How to distinguish resonances from cusps in coupled channel systems

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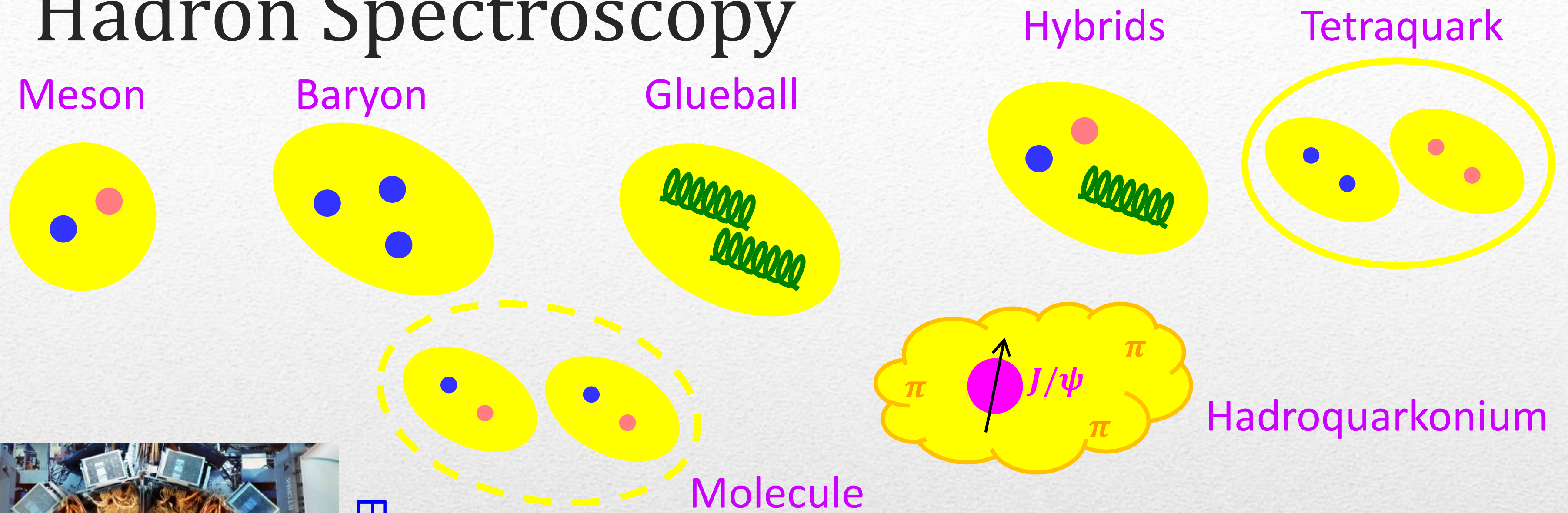
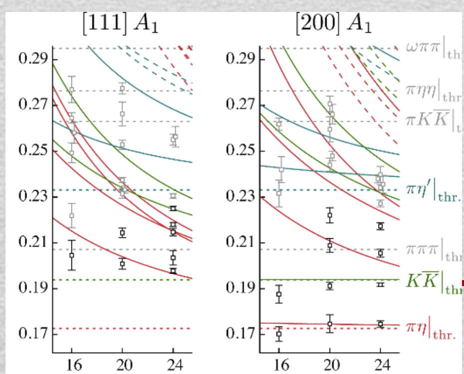
Hadron Phenomenology μWorkshop, CERN, November 7th, 2017

Jefferson Lab

Hadron Spectroscopy



Experiment

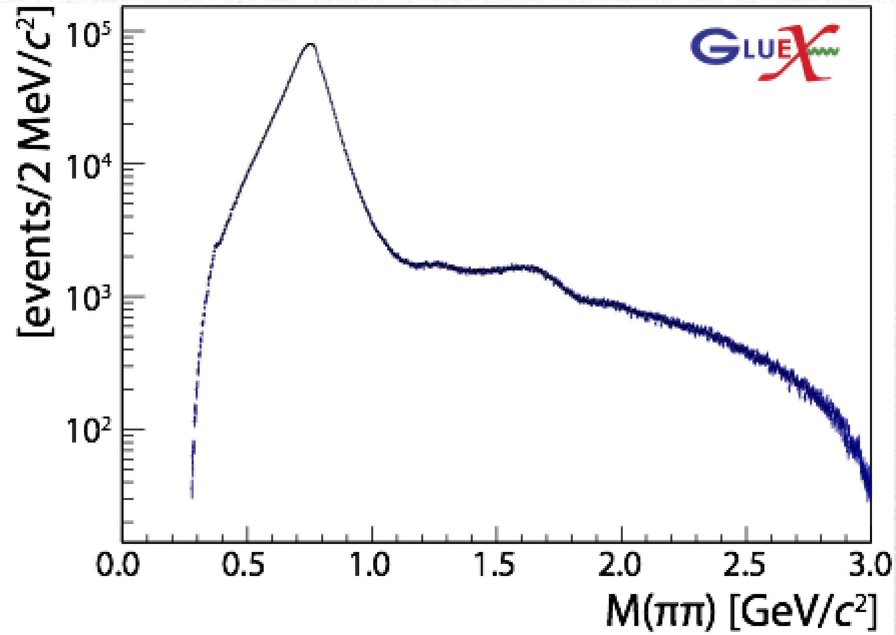


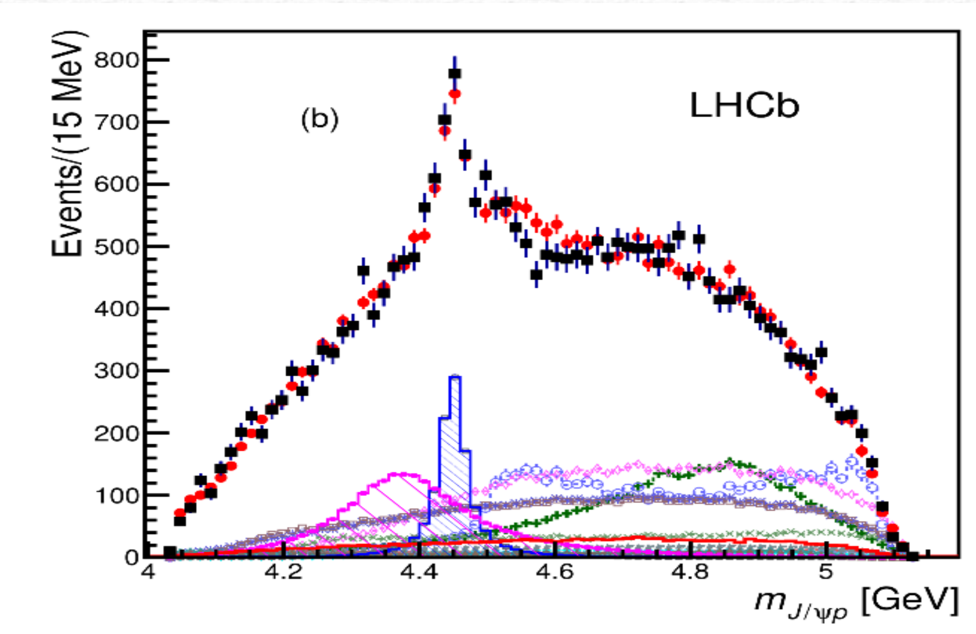
Lattice QCD

Data → ? → Fundamental properties, Model building

Interpretations on the spectrum leads to understanding fundamental laws of nature

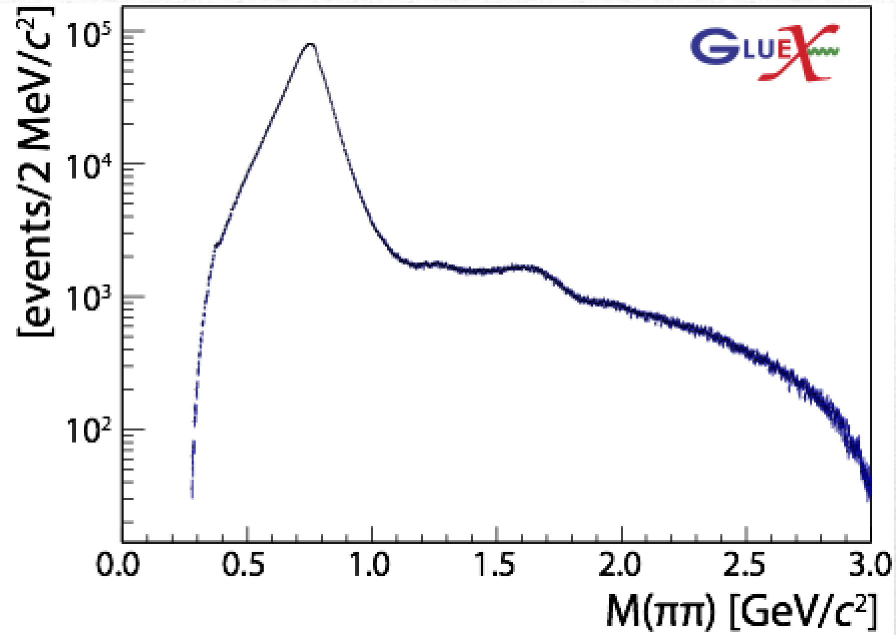
Hadron Spectroscopy

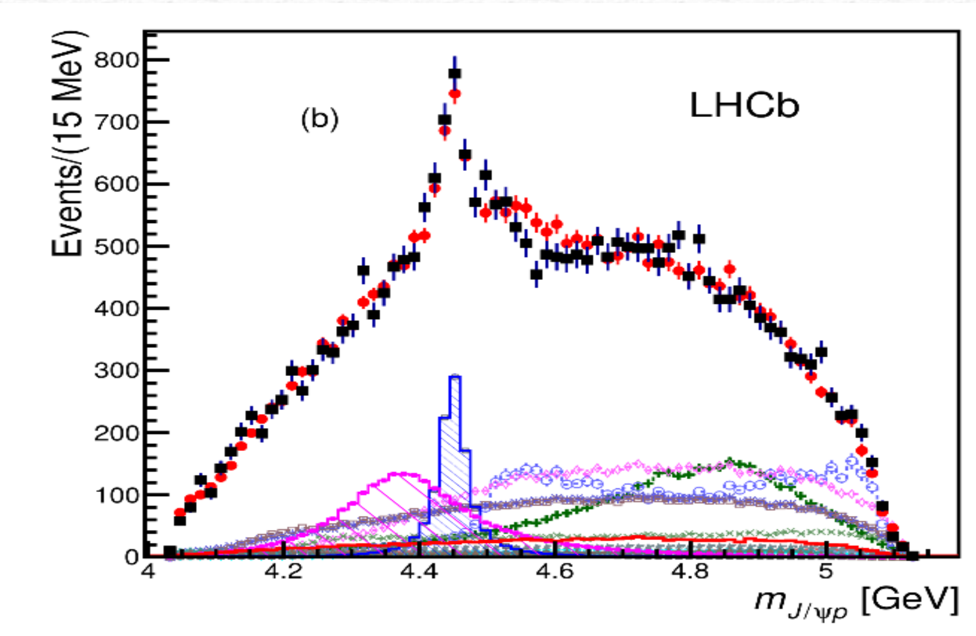




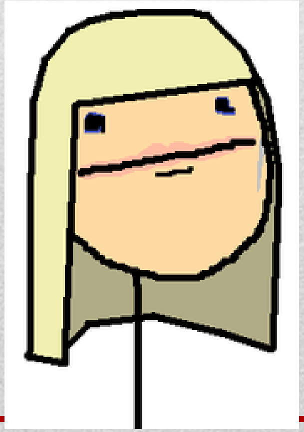
Data → ? → Fundamental properties, Model building

Hadron Spectroscopy



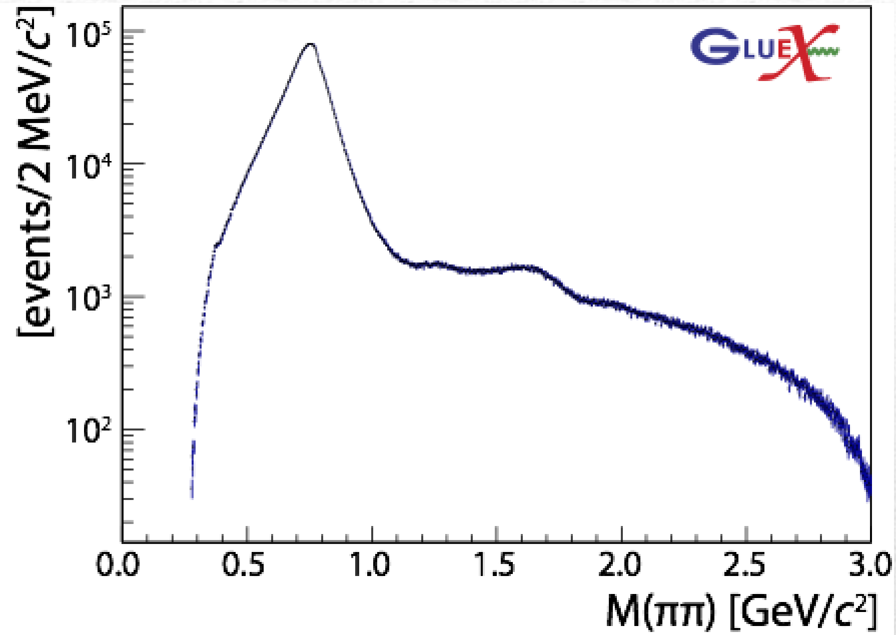


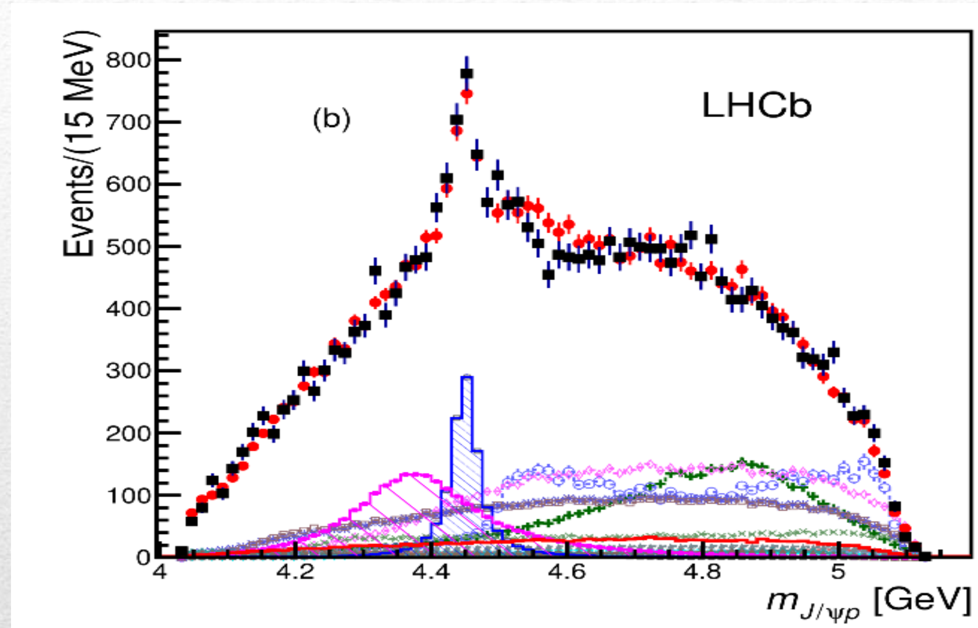
Data

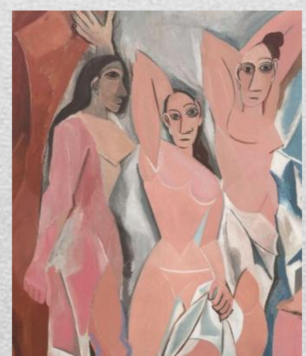


Fundamental properties, Model building

Hadron Spectroscopy





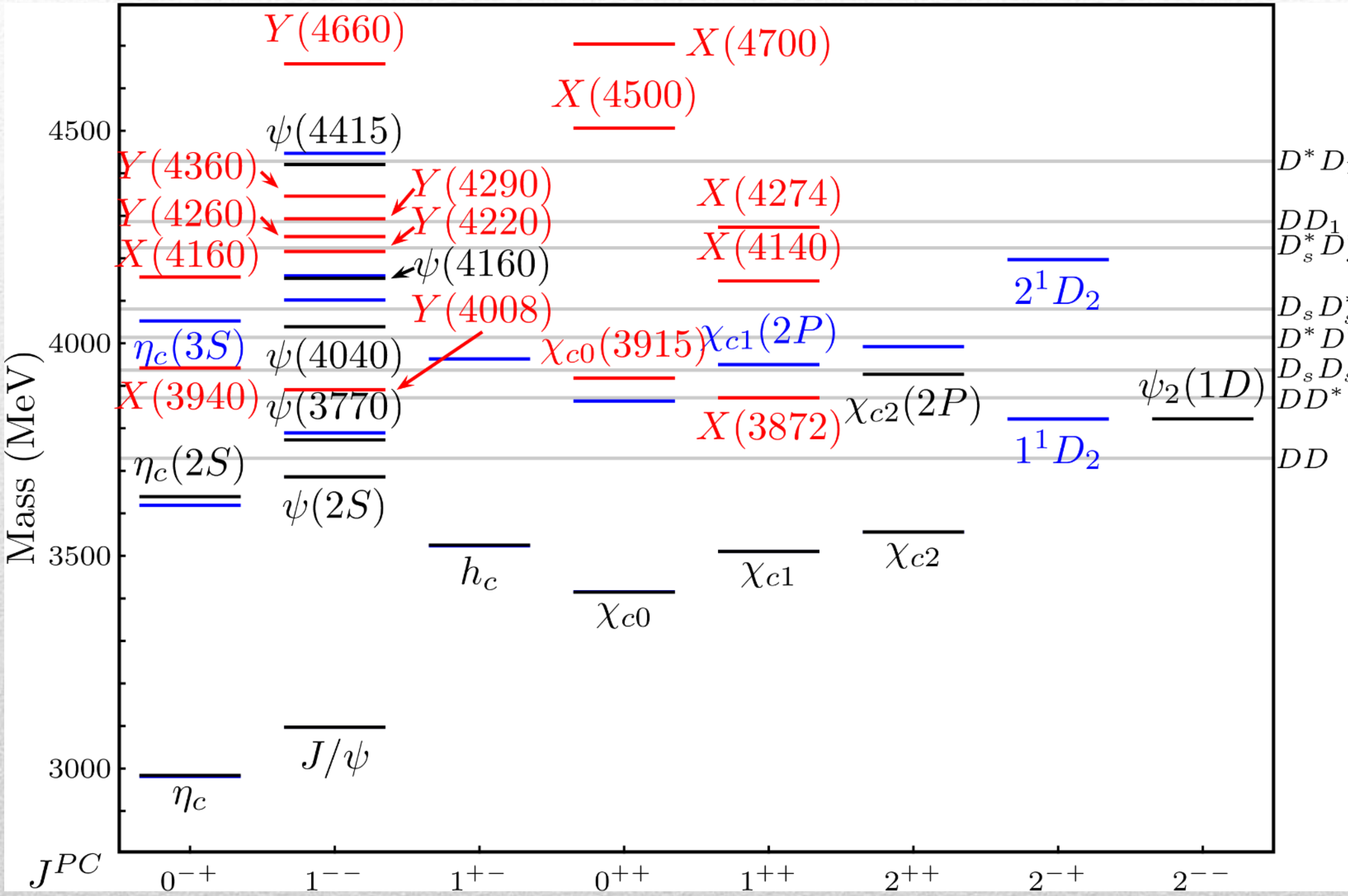
Data →  → Fundamental properties, Model building

Improvement needed! With great statistics comes great responsibility!

Peter Parker, Ph.D.

Exotic landscape

Esposito, AP, Polosa, Phys.Rept. 668



A host of unexpected resonances have appeared

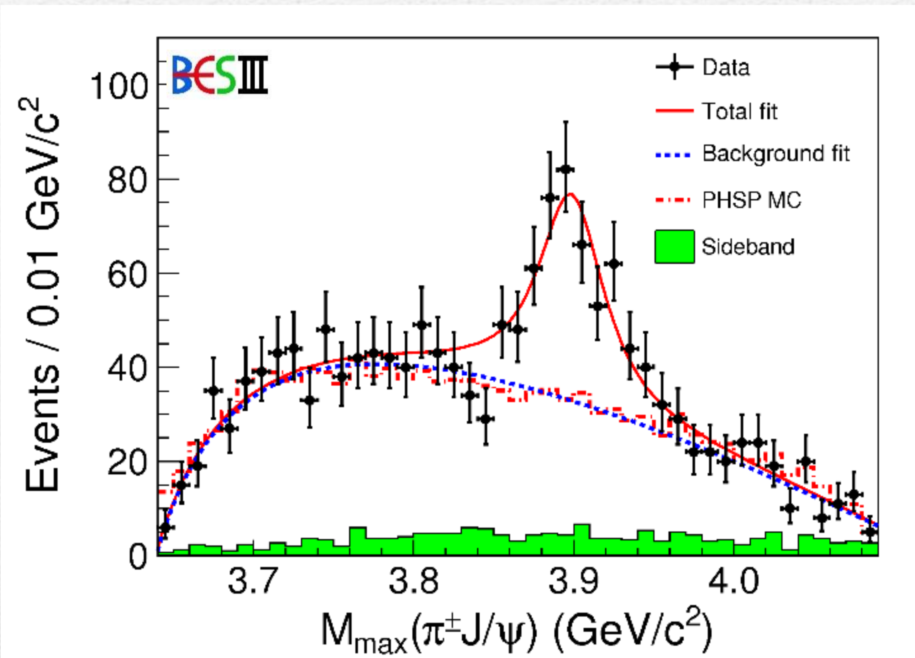
decaying mostly into charmonium + light

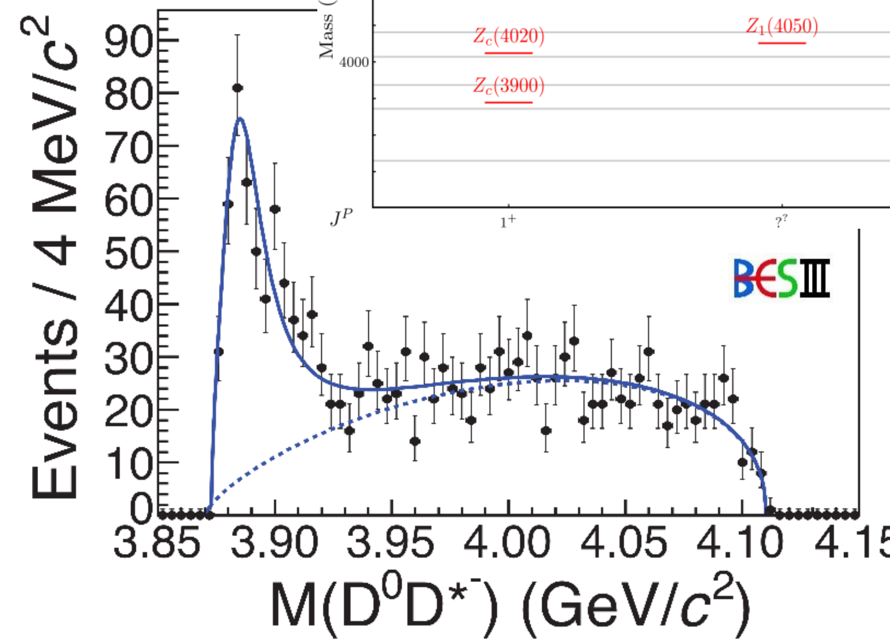
Hardly reconciled with usual charmonium interpretation

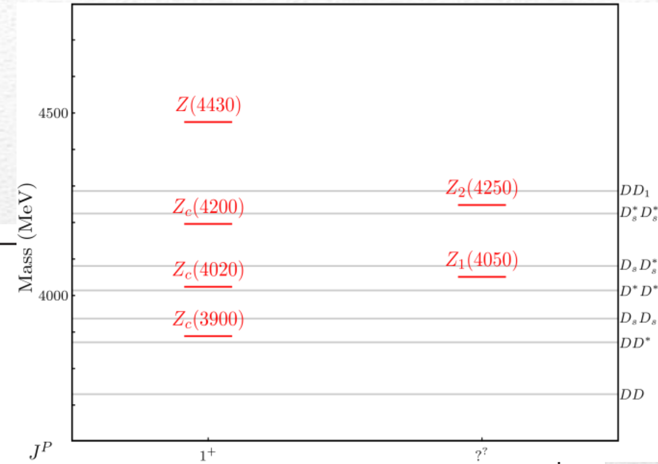
The $Z_c(3900)$

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

$$e^+e^- \to Z_c(3900)\pi \to J/\psi\, \pi\pi \text{ and} \to D\bar{D}^*\pi$$
$$M = 3886.6 \pm 2.4 \text{ MeV}, \Gamma = 28.1 \pm 2.6 \text{ MeV}$$

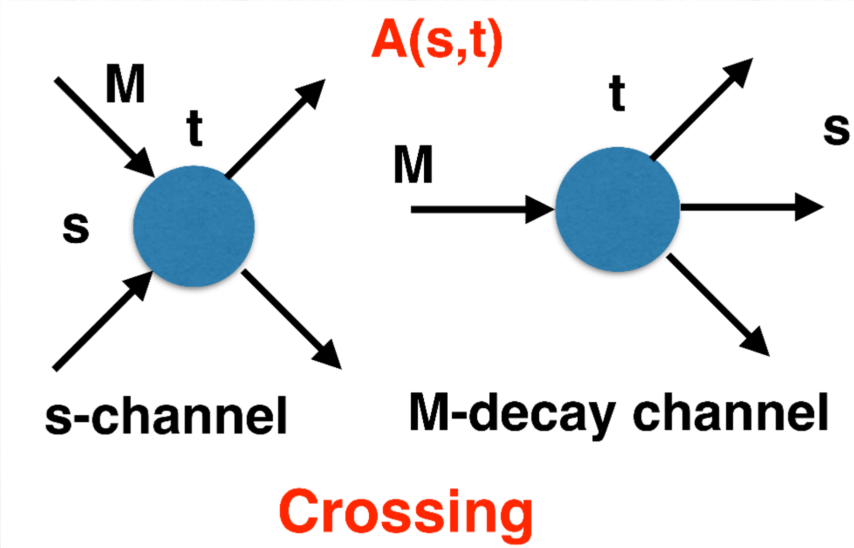






...but not observed in $B \to K\, Z_c(3900) \to K\, J/\psi\, \pi$ (?)

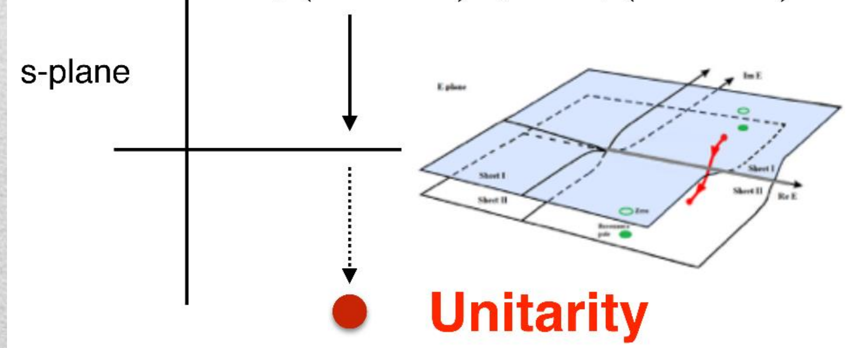
S-Matrix principles



$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

Analyticity

$$A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)$$



$$A_l(s + i\epsilon) \neq A_l(s - i\epsilon)$$

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

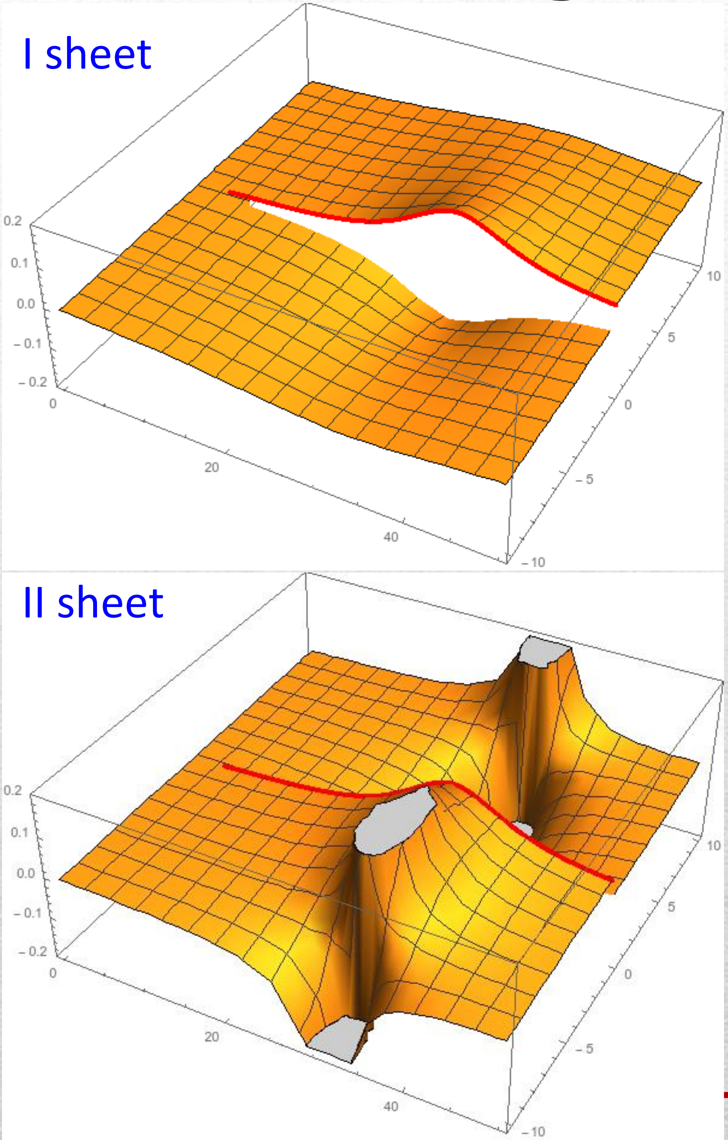
Resonances (QCD states) are poles in the unphysical Riemann sheets

Dictionary

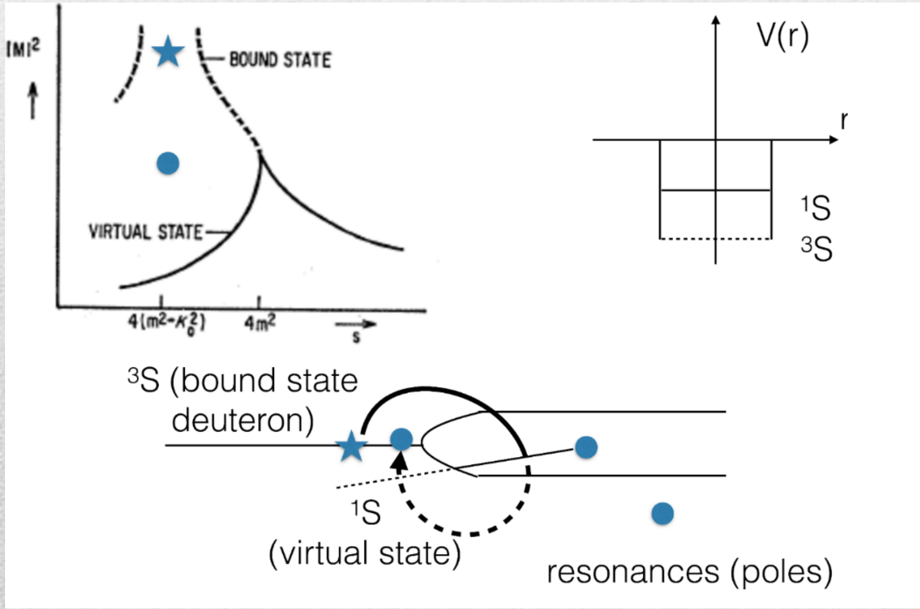
The term cusp has been used with different meanings:

- The threshold cusp: a kink generated by the opening of a new channel
- The virtual cusp: a state like the $a_0(980)$, if laying on the IV Riemann sheet (example later)
- The Swanson cusp: you write a model that you believe it has nothing to do with a real state, but you forget to check
- The triangle cusp: a cusp generated by a branching point and not by a real state

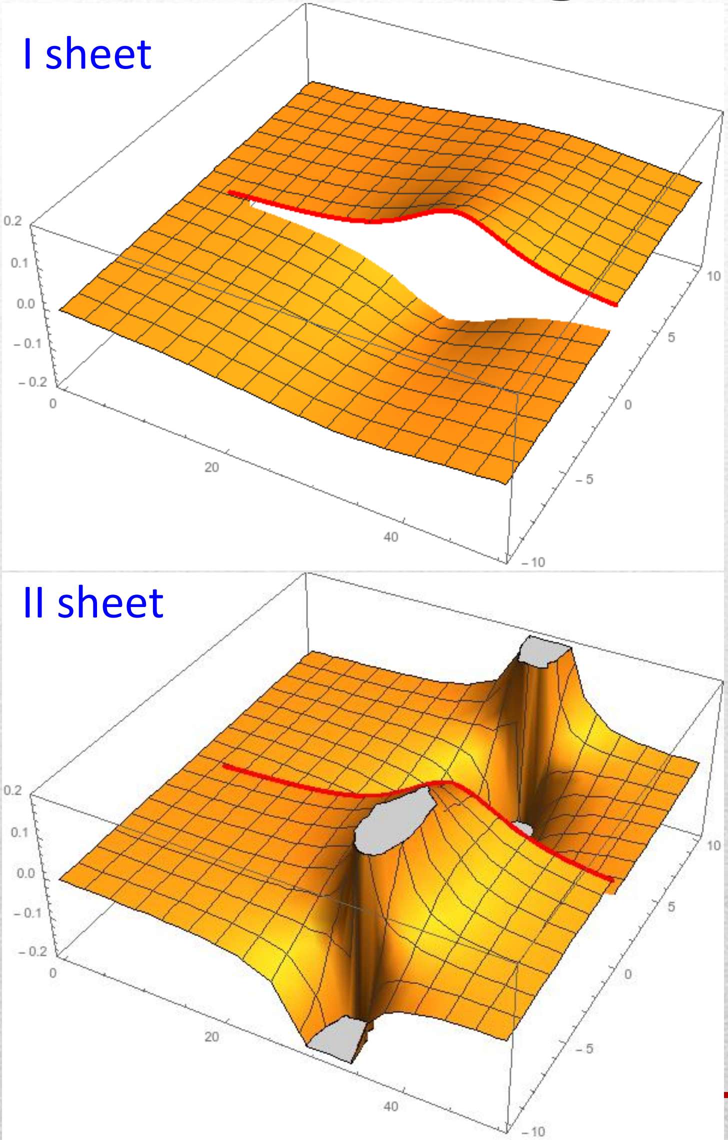
Pole hunting



Bound states on the real axis 1st sheet
Not-so-bound (virtual) states on the real axis 2nd sheet

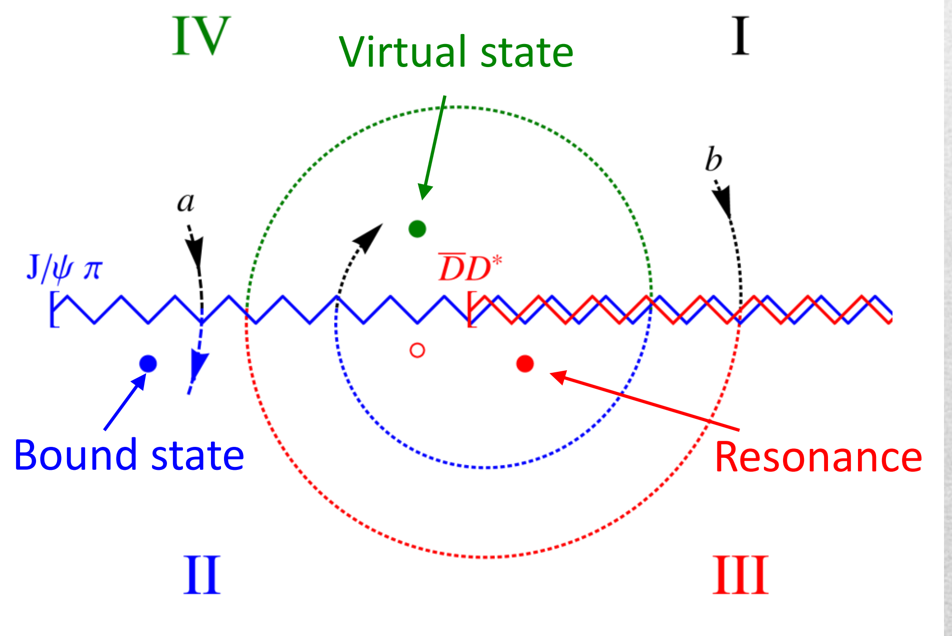


Pole hunting

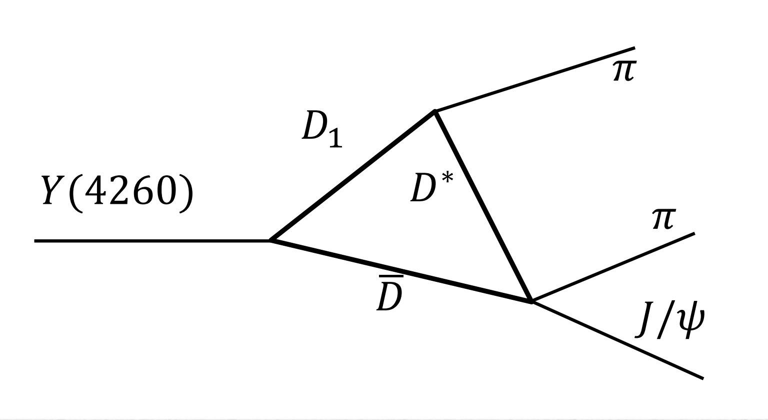


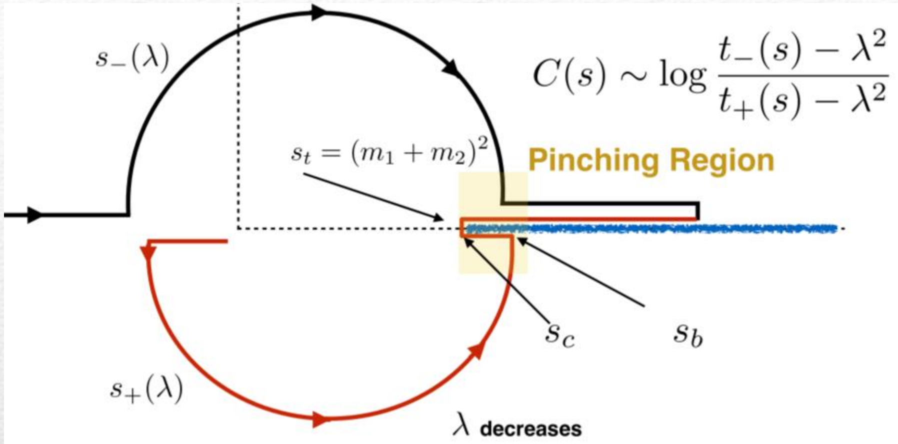
More complicated structure when
more thresholds arise:
two sheets for each new threshold

III sheet: usual resonances
IV sheet: cusps (virtual states)



Triangle singularity





Logarithmic branch points due to exchanges in the cross channels can simulate a resonant behavior, only in very special kinematical conditions (Coleman and Norton, Nuovo Cim. 38, 438), However, this effects cancels in Dalitz projections, no peaks (Schmid, Phys.Rev. 154, 1363)

$$f_{0,i}(s) = b_{0,i}(s) + \frac{t_{ij}}{\pi} \int_{s_i}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s' - s}$$

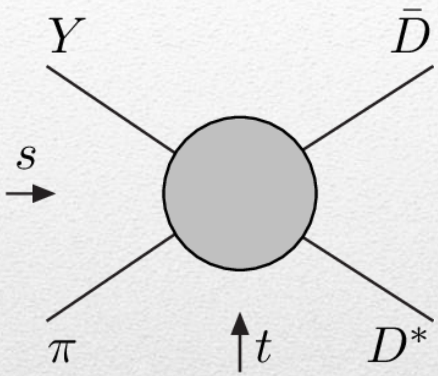
...but the cancellation can be spread in different channels, you might still see peaks in other channels only!

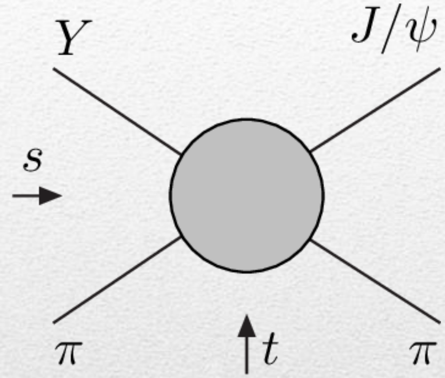
Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo, Meissner, Wang, Yang PRD92, 071502

Amplitude analysis for $Z_c(3900)$

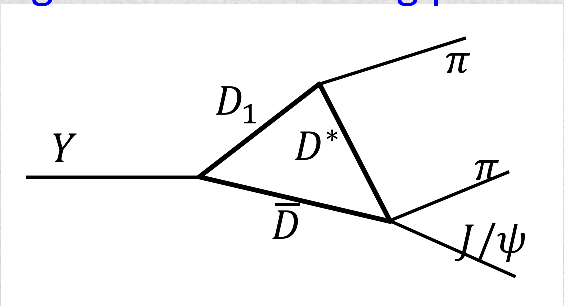
One can test different parametrizations of the amplitude, which correspond to
different singularities → different natures

AP *et al.* (JPAC), PLB772, 200-209



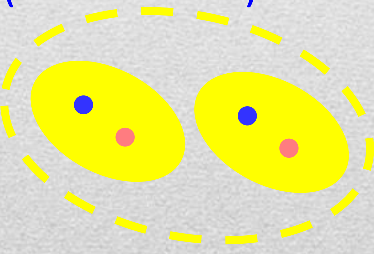


Triangle rescattering,
logarithmic branching point



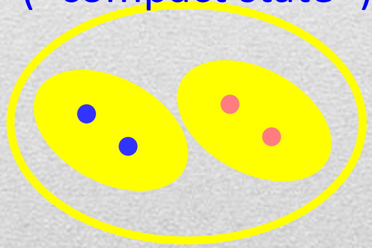
Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo *et al.* PRD92, 071502

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



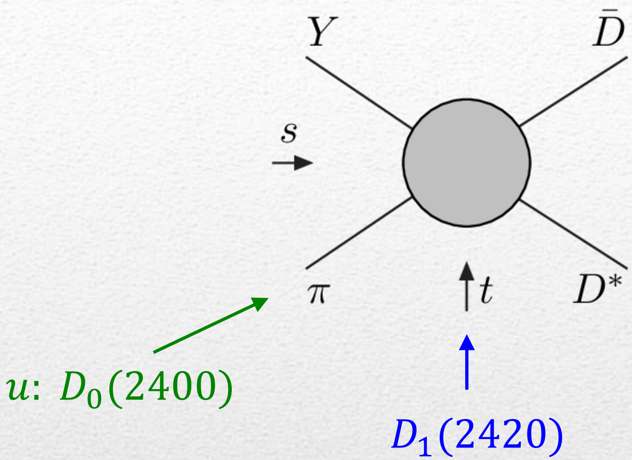
Tornqvist, Z.Phys. C61, 525
Swanson, Phys.Rept. 429
Hanhart *et al.* PRL111, 132003

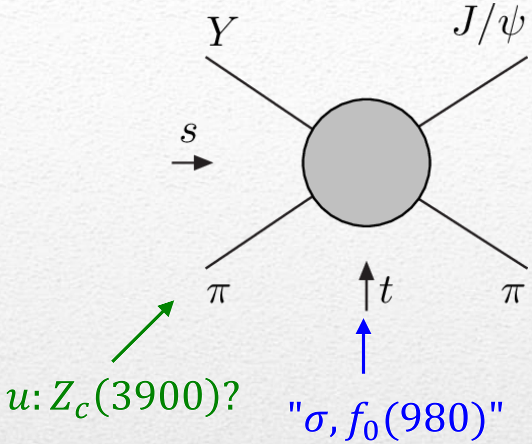
Resonance,
III sheet pole
(«compact state»)



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

Amplitude model





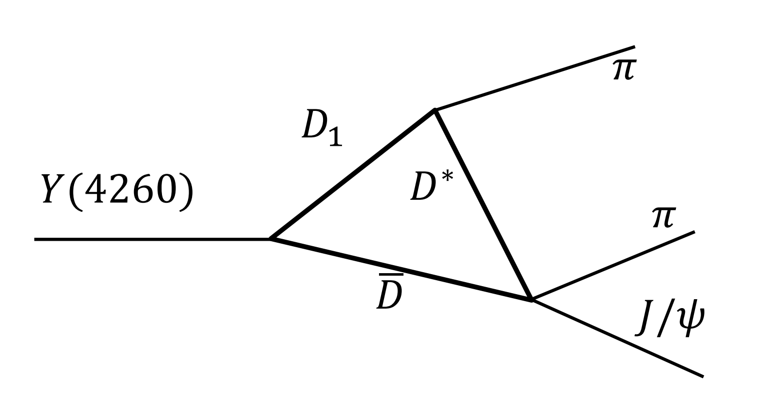
$$f_i(s,t,u) = 16\pi \sum_{l=0}^{L_{\max}} (2l+1)\left(a_{l,i}^{(s)}(s)P_l(z_s) + a_{l,i}^{(t)}(t)P_l(z_t) + a_{l,i}^{(u)}(u)P_l(z_u)\right)$$ Khuri-Treiman

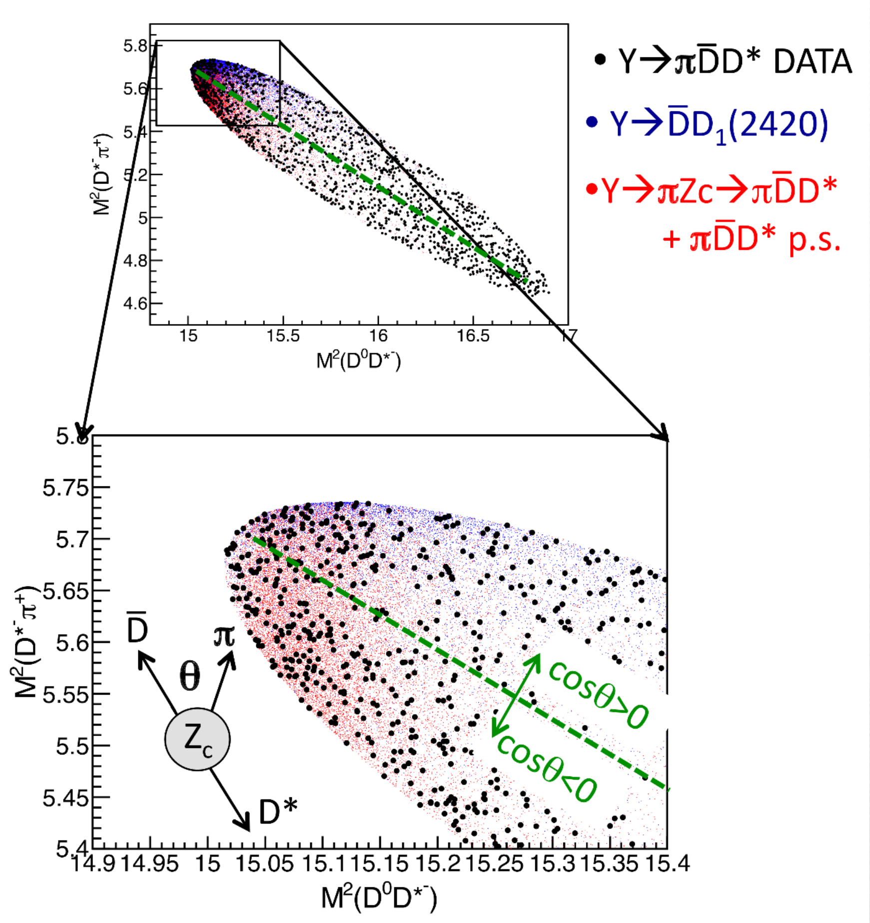
$$f_{0,i}(s) = \frac{1}{32\pi}\int_{-1}^{1} dz_s\, f_i\left(s, t(s,z_s), u(s,z_s)\right) = a_{0,i}^{(s)} + \frac{1}{32\pi}\int_{-1}^{1} dz_s \left(a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u)\right) \equiv a_{0,i}^{(s)} + b_{0,i}(s)$$

$$f_{l,i}(s) = \frac{1}{32\pi}\int_{-1}^{1} dz_s\, P_l(z_s)\left(a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u)\right) \equiv b_{l,i}(s) \quad \text{for } l > 0. \quad f_{0,i}(s) = b_{0,i}(s) + \sum_j t_{ij}(s)\frac{1}{\pi}\int_{s_j}^{\infty} ds' \frac{\rho_j(s')b_{0,j}(s')}{s'-s},$$

$$f_i(s,t,u) = 16\pi\left[a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) + \sum_j t_{ij}(s)\left(c_j + \frac{s}{\pi}\int_{s_j}^{\infty} ds' \frac{\rho_j(s')b_{0,j}(s')}{s'(s'-s)}\right)\right],$$

Triangle singularity





The dominance of $\bar{D}D_1$ in the $Y(4260)$ decay is neither supported nor disproofed by data – the measurement of the asymmetry of the angular distribution across the Dalitz plot is inconclusive

Higher statistics will allow to constrain the $Y\bar{D}D_1$ coupling, and consequently the intensity of the triangle singularity

Testing scenarios

- We approximate all the particles to be scalar – this affects the value of couplings, which are not normalized anyway – but not the position of singularities.
  This also limits the number of free parameters

$$f_i(s,t,u) = 16\pi \left[a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) + \sum_j t_{ij}(s) \left(c_j + \frac{s}{\pi} \int_{s_j}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s'(s'-s)} \right) \right],$$

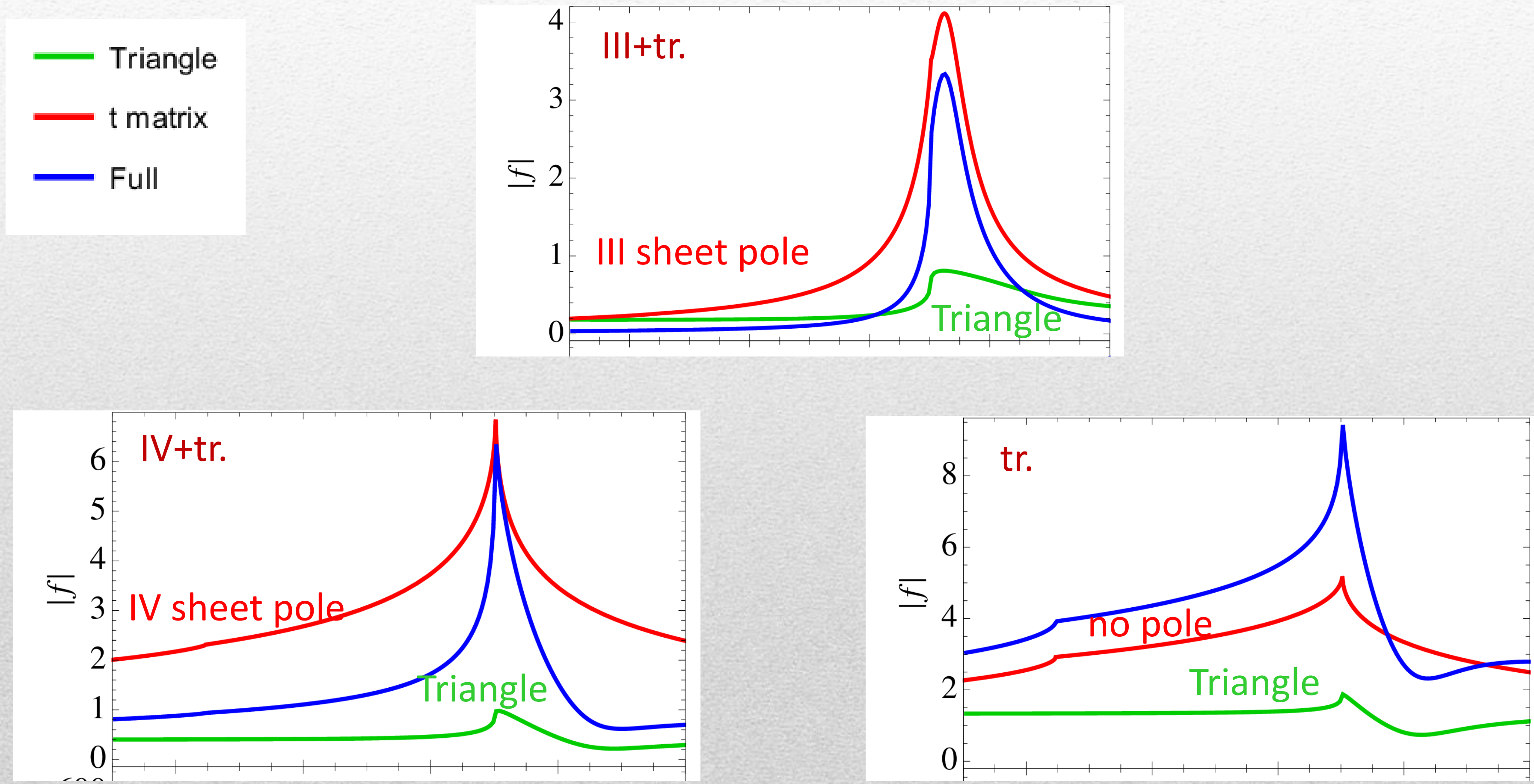
The scattering matrix is parametrized as $(t^{-1})_{ij} = K_{ij} - i\,\rho_i\,\delta_{ij}$

Four different scenarios considered:

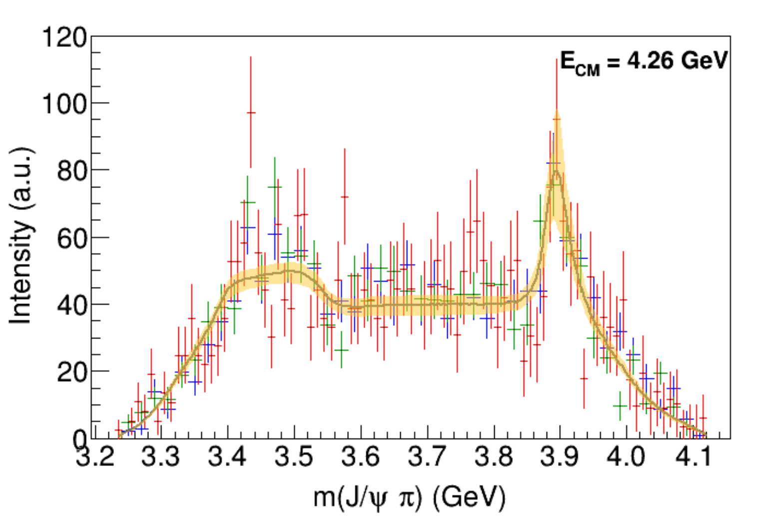
- «III»: the K matrix is $\frac{g_i\,g_j}{M^2-s}$, this generates a pole in the closest unphysical sheet the rescattering integral is set to zero
- «III+tr.»: same, but with the correct value of the rescattering integral
- «IV+tr.»: the K matrix is constant, this generates a pole in the IV sheet
- «tr.»: same, but the pole is pushed far away by adding a penalty in the χ^2

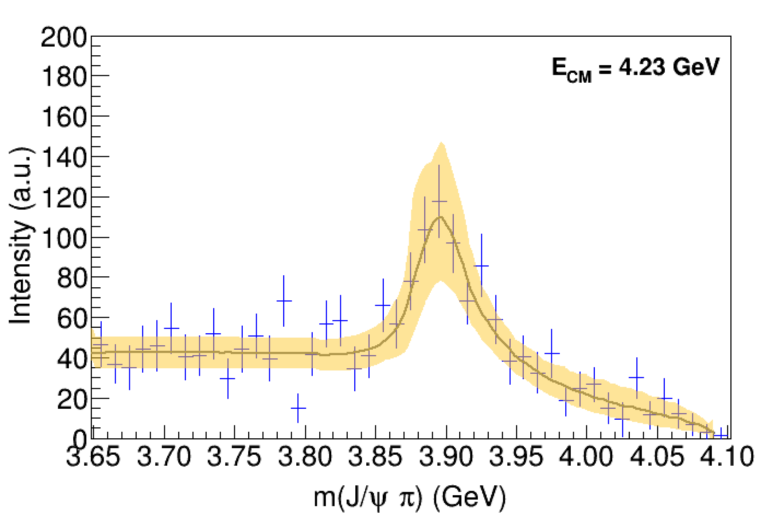
Singularities and lineshapes

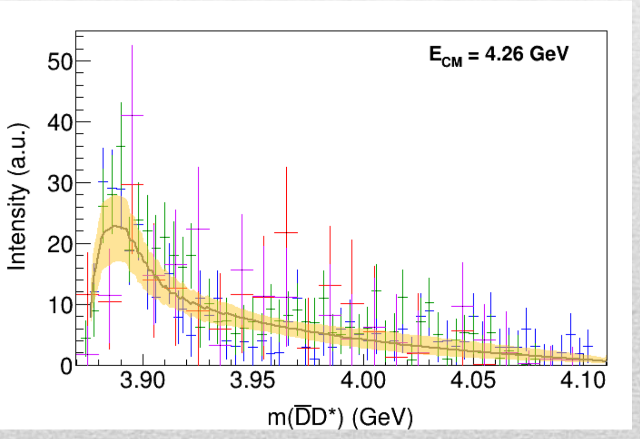
Different lineshapes according to different singularities

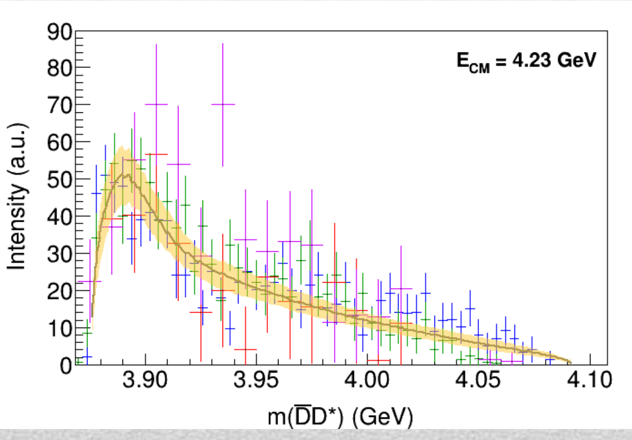


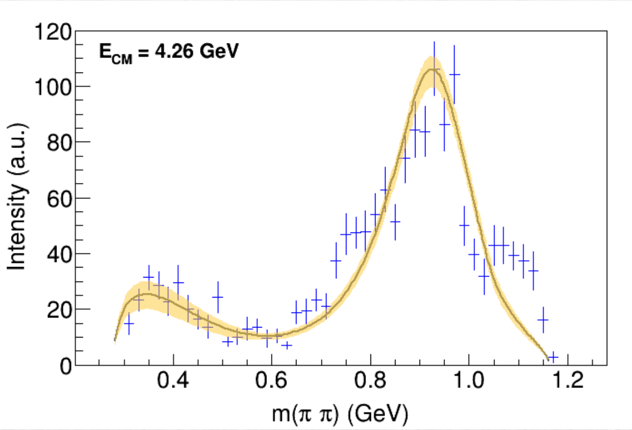
Fit: III


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

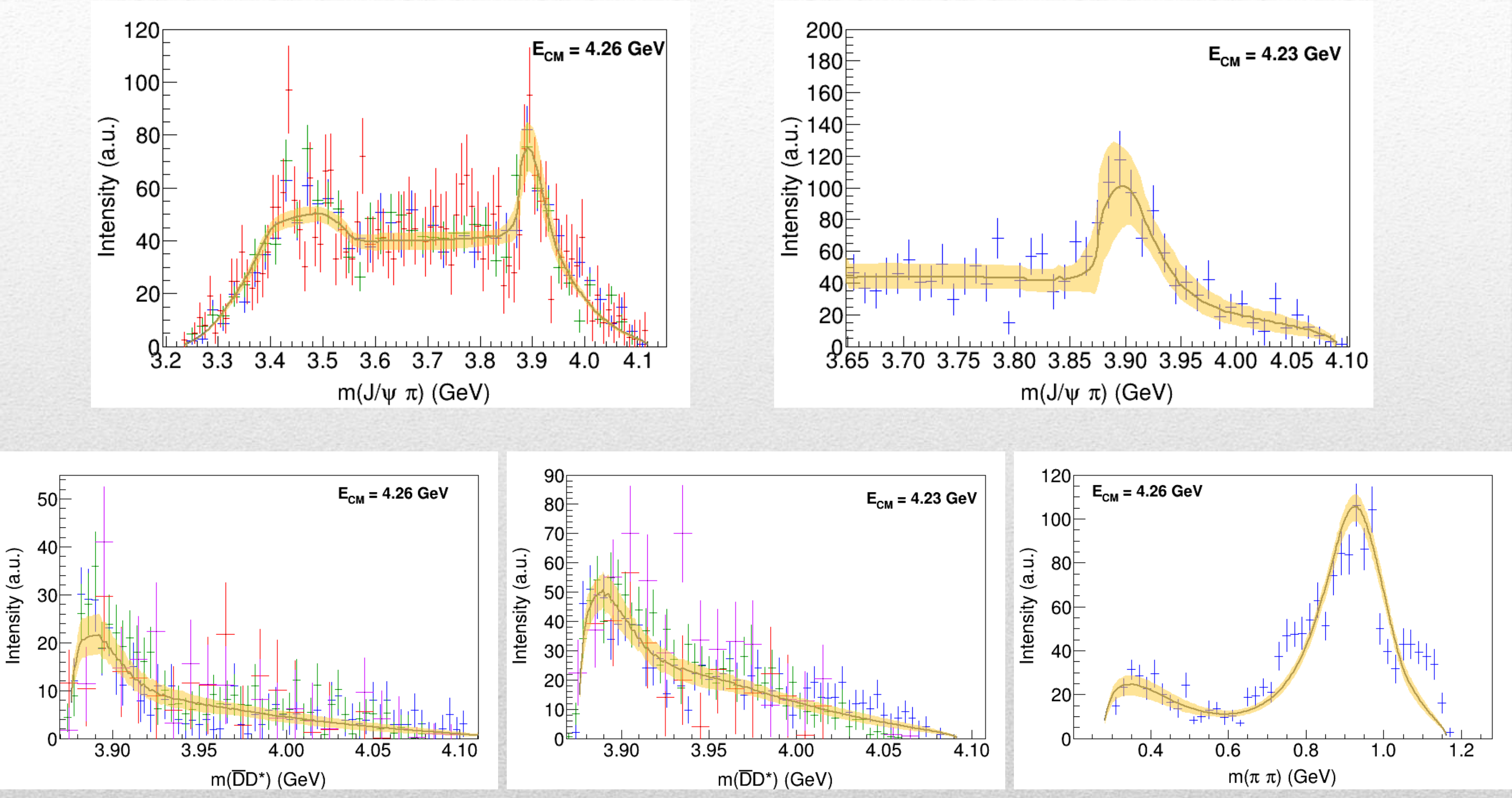

E$_{CM}$ = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)


E$_{CM}$ = 4.26 GeV
Intensity (a.u.)
m($\bar{D}$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)

Fit: III+tr.



E$_{CM}$ = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
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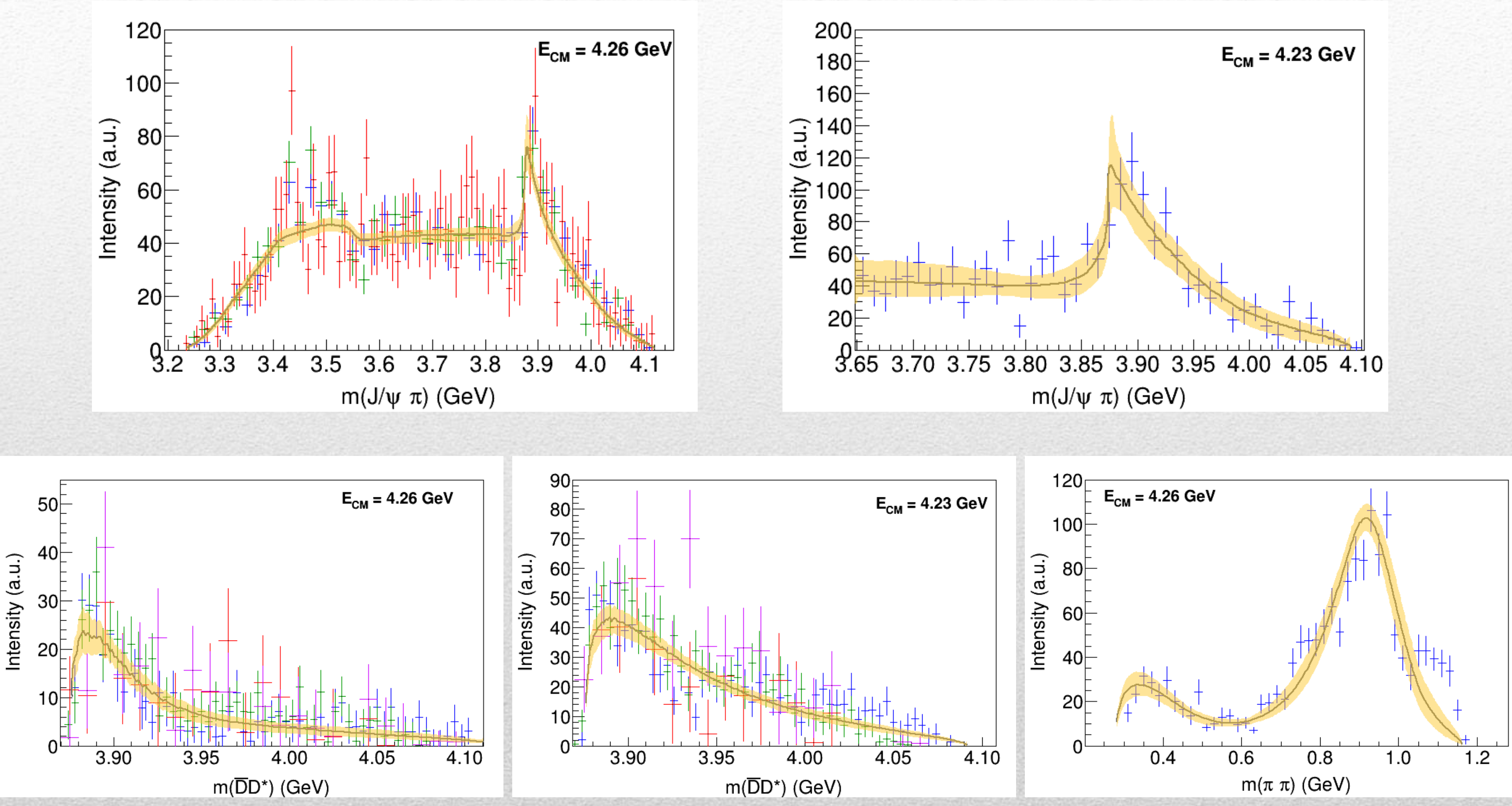
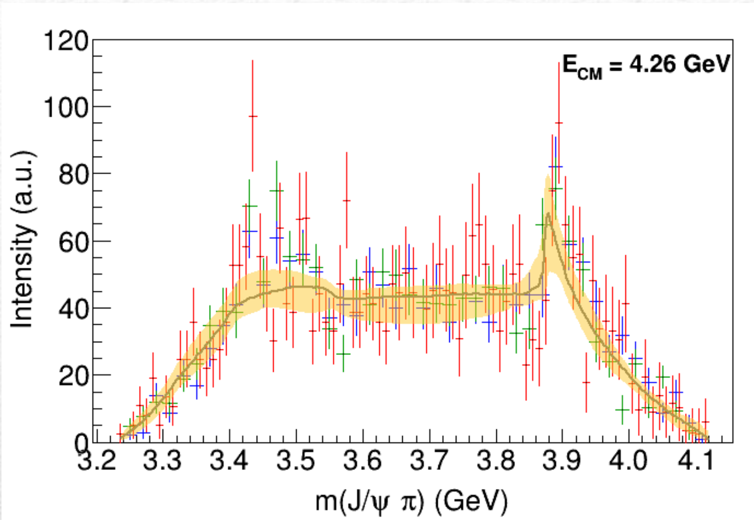
Intensity (a.u.)
m(J/ψ π) (GeV)
E$_{CM}$ = 4.26 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)
E$_{CM}$ = 4.23 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)
E$_{CM}$ = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

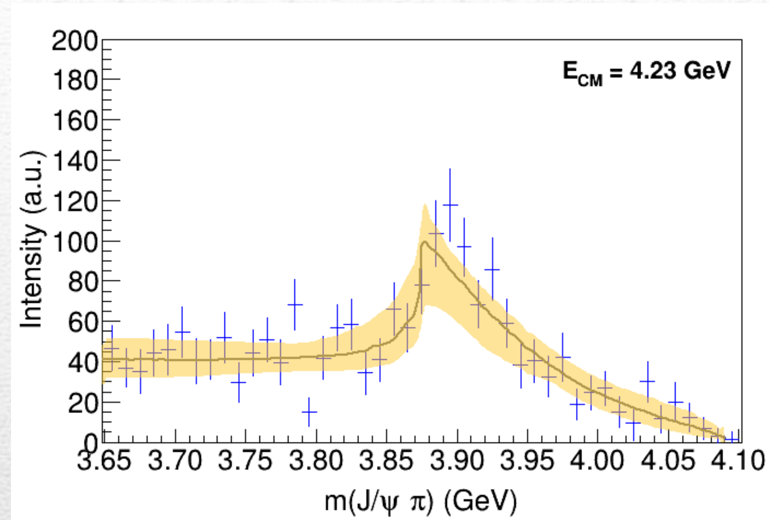
Fit: IV+tr.


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

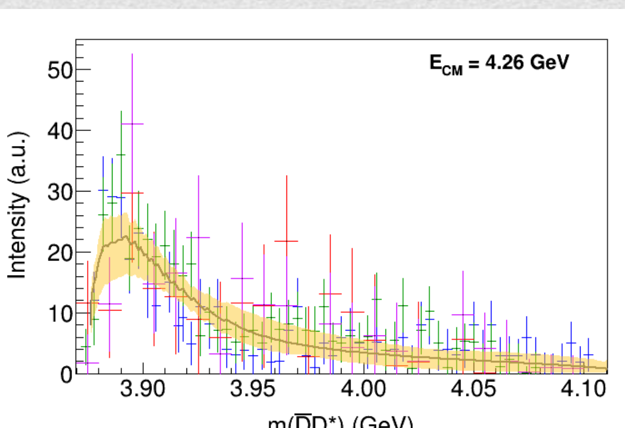
Fit: tr.



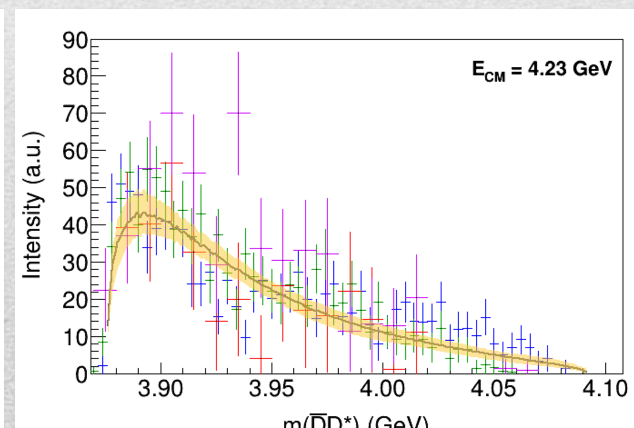
E_CM = 4.26 GeV
Intensity (a.u.)
0
20
40
60
80
100
120
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4.0
4.1
m(J/ψ π) (GeV)



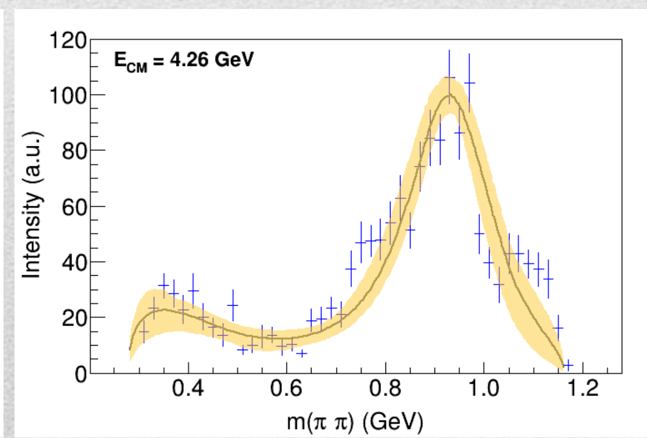
E_CM = 4.23 GeV
Intensity (a.u.)
0
20
40
60
80
100
120
140
160
180
200
3.65
3.70
3.75
3.80
3.85
3.90
3.95
4.00
4.05
4.10
m(J/ψ π) (GeV)



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

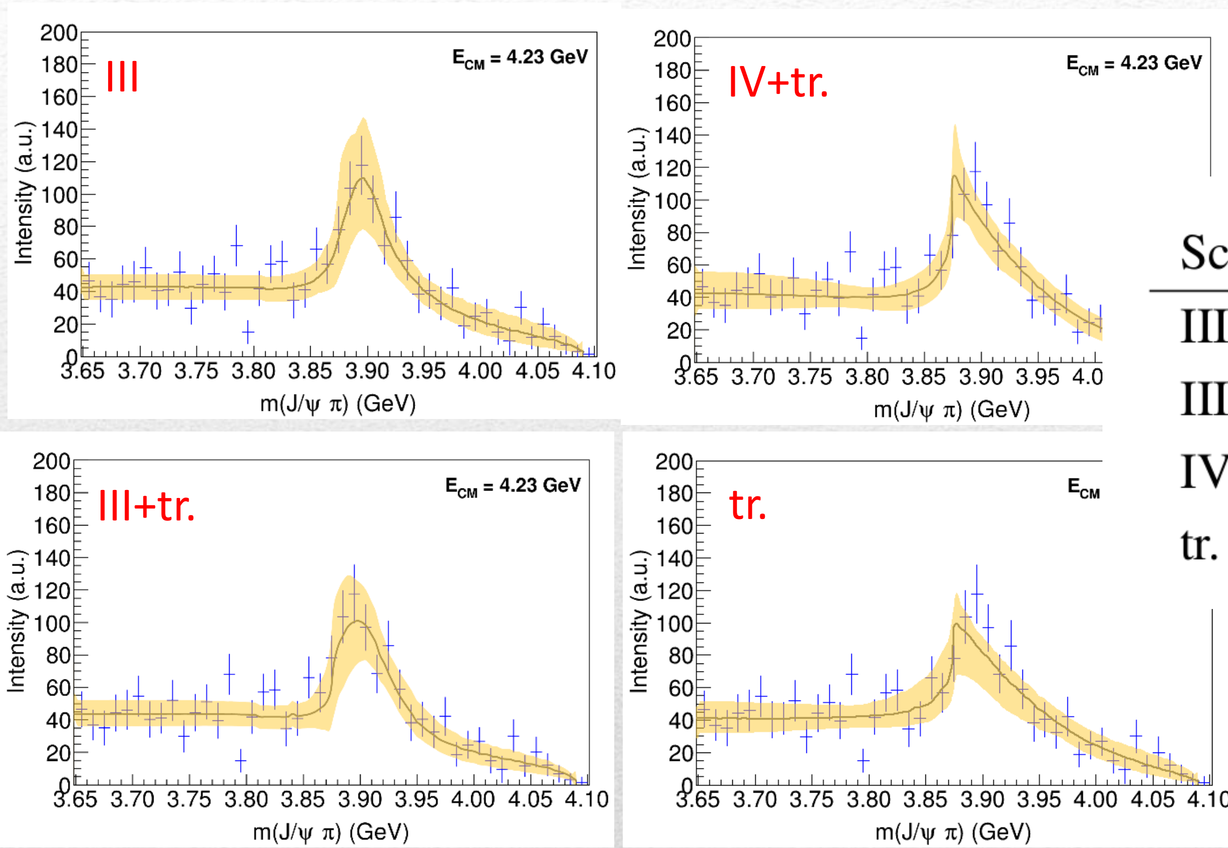


E_CM = 4.23 GeV
Intensity (a.u.)
0
10
20
30
40
50
60
70
80
90
3.90
3.95
4.00
4.05
4.10
m(D̄D*) (GeV)



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

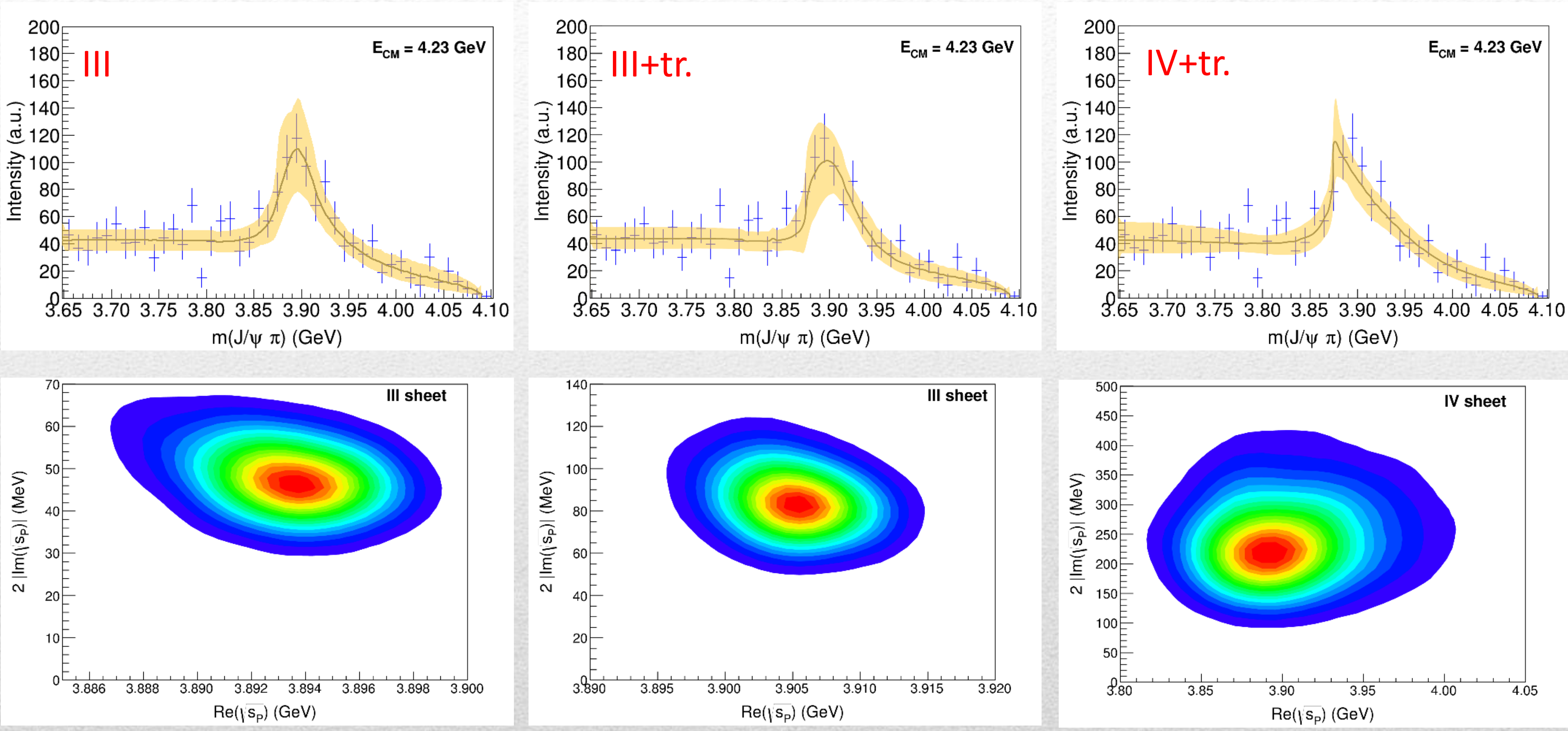
Fit summary



Scenario	χ^2	DOF	χ^2/DOF
III	644	532	1.21
III+tr.	642	532	1.21
IV+tr.	666	532	1.25
tr.	695	532	1.31

Naive loglikelihood ratio test give a $\sim 4\sigma$ significance of the scenario III+tr. over IV+tr., looking at plots it looks too much – better using some more solid test

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

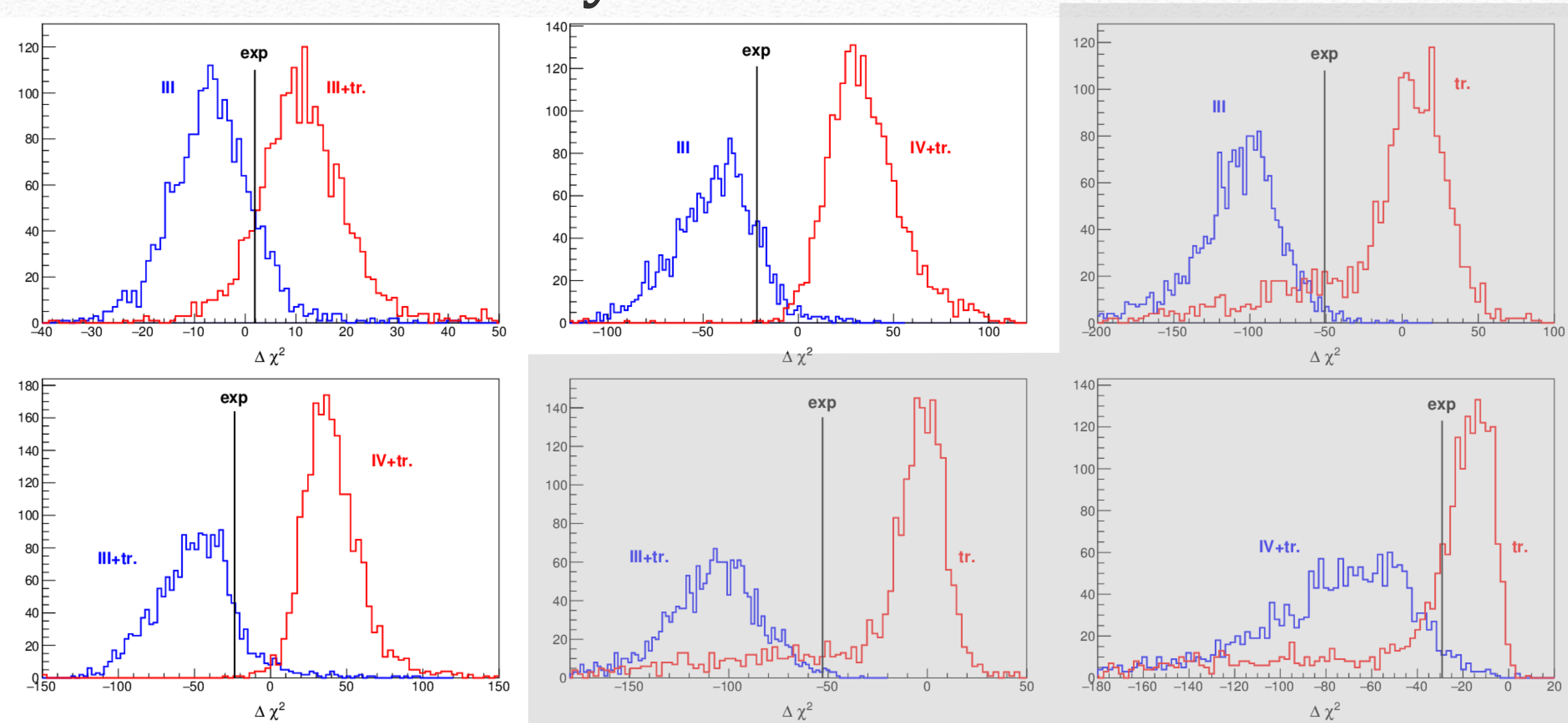
Summary

- No strong conclusion can be driven yet, but we are establishing the method to use when higher statistics will be available (e.g. to constrain the $D_1(2420)$)
- In particular, we stress the importance of going beyond 1D distributions
- Information about pole position can help the phenomenological models to provide a better description of the sector and give insights about the nature of these states

Thank you!

BACKUP

Statistical analysis



Toy experiments according to the different hypotheses, to estimate the relative rejection of various scenarios

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")

Not conclusive at this stage

Strategy

- We fit the following invariant mass distributions:
  - BESIII PRL110, 252001 $J/\psi\,\pi^+$, $J/\psi\,\pi^-$, $\pi^+\pi^-$ at $E_{CM} = 4.26$ GeV
  - BESIII PRL110, 252001 $J/\psi\,\pi^0$ at $E_{CM} = 4.23, 4.26,$ ~~4.36~~ GeV
  - BESIII PRD92, 092006 $\overline{D^0}D^{*+}$, $\overline{D^{*0}}D^+$ (double tag) at $E_{CM} = 4.23, 4.26$ GeV
  - BESIII PRL115, 222002 $\overline{D^0}D^{*0}$, $\overline{D^{*0}}D^0$ at $E_{CM} = 4.23, 4.26$ GeV
  - ~~BESIII PRL112, 022001 $\overline{D^0}D^{*+}$, $\overline{D^{*0}}D^+$ (single tag) at $E_{CM} = 4.26$ GeV~~
  - ~~Belle PRL110, 252002 $J/\psi\,\pi^\pm$ at $E_{CM} = 4.26$ GeV~~
  - ~~CLEO-c data PLB727, 366 $J/\psi\,\pi^\pm$, $J/\psi\,\pi^0$ at at $E_{CM} = 4.17$ GeV~~
- Published data are not efficiency/acceptance corrected,
  → we are not able to give the absolute normalization of the amplitudes
- No given dependence on E_{CM} is assumed – the couplings at different E_{CM} are independent parameters

Strategy

- Reducible (incoherent) backgrounds are pretty flat and do not influence the analysis, except the peaking background in $\overline{D^0}D^{*0}$, $\overline{D^{*0}}D^0$ (subtracted)
- Some information about angular distributions has been published, but it's not constraining enough → we do not include in the fit
- Because of that, we approximate all the particles to be scalar – this affects the value of couplings, which are not normalized anyway – but not the position of singularities. This also limits the number of free parameters