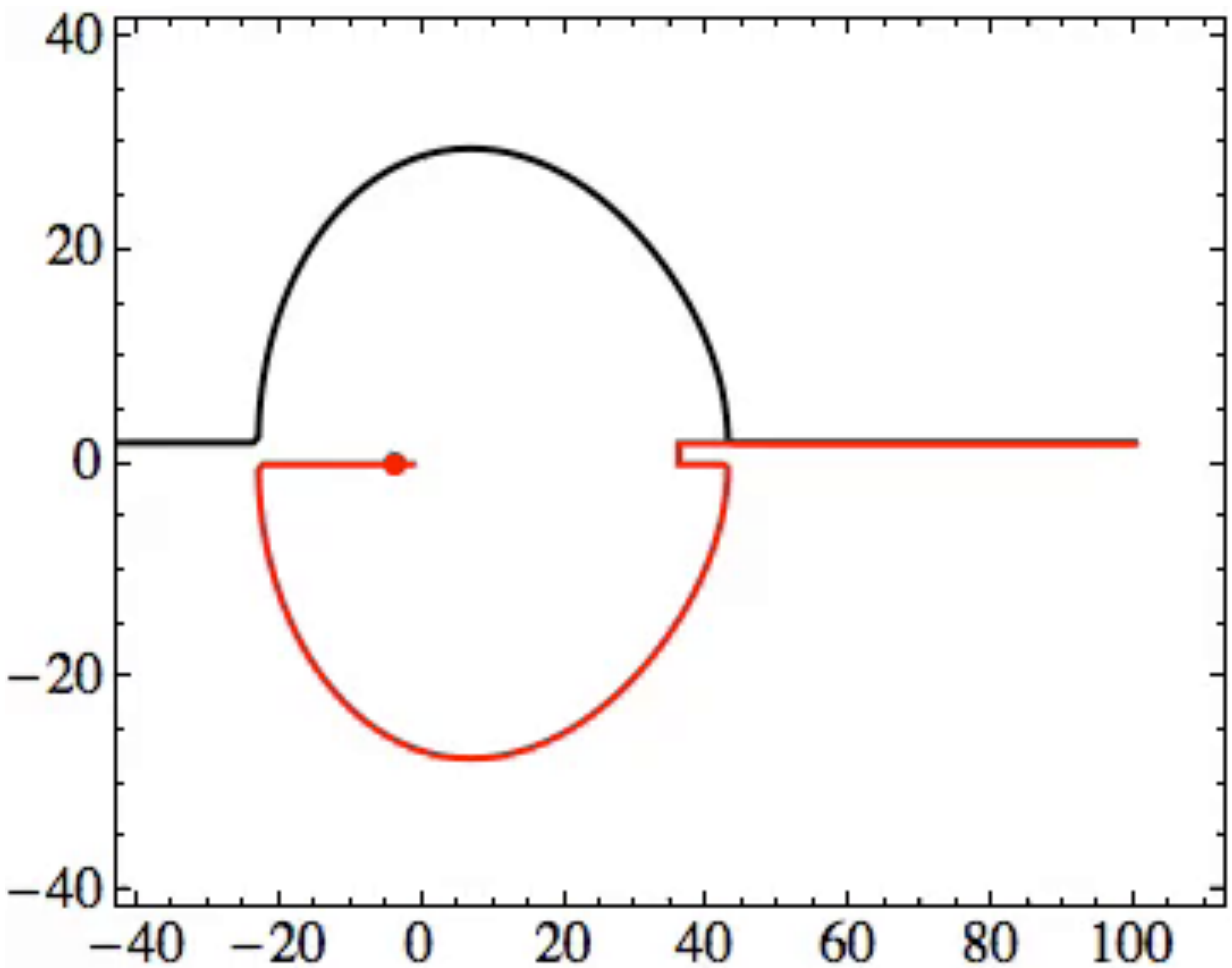
Triangle Branch Points

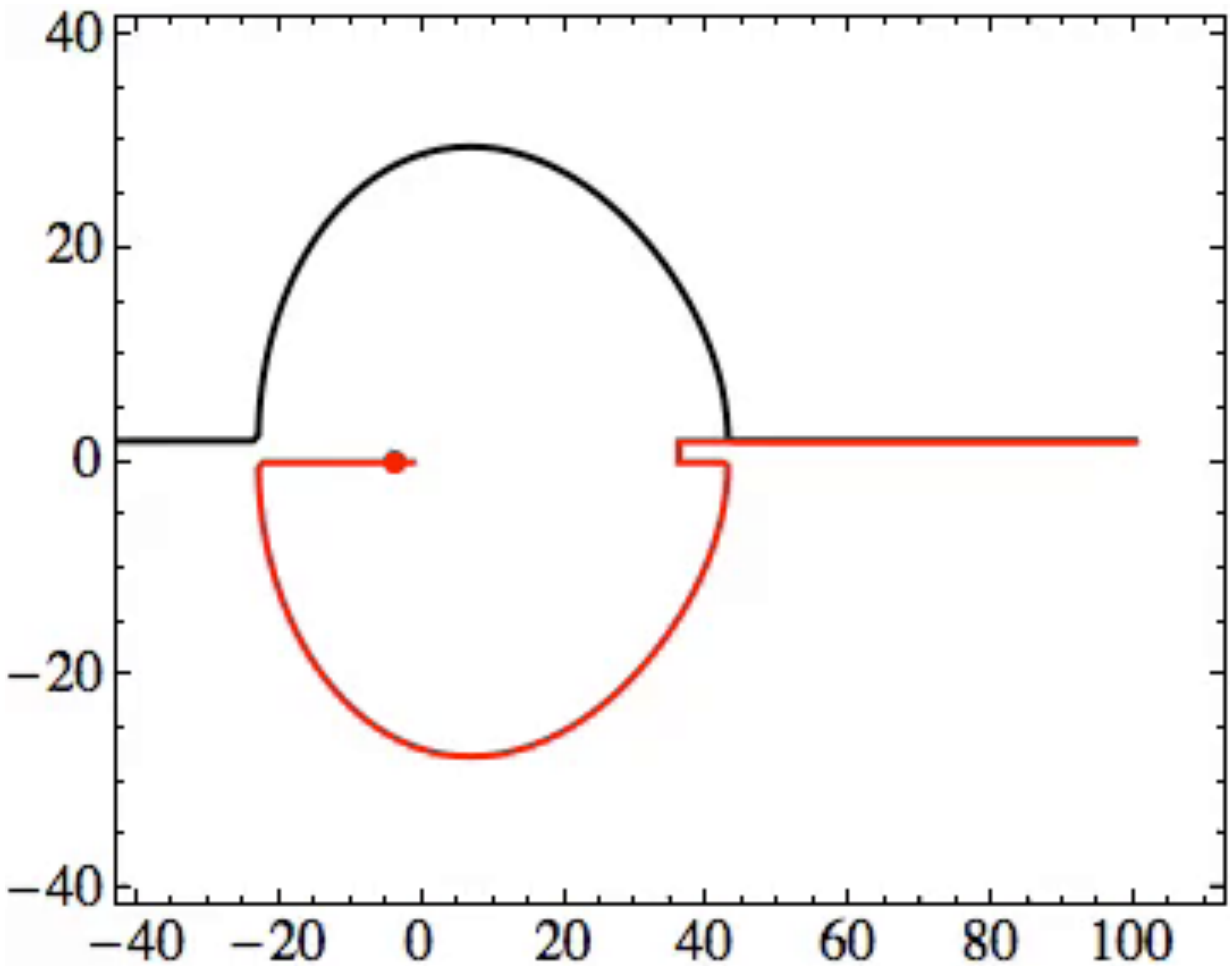
- Find 2 solutions $s_{+,-}$ as a function of λ



Movement of Branch Points



Movement of Branch Points



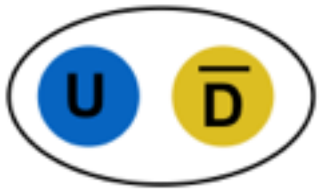
Hybrid Mesons

0^{--}	0^{-+}	0^{+-}	0^{++}
1^{--}	1^{-+}	1^{+-}	1^{++}
2^{--}	2^{-+}	2^{+-}	2^{++}
3^{--}	3^{-+}	3^{+-}	3^{++}
4^{--}	4^{-+}	4^{+-}	4^{++}

...

J^{PC} $q\bar{q}$ **allowed**

Ordinary



J^{PC} $q\bar{q}$ **not allowed**

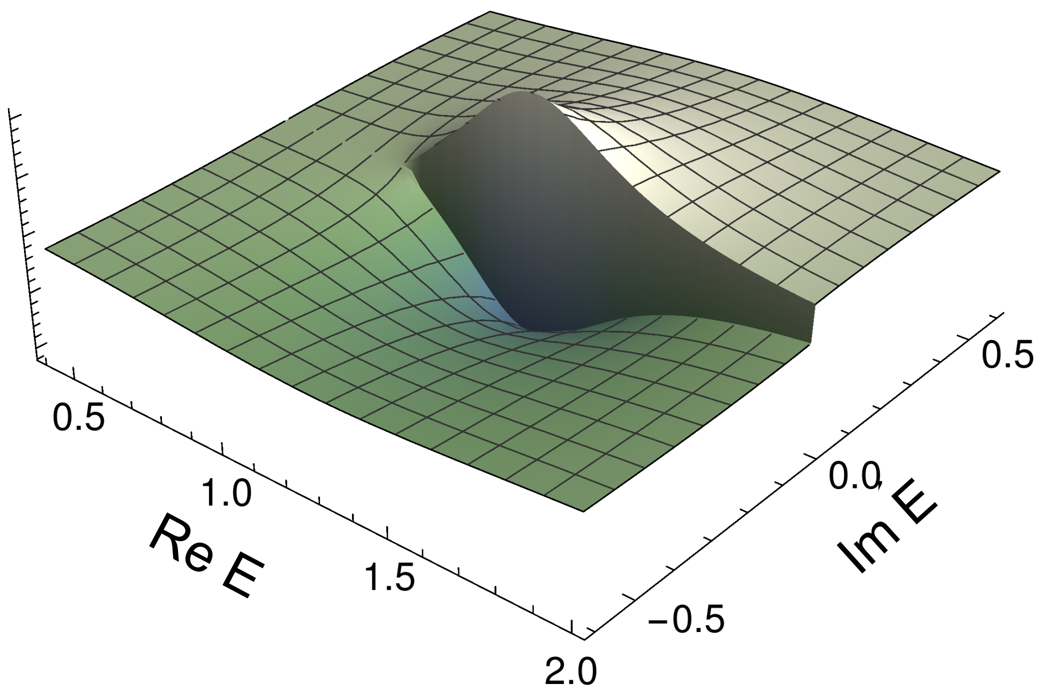
Hybrid

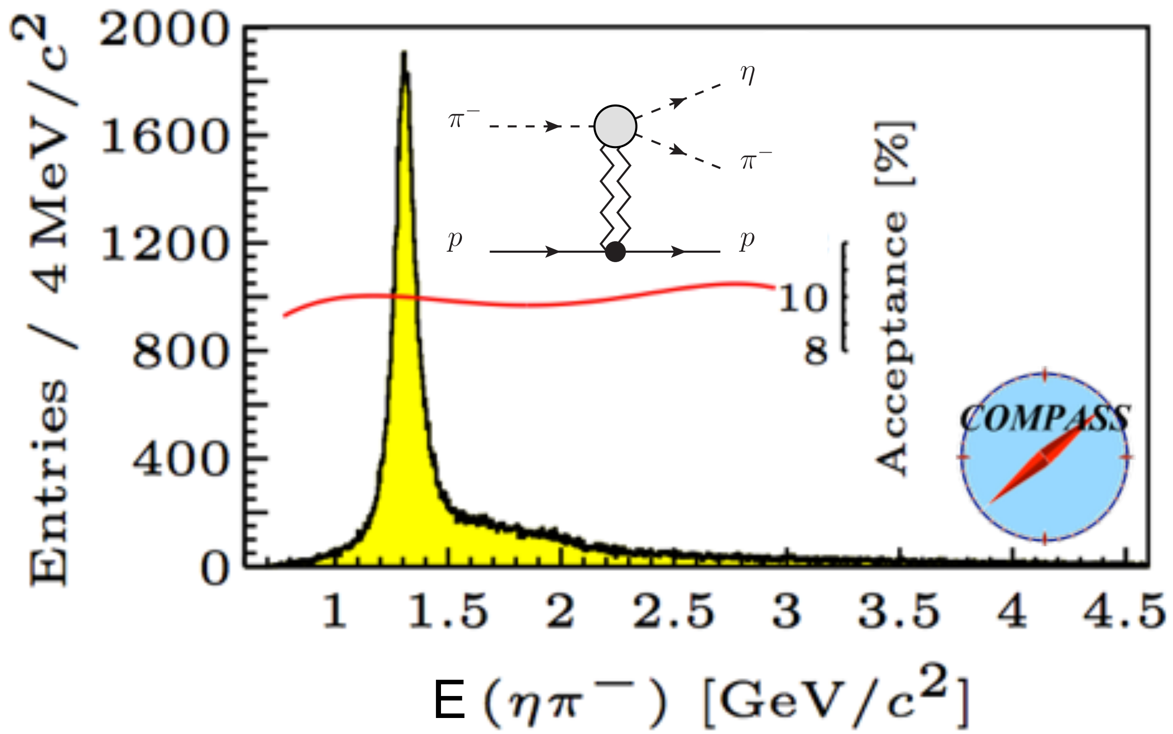
Quantum numbers filter ordinary mesons

Glueballs have ‘ordinary mesons’ quantum numbers

Easier identification of hybrid mesons with exotic quantum numbers

Resonances as poles



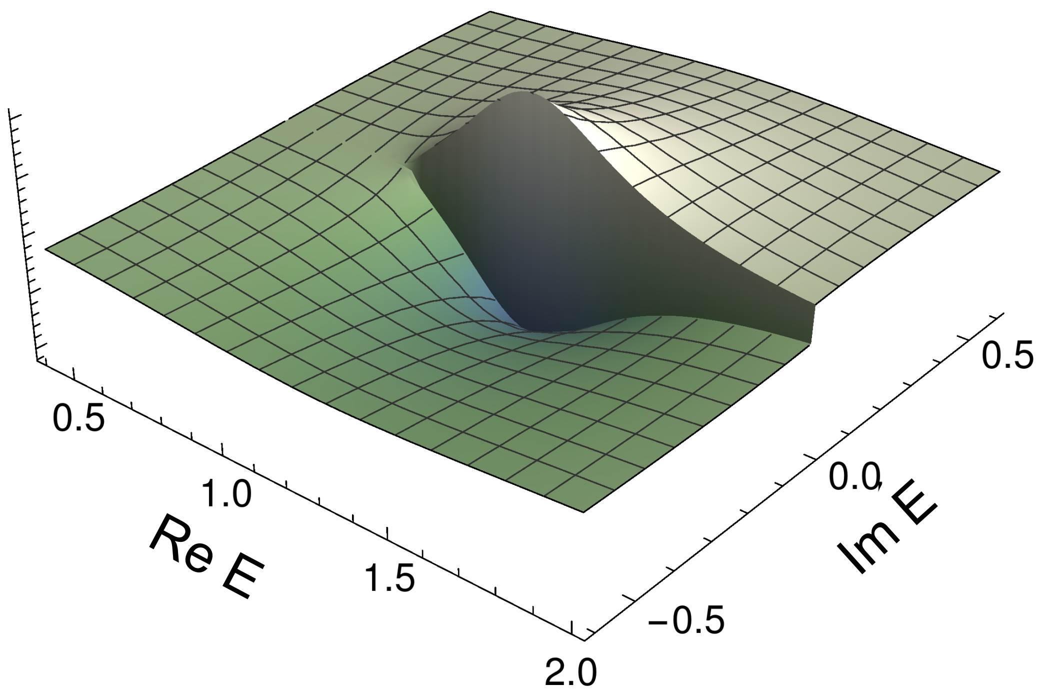


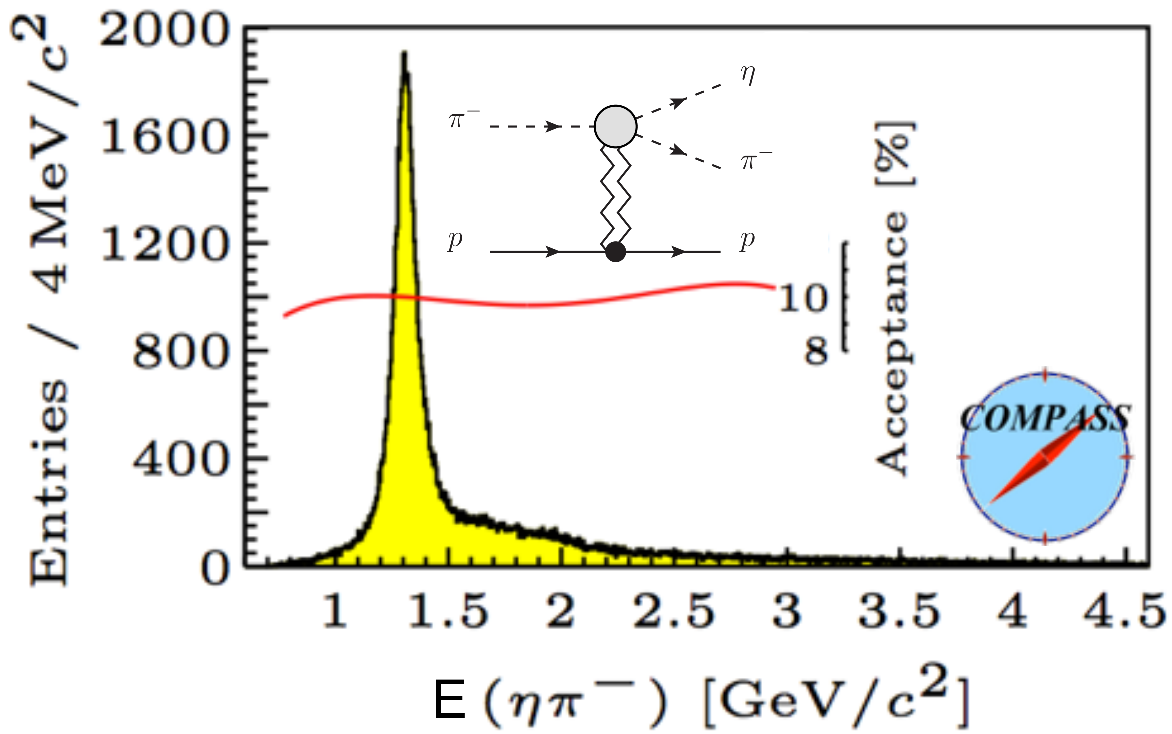
Poles in the complex energy plane:

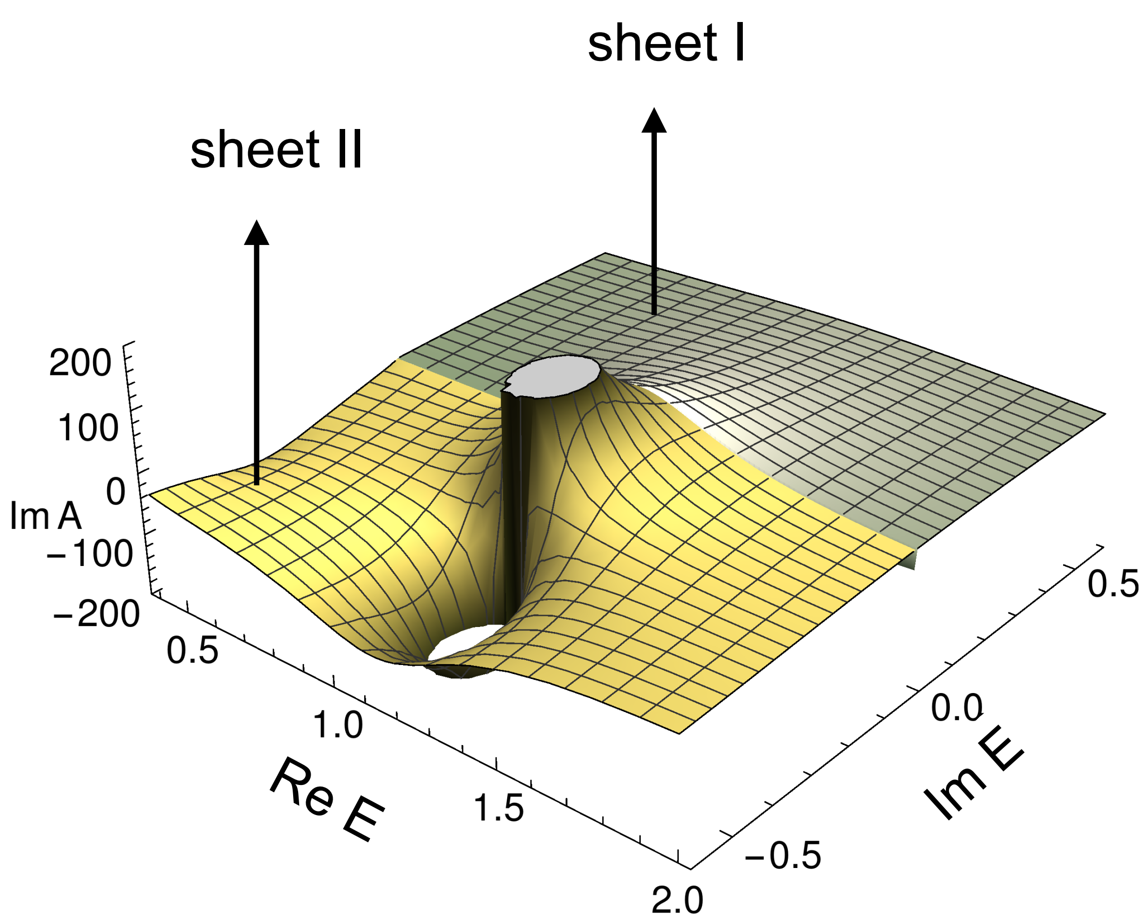
- **Real part ~ mass**
- **Imaginary part ~ width**
- **Residue ~ coupling**

Poles or resonances are the universal building blocks of reactions

Resonances as poles







Poles in the complex energy plane:

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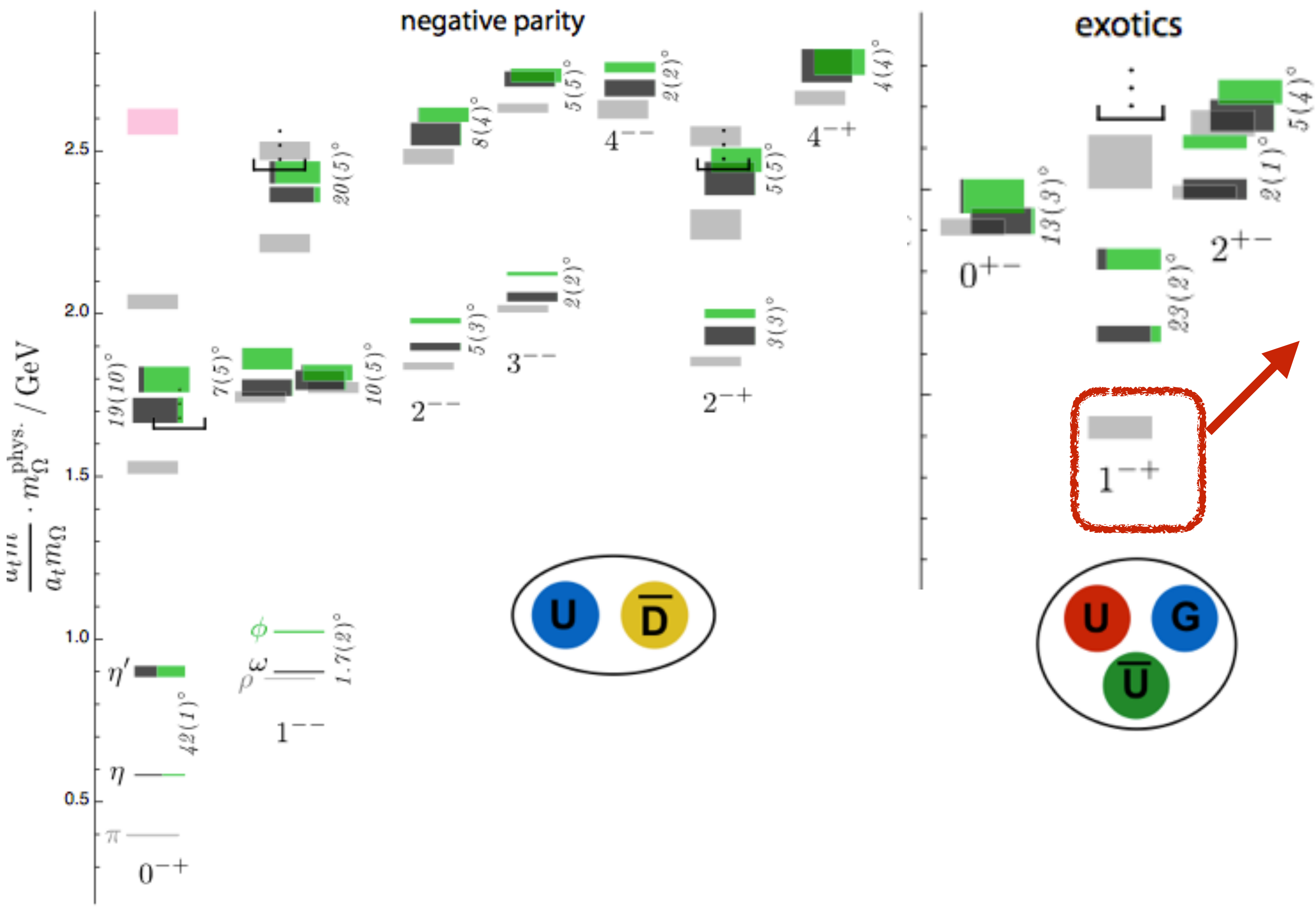
Hybrid Mesons

Evidence for hybrid mesons from numerical simulations



lightest hybrid couples to

$$\eta\pi$$

$$\eta'\pi$$

$$3\pi$$

Dudek, PRD 84 (2011)
Dudek et al, PRL 103 (2009)