Using πK to understand heavy meson decays

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Joint Physics Analysis Center

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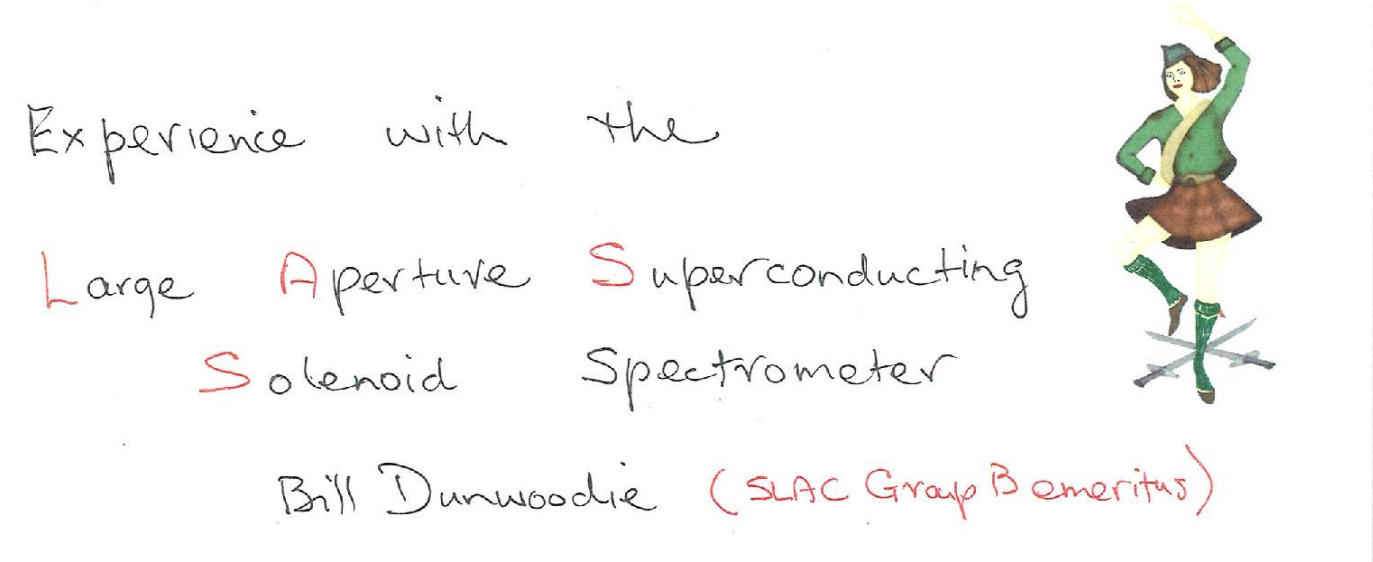
Outline

- The exotic XYZ states
- The $Z(4430)$
- Helicity and covariant formalism
- Playing with fits
- Conclusions

$K\pi$ interactions



The major source of data for $K\pi$ scattering is the LASS experiment

$K\pi$ interactions

Experience with the

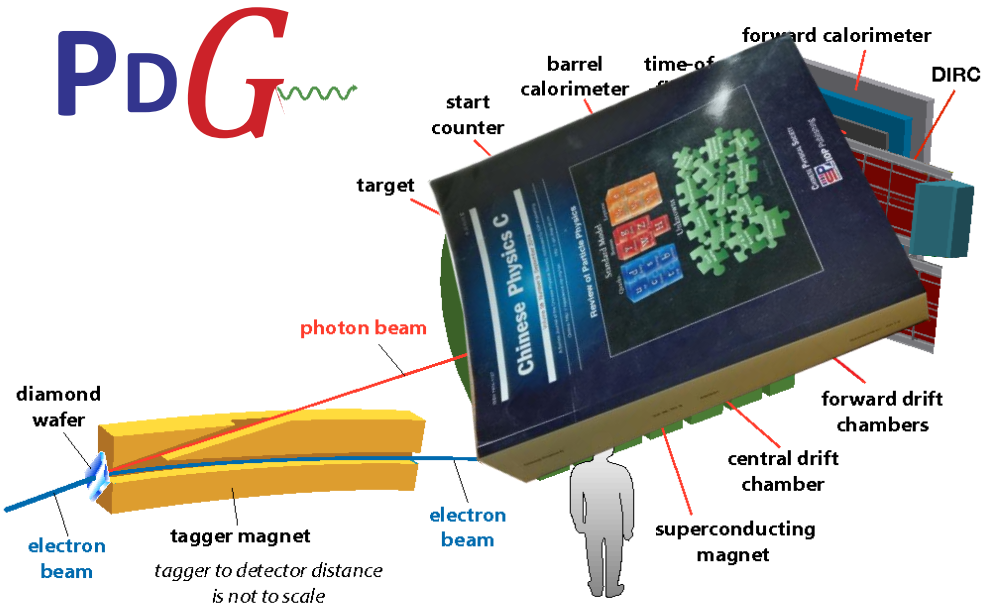
Large Aperture Superconducting

Solenoid Spectrometer

Bill Dunwoodie (SLAC Group B emeritus)

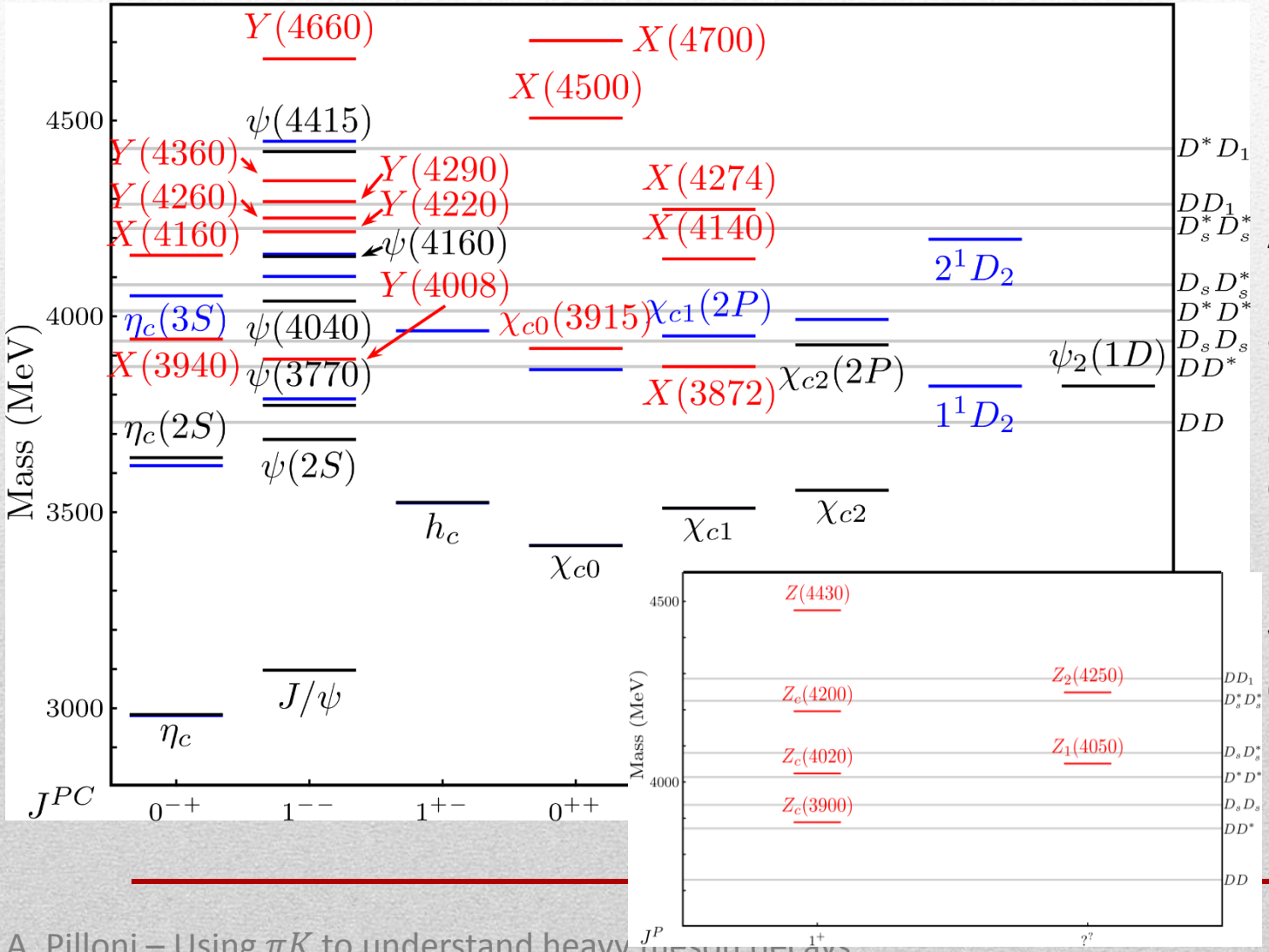
The major source of data for $K\pi$ scattering is the LASS experiment

although several people believe it is the PDG with photon beam



Exotic XYZ landscape

Esposito, AP, Polosa, Phys.Rept. 668



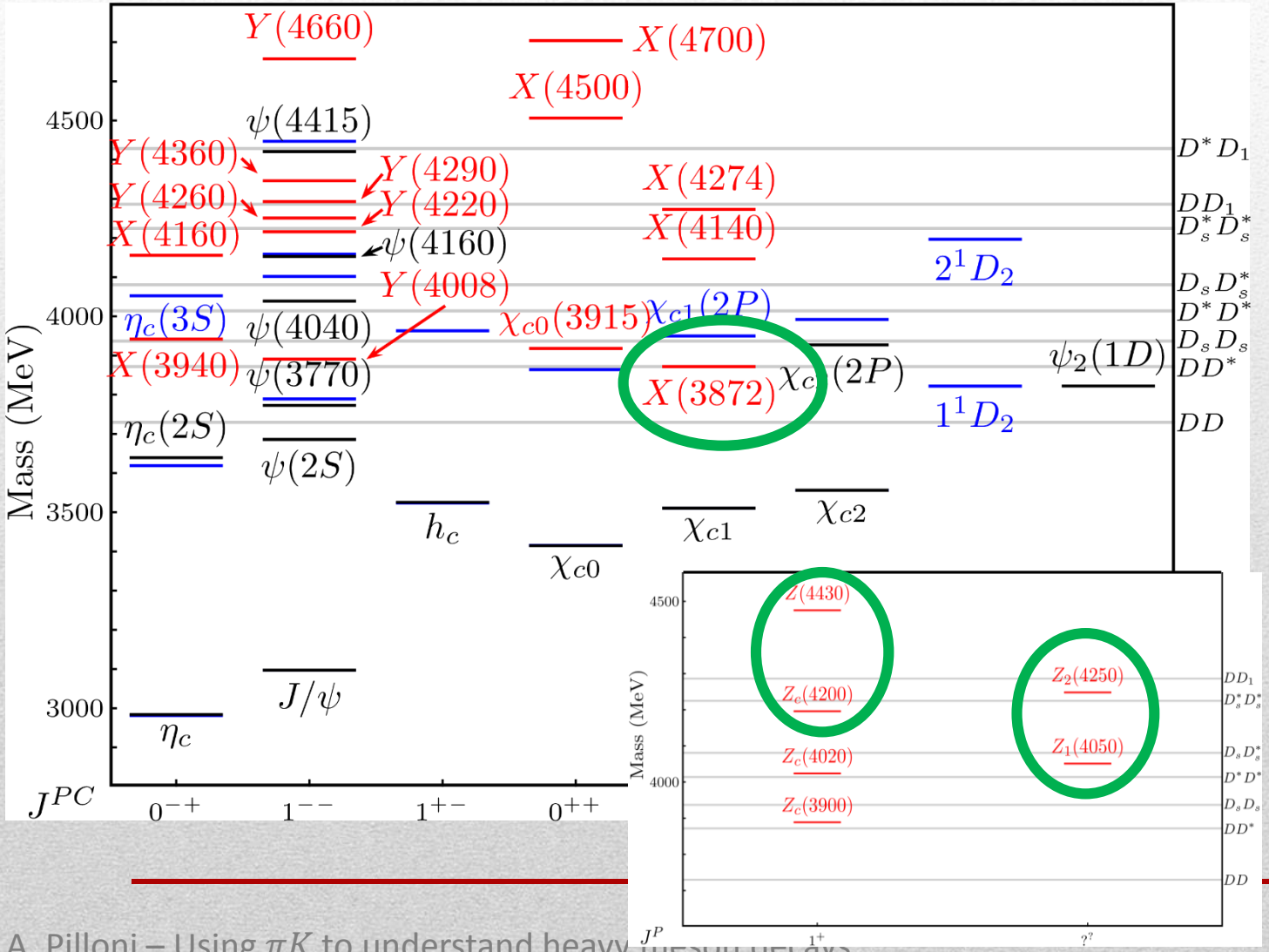
A host of unexpected resonances have appeared

decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

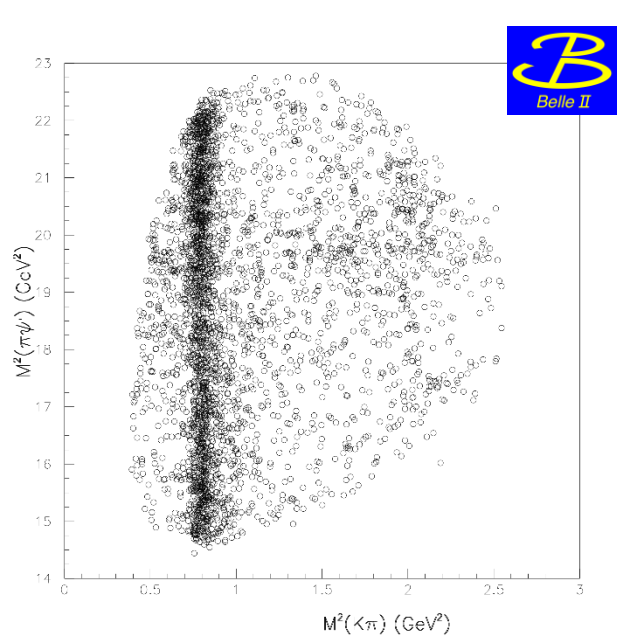
Exotic XYZ landscape

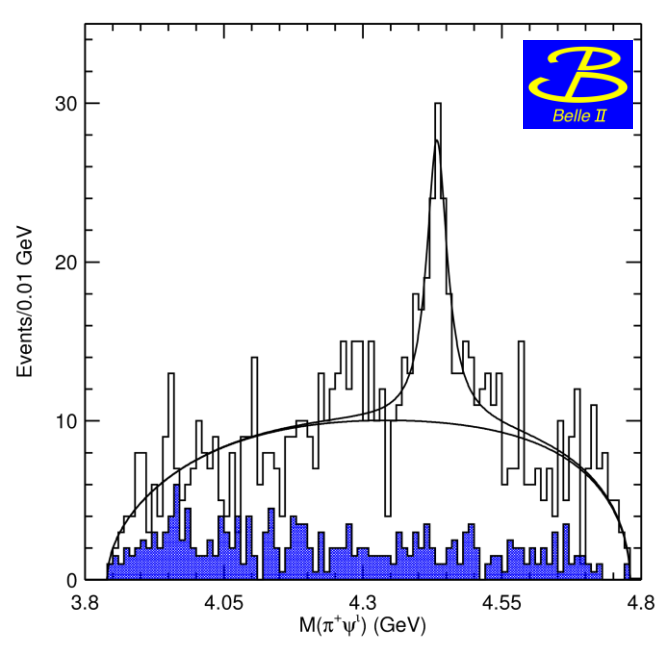
Esposito, AP, Polosa, Phys.Rept. 668



Several of them have been observed in $B \to (c\bar{c}\,\pi)K$ or $B \to (c\bar{c}\,\pi\pi)K$

The $Z(4430)$





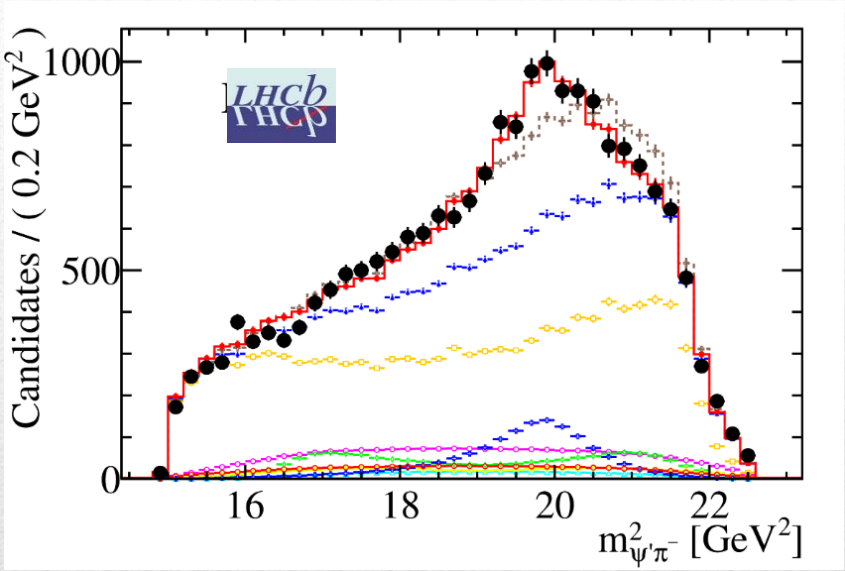
In 2007, Belle claimed the observation of an exotic charged charmoniumlike state in the $B^+ \to (\psi'\pi^-)K^+$ decay

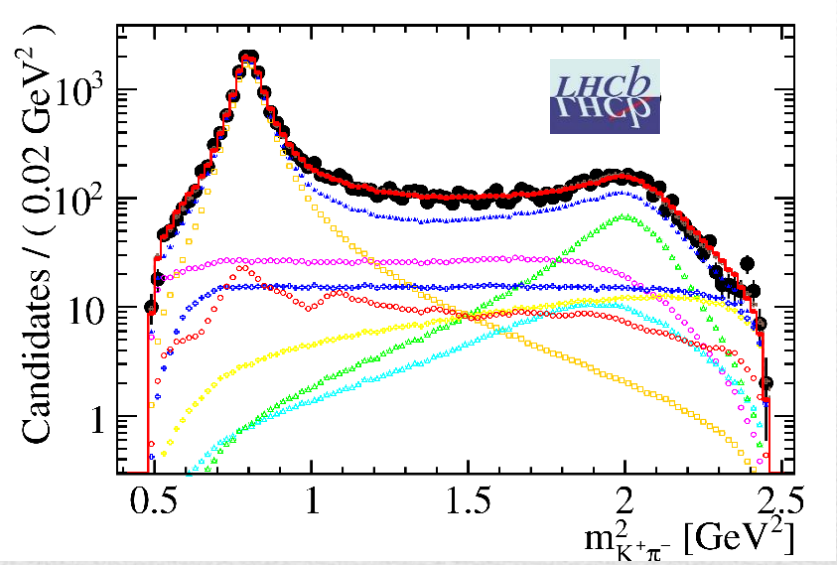
Belle, PRL100, 142001; PRD80, 031104; PRD88, 074026

BaBar did not confirm the observation

BaBar PRD79, 112001

The $Z(4430)$





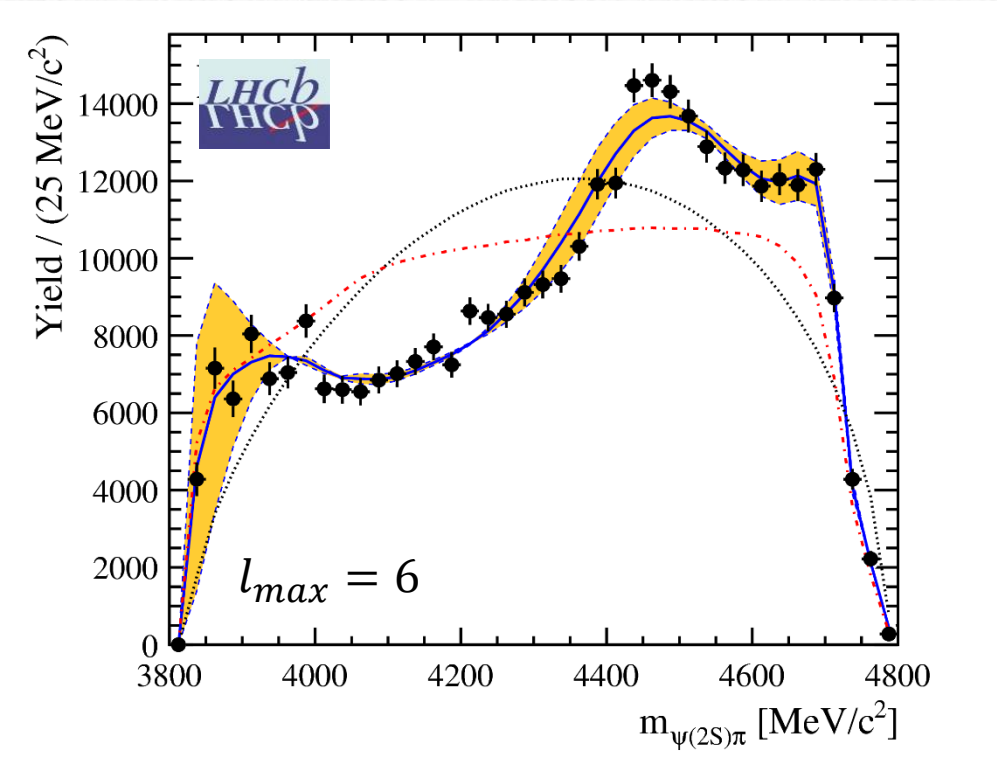
LHCb presented the full 4D analysis estimating a 14σ significance for an exotic Z

The structure of K^* is very rich

Resonance	Mass (MeV/c^2)	Γ (MeV/c^2)	J^P
$K^*(800)^0$	682±29	547±24	0^+
$K^*(892)^0$	895.81±0.19	47.4±0.6	1^-
$K^*(1410)^0$	1414±15	232±21	1^-
$K_0^*(1430)^0$	1425±50	270±80	0^+
$K_2^*(1430)^0$	1432.4±1.3	109±5	2^+
$K^*(1680)^0$	1717±27	322±110	1^-
$K_3^*(1780)^0$	1776±7	159±21	3^-

LHCb, PRL112, 222002

The $Z(4430)$



A model-independent analysis confirmed the need for an exotic component

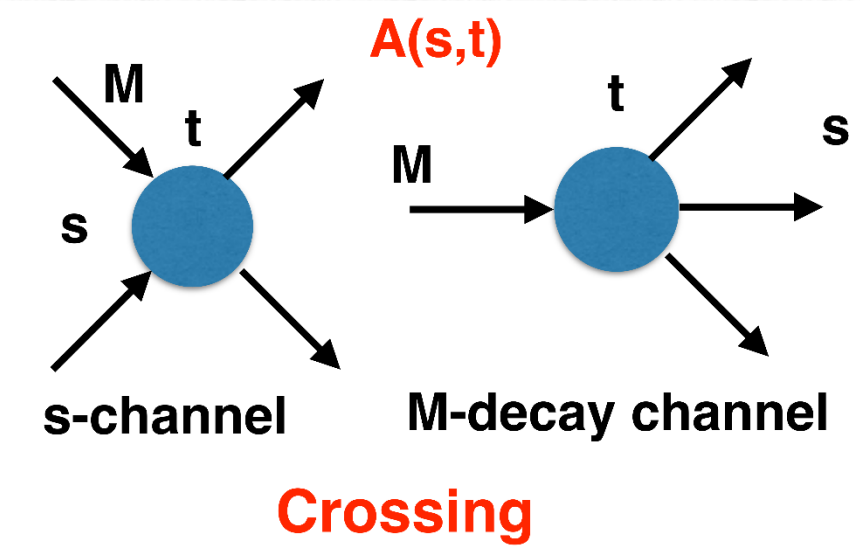
LHCb, PRD92, 112009

Caveat: the analysis is based on the expansion of the Dalitz plot in Legendre momenta, each one having contributions from infinite partial waves

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

$$M = 4475 \pm 7^{+15}_{-25}\ \text{MeV}$$
$$\Gamma = 172 \pm 13^{+37}_{-34}\text{MeV}$$

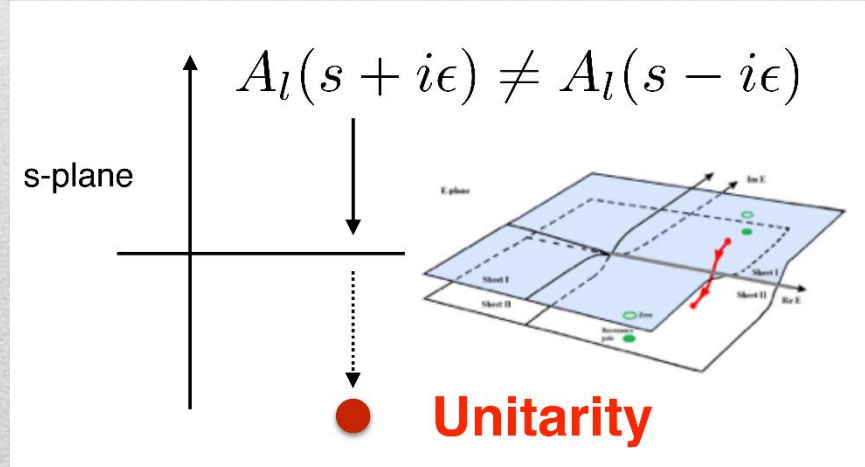
S-Matrix principles



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

Analyticity

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

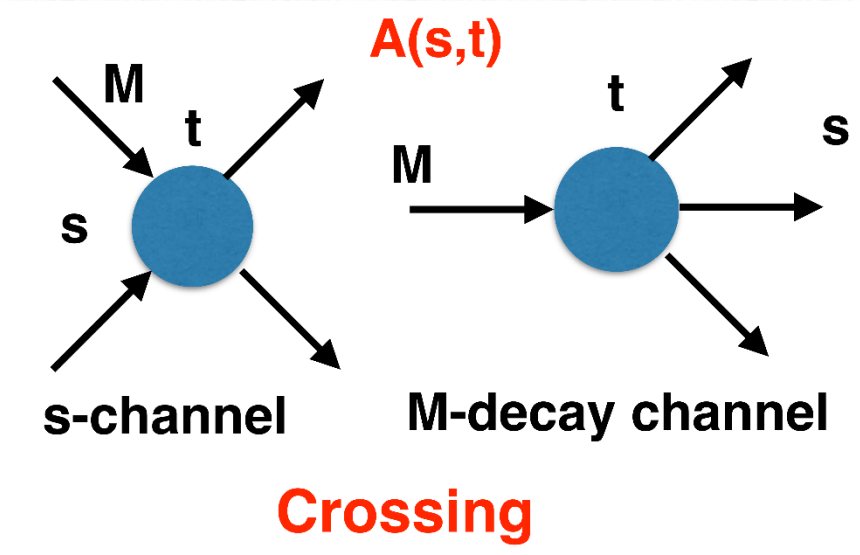


These are constraints the amplitudes have to satisfy, but do not fix the dynamics

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

See talk by B. Kubis

S-Matrix principles



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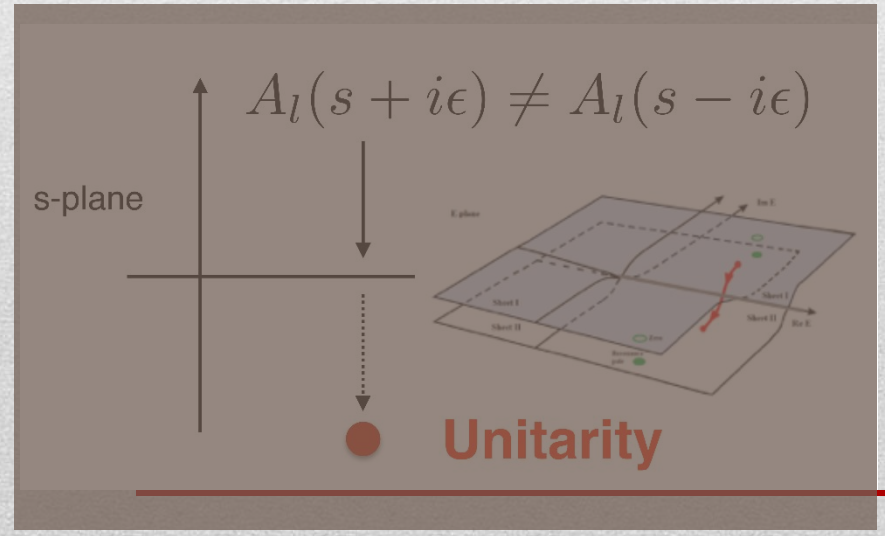

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See talk by B. Kubis

Recipes to build an amplitude

M. Mikhasenko, AP, J. Nys et al. (JPAC), arXiv:1712.02815

The literature abounds with discussions on the optimal approach to construct the amplitudes for the hadronic reactions

- Helicity formalism

  Jacob, Wick, Annals Phys. 7, 404 (1959)

- Covariant tensor formalisms

  Chung, PRD48, 1225 (1993)
  Chung, Friedrich, PRD78, 074027 (2008)
  Filippini, Fontana, Rotondi, PRD51, 2247 (1995)
  Anisovich, Sarantsev, EPJA30, 427 (2006)

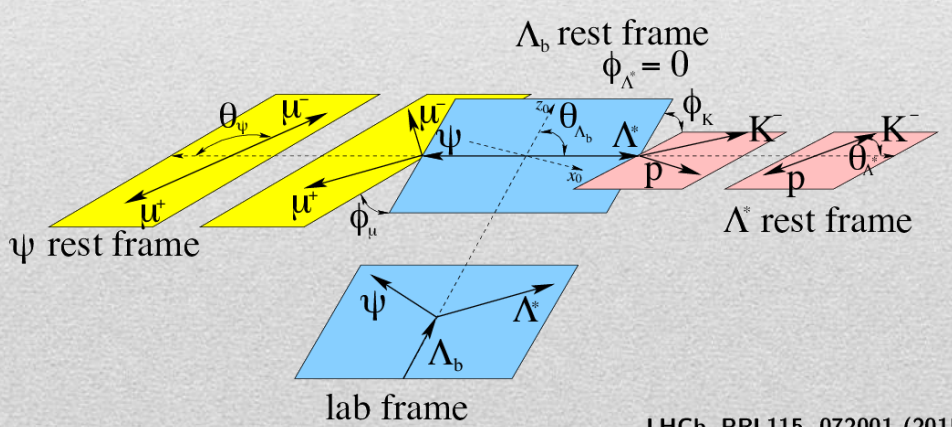
The common lore is that the former one is nonrelativistic, especially when expressed in terms of LS couplings and the latter takes into account the proper relativistic corrections

How helicity formalism works

- Helicity formalism enforces the constraints about rotational invariance
- It allows us to fix the angular dependence of the amplitude
- What about energy dependence?

Example: $B \to \psi K^* \to \pi K$

$$\mathcal{M}^{K^*}_{\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{K^*}} \sum_{\lambda_\psi} \mathcal{H}^{B\to K^*_n \psi}_{\lambda_{K^*},\,\lambda_\psi} \delta_{\lambda_{K^*},\lambda\psi}$$



LHCb. PRL115. 072001 (2015)

$$\mathcal{H}^{K^*_n \to K\pi} D^{J_{K^*_n}}_{\lambda_{K^*},\,0}(\phi_K, \theta_{K^*}, 0)^* \; R_{K^*{}_n}(m_{K\pi}) D^1_{\lambda_\psi,\,\Delta\lambda_\mu}(\phi_\mu, \theta_\psi, 0)^*,$$

Each set of angles is defined in a different reference frame

How tensor formalism works

The method is based on the construction of explicitly covariant expressions.

- To describe the decay $a \to bc$, we first consider the polarization tensor of each particle, $\varepsilon^{i}_{\mu_1 \ldots \mu_{j_i}}(p_i)$
- We combine the polarizations of b and c into a "total spin" tensor $S_{\mu_1 \ldots \mu_S}(\varepsilon_b, \varepsilon_c)$
- Using the decay momentum, we build a tensor $L_{\mu_1 \ldots \mu_L}(p_{bc})$ to represent the orbital angular momentum of the bc system, orthogonal to the total momentum of p_a
- We contract S and L with the polarization of a

Tensor $\times R_X(m)$ which contain resonances and form factors

What do we know?

- Energy dependence is not constrained by symmetry
- Still, there are some known properties one can enforce

$$R_X(m) = B'_{L^X_{\Lambda_b^0}}(p, p_0, d)\left(\frac{p}{M_{\Lambda_b^0}}\right)^{L^X_{\Lambda_b^0}}$$

$$\mathrm{BW}(m|M_{0X}, \Gamma_{0X})\, B'_{L_X}(q, q_0, d)\left(\frac{q}{M_{0X}}\right)^{L_X}$$

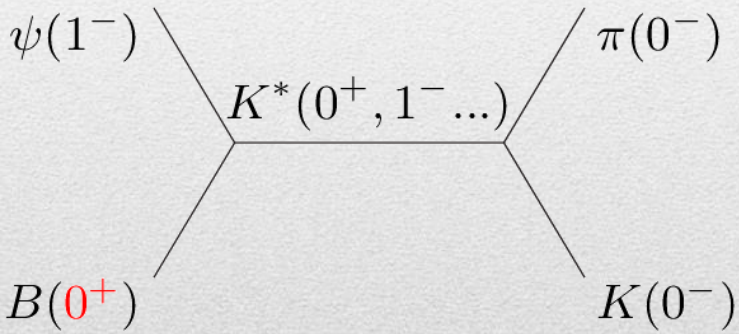
- Kinematical singularities: e.g. barrier factors (known)
- Left hand singularities (need model, e.g. Blatt-Weisskopf)
- Right hand singularities = resonant content (Breit Wigner, K-matrix...)

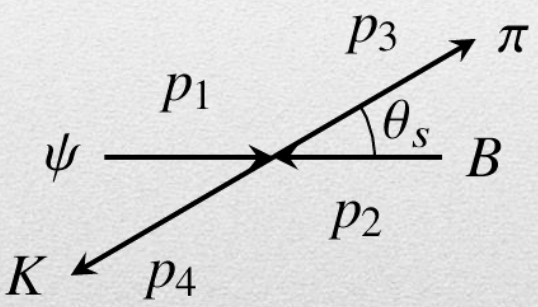
Kinematics

- Kinematical singularities appear because of the spin of the external particle involved
- We can write the most general covariant parametrization of the amplitude as
  tensor of external polarizations $\otimes$ scalar amplitudes
- Scalar amplitudes must be kinematical singularities free
- They can be matched to the helicity amplitudes
- We can get the minimal energy dependent factor
- Any other additional energy factor would be model-dependent

$B \to \psi\, \pi K$

To consider the effect of spin, let's consider $B \to \psi \pi K$
We focus on the parity violating amplitude for the K^* isobars, scattering kinematics





$$p = \text{incoming 3-momentum in the COM} = \frac{\lambda_{12}^{1/2}}{2\sqrt{s}}$$

$$= \frac{\sqrt{[s-(m_1+m_2)^2]\,[s-(m_1-m_2)^2]}}{2\sqrt{s}}$$

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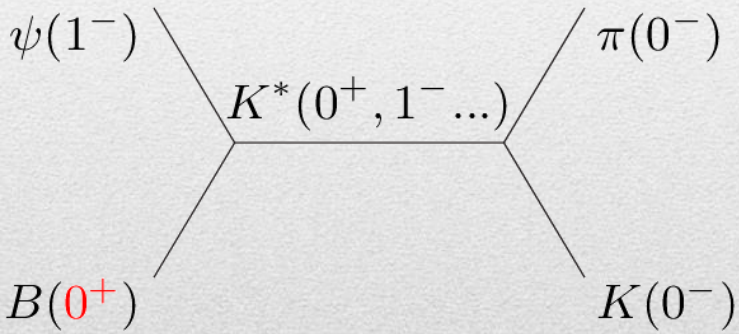

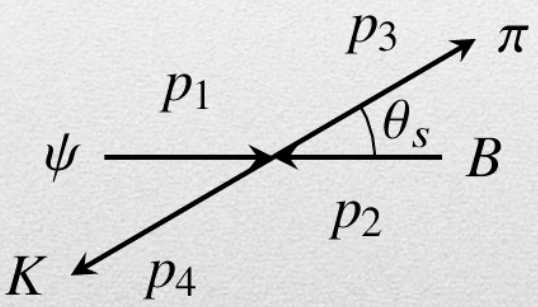

$$q = \text{outgoing 3-momentum in the COM} = \frac{\lambda_{34}^{1/2}}{2\sqrt{s}}$$

$$= \frac{\sqrt{[s-(m_3+m_4)^2]\,[s-(m_3-m_4)^2]}}{2\sqrt{s}}$$

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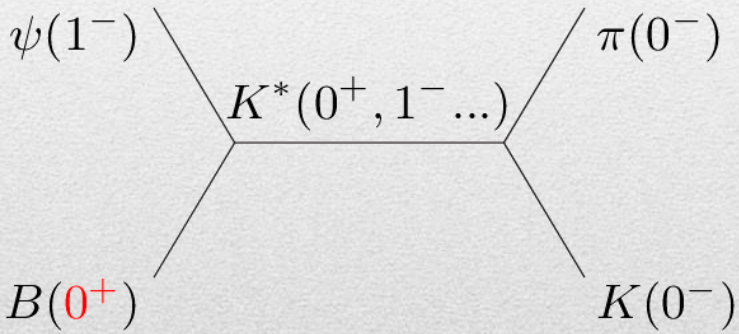
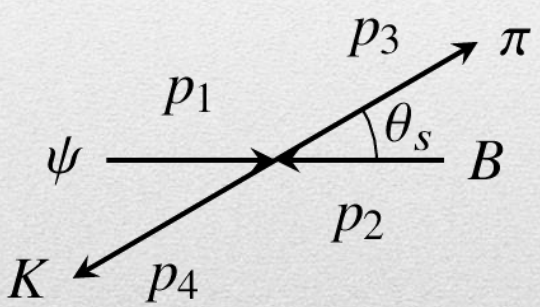




z_s = cosine of the scatt. angle in the COM

$$= \frac{s(t-u) + (m_1^2 - m_2^2)(m_3^2 - m_4^2)}{\lambda_{12}^{1/2}\lambda_{34}^{1/2}} = \frac{\text{polynomial}}{\lambda_{12}^{1/2}\lambda_{34}^{1/2}}$$

Helicity amplitudes

$$A_\lambda = \frac{1}{4\pi} \sum_{j=|\lambda|}^{\infty} (2j+1) A^j_\lambda(s)\, d^j_{\lambda 0}(z_s)$$

$$d^j_{\lambda 0}(z_s) = \hat{d}^j_{\lambda 0}(z_s) \xi_{\lambda 0}(z_s), \qquad \xi_{\lambda 0}(z_s) = \left(\sqrt{1 - z_s^2}\right)^\lambda$$

$\hat{d}^j_{\lambda 0}(z_s)$ is a polynomial of order $j - |\lambda|$ in z_s,
The kinematical singularities of $A^j_\lambda(s)$ can be isolated by writing

$$A^j_0 = \frac{m_1}{p\sqrt{s}}\, (pq)^j\ \hat{A}^j_0 \qquad \text{for } j \geq 1,$$

$$A^j_\pm = q\ (pq)^{j-1}\ \hat{A}^j_\pm \qquad \text{for } j \geq 1,$$

$$A^0_0 = \frac{p\sqrt{s}}{m_1}\, \hat{A}^0_0 \qquad \text{for } j = 0,$$

Identify covariants

Two helicity couplings $\rightarrow$ two independent covariant structures

Important: we are not imposing any intermediate isobar

$$A_\lambda(s,t) = \varepsilon_\mu(\lambda, p_1)\left[(p_3 - p_4)^\mu - \frac{m_3^2 - m_4^2}{s}(p_3 + p_4)^\mu\right] C(s,t)$$
$$+ \varepsilon_\mu(\lambda, p_1)(p_3 + p_4)^\mu B(s,t)$$

$$C(s,t) = \frac{1}{4\pi\sqrt{2}} \sum_{j>0} (2j+1)(pq)^{j-1} \hat{A}_+^j(s)\, \hat{d}_{10}^j(z_s)$$

$$B(s,t) = \frac{1}{4\pi}\hat{A}_0^0 + \frac{1}{4\pi}\frac{4m_1^2}{\lambda_{12}} \sum_{j>0} (2j+1)(pq)^j \left[\hat{A}_0^j(s)\hat{d}_{00}^j(z_s) + \frac{s + m_1^2 - m_2^2}{\sqrt{2}m_1^2}\hat{A}_+^j(s)\, z_s \hat{d}_{10}^j(z_s)\right]$$

Everything looks fine but the λ_{12} in the denominator

The brackets must vanish at $\lambda_{12} = 0 \Rightarrow s = s_\pm = (m_1 \pm m_2)^2$,

$\hat{A}_+^j$ and $\hat{A}_0^j$ cannot be independent

General expression and comparison

$$\hat{A}^j_+ = \langle j-1,0;1,1|j,1\rangle g_j(s) + f_j(s)$$

$$\hat{A}^j_0 = \langle j-1,0;1,0|j,0\rangle \frac{s+m_1^2-m_2^2}{2m_1^2} g_j'(s) + f_j'(s)$$

$g_j(s_\pm) = g_j'(s_\pm)$, and $f_j(s), f_j'(s) \sim O(s-s_\pm)$
All these four functions are free of kinematic singularity.

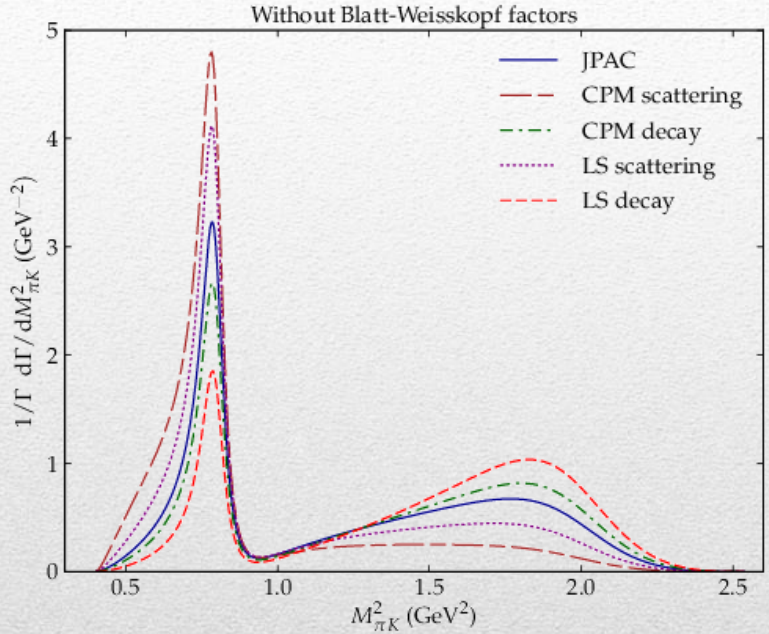
Comparison with tensor formalisms ($j=1$)

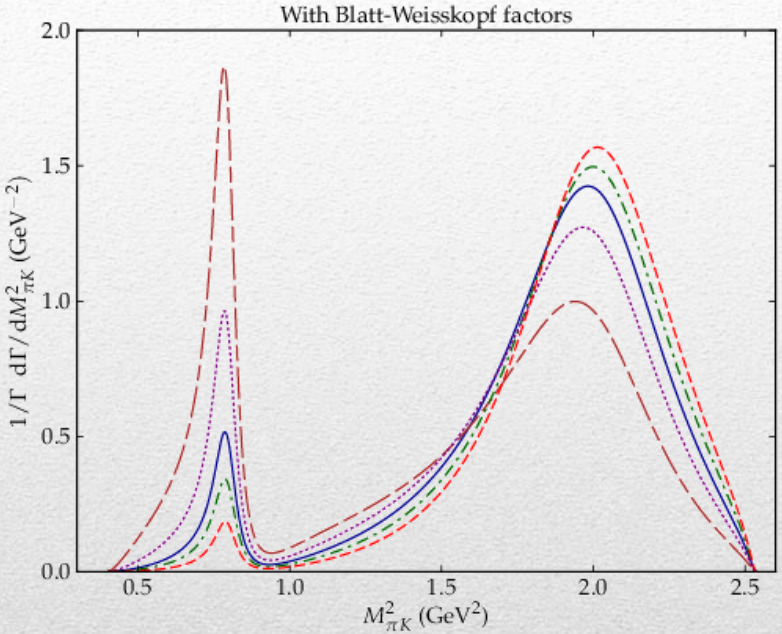
$$g_1 = g_1' = \frac{4\pi}{3} g_S, \quad f_1 = \frac{2\pi\lambda_{12}}{3s} g_D, \quad f_1' = -\frac{4\pi\lambda_{12}}{3s}\frac{s+m_1^2-m_2^2}{m_1^2} g_D.$$

If the g_S, g_D are the usual Breit-Wigner, the g', f' are fine

There is no unique recipe to build the right amplitude, but one can ensure the right singularities to be respected

General expression and comparison





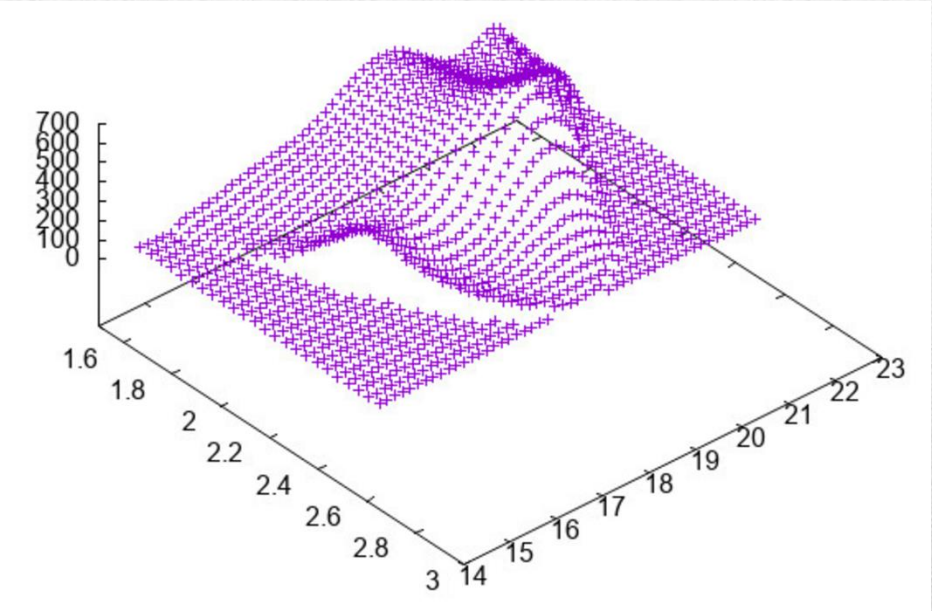
We consider the example of two intermediate $K^*(892)$ and $K^*(1410)$

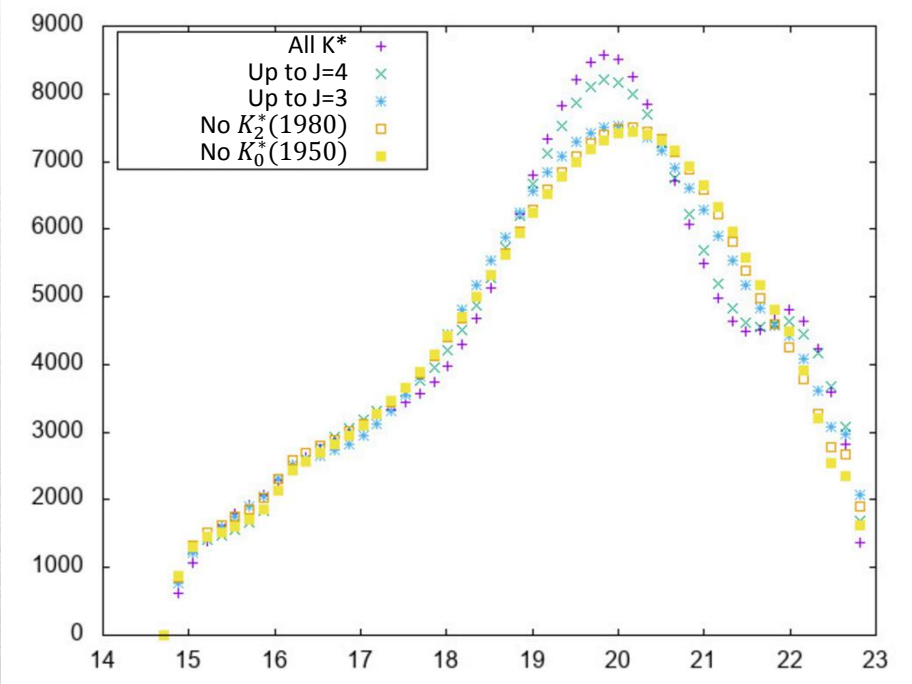
We set $g_S(s) = 0$ and $g_D(s) =$ sum of Breit-Wigner

For the plot on the right we multiply the amplitudes by the Blatt-Weisskopf barrier factors

Playing with fits

Disclaimer: The following fits are just qualitative, based on fits on 2D Dalitz plots. This is to estimate the model dependence





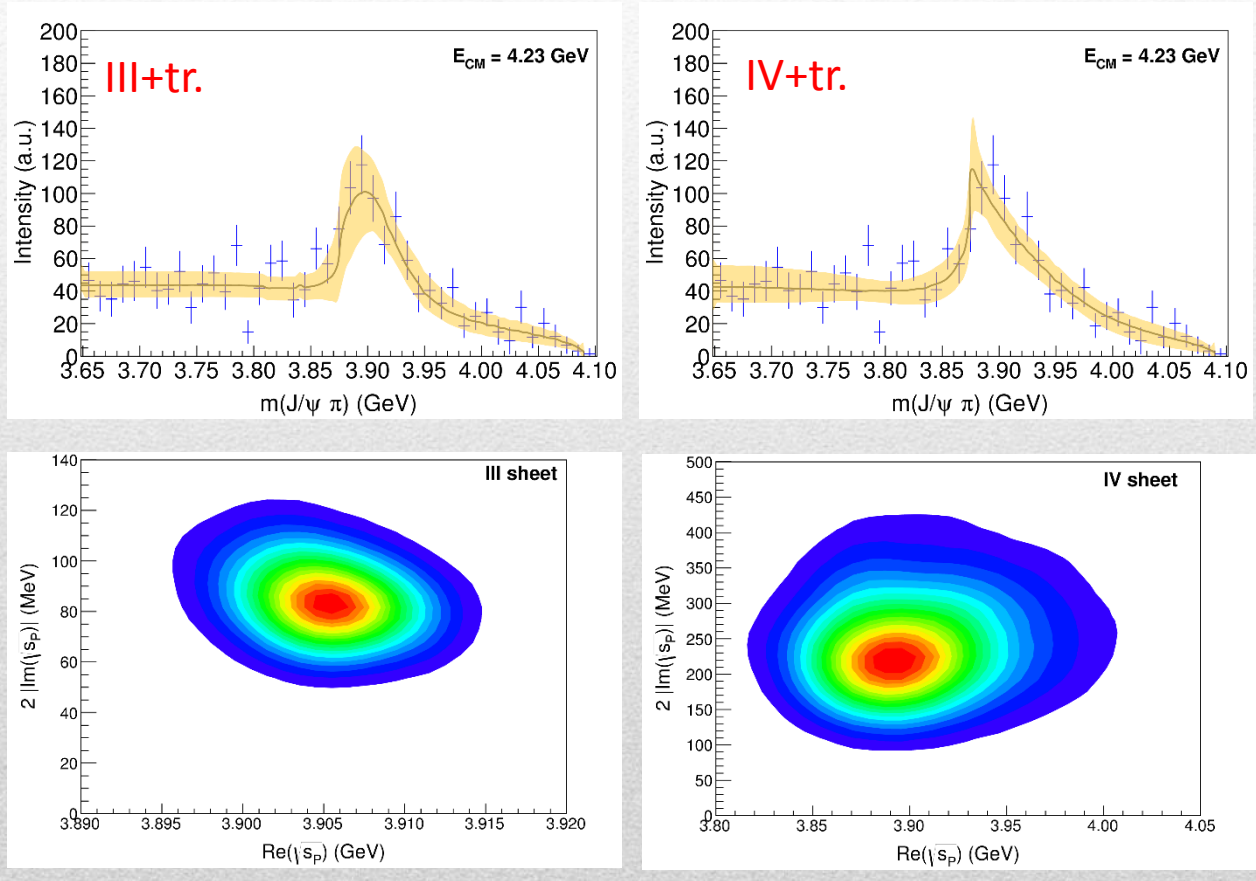
Using the JPAC model & adding higher spin resonances reproduces a peak similar to the $Z(4430)$

Model dependence and physics

Understanding the model dependence is mandatory: models with similar fit qualities can lead to dramatically different physical interpretations

E.g. $e^+e^- \to J/\psi\,\pi\pi$ and the $Z_c(3900)$

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



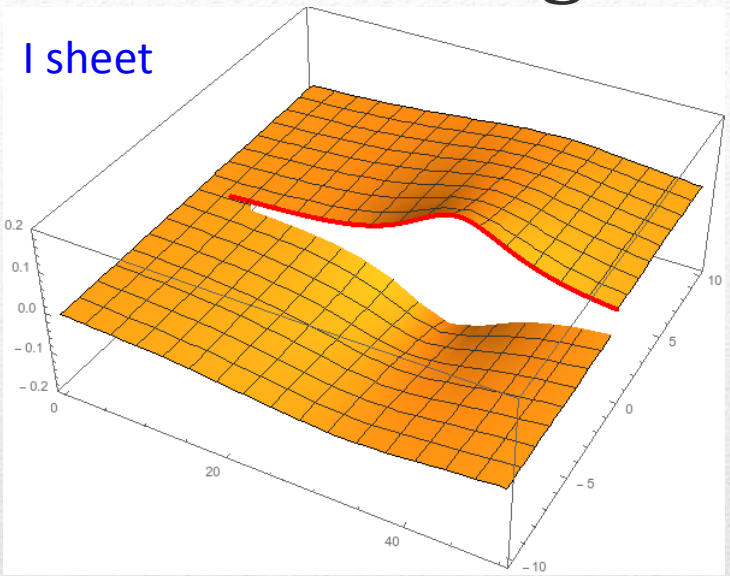
Conclusions

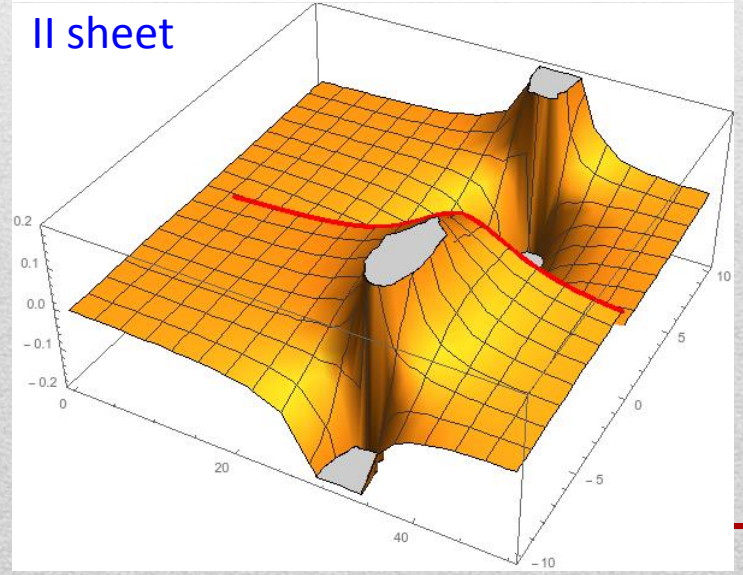
- The knowledge of $K\pi$ interactions is not only important *per se*, but it can help constrain the XYZ sector
- Several states observed in B decays involving $K\pi$ or $K\pi\pi$ and charmonium
  - $X(3872)$, $Z(4430)$, $Z(4200)$, $Z(4050)$, $Z(4250)$
- Despite the high significance, the systematic due to the model dependence is often not estimated
- Approaches *à la* Khuri-Treiman allow for the direct implementation of partial waves into these analyses
- More «exotic» descriptions based on dual models can also give a complementary insights on the behavior of the Dalitz plots

Thank you!

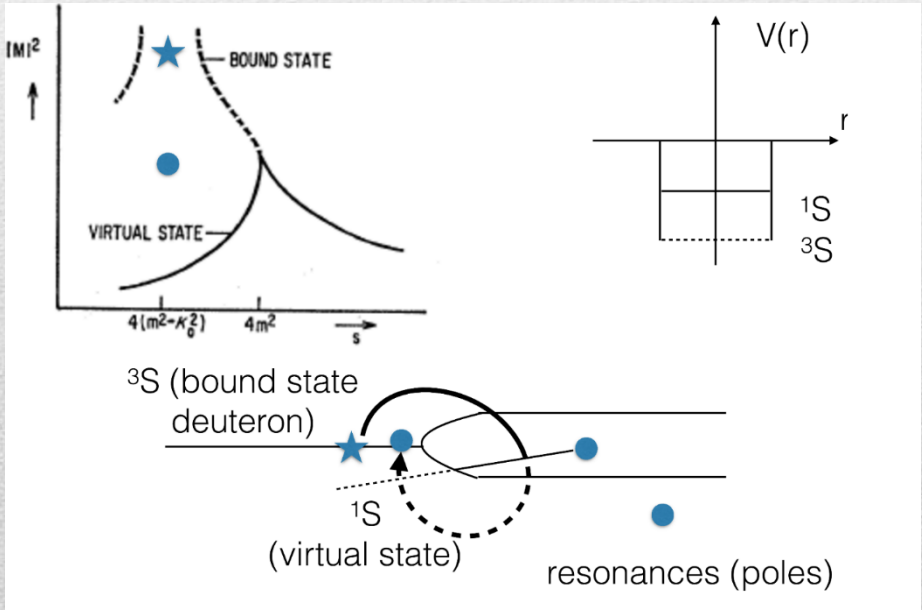
BACKUP

Pole hunting

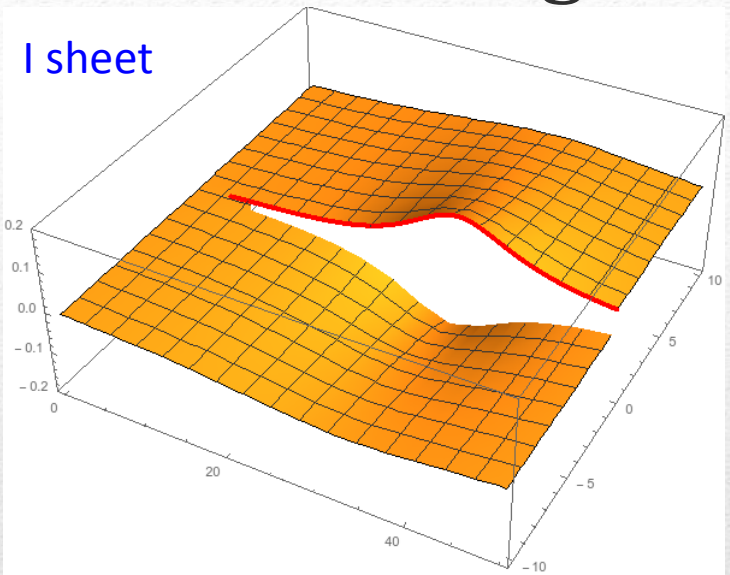


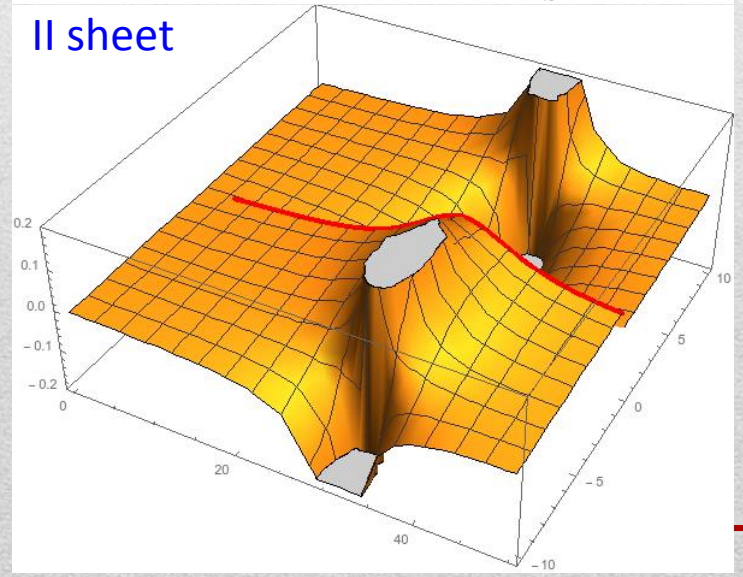


Bound states on the real axis 1st sheet
Not-so-bound (virtual) states on the real axis 2nd sheet



Pole hunting

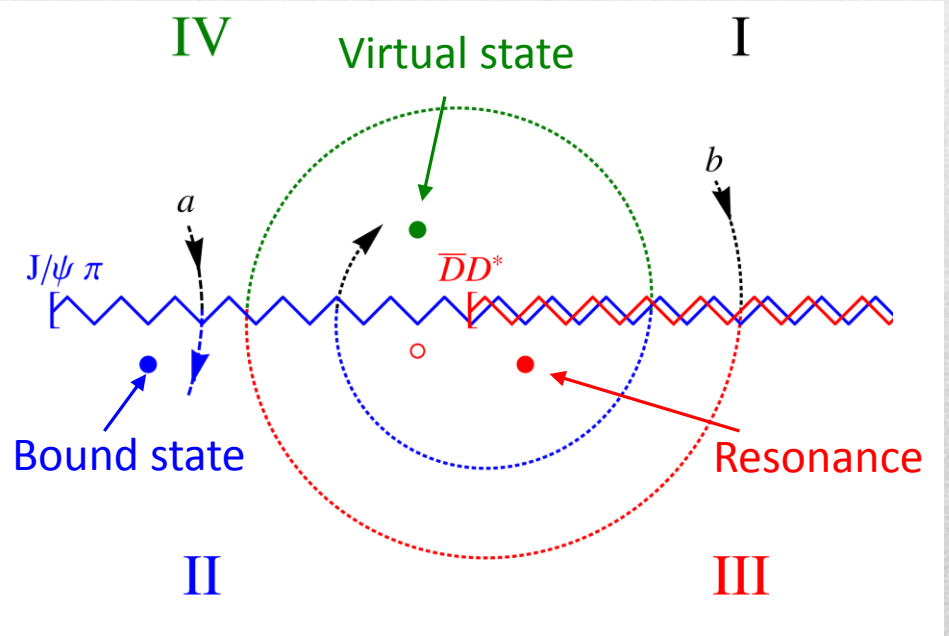




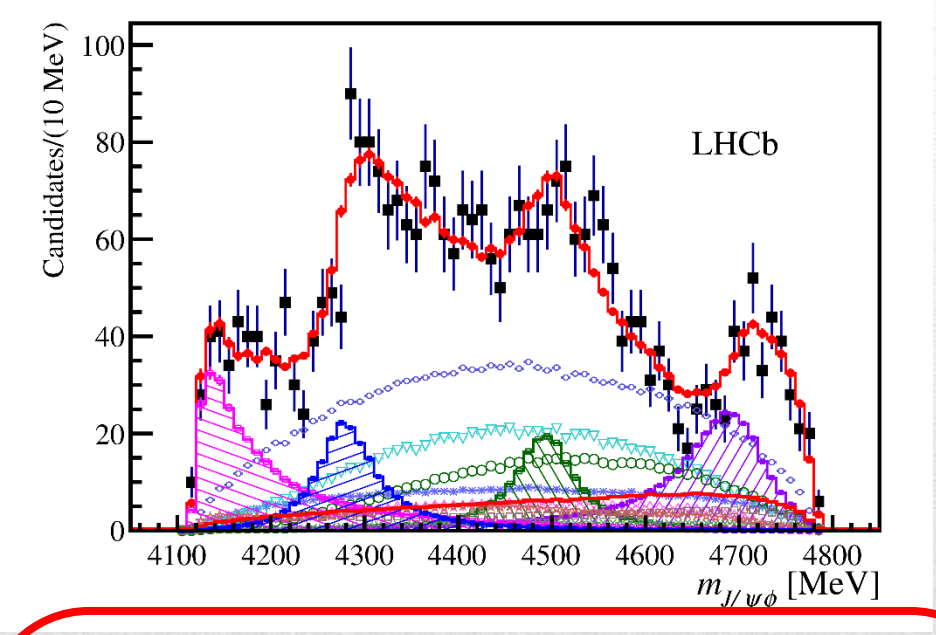
More complicated structure when more thresholds arise: two sheets for each new threshold

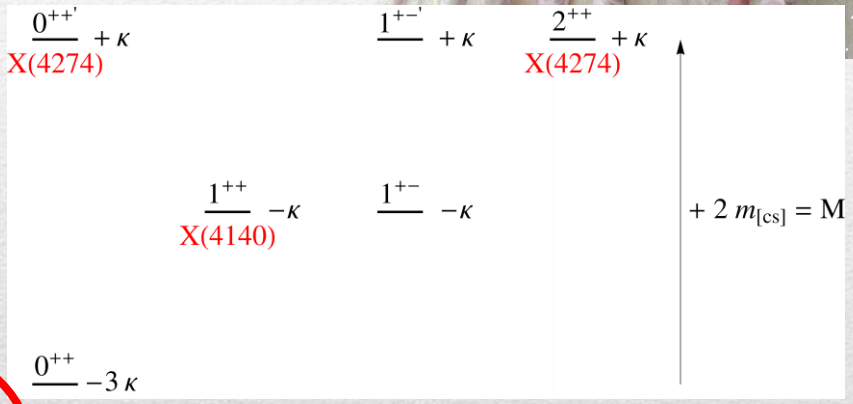
III sheet: usual resonances

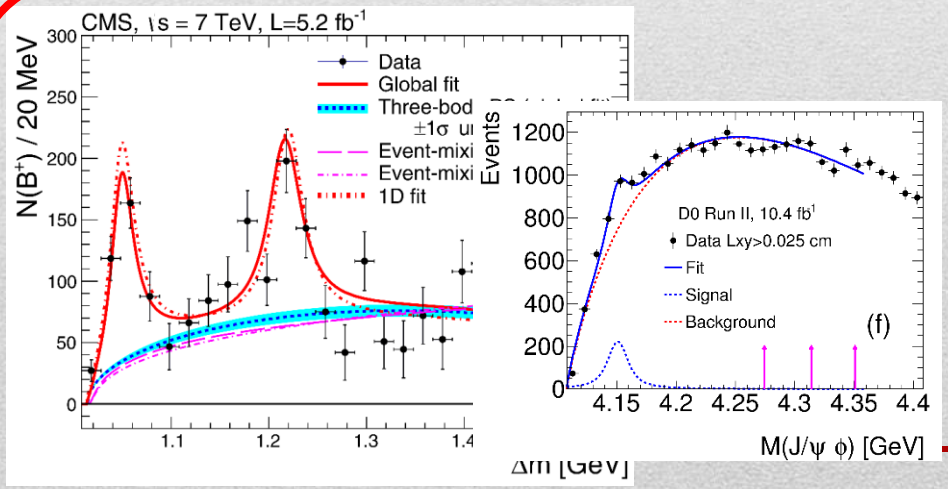
IV sheet: cusps (virtual states)



Tetraquark: the $c\bar{c}s\bar{s}$ states







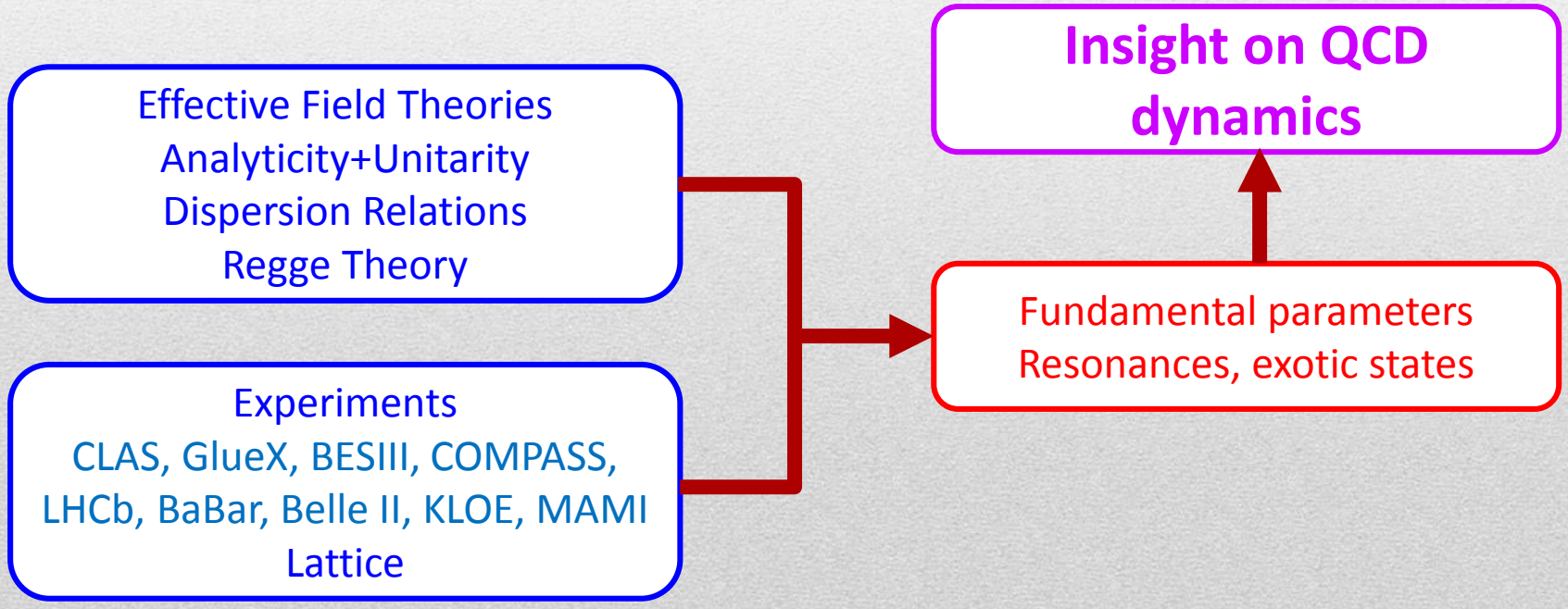
Good description of the spectrum **but** one has to assume the axial assignment for the $X(4274)$ to be incorrect (two unresolved states with 0^{++} and 2^{++})

Maiani, Polosa and Riquer, PRD 94, 054026

Much narrower than LHCb! Look for prompt!

Joint Physics Analysis Center

- Joint effort between theorists and experimentalists to work together to make the best use of the next generation of very precise data taken at JLab and in the world
- Created in 2013 by JLab & IU agreement
- It is engaged in education of further generations of hadron physics practitioners



Strategy

AP *et al.* (JPAC), arXiv:1612.06490

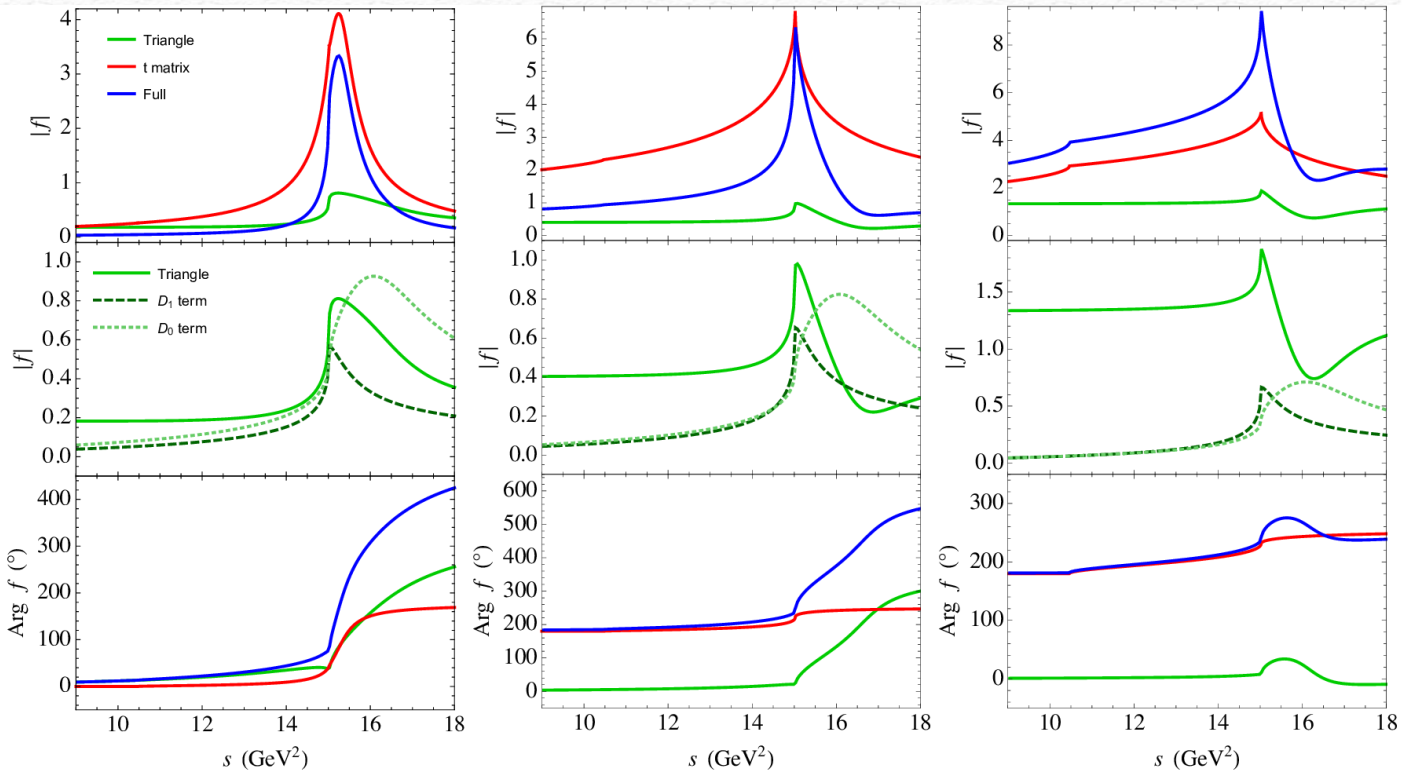
- We fit the following invariant mass distributions:
  - BESIII PRL110, 252001 $J/\psi\,\pi^+, J/\psi\,\pi^-, \pi^+\pi^-$ at $E_{CM} = 4.26$ GeV
  - BESIII PRL110, 252001 $J/\psi\,\pi^0$ at $E_{CM} = 4.23, 4.26,$ ~~4.36~~ GeV
  - BESIII PRD92, 092006 $\overline{D^0}D^{*+}, \overline{D^{*0}}D^+$ (double 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

AP *et al.* (JPAC), arXiv:1612.06490

- 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

Lineshapes at 4260



(a) III+tr. (b) IV+tr. (c) tr.

Figure 7: Interplay of scattering amplitude poles and triangle singularity to reconstruct the peak. We focus on the $J/\psi\pi$ channel, at $E_{CM} = 4.26$ GeV. The red curve is the t_{12} scattering amplitude, the green curve is the $c_1 + H(s, D_1) + +H(s, D_0)$ term in Eq. (9), and the blue curve is the product of the two. The upper plots show the magnitudes of these terms, the lower plots the phases. The middle row shows the contributions to the unitarized term due to the D_1 (dashed) and the D_0 (dotted). Only for D_1 the singularity is close enough to the physical region to generate a large peak. (a) The pole on the III sheet generates a narrow Breit-Wigner-like peak. The contribution of the triangle is not particularly relevant. (b) The sharp cusp in the scattering amplitude is due to the IV sheet pole close by; the triangle contributes to make the peak sharper. (c) The scattering amplitude has a small cusp due to the threshold factor, and the triangle is needed to make it sharp enough to fit the data.

Lineshapes at 4230

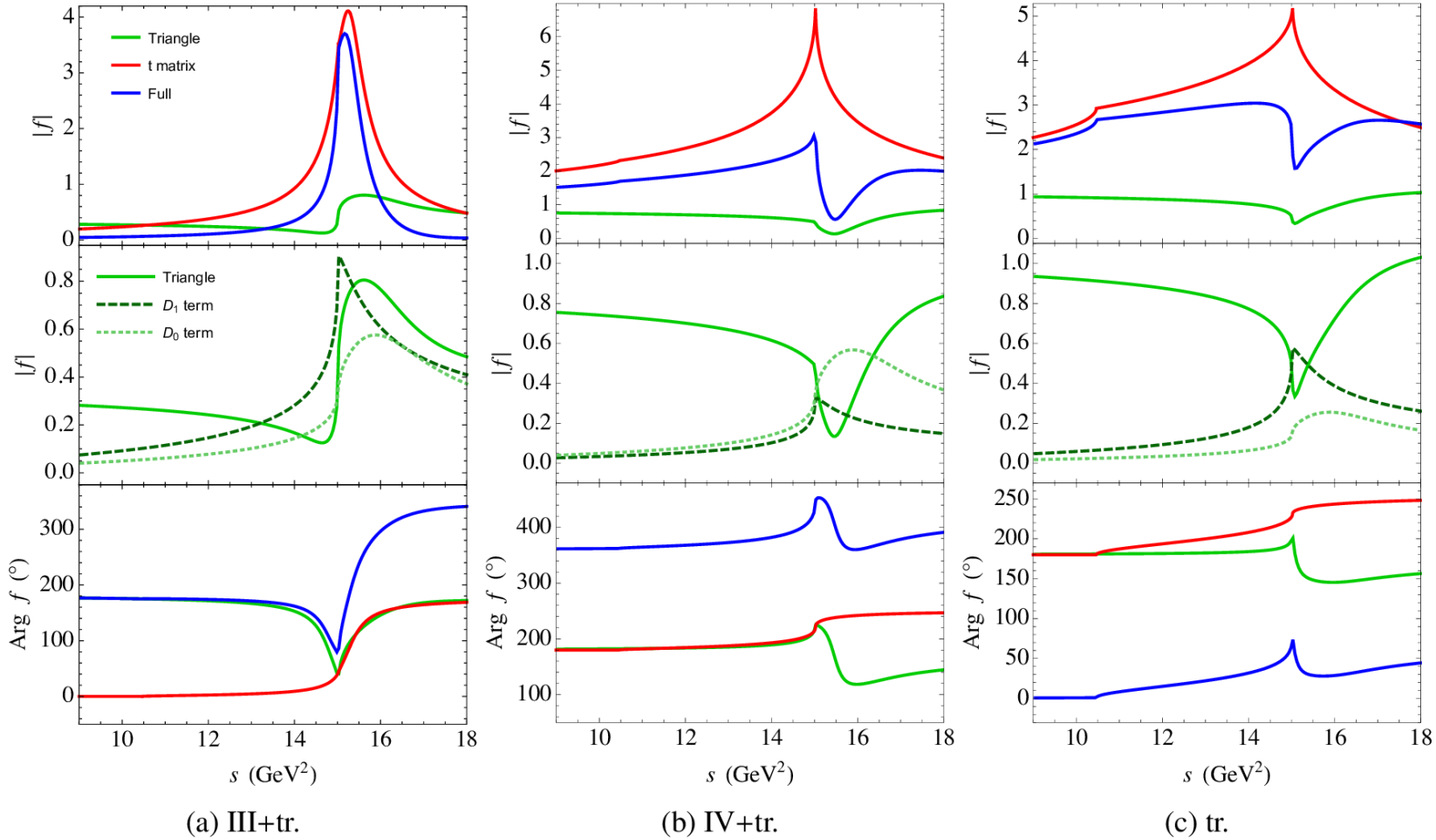
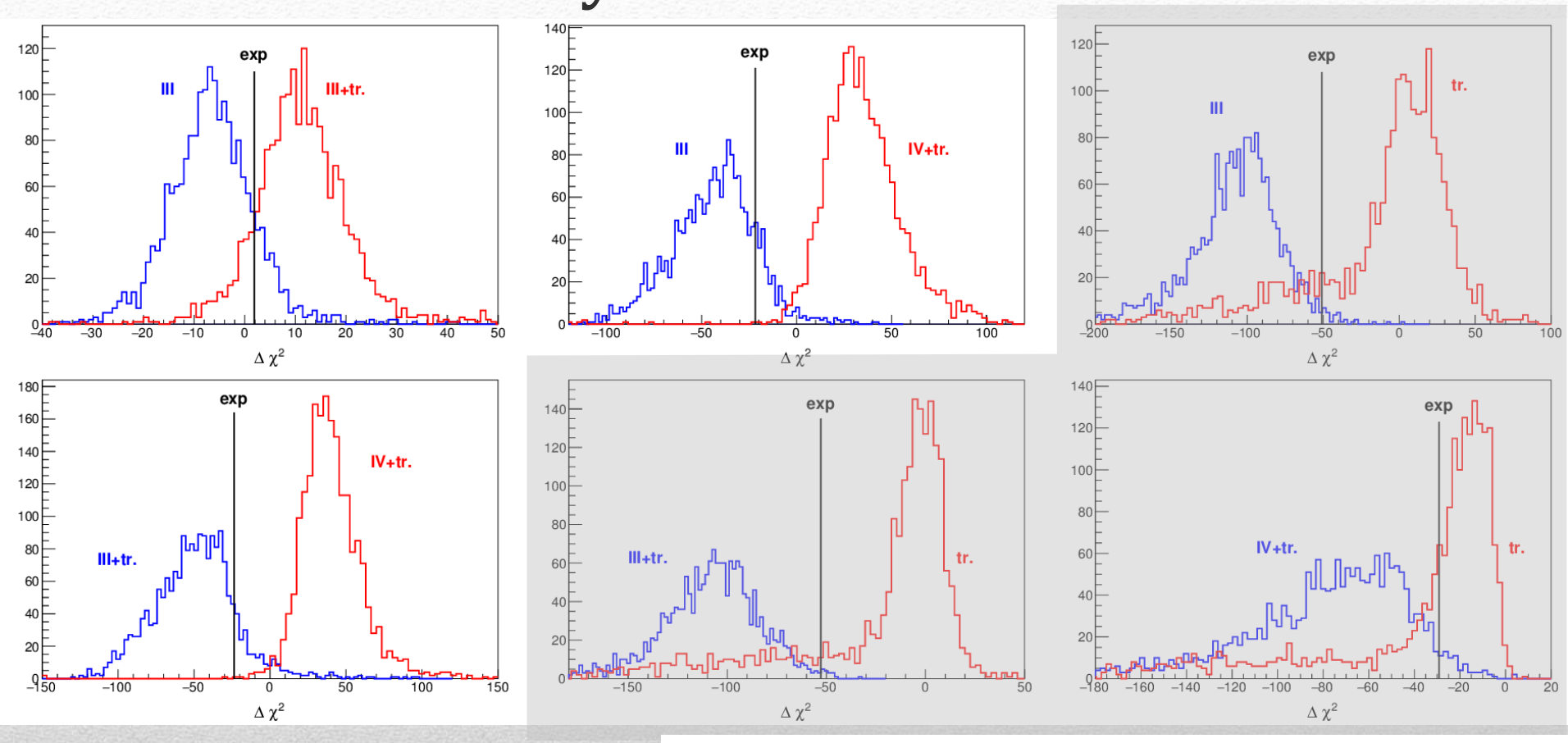


Figure 8: Same as Figure 7, but for E_{CM} = 4.23 GeV.

Statistical analysis



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

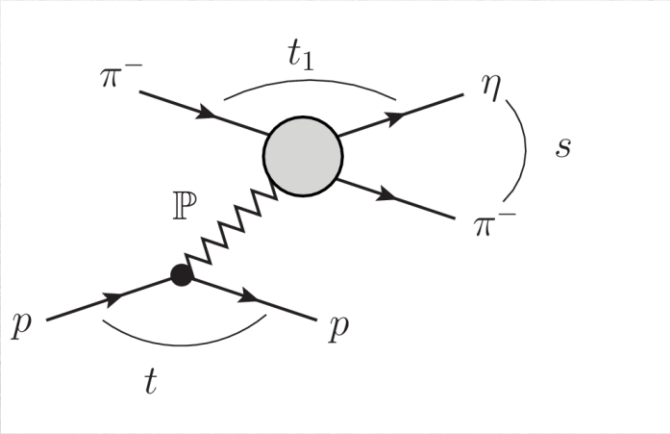
Scenario	III+tr.	IV+tr.	tr.
III	1.5σ (1.5σ)	1.5σ (2.7σ)	"2.4σ" ("1.4σ")
III+tr.	–	1.5σ (3.1σ)	"2.6σ" ("1.3σ")
IV+tr.			"2.1σ" ("0.9σ")

Not conclusive at this stage

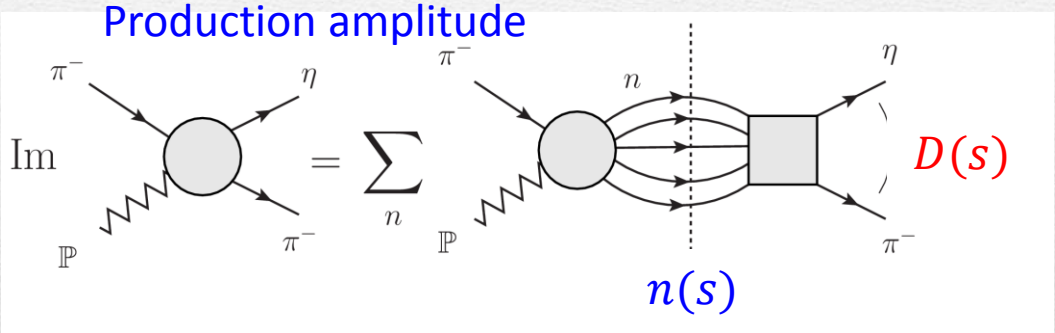
Searching for resonances in $\eta\pi$

- The $\eta\pi$ system is one of the golden modes for hunting hybrid mesons
- We build the partial waves amplitude according to the N/D method

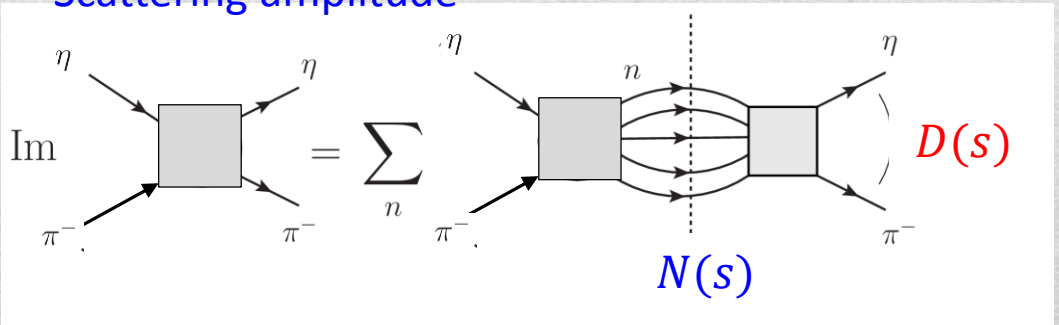
A. Jackura, *et al.* (JPAC & COMPASS), 1707.02848



Production amplitude



Scattering amplitude



The denominator $D(s)$ contains all the Final State Interactions constrained by unitarity → universal

The numerator $n(s)$ depends on the exchanges → process-dependent, smooth

Searching for resonances in $\eta\pi$

The denominator $D(s)$ contains all the FSI constrained by unitarity → universal

$$D(s)_{ij} = (K^{-1})_{ij}(s) - \frac{s}{\pi}\int_{s_i}^{\infty} \frac{\rho_i(s')N_{ij}(s')}{s'(s'-s)}ds'$$

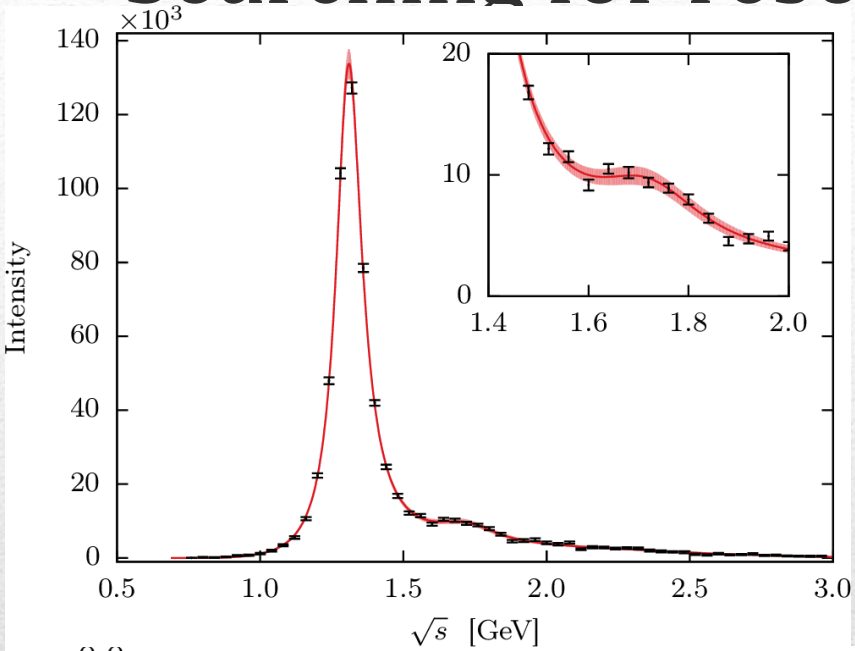
$$K_{ij}(s) = \sum_R \frac{g_i^R g_j^R}{M_R^2 - s}$$

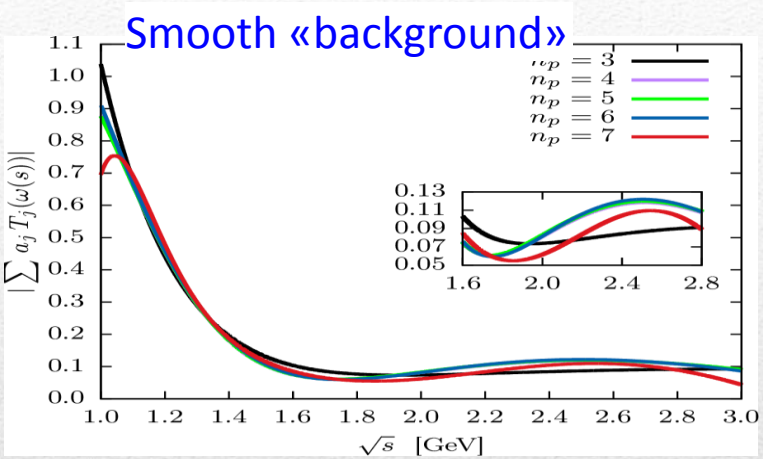
Standard K matrix, with usual trick for vanishing determinant

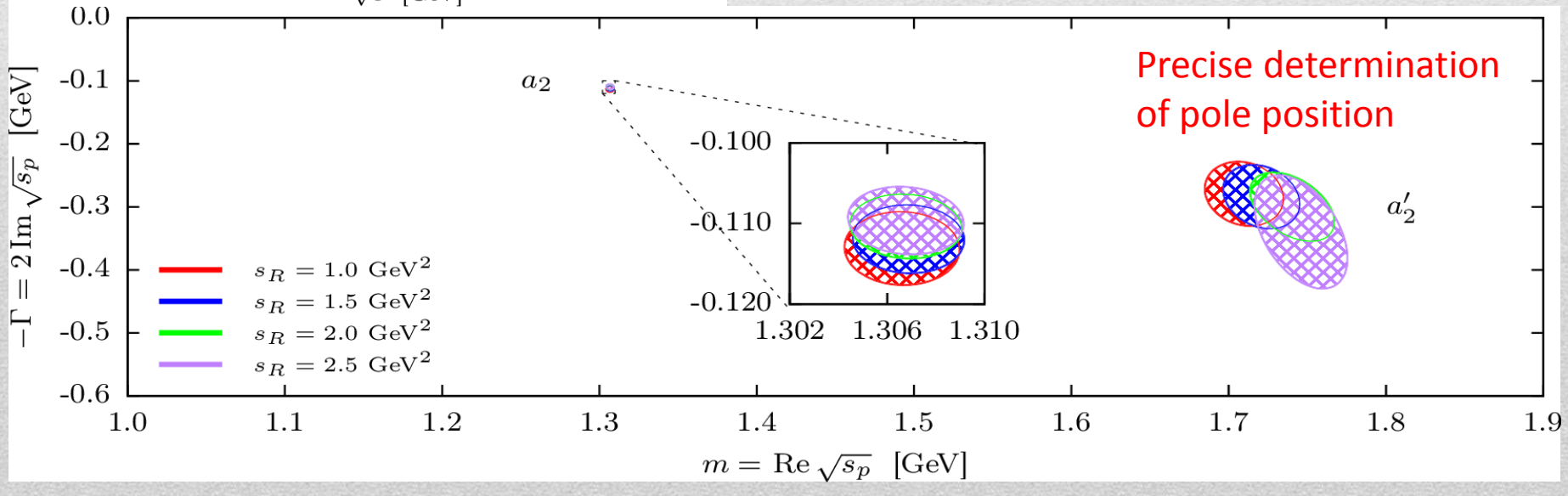
The numerator $n(s)$ depends on the exchanges → process-dependent, smooth

$$\rho_i(s)N_{ij}(s) = \frac{\lambda^{(2l+1)/2}\left(s, m_\pi^2, m_\eta^2\right)}{(s+\Lambda)^7}$$

Searching for resonances in $\eta\pi$

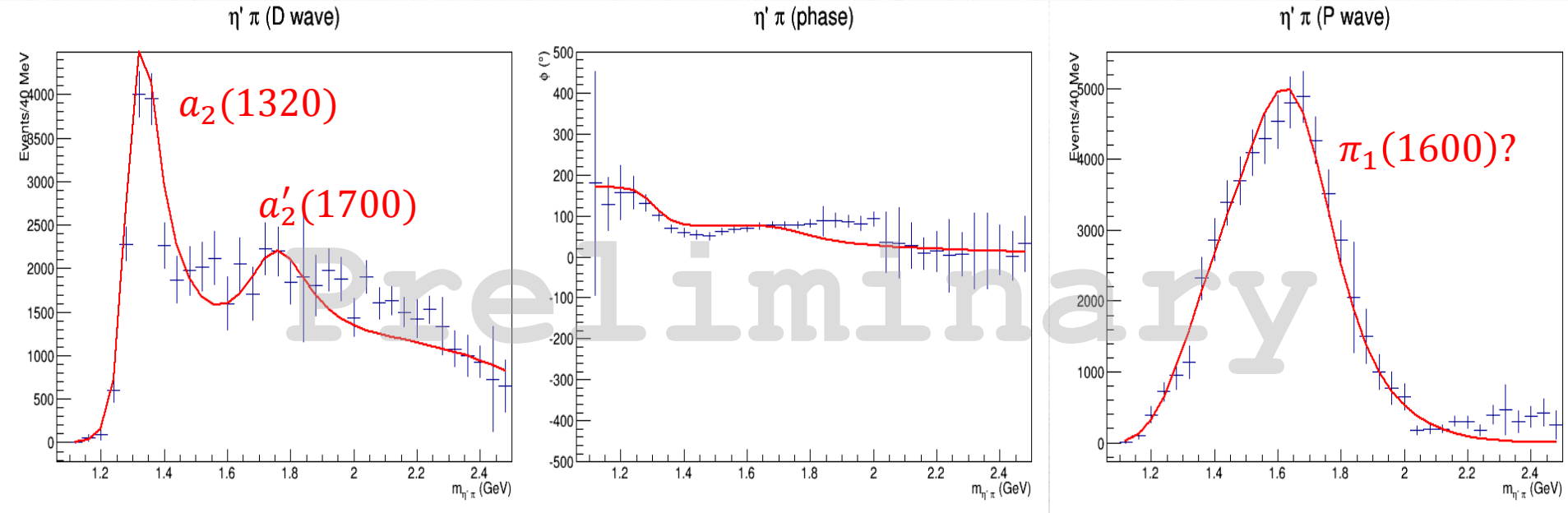


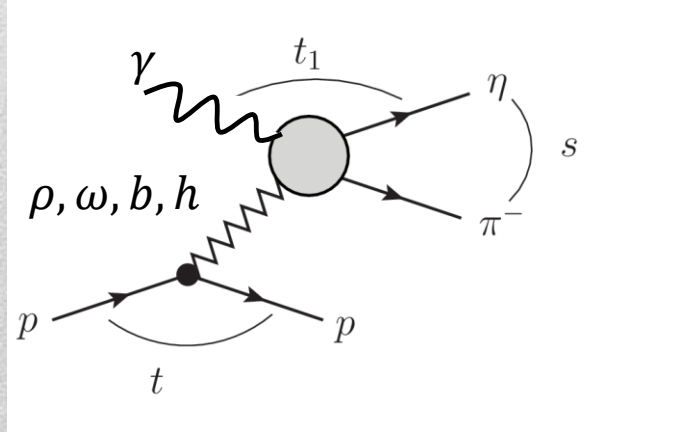




Searching for resonances in $\eta\pi$

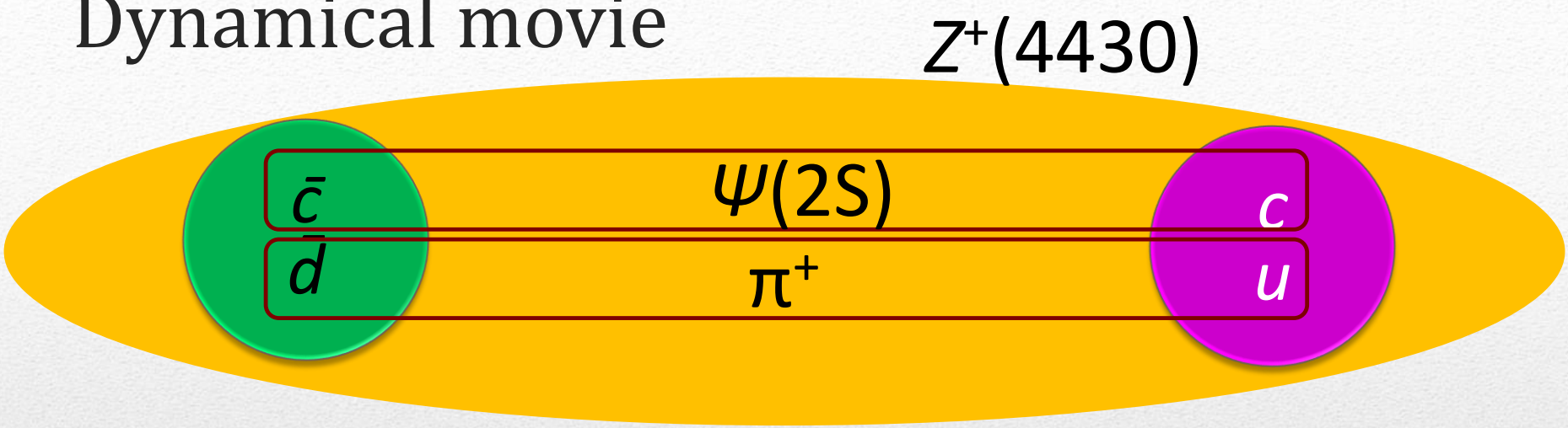
- The coupled channel analysis involving the $\eta\pi$ and $\eta'\pi$ for P- and D-wave is ongoing





- The extention to the GlueX production mechanism and kinematics is also ongoing
- Same $D(s)$, different numerator

Dynamical movie



Brodsky, Hwang, Lebed PRL 113 112001

- Since this is still a $\mathbf{3} \leftrightarrow \overline{\mathbf{3}}$ color interaction, just use the Cornell potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_{cq}^2}\left(\frac{\sigma}{\sqrt{\pi}}\right)^3 e^{-\sigma^2 r^2}\mathbf{S}_{cq}\cdot\mathbf{S}_{\overline{cq}},$$

e.g. Barnes *et al.*, PRD 72, 054026

- Use that the kinetic energy released in $\overline{B}^0 \longrightarrow K^- Z^+(4430)$ converts into potential energy until the diquarks come to rest
- Hadronization most effective at this point (WKB turning point)

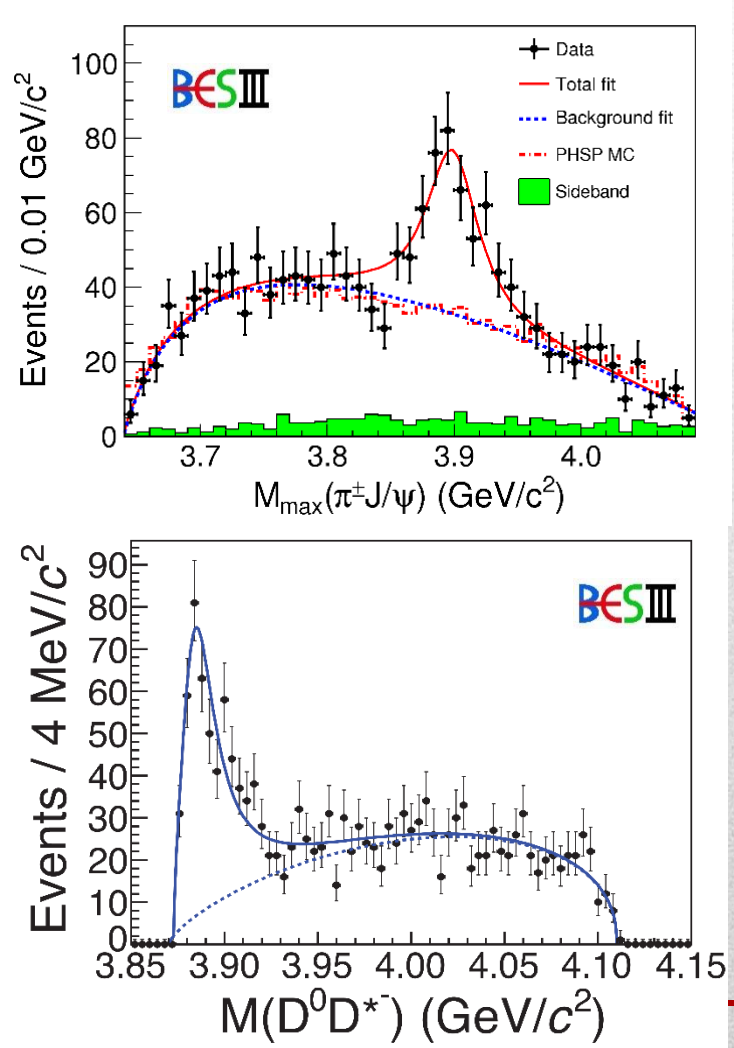
$r_Z = 1.16$ fm, $\langle r_{\psi(2S)}\rangle = 0.80$ fm, $\langle r_{J/\psi}\rangle = 0.39$ fm

$$\frac{B(Z^+(4430) \to \psi(2S)\pi^+)}{B(Z^+(4430) \to J/\psi\,\pi^+)} \sim 72$$

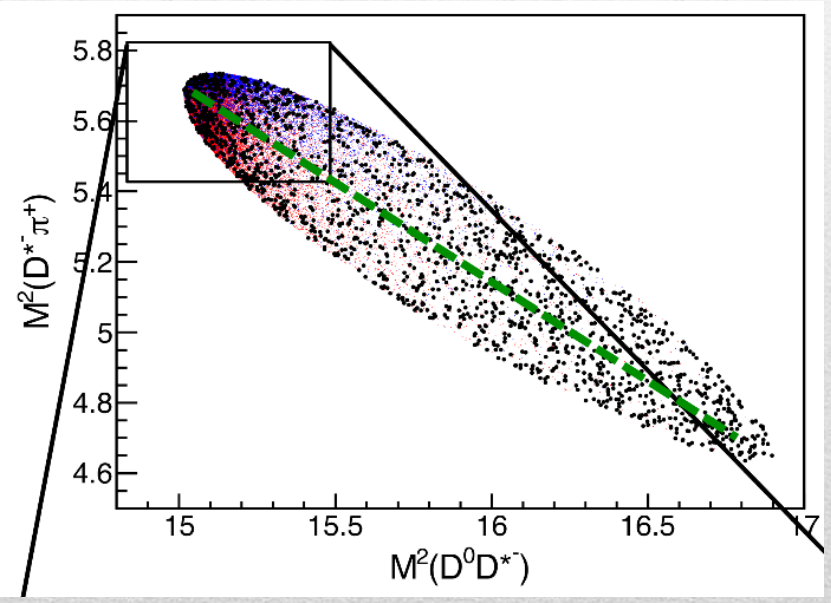
$(> 10$ exp.$)$

Example: The charged $Z_c(3900)$

A charged charmonium-like resonance has been claimed by BESIII in 2013.



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

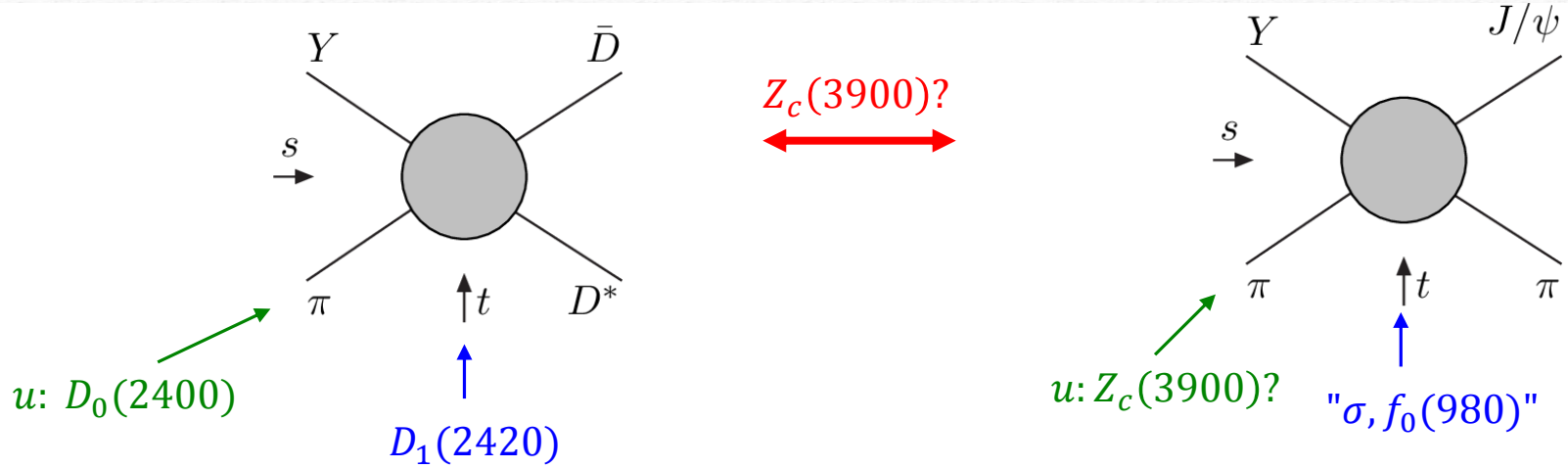


Such a state would require a minimal 4q content and would be manifestly exotic

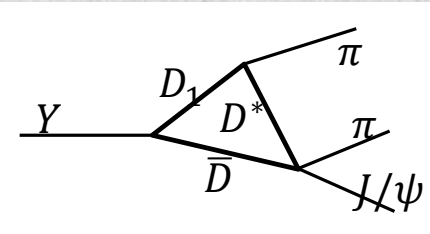
Amplitude analysis for $Z_c(3900)$

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

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

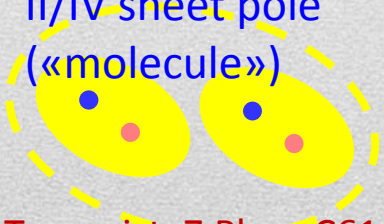


Triangle rescattering,
logarithmic branching point



Szczepaniak, PLB747, 410

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

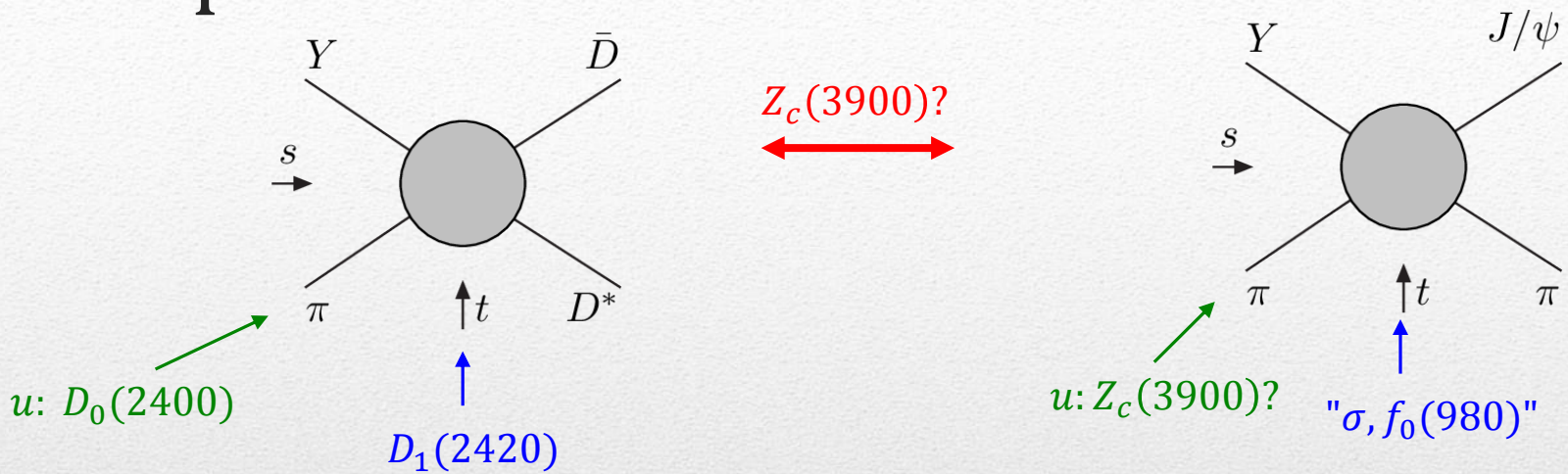


Tornqvist, Z.Phys. C61, 525
Swanson, Phys.Rept. 429
Hanhart *et al.* PRL111, 132003

Resonance,
III sheet pole
(«compact state»)

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

Amplitude model



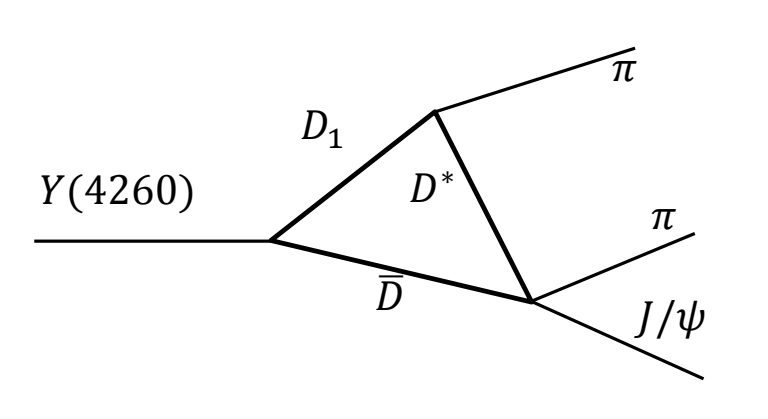
$$f_i(s,t,u) = 16\pi \sum_{l=0}^{L_{\max}} (2l+1)\left(a_{l,i}^{(s)}(s)P_l(z_s) + a_{l,i}^{(t)}(t)P_l(z_t) + a_{l,i}^{(u)}(u)P_l(z_u)\right)$$ Khuri-Treiman

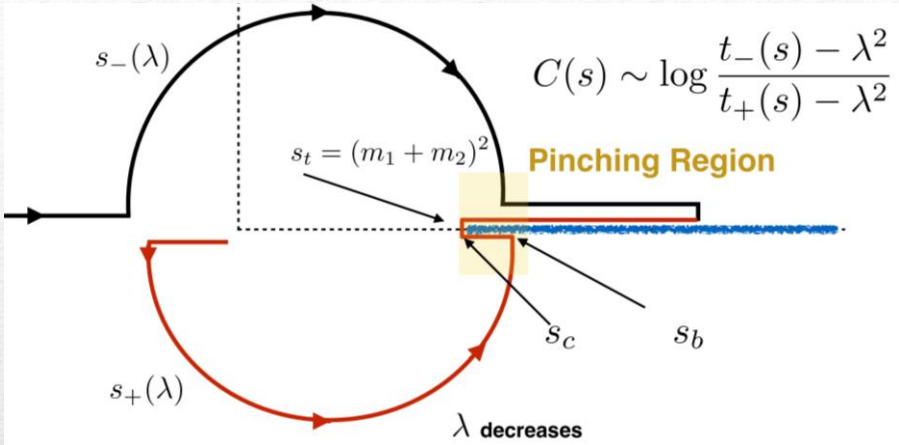
$$f_{0,i}(s) = \frac{1}{32\pi}\int_{-1}^{1} dz_s\, f_i\left(s, t(s,z_s), u(s,z_s)\right) = a_{0,i}^{(s)} + \frac{1}{32\pi}\int_{-1}^{1} dz_s \left(a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u)\right) \equiv a_{0,i}^{(s)} + b_{0,i}(s)$$

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

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

Triangle singularity





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

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

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

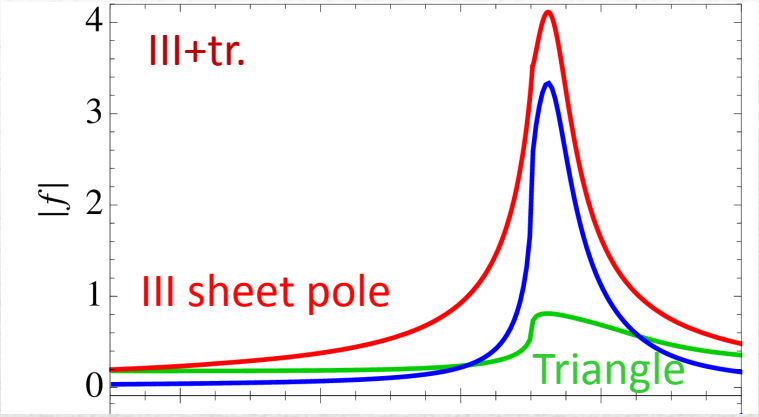
The scattering matrix is parametrized as $(t^{-1})_{ij} = K_{ij} - i\,\rho_i\,\delta_{ij}$

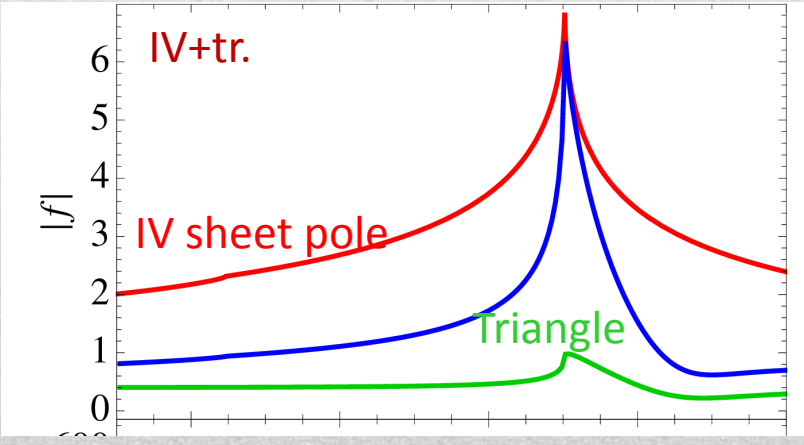
Four different scenarios considered:

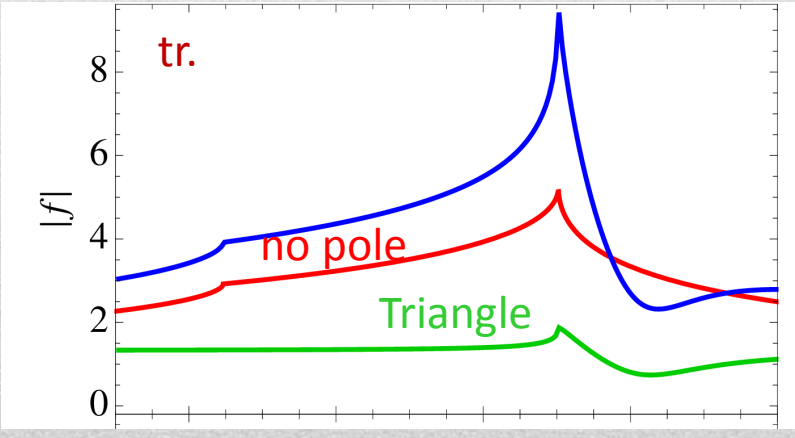
- «III»: the K matrix is $\frac{g_i\,g_j}{M^2-s}$, this generates a pole in the closest unphysical sheet the rescattering integral is set to zero
- «III+tr.»: same, but with the correct value of the rescattering integral
- «IV+tr.»: the K matrix is constant, this generates a pole in the IV sheet
- «tr.»: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

Singularities and lineshapes

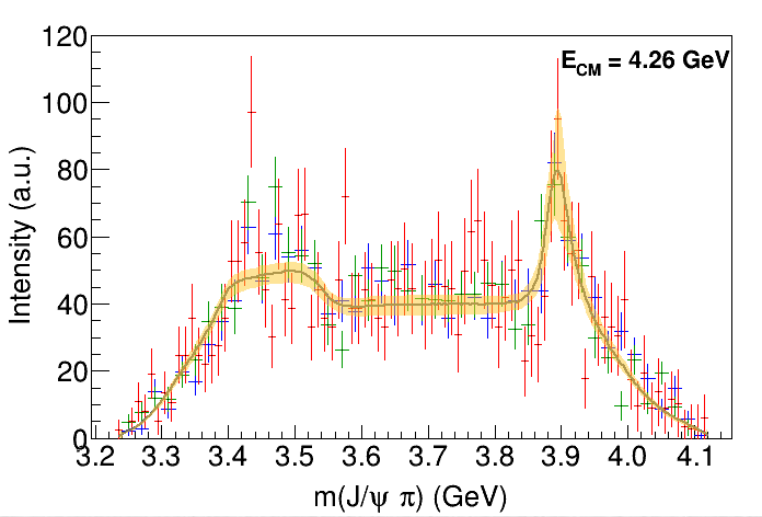
Different lineshapes according to different singularities

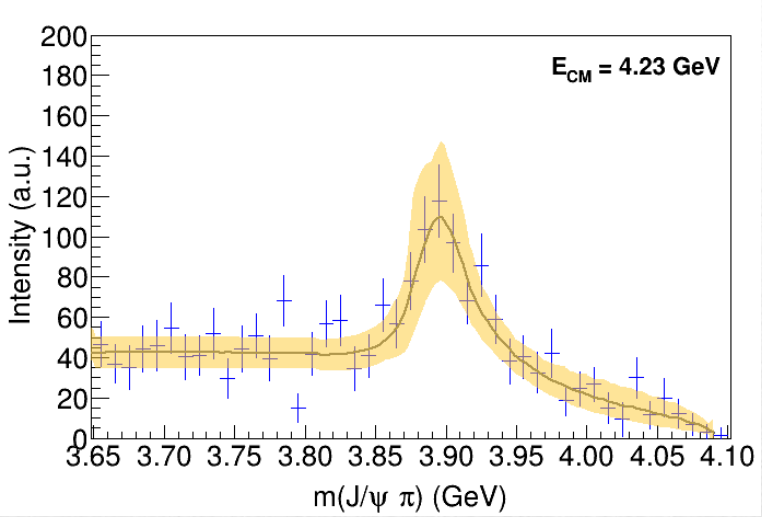


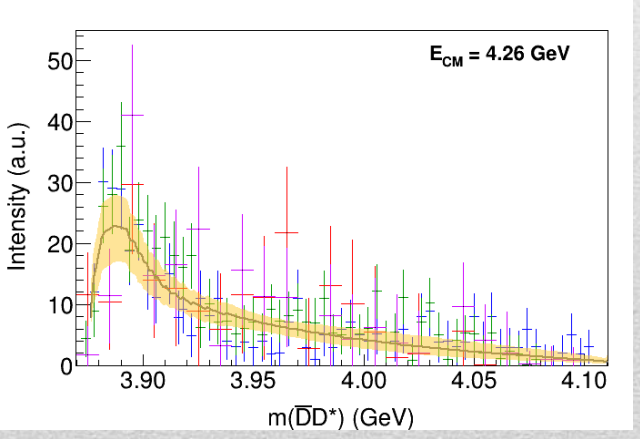


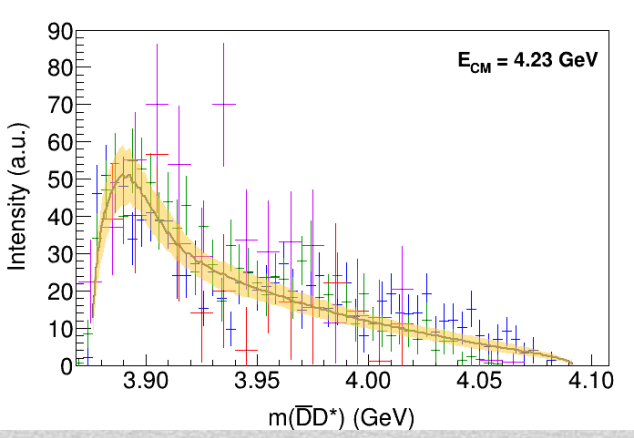


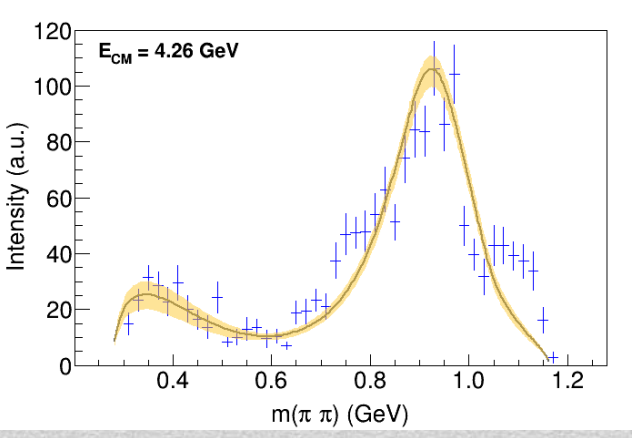
Fit: III


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

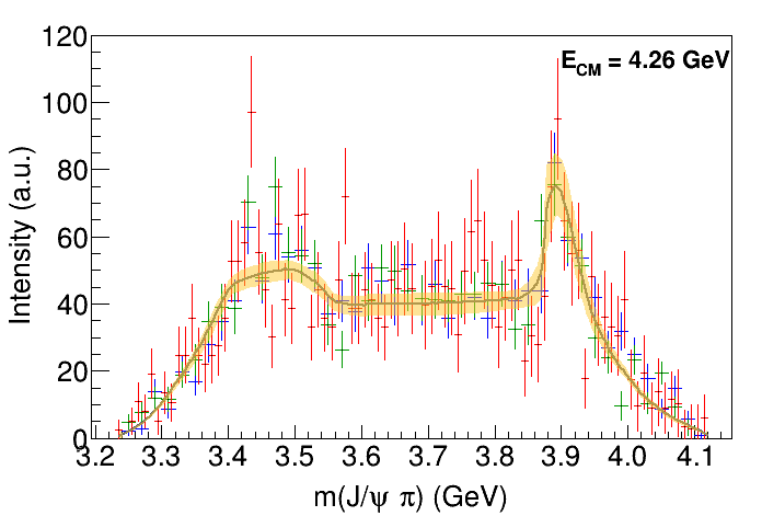

E_{CM} = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)

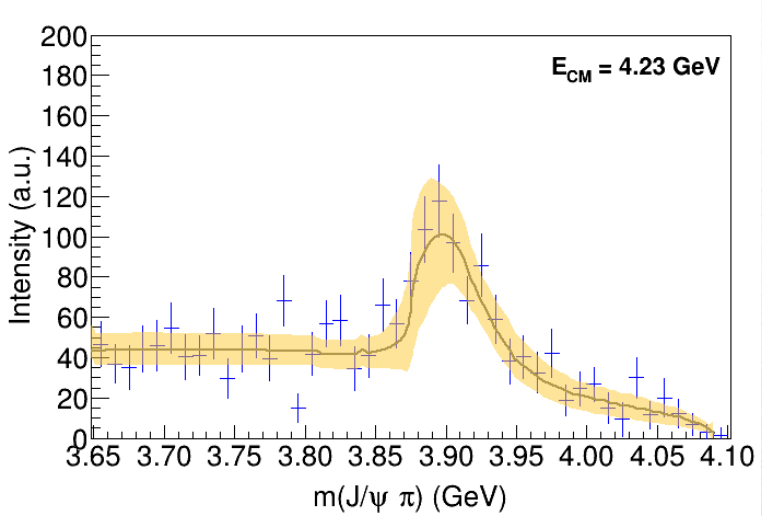

E_{CM} = 4.26 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)

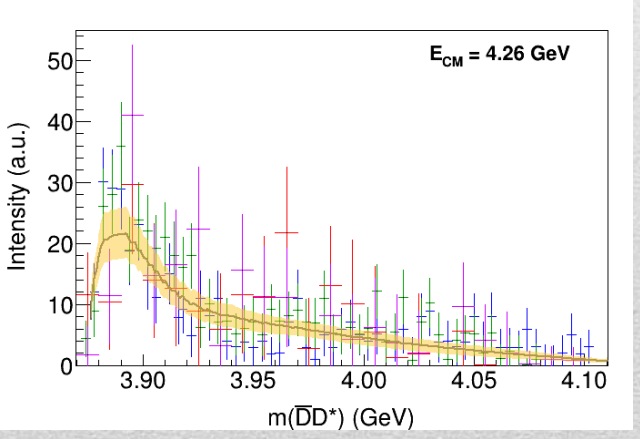

E_{CM} = 4.23 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)

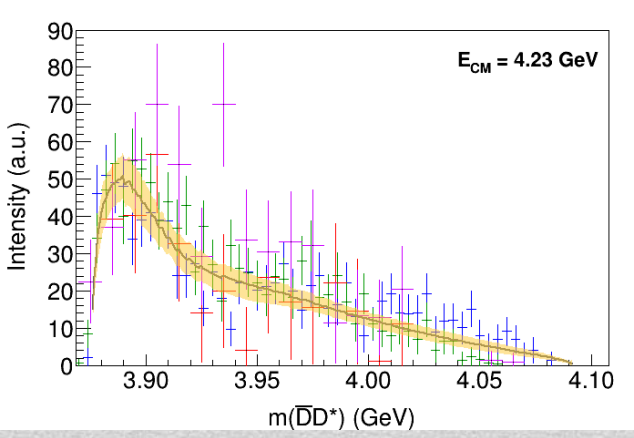

E_{CM} = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

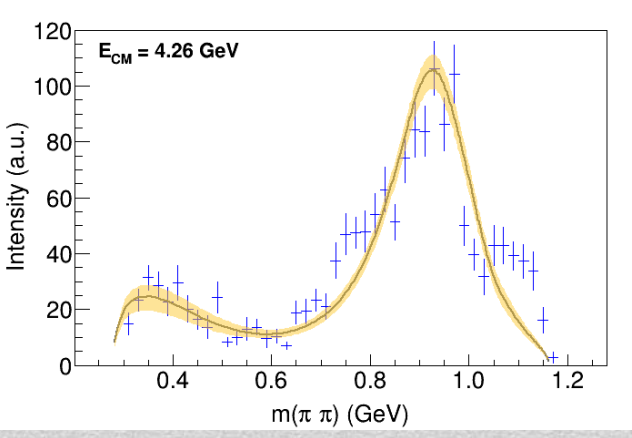
Fit: III+tr.


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

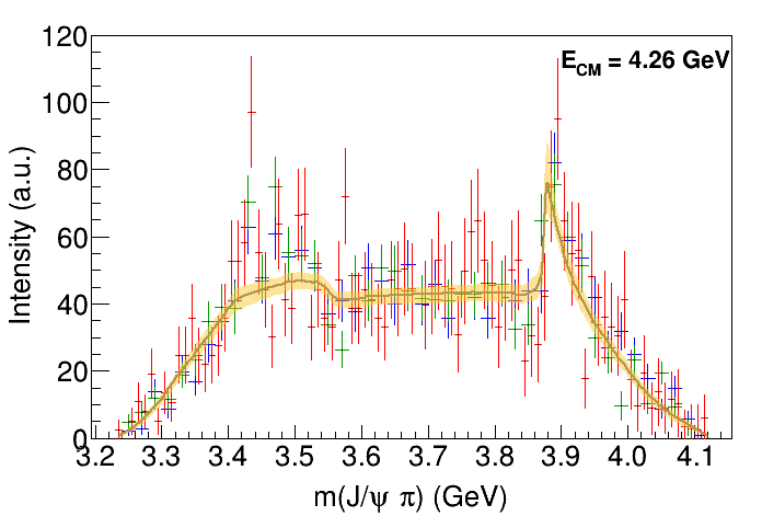

E_{CM} = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)

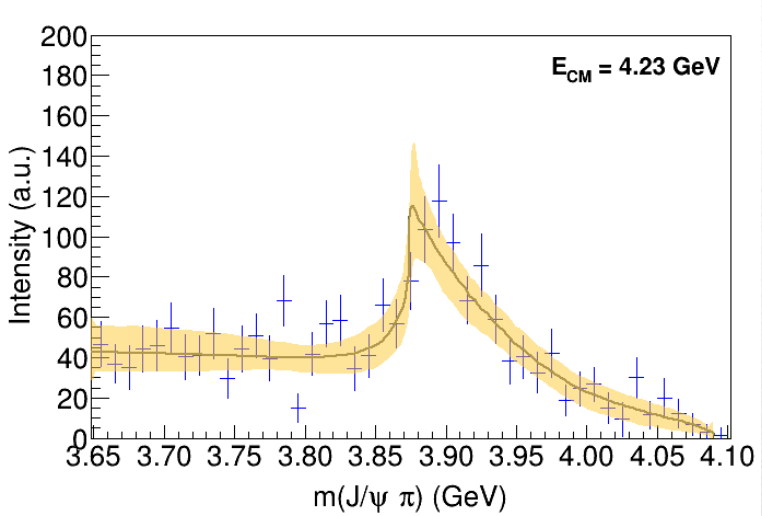

E_{CM} = 4.26 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)

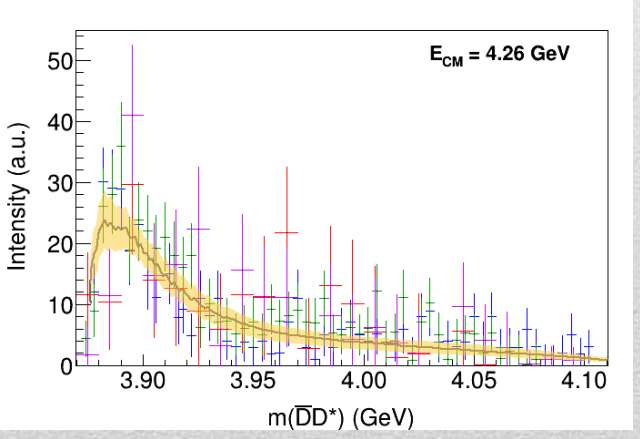

E_{CM} = 4.23 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)

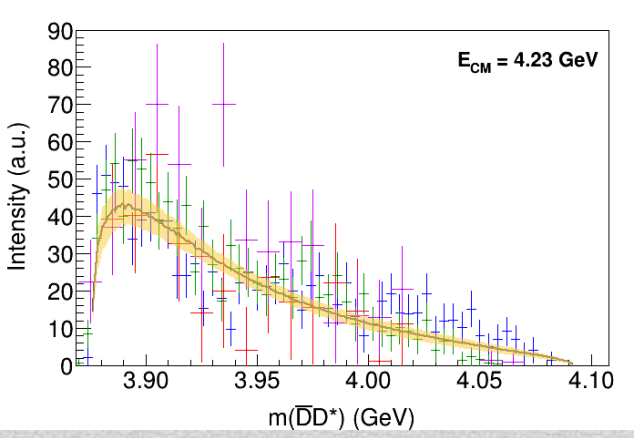

E_{CM} = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

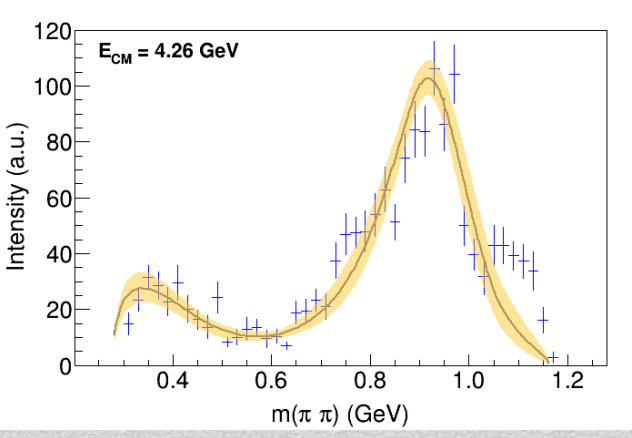
Fit: IV+tr.


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

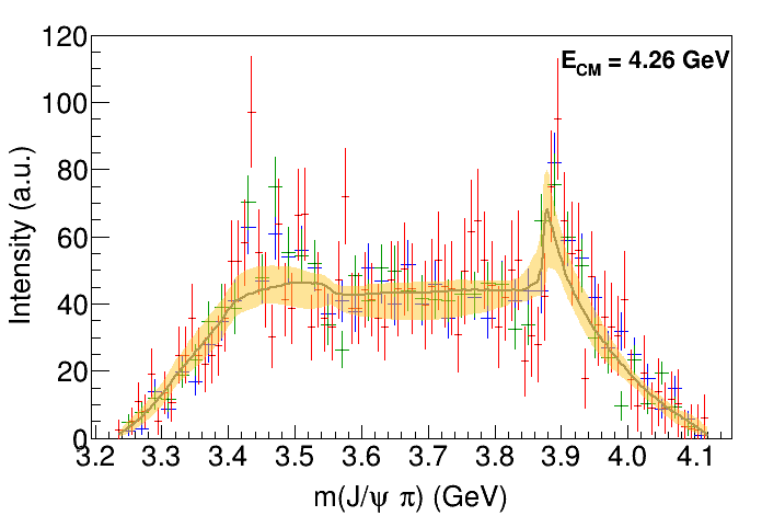

E_{CM} = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)

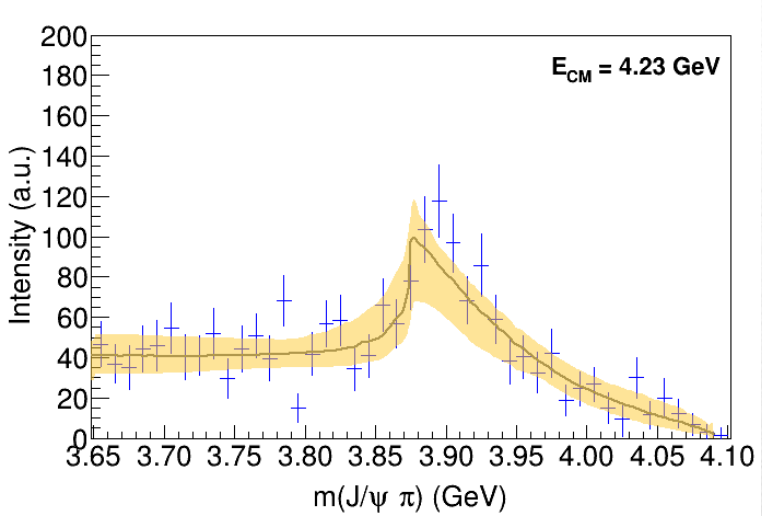

E_{CM} = 4.26 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)

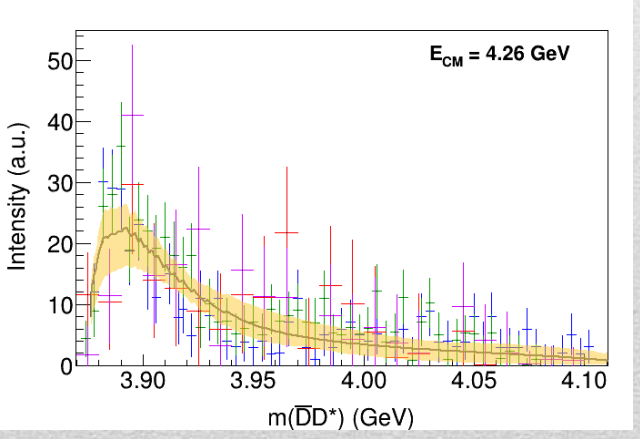

E_{CM} = 4.23 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)

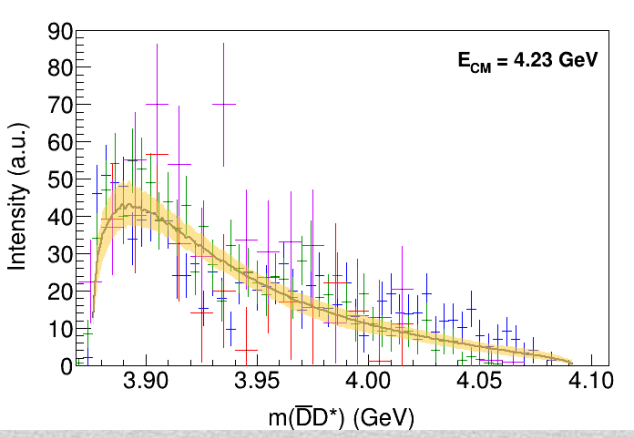

E_{CM} = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

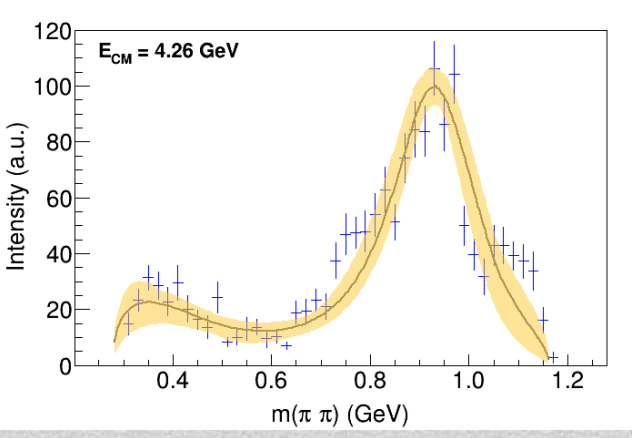
Fit: tr.


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

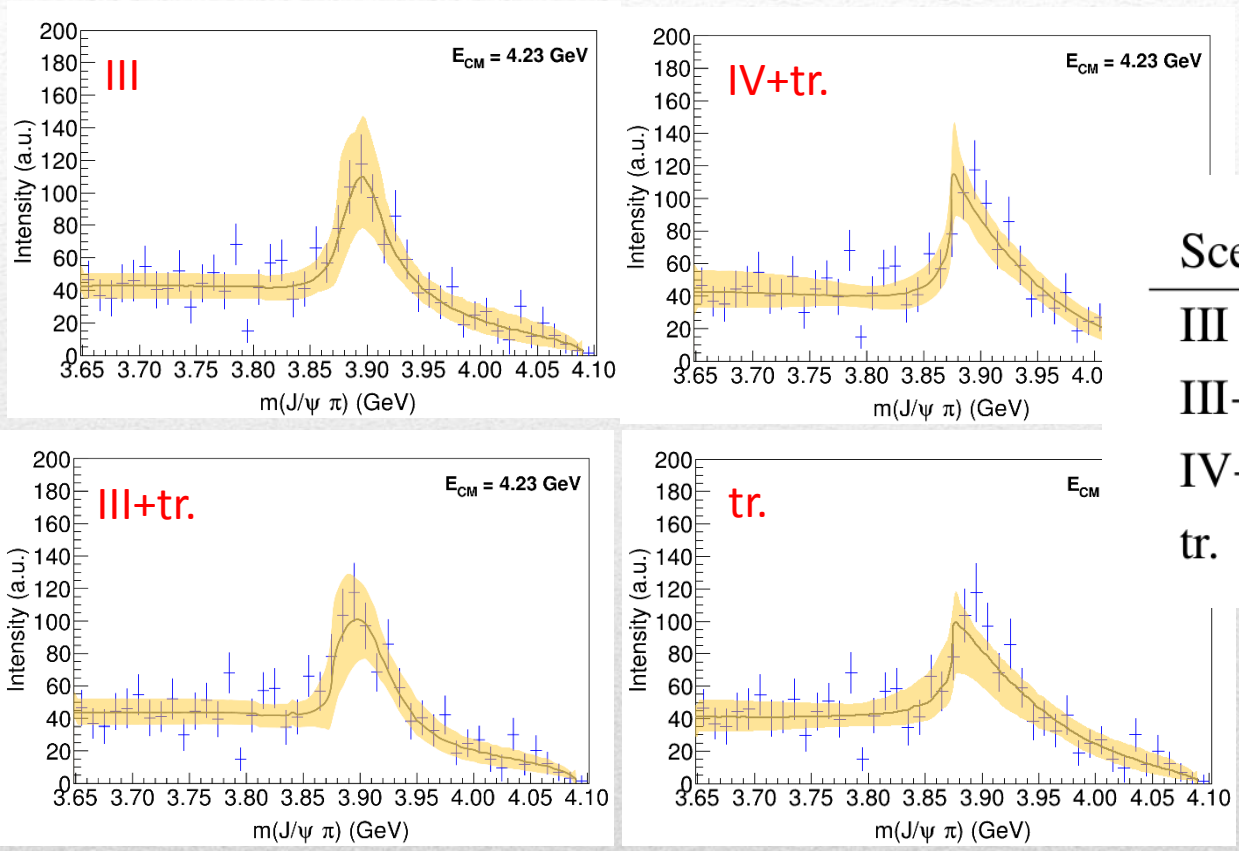

E_{CM} = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)


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)

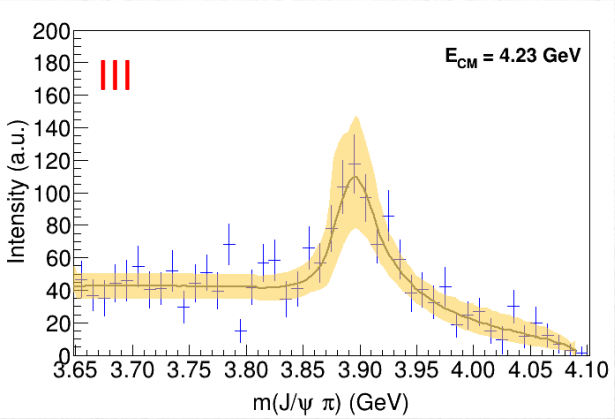
Fit summary

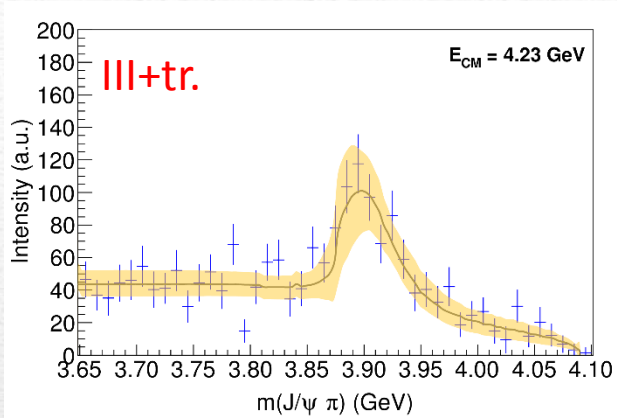


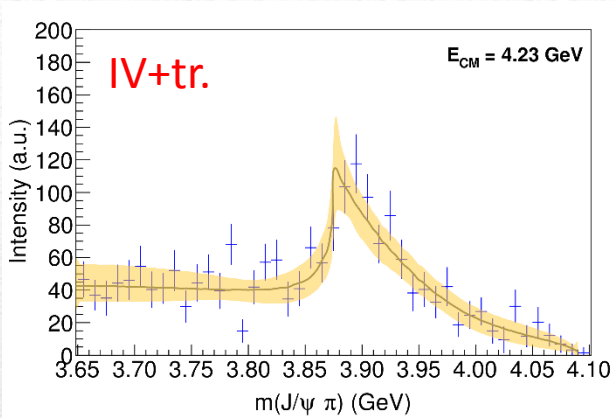
Scenario	χ^2	DOF	χ^2/DOF
III	644	532	1.21
III+tr.	642	532	1.21
IV+tr.	666	532	1.25
tr.	695	532	1.31

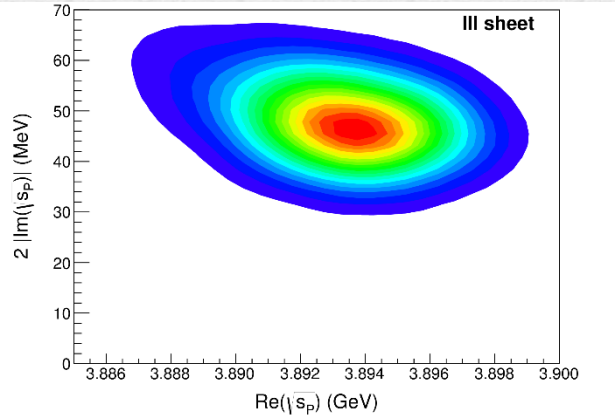
Naive loglikelihood ratio test give a $\sim 4\sigma$ significance of the scenario III+tr. over IV+tr., looking at plots it looks too much – better using some more solid test

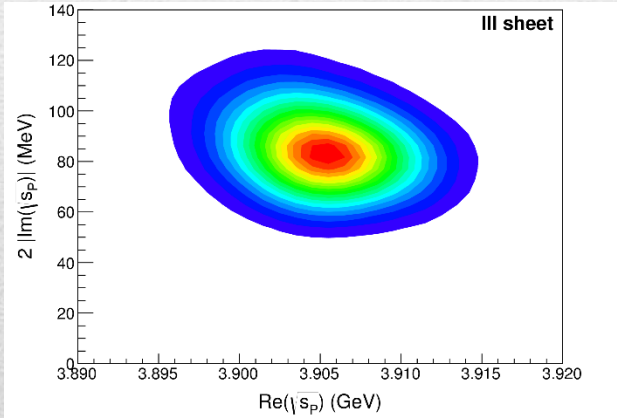
Pole extraction

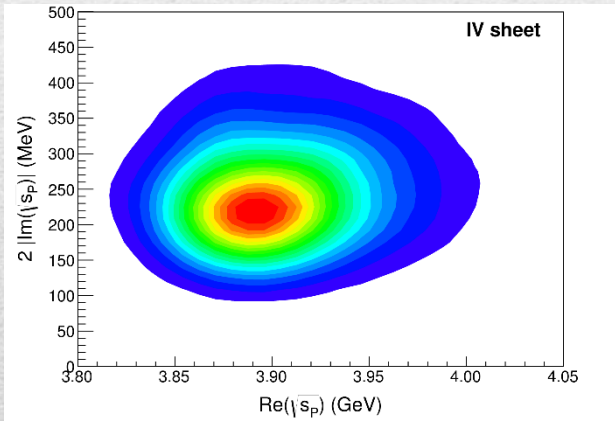












Scenario	III+tr.	IV+tr.	tr.
III	1.5σ (1.5σ)	1.5σ (2.7σ)	"2.4σ" ("1.4σ")
III+tr.	–	1.5σ (3.1σ)	"2.6σ" ("1.3σ")
IV+tr.	–	–	"2.1σ" ("0.9σ")

	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