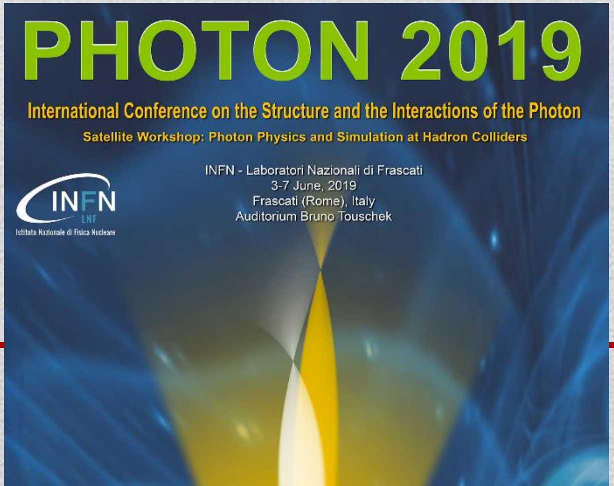
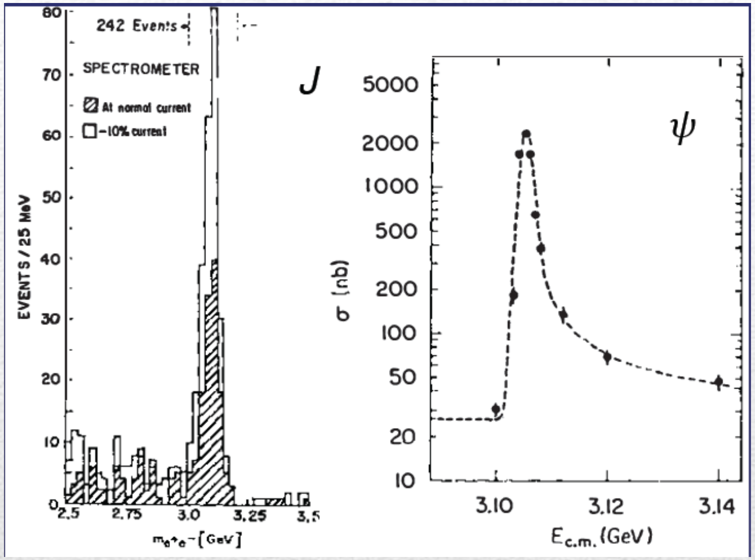
Heavy quark Spectroscopy

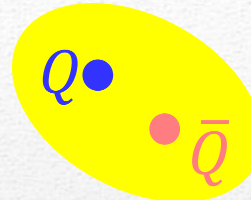
Alessandro Pilloni

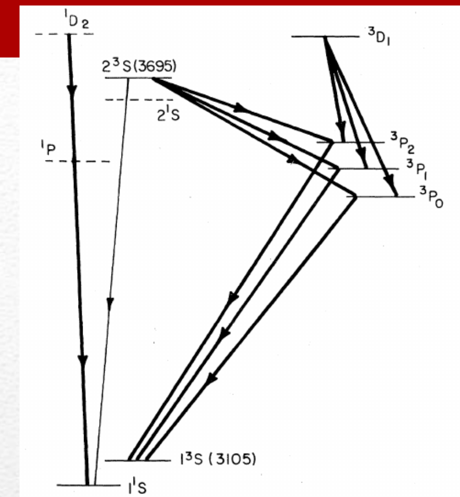
PHOTON 2019, June 3rd, 2019



Quarkonium orthodoxy







$\alpha_s(M_Q) \sim 0.3$

(perturbative regime)

OZI-rule, QCD multipole

Heavy quark spin flip suppressed by quark mass, approximate heavy quark spin symmetry (HQSS)

Potential models

(meaningful when $M_Q \to \infty$)

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

(Cornell potential)

Solve NR Schrödinger eq. → spectrum

Effective theories

(HQET, NRQCD, pNRQCD...)

Integrate out heavy DOF

↓

(spectrum), decay & production rates

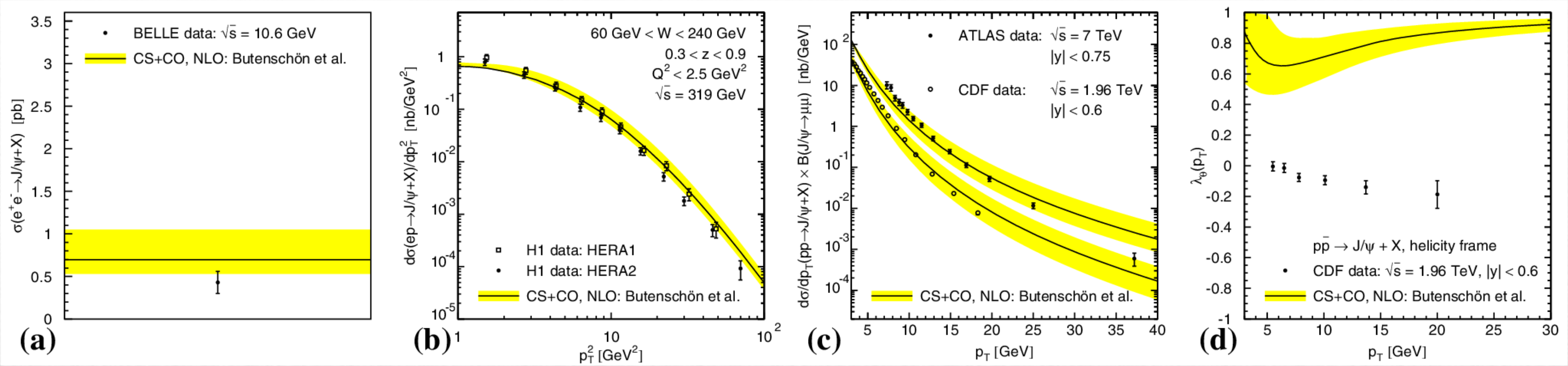
Multiscale system

Systematically integrate out the heavy scale, $m_Q \gg \Lambda_{QCD}$

$$m_Q \gg m_Q v \gg m_Q v^2$$

Full QCD → NRQCD → pNRQCD

$m_b \sim 5$ GeV, $m_c \sim 1.5$ GeV
$v_b^2 \sim 0.1, v_c^2 \sim 0.3$

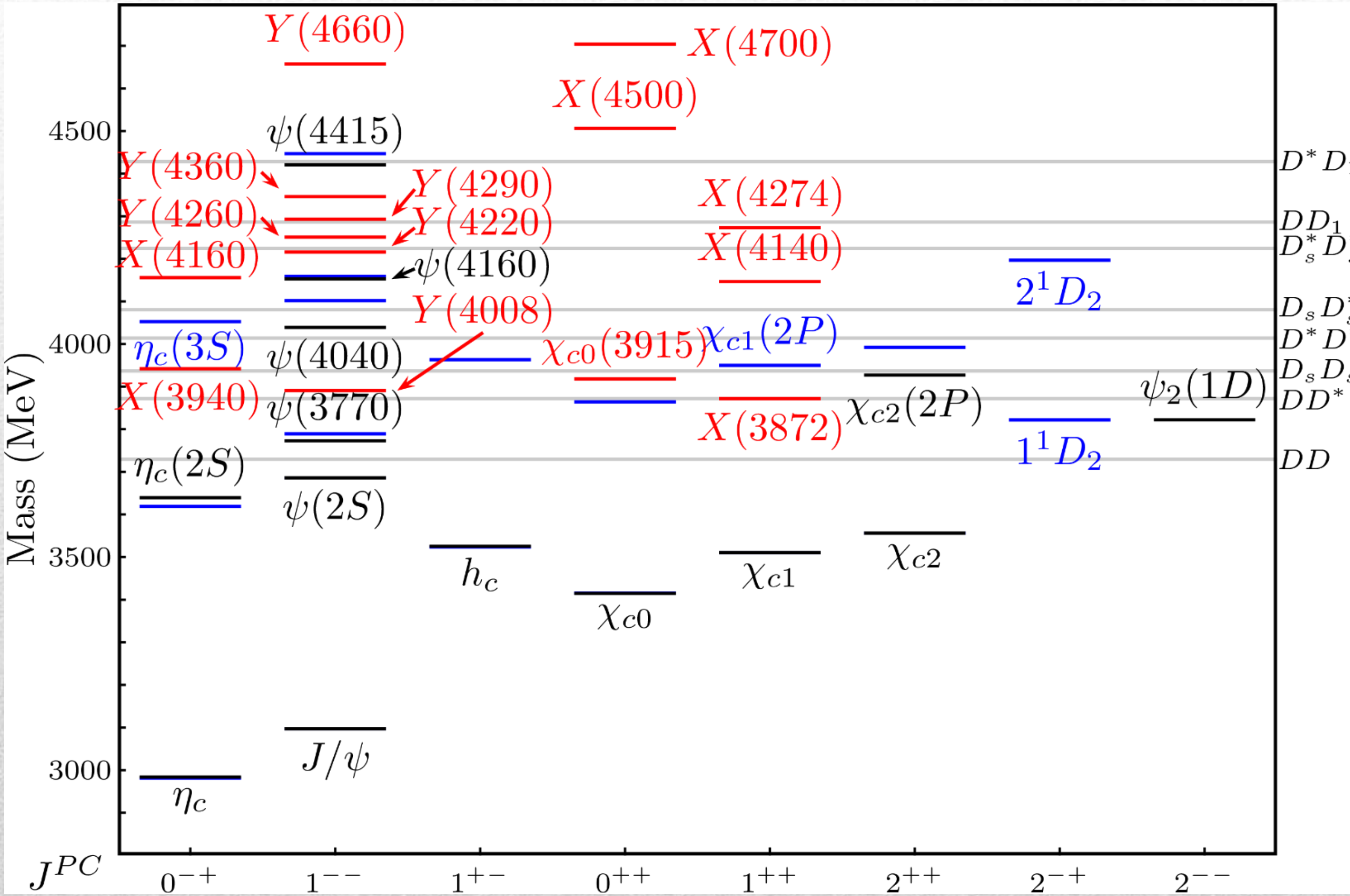


Factorization (to be proved) of universal LDMEs

Good description of many production channels, some known puzzles (polarizations)

Exotic landscape

Esposito, AP, Polosa, Phys.Rept. 668



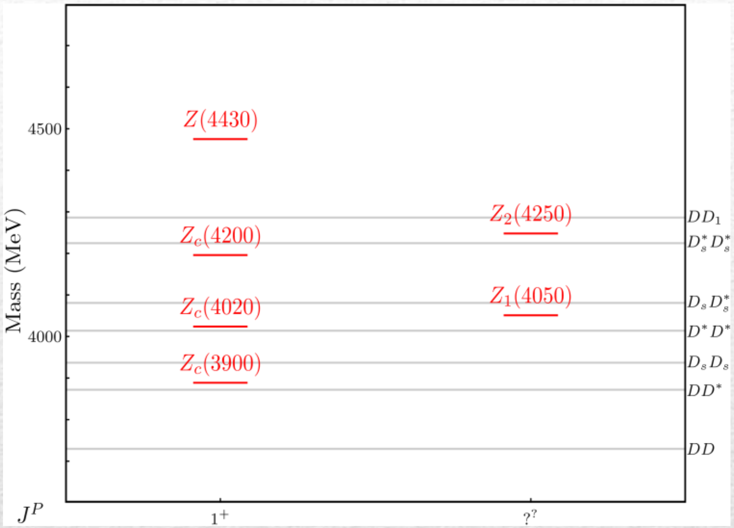
A host of unexpected resonances have appeared

decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

Charged Z states: $Z_c(3900), Z_c'(4020)$

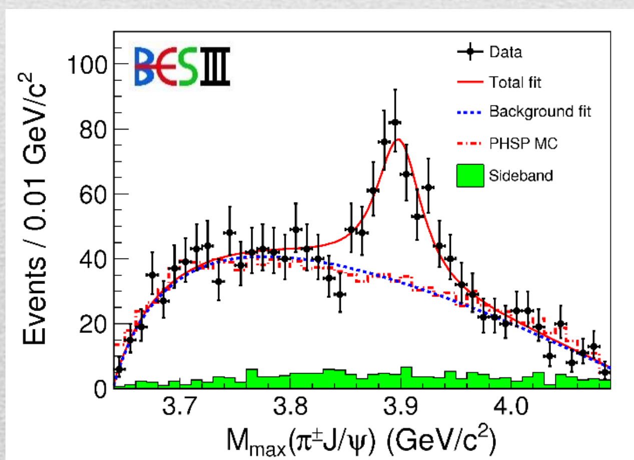
Charged quarkonium-like resonances have been found, **4q needed**

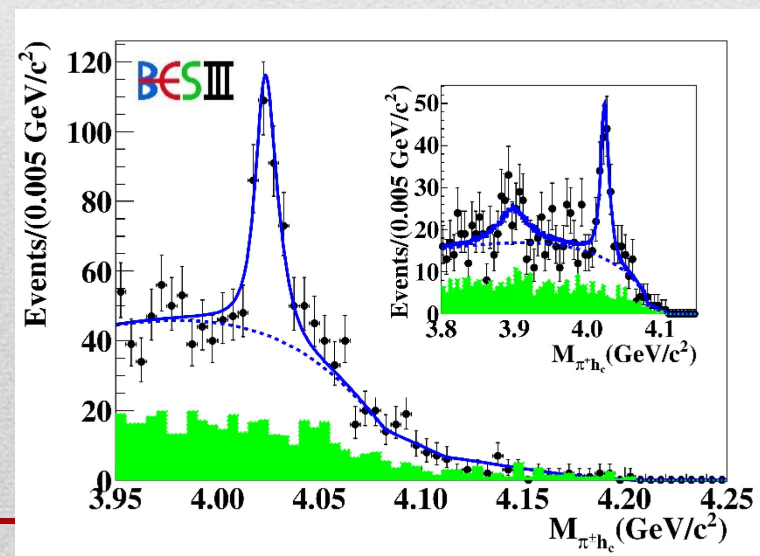


Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

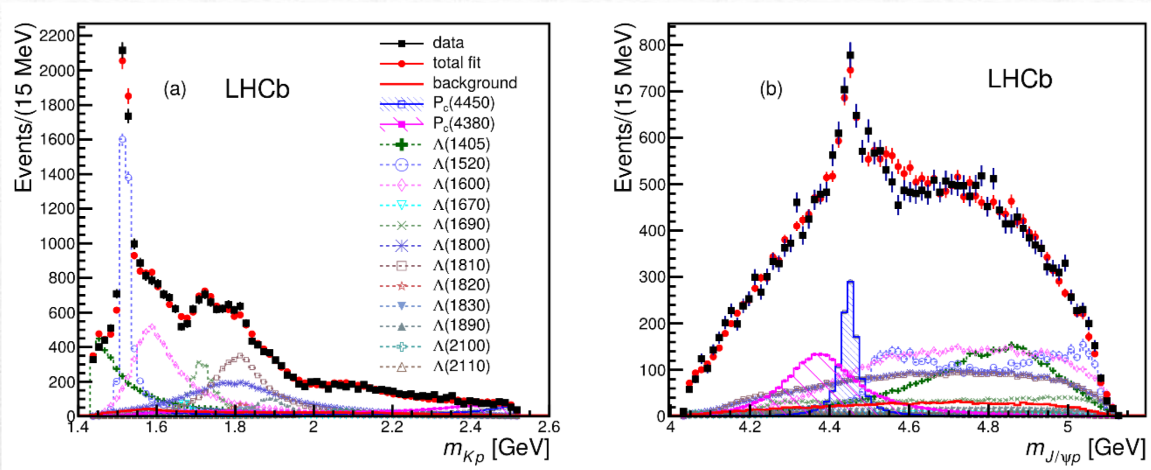
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV





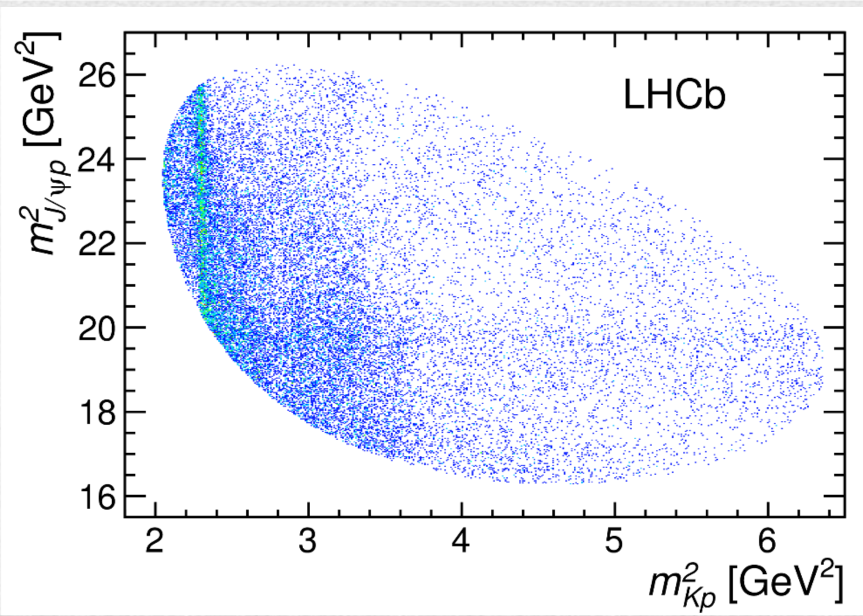
Pentaquarks!



LHCb, PRL 115, 072001
LHCb, PRL 117, 082003

Two states seen in $\Lambda_b \to (J/\psi\, p)\, K^-$, evidence in $\Lambda_b \to (J/\psi\, p)\, \pi^-$

$$M_1 = 4380 \pm 8 \pm 29 \text{ MeV}$$
$$\Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV}$$
$$M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$
$$\Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV}$$



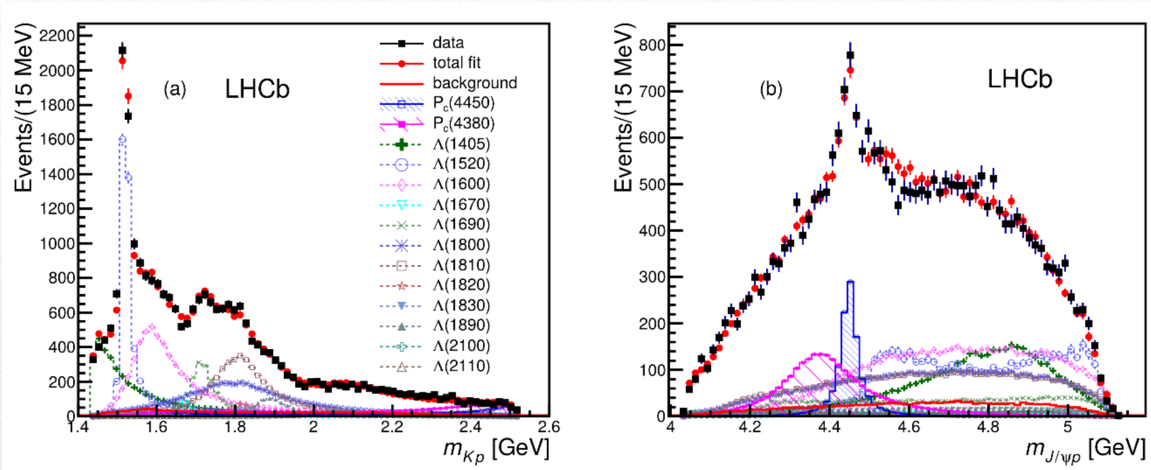
Quantum numbers

$$J^P = \left(\frac{3}{2}^-, \frac{5}{2}^+\right) \text{ or } \left(\frac{3}{2}^+, \frac{5}{2}^-\right) \text{ or } \left(\frac{5}{2}^+, \frac{3}{2}^-\right)$$

Opposite parities needed for the interference to correctly describe angular distributions, low mass region contaminated by Λ^* (model dependence?)

No obvious threshold nearby

Pentaquarks!



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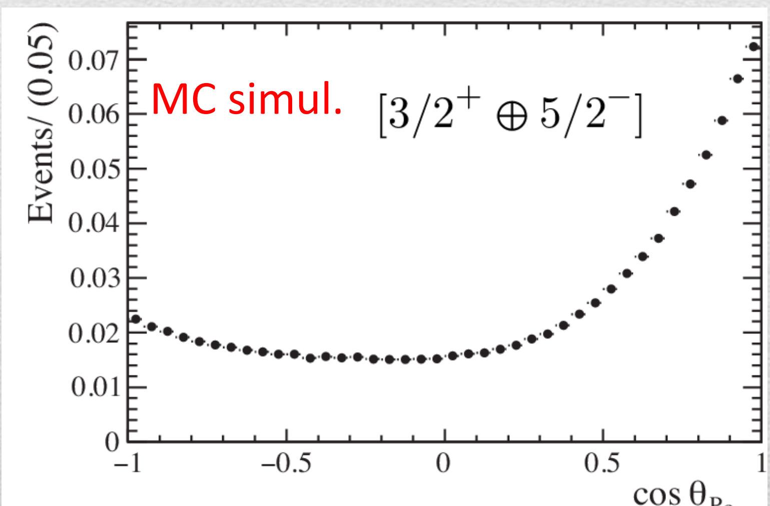

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Opposite parities needed for the interference to correctly describe angular distributions, low mass region contaminated by Λ^* (model dependence?)

No obvious threshold nearby

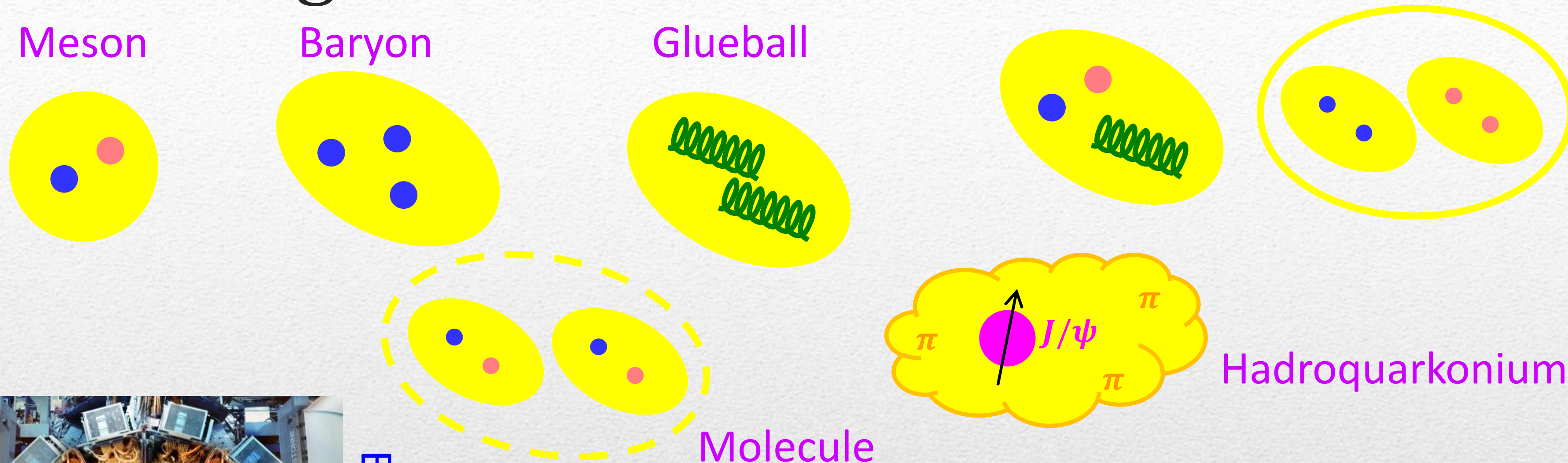
Life is not easy...

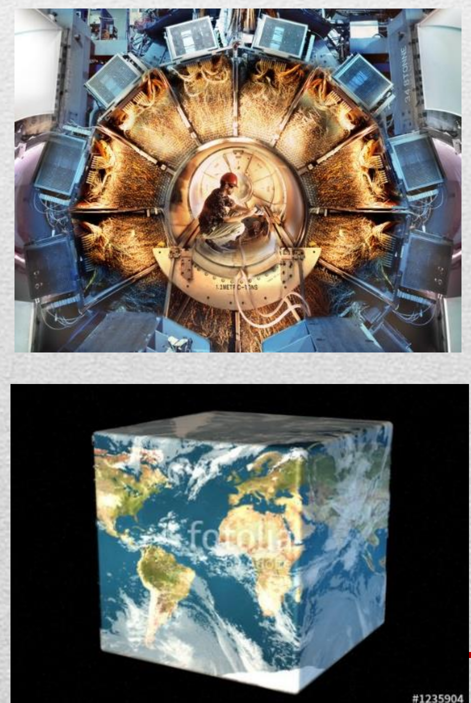
$a_1(1260)$ WIDTH

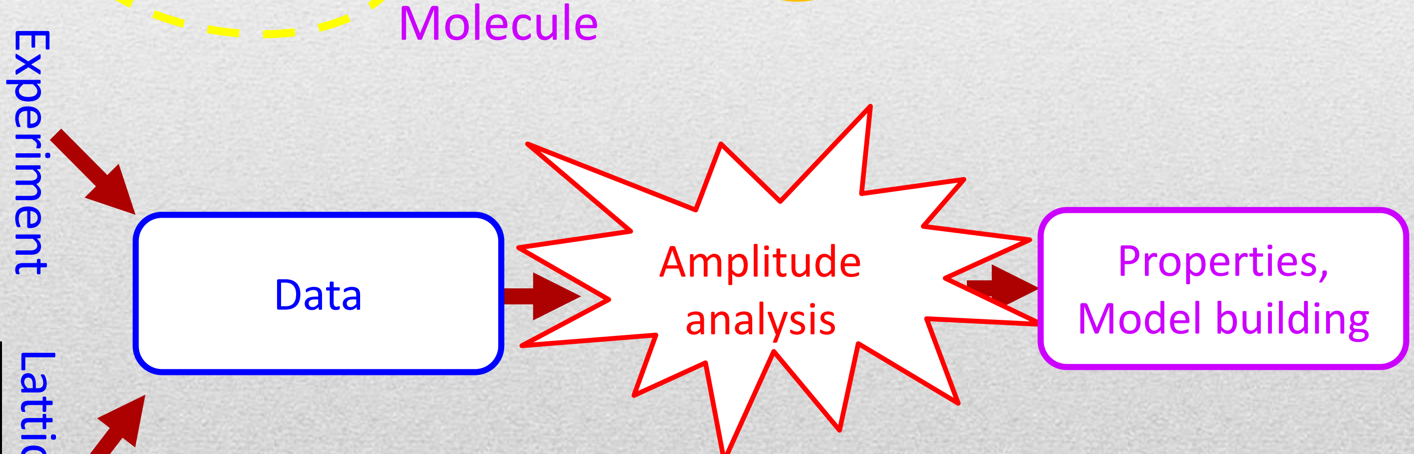
INSPIRE search

VALUE (MeV)	EVTS		DOCUMENT ID		TECN	COMMENT
250 to 600	**OUR ESTIMATE**					
$367 \pm 9 ^{+28}_{-25}$	420k		ALEKSEEV	2010	COMP	$190\ \pi^- \to \pi^-\pi^-\pi^+ Pb'$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$410 \pm 31 \pm 30$		1	AUBERT	2007AU	BABR	$10.6\ e^+ e^- \to \rho^0 \rho^\pm \pi^\mp \gamma$
520 - 680	6360	2	LINK	2007A	FOCS	$D^0 \to \pi^-\pi^+\pi^-\pi^+$
480 ± 20		3	GOMEZ-DUMM	2004	RVUE	$\tau^+ \to \pi^+\pi^+\pi^-\nu_\tau$
580 ± 41	90k		SALVINI	2004	OBLX	$\bar{p} p \to 2\pi^+ 2\pi^-$
460 ± 85	205	4	DRUTSKOY	2002	BELL	$B^{(*)} K^- K^{*0}$
$814 \pm 36 \pm 13$	37k	5	ASNER	2000	CLE2	$10.6\ e^+ e^- \to \tau^+\tau^-,\ \tau^- \to \pi^-\pi^0\pi^0\nu_\tau$

Building Hadrons

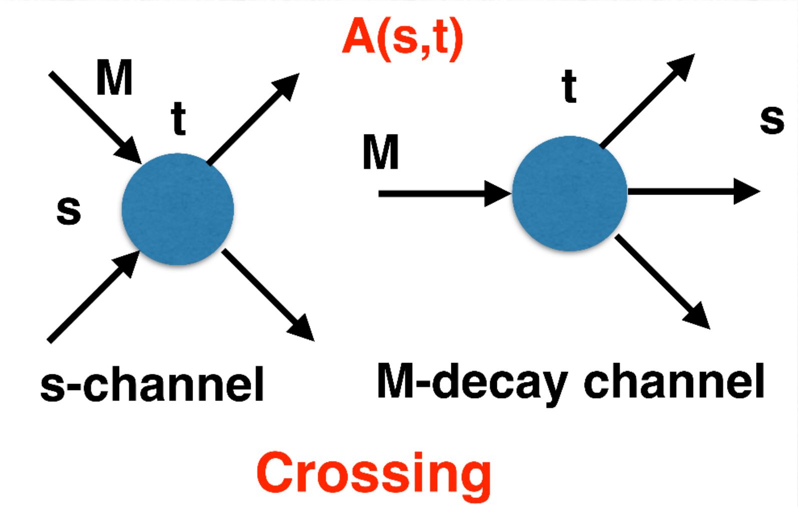


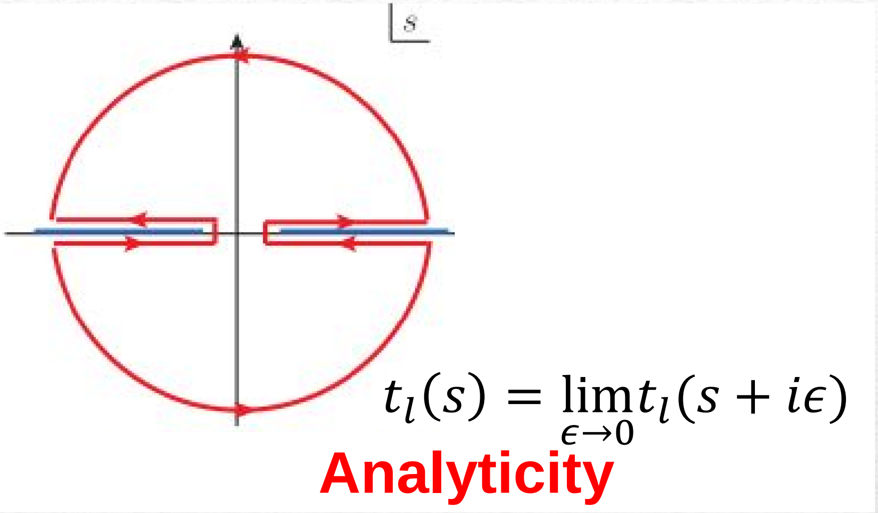


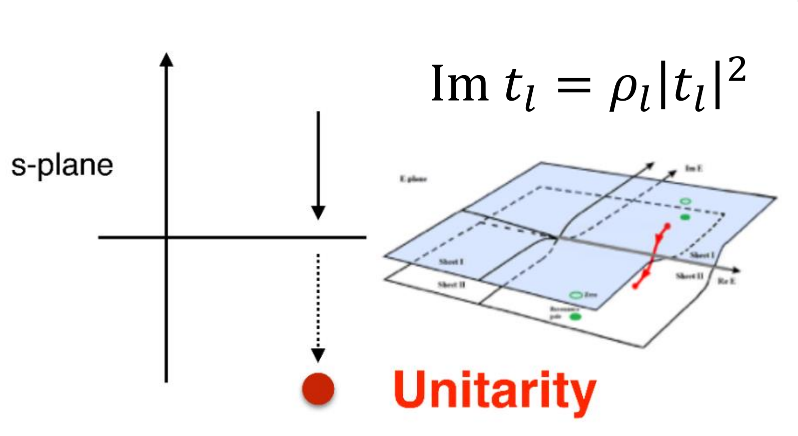


Interpretations on the spectrum leads to understanding fundamental laws of nature

S-Matrix principles







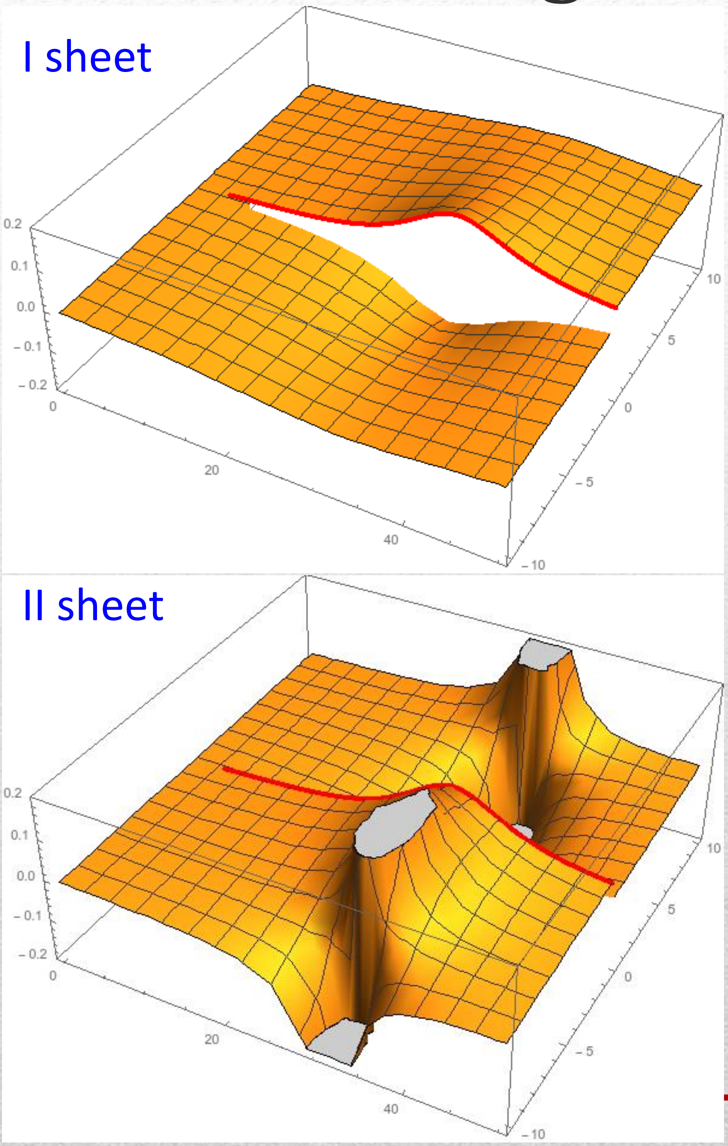
+ Lorentz, discrete & global symmetries

These are constraints the amplitudes have to satisfy, but do not fix the dynamics

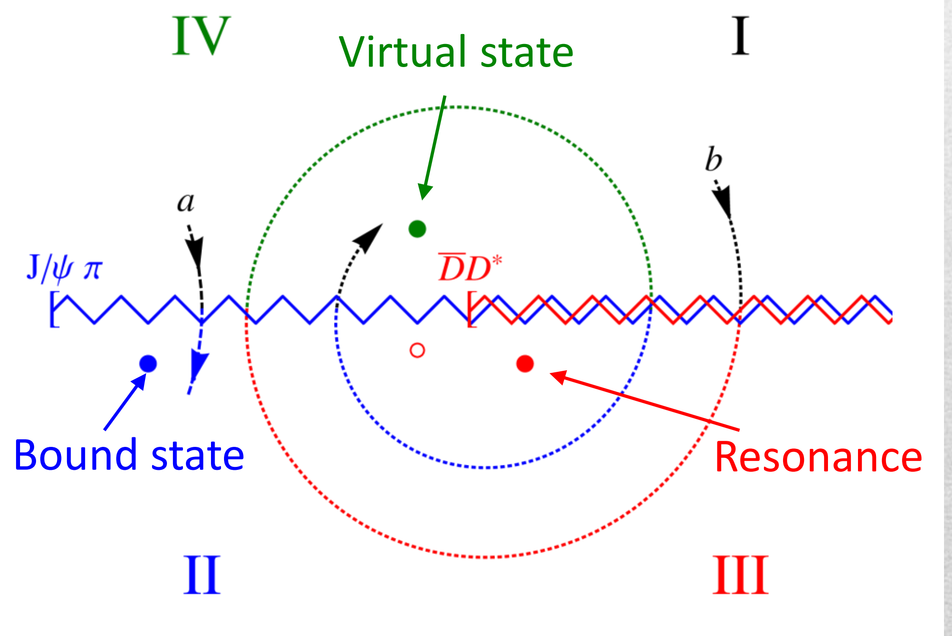
They can be imposed with an increasing amount of rigor, to extract robust physics information

The «background» phenomena can be effectively parameterized in a controlled way

Pole hunting

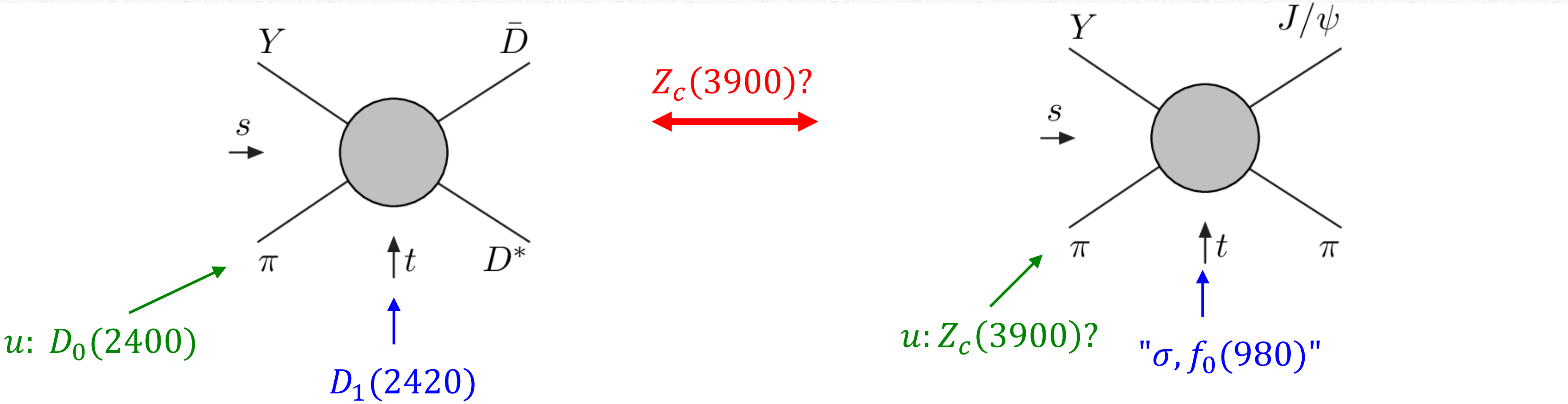


- Resonances are identified as poles in the unphysical Riemann sheets.
- The analytic structure (lineshape) can also provide hints about their nature
- Analytic continuation is always model-dependent, and requires careful systematic checks

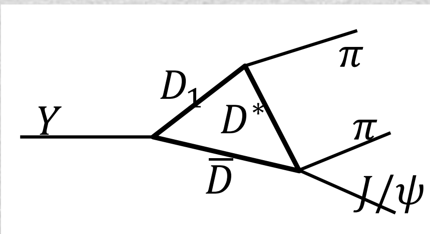


Amplitude analysis for $Z_c(3900)$

One can test different parametrizations of the amplitude, which correspond to
different singularities → different natures AP *et al.* (JPAC), PLB772, 200

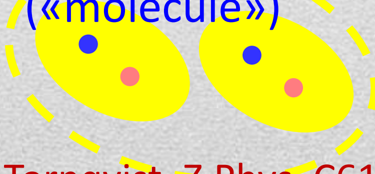


Triangle rescattering,
logarithmic branching point



Szczepaniak, PLB747, 410

(anti)bound state,
II/IV sheet pole
(«molecule»)

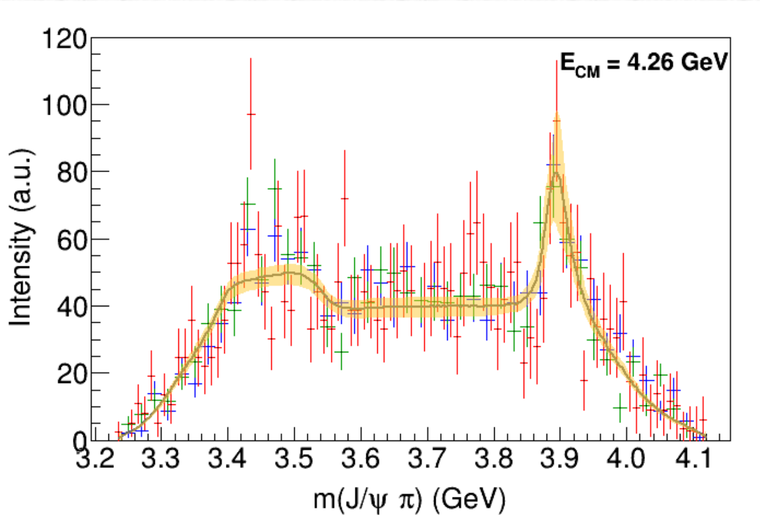


Tornqvist, Z.Phys. C61, 525
Swanson, Phys.Rept. 429
Hanhart *et al.* PRL111, 132003

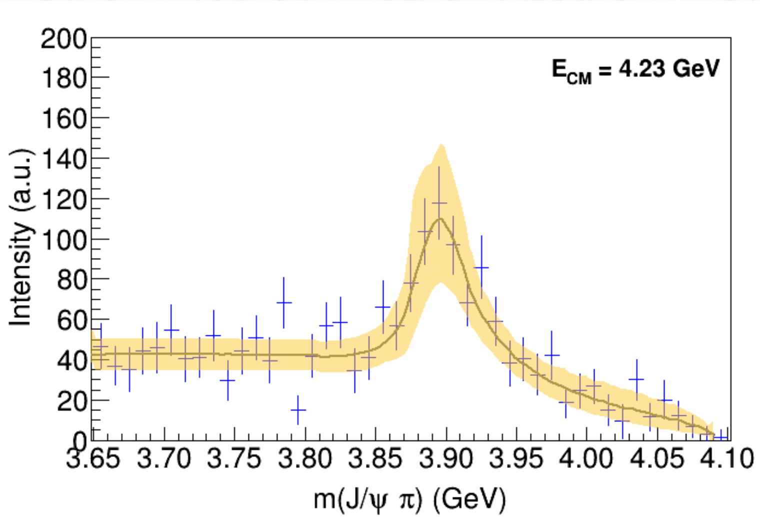
Resonance,
III sheet pole
(«compact state»)

Maiani *et al.*, PRD71, 014028
Faccini *et al.*, PRD87, 111102
Esposito *et al.*, Phys.Rept. 668

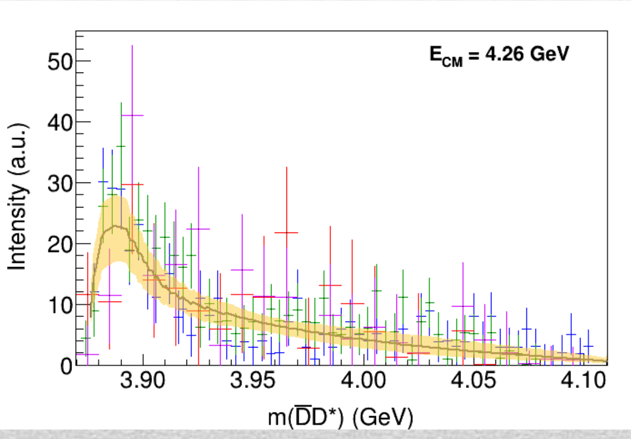
Fit: III



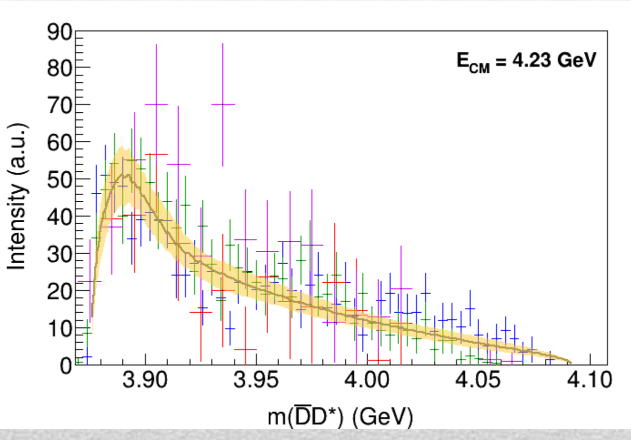
E_CM = 4.26 GeV
Intensity (a.u.)
120
100
80
60
40
20
0
3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 4.0 4.1
m(J/ψ π) (GeV)



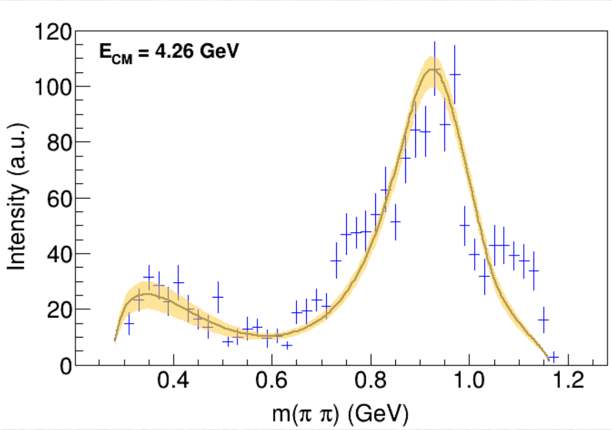
E_CM = 4.23 GeV
Intensity (a.u.)
200
180
160
140
120
100
80
60
40
20
0
3.65 3.70 3.75 3.80 3.85 3.90 3.95 4.00 4.05 4.10
m(J/ψ π) (GeV)



E_CM = 4.26 GeV
Intensity (a.u.)
50
40
30
20
10
0
3.90 3.95 4.00 4.05 4.10
m(D̄D*) (GeV)



E_CM = 4.23 GeV
Intensity (a.u.)
90
80
70
60
50
40
30
20
10
0
3.90 3.95 4.00 4.05 4.10
m(D̄D*) (GeV)



E_CM = 4.26 GeV
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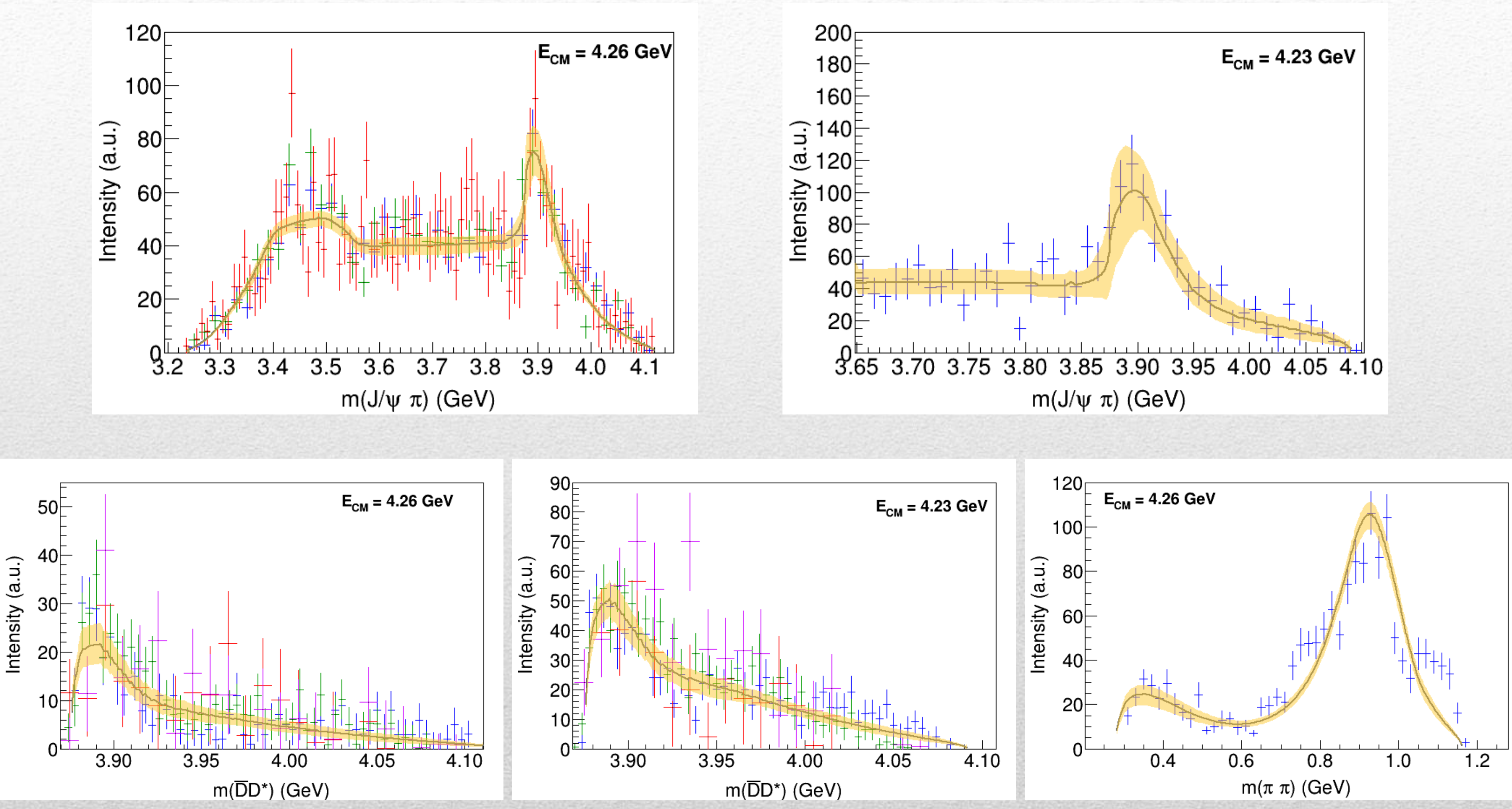
120
100
80
60
40
20
0
0.4 0.6 0.8 1.0 1.2
m(π π) (GeV)

Fit: III+tr.



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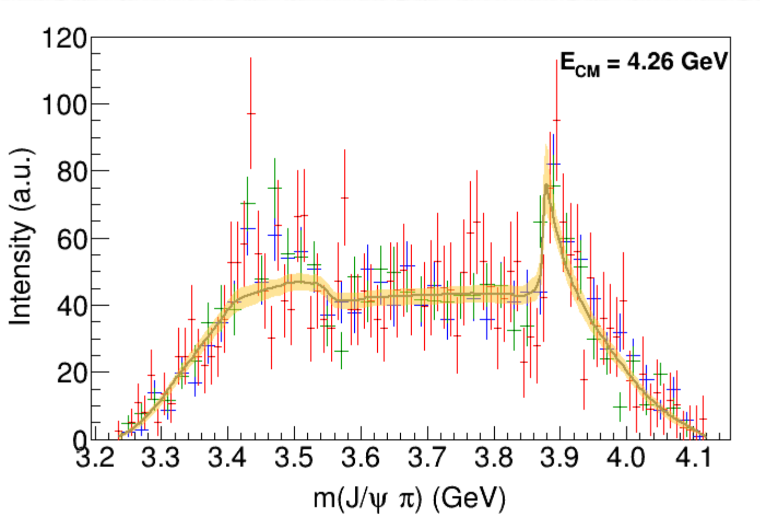
Intensity (a.u.)
m(π π) (GeV)

Fit: IV+tr.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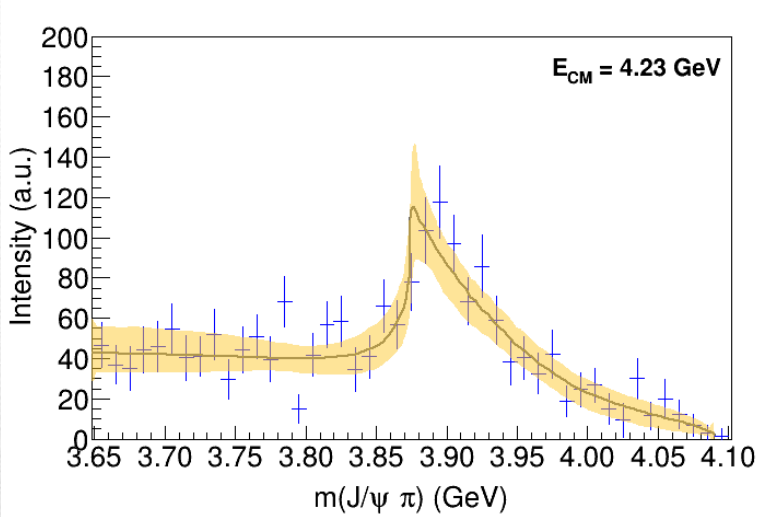
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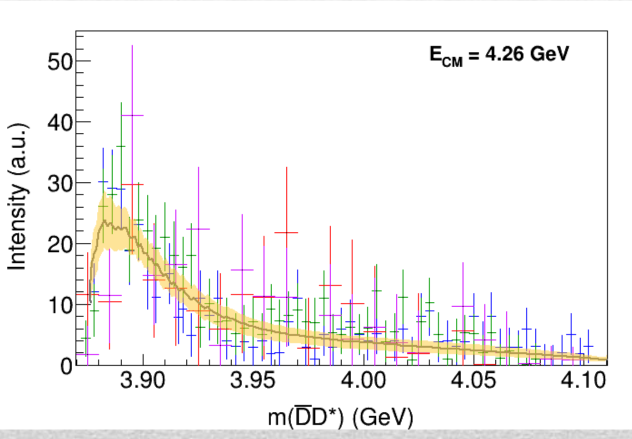
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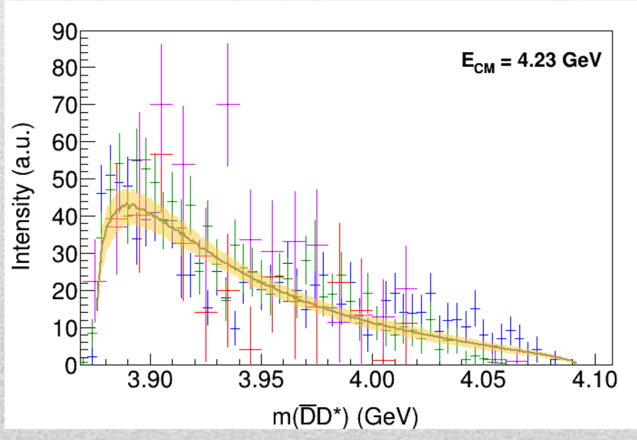
Intensity (a.u.)
m(D̄D*) (GeV)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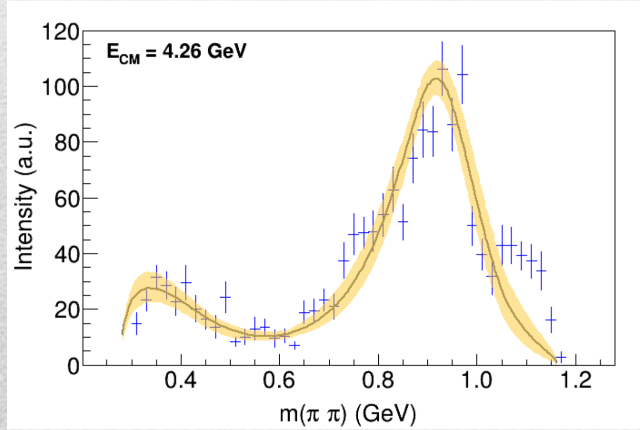
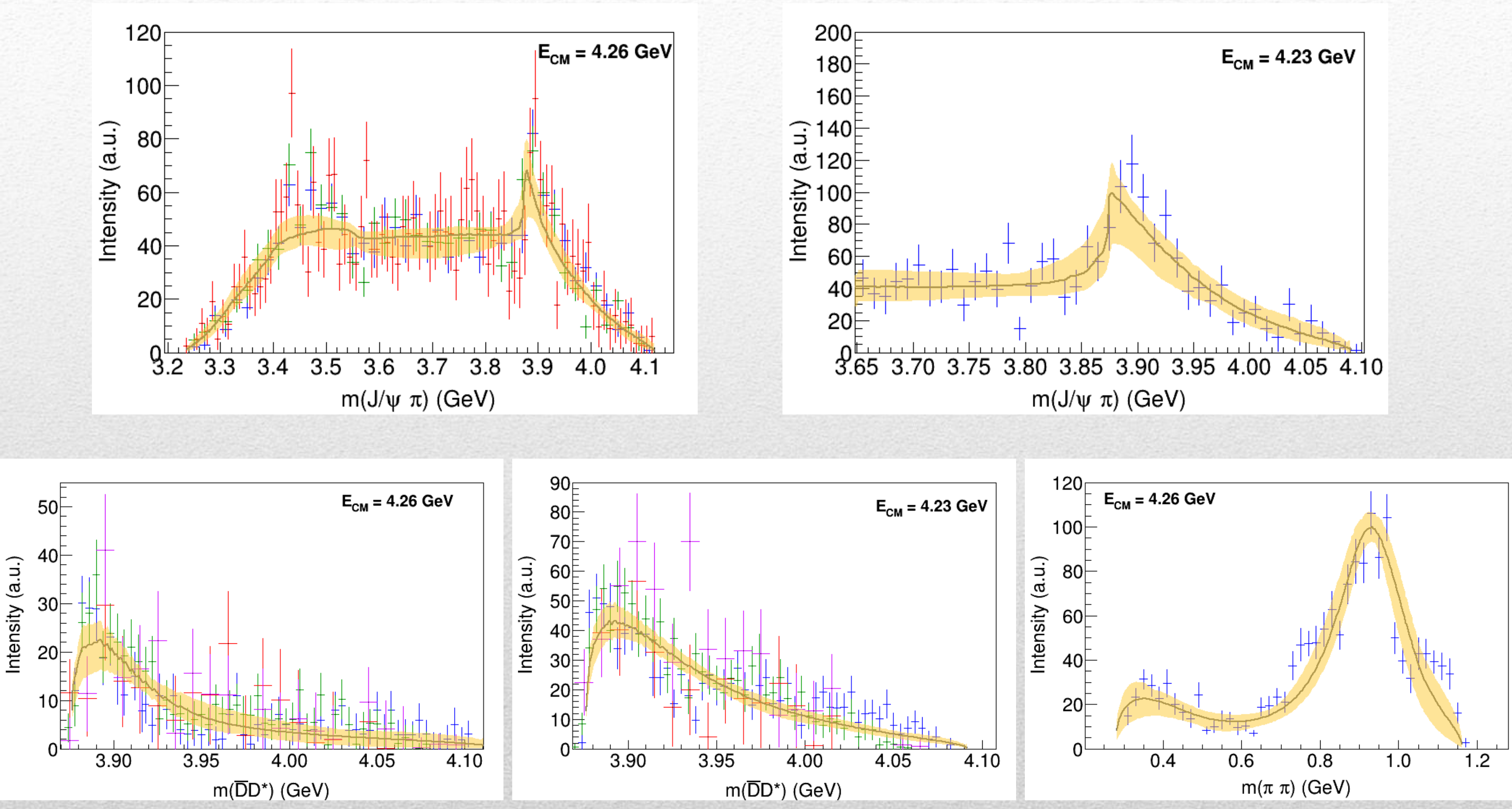

E_CM = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

Fit: tr.



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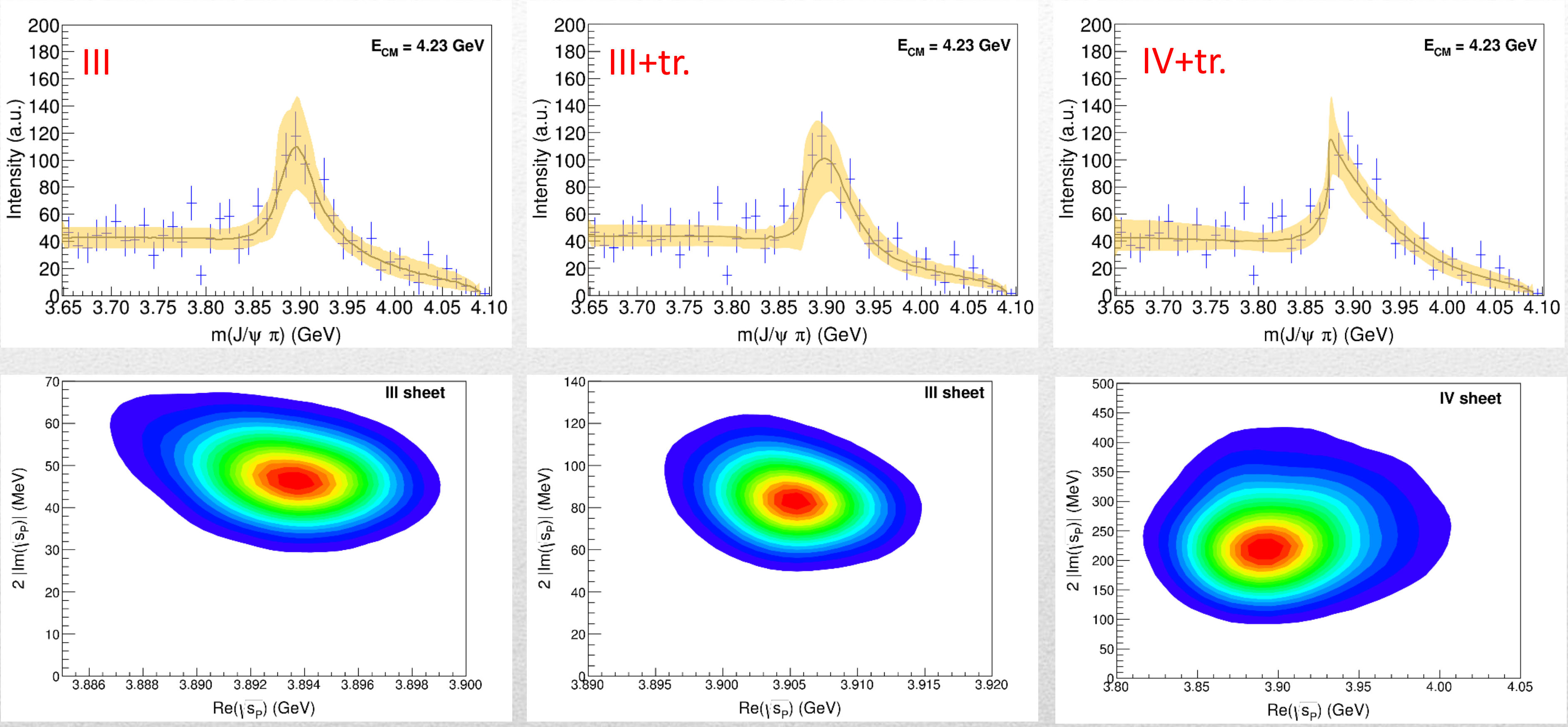
Intensity (a.u.)
m(π π) (GeV)

Pole extraction

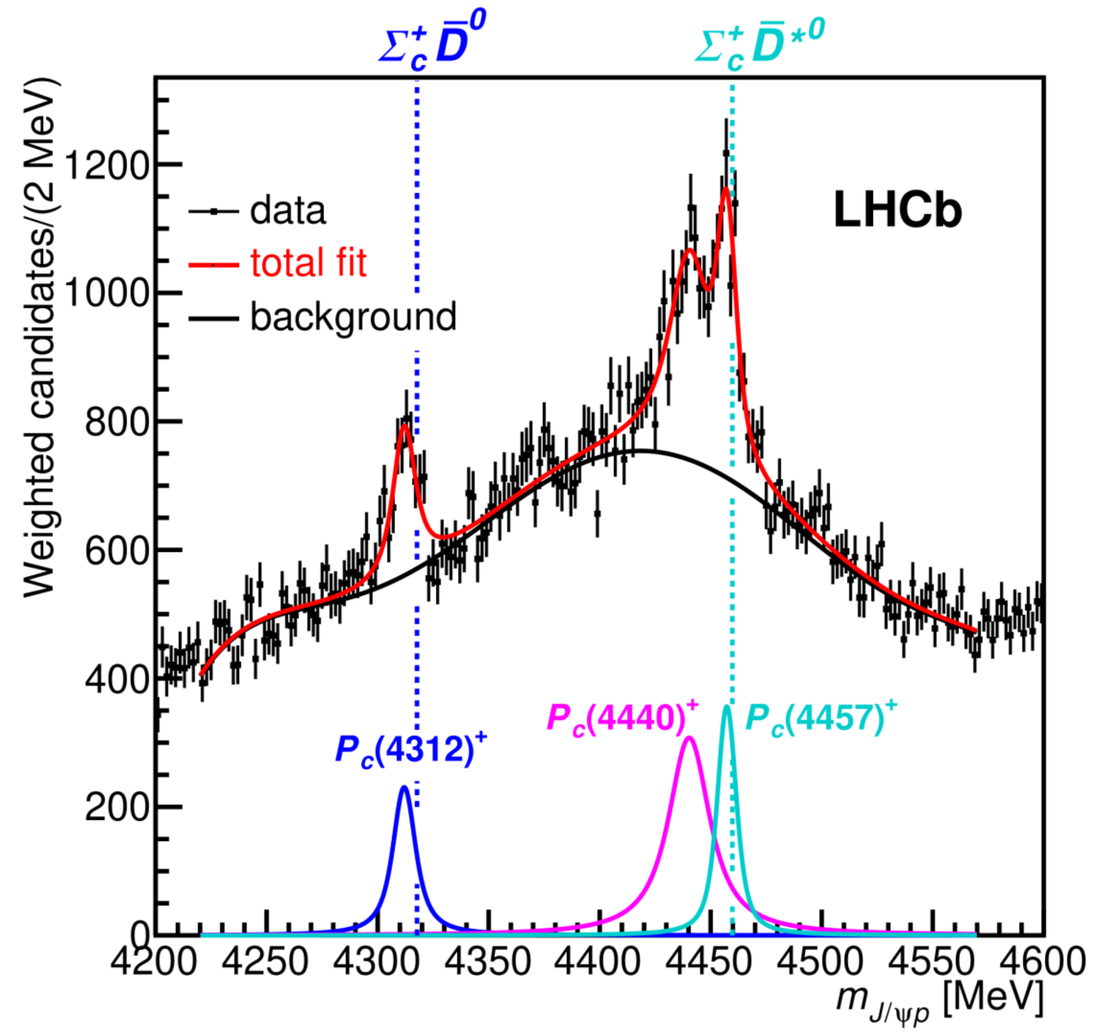


Scenario	III+tr.	IV+tr.	tr.
III	1.5σ (1.5σ)	1.5σ (2.7σ)	"2.4σ" ("1.4σ")
III+tr.	–	1.5σ (3.1σ)	"2.6σ" ("1.3σ")
IV+tr.	–	–	"2.1σ" ("0.9σ")

	III	III+tr.	IV+tr.
M (MeV)	$3893.2^{+5.5}_{-7.7}$	3905^{+11}_{-9}	3900^{+140}_{-90}
Γ (MeV)	48^{+19}_{-14}	85^{+45}_{-26}	240^{+230}_{-130}

Not conclusive at this stage

New pentaquarks discovered



LHCb, 1904.03947

The lowest $P_c(4312)$ appears as an isolated peak at the $\Sigma_c^+ \bar{D}^0$ threshold

A detailed study of the lineshape provides insight on its nature

Minimal(istic) model

Fernandez-Ramirez, AP et al. (JPAC), 1904.10021

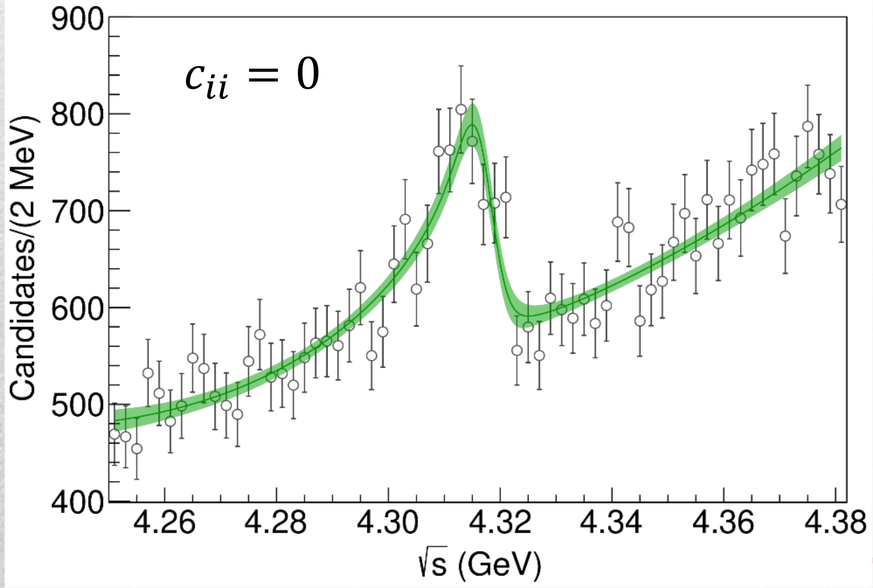
$$\frac{dN}{d\sqrt{s}} = \rho(s)\left[|F(s)|^2 + b_0 + b_1 s\right]$$

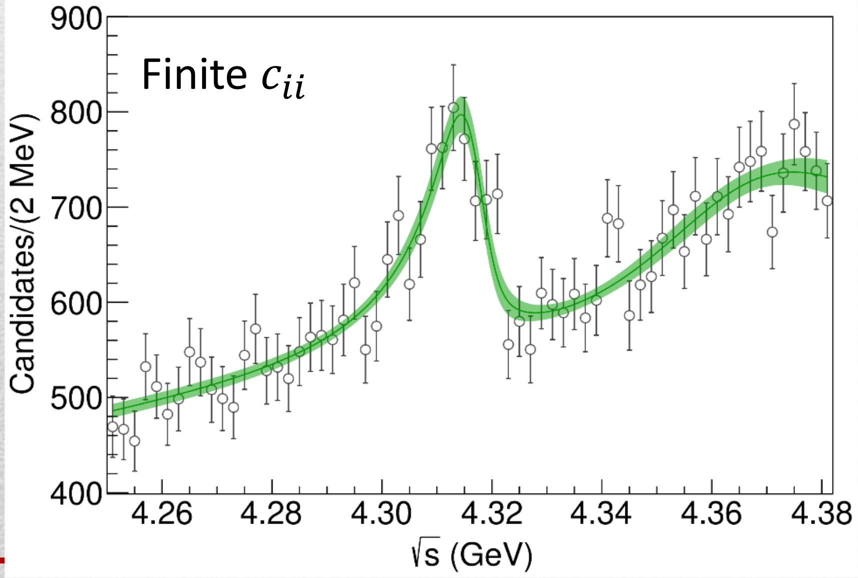
Effective range expansion

$$F(s) = (N_1 + N_2 s)\, T_{11}(s)$$

We can set $c_{ii} = 0$ to reduce to the scattering length approximation

$$T(s) = \begin{pmatrix} m_{11} - c_{11}s - i\rho_1(s) & m_{12} \\ m_{12} & m_{22} - c_{22}s - i\rho_2(s) \end{pmatrix}^{-1}$$





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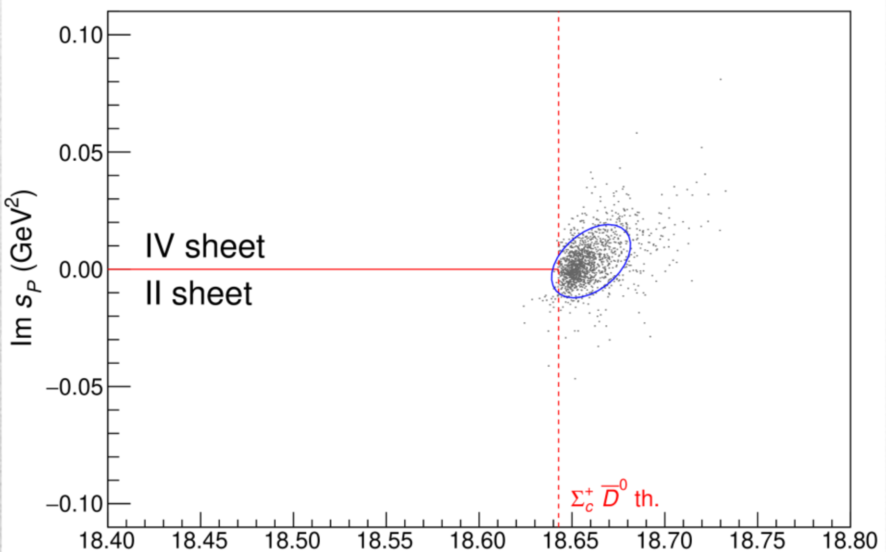
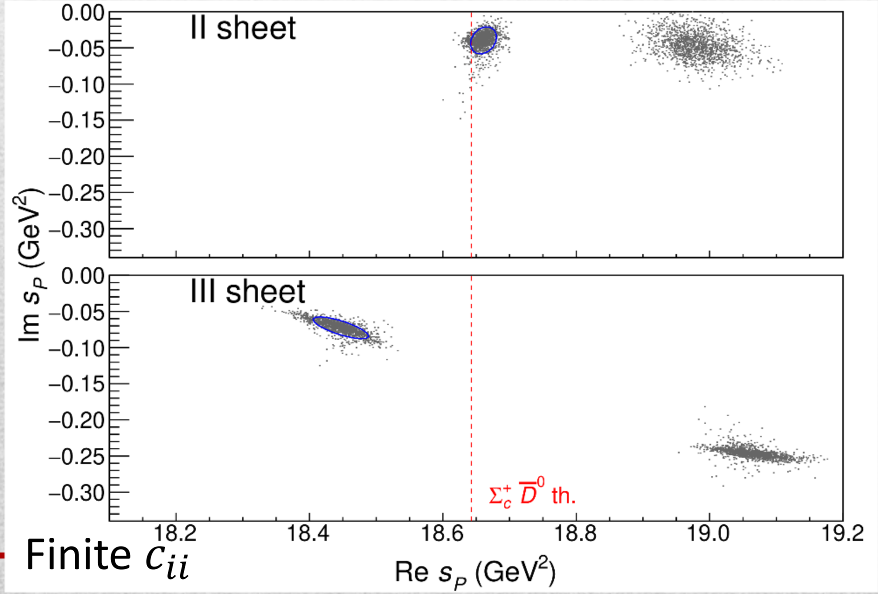


$c_{ii} = 0$



Finite c_{ii}

Minimal(istic) model

Fernandez-Ramirez, AP et al. (JPAC), 1904.10021

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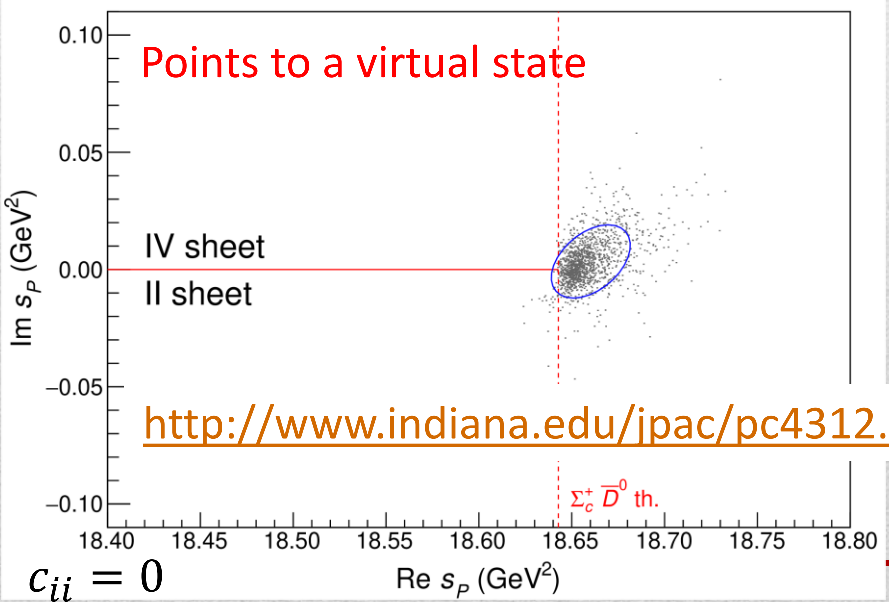
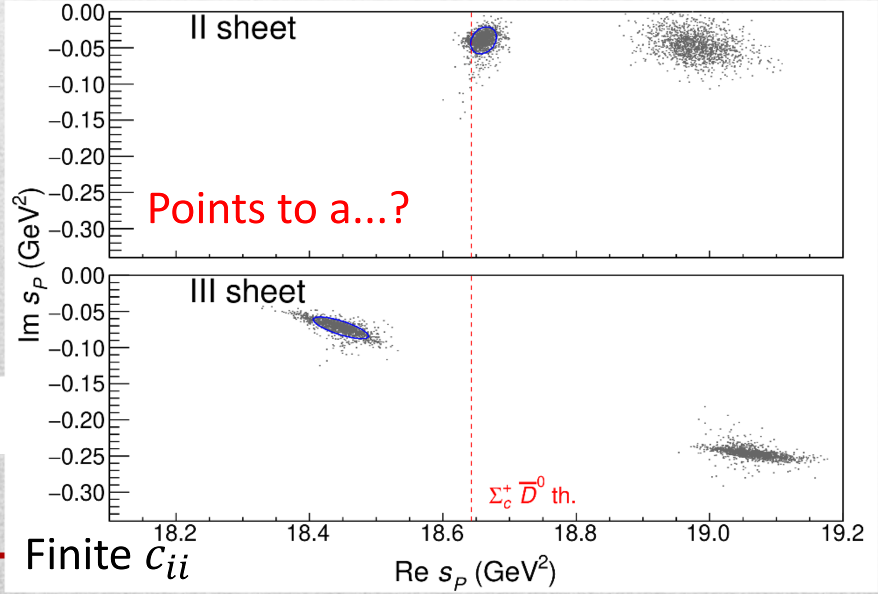


$c_{ii} = 0$

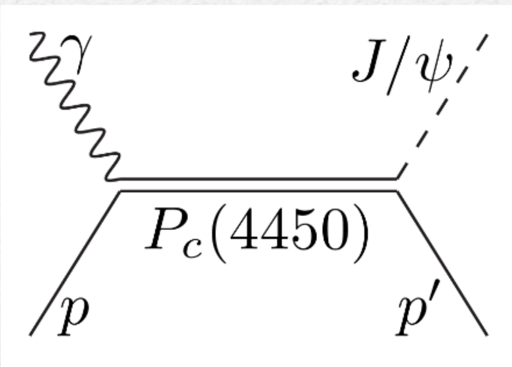
http://www.indiana.edu/jpac/pc4312.php



Finite c_{ii}

P_c photoproduction

To exclude any rescattering mechanism, we propose to search the $P_c(4450)$ state in photoproduction.



Hadronic vertex EM vertex

$$\langle \lambda_\psi \lambda_{p'} | T_r | \lambda_\gamma \lambda_p \rangle = \frac{\langle \lambda_\psi \lambda_{p'} | T_{\text{dec}} | \lambda_R \rangle \langle \lambda_R | T^\dagger_{\text{em}} | \lambda_\gamma \lambda_p \rangle}{M_r^2 - W^2 - i\Gamma_r M_r}$$

Hadronic part

- 3 independent helicity couplings,
  → approx. equal, $g_{\lambda_\psi, \lambda_{p'}} \sim g$
- g extracted from total width and (unknown) branching ratio

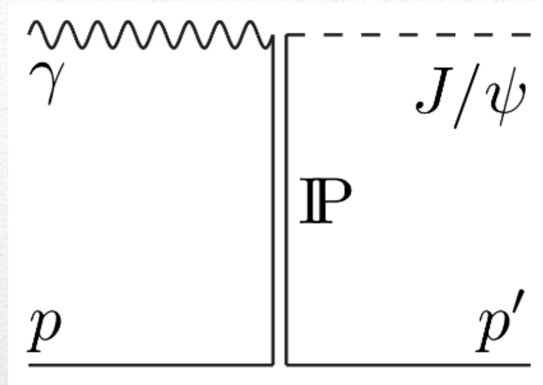
Vector meson dominance relates the radiative width to the hadronic width

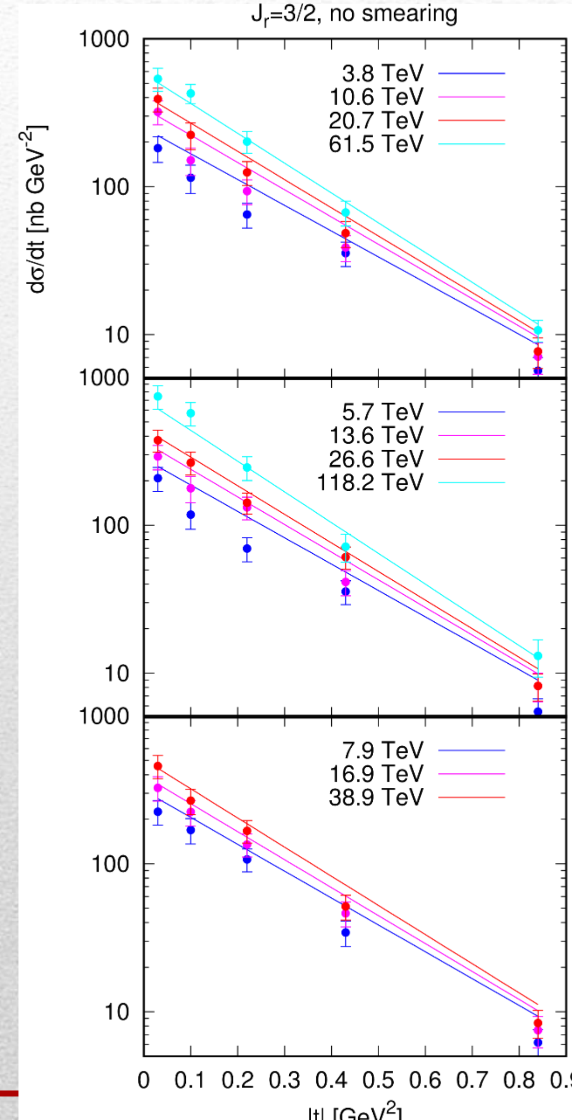
$$\Gamma_\gamma = 4\pi\alpha\,\Gamma_{\psi p} \left(\frac{f_\psi}{M_\psi}\right)^2 \left(\frac{\bar{p}_i}{\bar{p}_f}\right)^{2\ell+1} \times \frac{4}{6}$$

Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Background parameterization

The background is described via an Effective Pomeron, whose parameters are fitted to high energy data from Hera





$$\langle \lambda_\psi \lambda_{p'} | T_P | \lambda_\gamma \lambda_p \rangle = iA \left(\frac{s - s_t}{s_0} \right)^{\alpha(t)} e^{b_0 (t - t_{\min})} \delta_{\lambda_p \lambda_{p'}} \delta_{\lambda_\psi \lambda_\gamma}$$

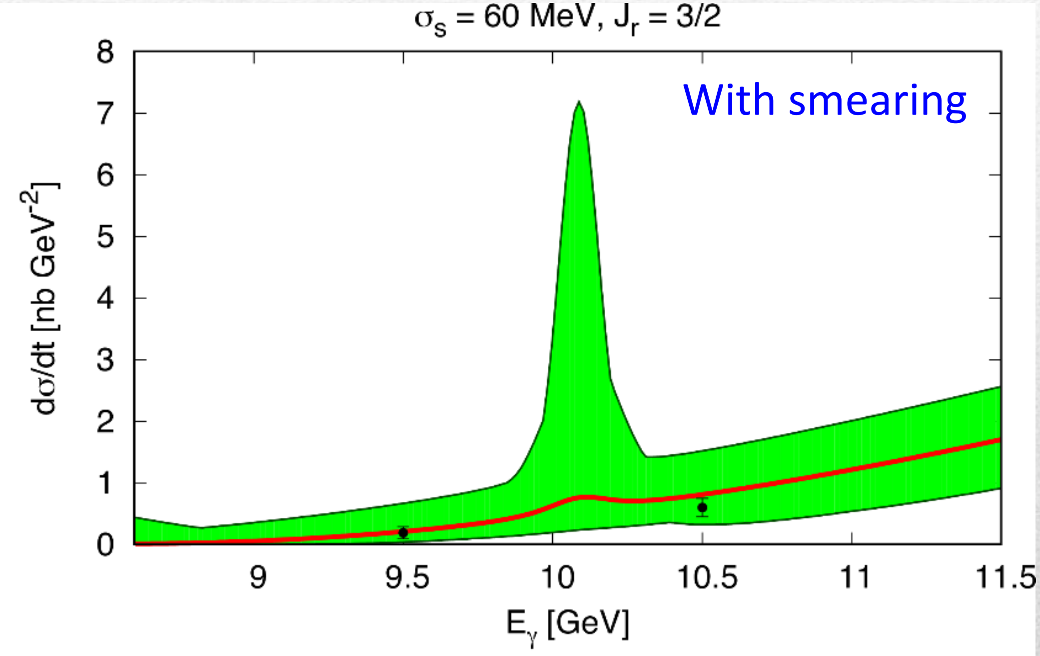
Asymptotic + Effective threshold

Helicity conservation

Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Pentaquark photoproduction

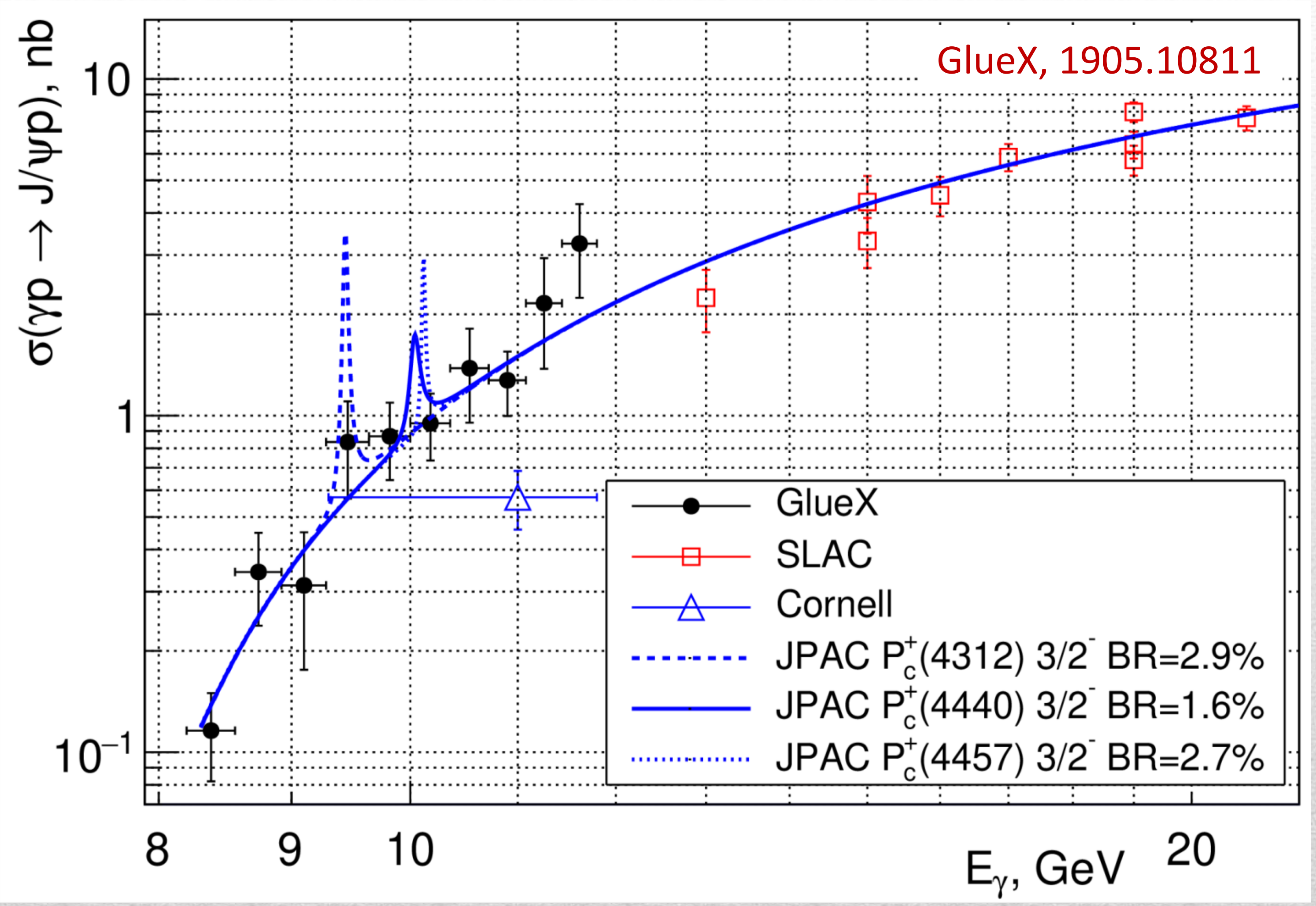
$J^P = (3/2)^-$



σ_s (MeV)	0	60
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$
b_0 (GeV^{-2})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$
$\mathcal{B}_{\psi p}$ (95% CL)	≤ 29 %	≤ 30 %

Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Photoproduction at GlueX

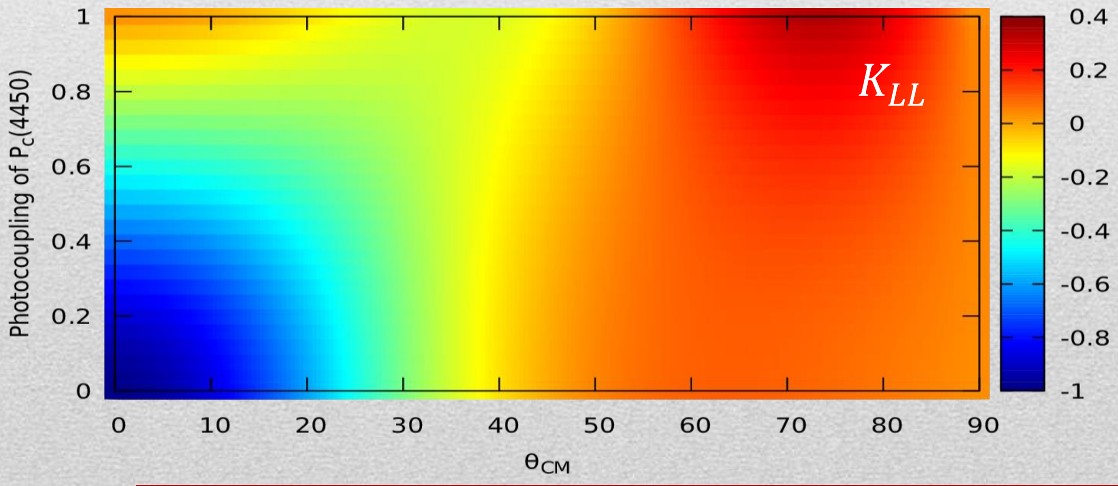


No evidence of pentaquark signals has been seen in GlueX, upper limits have been set

Polarization observables

One can take advantage of the polarized beam at JLab
High intensity beam in SBS (Hall A) looks promising
Need polarized target (A_{LL}) or polarization of recoiling proton (K_{LL})

$$\mathrm{A(K)_{LL}} = \frac{1}{2}\left[\frac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)} - \frac{d\sigma(-+) - d\sigma(--)}{d\sigma(-+) + d\sigma(--)}\right]$$



Fanelli, Pentchev, Wojtsekhowski,
LoI12-18-001
Winney, AP *et al.* (JPAC),
to appear

Epilogue

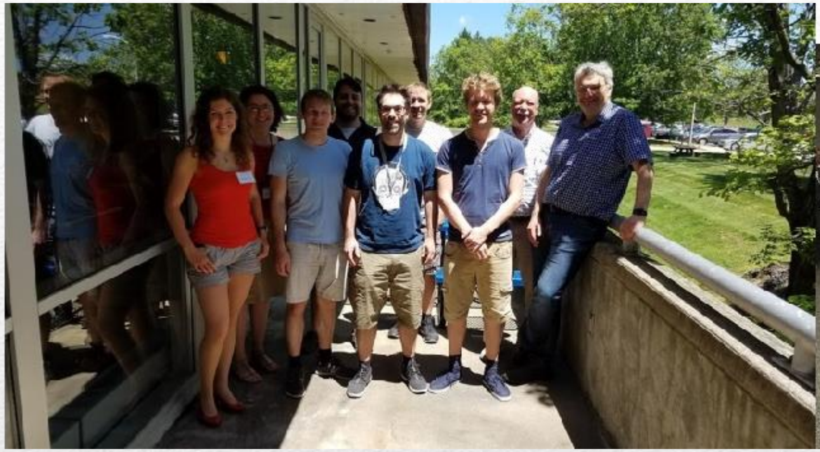
Studying exotic hadrons is challenging

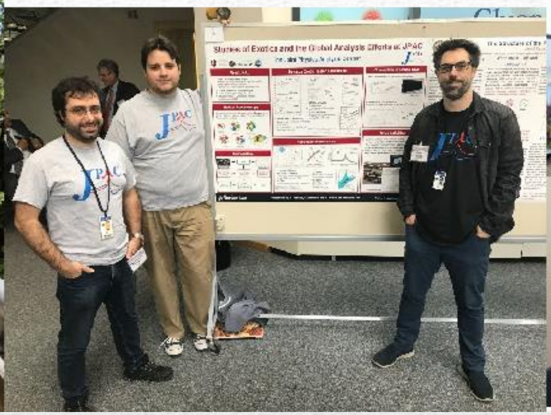
- They are related to dynamics of QCD building blocks
- They often appear as small fraction of cross sections, hard (but mandatory!) to find consistency between different channels
- Dispersive methods can improve the consistency, and offer insights into their nature

Thank you!

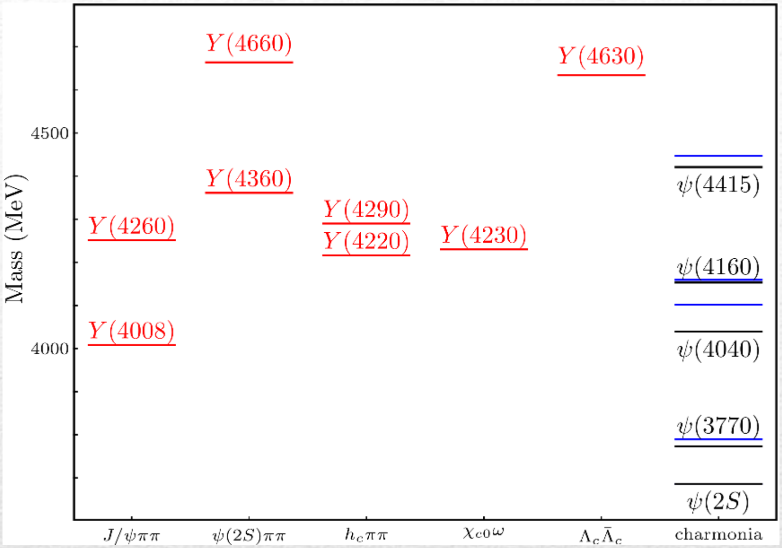
BACKUP

Joint Physics Analysis Center



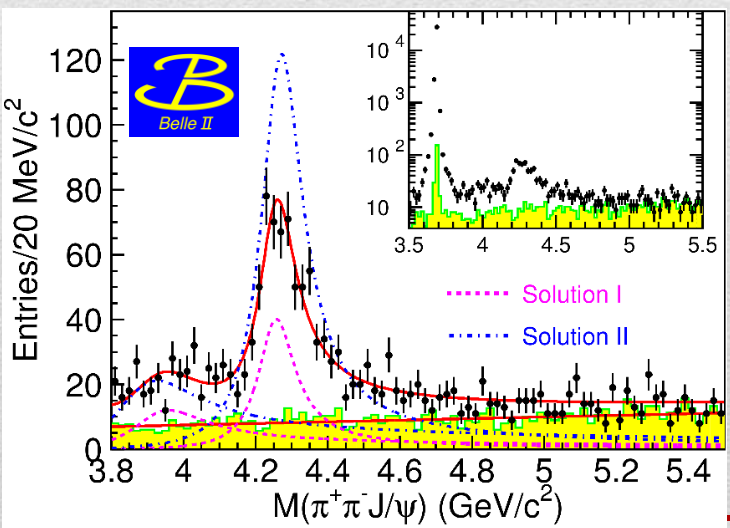


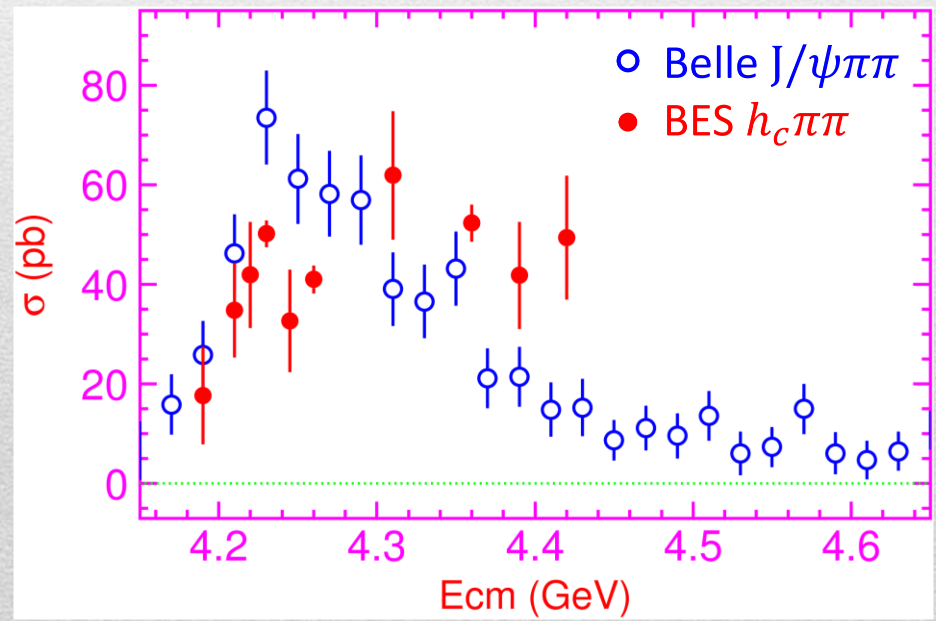
Vector Y states



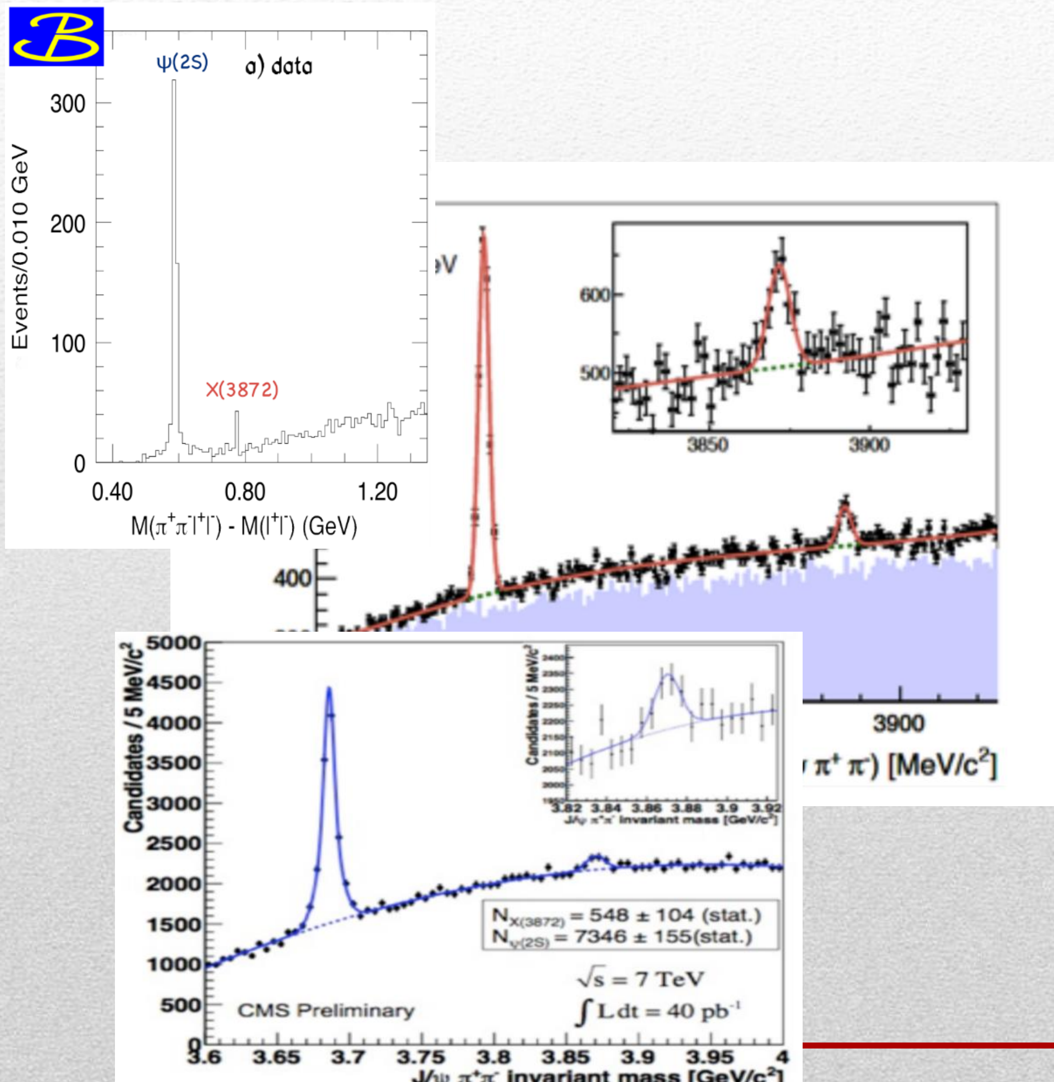
Lots of unexpected $J^{PC} = 1^{--}$ states
found in ISR/direct production (and nowhere else!)
Seen in few final states,
mostly $J/\psi\ \pi\pi$ and $\psi(2S)\ \pi\pi$

Not seen decaying into open charm pairs
Large HQSS violation





$X(3872)$



- Discovered in
  $B \to K\, X \to K\, J/\psi\, \pi\pi$
- Quantum numbers 1^{++}
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X\to J/\psi\ \omega)}{\Gamma(X\to J/\psi\ \rho)} \sim 0.8 \pm 0.3$
- Mass prediction not compatible with $\chi_{c1}(2P)$

$M = 3871.68 \pm 0.17$ MeV
$M_X - M_{DD^*} = -3 \pm 192$ keV
$\Gamma < 1.2$ MeV @90%

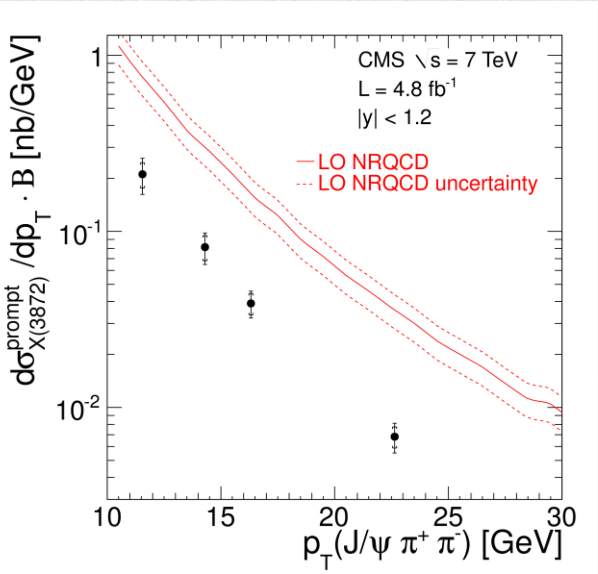
$X(3872)$

Large prompt production
at hadron colliders

$\sigma_B/\sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\%$

$\sigma_{PR} \times B(X \to J/\psi\pi\pi)$
$= (1.06 \pm 0.11 \pm 0.15)$ nb

CMS, JHEP 1304, 154

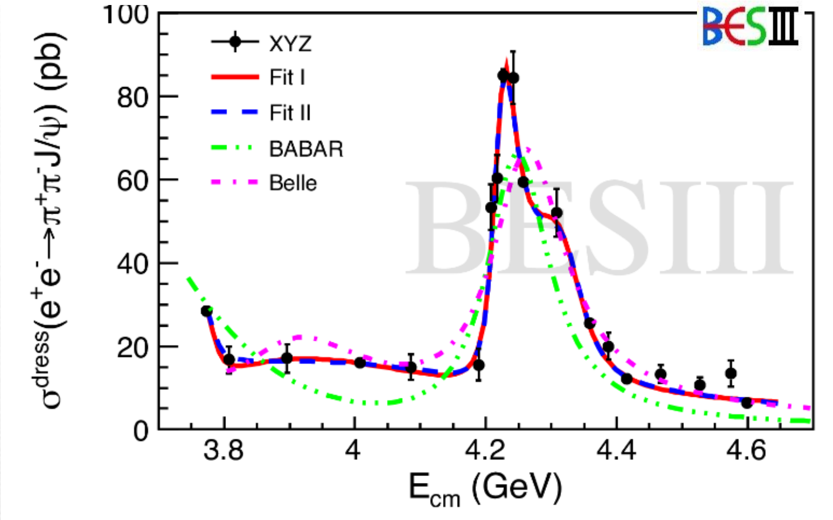


B decay mode	X decay mode	product branching fraction ($\times 10^5$)		B_{fit}	R_{fit}
K^+X	$X \to \pi\pi J/\psi$	$\mathbf{0.86 \pm 0.08}$	(BABAR,[26] Belle[25])	$0.081^{+0.019}_{-0.031}$	1
		$0.84 \pm 0.15 \pm 0.07$	BABAR[26]		
		$0.86 \pm 0.08 \pm 0.05$	Belle[25]		
K^0X	$X \to \pi\pi J/\psi$	$\mathbf{0.41 \pm 0.11}$	(BABAR,[26] Belle[25])		
		$0.35 \pm 0.19 \pm 0.04$	BABAR[26]		
		$0.43 \pm 0.12 \pm 0.04$	Belle[25]		
$(K^+\pi^-)_{NR}X$	$X \to \pi\pi J/\psi$	$0.81 \pm 0.20^{+0.11}_{-0.14}$	Belle[106]		
$K^{*0}X$	$X \to \pi\pi J/\psi$	< 0.34, 90% C.L.	Belle[106]		
KX	$X \to \omega J/\psi$	$R = 0.8 \pm 0.3$	BABAR[33]	$0.061^{+0.024}_{-0.036}$	$0.77^{+0.28}_{-0.32}$
K^+X		$0.6 \pm 0.2 \pm 0.1$	BABAR[33]		
K^0X		$0.6 \pm 0.3 \pm 0.1$	BABAR[33]		
KX	$X \to \pi\pi\pi^0 J/\psi$	$R = 1.0 \pm 0.4 \pm 0.3$	Belle[32]		
K^+X	$X \to D^{*0}\bar{D}^0$	$\mathbf{8.5 \pm 2.6}$	(BABAR,[38] Belle[37])	$0.614^{+0.166}_{-0.074}$	$8.2^{+2.3}_{-2.8}$
		$16.7 \pm 3.6 \pm 4.7$	BABAR[38]		
		$7.7 \pm 1.6 \pm 1.0$	Belle[37]		
K^0X	$X \to D^{*0}\bar{D}^0$	$\mathbf{12 \pm 4}$	(BABAR,[38] Belle[37])		
		$22 \pm 10 \pm 4$	BABAR[38]		
		$9.7 \pm 4.6 \pm 1.3$	Belle[37]		
K^+X	$X \to \gamma J/\psi$	$\mathbf{0.202 \pm 0.038}$	(BABAR,[35] Belle[34])	$0.019^{+0.005}_{-0.009}$	$0.24^{+0.05}_{-0.06}$
K^+X		$0.28 \pm 0.08 \pm 0.01$	BABAR[35]		
		$0.178^{+0.048}_{-0.044} \pm 0.012$	Belle[34]		
K^0X		$0.26 \pm 0.18 \pm 0.02$	BABAR[35]		
		$0.124^{+0.076}_{-0.061} \pm 0.011$	Belle[34]		
K^+X	$X \to \gamma\psi(2S)$	$\mathbf{0.44 \pm 0.12}$	BABAR[35]	$0.04^{+0.015}_{-0.020}$	$0.51^{+0.13}_{-0.17}$
K^+X		$0.95 \pm 0.27 \pm 0.06$	BABAR[35]		
		$0.083^{+0.198}_{-0.183} \pm 0.044$	Belle[34]		
		$R' = 2.46 \pm 0.64 \pm 0.29$	LHCb[36]		
K^0X		$1.14 \pm 0.55 \pm 0.10$	BABAR[35]		
		$0.112^{+0.357}_{-0.290} \pm 0.057$	Belle[34]		
K^+X	$X \to \gamma\chi_{c1}$	$< 9.6 \times 10^{-3}$	Belle[23]	$< 1.0 \times 10^{-3}$	< 0.014
K^+X	$X \to \gamma\chi_{c2}$	< 0.016	Belle[23]	$< 1.7 \times 10^{-3}$	< 0.024
KX	$X \to \gamma\gamma$	$< 4.5 \times 10^{-3}$	Belle[111]	$< 4.7 \times 10^{-4}$	$< 6.6 \times 10^{-3}$
KX	$X \to \eta J/\psi$	< 1.05	BABAR[112]	< 0.11	< 1.55
K^+X	$X \to p\bar{p}$	$< 9.6 \times 10^{-4}$	LHCb[110]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

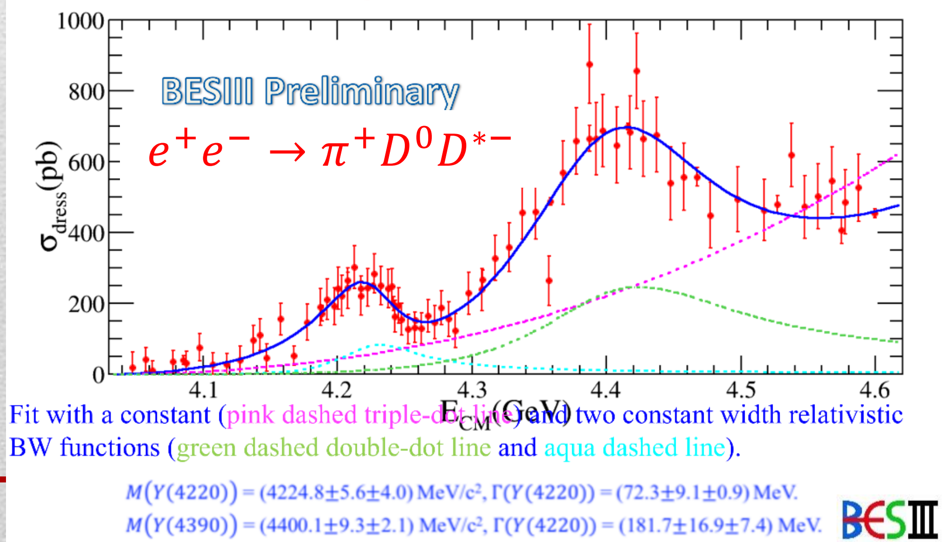
Vector Y states in BESIII

BESIII, PRL118, 092001 (2017) $e^+e^- \to J/\psi\,\pi\pi$

BESIII, PRL118, 092002 (2017)



Parameters	Solution I	Solution II
$\Gamma_{e^+e^-}\mathcal{B}[\psi(3770)\to\pi^+\pi^-J/\psi]$		0.5 ± 0.1 (0
$\Gamma_{e^+e^-}\mathcal{B}(R_1\to\pi^+\pi^-J/\psi)$	$8.8^{+1.5}_{-2.2}\,(\cdots)$	$6.8^{+1.1}_{-1.5}\,(\cdots)$
$\Gamma_{e^+e^-}\mathcal{B}(R_2\to\pi^+\pi^-J/\psi)$	$13.3\pm1.4\,(12.0\pm1.0)$	$9.2\pm0.7\,(8.9\pm0.6)$
$\Gamma_{e^+e^-}\mathcal{B}(R_3\to\pi^+\pi^-J/\psi)$	$21.1\pm3.9\,(17.9\pm3.3)$	$1.7^{+0.8}_{-0.6}\,(1.1^{+0.5}_{-0.4})$
ϕ_1	$-58\pm11\,(-33\pm8)$	$-116^{+9}_{-10}\,(-81^{+7}_{-8})$
ϕ_2	$-156\pm5\,(-132\pm3)$	$68\pm24\,(107\pm20)$

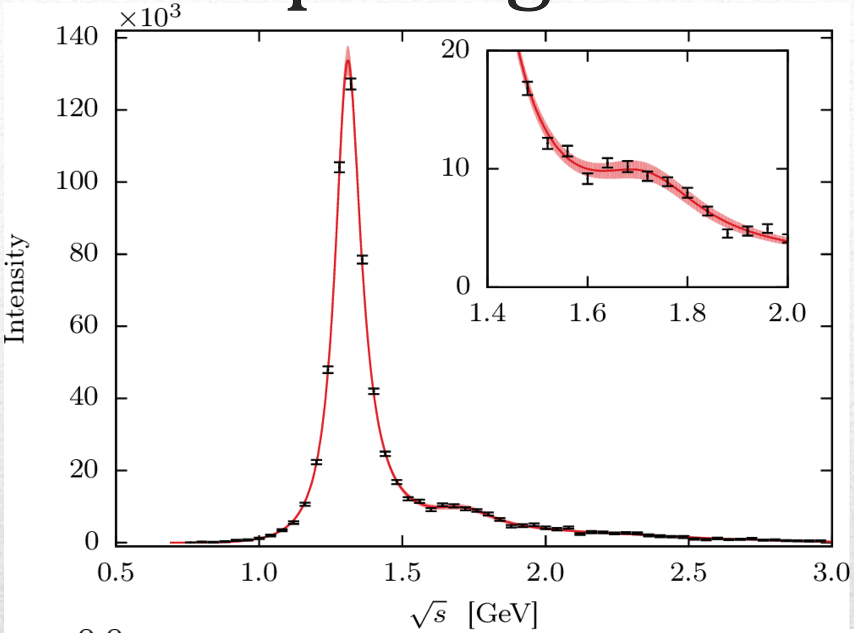


New BESIII data show a peculiar lineshape for the $Y(4260)$

The state appear lighter and narrower, compatible with the ones in $h_c\pi\pi$ and $\chi_{c0}\omega$

A broader old-fashioned $Y(4260)$ is appearing in $\bar{D}D^*\pi$, maybe indicating a $\bar{D}D_1$ dominance

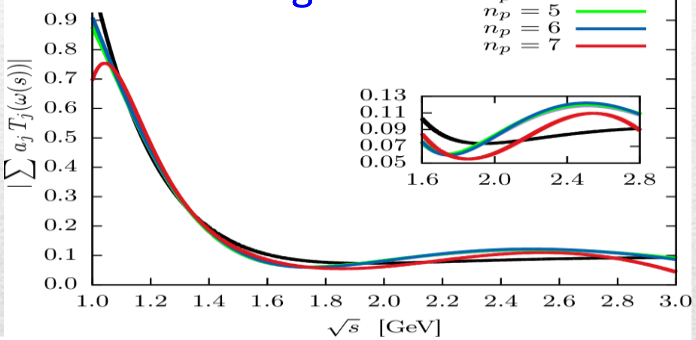
Recap: single channel $\eta\pi$



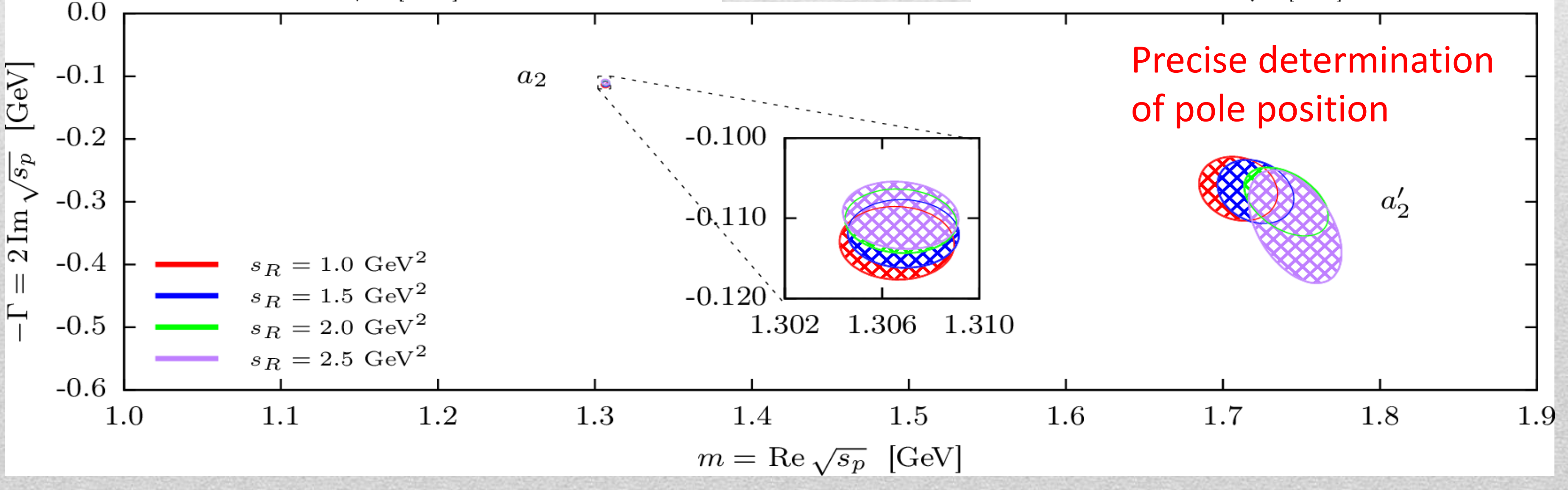
Test against the D-wave $\eta\pi$ data, where the a_2 and the a_2' show up

A. Jackura, M. Mikhasenko, AP *et al.* (JPAC & COMPASS), PLB779, 464-472

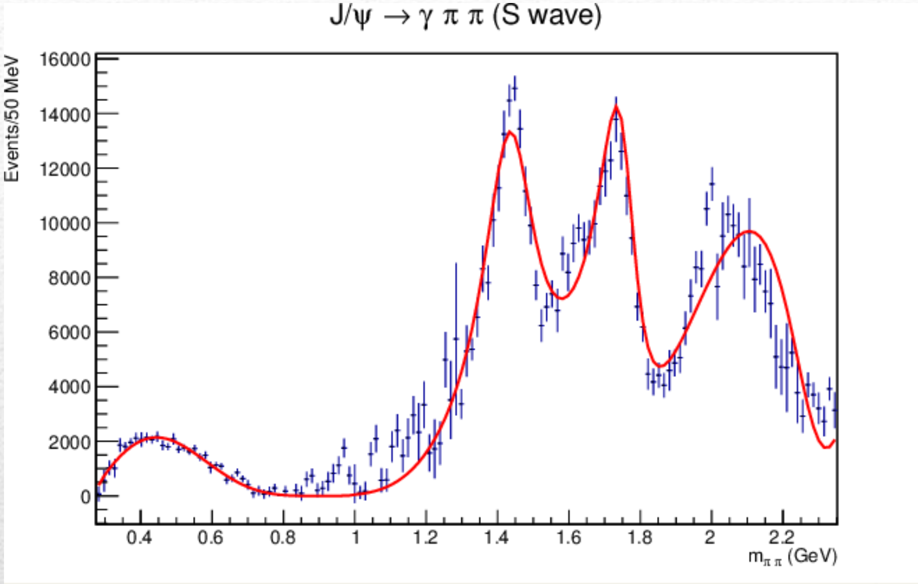
Smooth «background»

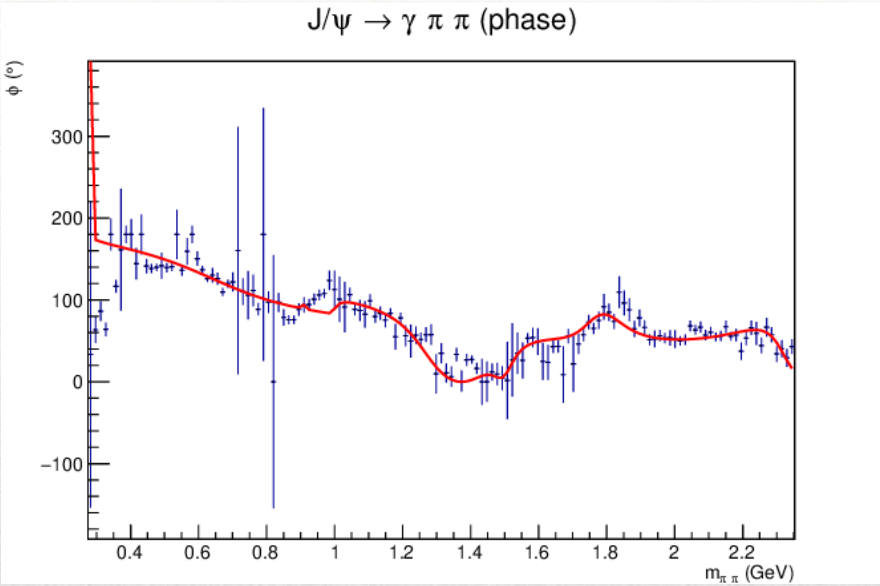


Precise determination of pole position

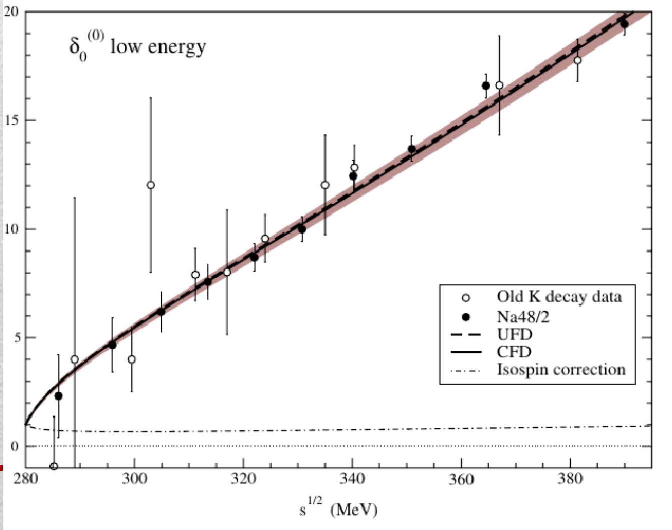


What about the σ?



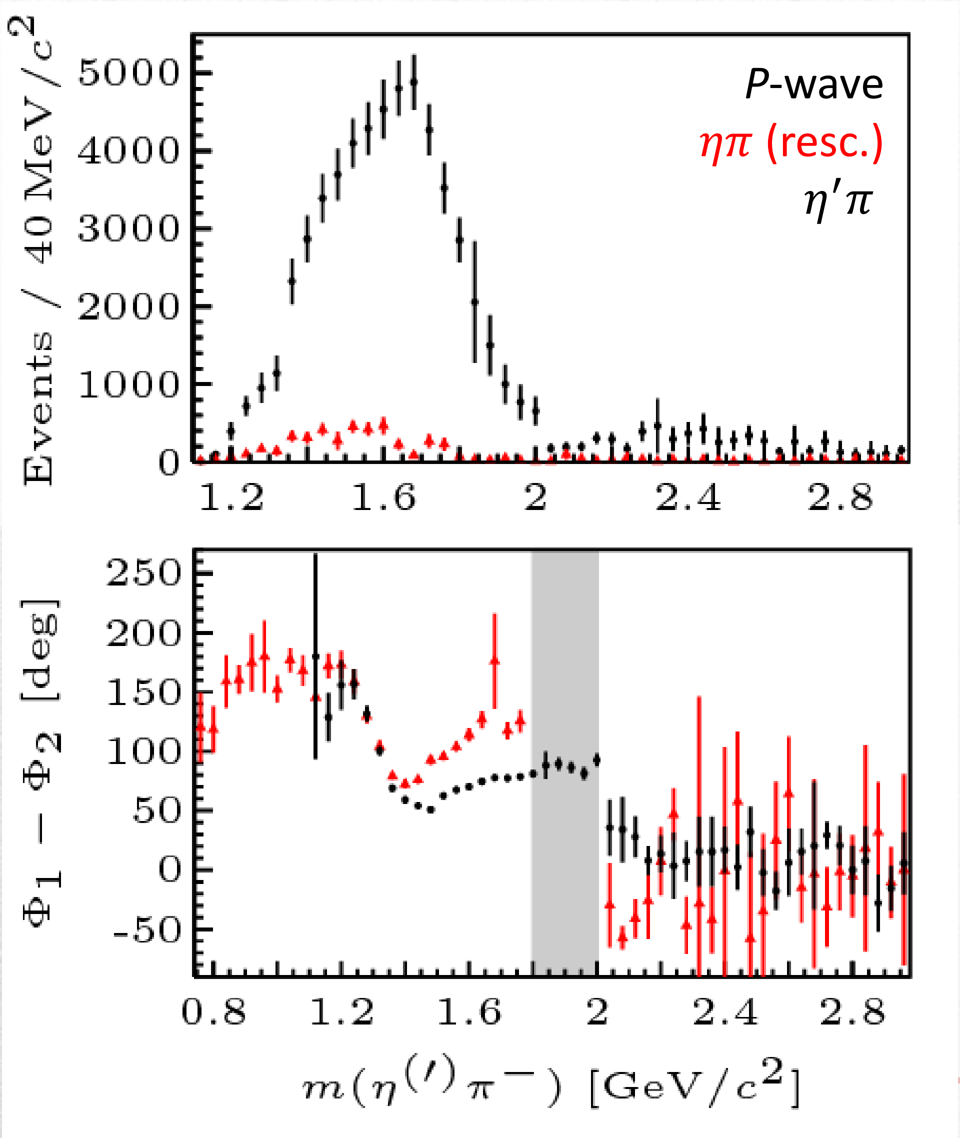


Even if an Adler zero is added,
hard to obtain a reasonable behavior of the phase in the σ region
We are exploring new parametrization



Data

COMPASS, PLB740, 303-311



A sharp drop appears at 2 GeV in *P*-wave intensity and phase

No convincing physical motivation for it

It affects the position of the $a_2'(1700)$

We decided to fit up to 2 GeV only

Systematic studies

- Change of functional form and parameters in the denominator

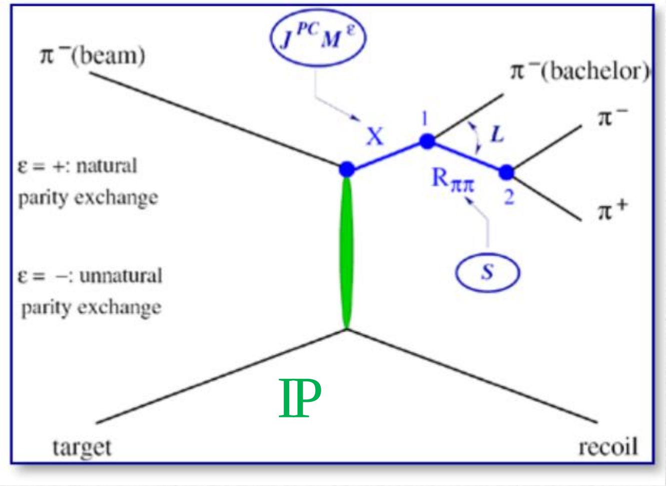
$$\rho N_{ki}^J(s') = g\,\delta_{ki}\,\frac{\lambda^{J+1/2}\left(s', m^2_{\eta^{(\prime)}}, m^2_\pi\right)}{(s'+s_R)^{2J+1+\alpha}}$$

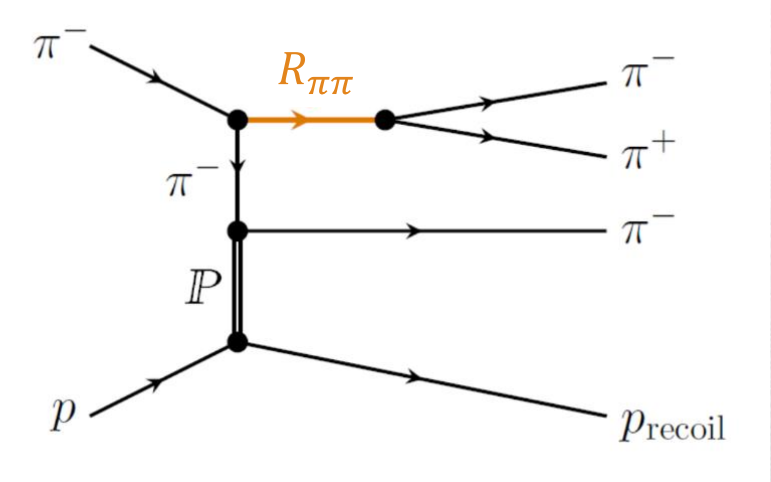
  - Default: $s_R = 1\text{ GeV}^2$. We try $s_R = 0.8, 1.8\text{ GeV}^2$
  - Default: $\alpha = 2$. We try $\alpha = 1$
  - We also try a different function: $\rho N_{ki}^J(s') = g\,\delta_{ki}\,\frac{Q_J(z_{s'})}{s'^\alpha \lambda^{1/2}(s', m_{\eta^{(\prime)}}, m_\pi)}$ with $\alpha = 2, 1.5, 1$

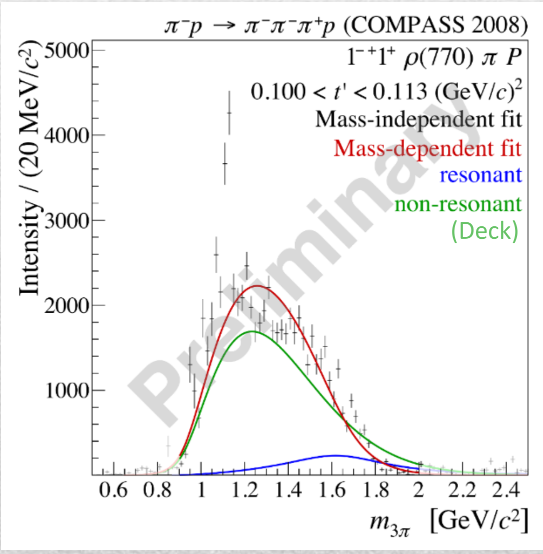
- Change of parameters in the numerator

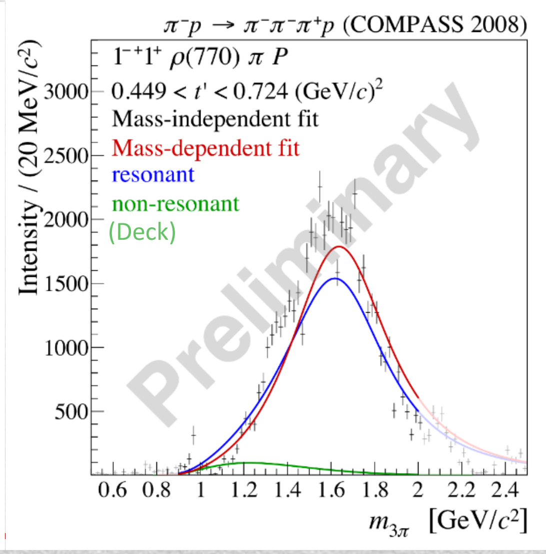
  - Default: $t_{\text{eff}} = -0.1\text{ GeV}^2$. We try$t_{\text{eff}} = -0.5\text{ GeV}^2$
  - Default: 3rd order polynomial. We try 4th

$\rho\pi$ channel and Deck amplitude





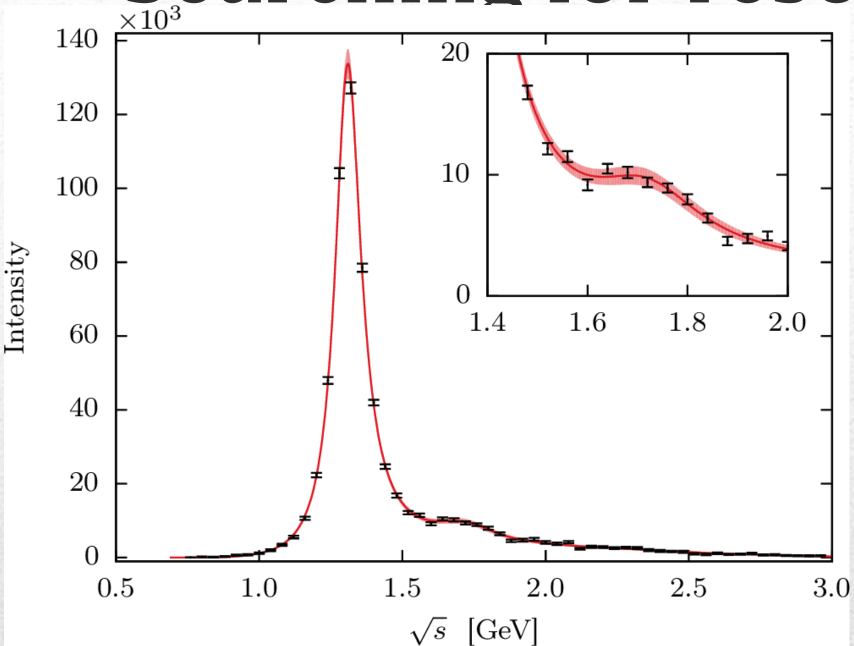


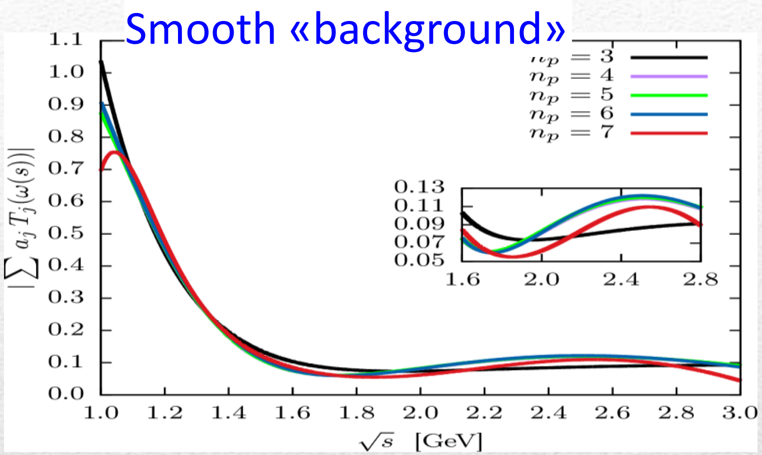


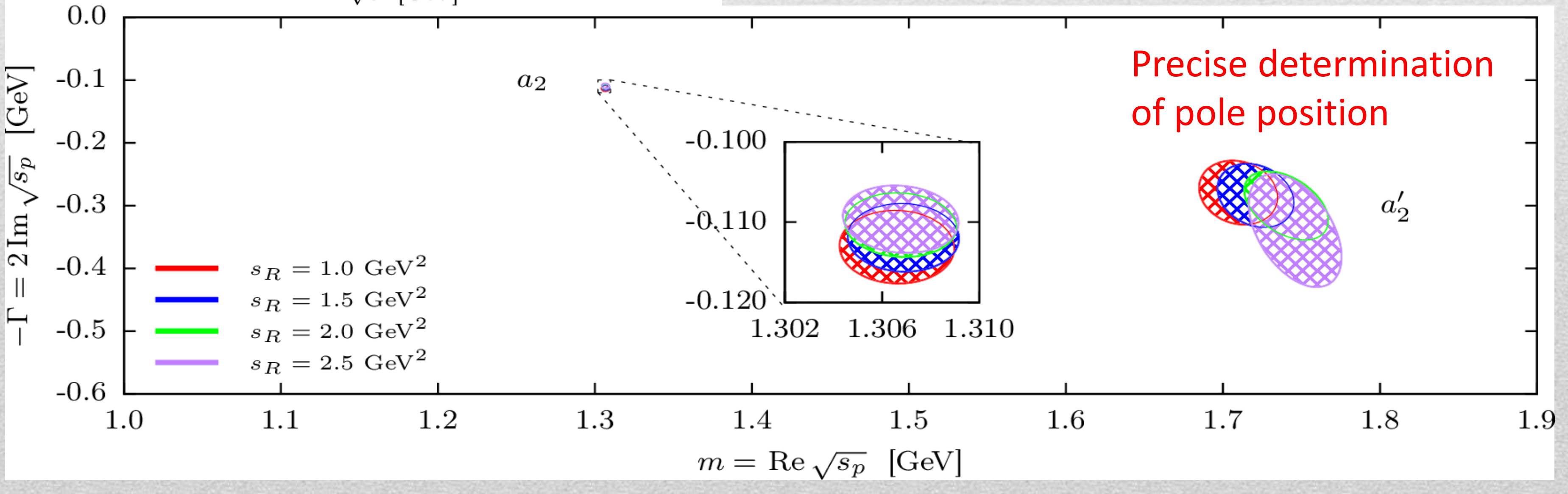
The production allows for a nonresonant component (Deck effect)
The singularity is close to the physical region, peaking background

We do not include this channel

Searching for resonances in $\eta\pi$





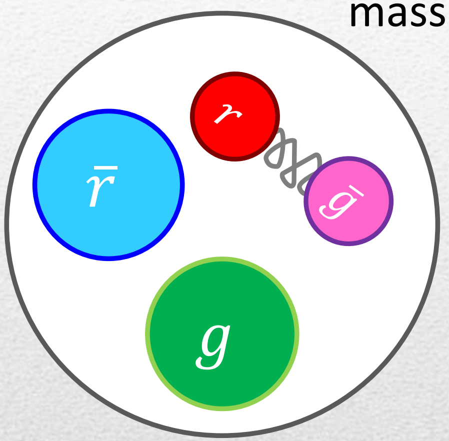


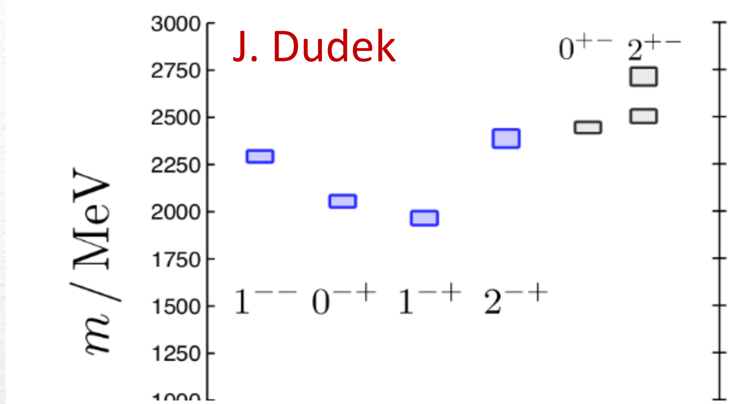
The hybrid π_1

A. Rodas, AP *et al.* (JPAC) PRL122, 042002

Hybrid hunting

Excited gluon,
$J^{PC} = 1^{+-}$
mass ~ 1.0—1.5 GeV

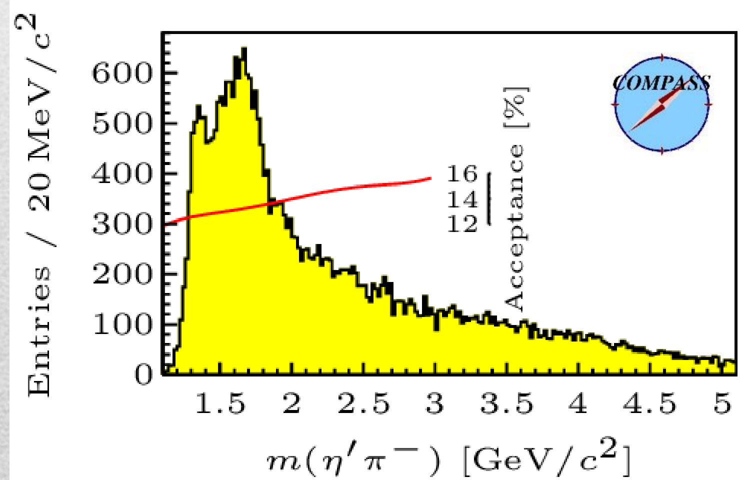




excitation of a quasiparticle?
→ degenerate $J^{PC} = (0, \mathbf{1}, 2)^{-+}, 1^{--}$

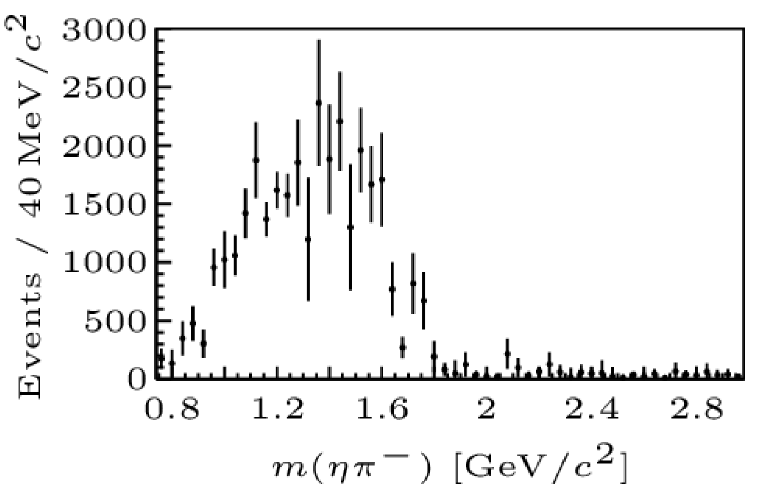
Look for a π_1 state with $\boldsymbol{J^{PC} = 1^{-+}}$

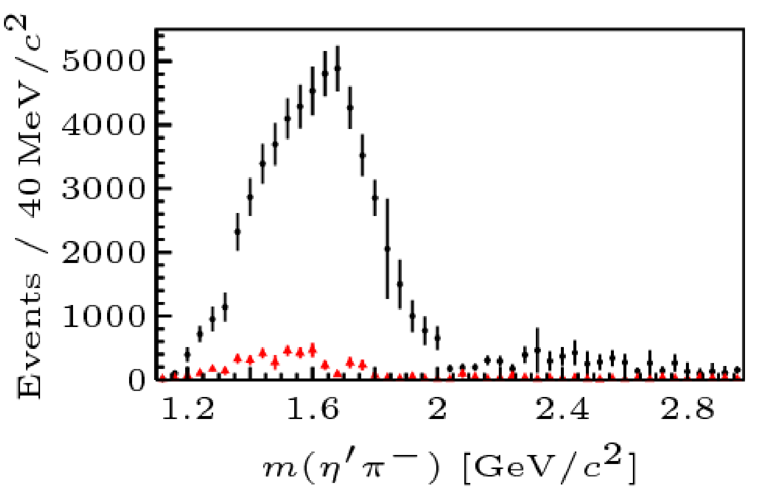
$$\text{decaying into} \begin{cases} \eta\,\pi \text{ and } \eta'\pi \\ \rho\,\pi \to 3\pi \\ b_1\pi \to 5\pi \end{cases}$$



Small signal in data

Two hybrid states???





$\pi_1(1400)$ $I^G(J^{PC}) = 1^-(1^{-+})$

See also the mini-review under non-$q\bar{q}$ candidates in PDG 2006 , Journal of Physics G33 1 (2006).

$\pi_1(1400)$ MASS	1354 ± 25 MeV (S = 1.8)
$\pi_1(1400)$ WIDTH	330 ± 35 MeV

Decay Modes

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level
Γ_1	$\eta\pi^0$	seen	
Γ_2	$\eta\pi^-$	seen	
Γ_3	$\eta'\pi$		

Neither lattice nor models predict two 1^{-+} states in this region!

$\pi_1(1600)$ $I^G(J^{PC}) = 1^-(1^{-+})$

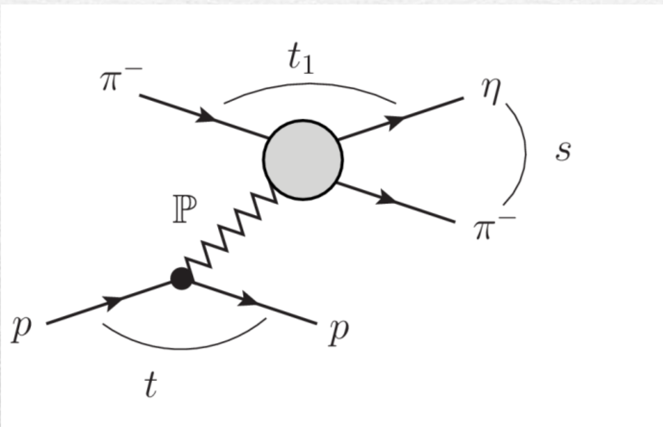
$\pi_1(1600)$ MASS	1662^{+8}_{-9} MeV
$\pi_1(1600)$ WIDTH	241 ± 40 MeV (S = 1.4)

Decay Modes

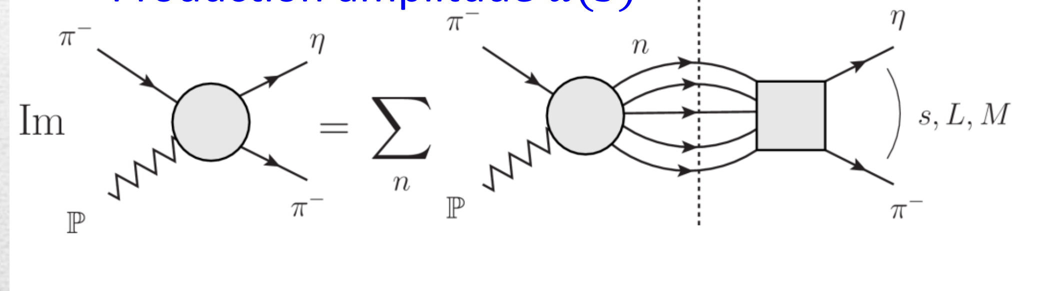
	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level
Γ_1	$\pi\pi\pi$	seen	
Γ_2	$\rho^0\pi^-$	seen	
Γ_3	$f_2(1270)\pi^-$	not seen	
Γ_4	$b_1(1235)\pi$	seen	
Γ_5	$\eta'(958)\pi^-$	seen	
Γ_6	$f_1(1285)\pi$	seen	

Amplitudes for $\eta^{(\prime)}\pi$

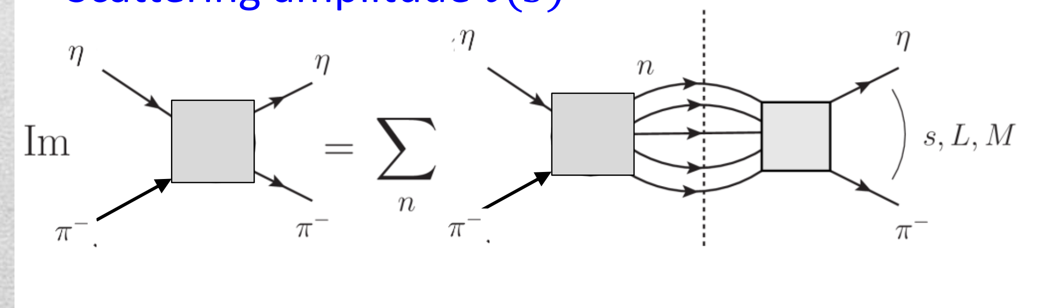
We build the partial wave amplitudes according to the N/D method



Production amplitude $a(s)$



Scattering amplitude $t(s)$



$$\mathrm{Im}\, a(s) = \rho\, a(s)\, t^*(s)$$

$$\frac{d\sigma}{d\sqrt{s}} \propto \frac{\rho}{\sqrt{s}} |p^L q^{L-1}\, a(s)|^2$$

Amplitudes for $\eta^{(\prime)}\pi$

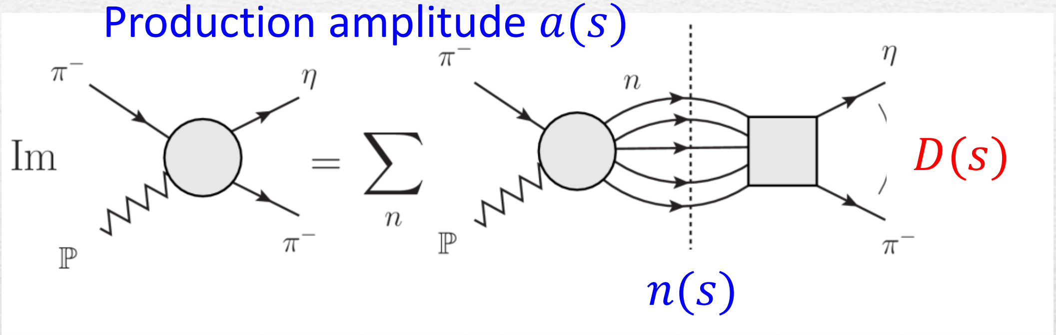
We build the partial wave amplitudes according to the N/D method

$$t(s) = \frac{N(s)}{D(s)},\, a(s) = \frac{n(s)}{D(s)}$$

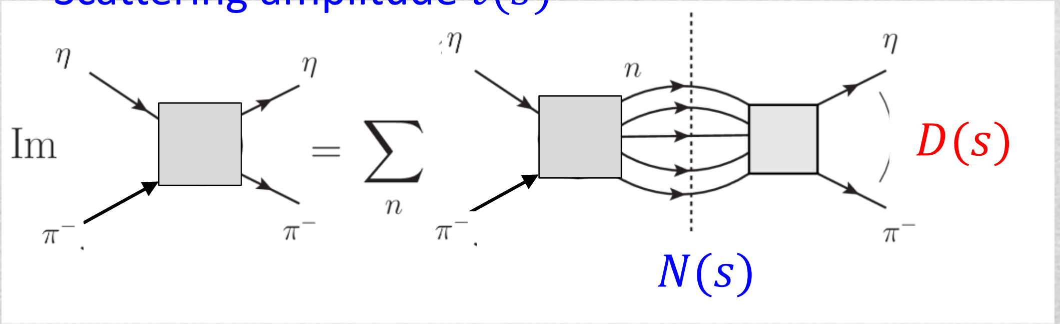
The $D(s)$ has only right hand cuts;
it contains all the Final State Interactions constrained by unitarity → universal

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

Production amplitude $a(s)$



Scattering amplitude $t(s)$

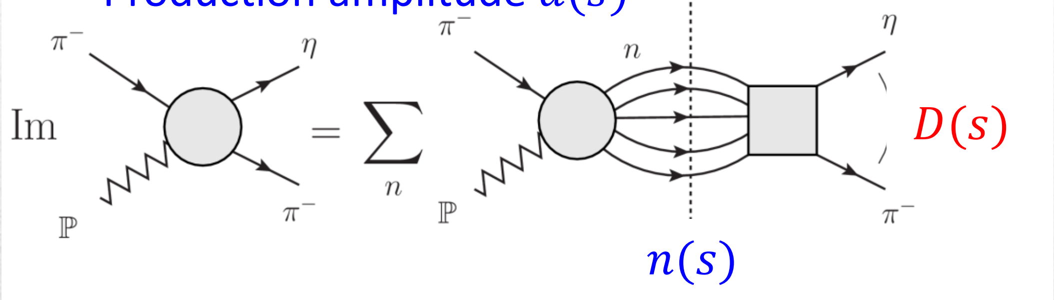


Amplitudes for $\eta^{(\prime)}\pi$

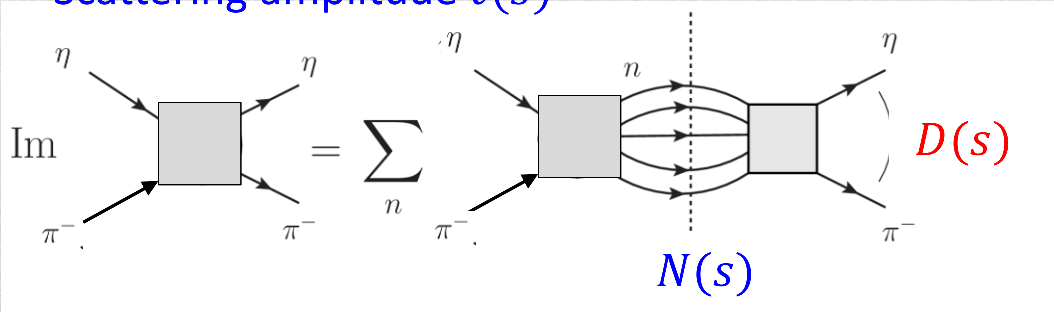
We build the partial wave amplitudes according to the N/D method

$$t(s) = \frac{N(s)}{D(s)}, a(s) = \frac{n(s)}{D(s)}$$

Production amplitude $a(s)$



Scattering amplitude $t(s)$



The $n(s), N(s)$ have left hand cuts only, they depend on the exchanges → process-dependent, smooth

Coupled channel: the model

A. Rodas, AP *et al.* (JPAC) PRL122, 042002

Two channels, $i, k = \eta\pi, \eta'\pi$

Two waves, $J = P, D$

37 fit parameters

$$D^J_{ki}(s) = \left[K^J(s)^{-1}\right]_{ki} - \frac{s}{\pi}\int_{s_k}^{\infty} ds' \frac{\rho N^J_{ki}(s')}{s'(s'-s-i\epsilon)}$$

$$K^J_{ki}(s) = \sum_R \frac{g_k^{(R)} g_i^{(R)}}{m_R^2 - s} + c^J_{ki} + d^J_{ki}\, s$$

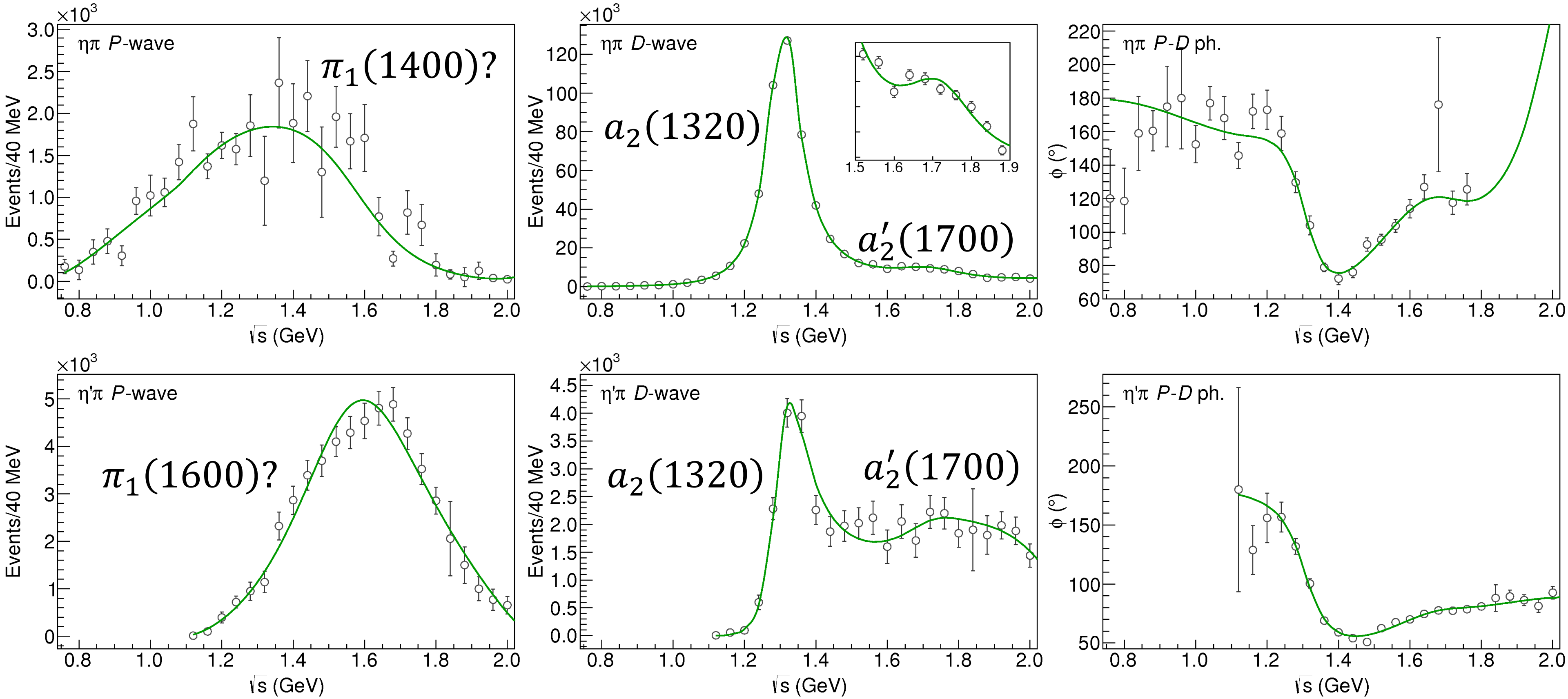
1 K-matrix pole for the P-wave
2 K-matrix poles for the D-wave

$$\rho N^J_{ki}(s') = \delta_{ki} \frac{\lambda^{J+1/2}\left(s', m^2_{\eta^{(\prime)}}, m^2_\pi\right)}{(s'+s_R)^{2J+1+\alpha}}$$

$$n^J_k(s) = \sum_{n=0}^{3} a_n^{J,k}\, T_n\left(\frac{s}{s+s_0}\right)$$

Left-hand scale (Blatt-Weisskopf radius) $s_R = s_0 = 1\ \text{GeV}^2$
$\alpha = 2$, 3rd order polynomial for $n^J_k(s)$

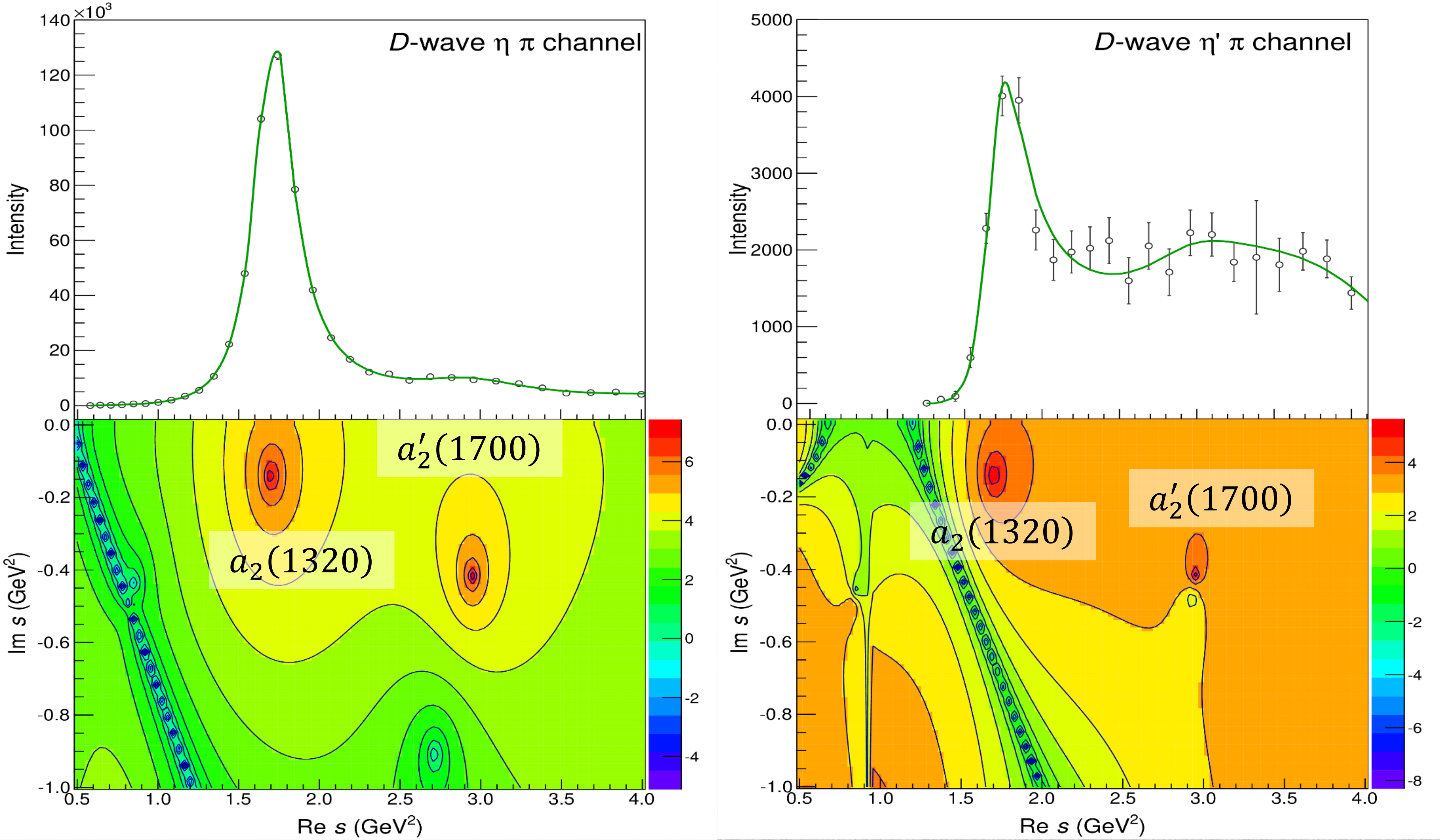
Fit to $\eta^{(\prime)}\pi$



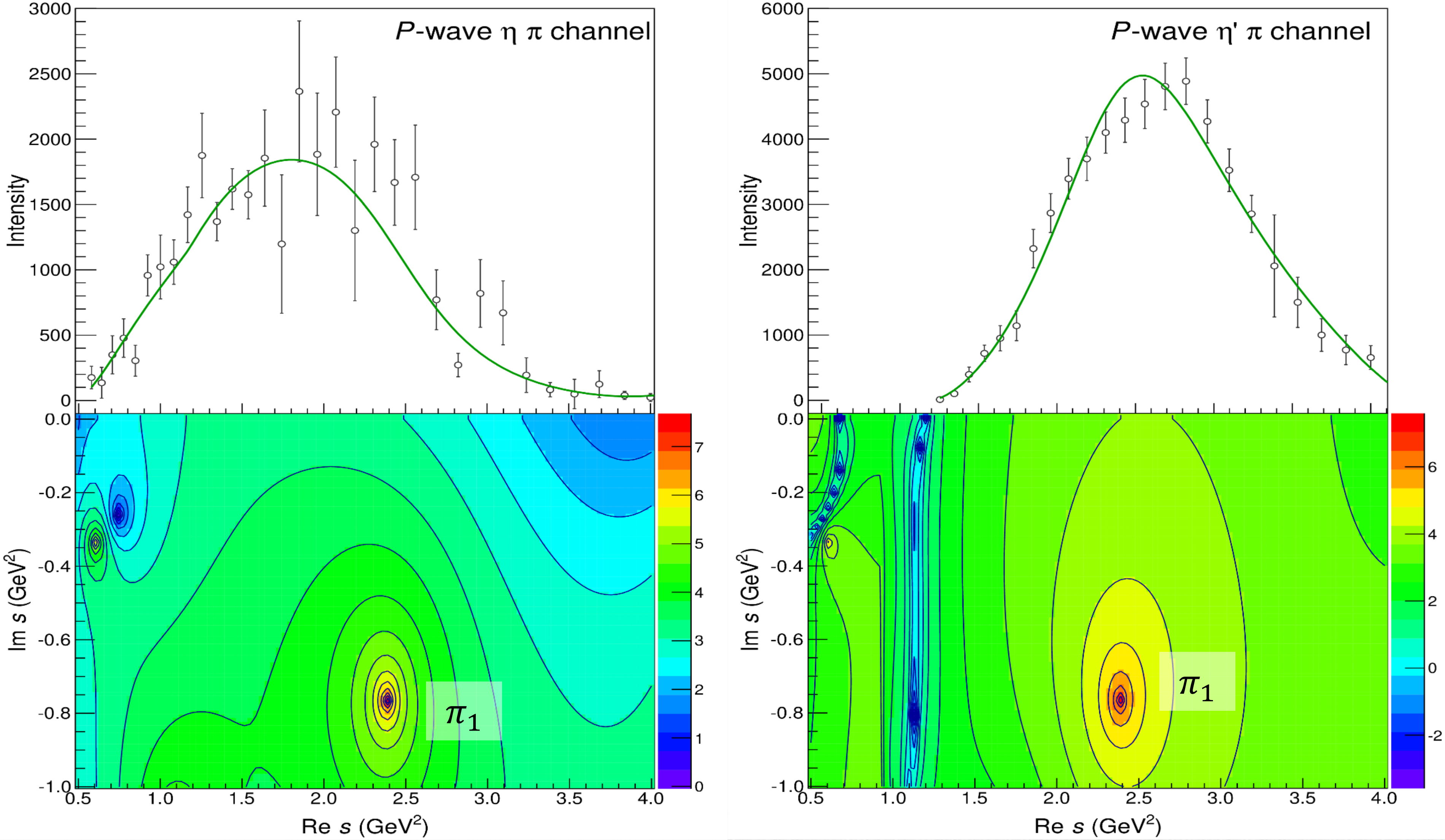
$J^{PC} = 1^{-+}$

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

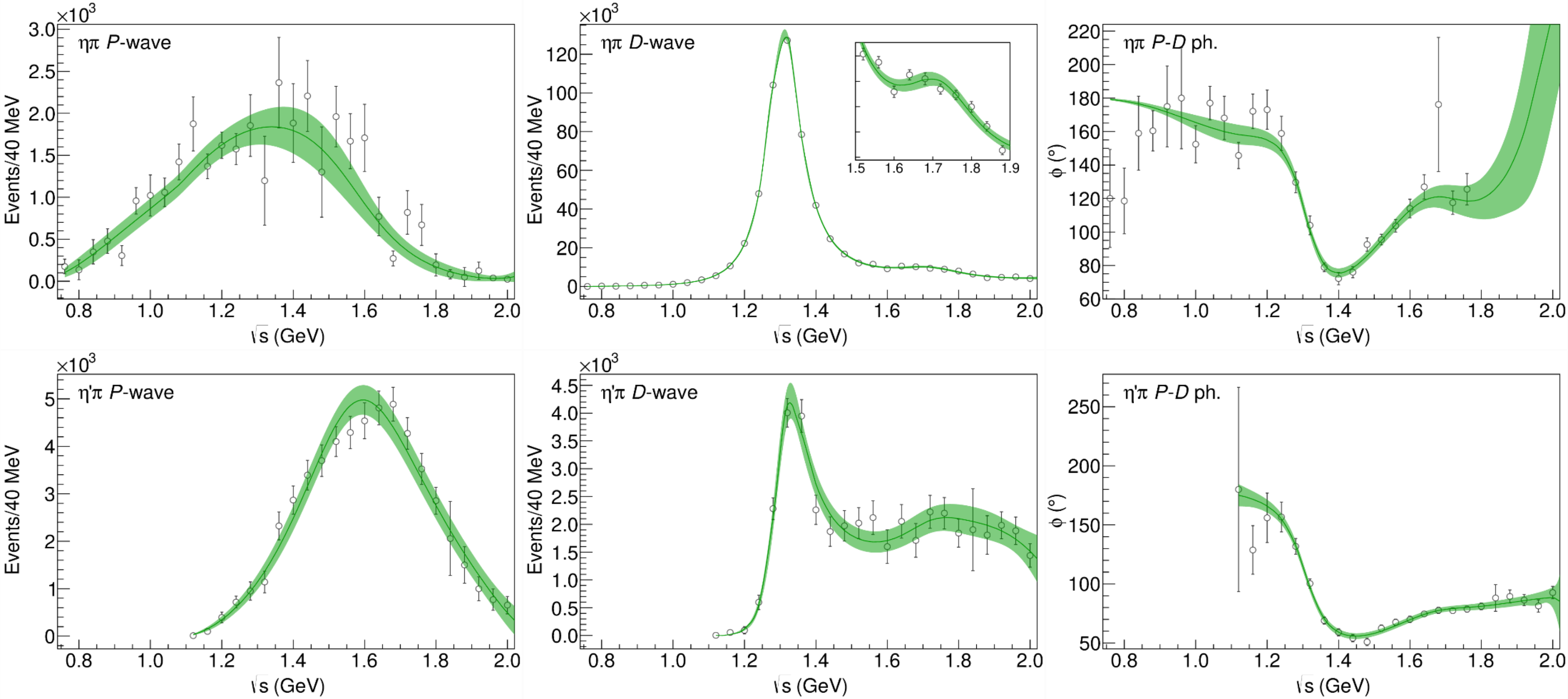
Pole hunting



Pole hunting



Statistical Bootstrap



Correlations

Denominator parameters uncorrelated with the numerator ones ✓

Denominator parameters uncorrelated between *P*- and *D*-wave ✓

Production (numerator) parameters

K-matrix «pole» parameters

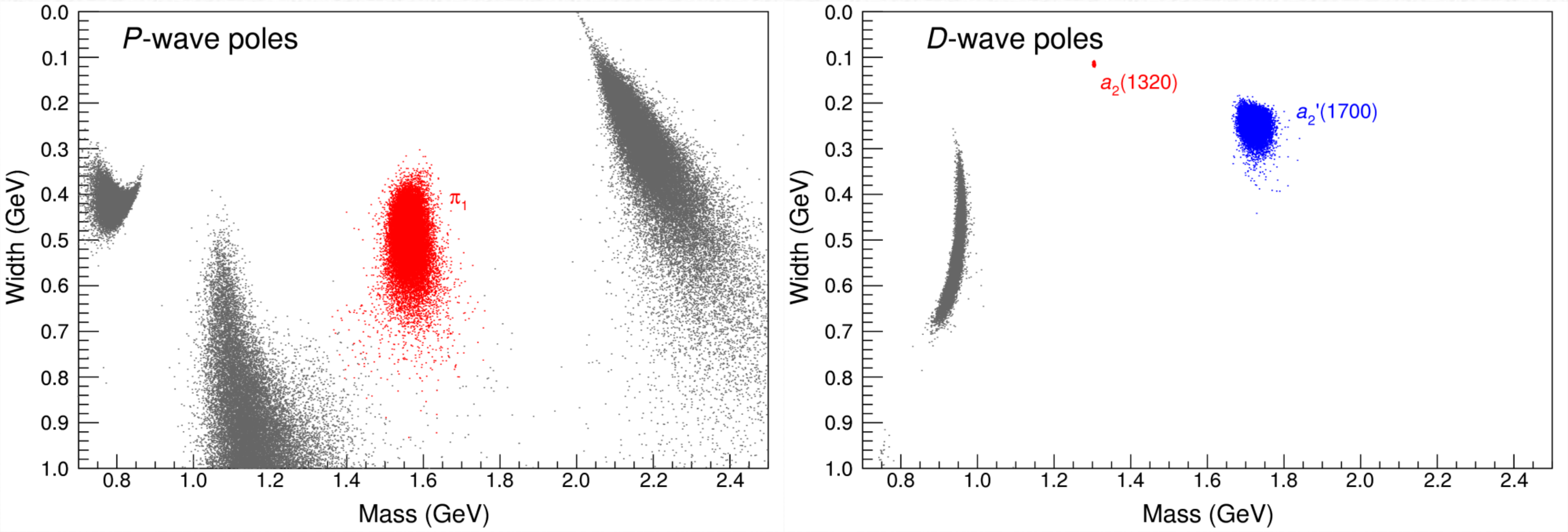
	$a_0^{P,\eta\pi}$	$a_1^{P,\eta\pi}$	$a_2^{P,\eta\pi}$	$a_3^{P,\eta\pi}$	$a_0^{D,\eta\pi}$	$a_1^{D,\eta\pi}$	$a_2^{D,\eta\pi}$	$a_3^{D,\eta\pi}$	$a_0^{P,\eta'\pi}$	$a_1^{P,\eta'\pi}$	$a_2^{P,\eta'\pi}$	$a_3^{P,\eta'\pi}$	$a_0^{D,\eta'\pi}$	$a_1^{D,\eta'\pi}$	$a_2^{D,\eta'\pi}$	$a_3^{D,\eta'\pi}$
$m^2_{D,2}$	16	-16	16	-15	-20	16	-19	1	-5	5	-5	6	15	-19	6	-7
$g^{D,2}_{\eta'\pi}$	45	-45	44	-43	-8	-3	-5	-8	-40	41	-41	41	-4	-2	-4	-6
$g^{D,2}_{\eta\pi}$	13	-13	13	-13	-3	-8	-2	-8	-1	2	-3	7	-10	5	-8	-4
$m^2_{D,1}$	24	-23	21	-15	-4	5	-15	1	-25	20	-9	-12	5	-4	-13	2
$g^{D,1}_{\eta'\pi}$	9	-9	10	-12	18	4	-27	32	-5	7	-11	19	9	10	-24	35
$g^{D,1}_{\eta\pi}$	23	-22	20	-15	-0	1	-13	1	-24	20	-9	-12	1	-0	-16	4
$m^2_{P,1}$	25	-24	24	-23	-21	12	-9	-6	-26	28	-31	36	2	-10	7	-12
$g^{P,1}_{\eta'\pi}$	-12	11	-11	9	8	-7	7	-0	14	-13	12	-9	5	-5	7	-2
$g^{P,1}_{\eta\pi}$	-6	6	-7	10	-6	10	-3	3	5	-5	8	-11	11	-11	11	-4
Γ_{π_1}	22	-23	23	-25	-4	5	-9	3	-3	2	1	-5	6	-6	0	-1
m_{π_1}	-10	9	-8	4	12	-8	3	3	6	-6	7	-7	-6	11	-9	8
$\Gamma_{a'_2}$	-17	17	-16	14	-21	25	-8	6	17	-15	8	4	26	-27	28	-10
$m_{a'_2}$	8	-9	9	-11	-17	21	-13	8	-3	4	-8	16	19	-21	17	-7
Γ_{a_2}	-3	3	-4	4	-6	4	1	-4	2	-3	4	-7	5	-7	6	-4
m_{a_2}	-6	6	-5	5	-12	14	-5	3	7	-6	4	-0	13	-15	15	-7

K-matrix «bkg» parameters

K-matrix «bkg» parameters

	$c^P_{\eta\pi,\eta\pi}$	$c^P_{\eta\pi,\eta'\pi}$	$c^P_{\eta'\pi,\eta'\pi}$	$c^D_{\eta\pi,\eta\pi}$	$c^D_{\eta\pi,\eta'\pi}$	$c^D_{\eta'\pi,\eta'\pi}$	$d^P_{\eta\pi,\eta\pi}$	$d^P_{\eta\pi,\eta'\pi}$	$d^P_{\eta'\pi,\eta'\pi}$	$d^D_{\eta\pi,\eta\pi}$	$d^D_{\eta\pi,\eta'\pi}$	$d^D_{\eta'\pi,\eta'\pi}$
$d^D_{\eta'\pi,\eta'\pi}$	-27	0	-22	-57	-53	84	22	-3	20	-20	-91	100
$d^D_{\eta\pi,\eta'\pi}$	32	-4	22	32	63	-76	-29	4	-18	-18	100	-91
$d^D_{\eta\pi,\eta\pi}$	-22	11	1	67	-15	-17	24	-4	-4	100	-18	-20
$d^P_{\eta'\pi,\eta'\pi}$	-28	-74	-90	-8	-17	20	23	72	100	-4	-18	20
$d^P_{\eta\pi,\eta'\pi}$	-45	-94	-60	2	-5	2	45	100	72	-4	4	-3
$d^P_{\eta\pi,\eta\pi}$	-92	-30	-24	-8	-9	13	100	45	23	24	-29	22
$c^D_{\eta'\pi,\eta'\pi}$	-18	-7	-19	-26	-84	100	13	2	20	-17	-76	84
$c^D_{\eta\pi,\eta'\pi}$	10	6	16	-19	100	-84	-9	-5	-17	-15	63	-53
$c^D_{\eta\pi,\eta\pi}$	14	3	10	100	-19	-26	-8	2	-8	67	32	-57
$c^P_{\eta'\pi,\eta'\pi}$	31	67	100	10	16	-19	-24	-60	-90	1	22	-22
$c^P_{\eta\pi,\eta'\pi}$	41	100	67	3	6	-7	-30	-94	-74	11	-4	0
$c^P_{\eta\pi,\eta\pi}$	100	41	31	14	10	-18	-92	-45	-28	-22	32	-27

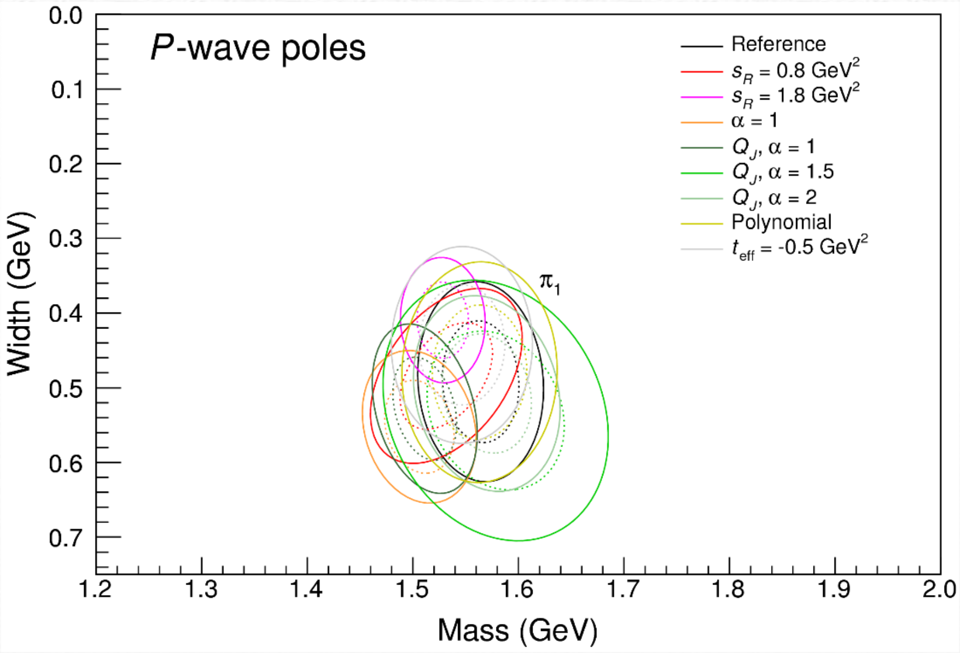
Bootstrap

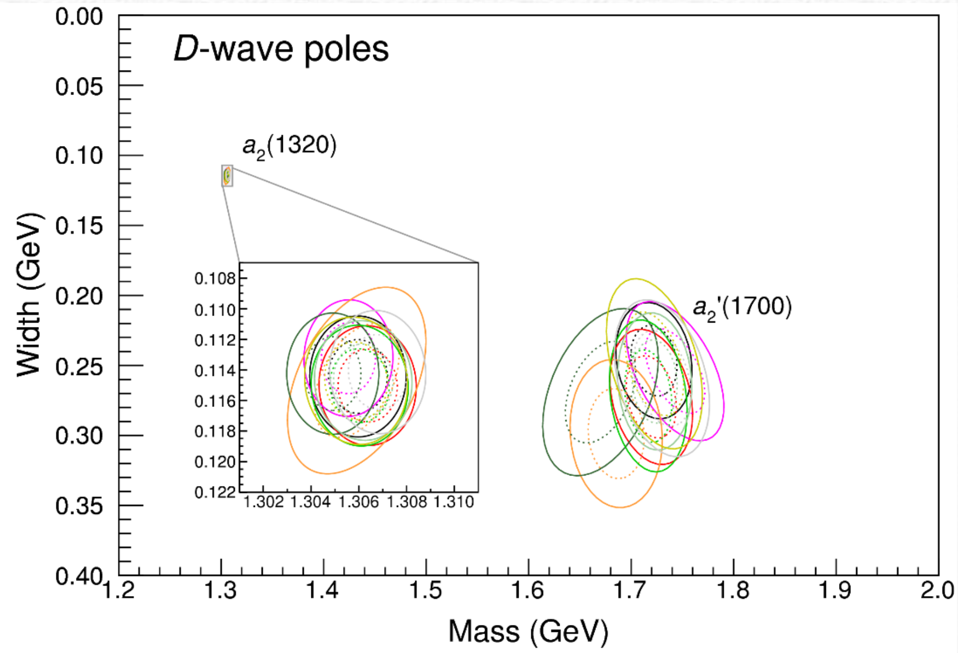


We can identify the poles in the region $m \in [1.2, 2]$ GeV, $\Gamma \in [0, 1]$ GeV

Two stable isolated poles are indentifiable in the *D*-wave
Only one is stable in the *P*-wave

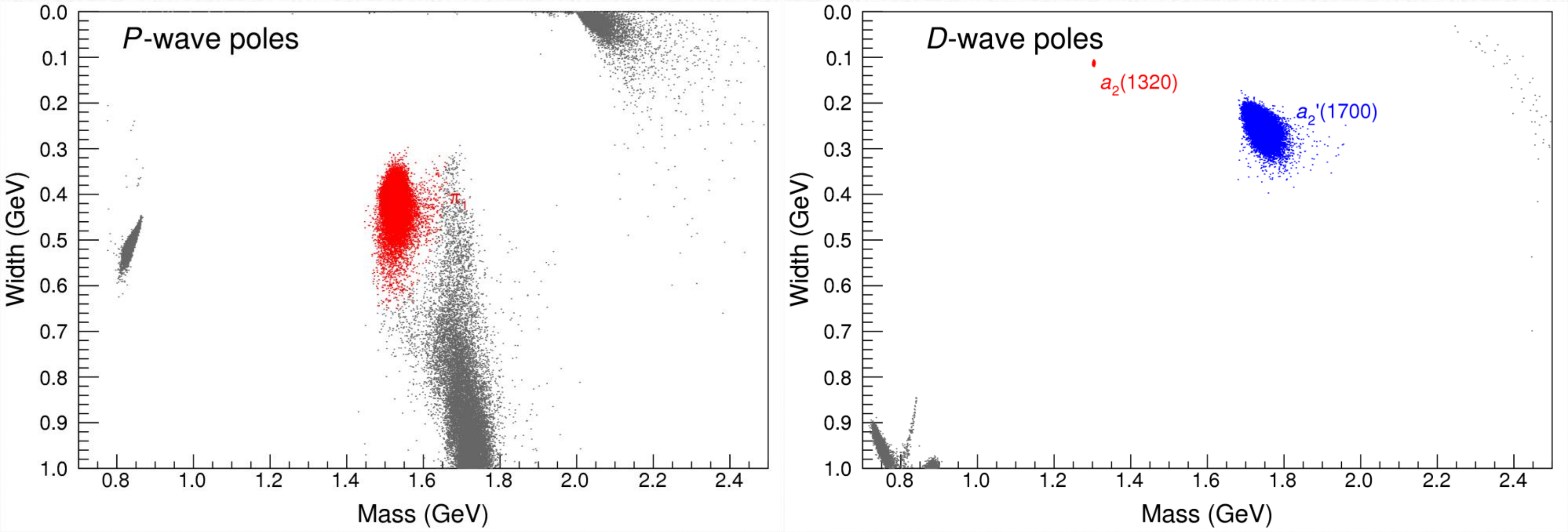
Systematic studies





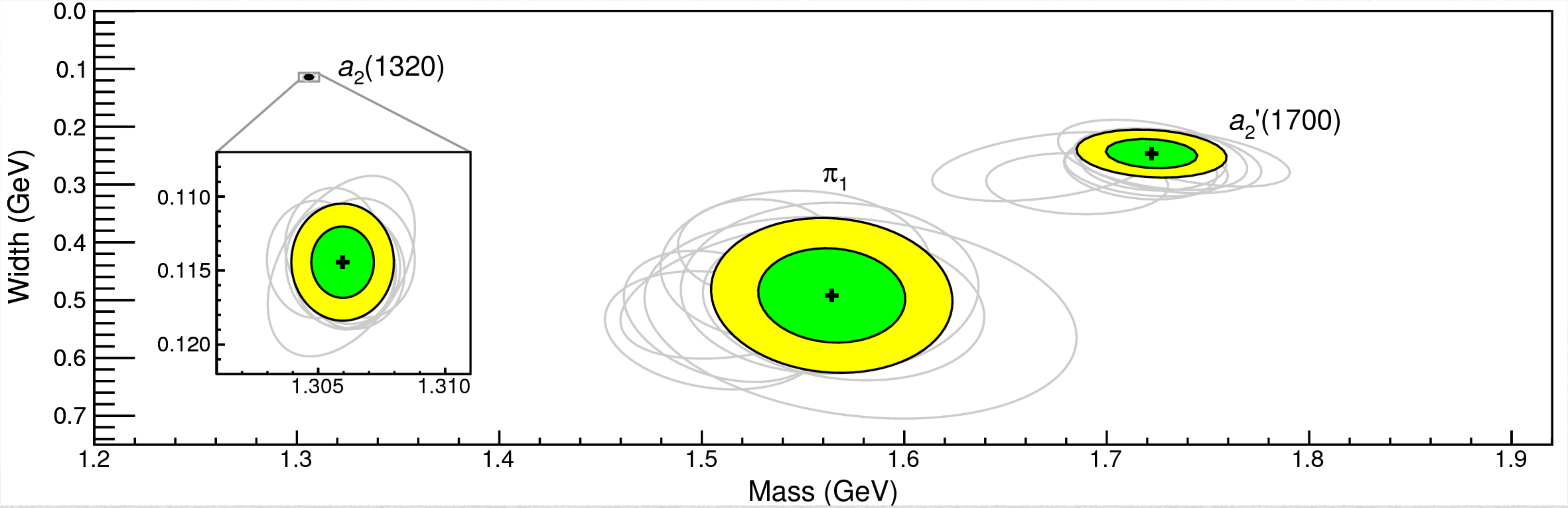
For each class, the maximum deviation of mass and width is taken as a systematic error
Deviation smaller than the statistical error are neglected
Systematic of different classes are summed in quadrature

Bootstrap for $s_R = 1.8\ \mathrm{GeV}^2$



Our skepticism about a second pole in the relevant region is confirmed:
It is unstable and not trustable

Final results



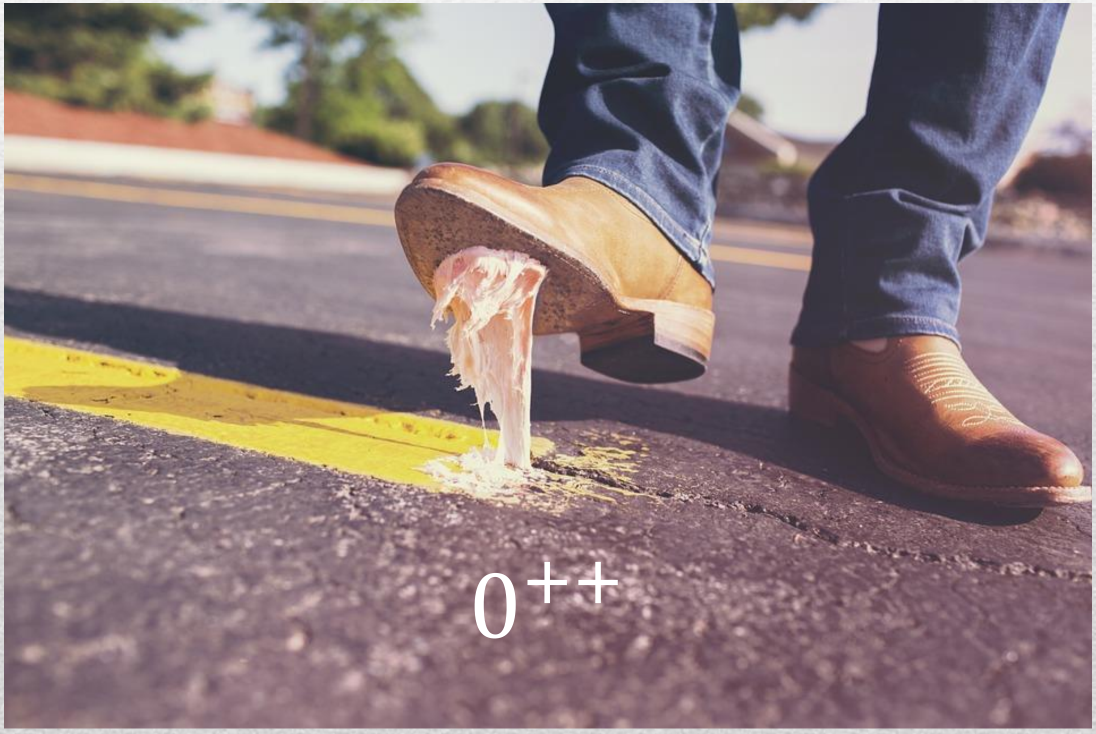
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

Agreement with Lattice is restored

That's the most rigorous extraction of an exotic meson available so far!

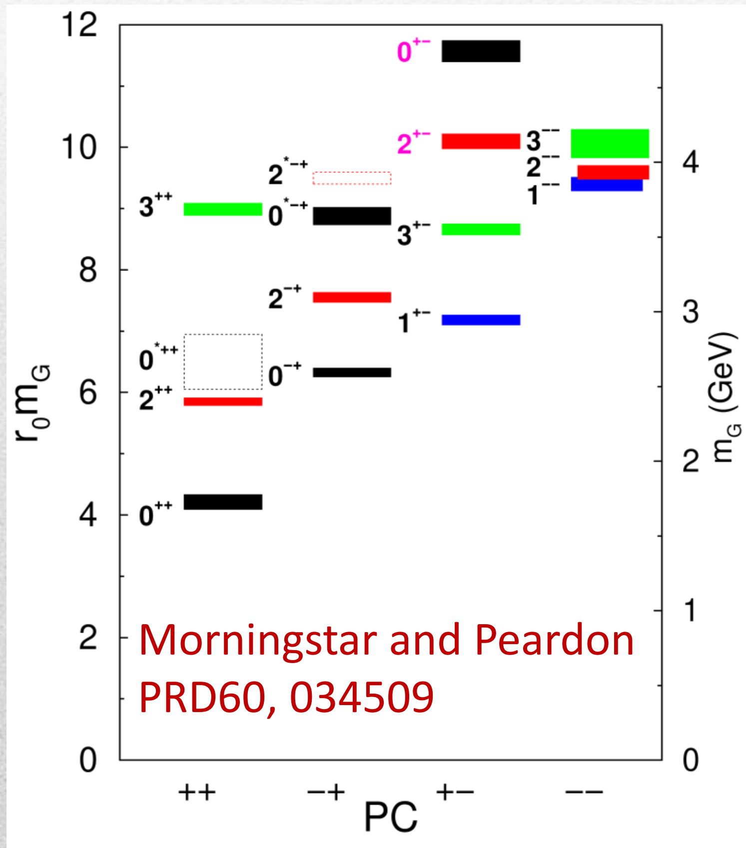
The scalar glueball

A. Rodas, AP *et al.* (JPAC) in progress



Glueballs

The clearest sign of confinement in pure Yang-Mills
The worst state to search in real life

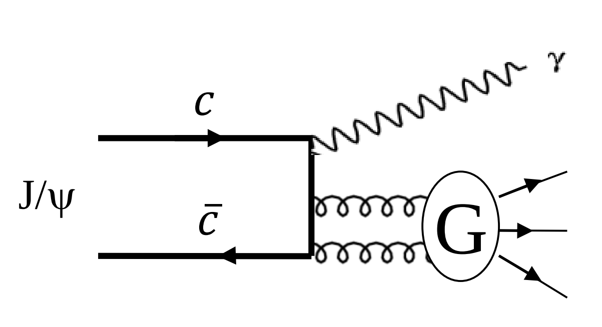


Morningstar and Peardon
PRD60, 034509

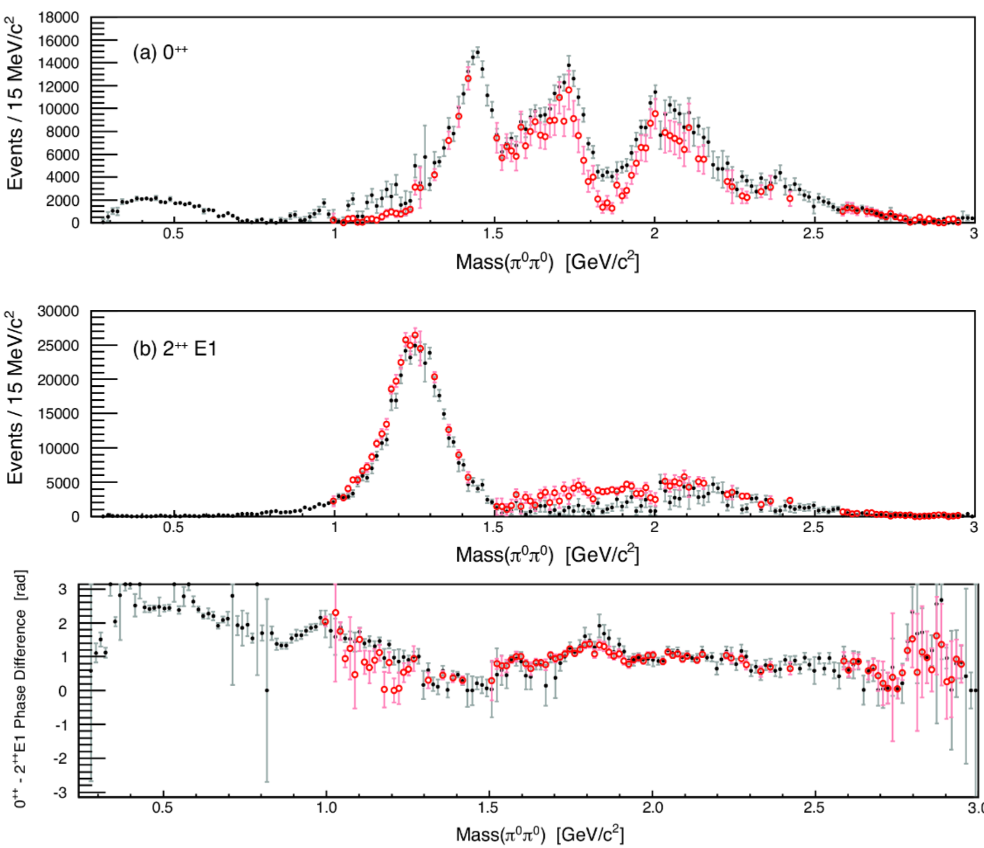
J^{PC}	Mass MeV			
	Unquenched	Quenched		
	This work	M&P	Ky	Meyer
0^{-+}		2590(40)(130)	2560(35)(120)	2250(60)(100)
2^{-+}	3460(320)	3100(30)(150)	3040(40)(150)	2780(50)(130)
0^{-+}	4490(590)	3640(60)(180)		3370(150)(150)
2^{-+}				3480(140)(160)
5^{-+}				3942(160)(180)
0^{--} (exotic)	5166(1000)			
1^{--}		3850(50)(190)	3830(40)(190)	3240(330)(150)
2^{--}	4590(740)	3930(40)(190)	4010(45)(200)	3660(130)(170)
2^{--}				3.740(200)(170)
3^{--}		4130(90)(200)	4200(45)(200)	4330(260)(200)
1^{+-}	3270(340)	2940(30)(140)	2980(30)(140)	2670(65)(120)
3^{+-}	3850(350)	3550(40)(170)	3600(40)(170)	3270(90)(150)
3^{+-}				3630(140)(160)
2^{+-} (exotic)		4140(50)(200)	4230(50)(200)	
0^{+-} (exotic)	5450(830)	4740(70)(230)	4780(60)(230)	
5^{+-}				4110(170)(190)
0^{++}	1795(60)	1730(50)(80)	1710(50)(80)	1475(30)(65)
2^{++}	2620(50)	2400(25)(120)	2390(30)(120)	2150(30)(100)
0^{++}	3760(240)	2670(180)(130)		2755(30)(120)
3^{++}		3690(40)(180)	3670(50)(180)	3385(90)(150)
0^{++}				3370(100)(150)
0^{++}				3990(210)(180)
2^{++}				2880(100)(130)
4^{++}				3640(90)(160)
6^{++}				4360(260)(200)

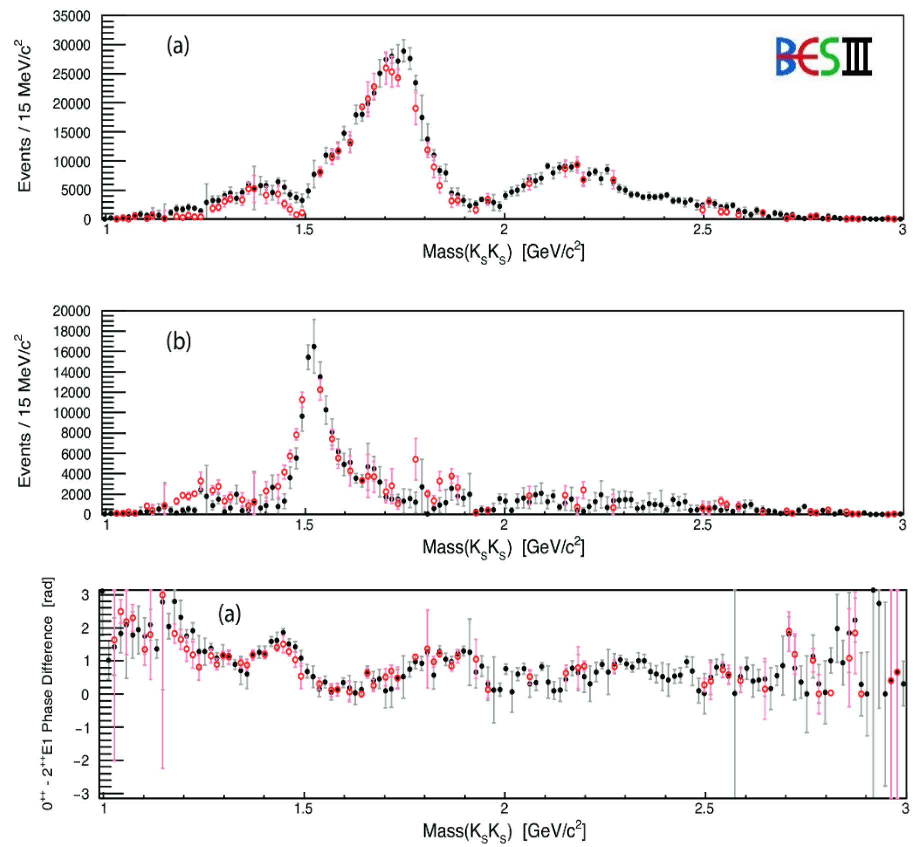
Gregory *et al.*
JHEP1210, 170

$J/\psi \to \gamma\, \pi^0\pi^0$ and $\to \gamma\, K_S^0 K_S^0$



This is a gluon-rich process, expected to be one of the golden channels for the search of the scalar glueball





Same model as before

Two channels, $i, k = \pi\pi, KK$ Two waves, $J = S, D$ 52 parameters

$$D^J_{ki}(s) = \left[K^J(s)^{-1}\right]_{ki} - \frac{s}{\pi}\int_{s_k}^{\infty} ds' \frac{\rho N^J_{ki}(s')}{s'(s'-s-i\epsilon)}$$

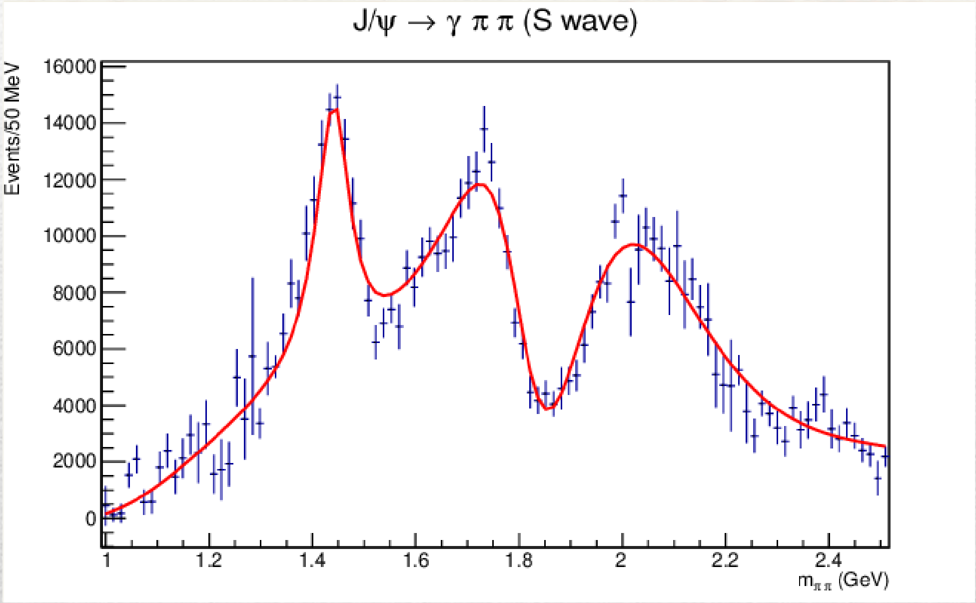
$$K^J_{ki}(s) = \sum_R \frac{g_k^{(R)} g_i^{(R)}}{m_R^2 - s} + c^J_{ki} + d^J_{ki}\, s$$

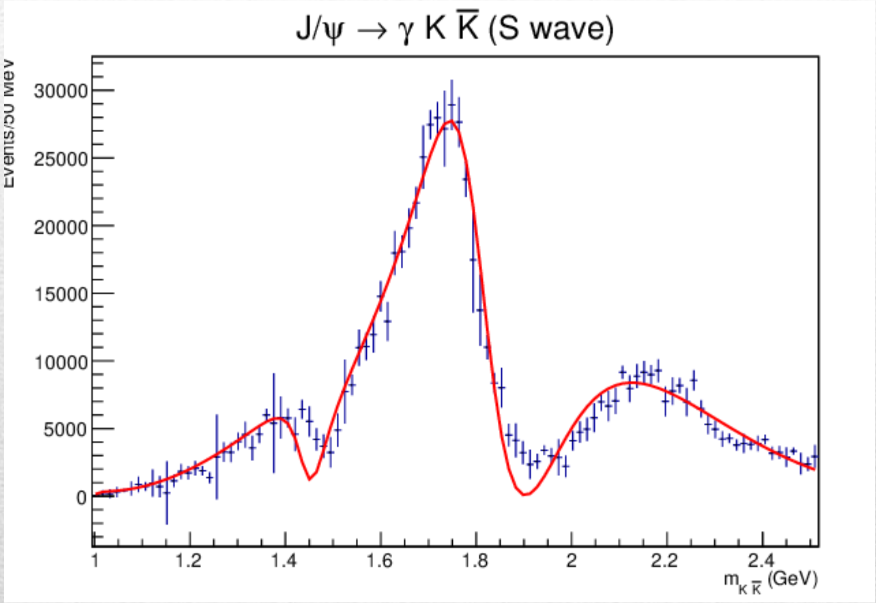
3 K-matrix pole for the S-wave
3 K-matrix poles for the D-wave

$$\rho N^J_{ki}(s') = \delta_{ki} \frac{\lambda^{J+1/2}\left(s', m^2_{\eta^{(\prime)}}, m^2_\pi\right)}{(s'+s_R)^{2J+1+\alpha}}$$

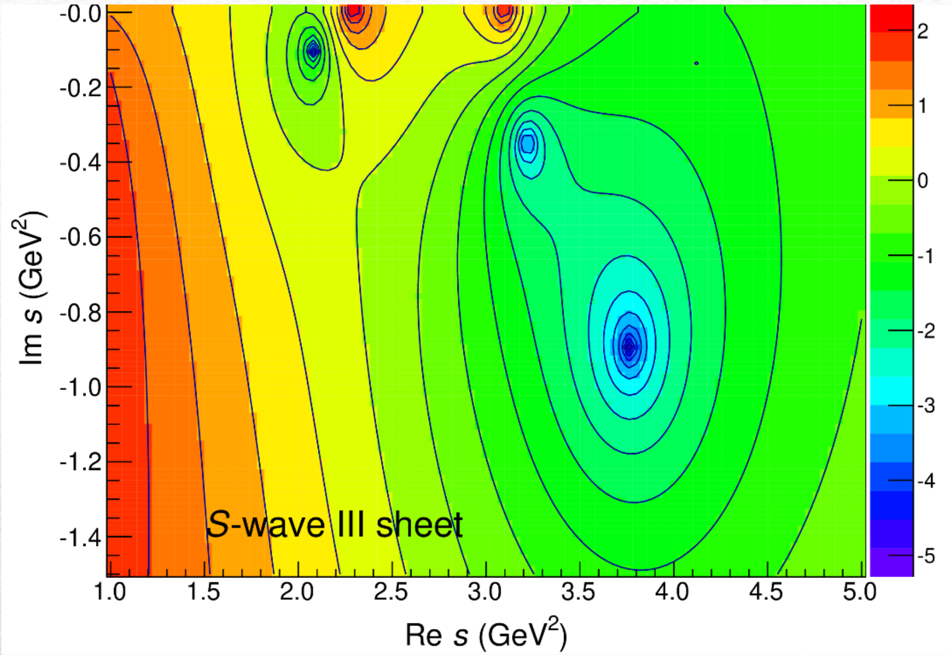
$$n^J_k(s) = \sum_{n=0}^{3} a^{J,k}_n T_n\left(\frac{s}{s+s_0}\right)$$

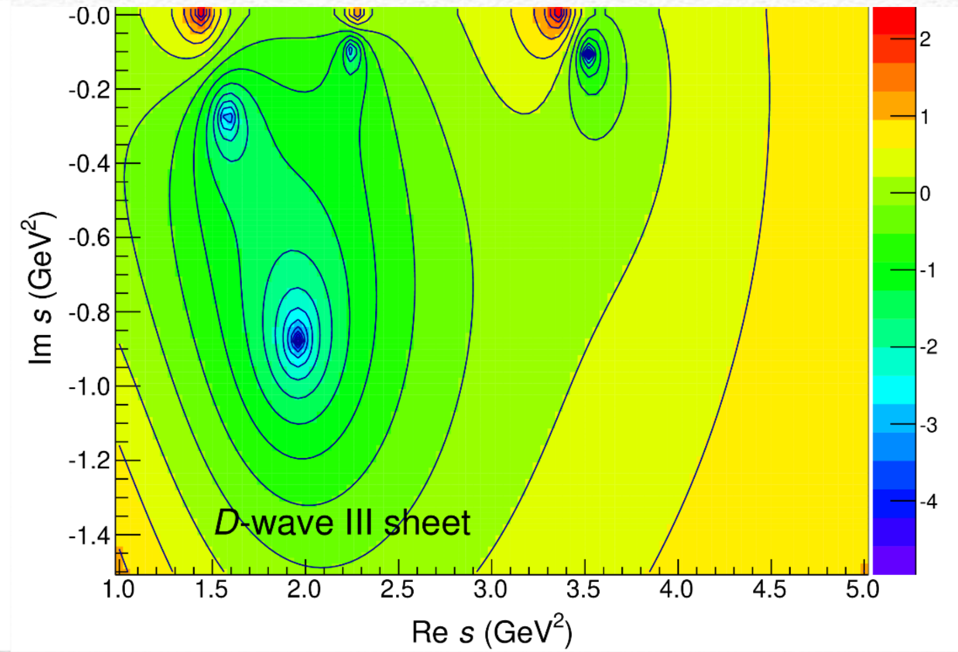
Fit results (preliminary)





Pole position (preliminary)



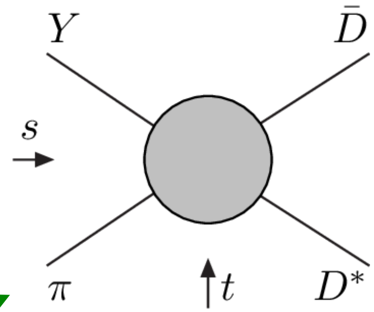


$M(f_0(1500)) = 1460$ MeV	$\Gamma(f_0(1500)) = 85$ MeV
$M(f_0(1710)) = 1800$ MeV	$\Gamma(f_0(1710)) = 190$ MeV
$M(f_0(2020)) = 1970$ MeV	$\Gamma(f_0(2020)) = 490$ MeV

Amplitude analysis for $Z_c(3900)$

One can test different parametrizations of the amplitude, which correspond to
different singularities → different natures

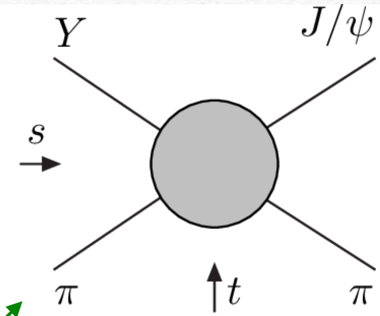
AP *et al.* (JPAC), PLB772, 200



u: $D_0(2400)$

$D_1(2420)$

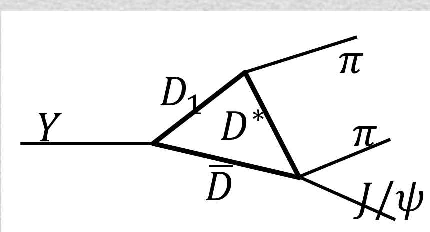
$Z_c(3900)$?



u: $Z_c(3900)$?

"$\sigma, f_0(980)$"

Triangle rescattering,
logarithmic branching point

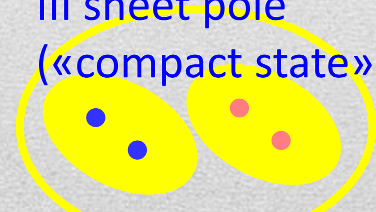


Szczepaniak, PLB747, 410

(anti)bound state,
II/IV sheet pole
(«molecule»)

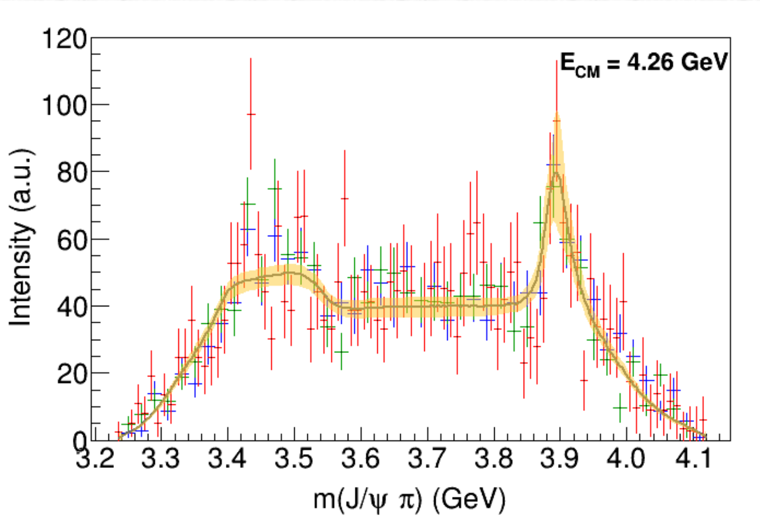
Tornqvist, Z.Phys. C61, 525
Swanson, Phys.Rept. 429
Hanhart *et al.* PRL111, 132003

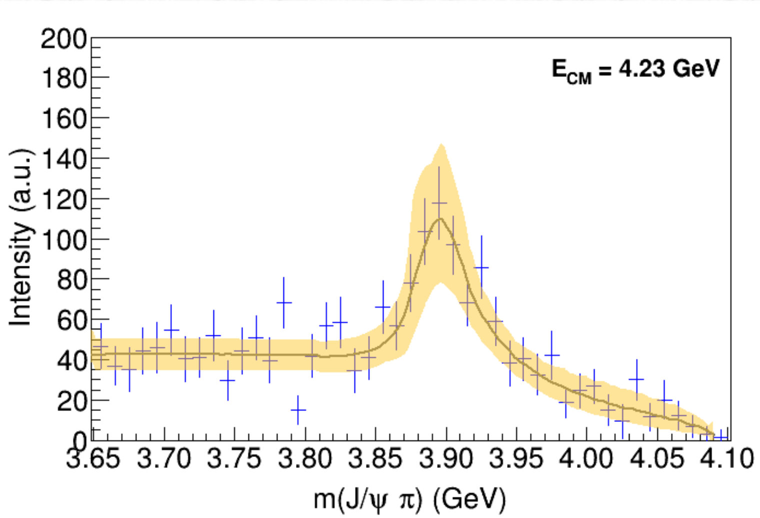
Resonance,
III sheet pole
(«compact state»)

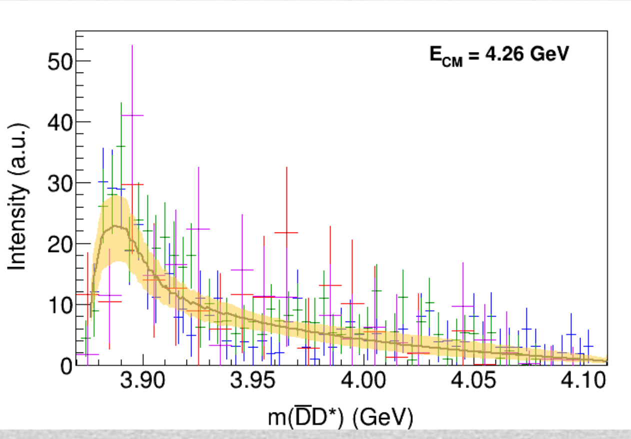


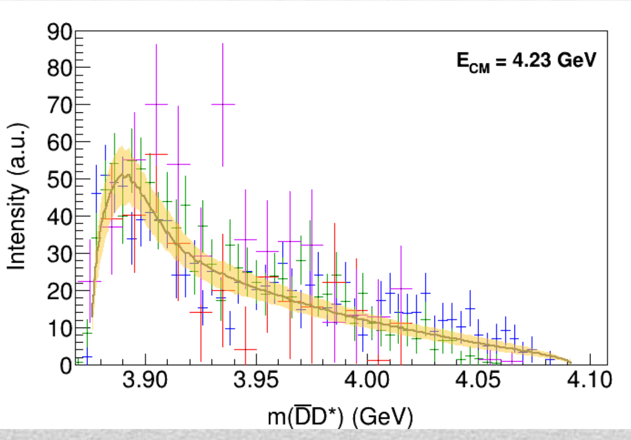
Maiani *et al.*, PRD71, 014028
Faccini *et al.*, PRD87, 111102
Esposito *et al.*, Phys.Rept. 668

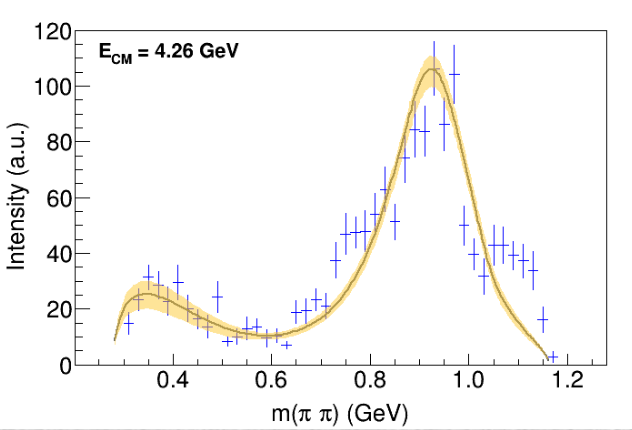
Fit: III


E_CM = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)

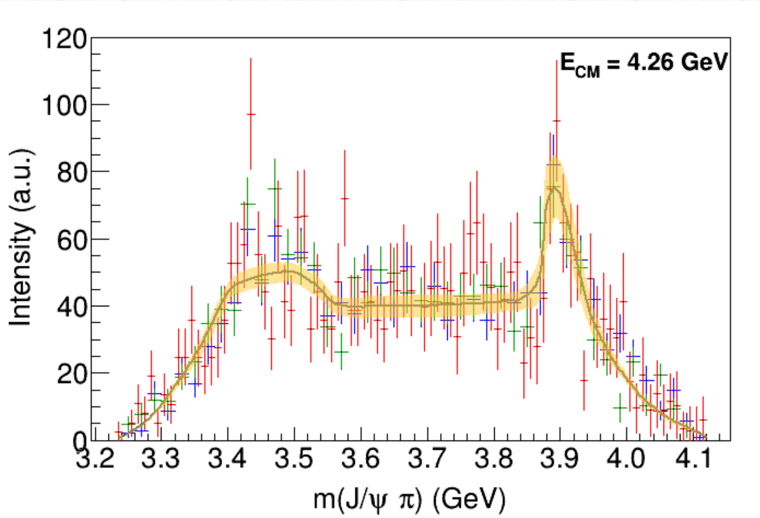

E_CM = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)


E_CM = 4.26 GeV
Intensity (a.u.)
m(D̄D*) (GeV)

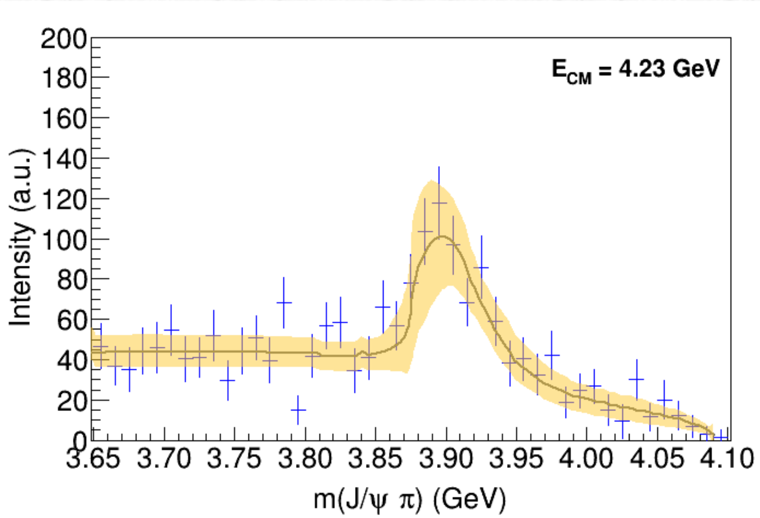

E_CM = 4.23 GeV
Intensity (a.u.)
m(D̄D*) (GeV)


E_CM = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

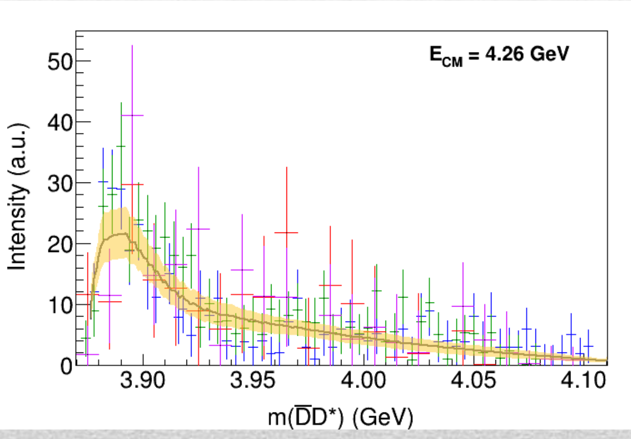
Fit: III+tr.



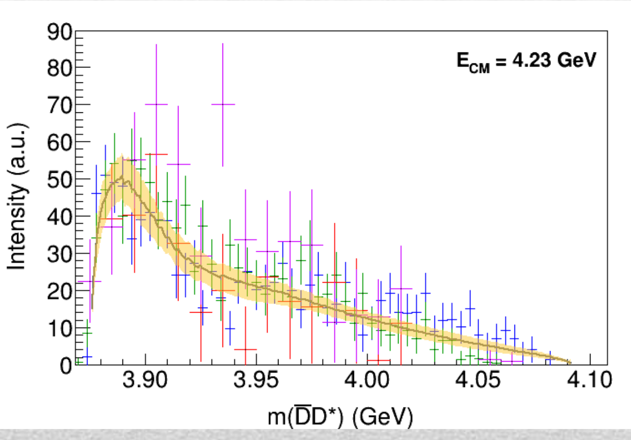
E_CM = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)



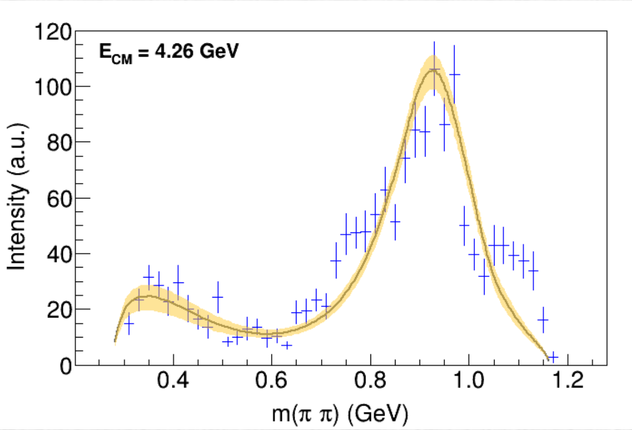
E_CM = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)



E_CM = 4.26 GeV
Intensity (a.u.)
m(D̄D*) (GeV)

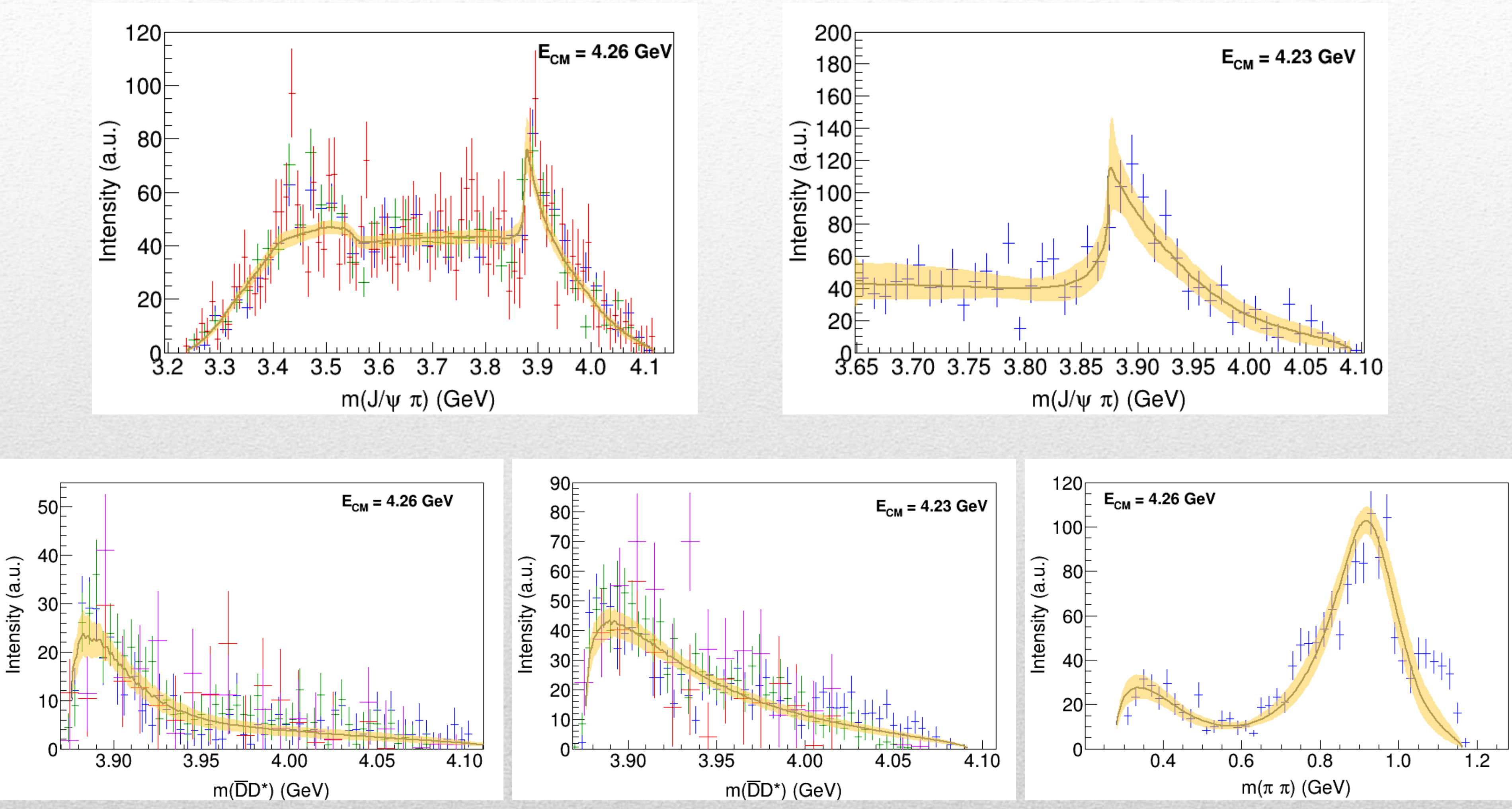


E_CM = 4.23 GeV
Intensity (a.u.)
m(D̄D*) (GeV)



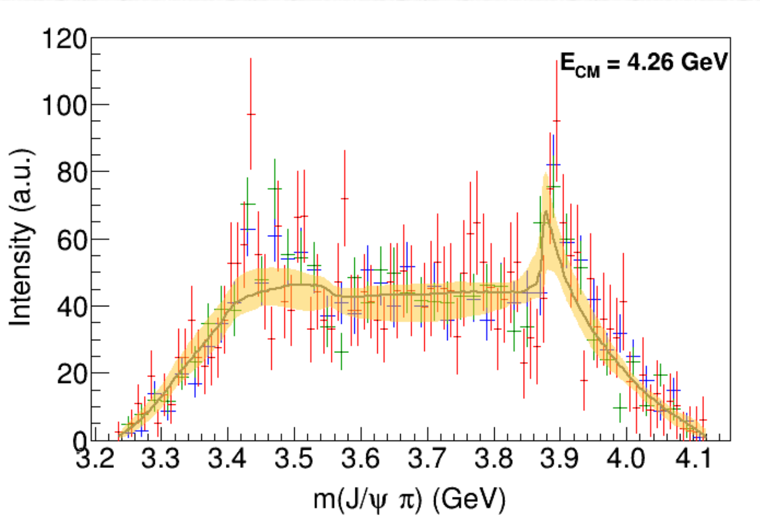
E_CM = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

Fit: IV+tr.

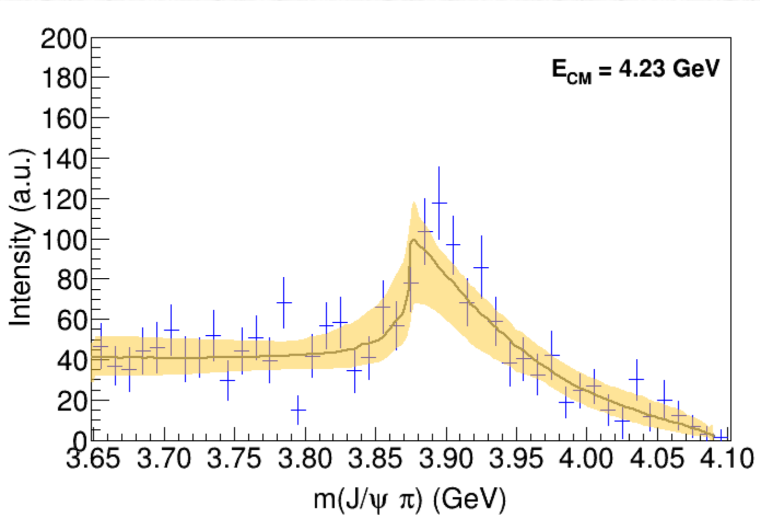


E_CM = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
E_CM = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
E_CM = 4.26 GeV
Intensity (a.u.)
m(D̄D*) (GeV)
E_CM = 4.23 GeV
Intensity (a.u.)
m(D̄D*) (GeV)
E_CM = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

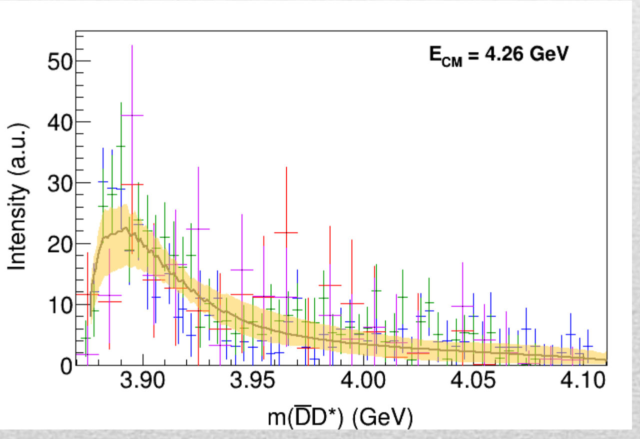
Fit: tr.



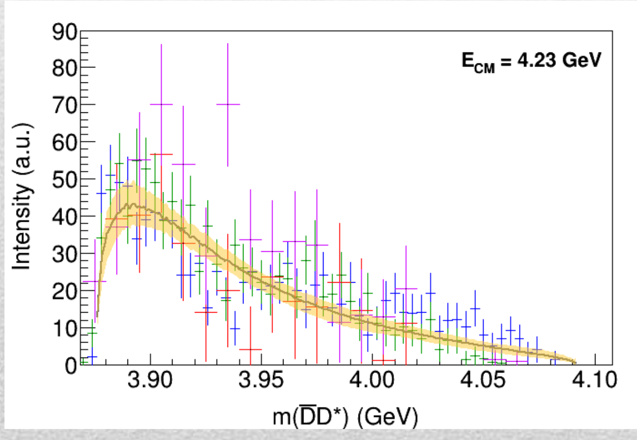
E_{CM} = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)



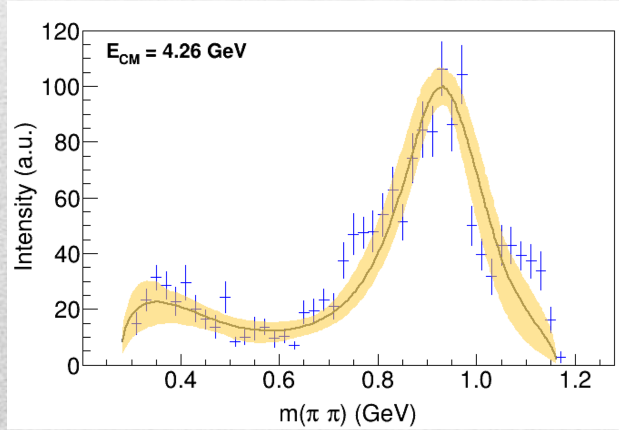
E_{CM} = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)



E_{CM} = 4.26 GeV
Intensity (a.u.)
m($\bar{D}D^*$) (GeV)

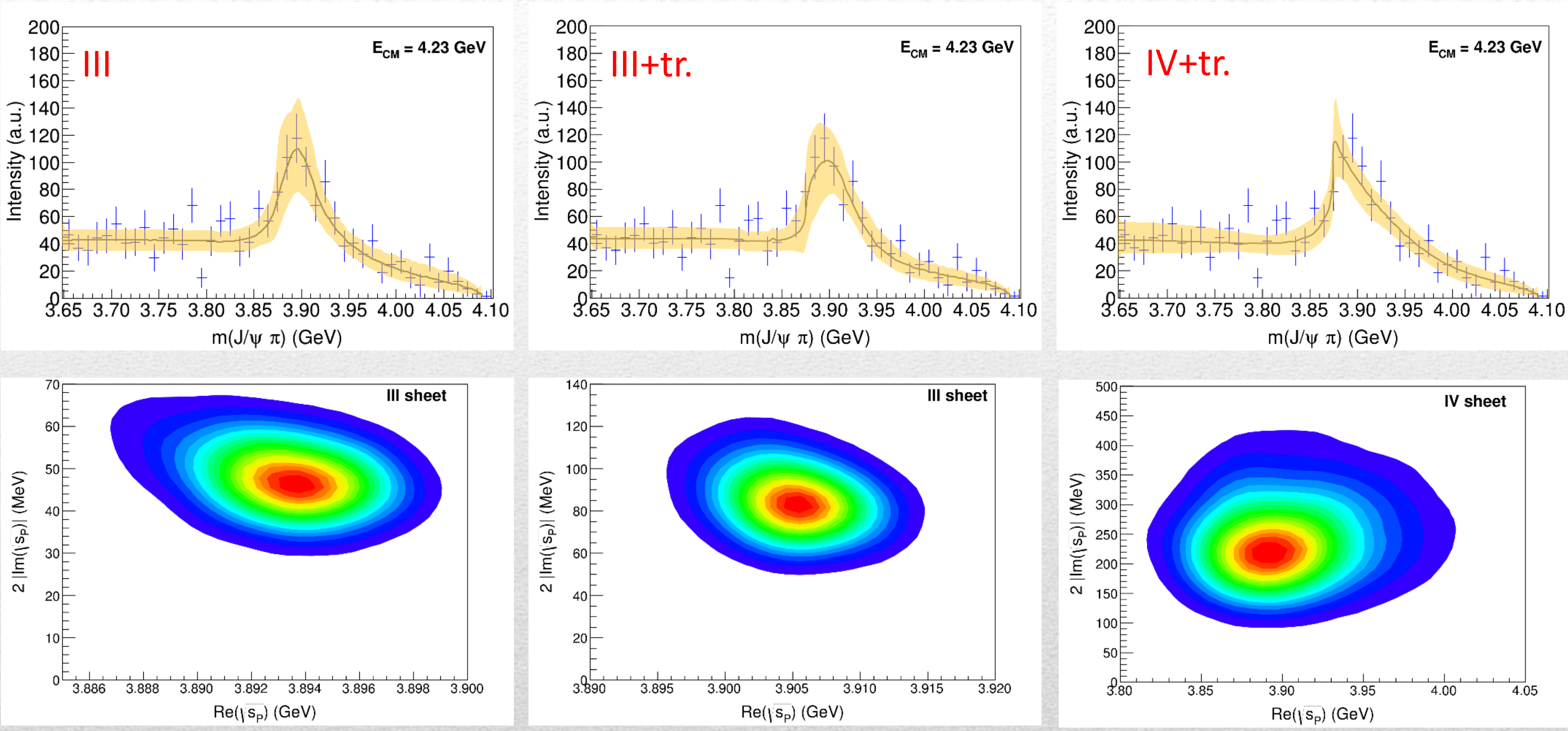


E_{CM} = 4.23 GeV
Intensity (a.u.)
m($\bar{D}D^*$) (GeV)



E_{CM} = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

Pole extraction

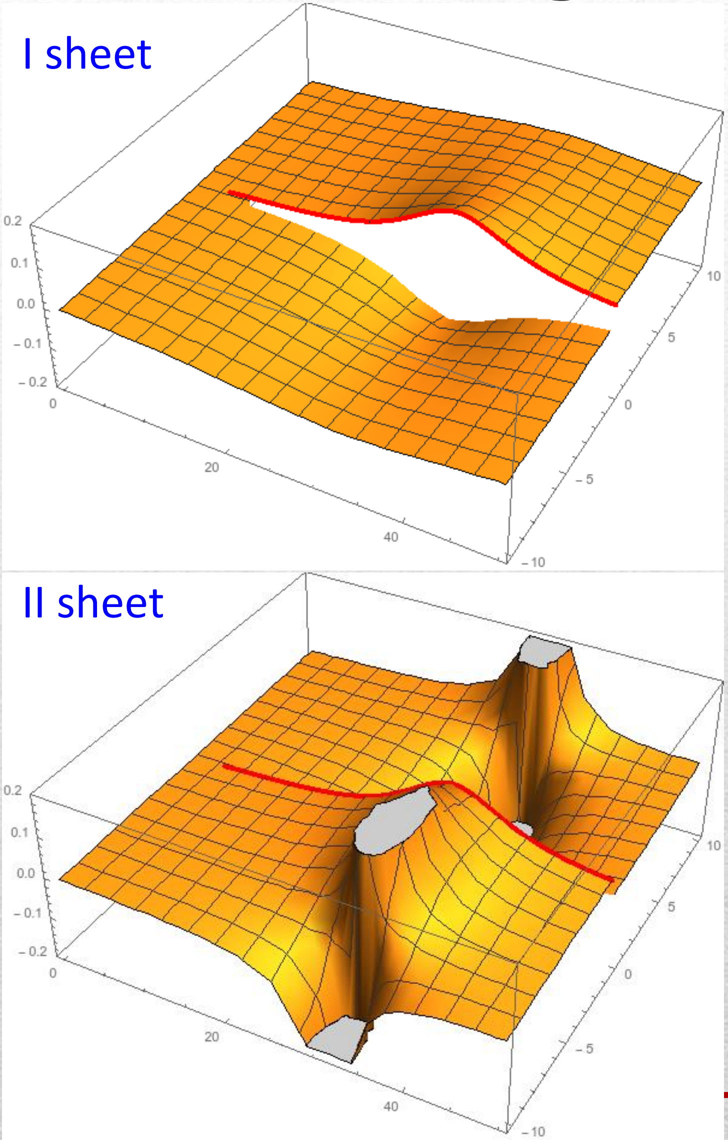


Scenario	III+tr.	IV+tr.	tr.
III	1.5σ (1.5σ)	1.5σ (2.7σ)	“2.4σ” (“1.4σ”)
III+tr.	–	1.5σ (3.1σ)	“2.6σ” (“1.3σ”)
IV+tr.	–	–	“2.1σ” (“0.9σ”)

	III	III+tr.	IV+tr.
M (MeV)	$3893.2^{+5.5}_{-7.7}$	3905^{+11}_{-9}	3900^{+140}_{-90}
Γ (MeV)	48^{+19}_{-14}	85^{+45}_{-26}	240^{+230}_{-130}

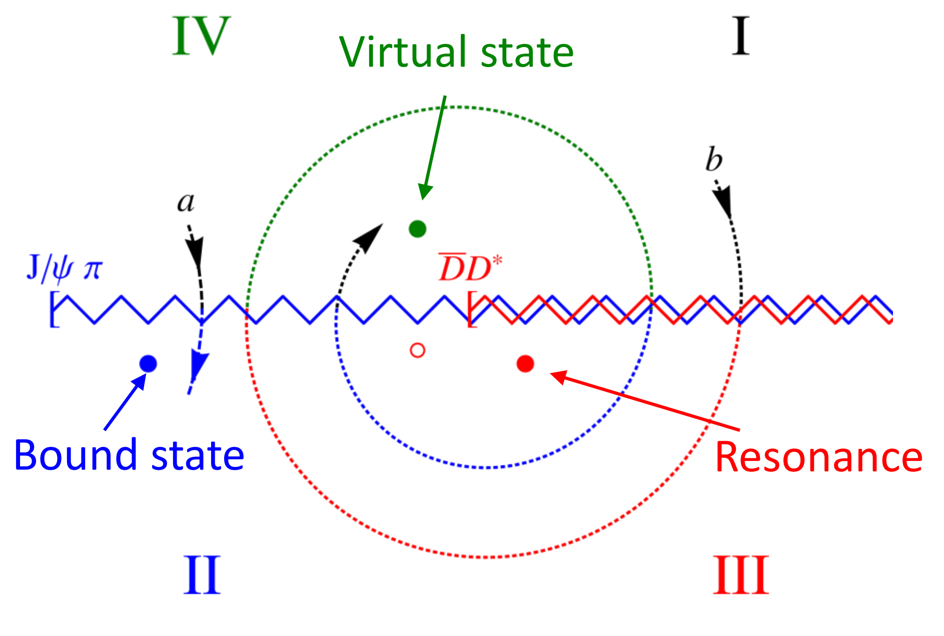
Not conclusive at this stage

Pole hunting

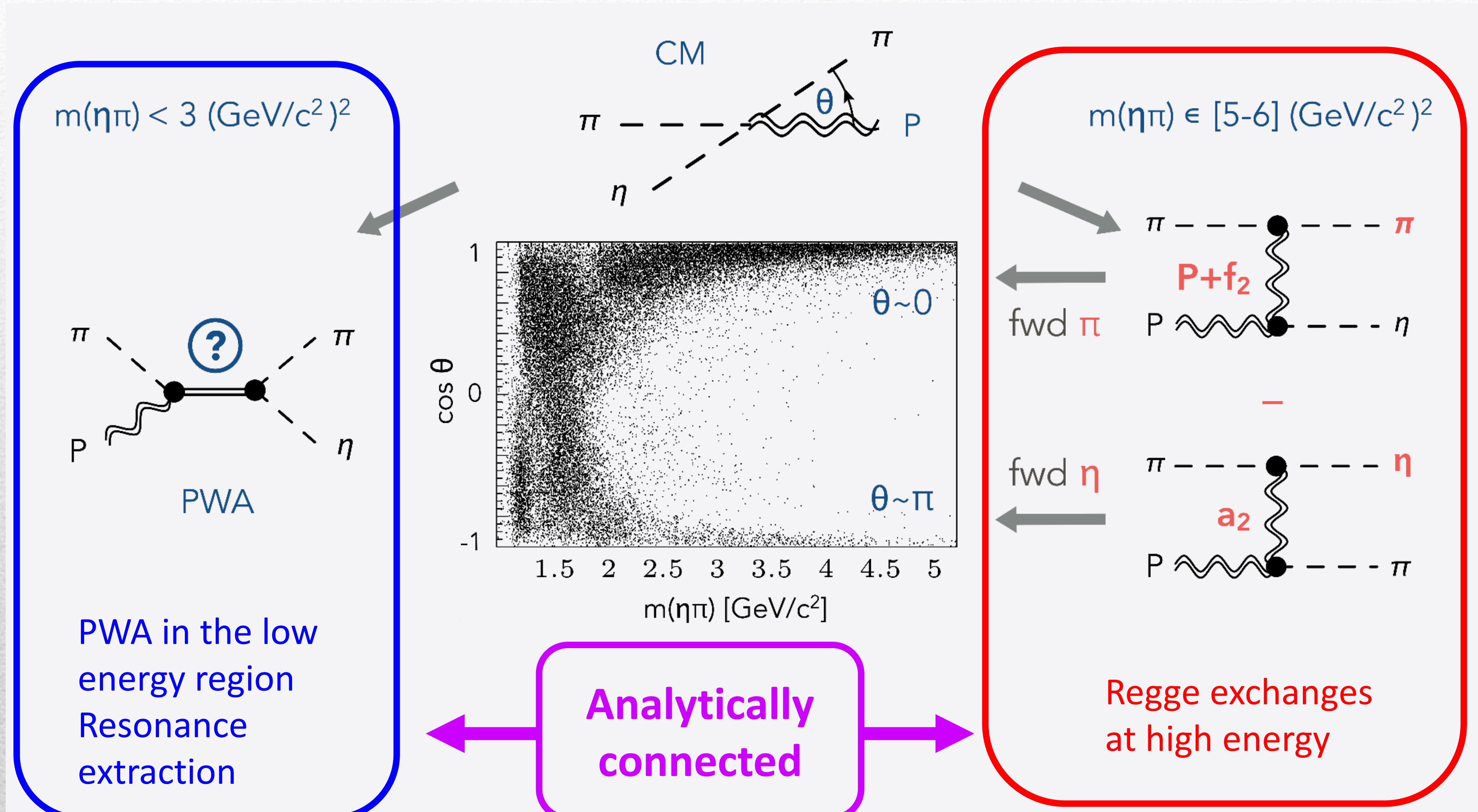


Extracting physics information means to hunt for poles in the complex plane

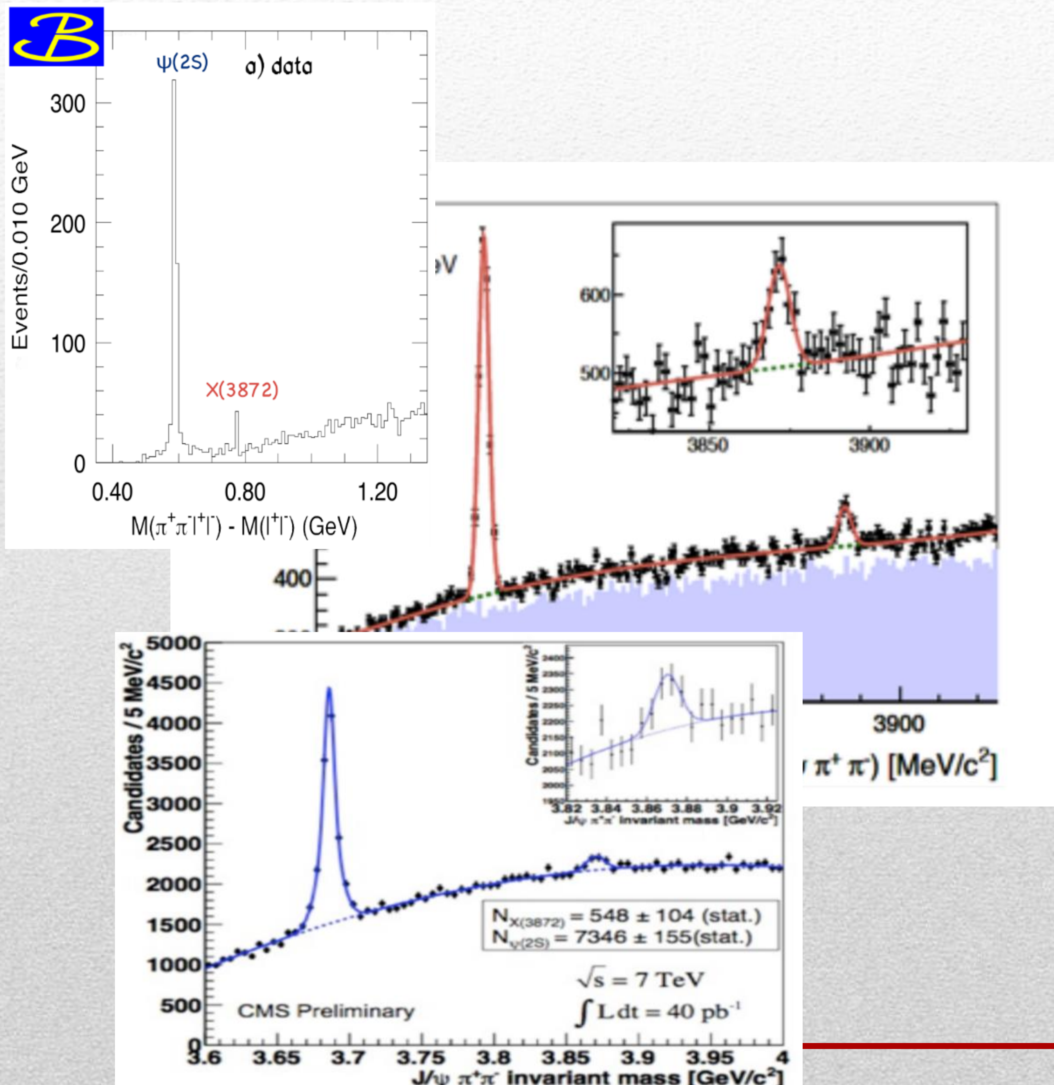
Pole position → Mass and width
Residues → Couplings



Finite energy sum rules



$X(3872)$



- Discovered in
  $B \to K\, X \to K\, J/\psi\, \pi\pi$
- Quantum numbers 1^{++}
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X \to J/\psi\ \omega)}{\Gamma(X \to J/\psi\ \rho)} \sim 0.8 \pm 0.3$
- Mass prediction not compatible with $\chi_{c1}(2P)$

$M = 3871.68 \pm 0.17$ MeV
$M_X - M_{DD^*} = -3 \pm 192$ keV
$\Gamma < 1.2$ MeV @90%

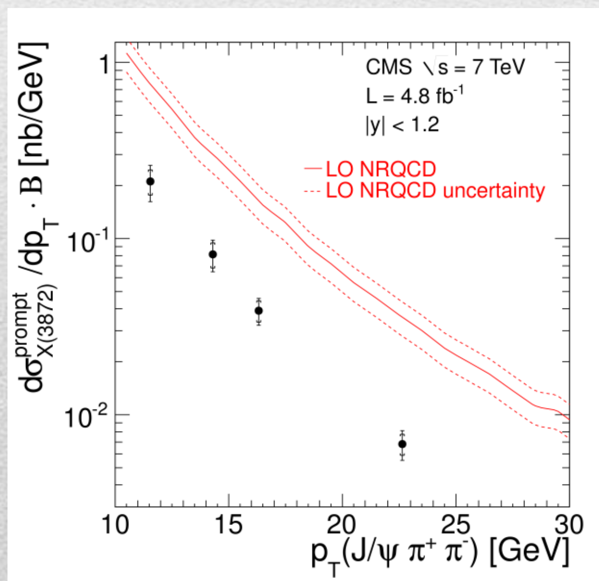
$X(3872)$

Large prompt production
at hadron colliders

$\sigma_B/\sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\%$

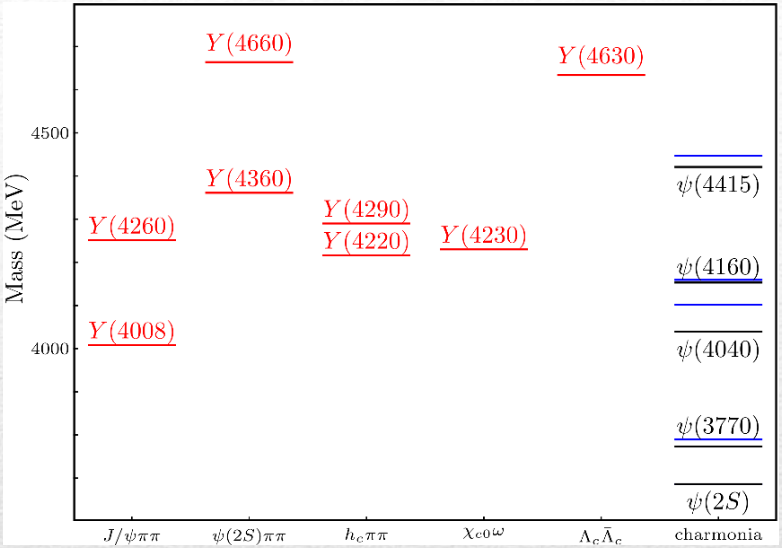
$\sigma_{PR} \times B(X \to J/\psi\pi\pi)$
$= (1.06 \pm 0.11 \pm 0.15)$ nb

CMS, JHEP 1304, 154



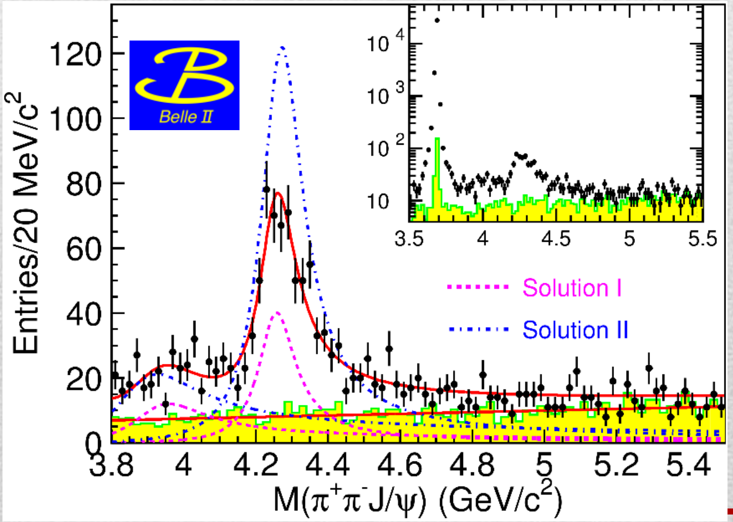
B decay mode	X decay mode	product branching fraction ($\times 10^5$)		B_{fit}	R_{fit}
K^+X	$X \to \pi\pi J/\psi$	$\mathbf{0.86 \pm 0.08}$	(*BABAR*,[26] Belle[25])	$0.081^{+0.019}_{-0.031}$	1
		$0.84 \pm 0.15 \pm 0.07$	*BABAR*[26]		
		$0.86 \pm 0.08 \pm 0.05$	Belle[25]		
K^0X	$X \to \pi\pi J/\psi$	$\mathbf{0.41 \pm 0.11}$	(*BABAR*,[26] Belle[25])		
		$0.35 \pm 0.19 \pm 0.04$	*BABAR*[26]		
		$0.43 \pm 0.12 \pm 0.04$	Belle[25]		
$(K^+\pi^-)_{NR}X$	$X \to \pi\pi J/\psi$	$0.81 \pm 0.20^{+0.11}_{-0.14}$	Belle[106]		
$K^{*0}X$	$X \to \pi\pi J/\psi$	< 0.34, 90% C.L.	Belle[106]		
KX	$X \to \omega J/\psi$	$R = 0.8 \pm 0.3$	*BABAR*[33]	$0.061^{+0.024}_{-0.036}$	$0.77^{+0.28}_{-0.32}$
K^+X		$0.6 \pm 0.2 \pm 0.1$	*BABAR*[33]		
K^0X		$0.6 \pm 0.3 \pm 0.1$	*BABAR*[33]		
KX	$X \to \pi\pi\pi^0 J/\psi$	$R = 1.0 \pm 0.4 \pm 0.3$	Belle[32]		
K^+X	$X \to D^{*0}\bar{D}^0$	$\mathbf{8.5 \pm 2.6}$	(*BABAR*,[38] Belle[37])	$0.614^{+0.166}_{-0.074}$	$8.2^{+2.3}_{-2.8}$
		$16.7 \pm 3.6 \pm 4.7$	*BABAR*[38]		
		$7.7 \pm 1.6 \pm 1.0$	Belle[37]		
K^0X	$X \to D^{*0}\bar{D}^0$	$\mathbf{12 \pm 4}$	(*BABAR*,[38] Belle[37])		
		$22 \pm 10 \pm 4$	*BABAR*[38]		
		$9.7 \pm 4.6 \pm 1.3$	Belle[37]		
K^+X	$X \to \gamma J/\psi$	$\mathbf{0.202 \pm 0.038}$	(*BABAR*,[35] Belle[34])	$0.019^{+0.005}_{-0.009}$	$0.24^{+0.05}_{-0.06}$
K^+X		$0.28 \pm 0.08 \pm 0.01$	*BABAR*[35]		
		$0.178^{+0.048}_{-0.044} \pm 0.012$	Belle[34]		
K^0X		$0.26 \pm 0.18 \pm 0.02$	*BABAR*[35]		
		$0.124^{+0.076}_{-0.061} \pm 0.011$	Belle[34]		
K^+X	$X \to \gamma\psi(2S)$	$\mathbf{0.44 \pm 0.12}$	*BABAR*[35]	$0.04^{+0.015}_{-0.020}$	$0.51^{+0.13}_{-0.17}$
K^+X		$0.95 \pm 0.27 \pm 0.06$	*BABAR*[35]		
		$0.083^{+0.198}_{-0.183} \pm 0.044$	Belle[34]		
		$R' = 2.46 \pm 0.64 \pm 0.29$	LHCb[36]		
K^0X		$1.14 \pm 0.55 \pm 0.10$	*BABAR*[35]		
		$0.112^{+0.357}_{-0.290} \pm 0.057$	Belle[34]		
K^+X	$X \to \gamma\chi_{c1}$	$< 9.6 \times 10^{-3}$	Belle[23]	$< 1.0 \times 10^{-3}$	< 0.014
K^+X	$X \to \gamma\chi_{c2}$	< 0.016	Belle[23]	$< 1.7 \times 10^{-3}$	< 0.024
KX	$X \to \gamma\gamma$	$< 4.5 \times 10^{-3}$	Belle[111]	$< 4.7 \times 10^{-4}$	$< 6.6 \times 10^{-3}$
KX	$X \to \eta J/\psi$	< 1.05	*BABAR*[112]	< 0.11	< 1.55
K^+X	$X \to p\bar{p}$	$< 9.6 \times 10^{-4}$	LHCb[110]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

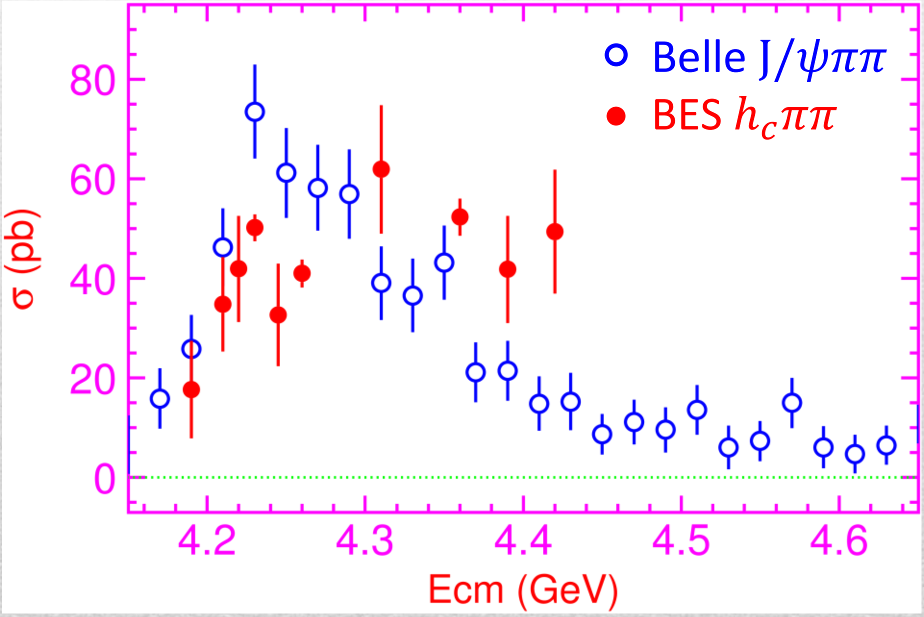
Vector Y states



Lots of unexpected $J^{PC} = 1^{--}$ states
found in ISR/direct production (and nowhere else!)
Seen in few final states,
mostly $J/\psi\ \pi\pi$ and $\psi(2S)\ \pi\pi$

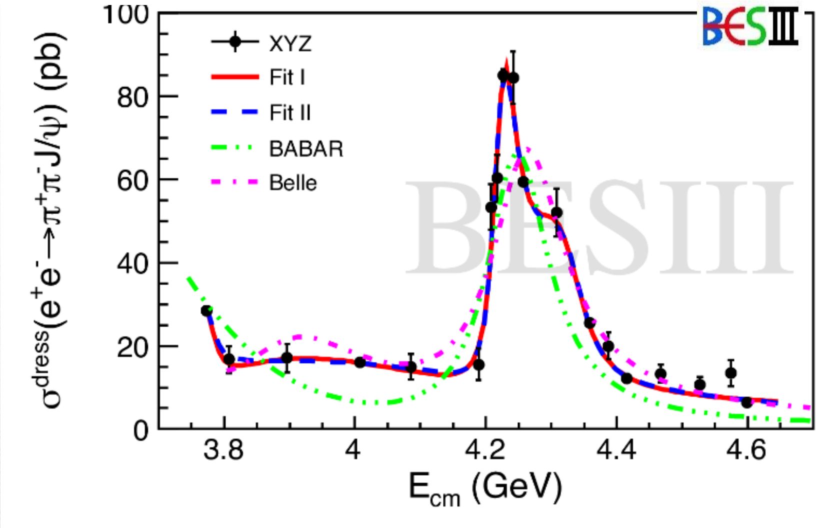
Not seen decaying into open charm pairs
Large HQSS violation



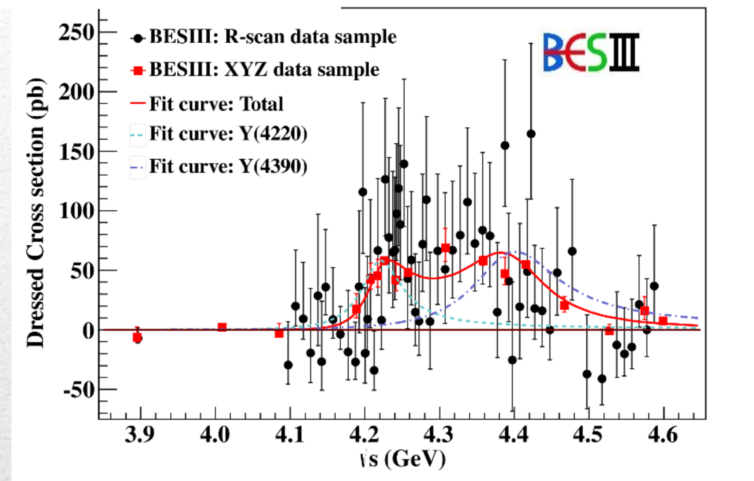


Vector Y states in BESIII

BESIII, PRL118, 092001 (2017) $e^+e^- \to J/\psi\,\pi\pi$



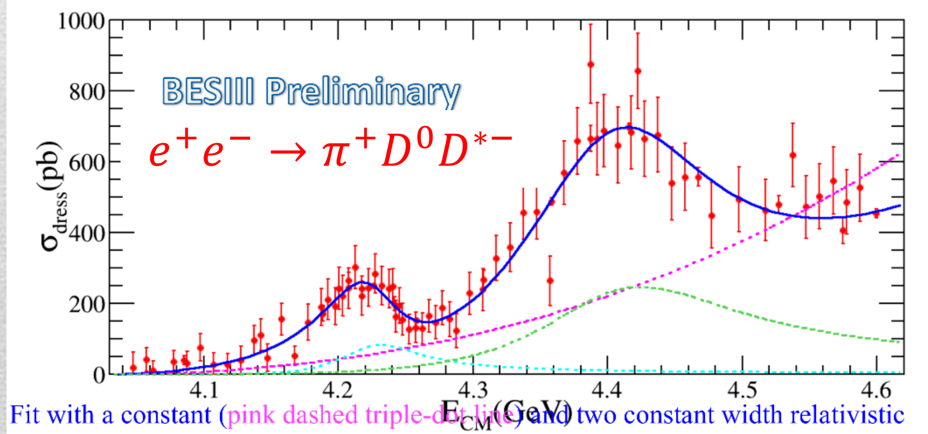
BESIII, PRL118, 092002 (2017) $e^+e^- \to h_c\,\pi\pi$



New BESIII data show a peculiar lineshape for the $Y(4260)$

The state appear lighter and narrower, compatible with the ones in $h_c\pi\pi$ and $\chi_{c0}\omega$

A broader old-fashioned $Y(4260)$ is appearing in $\bar{D}D^*\pi$, maybe indicating a $\bar{D}D_1$ dominance



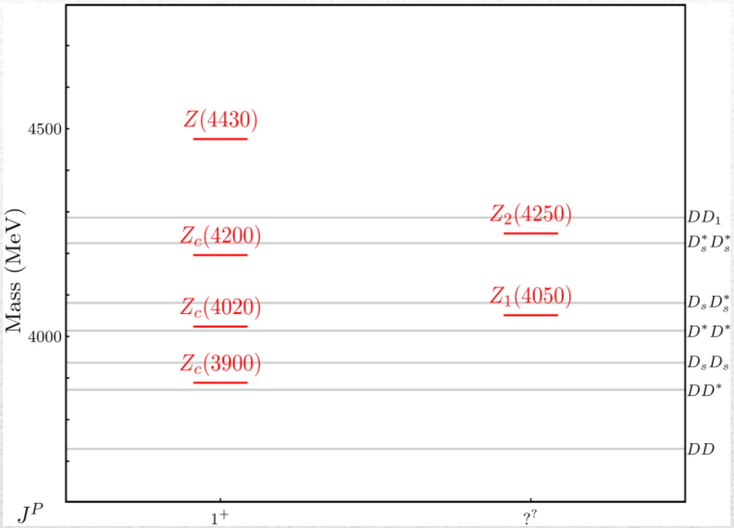
Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

$M(Y(4220)) = (4224.8\pm5.6\pm4.0)$ MeV/c^2, $\Gamma(Y(4220)) = (72.3\pm9.1\pm0.9)$ MeV.

$M(Y(4390)) = (4400.1\pm9.3\pm2.1)$ MeV/c^2, $\Gamma(Y(4220)) = (181.7\pm16.9\pm7.4)$ MeV.

Charged Z states: $Z_c(3900), Z_c'(4020)$

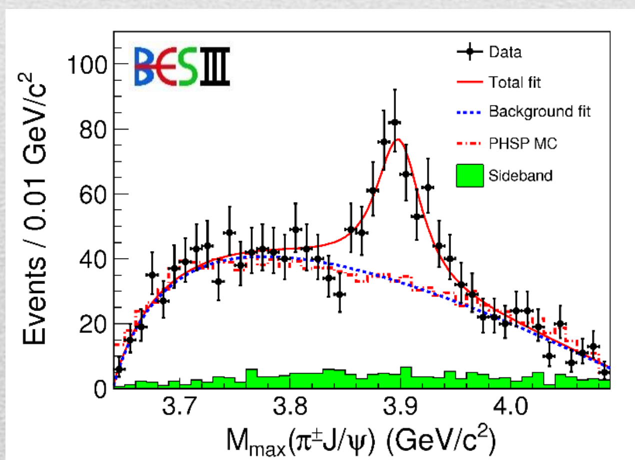
Charged quarkonium-like resonances have been found, **4q needed**

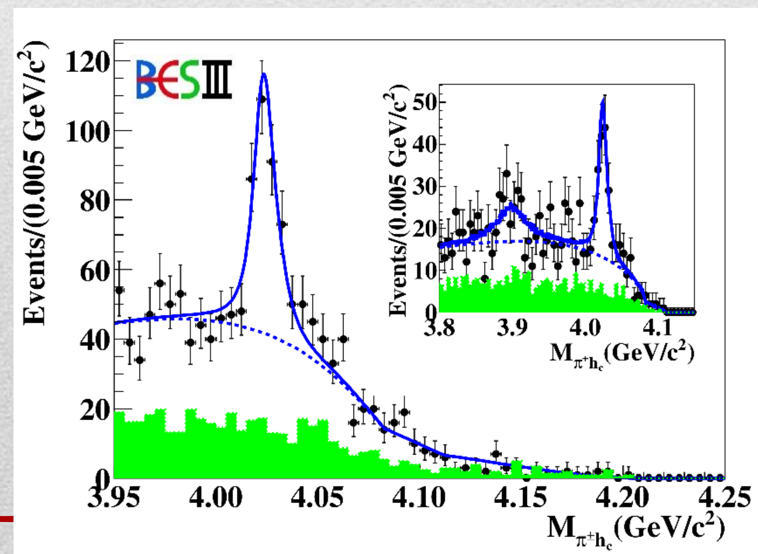


Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

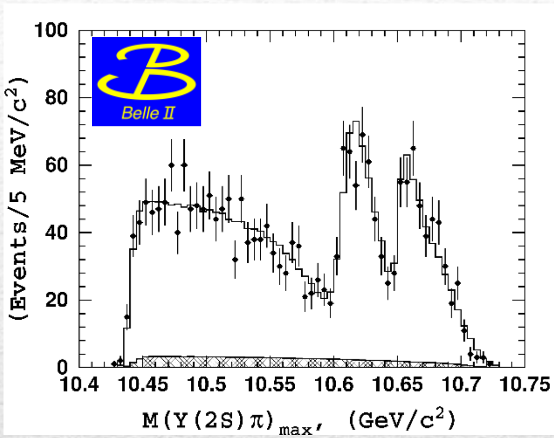
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\, \pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

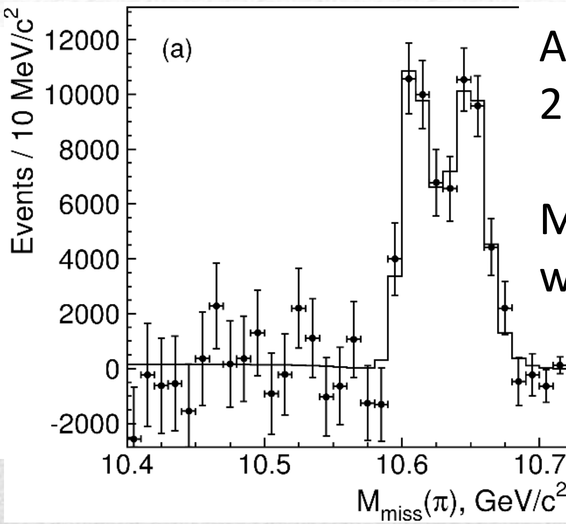
$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\, \pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV





Charged Z states: $Z_b(10610), Z_b'(10650)$





Anomalous dipion width in $\Upsilon(5S)$,
2 orders of magnitude larger than $\Upsilon(nS)$

Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$
which violates HQSS

2 twin resonances!

$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to (BB^*)^+\pi^-$
$M = 10607.2 \pm 2.0$ MeV, $\Gamma = 18.4 \pm 2.4$ MeV

$\Upsilon(5S) \to Z_b'(10650)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to \bar{B}^{*0}B^{*+}\pi^-$
$M = 10652.2 \pm 1.5$ MeV, $\Gamma = 11.5 \pm 2.2$ MeV