Prospects in Hadron Spectroscopy

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-
Joint Physics Analysis Center

Mons University
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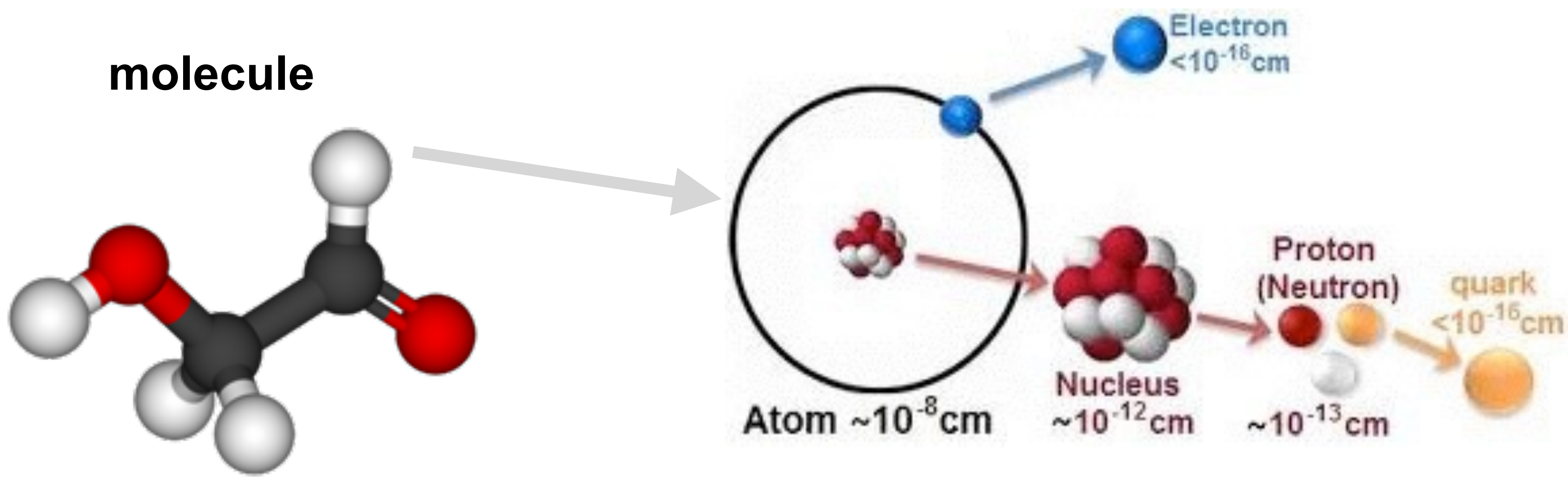
Introduction

- Understanding Nature's laws
  - Describe phenomena
    - need to identify relevant d.o.f

description of storms in terms of individual molecules or collective properties ?

Degrees of Freedom in Hadronic Physics



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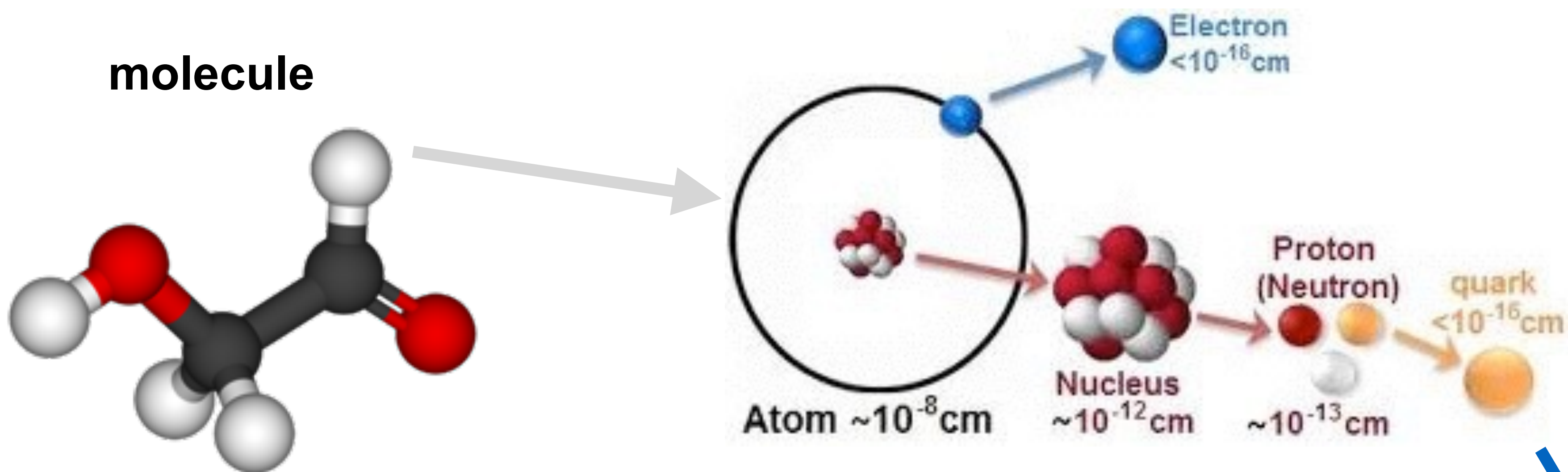


quark d.o.f.
(matter)

$$\mathcal{L}_{QCD} = -\frac{1}{4}\left(\partial \cdot \vec{A} + g\vec{A} \times \vec{A}\right)^2 + \sum_f \bar{q}_f \left(\gamma \cdot \partial - ig\gamma \cdot \vec{A} - m_f\right) q_f$$

gluon d.o.f.
(force)

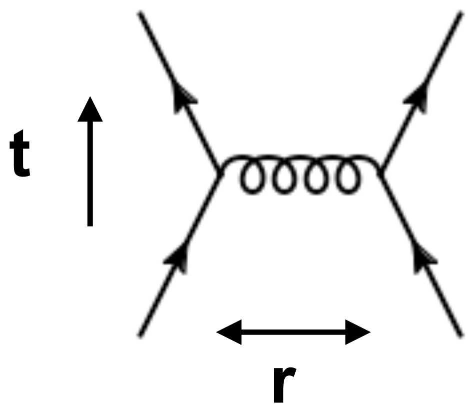
interaction

mass quark

Strong Interaction

$$\mathcal{L}_{QCD} = -\frac{1}{4}\left(\partial \cdot \vec{A} + g\vec{A} \times \vec{A}\right)^2 + \sum_f \bar{q}_f \left(\gamma \cdot \partial - ig\gamma \cdot \vec{A} - m_f\right) q_f$$

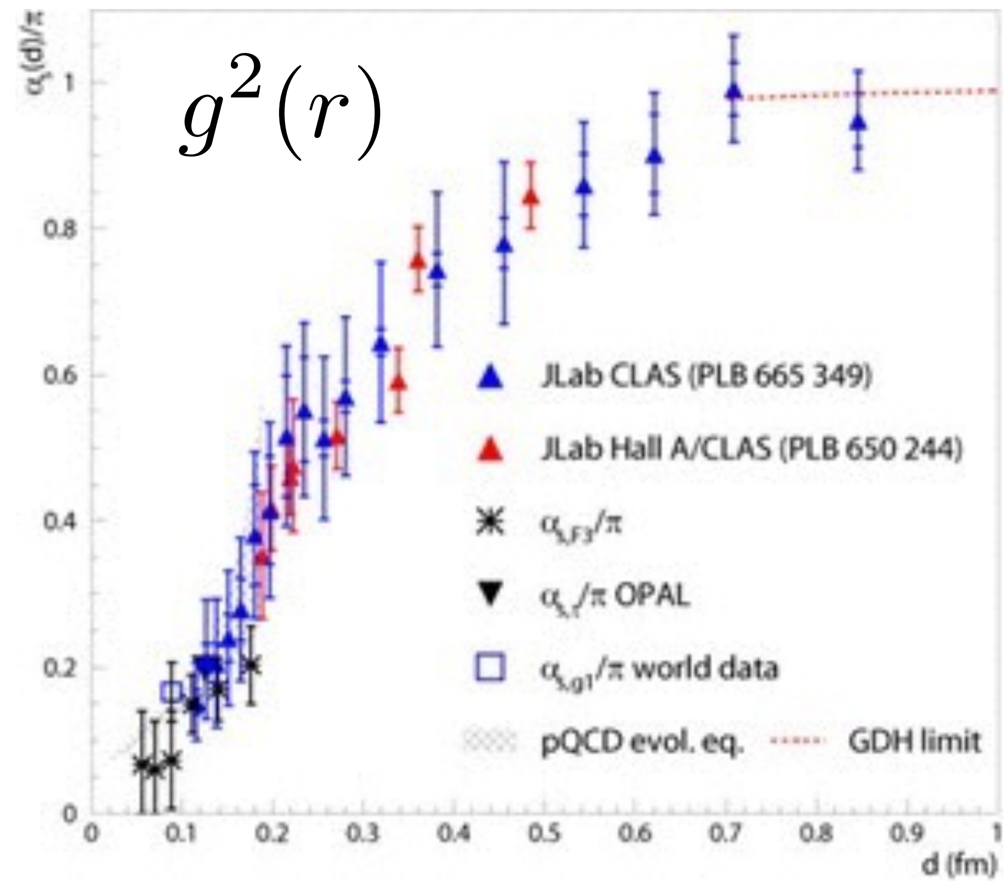
quark interaction via gluon exchange



gluon = spring

⟶ confinement

How can we understand that ?



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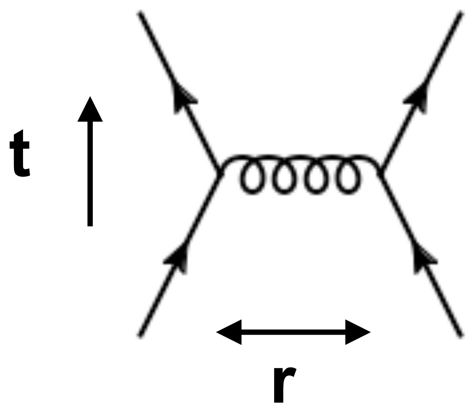

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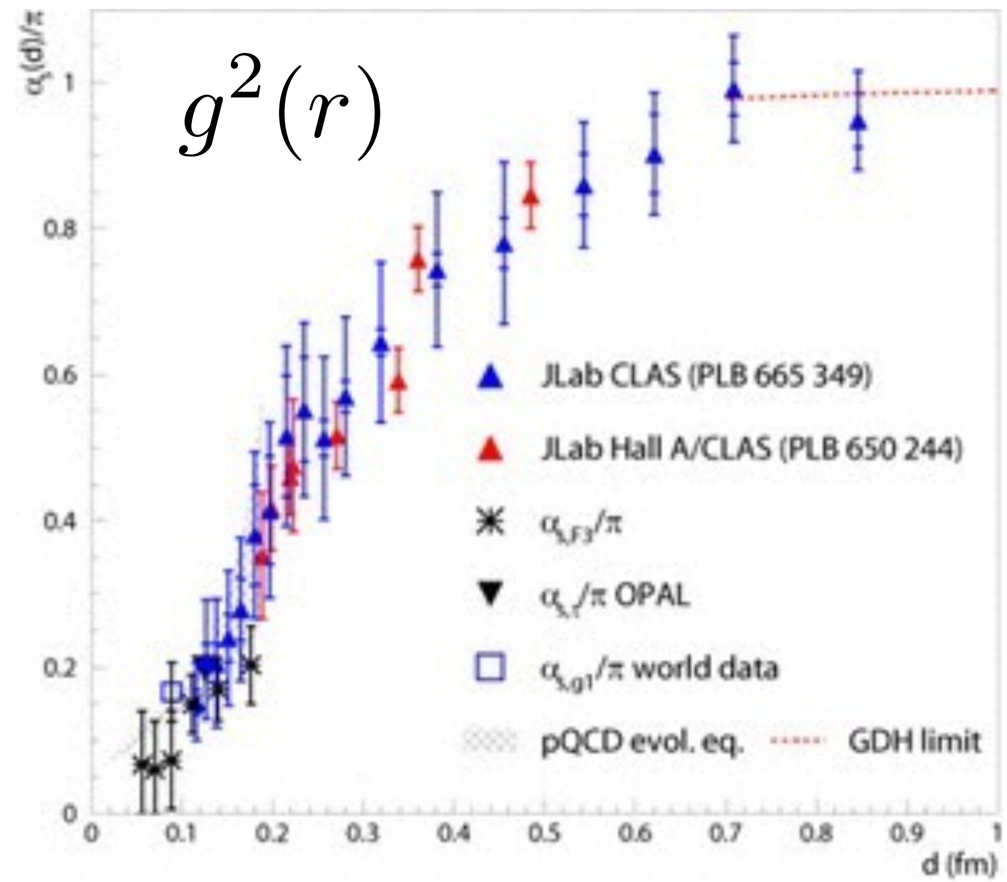
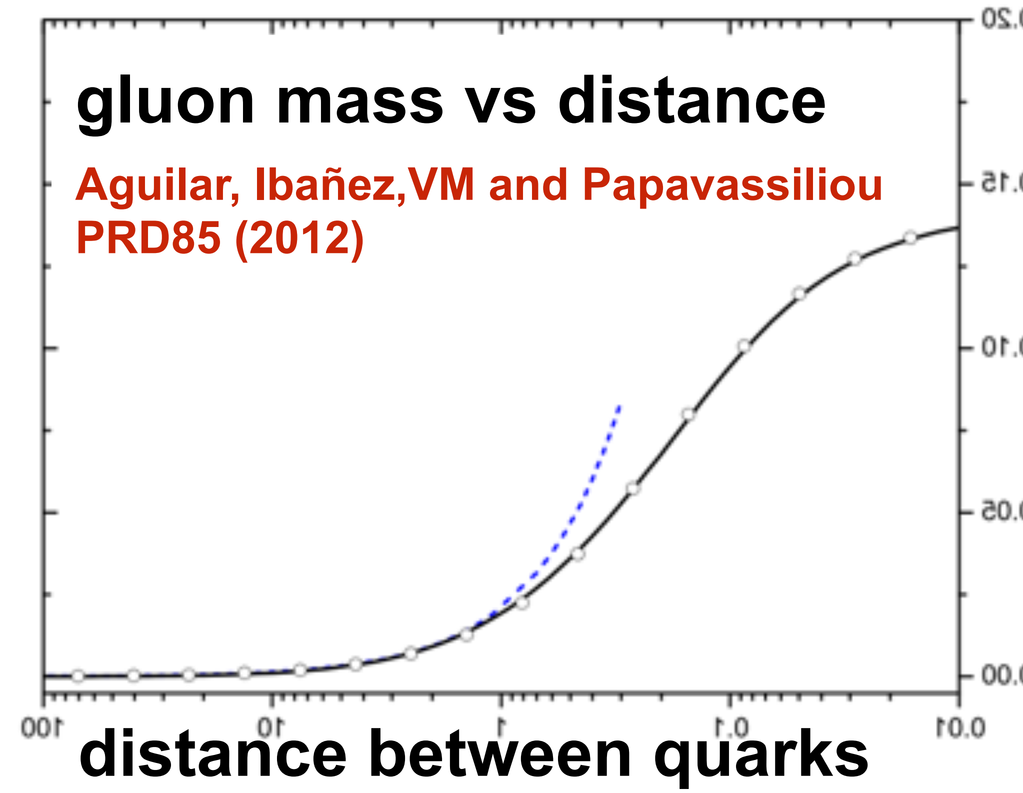


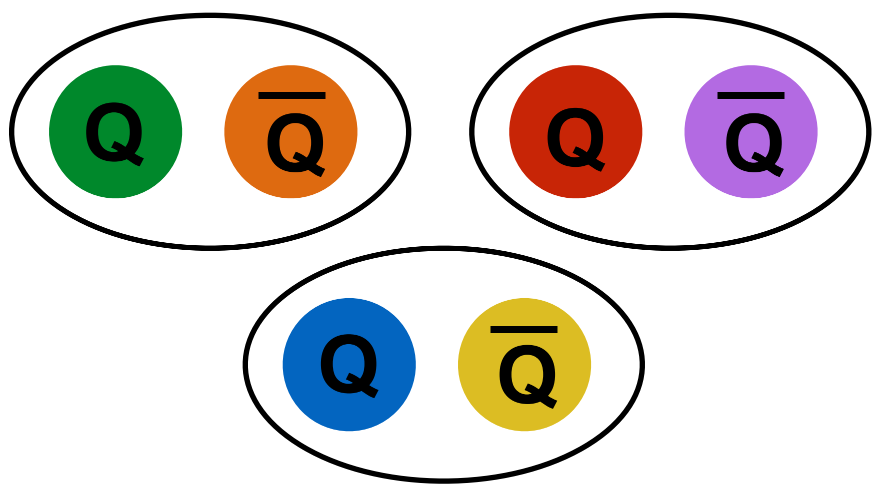
Interaction strength depends of the exchanged particle mass

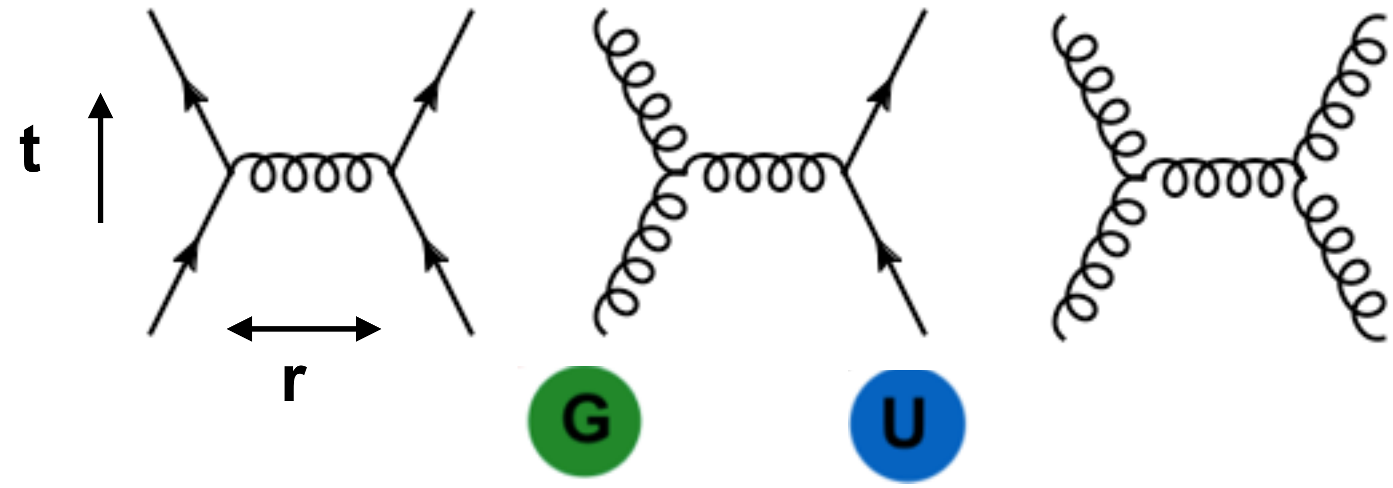
⟶ dynamical gluon mass generation



Exotic Matter

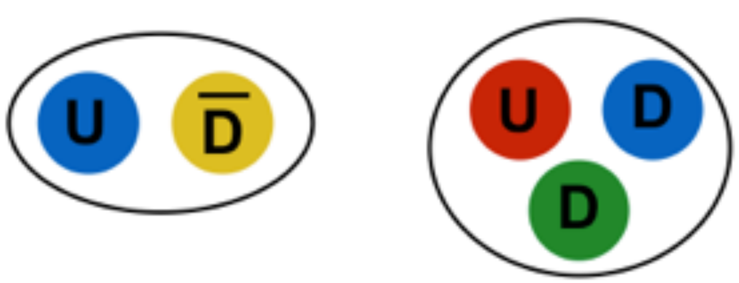
quarks can appear in 3 colors
gluons can appear in 8 colors
Observable states are white





“color” charge: resonances are “white”

Ordinary matter



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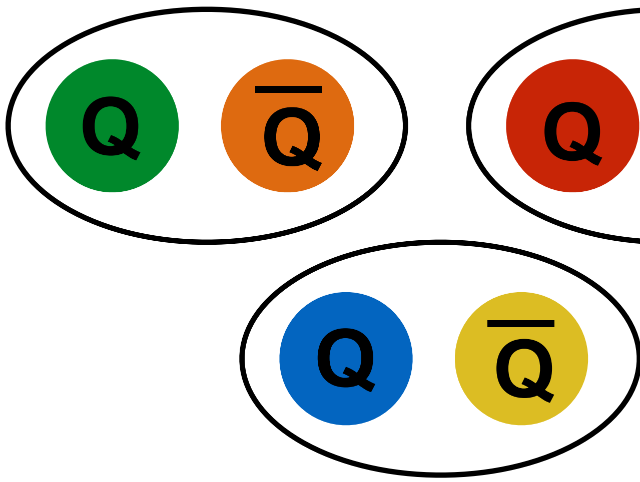
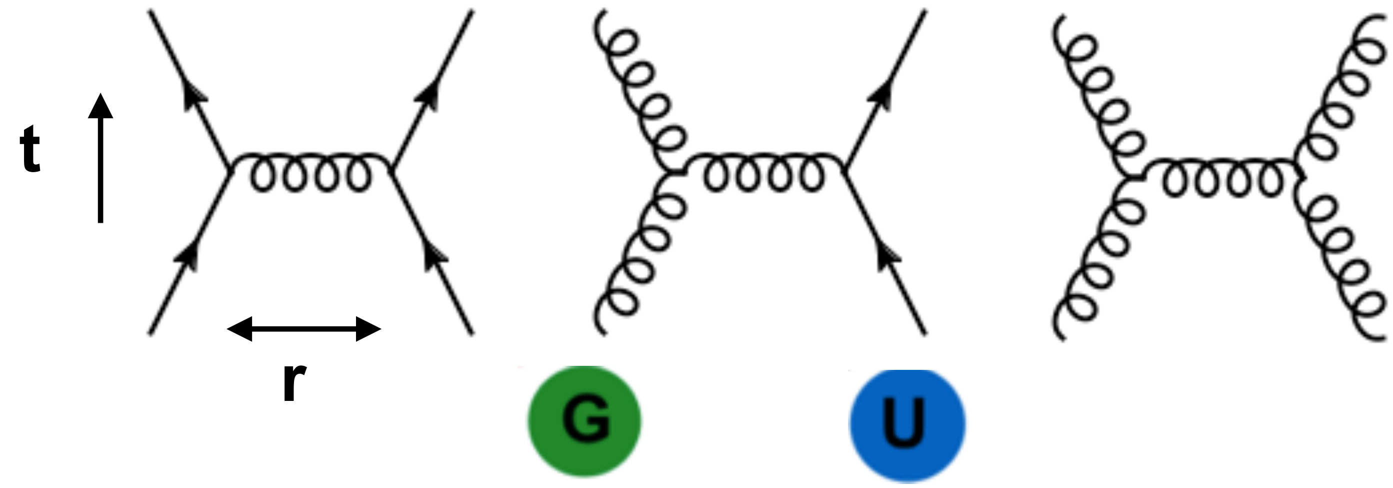
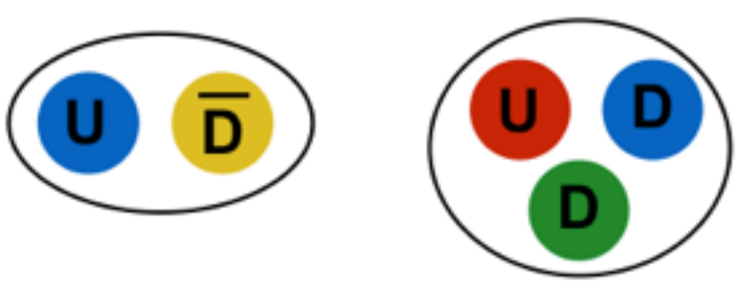




"color" charge: resonances are "white"

Theory predicts 'exotic' resonances

Ordinary matter

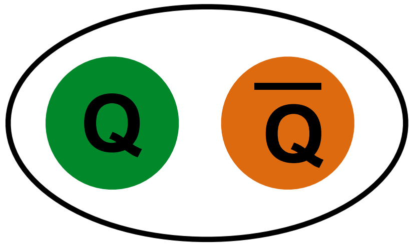


Exotic matter

Exotic Mesons

2 fermions: $J = L + S \qquad P = (-1)^{L+1} \qquad C = (-1)^{L+S}$

Normal

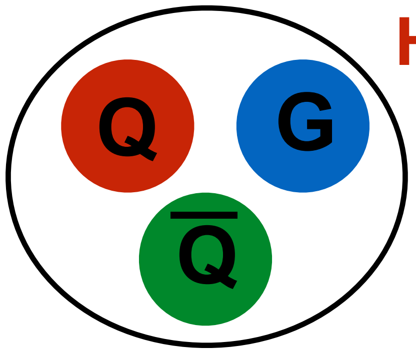


0^{--} 0^{-+} 0^{+-} 0^{++} $\qquad J^{PC} \quad q\bar{q}$ **allowed**

1^{--} 1^{-+} 1^{+-} 1^{++}

2^{--} 2^{-+} 2^{+-} 2^{++}

Hybrid



3^{--} 3^{-+} 3^{+-} 3^{++} $\qquad J^{PC} \quad q\bar{q}$ **not allowed**

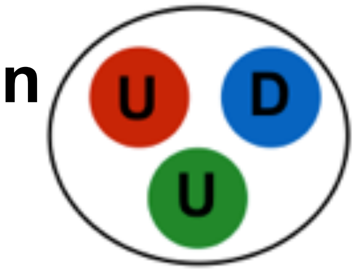
4^{--} 4^{-+} 4^{+-} 4^{++}

...

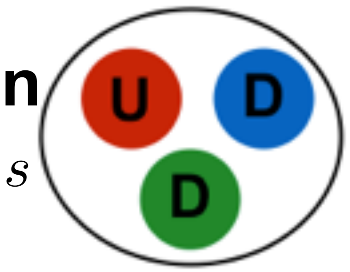
Stable Matter

stable matter is made of light quark
$(\tau >> 10^{-10} s)$

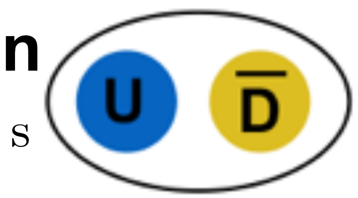
proton



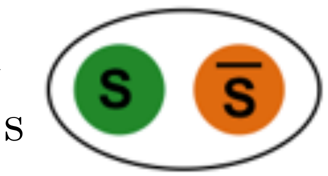
neutron
$\tau \sim 10^{3} s$



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



eta
$\tau \sim 10^{-19}$ s



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

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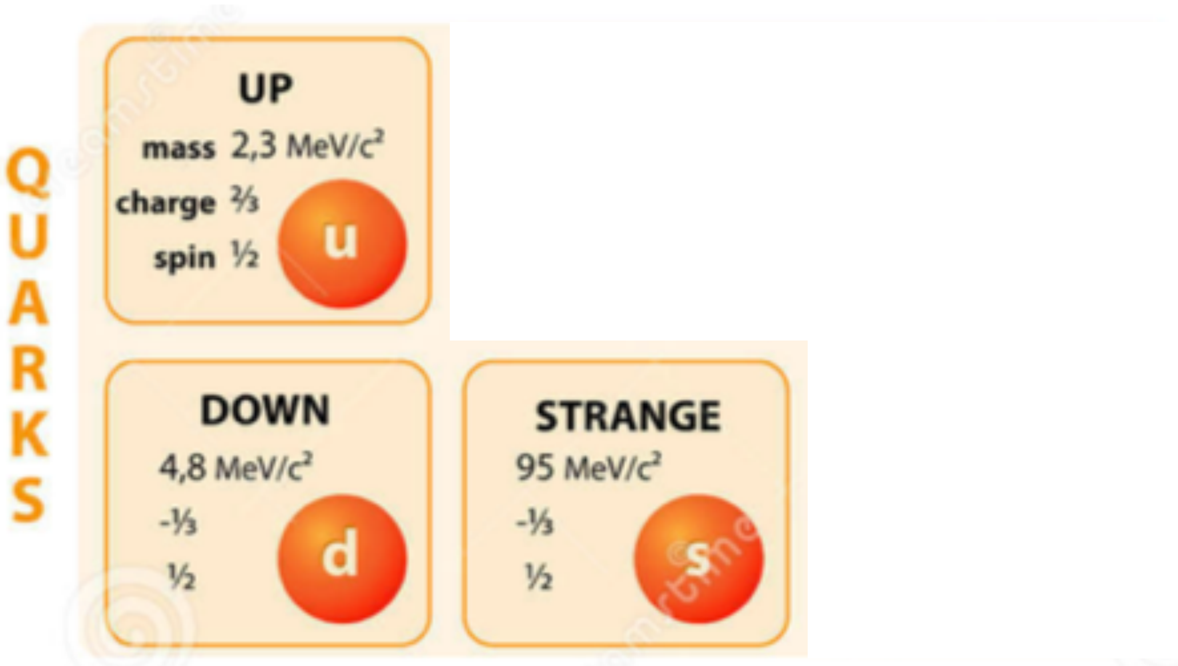

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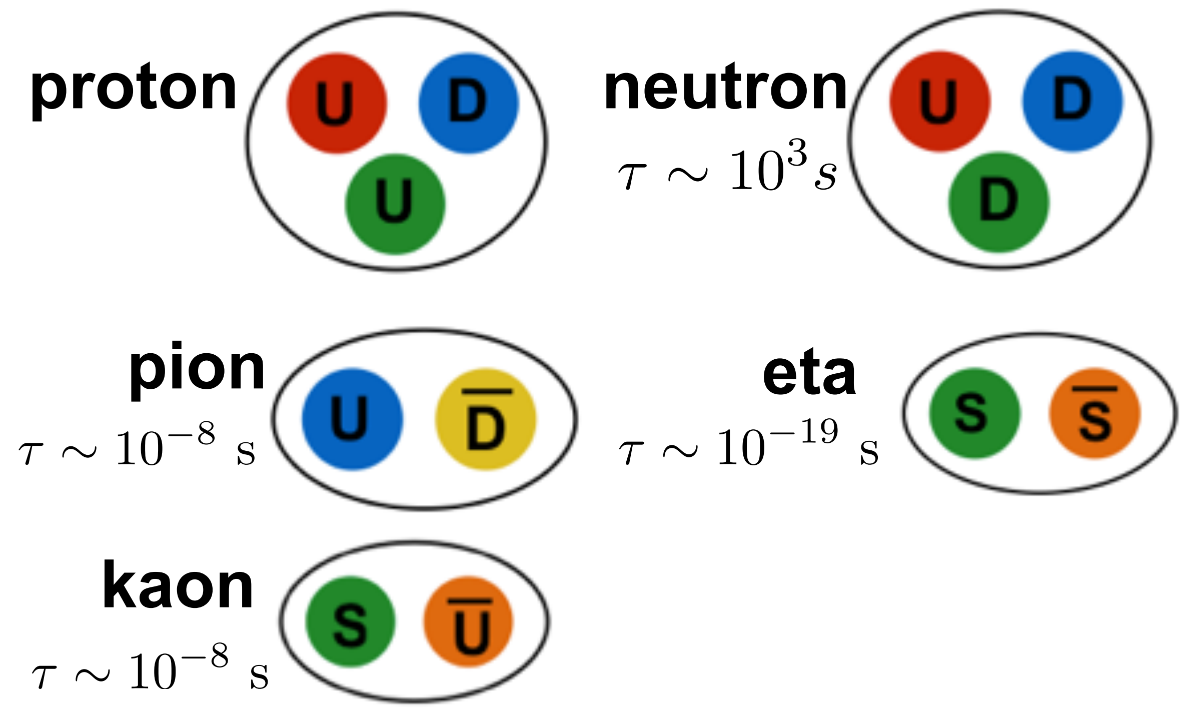

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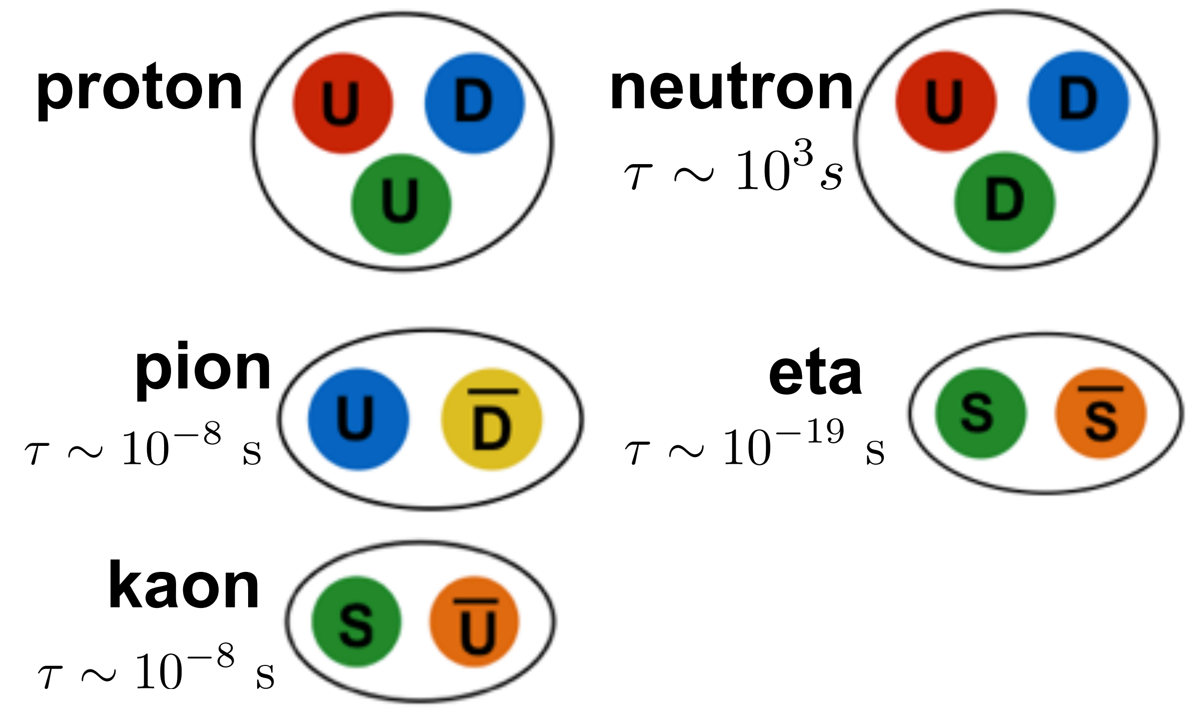
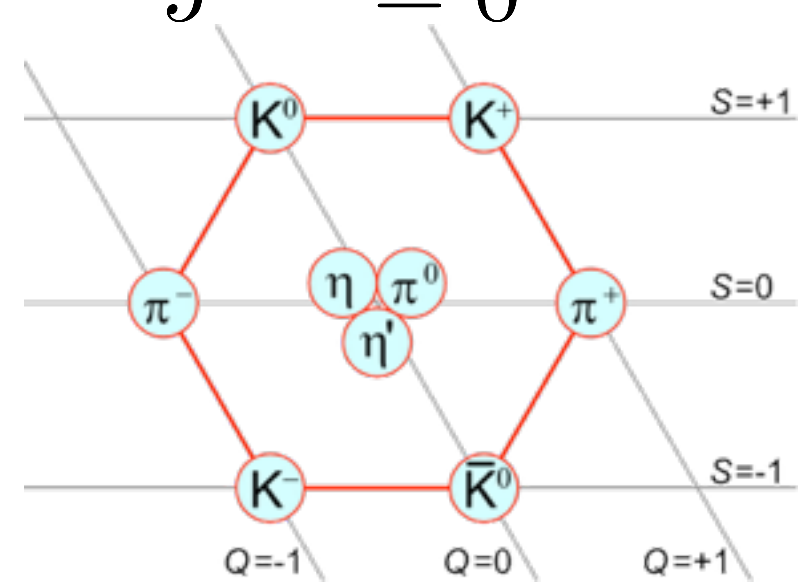


Octet and singlet of meson

$$3 \otimes \bar{3} = 1 \oplus 8$$

$$J^{PC} = 0^{-+}$$



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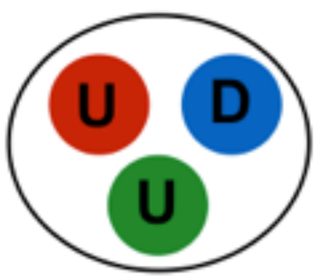
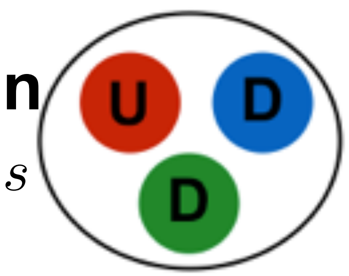


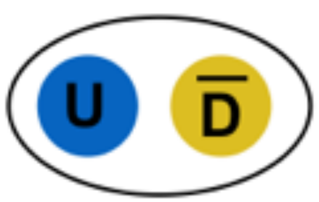
neutron

$\tau \sim 10^3 s$



pion

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

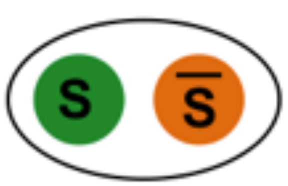


kaon

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

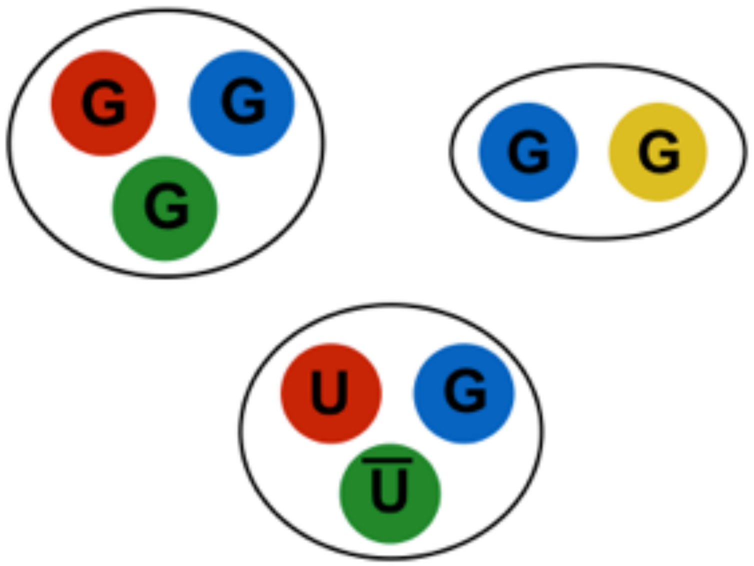
eta

$\tau \sim 10^{-19}$ s



Exotic Matter

Exotic matter with gluon



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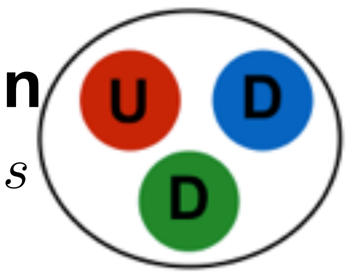

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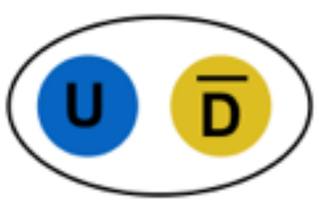

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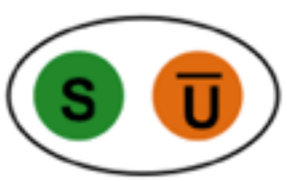

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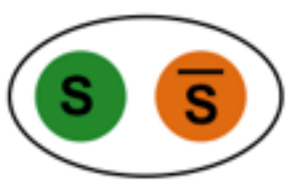
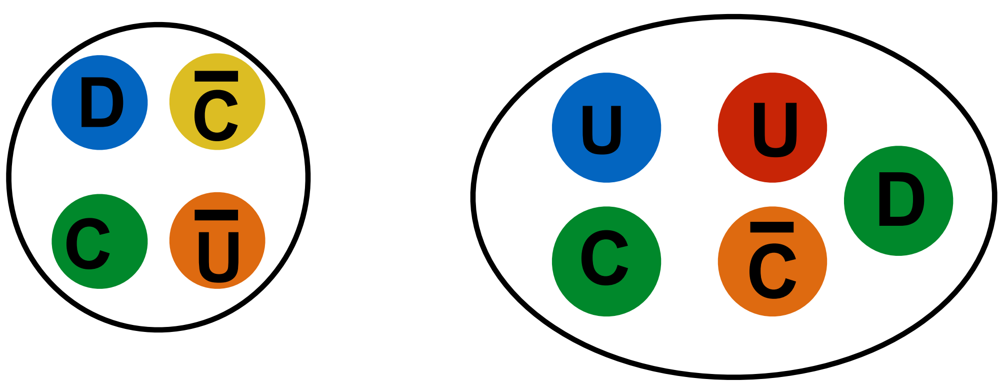


Exotic matter with heavy quarks

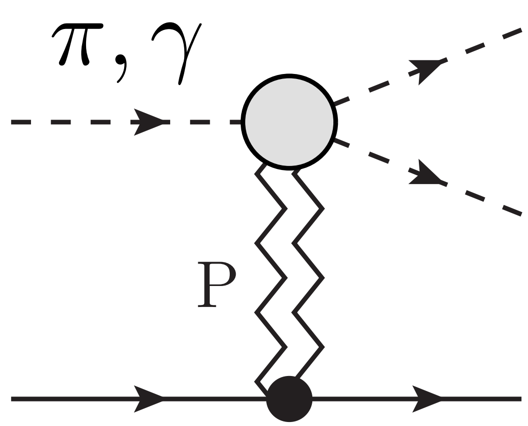


Hadron Spectroscopy Experiments

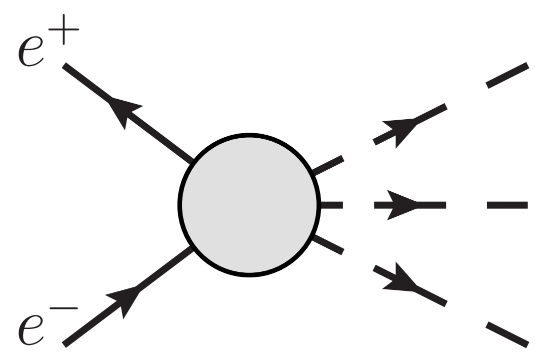
Light Quarks Sector

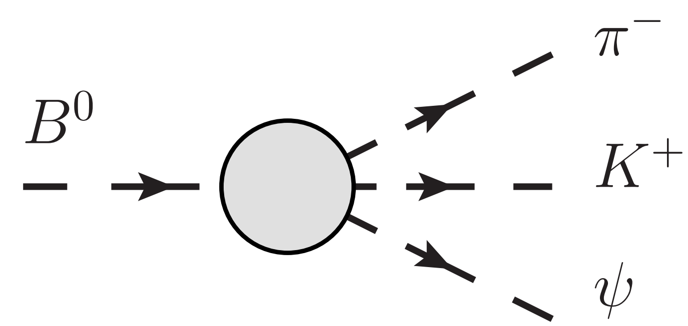
Heavy Quarks Sector

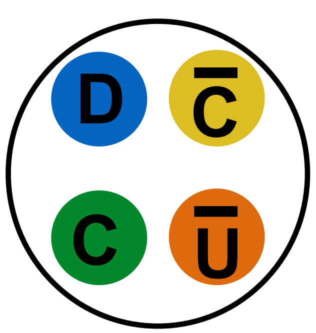
Beam Fragmentation

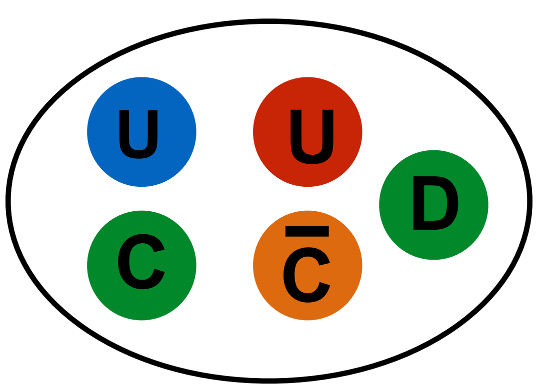


Three body decays

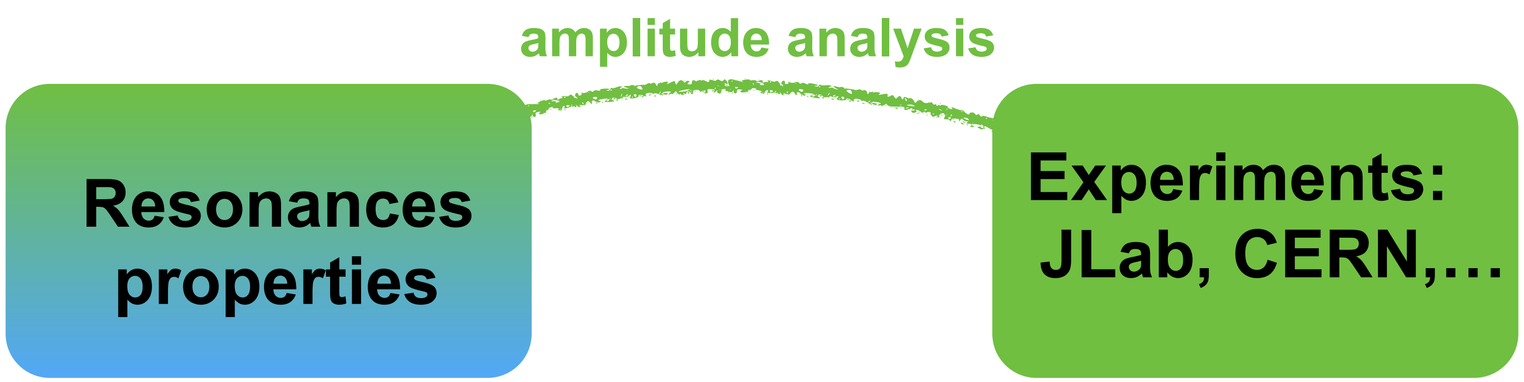








Extracting Resonance Properties



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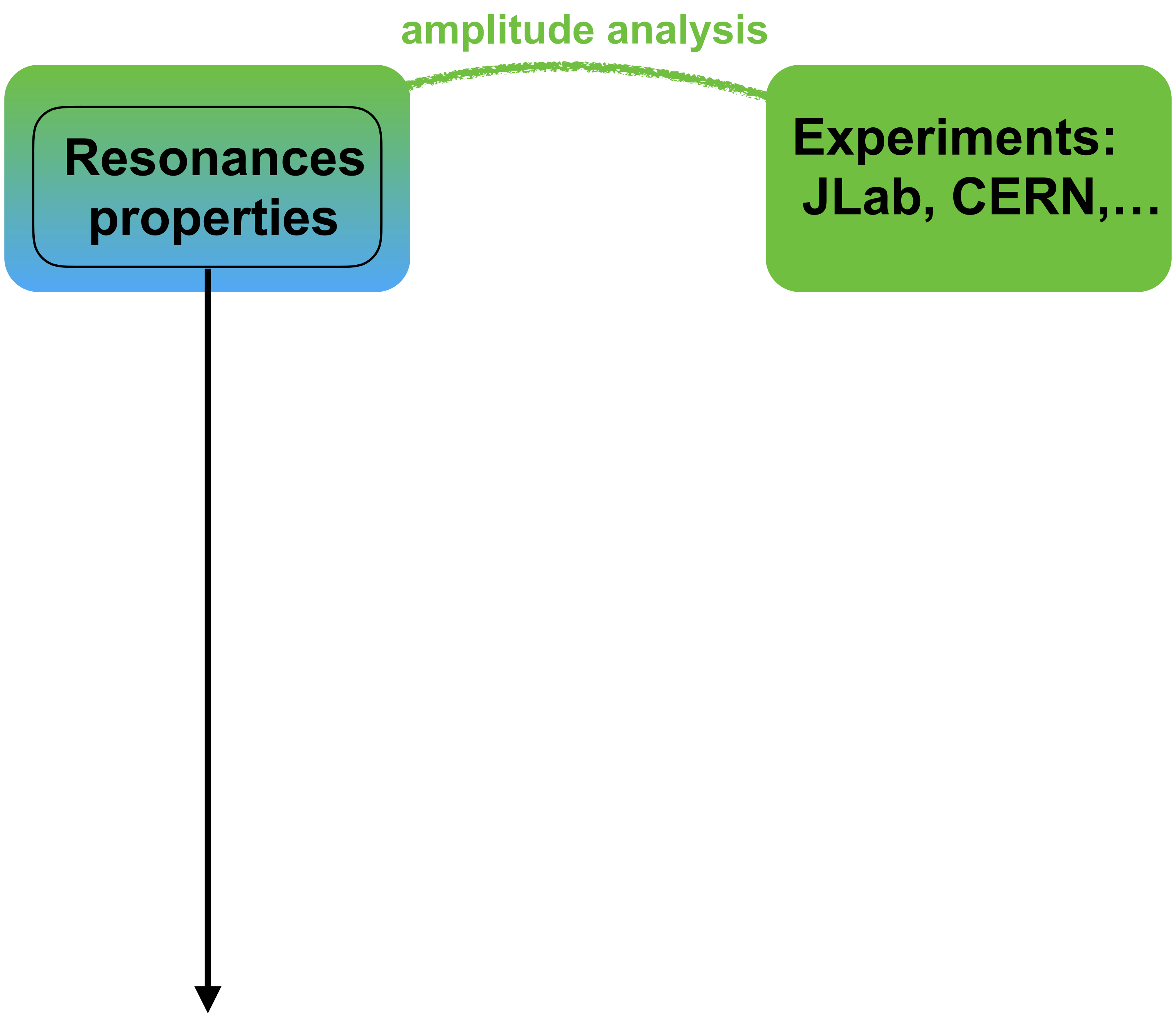
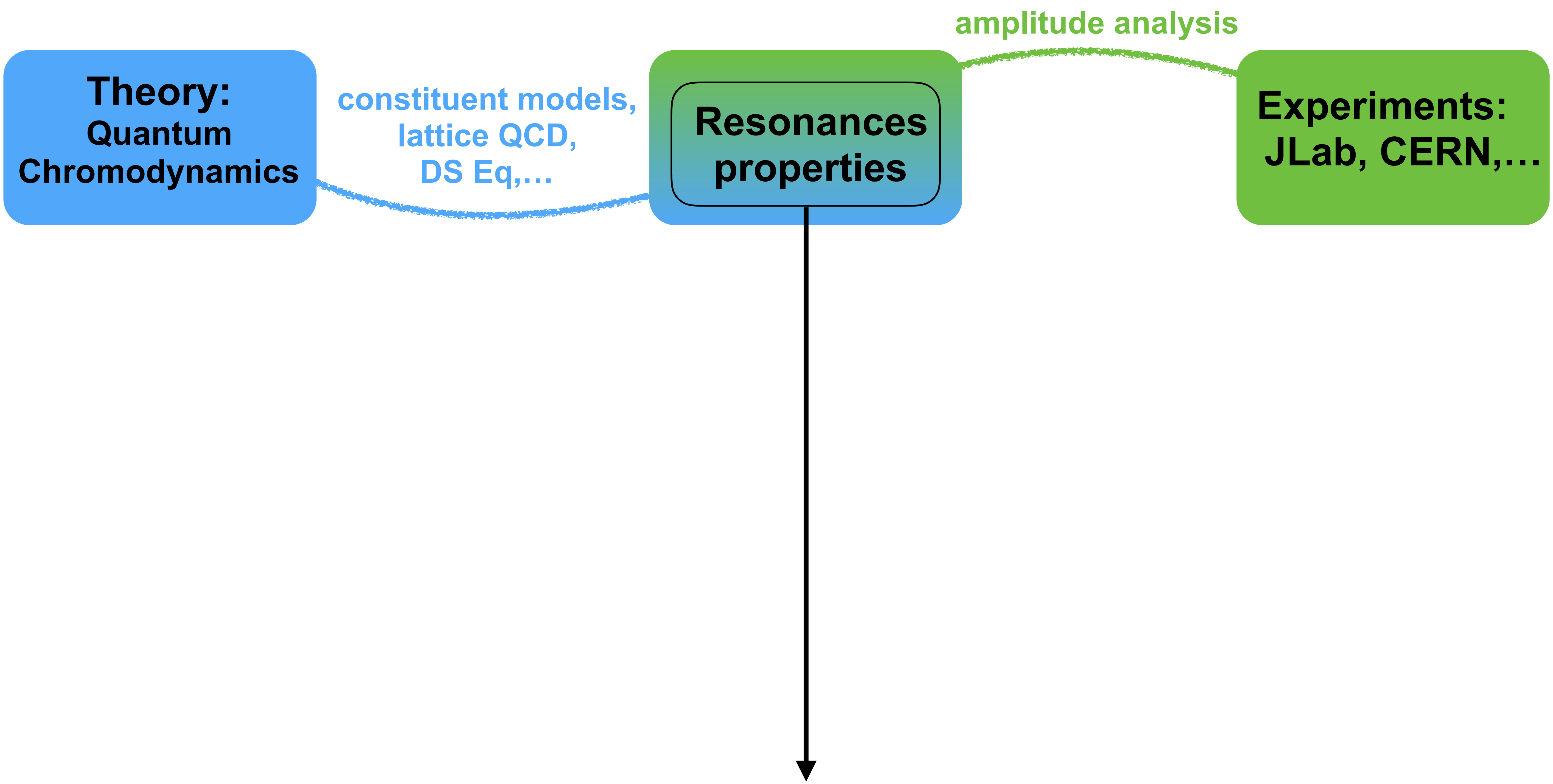


Review of Particle Physics

(masses, widths and couplings)

Extracting Resonance Properties



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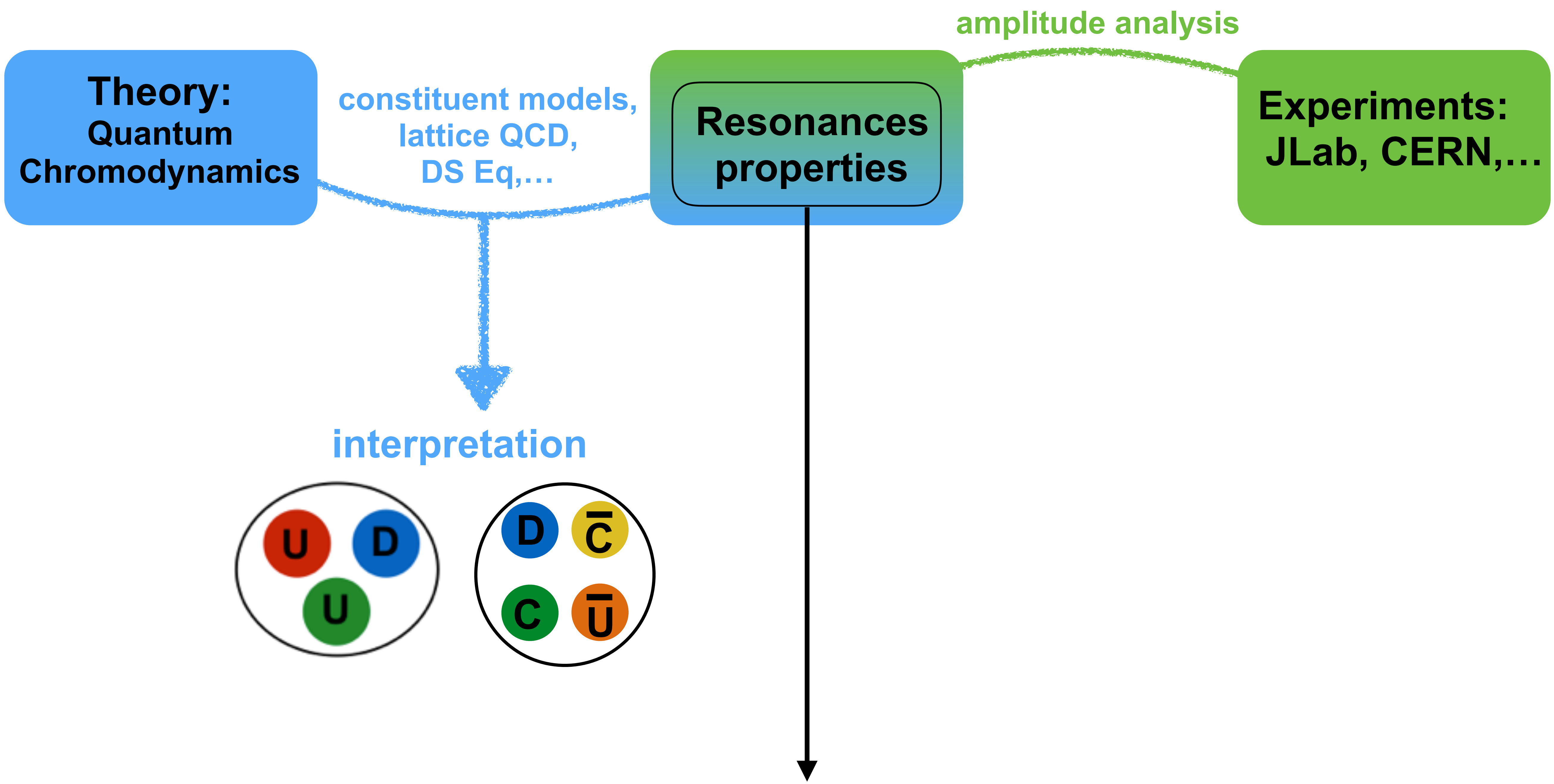


Review of Particle Physics

(masses, widths and couplings)

Extracting Resonance Properties

amplitude analysis

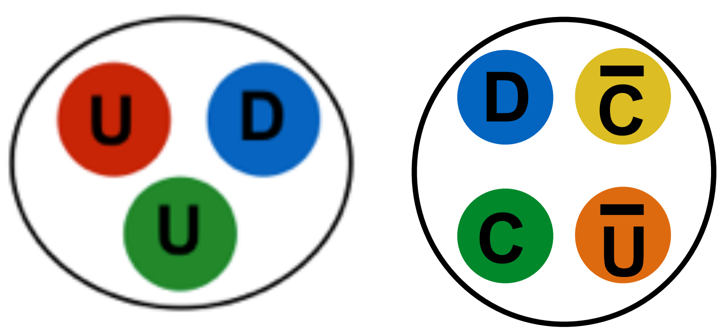
Theory:
Quantum Chromodynamics

constituent models,
lattice QCD,
DS Eq,…

Resonances properties

Experiments:
JLab, CERN,…

interpretation



Parametrizing data constrained by S-Matrix principles:

- **unitarity**
- **crossing symmetry**
- **analyticity**

Joint Physics Analysis Center

Review of Particle Physics

(masses, widths and couplings)

Extracting Resonance Properties

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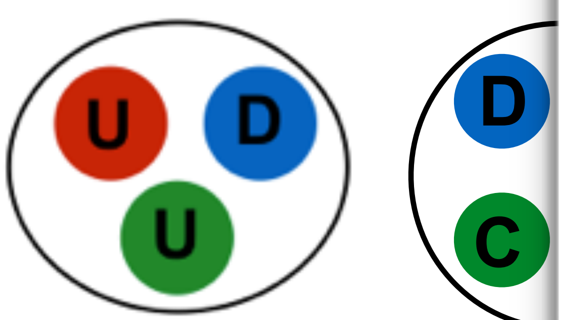

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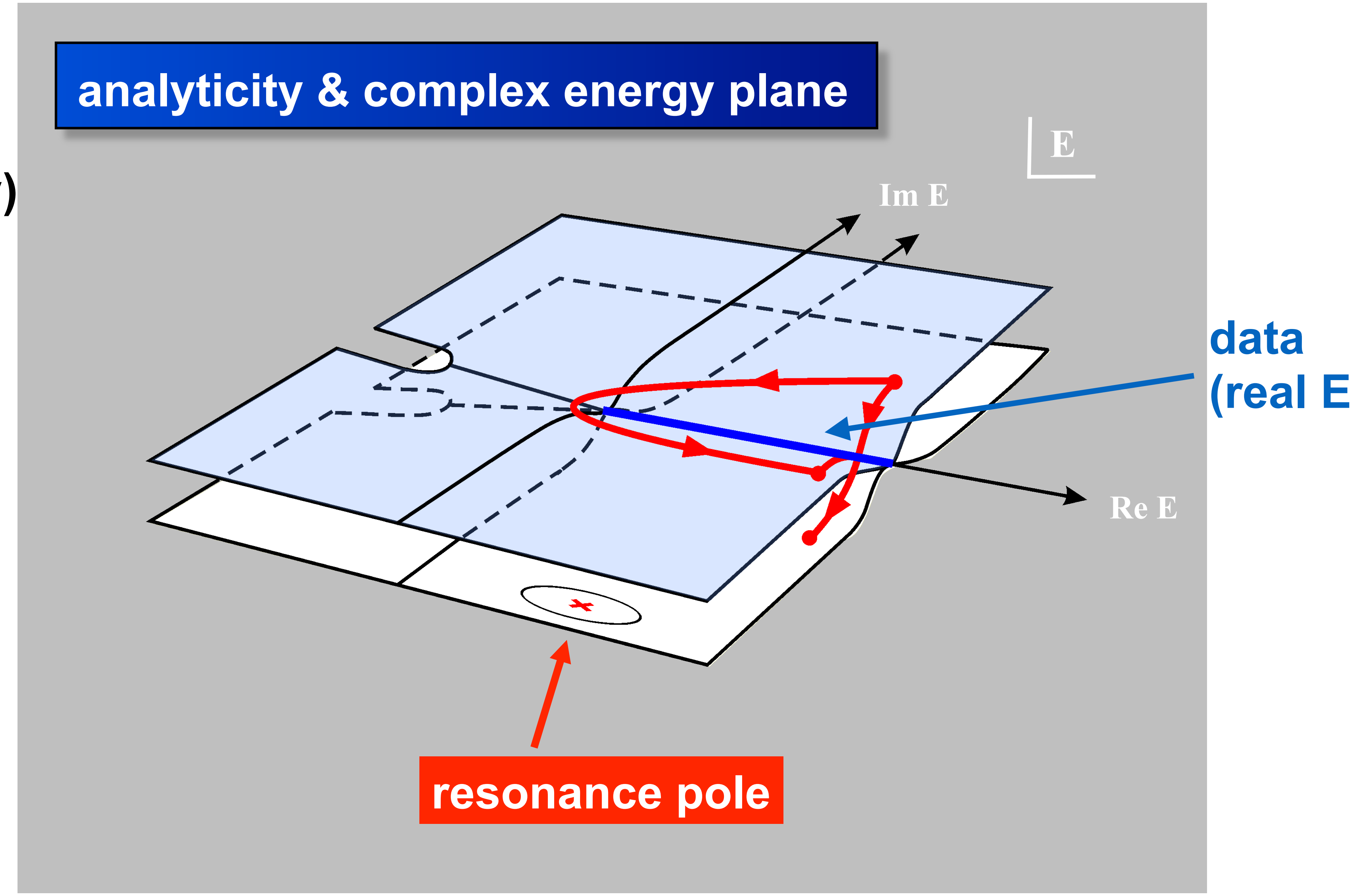
The Scattering-Matrix

- **Unitarity (cons. of probability)**
- **Analyticity (causality)**
- **crossing symmetry (CPT invariance)**



VM et al arXiv:1412.6393

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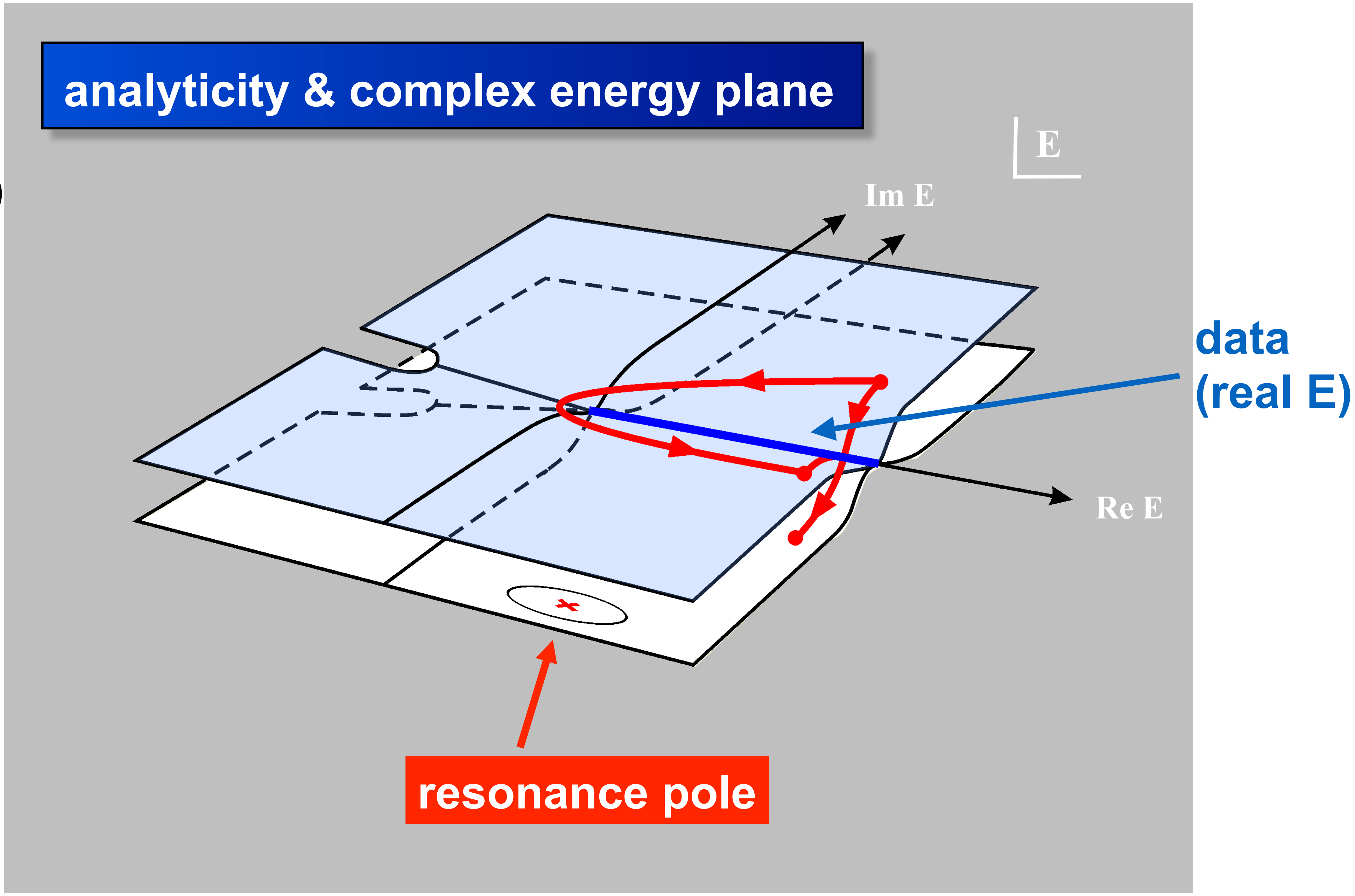


Procedure:

Amplitudes are

1. **fitted on data**
2. **checked constrains (proba. cons, causality, CPT inv.)**
3. **continued on sheet II**

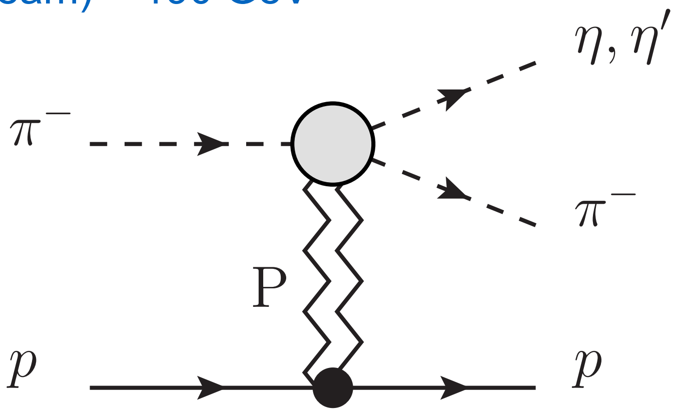
iterative procedure

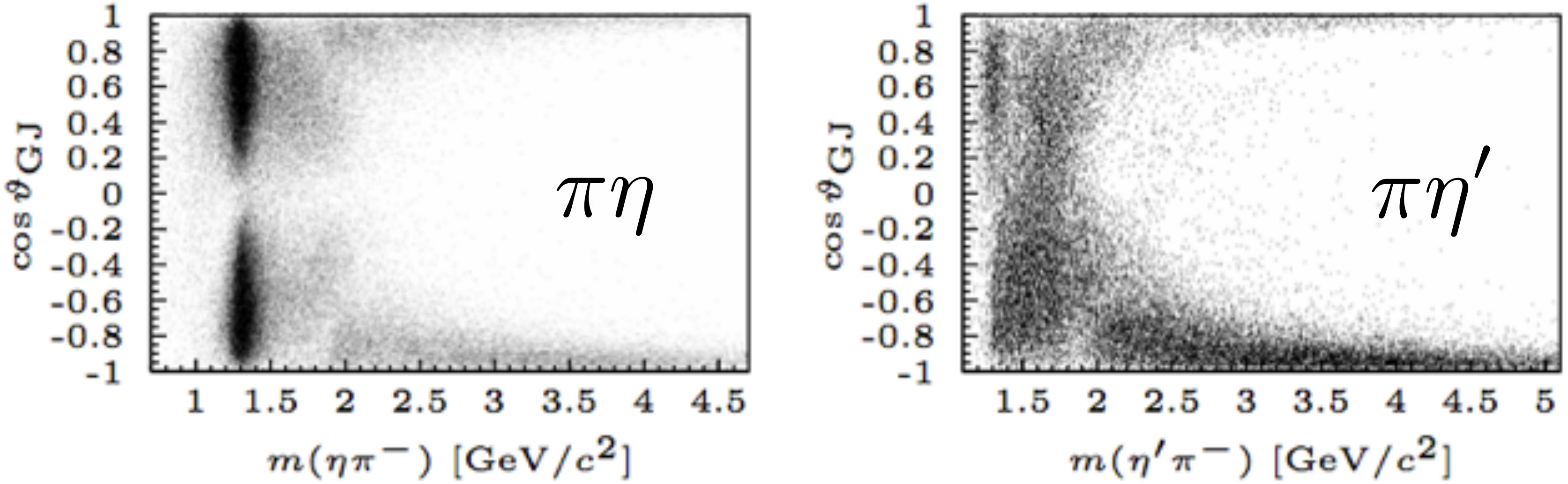
VM et al arXiv:1412.6393

Eta-Pi @COMPASS

COMPASS Phys. Lett. B740 (2015)

E(beam) = 190 GeV





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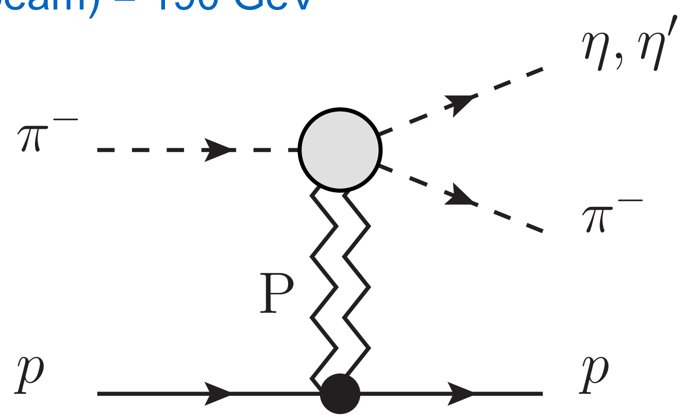
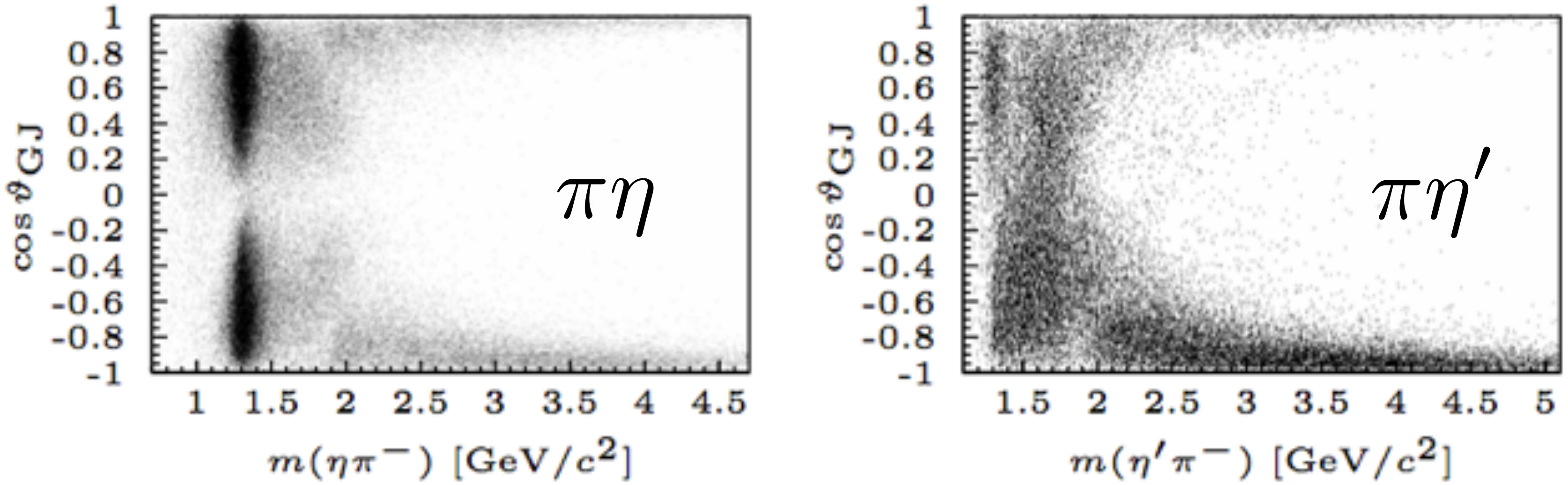
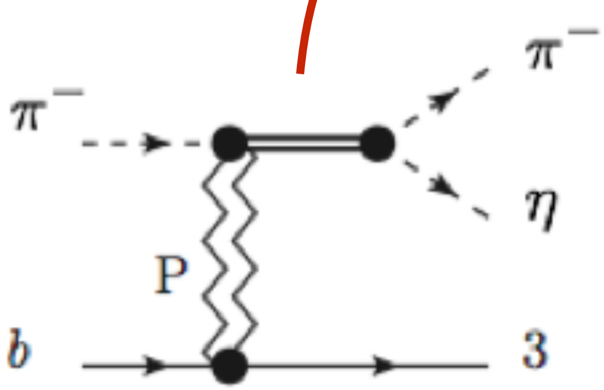




$$J^{PC} = 0^{++}, 1^{-+}, 2^{++}, 3^{-+}, 4^{++}, \ldots$$



0^{-+}

0^{-+}

$J = L$

$P = (-1)^L$

Eta-Pi @COMPASS

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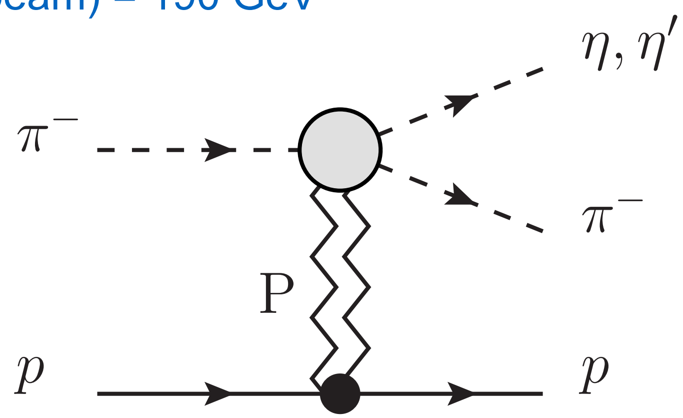

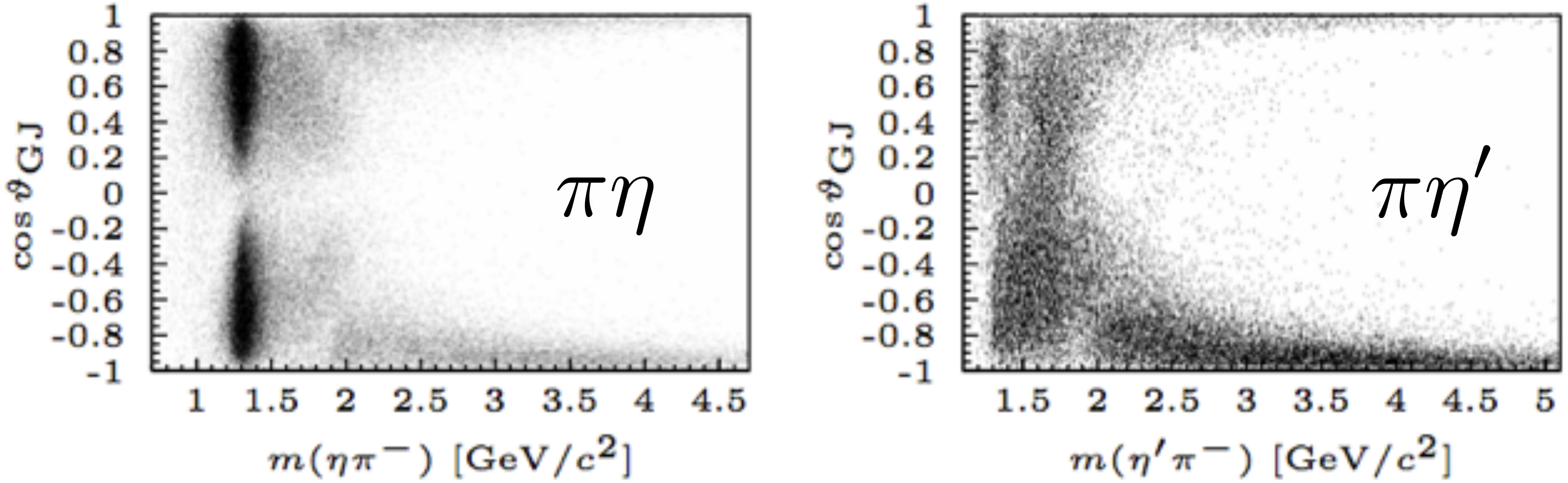

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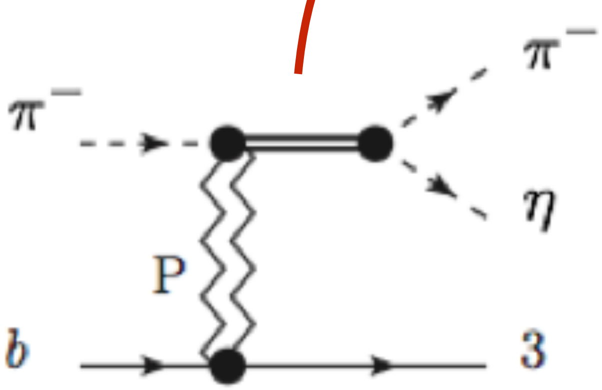
Exotic



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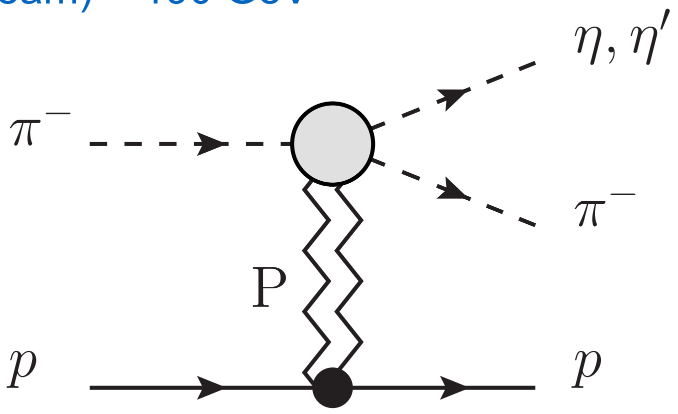
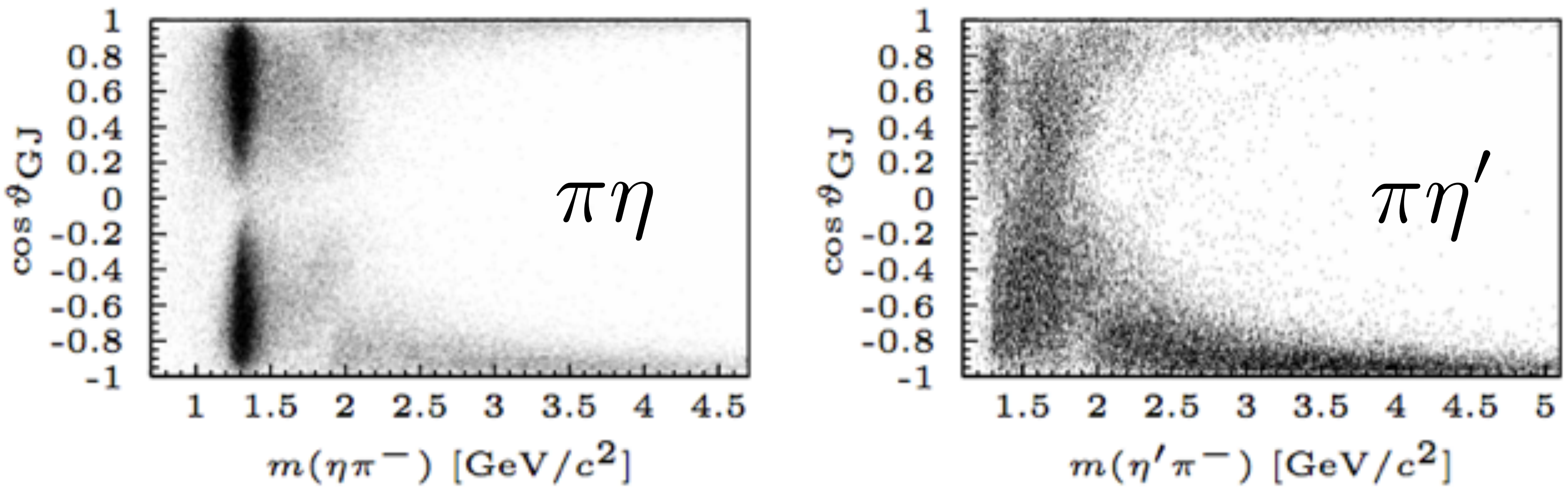
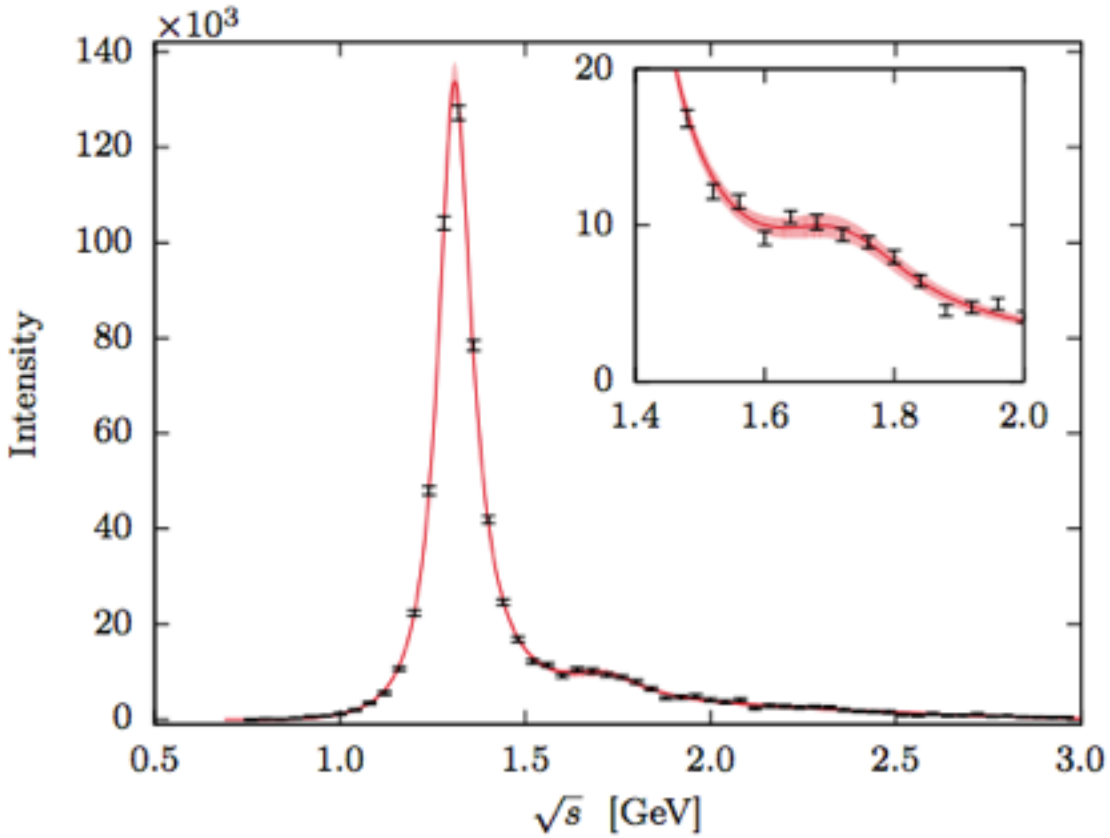




$$a_2(1320) : I^G J^{PC} = 1^- 2^{++}$$

$$d^2_{1,0}(\theta) \propto Y^1_2(\theta, 0) \propto \sin\theta\cos\theta$$



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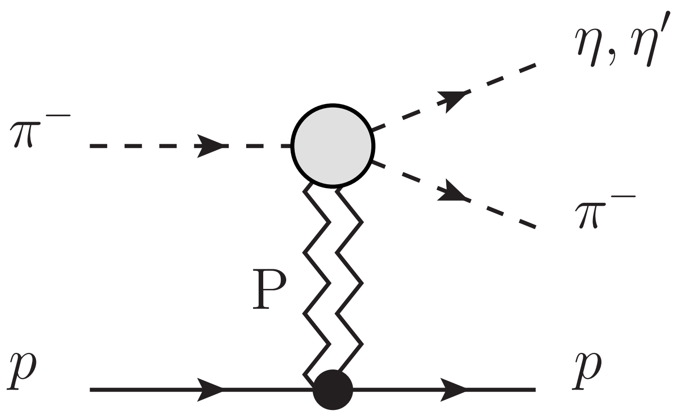
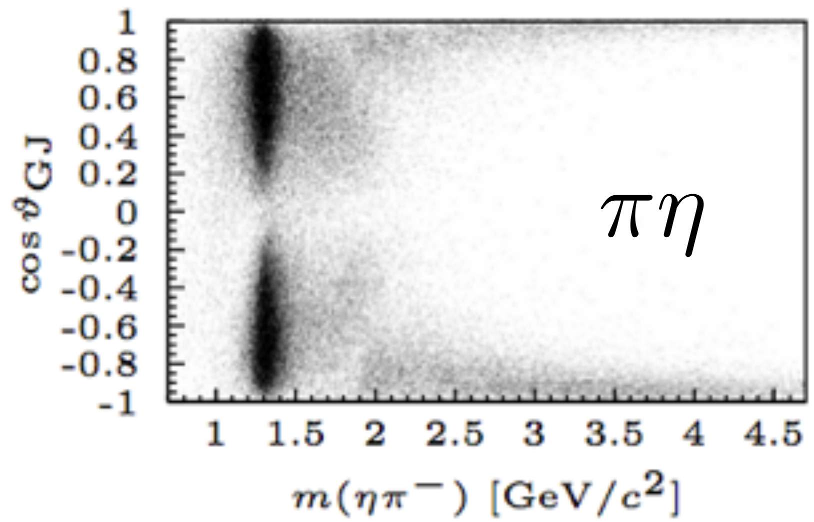
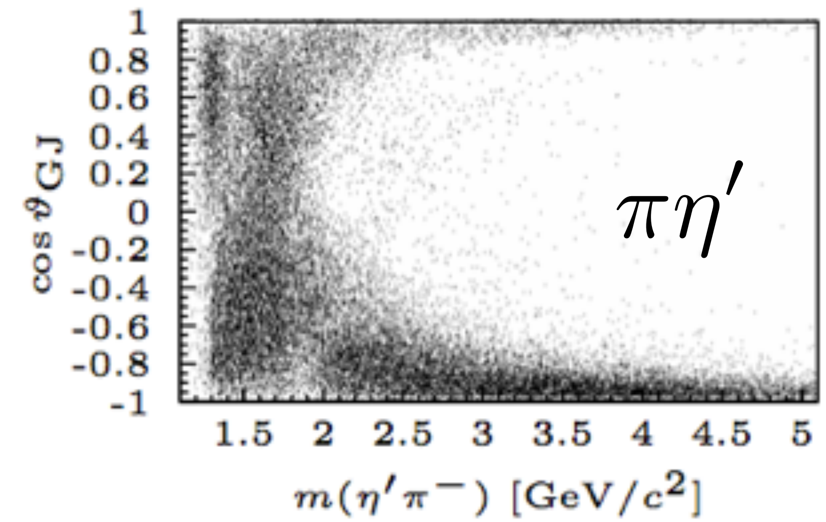
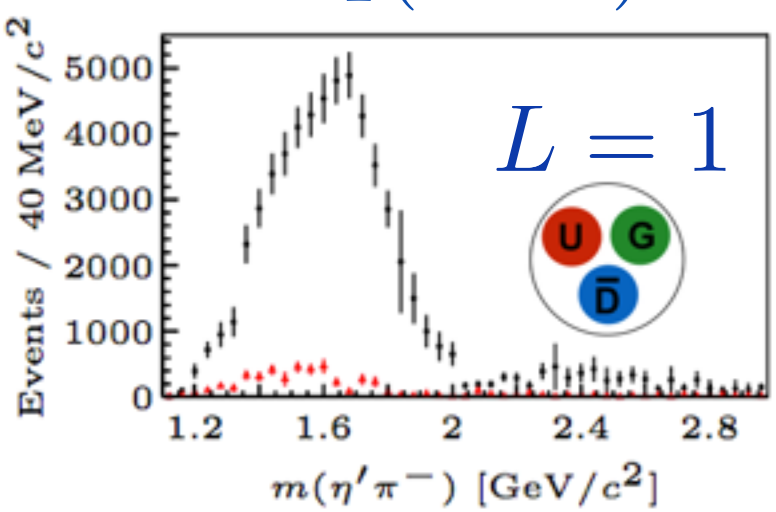


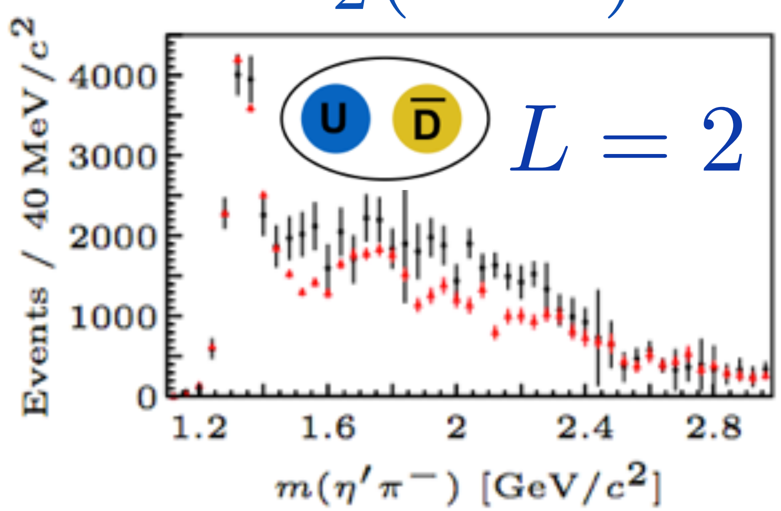




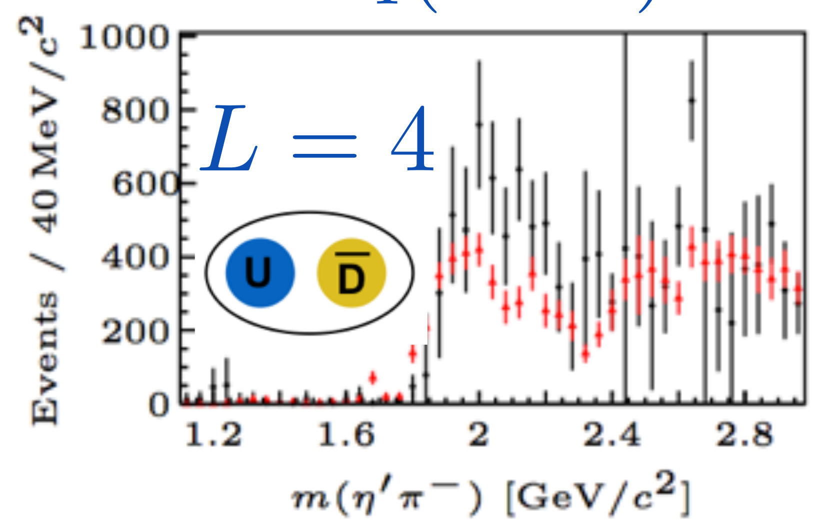
$\pi_1(1600)$?

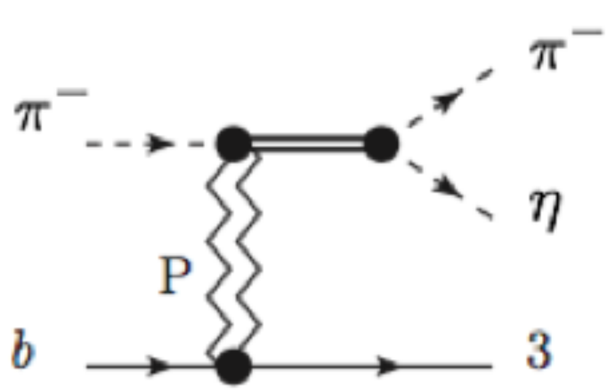


$a_2(1320)$



$a_4(2040)$





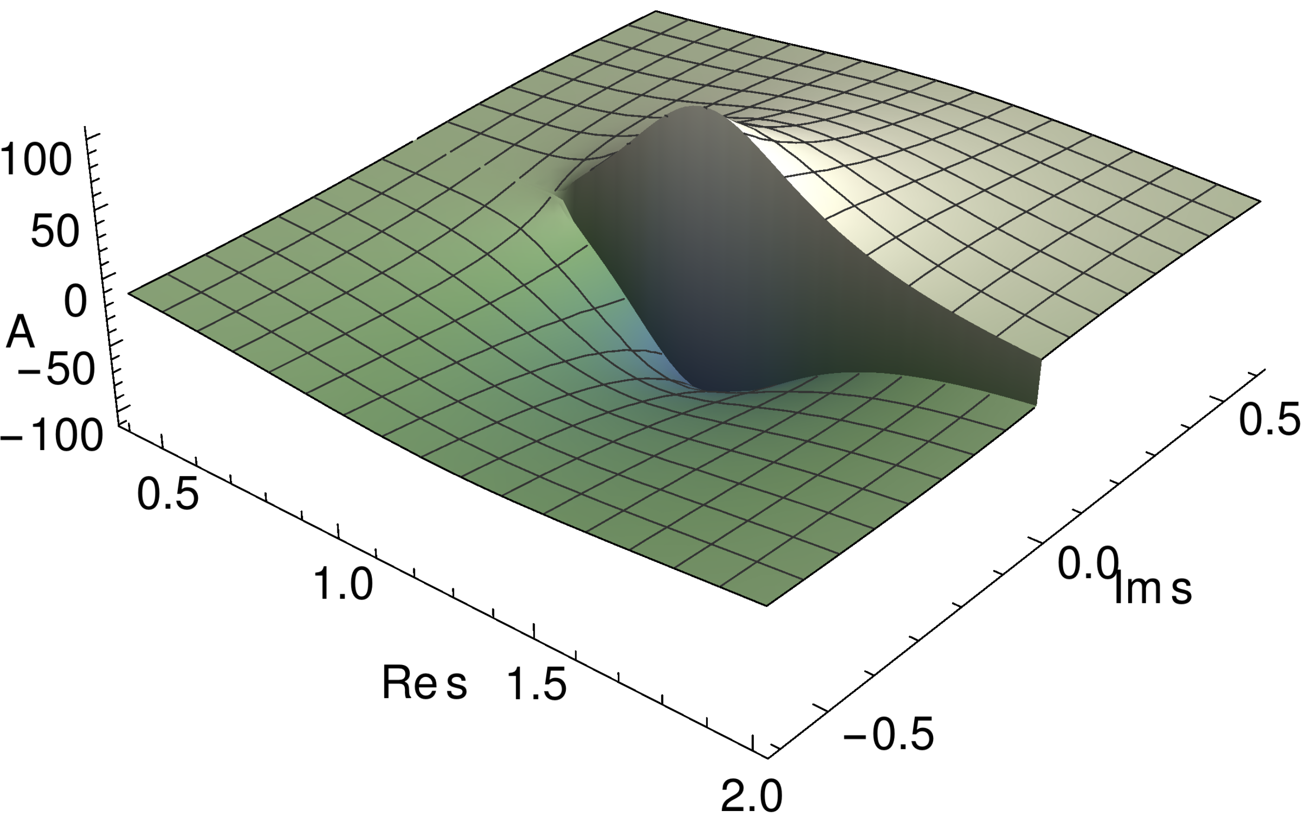
black: $\pi\eta'$

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

Resonance in angular mom. L = 1 ?

COMPASS Phys. Lett. B740 (2015)

Example: Breit-Wigner



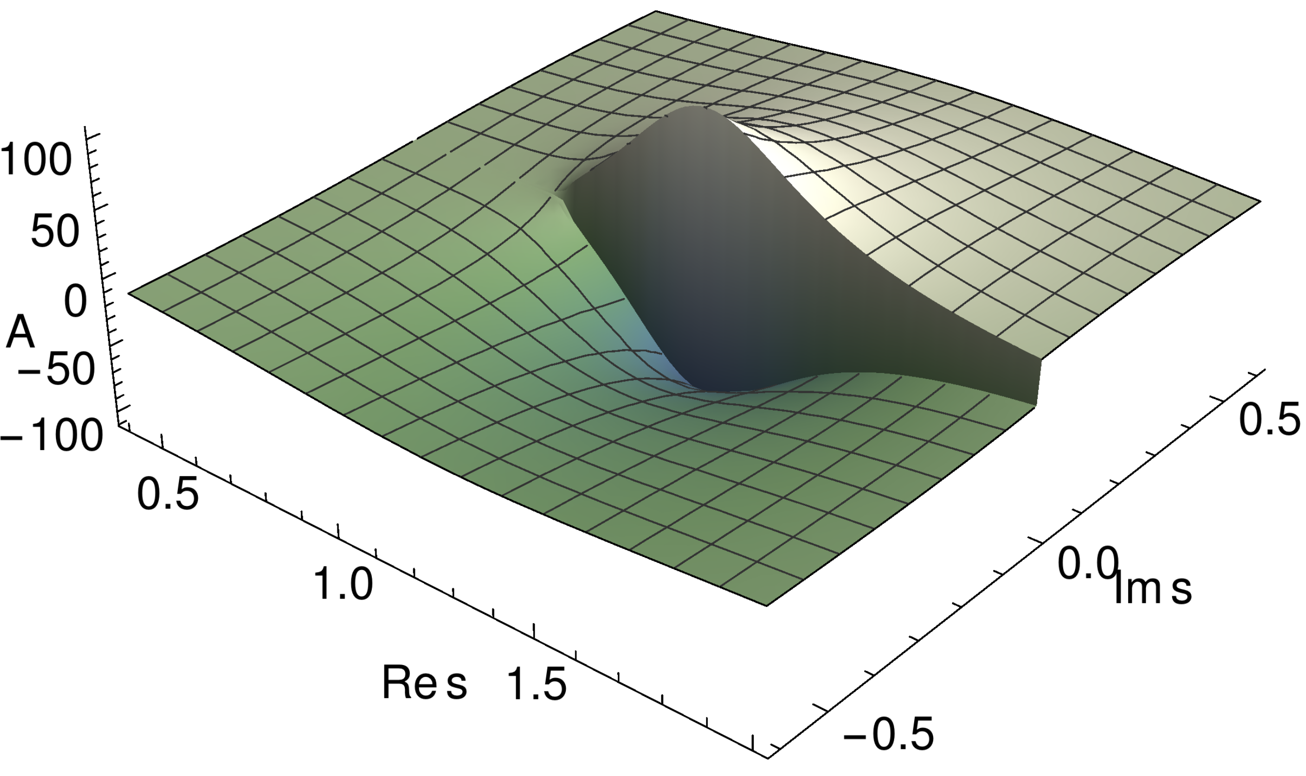
$$t_\ell(s \pm i\epsilon) = \frac{1}{K(s) \mp i\rho(s)}$$

Phase space $\rho(s) \propto \sqrt{1 - 4m^2/s}\ \theta(s - 4m^2)$

example: $K(s) = \dfrac{m^2 - s}{m\Gamma}$

satisfies causality
(regular outside the real axis)

Example: Breit-Wigner



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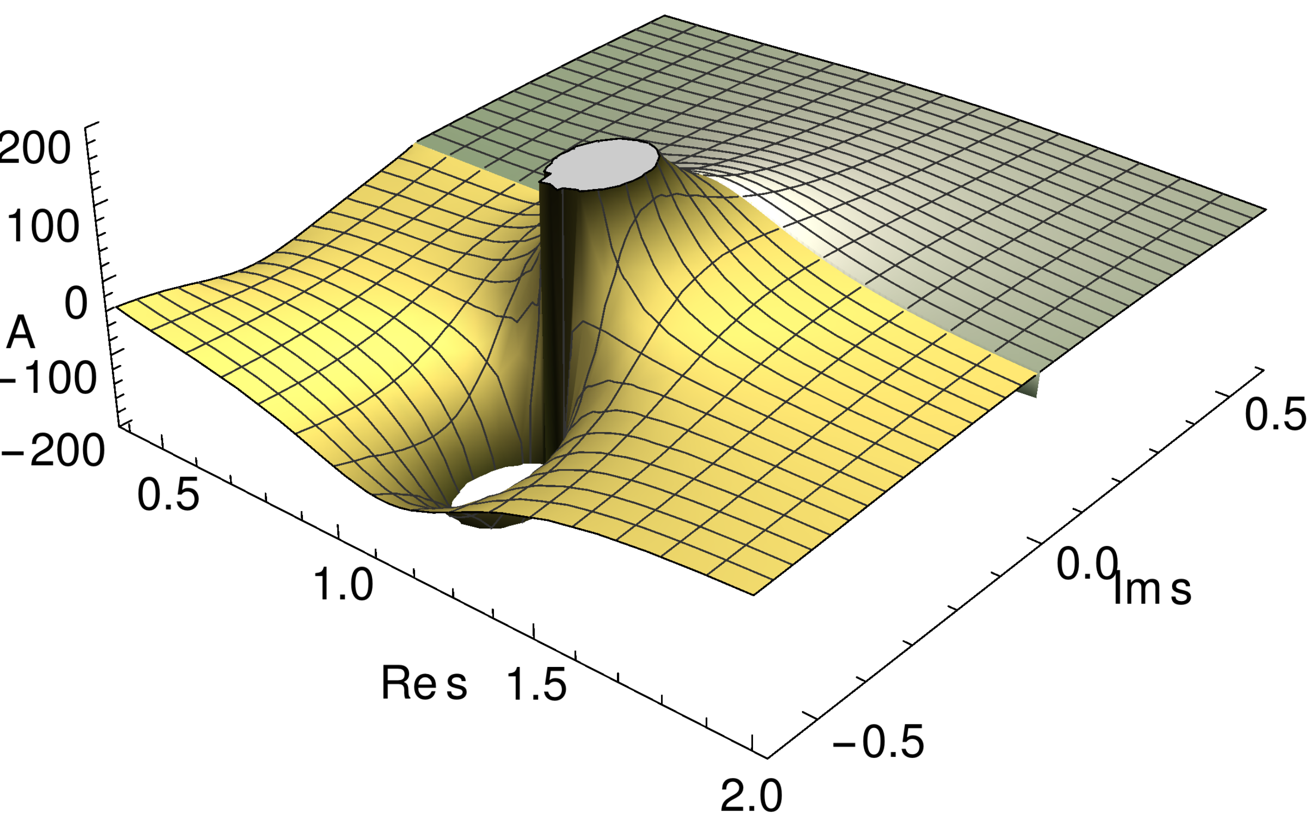


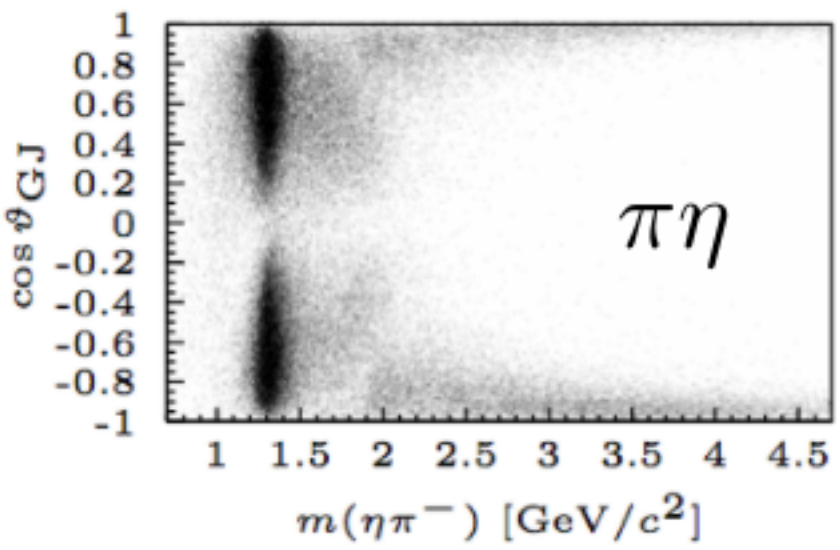
define function on sheet II
on the lower half plane

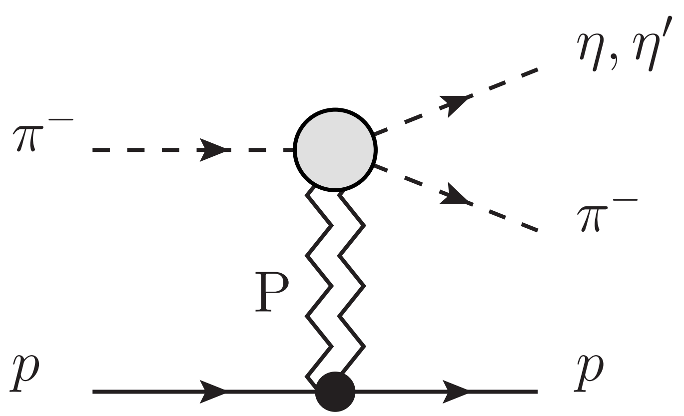
$$t_\ell^{II}(s) = \frac{1}{K(s) - i\rho(s)}$$

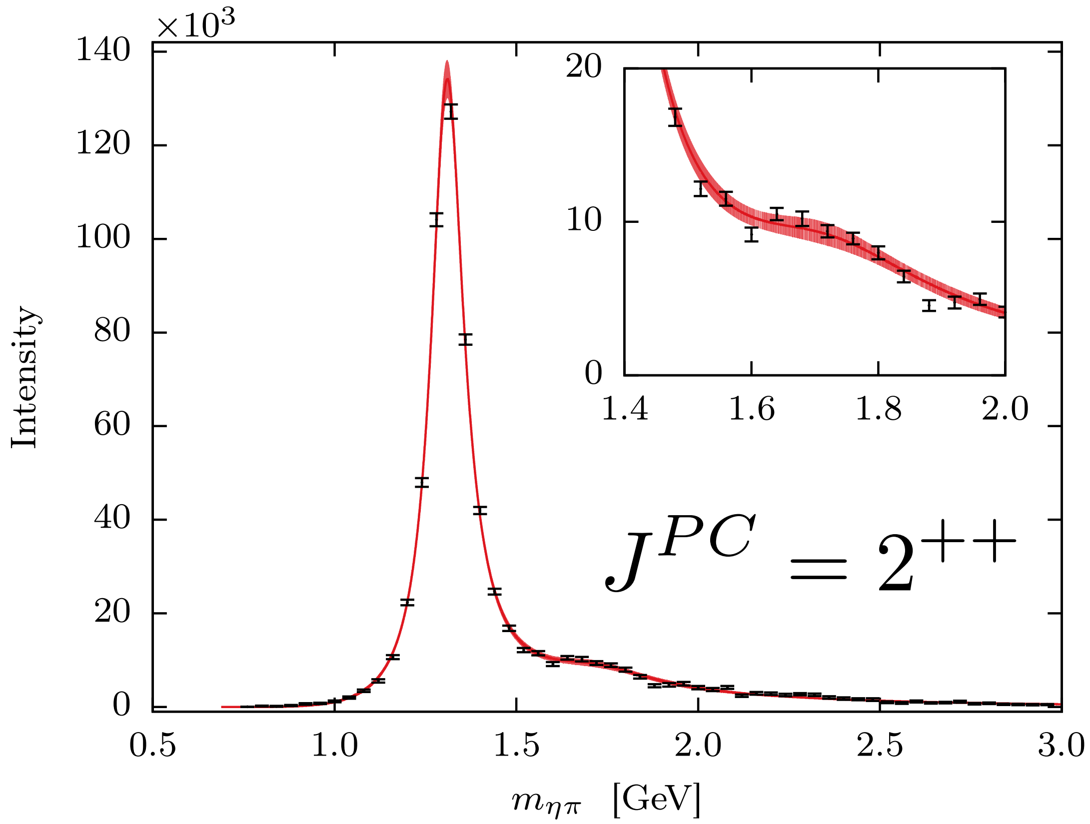
$$= \frac{m\Gamma}{m^2 - s - i\rho(s)m\Gamma}$$

Eta-Pi@COMPASS

A. Jackura et al (JPAC) and COMPASS, arXiv:1707.02848







Eta-Pi@COMPASS

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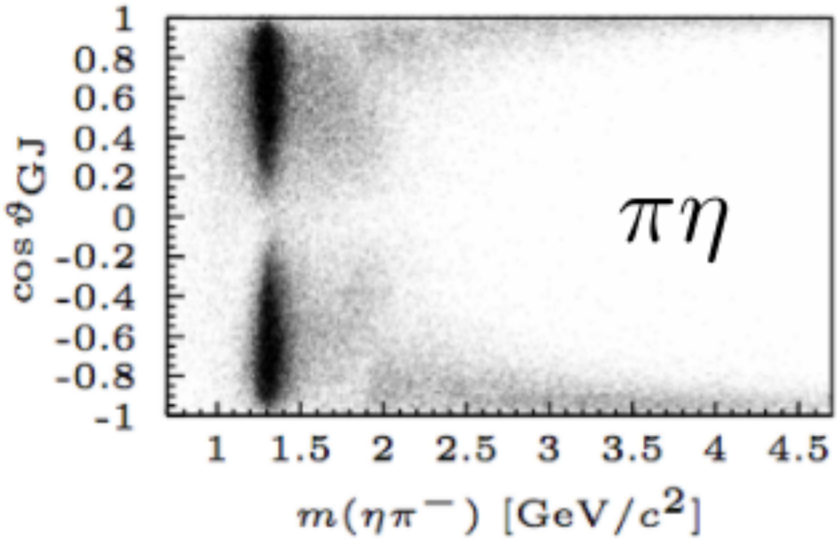

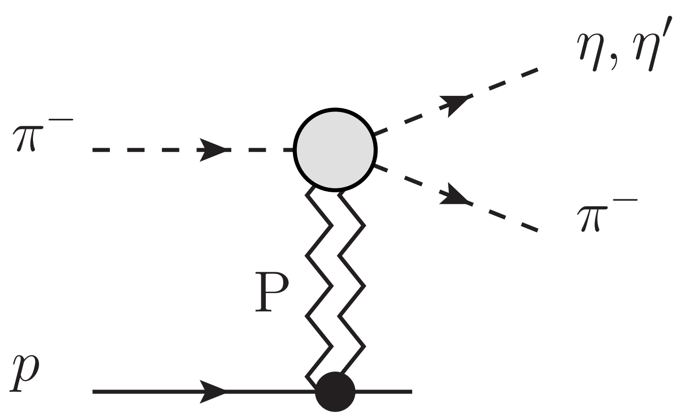

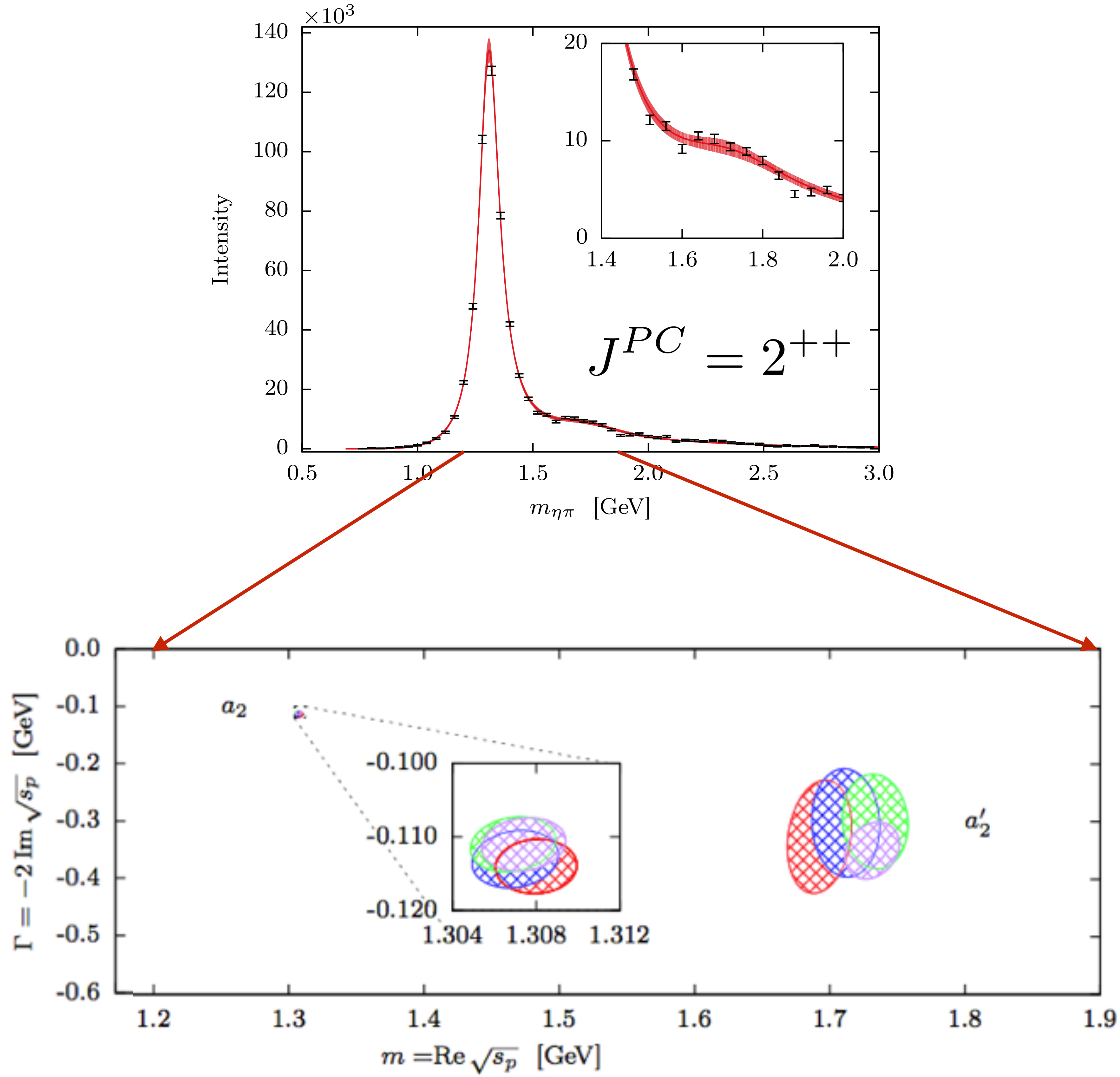

Eta-Pi@COMPASS

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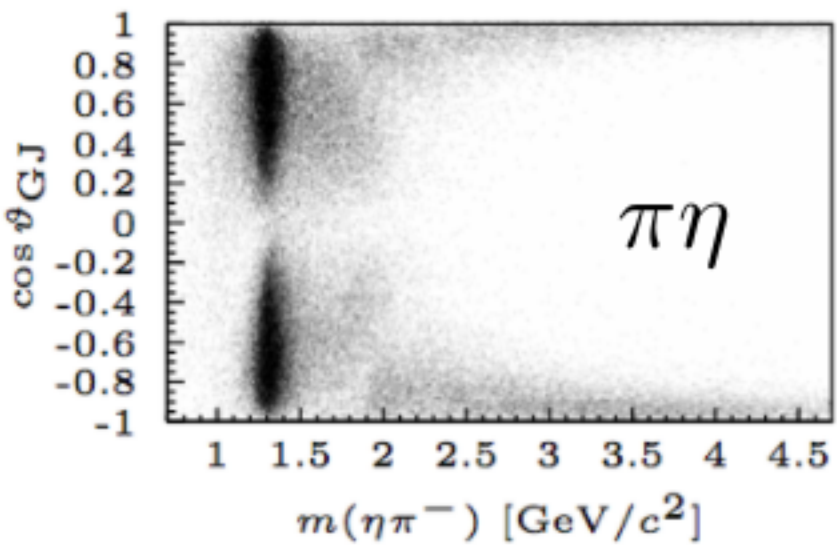

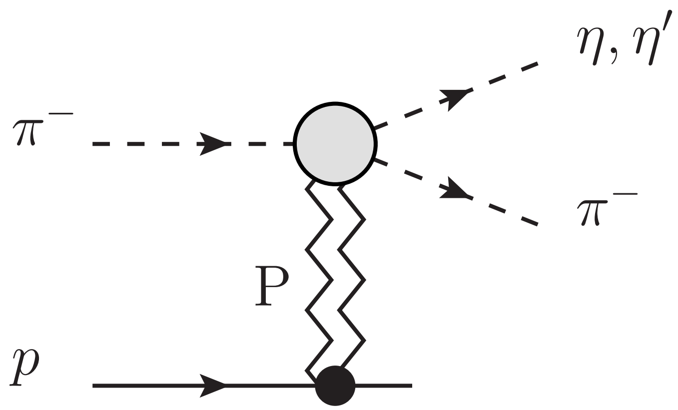

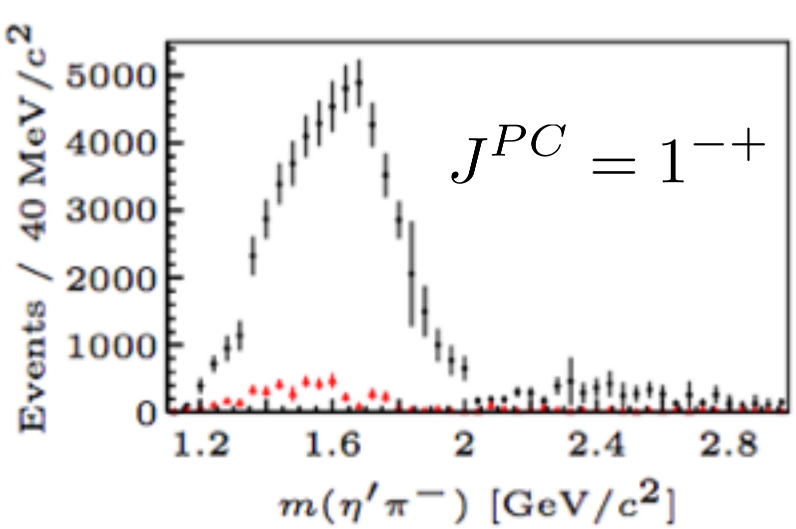

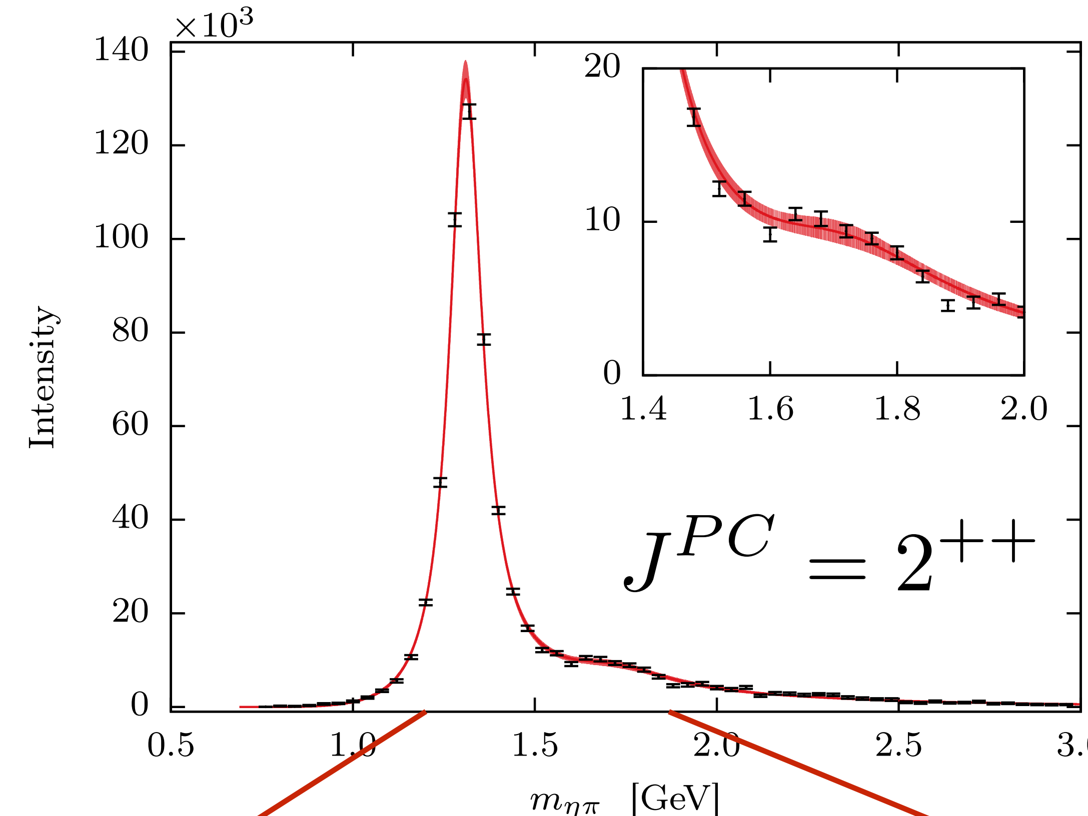

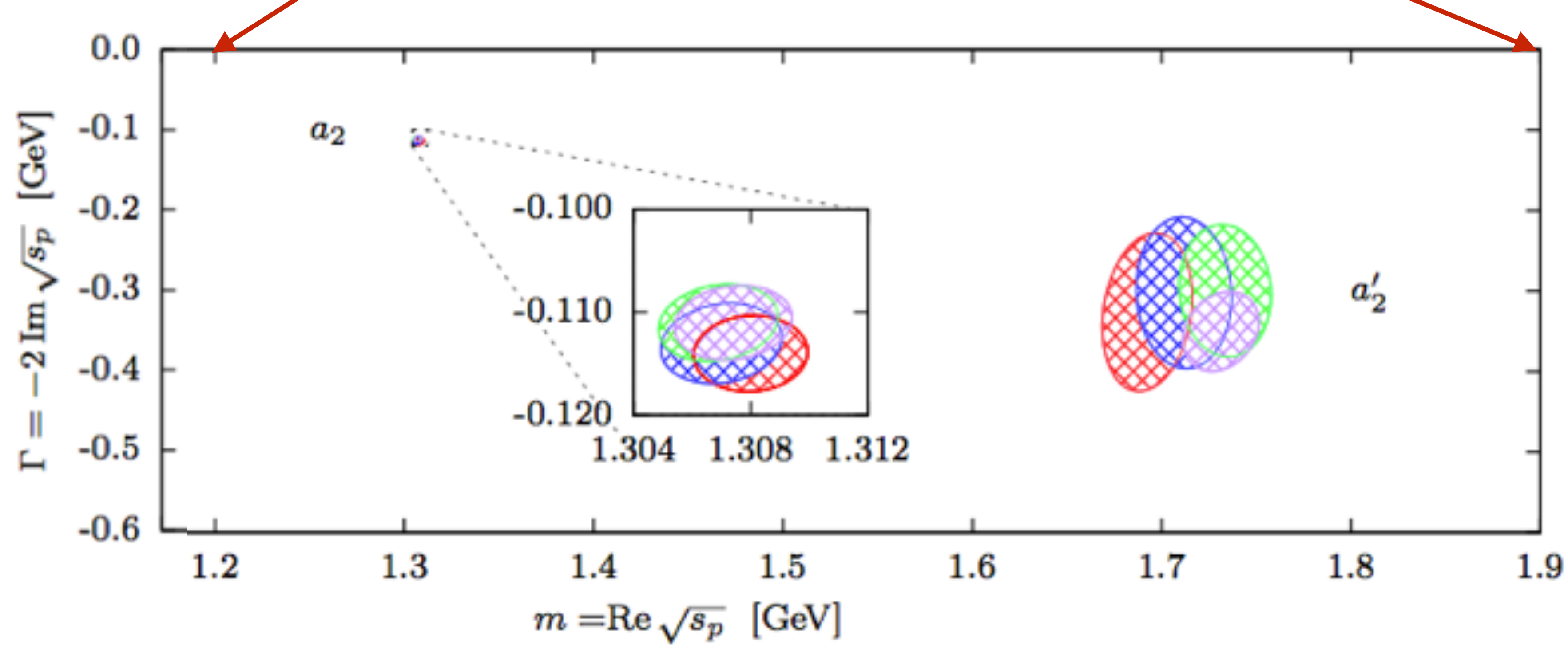

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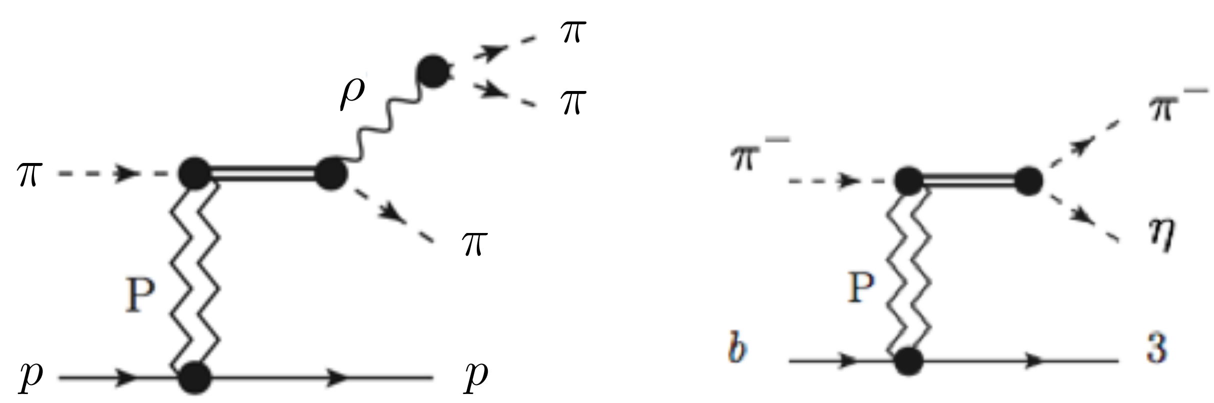
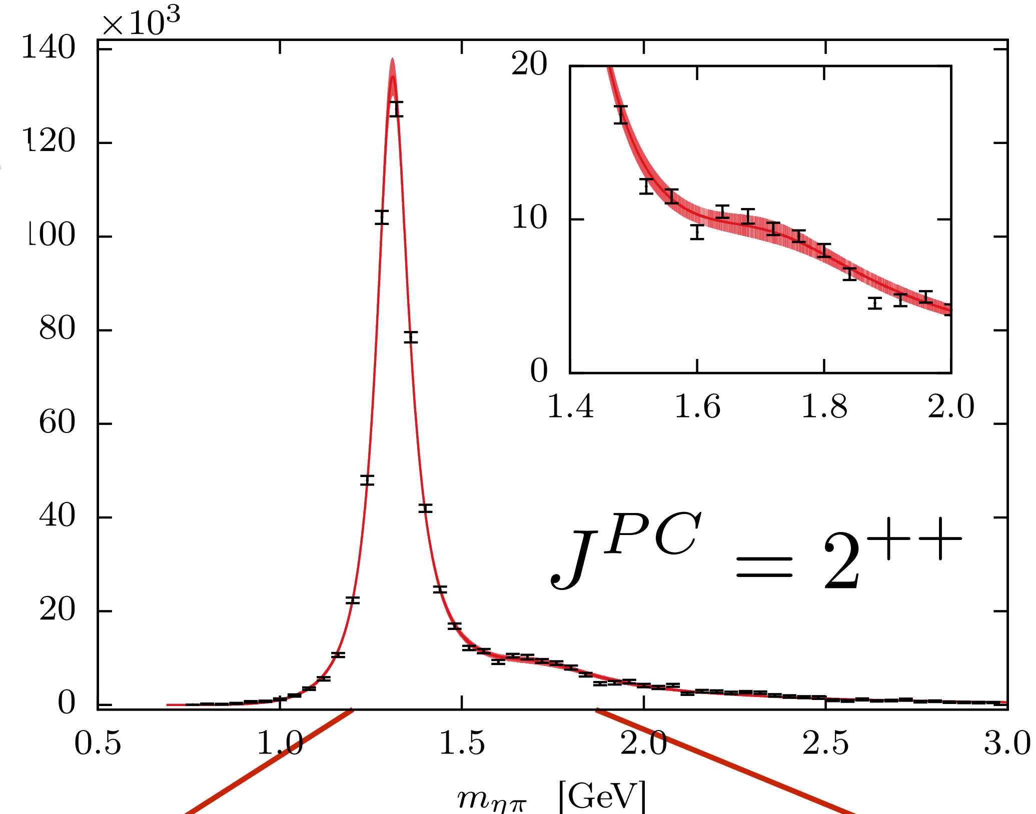
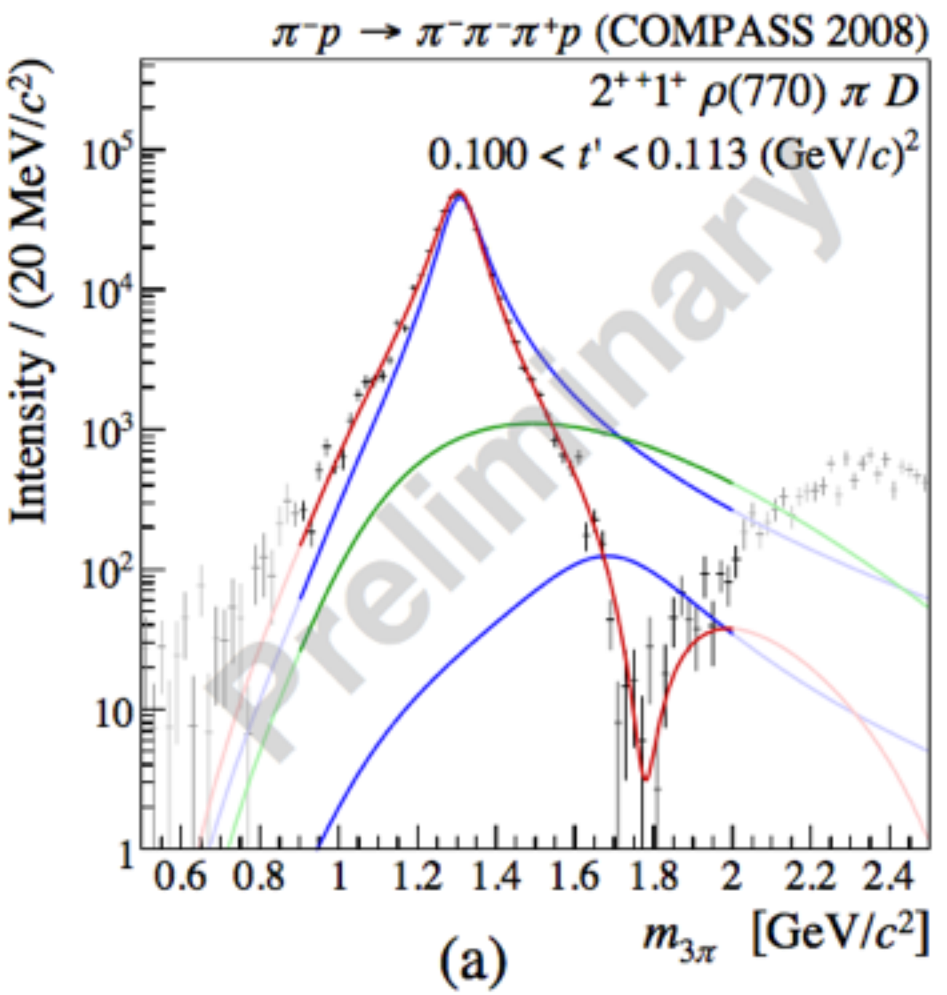
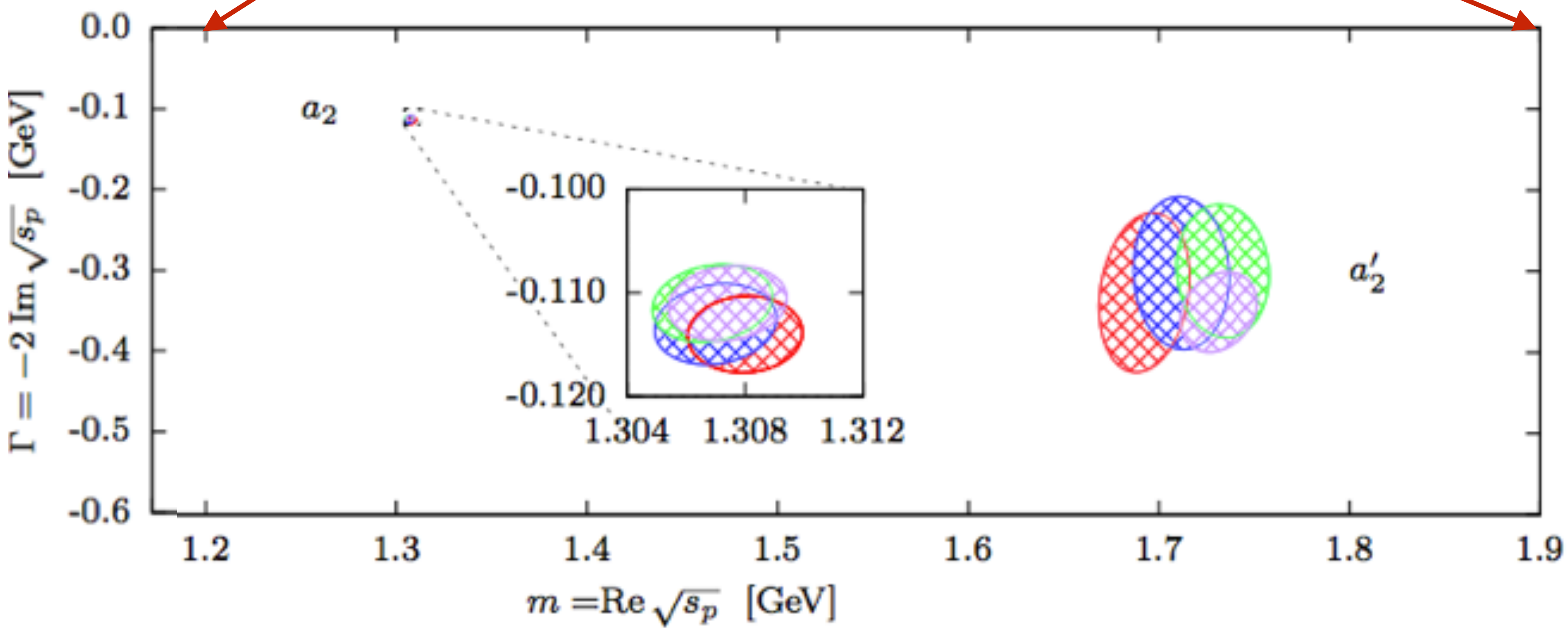




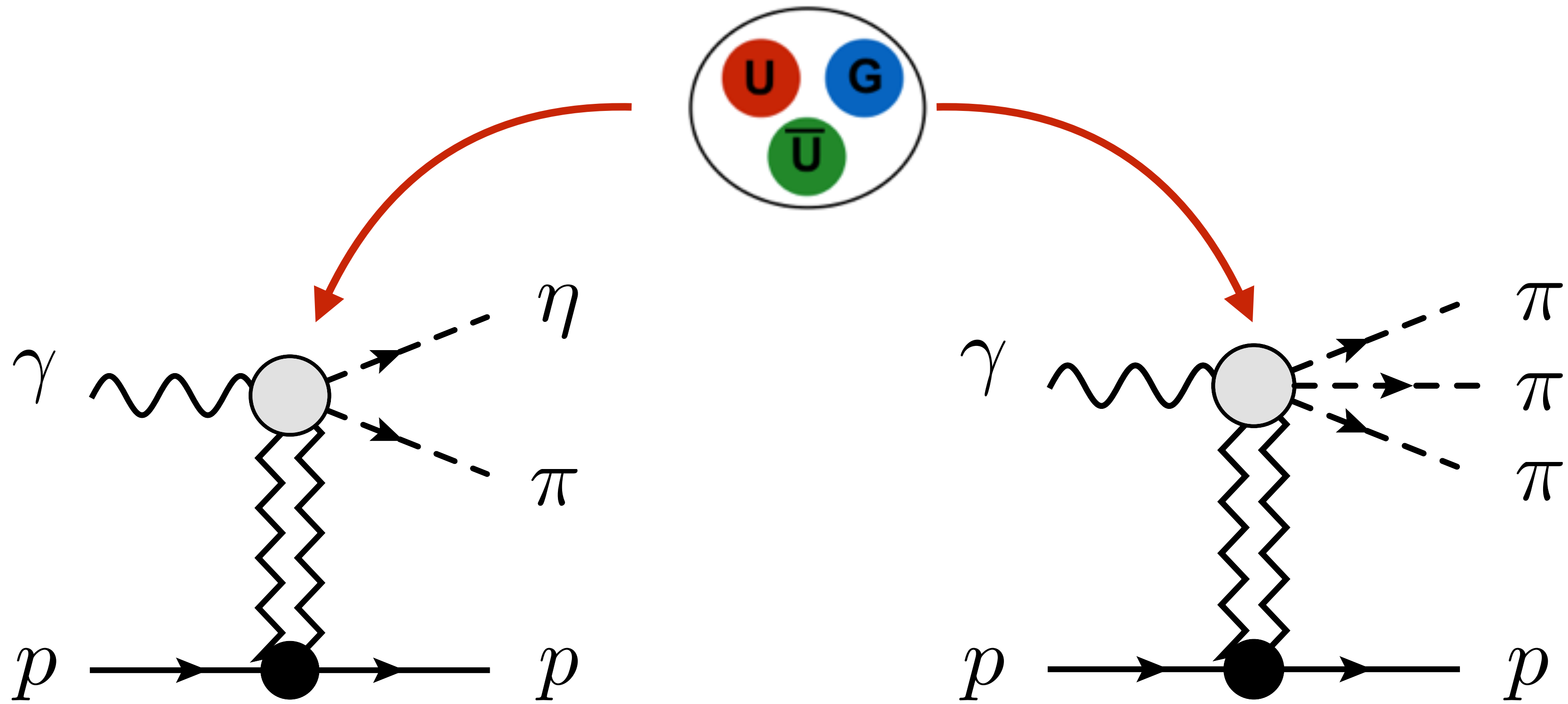


COMPASS, arXiv:1711.09782



GlueX stands for Gluonic Excitations

Golden channels:



First data taken in 2016
Second run in 2017

New results presented
in October 2017

$$\gamma p \to \pi^0 p, \eta p, \eta' p$$

$$\gamma p \to \omega p, \rho^0 p, \phi p$$

$$\gamma p \to \pi^- \Delta^{++}, \pi^+ \Delta^0$$

$$\gamma p \to J/\psi p$$

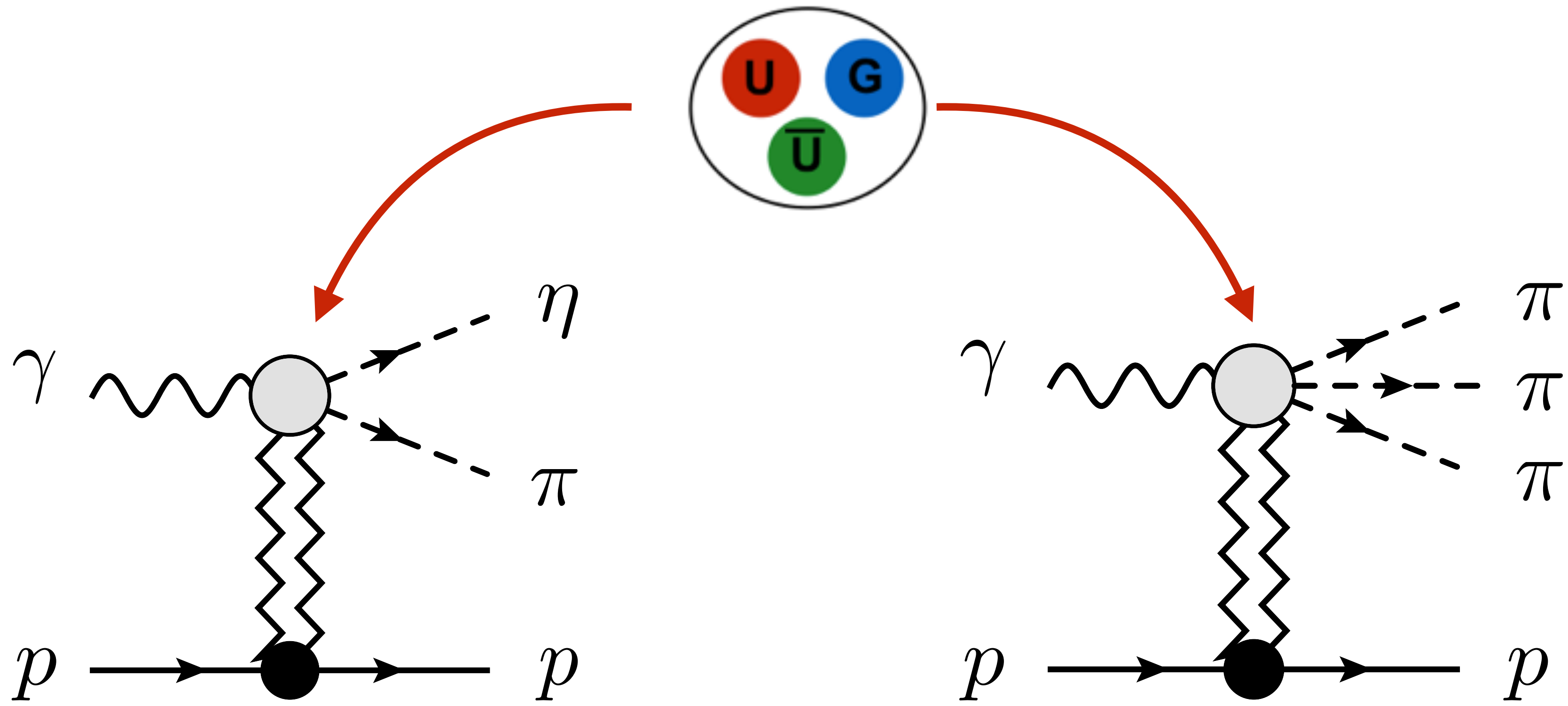
$$\gamma p \to \pi^0 \pi^0 p, \pi^0 \eta p$$

First publication

$$\gamma p \to \pi^0 p, \;\; \eta p$$

GlueX stands for Gluonic Excitations

Golden channels:



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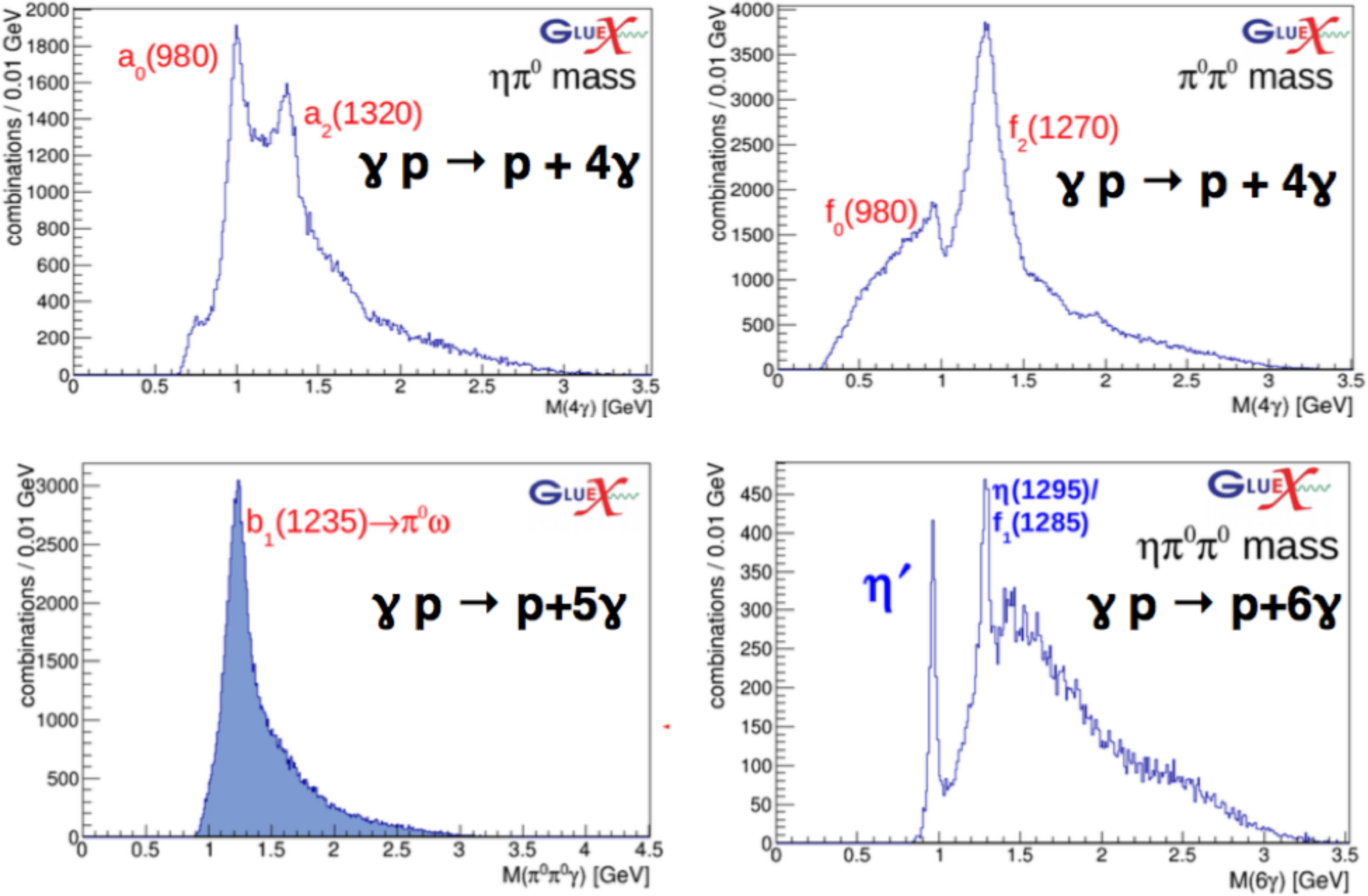
$$\gamma p \to \pi^0 p, \eta p, \eta' p \qquad \gamma p \to J/\psi p$$

$$\gamma p \to \omega p, \rho^0 p, \phi p \qquad \gamma p \to \pi^0 \pi^0 p, \pi^0 \eta p$$

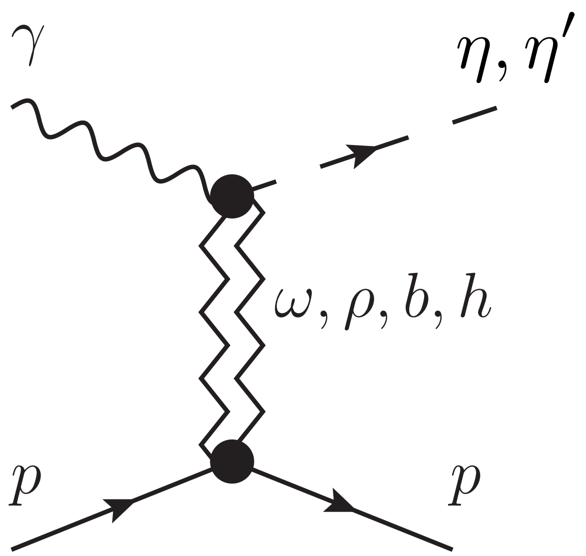
$$\gamma p \to \pi^- \Delta^{++}, \pi^+ \Delta^0$$

First publication $\quad \gamma p \to \pi^0 p, \;\; \eta p \quad$ GlueX, VM and J. Nys PRC (2017)



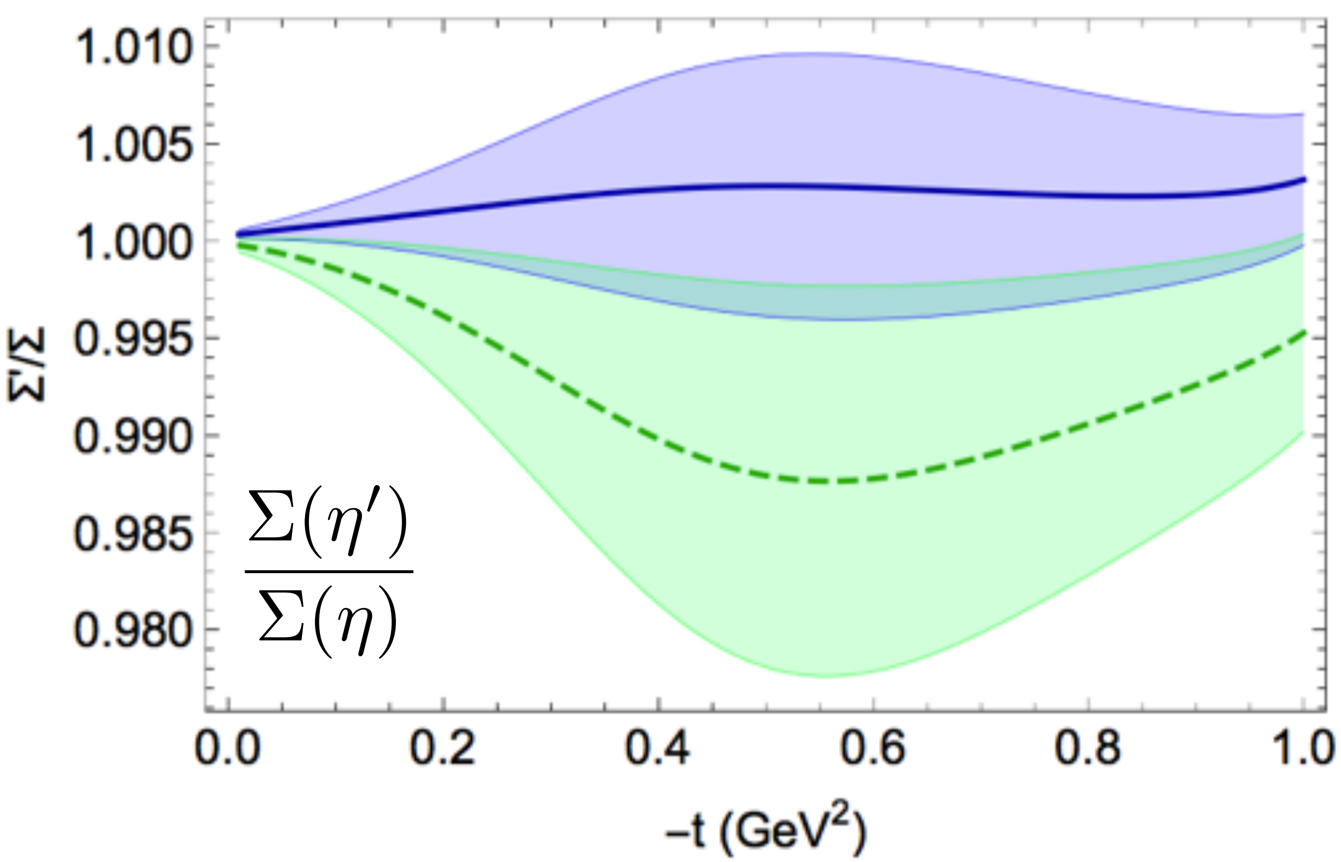
a0(980)
a2(1320)
ηπ0 mass
γ p → p + 4γ
combinations / 0.01 GeV
M(4γ) [GeV]
f0(980)
f2(1270)
π0π0 mass
γ p → p + 4γ
combinations / 0.01 GeV
M(4γ) [GeV]
b1(1235)→π0ω
γ p → p+5γ
combinations / 0.01 GeV
M(π0π0γ) [GeV]
η′
η(1295)/
f1(1285)
ηπ0π0 mass
γ p → p+6γ
combinations / 0.01 GeV
M(6γ) [GeV]

Pseudoscalar Meson Beam Asymmetry



$$\Sigma(\eta) = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$
$$= \Sigma(\eta')$$

$b_1 \to \gamma\eta^{(\prime)}$ not known



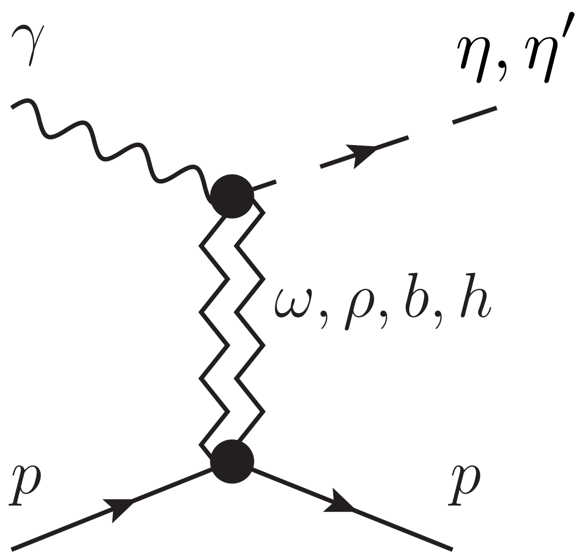
Beam asymmetry Difference probes strange exchanges contribution and deviation from quark model

blue and green models represent the estimation of systematic errors

See GlueX Preliminary results by T. Beatie

VM et al. (JPAC) PLB774 (2017) 362
arXiv:1704.07684

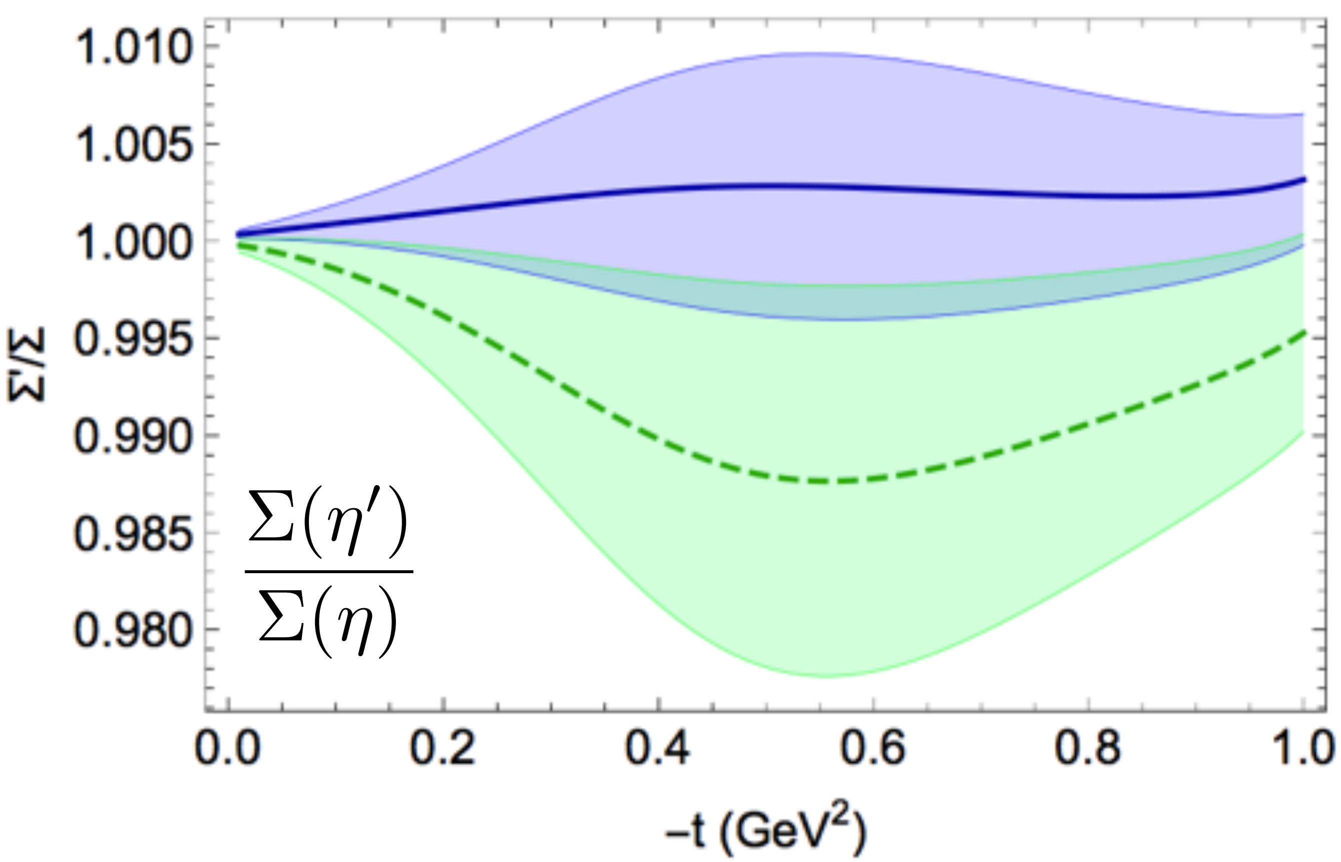
Pseudoscalar Meson Beam Asymmetry



$$\Sigma(\eta) = \frac{|\rho + \omega + \phi|^2 - |b + h + h'|^2}{|\rho + \omega + \phi|^2 + |b + h + h'|^2}$$

$$\neq \Sigma(\eta')$$

$b_1 \to \gamma\eta^{(\prime)}$ not known



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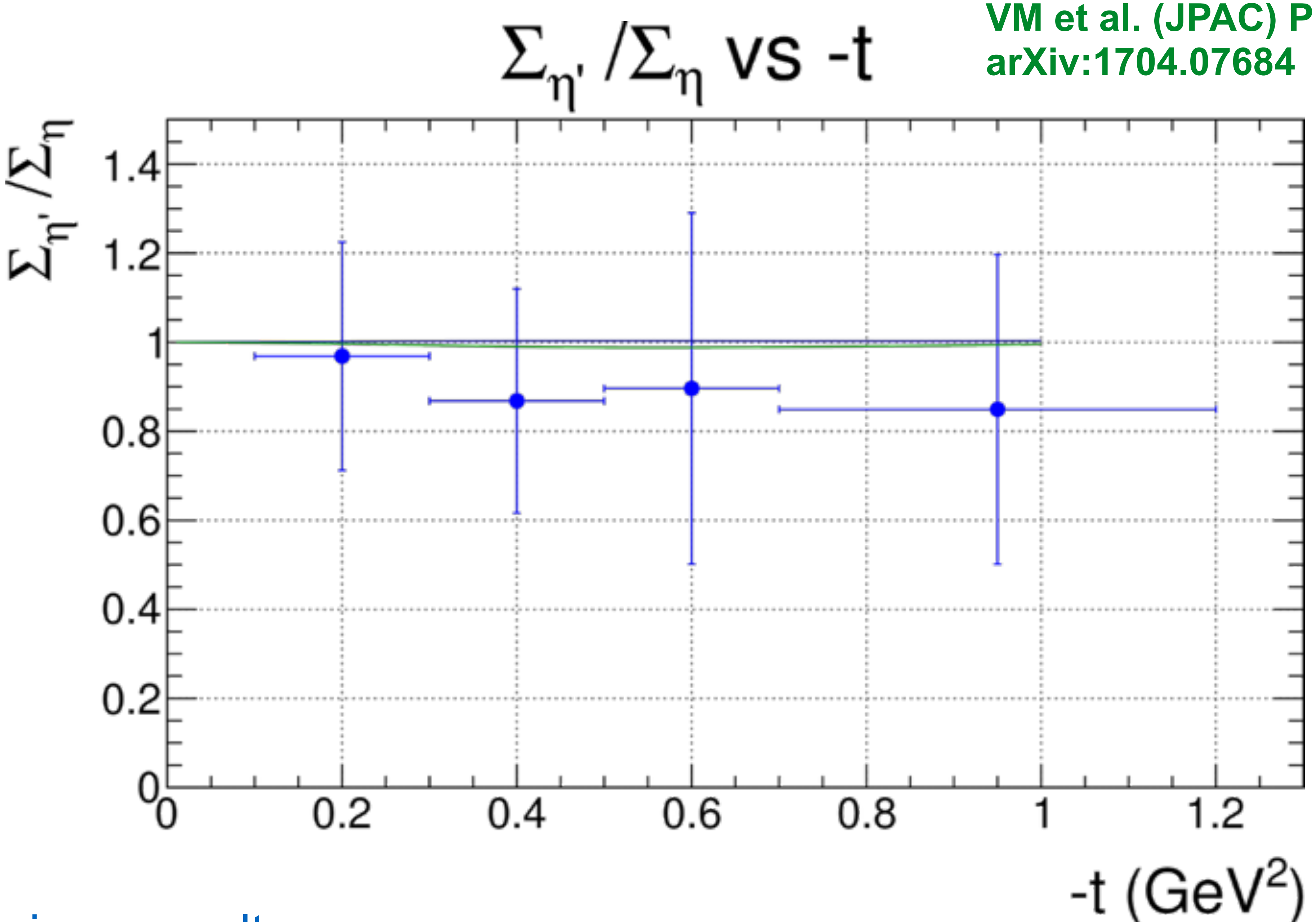
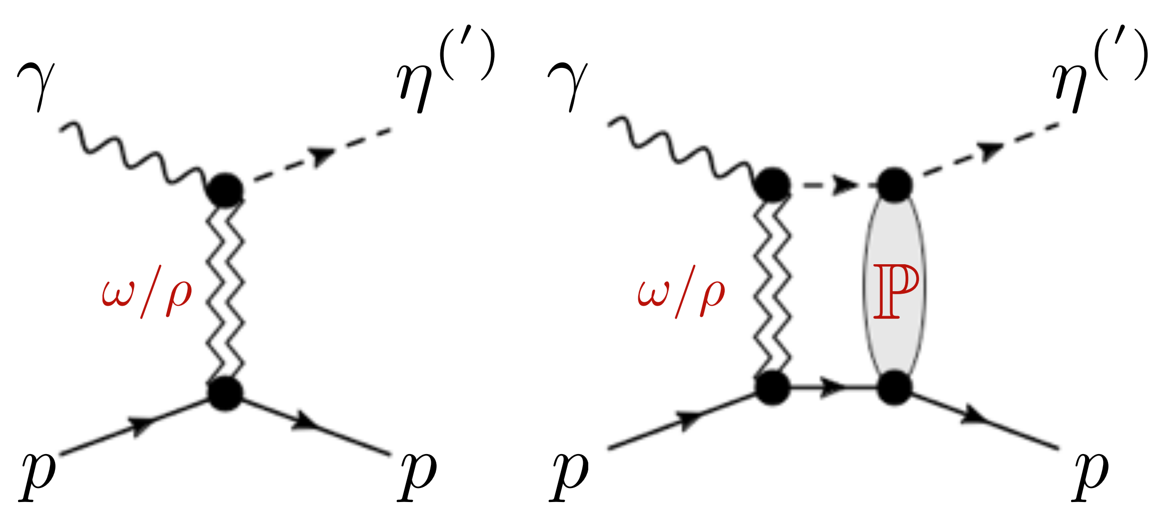


GlueX Preliminary results
presented at APS meeting Oct 2017
Courtesy of T. Beatie

Strong deviation from 1 would
suggest deviation from factorization



JPAC Interactive Website

INDIANA UNIVERSITY BLOOMINGTON

Jefferson Lab
Thomas Jefferson National Accelerator Facility

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

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U.S. DEPARTMENT OF ENERGY

National Science Foundation

JPAC acknowledges support from DOE and NSF

NEWS

Photoproduction:

1. High energy model for $\pi\Delta$ photoproduction beam asymmetry: (in construction)
2. High energy model for ρ, ω, ϕ photoproduction spin density matrix elements: (in construction)
3. High energy model for η' photoproduction beam asymmetry: $\gamma p \to \eta^{(')} p$ page
4. High energy model for η photoproduction: $\gamma p \to \eta p$ page
5. High energy model for π^0 photoproduction: $\gamma p \to \pi^0 p$ page
6. High energy model for J/ψ photoproduction: $\gamma p \to J/\psi p$ page

INDIANA UNIVERSITY

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

Simulation

Beam energy in the lab frame (target rest frame):

E_γ in GeV 9.00

Natural exchanges (vector exchanges): [show/hide]

ρ $g_{\rho\eta\gamma}$: 0.479 $g_{\rho\eta'\gamma}$: 0.401

$g_{1\rho}$: 13.49 $b_{1\rho}$: 0.00

$\gamma^{\rho}_{1,1}$: 0.00 $\gamma^{\rho}_{1,2}$: 0.00

ω $g_{\omega\eta\gamma}$: 0.136 $g_{\omega\eta'\gamma}$: 0.127

$g_{1\omega}$: 0.00 $b_{1\omega}$: 0.00

$\gamma^{\omega}_{1,1}$: 0.00 $\gamma^{\omega}_{1,2}$: 0.00

ϕ $g_{\phi\eta\gamma}$: 0.210 $g_{\phi\eta'\gamma}$: 0.217

$g_{1\phi}$: 0.00 $b_{1\phi}$: 0.00

$\gamma^{\phi}_{1,1}$: 0.00 $\gamma^{\phi}_{1,2}$: 0.00

Unnatural exchanges (axial exchanges):[show/hide]

Unnatural exchanges (pseudo-tensor exchanges):[show/hide]

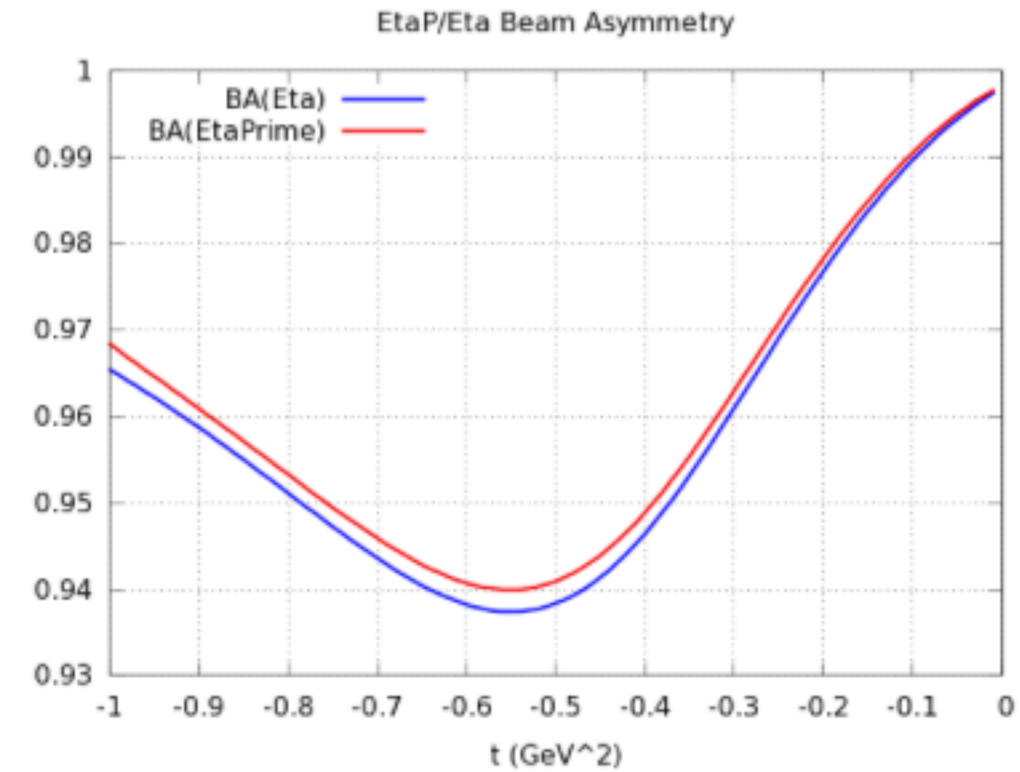
Resources

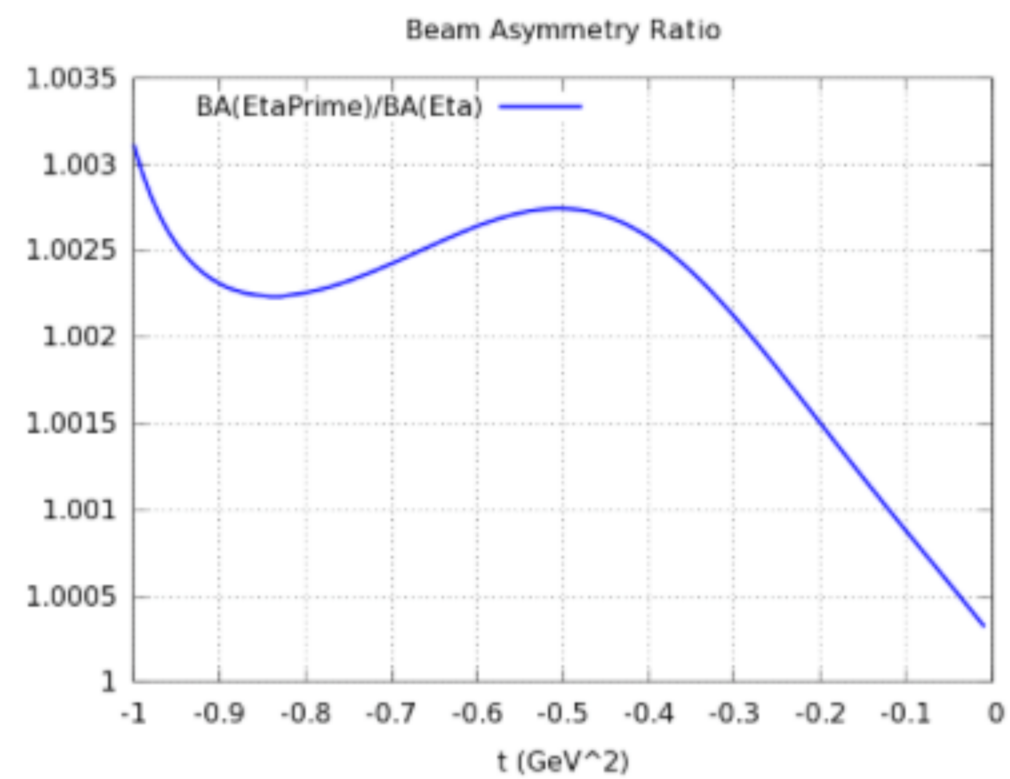
- **Publications:** [Mat17a]
- **C/C++:** C/C++ file
- **Input file:** param.txt , EtaBA.txt .
- **Output files:** EtaP-BA.txt .
- **Contact person:** Vincent Mathieu
- **Last update:** May 2017

Format of the input and output files: [show/hide]

Results

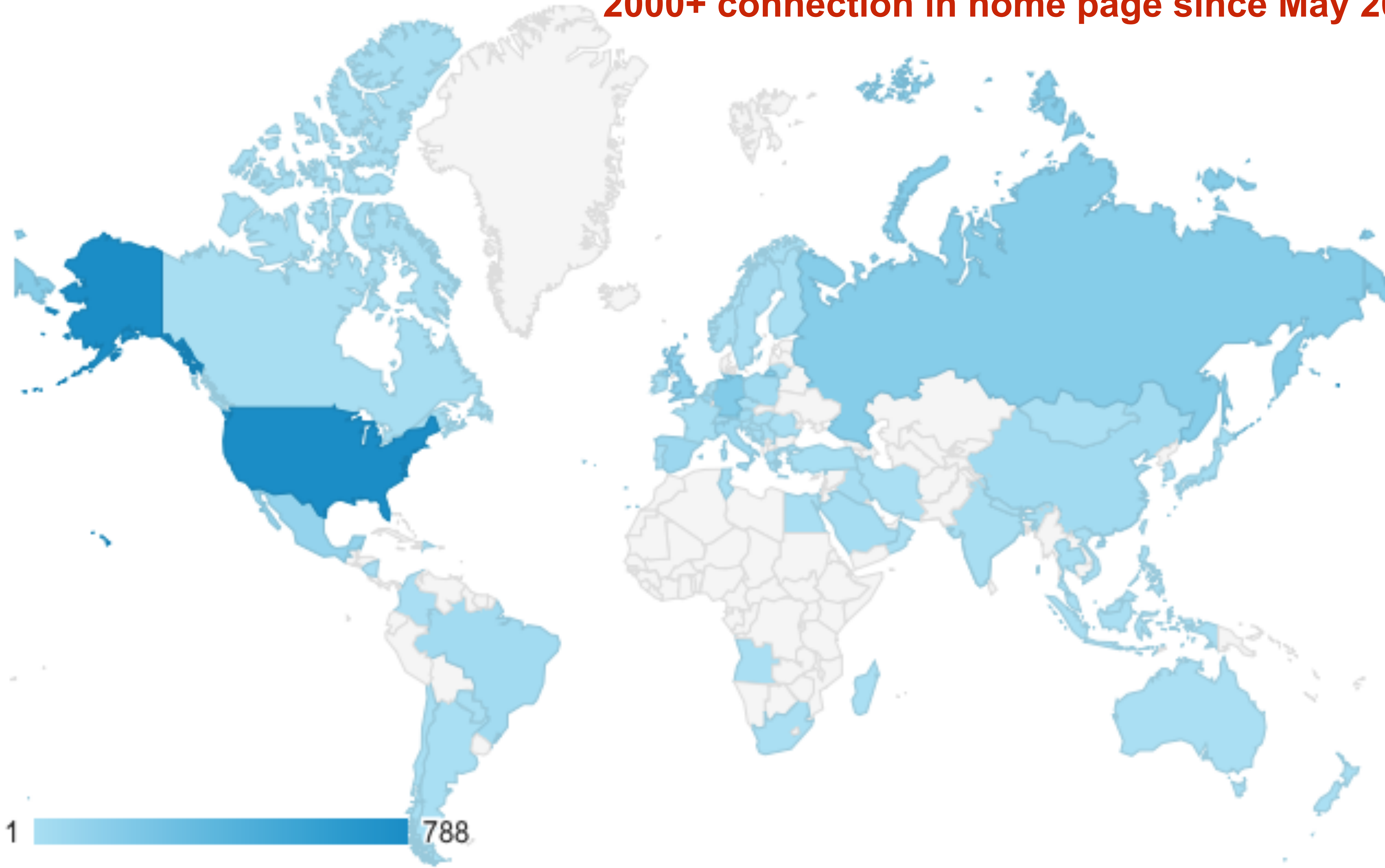
Download the output file: EtaP-BA.txt
Download the plots: BA.png , kVA.png , ratio.png





JPAC Interactive Website

2000+ connection in home page since May 2016



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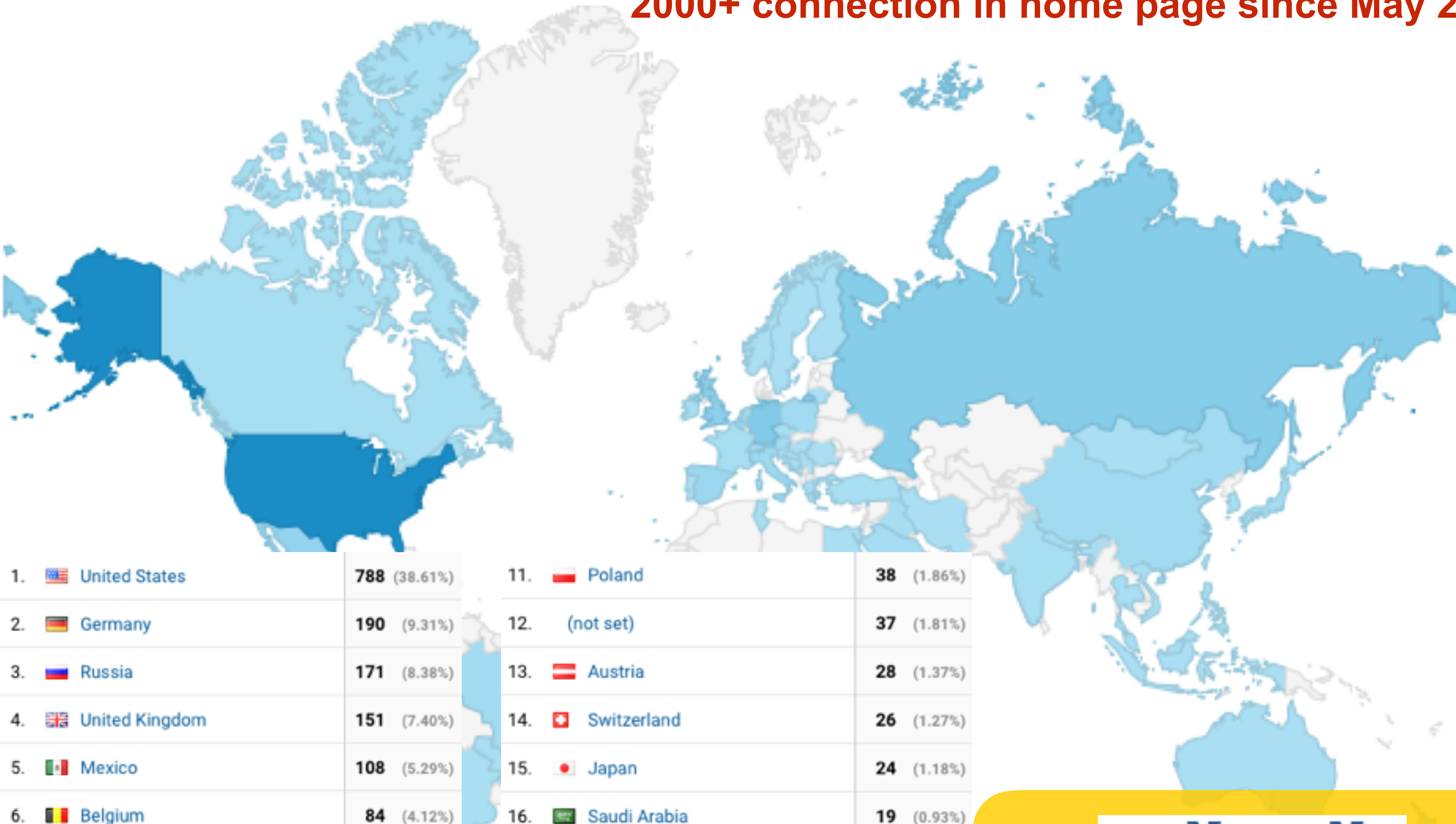
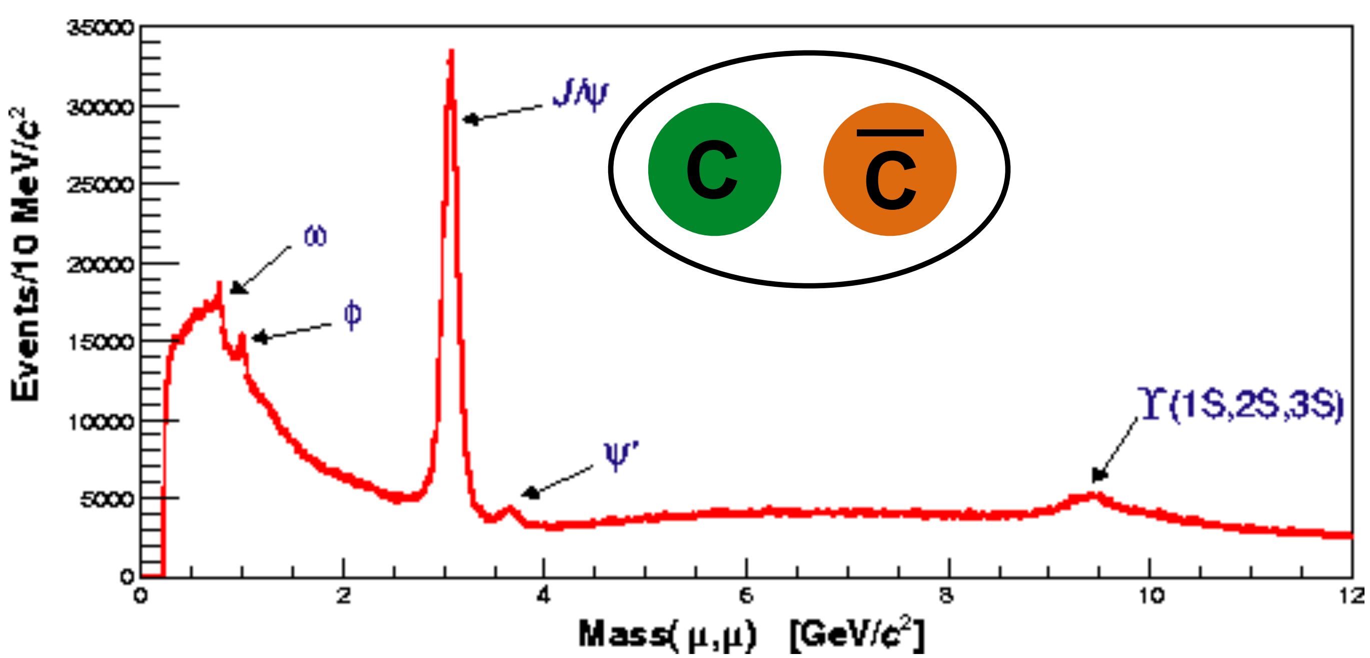


1.	United States	788	(38.61%)
2.	Germany	190	(9.31%)
3.	Russia	171	(8.38%)
4.	United Kingdom	151	(7.40%)
5.	Mexico	108	(5.29%)
6.	Belgium	84	(4.12%)
7.	Spain	67	(3.28%)
8.	Italy	56	(2.74%)
9.	Brazil	40	(1.96%)
10.	China	39	(1.91%)
11.	Poland	38	(1.86%)
12.	(not set)	37	(1.81%)
13.	Austria	28	(1.37%)
14.	Switzerland	26	(1.27%)
15.	Japan	24	(1.18%)
16.	Saudi Arabia	19	(0.93%)
17.	Iraq	17	(0.83%)
18.	France	13	(0.64%)
19.	Netherlands	13	(0.64%)
20.	Canada	11	(0.54%)

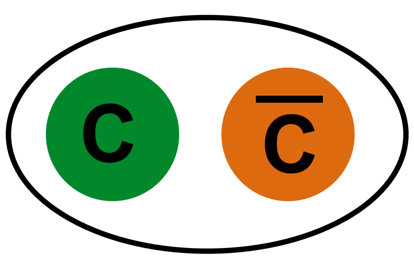
$$\pi N \to \pi N$$

This page has been accessed 2015 times.
Designed by Vincent Mathieu

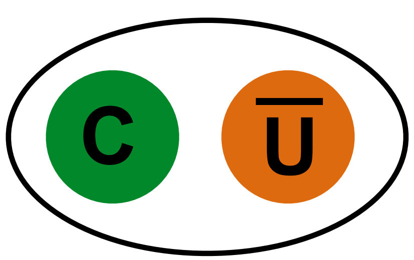
Heavy Quark Physics



$$M_{J/\psi} \sim 3.1 \text{ GeV}$$

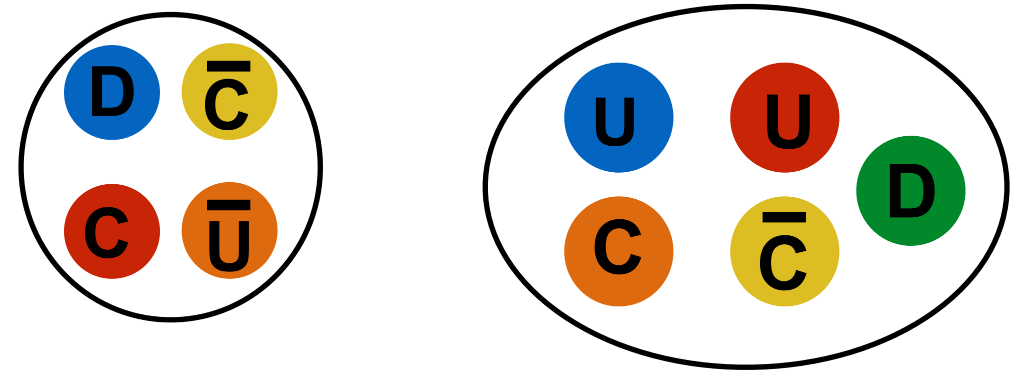


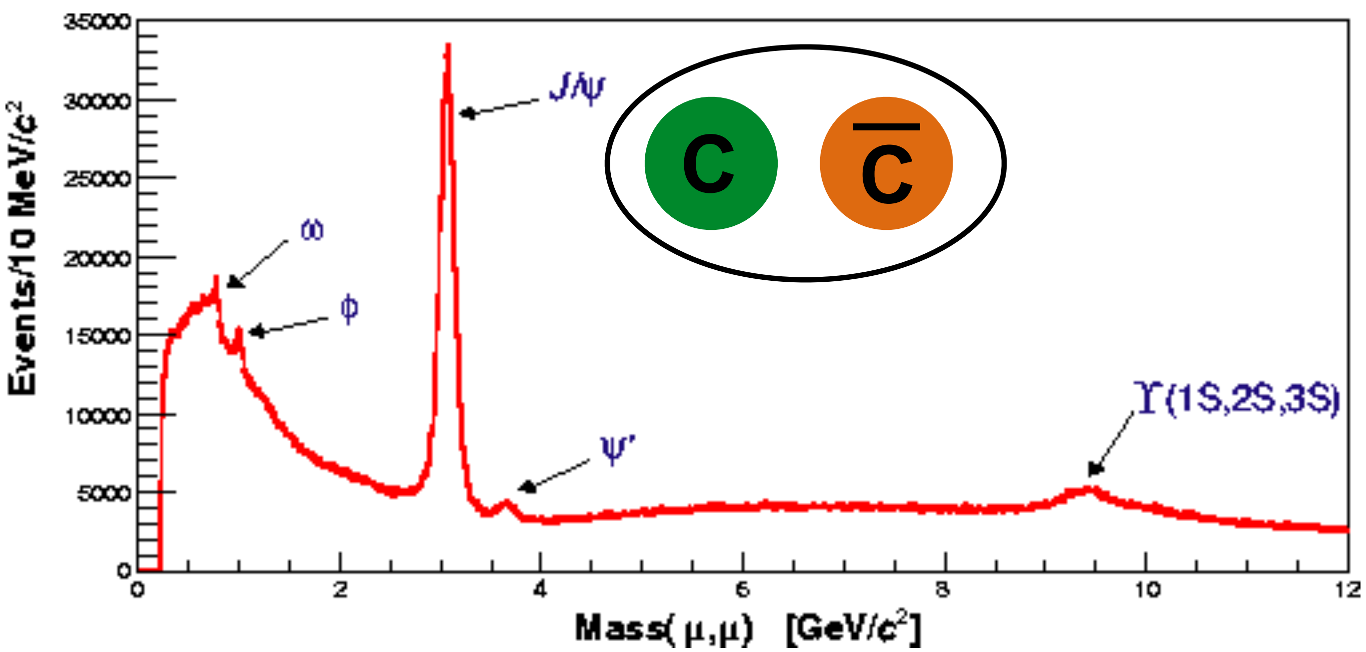
$$M_D \sim 1.9 \text{ GeV}$$



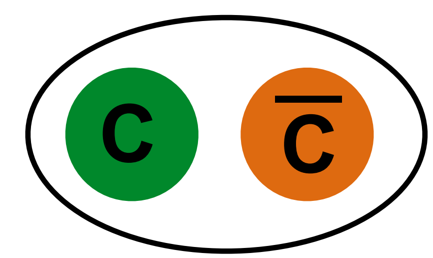
Heavy Quark Physics

Exotic matter with heavy quarks

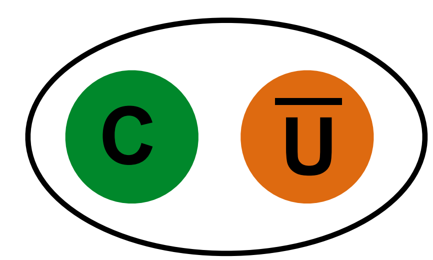




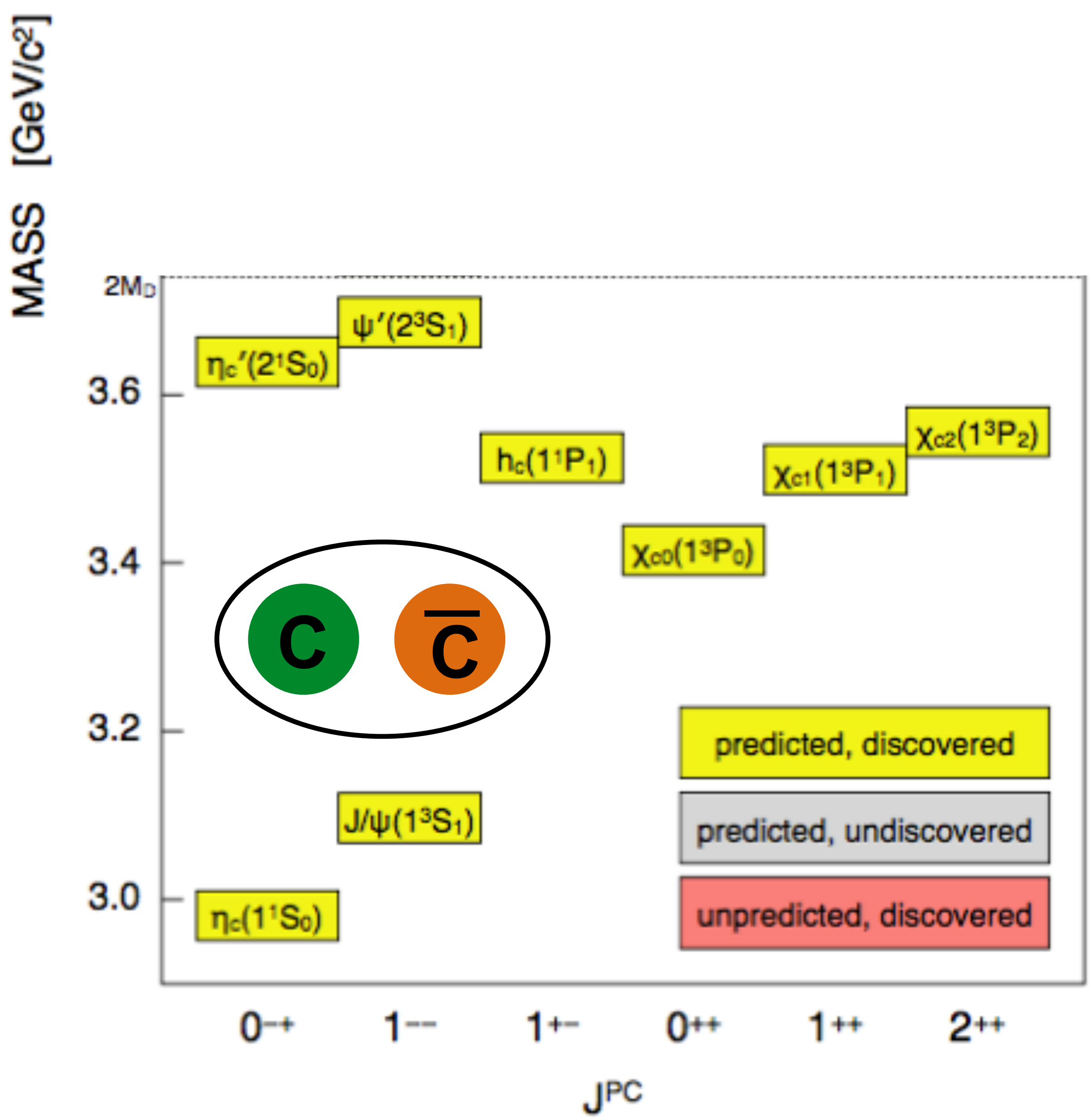
$M_{J/\psi} \sim 3.1 \text{ GeV}$



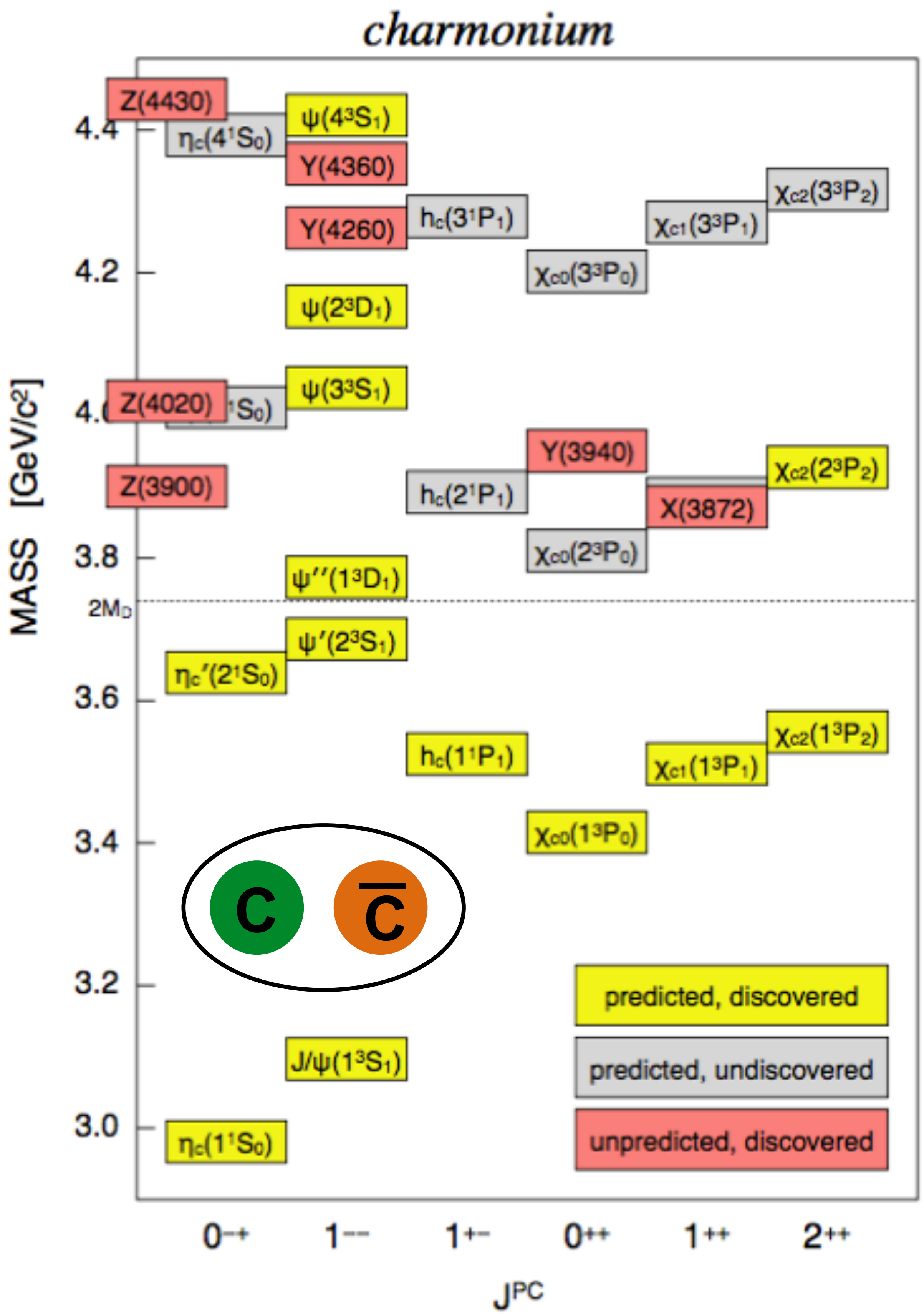
$M_D \sim 1.9 \text{ GeV}$



Introduction to Heavy Quark Exotica



Introduction to Heavy Quark Exotica



Q: What are heavy quark exotica?

A: Phenomena in the heavy quark sector that do not easily fit into the naive quark model picture of mesons and baryons.

Q: Why are they interesting?

A: They can be used to explore novel phenomena in QCD:

hybrid mesons, tetraquarks, pentaquarks, molecules, hadroquarkonium, thresholds

Q: Why are they called XYZ?

A: Mostly historical reasons.

But now there are patterns:

Z: electrically charged ($I = 1$).

Y: $J^{PC} = 1^{--}$, made directly in e^+e^-.

X: whatever is leftover.

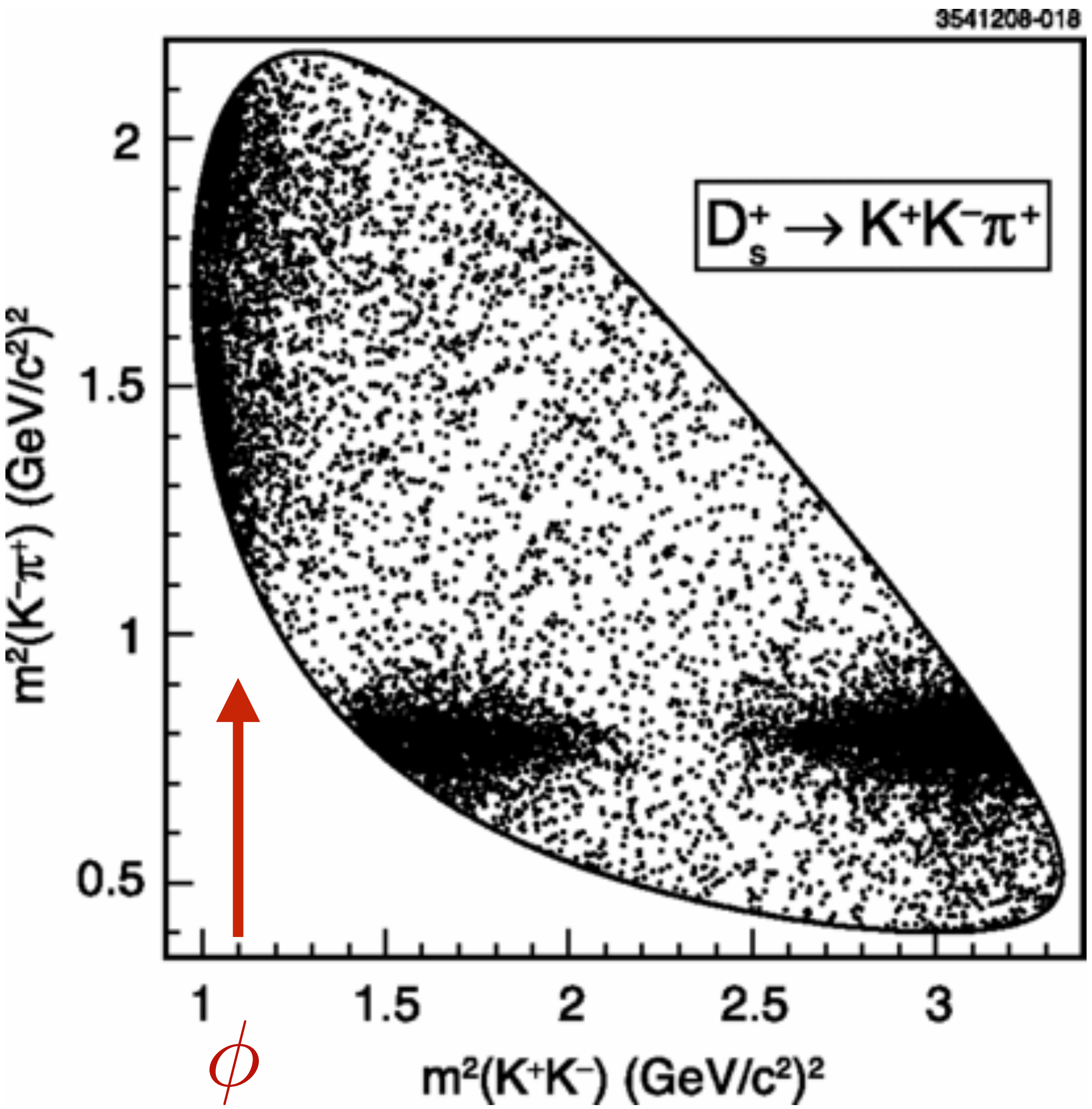
But there are many exceptions!

[The PDG will soon name them by IJ^{PC}.]

Q: How many have been found?

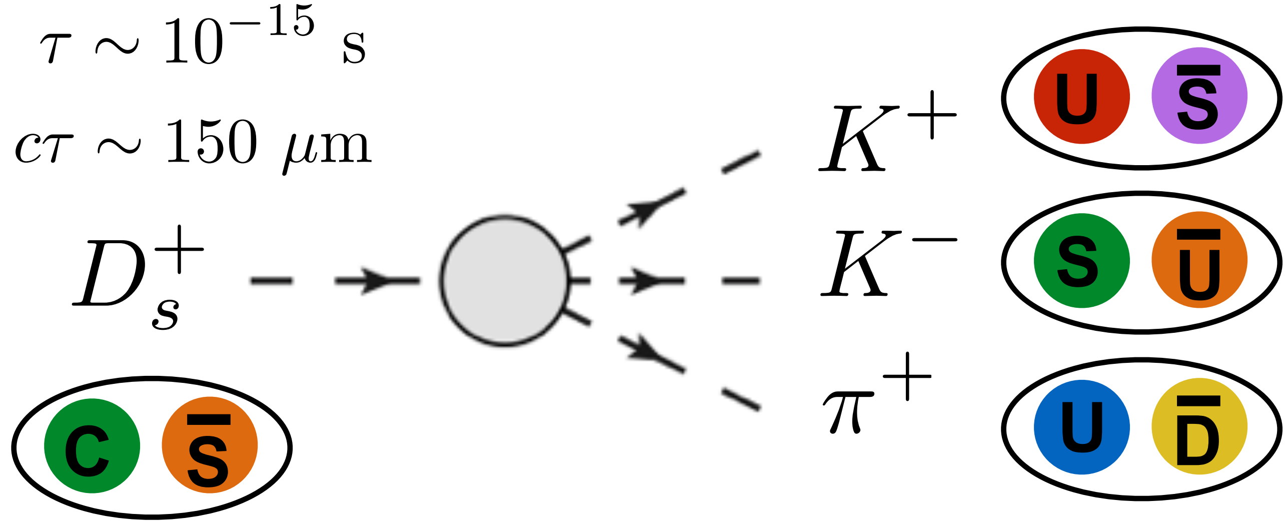
A: Many.

Dalitz Plot

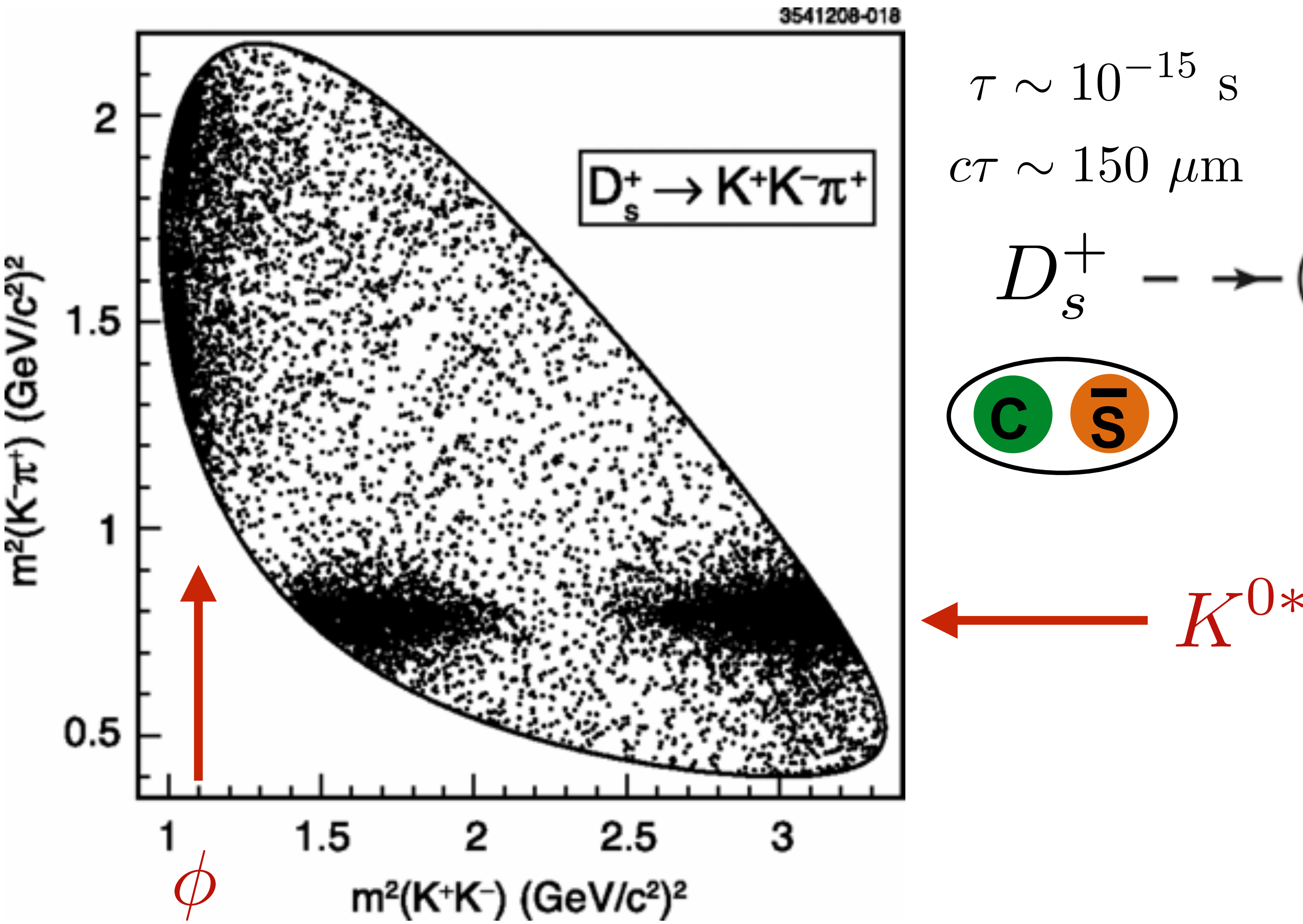


$\tau \sim 10^{-15}$ s

$c\tau \sim 150\ \mu m$



Dalitz Plot



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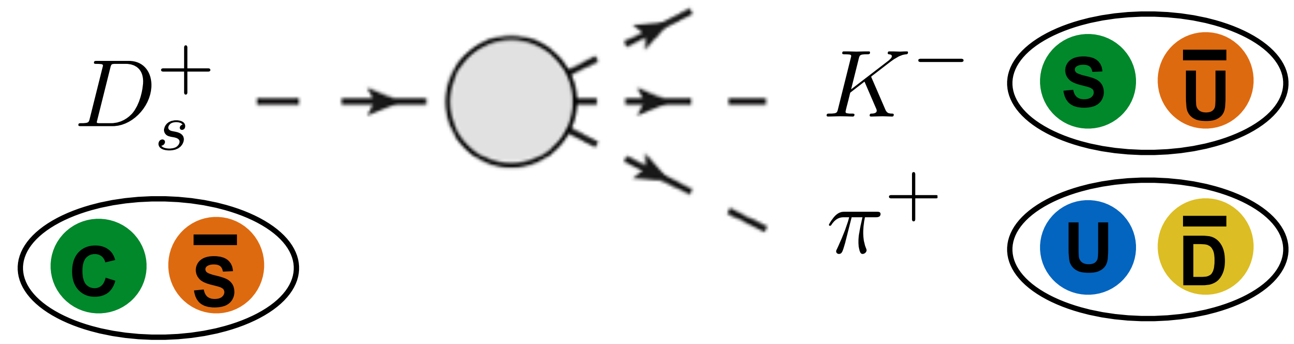
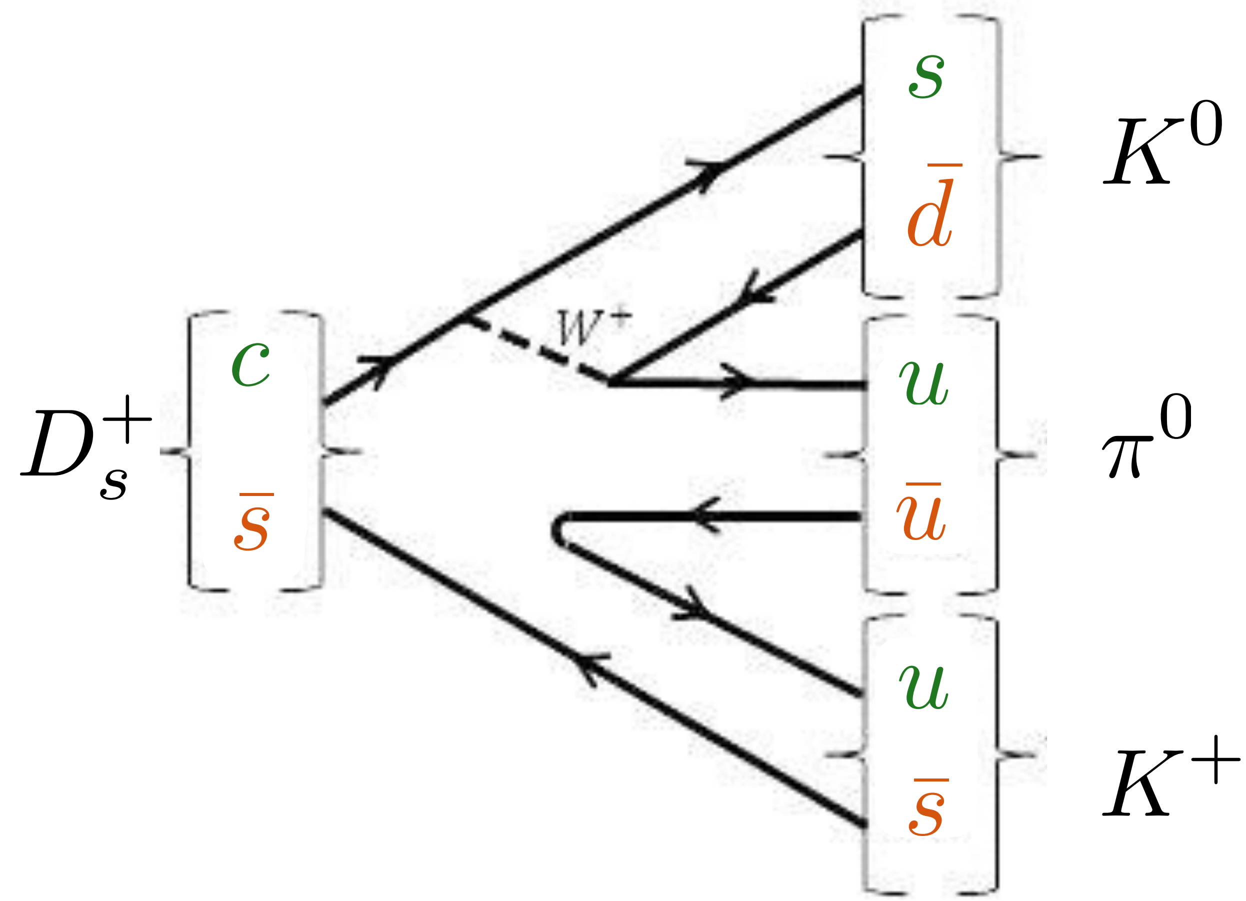
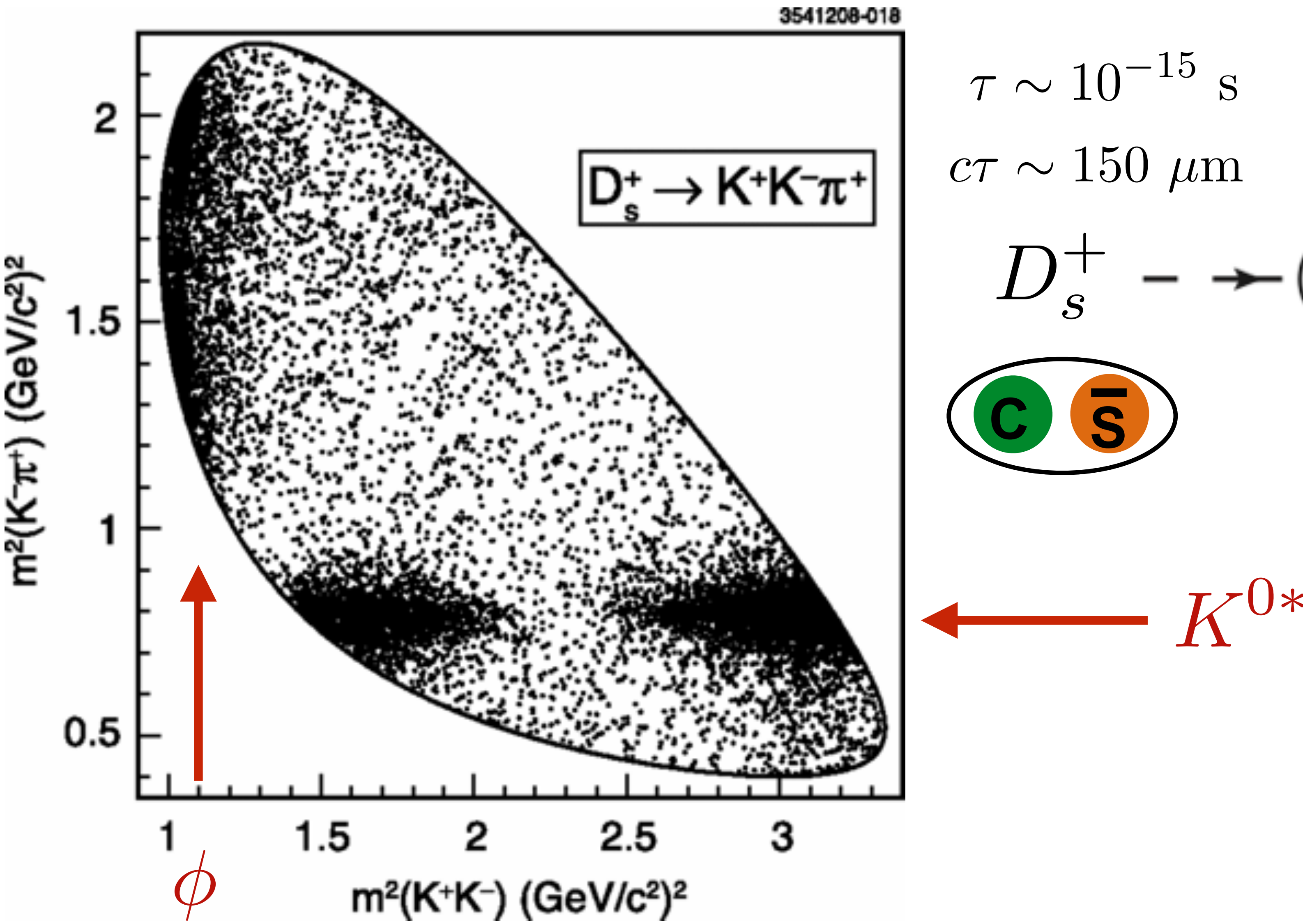


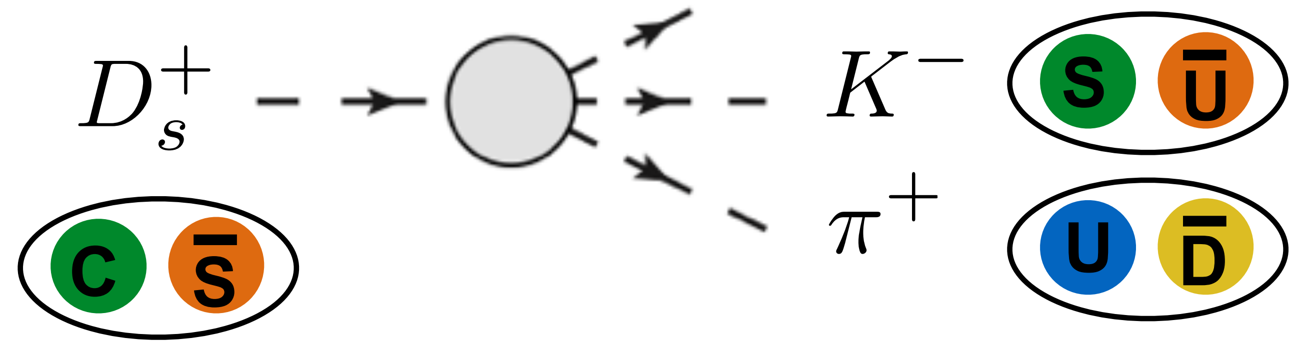


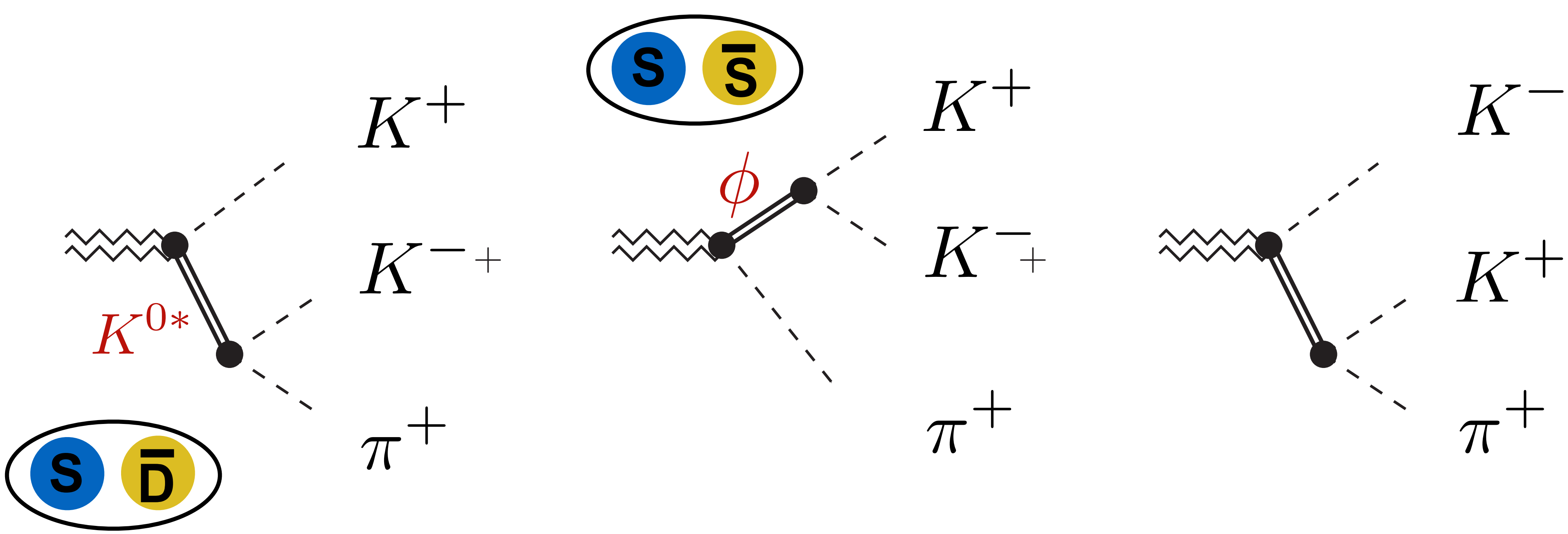
Dalitz Plot



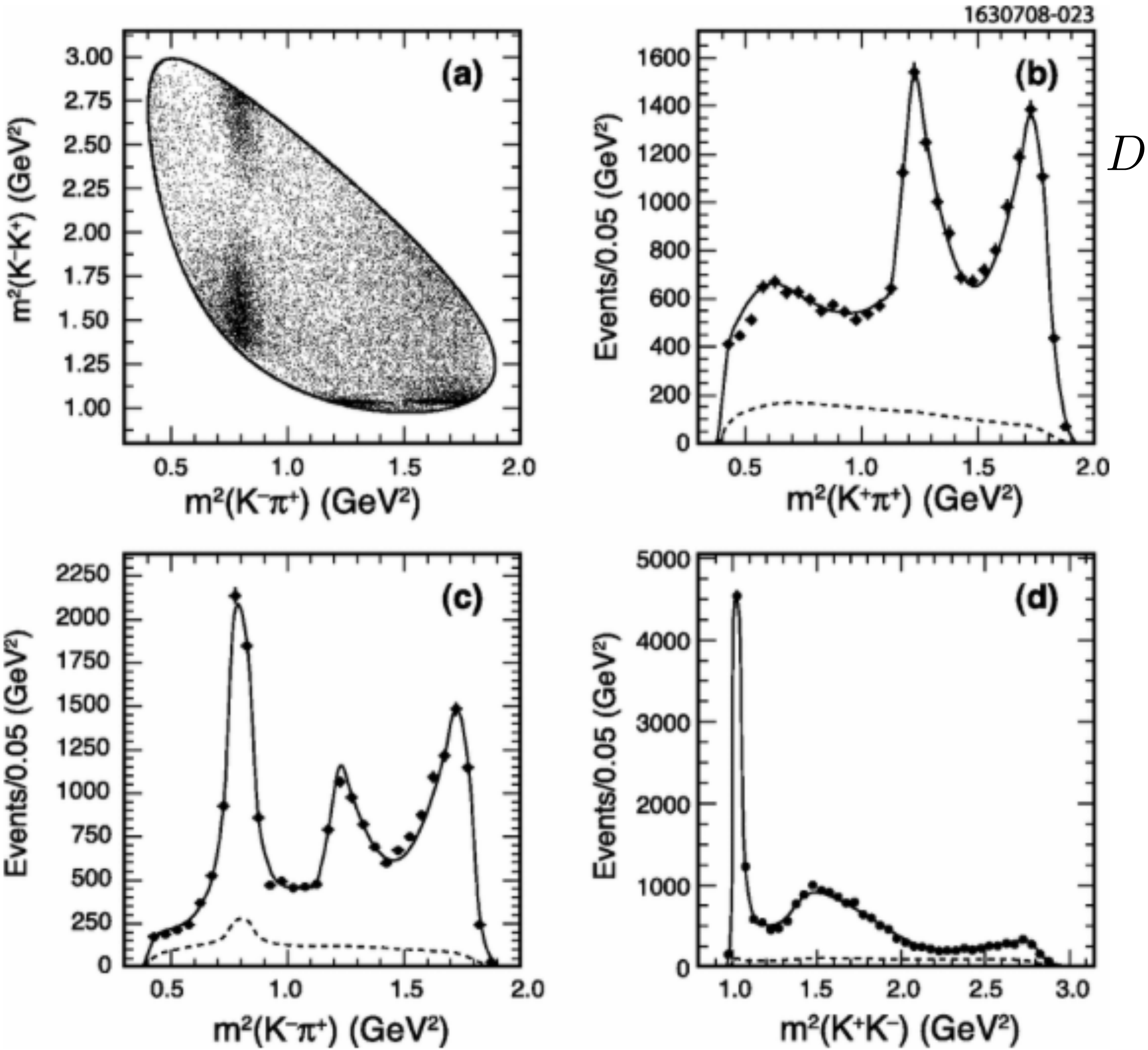
$\tau \sim 10^{-15}$ s

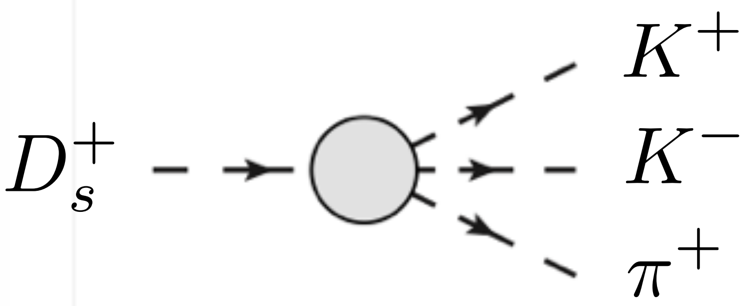
$c\tau \sim 150\ \mu$m

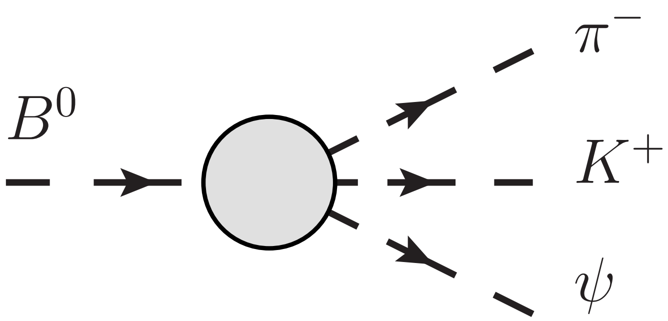




Dalitz Plot

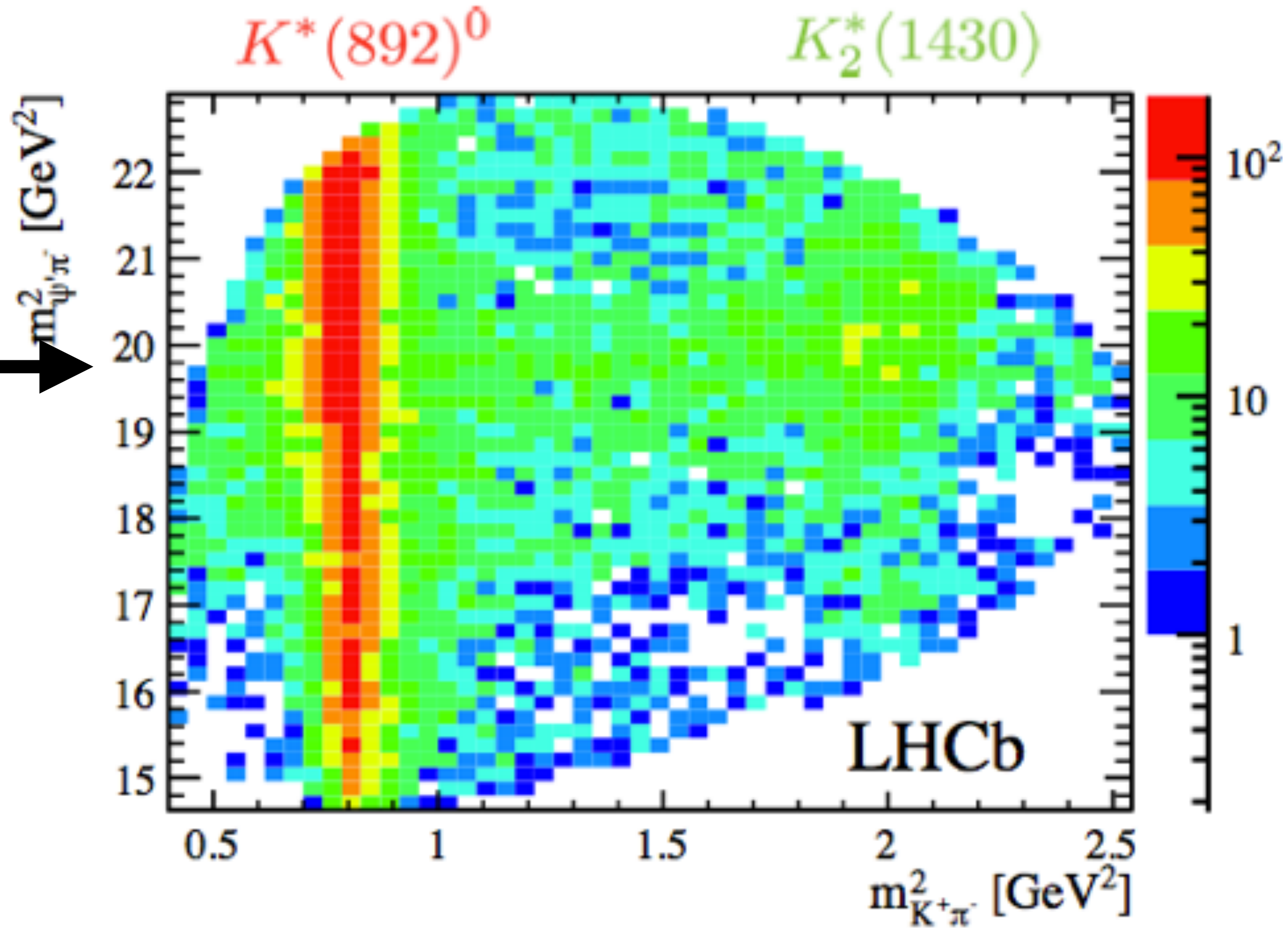

1630708-023
(a)
(b)
(c)
(d)
m²(K⁻K⁺) (GeV²)
m²(K⁻π⁺) (GeV²)
m²(K⁺π⁺) (GeV²)
m²(K⁺K⁻) (GeV²)
Events/0.05 (GeV²)


D_s^+
K^+
K^-
π^+

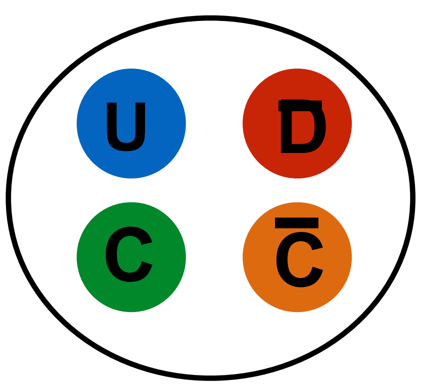


LHCb: 25.2k events

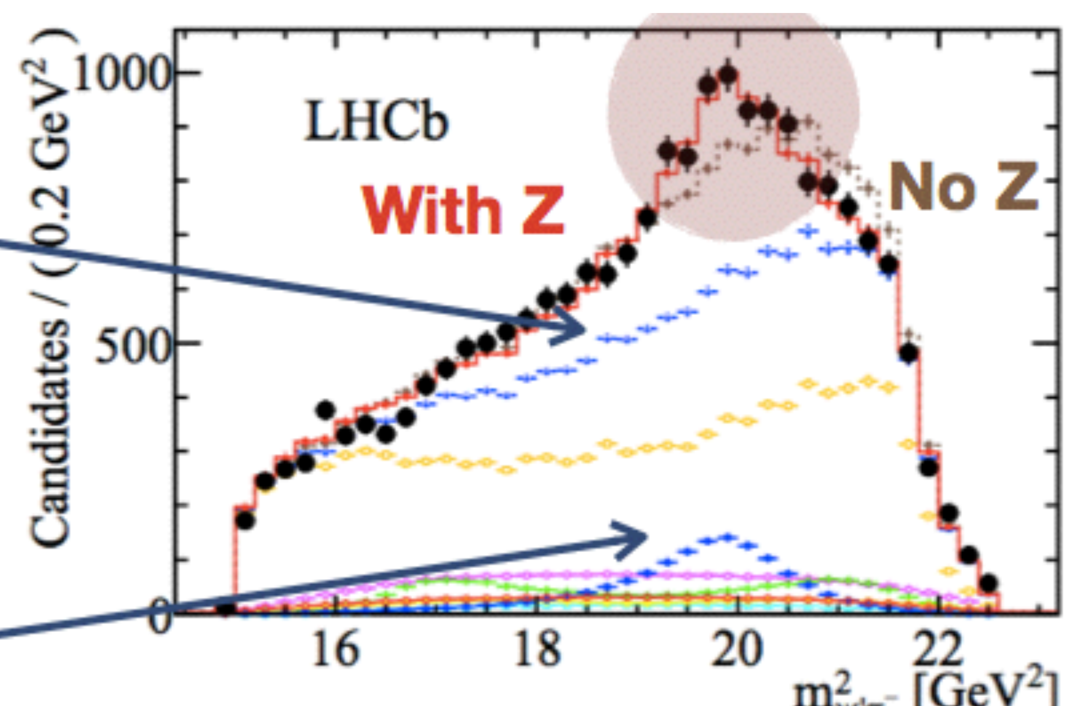
$Z(4430)^-$



Tetraquark ?



Everything except the Z ⇒ large interference between Z and $K^+\pi^-$ sector



$J^P = 1^+$
Z component

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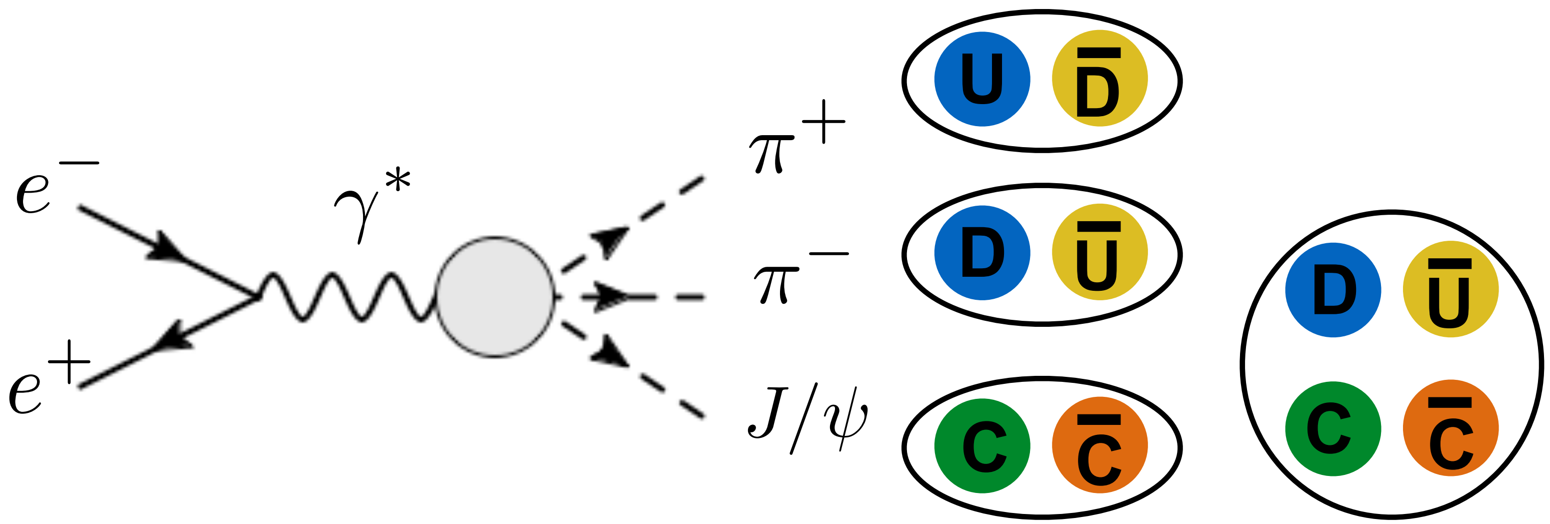
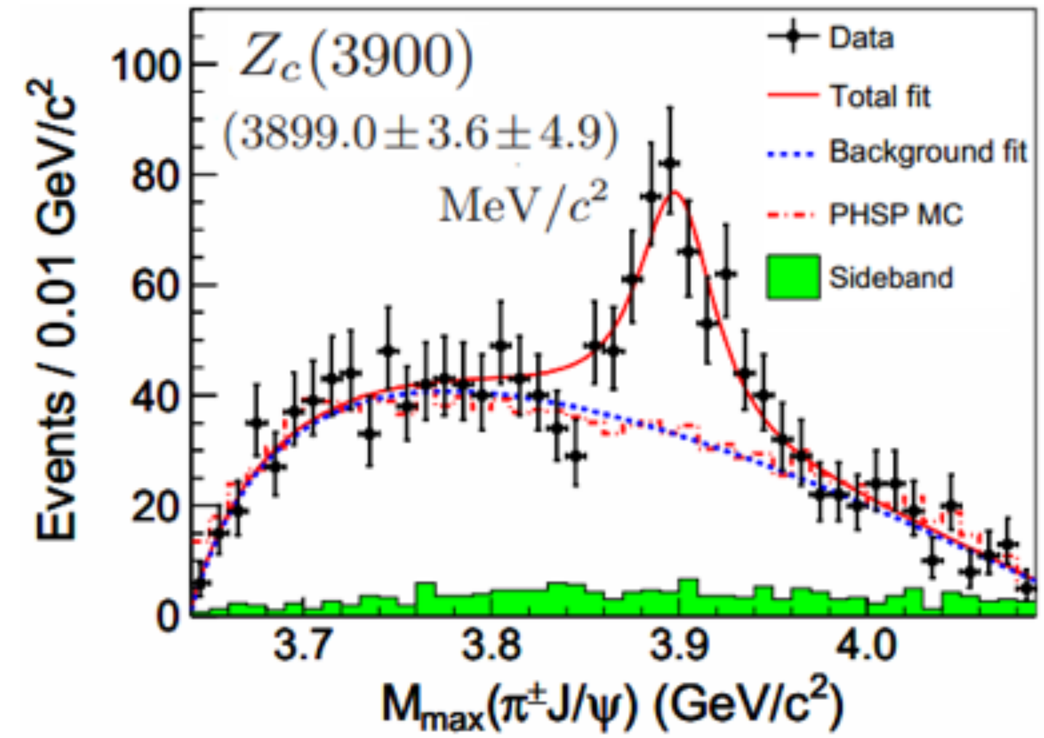
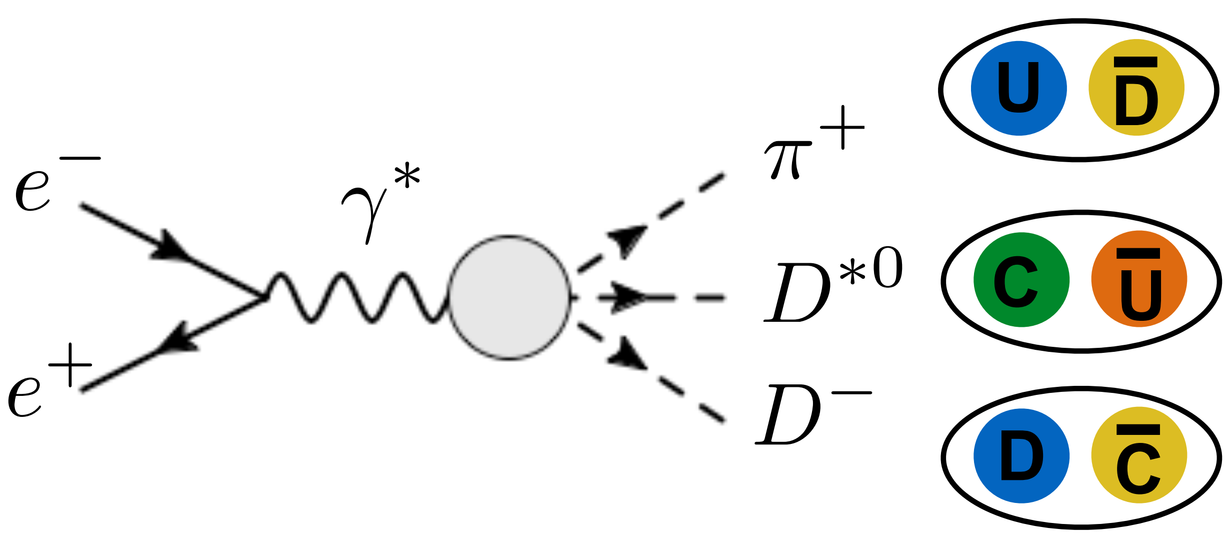
Z(3900)@Belle/BESIII

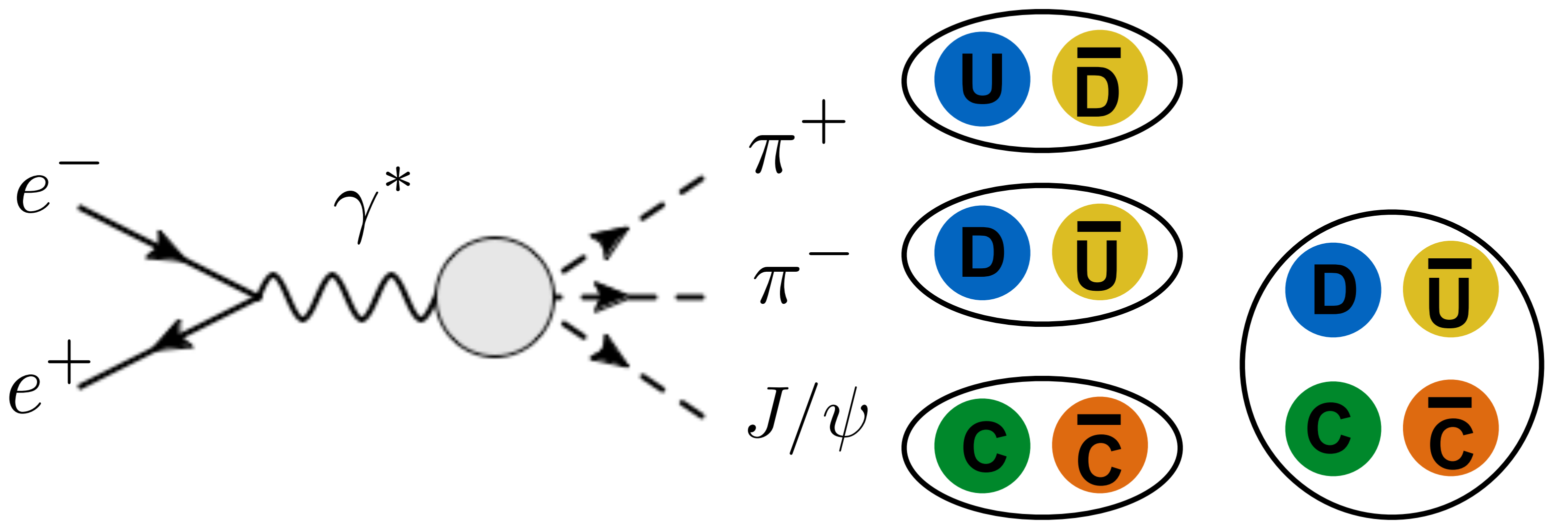


BESIII PRL 110 (2013)

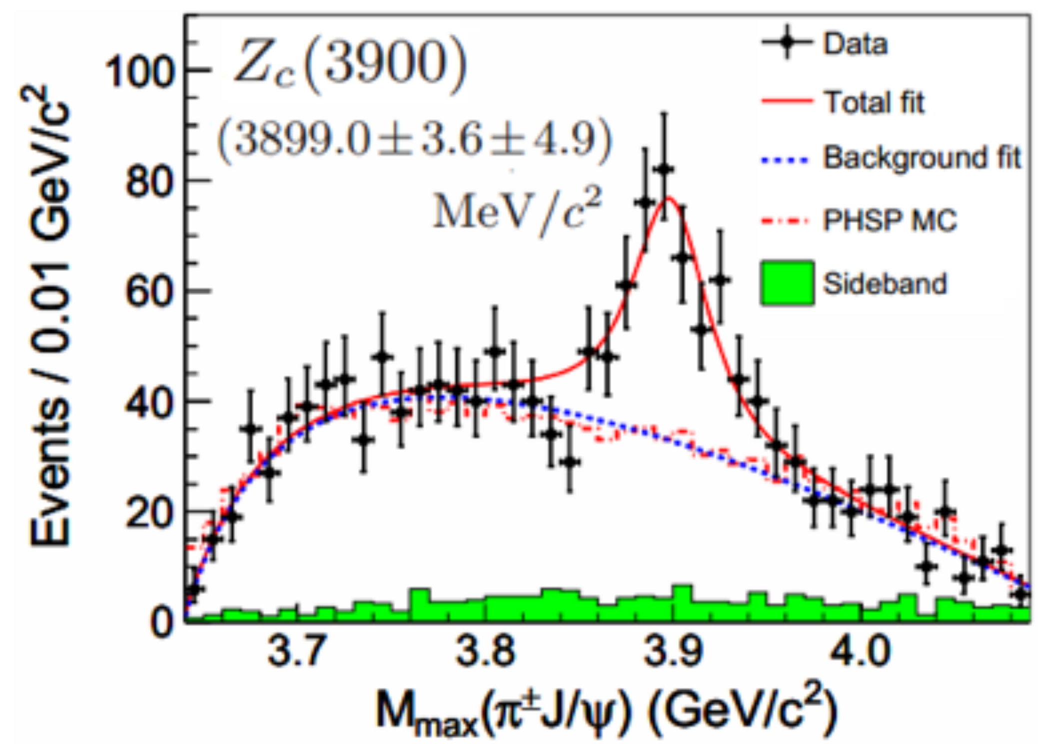


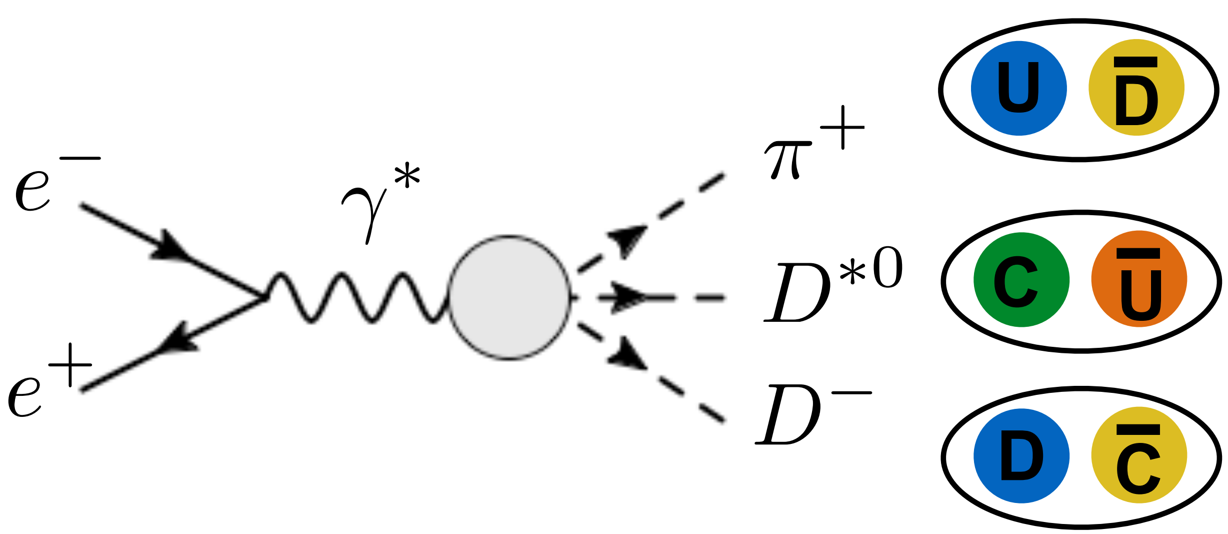


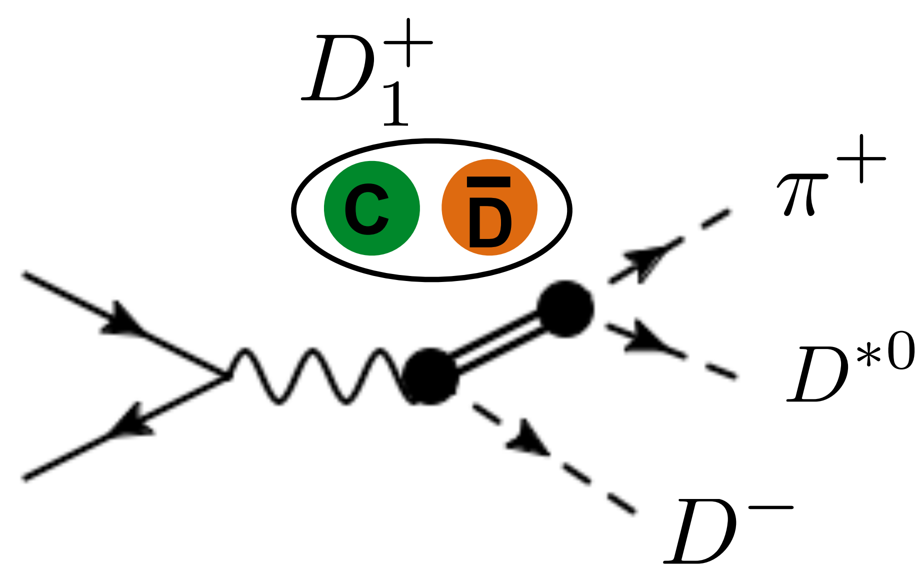
Z(3900)@Belle/BESIII



BESIII PRL 110 (2013)

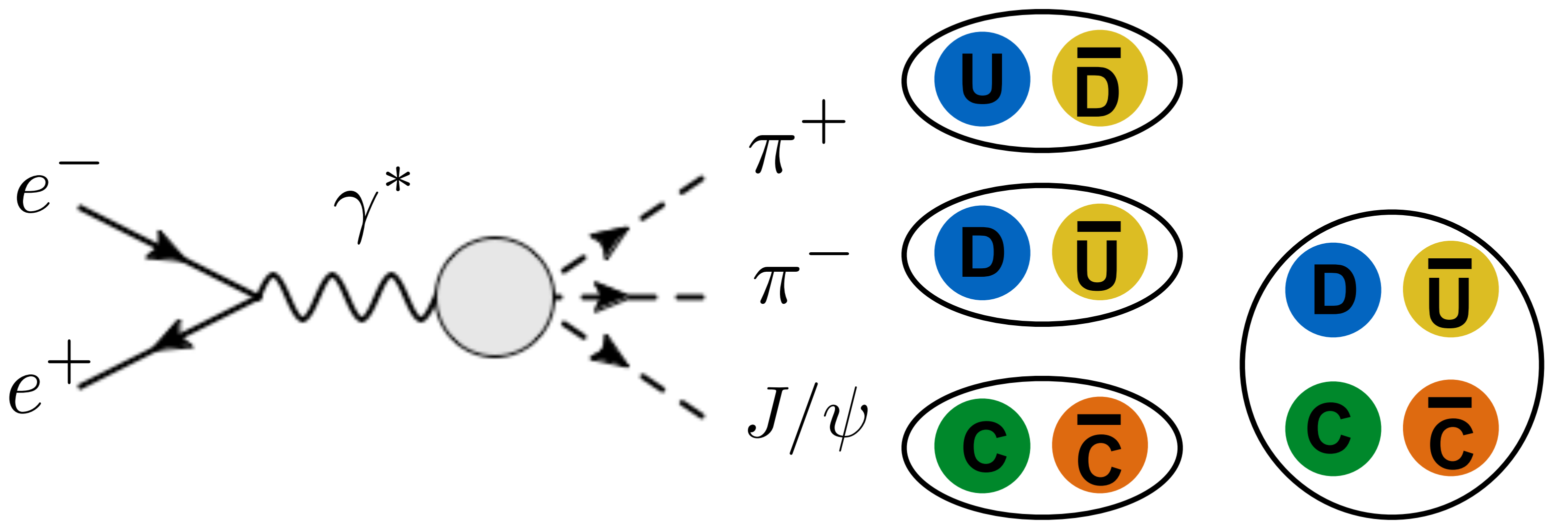






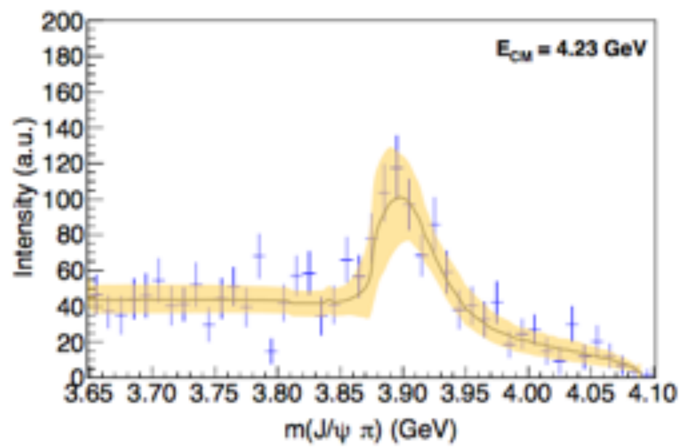
Z(3900)@Belle/BESIII

Pilloni et al (JPAC) PLB 772 (2017)

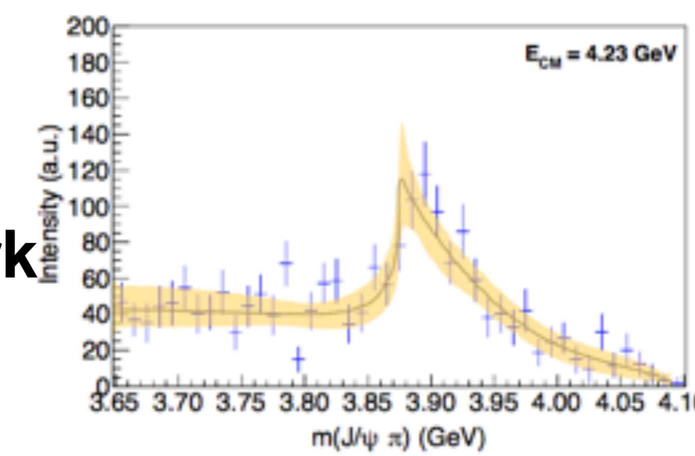


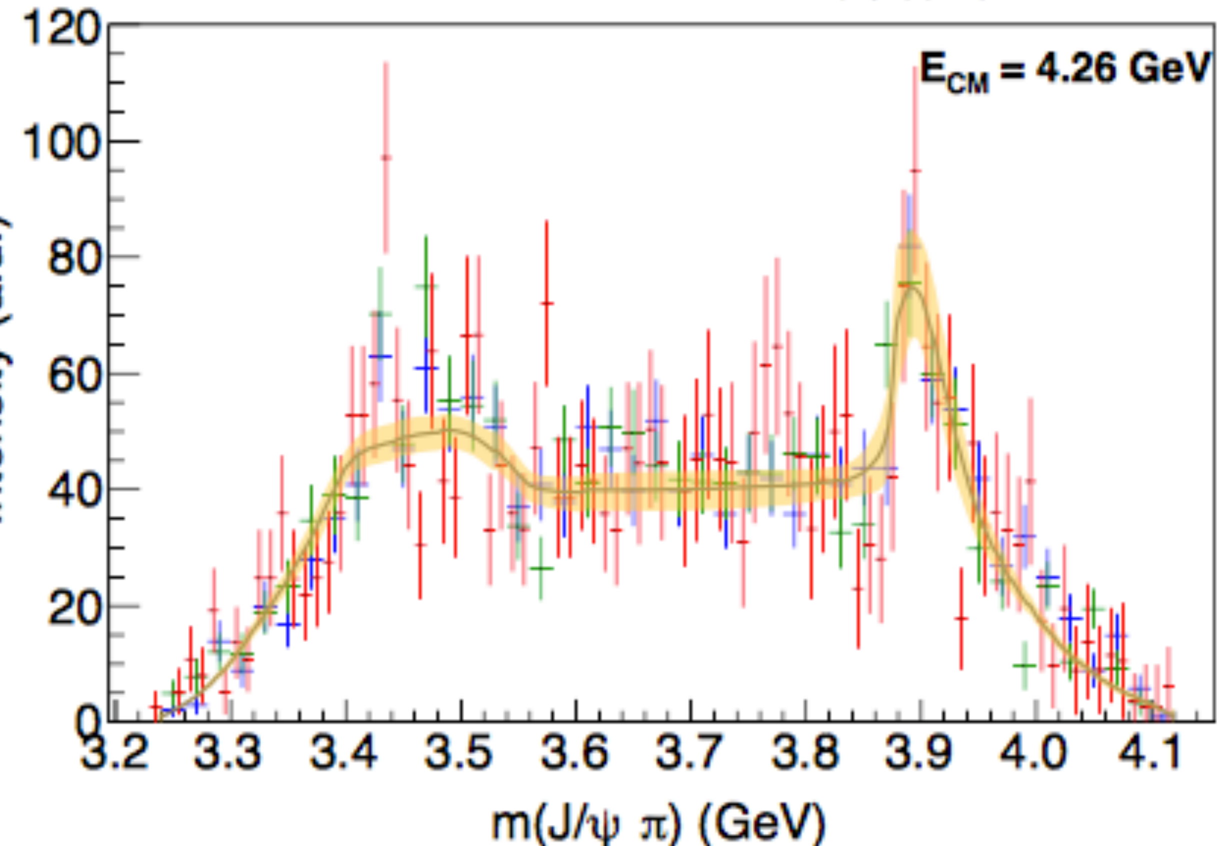
More data (coming soon !) to draw firm conclusion

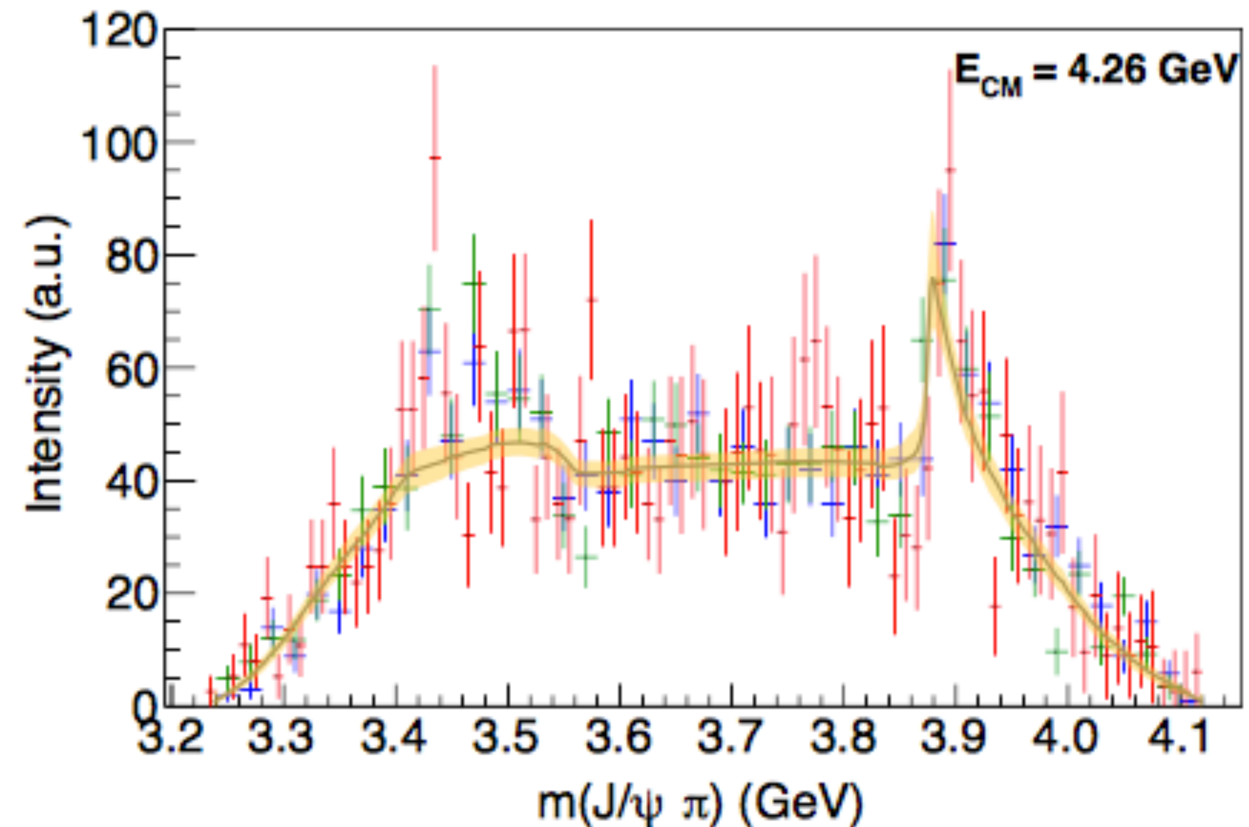
with tetraquark



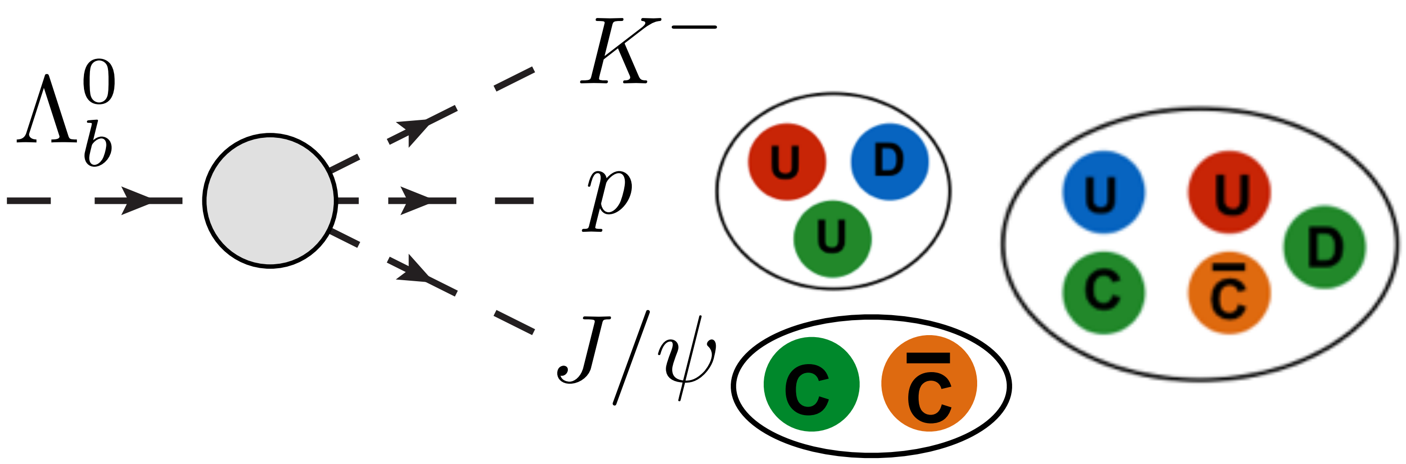
without tetraquark

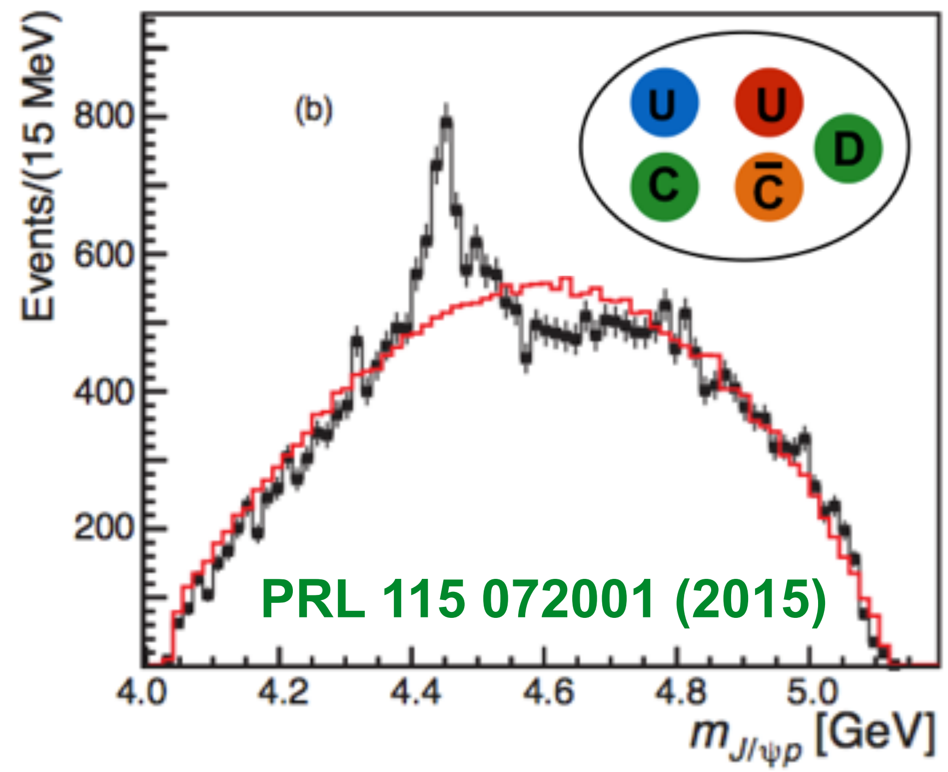






Pentaquark@LHCb





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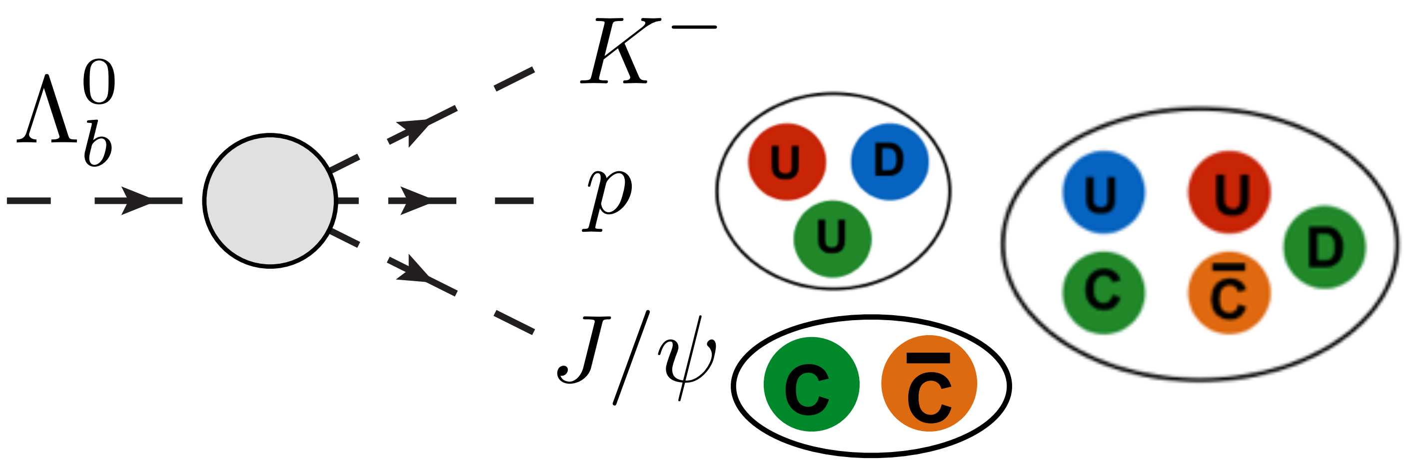
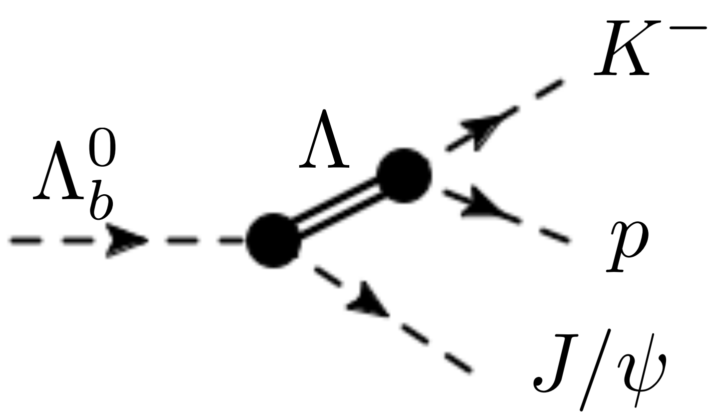
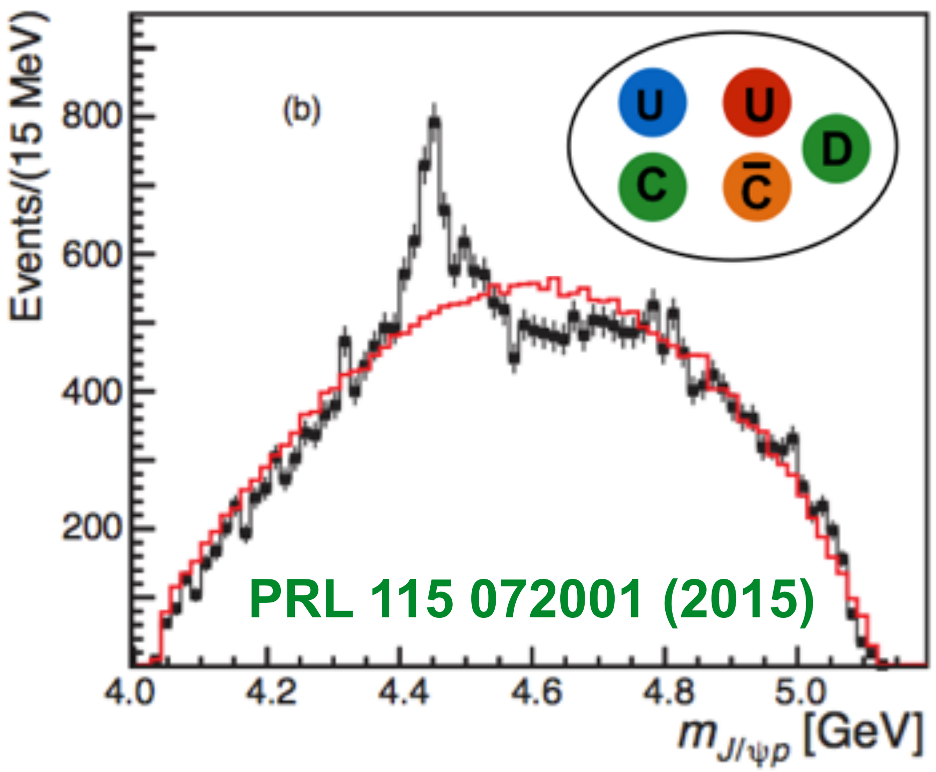
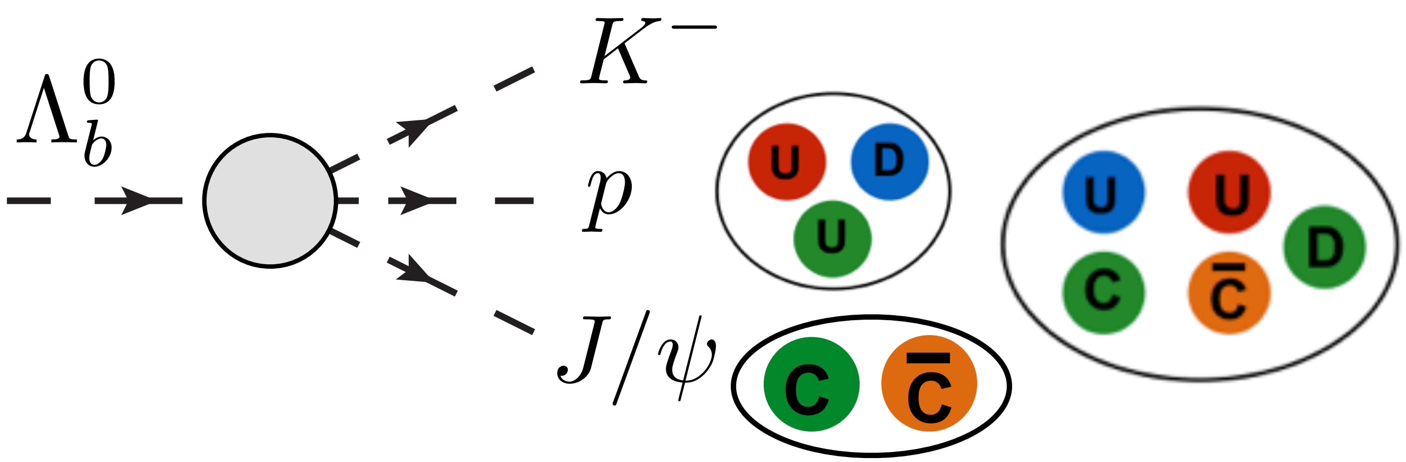
Pentaquark@LHCb

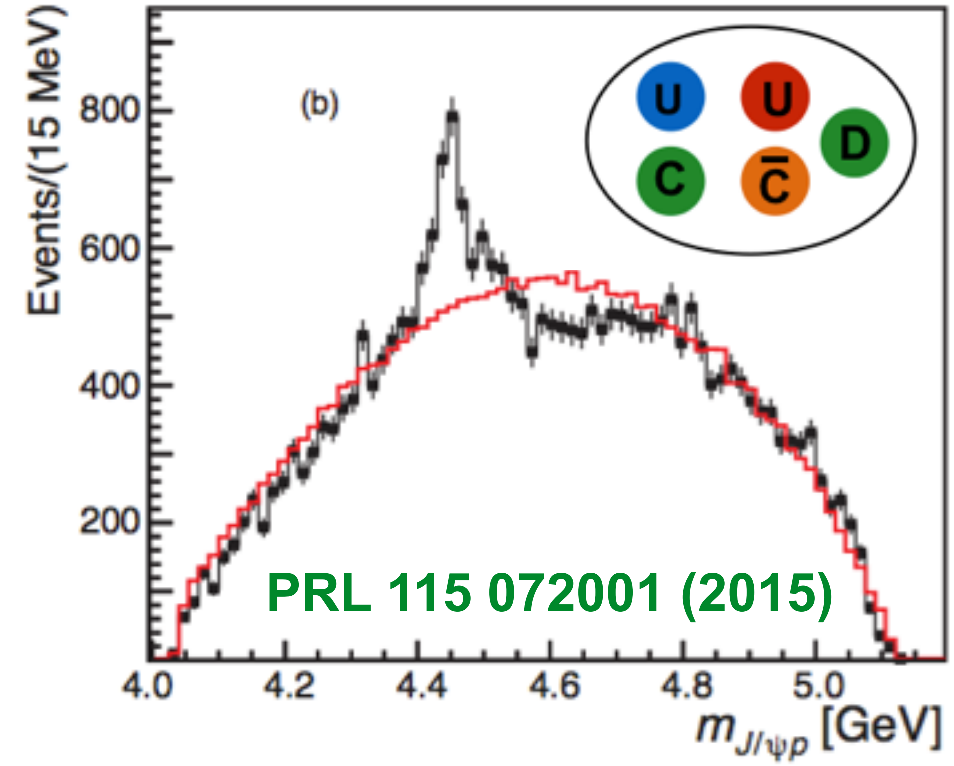


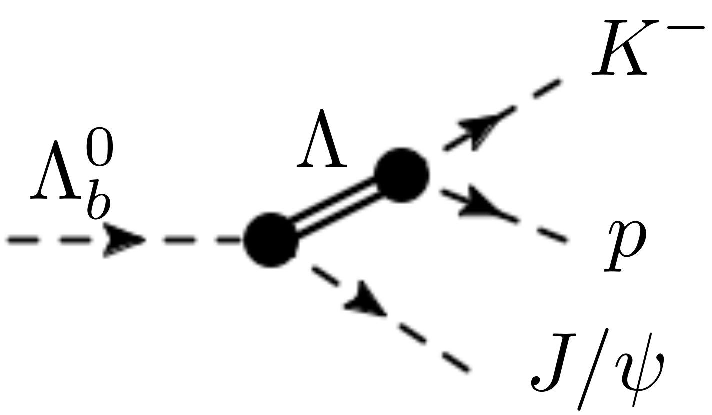


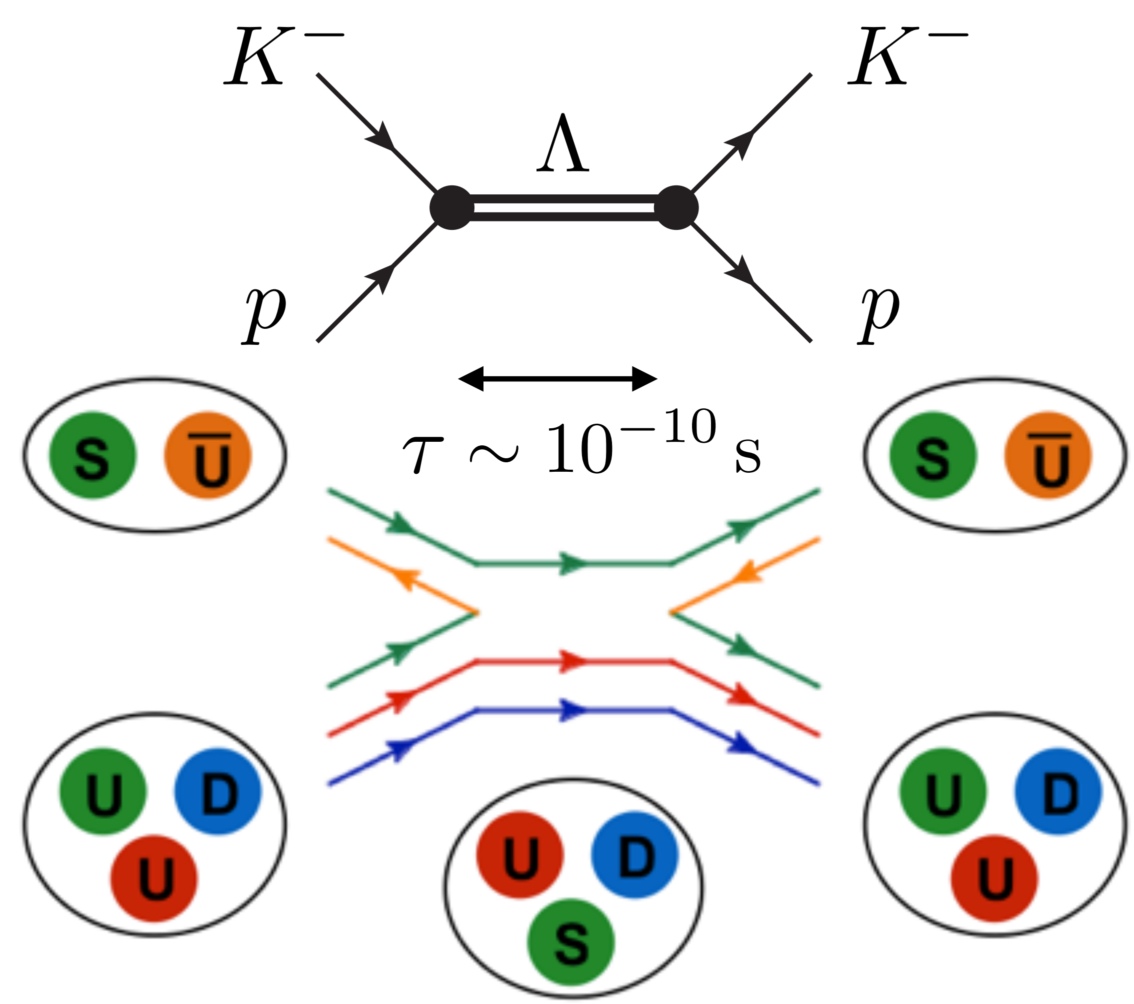


Pentaquark@LHCb

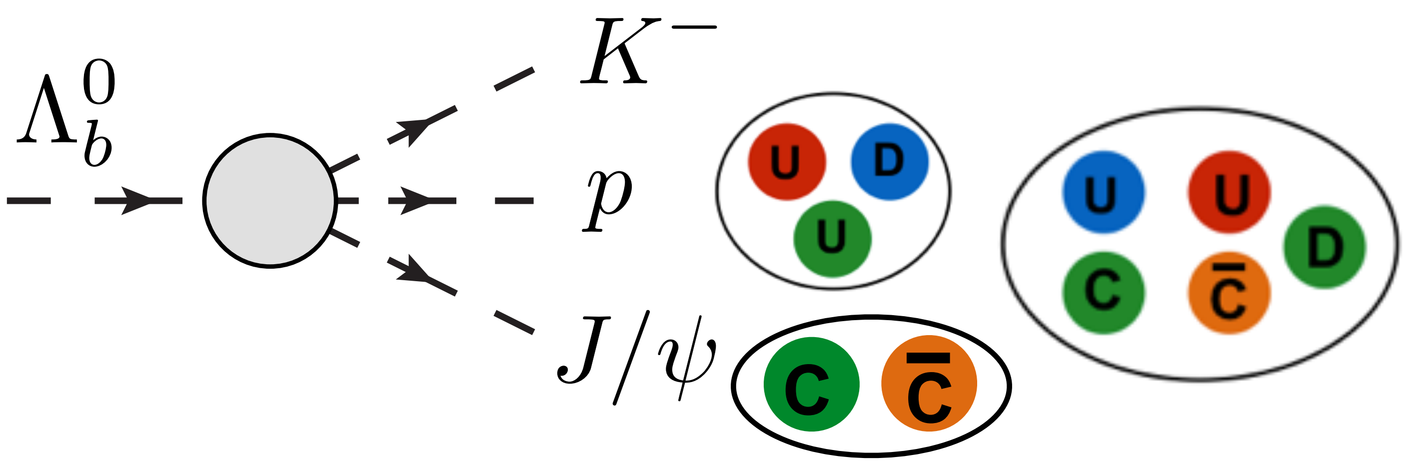


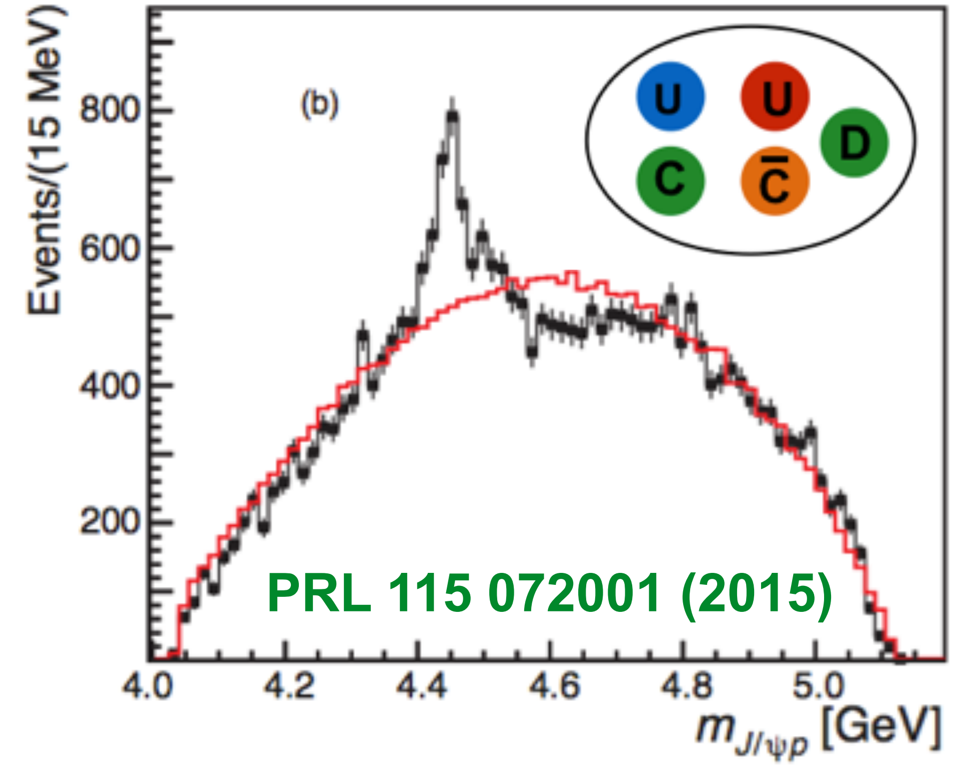


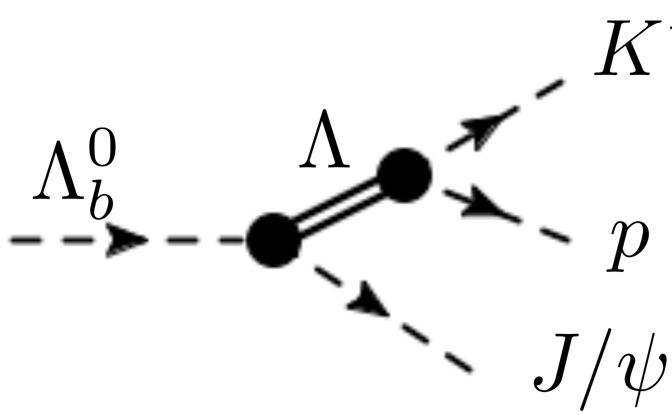


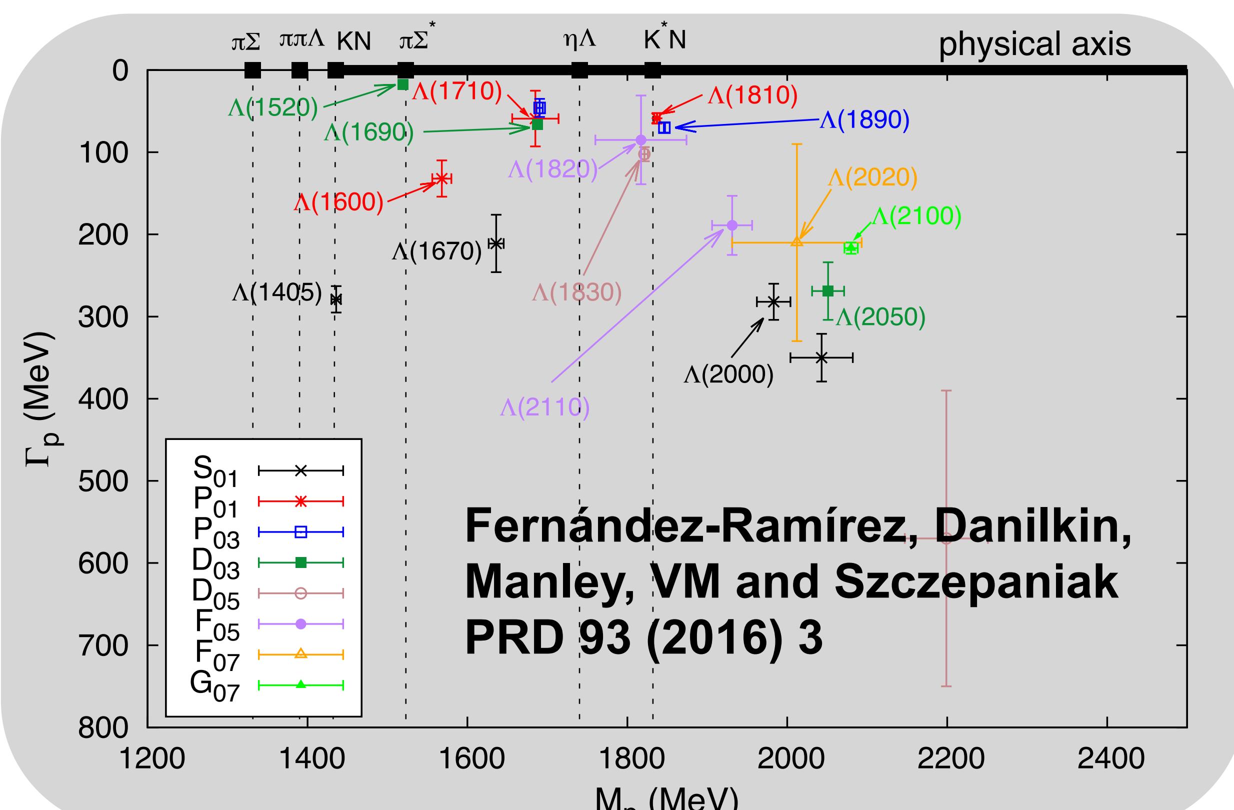


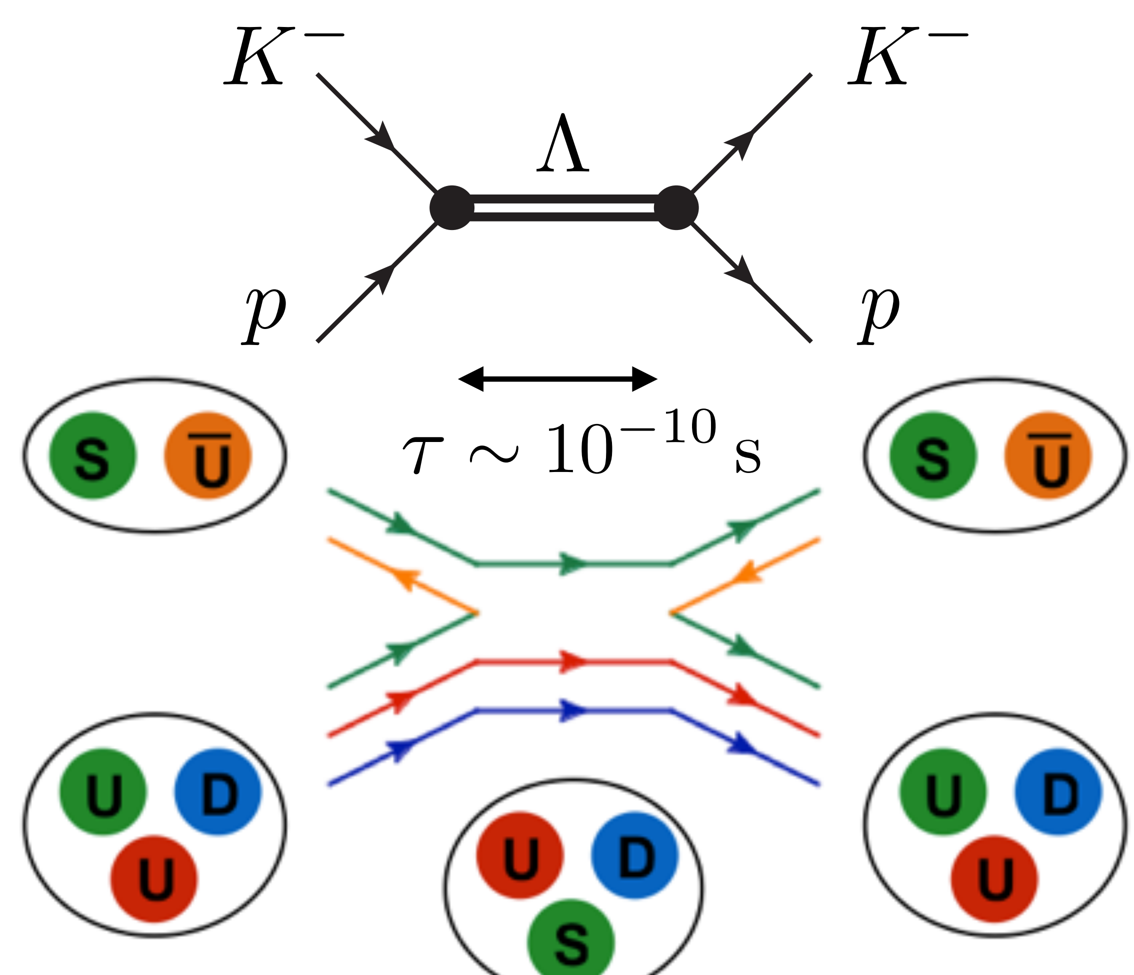
Pentaquark@LHCb



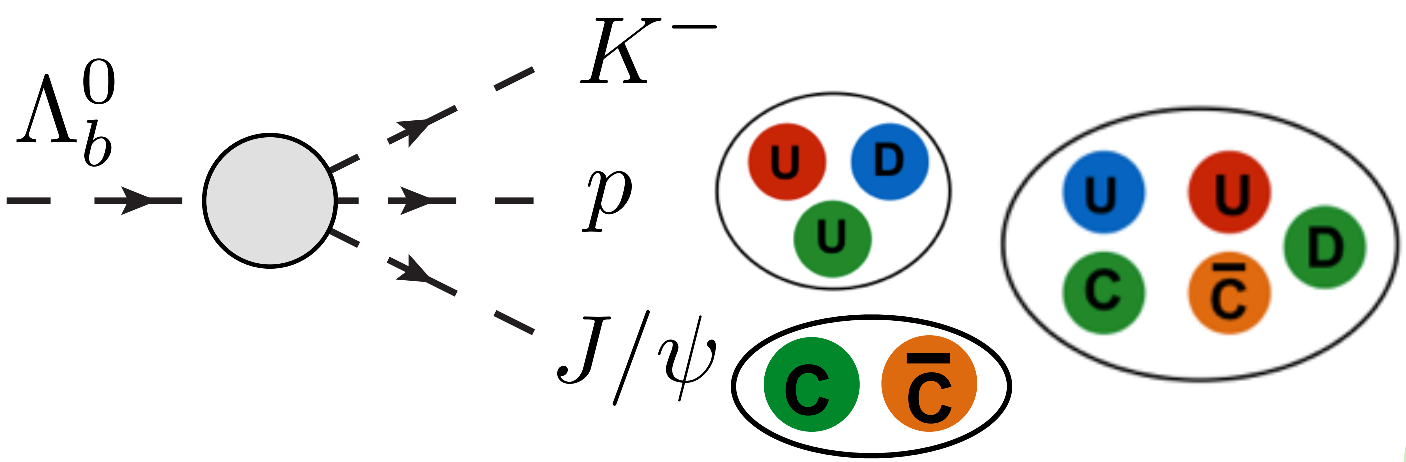


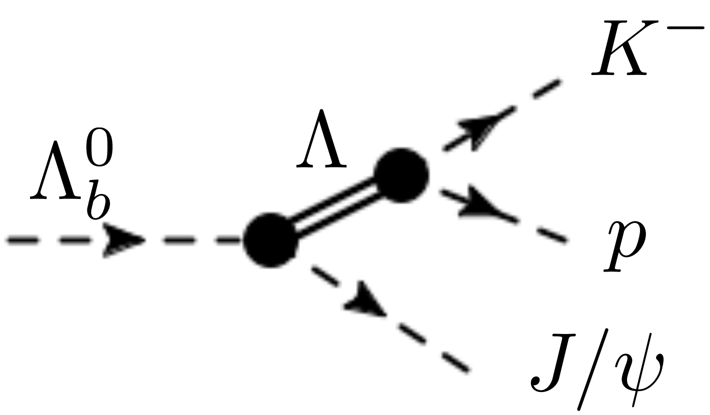


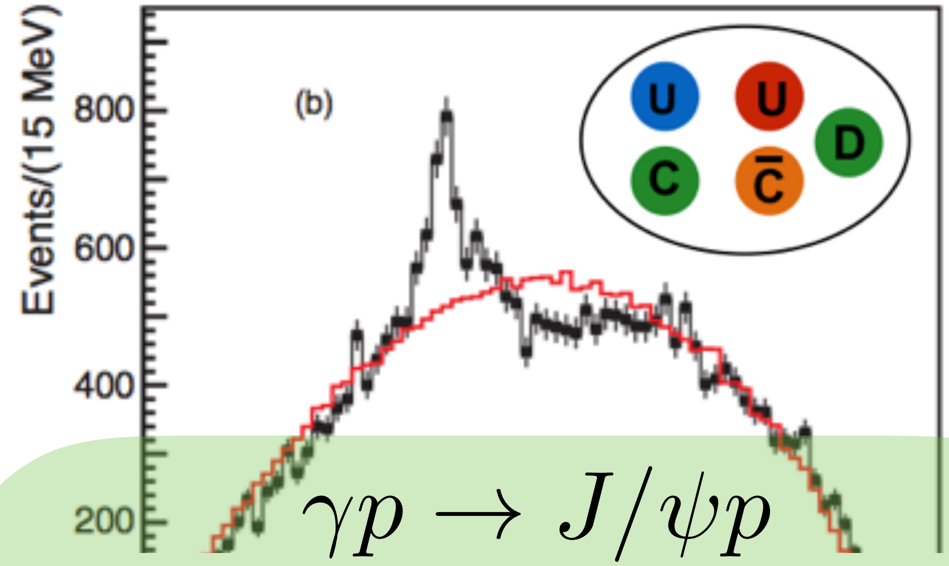


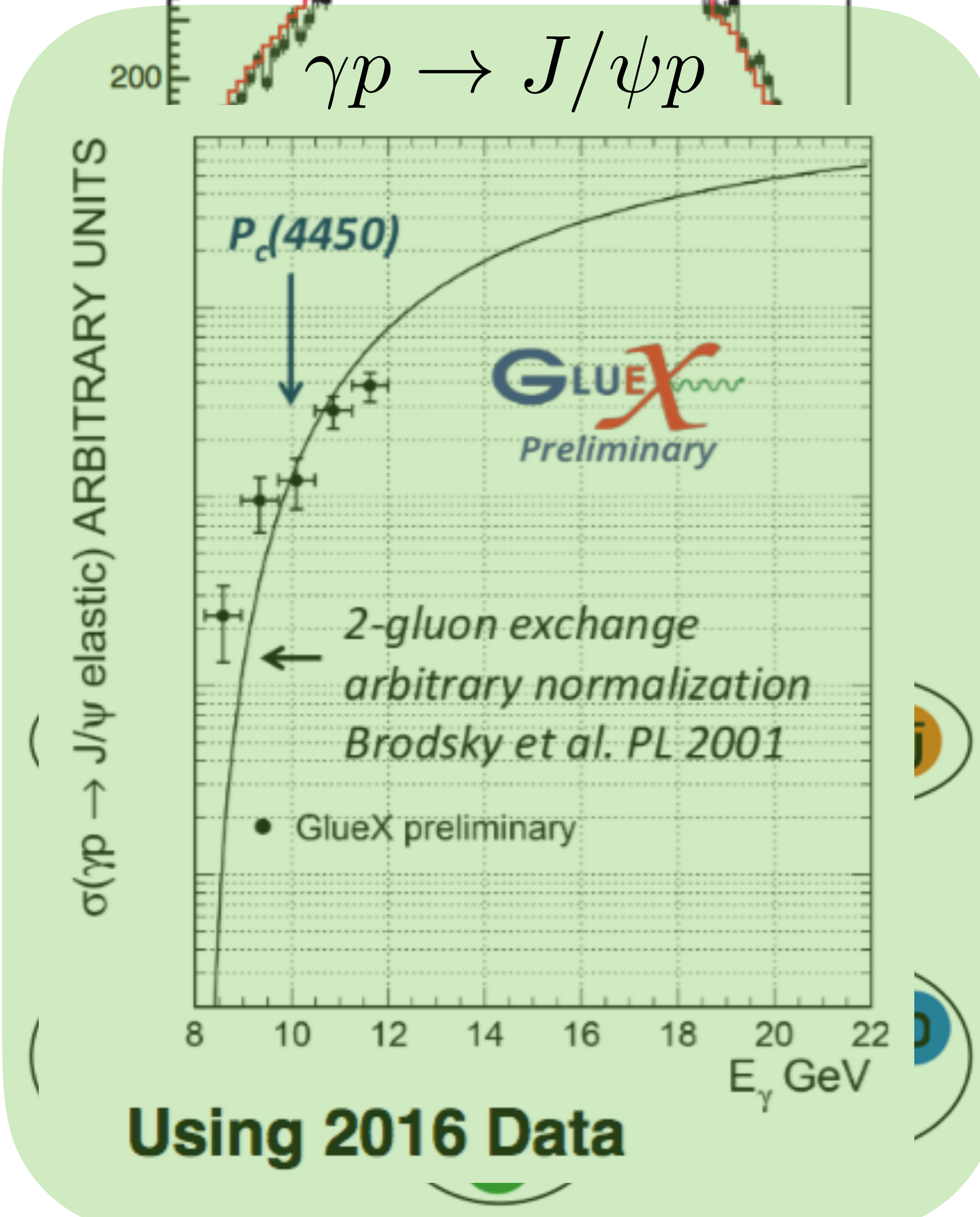


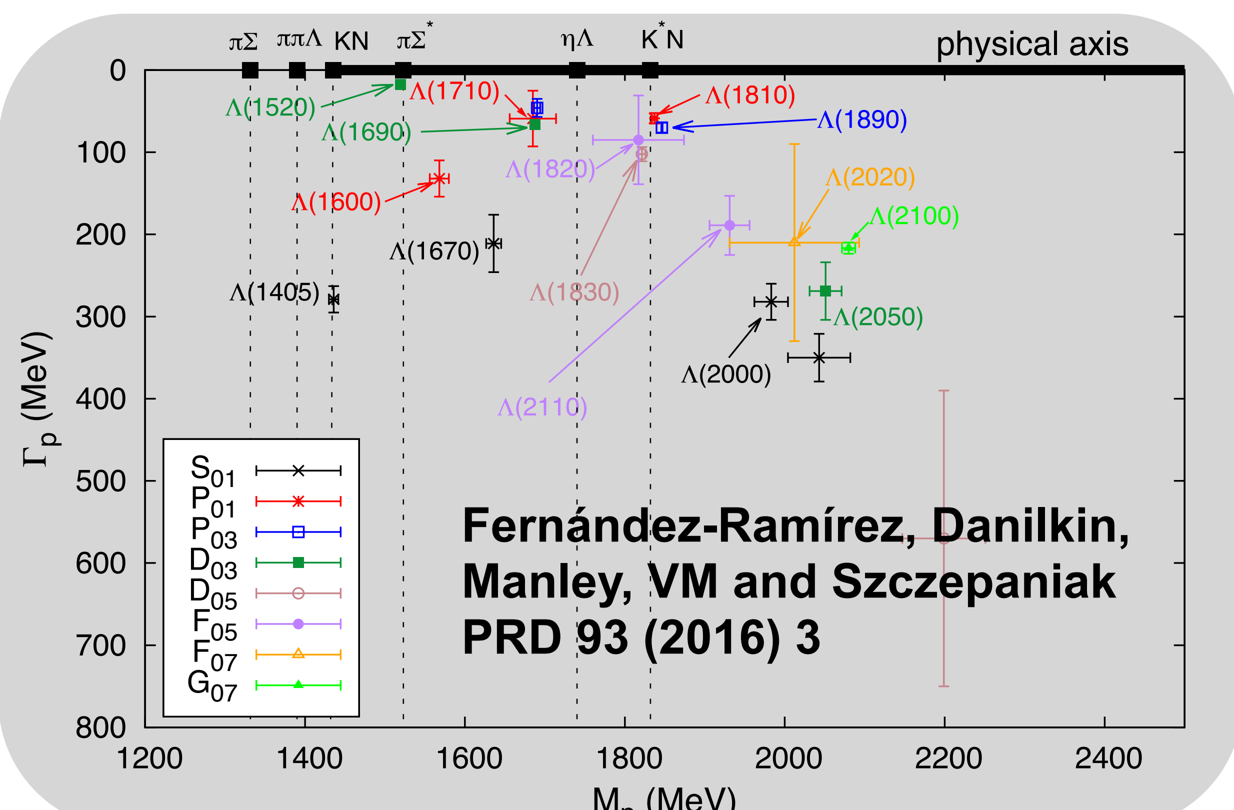
Pentaquark@LHCb







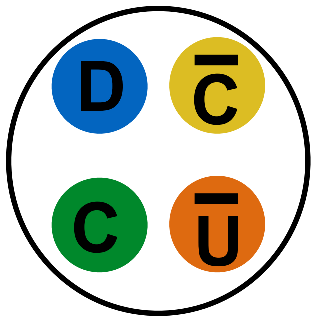


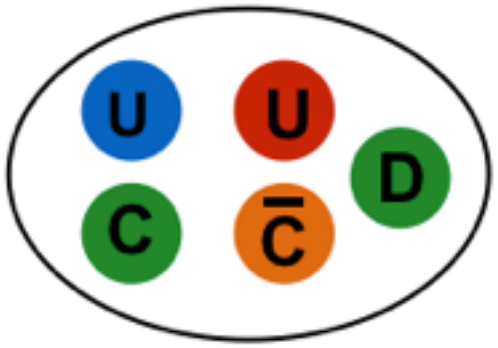


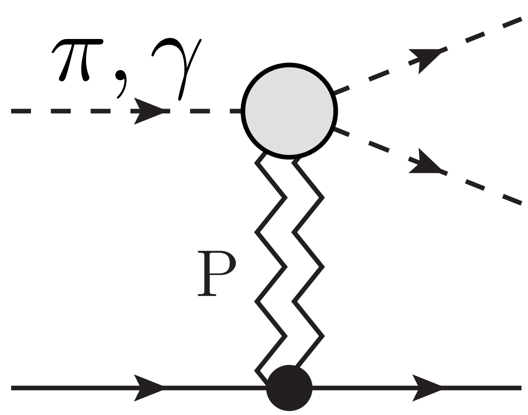
Summary

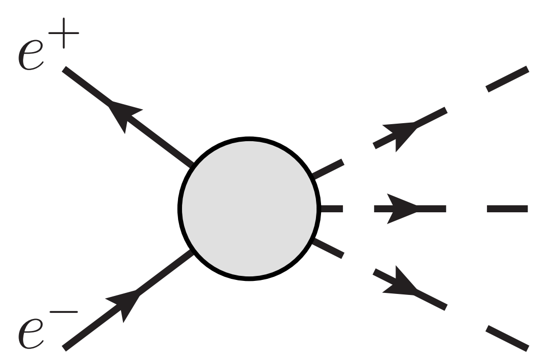
Several hadronic experiments are currently undergoing

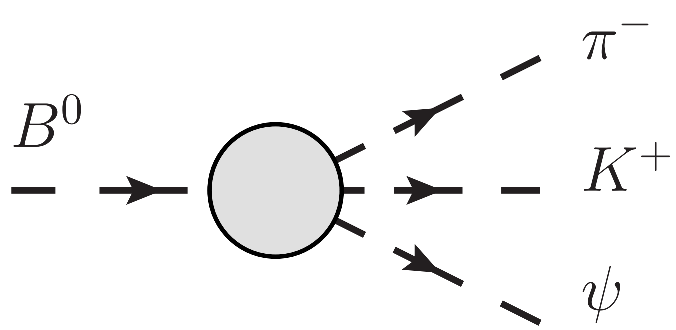
There are hints of exotic resonances
but detailed analysis are required











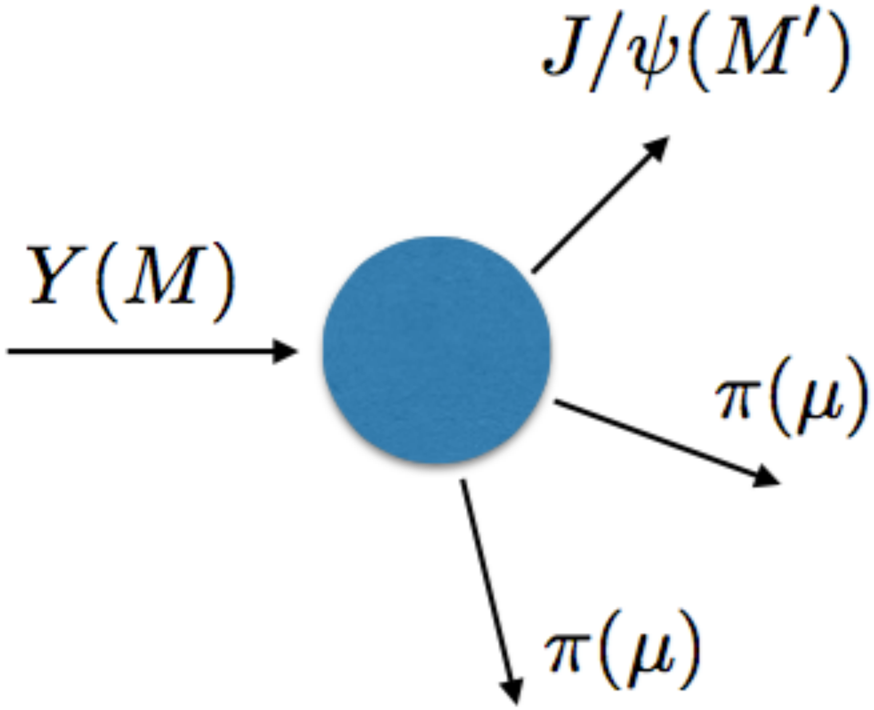
COMPASS clas GlueX BESIII LHCb

Interactive webpage: **http://www.indiana.edu/~jpac/index.html**

INDIANA UNIVERSITY NSF

Backup Slides

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



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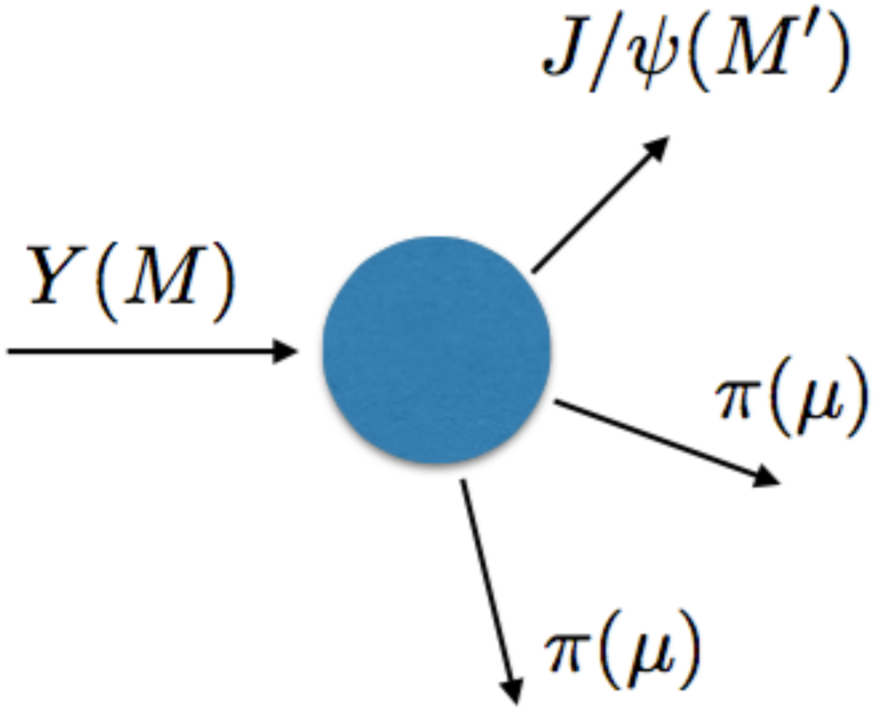

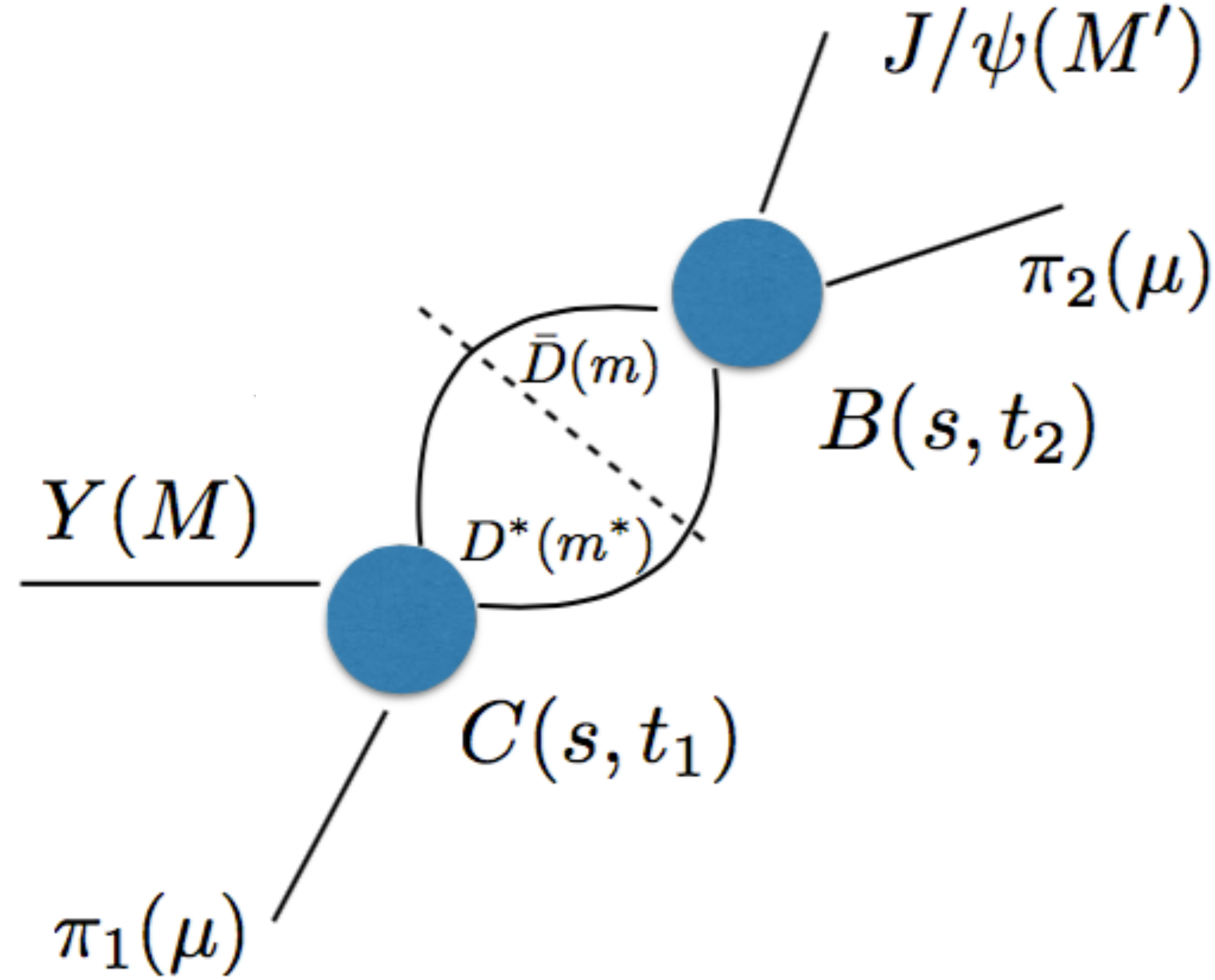

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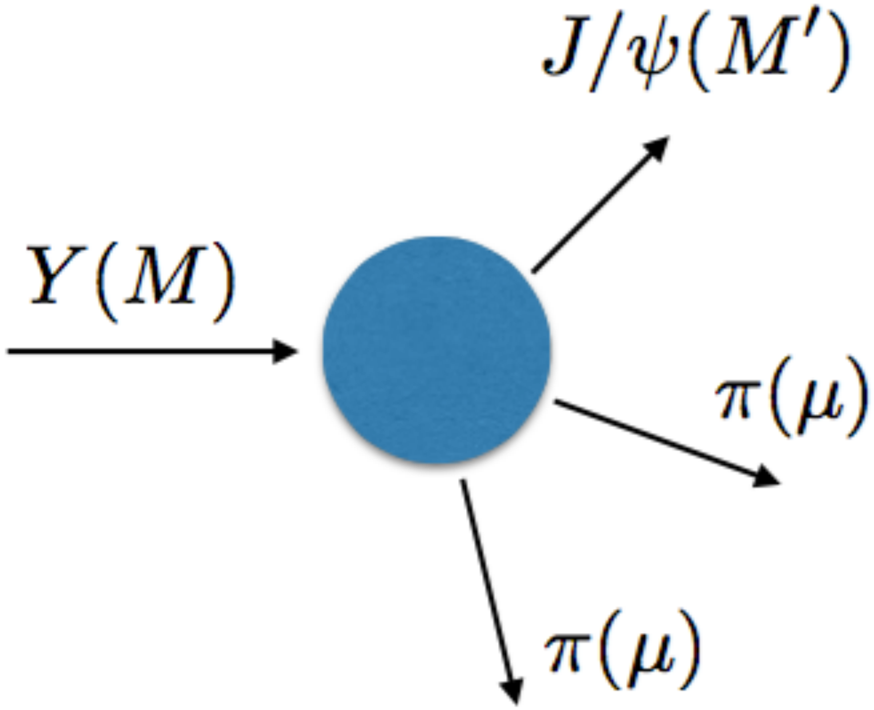
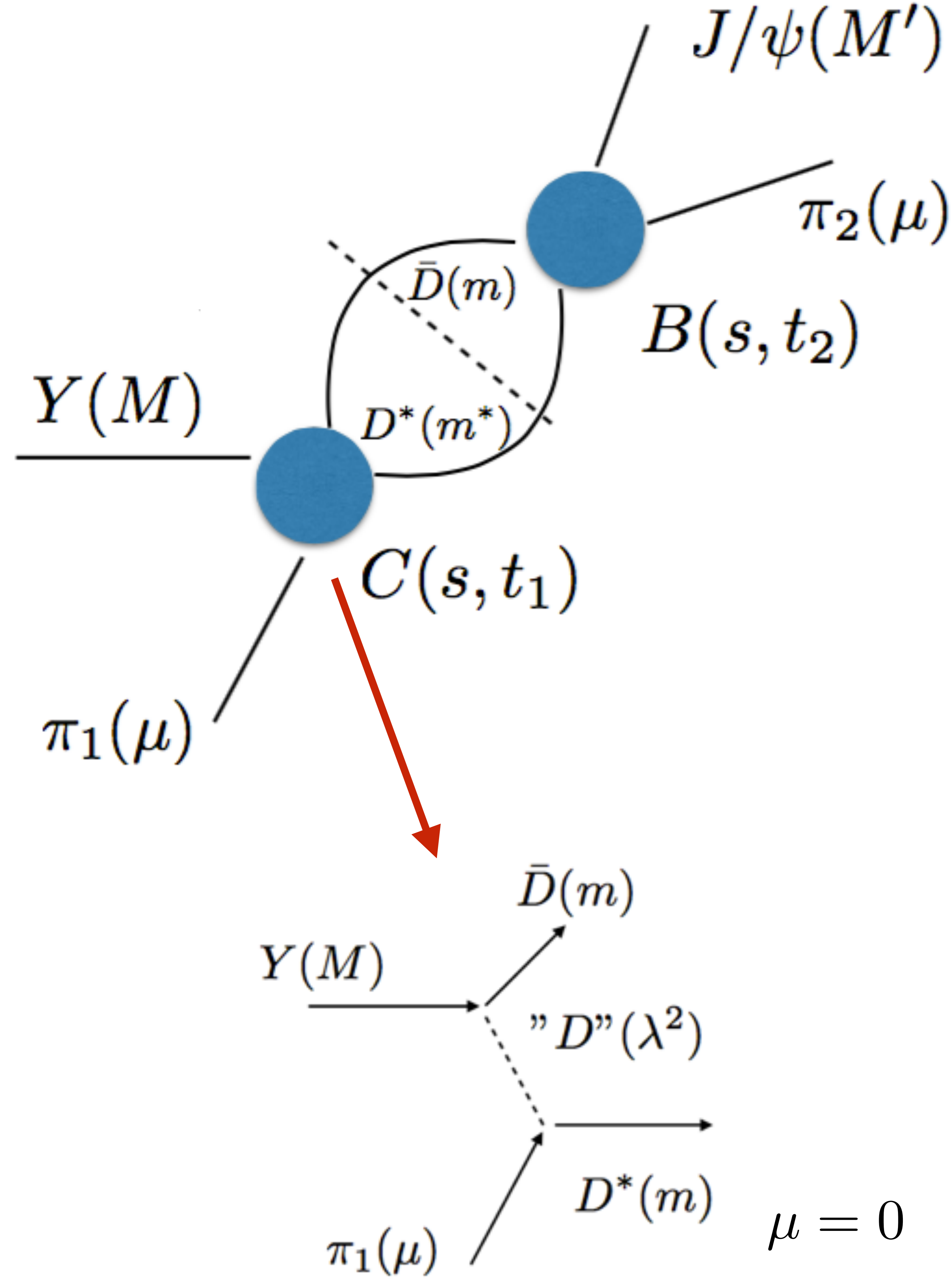
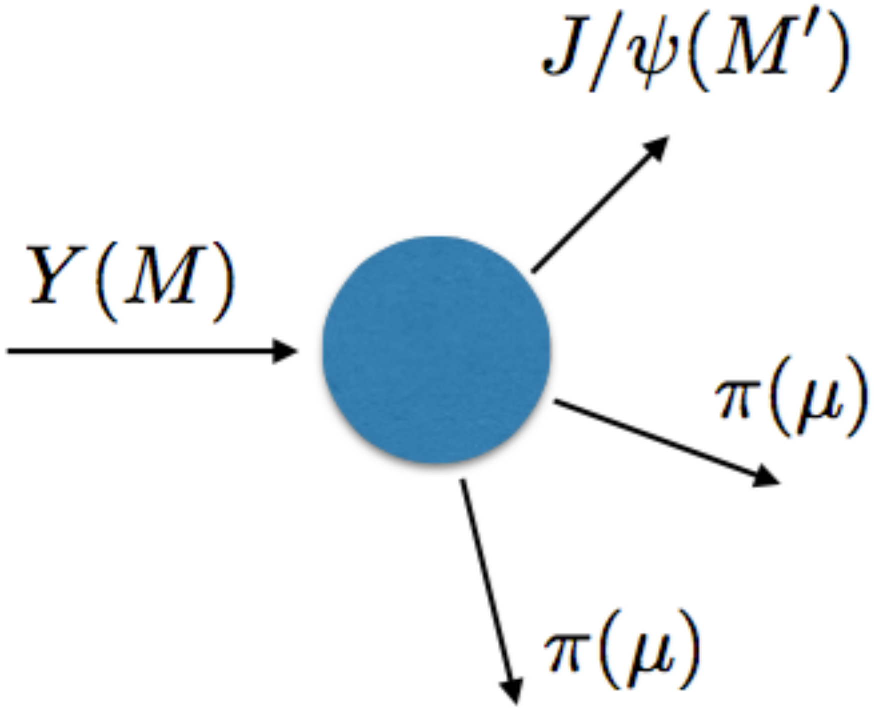


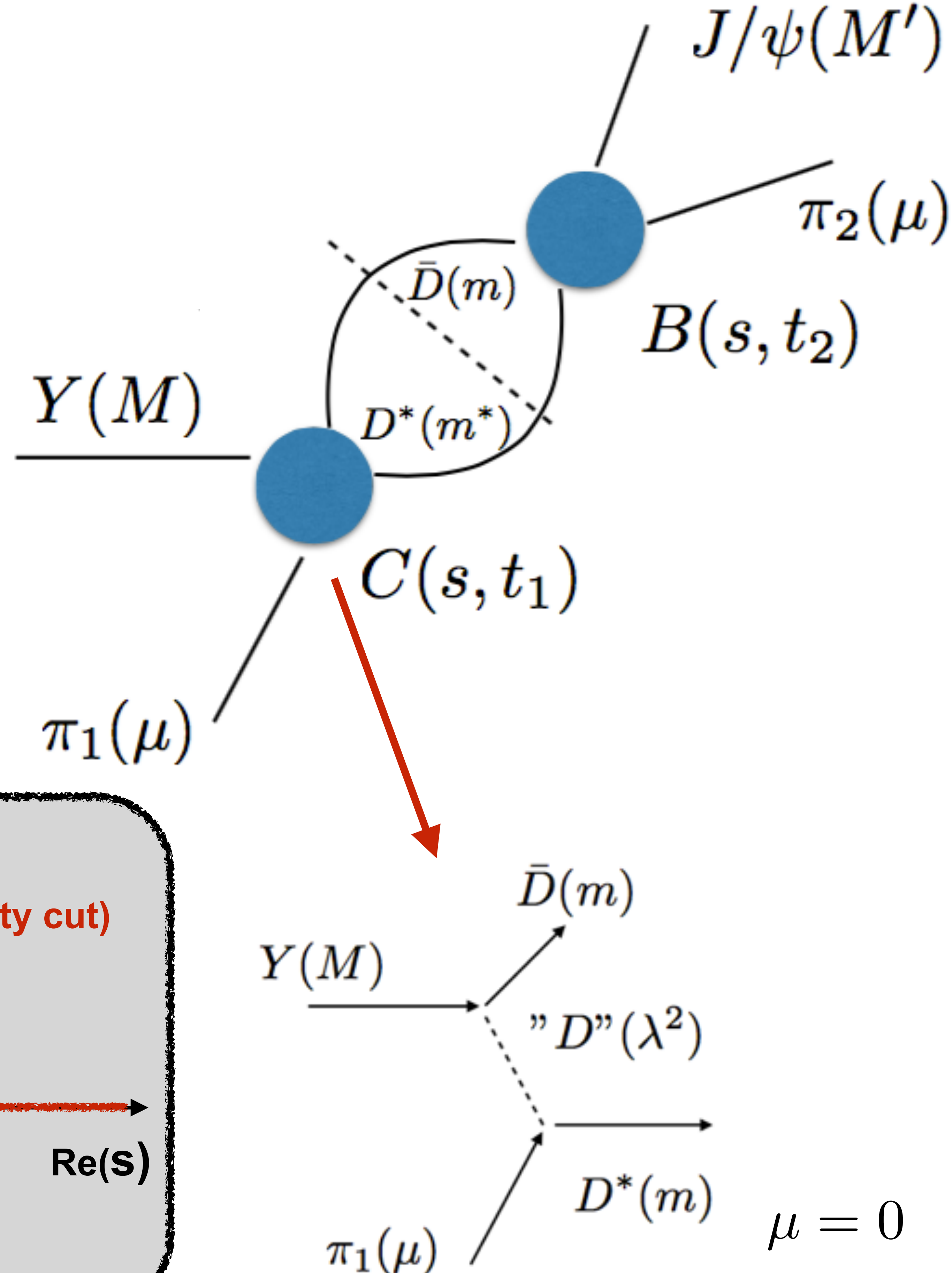


$\mu = 0$

$m = m^*$

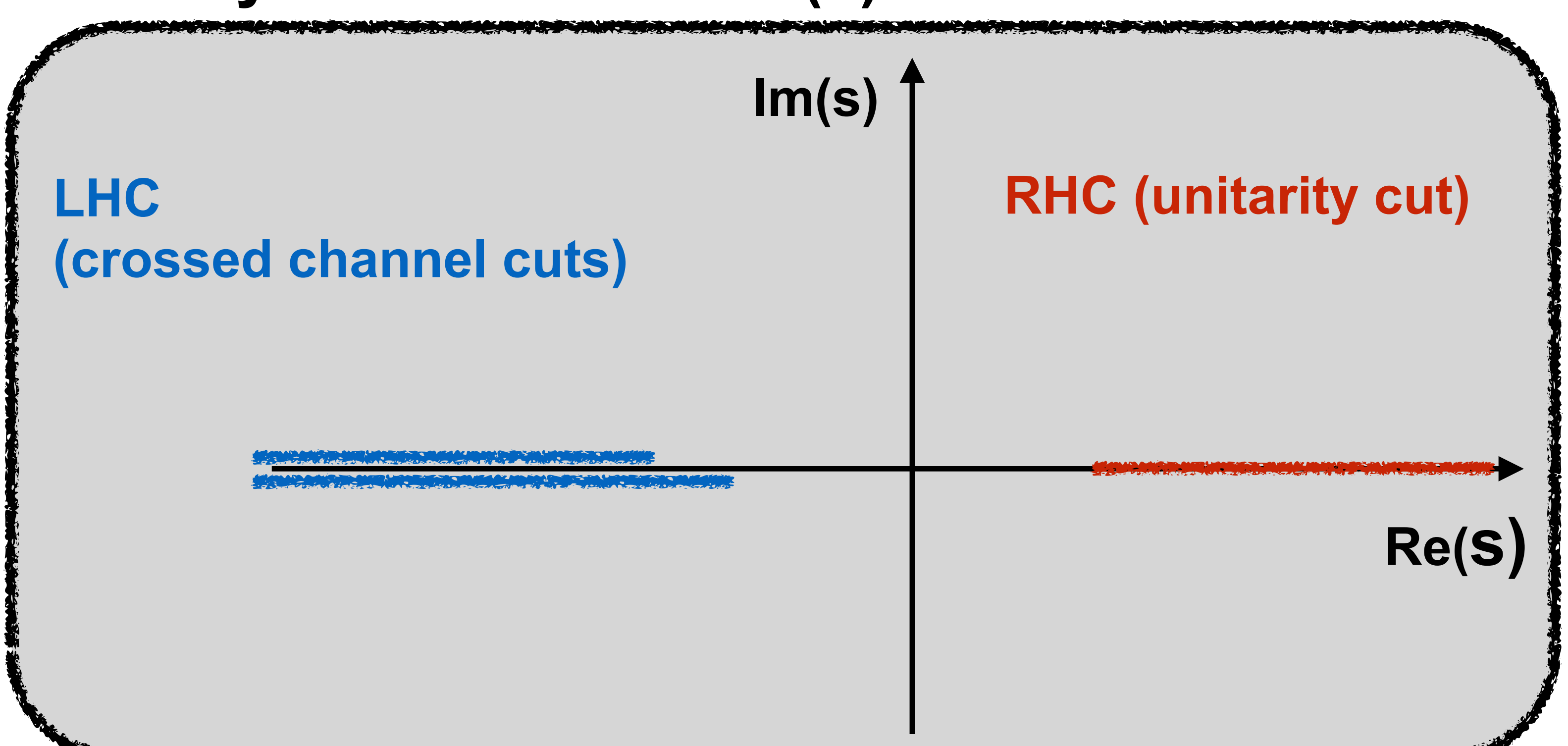
Special case: Szczepaniak arXiv:1501.01691
Real case: JPAC, in preparation





$$\mu = 0$$
$$m = m^*$$

Analytic structure of C(s) S-wave



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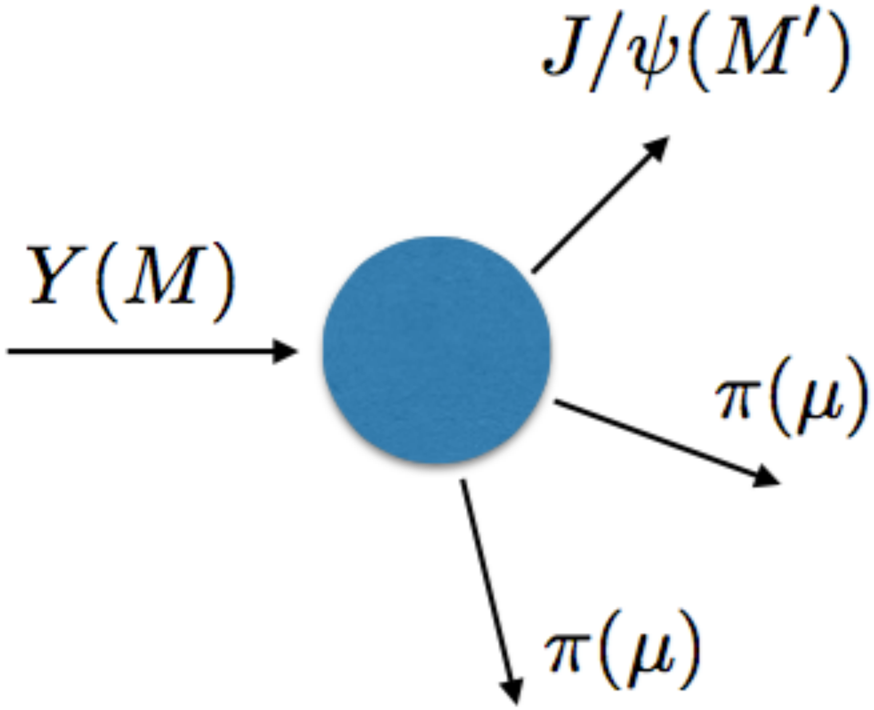
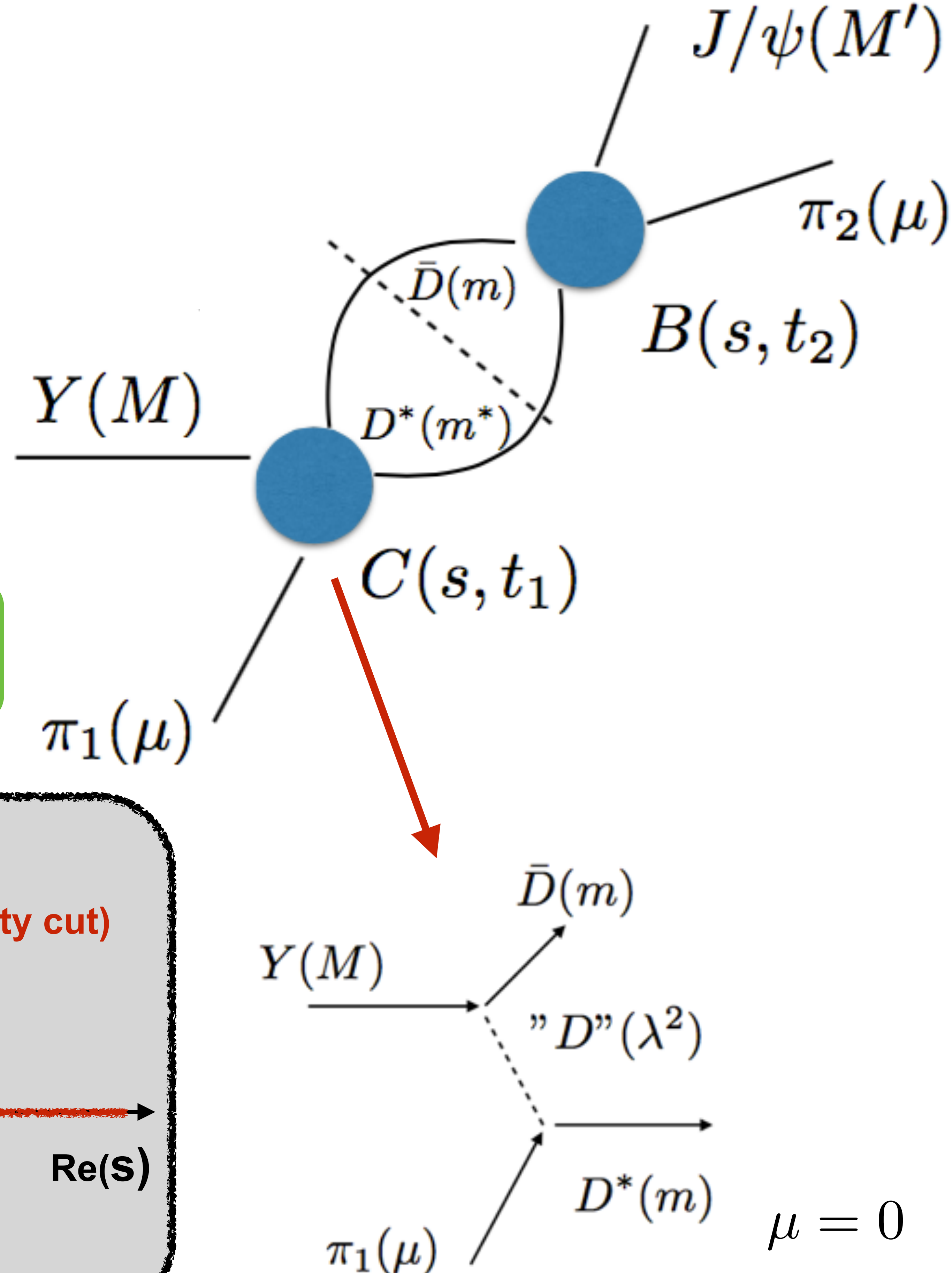


$$(M-m)^2 > \lambda^2 > M^2/2 - m^2$$



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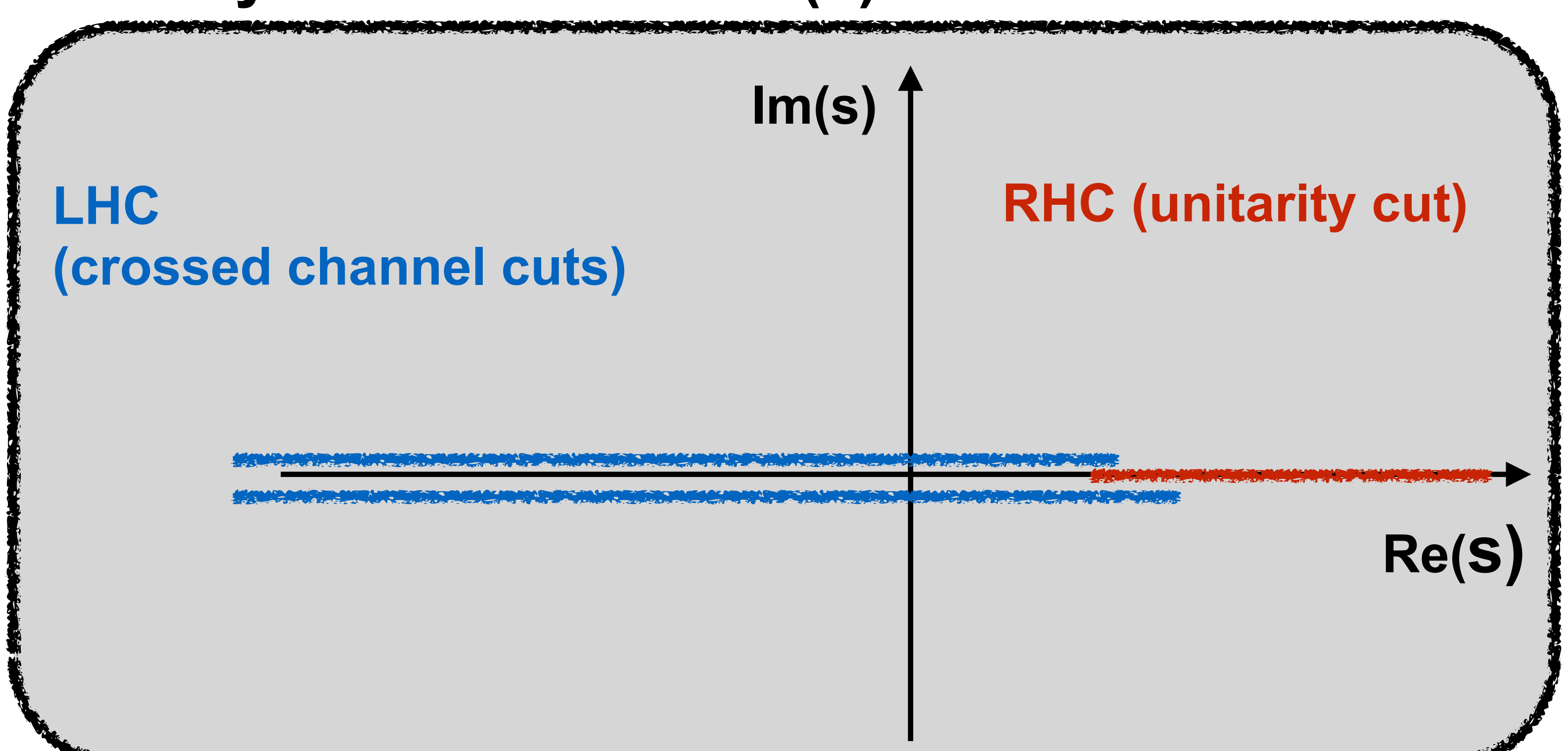

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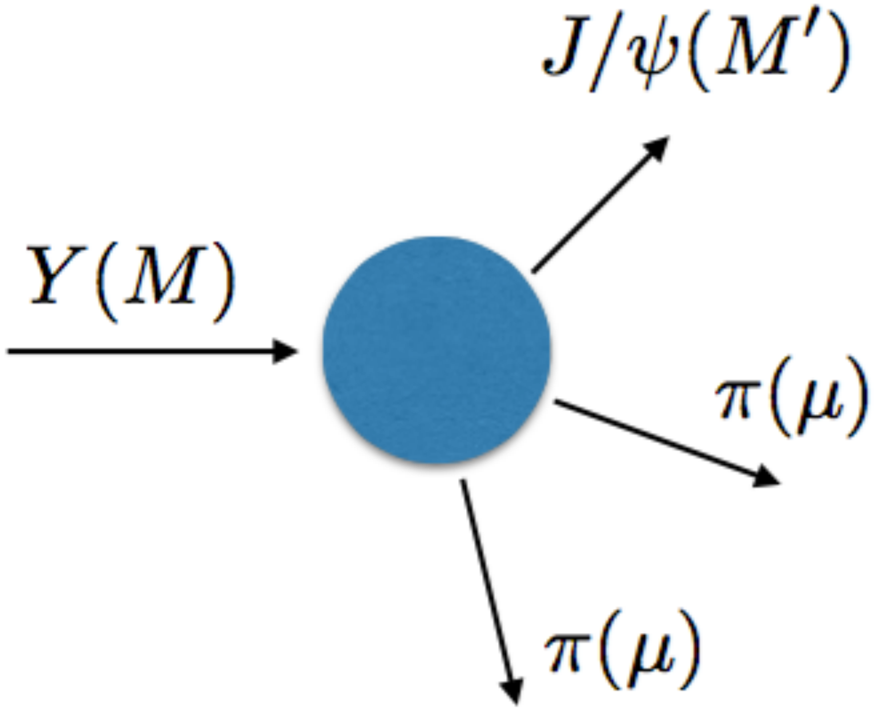

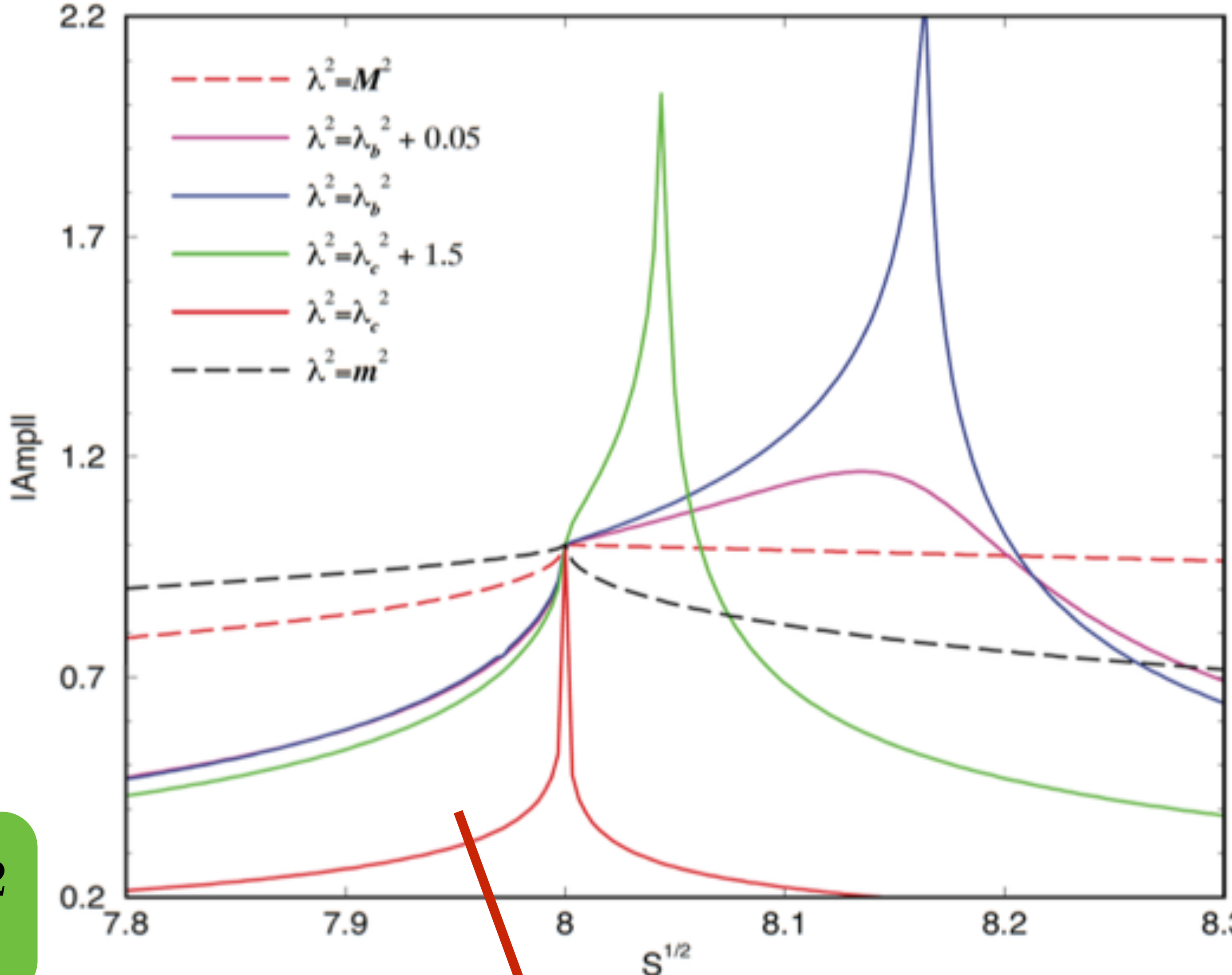

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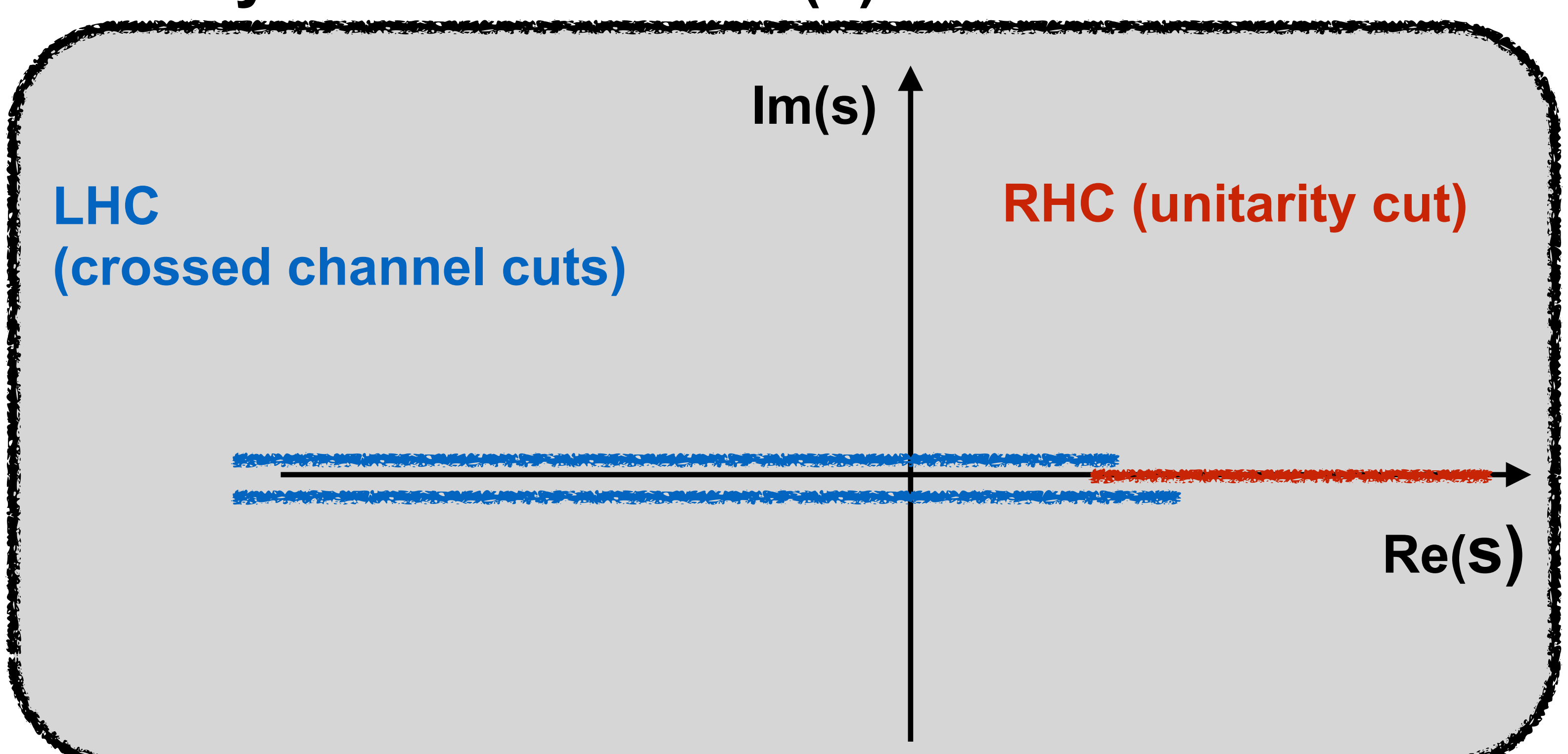
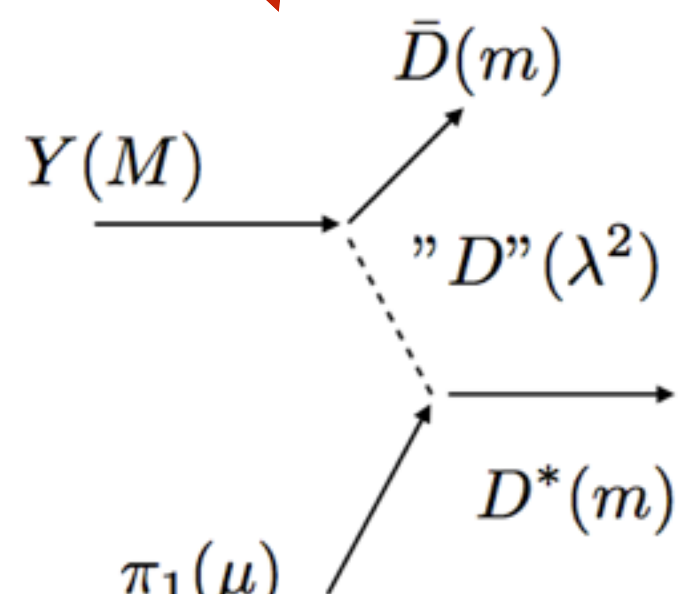
Analytic structure of C(s) S-wave





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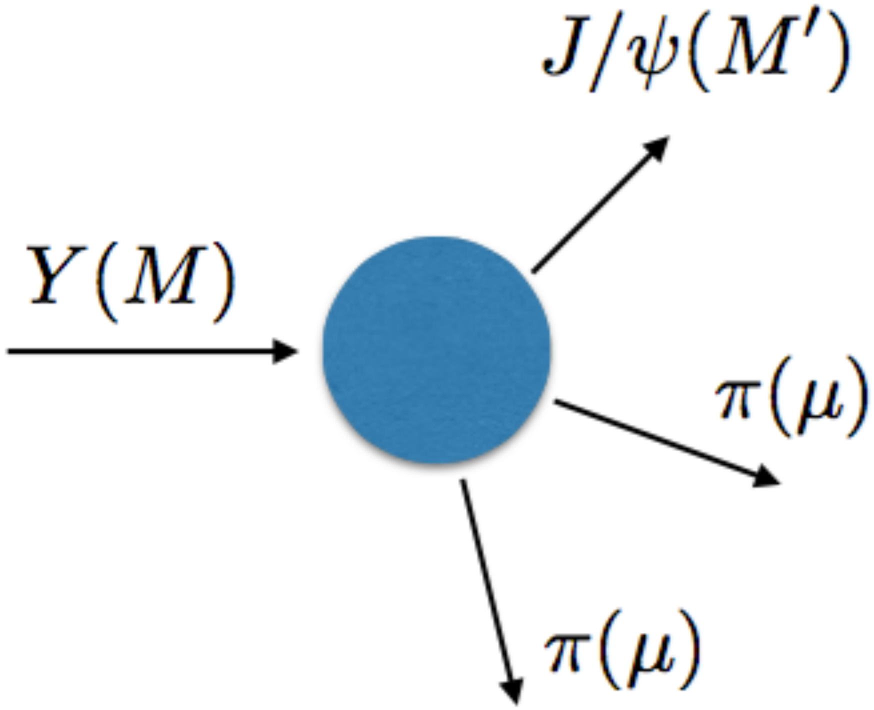
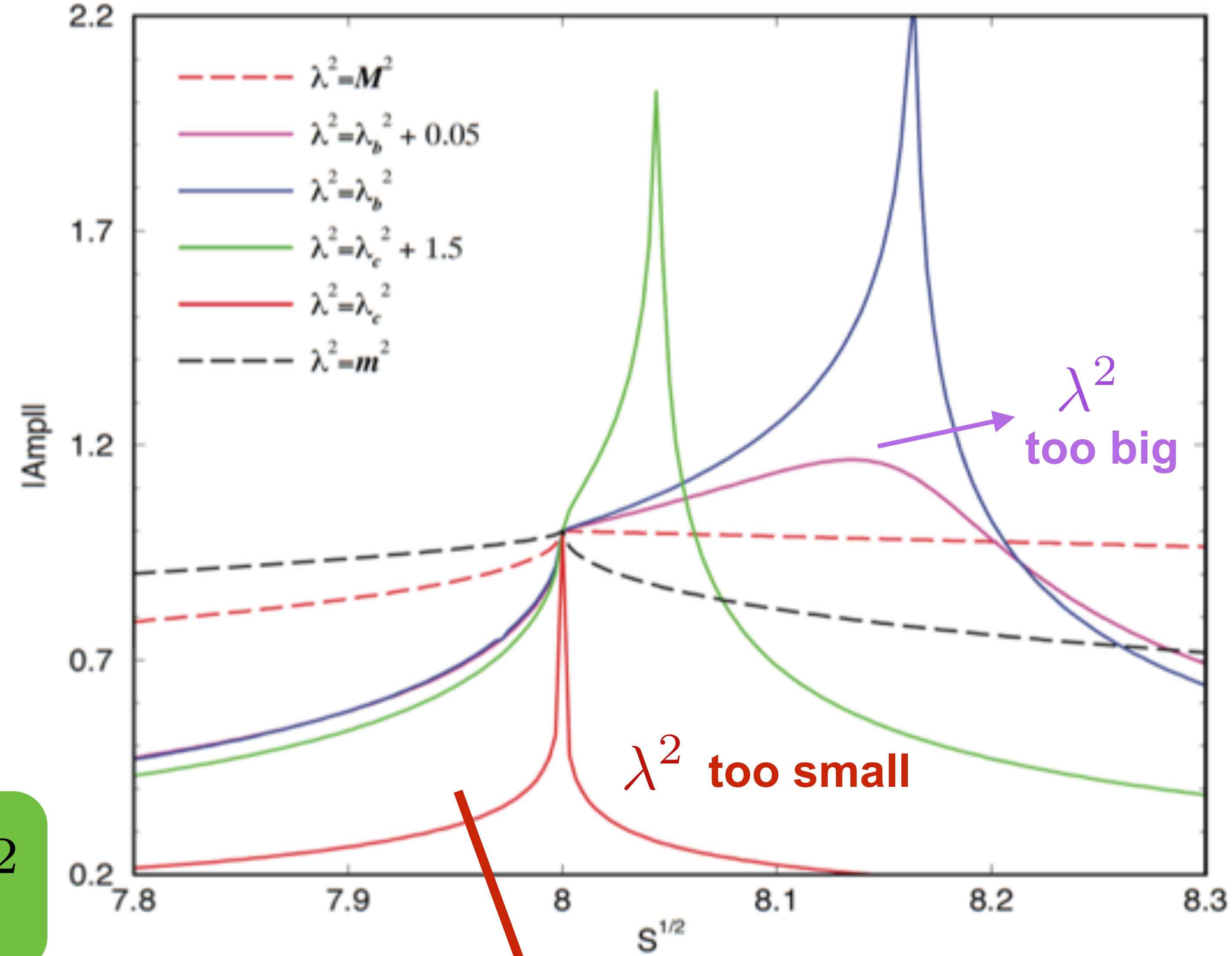
Real case: JPAC, in preparation





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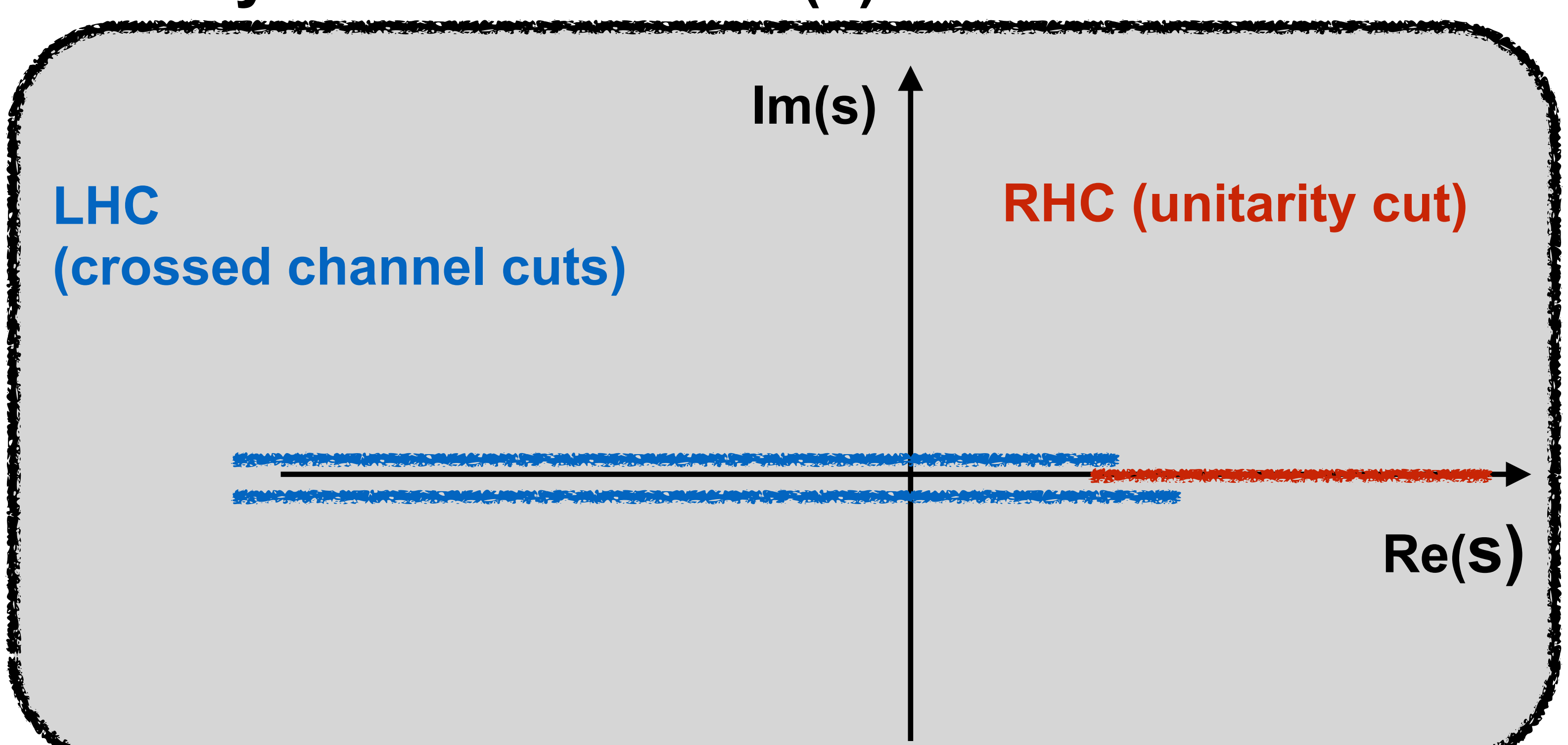
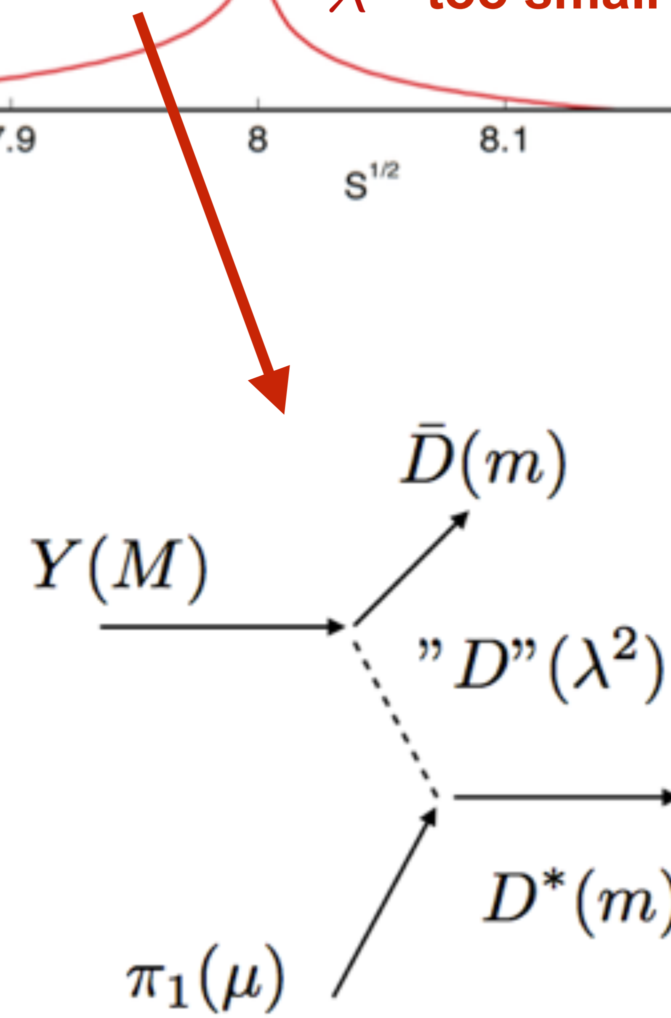
Analytic structure of C(s) S-wave





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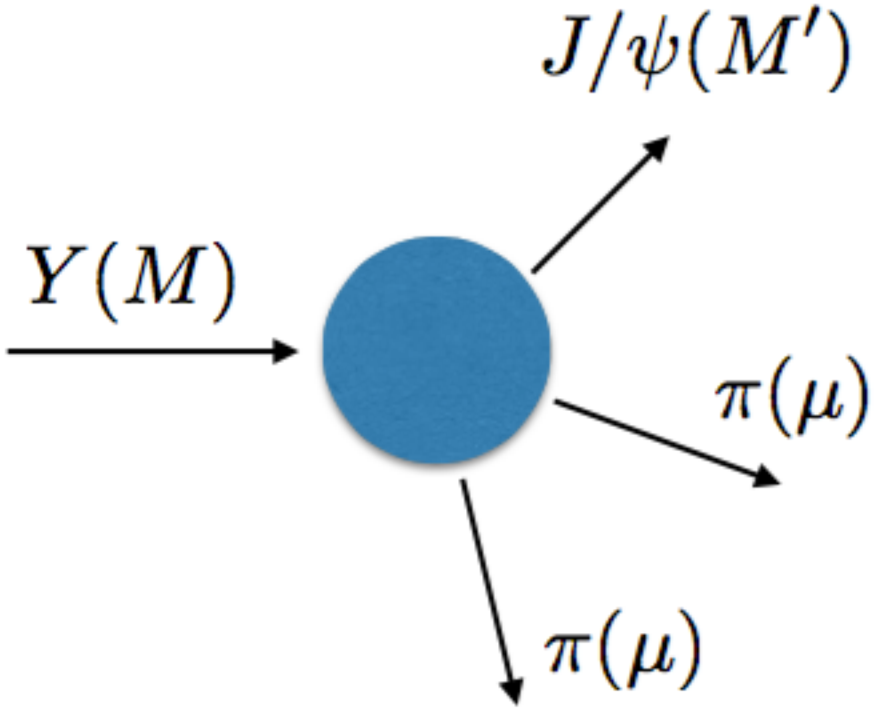
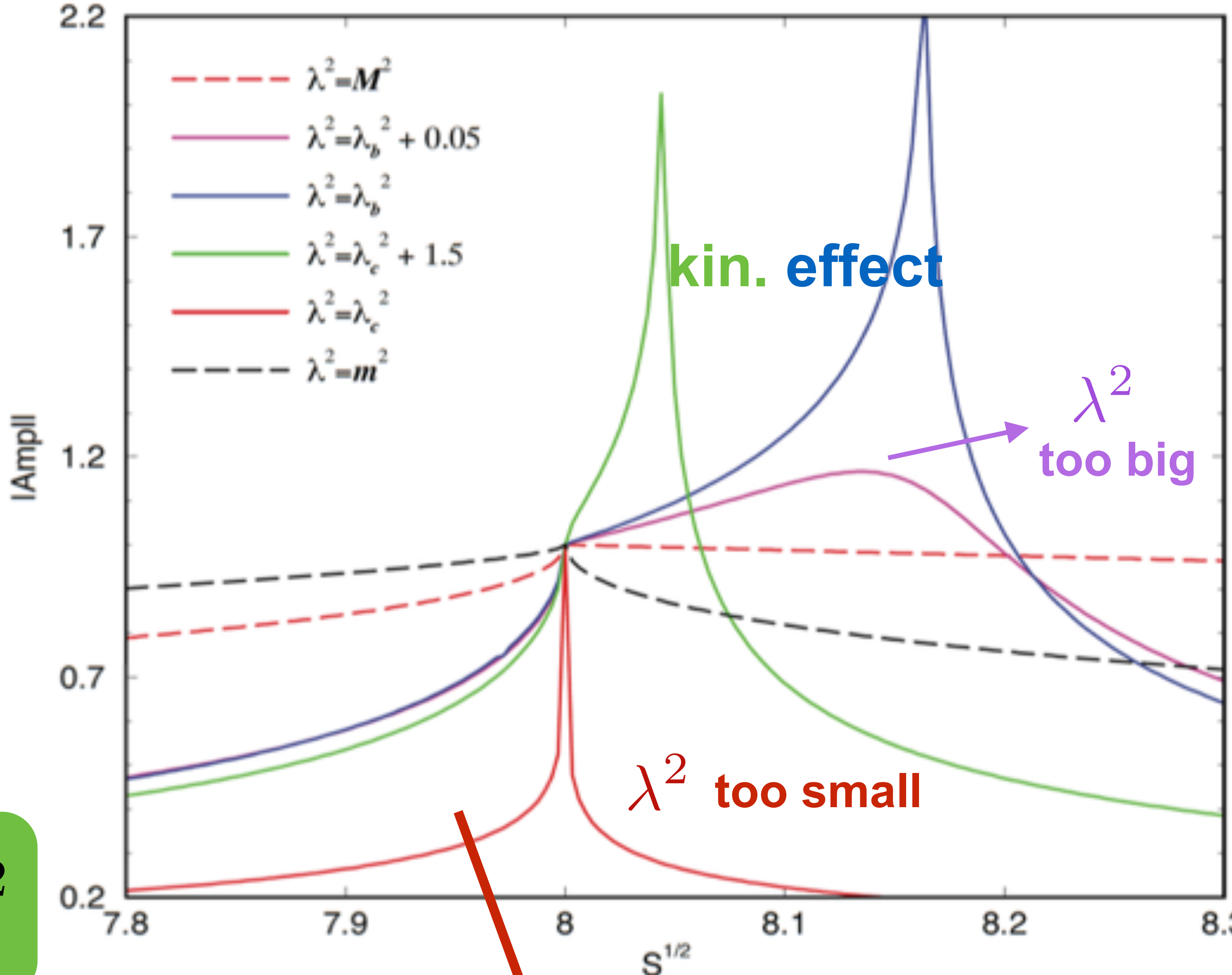
Real case: JPAC, in preparation





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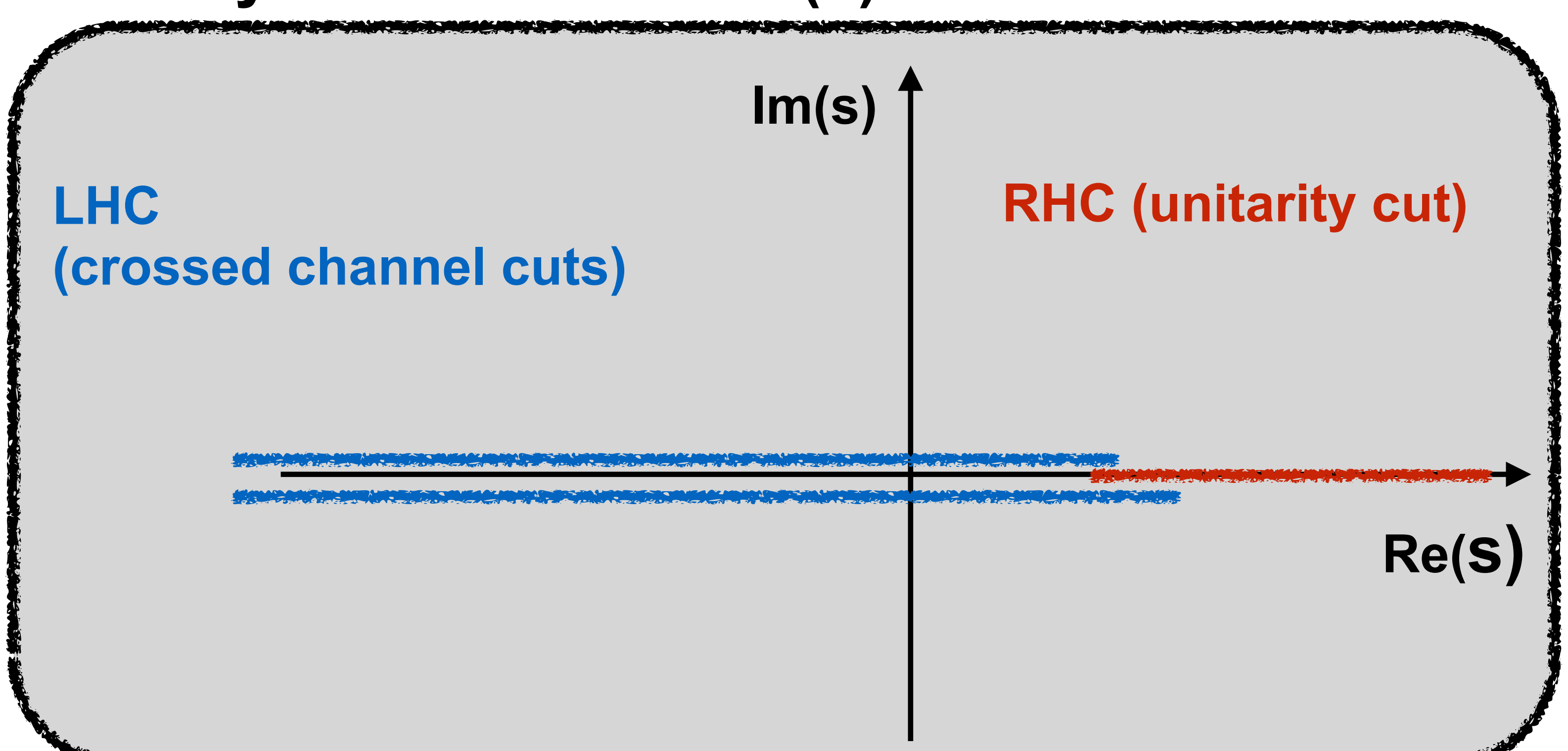
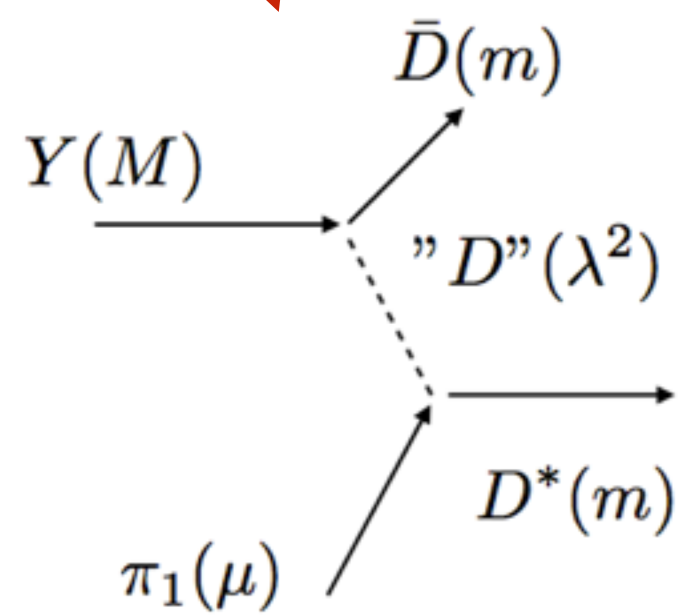
Analytic structure of C(s) S-wave



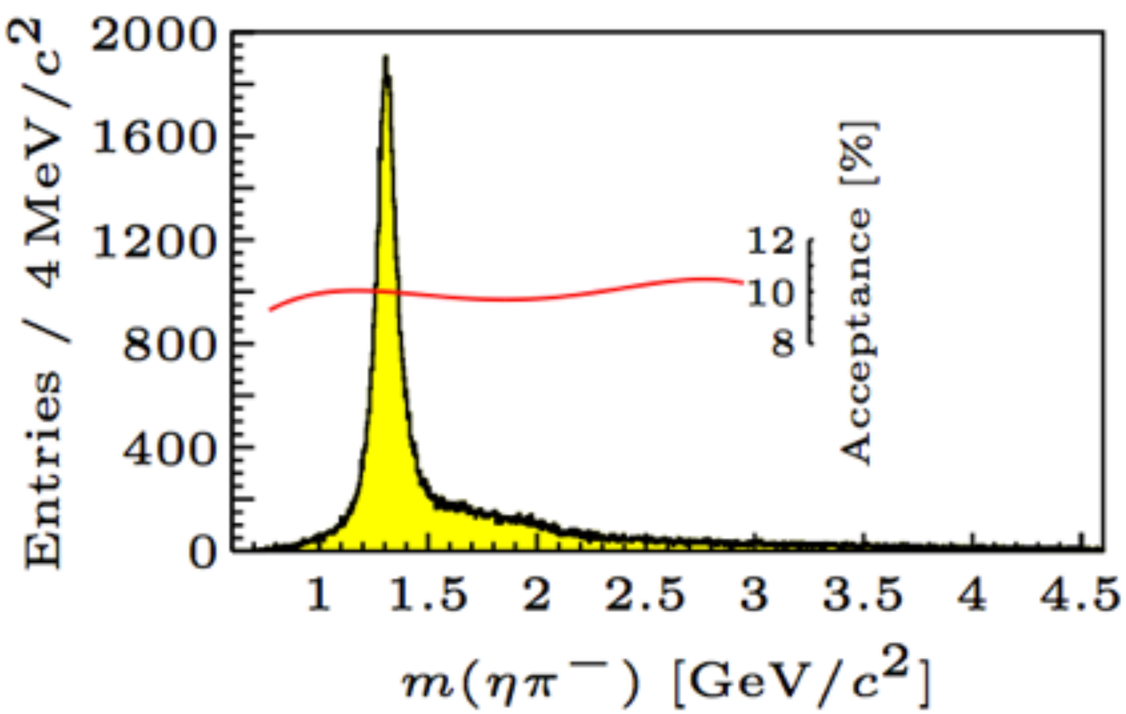


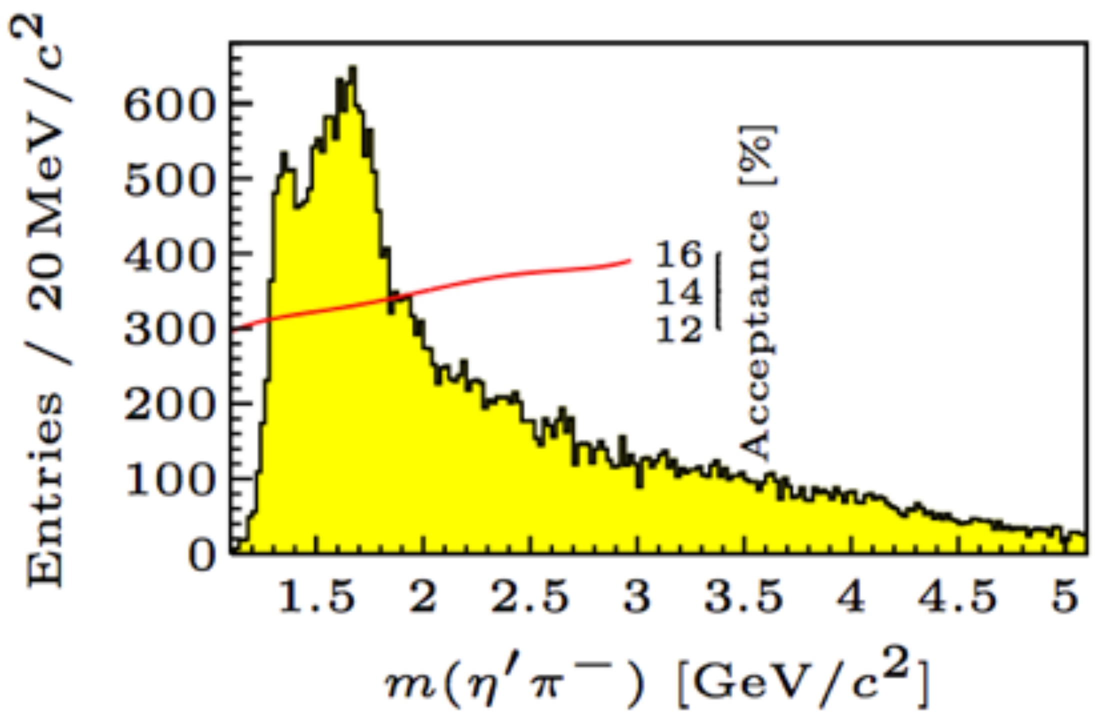
$$\mu = 0$$
$$m = m^*$$

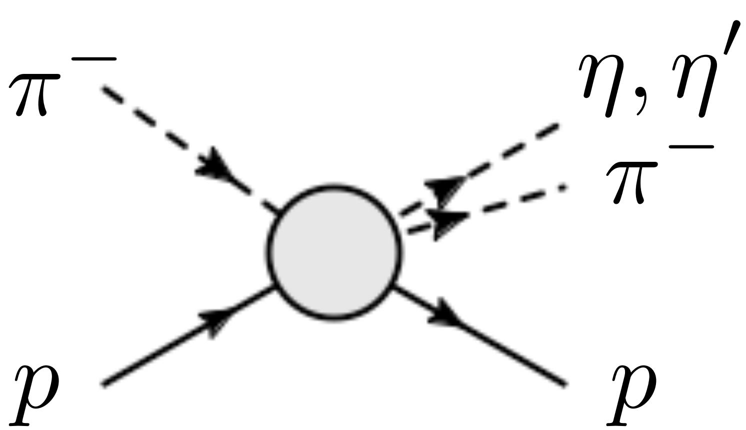
Eta-Pi @COMPASS

High energy beam: $p_{\text{lab}} = 190\ \text{GeV}$

final state: $\underbrace{\pi^-\pi^+\pi^-\gamma\gamma}_{\eta \text{ or } \eta'}$ **with** $\gamma\gamma : \pi^0 \text{ or } \eta$







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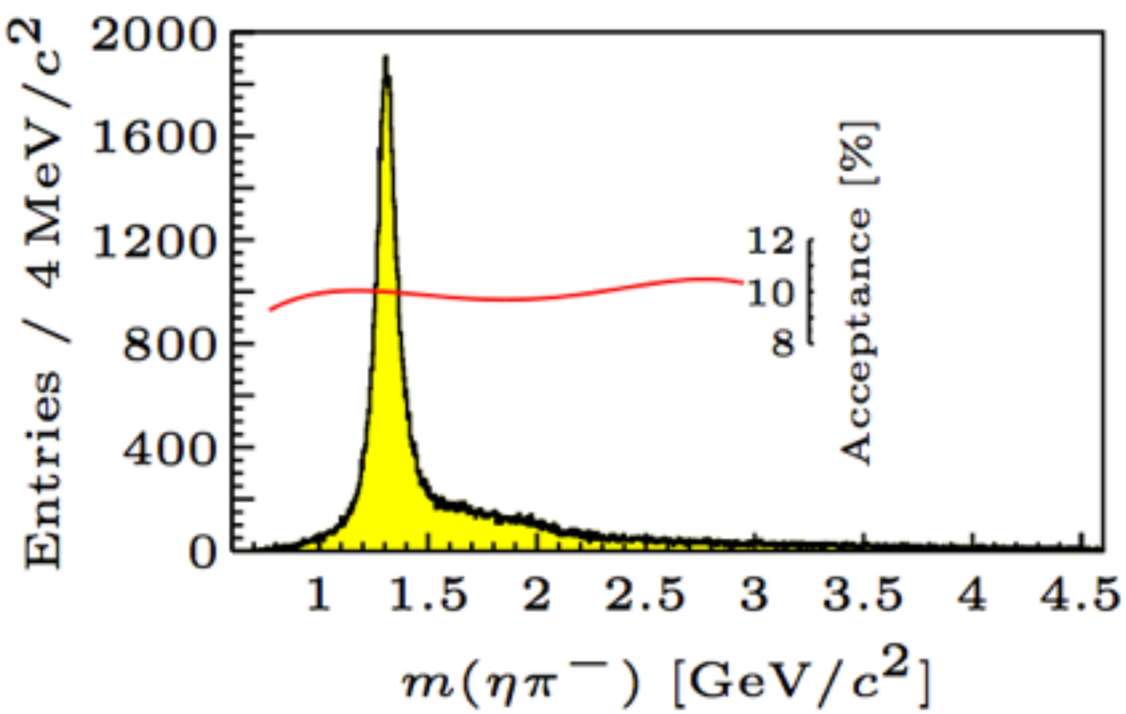
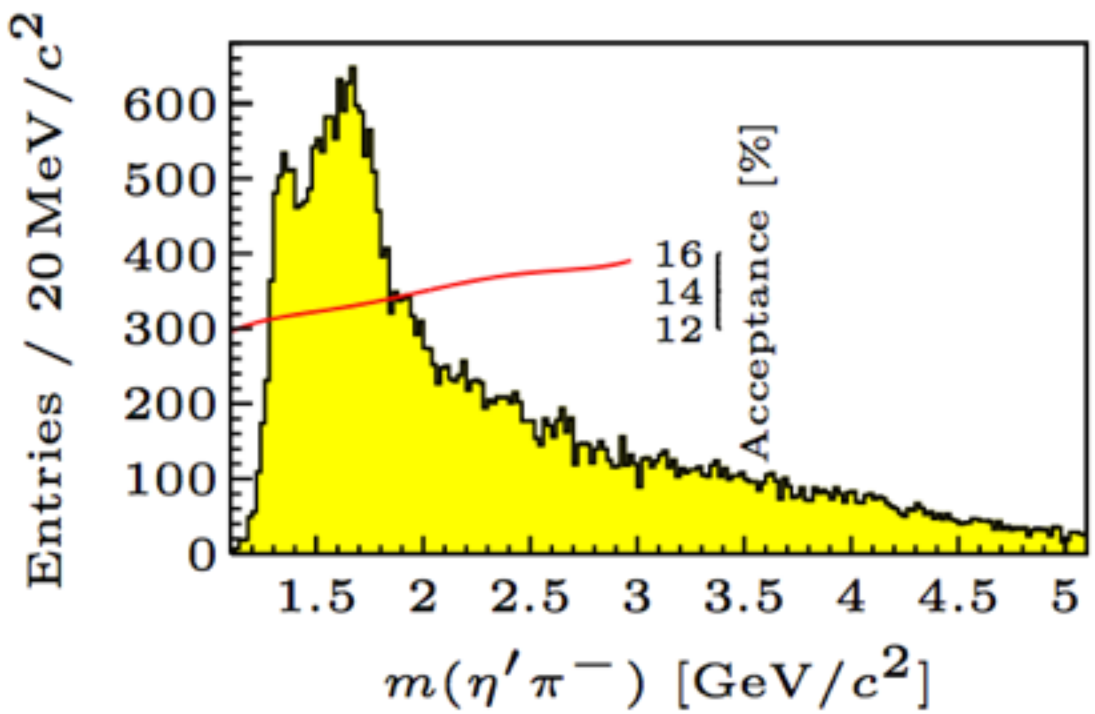
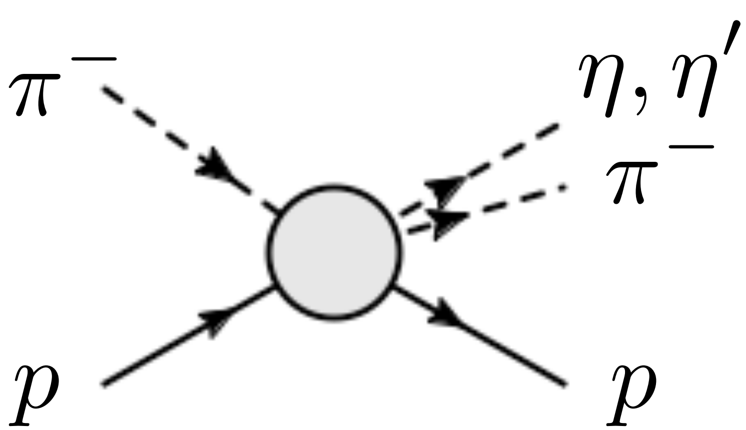
Eta-Pi @COMPASS

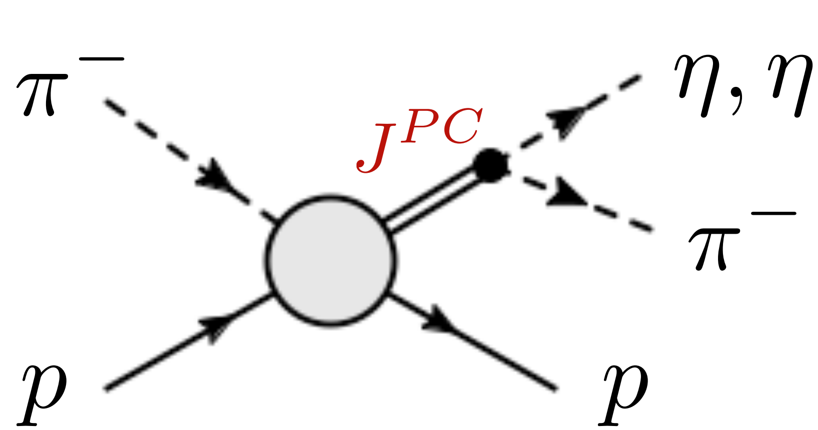
High energy beam: $p_{\text{lab}} = 190 \text{ GeV}$

final state: $\pi^-\underbrace{\pi^+\pi^-\gamma\gamma}_{\eta \text{ or } \eta'}$ **with** $\gamma\gamma : \pi^0 \text{ or } \eta$







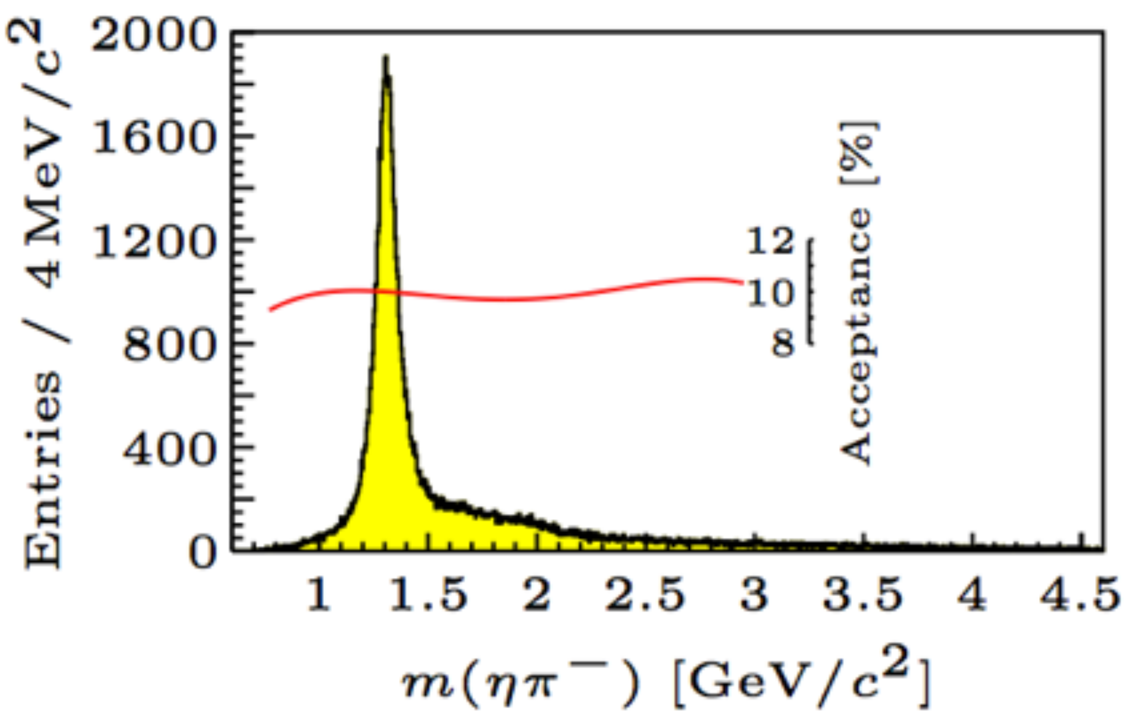


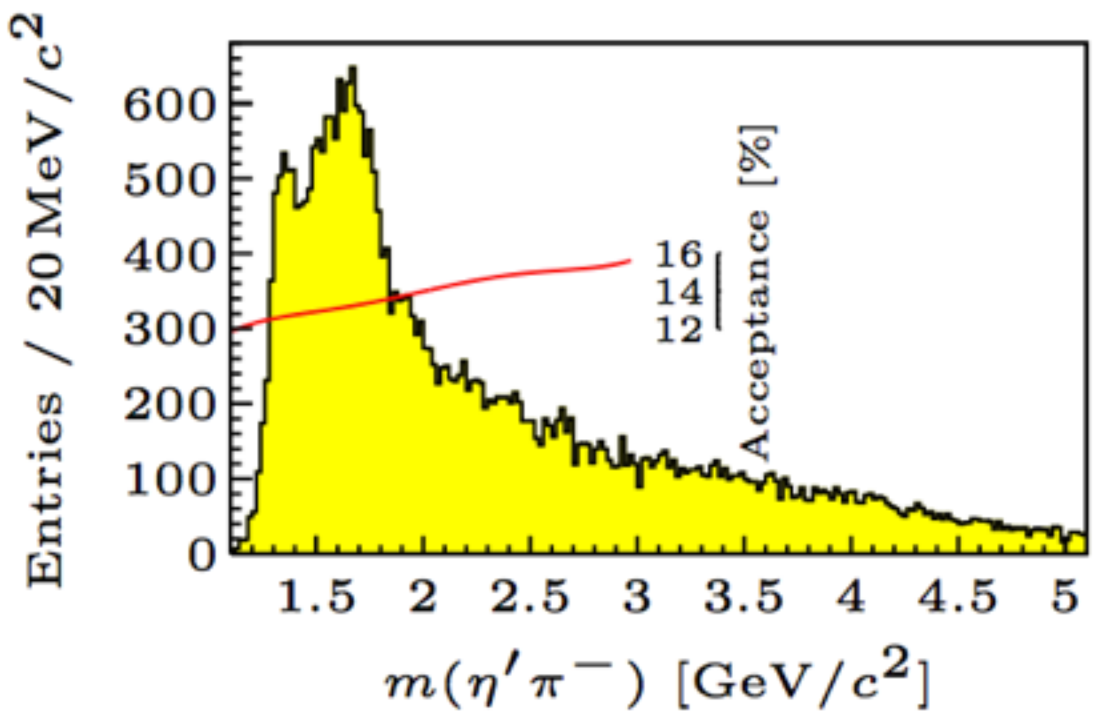
COMPASS Phys. Lett. B740 (2015)

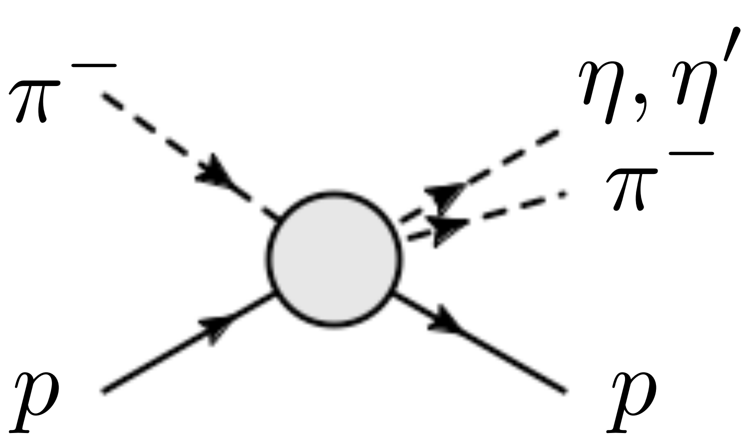
Eta-Pi @COMPASS

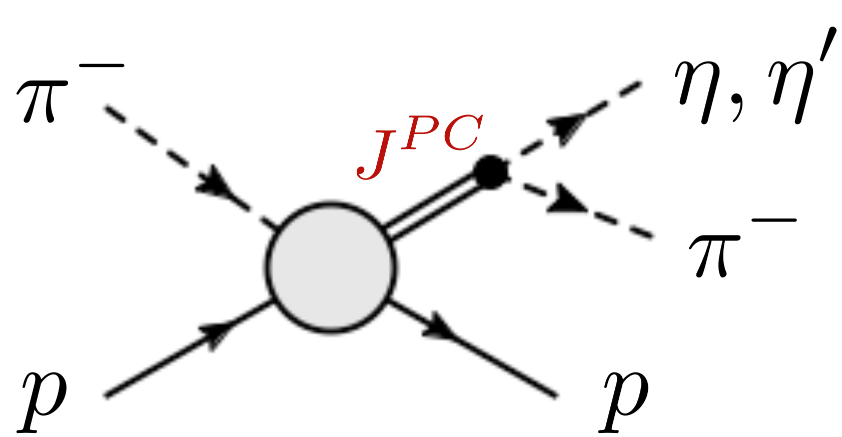
High energy beam: $p_{\mathrm{lab}} = 190 \text{ GeV}$

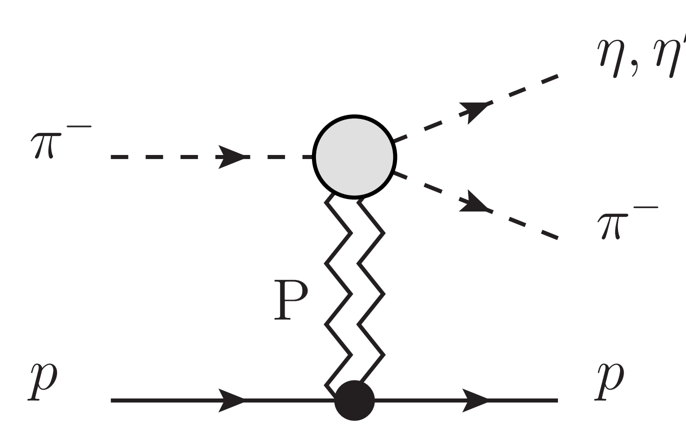
final state: $\underbrace{\pi^- \pi^+ \pi^- \gamma\gamma}_{\eta \text{ or } \eta'}$ **with** $\gamma\gamma : \pi^0 \text{ or } \eta$











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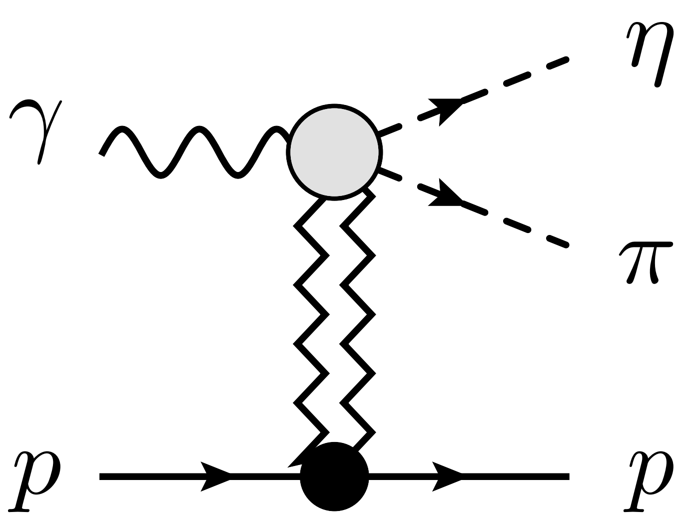
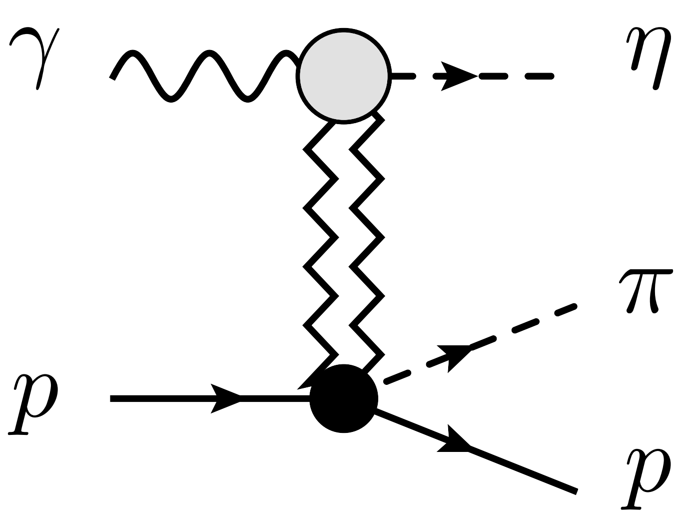
Contamination by Target Fragmentation

How do we select beam fragmentation ?



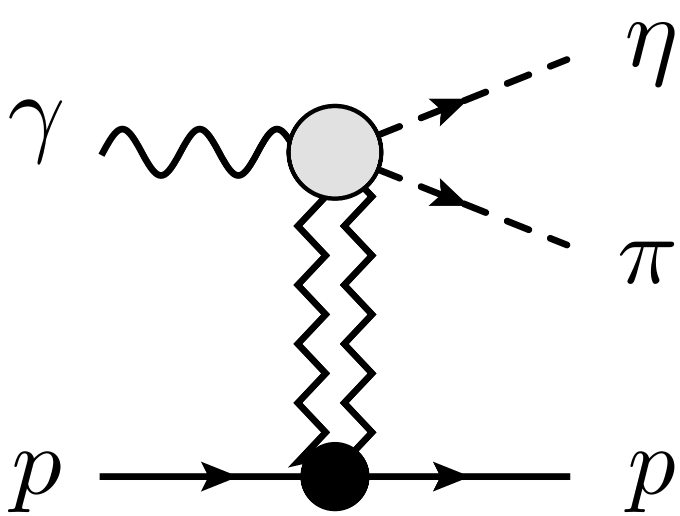


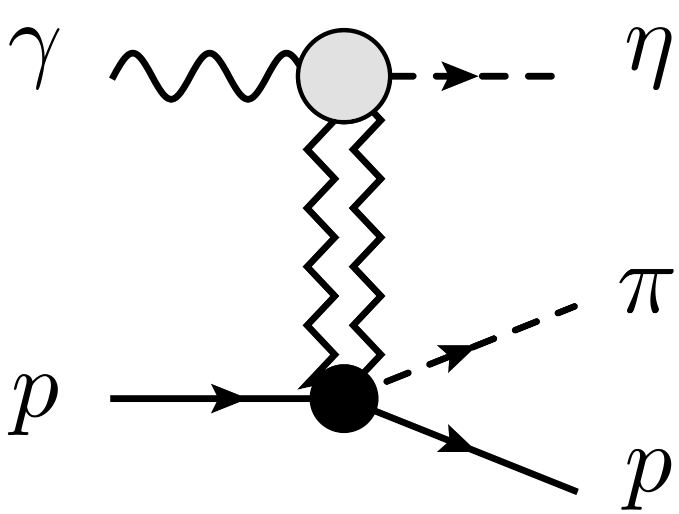
[Van Hove 1969]

[JPAC PRD91 (2015) 034007]

Contamination by Target Fragmentation

How do we select beam fragmentation ? → **Boost in the rest frame**



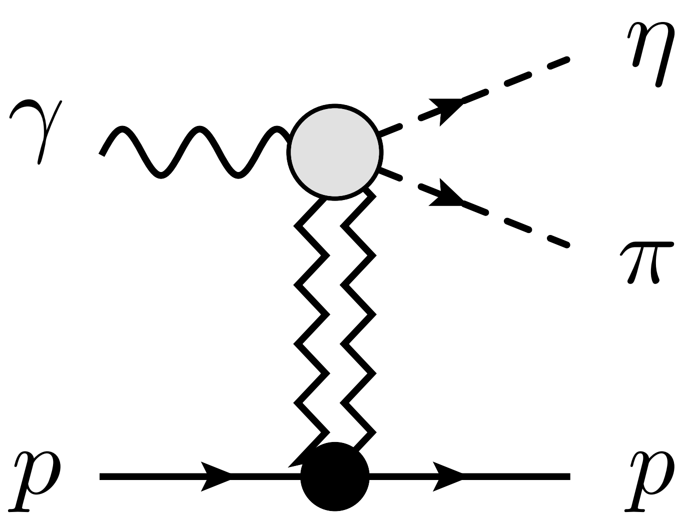


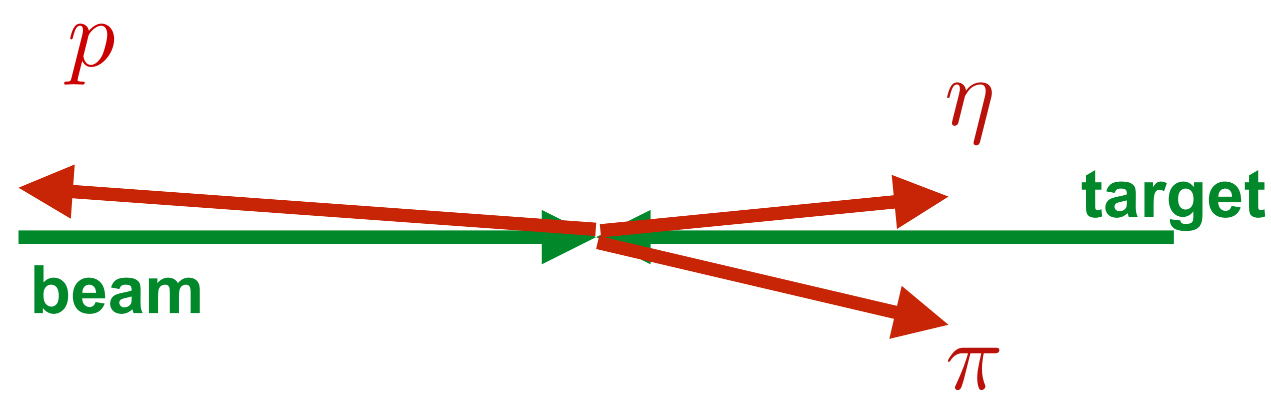
[Van Hove 1969]

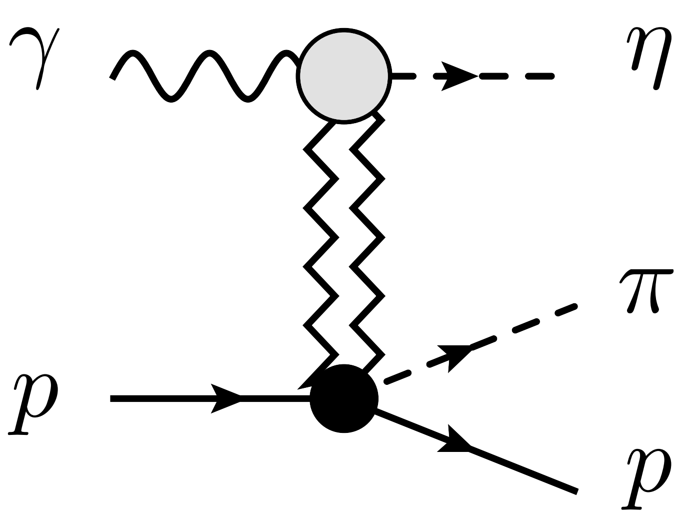
[JPAC PRD91 (2015) 034007]

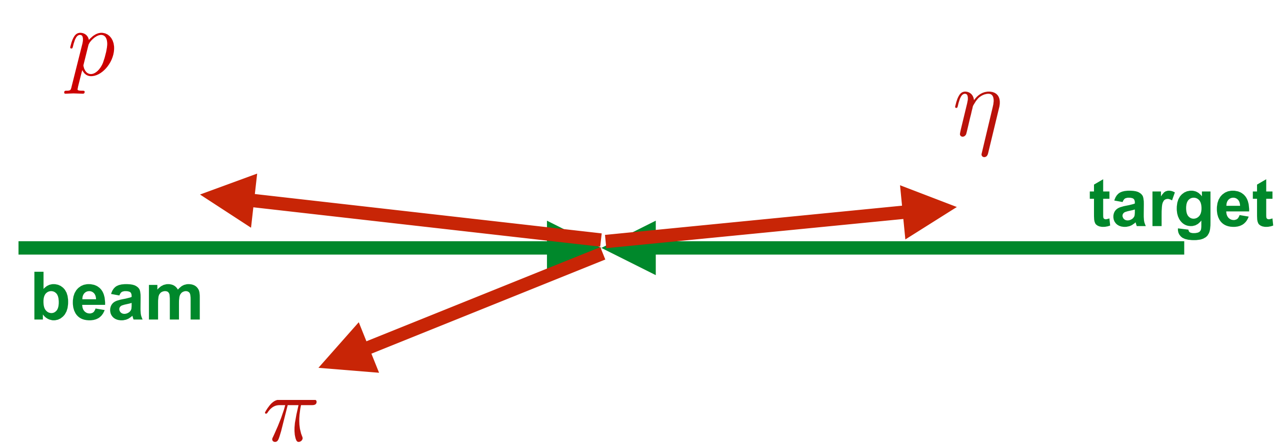
Contamination by Target Fragmentation

How do we select beam fragmentation ? → **Boost in the rest frame**









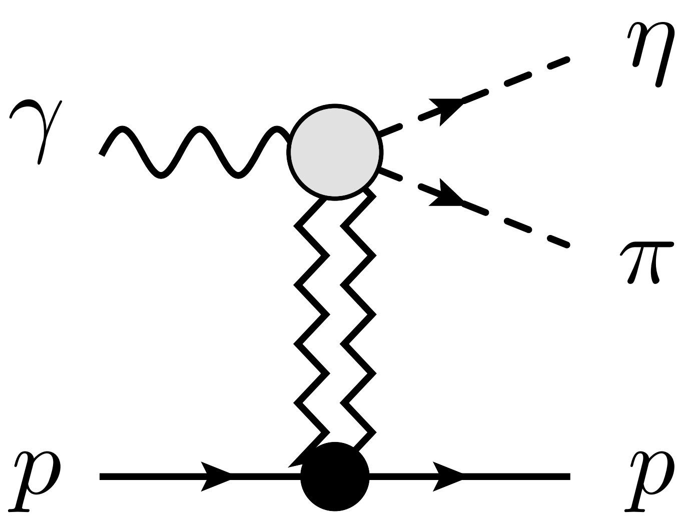
Easy way to cut !

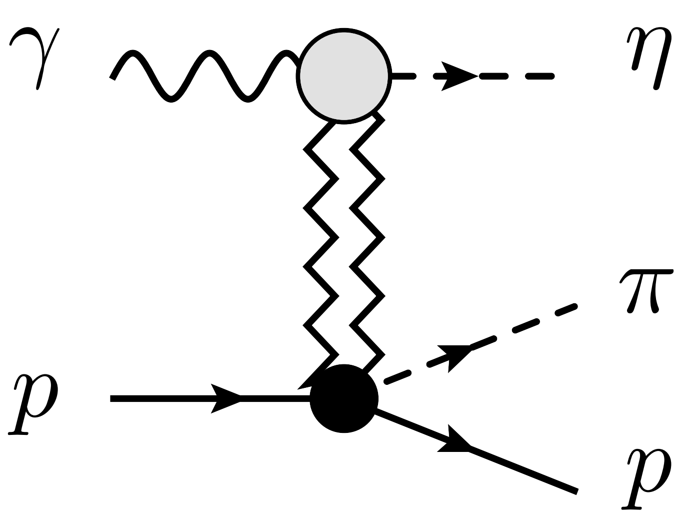
[Van Hove 1969]

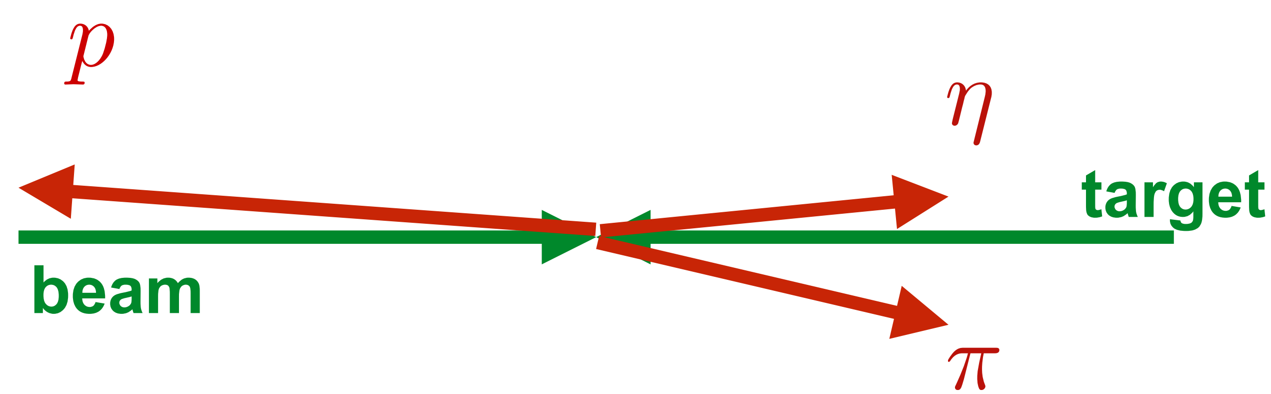
[JPAC PRD91 (2015) 034007]

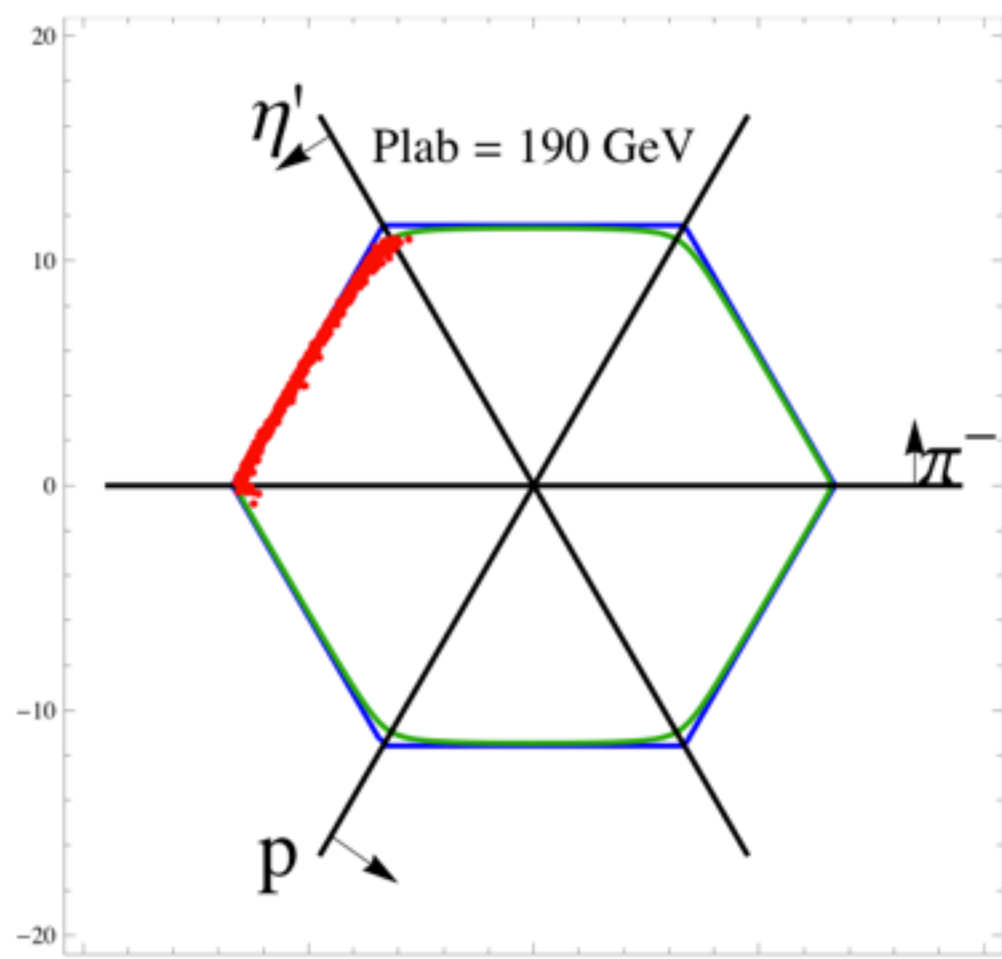
Contamination by Target Fragmentation

How do we select beam fragmentation ? → **Boost in the rest frame**

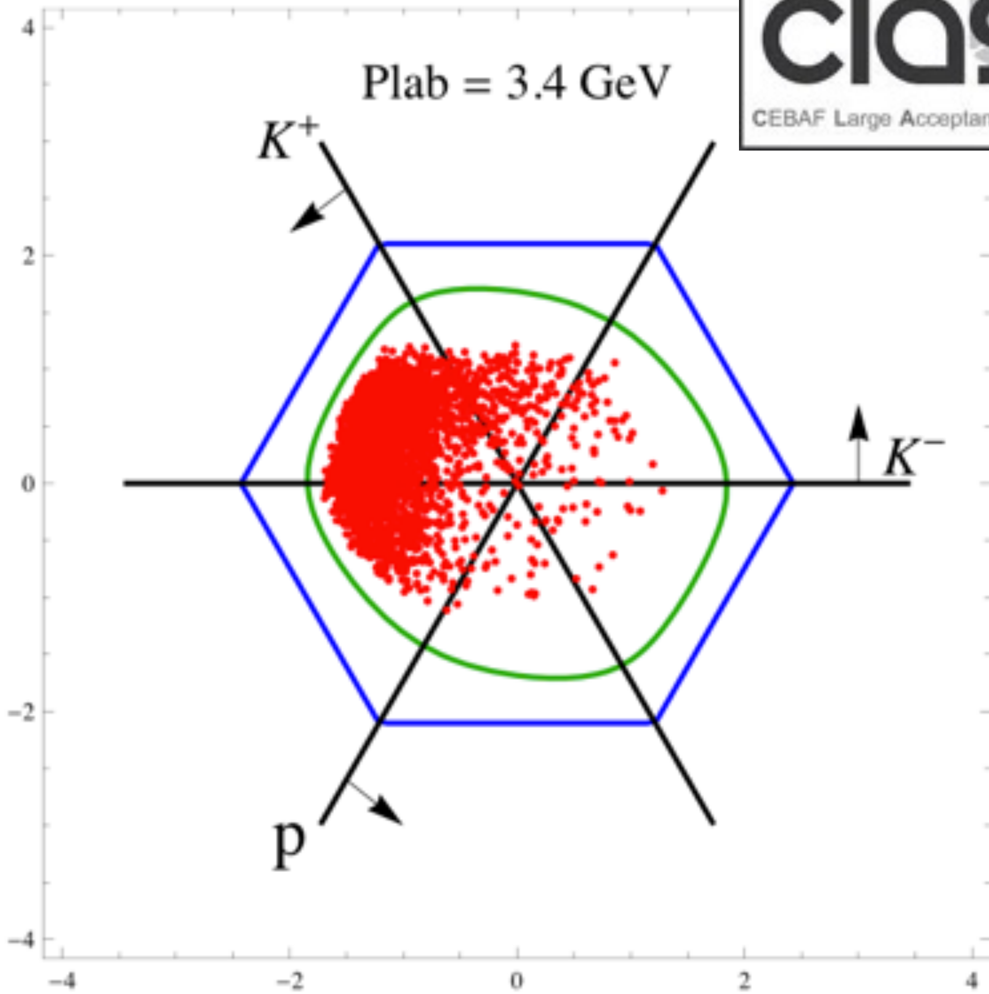






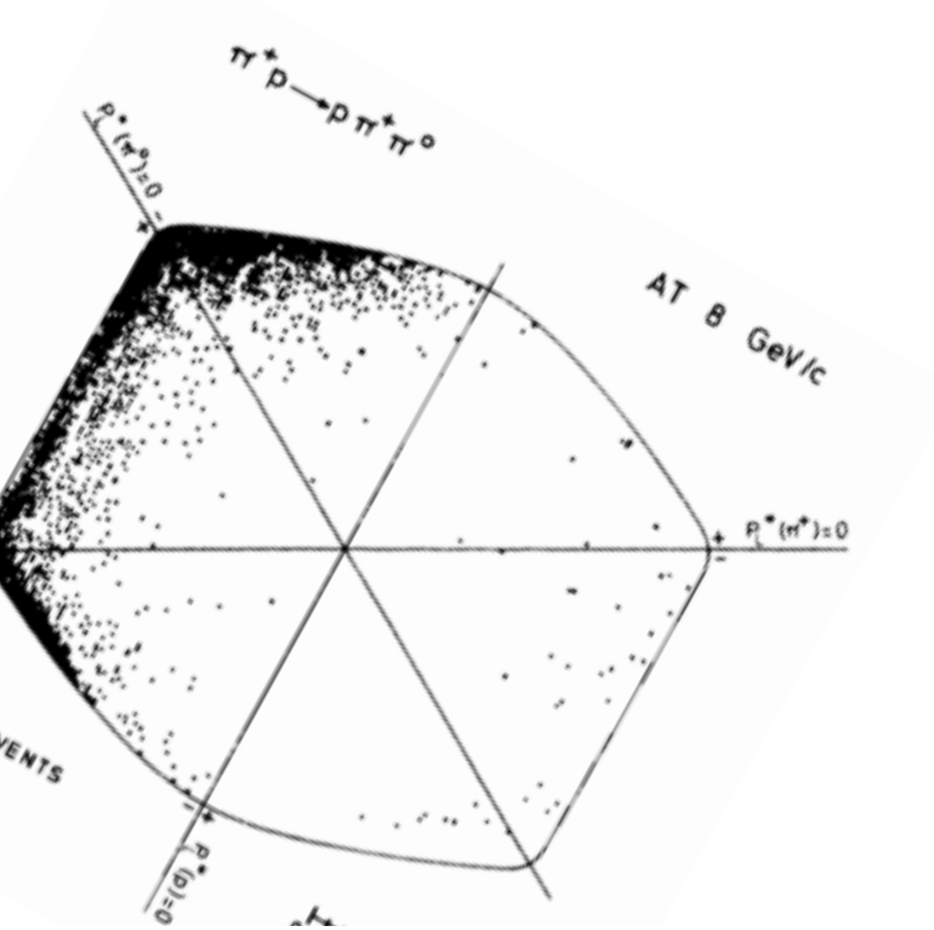


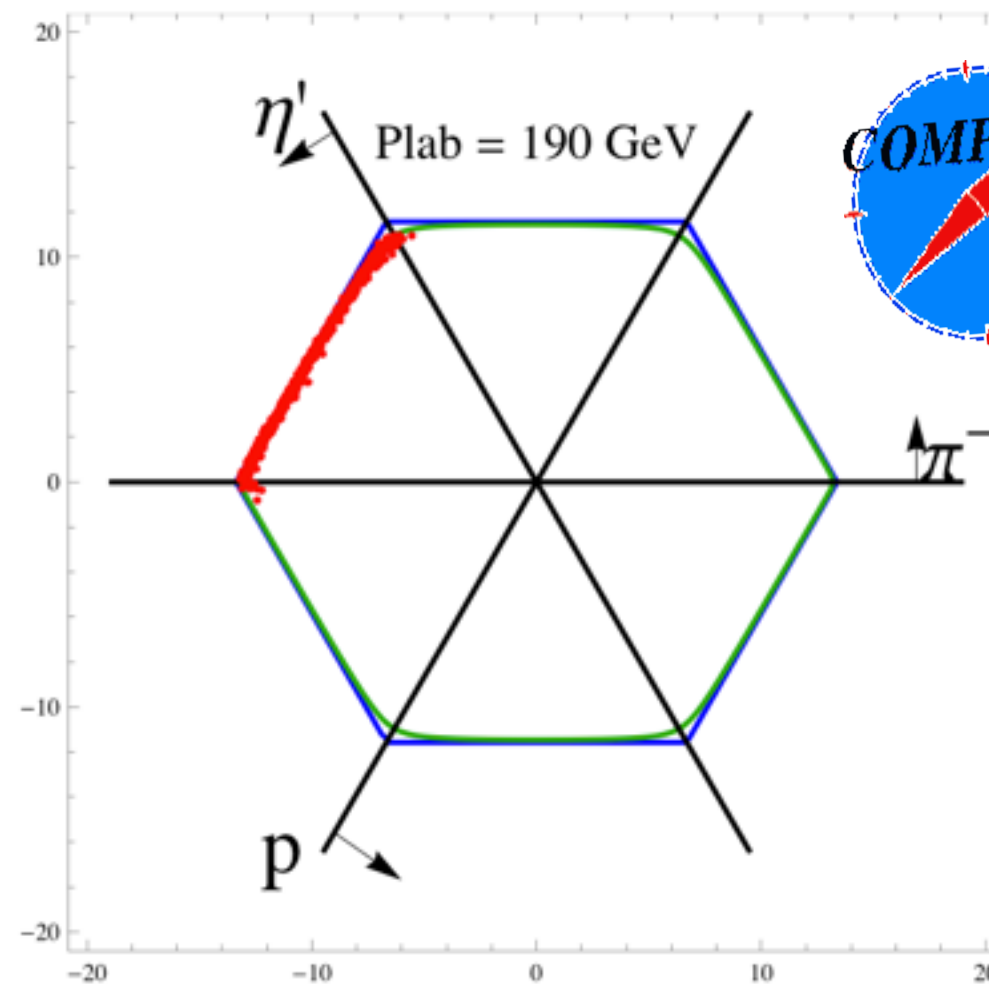
[Van Hove 1969]
[JPAC PRD91 (2015) 034007]



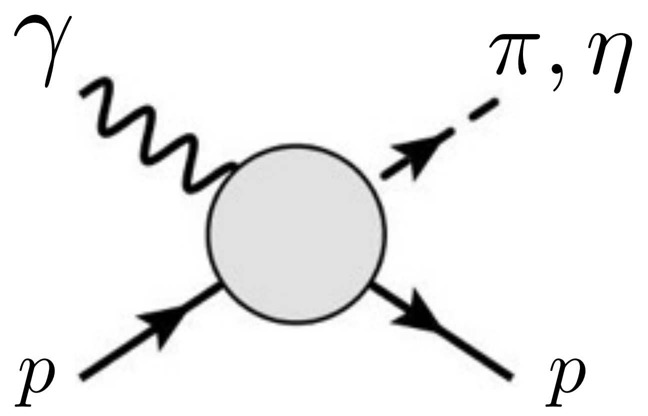
meson

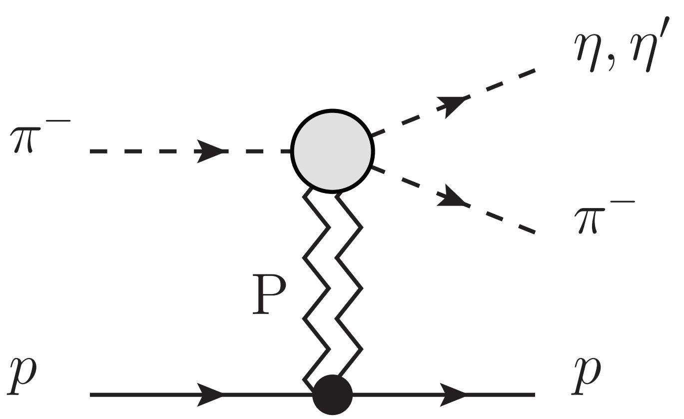
baryon



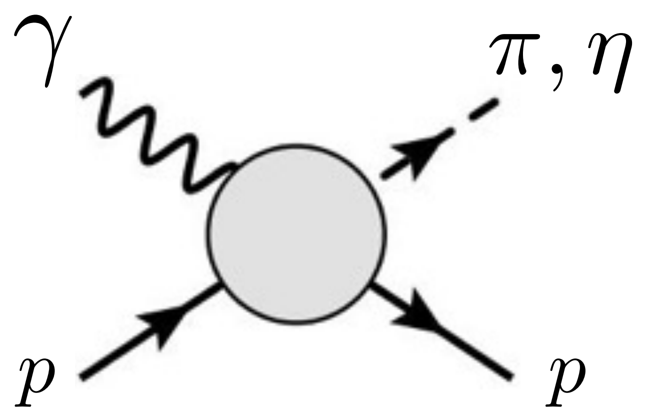


How Many Variables?





How Many Variables?



4 external particles on-shell: 4x3

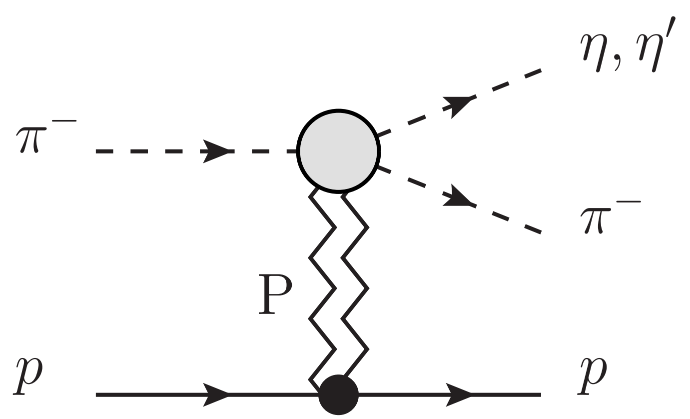
conservation of momentum: -3

conservation of angular momentum: -3

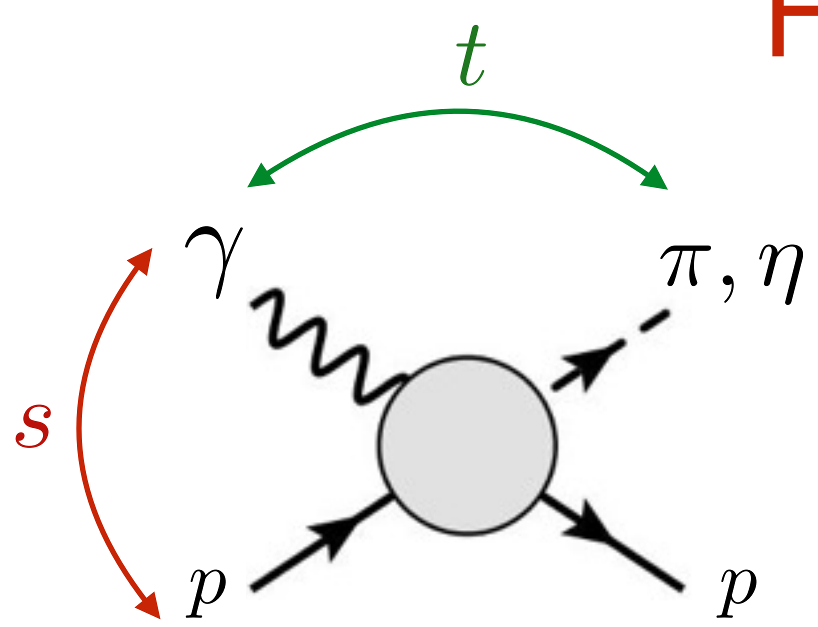
conservation of energy: -1

choose a frame: -3

$$\text{Total: } 4 \times 3 - 10 = 2$$



How Many Variables?



$$(E_{\rm cm}, \theta_{\rm cm})$$
$$(s, t)$$

4 external particles on-shell: 4x3

conservation of momentum: -3

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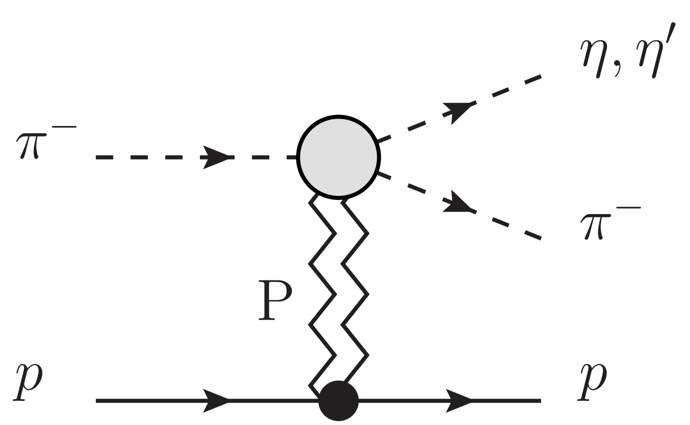
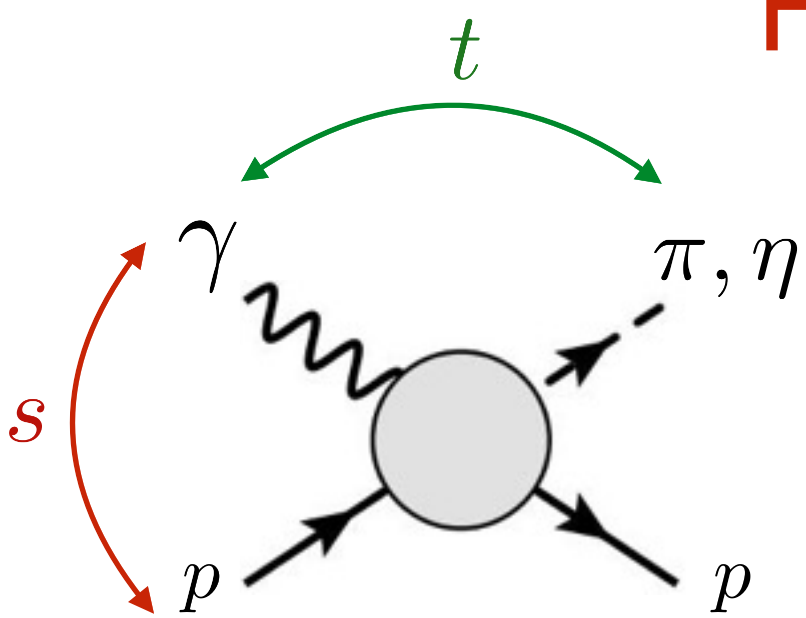
$$\text{Total: } 4 \times 3 - 10 = 2$$



How Many Variables?



$$(E_{\mathrm{cm}}, \theta_{\mathrm{cm}})$$

$$(s, t)$$

4 external particles on-shell: 4x3

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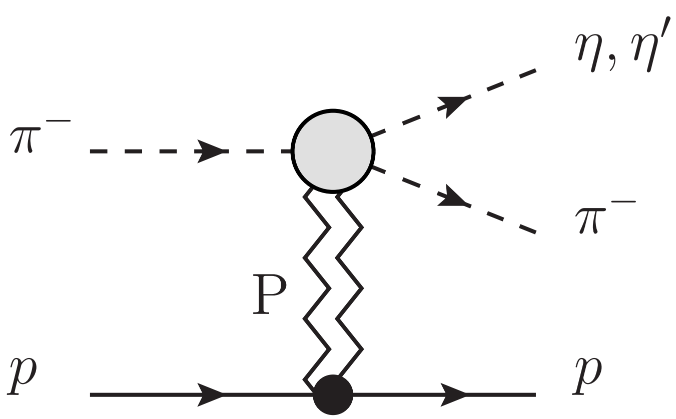
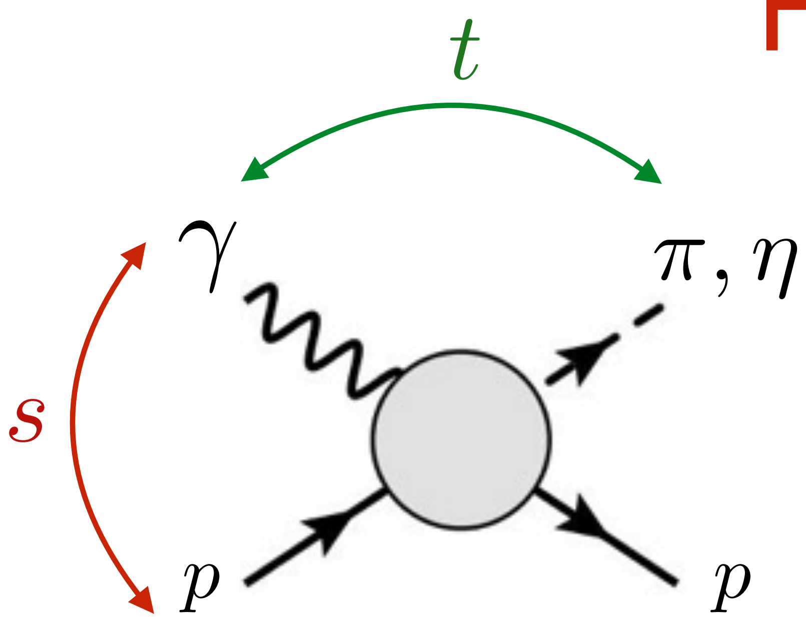
choose a frame: -3

$$\text{Total: } 4 \times 3 - 10 = 2$$



$$\text{Total: } 5 \times 3 - 10 = 5$$

How Many Variables?



$(E_{\mathrm{cm}}, \theta_{\mathrm{cm}})$

(s, t)

4 external particles on-shell: 4x3

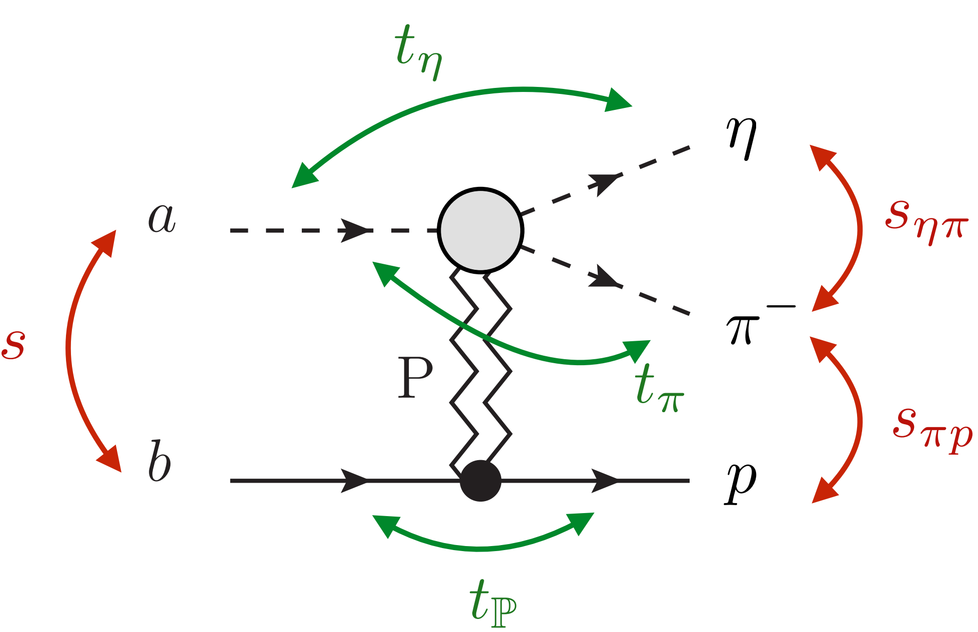
conservation of momentum: -3

conservation of angular momentum: -3

conservation of energy: -1

choose a frame: -3

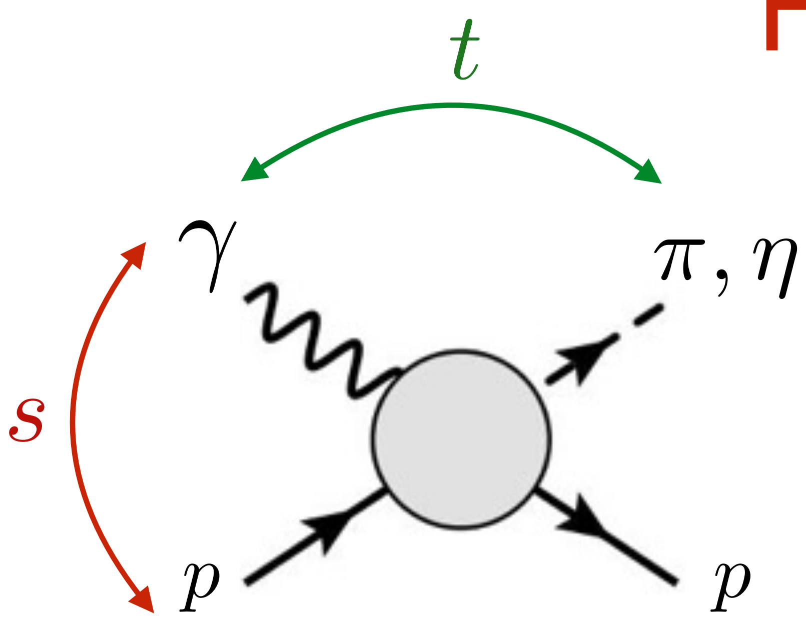
$$\text{Total: } 4 \times 3 - 10 = 2$$



$$\text{Total: } 5 \times 3 - 10 = 5$$

$$(s, t_{\mathbb{P}}, s_{\eta\pi}, s_{\pi p}, t_\eta)$$

How Many Variables?



$$(E_{\rm cm}, \theta_{\rm cm})$$

$$(s, t)$$

4 external particles on-shell: 4x3

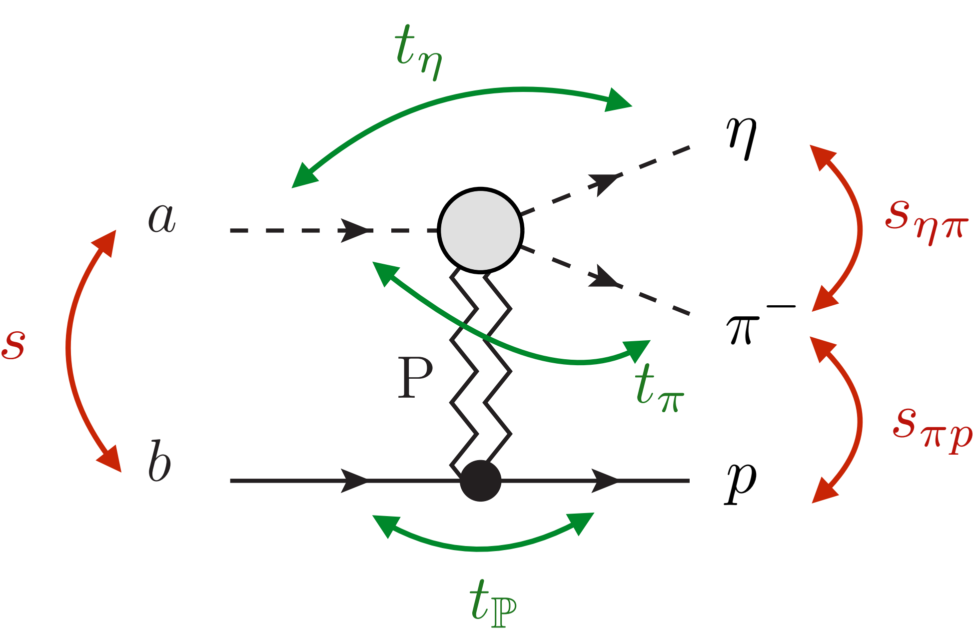
conservation of momentum: -3

conservation of angular momentum: -3

conservation of energy: -1

choose a frame: -3

$$\text{Total: } 4 \times 3 - 10 = 2$$

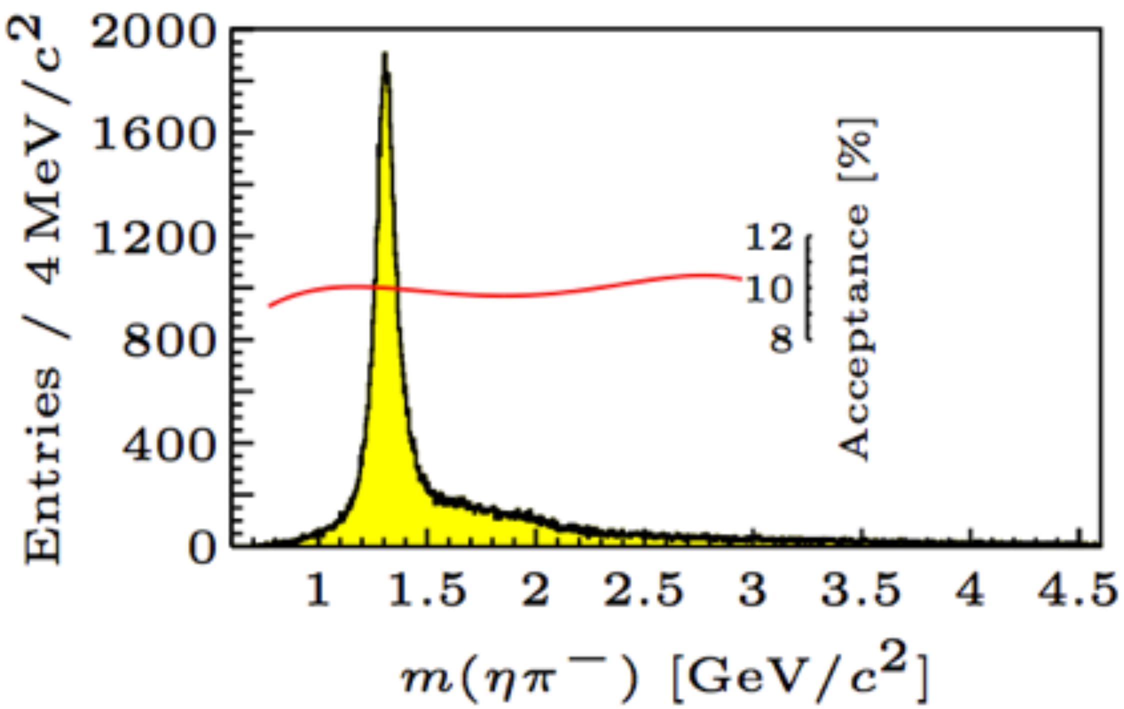


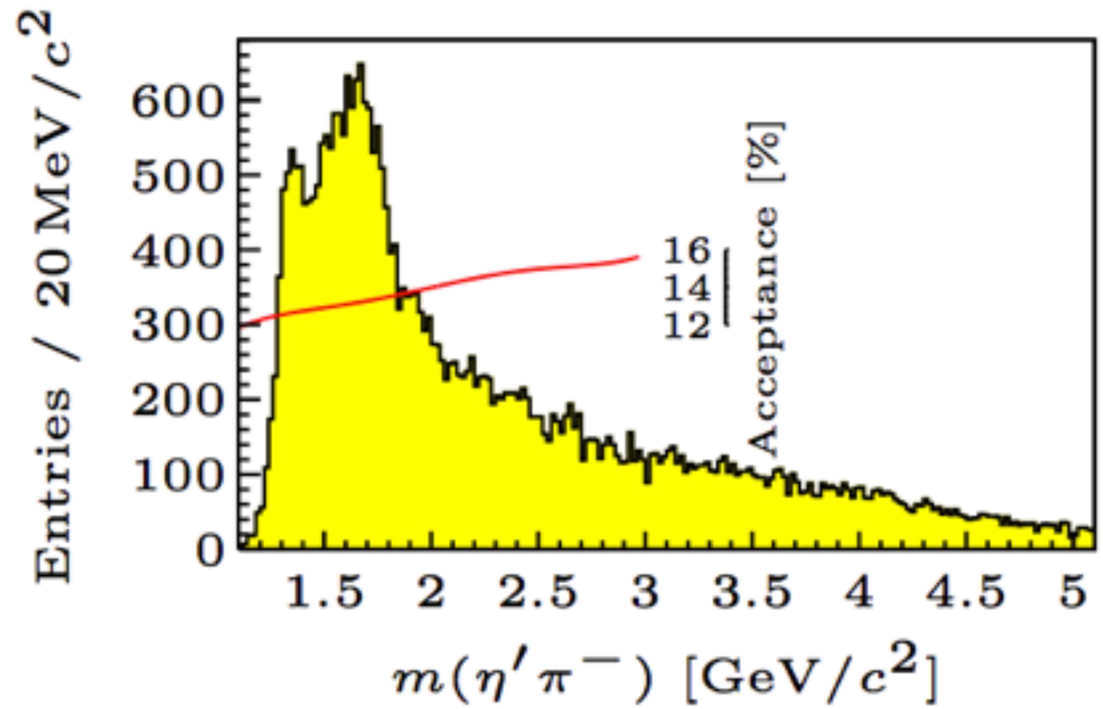
$$\text{Total: } 5 \times 3 - 10 = 5$$

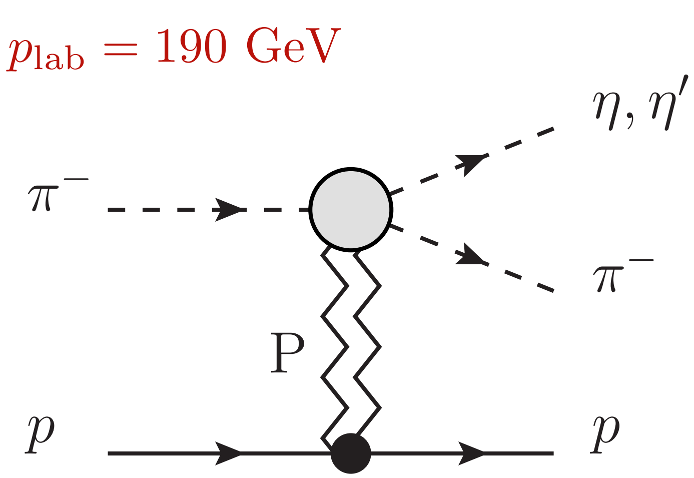
$$(s, t_{\mathbb{P}}, s_{\eta\pi}, s_{\pi p}, t_\eta)$$

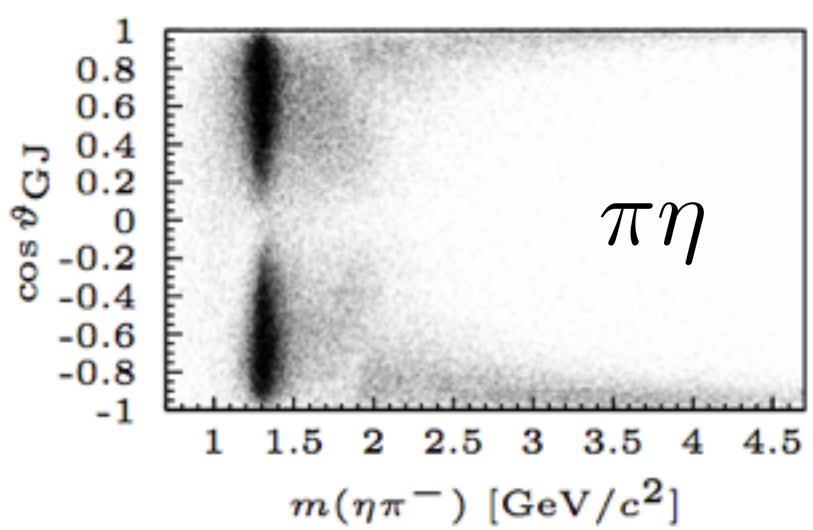
$$(s, t_{\mathbb{P}}, s_{\eta\pi}, \theta, \phi)$$

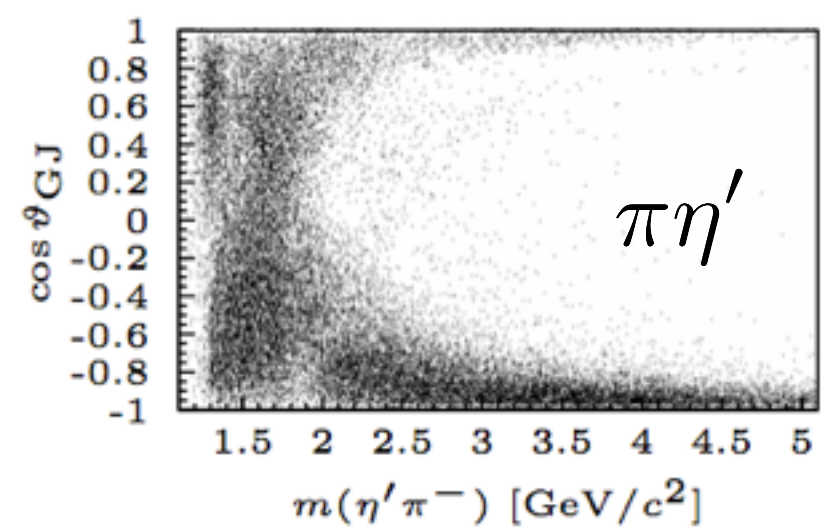
Eta-Pi @COMPASS











$$(s, t_{\mathbb{P}}, s_{\eta\pi}, \theta, \phi)$$

Gottfried-Jackson frame

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Gottfried-Jackson Frame

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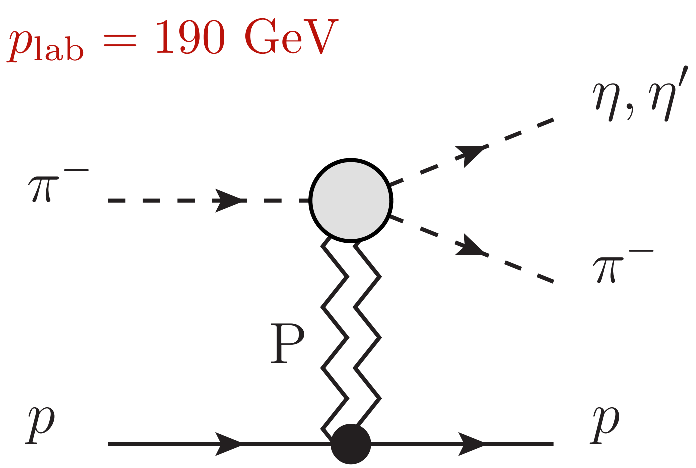

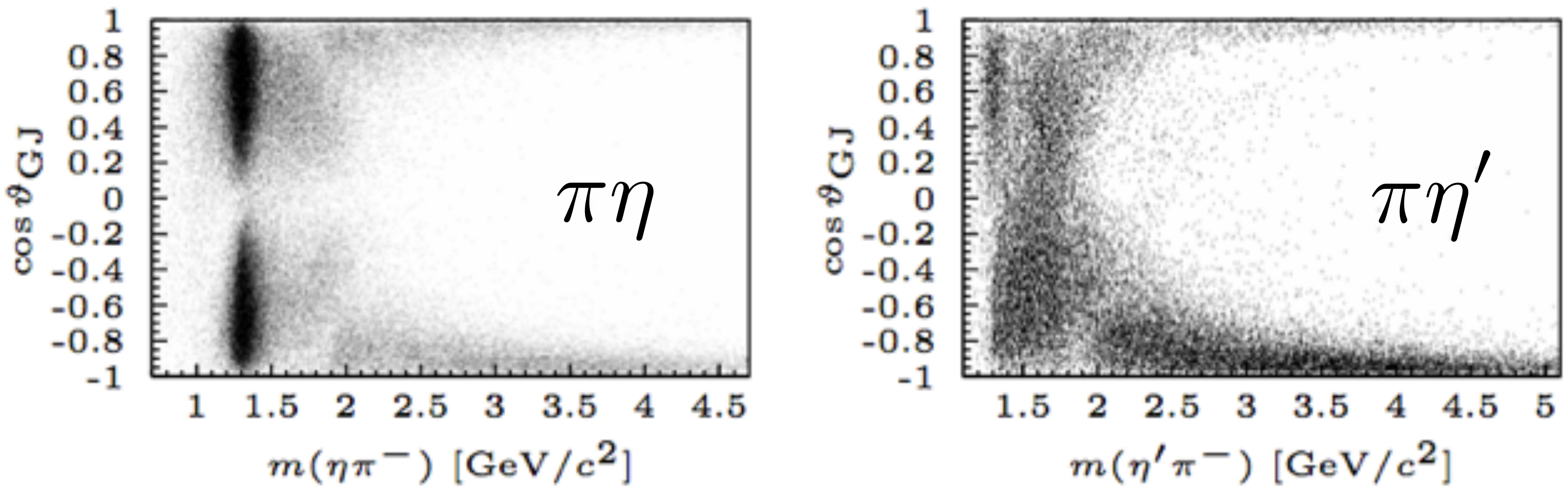

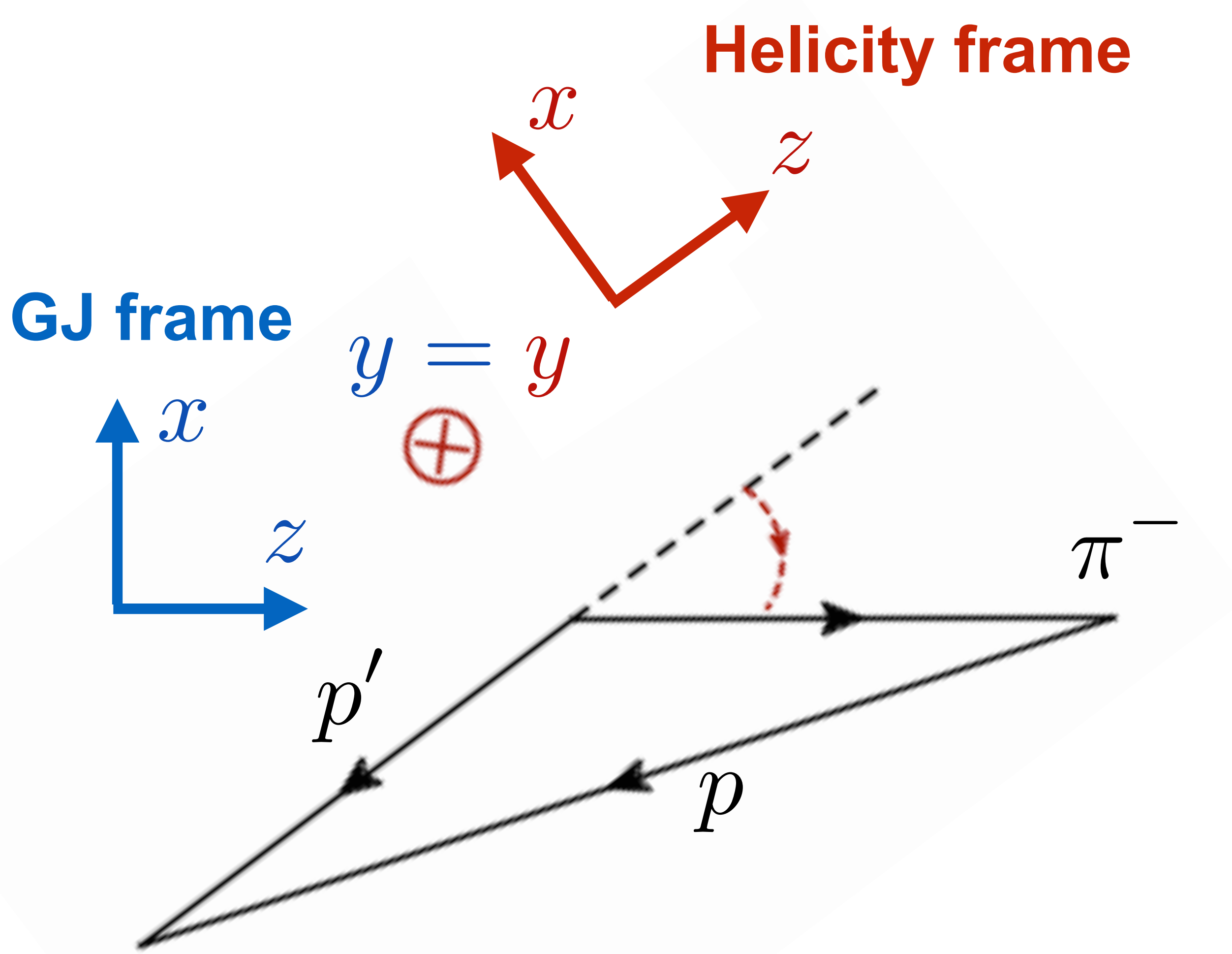

Gottfried-Jackson Frame

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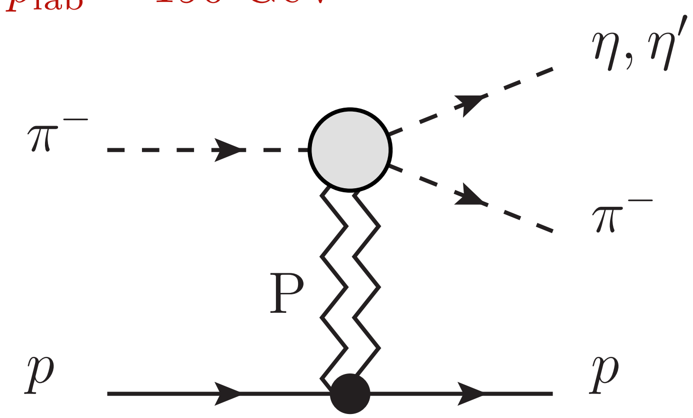
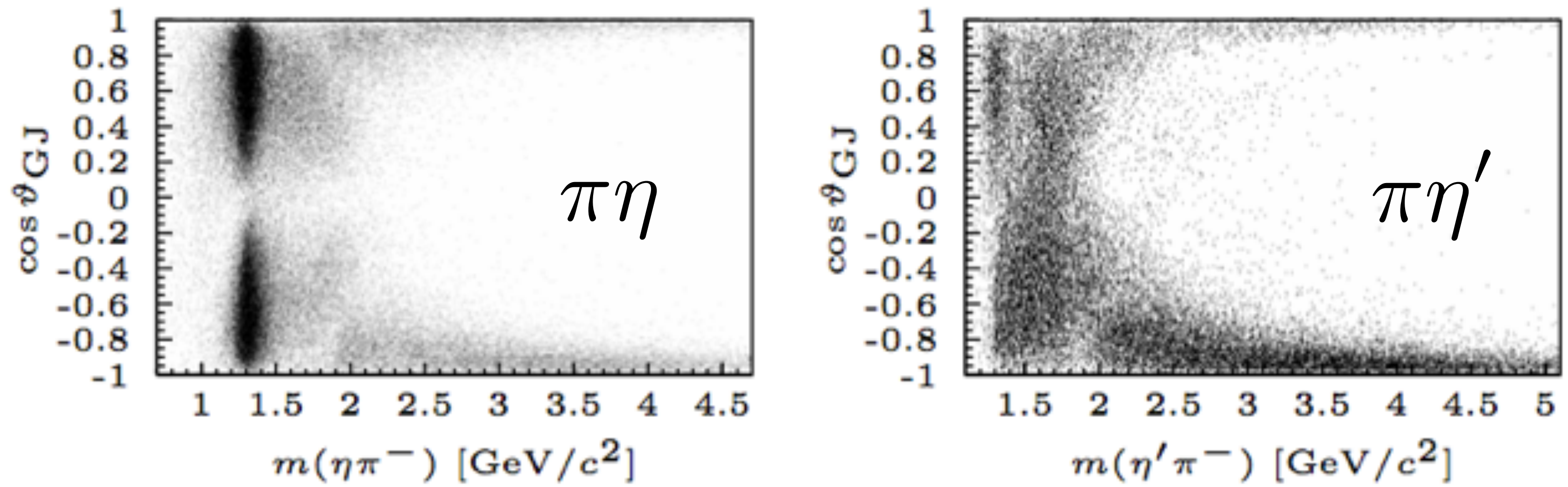
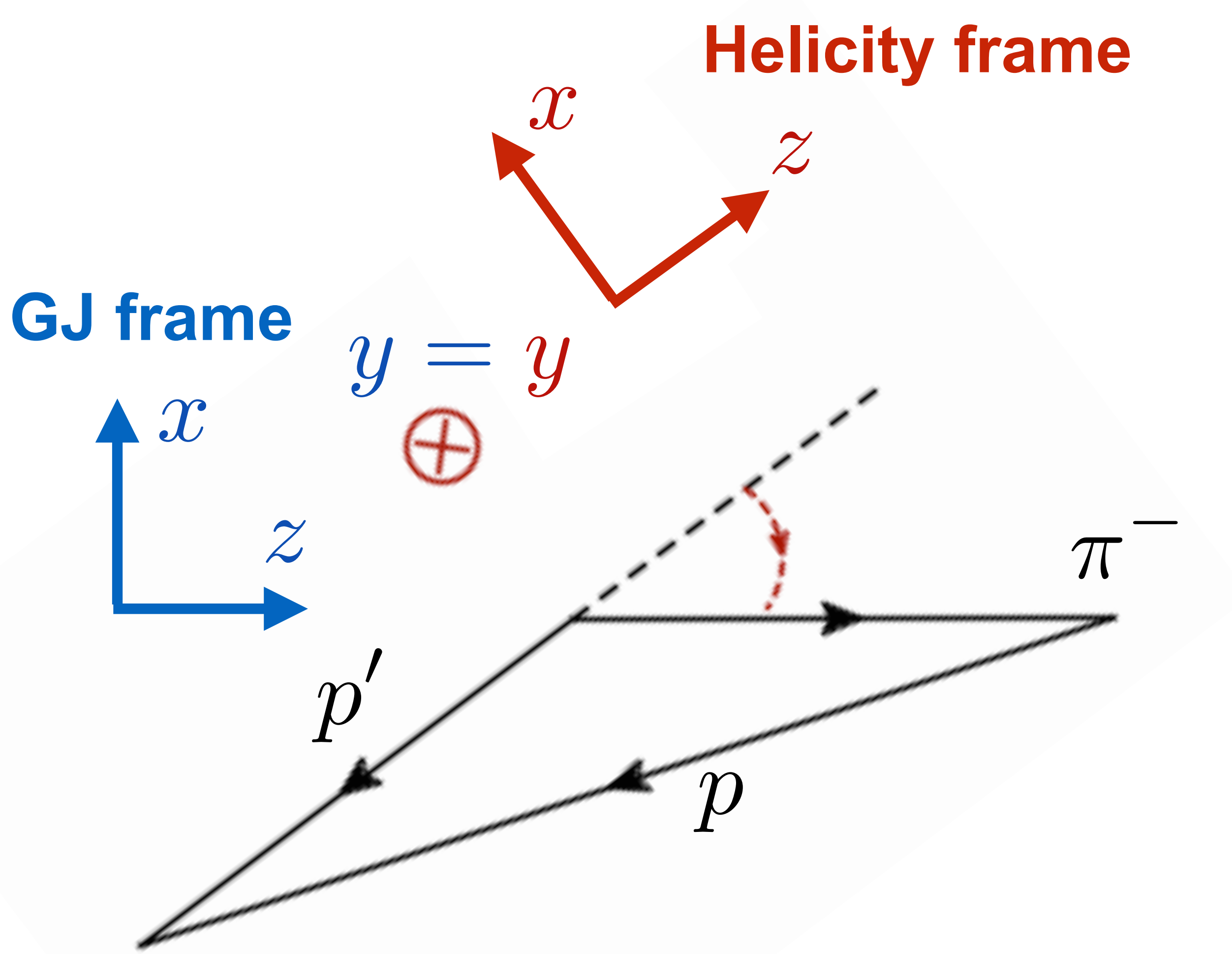
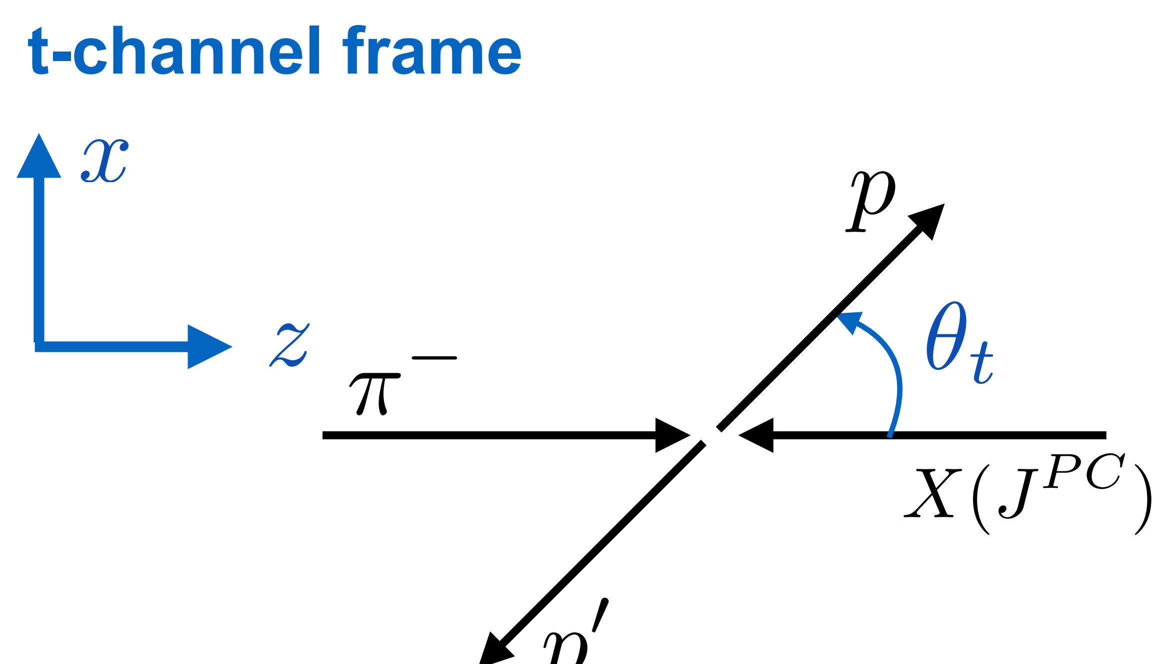
$p_{\text{lab}} = 190$ GeV









Reflectivity Basis

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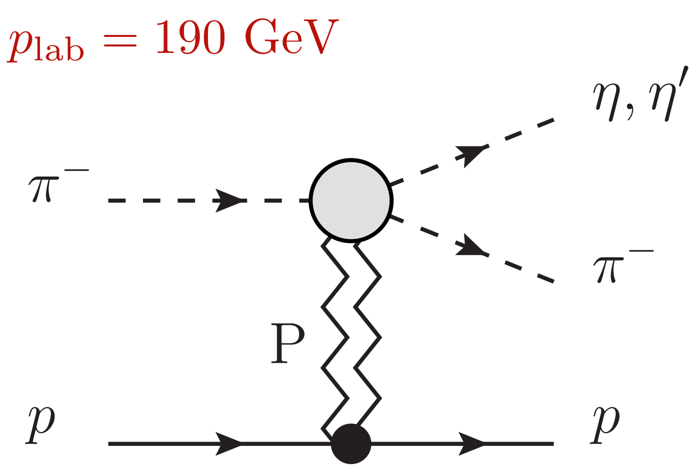
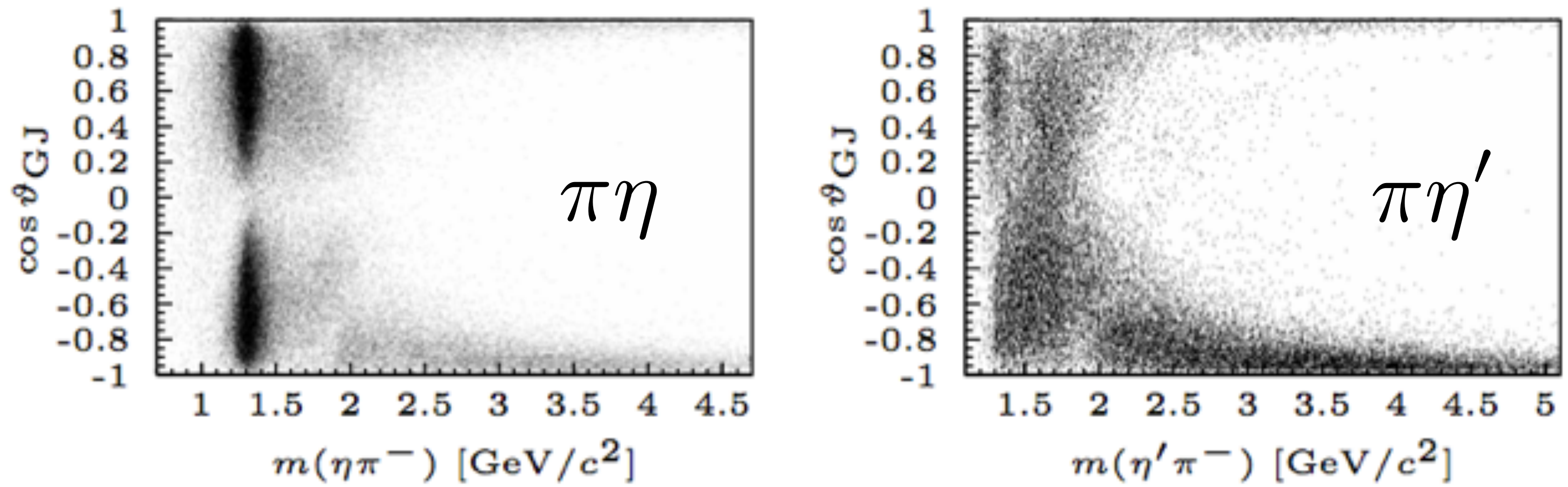
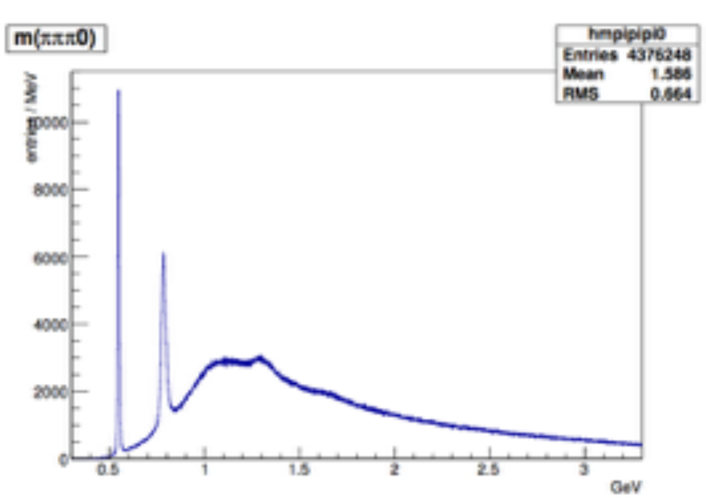




$$I(\tau) = \sum_{\epsilon} \left| \sum_{L,M} A^{\epsilon}_{LM} \psi^{\epsilon}_{LM}(\tau) \right|^2 + \text{non-}\eta^{(\prime)} \text{ background}$$

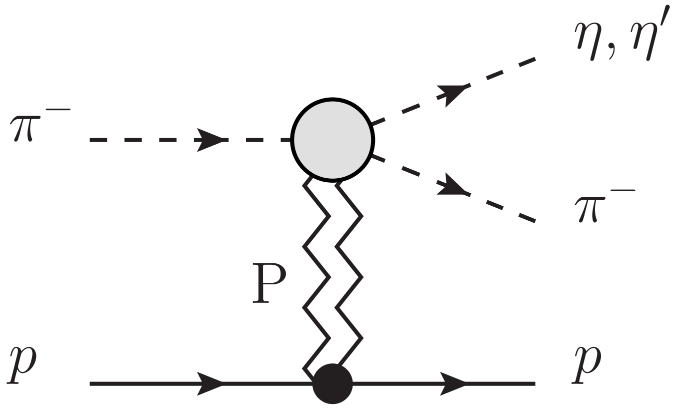
$$\psi^{\epsilon}_{LM}(\tau) = f_{\eta}(p_{\pi^-}, p_{\pi^+}, p_{\pi^0}) \times Y^M_L(\vartheta_{\rm GJ}, 0) \times \begin{cases} \sin M\varphi_{\rm GJ} & \text{for } \epsilon = +1 \\ \cos M\varphi_{\rm GJ} & \text{for } \epsilon = -1 \end{cases}$$

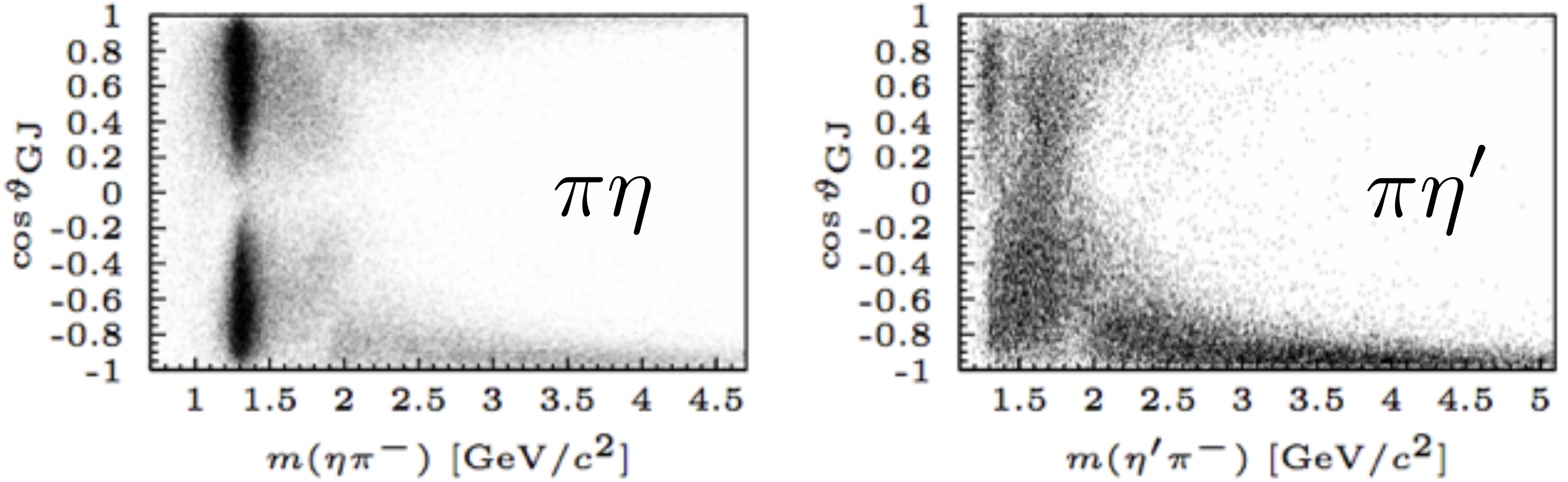


Reflectivity Basis

COMPASS Phys. Lett. B740 (2015)

$p_{\mathrm{lab}} = 190$ GeV

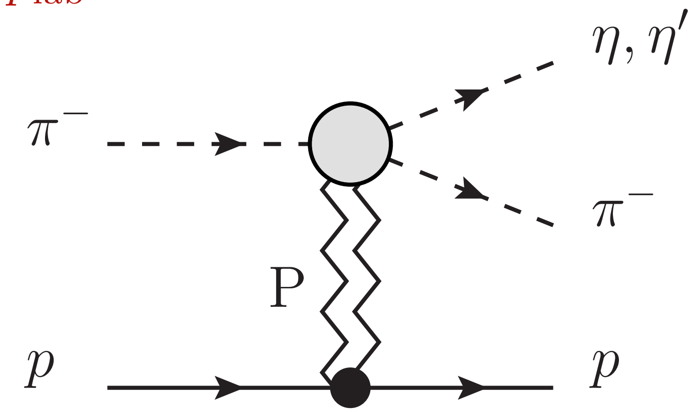


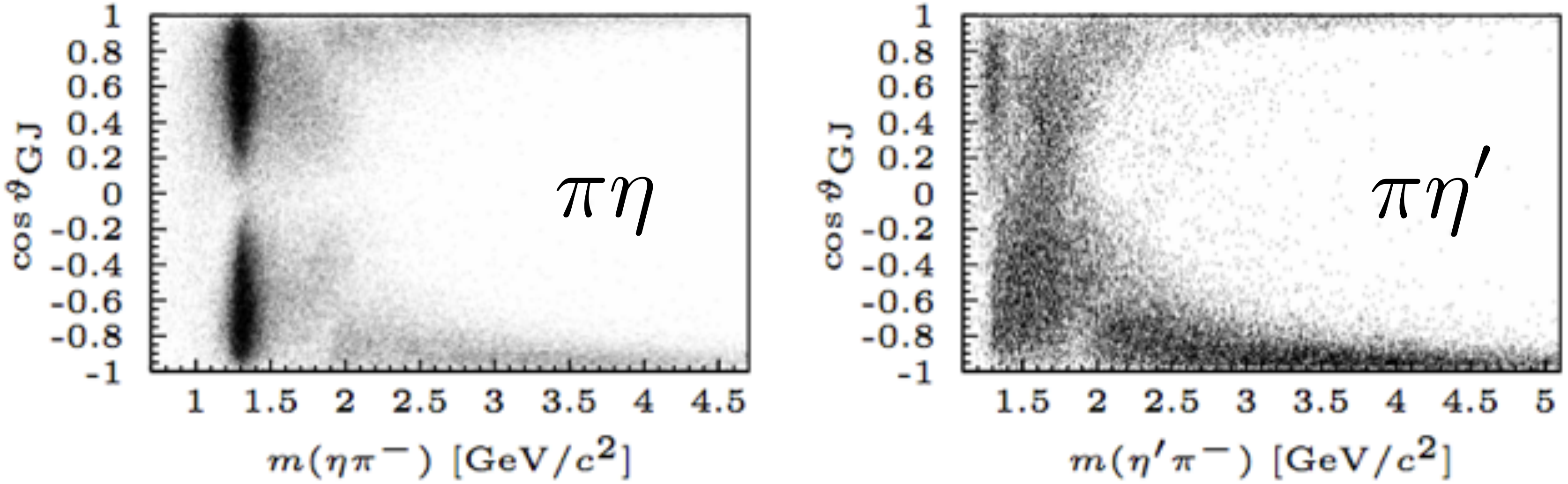


Reflectivity Basis

COMPASS Phys. Lett. B740 (2015)

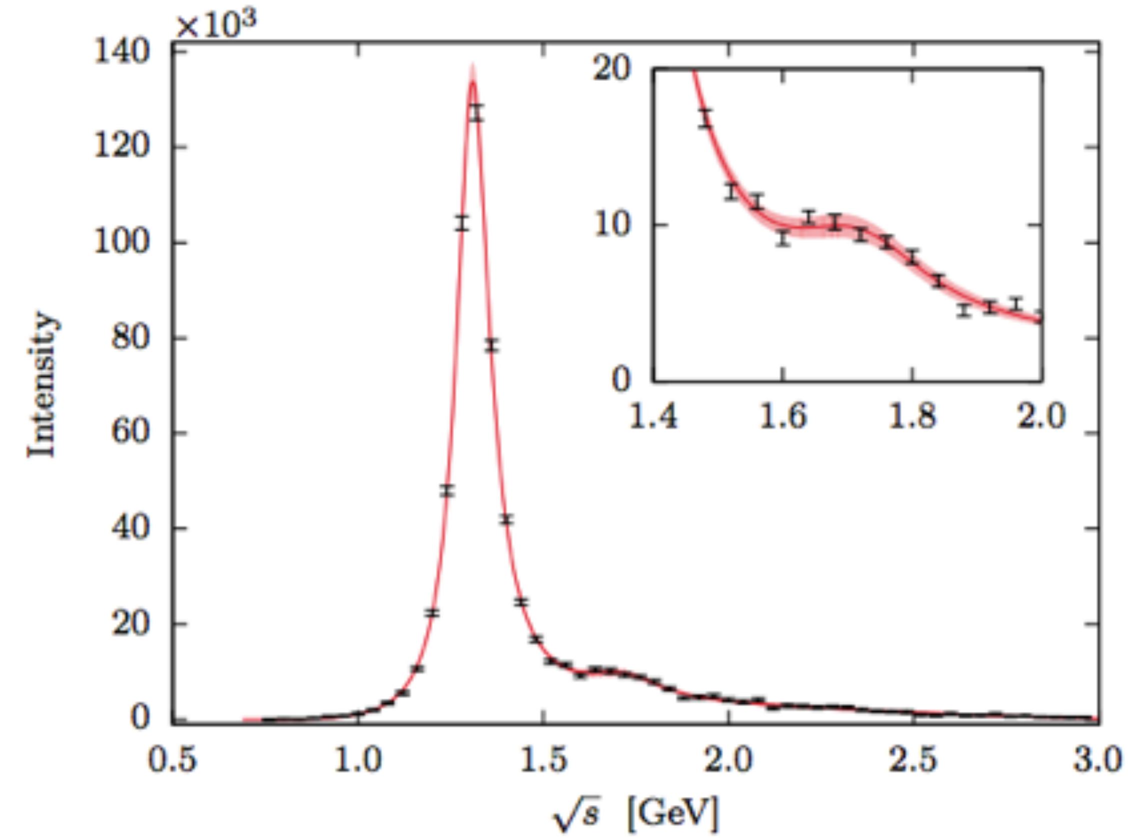
$p_{\mathrm{lab}} = 190$ GeV



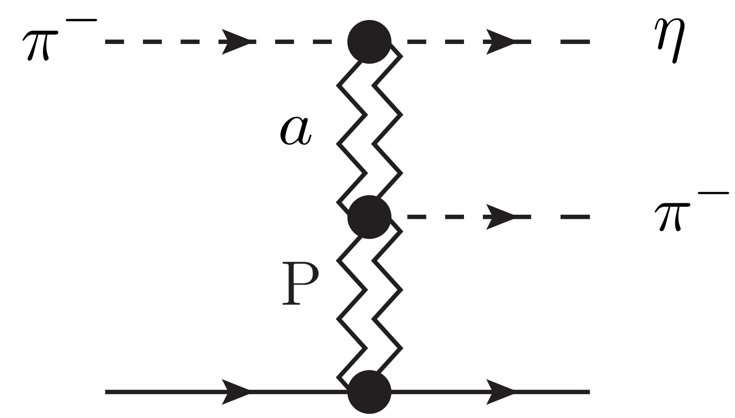


$$a_2(1320) : I^G J^{PC} = 1^- 2^{++}$$

$$d^2_{1,0}(\theta) \propto Y^1_2(\theta, 0) \propto \sin\theta\cos\theta$$

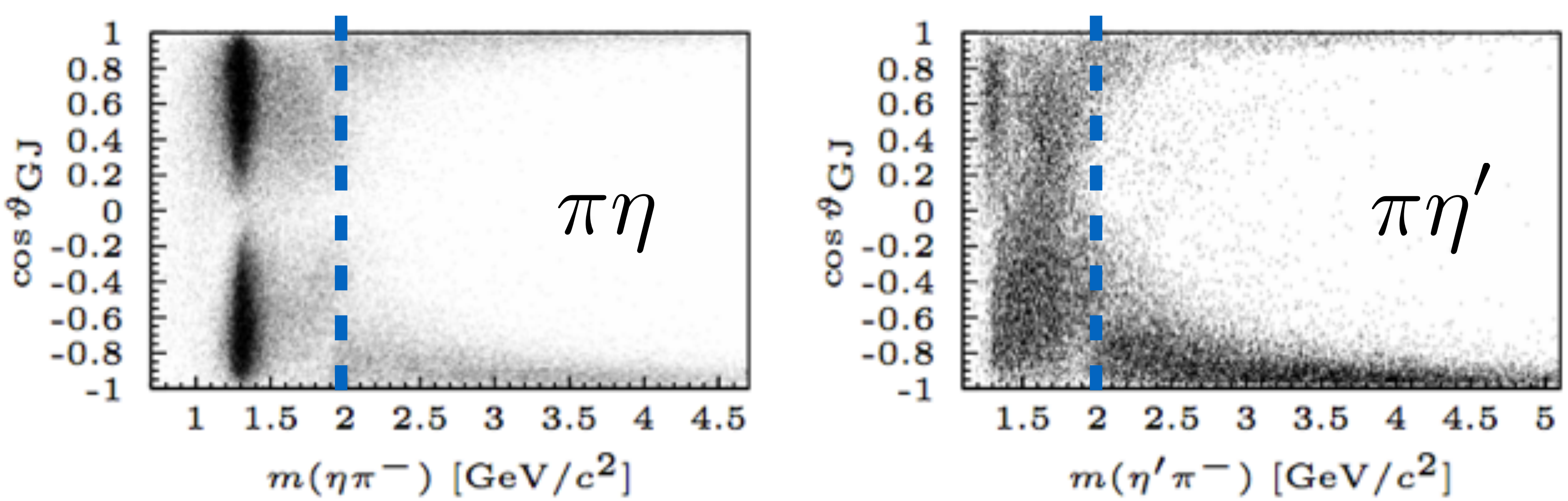


High Mass Region

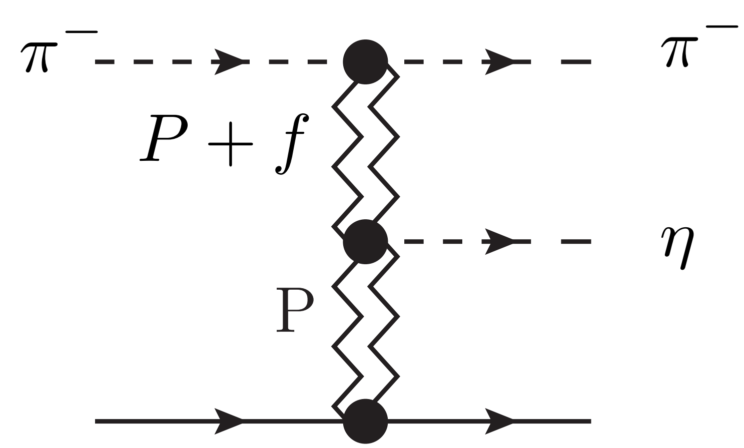


$a : I^G J^{PC} = 1^-(0, 2, 4, 6, \ldots)^{++}$

$\cos\theta_{GF} \sim 1 \rightarrow \eta$ forward



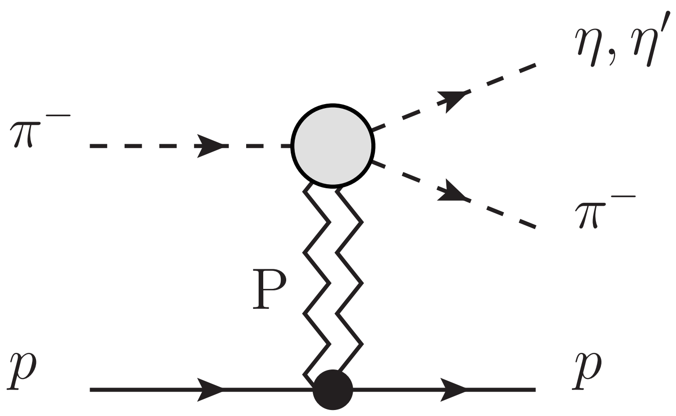
$\cos\theta_{GF} \sim -1 \rightarrow \eta$ backward

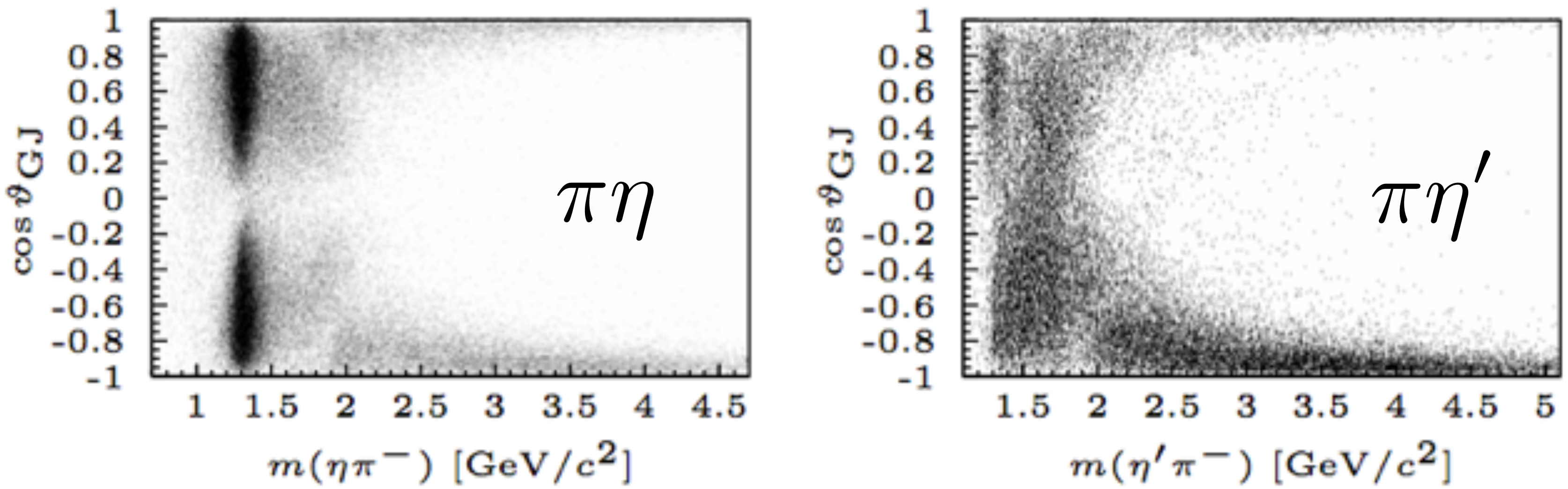


$f : I^G J^{PC} = 0^+(0, 2, 4, 6, \ldots)^{++}$

Eta-Pi @COMPASS

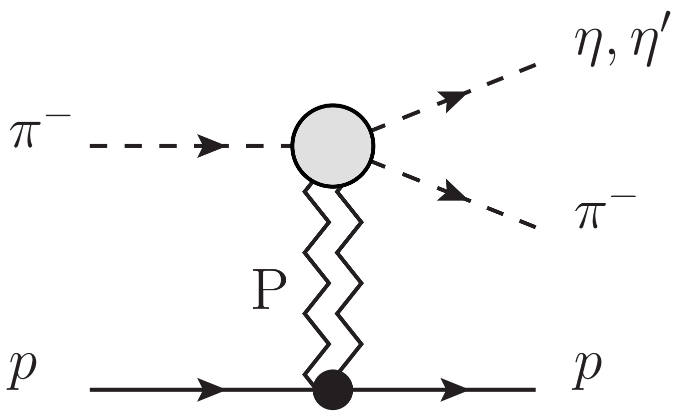
COMPASS Phys. Lett. B740 (2015)

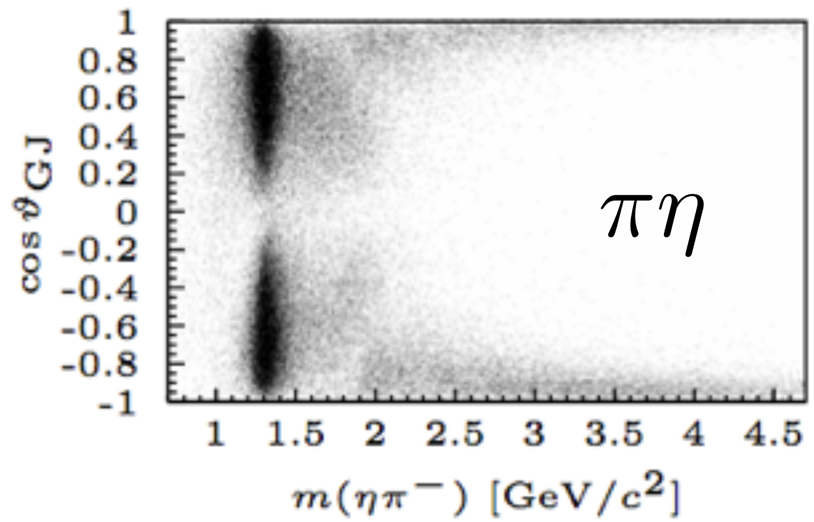


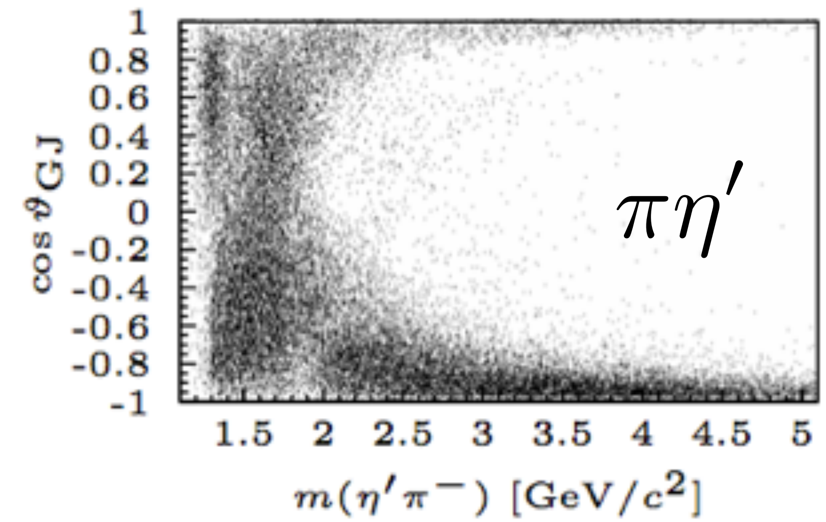


Eta-Pi @COMPASS

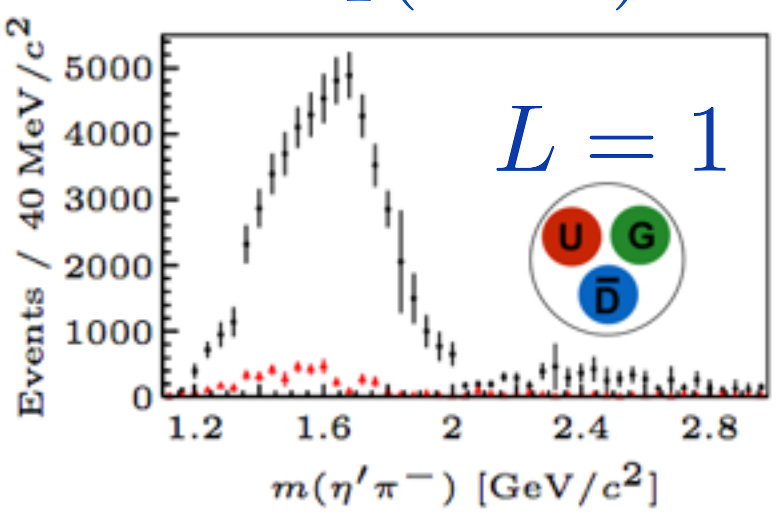
COMPASS Phys. Lett. B740 (2015)



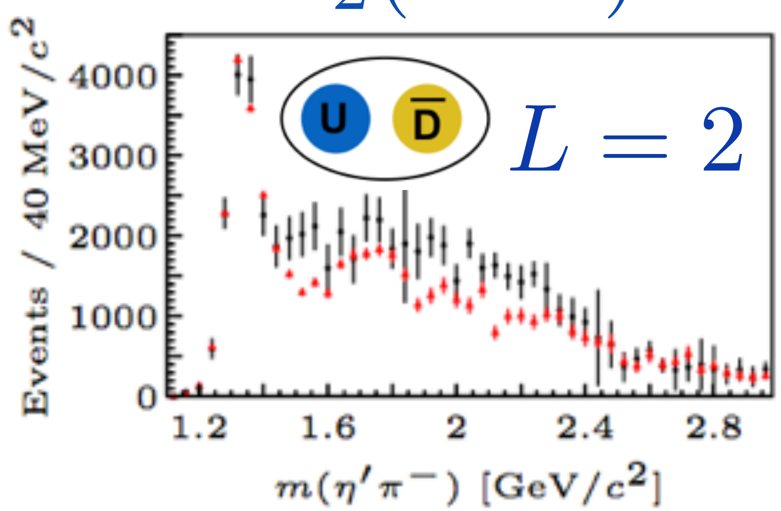




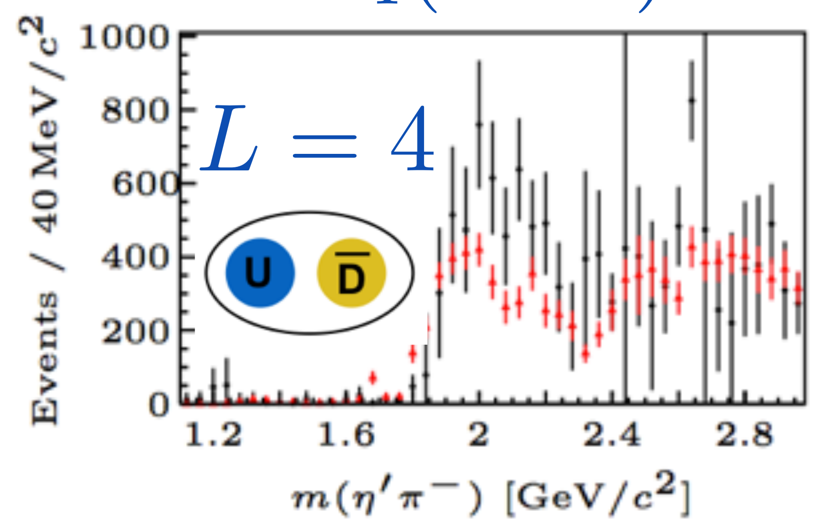
$\pi_1(1600)$?

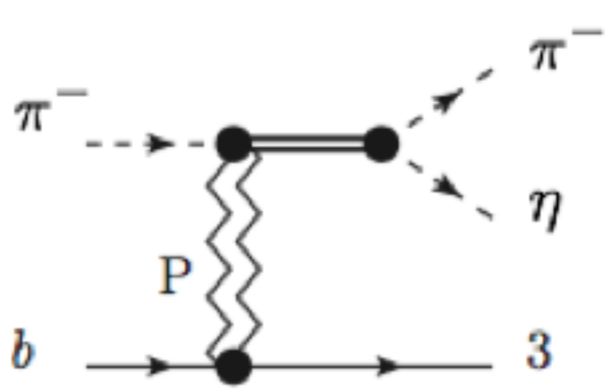


$a_2(1320)$



$a_4(2040)$



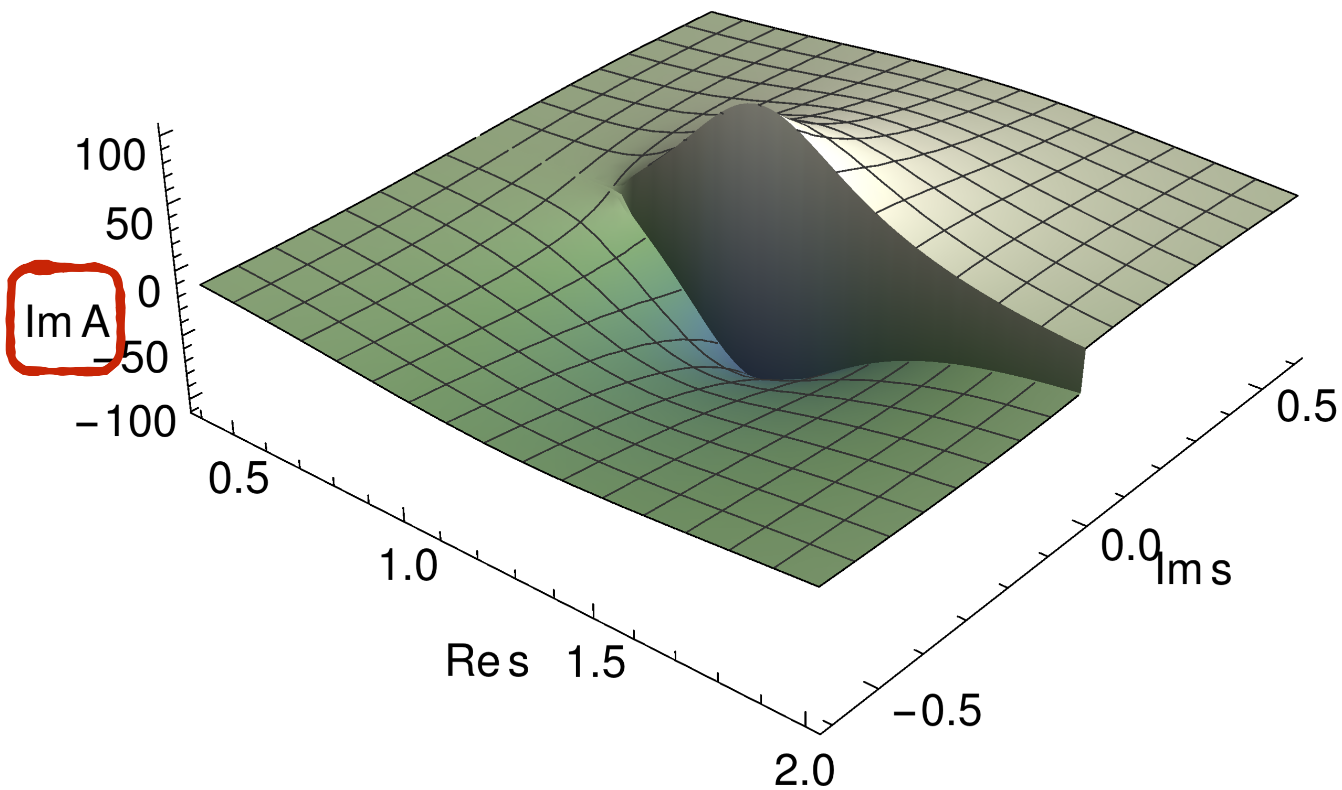


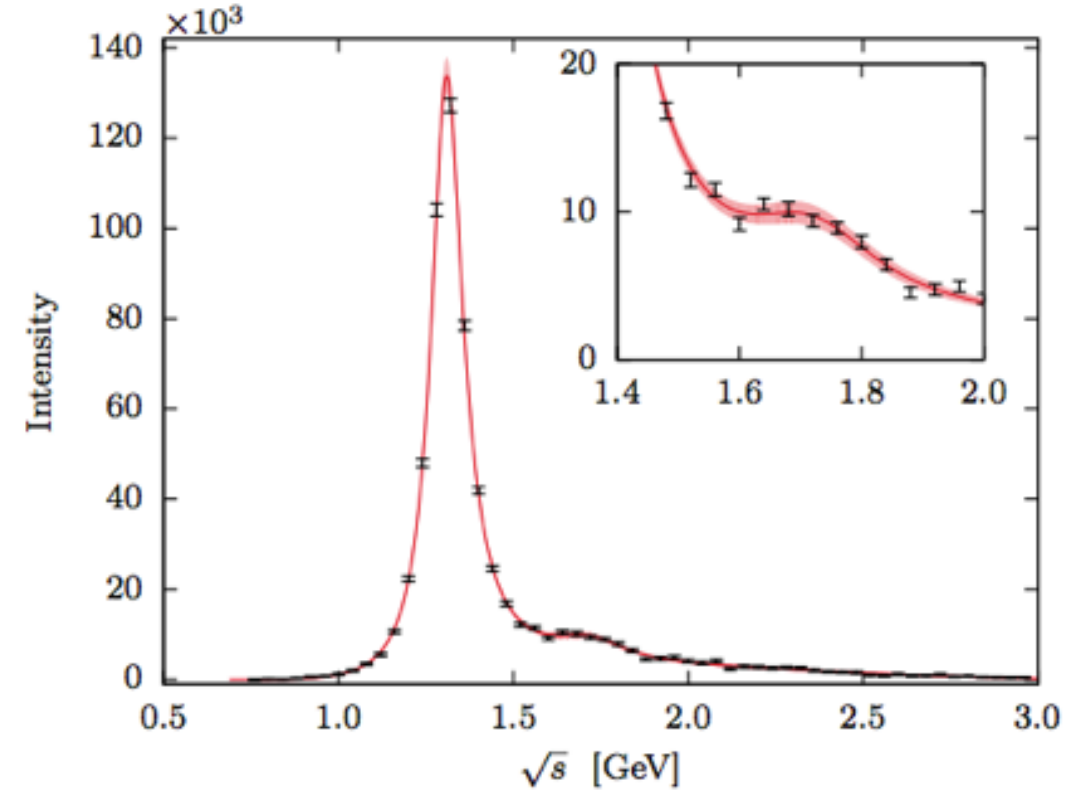
black: $\pi\eta'$

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

Resonance in angular mom. L = 1 ?

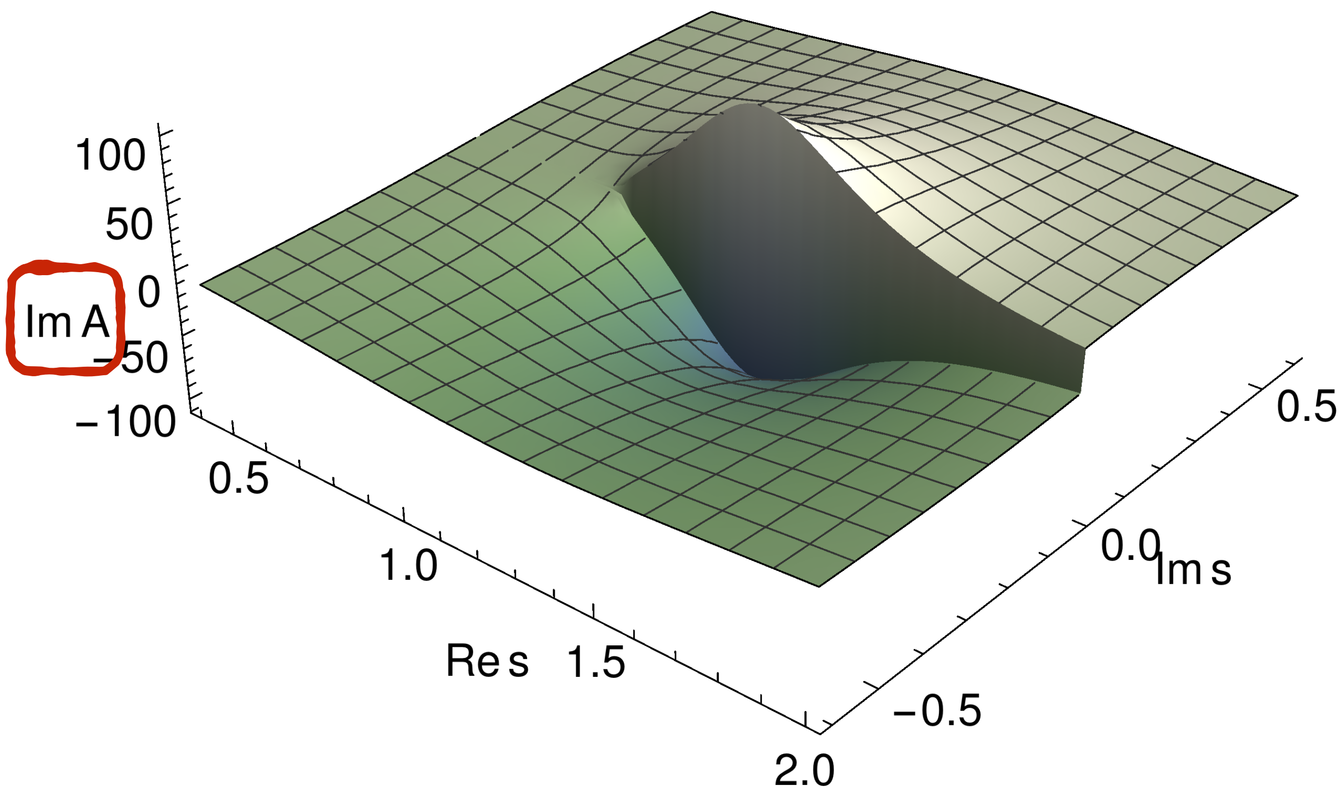
Analytic Structure of Partial Wave

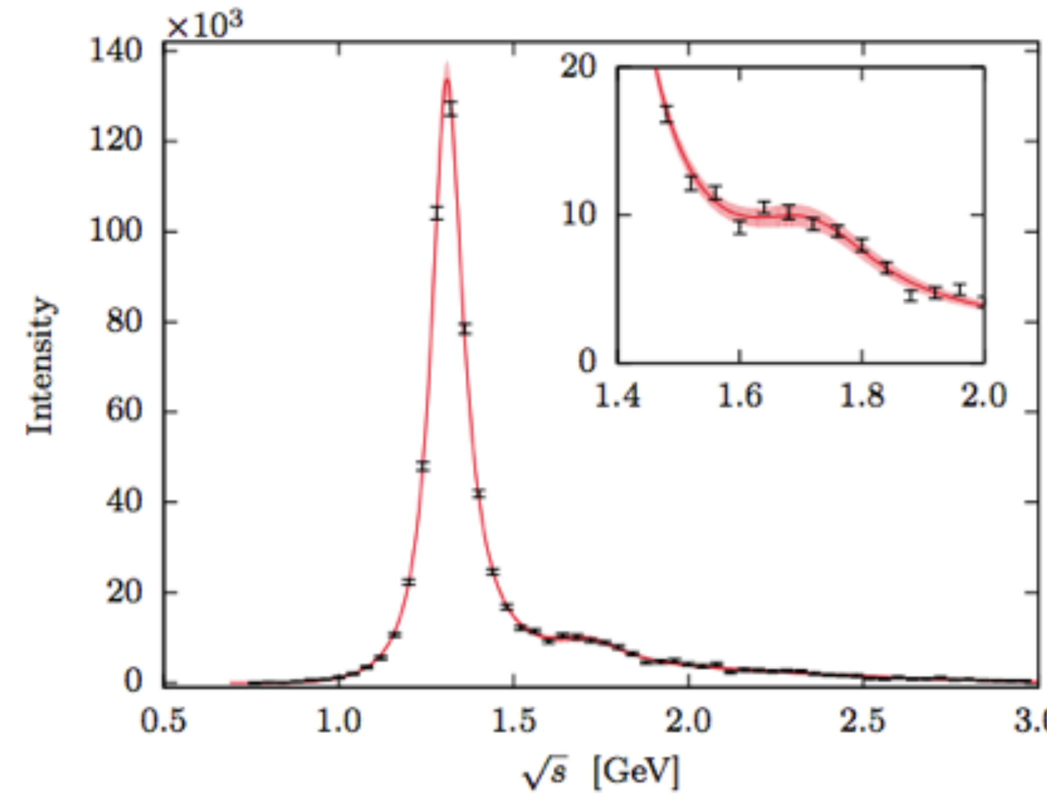


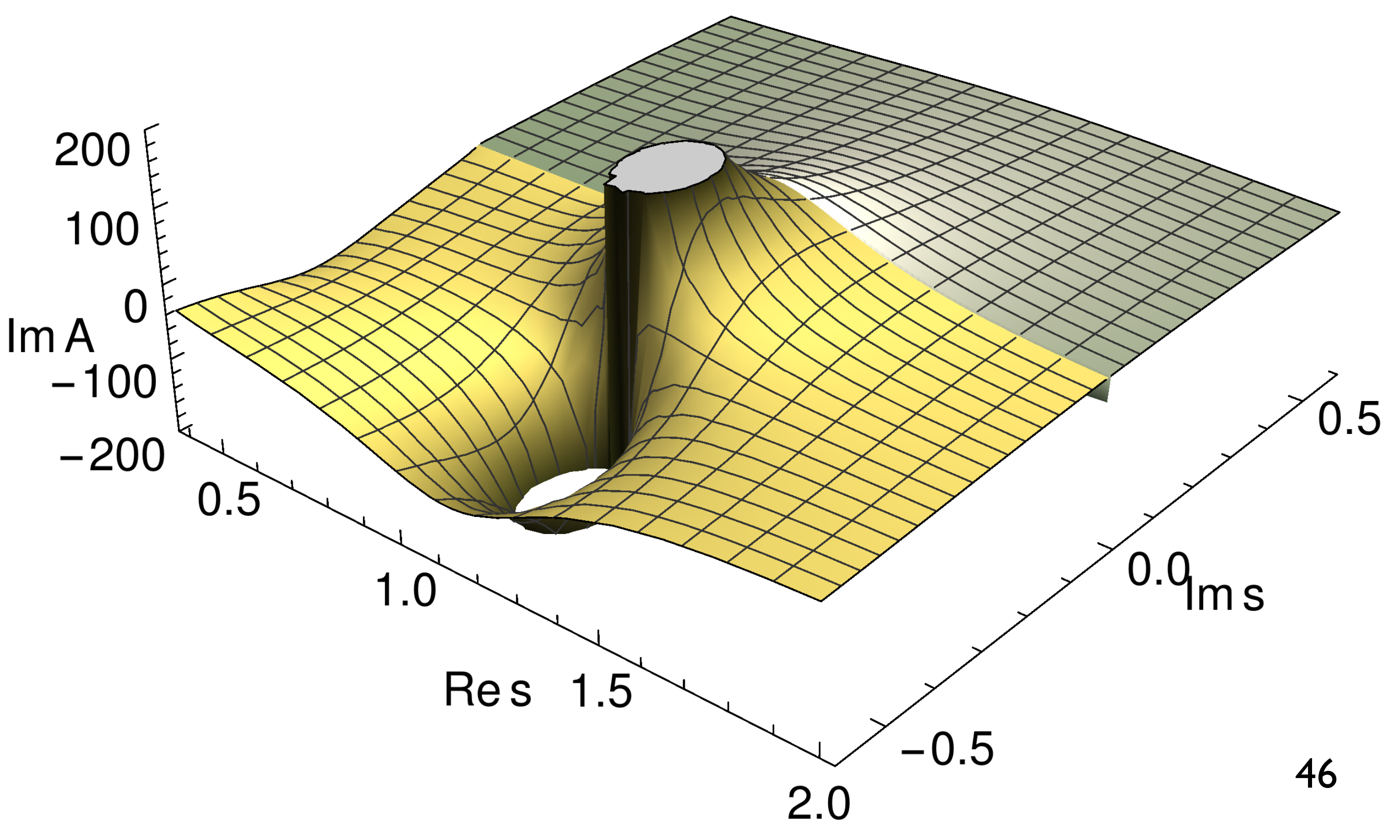


$$\mathrm{Disc}\, F(s) = 2i \mathrm{Im}\, F(s)$$

Analytic Structure of Partial Wave

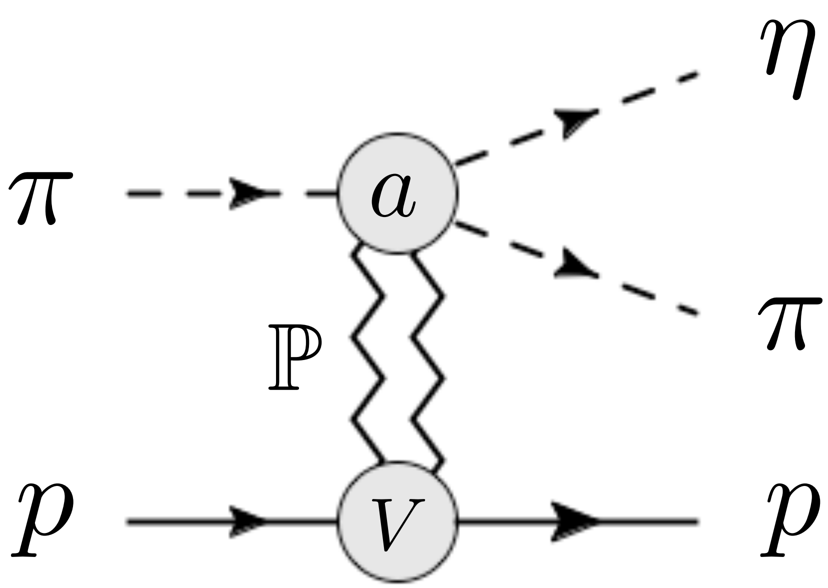


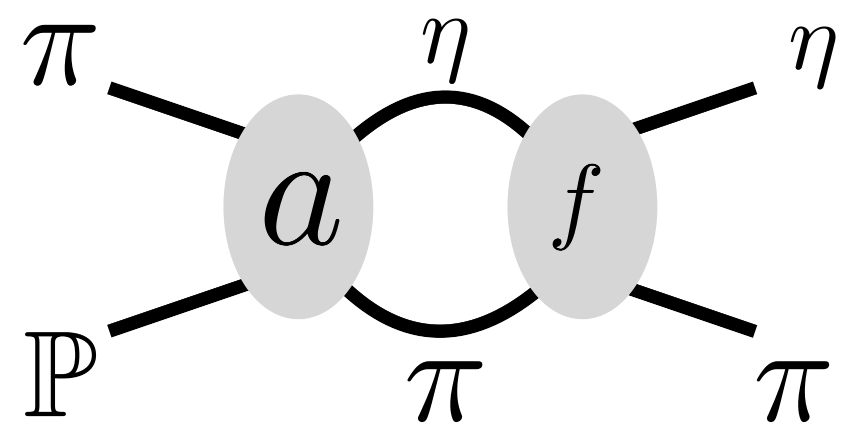


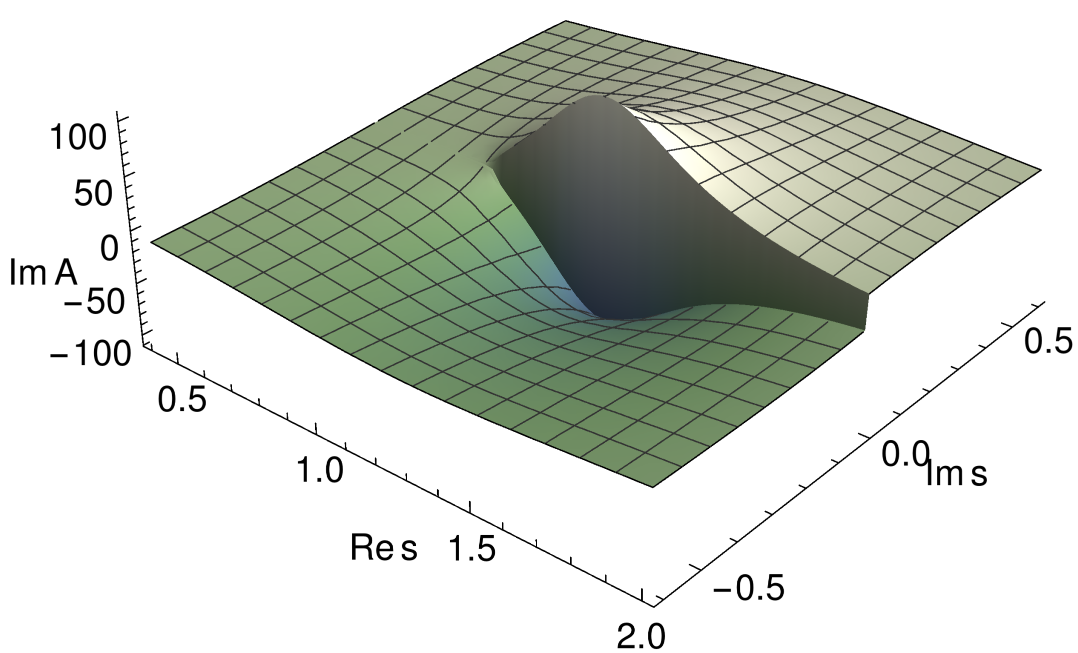


$$\mathrm{Disc}\, F(s) = 2i \mathrm{Im}\, F(s)$$

Unitarity



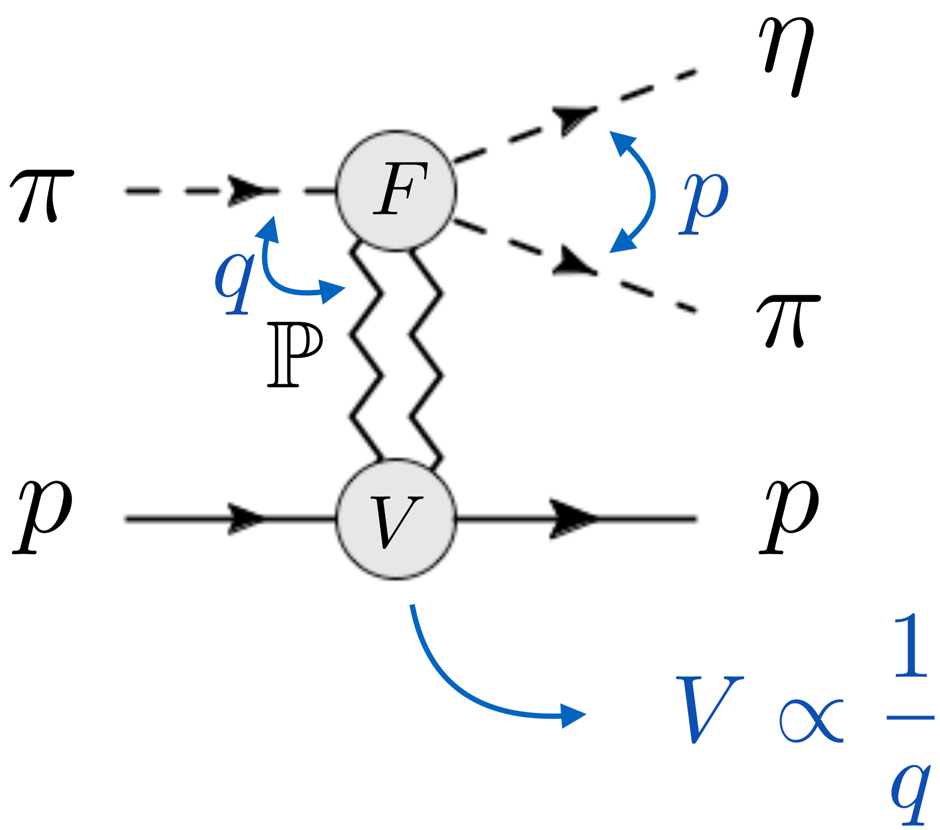




$$\boxed{\begin{aligned}\mathrm{Im}\ a(s) &= \rho(s) f^*(s) a(s)\\ \mathrm{Im}\ f(s) &= \rho(s)|f(s)|^2\end{aligned}}$$

or $$\mathrm{Im}\ \hat{f}^{-1}(s) = -\rho(s)$$

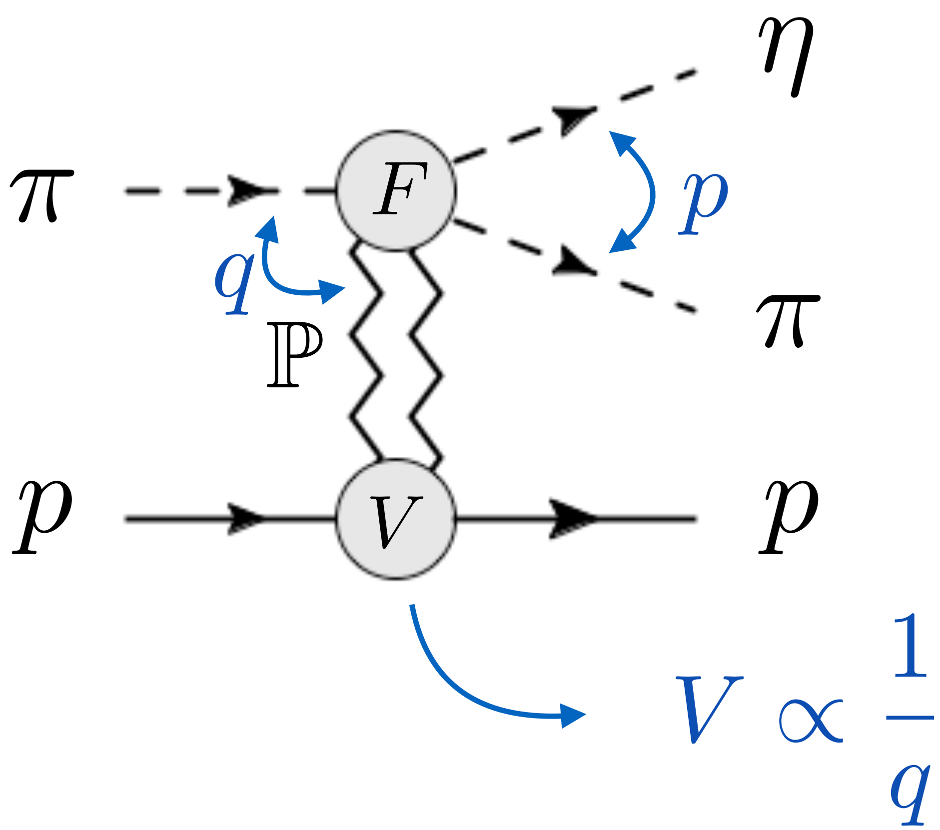
Barrier Factors



$$0^- \times 0^- \times (1^-)^2 = 2^+ \rightarrow p^2$$

$$0^- \times 1^- \times (1^-)^2 = 2^+ \rightarrow q^2$$

Barrier Factors



$$0^- \times 0^- \times (1^-)^2 = 2^+ \to p^2$$

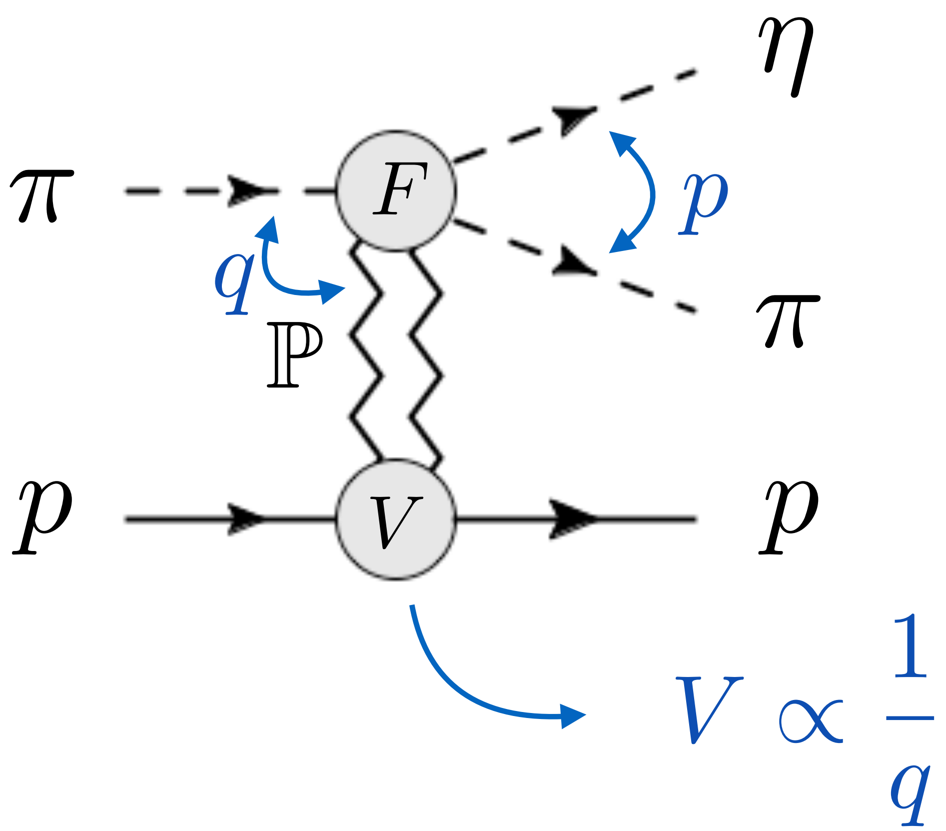
$$0^- \times 1^- \times (1^-)^2 = 2^+ \to q^2$$

$$a(a) = p^2 q \; \hat{a}(s)$$

$$f(s) = p^4 \; \hat{f}(s)$$

$$\boxed{\begin{aligned} \mathrm{Im}\; \hat{a}(s) &= \rho(s)\hat{f}^*(s)\hat{a}(s) \\ \mathrm{Im}\; \hat{f}(s) &= \rho(s)|\hat{f}(s)|^2 \end{aligned}}$$

Barrier Factors



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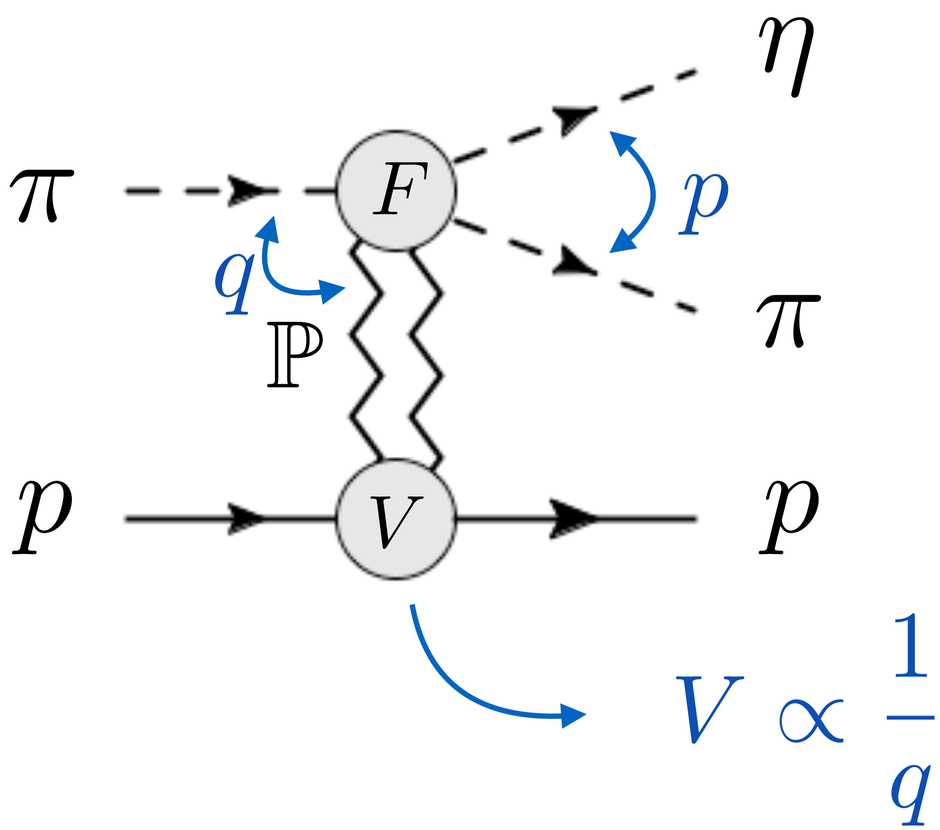
$$\mathrm{Im}\; \hat{f}(s) = \rho(s)|\hat{f}(s)|^2$$

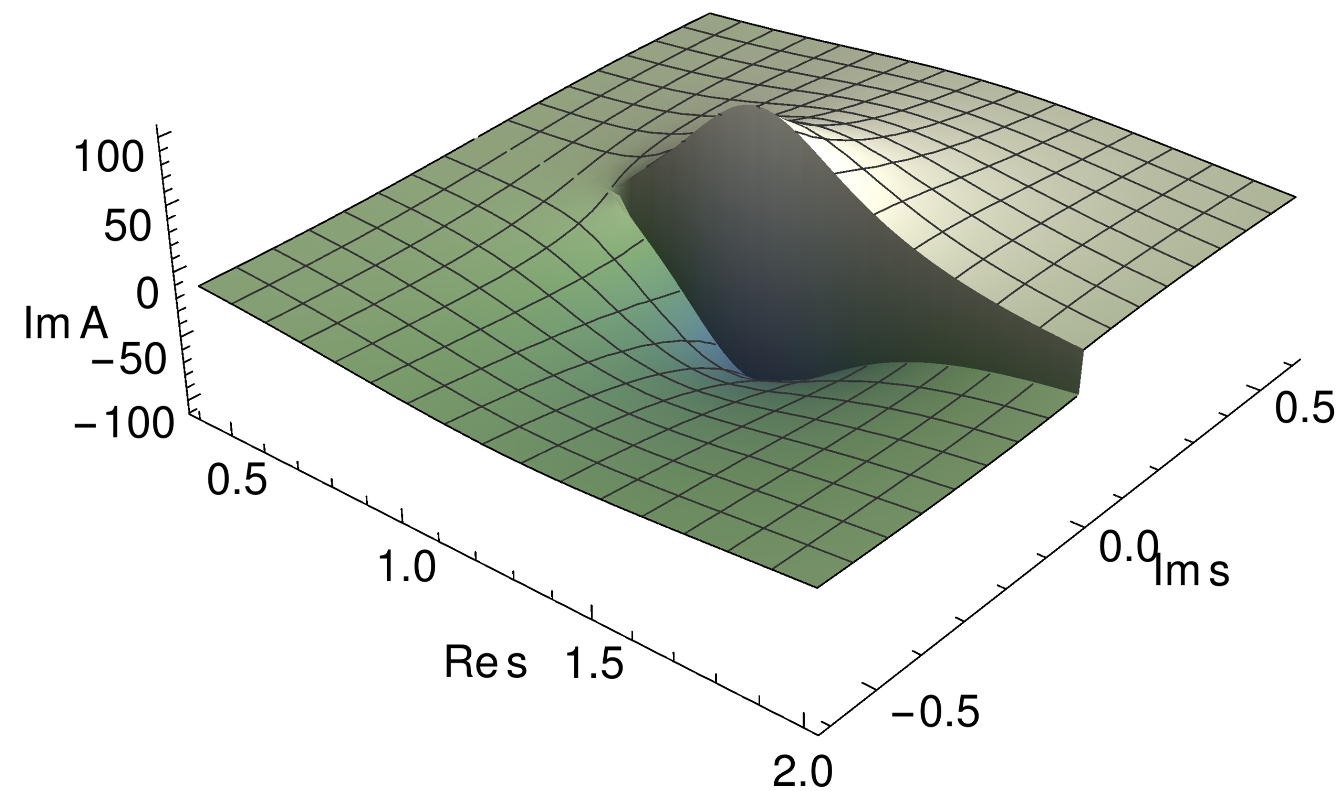
$$\mathrm{Im}\; \hat{f}^{-1}(s) = -\rho(s)$$

$$\hat{a}(s) = \frac{n(s)}{D(s)}$$

$$\mathrm{Im}\; D(s) = -\rho(s)$$

Barrier Factors





$$a(a) = p^2 q \; \hat{a}(s)$$

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$$\hat{a}(s) = \frac{n(s)}{D(s)}$$

$$\operatorname{Im} \, D(s) = -\rho(s)$$

$$\operatorname{Im} \, \hat{a}(s) = \rho(s) \hat{f}^*(s) \hat{a}(s)$$

$$\operatorname{Im} \, \hat{f}(s) = \rho(s) |\hat{f}(s)|^2$$

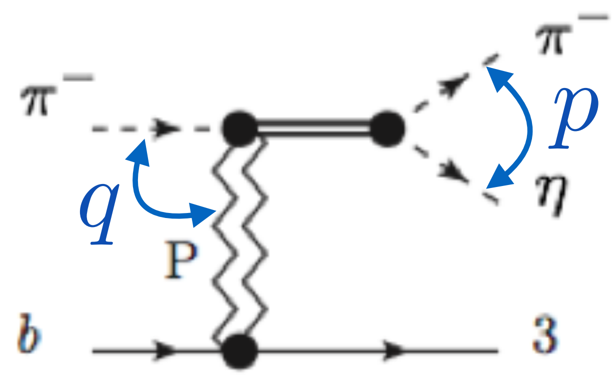
$$\operatorname{Im} \, \hat{f}^{-1}(s) = -\rho(s)$$

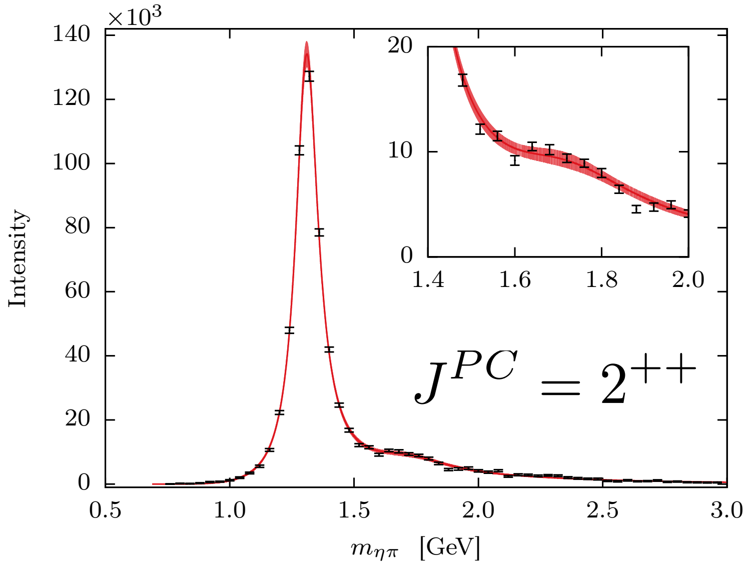
D(s) should NOT have zero on the first sheet

Eta-Pi@COMPASS

normalization

$$\frac{d\sigma}{d\sqrt{s}} = Np|a(s)|^2$$





$$a(s) = p^2 \frac{n(s)}{D(s)}$$

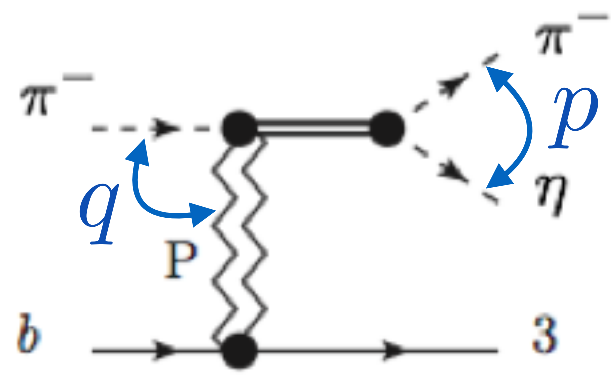
production

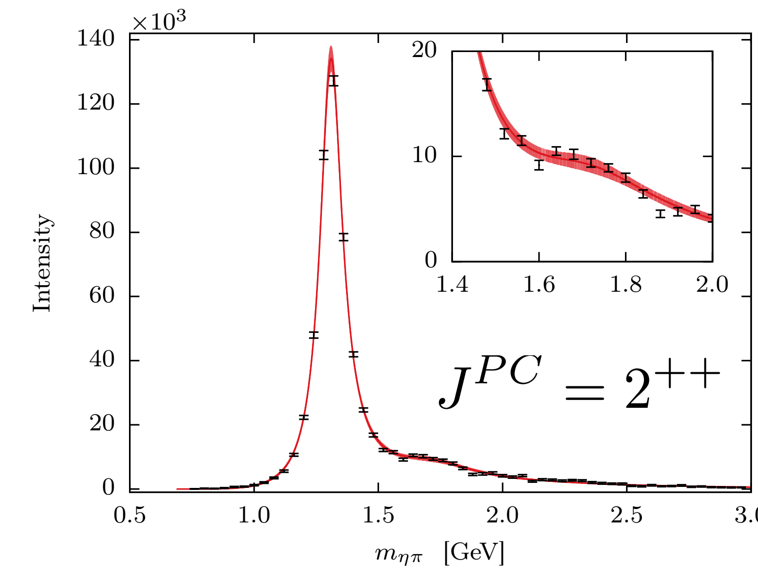
dynamics (poles)

Eta-Pi@COMPASS

normalization

$$\frac{d\sigma}{d\sqrt{s}} = Np|a(s)|^2$$





production

$$a(s) = p^2 \frac{n(s)}{D(s)}$$

dynamics (poles)

$$D(s) = D_0(s) - \frac{1}{\pi}\int_{s_{th}}^{\infty} ds' \frac{\rho(s')N(s')}{s'-s}$$

real (masses)

imaginary (widths)

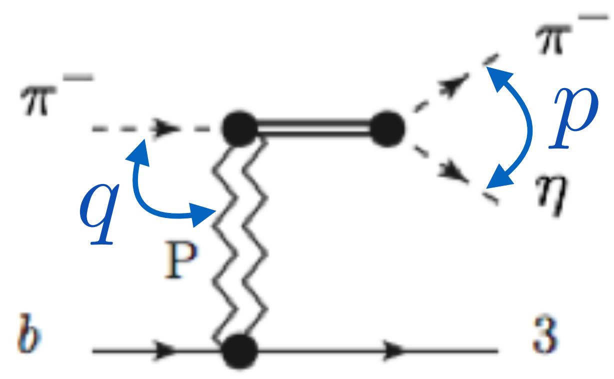
$$D_0(s) = c_0 - c_1 s$$

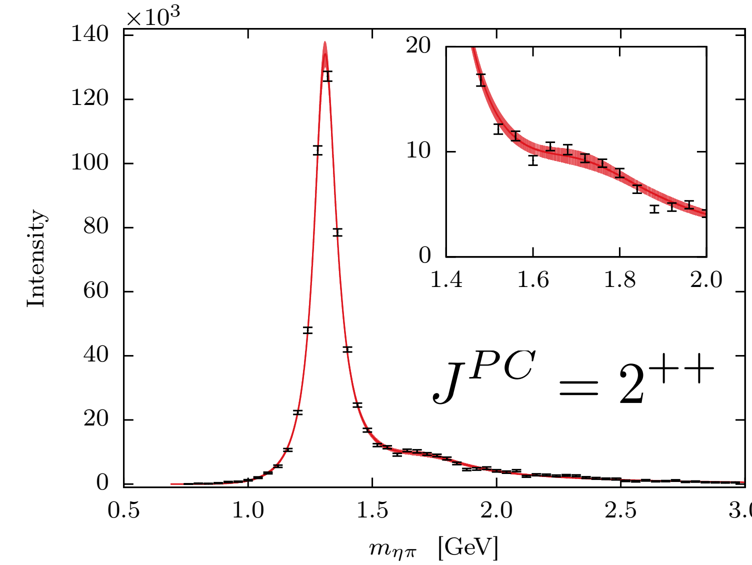
$$\rho(s)N(s) = g\frac{\lambda^{J+\frac{1}{2}}(s, m_\eta^2, m_\pi^2)}{(s+s_R)^{2J+3}}$$

Eta-Pi@COMPASS

normalization

$$\frac{d\sigma}{d\sqrt{s}} = Np|a(s)|^2$$





production

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$$D_0(s) = c_0 - c_1 s - \frac{c_2}{c_3 - s}$$

$$\rho(s)N(s) = g\frac{\lambda^{J+\frac{1}{2}}(s, m_\eta^2, m_\pi^2)}{(s+s_R)^{2J+3}}$$

Eta-Pi@COMPASS

normalization

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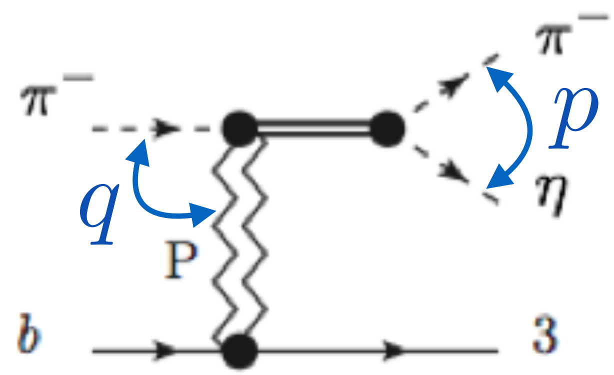

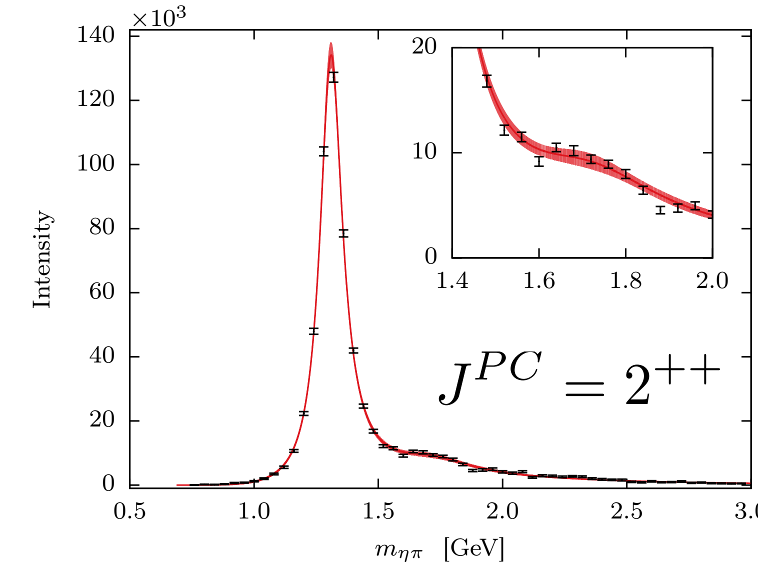

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Chebyshev polynomials

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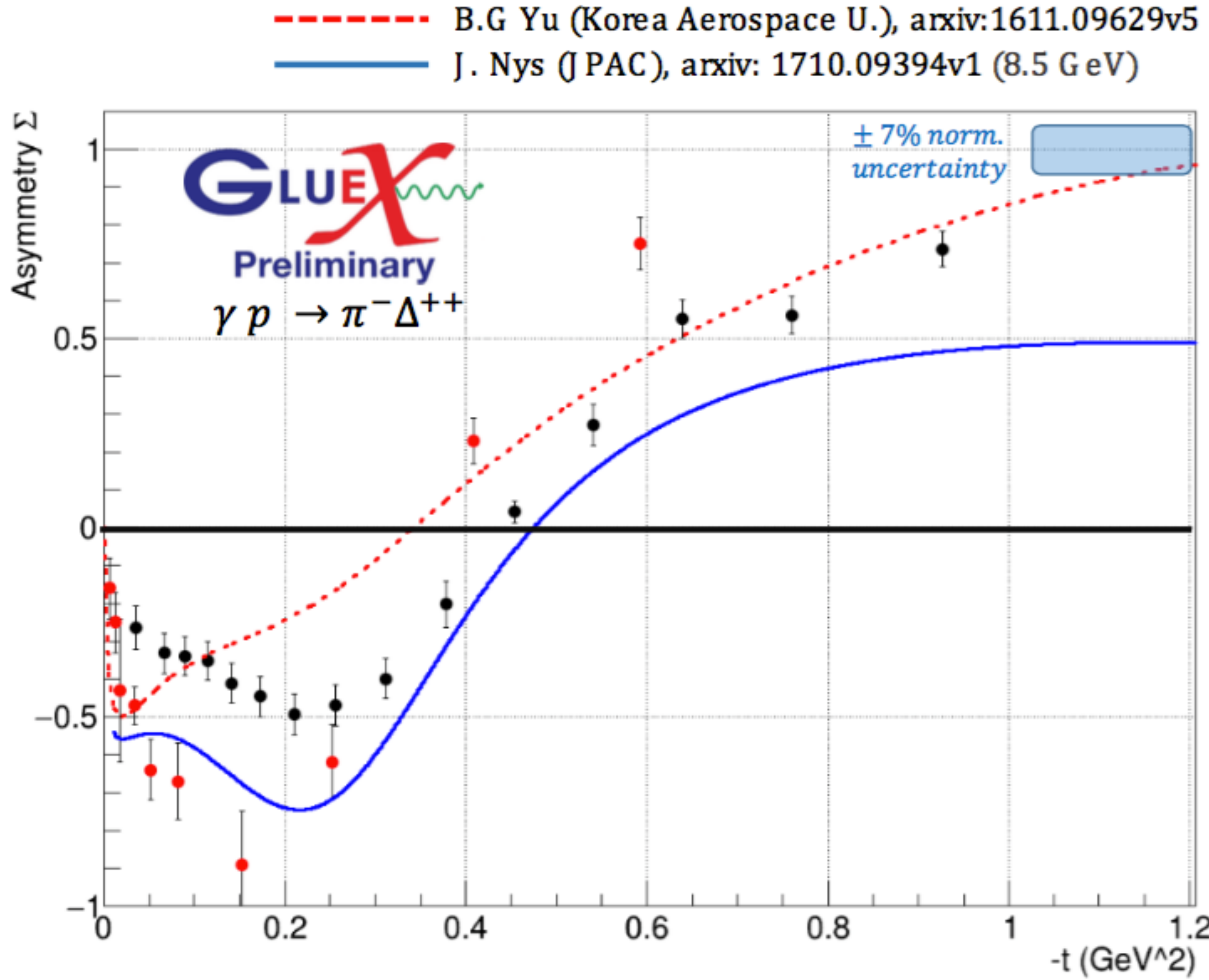
GlueX (8.5 GeV) + SLAC (16 GeV) Data



Black: GlueX data

Red: SLAC data (16 GeV)

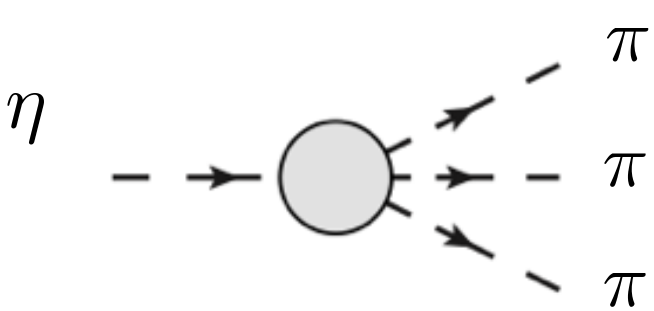
Phys. Rev. D **20**, 1553 (1979)

(error bars on points: statistical only)

Z. Zarling
APS meeting
Division of Nuclear Physics
Oct 27th 2017

Quark Mass Difference

$\eta, \pi \sim$ 



$$\eta \to \pi^+ \pi^- \pi^0$$

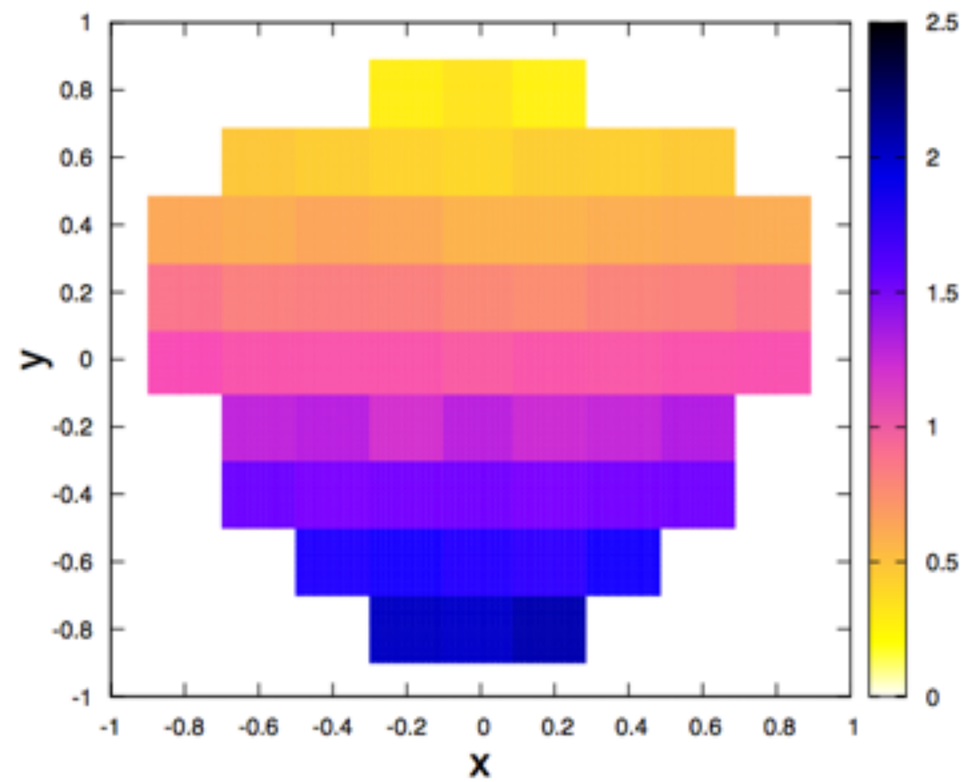
Isospin violating decay sensitive to quark mass difference

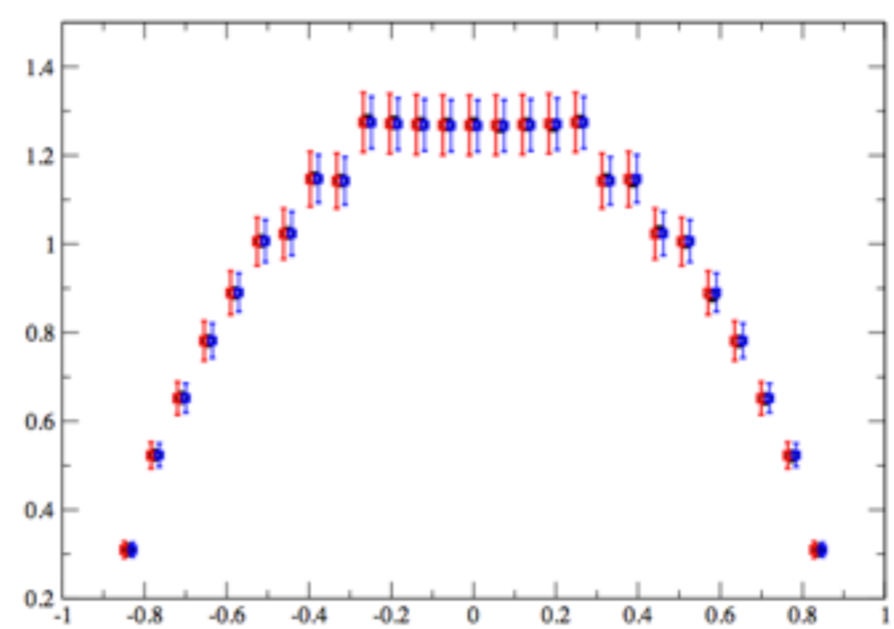
$$Q^2 = \frac{m_s^2 - (m_u + m_d)^2/4}{m_d^2 - m_u^2}$$

WASA@COSY	$Q = 21.4 \pm 1.1$	**[1]**
KLOE@DAPHNE	$Q = 21.6 \pm 1.1$	**[2]**

[1] P. Guo et al (JPAC) PRD 92 (2015)
[2] P. Guo et al (JPAC) PLB 771 (2017)

fit Dalitz distribution
WASA@COSY





2nd Workshop on Future Directions in Spectroscopy Analysis (FDSA2017)

- Home
- Local Organizing Committee
- Registration
- Scientific Program
- Scientific Advisory Committee
- Lodging

November 7-11, 2017. Museum of Light, Mexico City, Mexico

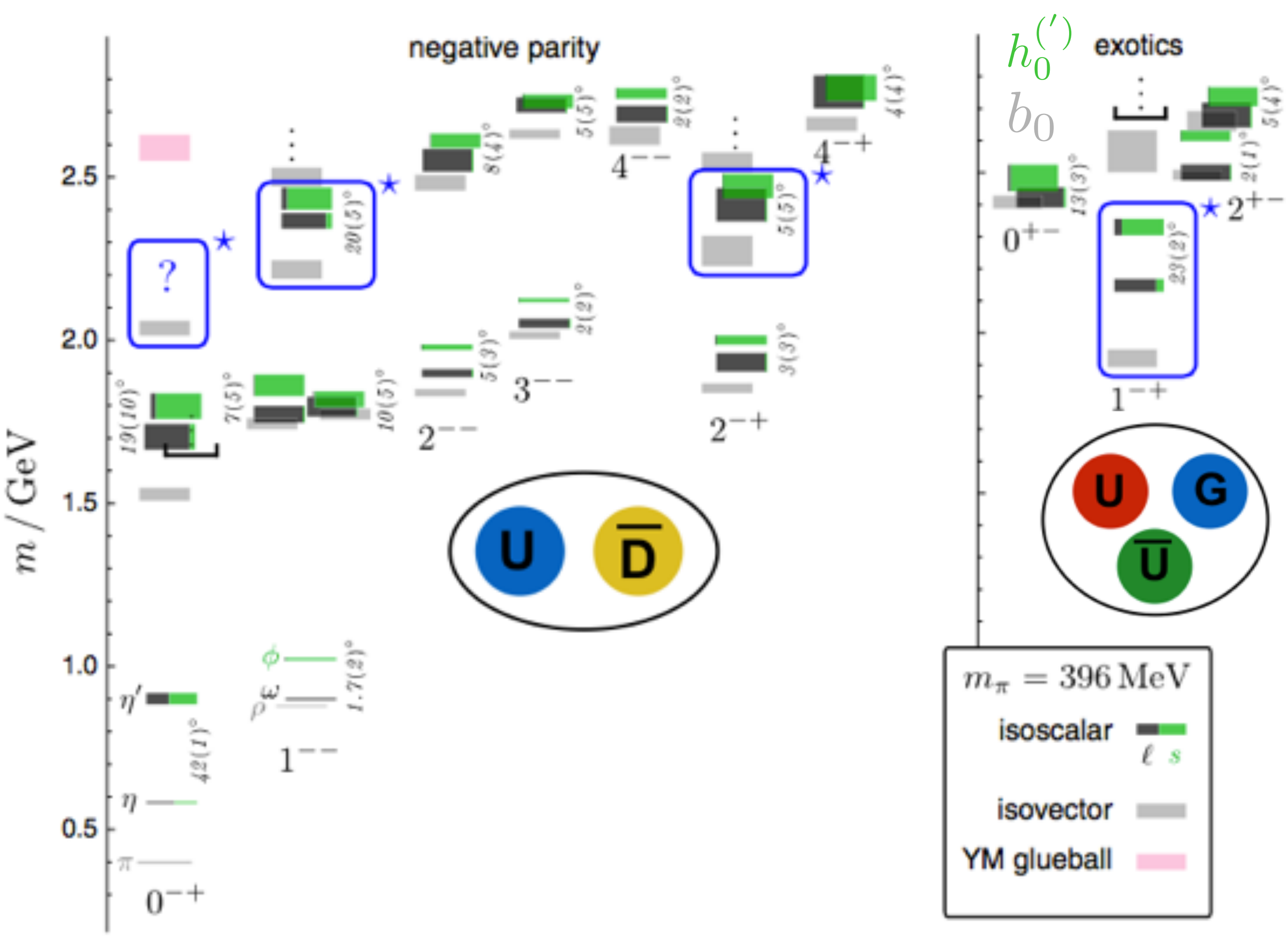
Selected Topics:

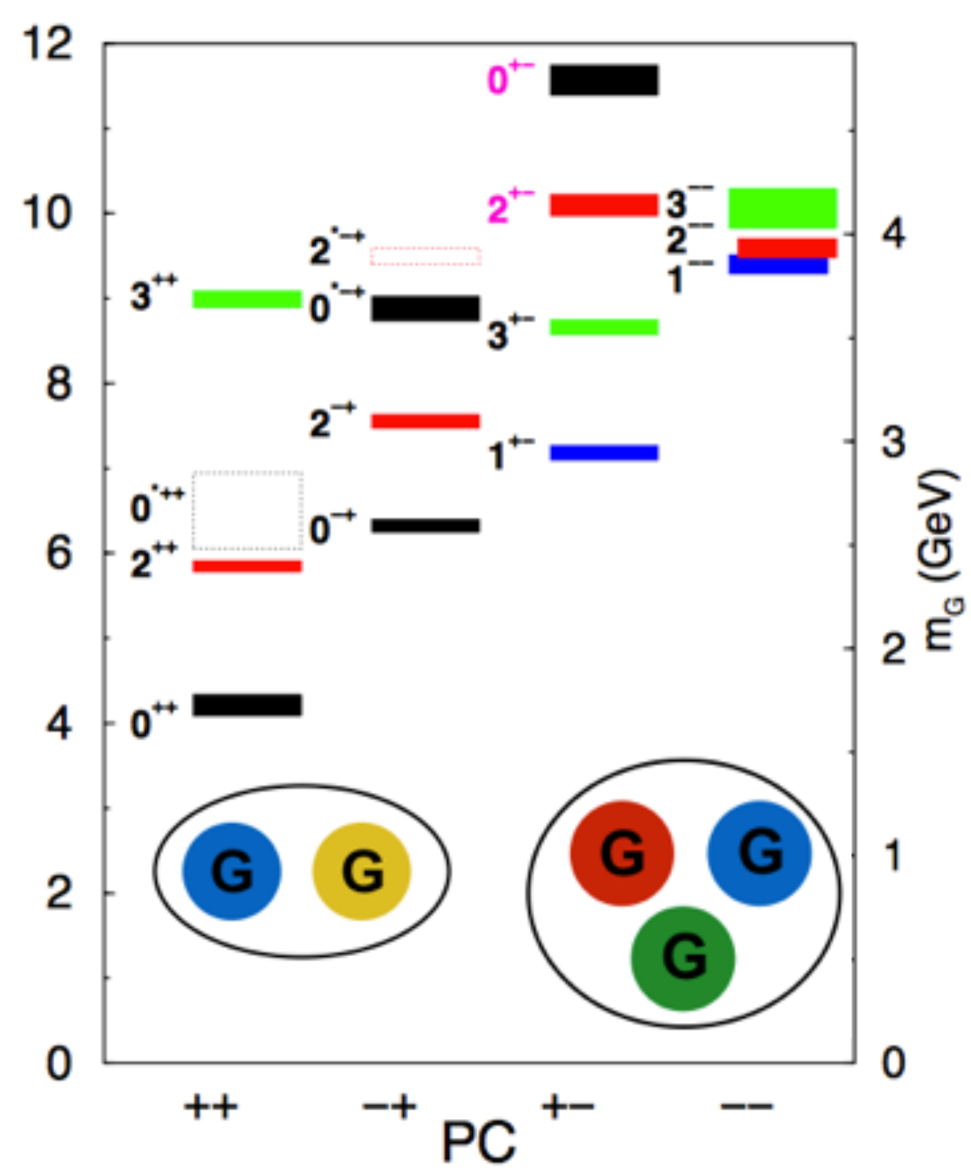
- Amplitude Analysis for Hadron Reactions
- Hadron Spectroscopy
- Lattice Predictions for Masses and Decays
- Hadronic Amplitudes for Beyond Standard Model Physics
- Regge Phenomenology
- Three-Body Decays
- Quark Models
- Effective QCD Models
- Tetraquarks, Pentaquarks, Exotics, Molecular States and Glueballs
- Physics at BaBar, Belle, BES III, CLAS12, CMS, COMPASS, GlueX, LHCb and PANDA
- Hadron Physics Through Schwinger-Dyson Equations
- In general, topics of interest to the Hadron Physics Community

Bound States of Gluons

gluon has mass and strong interaction = string

→ **bound states of gluons ?**



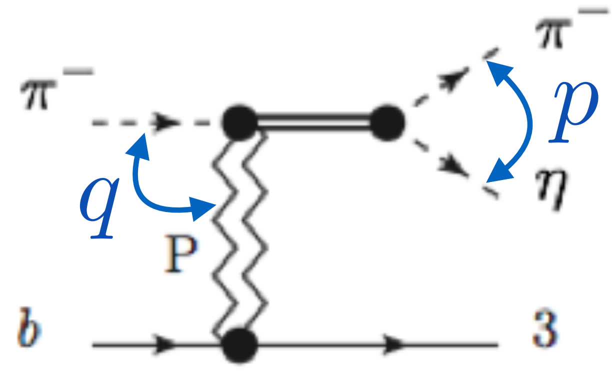


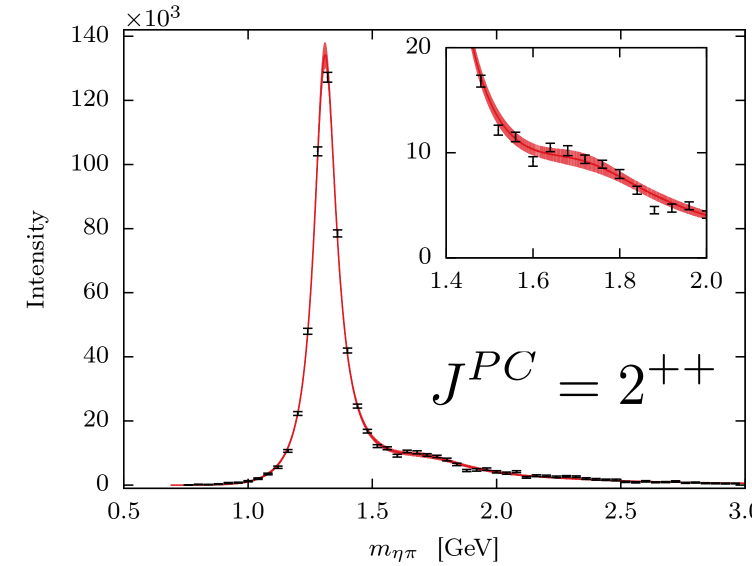
J. Dudek PRD84 (2011)

J. Dudek et al. PRD83 (2011)

Morningstar and Peardon 1999

Eta-Pi@COMPASS





normalization

$$\frac{d\sigma}{d\sqrt{s}} = Np|a(s)|^2$$

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production

Chebyshev polynomials

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Eta-Pi@COMPASS

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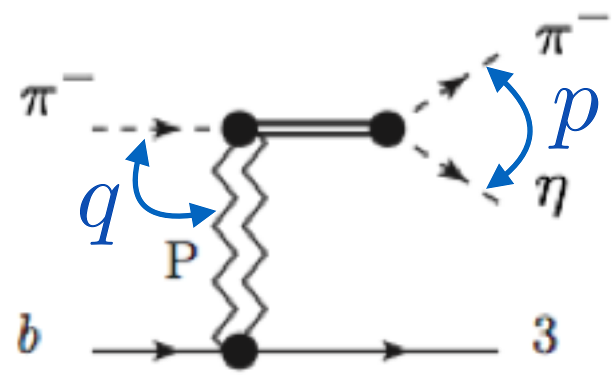

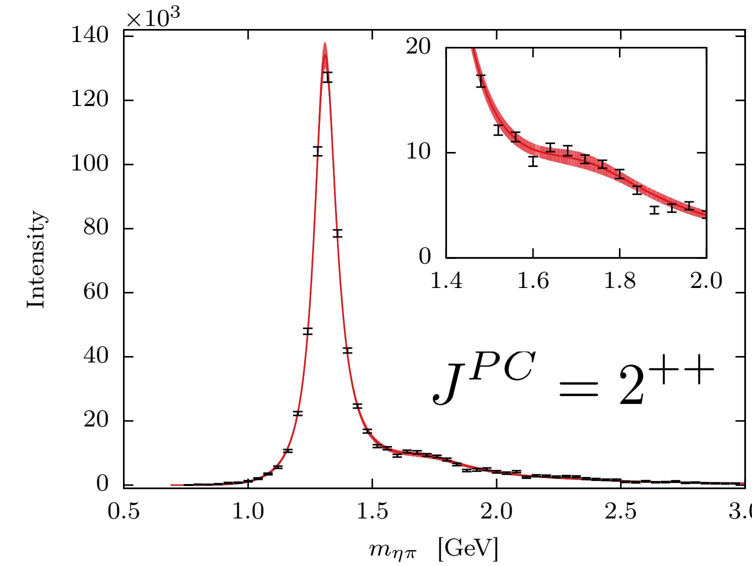

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cf. A. Jackura's talk
Wednesday 10am
Spectroscopy of Mesons

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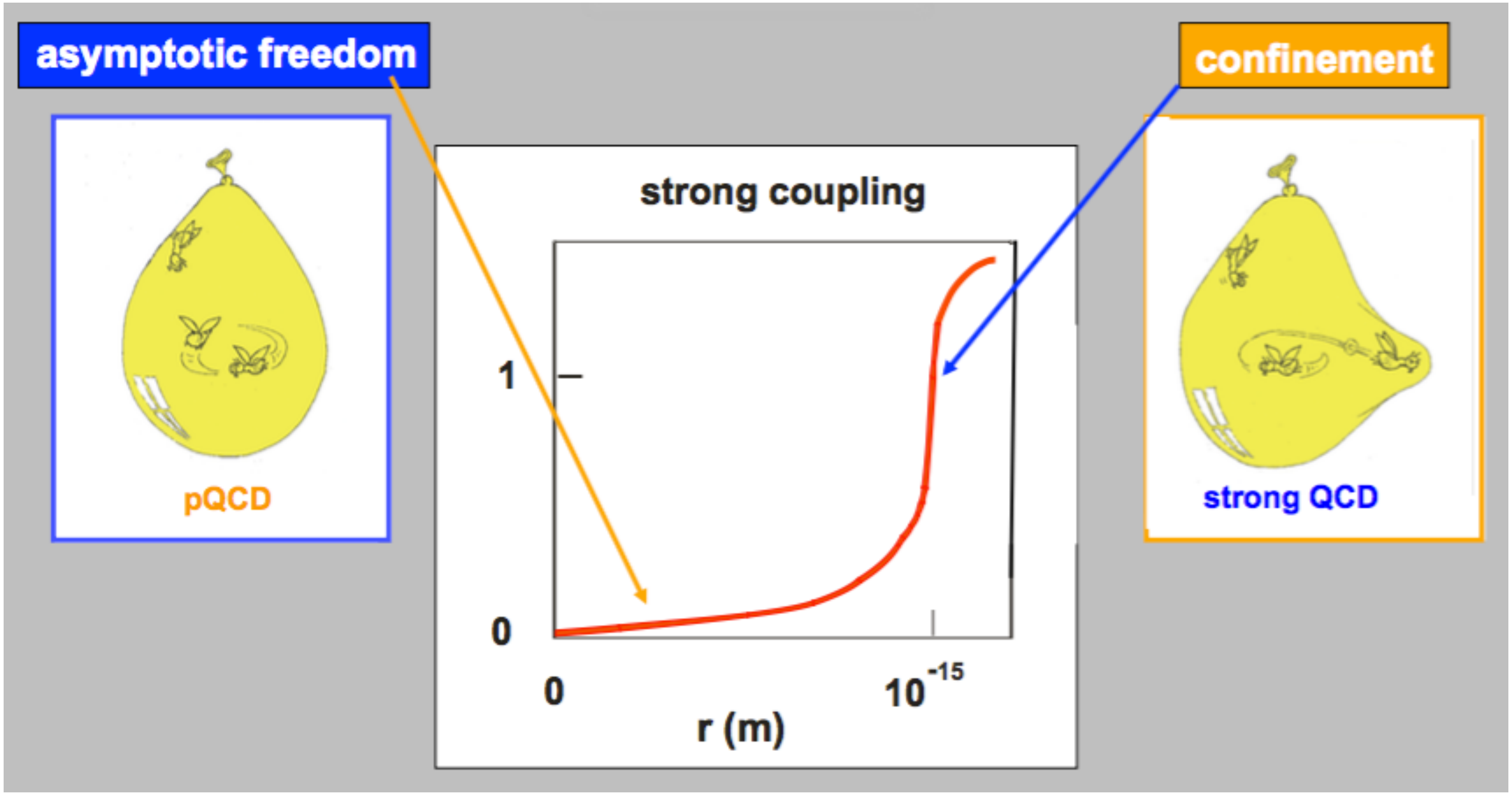
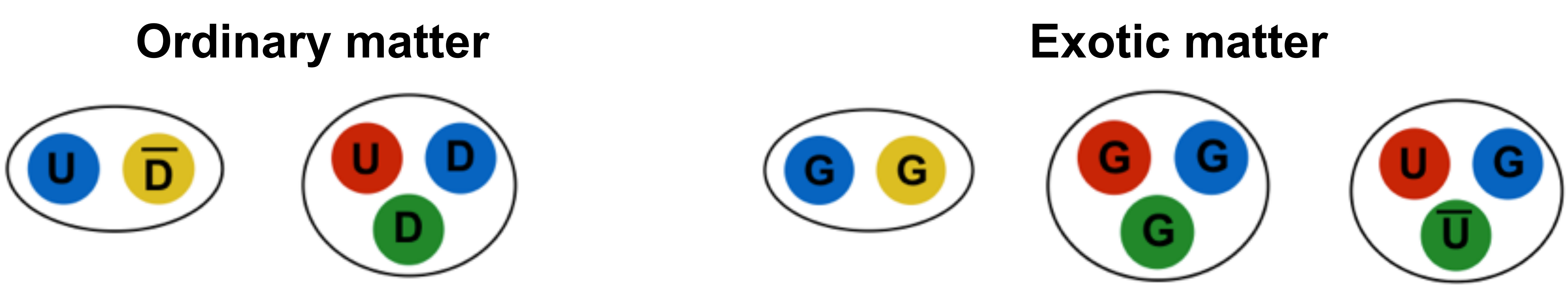
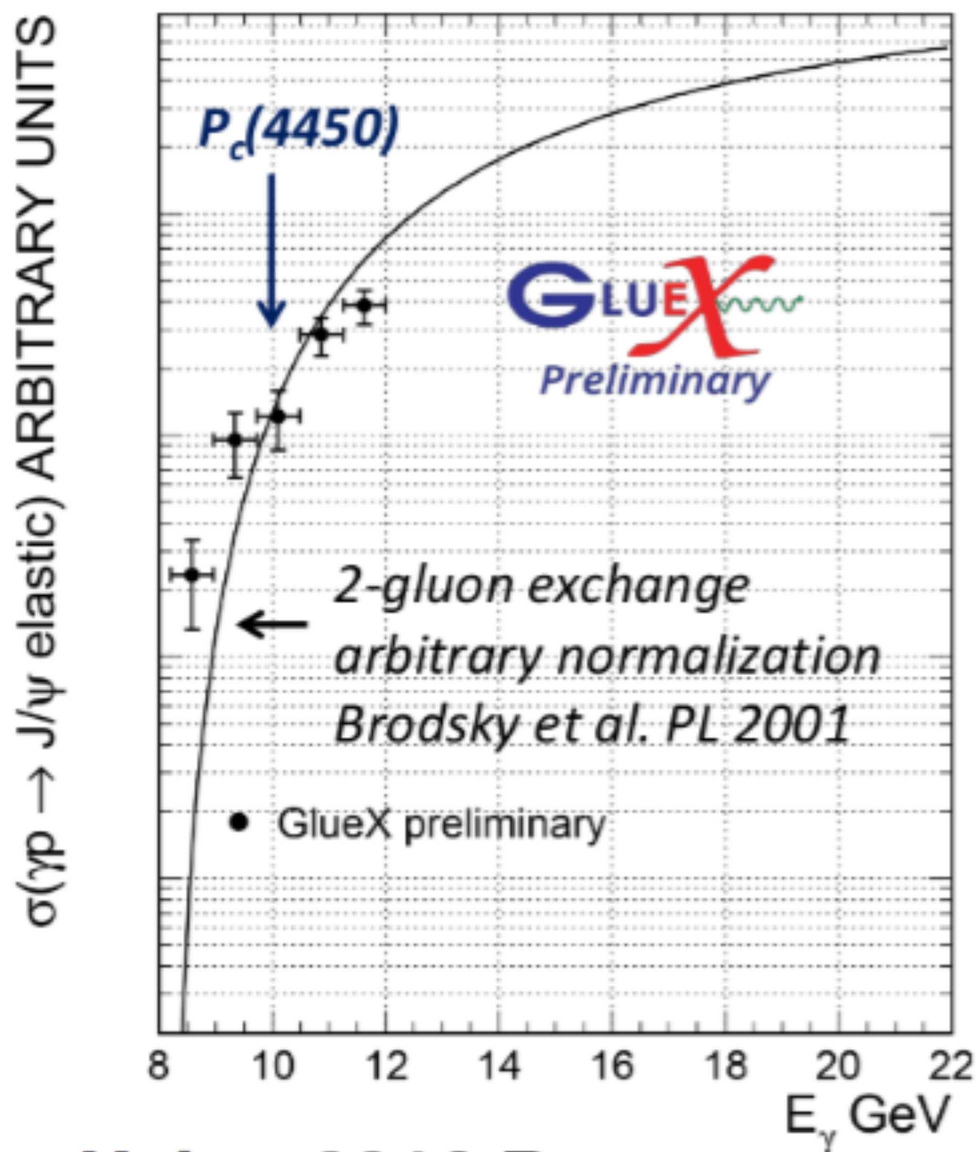
Nuclear Strong Interactions



Theory predicts 'exotic' resonances



$$\gamma p \to J/\psi p$$



Using 2016 Data