

Hadron Spectroscopy Theory and Phenomenology: The $\eta\pi$ and $\eta'\pi$ Final States

Vincent MATHIEU

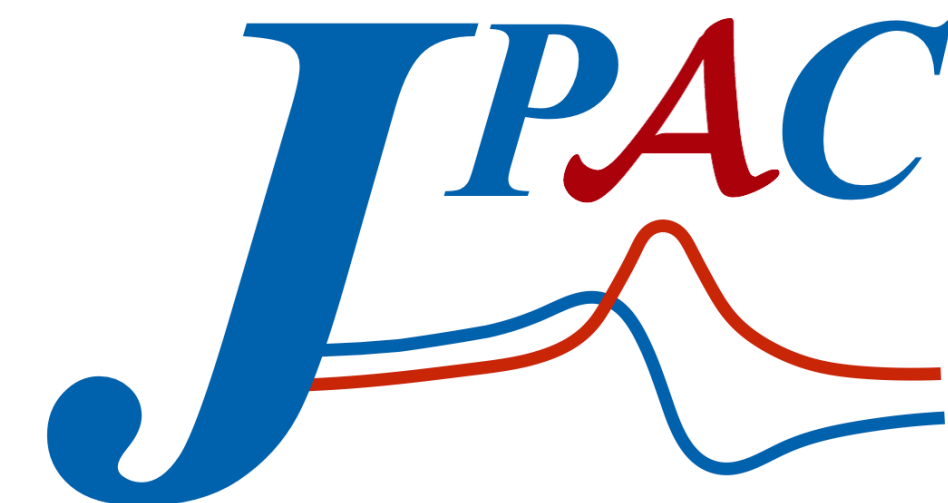
University of Barcelona
Joint Physics Analysis Center

International Workshop on
Hadron Structure and Spectroscopy

August 2022



UNIVERSITAT DE
BARCELONA



*Joint
Physics
Analysis
Center*



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CSIC-Valencia



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Pedagogical University of
Kracow



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National Autonomous
University of Mexico



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Tübingen University



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TU Munich



Alessandro Piloni
U. Messina



Adam Szczepaniak
Indiana University



Daniel Winney
South China Normal
University



Lawrence Ng
Florida State
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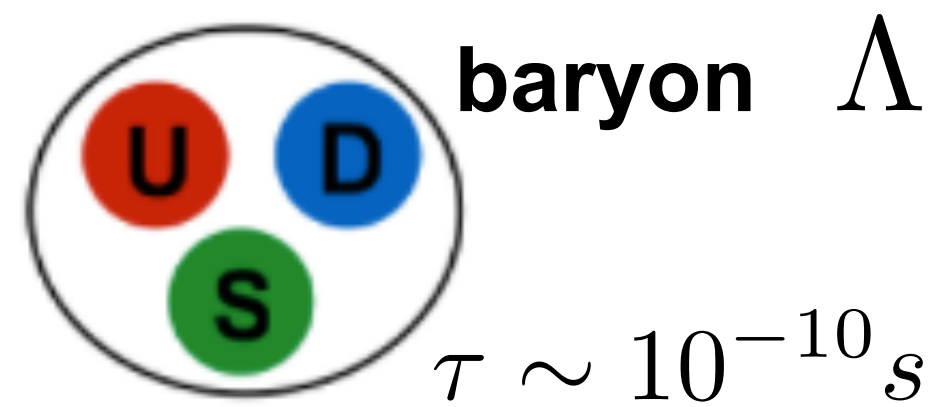
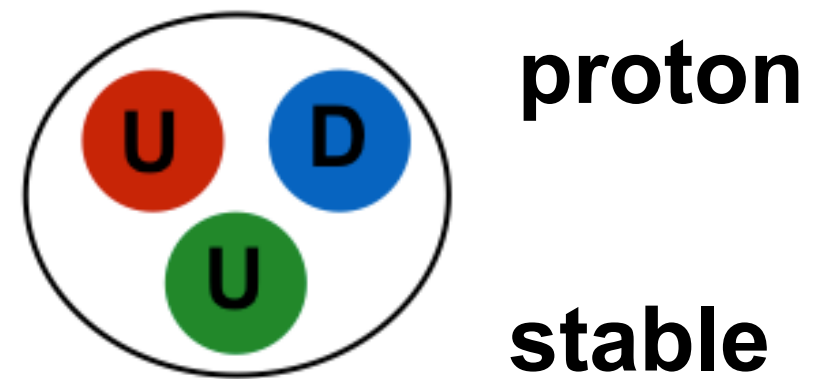
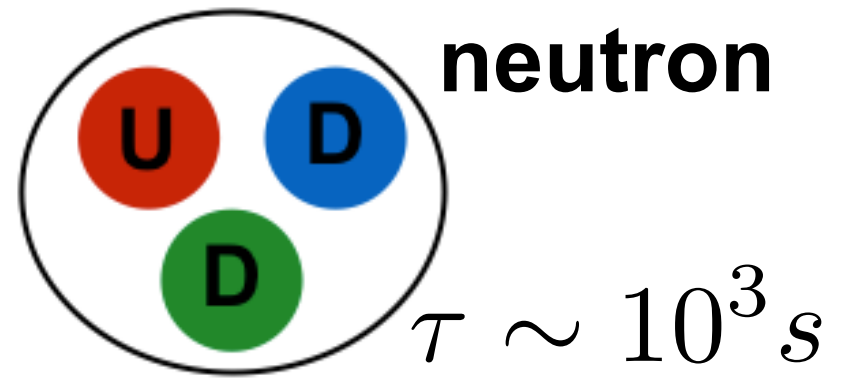
Arkaitz Rodas
College of
William and Mary



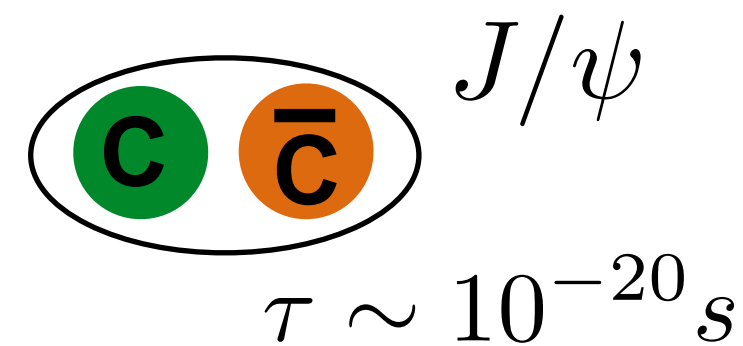
Robert Perry
National Chiao-Tung
University

Ordinary and Exotic Hadrons

Ordinary baryons:



Ordinary mesons

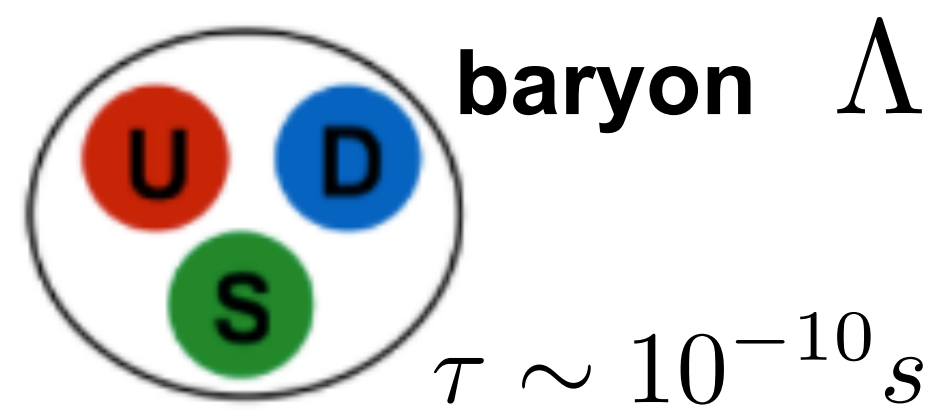
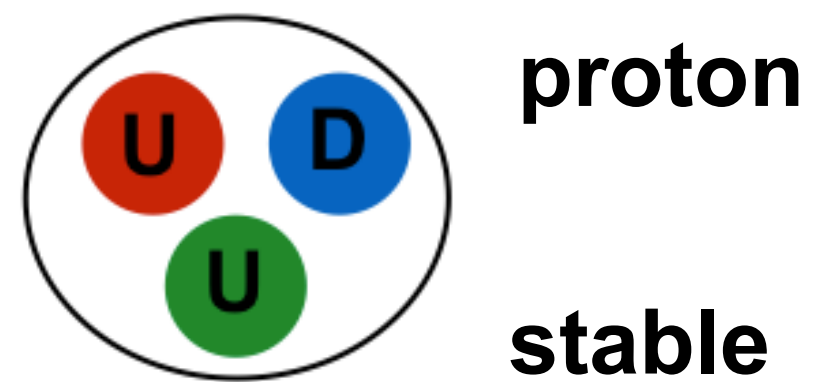
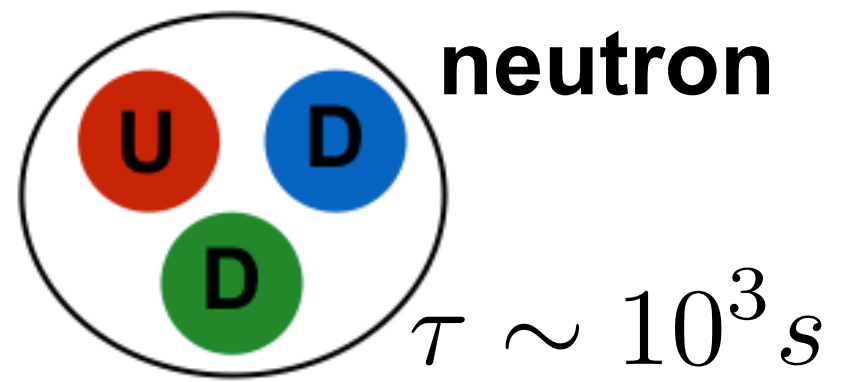


QUARKS

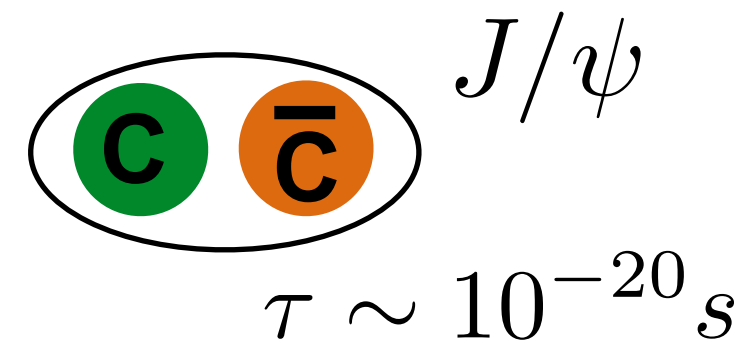
<p>UP</p> <p>mass 2,3 MeV/c²</p> <p>charge 2/3</p> <p>spin 1/2</p>	<p>CHARM</p> <p>1,275 GeV/c²</p> <p>2/3</p> <p>1/2</p>	<p>TOP</p> <p>173,07 GeV/c²</p> <p>2/3</p> <p>1/2</p>
<p>DOWN</p> <p>4,8 MeV/c²</p> <p>-1/3</p> <p>1/2</p>	<p>STRANGE</p> <p>95 MeV/c²</p> <p>-1/3</p> <p>1/2</p>	<p>BOTTOM</p> <p>4,18 GeV/c²</p> <p>-1/3</p> <p>1/2</p>

Ordinary and Exotic Hadrons

Ordinary baryons:



Ordinary mesons

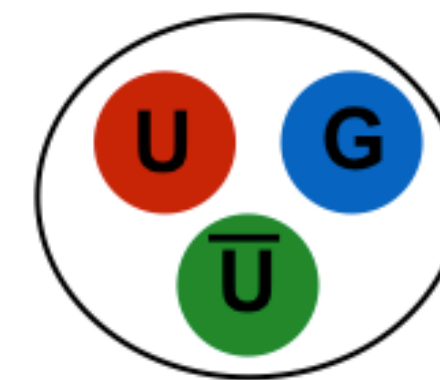


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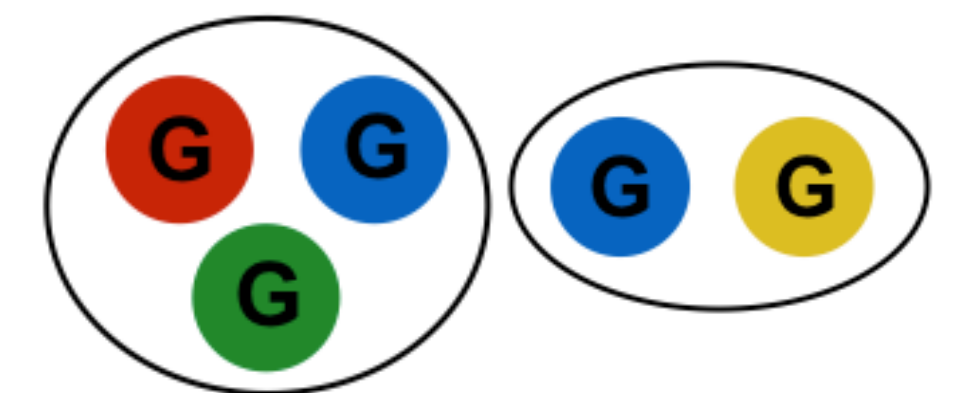
UP mass 2,3 MeV/c ² charge 2/3 spin 1/2 	CHARM 1,275 GeV/c ² 2/3 1/2 	TOP 173,07 GeV/c ² 2/3 1/2
DOWN 4,8 MeV/c ² -1/3 1/2 	STRANGE 95 MeV/c ² -1/3 1/2 	BOTTOM 4,18 GeV/c ² -1/3 1/2

Exotic matter

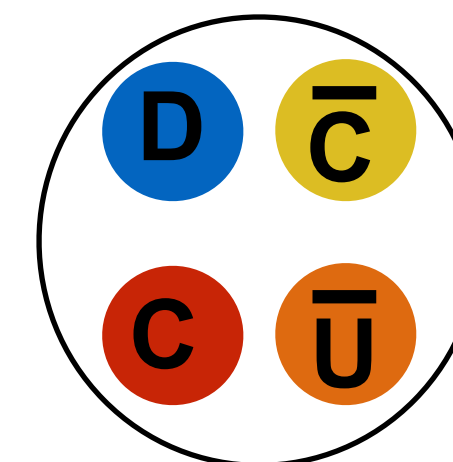
hybrid mesons



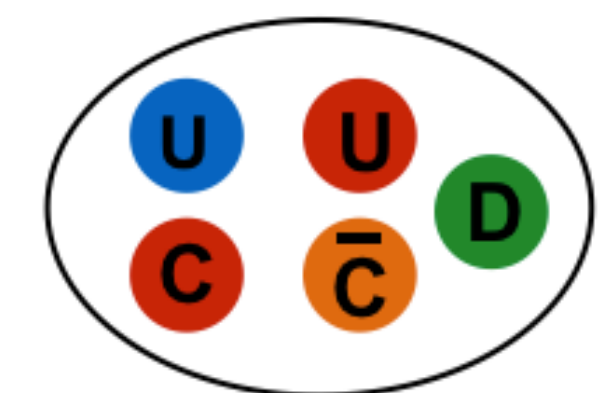
glueballs



tetraquarks

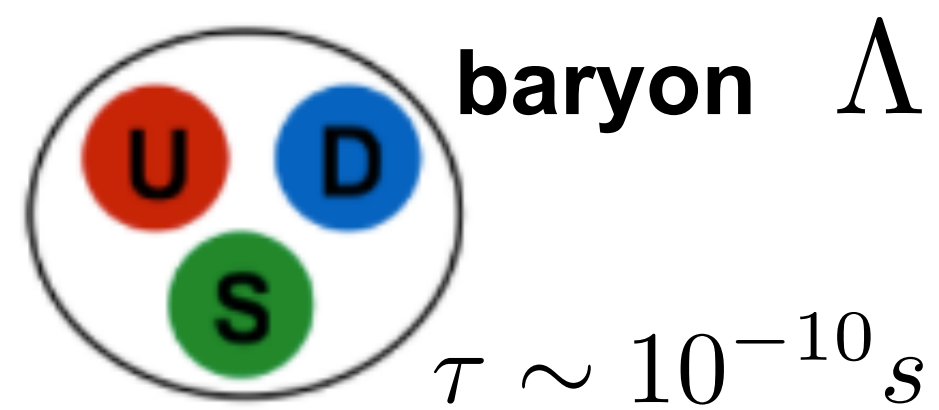
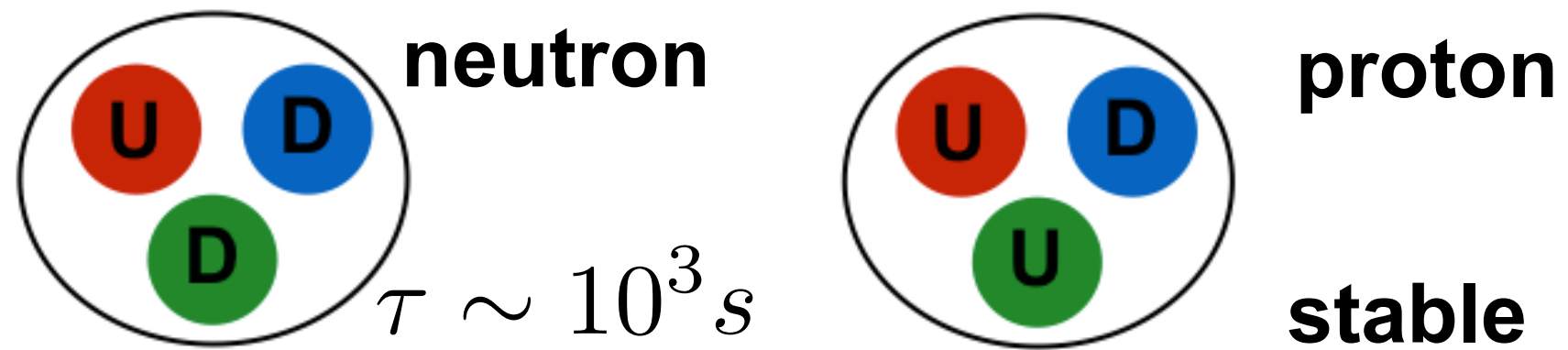


pentaquarks

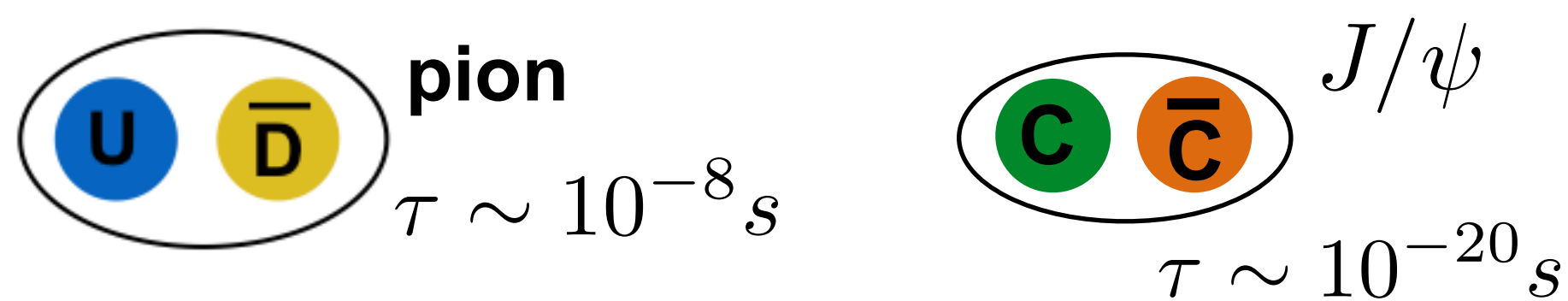


Ordinary and Exotic Hadrons

Ordinary baryons:



Ordinary mesons

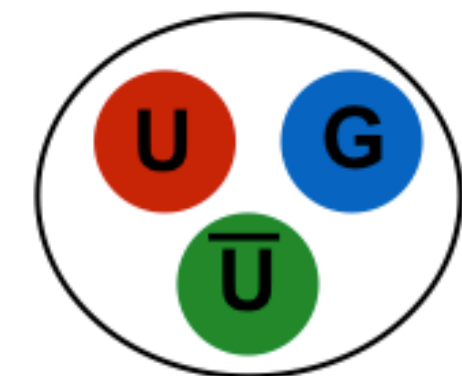


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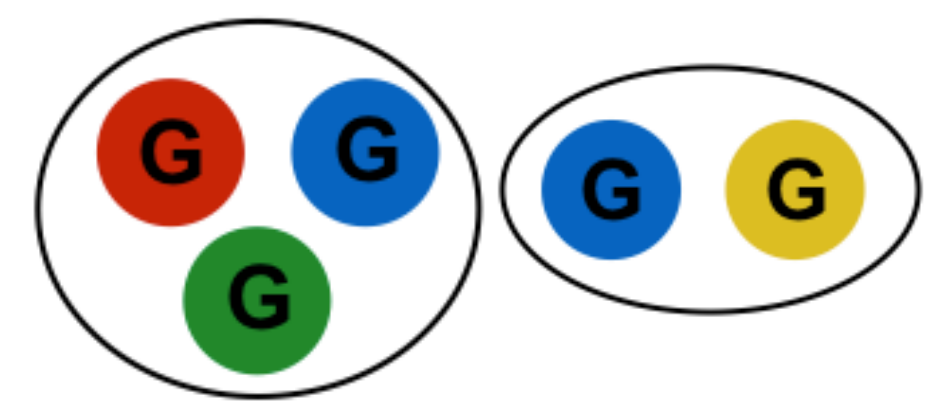
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Exotic matter

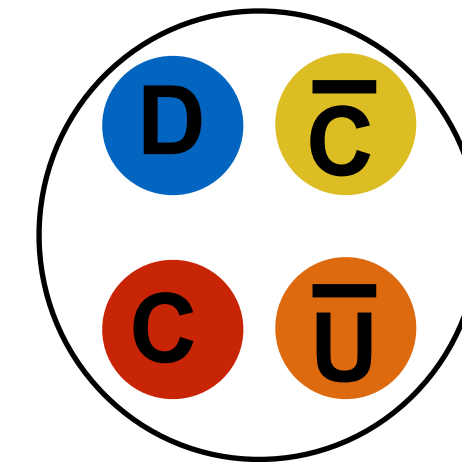
hybrid mesons



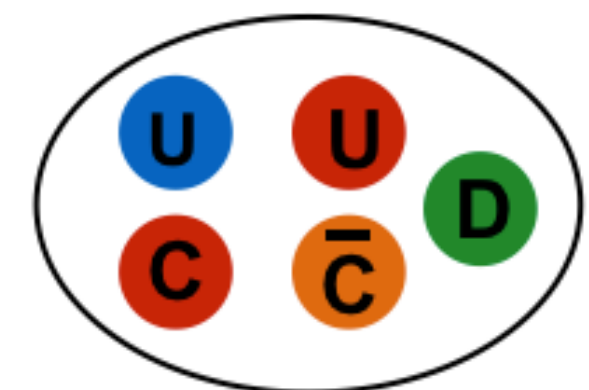
glueballs



tetraquarks



pentaquarks



Hybrid Mesons Production

Ordinary mesons



$$\vec{J} = \vec{L} \oplus \vec{S}$$

$$P = -(-1)^L$$

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

0^{--} 0^{-+} 0^{+-} 0^{++}

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

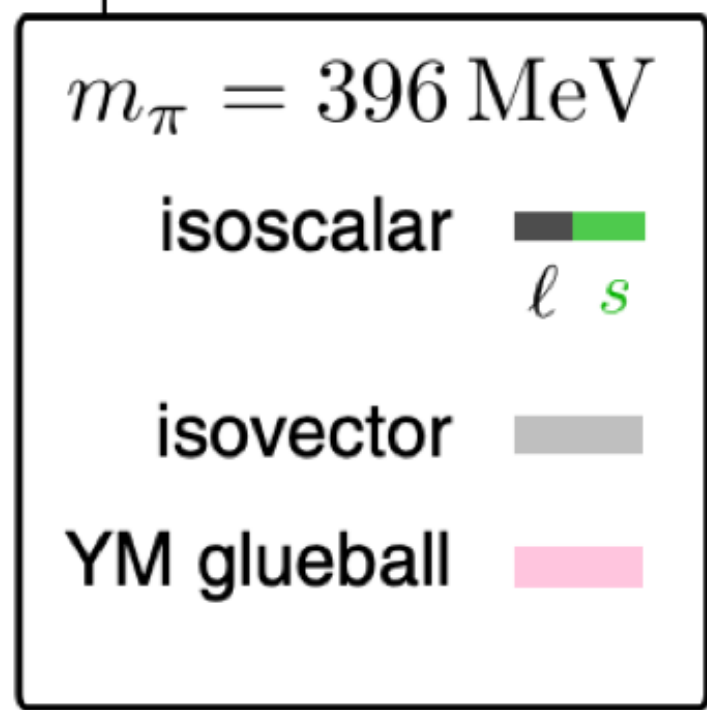
2^{--} 2^{-+} 2^{+-} 2^{++}

3^{--} 3^{-+} 3^{+-} 3^{++}

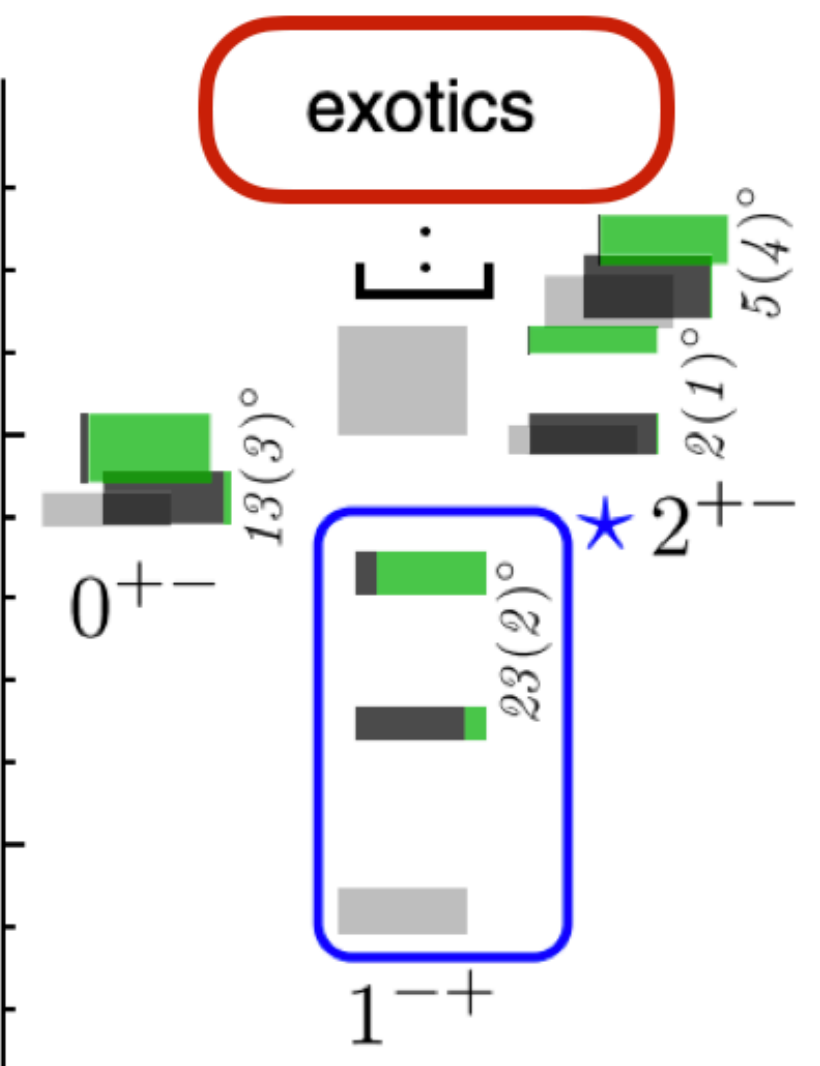
• • •

Hybrid Mesons Production

Dudek PRD84 (2011)



exotics



0^{--} 0^{-+} 0^{+-} 0^{++}

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

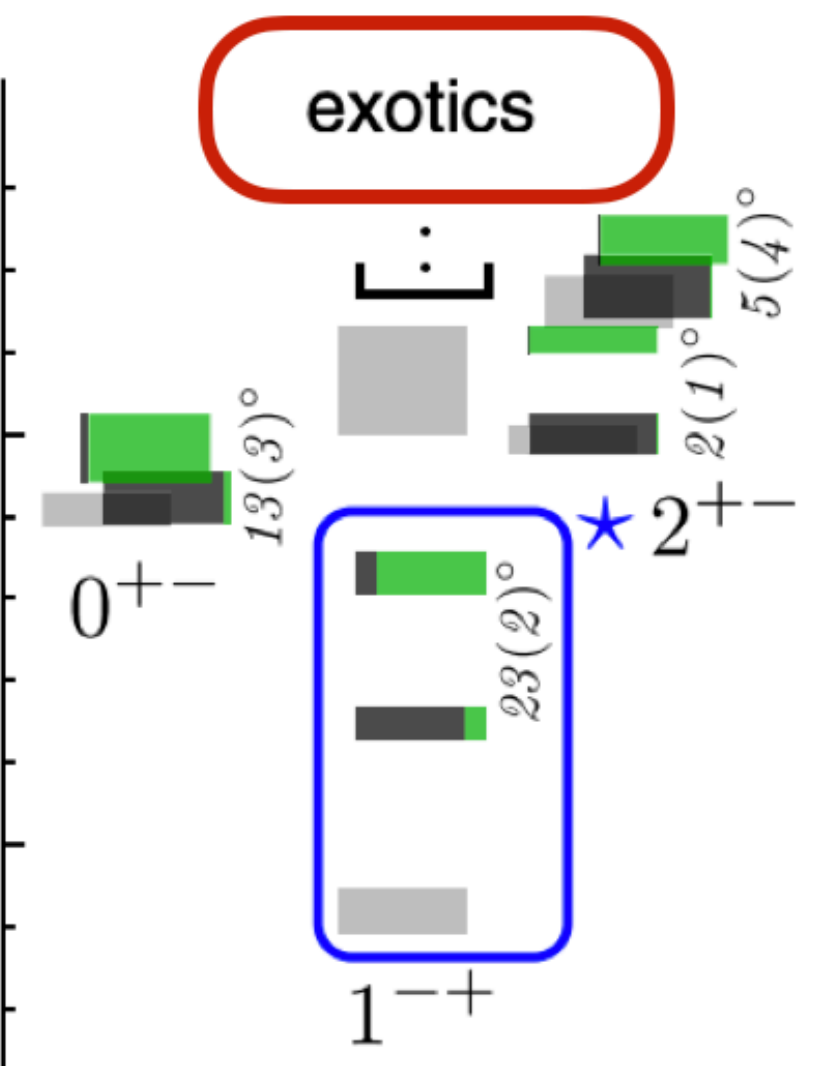
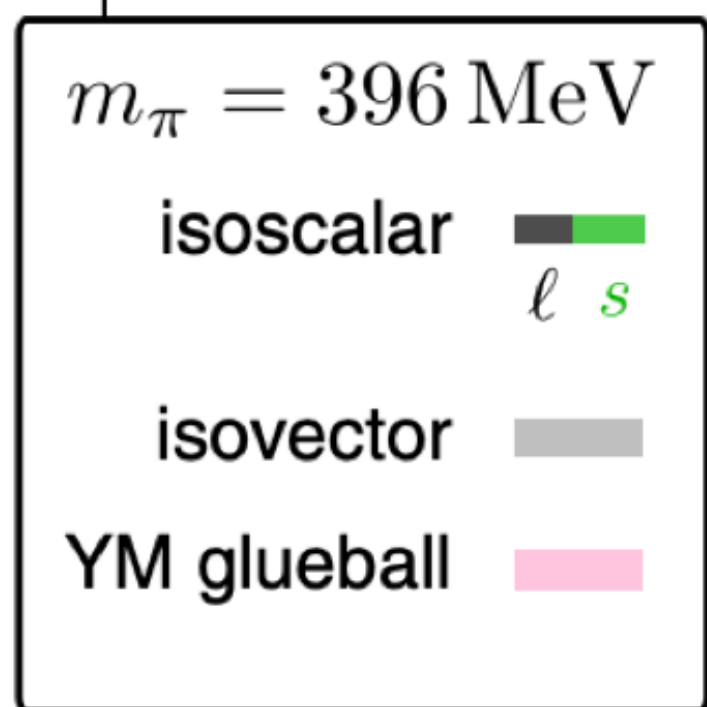
2^{--} 2^{-+} 2^{+-} 2^{++}

3^{--} 3^{-+} 3^{+-} 3^{++}

• • •

Hybrid Mesons Production

Dudek PRD84 (2011)



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

Exotic mesons



Decay mode

The lightest π_1

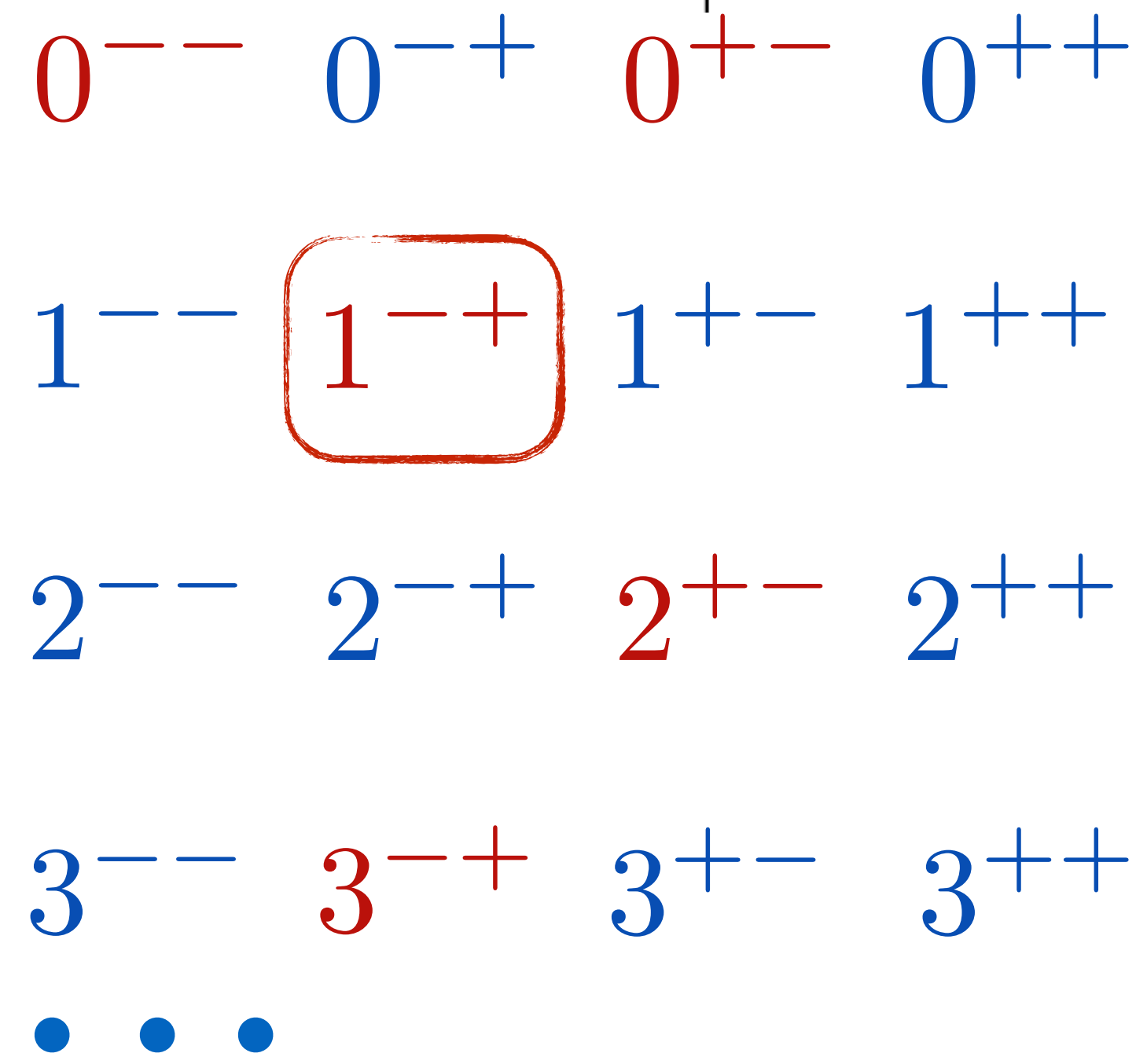
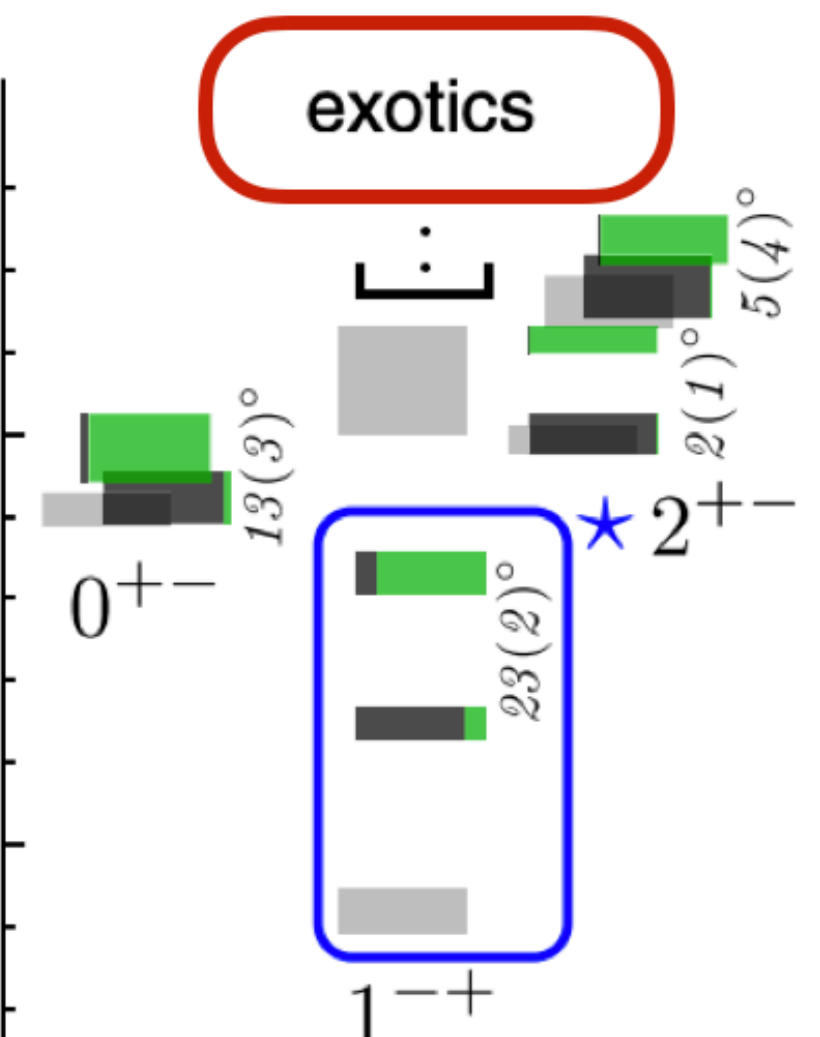
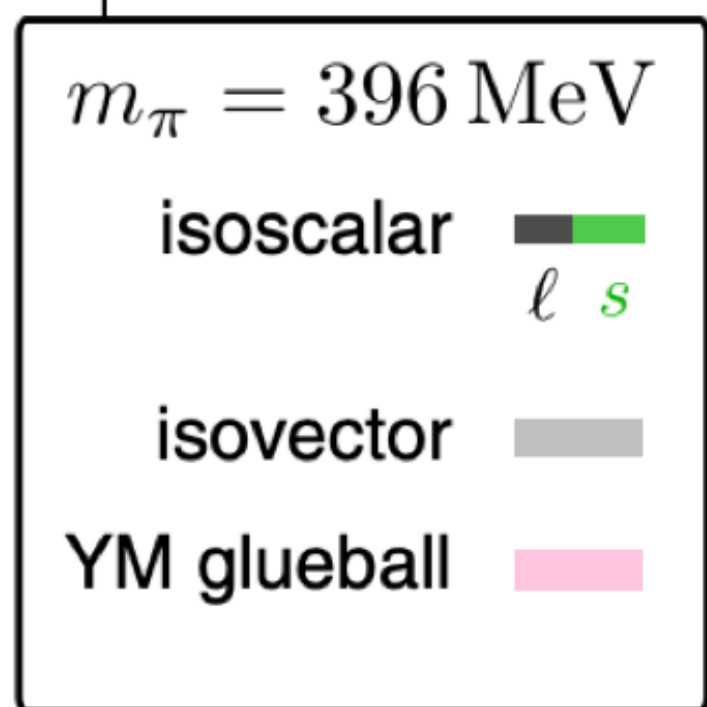
$$J^{PC} = 1^{-+}$$

$$\pi_1 \rightarrow \pi\eta$$

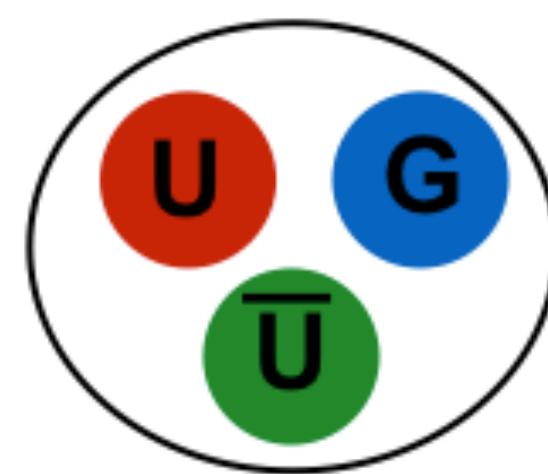
$$1^{-+} = (0^{-+} \otimes 0^{-+})_{P\text{-wave}}$$

Hybrid Mesons Production

Dudek PRD84 (2011)



Exotic mesons



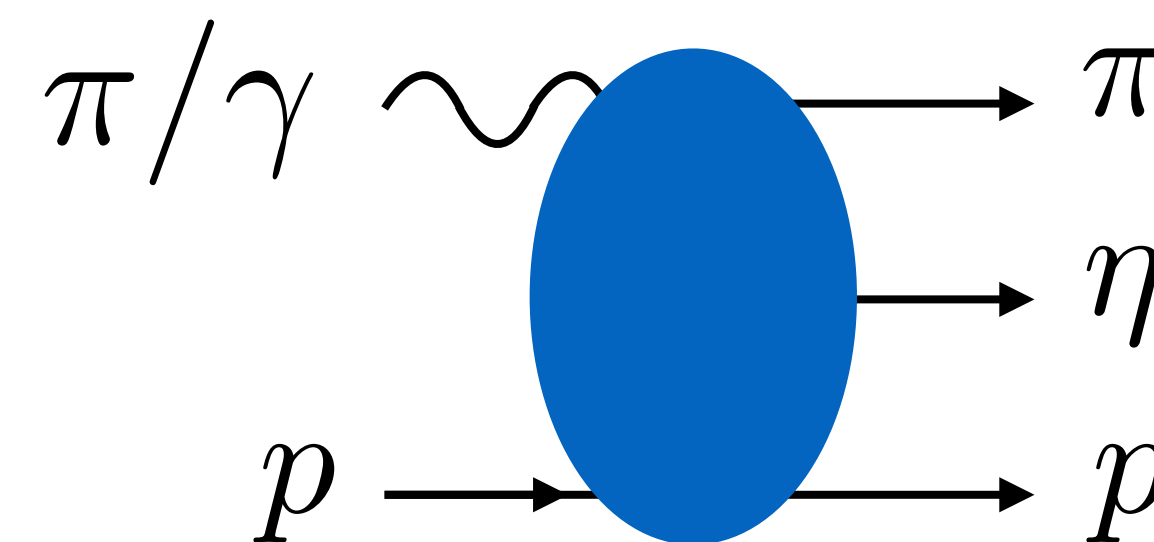
Decay mode

The lightest π_1

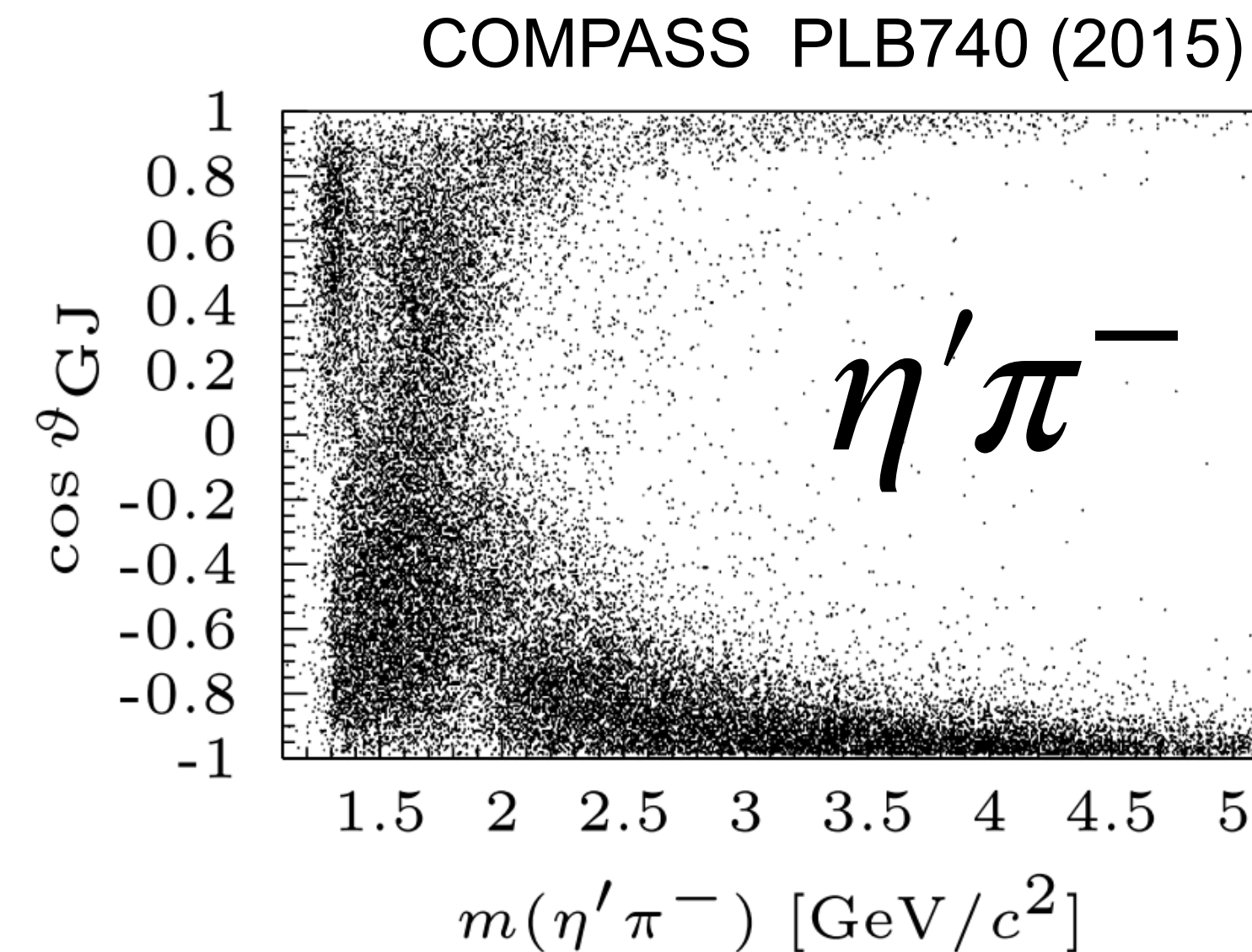
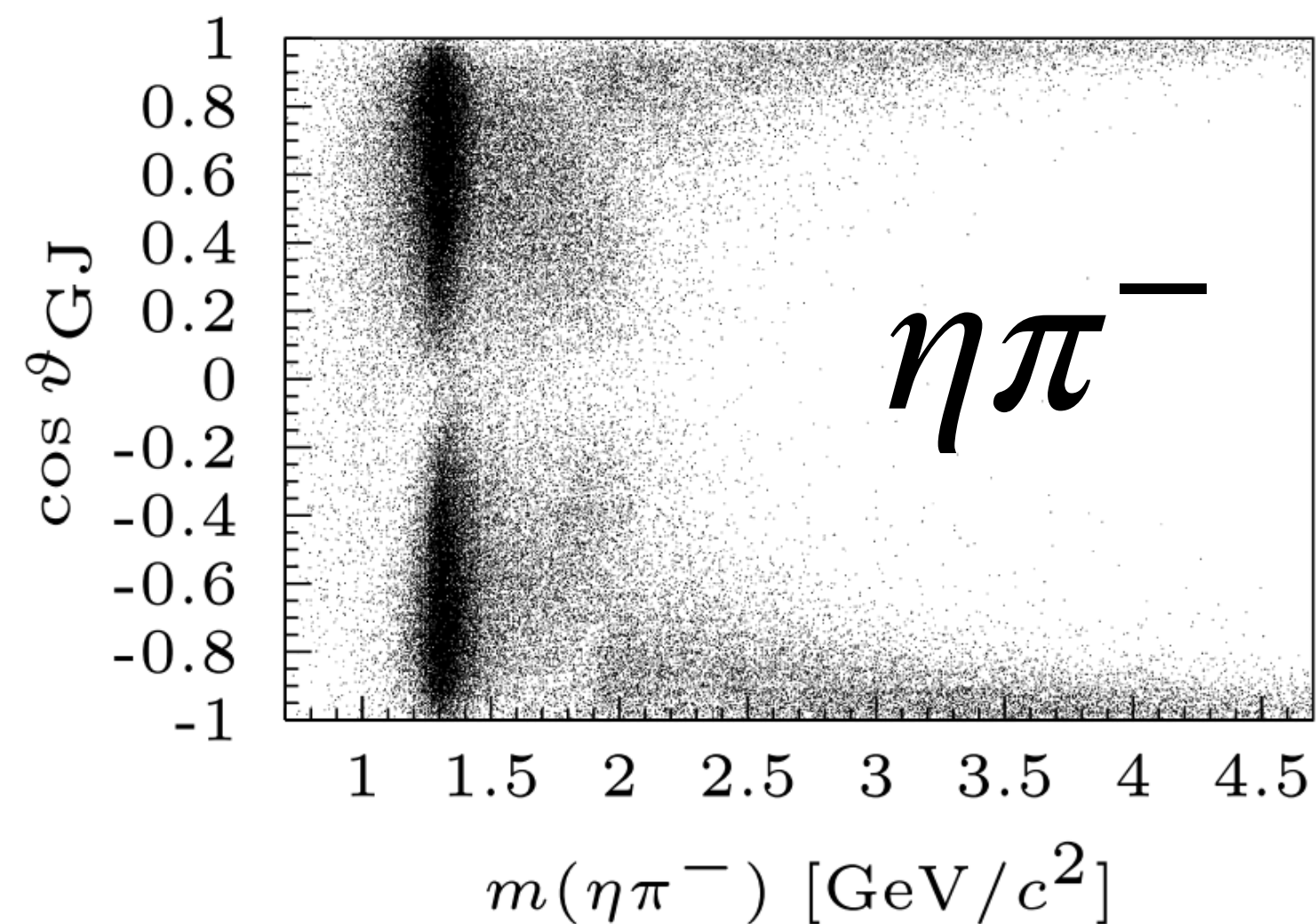
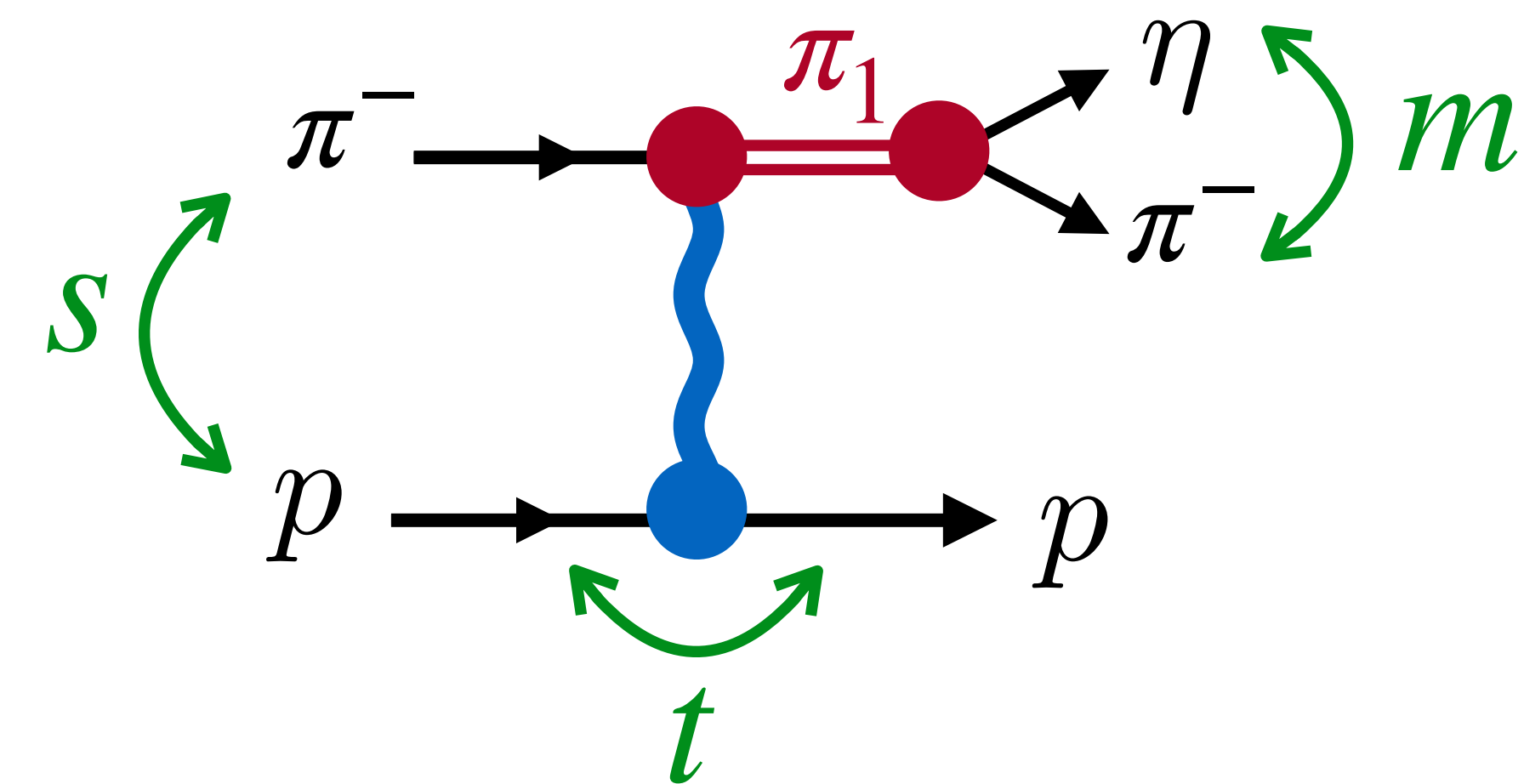
$$J^{PC} = 1^{-+}$$

$$\pi_1 \rightarrow \pi\eta$$

$$1^{-+} = (0^{-+} \otimes 0^{-+})_{P\text{-wave}}$$



Eta-Pi @COMPASS



of independent variables:

Total energy squared s : fixed

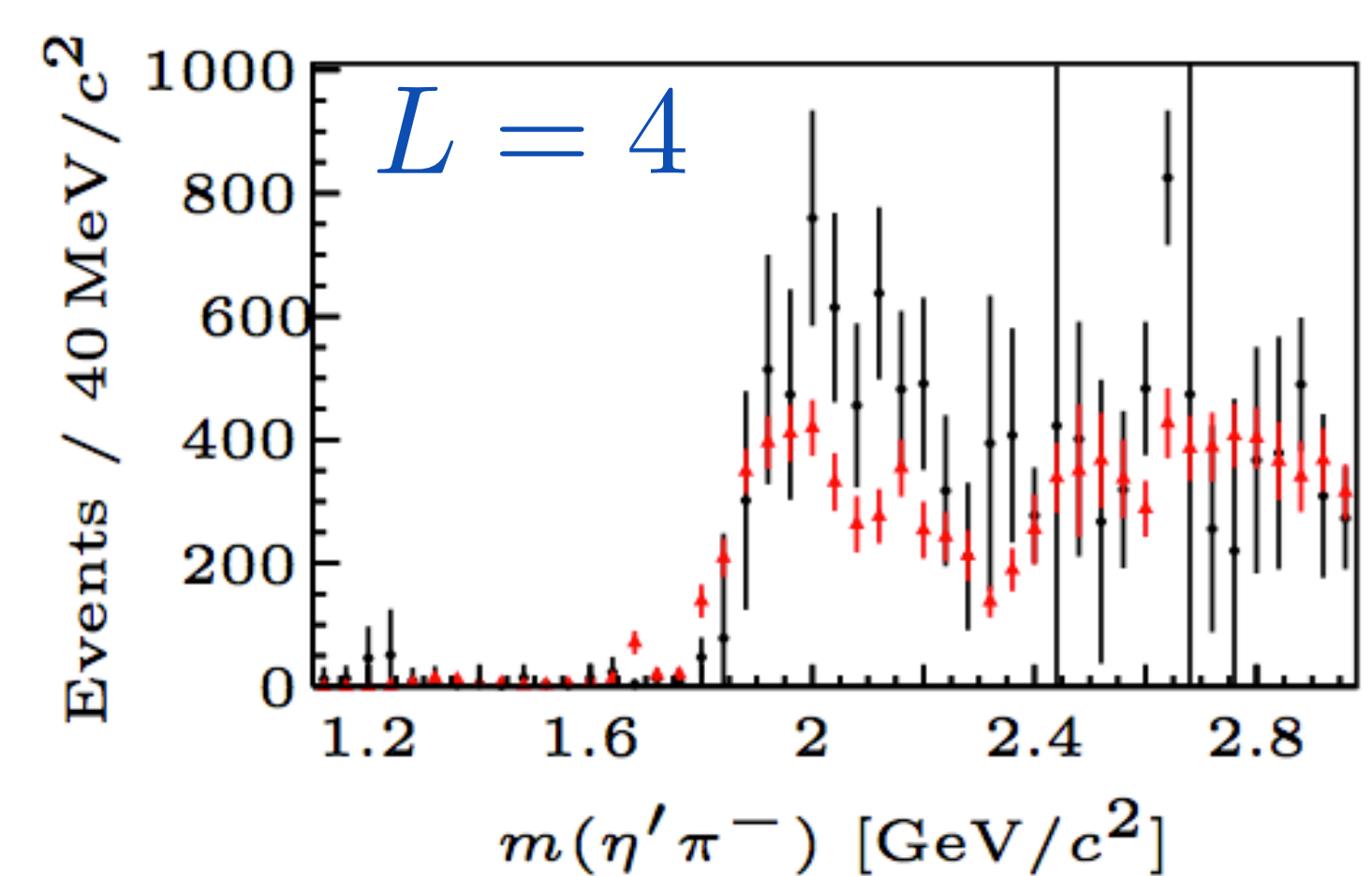
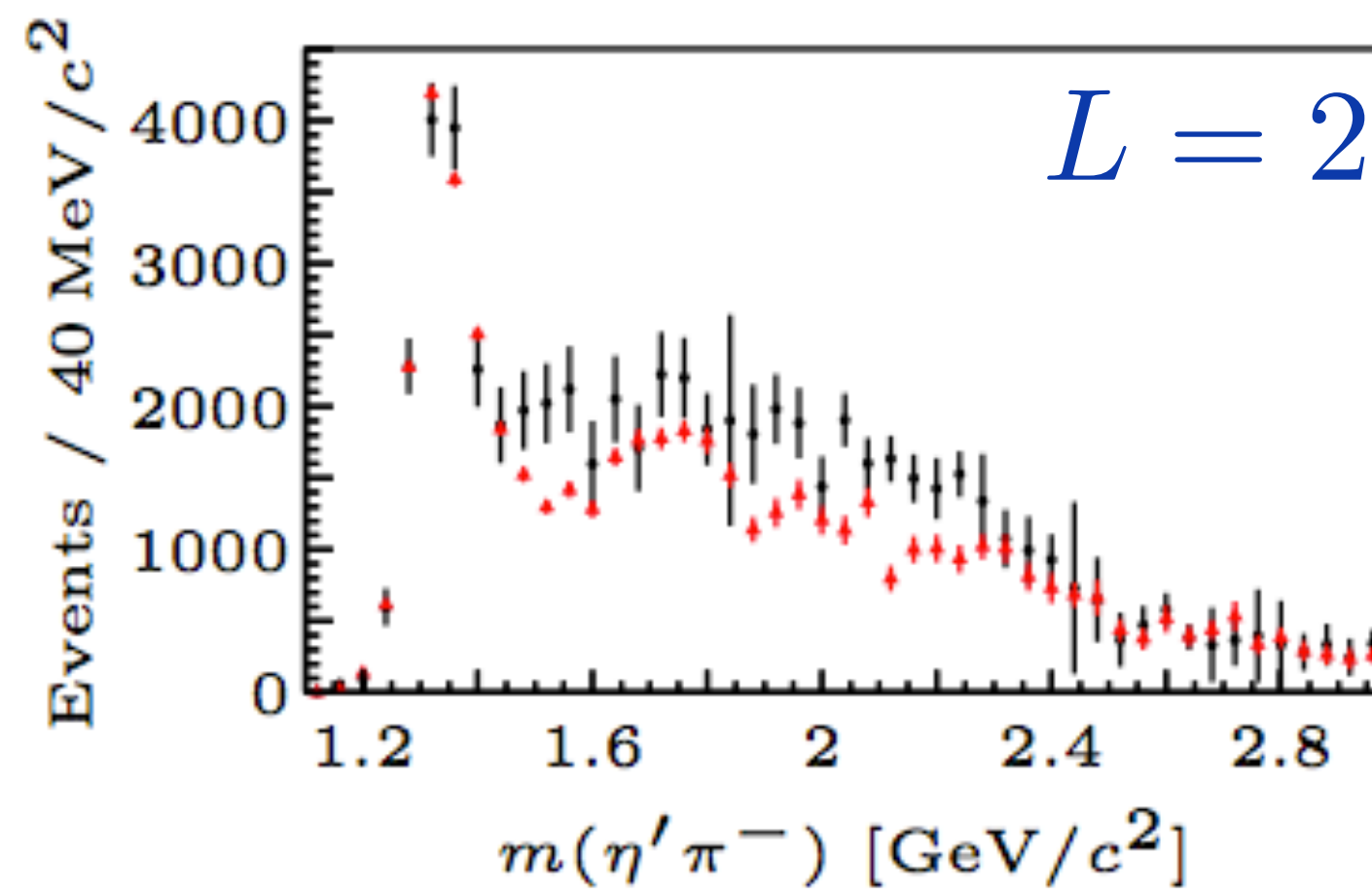
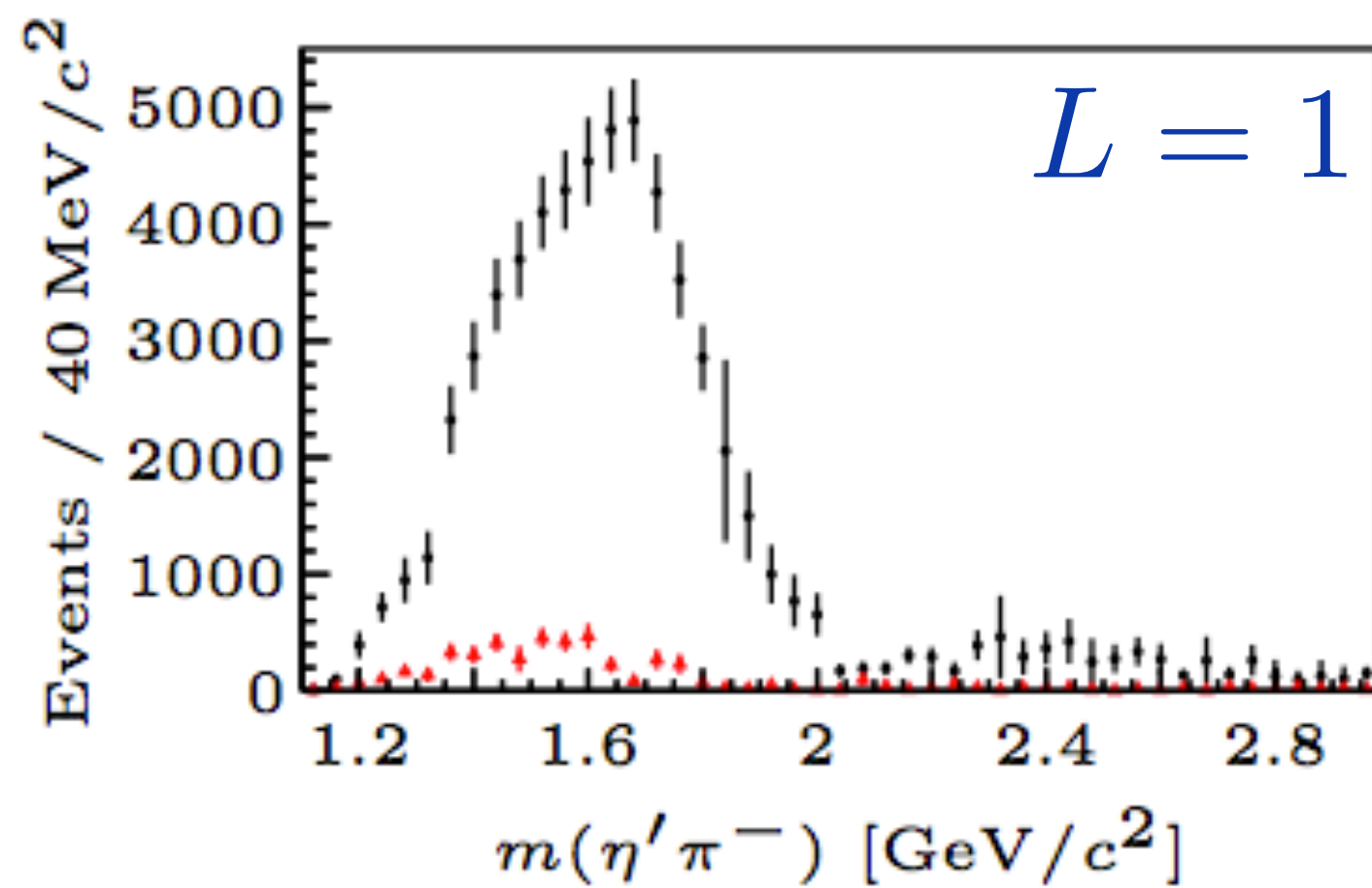
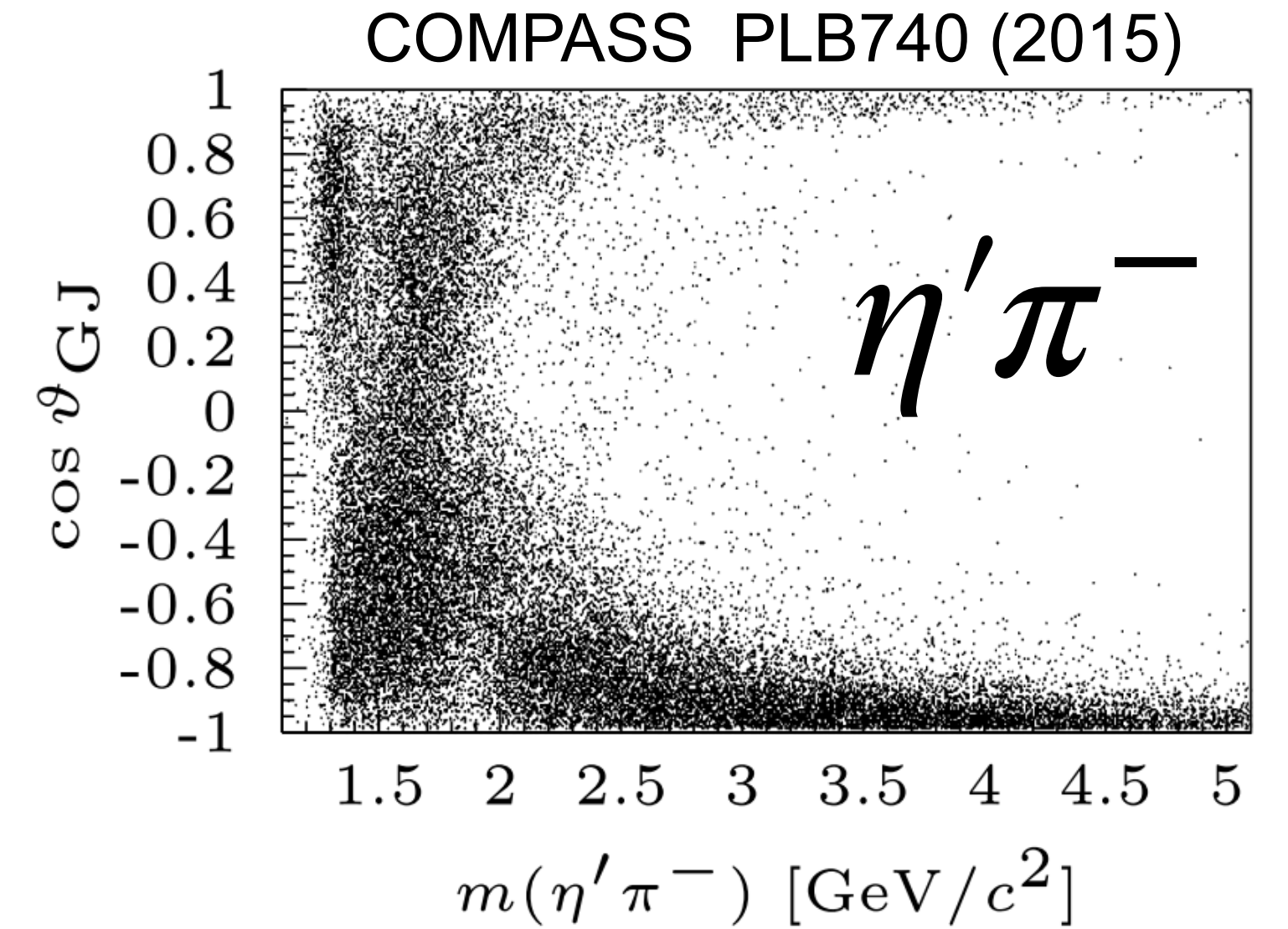
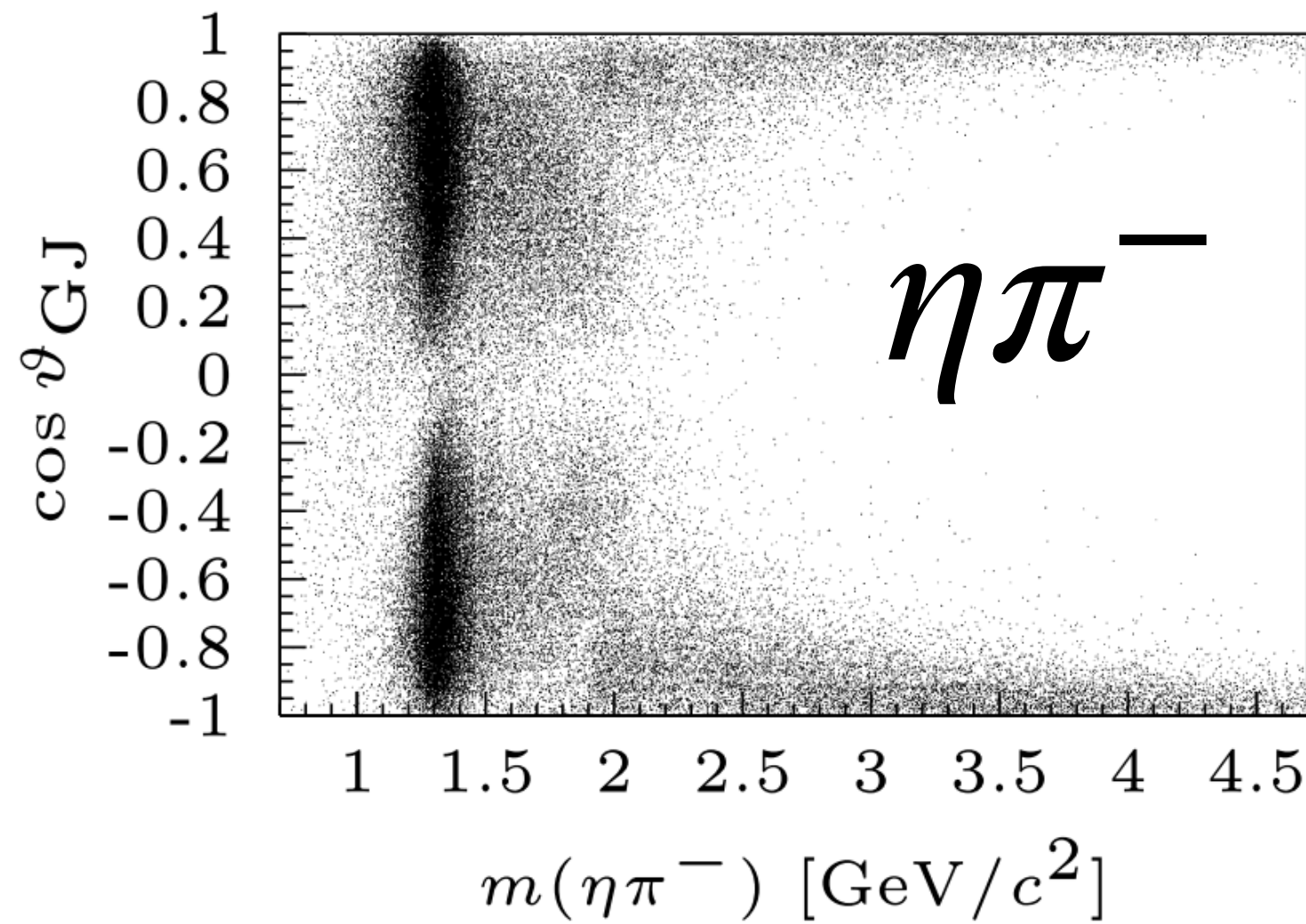
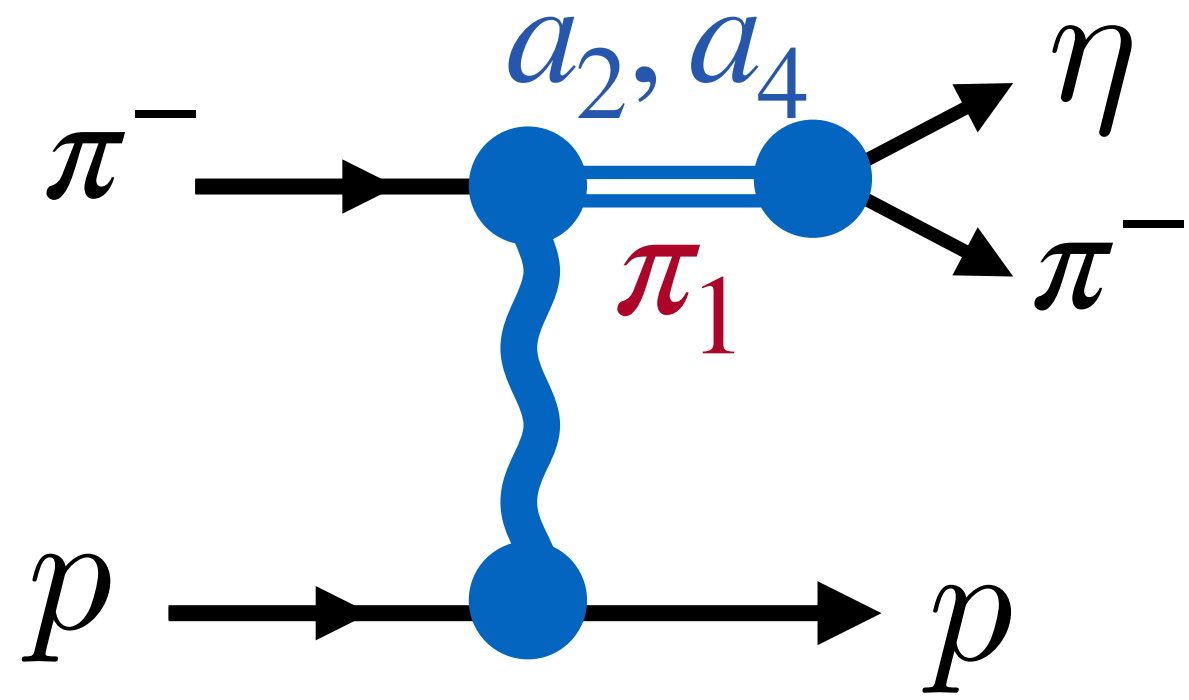
Momentum transferred squared t : 1 bin

$\eta\pi$ mass m

Decay angles (θ, ϕ) in the $\eta\pi$ rest frame

ϕ dependence: (almost) only $\sin \phi$

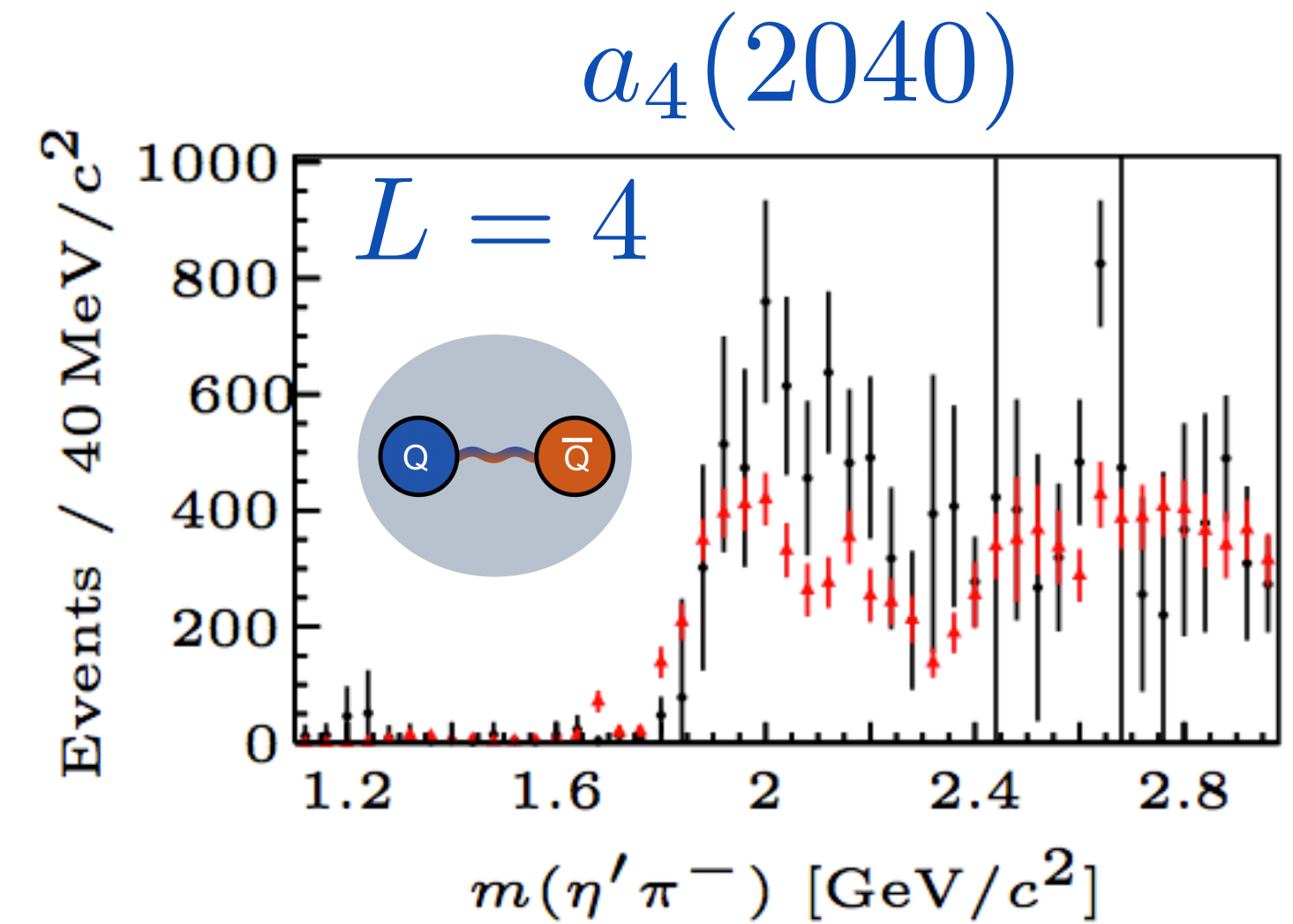
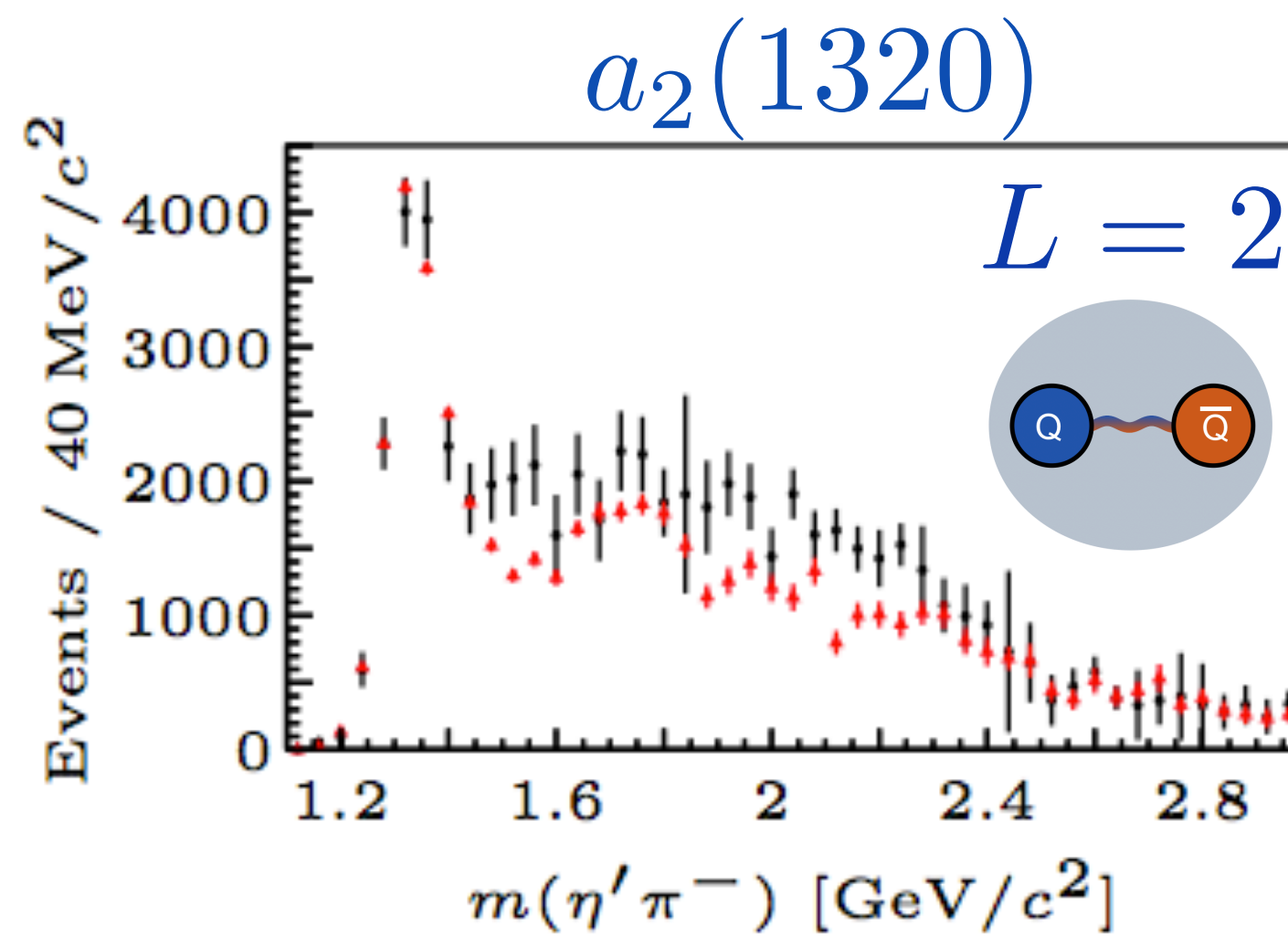
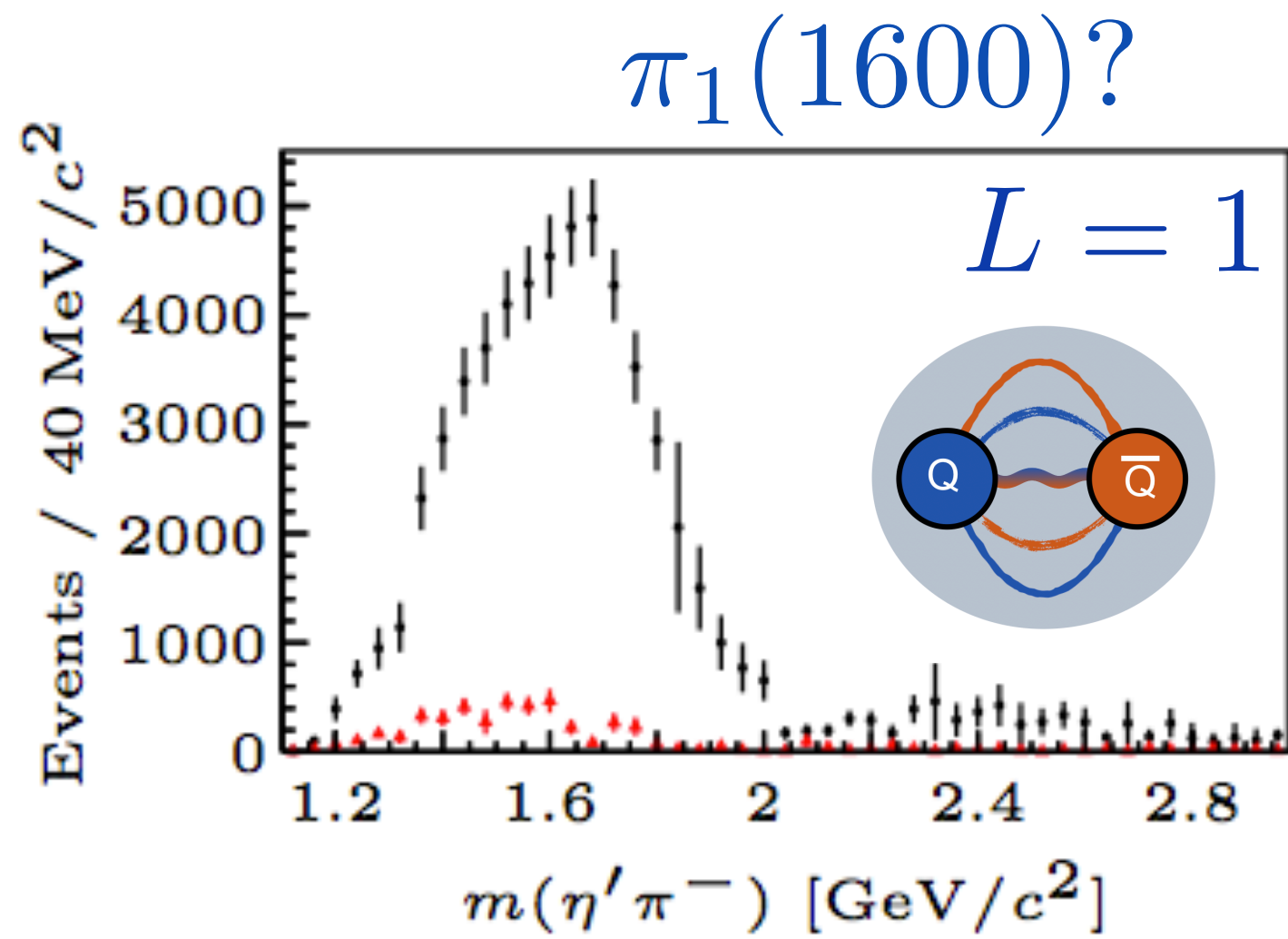
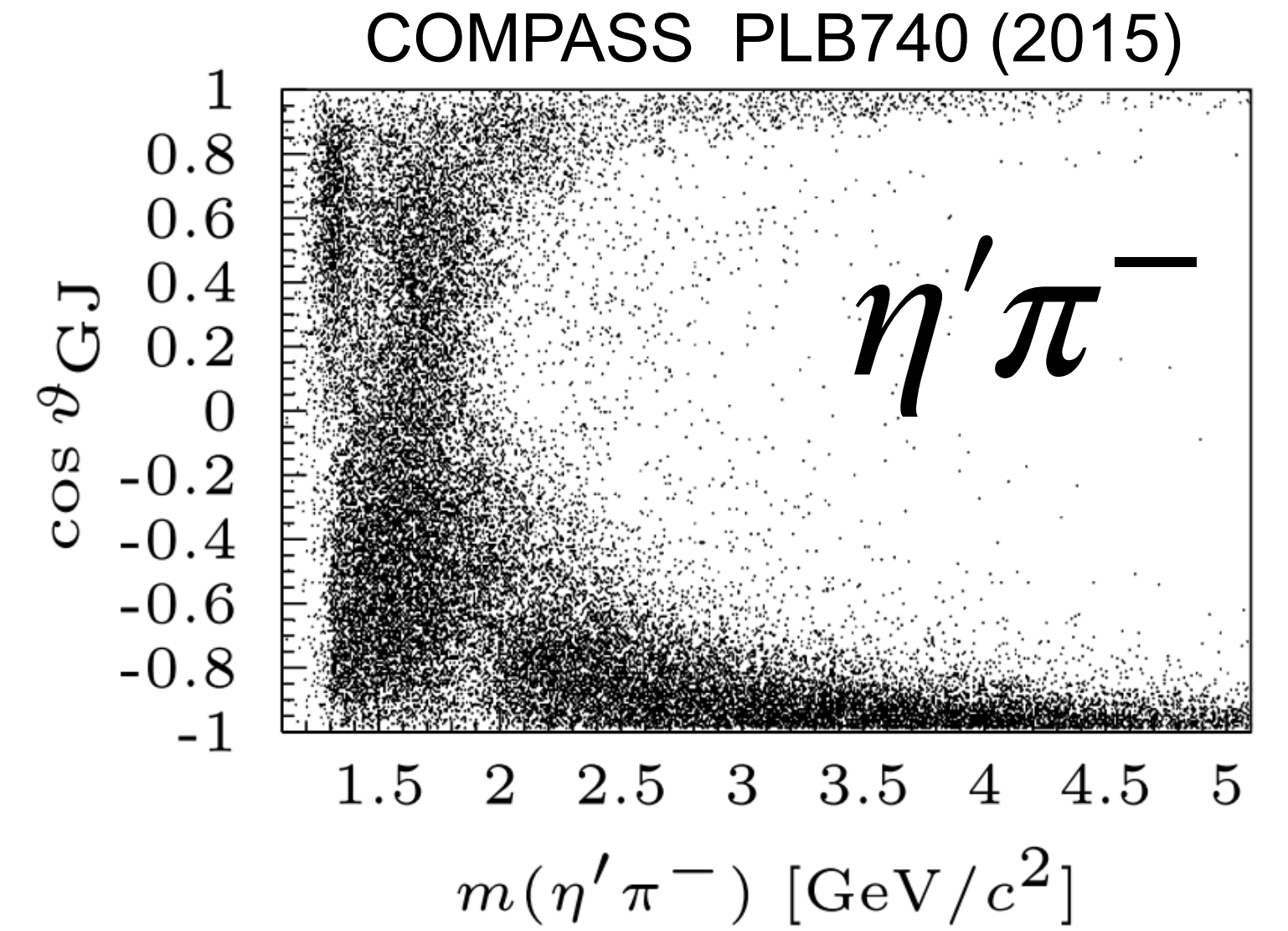
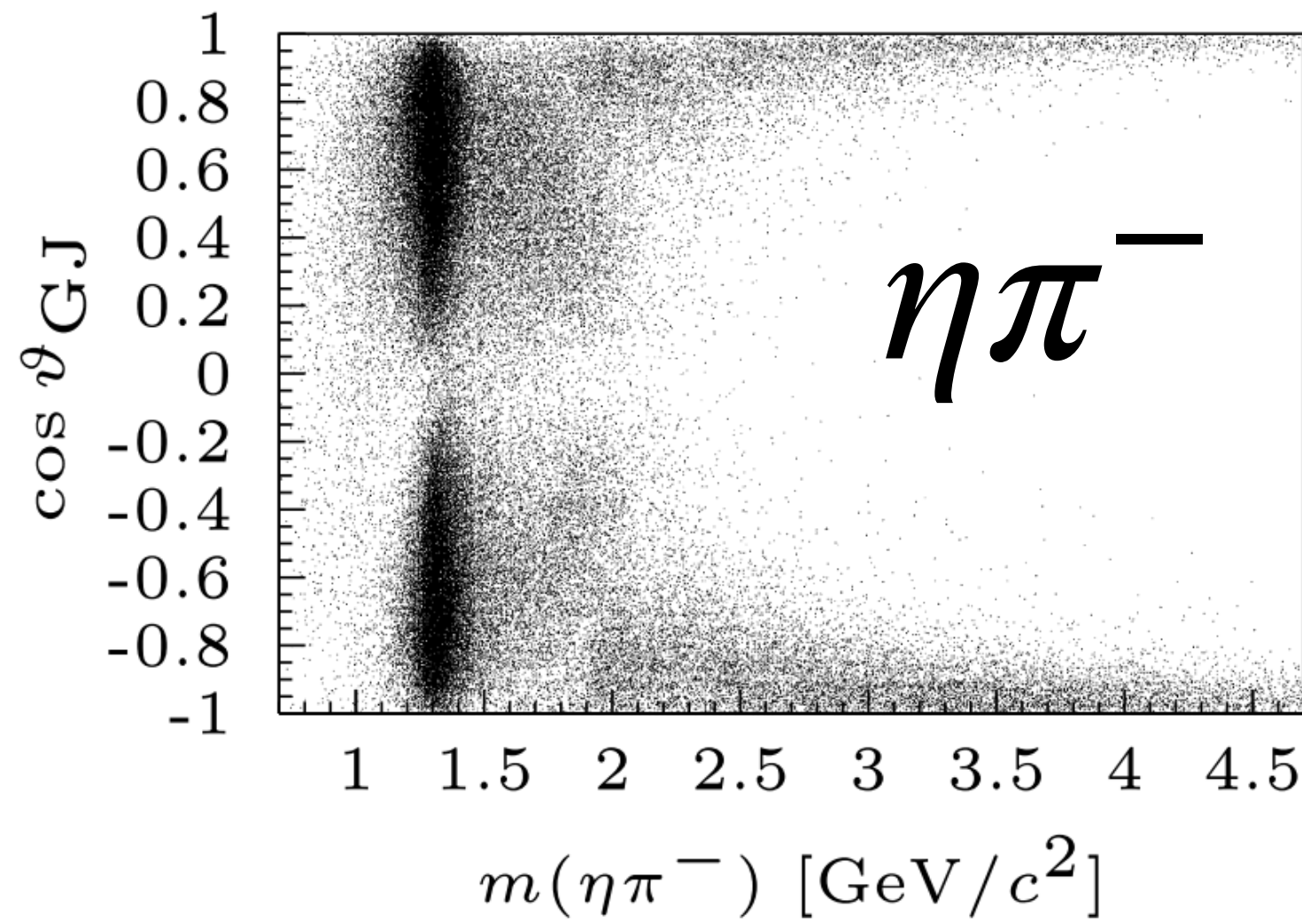
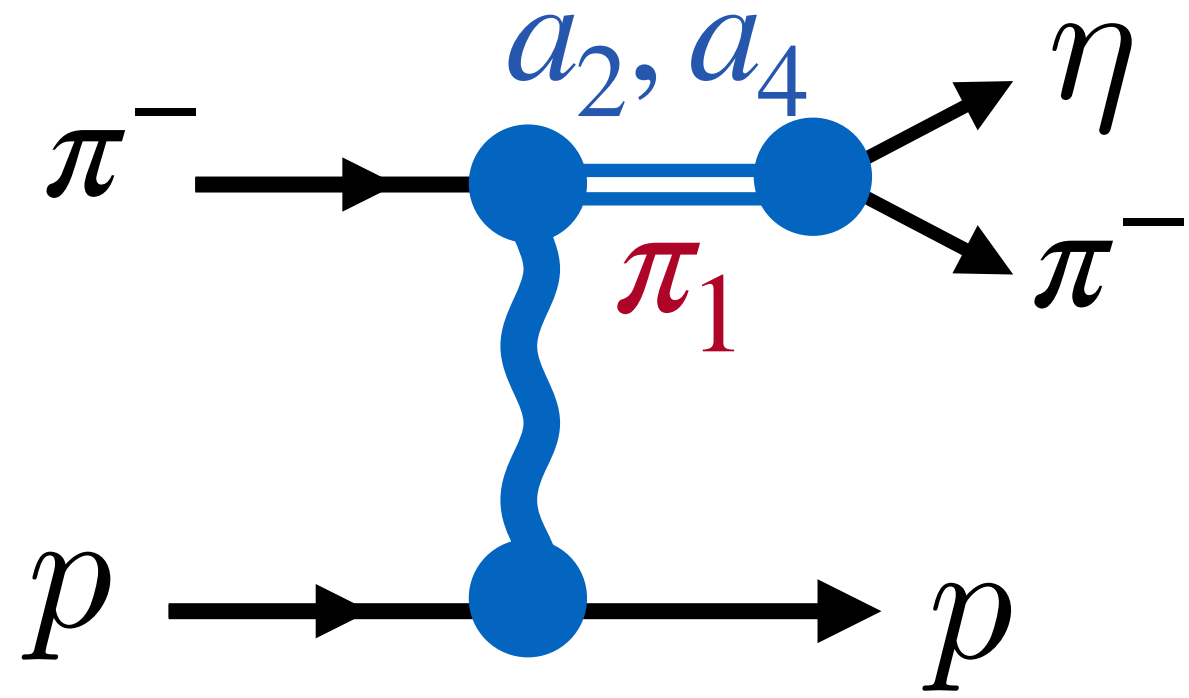
Partial Waves Expansion



Resonance in angular mom. $L = 1$?

black: $\pi\eta'$ red: $\pi\eta$ (scaled)

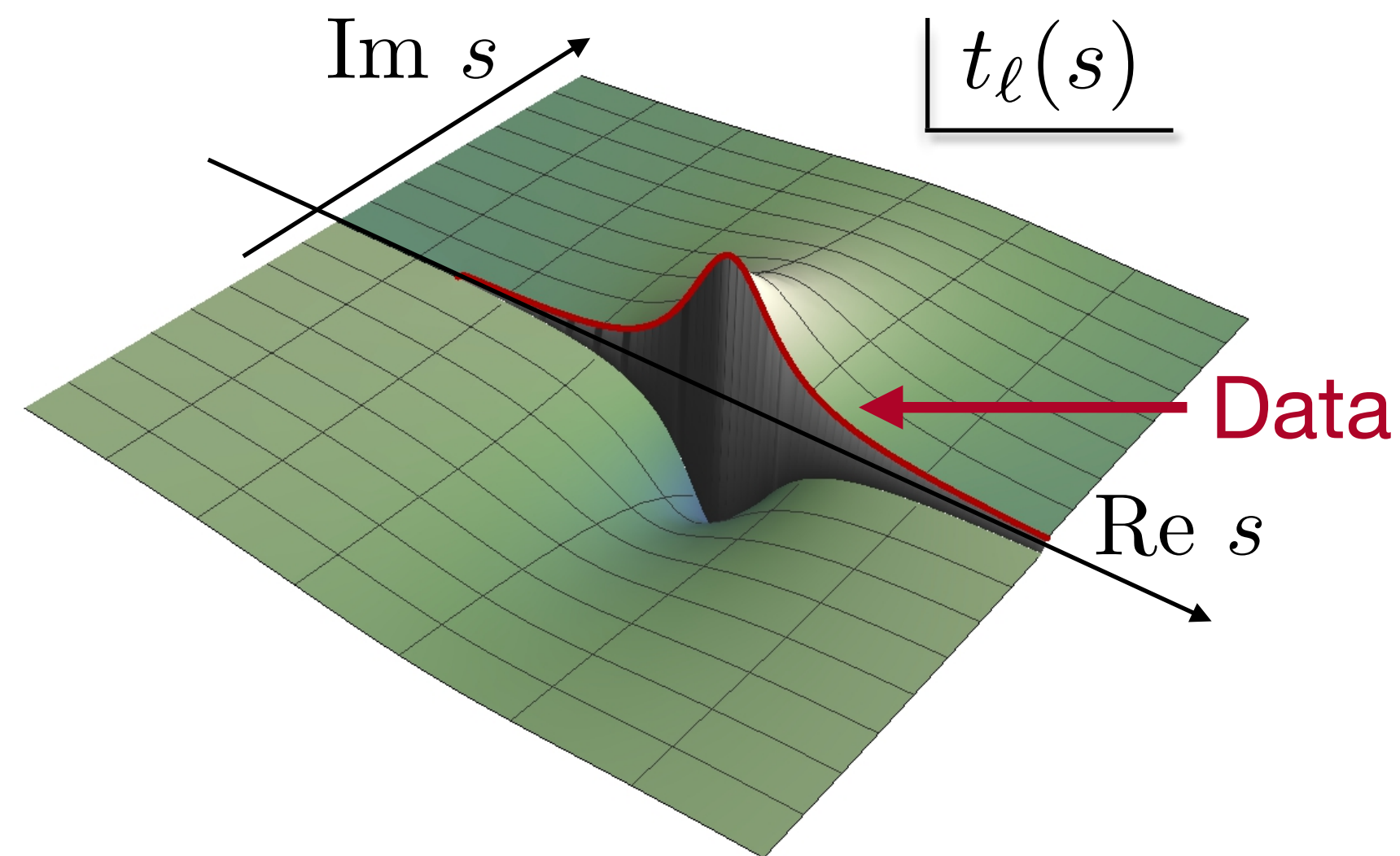
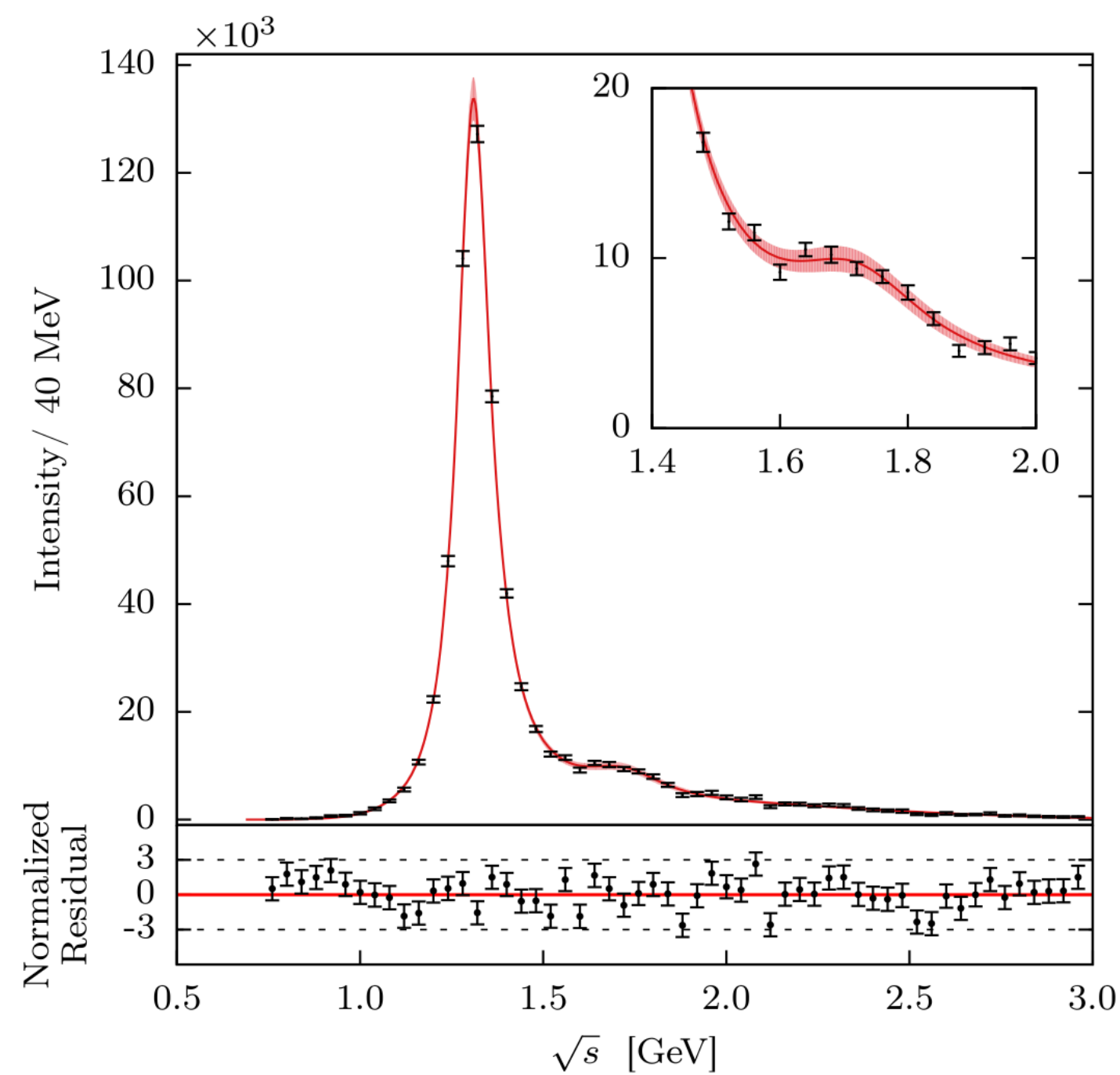
Partial Waves Expansion



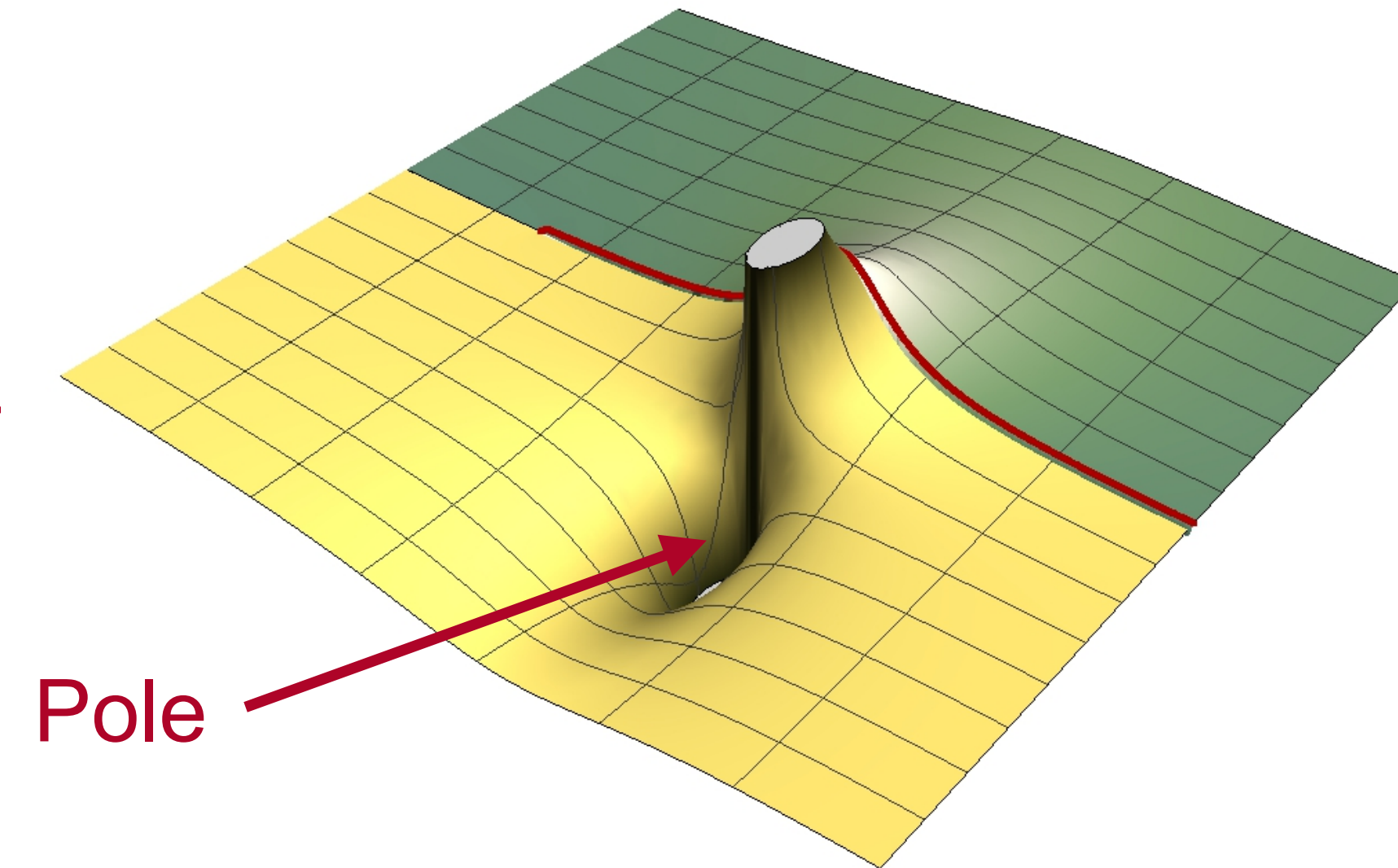
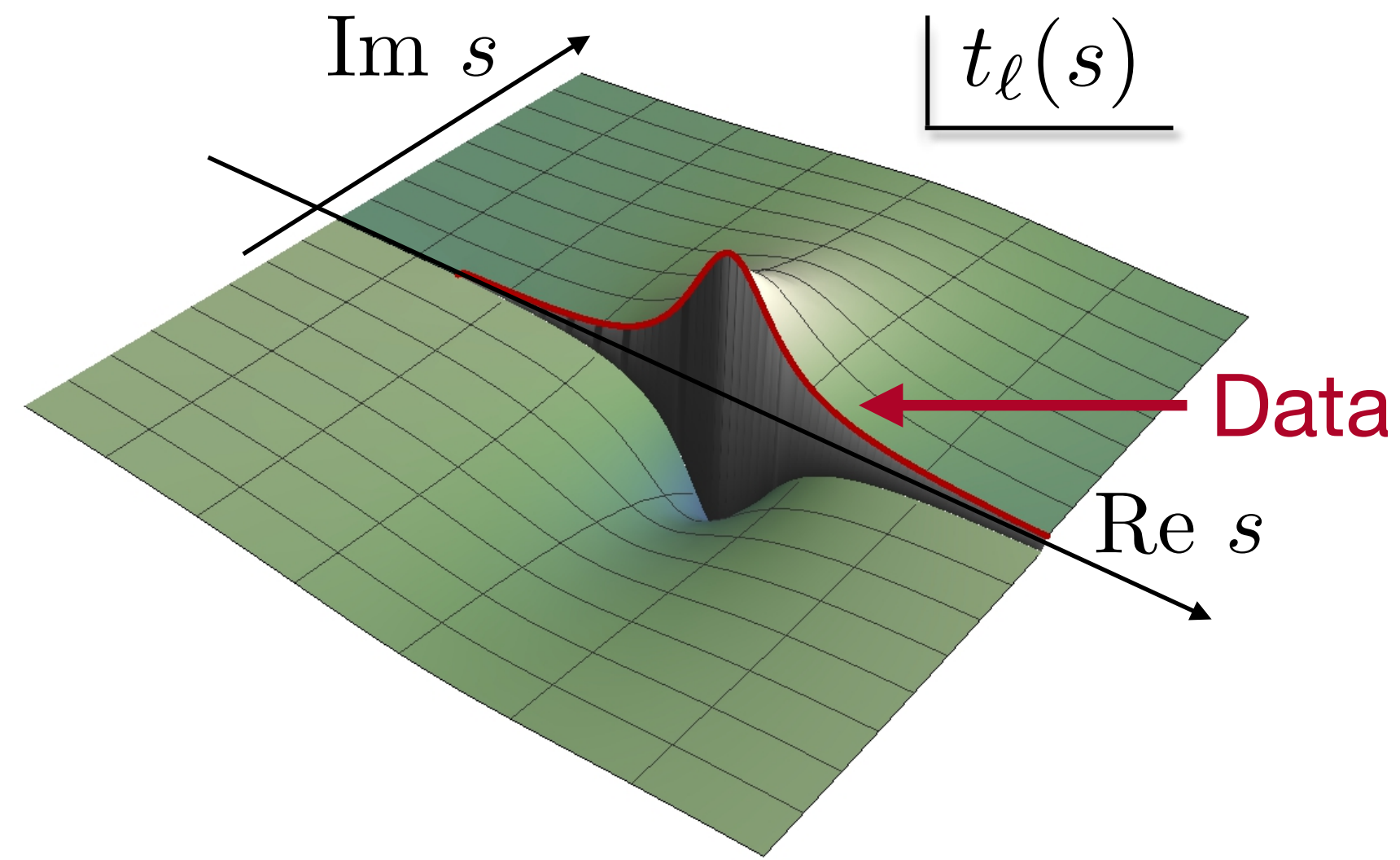
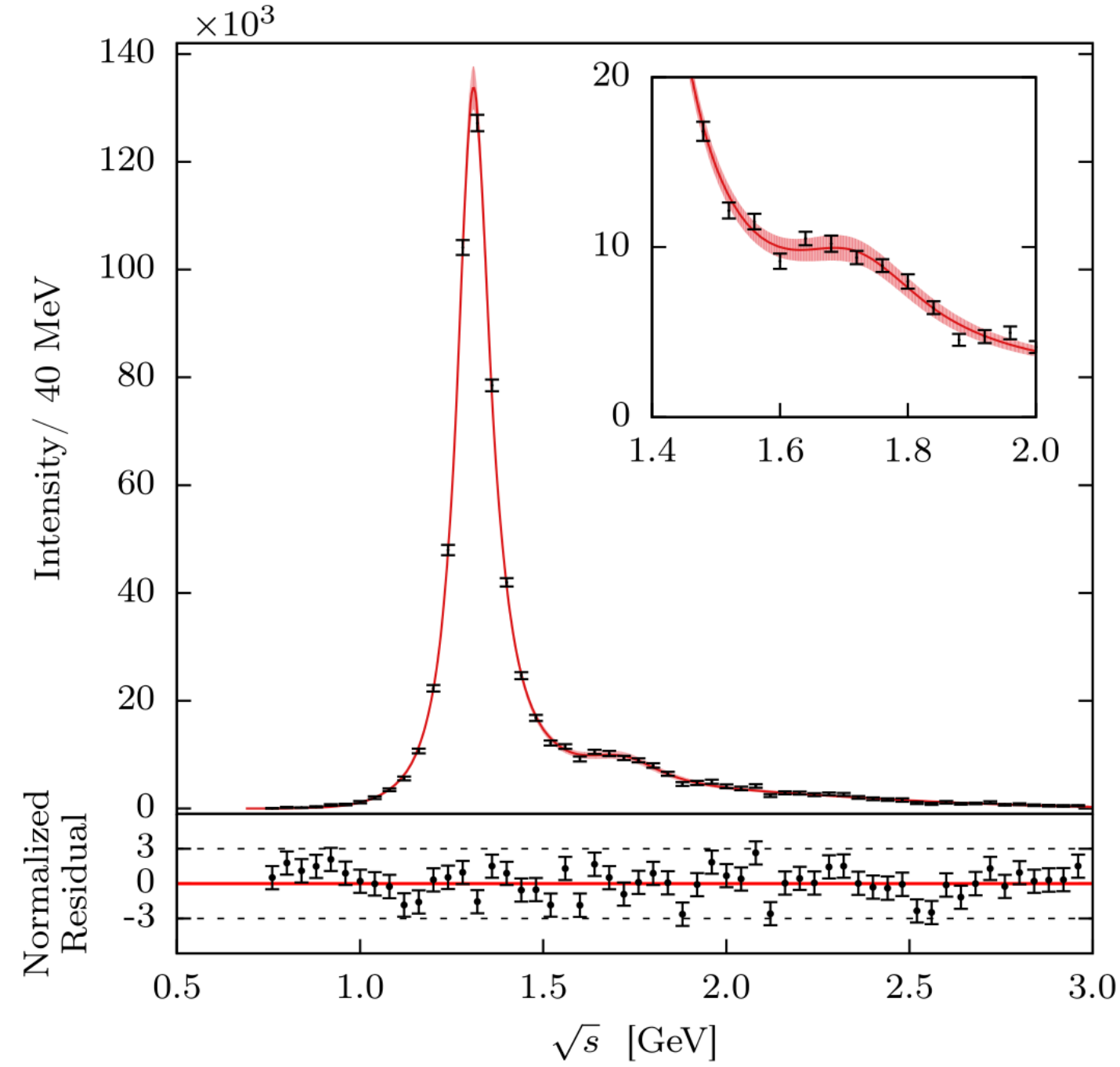
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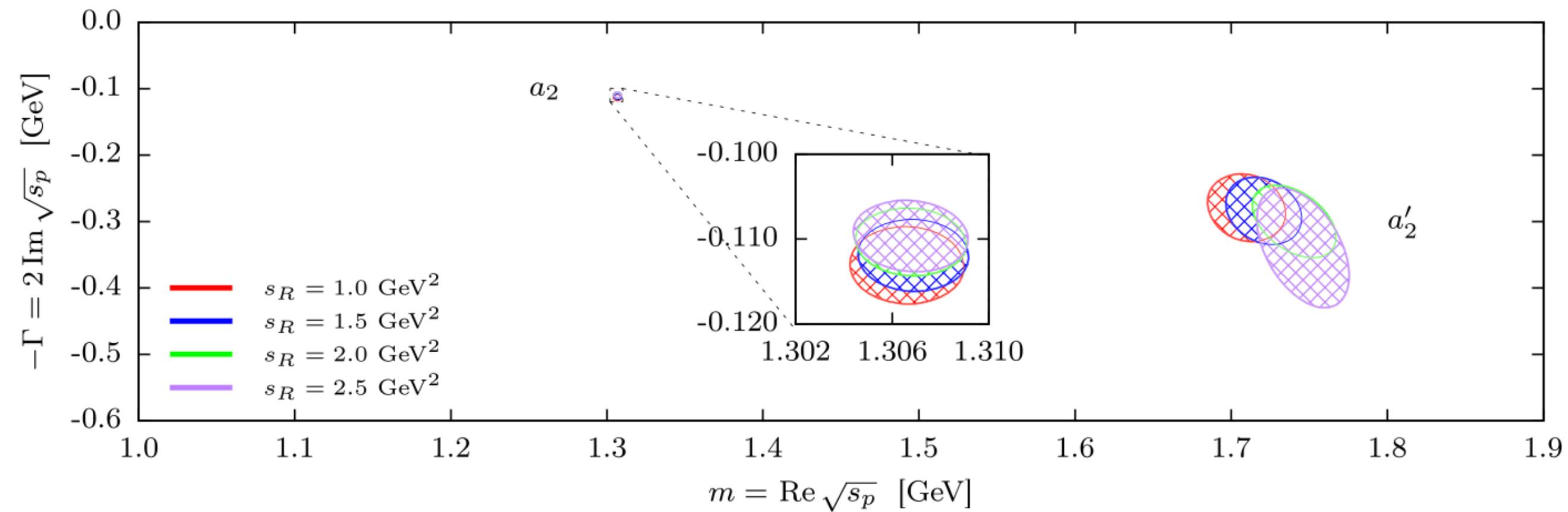
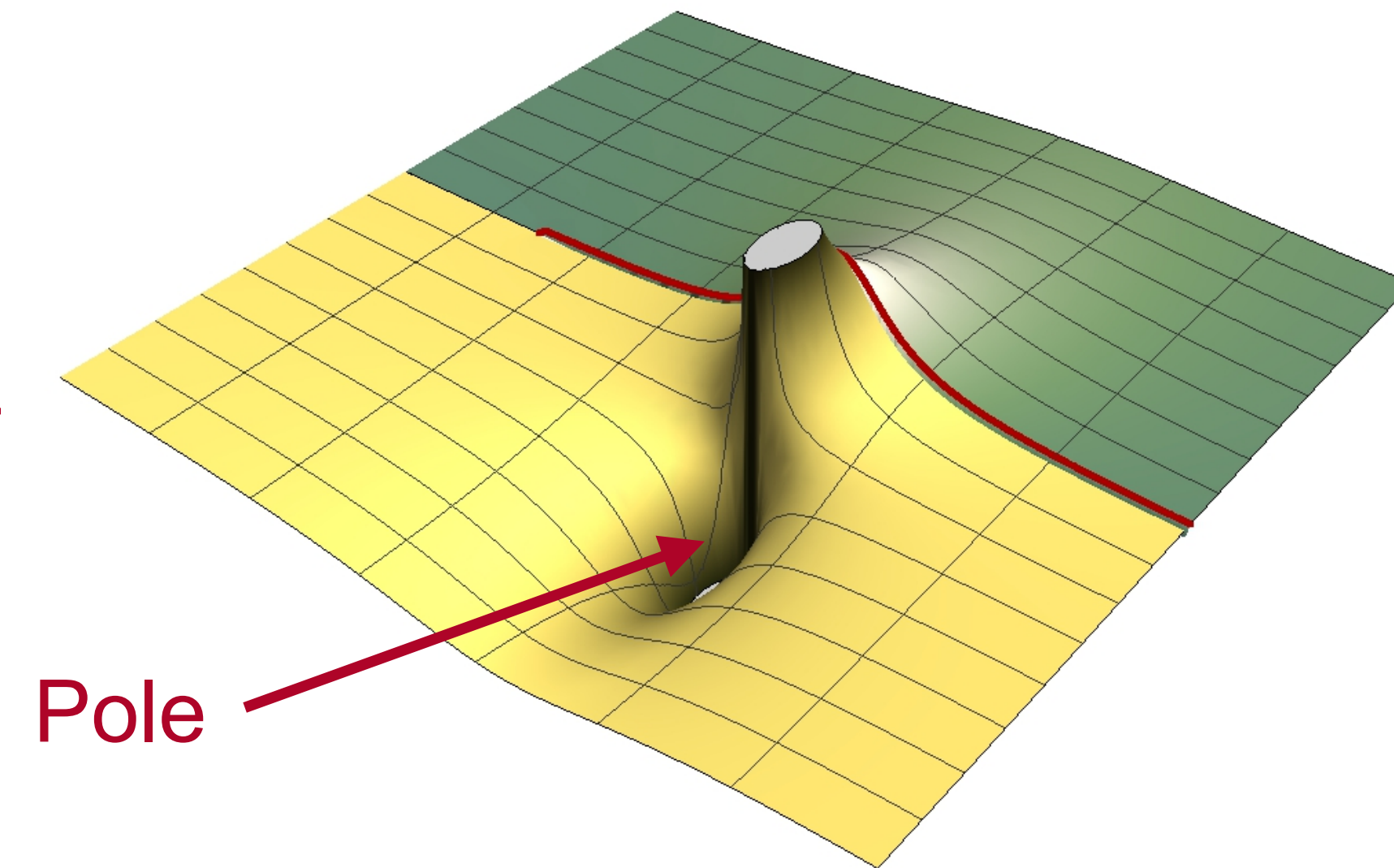
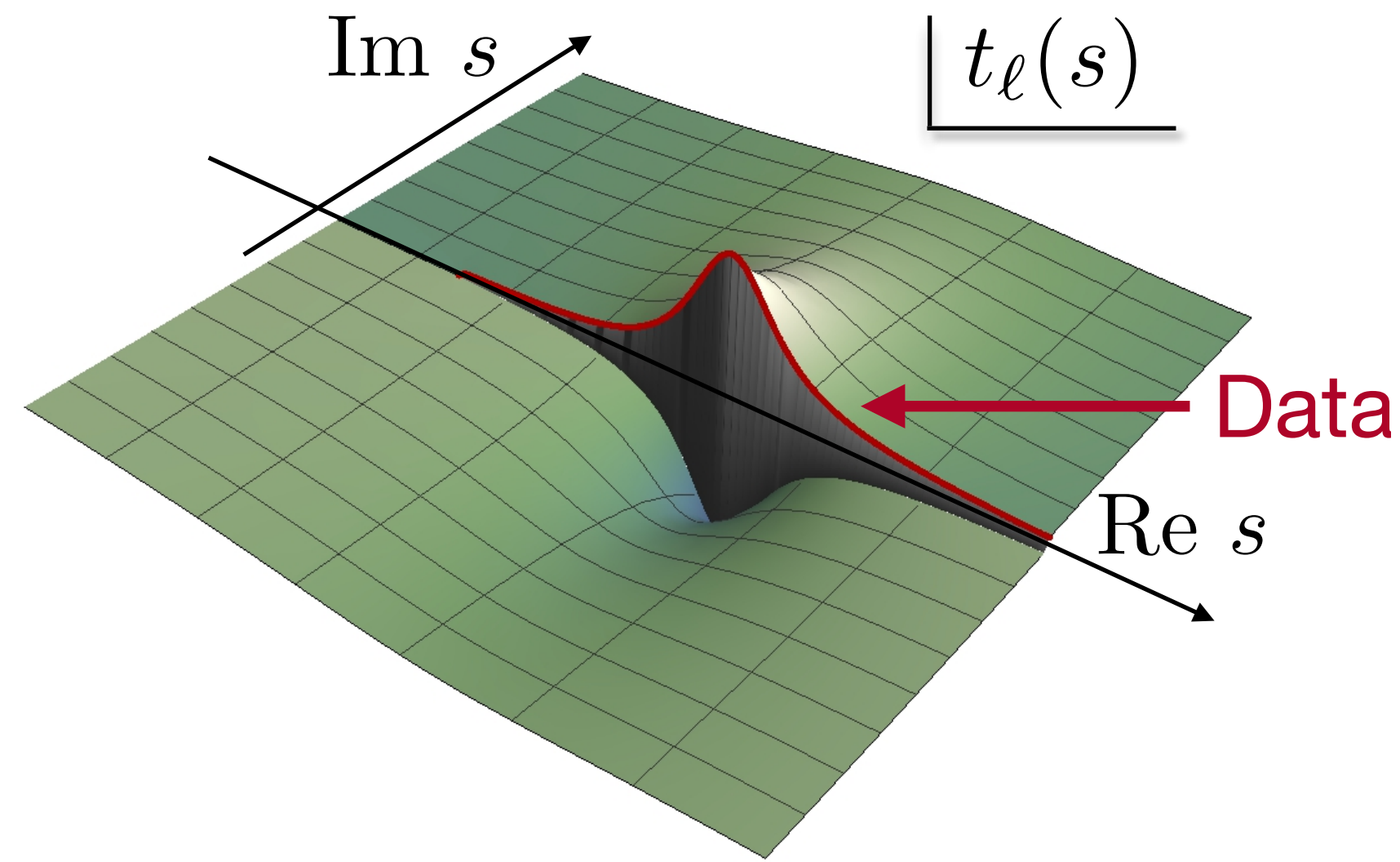
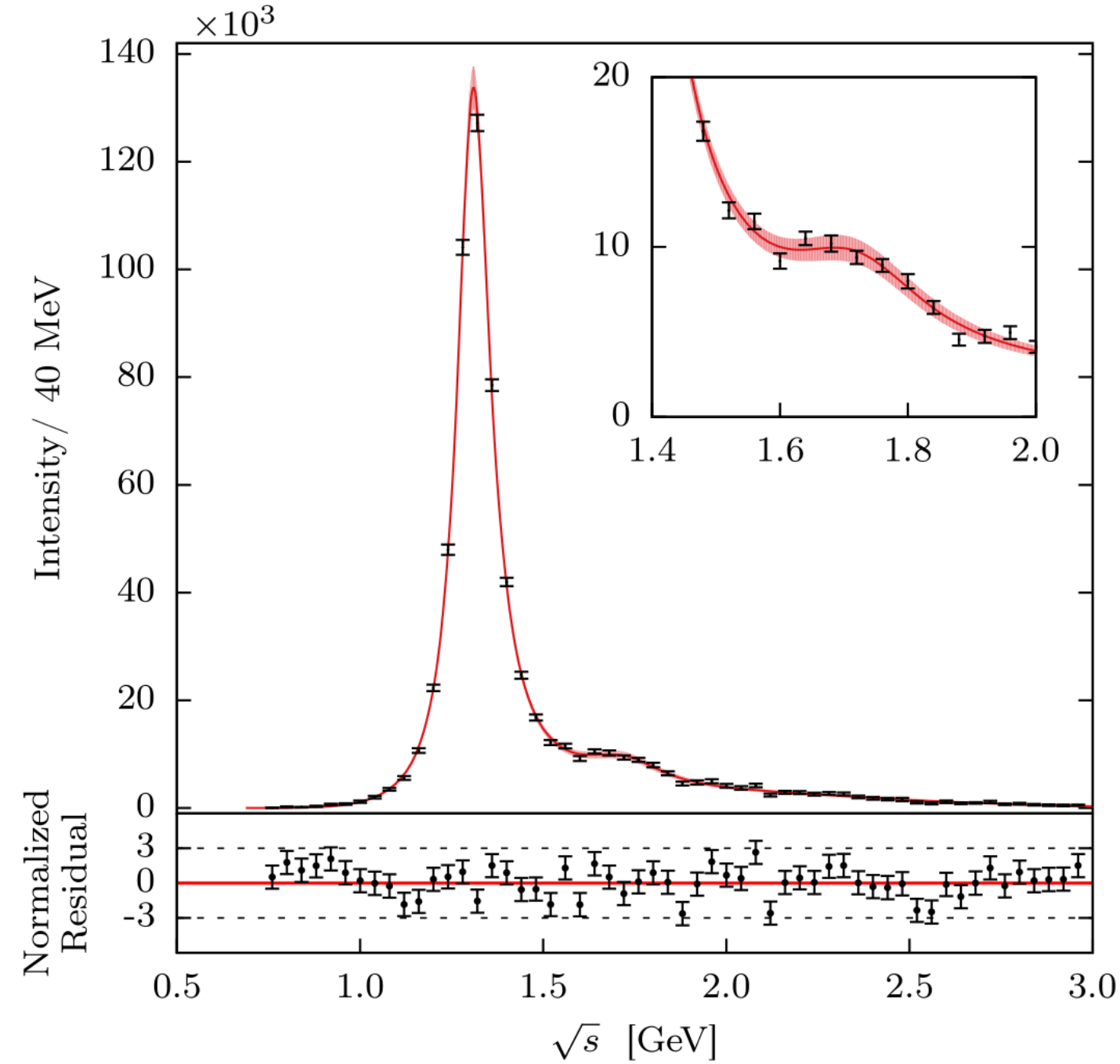
$a_2(1320)^-$ Pole Position in $\eta\pi^-$



$a_2(1320)^-$ Pole Position in $\eta\pi^-$



$a_2(1320)^-$ Pole Position in $\eta\pi^-$



D-wave parametrization satisfying S-matrix constraints (unitarity and analyticity)



New analysis of $\eta\pi$ tensor resonances measured at the COMPASS experiment

JPAC Collaboration

A. Jackura^{a,b,*}, C. Fernández-Ramírez^{c,2}, M. Mikhasenko^{d,3}, A. Pilloni^{e,1},
V. Mathieu^{a,b,4}, J. Nys^{f,4,5}, V. Pauk^{e,1}, A.P. Szczepaniak^{a,b,e,1,4}, G. Fox^{g,4}

COMPASS Collaboration

JPAC Collaboration, COMPASS Collaboration / Physics Letters B 779 (2018) 464–472

M. Aghasyan^{ae}, R. Akhunzyanovⁿ, M.G. Alexeev^{af}, G.D. Alexeevⁿ, A. Amoroso^{af,ag},
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W. Augustyniak^{aj}, A. Austregesilo^v, C.D.R. Azevedo^h, B. Badełek^{ak}, F. Balestra^{af,ag},
M. Ball^j, J. Barth^k, R. Beck^j, Y. Bedfer^{aa}, J. Bernhard^{s,p}, K. Bicker^{v,p}, E.R. Bielert^p,
R. Birsa^{ae}, M. Bodlak^x, P. Bordalo^{r,8}, F. Bradamante^{ad,ae}, A. Bressan^{ad,ae}, M. Büchele^o,
V.E. Burtsev^{ah}, W.-C. Chang^{ab}, C. Chatterjee^m, M. Chiosso^{af,ag}, I. Choi^{ai}, A.G. Chumakov^{ah},
S.-U. Chung^{v,9}, A. Cicuttin^{ae,10}, M.L. Crespo^{ae,10}, S. Dalla Torre^{ae}, S.S. Dasgupta^m,
S. Dasgupta^{ad,ae}, O.Yu. Denisov^{ag,**}, L. Dhara^m, S.V. Donskov^z, N. Doshita^{am},
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P.D. Eversheim^j, M. Faessler¹¹, A. Ferrero^{aa}, M. Finger^x, M. Finger jr.^x, H. Fischer^o,
C. Franco^r, N. du Fresne von Hohenesche^{s,p}, J.M. Friedrich^{v,**}, V. Frolov^{n,p}, E. Fuchey^{aa,12},
F. Gautheronⁱ, O.P. Gavrichtchoukⁿ, S. Gerassimov^{u,v}, J. Giarra^s, F. Giordano^{ai},
I. Gnesi^{af,ag}, M. Gorzellik^{o,24}, A. Grasso^{af,ag}, M. Grosse Perdekamp^{ai}, B. Grube^v,
T. Grussenmeyer^o, A. Guskovⁿ, D. Hahne^k, G. Hamar^{ae}, D. von Harrach^s, F.H. Heinsius^o,
R. Heitz^{ai}, F. Herrmann^o, N. Horikawa^{w,13}, N. d'Hose^{aa}, C.-Y. Hsieh^{ab,14}, S. Huber^v,
S. Ishimoto^{am,15}, A. Ivanov^{af,ag}, Yu. Ivanshin^{n,18}, T. Iwata^{am}, V. Jary^y, R. Joosten^j, P. Jörg^o,
E. Kabuß^s, A. Kerbizi^{ad,ae}, B. Ketzer^j, G.V. Khaustov^z, Yu.A. Khokhlov^{z,16}, Yu. Kisselevⁿ,
F. Klein^k, J.H. Koivuniemi^{i,ai}, V.N. Kolosov^z, K. Kondo^{am}, K. Königsman^o, I. Konorov^{u,v},

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P. Kremser^o, F. Krinner^v, Z.V. Kroumchtein^{n,7}, Y. Kulinich^{ai}, F. Kunne^{aa}, K. Kurek^{aj},
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V.E. Lyubovitskij^{ah}, A. Maggiora^{ag}, A. Magnon^{ai}, N. Makins^{ai}, N. Makke^{ae,10}, G.K. Mallot^p,
S.A. Mamon^{ah}, B. Marianski^{aj}, A. Martin^{ad,ae}, J. Marzec^{al}, J. Matoušek^{ad,ae,x},
H. Matsuda^{am}, T. Matsuda^t, G.V. Meshcheryakovⁿ, M. Meyer^{ai,aa}, W. Meyerⁱ,
Yu.V. Mikhailov^z, M. Mikhasenko^j, E. Mitrofanovⁿ, N. Mitrofanovⁿ, Y. Miyachi^{am},
A. Nagaytsevⁿ, F. Nerling^s, D. Neyret^{aa}, J. Nový^{y,p}, W.-D. Nowak^s, G. Nukazuka^{am},
A.S. Nunes^r, A.G. Olshevskyⁿ, I. Orlovⁿ, M. Ostrick^s, D. Panzieri^{ag,22}, B. Parsamyan^{af,ag},
S. Paul^v, J.-C. Peng^{ai}, F. Pereira^h, M. Pešek^x, M. Pešková^x, D.V. Peshekhonovⁿ,
N. Pierre^{s,aa}, S. Platchkov^{aa}, J. Pochodzalla^s, V.A. Polyakov^z, J. Pretz^{k,17}, M. Quaresma^r,
C. Quintans^r, S. Ramos^{r,8}, C. Regali^o, G. Reicherzⁱ, C. Riedl^{ai}, N.S. Rogachevaⁿ,
D.I. Ryabchikov^{z,v}, A. Rybnikovⁿ, A. Rychter^{al}, R. Salac^y, V.D. Samoylenko^z, A. Sandacz^{aj},
C. Santos^{ae}, S. Sarkar^m, I.A. Savin^{n,18}, T. Sawada^{ab}, G. Sbrizzai^{ad,ae}, P. Schiavon^{ad,ae},
T. Schlüter¹⁹, K. Schmidt^{o,24}, H. Schmieden^k, K. Schönning^{p,23}, E. Seder^{aa}, A. Selyuninⁿ,
L. Silva^r, L. Sinha^m, S. Sirtl^o, M. Sluneckaⁿ, J. Smolikⁿ, A. Srnka^l, D. Steffen^{p,v},
M. Stolarski^r, O. Subrt^{p,y}, M. Sulc^q, H. Suzuki^{am,13}, A. Szabelski^{ad,ae,aj}, T. Szameitat^{o,24},
P. Sznajder^{aj}, M. Tasevskyⁿ, S. Tessaro^{ae}, F. Tessarotto^{ae}, A. Thiel^j, J. Tomsa^x, F. Tosello^{ag},
V. Tskhay^u, S. Uhl^v, B.I. Vasilishin^{ah}, A. Vauth^p, J. Veloso^h, A. Vidon^{aa}, M. Virius^y,
S. Wallner^v, T. Weisrock^s, M. Wilfert^s, J. ter Wolbeek^{o,24}, K. Zaremba^{al}, P. Zavadaⁿ,
M. Zavertyaev^u, E. Zemlyanichkina^{n,18}, N. Zhuravlevⁿ, M. Ziembicki^{al}



New analysis of $\eta\pi$ tensor resonances measured at the COMPASS experiment

JPAC Collaboration

A. Jackura^{a,b,*}, C. Fernández-Ramírez^{c,2}, **M. Mikhasenko**^{d,3}, A. Pilloni^{e,1},
V. Mathieu^{a,b,4}, J. Nys^{f,4,5}, V. Pauk^{e,1}, A.P. Szczepaniak^{a,b,e,1,4}, G. Fox^{g,4}

COMPASS Collaboration

JPAC Collaboration, COMPASS Collaboration / Physics Letters B 779 (2018) 464–472

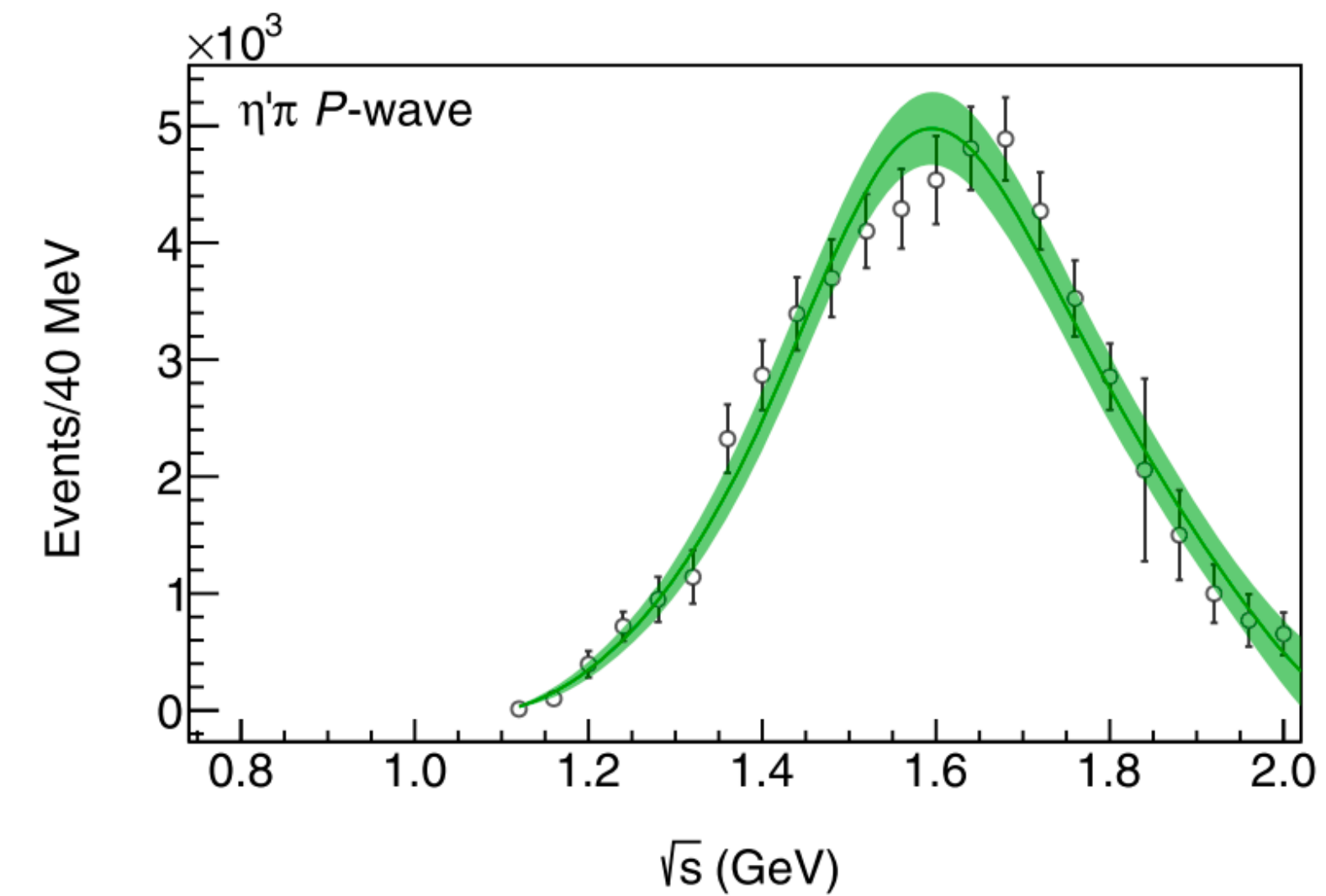
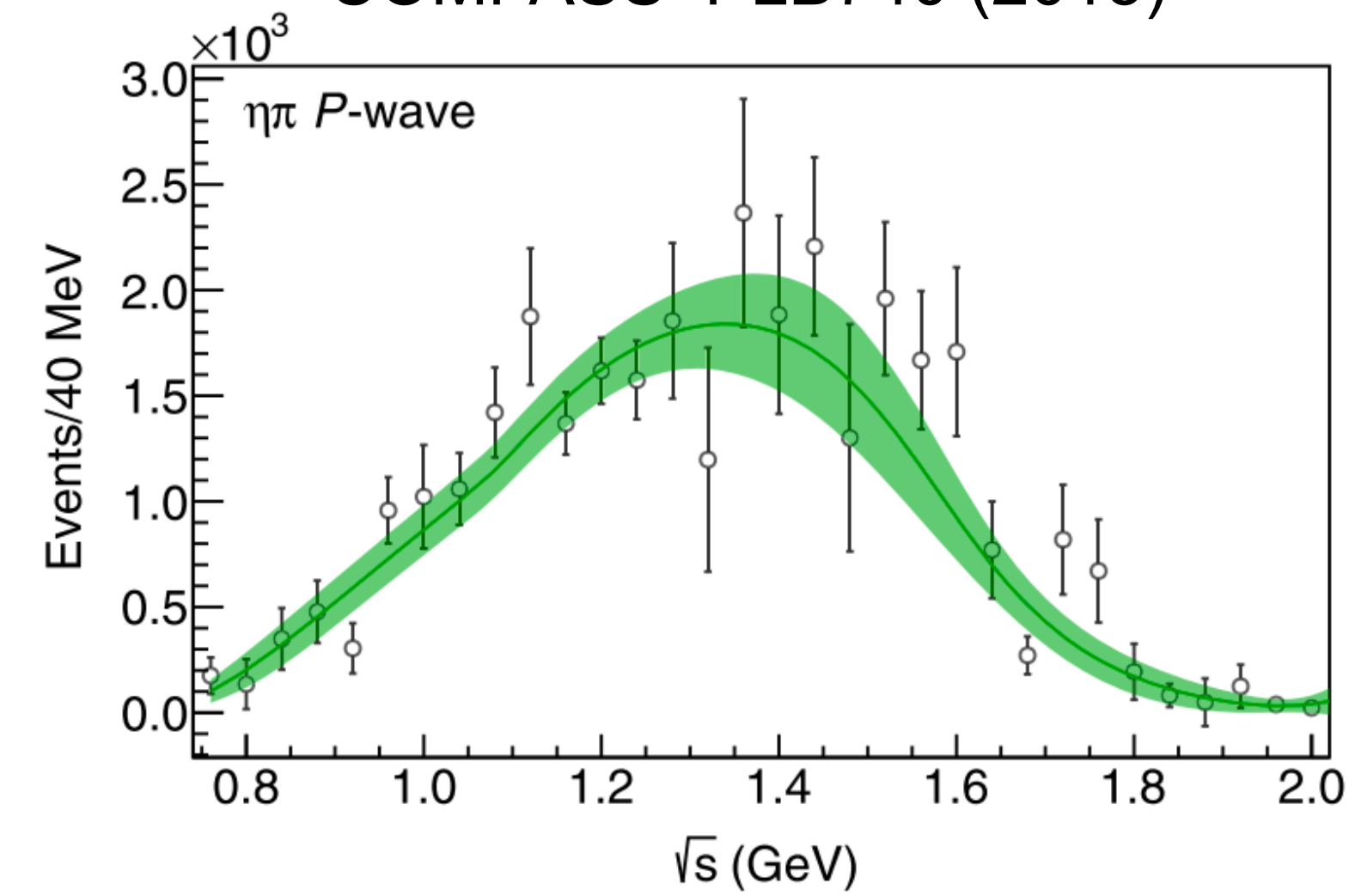
M. Aghasyan^{ae}, R. Akhunzyanovⁿ, M.G. Alexeev^{af}, G.D. Alexeevⁿ, A. Amoroso^{af,ag},
V. Andrieux^{ai,aa}, N.V. Anfimovⁿ, V. Anosovⁿ, A. Antoshkinⁿ, K. Augsten^{n,y},
W. Augustyniak^{aj}, A. Austregesilo^v, C.D.R. Azevedo^h, B. Badełek^{ak}, F. Balestra^{af,ag},
M. Ball^j, J. Barth^k, R. Beck^j, Y. Bedfer^{aa}, J. Bernhard^{s,p}, K. Bicker^{v,p}, E.R. Bielert^p,
R. Birsa^{ae}, M. Bodlak^x, P. Bordalo^{r,8}, F. Bradamante^{ad,ae}, A. Bressan^{ad,ae}, M. Büchele^o,
V.E. Burtsev^{ah}, W.-C. Chang^{ab}, C. Chatterjee^m, M. Chiosso^{af,ag}, I. Choi^{ai}, A.G. Chumakov^{ah},
S.-U. Chung^{v,9}, A. Cicuttin^{ae,10}, M.L. Crespo^{ae,10}, S. Dalla Torre^{ae}, S.S. Dasgupta^m,
S. Dasgupta^{ad,ae}, O.Yu. Denisov^{ag,**}, L. Dhara^m, S.V. Donskov^z, N. Doshita^{am},
Ch. Dreisbach^v, W. Dünneweber¹¹, R.R. Dusaev^{ah}, M. Dziewiecki^{al}, A. Efremov^{n,18},
P.D. Eversheim^j, M. Faessler¹¹, A. Ferrero^{aa}, M. Finger^x, M. Finger jr.^x, H. Fischer^o,
C. Franco^r, N. du Fresne von Hohenesche^{s,p}, J.M. Friedrich^{v,**}, V. Frolov^{n,p}, E. Fuchey^{aa,12},
F. Gautheronⁱ, O.P. Gavrichtchoukⁿ, S. Gerassimov^{u,v}, J. Giarra^s, F. Giordano^{ai},
I. Gnesi^{af,ag}, M. Gorzelli^{o,24}, A. Grasso^{af,ag}, M. Grosse Perdekamp^{ai}, B. Grube^v,
T. Grussenmeyer^o, A. Guskovⁿ, D. Hahne^k, G. Hamar^{ae}, D. von Harrach^s, F.H. Heinsius^o,
R. Heitz^{ai}, F. Herrmann^o, N. Horikawa^{w,13}, N. d'Hose^{aa}, C.-Y. Hsieh^{ab,14}, S. Huber^v,
S. Ishimoto^{am,15}, A. Ivanov^{af,ag}, Yu. Ivanshin^{n,18}, T. Iwata^{am}, V. Jary^y, R. Joosten^j, P. Jörg^o,
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F. Klein^k, J.H. Koivuniemi^{i,ai}, V.N. Kolosov^z, K. Kondo^{am}, K. Königsmann^o, I. Konorov^{u,v},

V.F. Konstantinov^z, A.M. Kotzinian^{ag,20}, O.M. Kouznetsovⁿ, Z. Kral^y, M. Krämer^v,
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M. Levillain^{aa}, S. Levorato^{ae}, Y.-S. Lian^{ab,21}, J. Lichtenstadt^{ac}, R. Longo^{af,ag},
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H. Matsuda^{am}, T. Matsuda^t, G.V. Meshcheryakovⁿ, M. Meyer^{ai,aa}, W. Meyerⁱ,
Yu.V. Mikhailov^z, **M. Mikhasenko**^j, E. Mitrofanovⁿ, N. Mitrofanovⁿ, Y. Miyachi^{am},
A. Nagaytsevⁿ, F. Nerling^s, D. Neyret^{aa}, J. Nový^{y,p}, W.-D. Nowak^s, G. Nukazuka^{am},
A.S. Nunes^r, A.G. Olshevskyⁿ, I. Orlovⁿ, M. Ostrick^s, D. Panzieri^{ag,22}, B. Parsamyan^{af,ag},
S. Paul^v, J.-C. Peng^{ai}, F. Pereira^h, M. Pešek^x, M. Pešková^x, D.V. Peshekhonovⁿ,
N. Pierre^{s,aa}, S. Platchkov^{aa}, J. Pochodzalla^s, V.A. Polyakov^z, J. Pretz^{k,17}, M. Quaresma^r,
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D.I. Ryabchikov^{z,v}, A. Rybnikovⁿ, A. Rychter^{al}, R. Salac^y, V.D. Samoylenko^z, A. Sandacz^{aj},
C. Santos^{ae}, S. Sarkar^m, I.A. Savin^{n,18}, T. Sawada^{ab}, G. Sbrizzai^{ad,ae}, P. Schiavon^{ad,ae},
T. Schlüter¹⁹, K. Schmidt^{o,24}, H. Schmieden^k, K. Schönning^{p,23}, E. Seder^{aa}, A. Selyuninⁿ,
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$\pi_1(1400)$ vs $\pi_1(1600)$

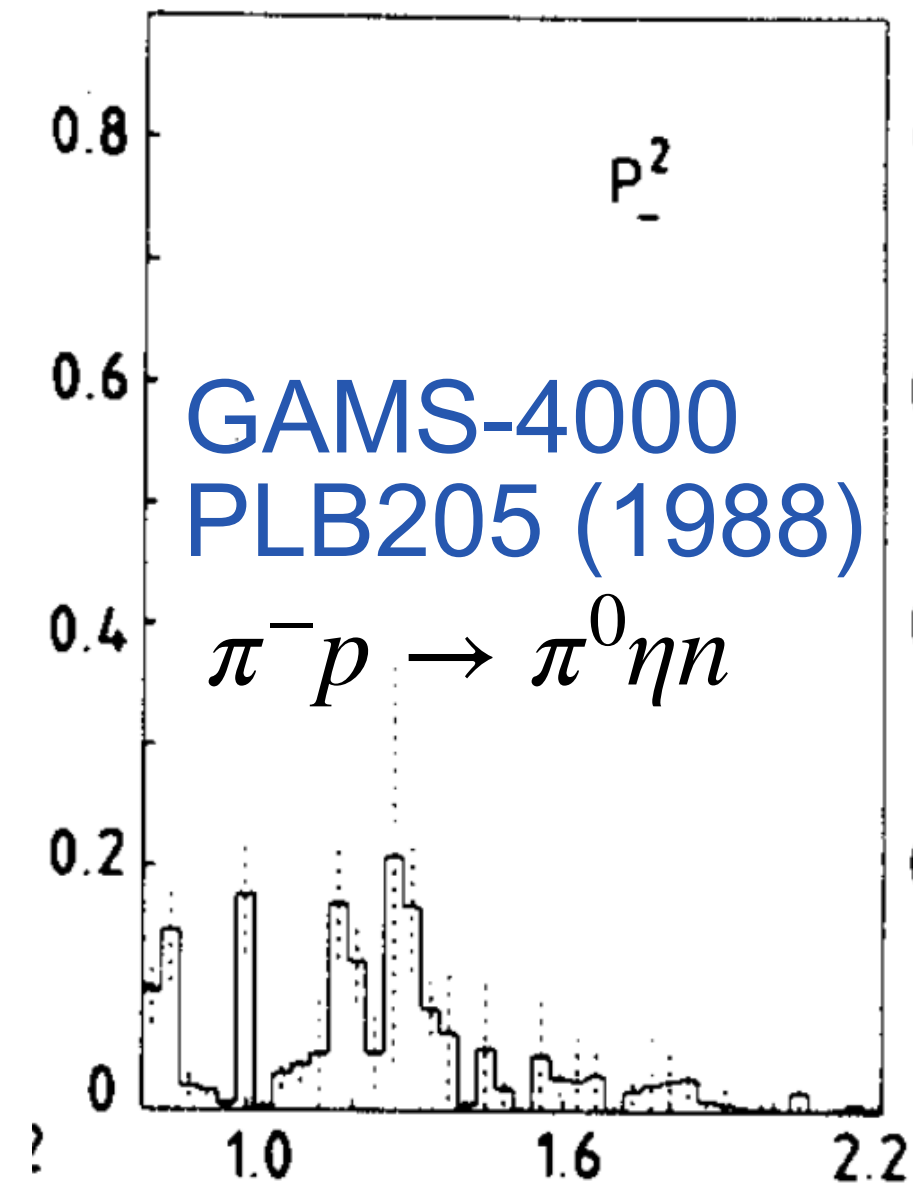
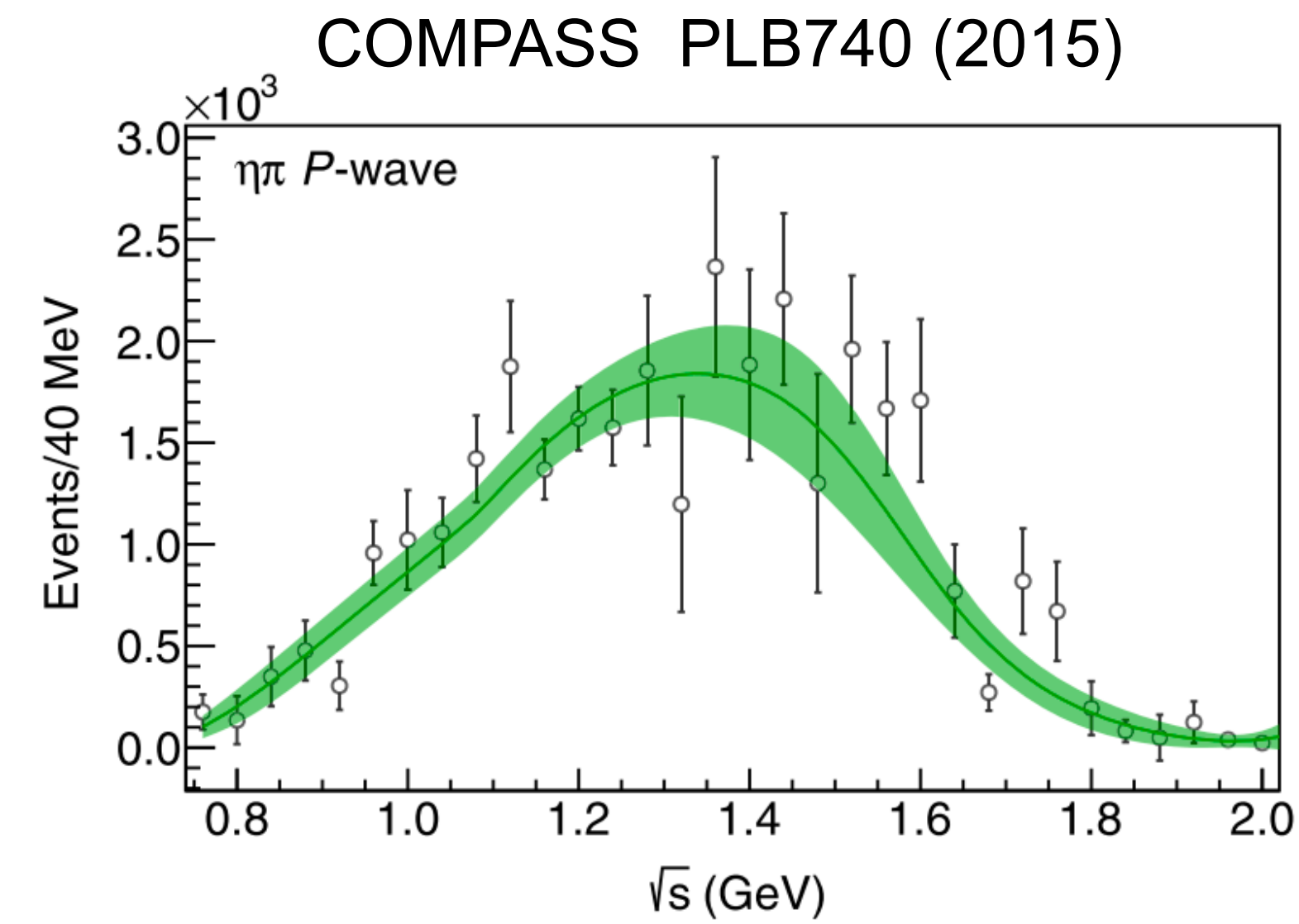
More refs. on <https://pdg.lbl.gov/>

COMPASS PLB740 (2015)

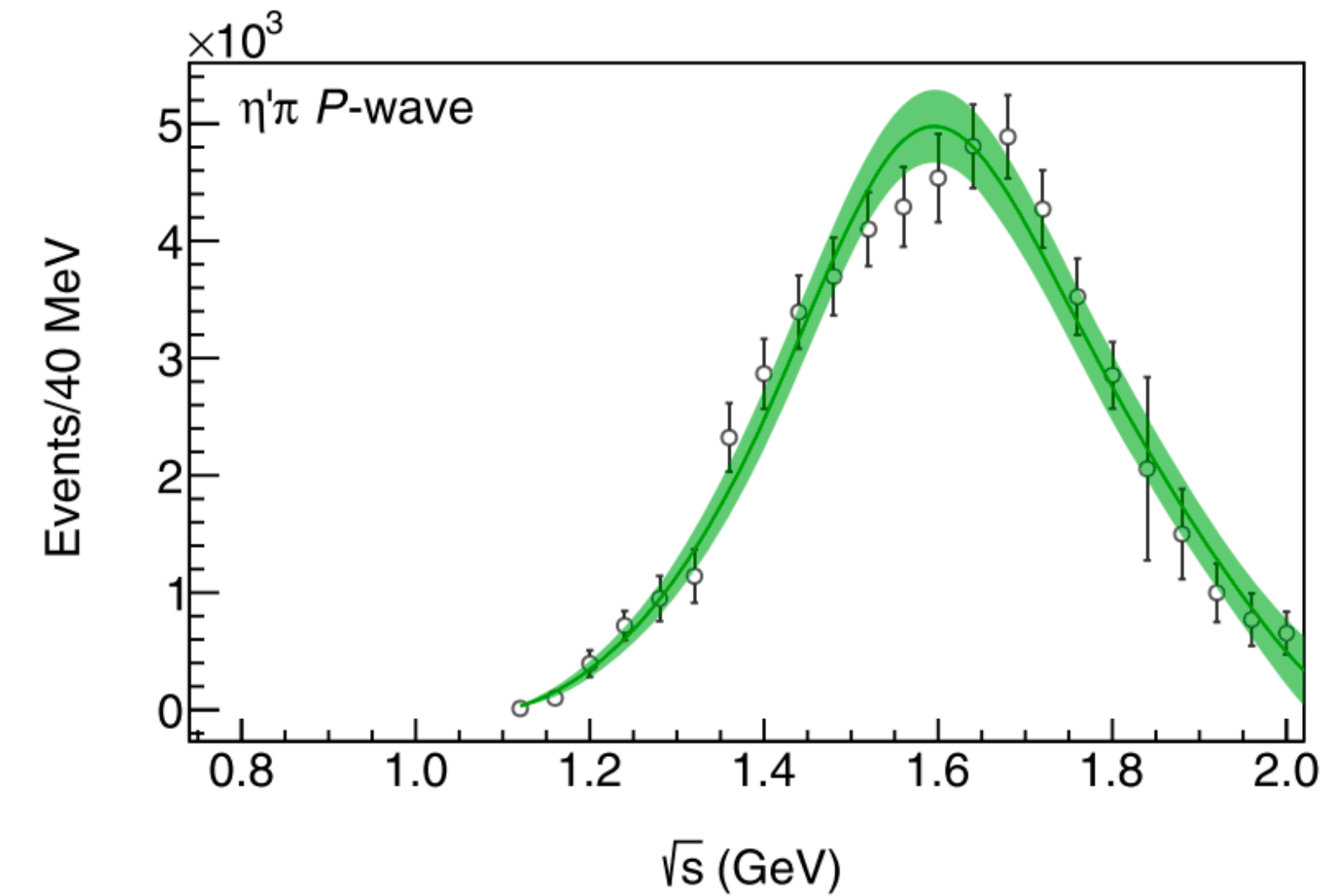
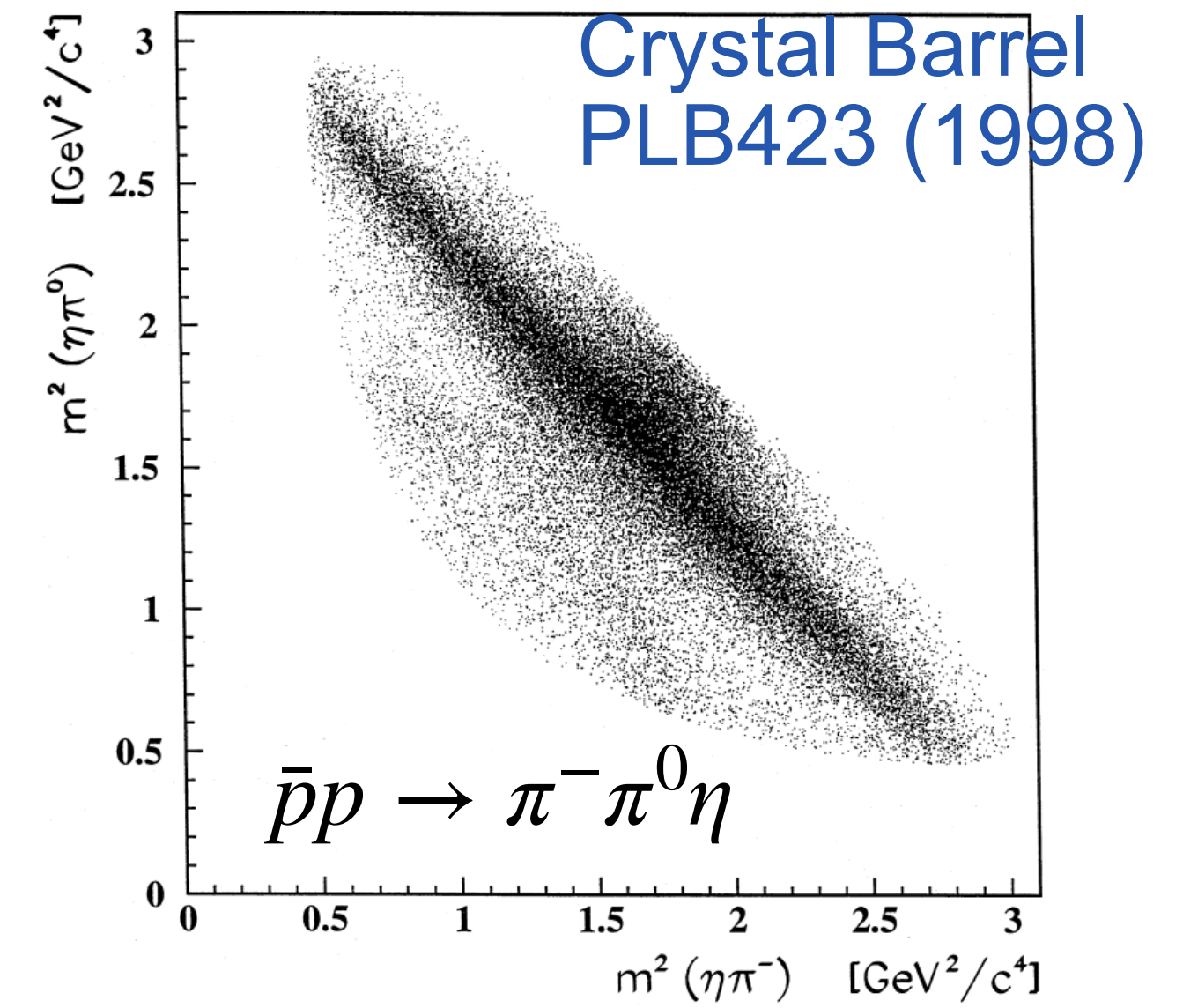


$\pi_1(1400)$ vs $\pi_1(1600)$

More refs. on <https://pdg.lbl.gov/>

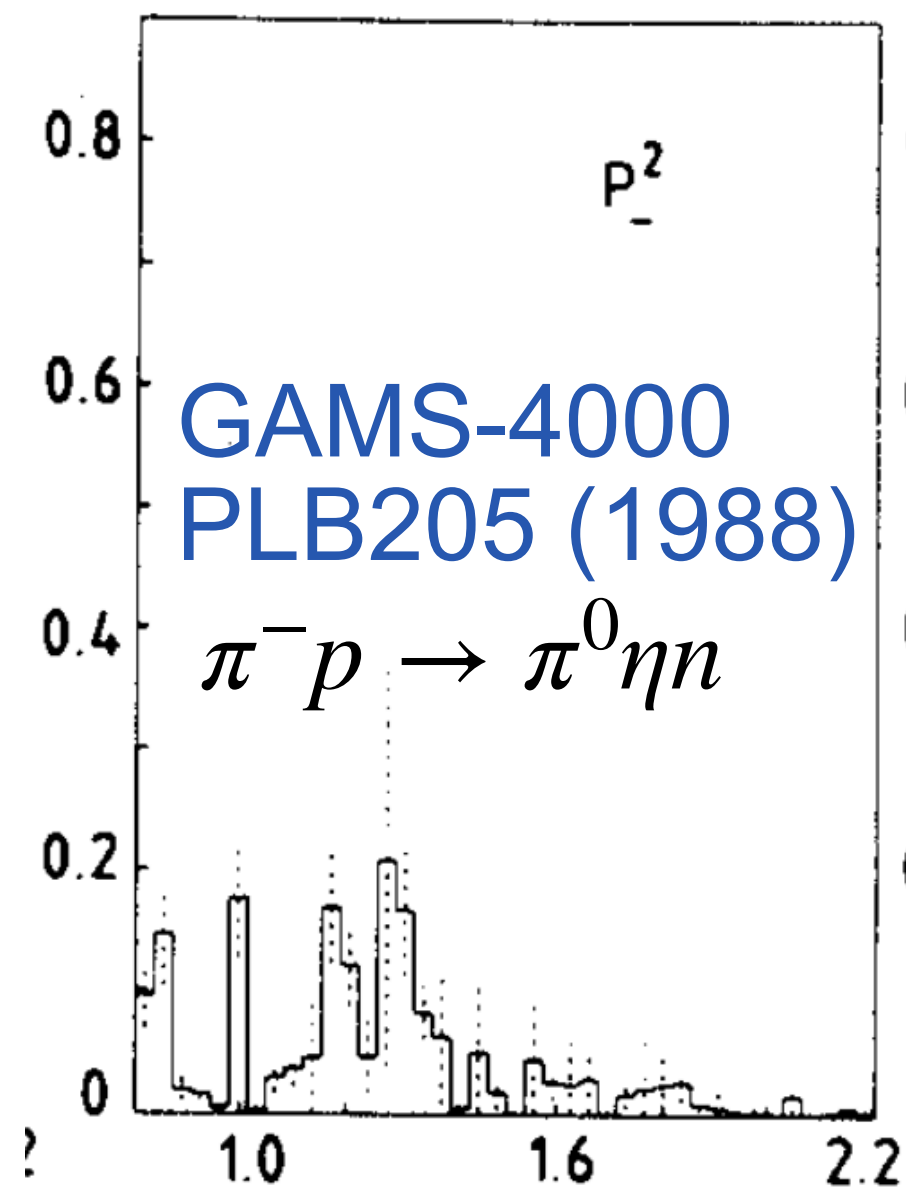
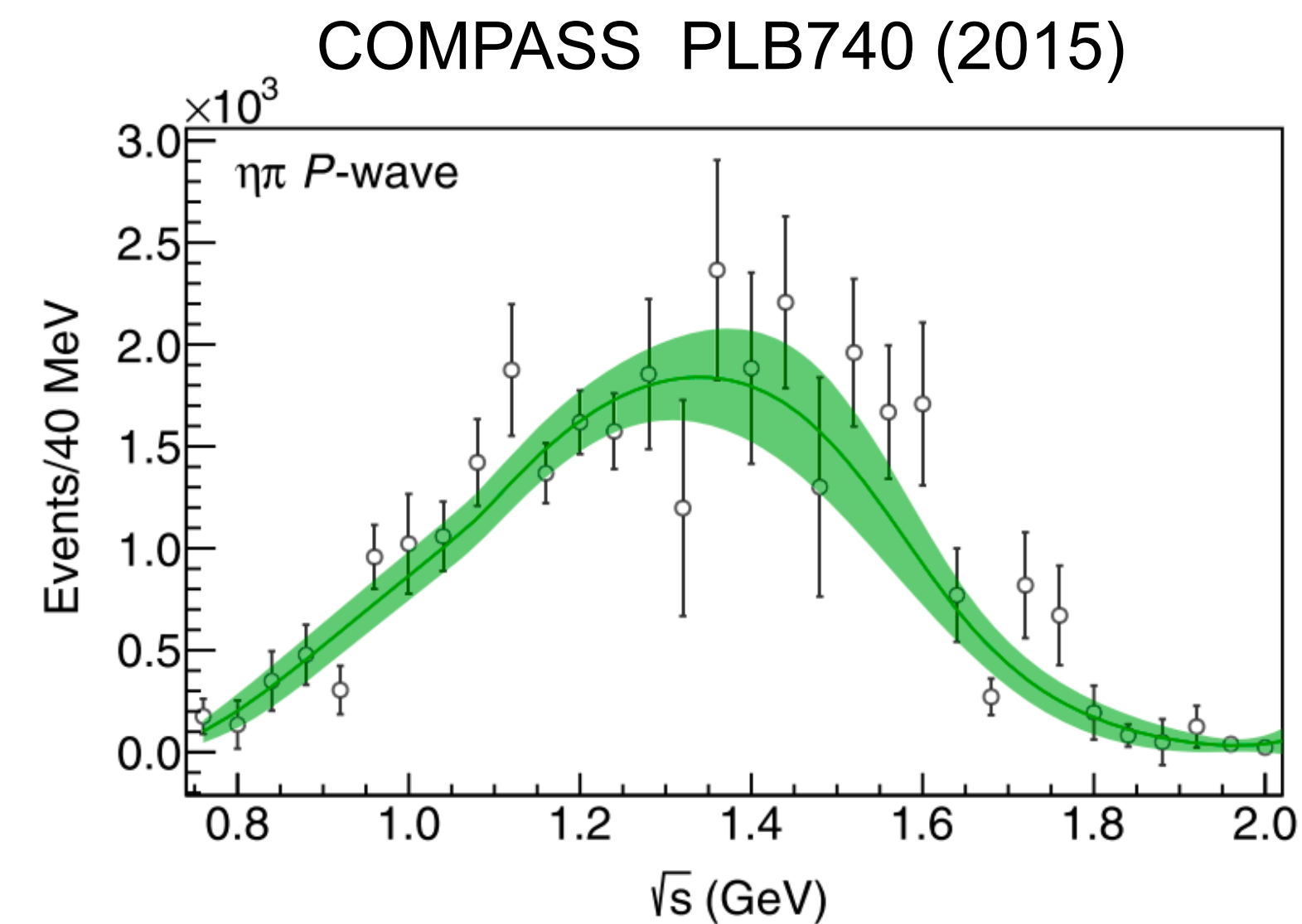


Mass ~ 1400 MeV

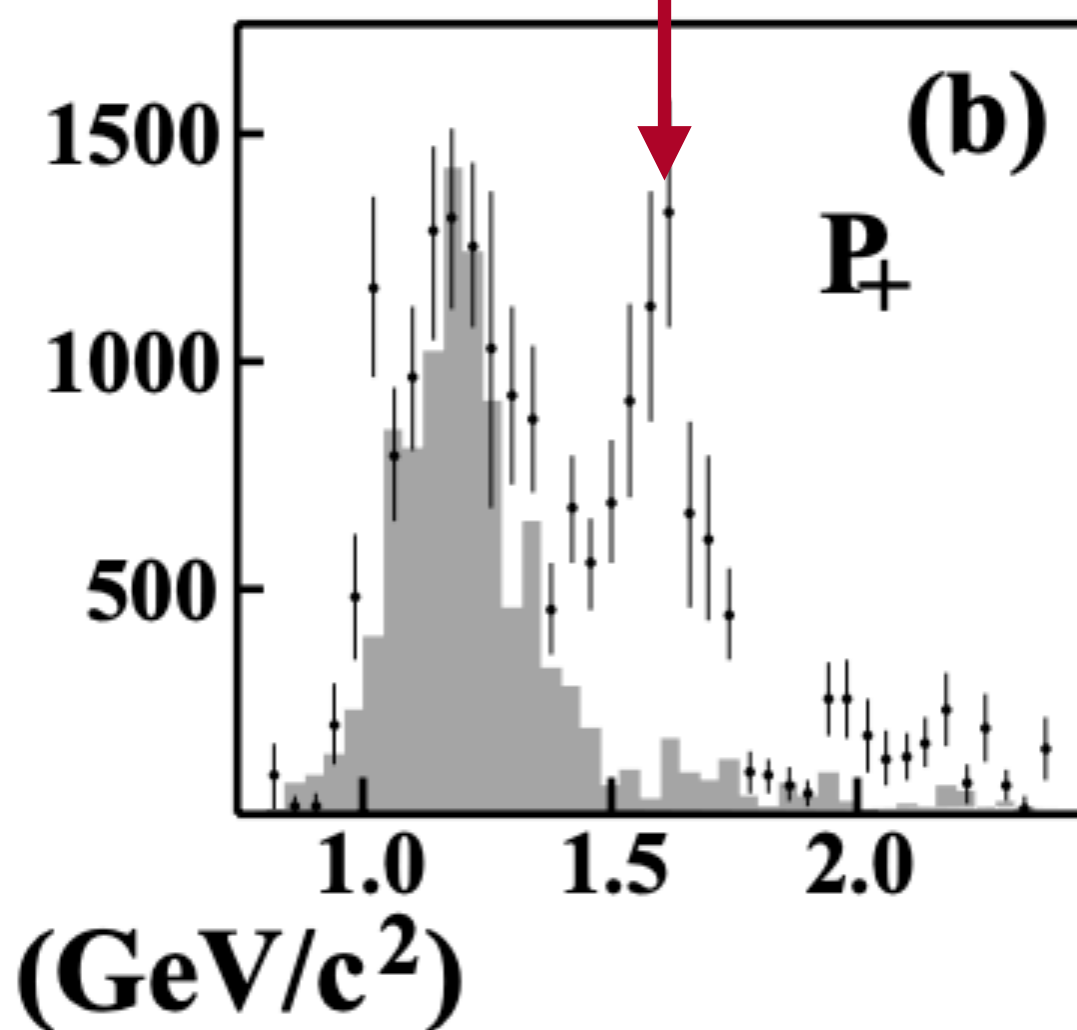
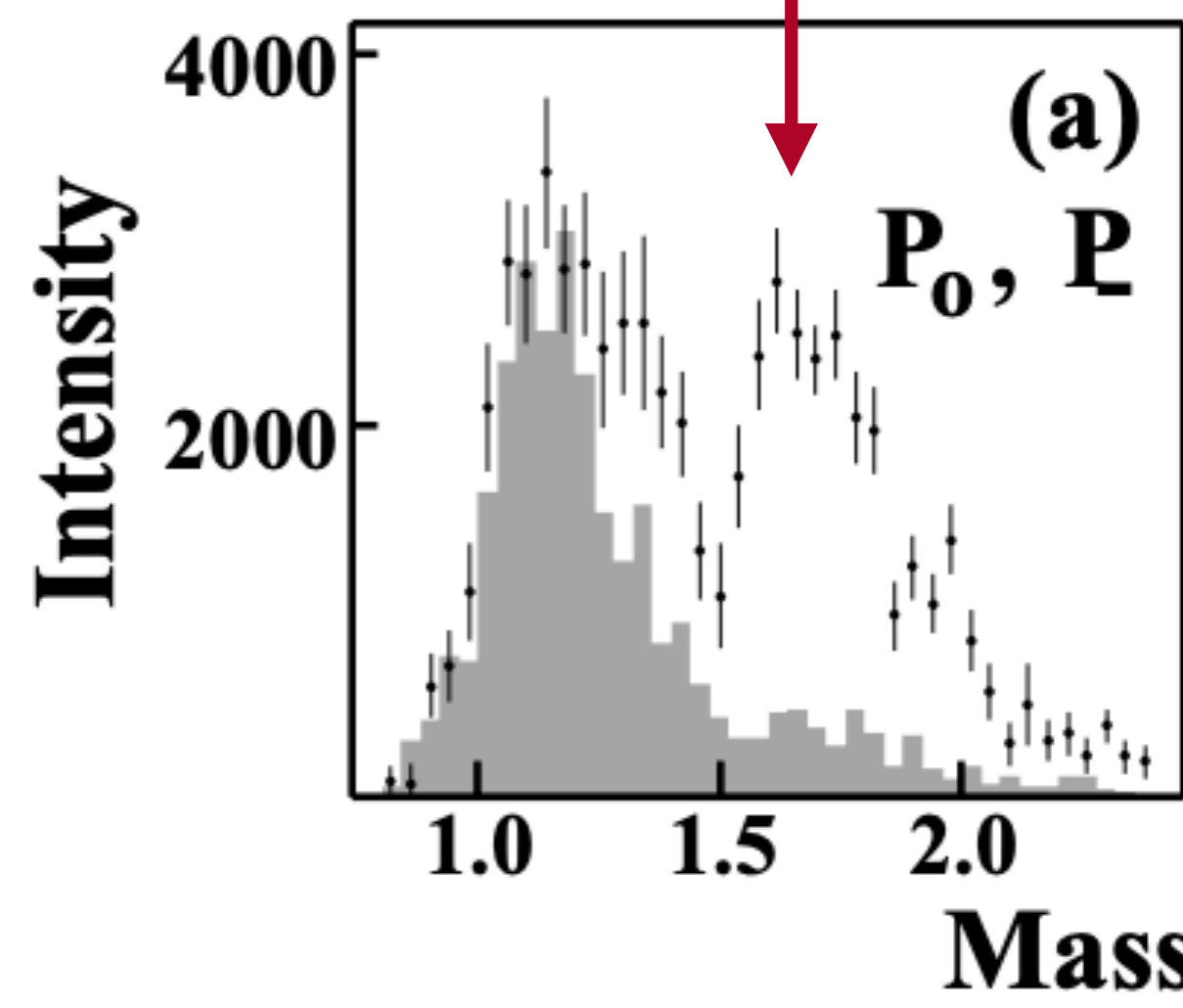
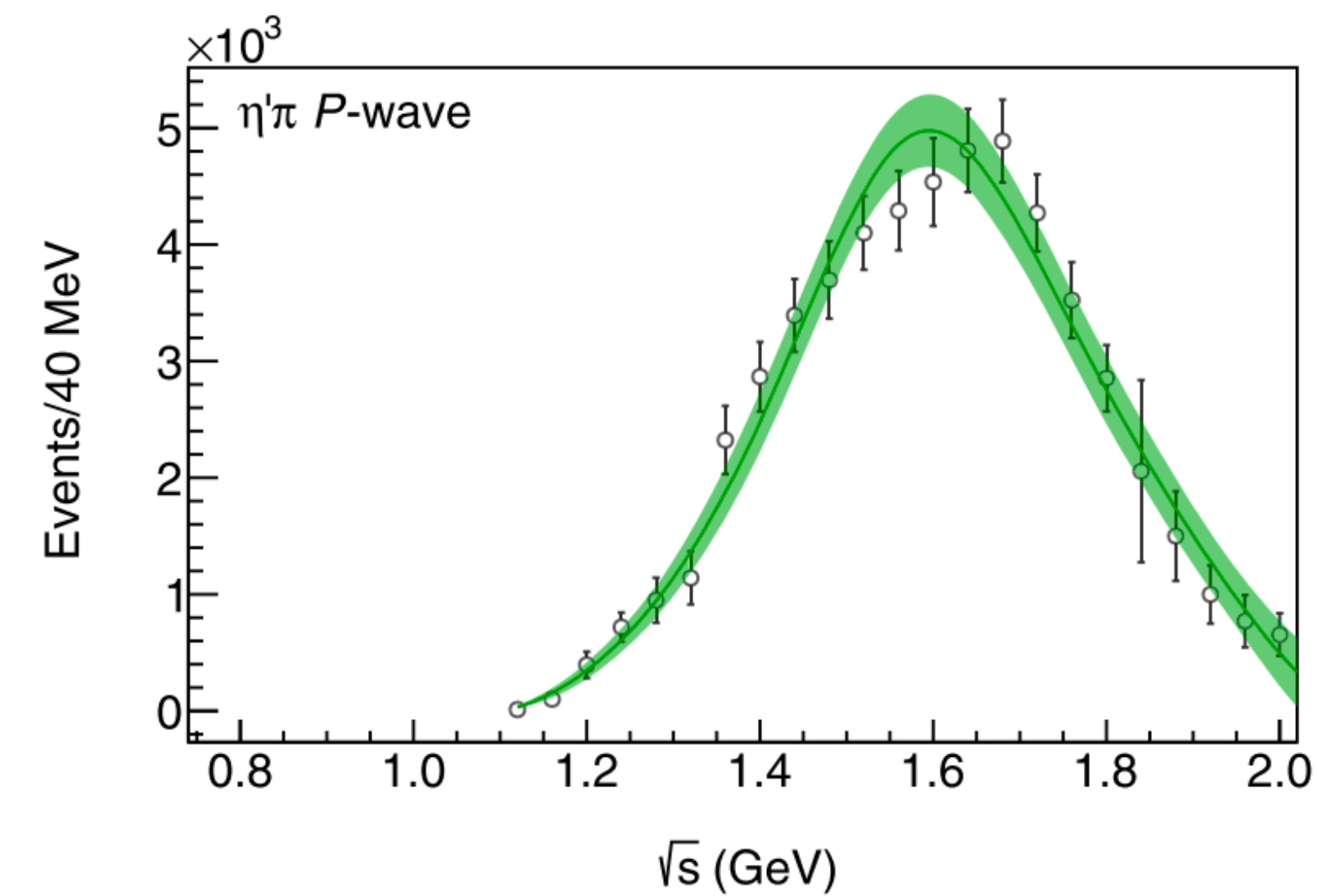
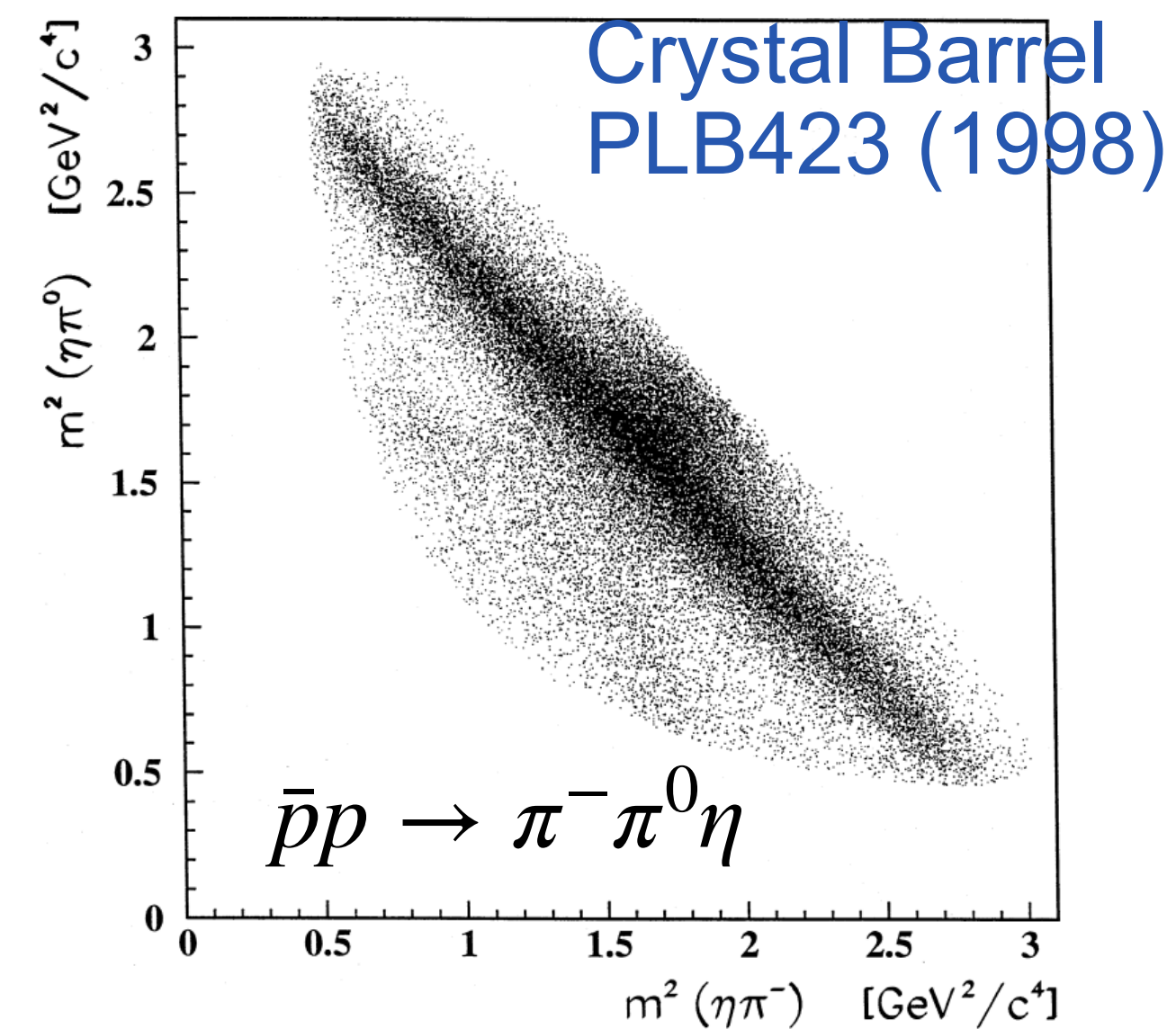


$\pi_1(1400)$ vs $\pi_1(1600)$

More refs. on <https://pdg.lbl.gov/>



Mass ~ 1400 MeV



E852 PRL81 (1998)

$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$

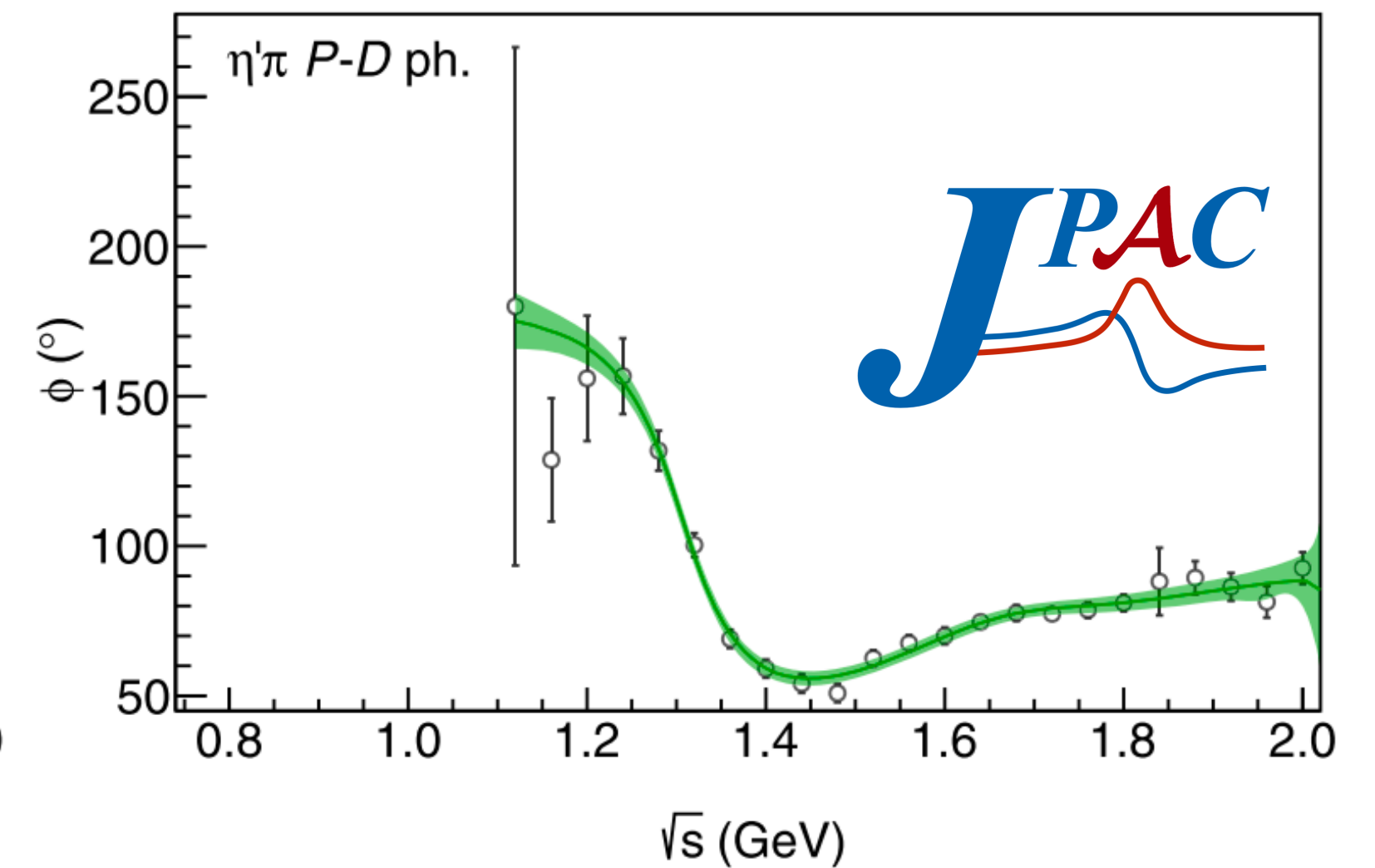
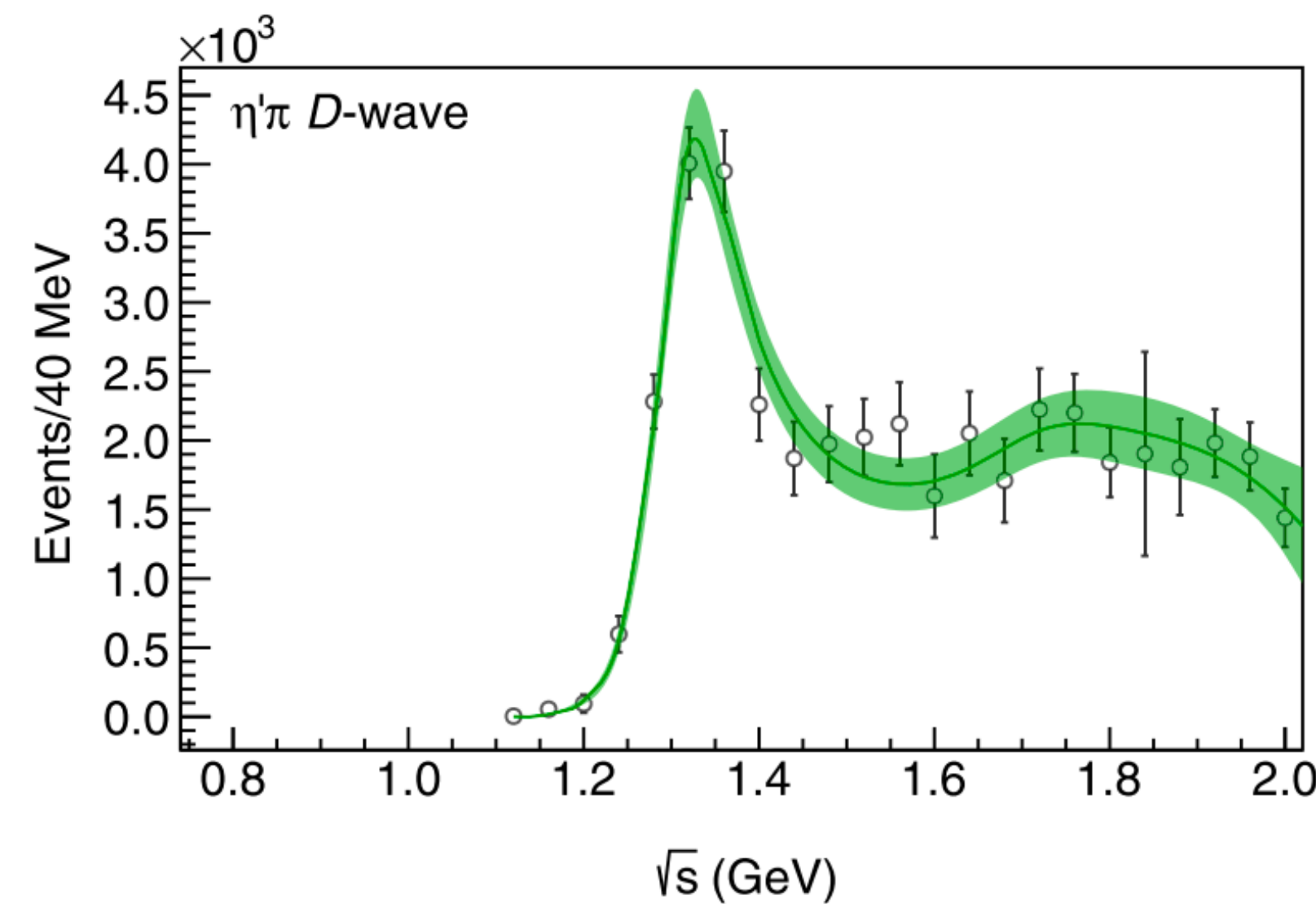
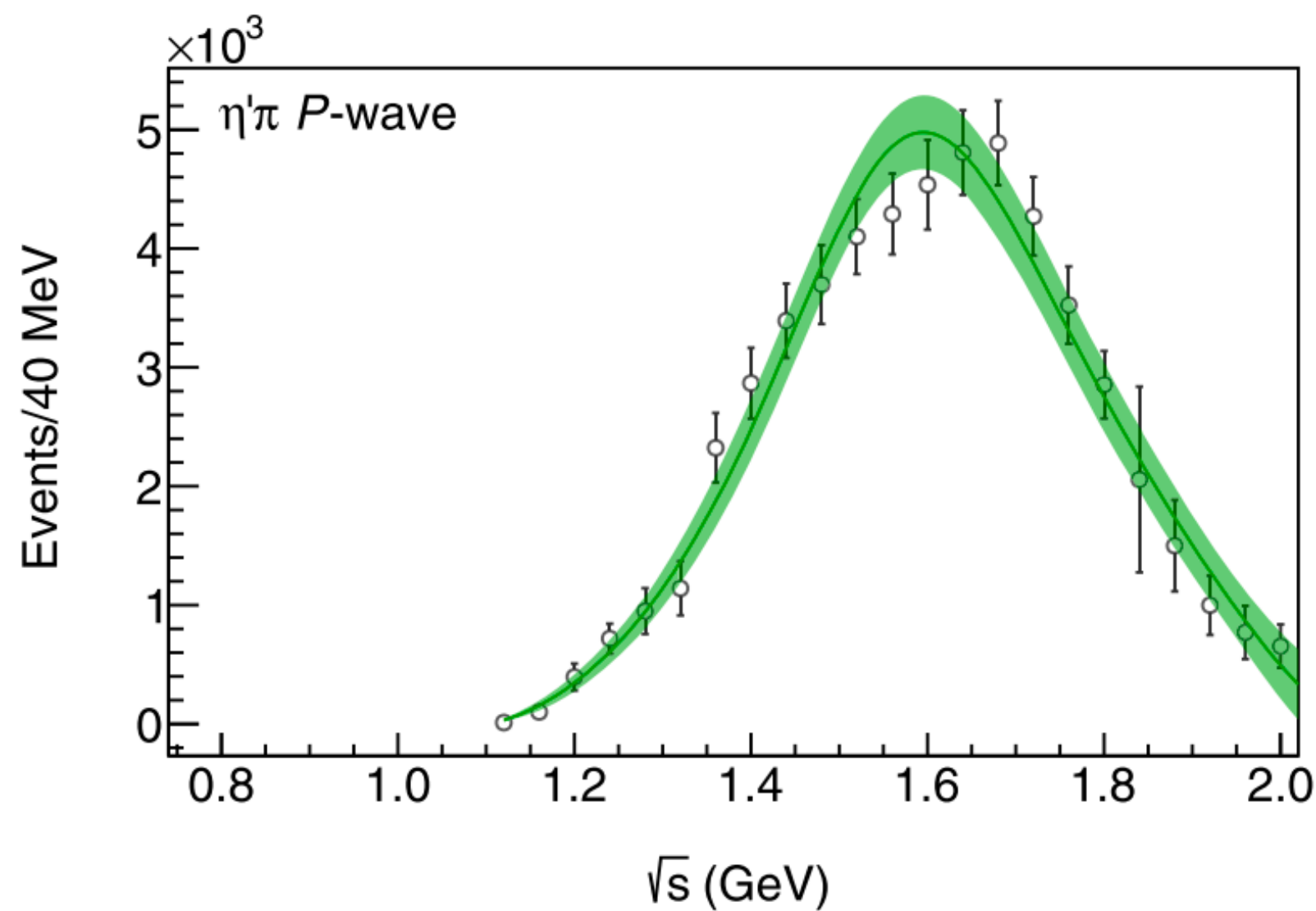
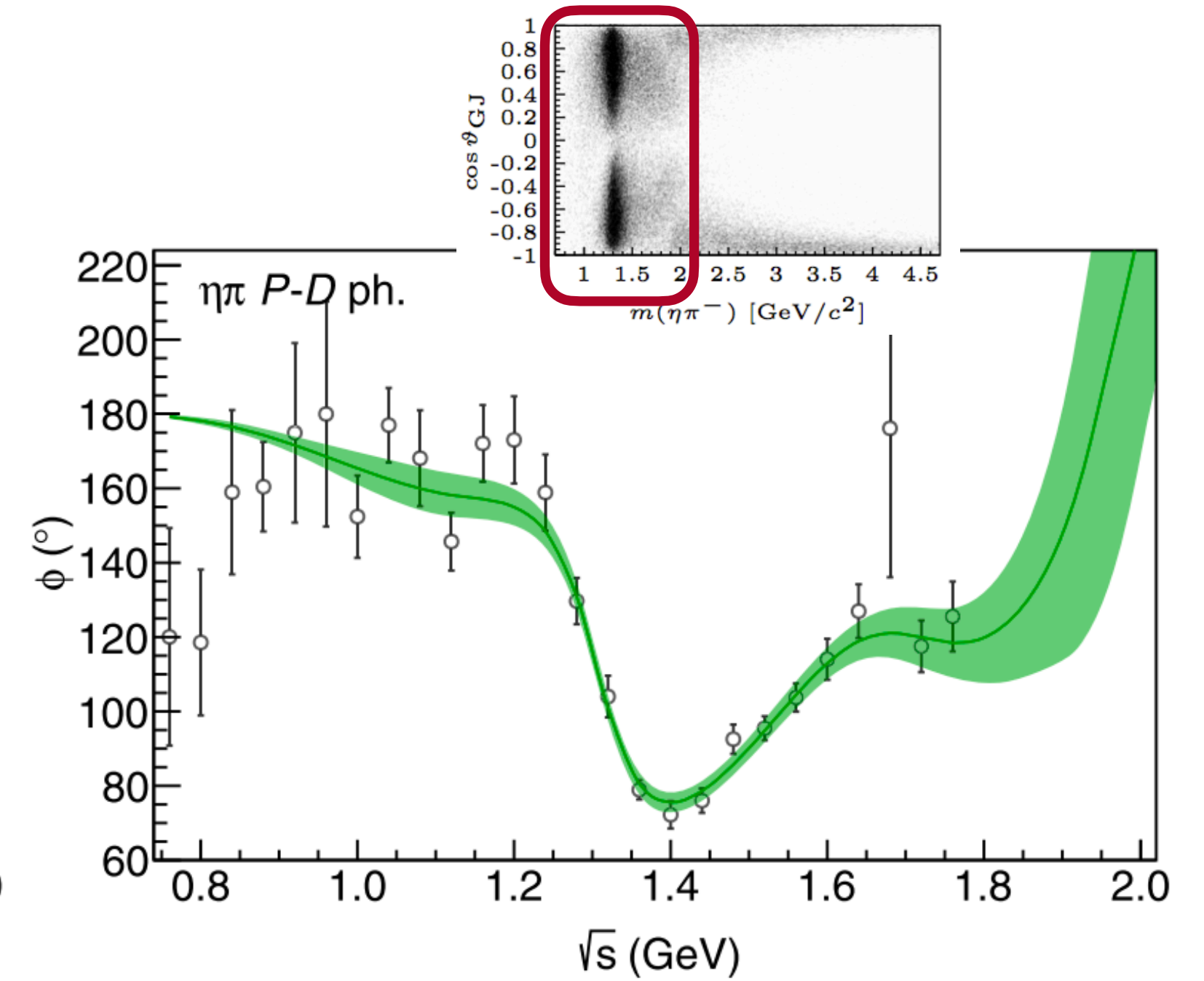
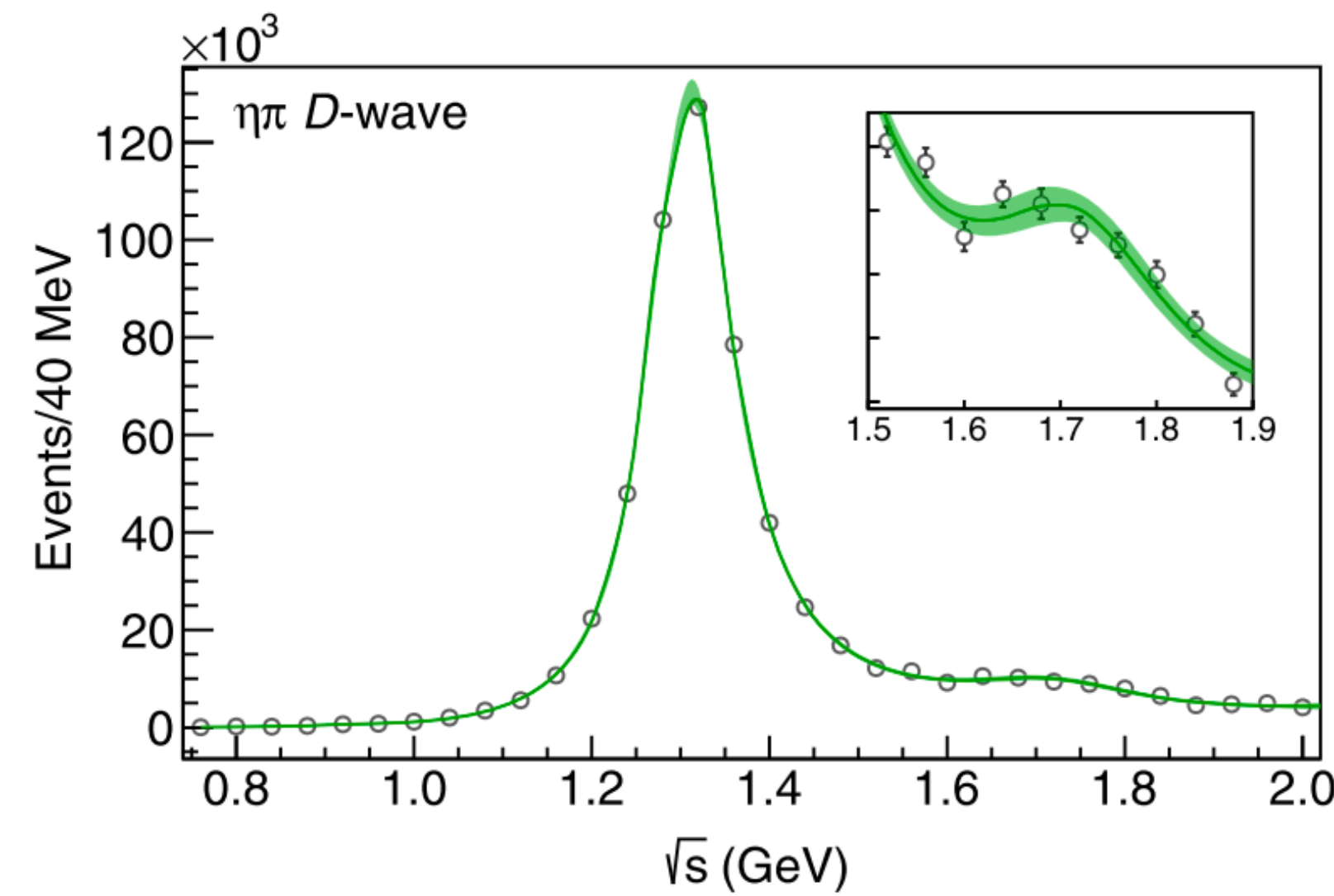
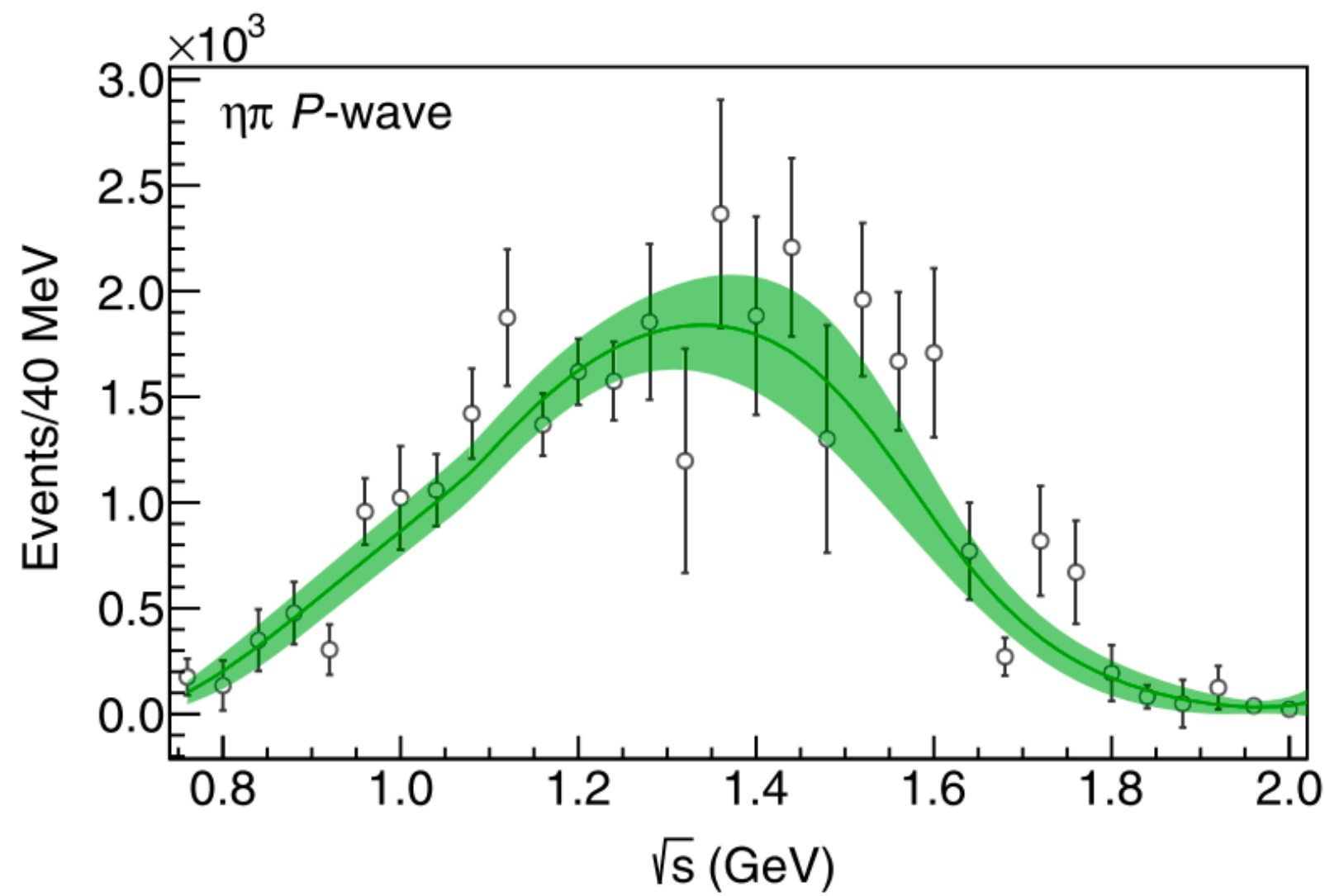
At 18 GeV

Mass ~ 1600 GeV

Low Energy Fit of $L = 1,2$

Rodas et al PRL122 (2019)

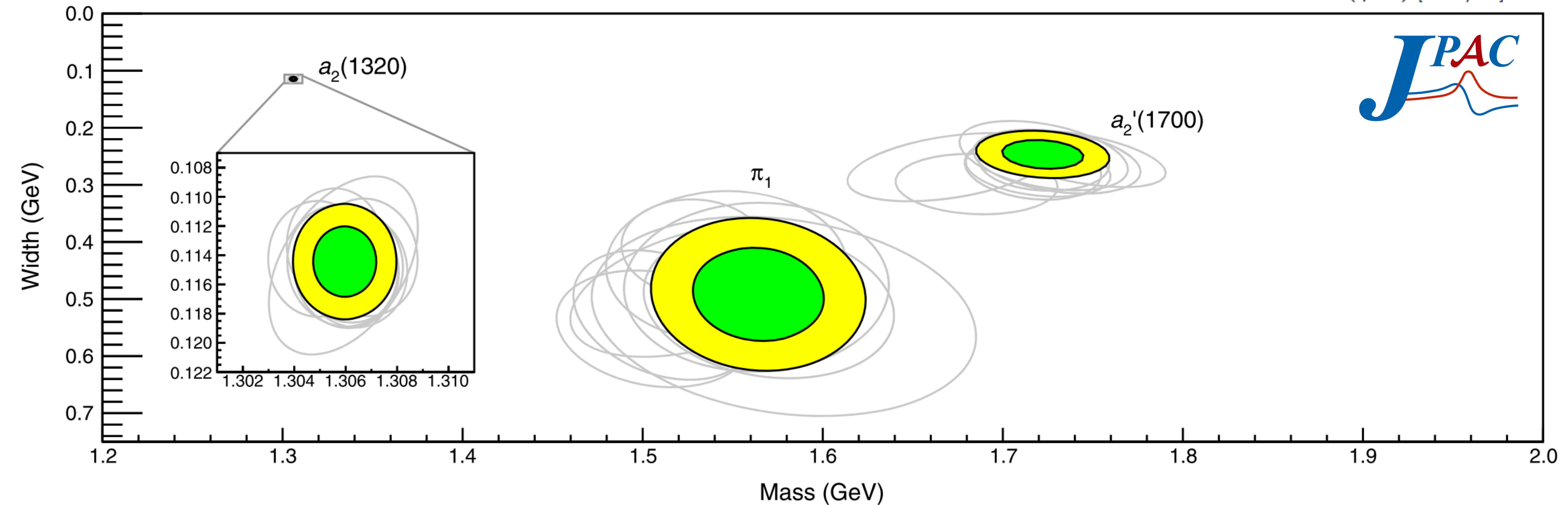
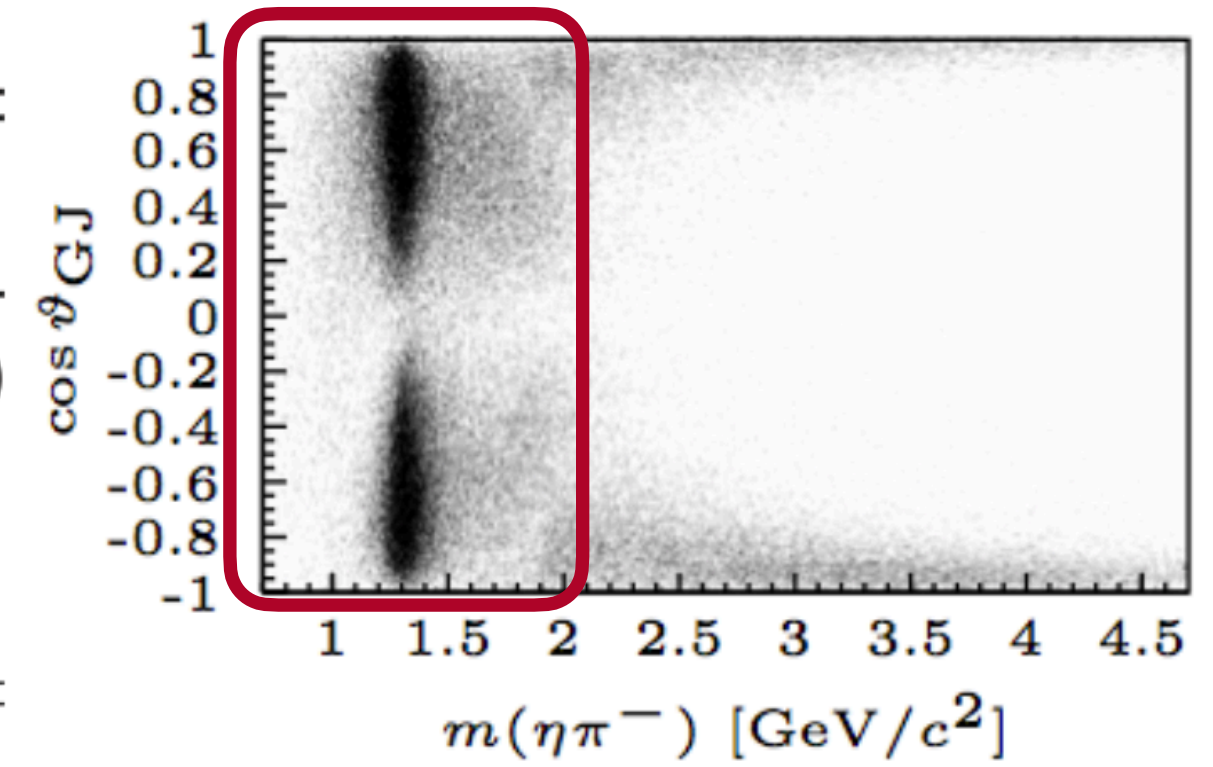
$\pi_1(1400)$ vs $\pi_1(1600)$

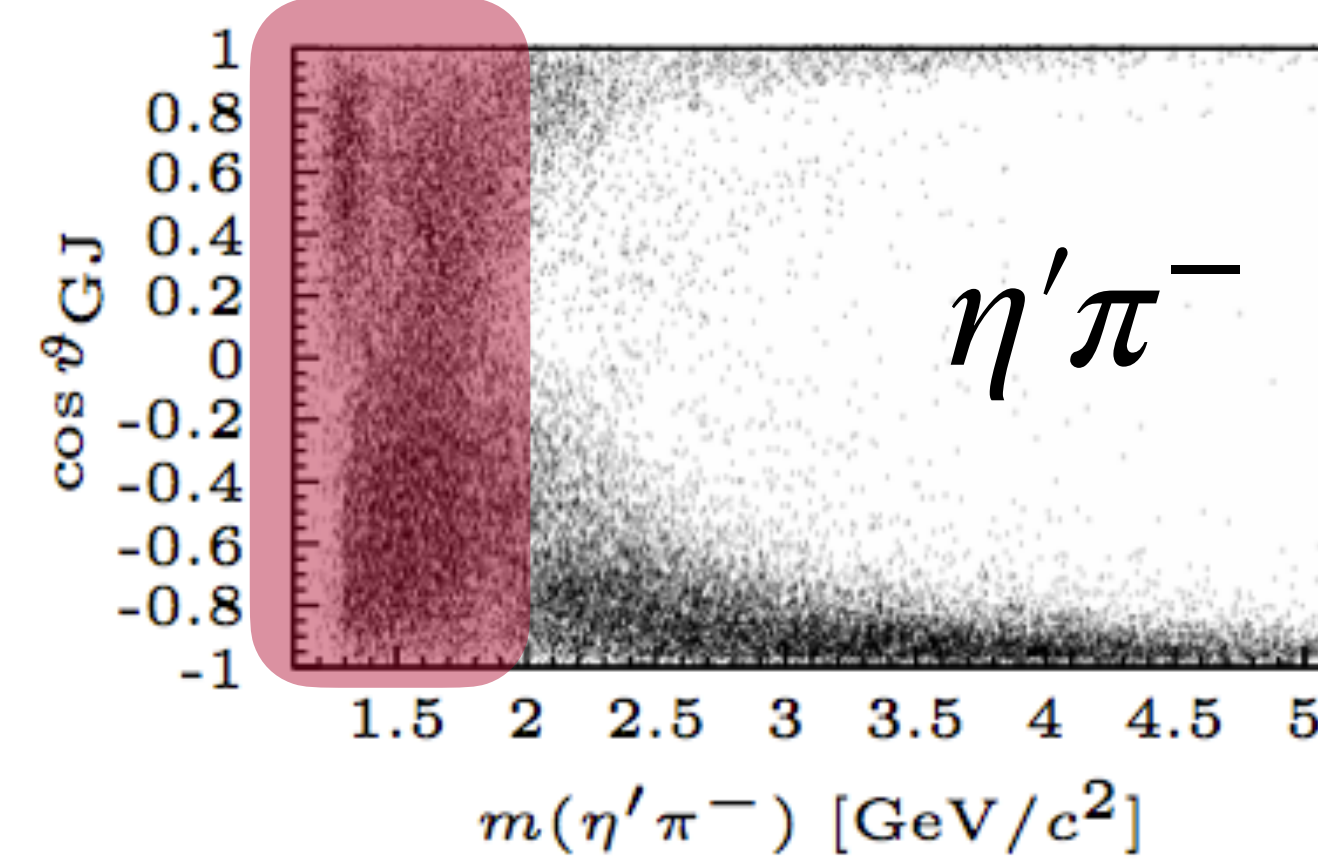
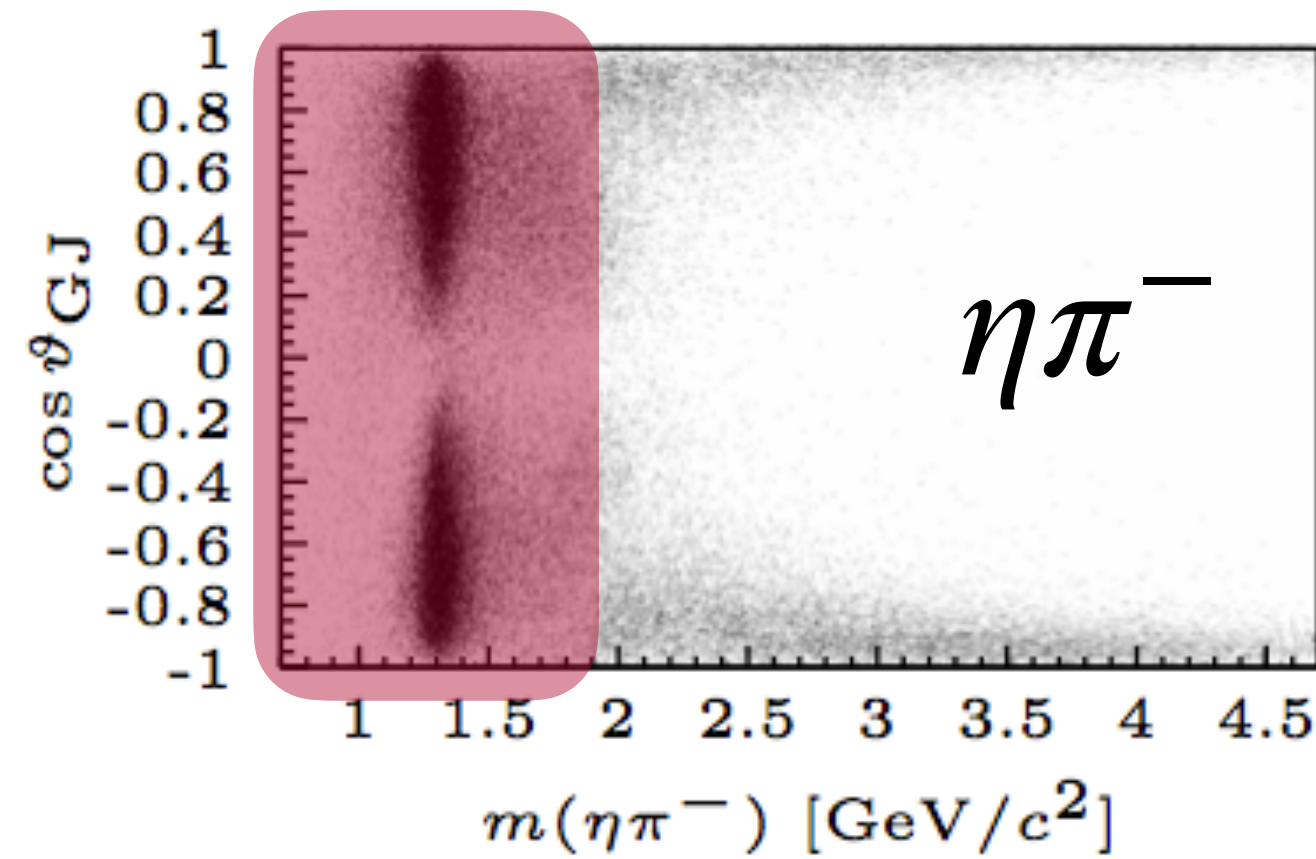
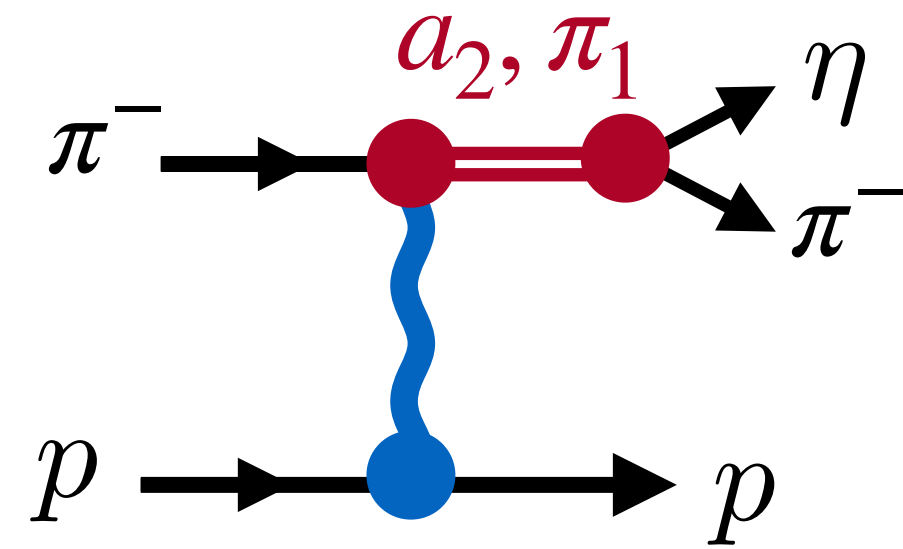
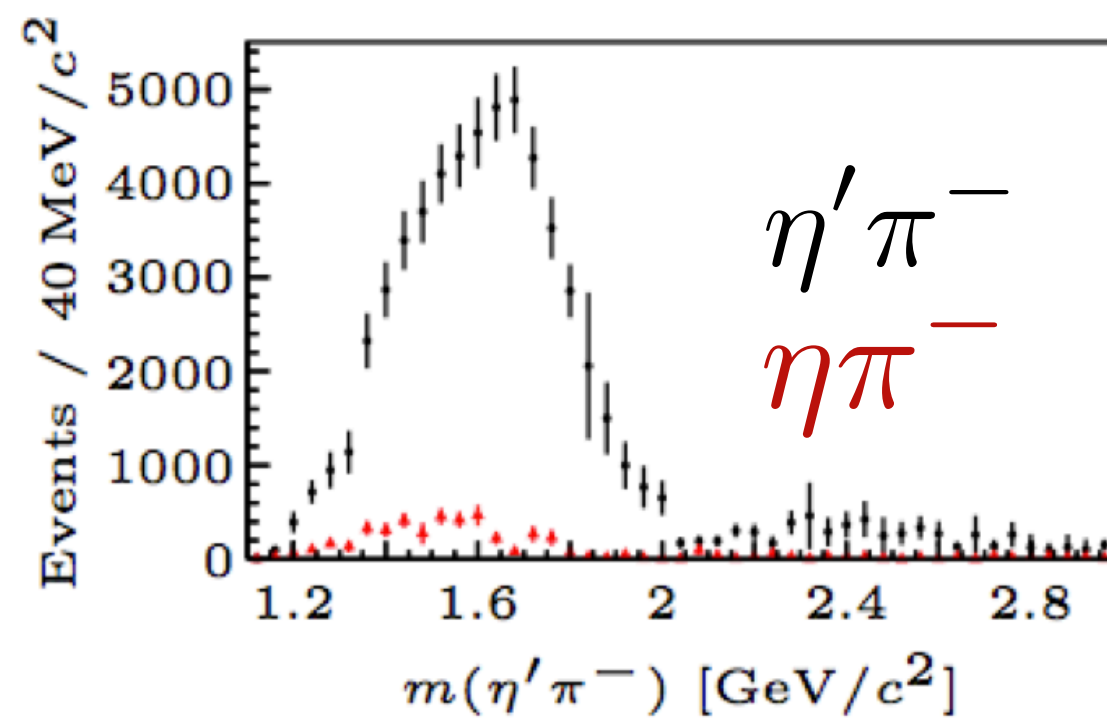


Low Energy Fit of $L = 1,2$

Rodas et al (JPAC) PRL122 (2019)

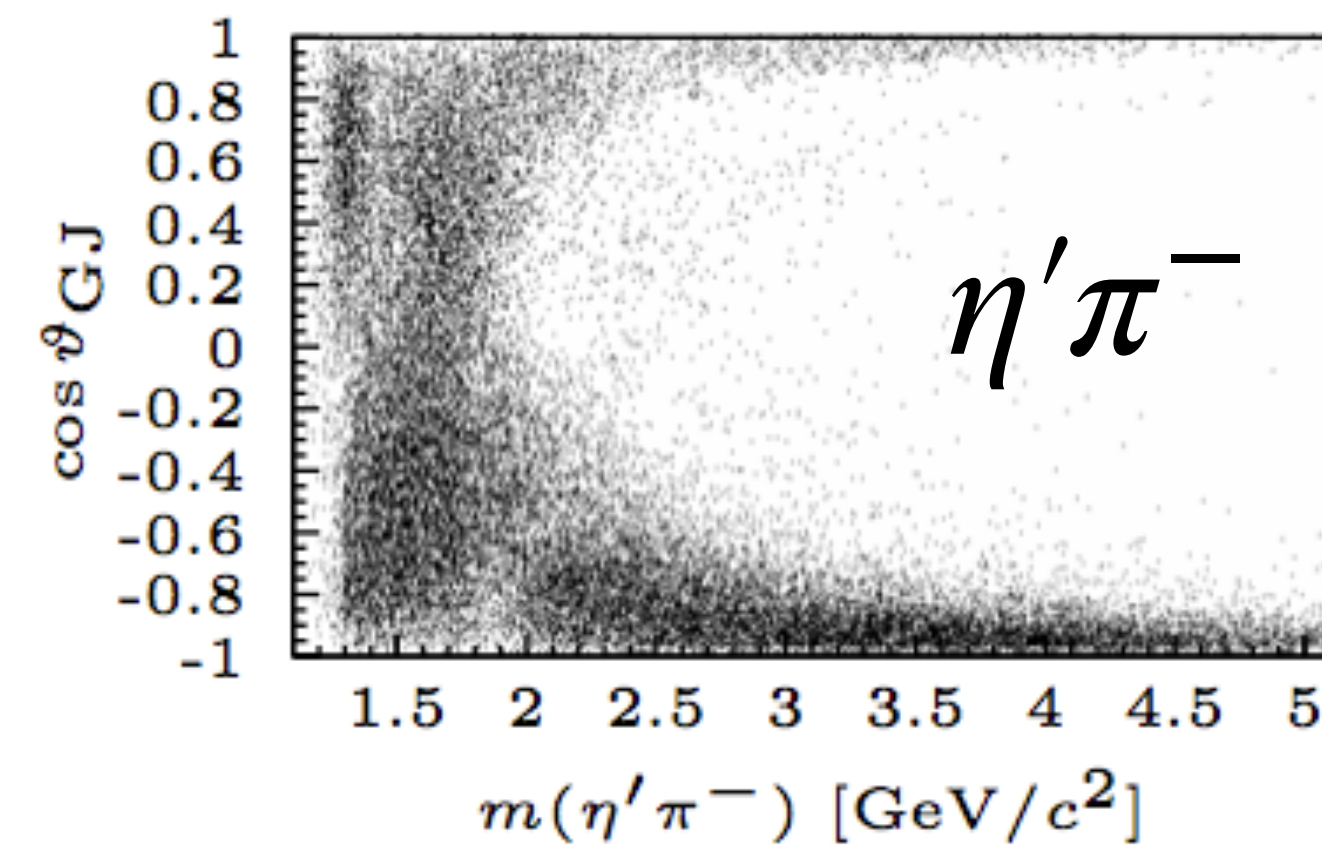
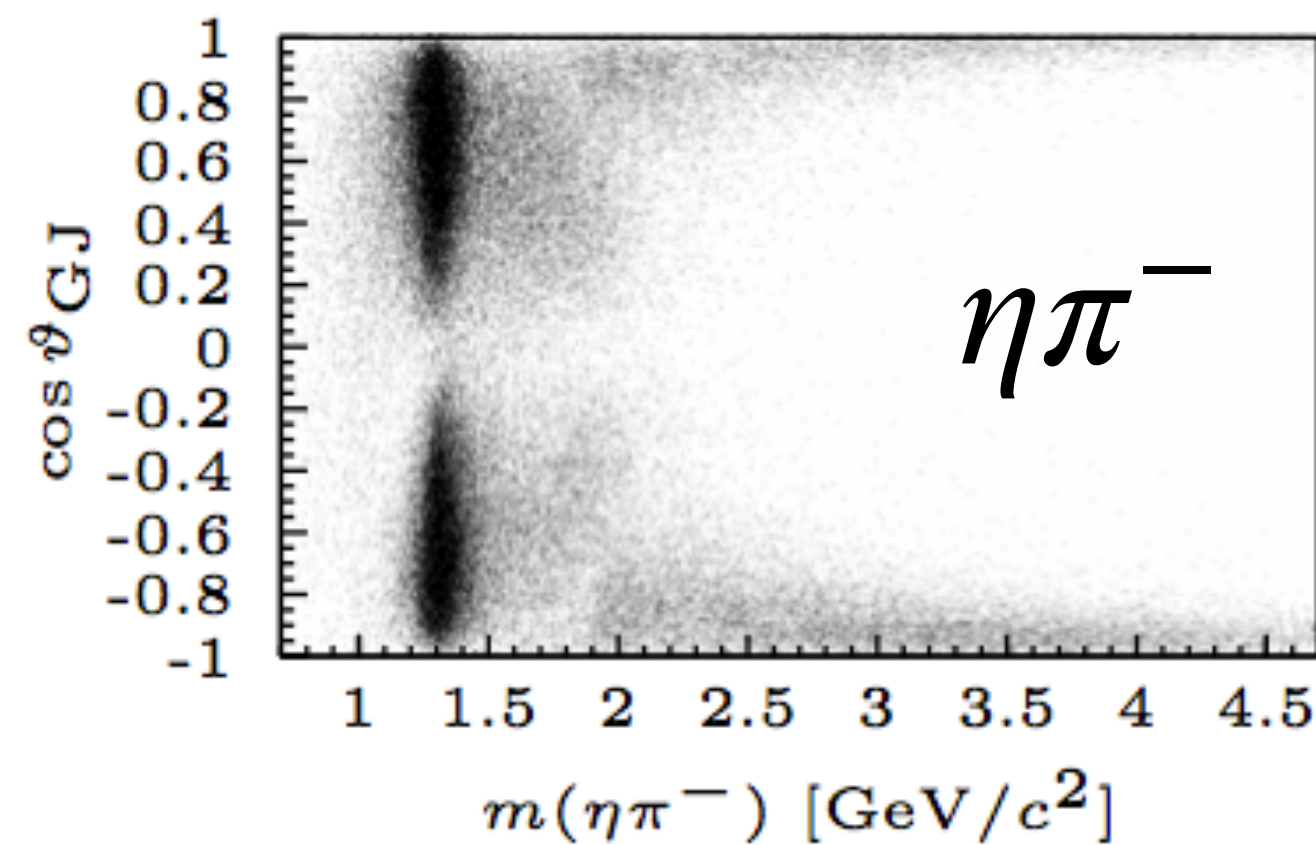
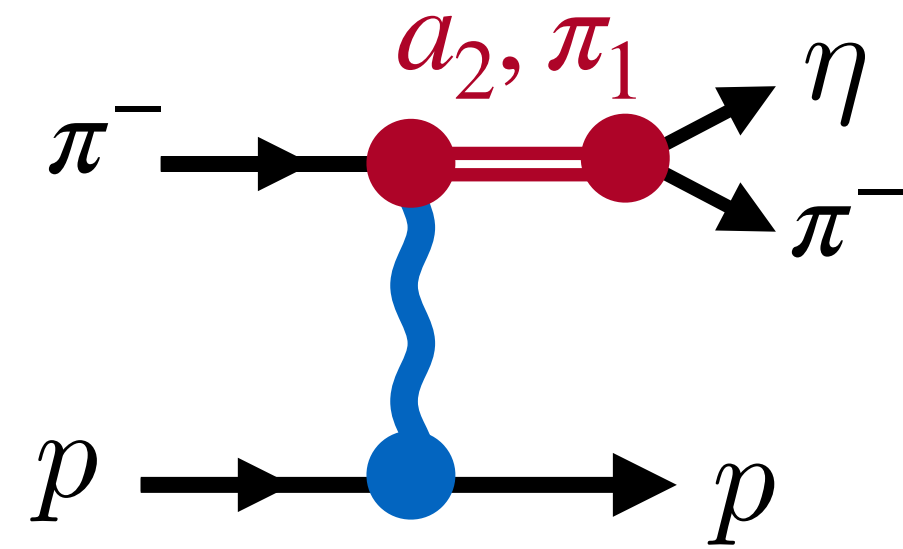
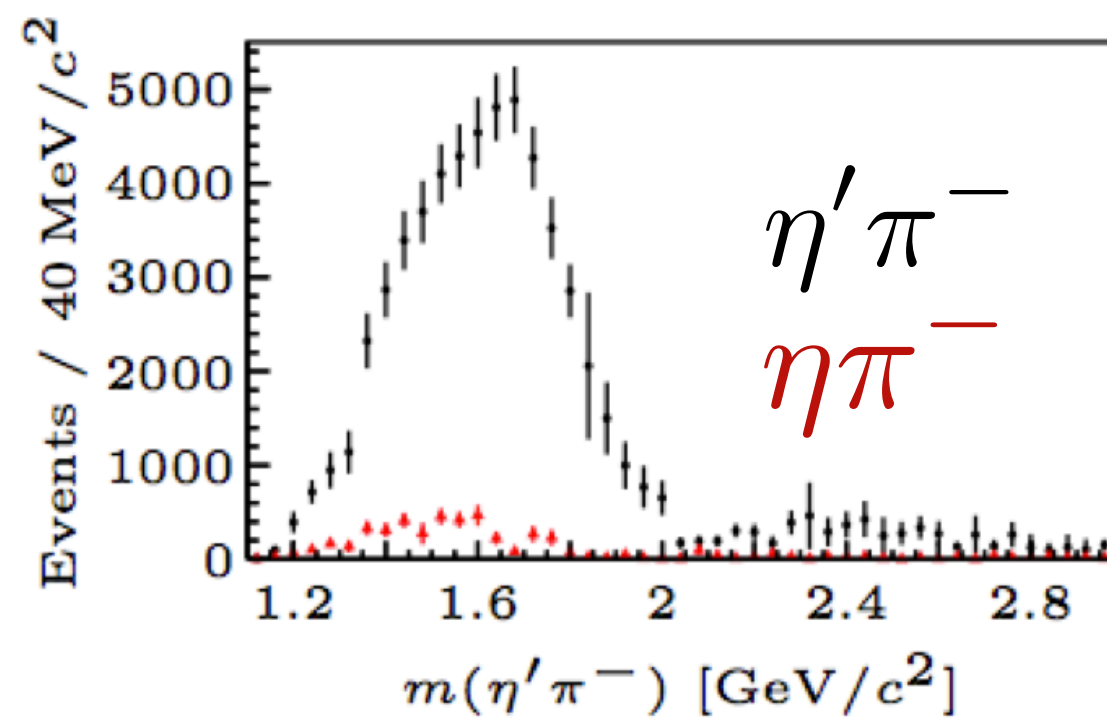
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$





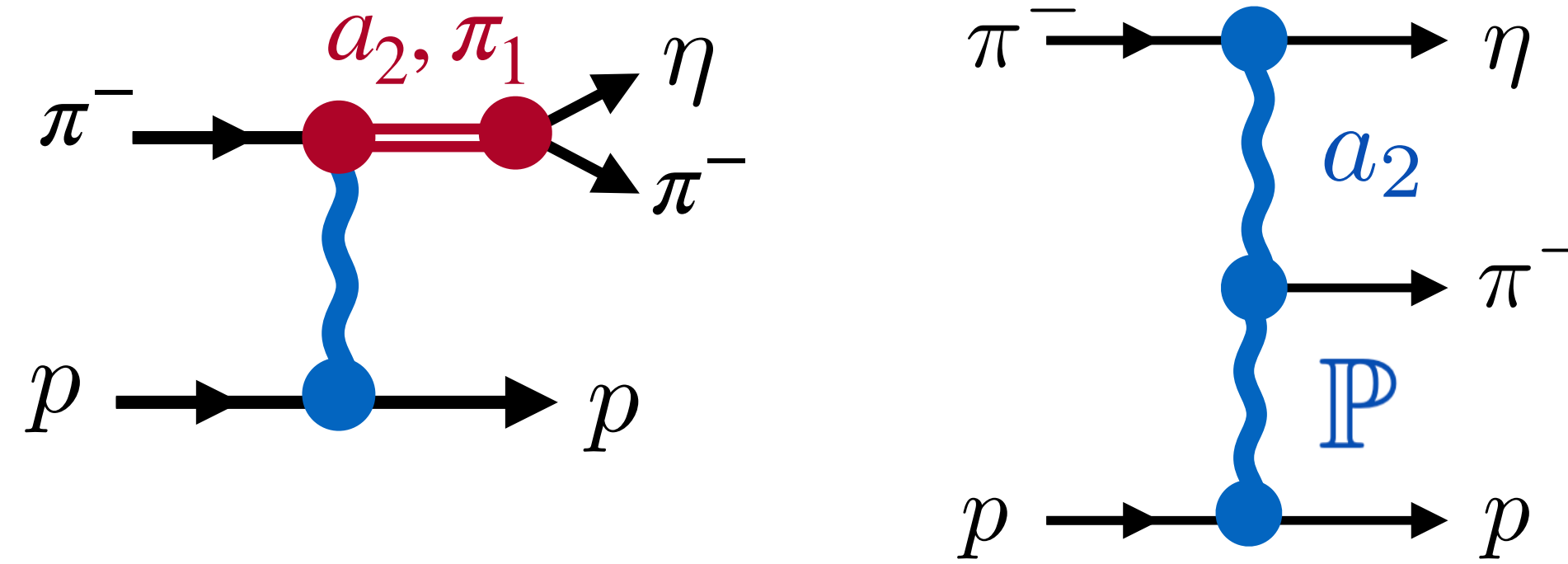
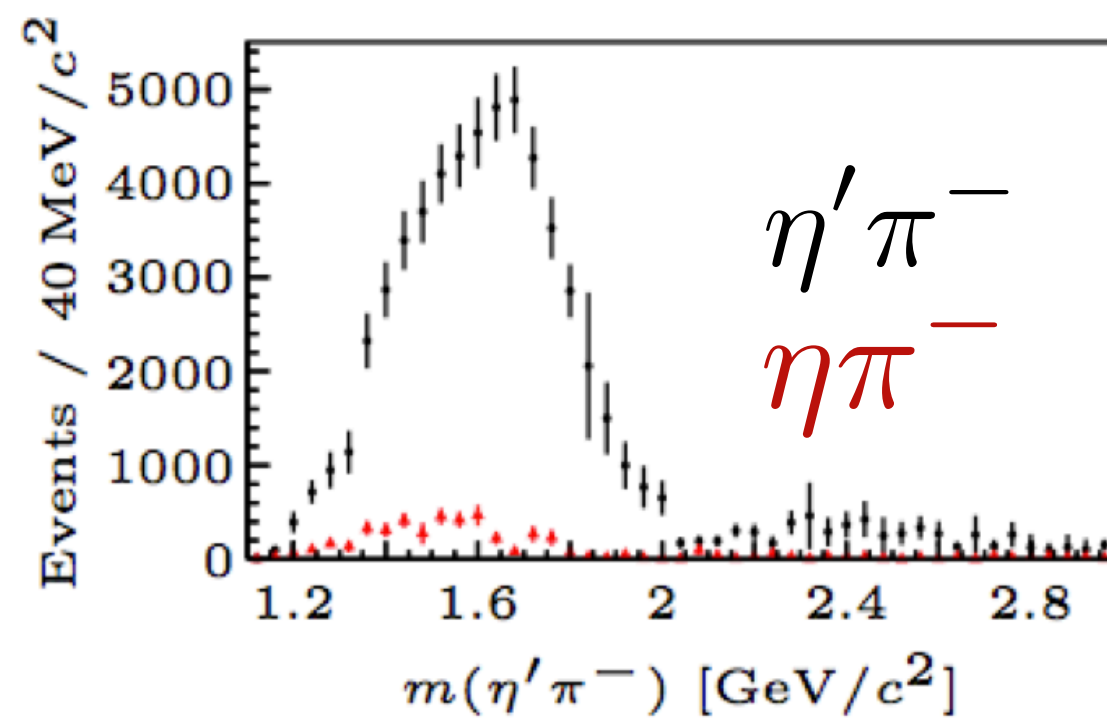
Exotic meson related to
Forward-backward asymmetry

Asymmetry related to
even-odd waves interferences

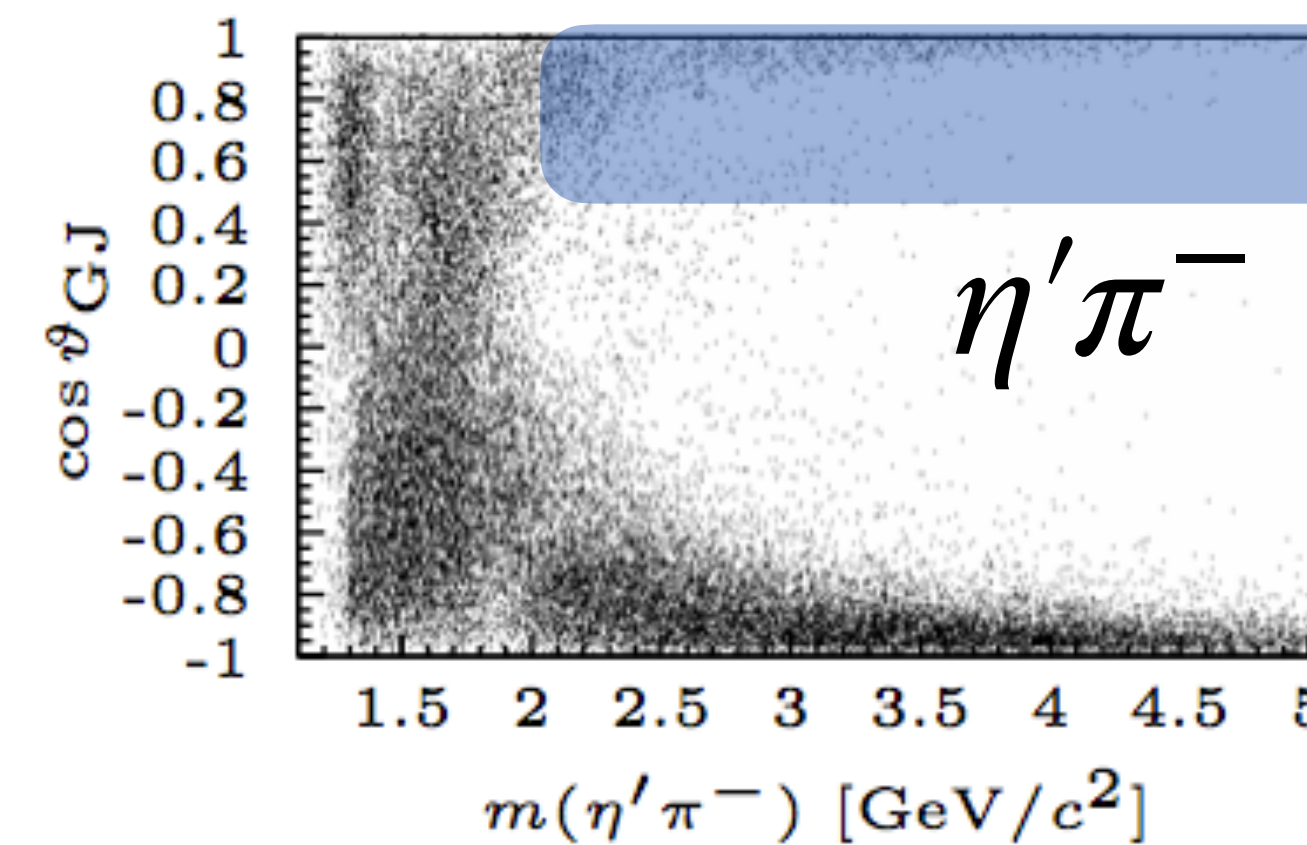
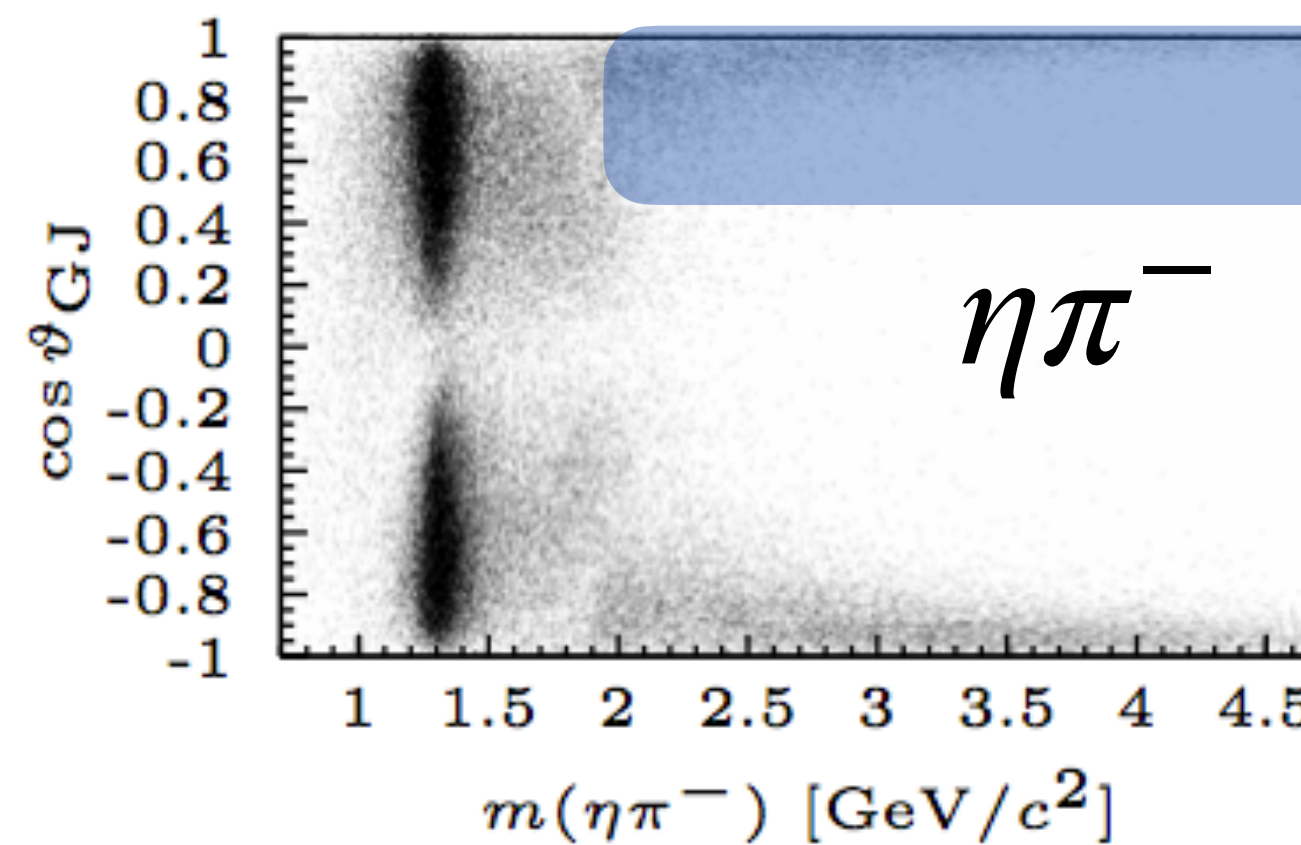


Exotic meson related to
Forward-backward asymmetry

Asymmetry related to
even-odd waves interferences



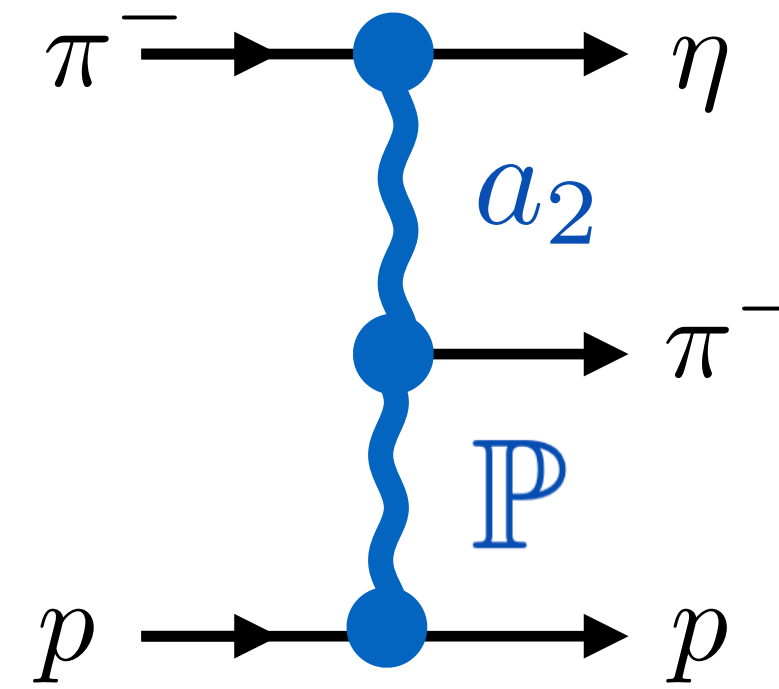
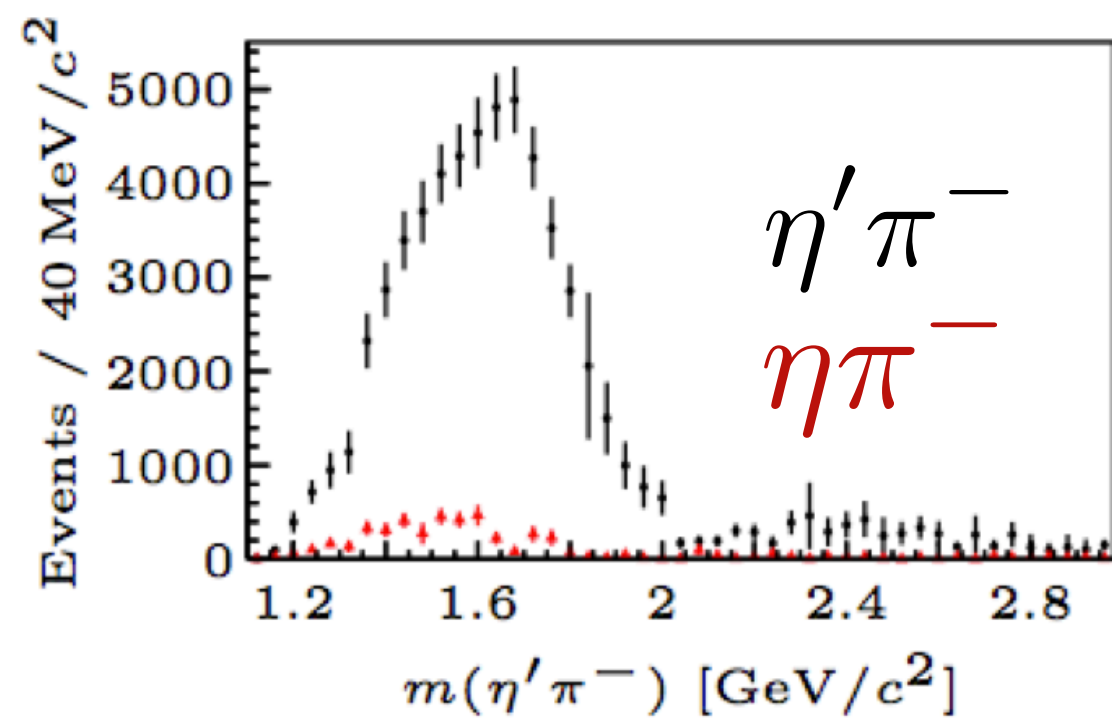
$\cos \theta_{GF} \sim 1 \rightarrow \eta$ forward



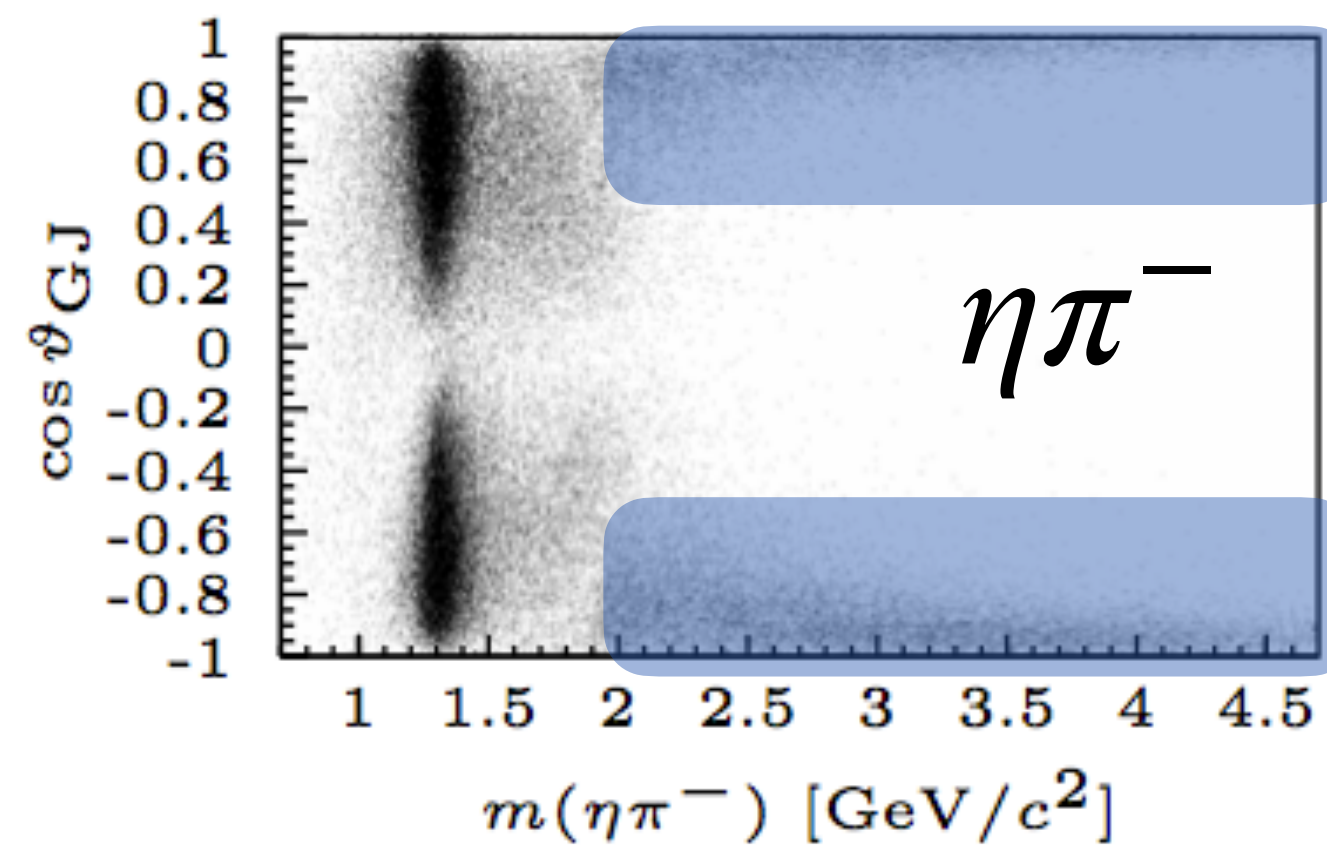
Exotic meson related to
Forward-backward asymmetry

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even-odd waves interferences

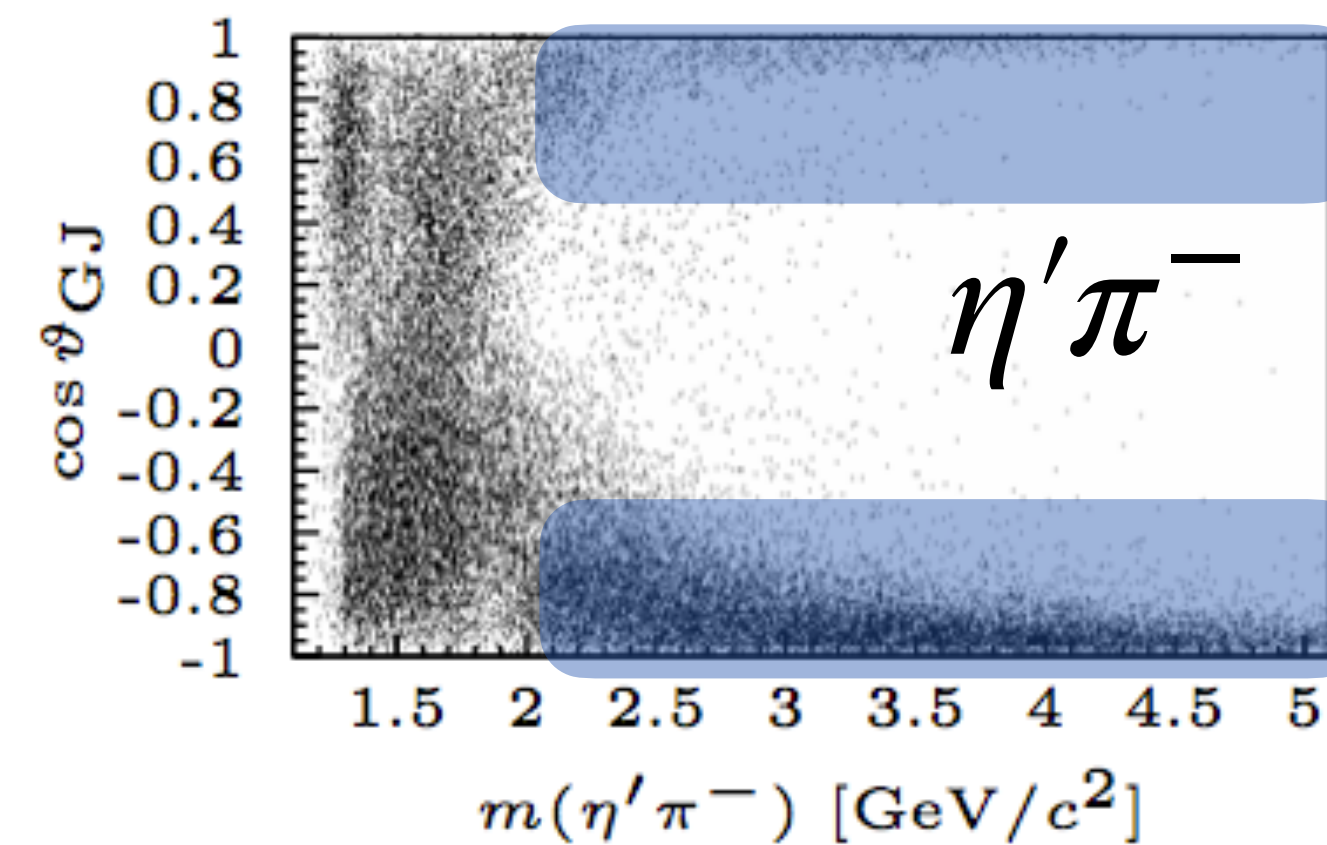
Origin of the Exotic Meson



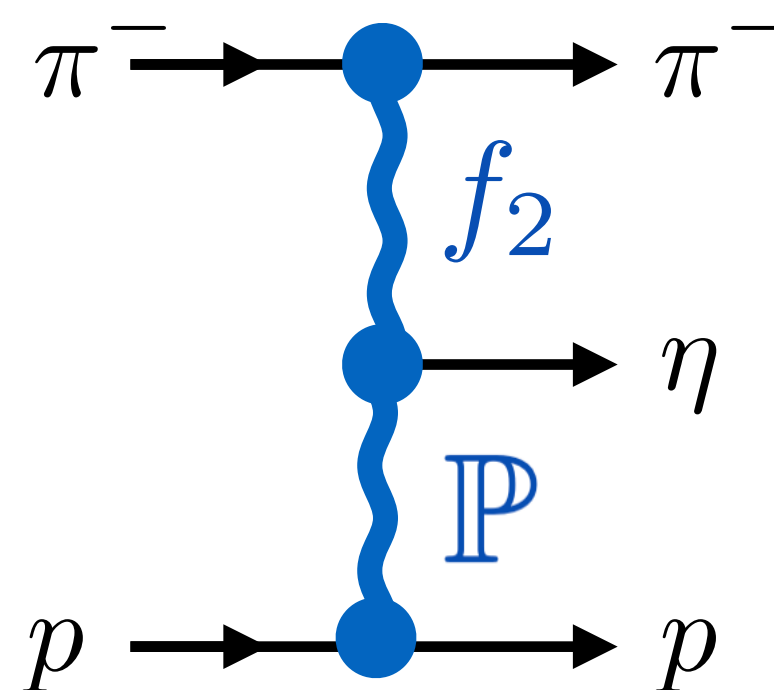
$\cos \theta_{GF} \sim 1 \rightarrow \eta$ forward



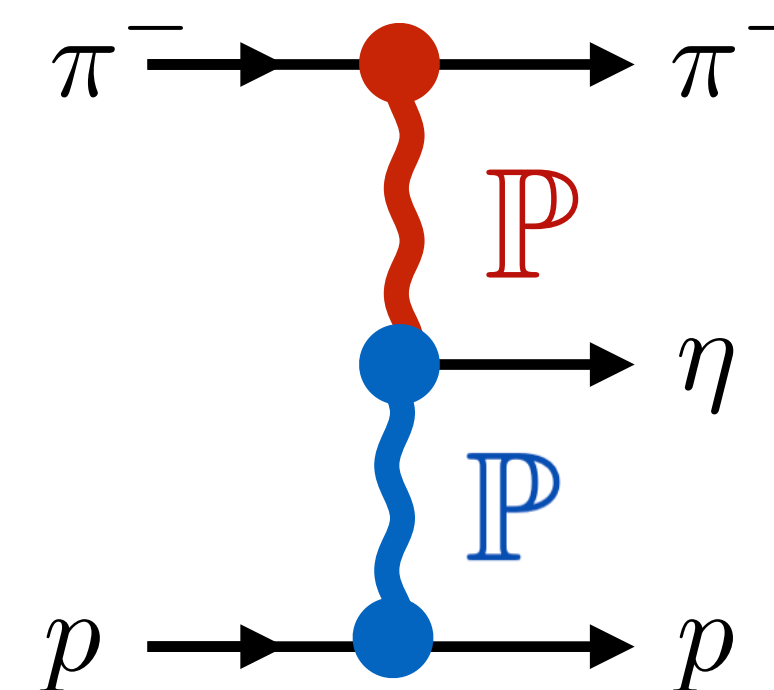
$\cos \theta_{GF} \sim -1 \rightarrow \eta$ backward



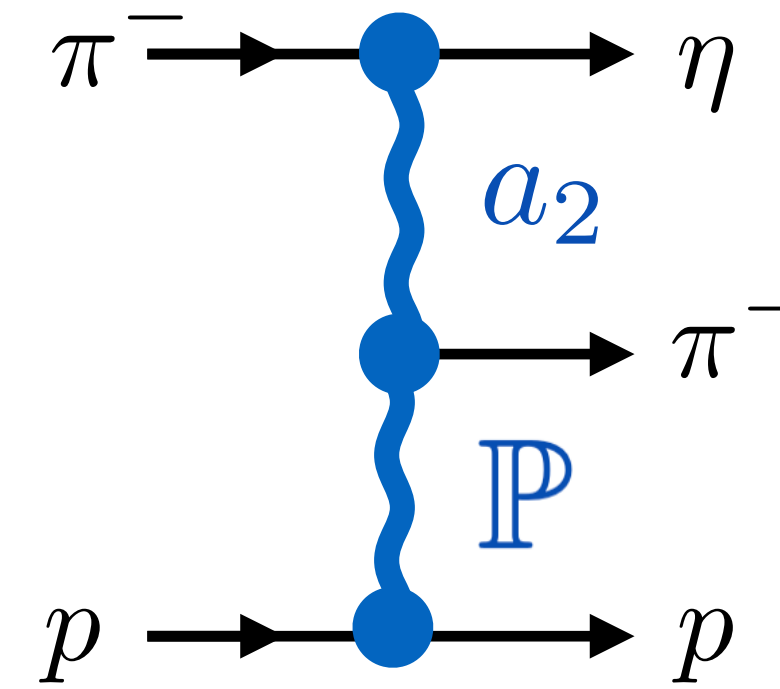
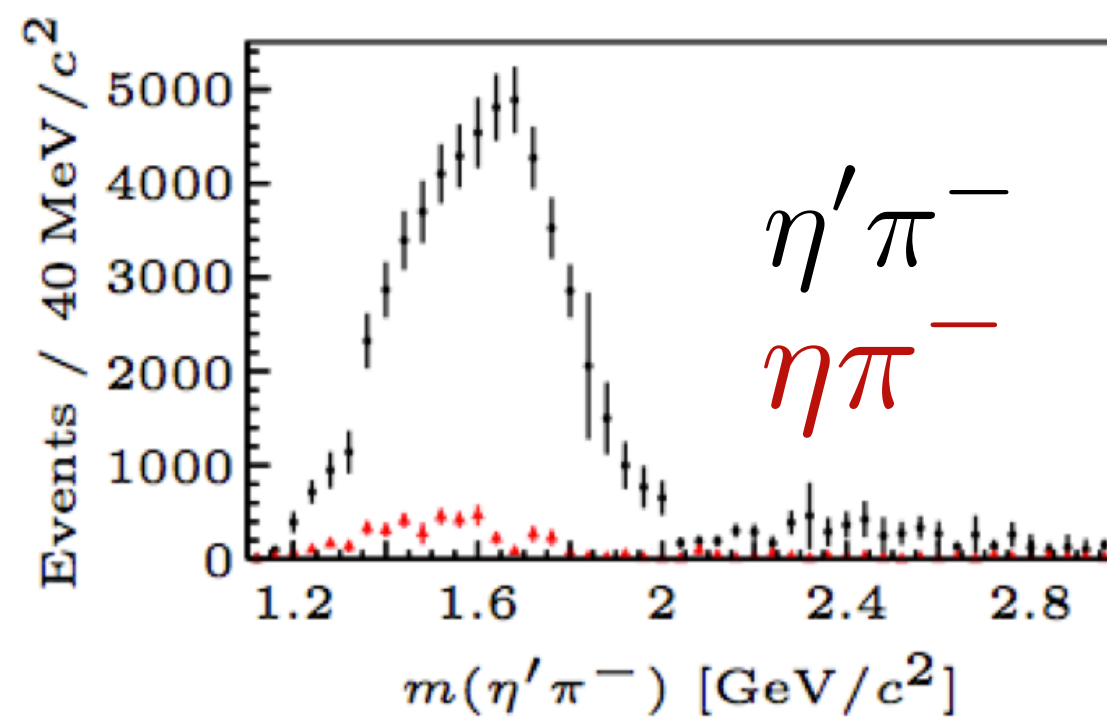
Exotic meson related to
Forward-backward asymmetry



Asymmetry related to
even-odd waves interferences



Origin of the Exotic Meson

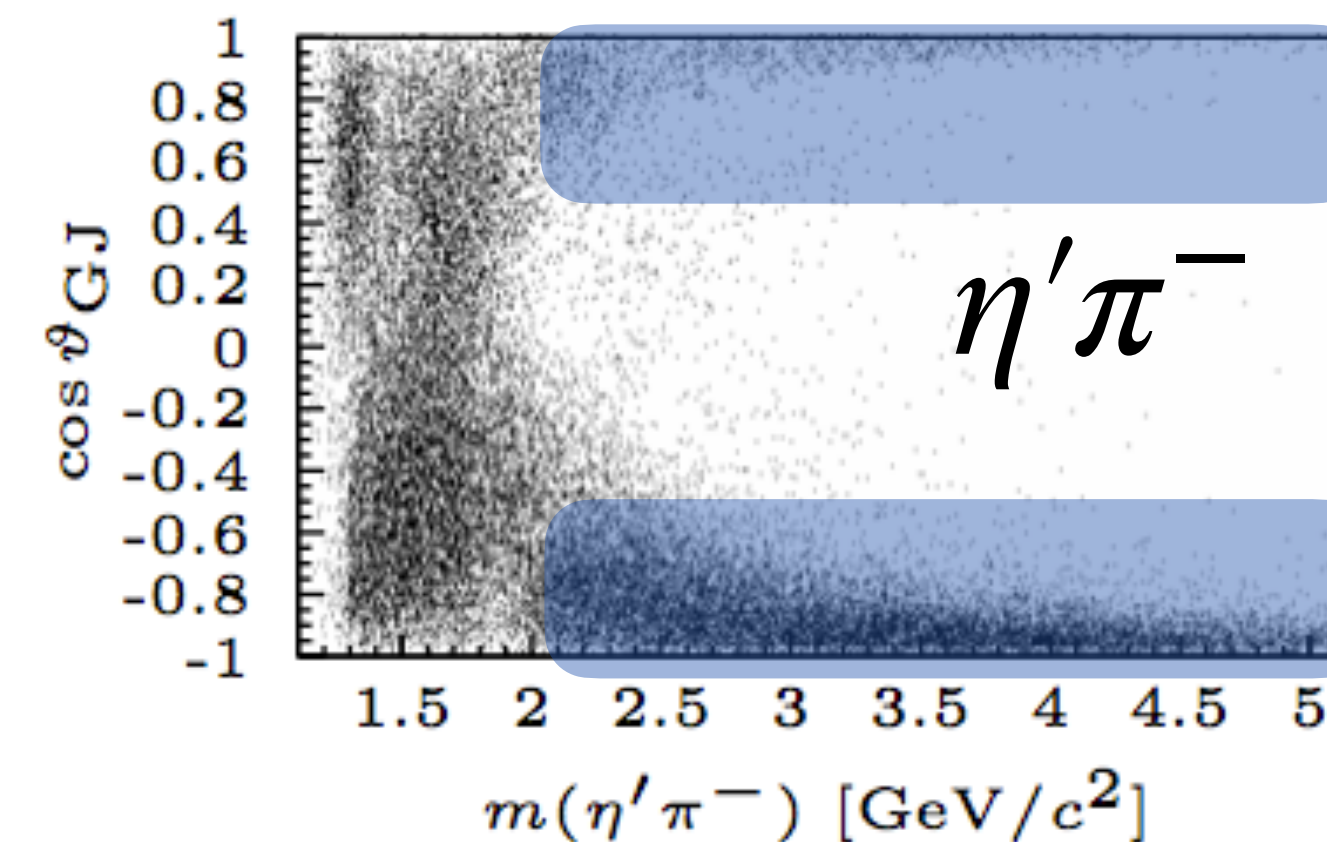
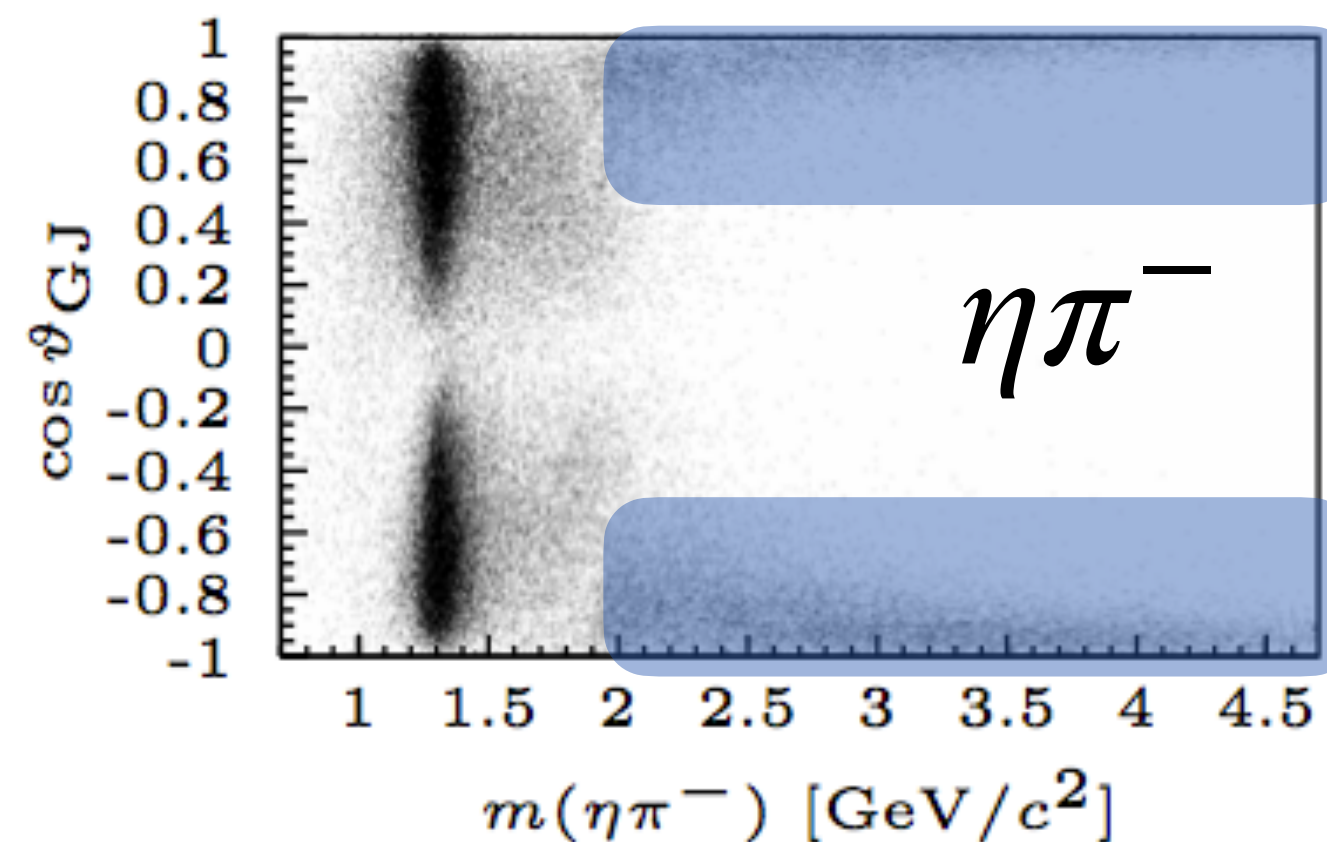


If a_2 and f_2 diagrams equal and no Pomeron

NO ASYMMETRY and NO π_1

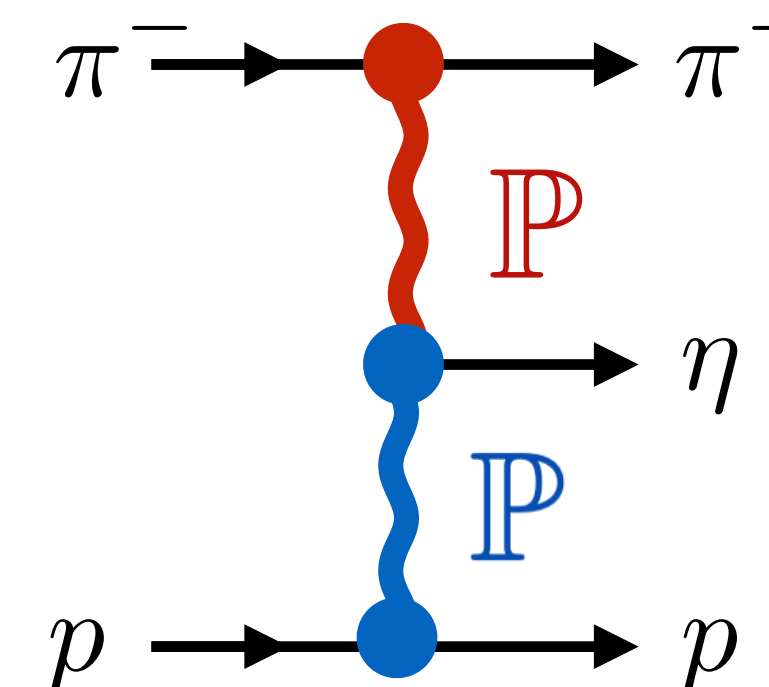
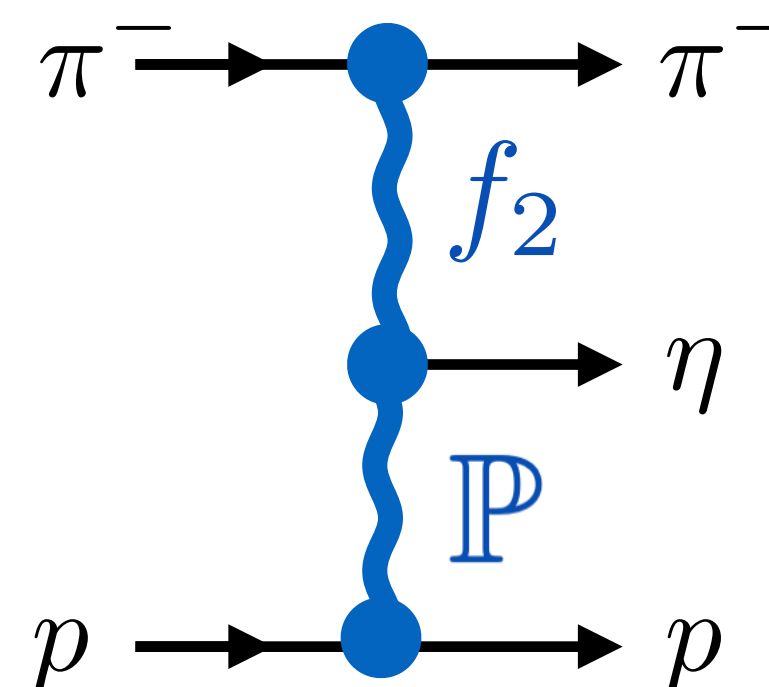
$\cos \theta_{GF} \sim 1 \rightarrow \eta$ forward

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



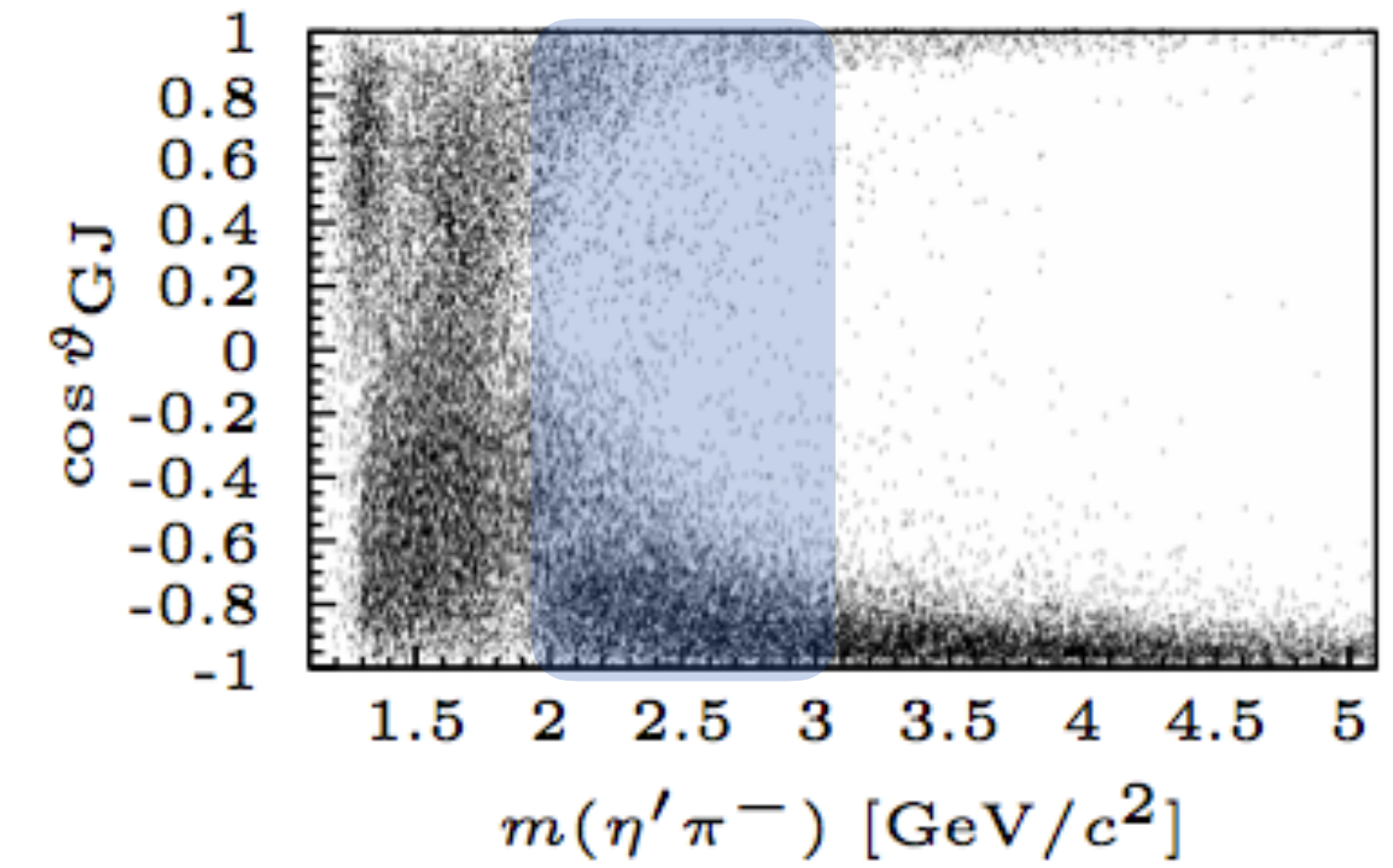
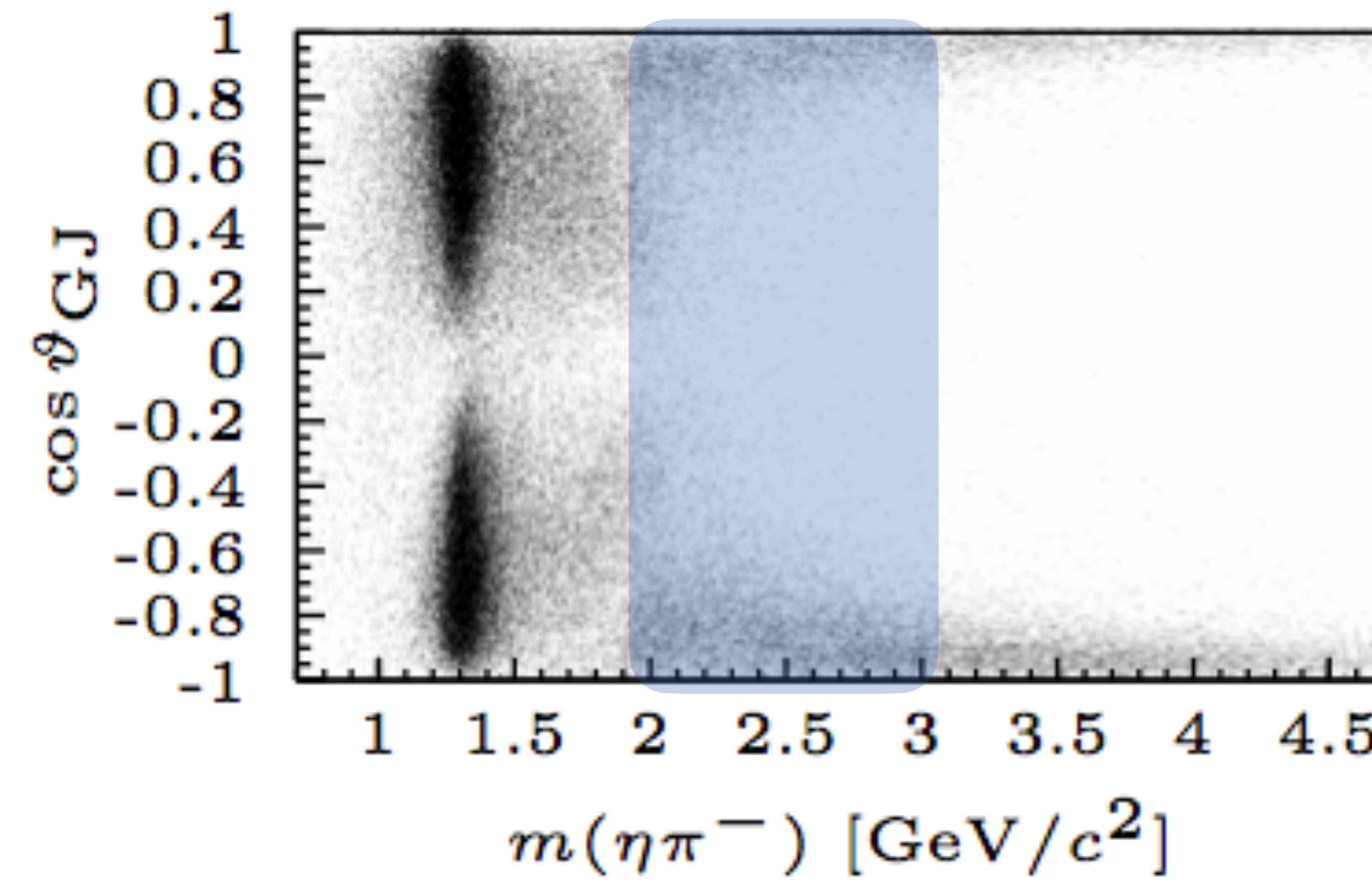
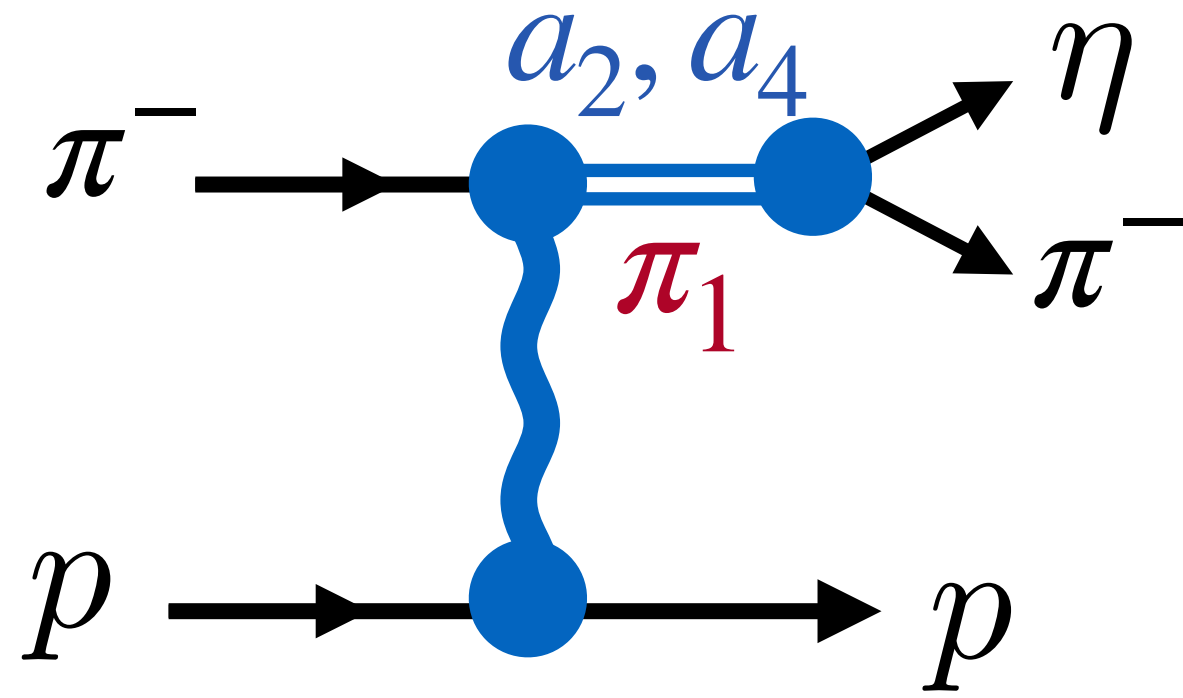
Exotic meson related to Forward-backward asymmetry

Asymmetry related to even-odd waves interferences



Responsible for asymmetry In eta-Prime - pion?

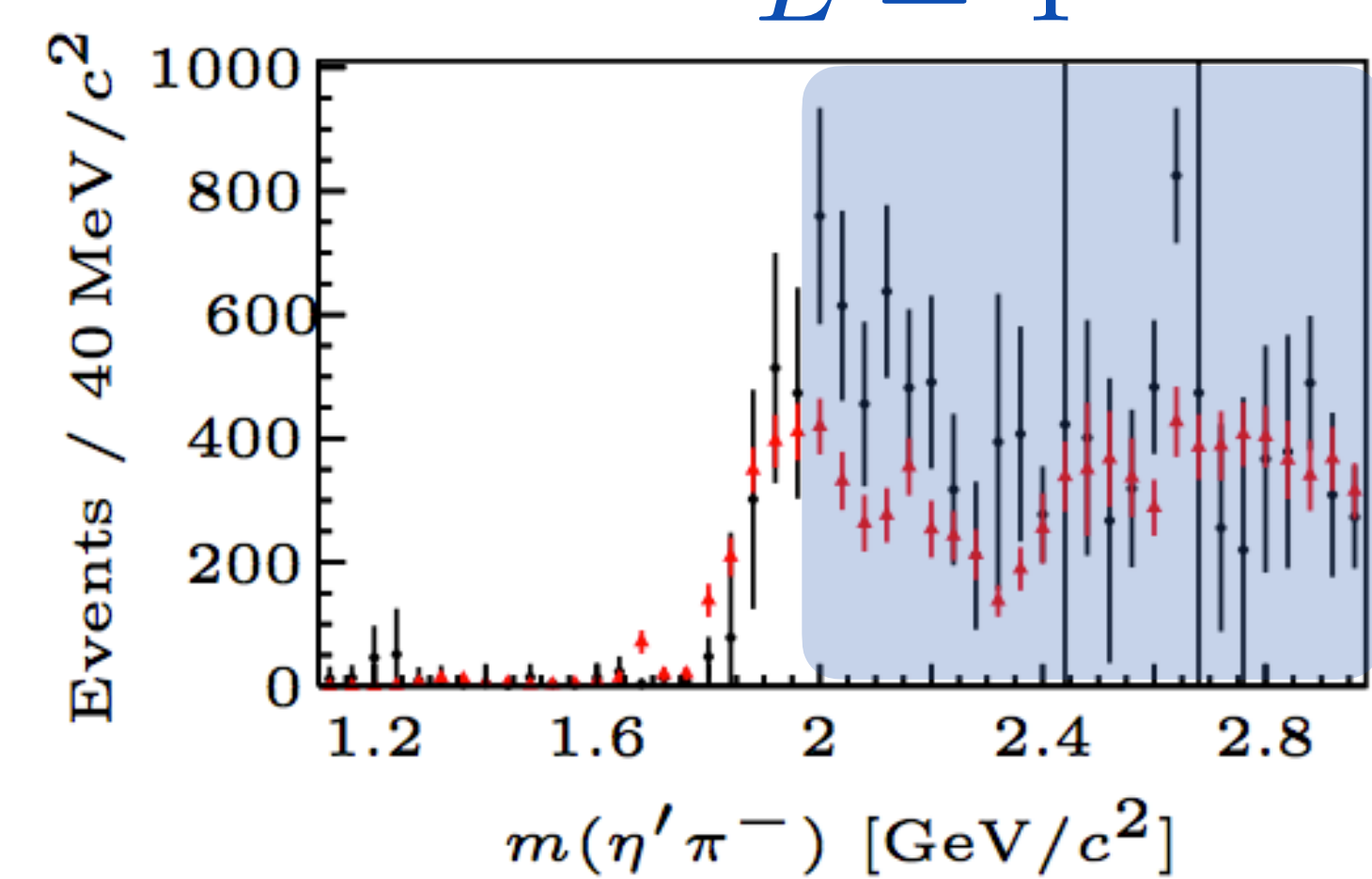
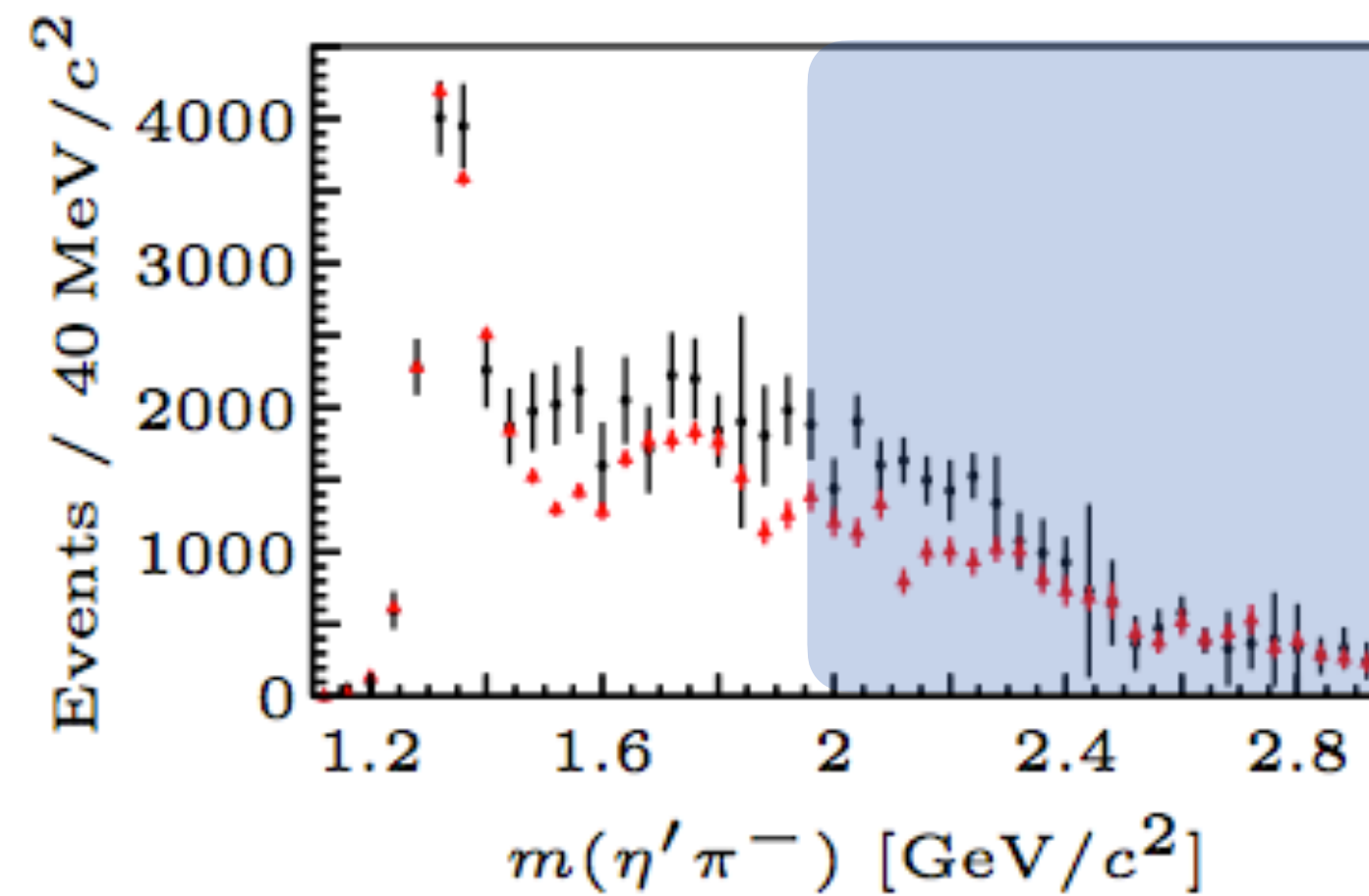
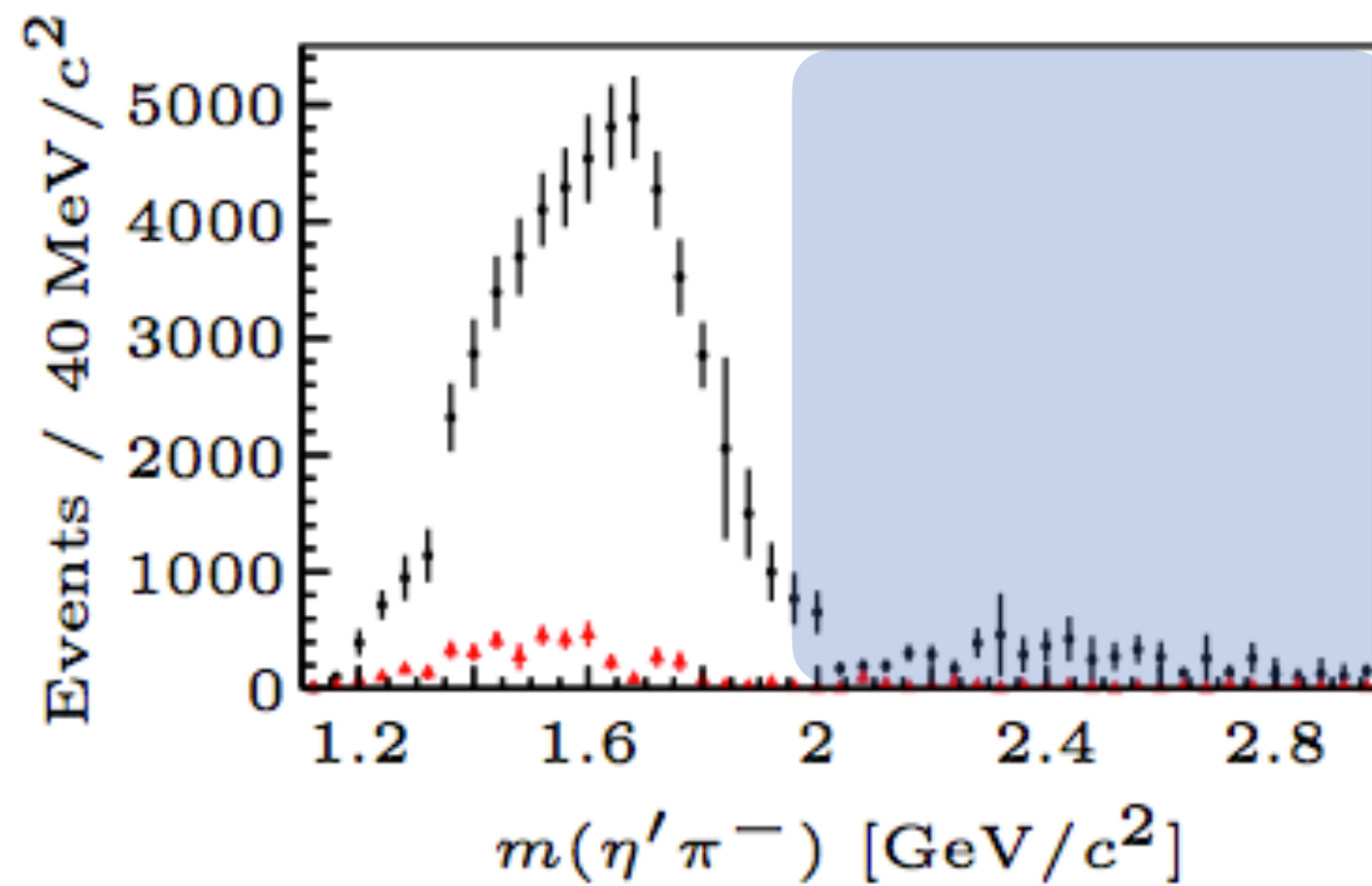
Partial Waves Expansion



$L = 1$

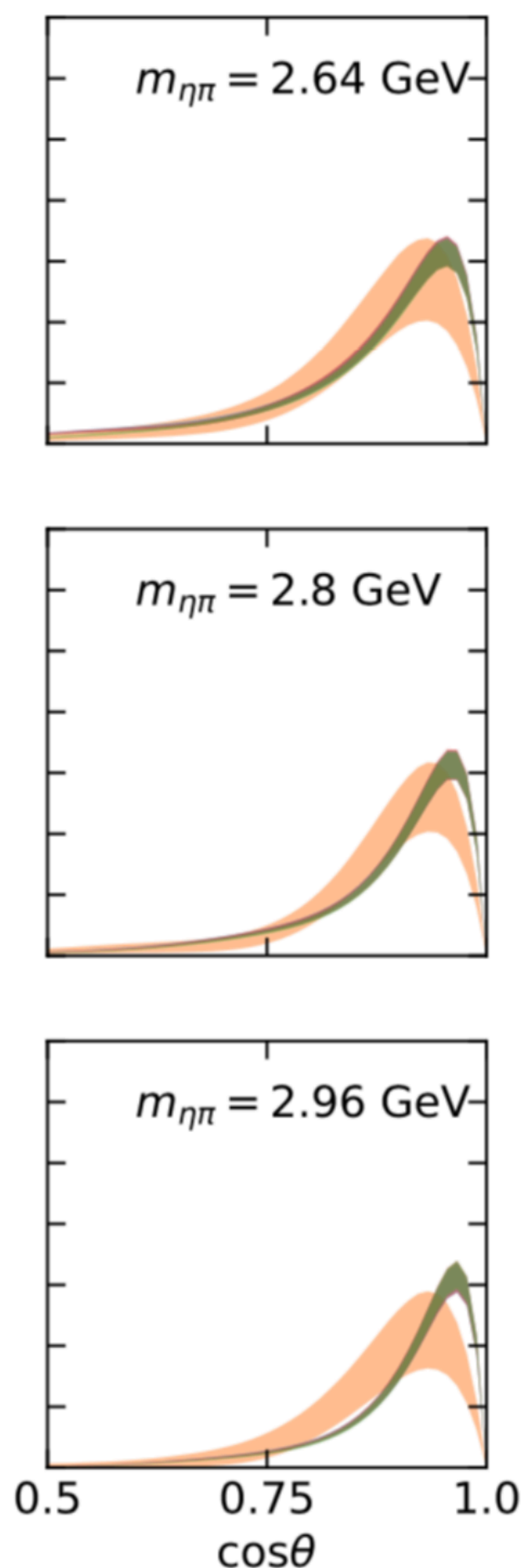
$L = 2$

$L = 4$



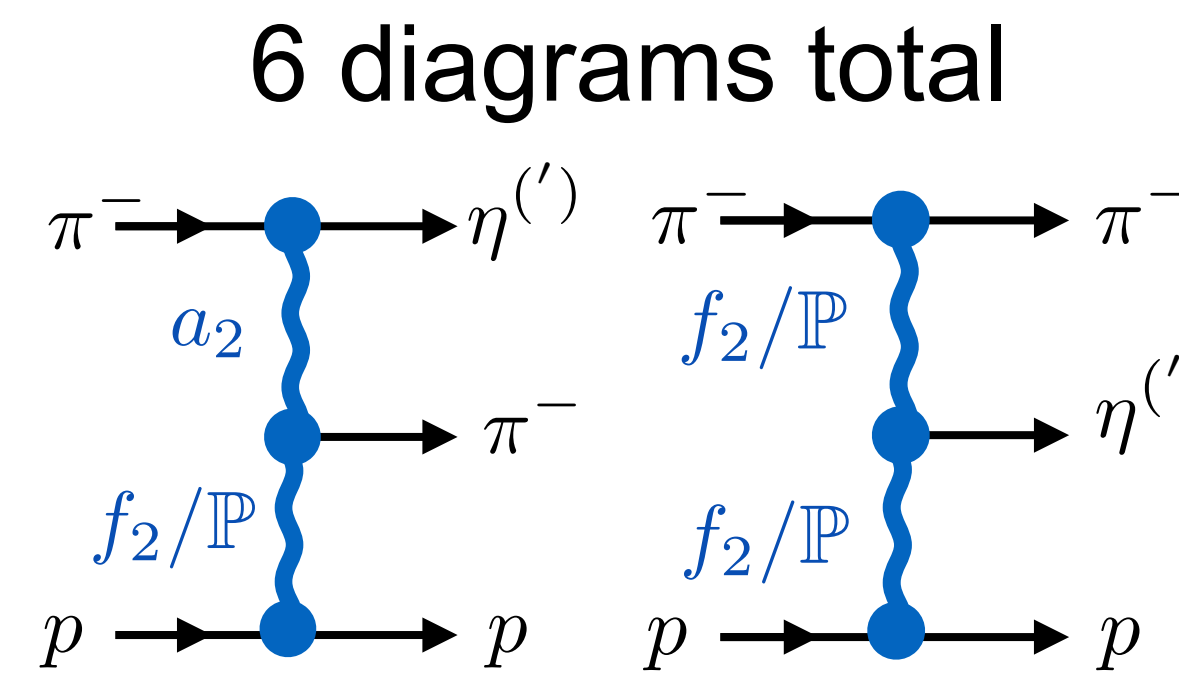
Resonance in angular mom. $L = 1$?

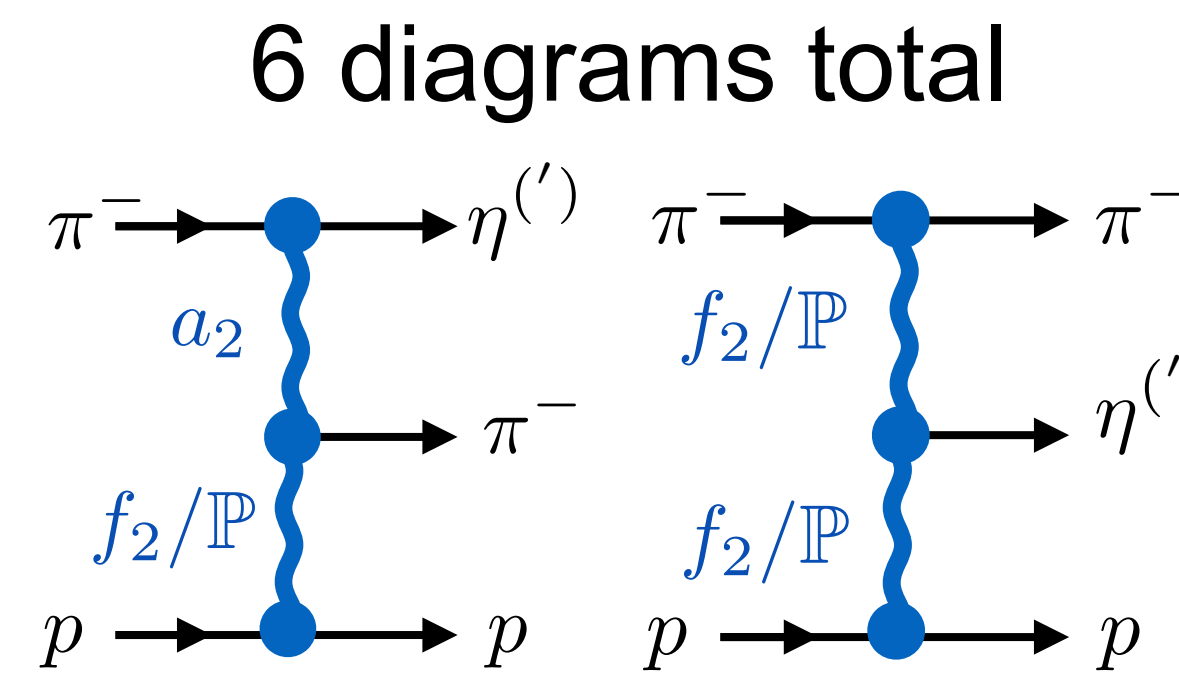
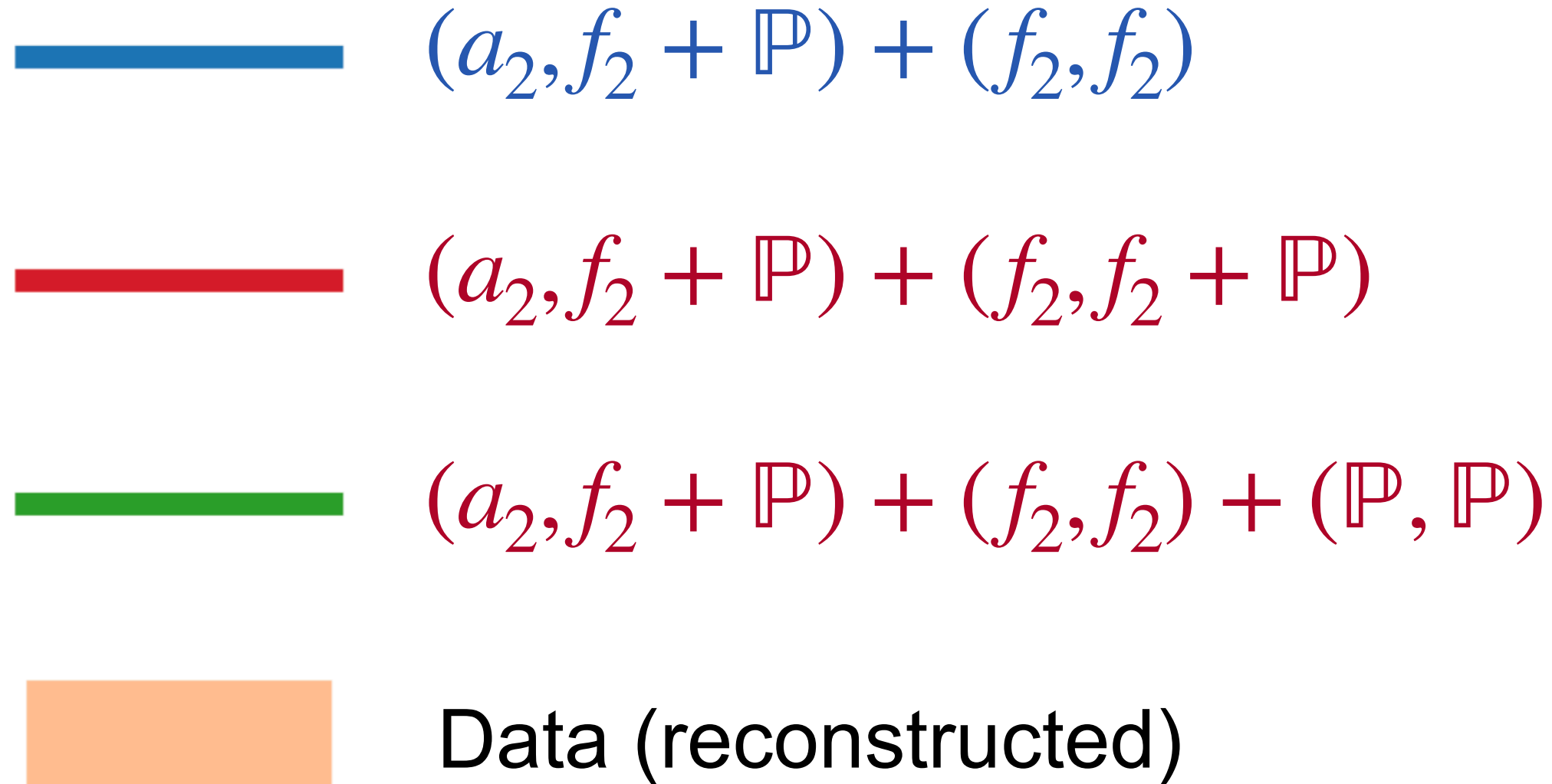
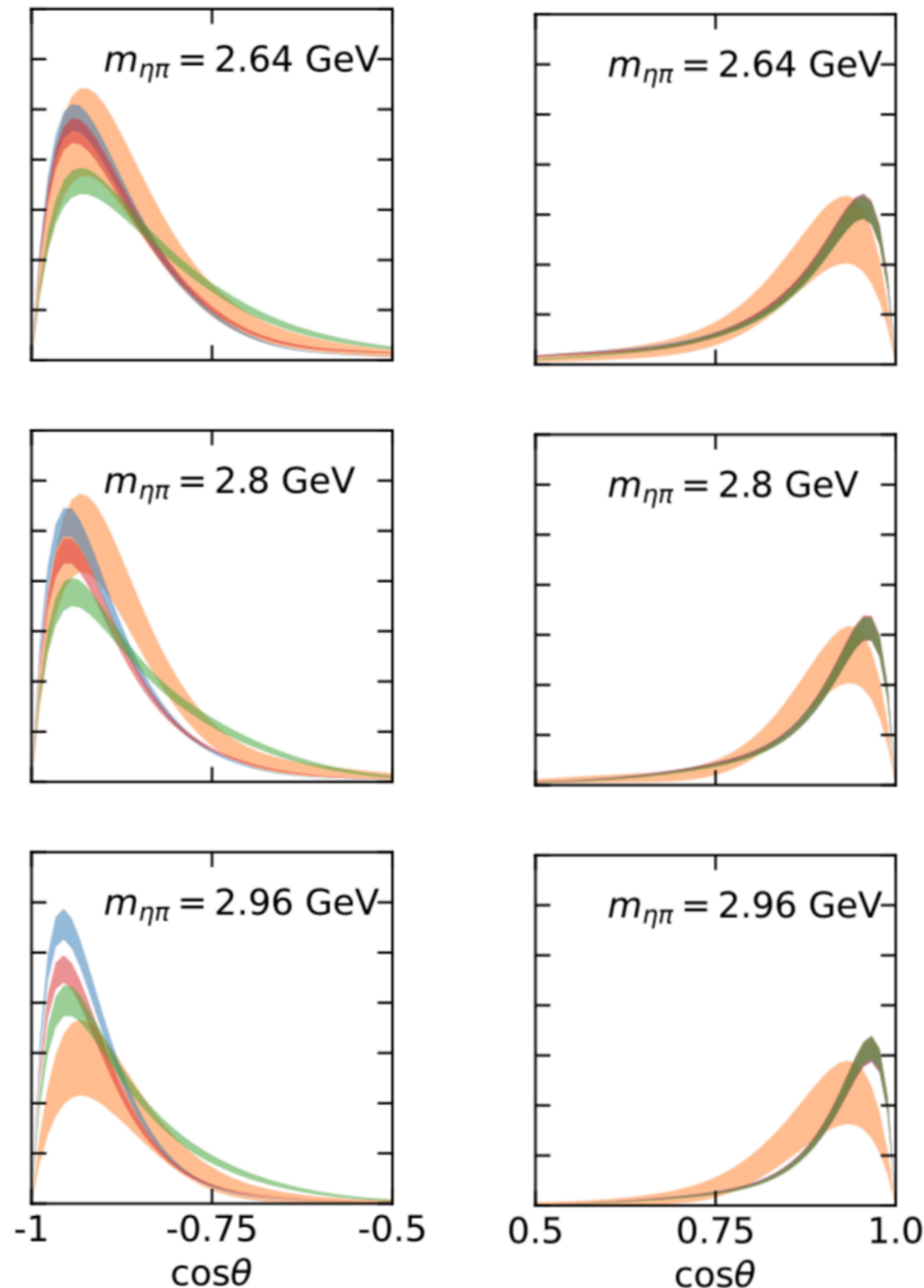
black: $\pi\eta'$ red: $\pi\eta$ (scaled)



- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$
- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$
- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$
- █ Data (reconstructed)

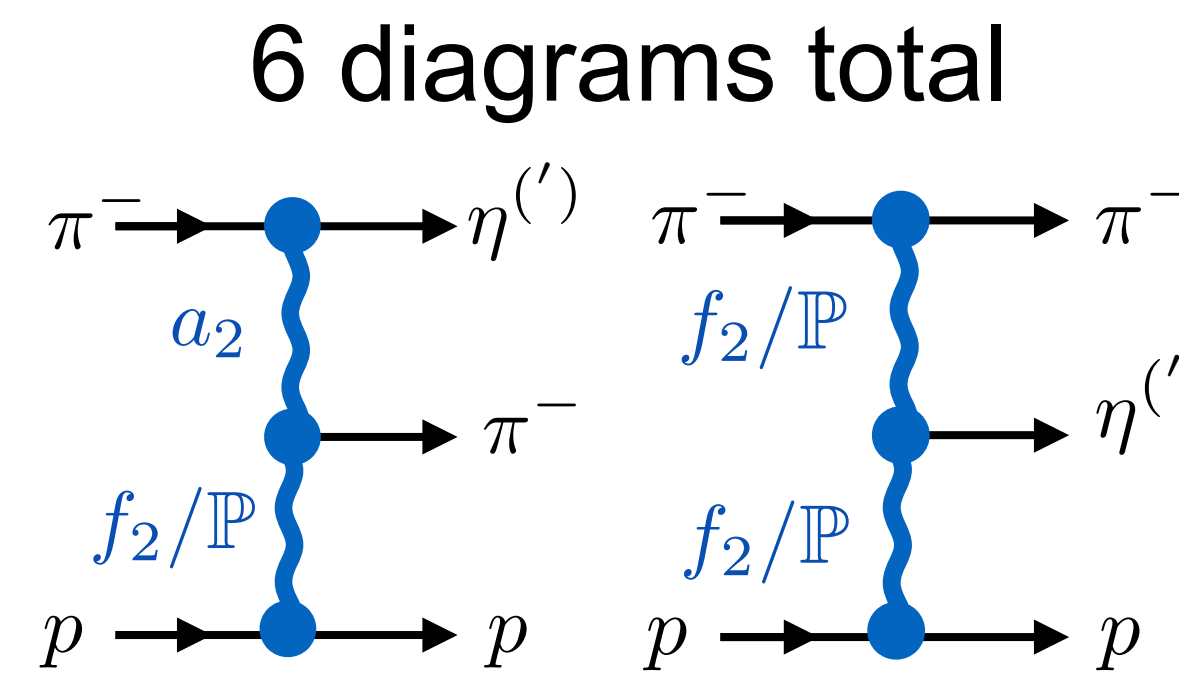
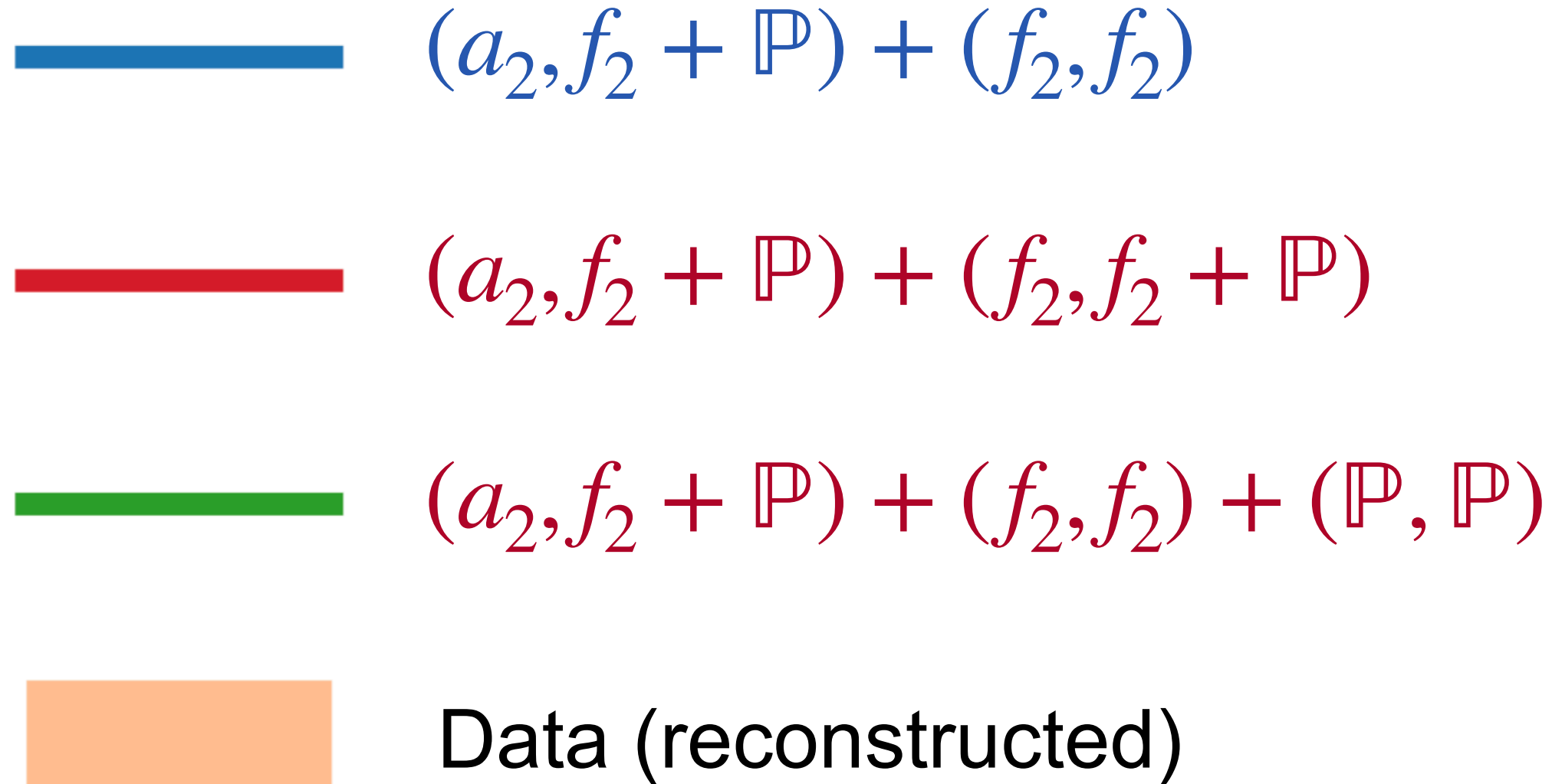
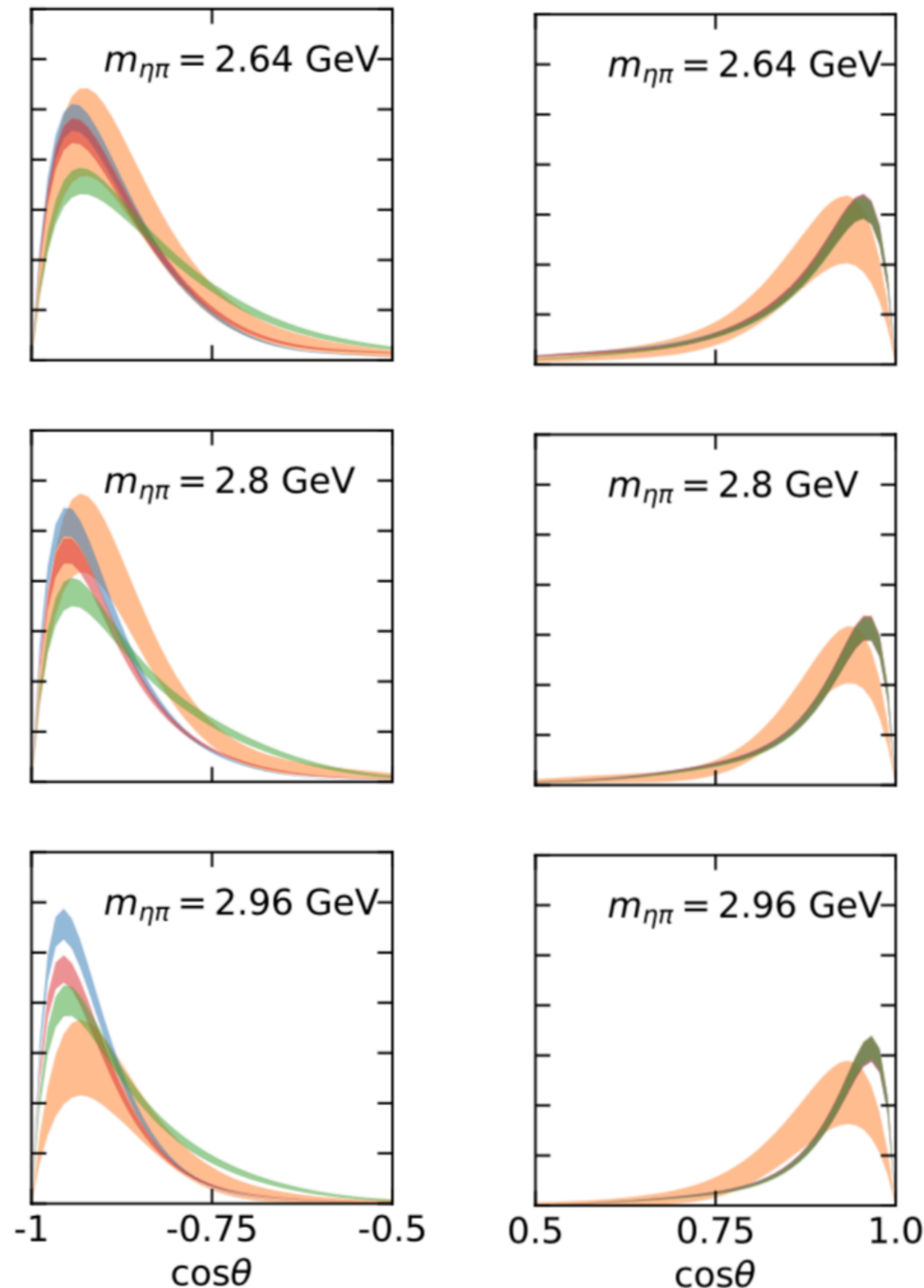
Forward intensity requires both (a_2, f_2) and (a_2, \mathbb{P})





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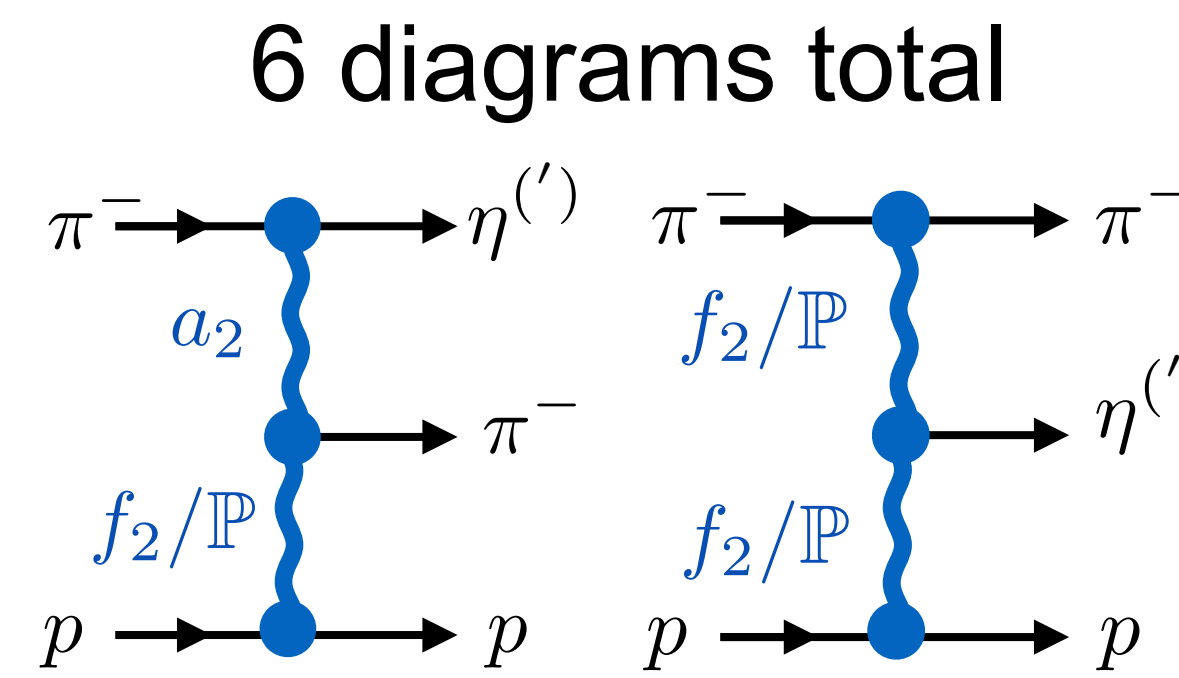
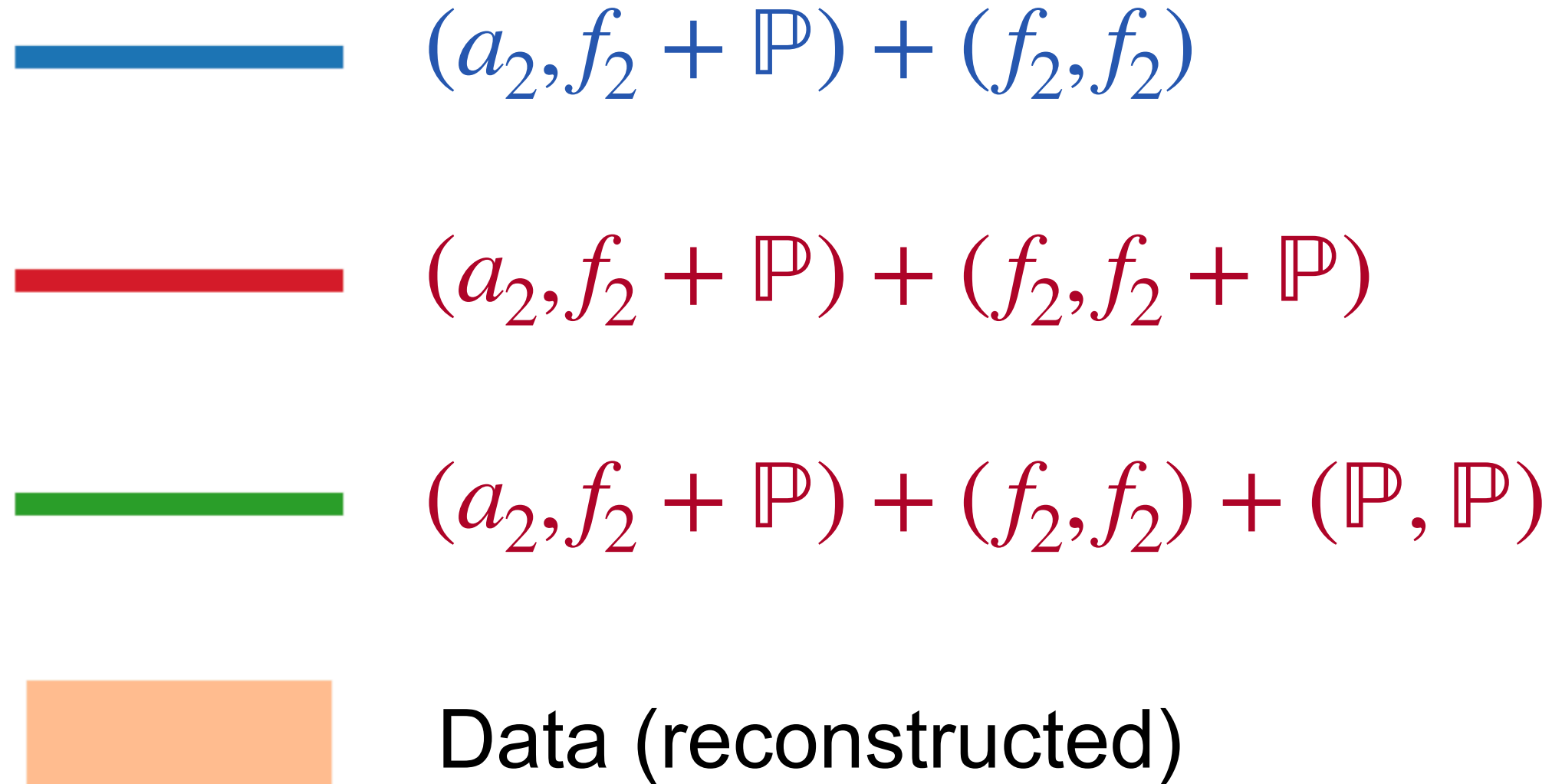
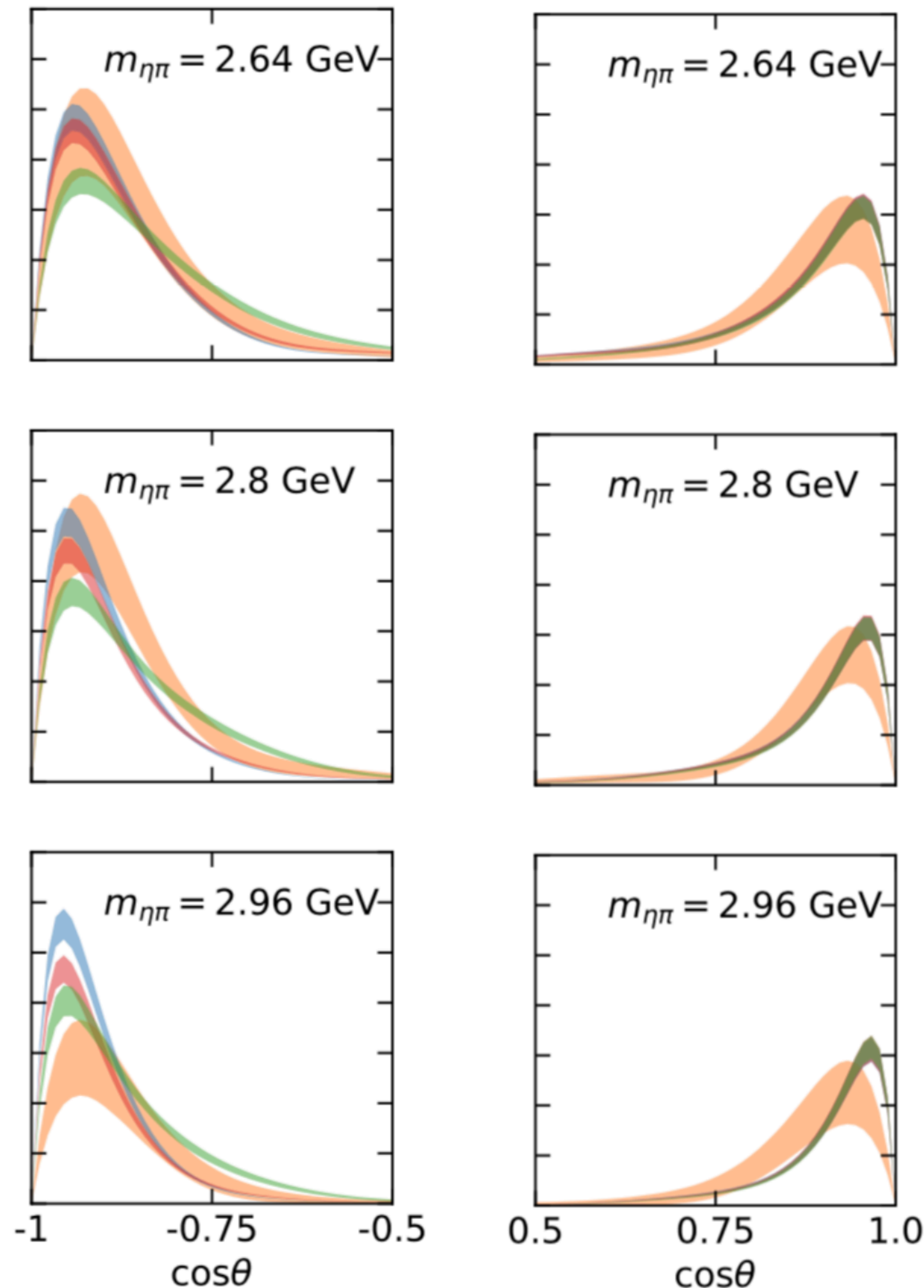
Backward intensity requires (f_2, f_2) and either (f_2, \mathbb{P}) or (\mathbb{P}, \mathbb{P})



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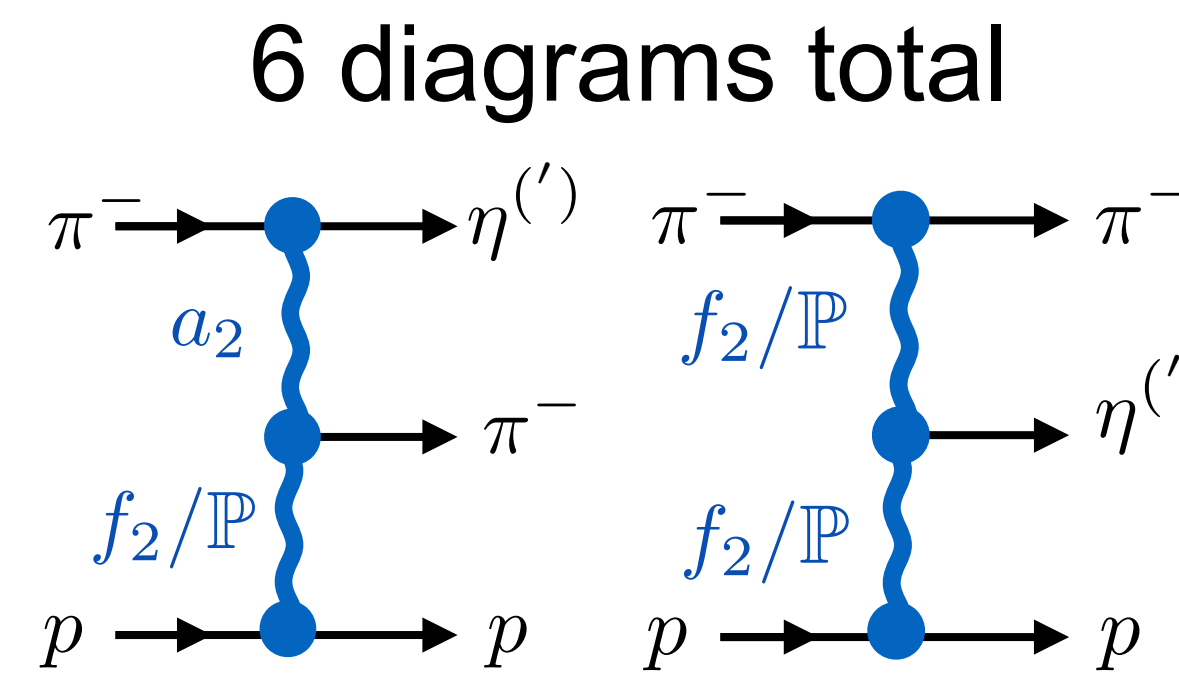
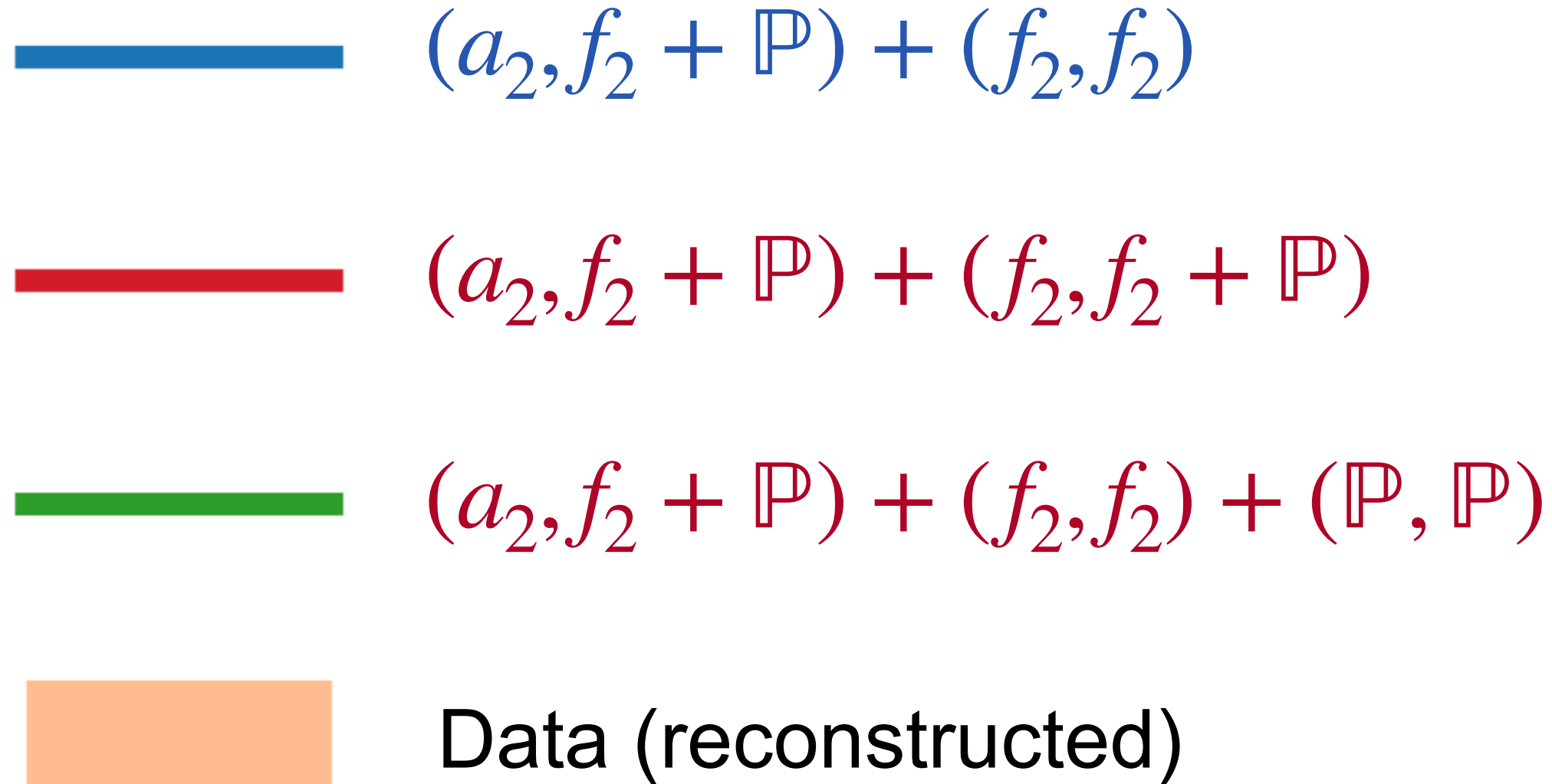
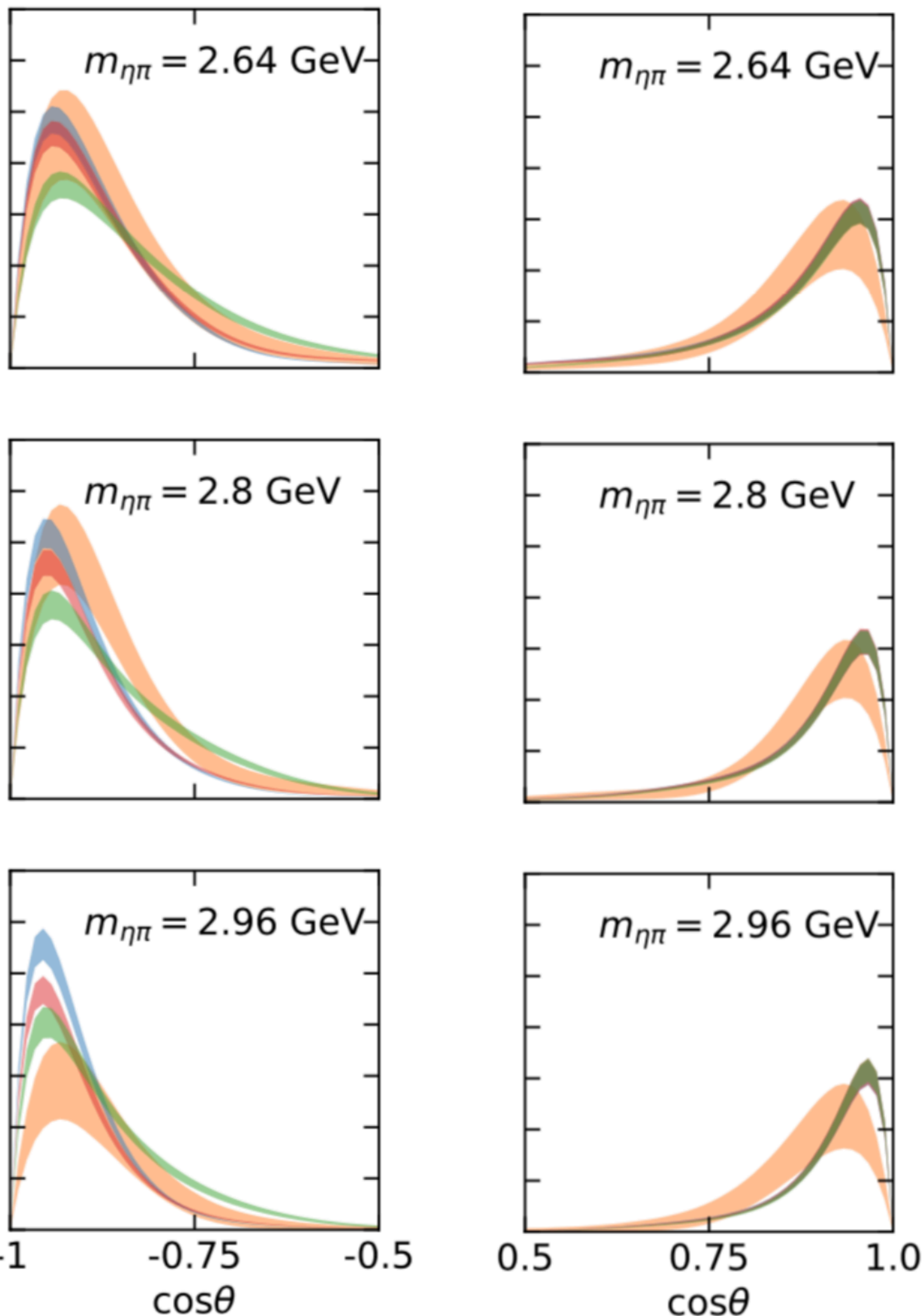
(a_2, \mathbb{P})	0.40 ± 0.04
(a_2, f_2)	3.4 ± 0.4
(f_2, \mathbb{P})	-0.30 ± 0.05
(f_2, f_2)	-6.6 ± 0.7



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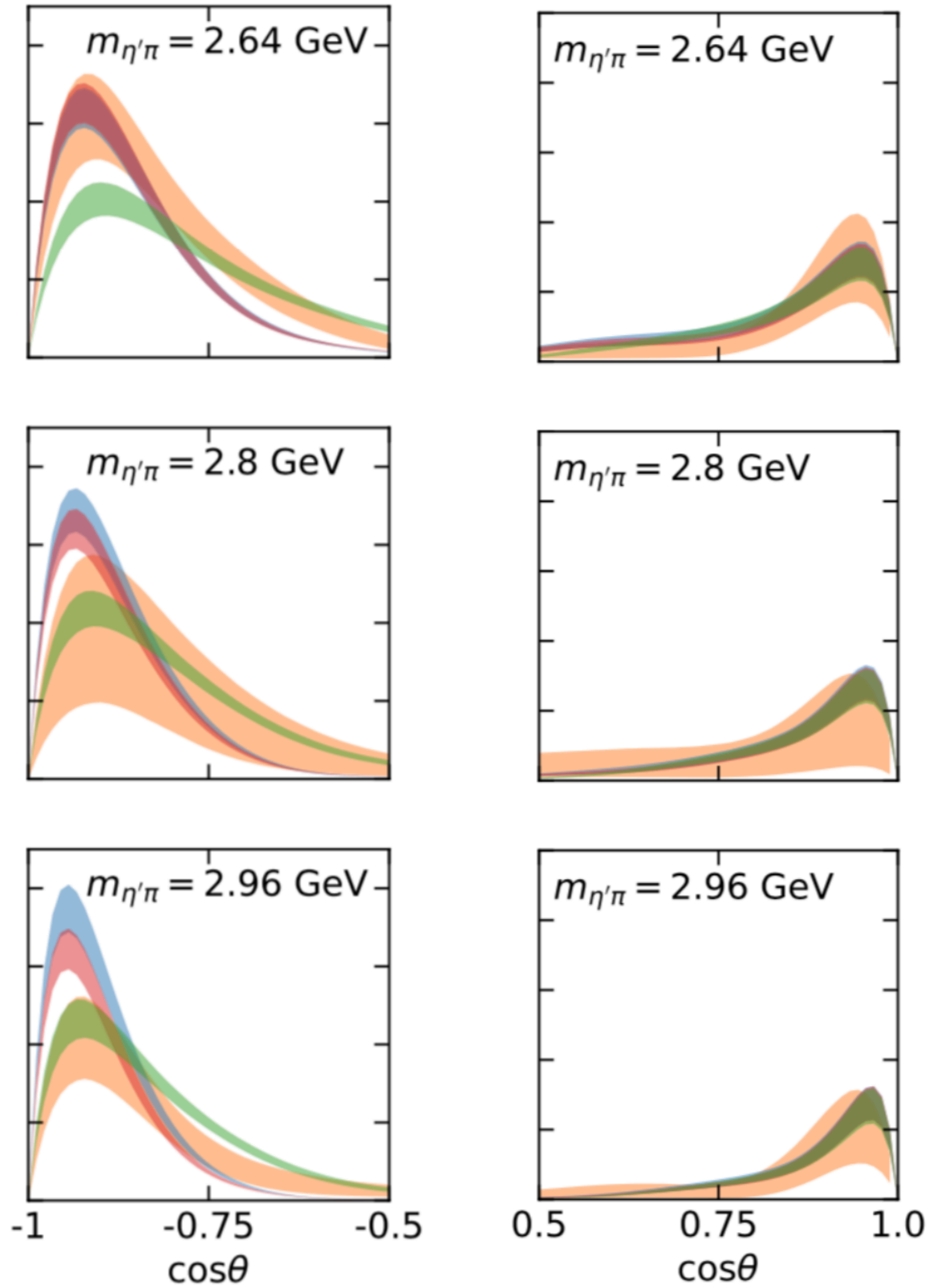


Forward intensity requires both (a_2, f_2) and (a_2, \mathbb{P})

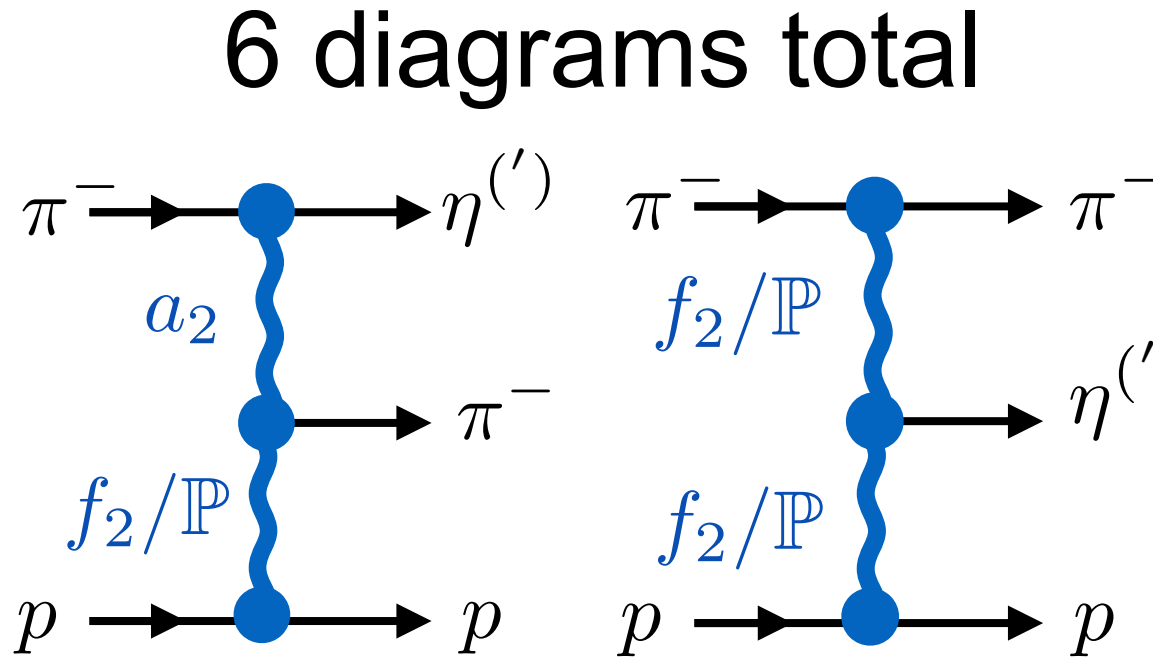
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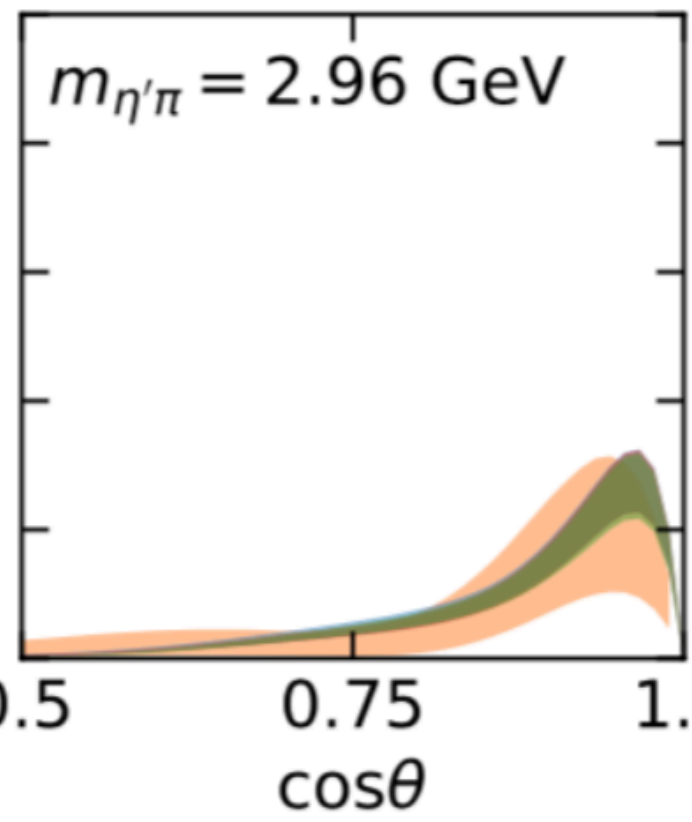
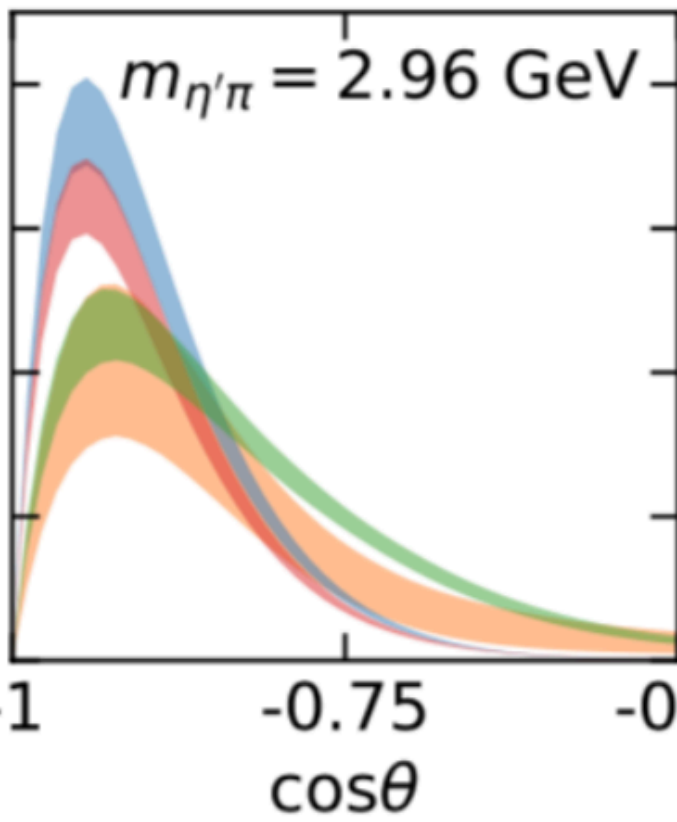
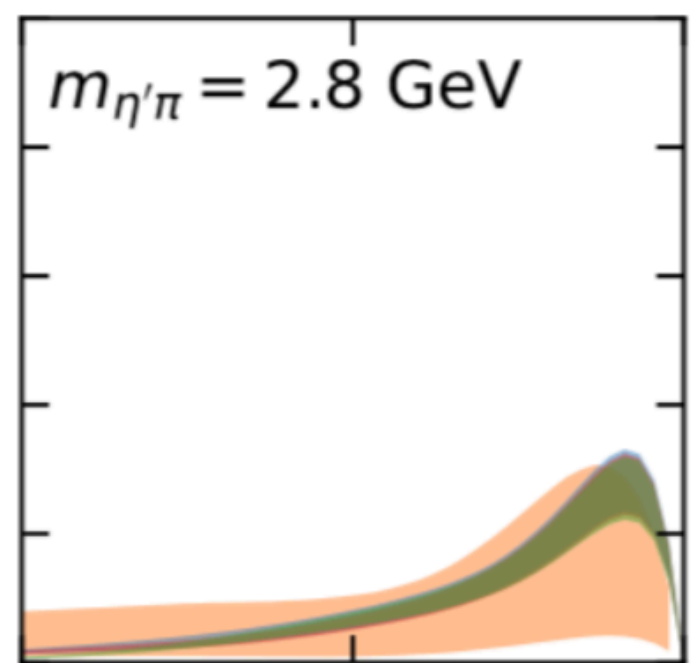
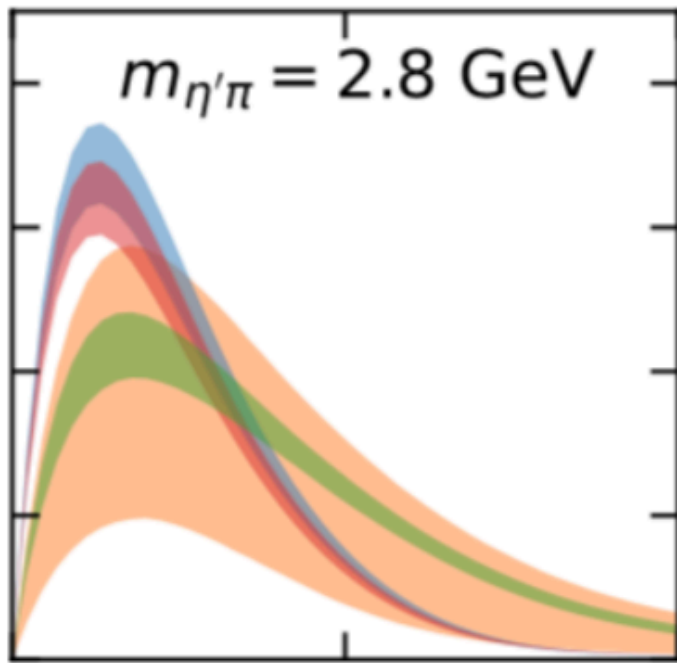
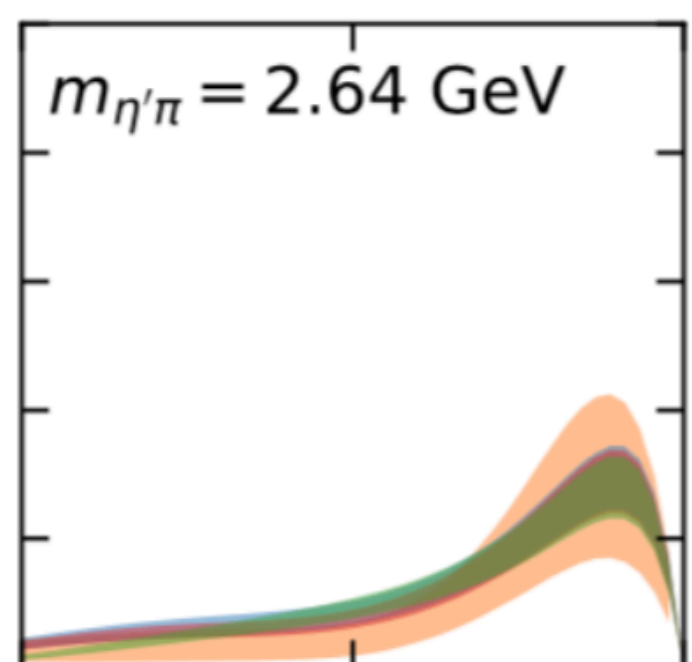
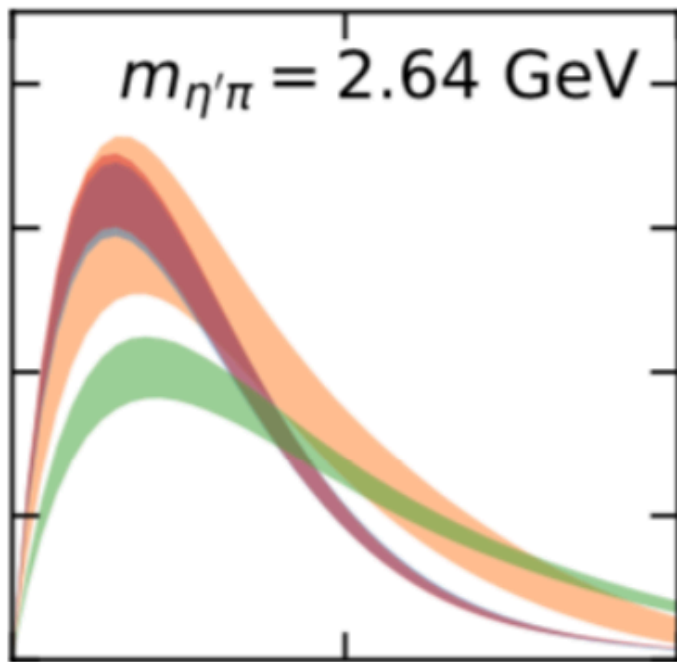
Asymmetry coming from difference between (a_2, f_2) and (f_2, f_2)



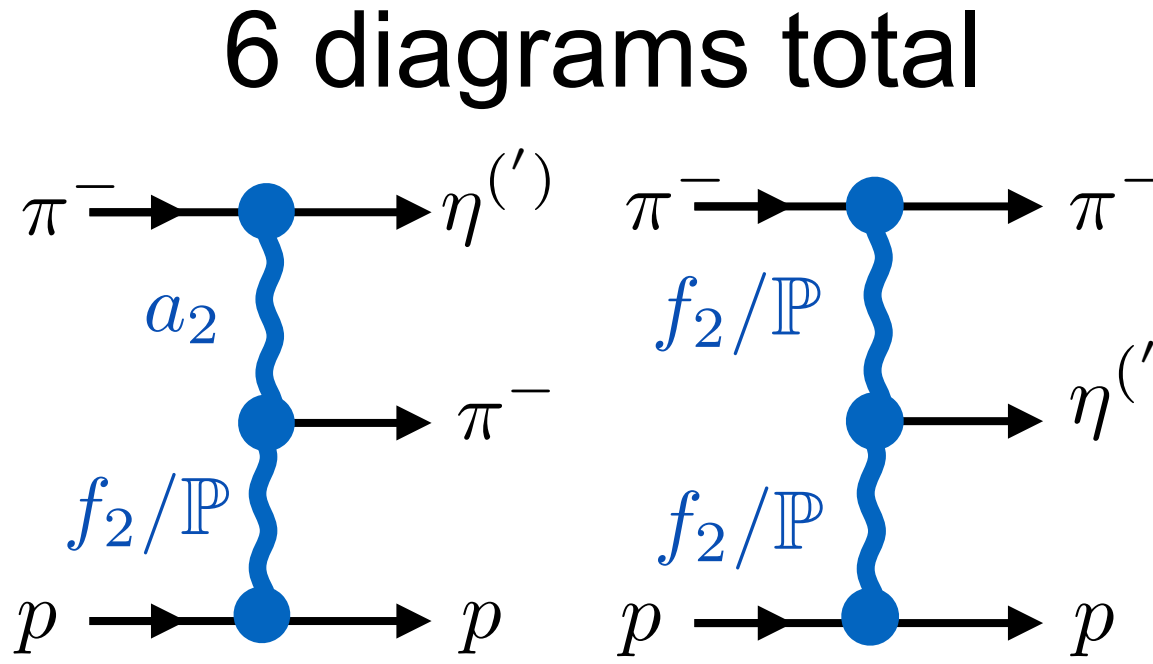
- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$
- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$
- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$
- █ Data (reconstructed)



Forward intensity requires both (a_2, f_2) and (a_2, \mathbb{P})
 Backward intensity requires (f_2, f_2) and (\mathbb{P}, \mathbb{P})

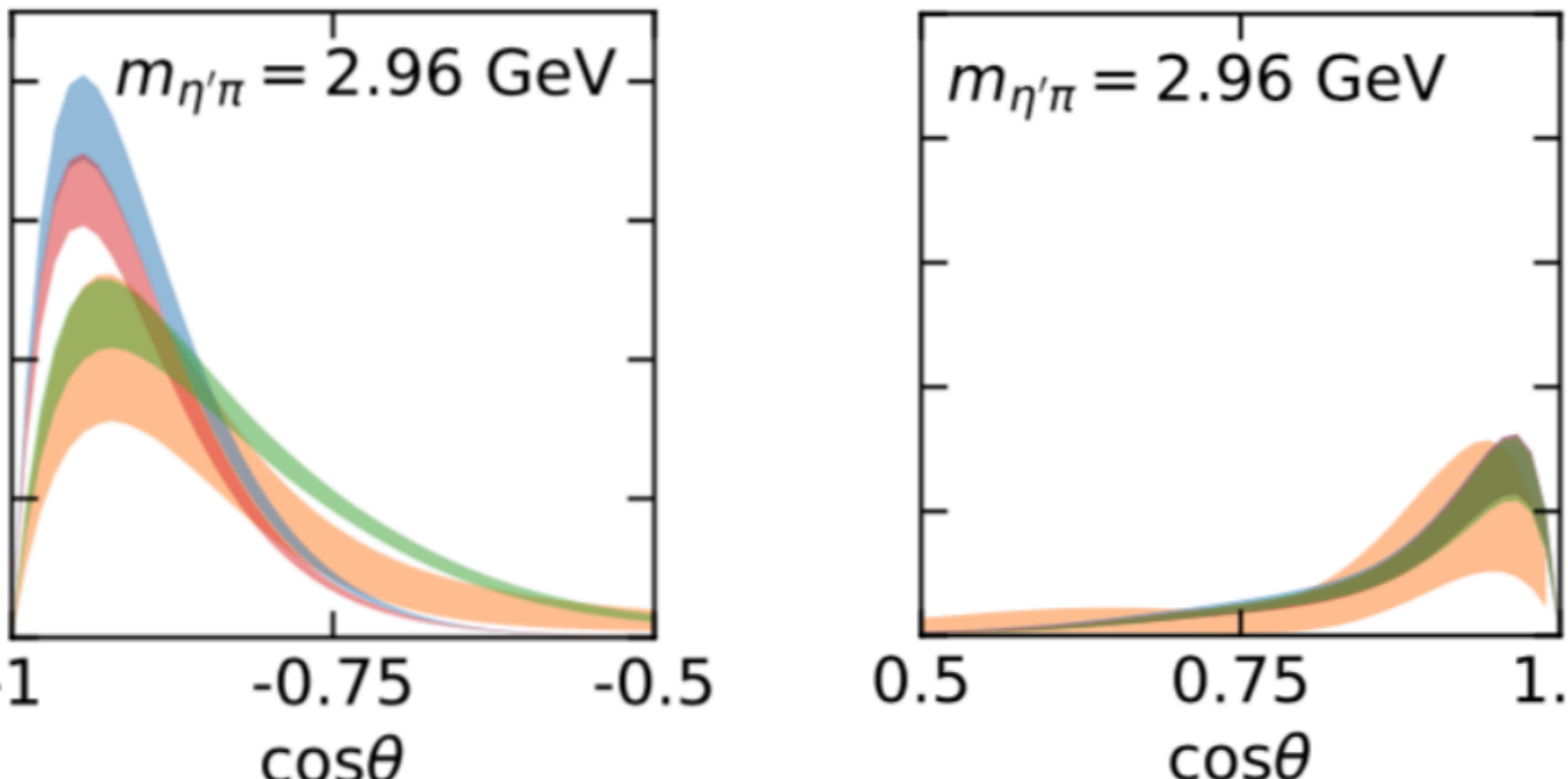
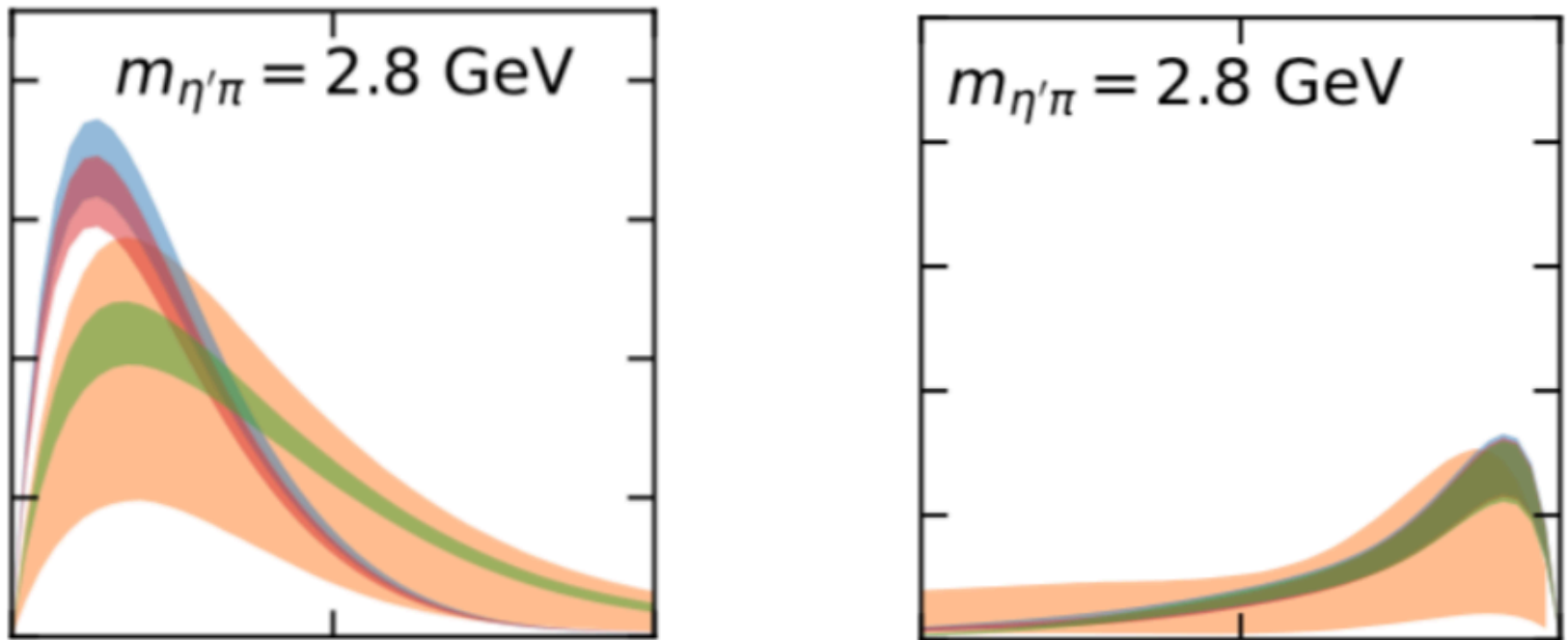
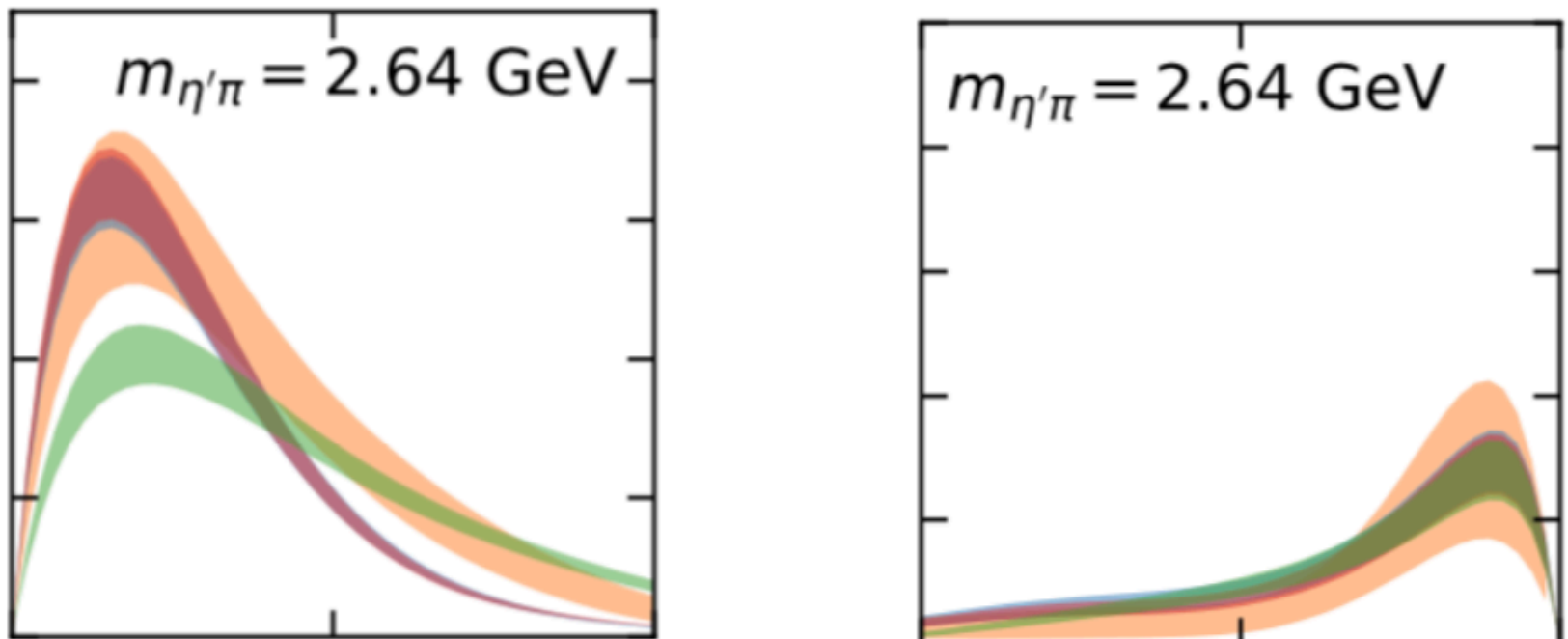


- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$
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- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$
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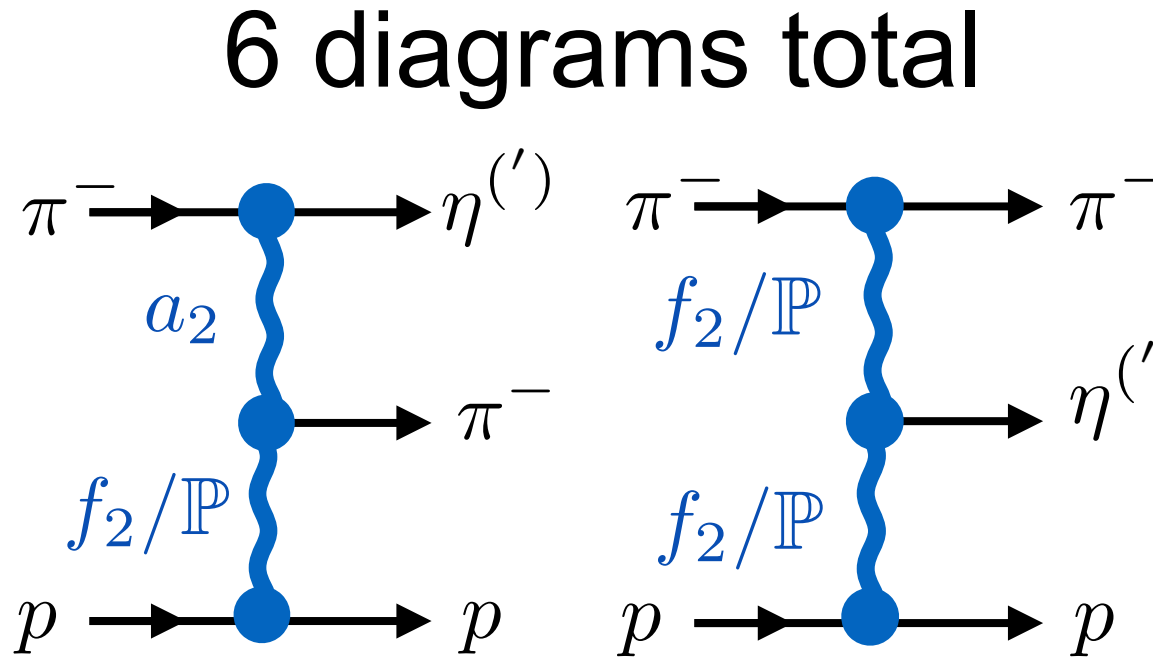


Forward intensity requires both (a_2, f_2) and (a_2, \mathbb{P})
 Backward intensity requires (f_2, f_2) and (\mathbb{P}, \mathbb{P})

(a_2, \mathbb{P})	0.35 ± 0.05
(a_2, f_2)	0.6 ± 0.5
(f_2, f_2)	-7.1 ± 0.6
(\mathbb{P}, \mathbb{P})	0.018 ± 0.002



- $(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$
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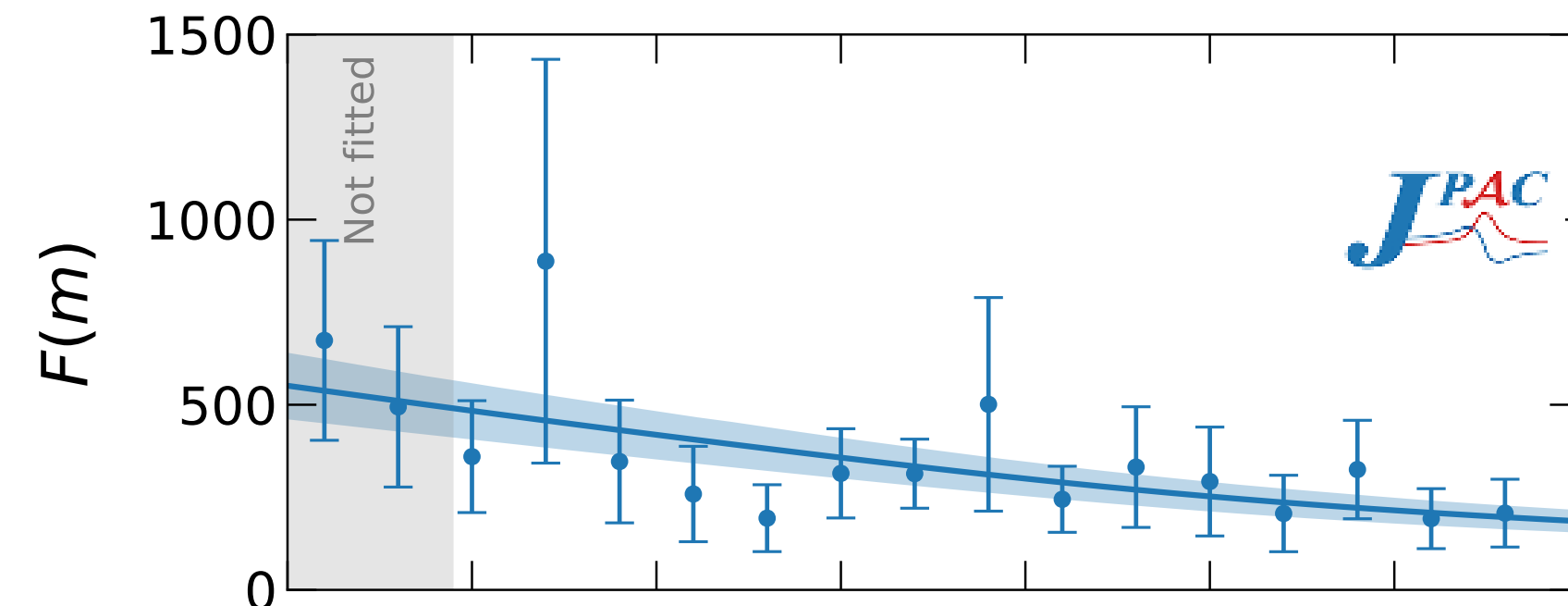
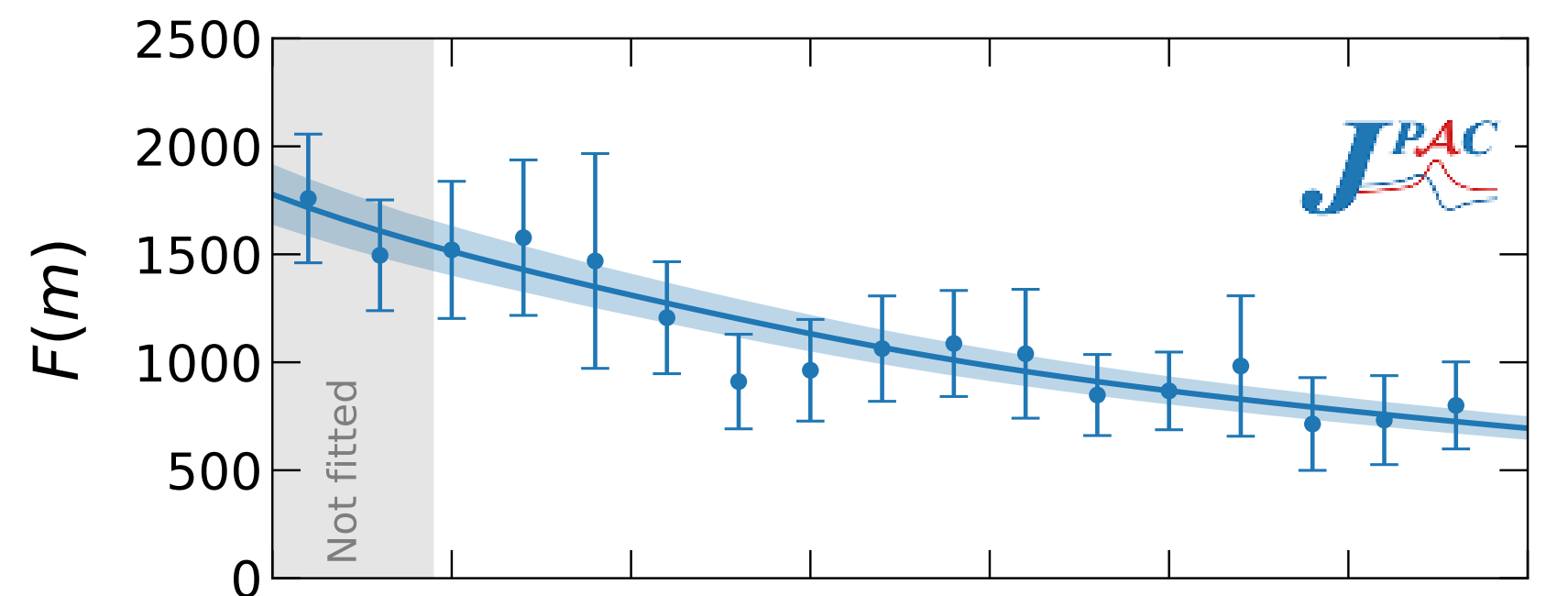
Asymmetry coming from difference between (a_2, f_2) and (f_2, f_2) + contribution from (\mathbb{P}, \mathbb{P})

Forward-Backward Asymmetry

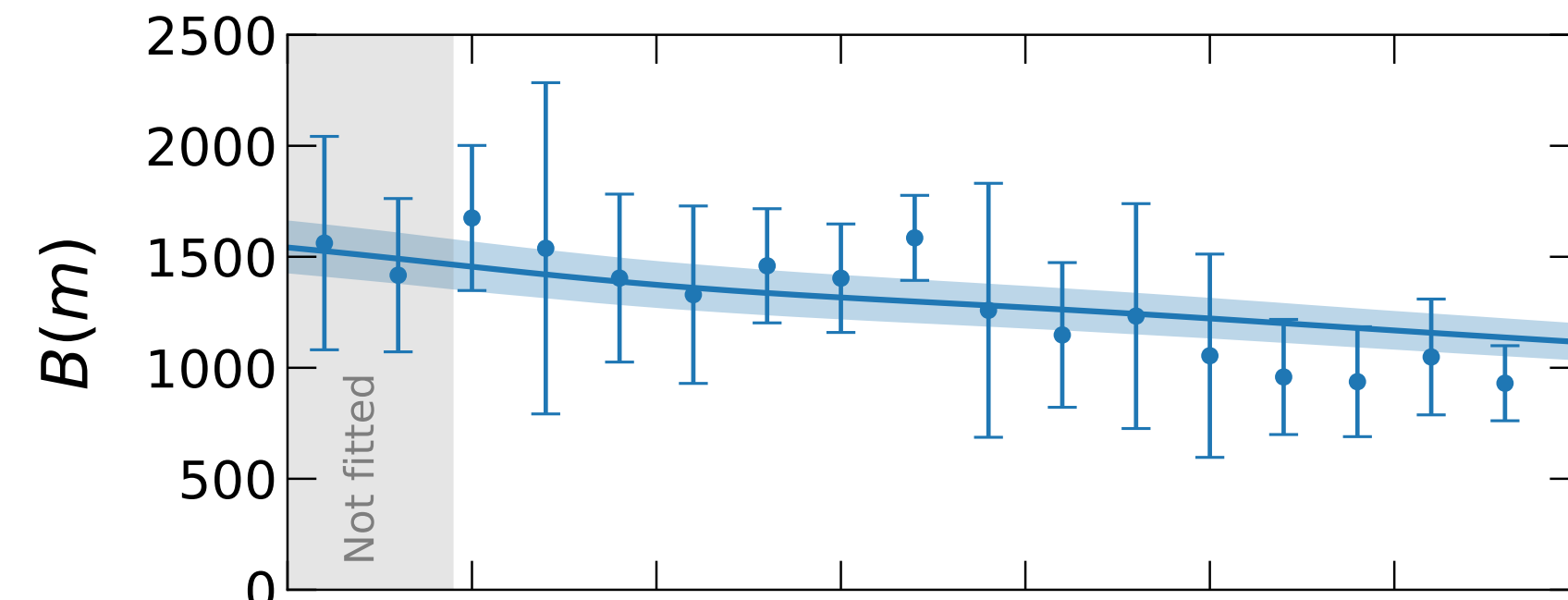
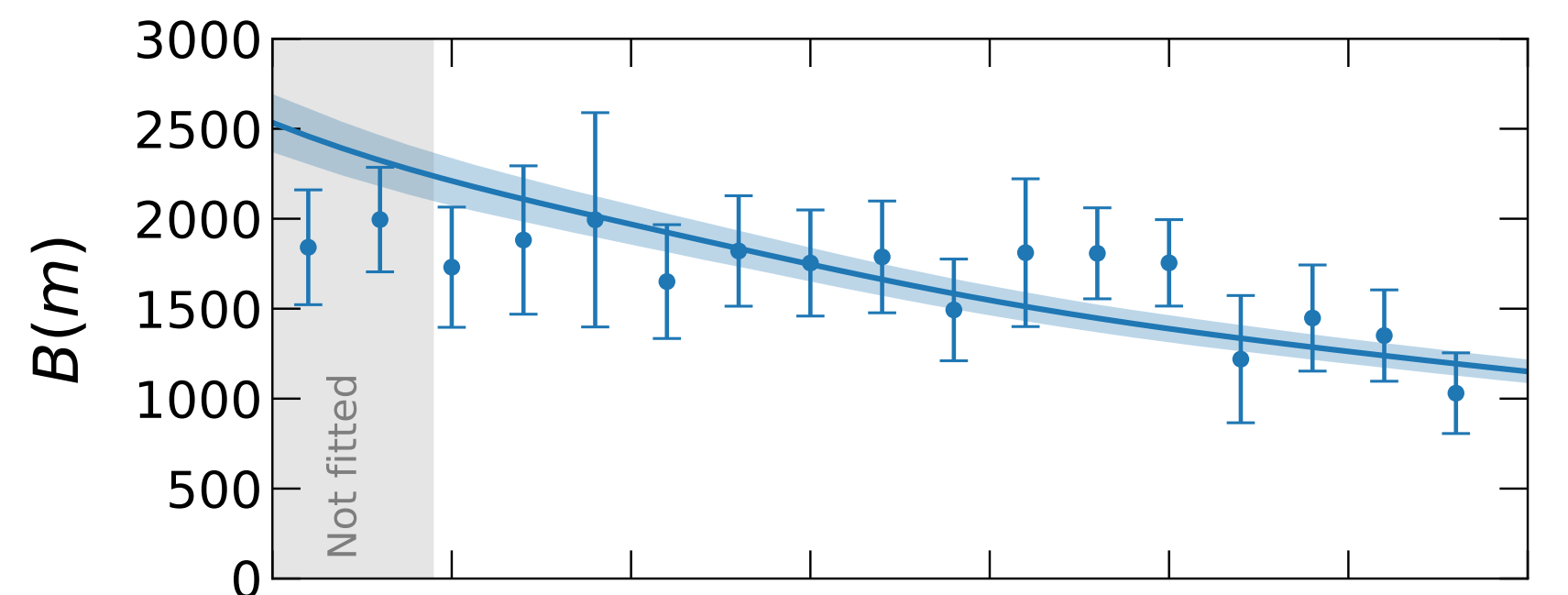
$\eta\pi$

$\eta'\pi$

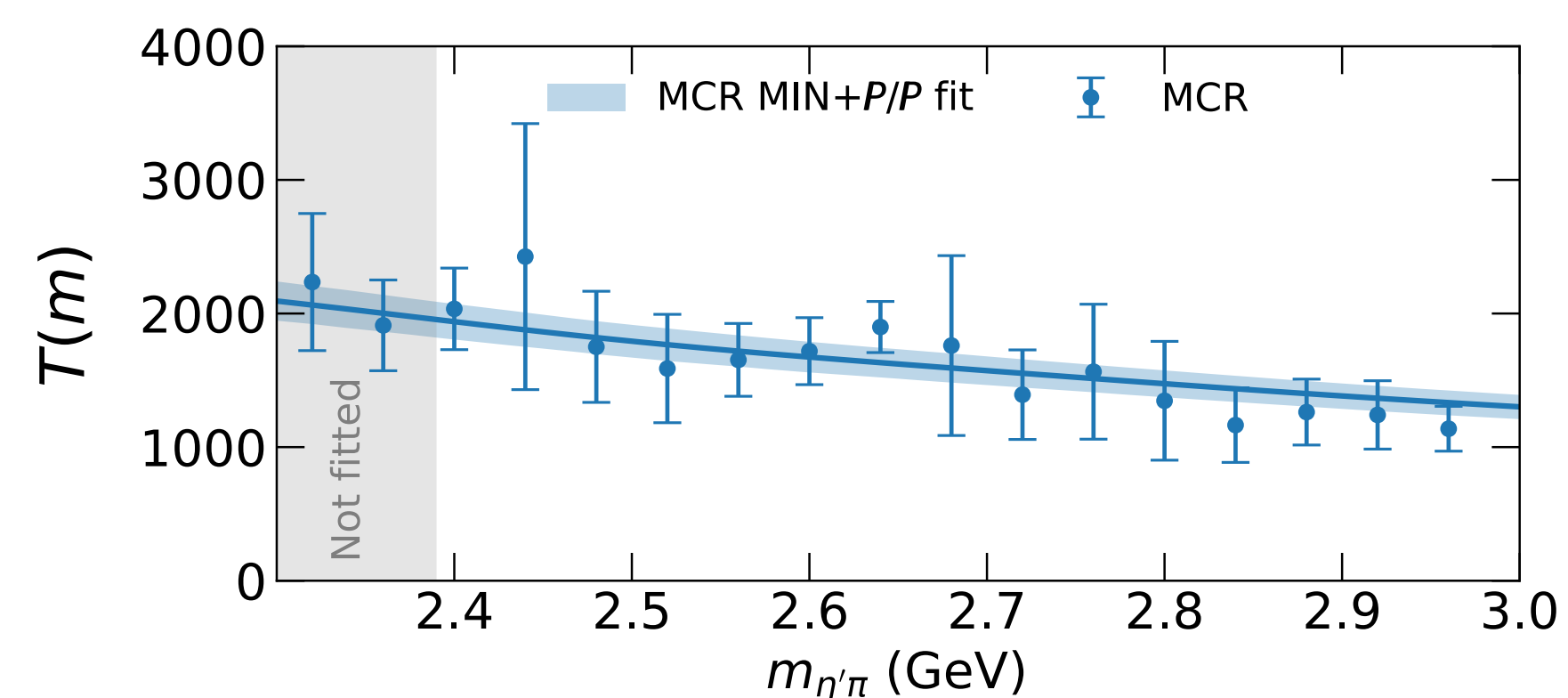
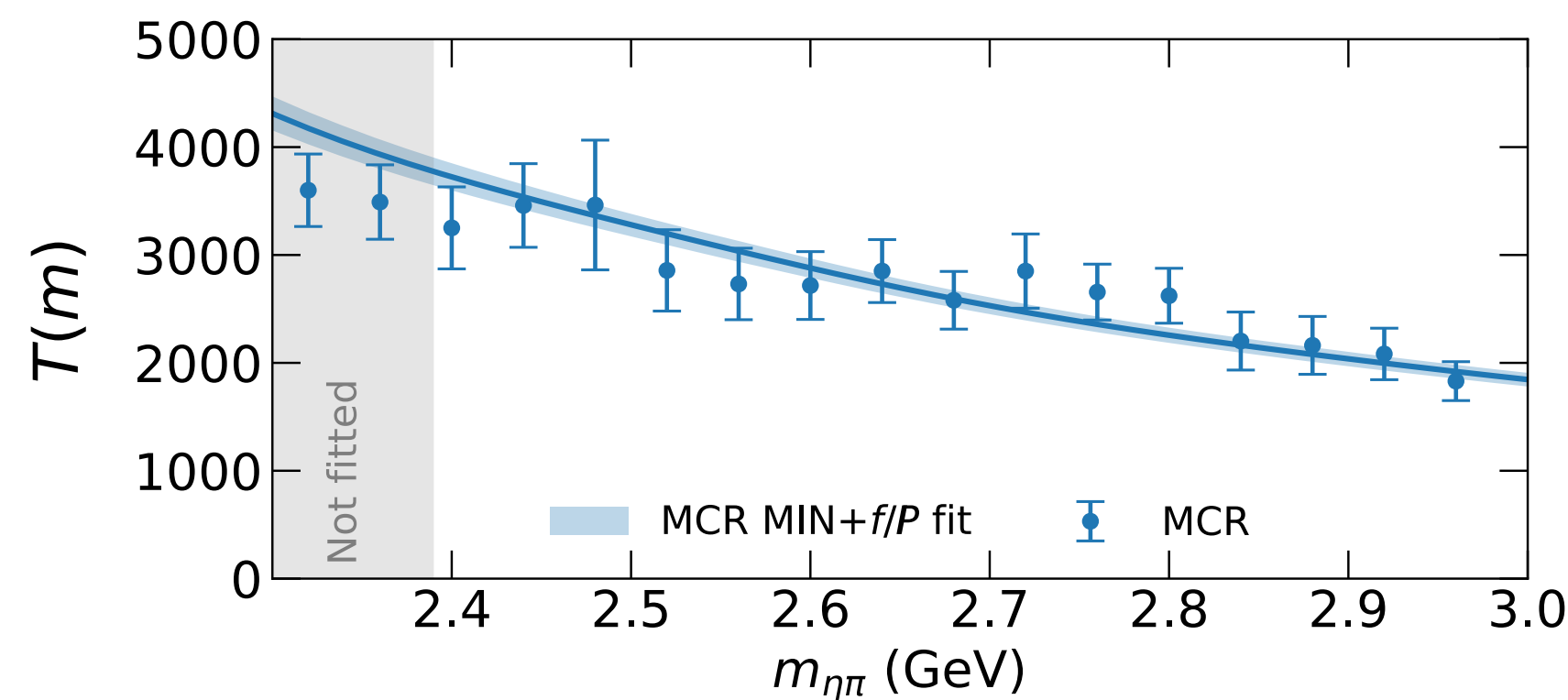
Forward intensity
 $\cos\theta \geq 0$



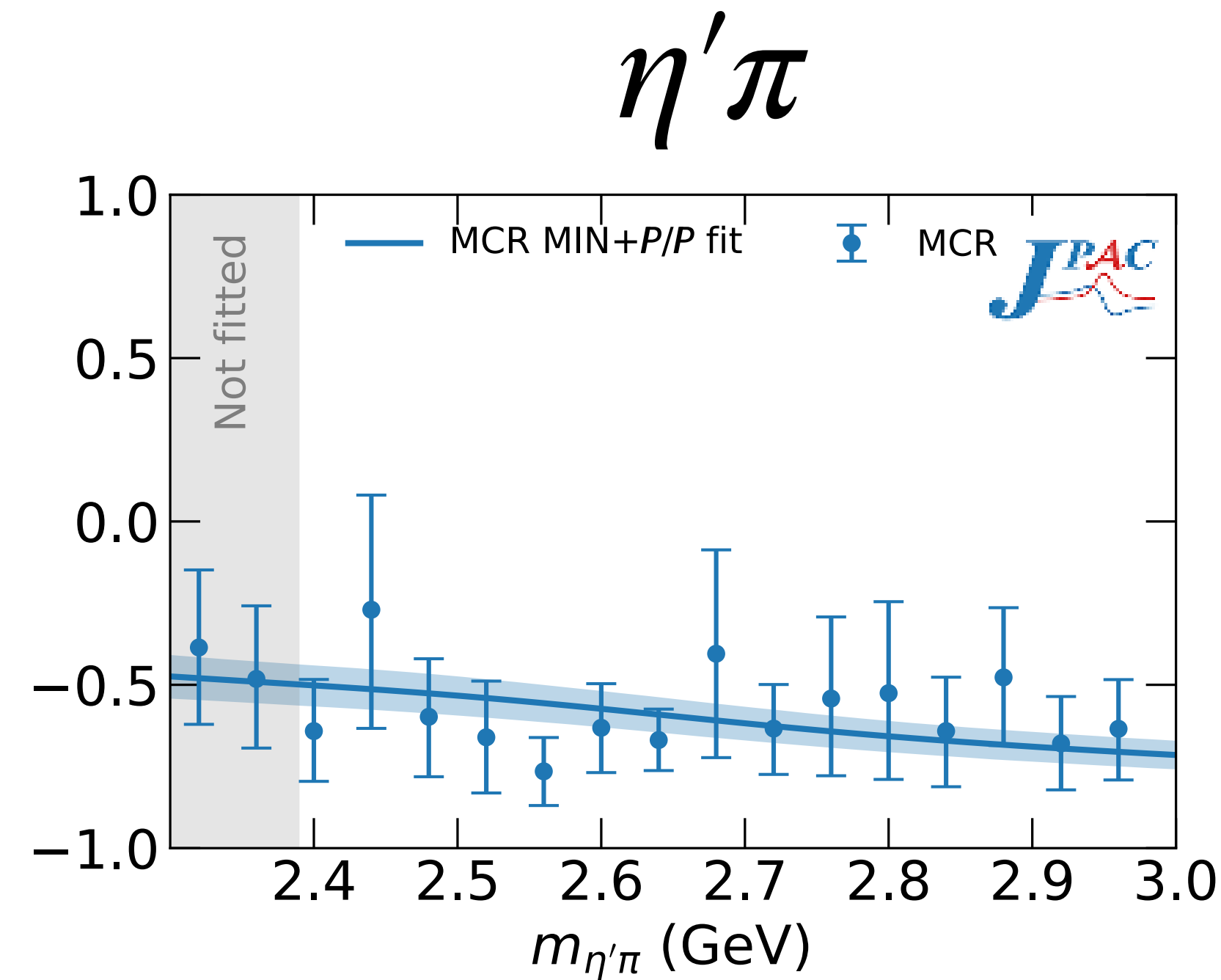
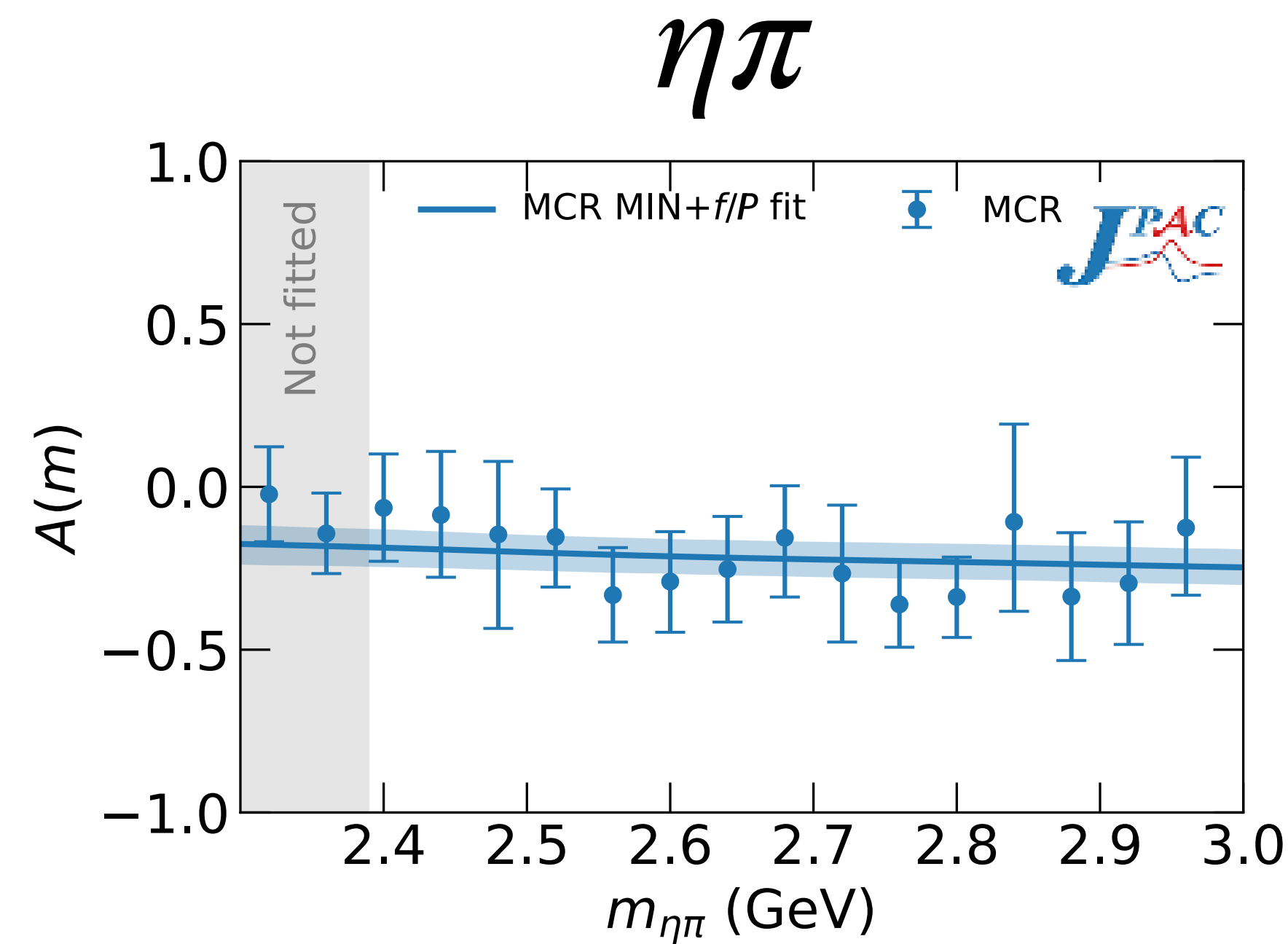
Backward intensity
 $\cos\theta \leq 0$



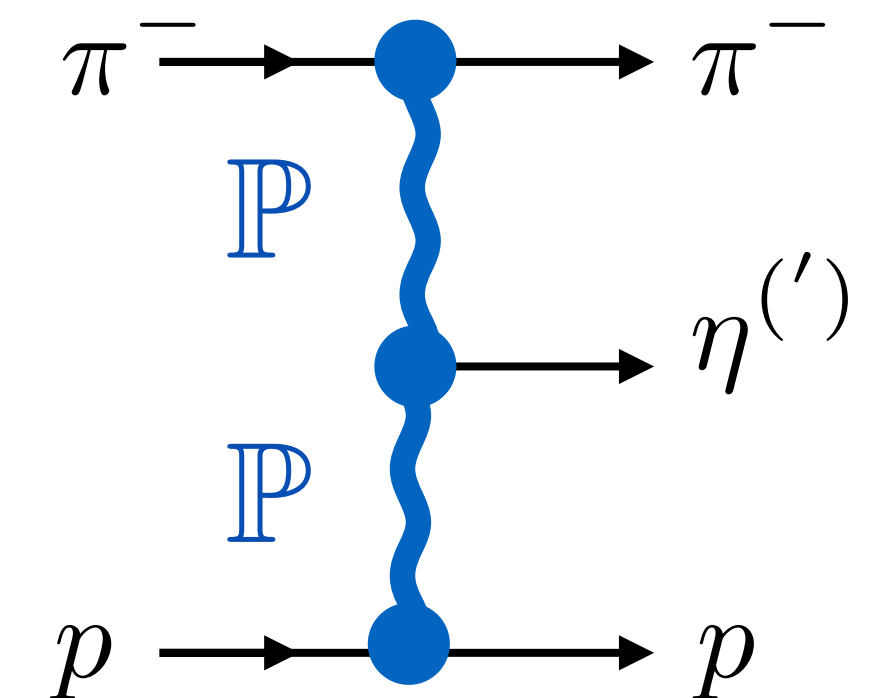
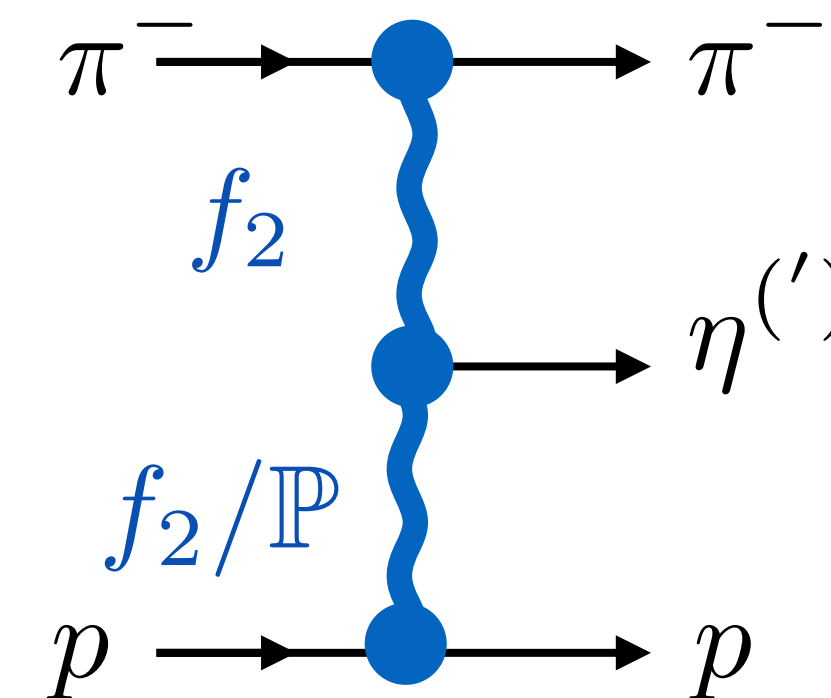
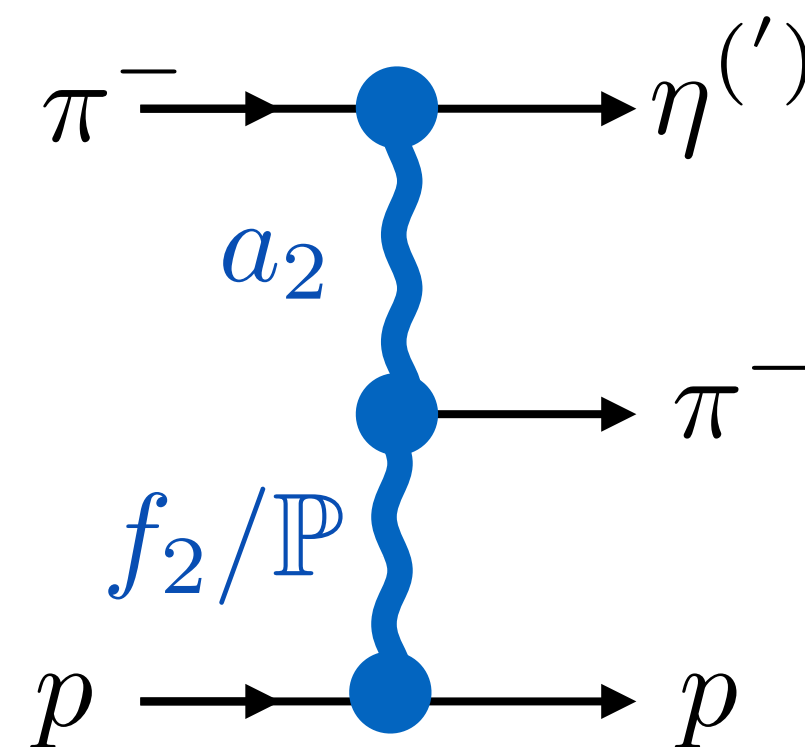
Total intensity

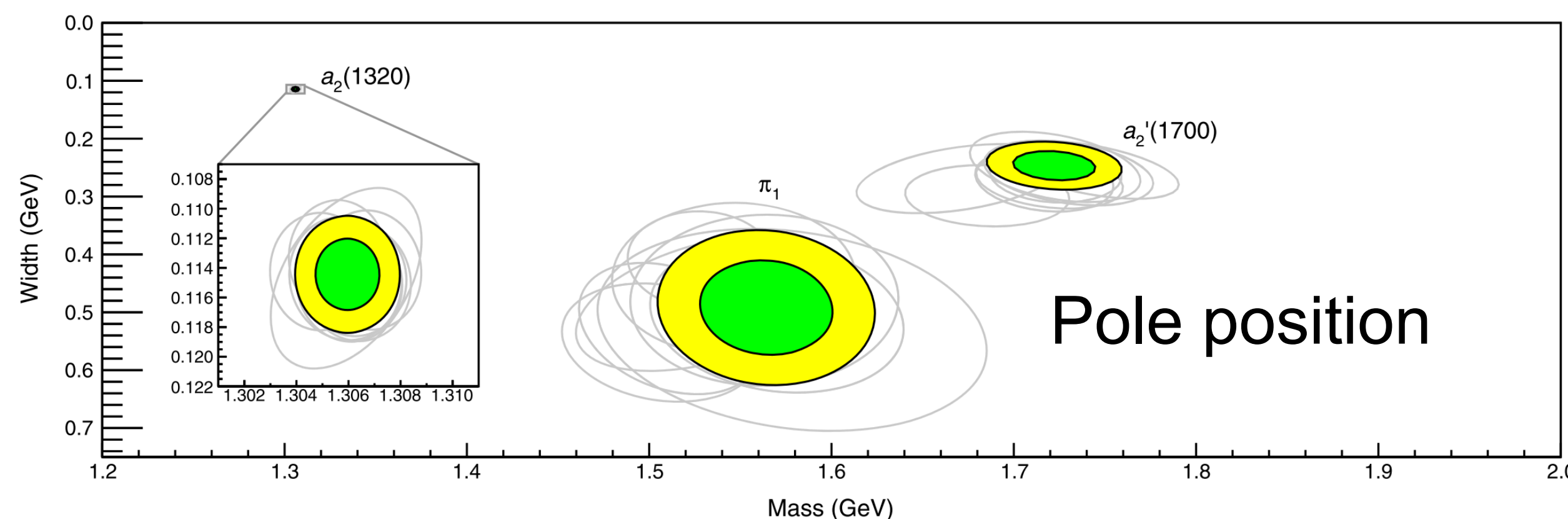
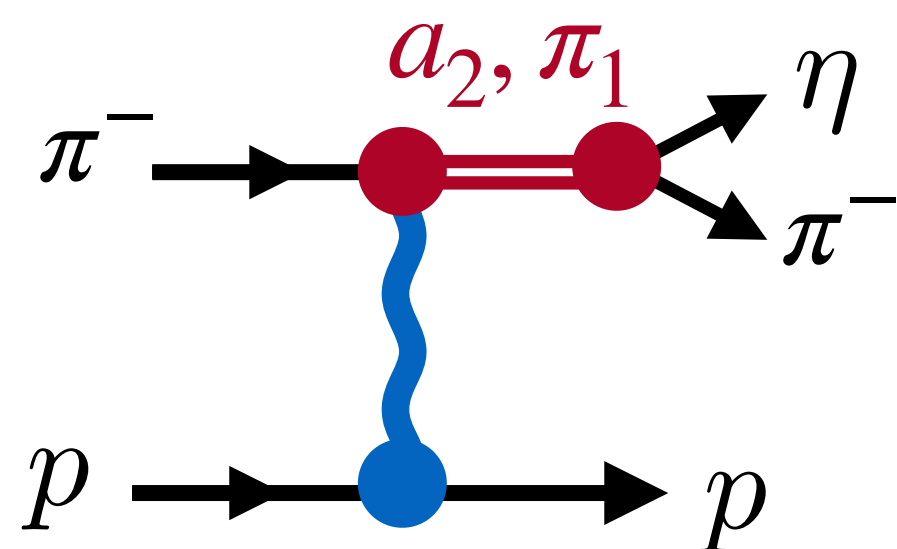
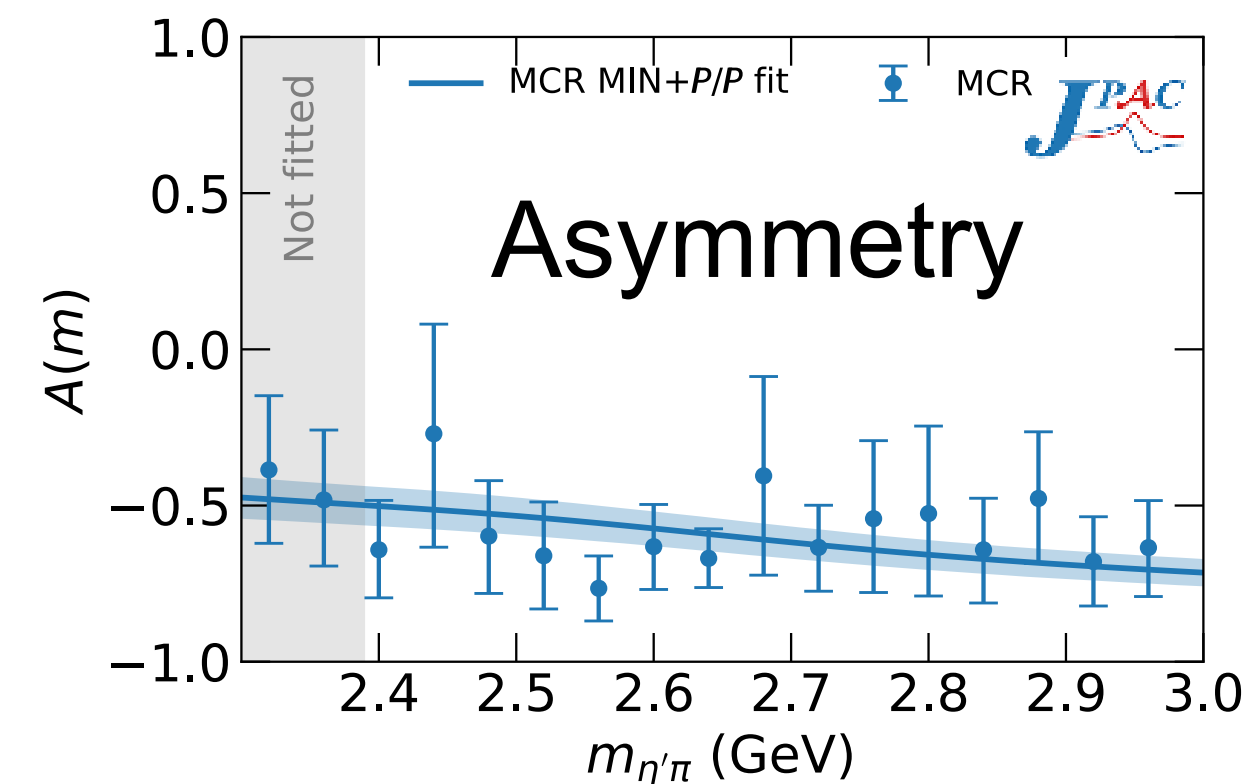
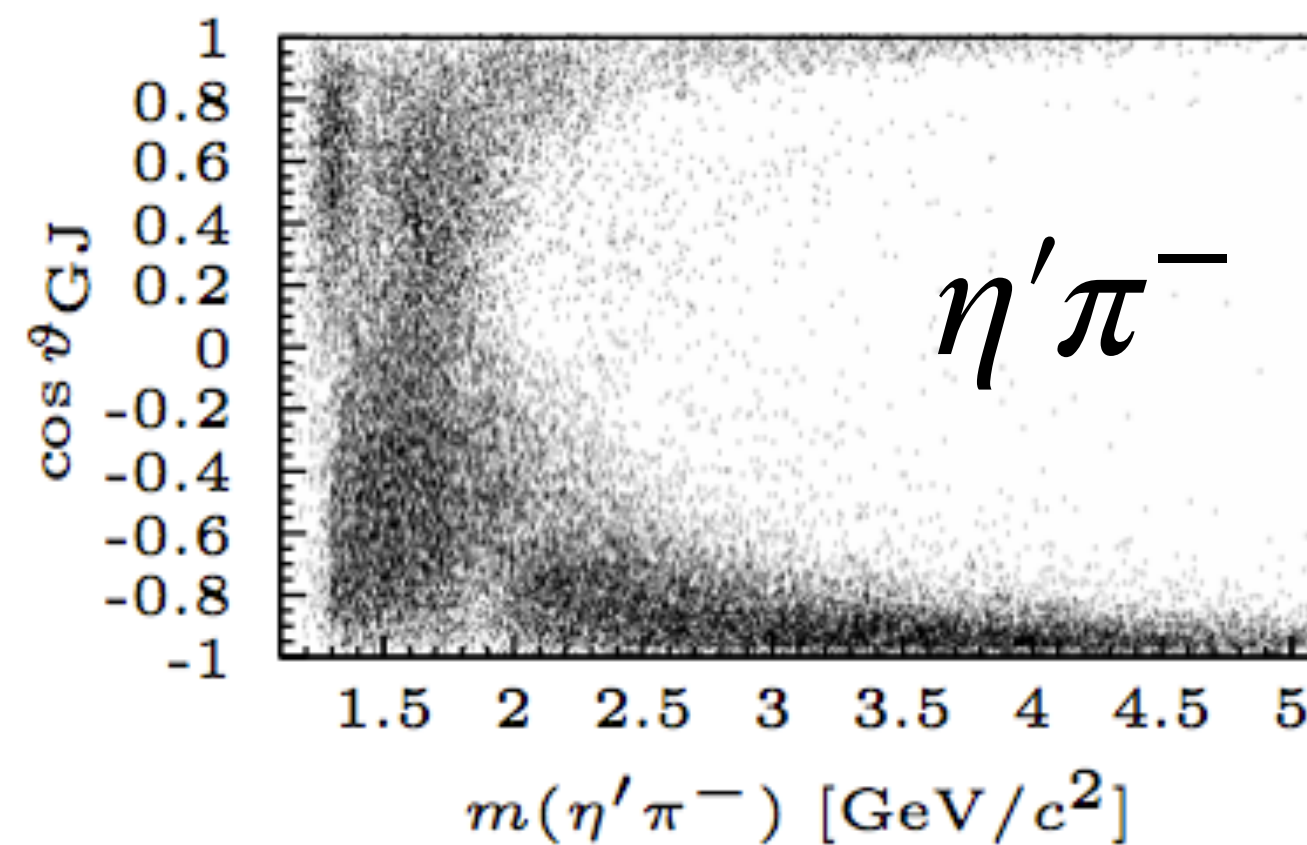
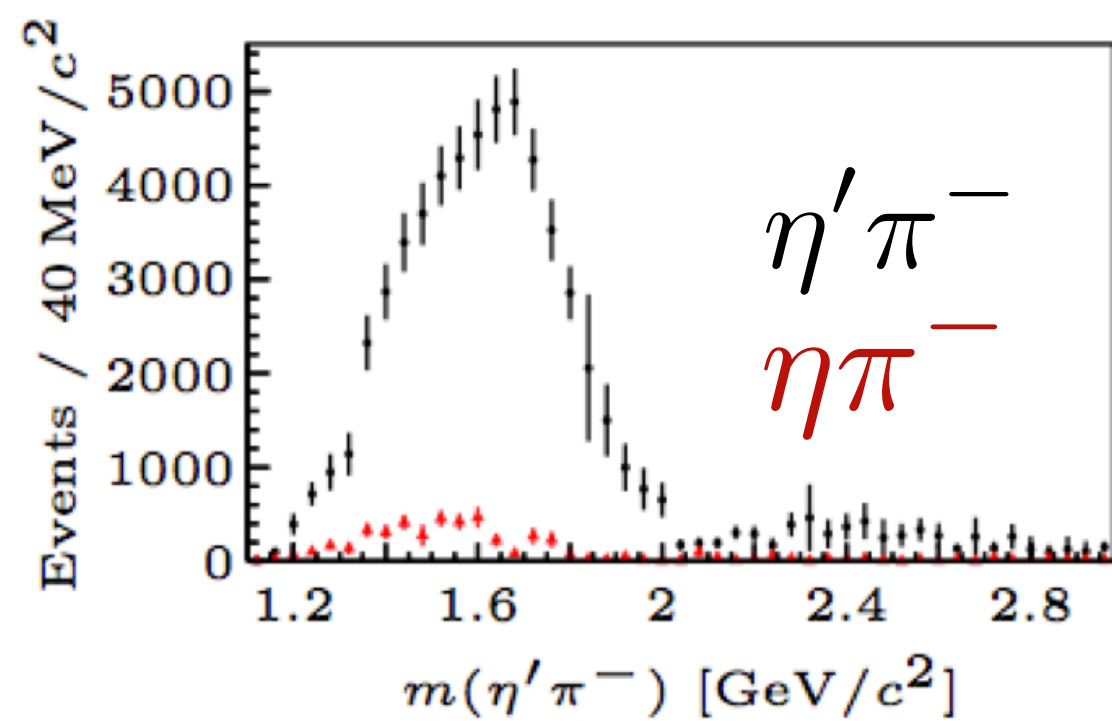


$$A = \frac{\text{Forward} - \text{Backward}}{\text{Forward} + \text{Backward}}$$



Asymmetry originating mainly from $(a_2, f_2/\mathbb{P}) \neq (f_2, f_2/\mathbb{P})$ and from (\mathbb{P}, \mathbb{P}) in $\eta'\pi$





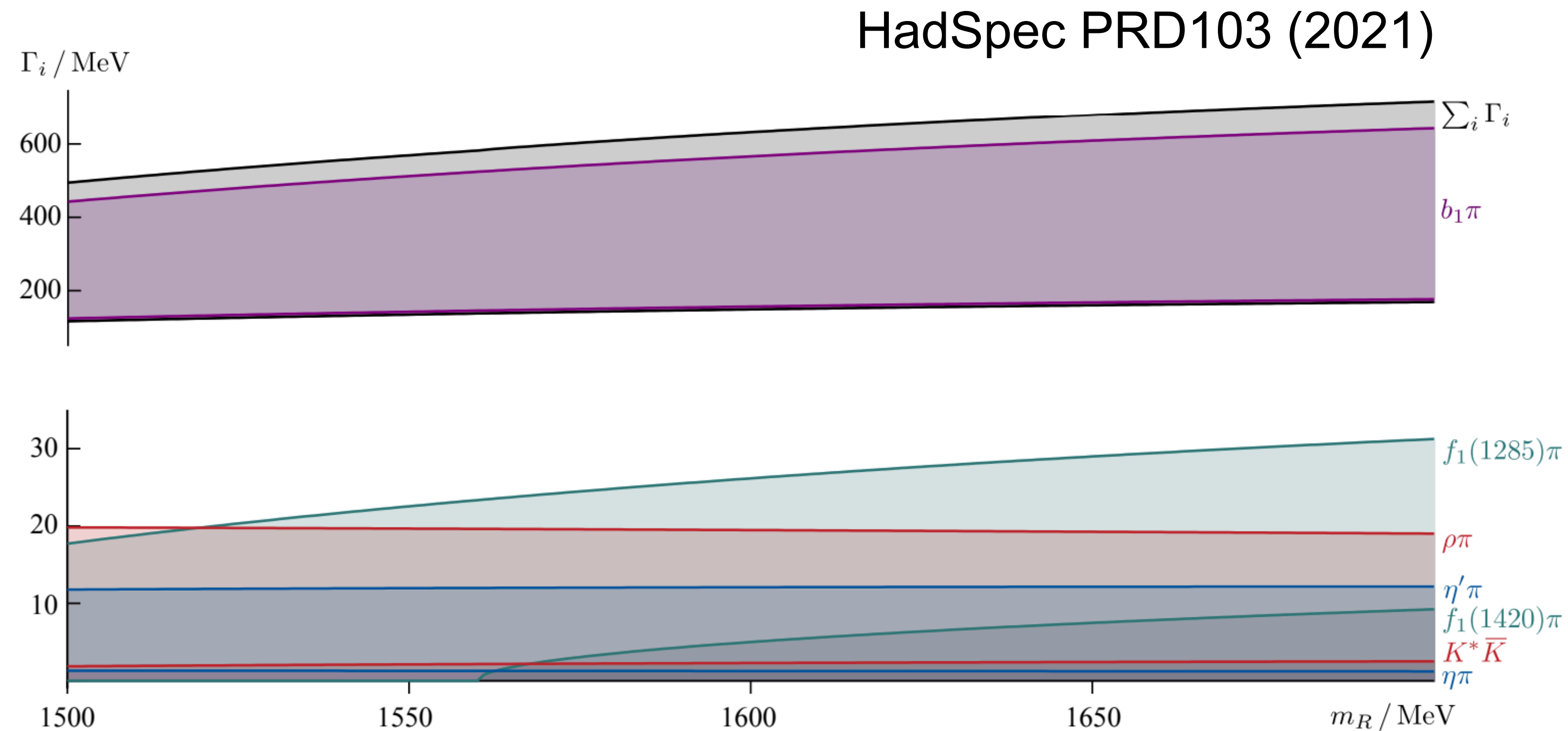
Impose dispersion relations between resonance region and double diffractive region

Future Works

Does the (experimental) $\pi_1(1600)$ matches its “QCD properties”?

Biggest branching ratio: $b_1\pi$

Ongoing analyses by
COMPASS and GlueX

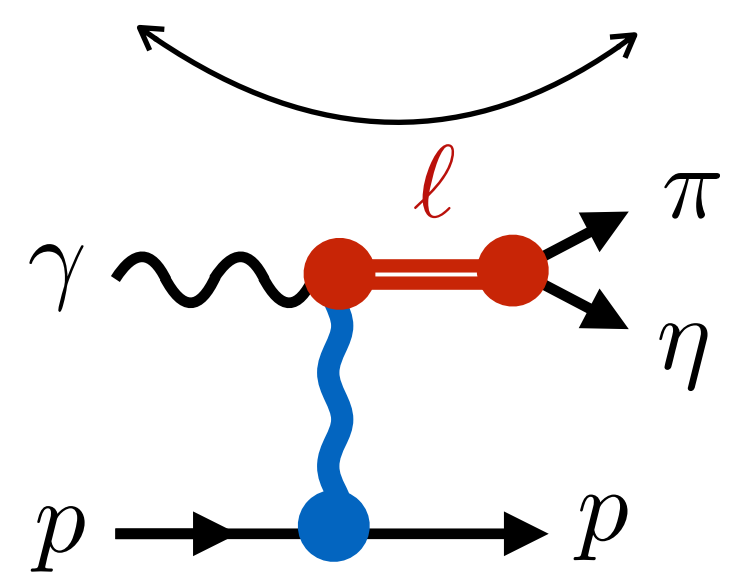
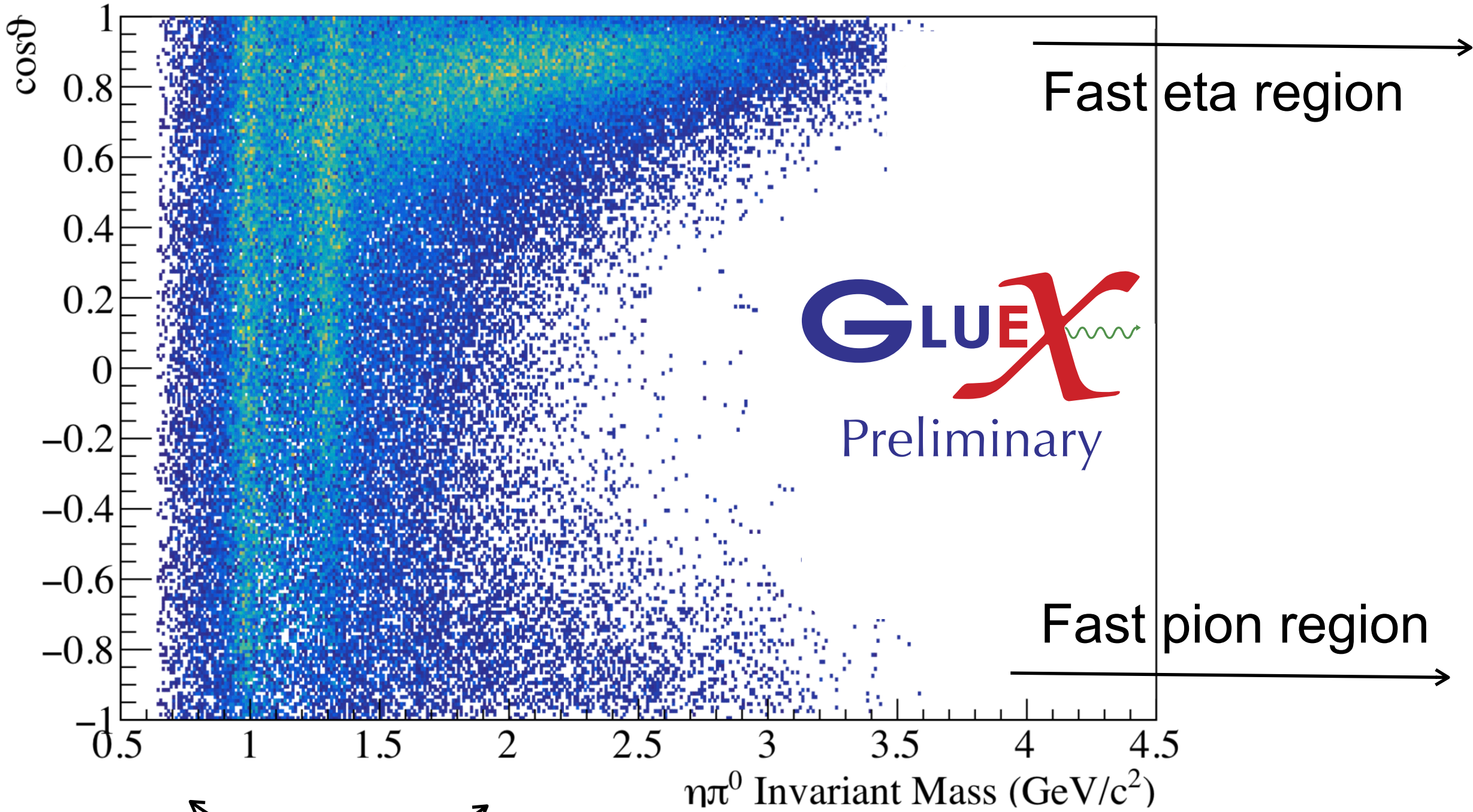


Eta-Pi @GlueX

Ongoing study with GlueX

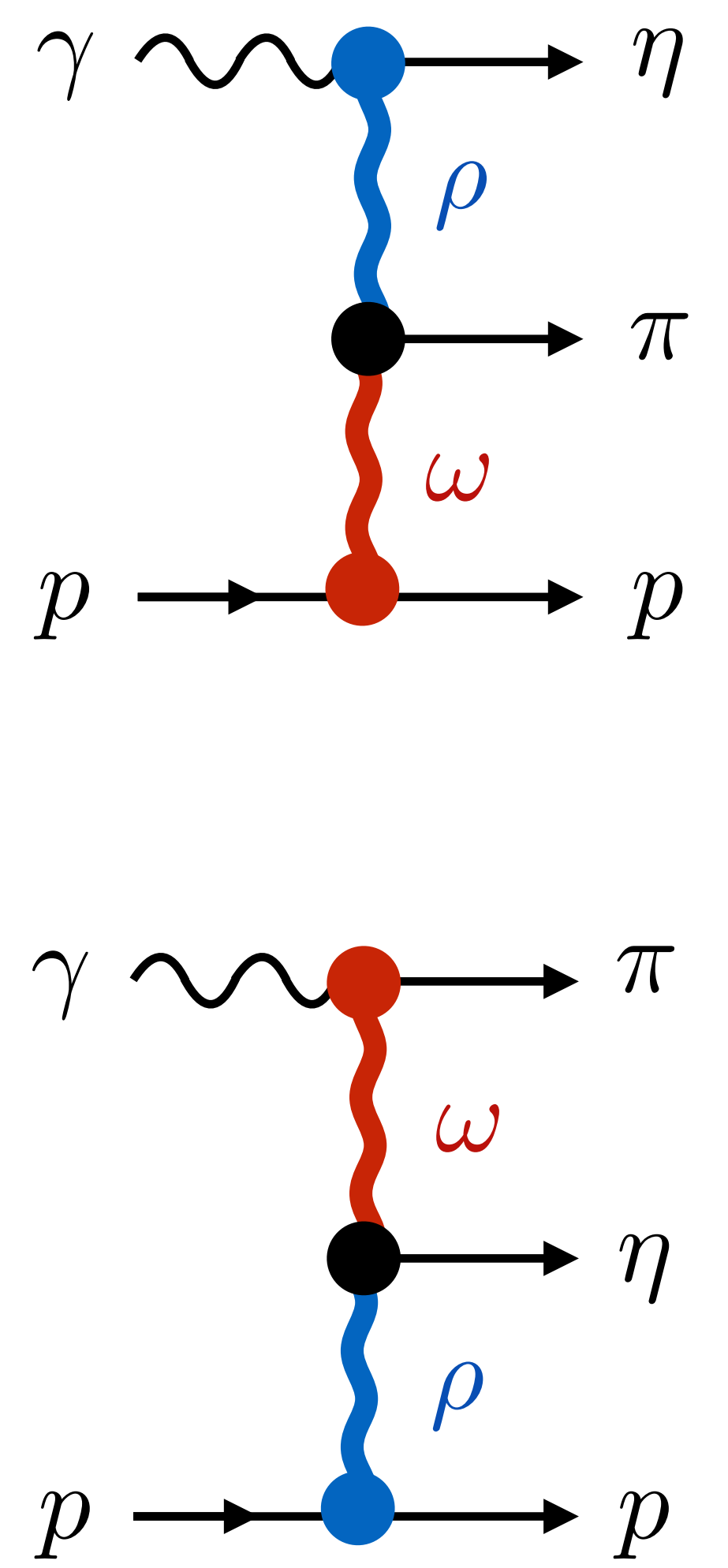
Fit data directly with double Regge amplitudes (with Barsotti and Shepherd)

Exotic mesons originate from asymmetry in the double Regge region



(not correct for detector acceptance)

dominant diagram



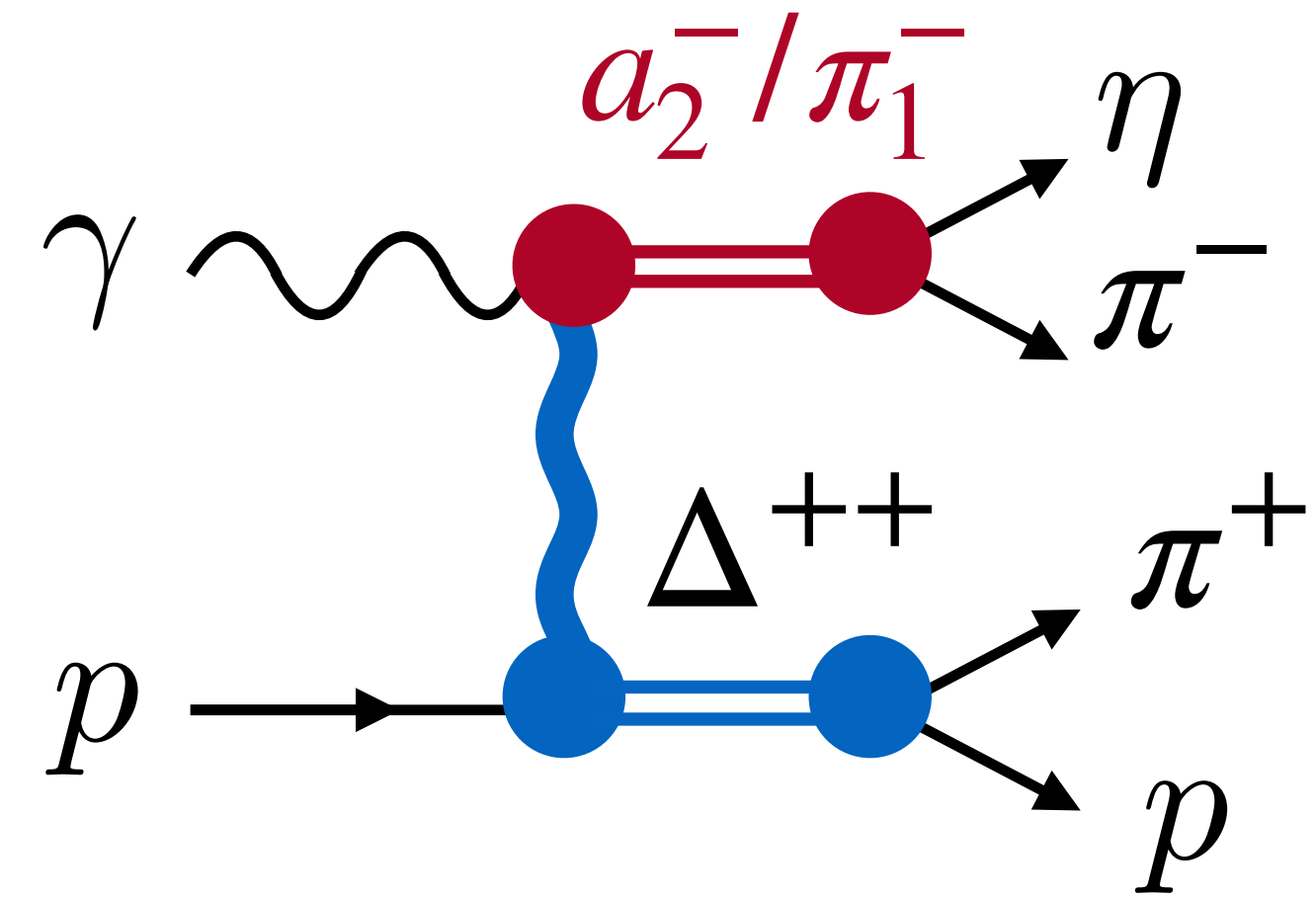
Conclusions & Future directions

Pole positions from coupled channels:

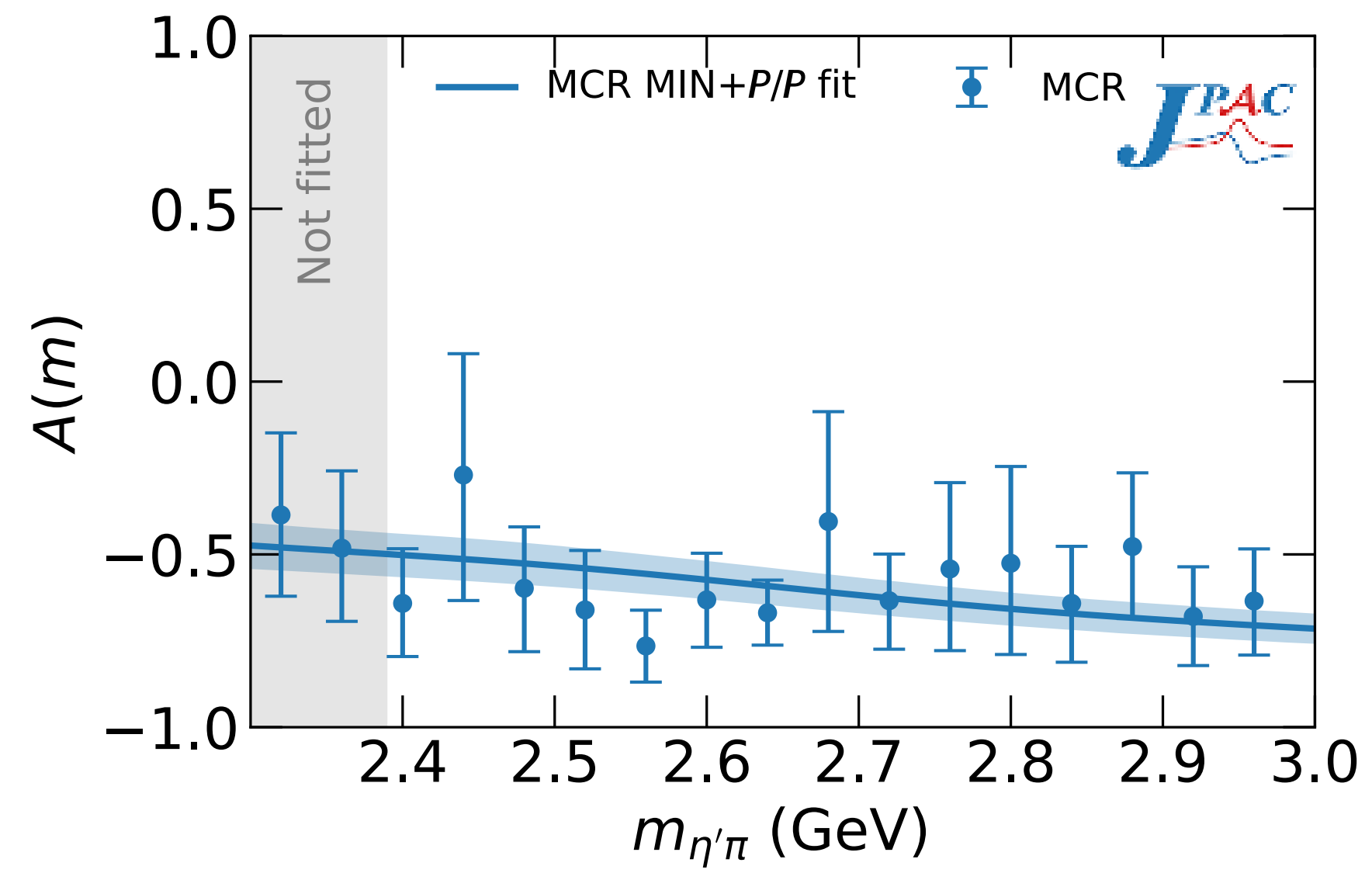
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a'_2(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

Codes available if more data available

Ongoing: charged reaction @GlueX



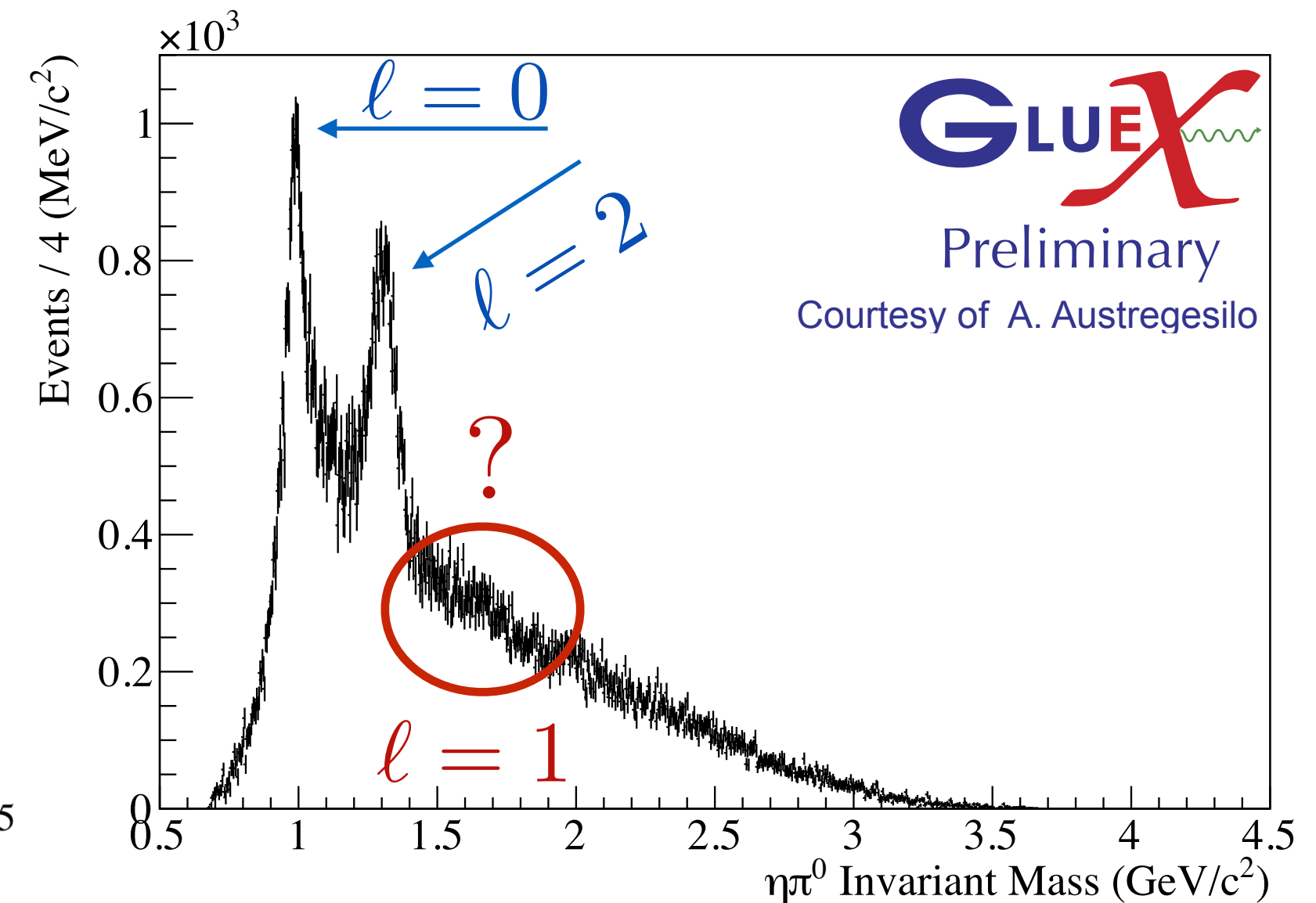
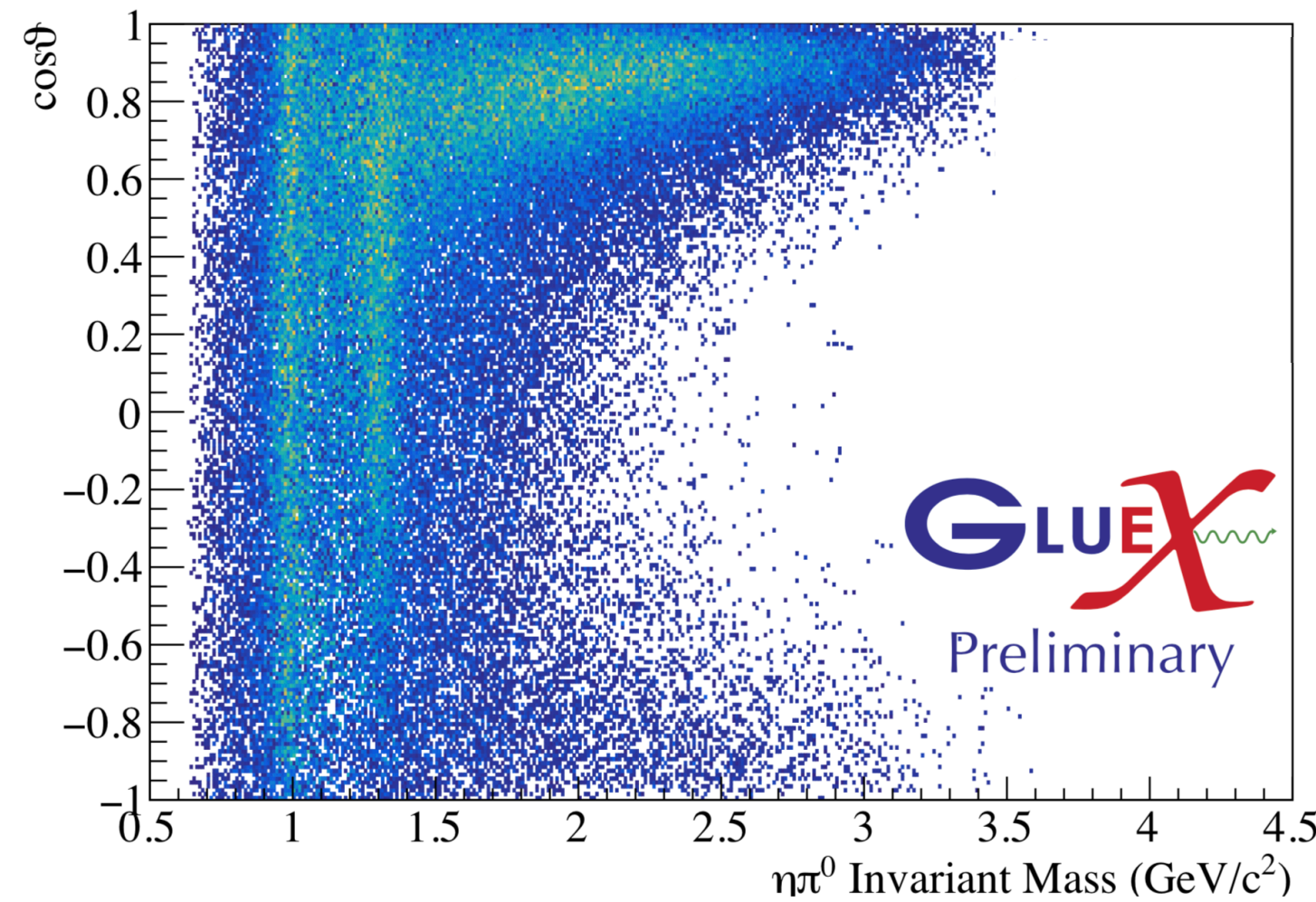
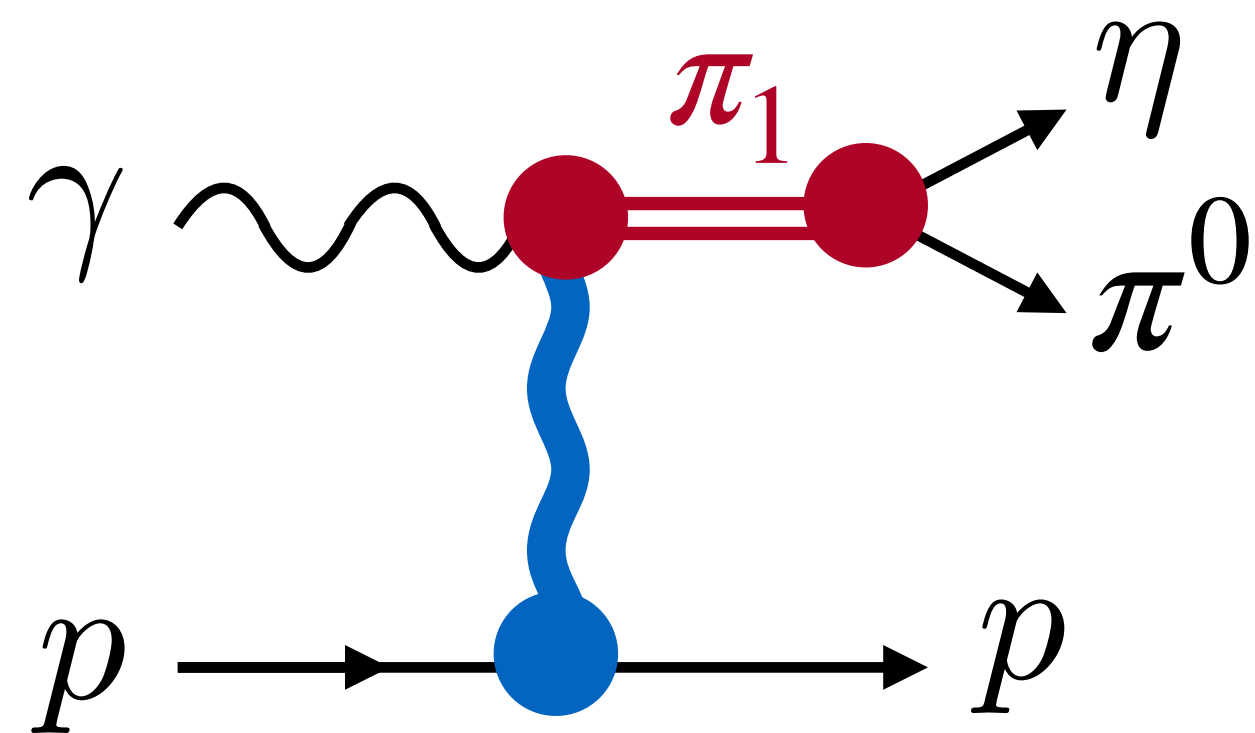
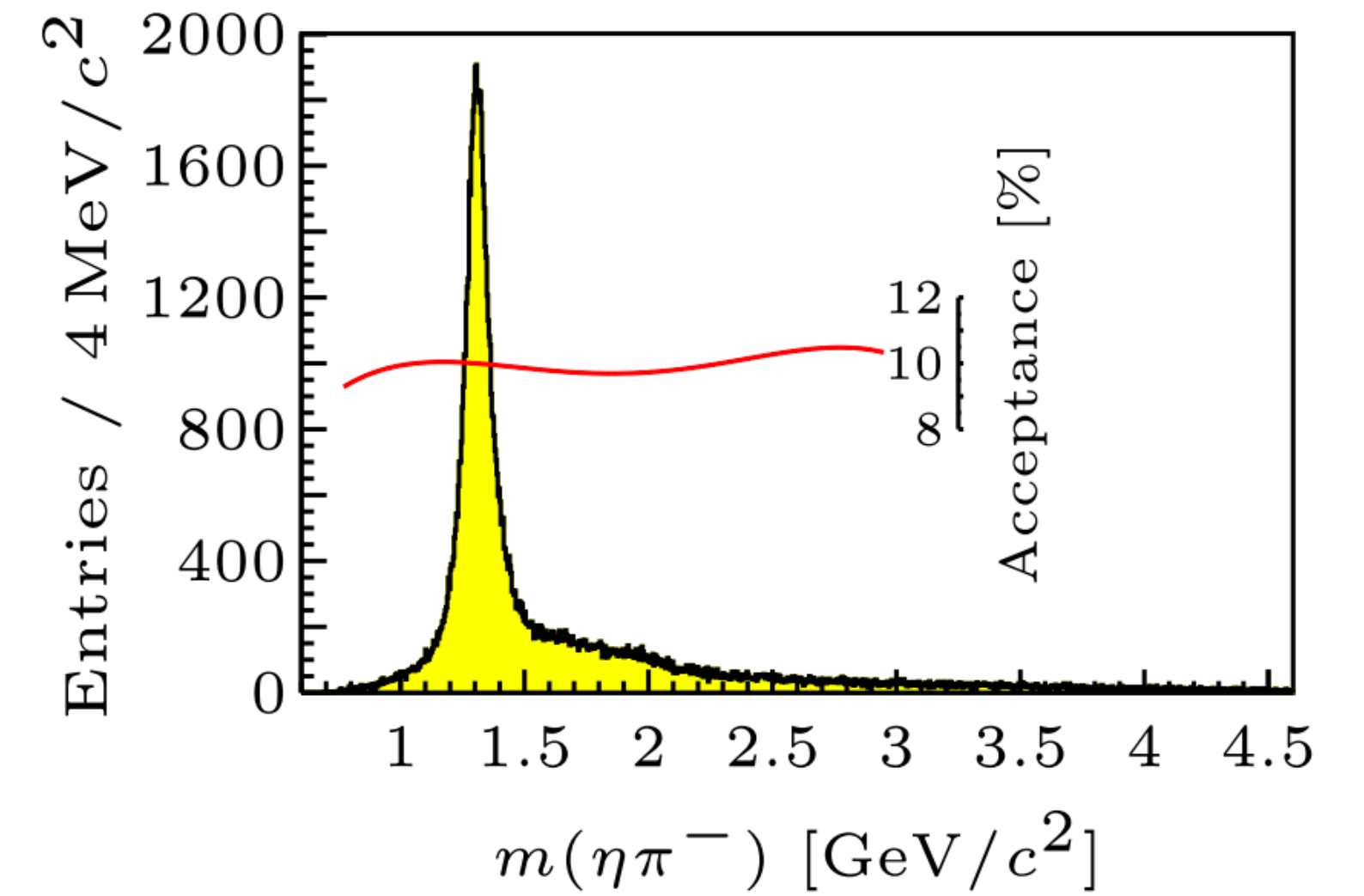
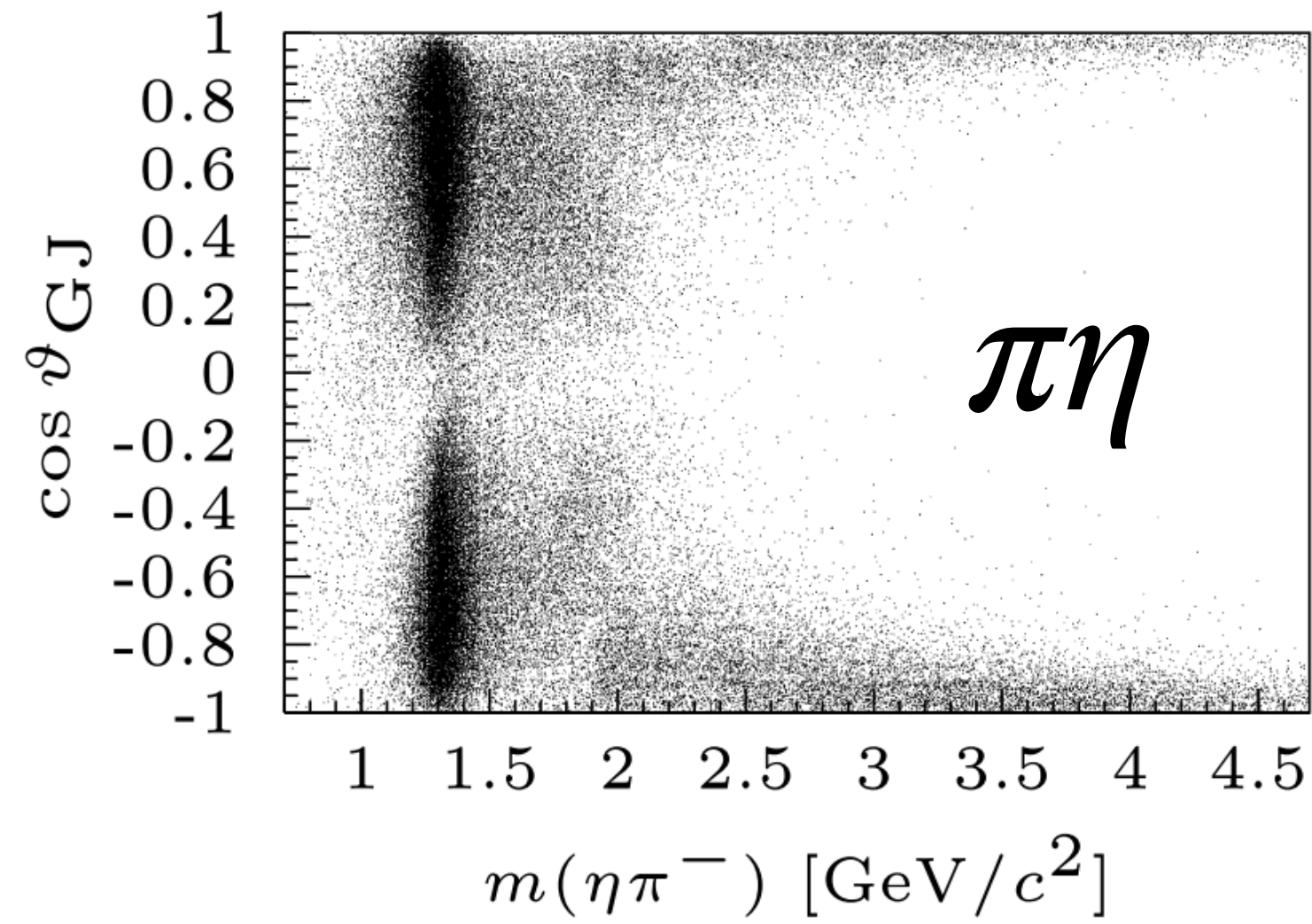
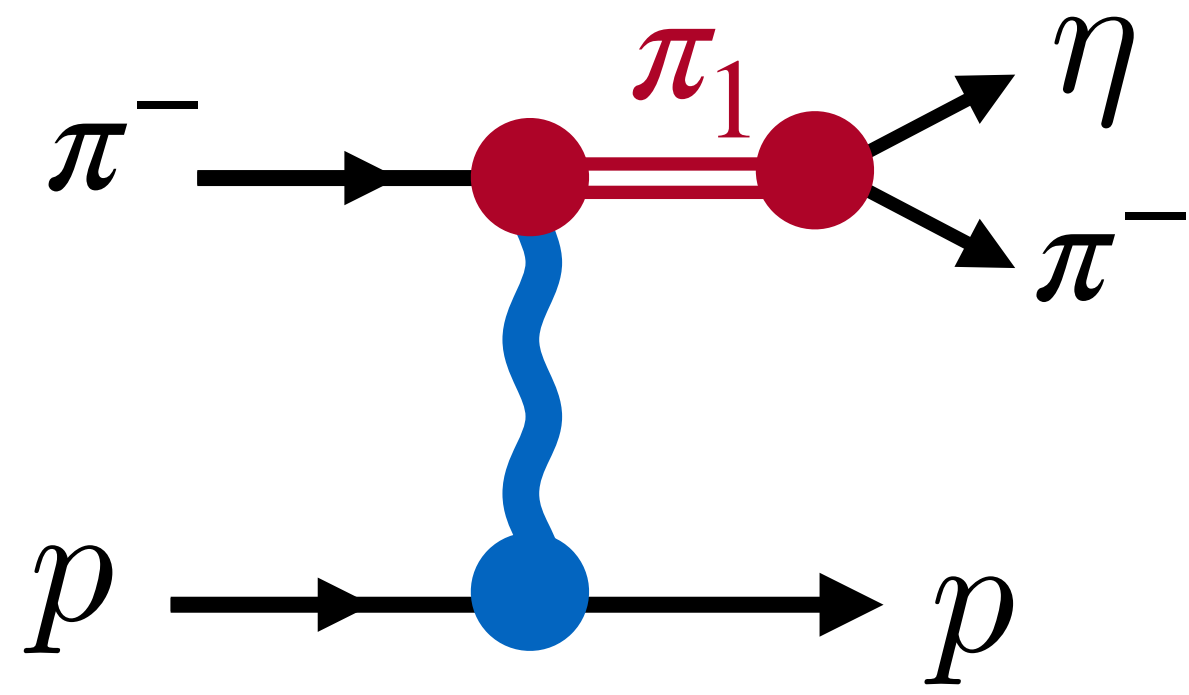
Asymmetry originating mainly from $(a_2, f_2/\mathbb{P}) \neq (f_2, f_2/\mathbb{P})$ and from (\mathbb{P}, \mathbb{P}) in $\eta'\pi$



Ongoing: similar procedure for neutral reaction @GlueX

Backup Slides

Eta-Pi @COMPASS and @GlueX



Partial Waves of Double Regge Diagrams

Bibrzycki et al (JPAC) EPJC81 (2021) 915

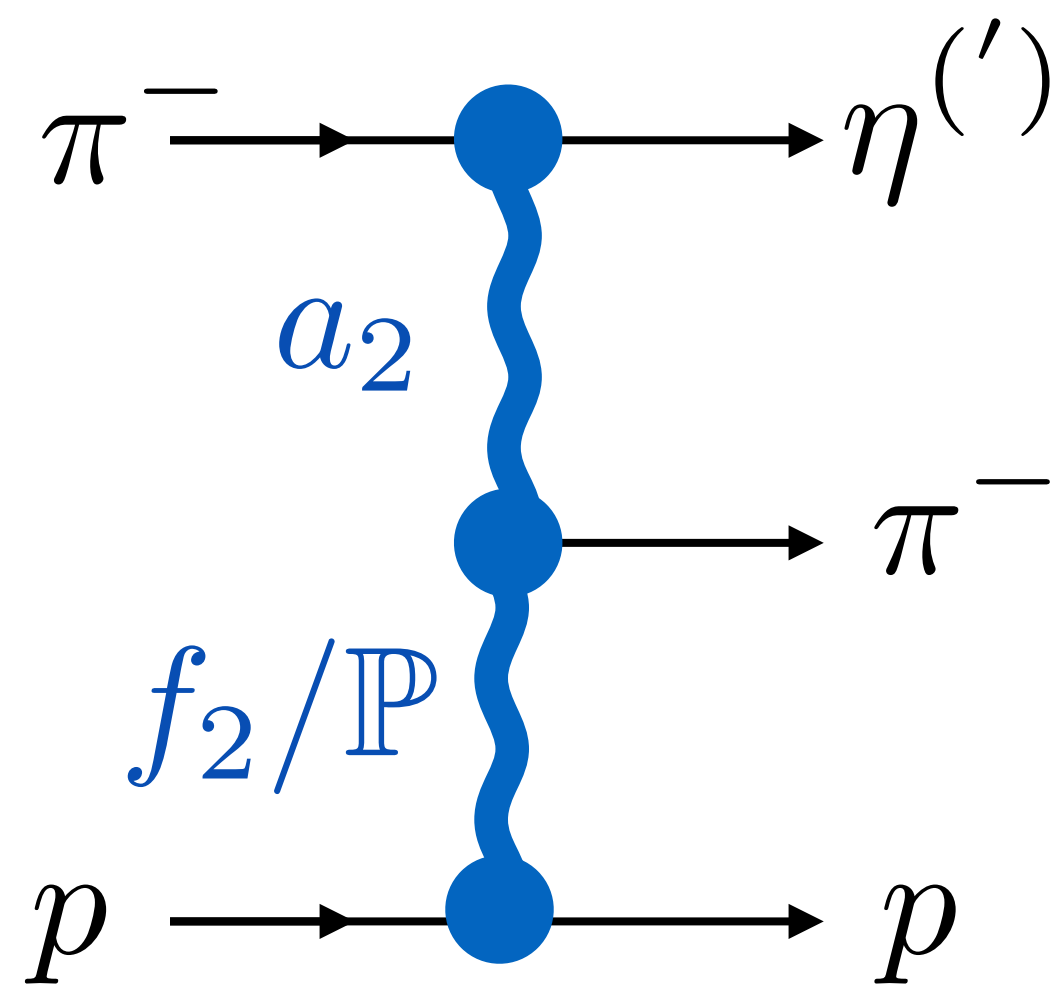
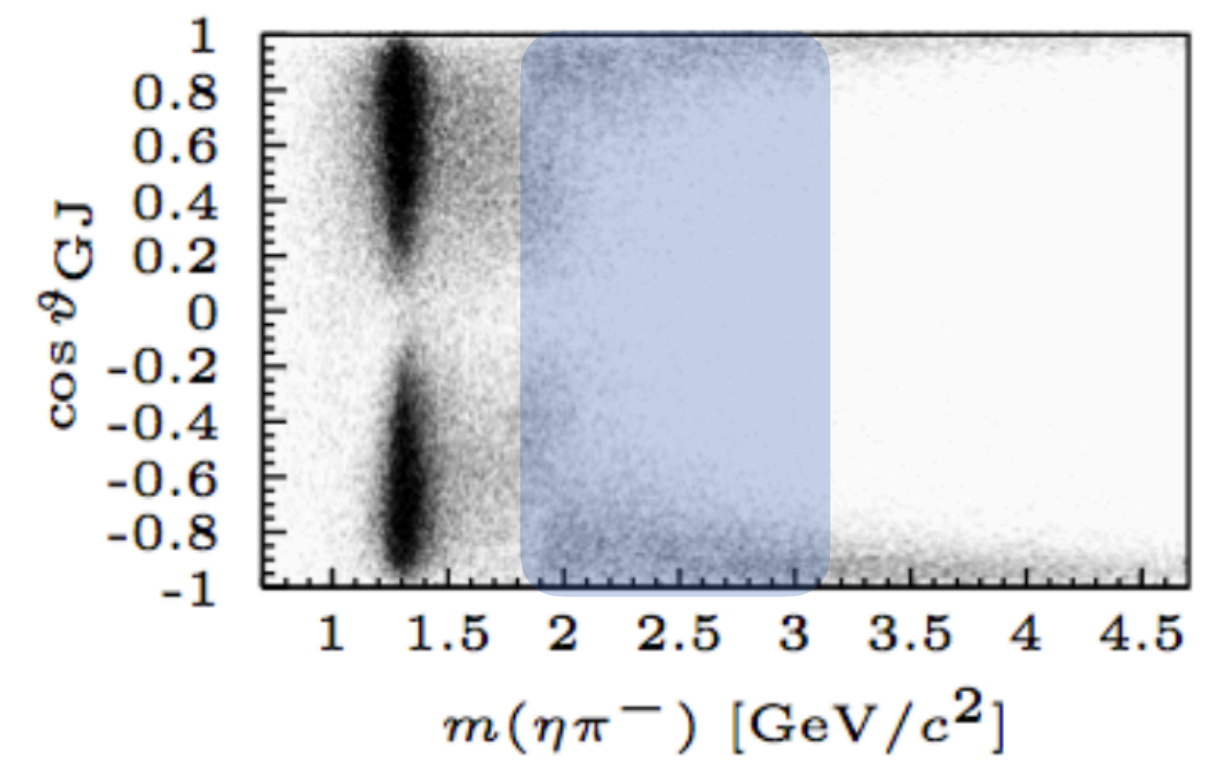
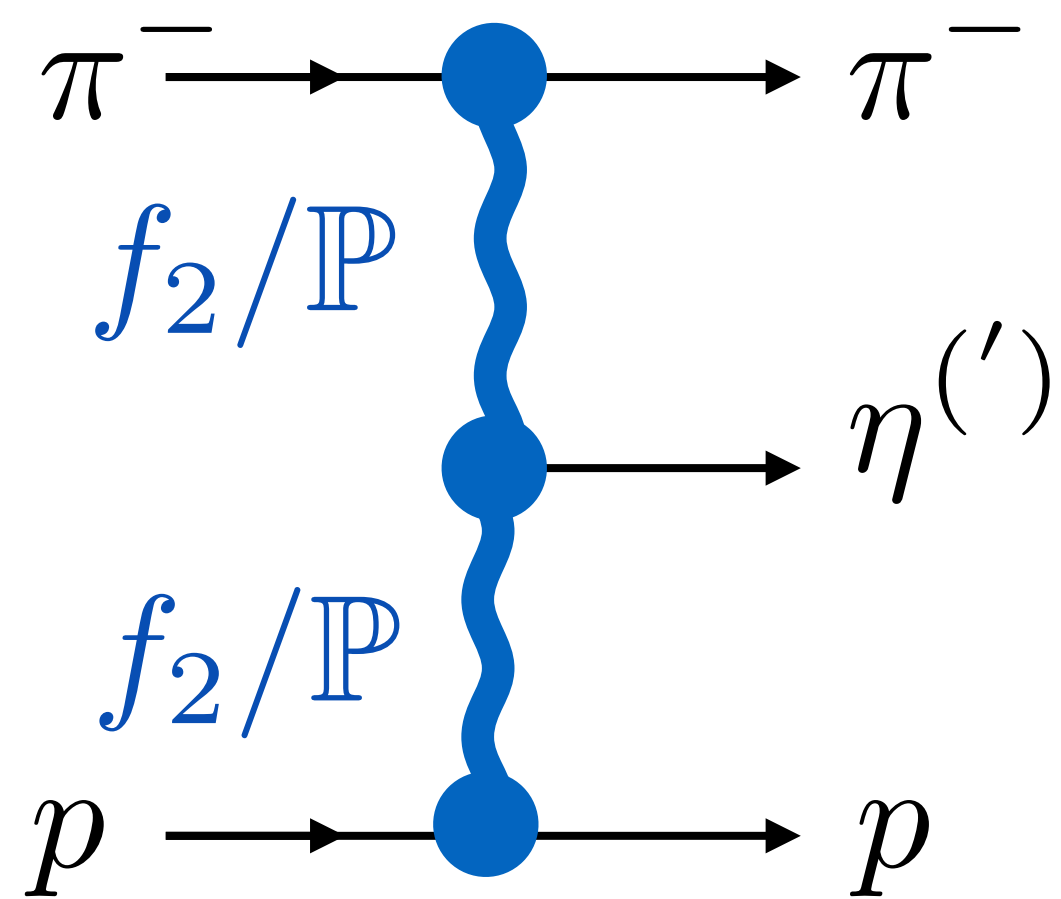


Diagram includes all partial waves

COMPASS describes intensity
with $L \leq 6$ waves



Partial Waves of Double Regge Diagrams

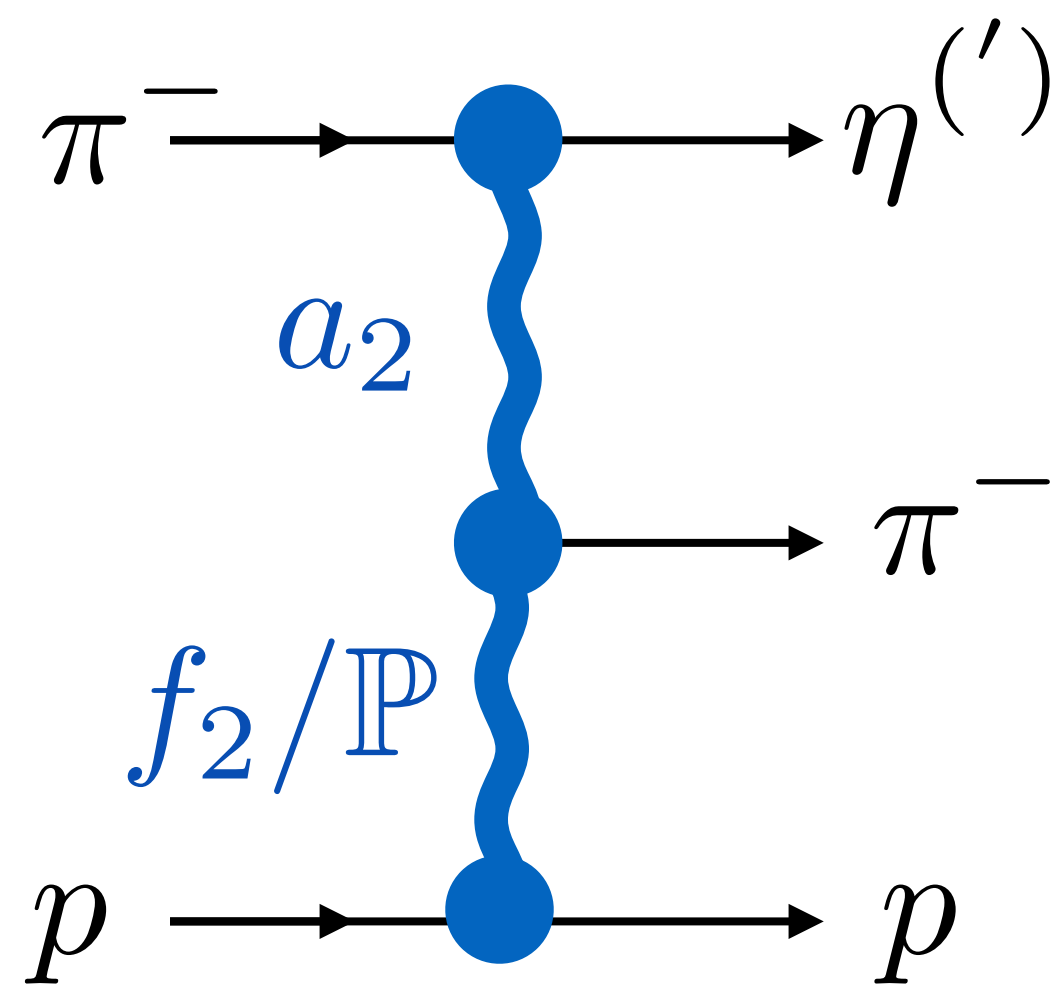
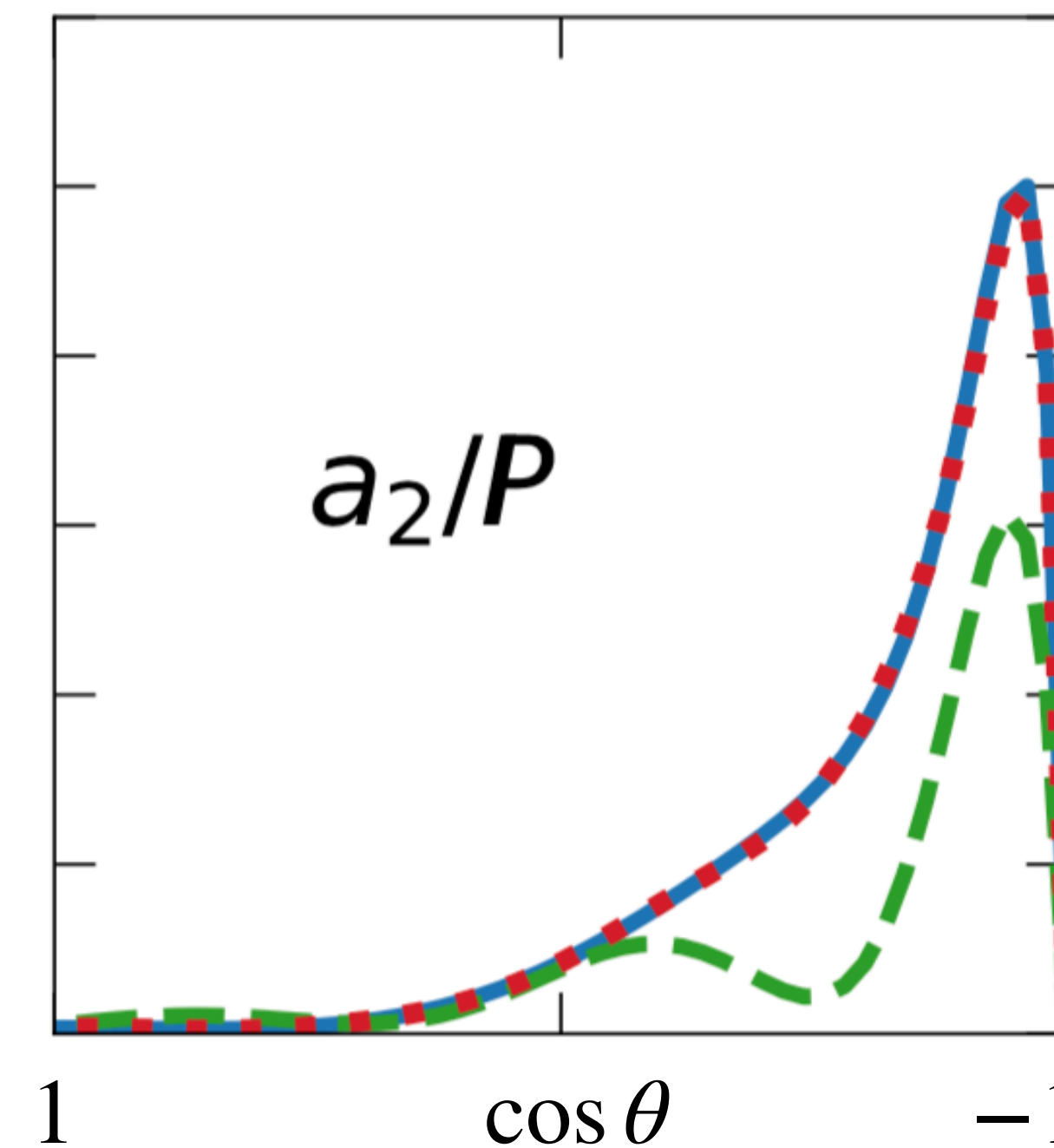
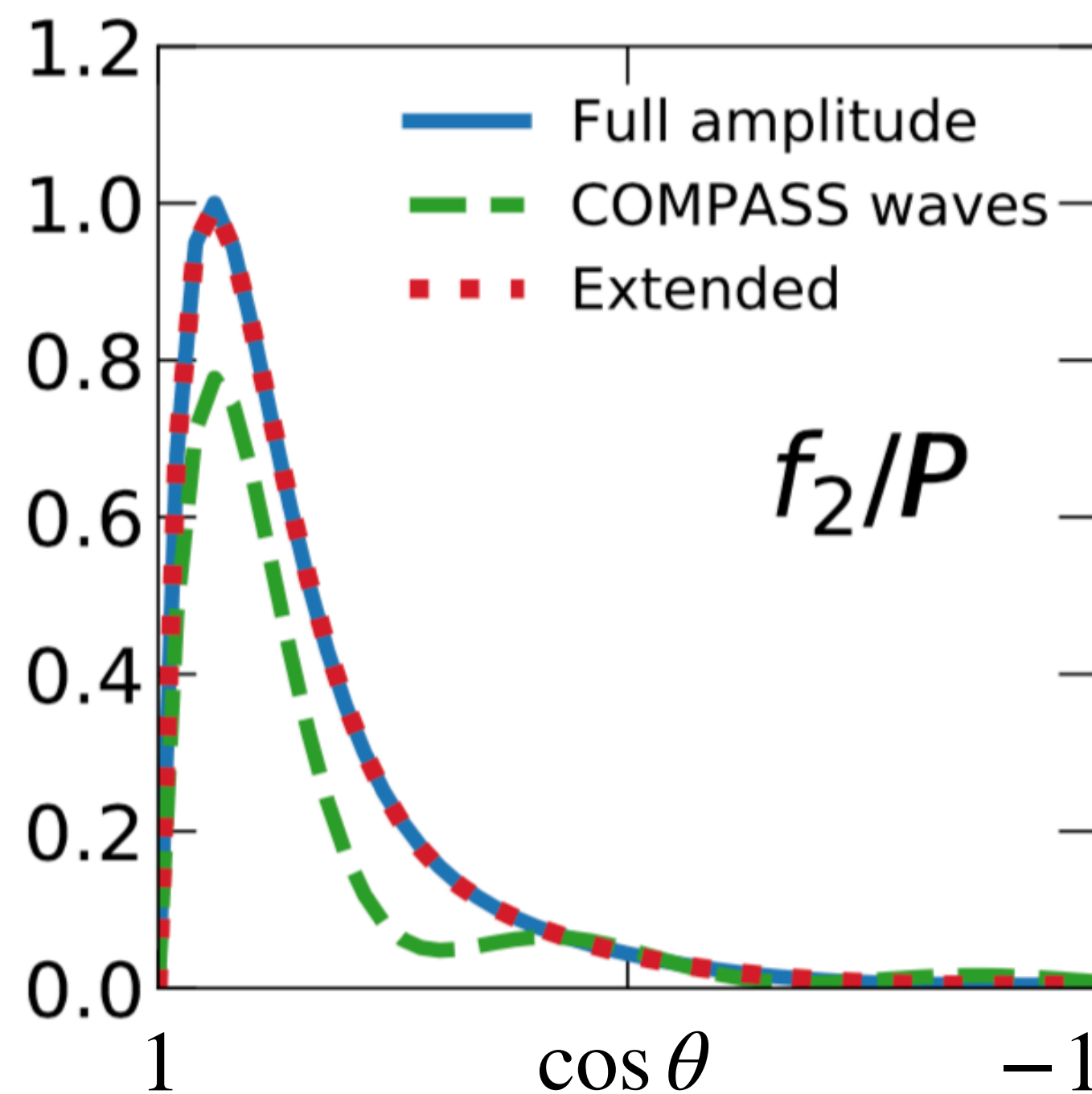
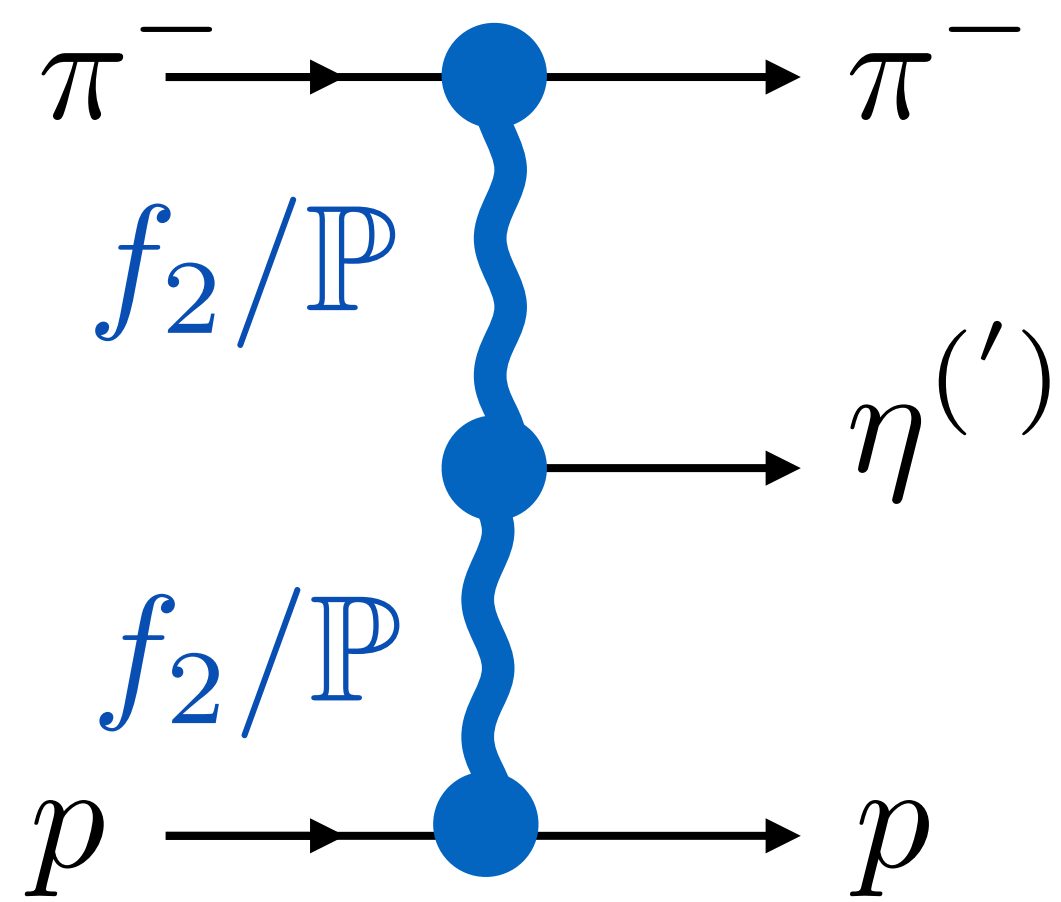
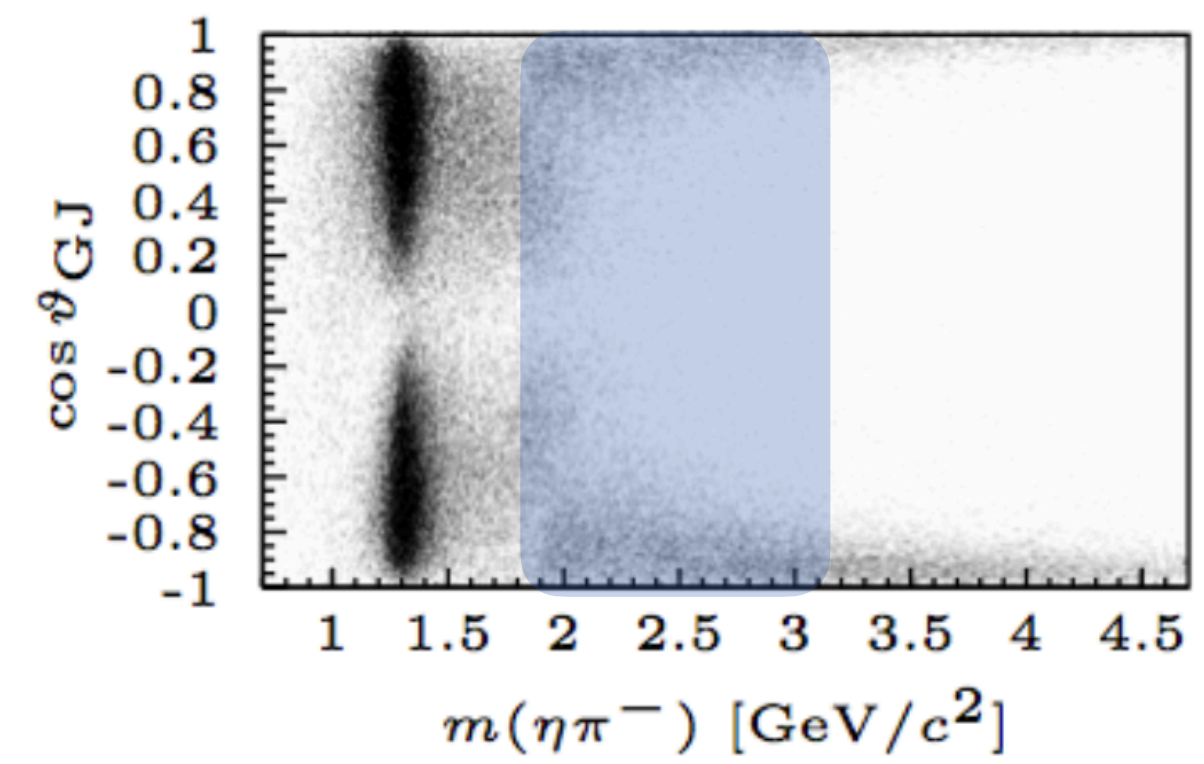


Diagram includes all partial waves

COMPASS describes intensity with $L \leq 6$ waves

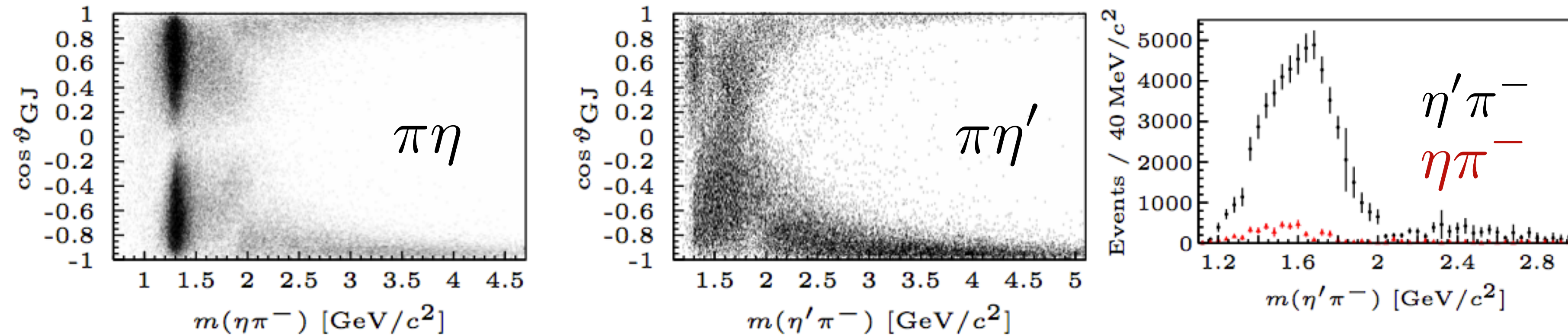
$L \leq 6$ waves only accounts for 60-80% of the diagram

→ Reconstruct intensity from partial waves

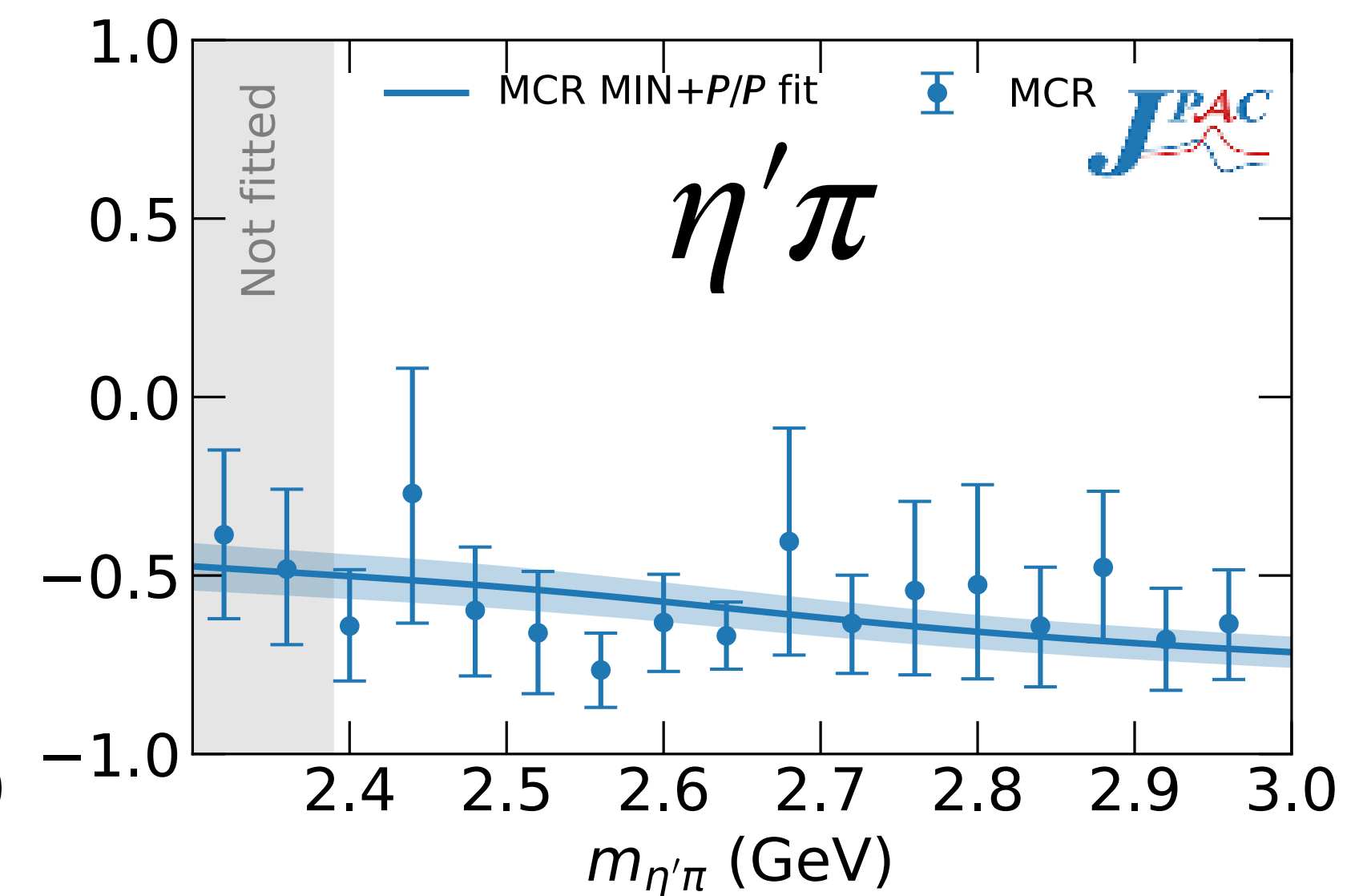
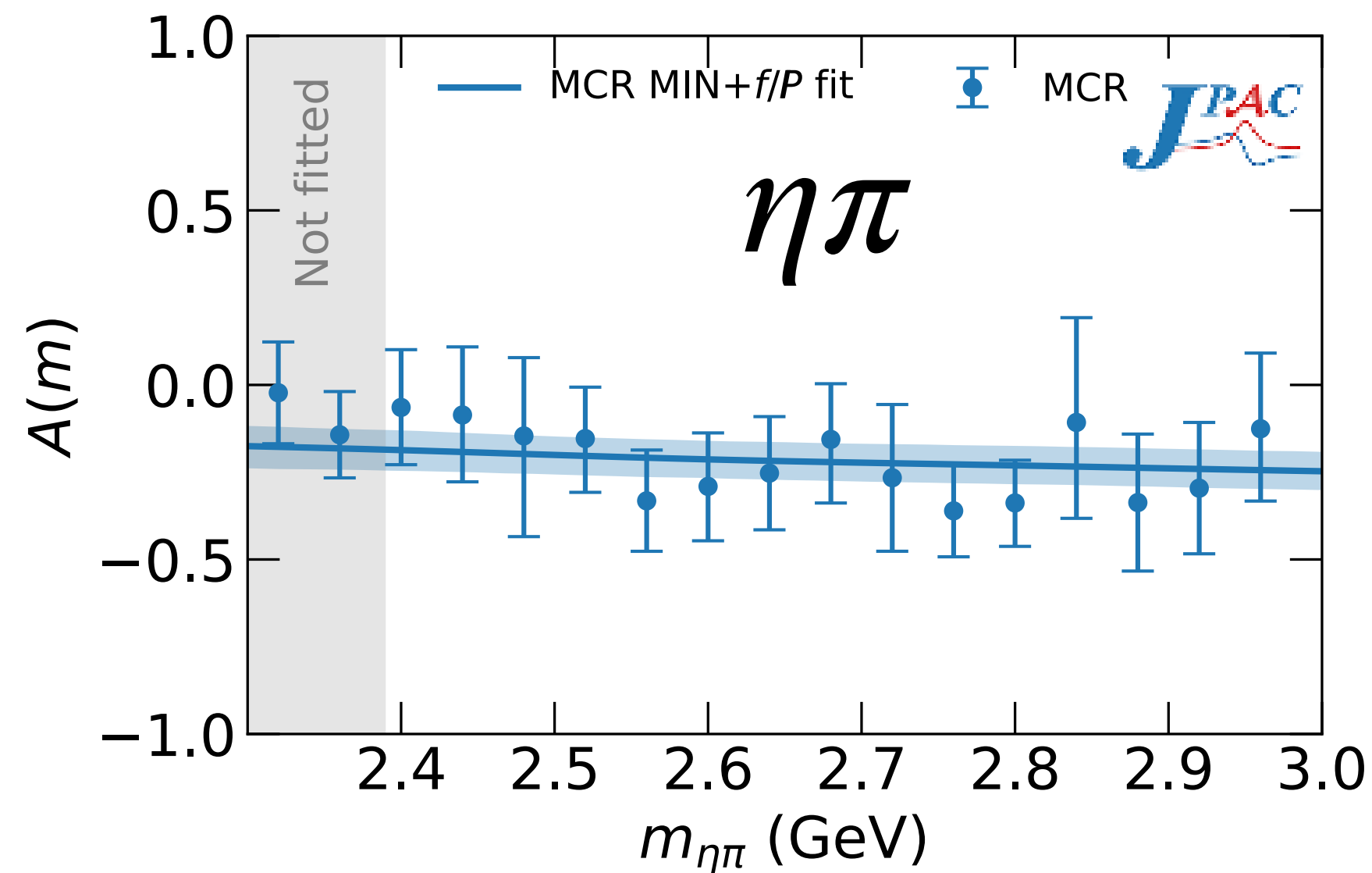
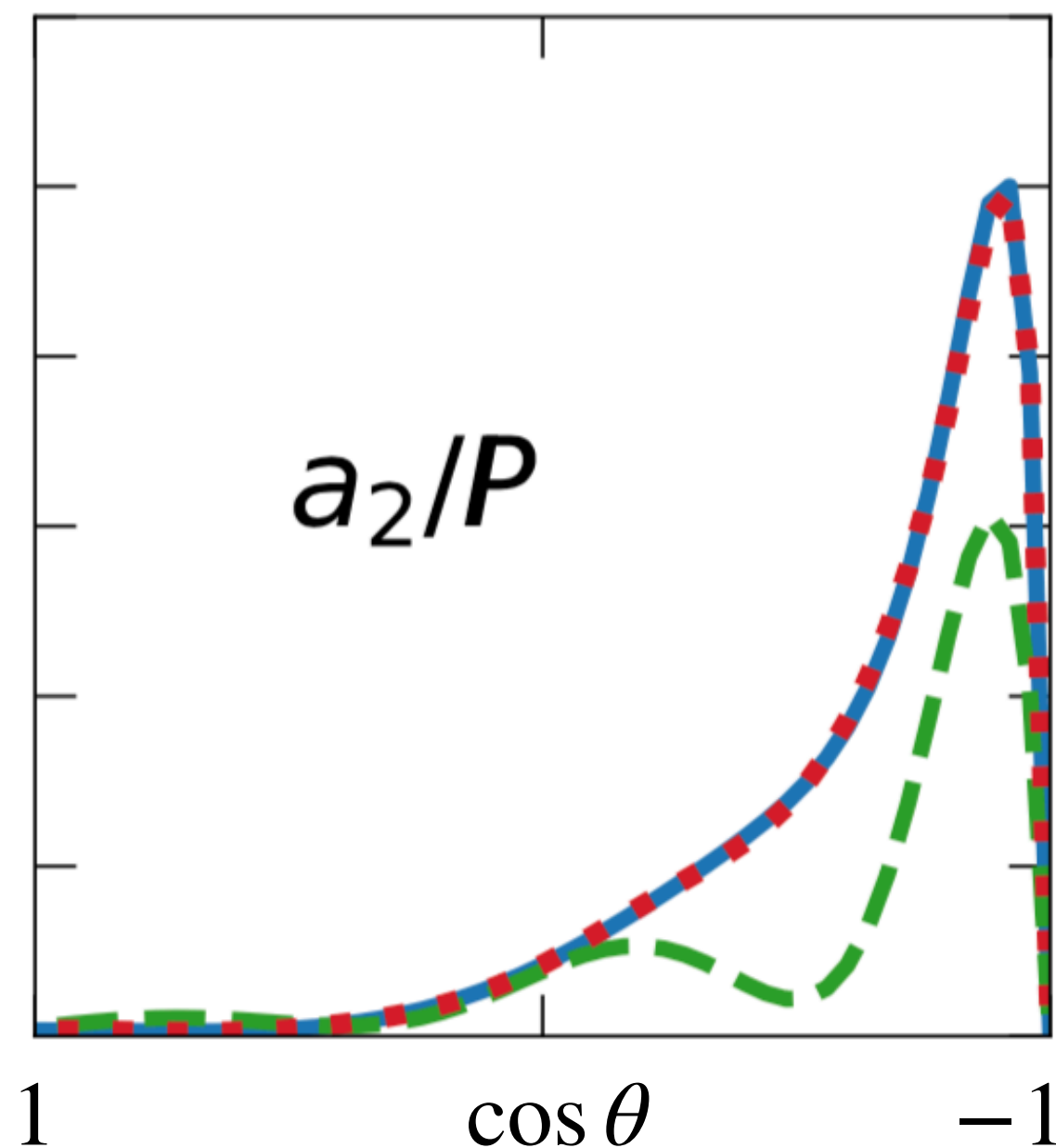


Exotic mesons originate from asymmetry in double Regge region

Can be formalised mathematically (in progress)



Partial waves not relevant in the double Regge region



Asymmetry originating from $(a_2, f_2/\mathbb{P}) \neq (f_2, f_2/\mathbb{P})$ and from (\mathbb{P}, \mathbb{P}) in $\eta'\pi$

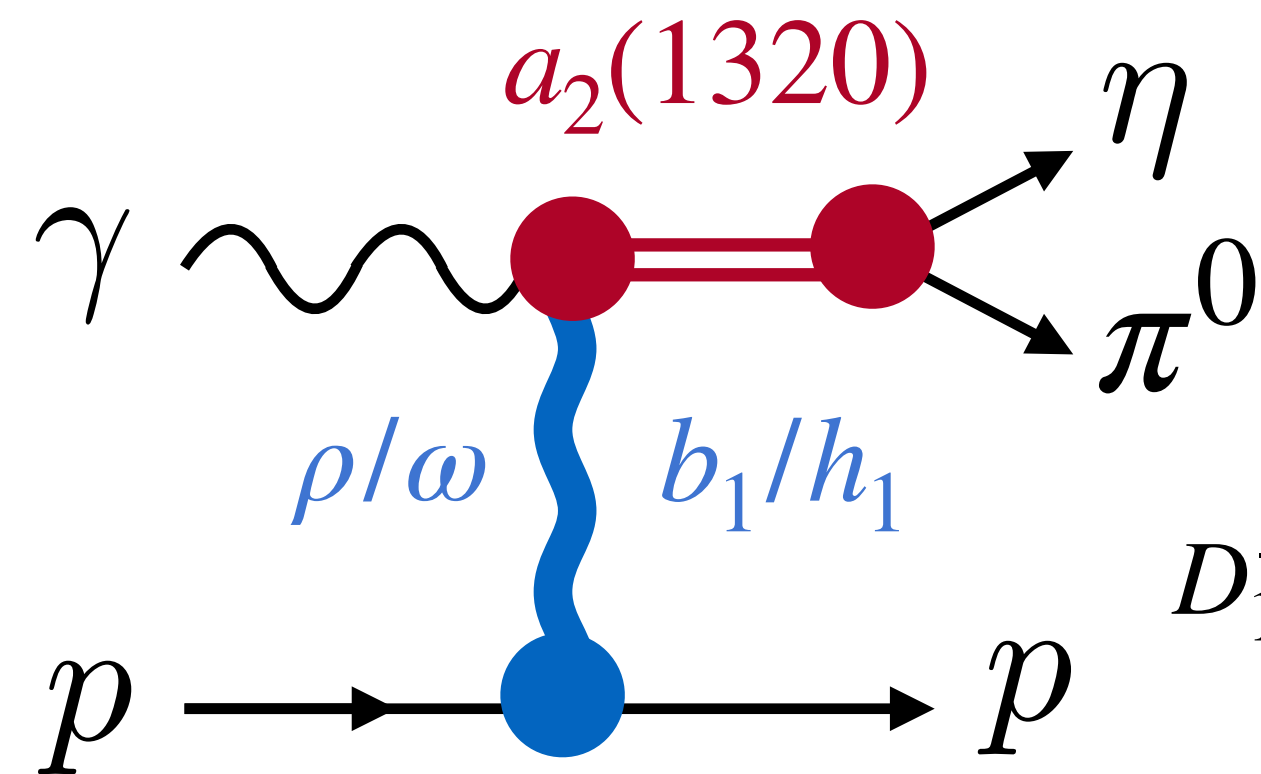
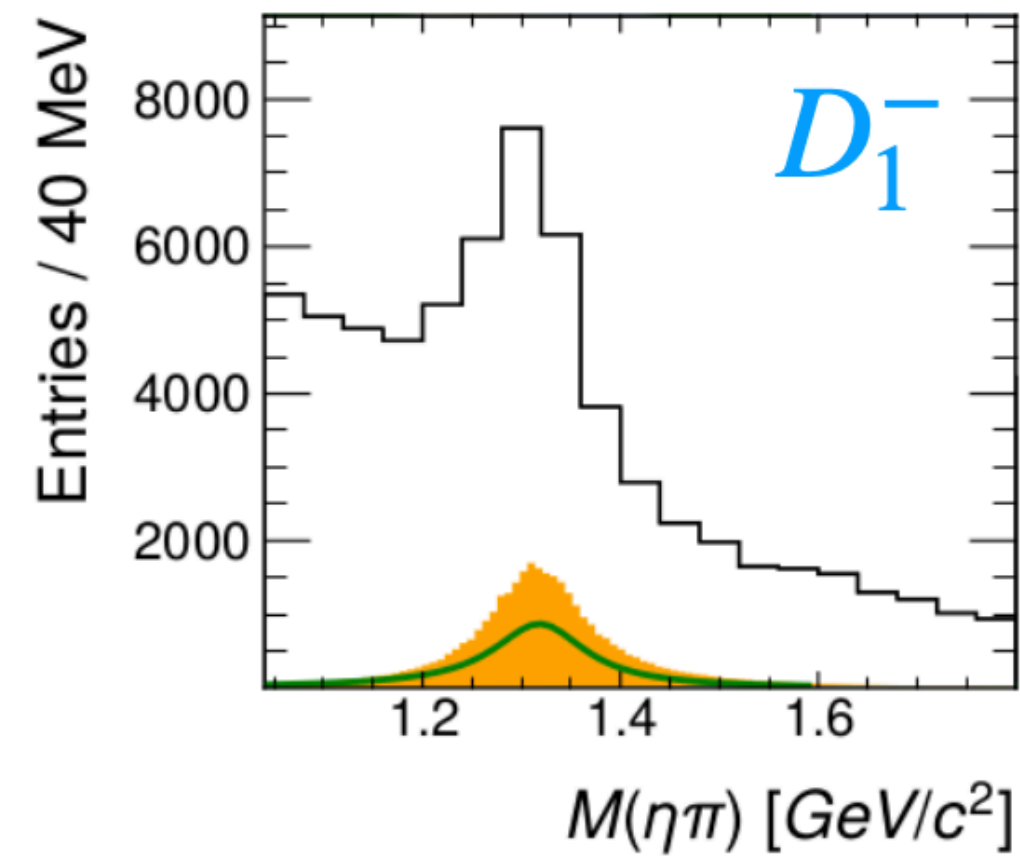
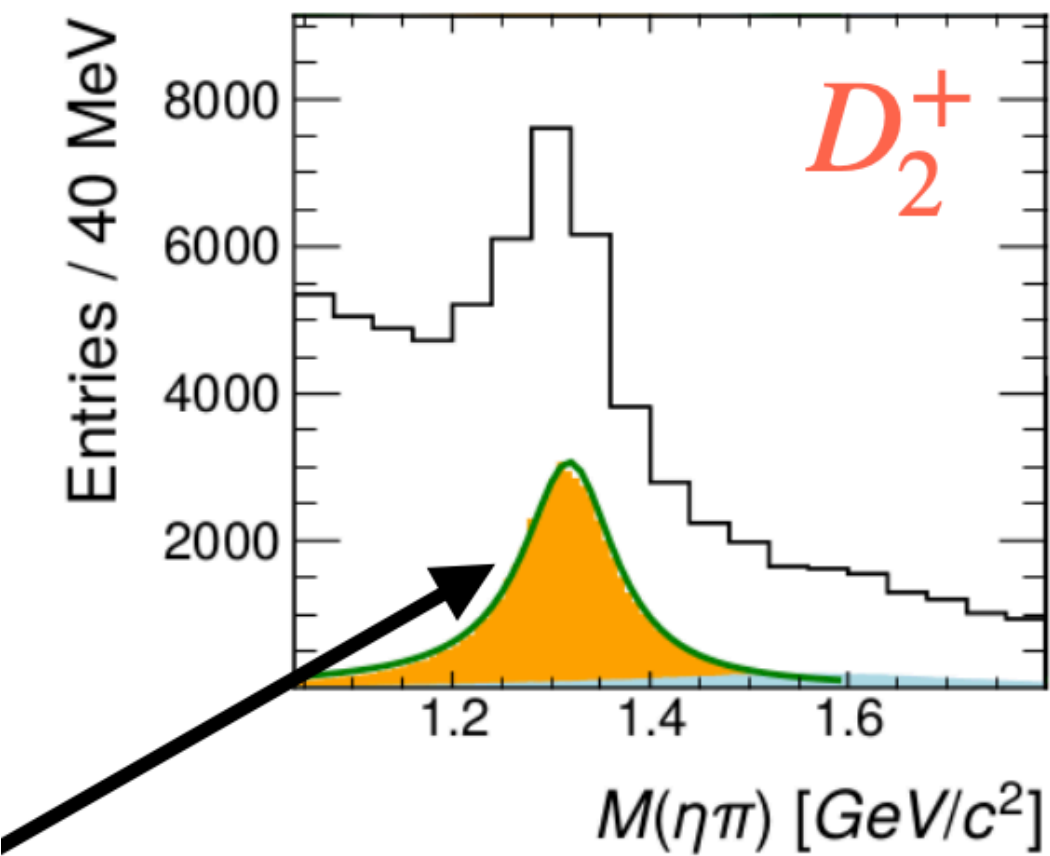
Vector exchange

Axial-Vector exchange

Notation D_m^ϵ :

Reflectivity ϵ matches naturality of exchange
(At leading order in energy squared)

D-wave have $2 \cdot 5 = 10$ complex functions of t



$$D_1^- = -\frac{\beta^U}{\sqrt{6}} \sqrt{\frac{-t}{m_{a_2}^2}}$$

$$D_1^- = \frac{\beta^U}{4} \quad D_{-1}^- = \frac{\beta^U}{4} \frac{-t}{m_{a_2}^2}$$

$$D_2^- = D_{-2}^- = 0$$

For axial, M1 transition:

Vector exchange

Axial-Vector exchange

Notation D_m^ϵ :

Reflectivity ϵ matches naturality of exchange
(At leading order in energy squared)

D-wave have $2 \cdot 5 = 10$ complex functions of t

Assumptions of TMD to reduce nb. of couplings:

$$\mathcal{L}_{TVV} = \beta_N T^{\mu\nu} F_{\mu\rho} F_\nu{}^\rho \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

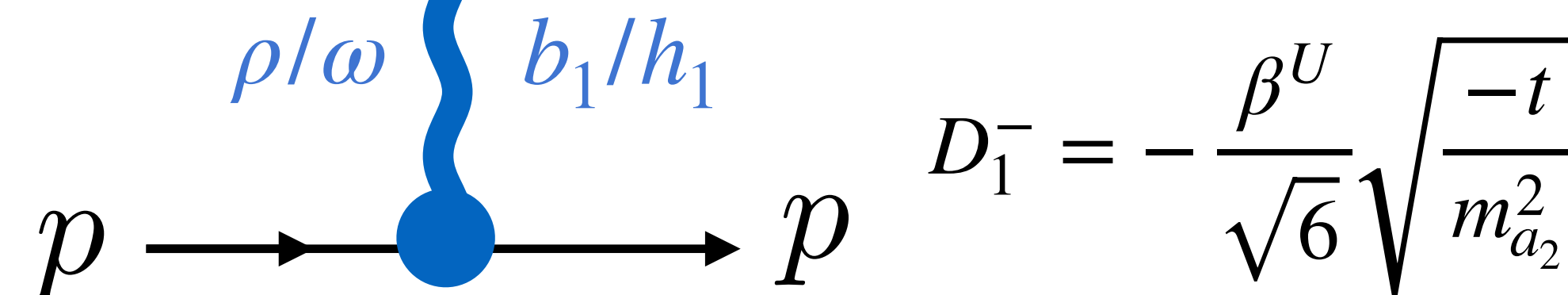
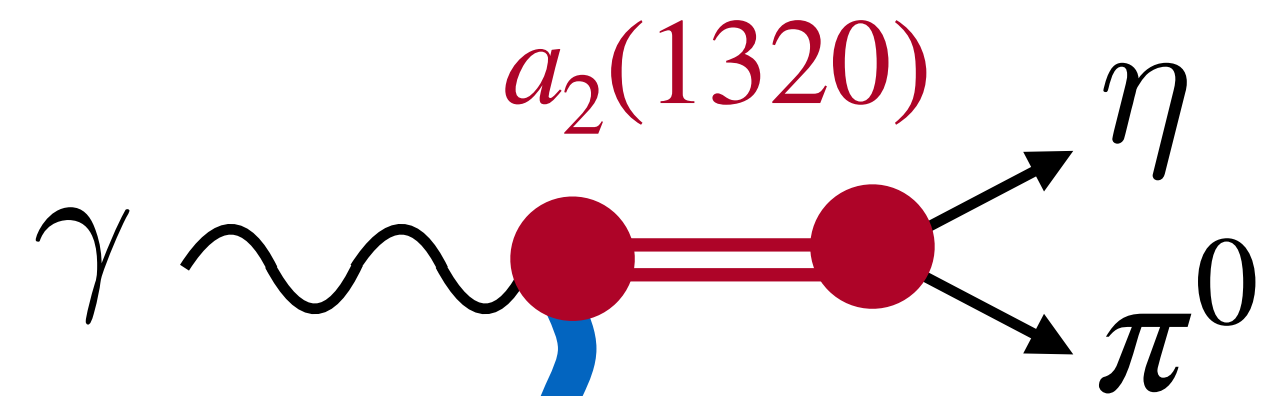
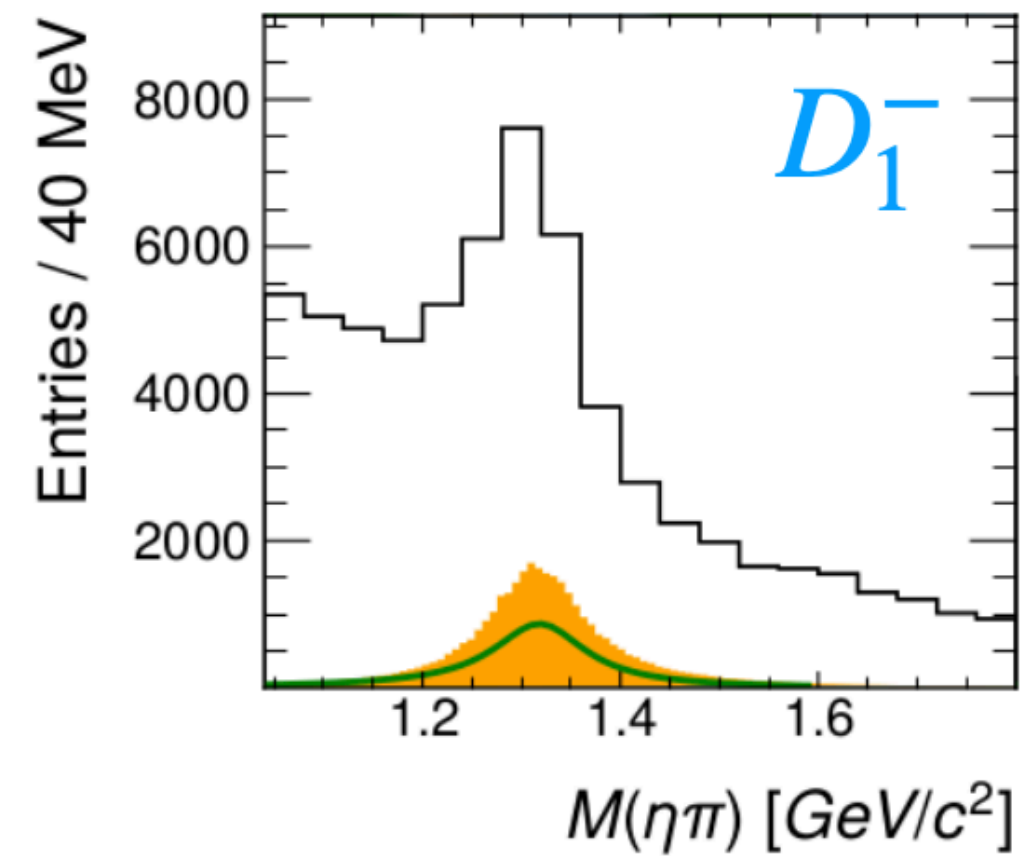
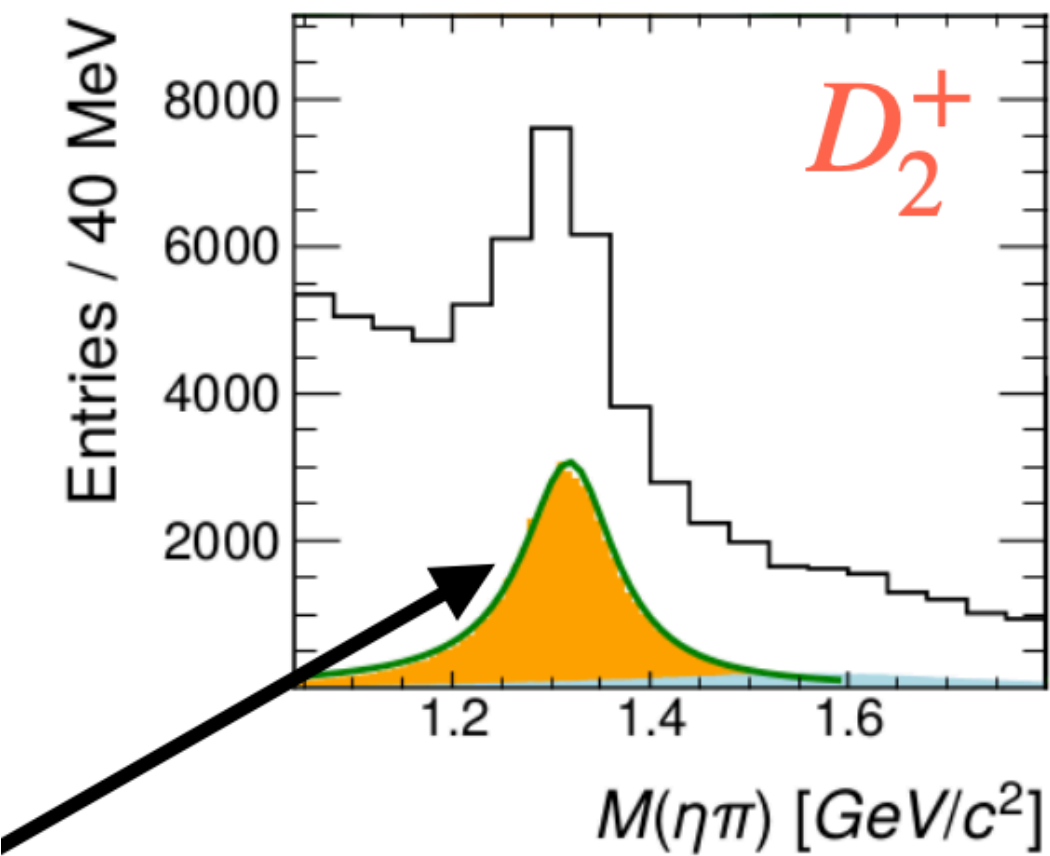
Leads to

$$D_2^+ = -\frac{\beta_N}{2} \sqrt{\frac{-t}{m_{a_2}^2}}$$

$$D_0^+ = \frac{\beta_N}{2} \frac{t}{\sqrt{6} m_{a_2}^2} \sqrt{\frac{-t}{m_{a_2}^2}}$$

$$D_1^+ = \frac{\beta_N}{2} \frac{-t}{m_{a_2}^2}$$

$$D_{-1}^+ = D_{-2}^+ = 0$$



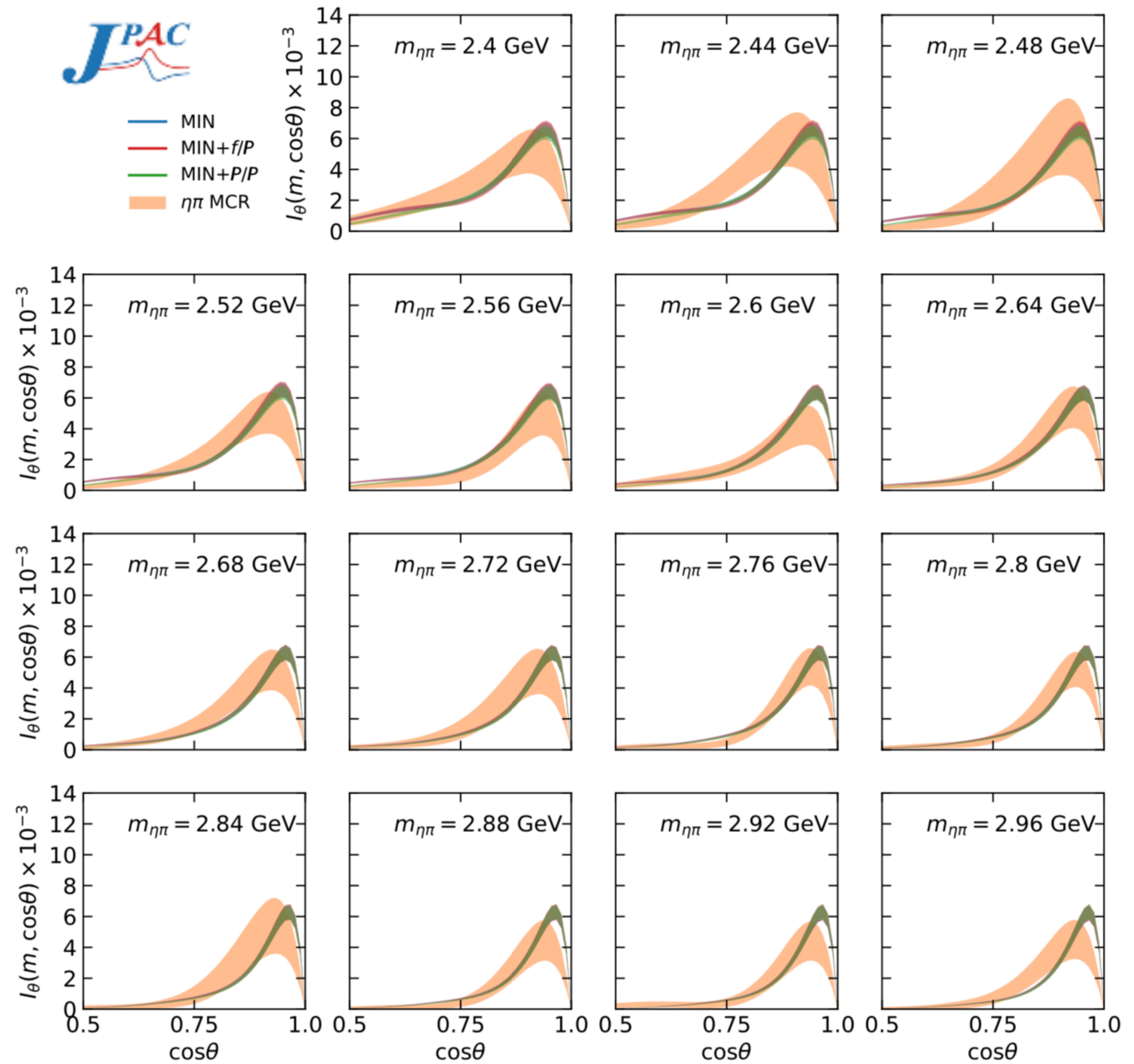
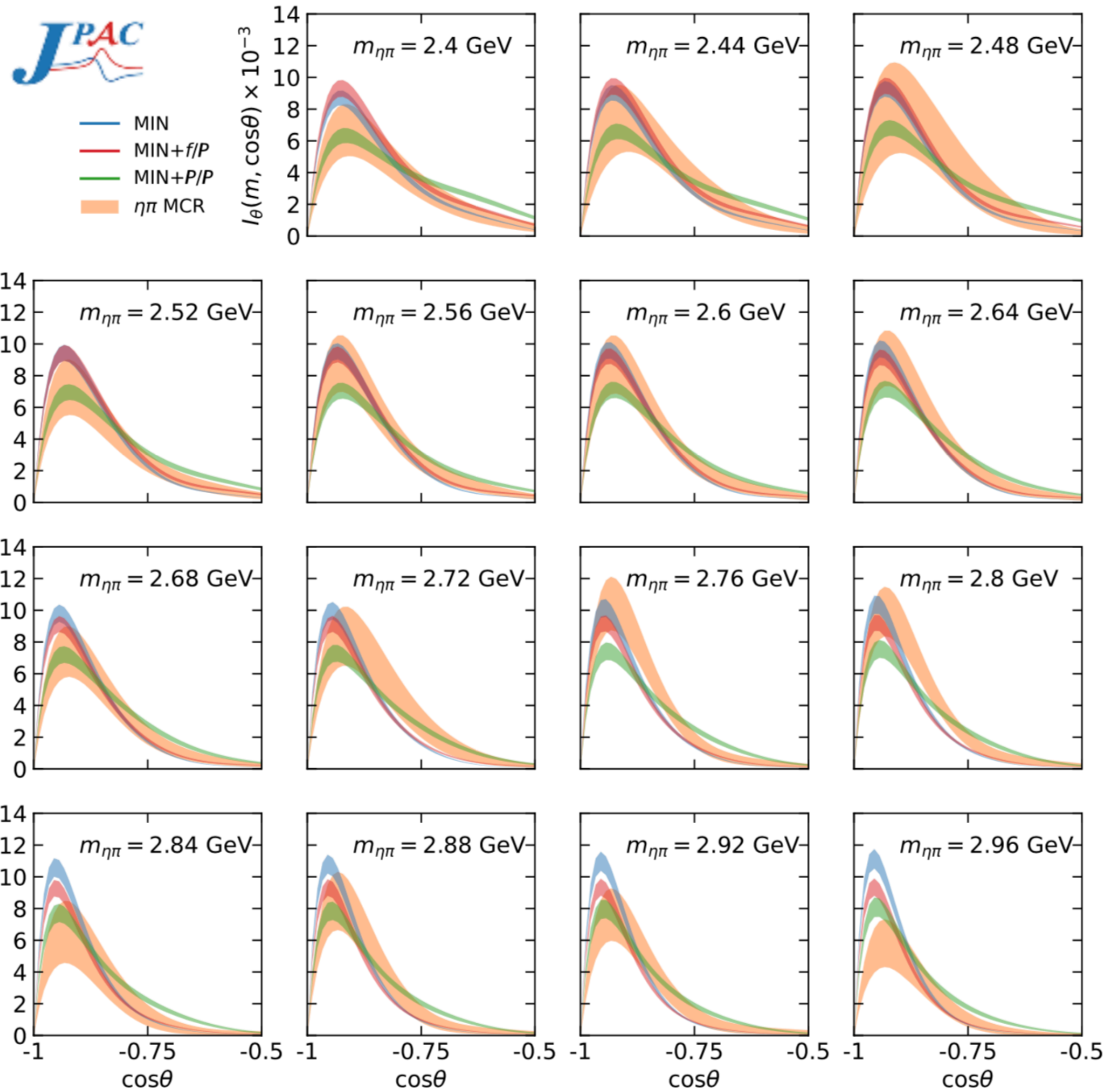
$$D_1^- = -\frac{\beta^U}{\sqrt{6}} \sqrt{\frac{-t}{m_{a_2}^2}}$$

$$D_1^- = \frac{\beta^U}{4} \quad D_{-1}^- = \frac{\beta^U}{4} \frac{-t}{m_{a_2}^2}$$

$$D_2^- = D_{-2}^- = 0$$

For axial, M1 transition:

$\eta\pi$



$\eta' \pi$

