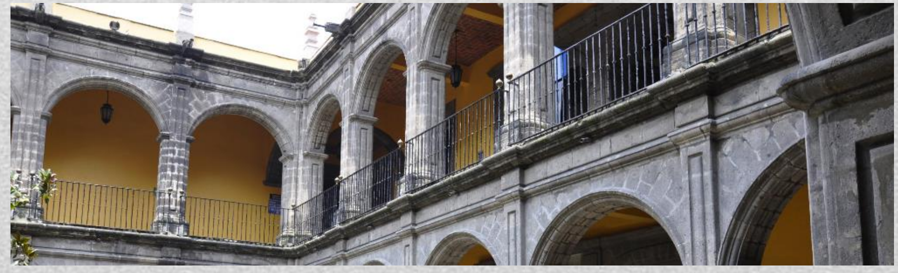
Amplitudes analysis and exotic states

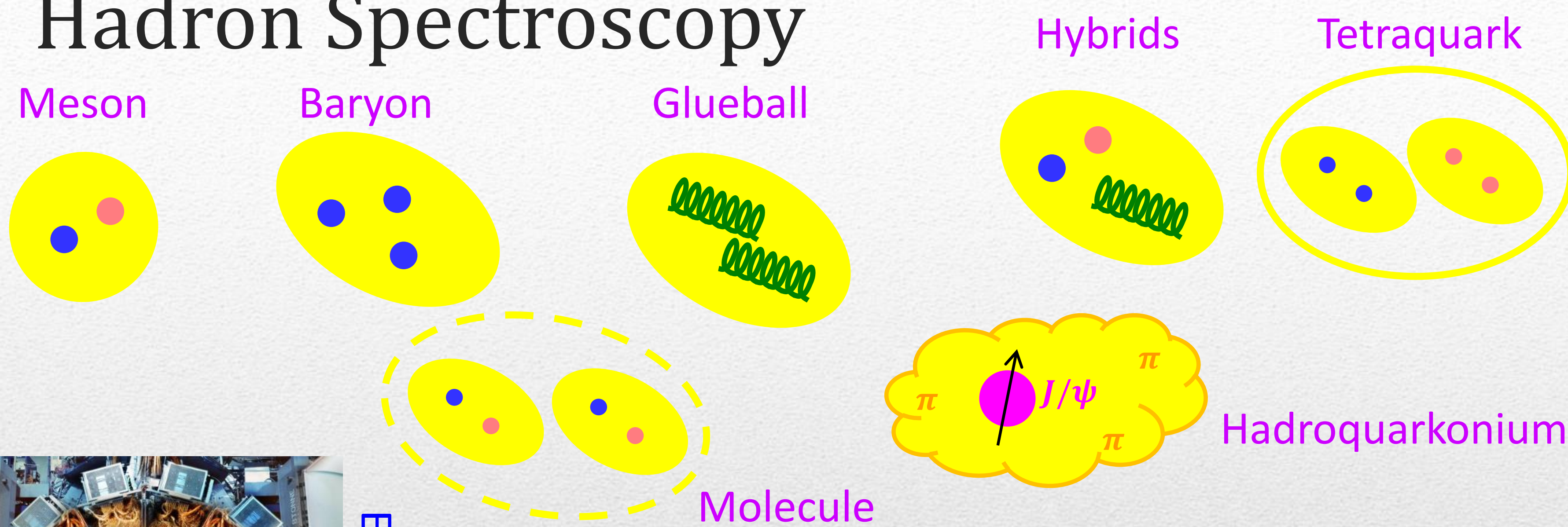
Alessandro Pilloni

FDSA2017, Mexico City, November 7th, 2017

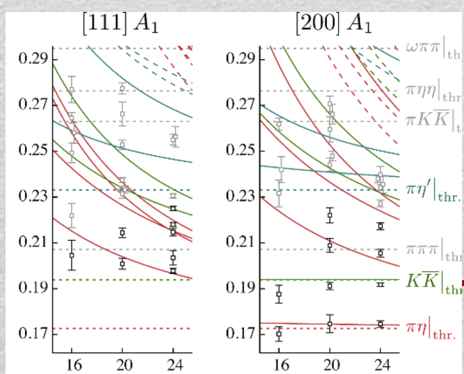
Jefferson Lab



Hadron Spectroscopy



Experiment

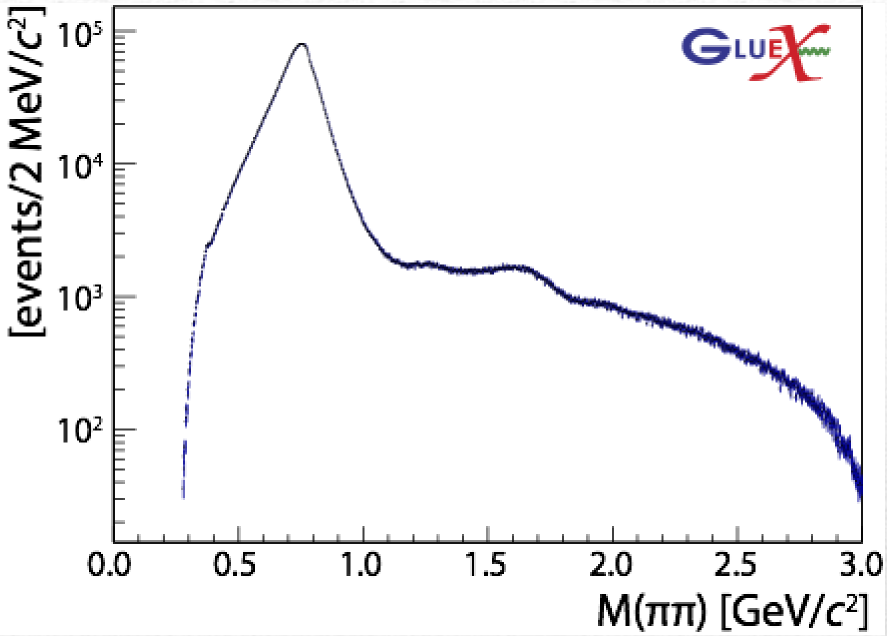


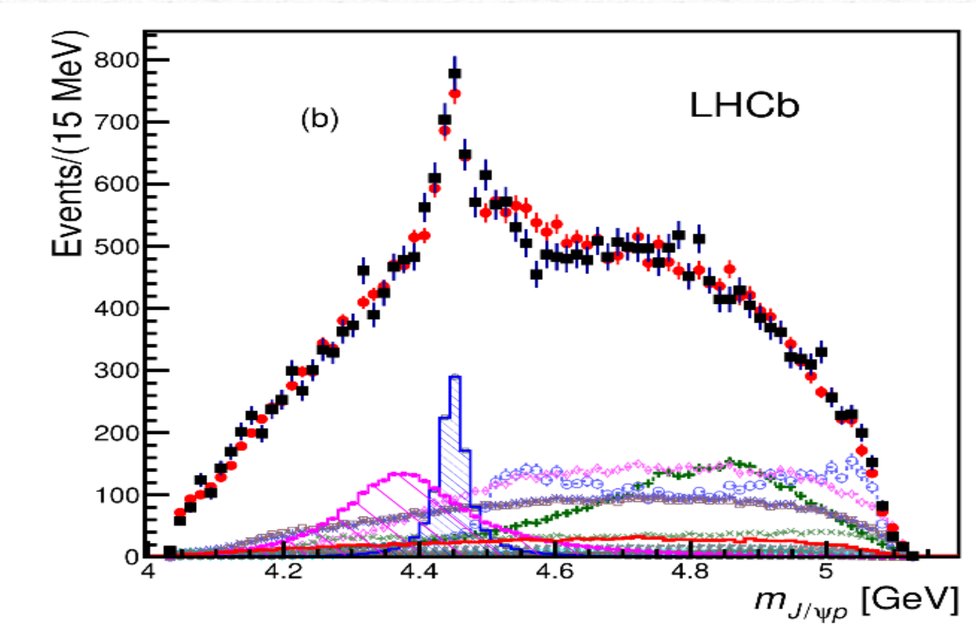
Lattice QCD

Data → ? → Fundamental properties, Model building

Interpretations on the spectrum leads to understanding fundamental laws of nature

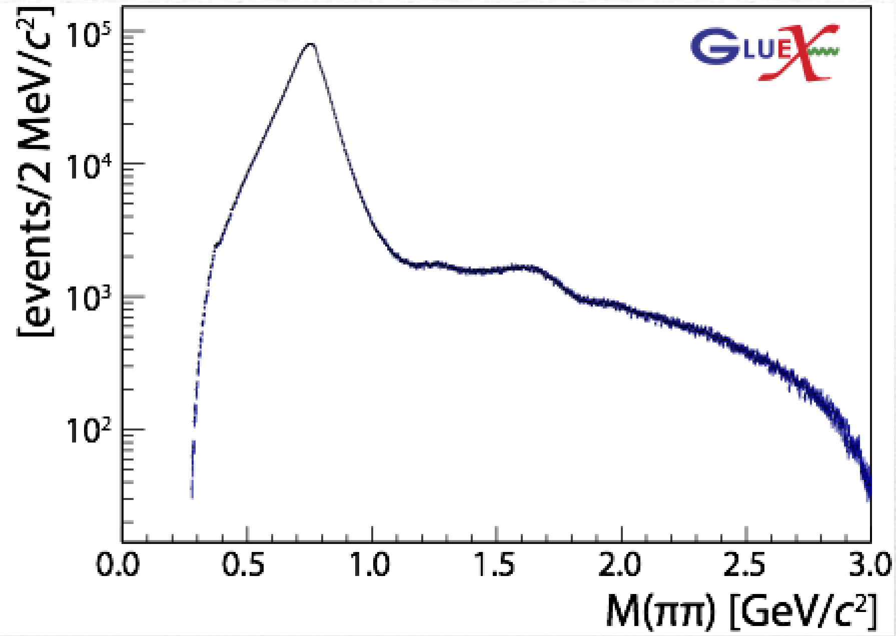
Hadron Spectroscopy

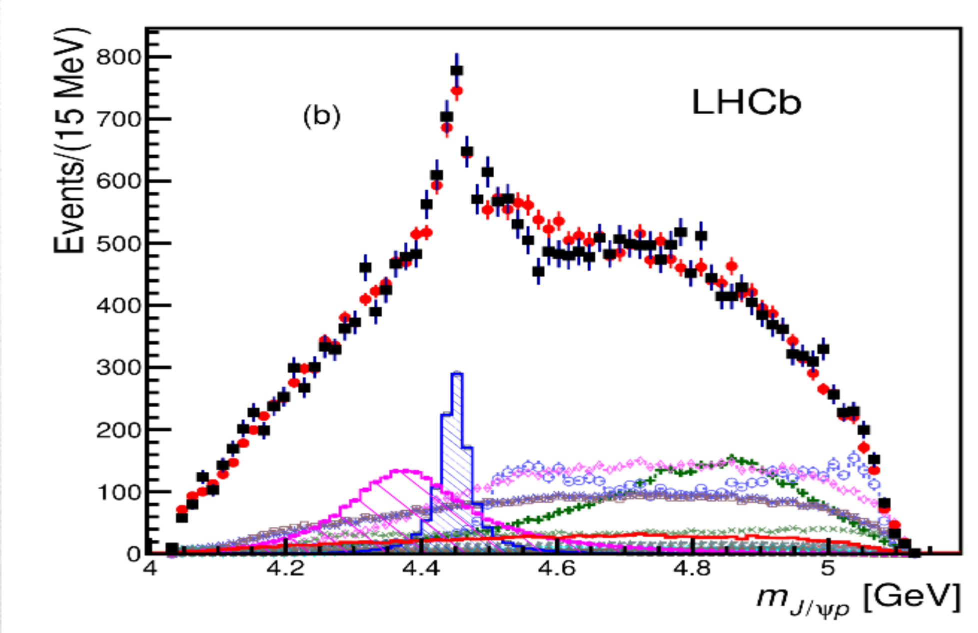


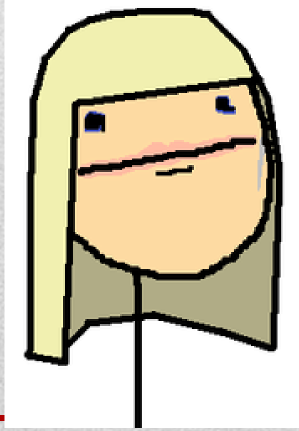


Data → ? → Fundamental properties, Model building

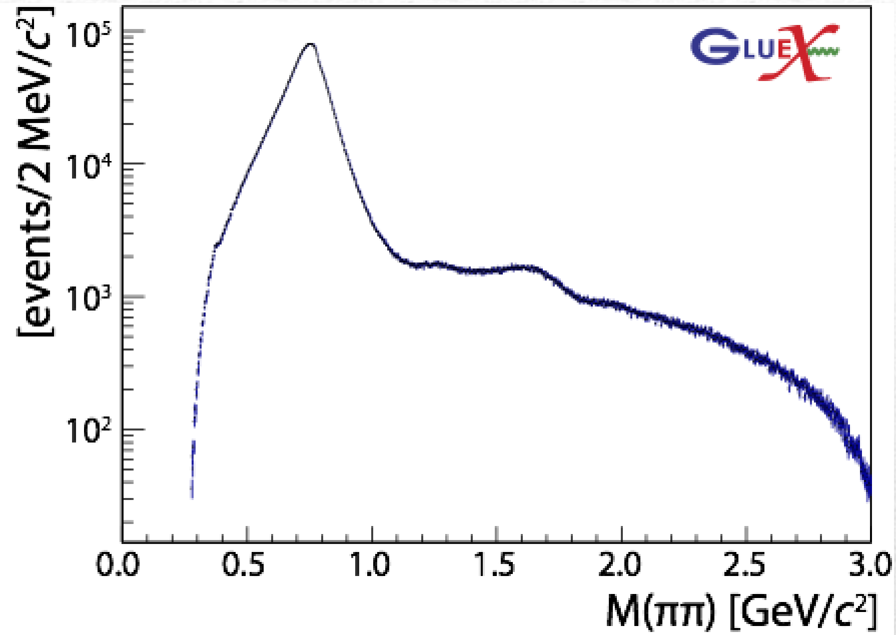
Hadron Spectroscopy

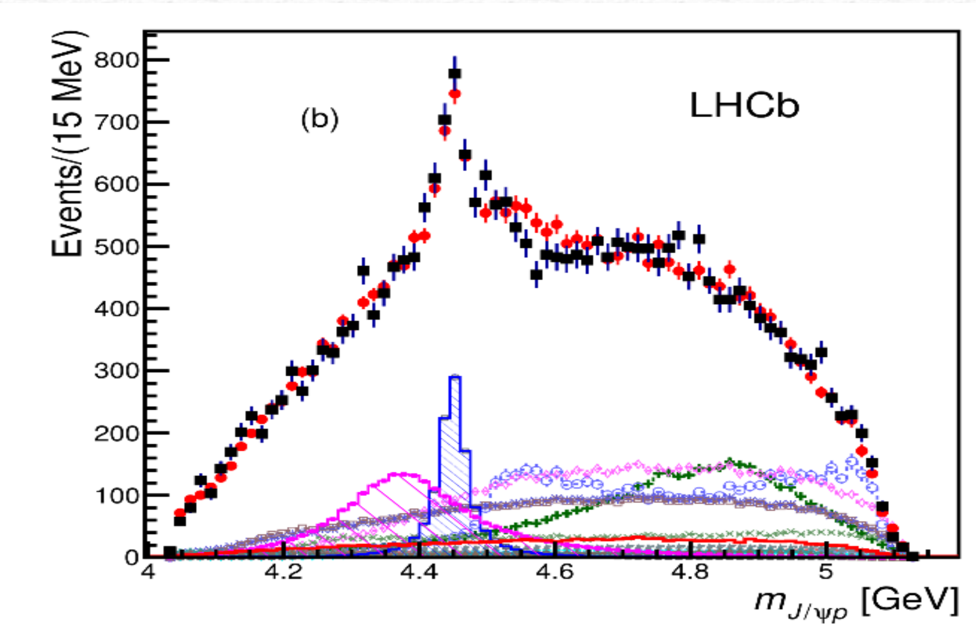


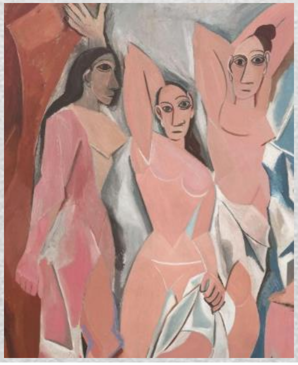


Data →  → Fundamental properties, Model building

Hadron Spectroscopy





Data →  → Fundamental properties, Model building

Improvement needed! With great statistics comes great responsibility!

Peter Parker, Ph.D.

Outline

- Recipes to build an amplitude
- The exotic charmonium sector
- Amplitude analysis for the $Z_c(3900)$
- The $X(3872)$, Weinberg and all that
- What's new for the $Y(4260)$
- (Production of exotics at colliders)

Recipes to build an amplitude

M. Mikhasenko, AP et al., to appear

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

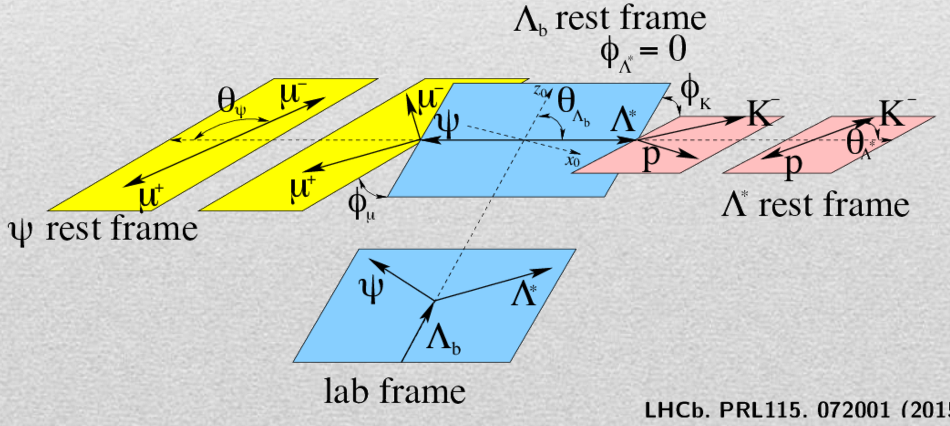
- Helicity formalism enforces the constraints about rotational invariance
- It allows us to fix the angular dependence of the amplitude
- What about energy dependence?

Example: $\Lambda_b \to \psi \Lambda^* \to pK$

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\,\lambda_p,\,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\,\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\,\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^*$$

$$\mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,\,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\,\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^*$$

$$R_{\Lambda_n^*}(m_{Kp}) D^{1}_{\lambda_\psi,\,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*,$$



LHCb, PRL115, 072001 (2015)

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

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

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

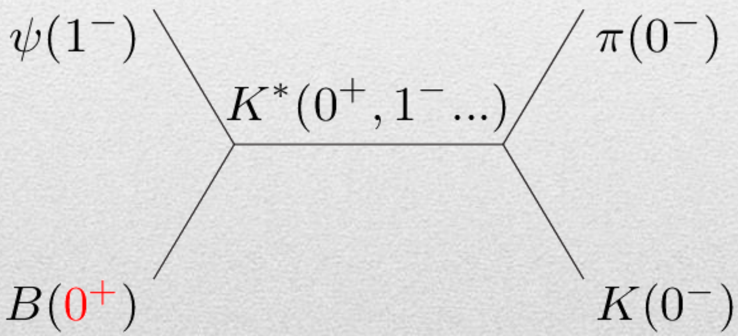
- Kinematical singularities: e.g. barrier factors (known)
- Left hand singularities (need model, e.g. Blatt-Weisskopf)
- Right hand singularities = resonant content (Breit Wigner, K-matrix…)

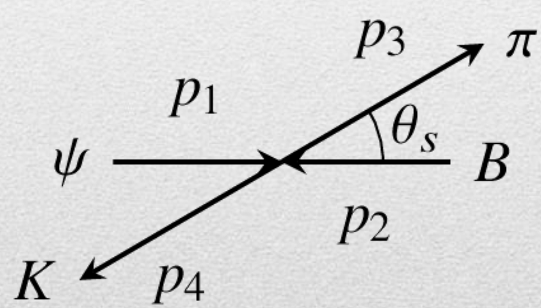
Kinematics

- 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

Example: $B \to J/\psi\, \pi K$

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





$$p = \frac{\lambda_{12}^{1/2}}{2\sqrt{s}}, \quad q = \frac{\lambda_{34}^{1/2}}{2\sqrt{s}}, \quad z_s = \frac{s(t-u) + (m_1^2 - m_2^2)(m_3^2 - m_4^2)}{\lambda_{12}^{1/2}\lambda_{34}^{1/2}}$$

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 $j-|\lambda|$

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

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

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

$$B(s,t) = \frac{1}{4\pi}\hat{A}^0_0 + \frac{1}{4\pi}\frac{4m_1^2}{\lambda_{12}} \sum_{j>0}(2j+1)(pq)^j \left[\hat{A}^j_0(s)\hat{d}^j_{00}(z_s) + \frac{s + m_1^2 - m_2^2}{\sqrt{2}m_1^2}\hat{A}^j_+(s)\, z_s \hat{d}^j_{10}(z_s)\right]$$

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 $\hat{A}^j_0$ 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.

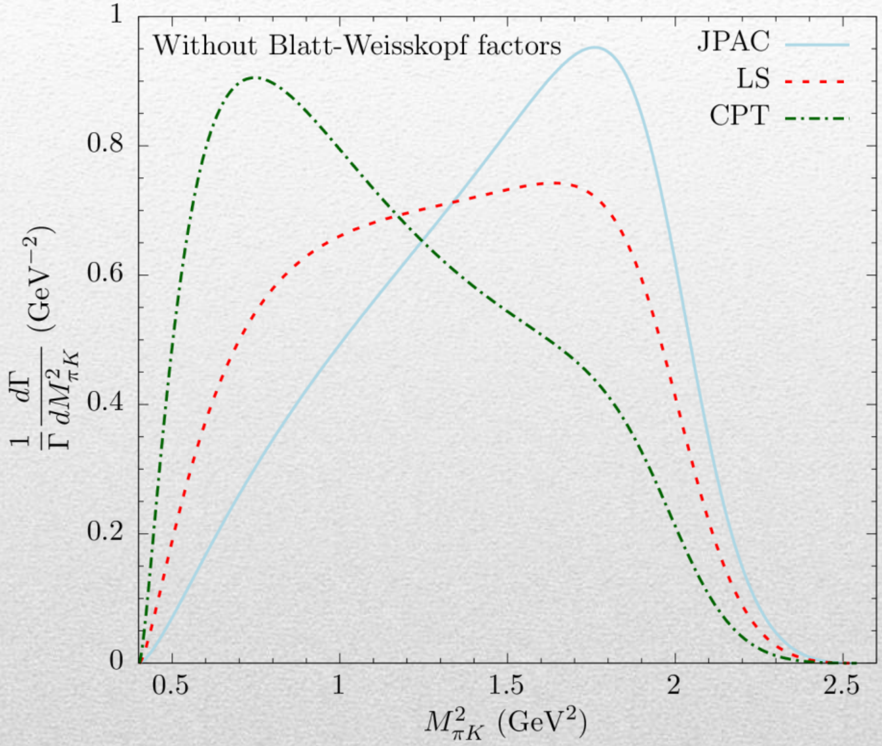
Comparison with tensor formalisms ($j=1$)

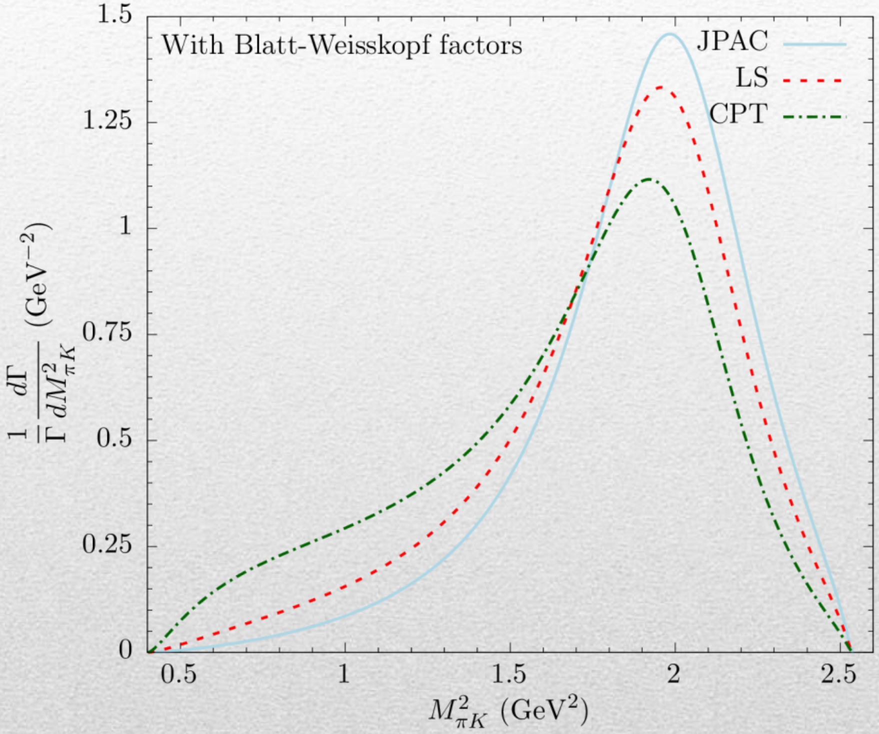
$$g_1 = g'_1 = \frac{4\pi}{3} g_S, \quad f_1 = \frac{2\pi\lambda_{12}}{3s} g_D, \quad f'_1 = -\frac{4\pi\lambda_{12}}{3s}\frac{s+m_1^2-m_2^2}{m_1^2} g_D.$$

If the g_S, g_D are the usual Breit-Wigner, the g', f' are fine
but for singularities at $s=0$

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

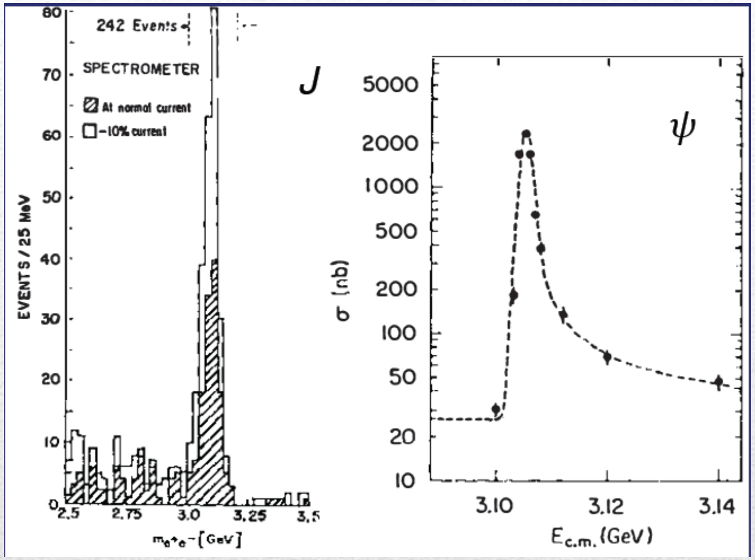
General expression and comparison

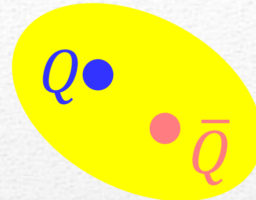


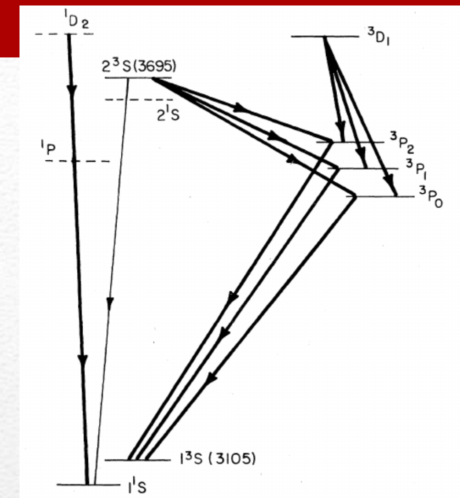


The differences can be relevant, in particular if one remove the Blatt-Weisskopf barrier factors

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...)

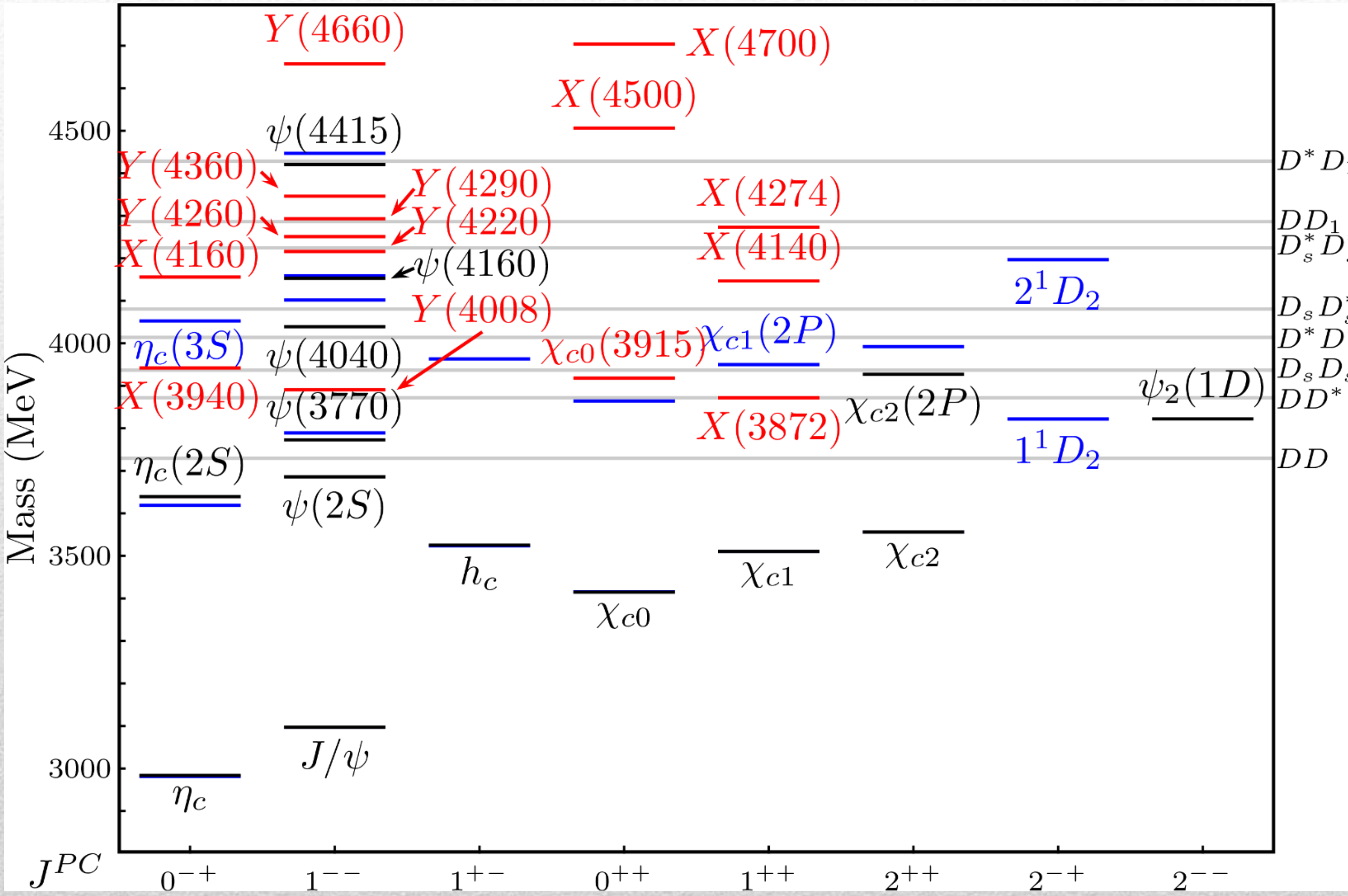
Integrate out heavy DOF

↓

(spectrum), decay & production rates

Exotic landscape

Esposito, AP, Polosa, Phys.Rept. 668



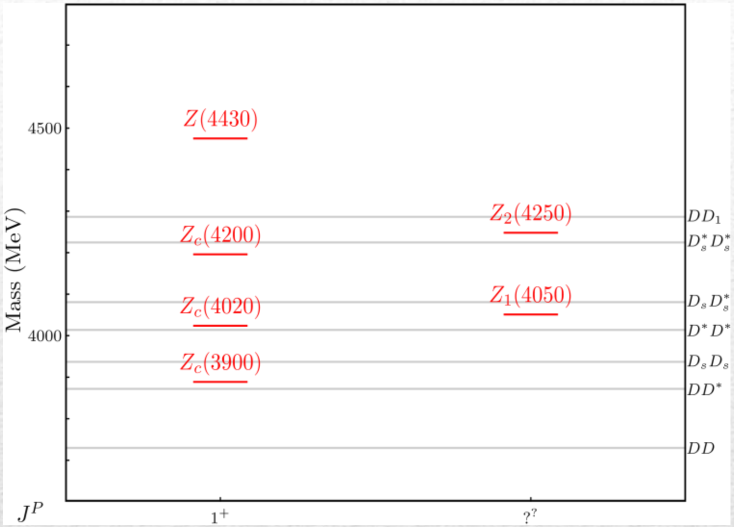
A host of unexpected resonances have appeared

decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

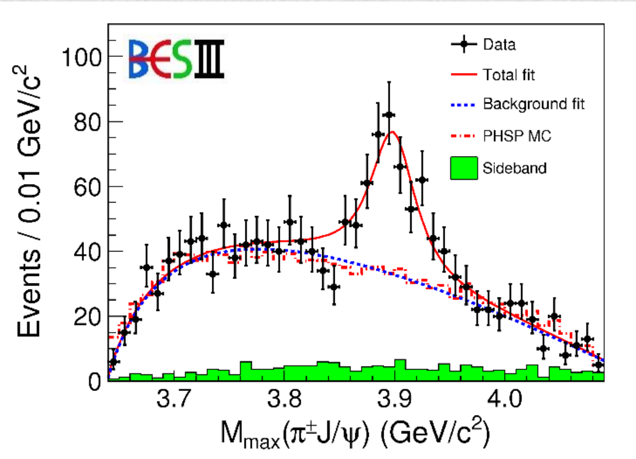
Charged Z states: $Z_c(3900), Z_c'(4020)$

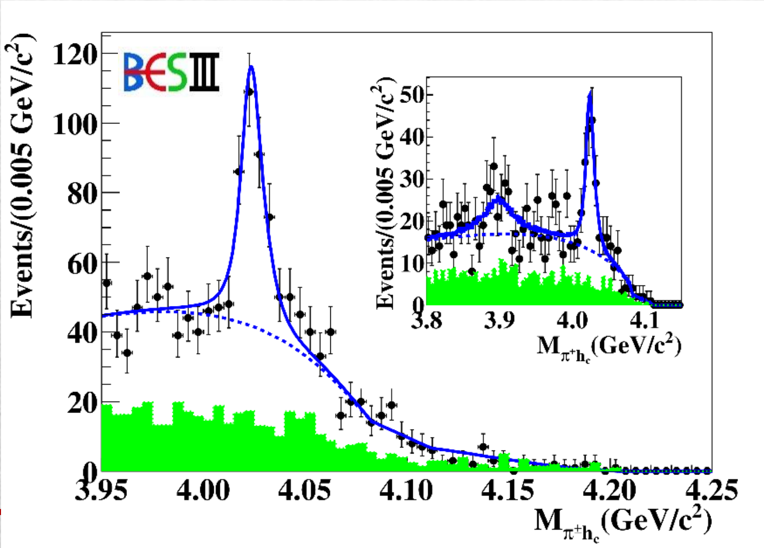
Charged quarkonium-like resonances have been found, **4q needed**



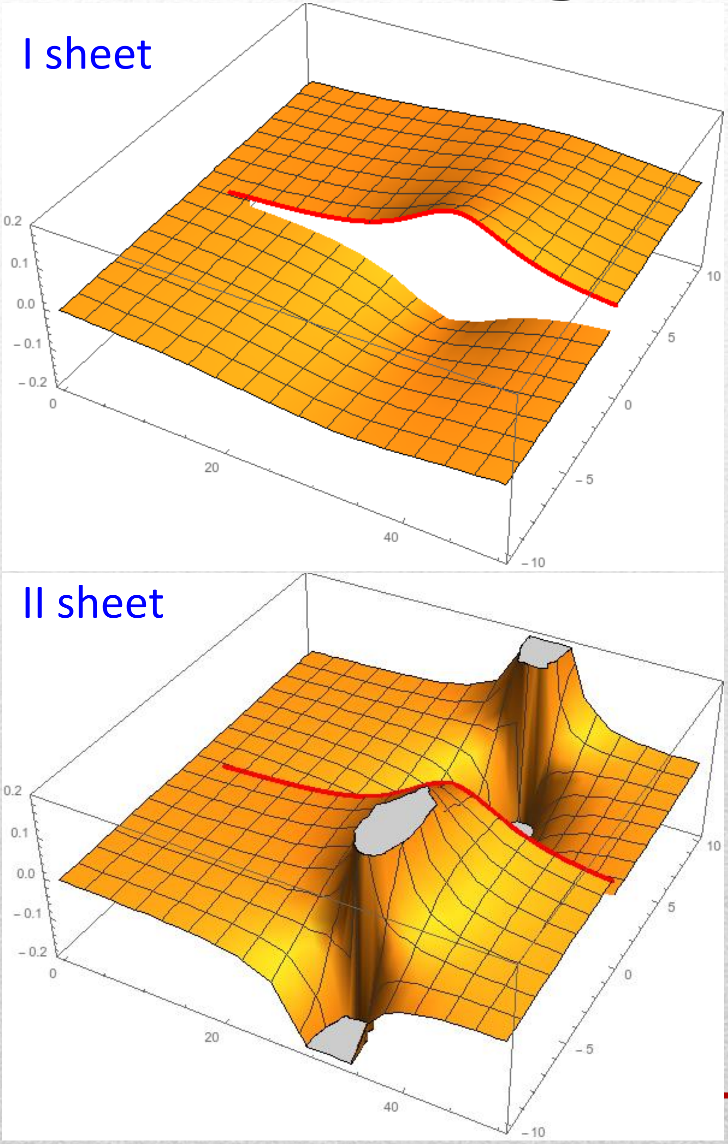
Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ 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





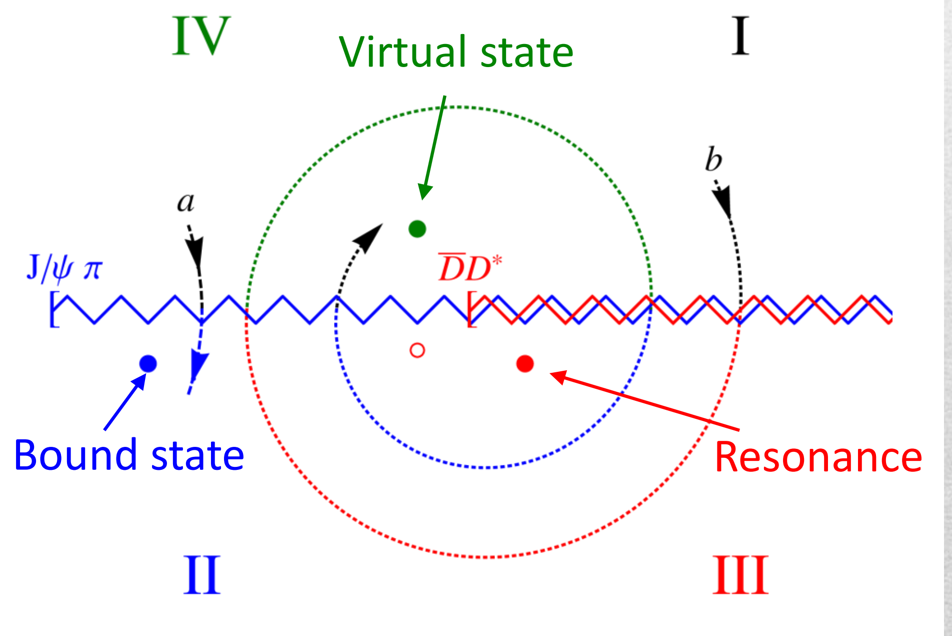
Pole hunting



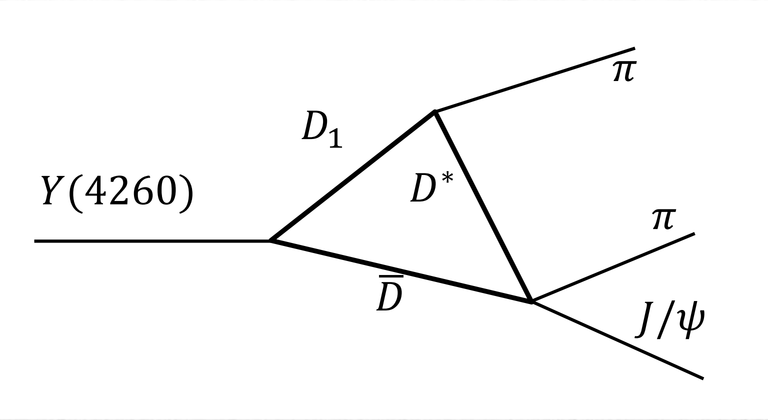
More complicated structure when more thresholds arise: two sheets for each new threshold

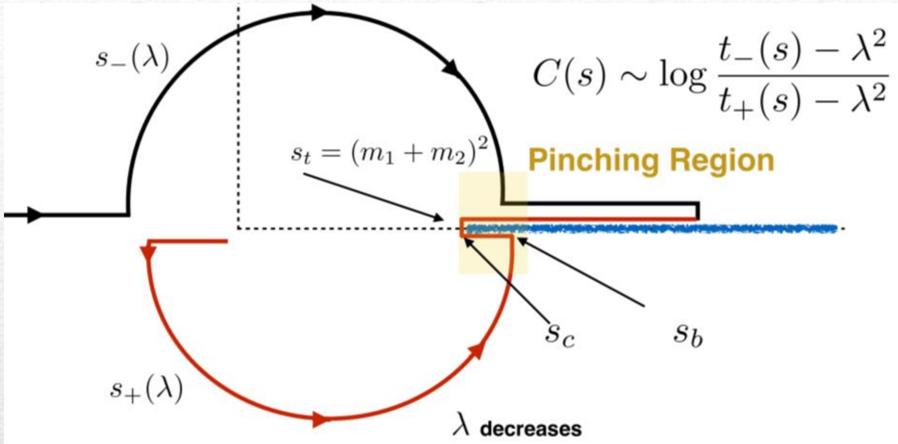
III sheet: usual resonances

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)

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

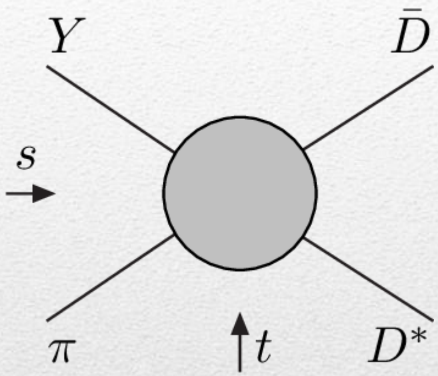
...but the cancellation can be spread in different channels, you might still see peaks in other channels only!

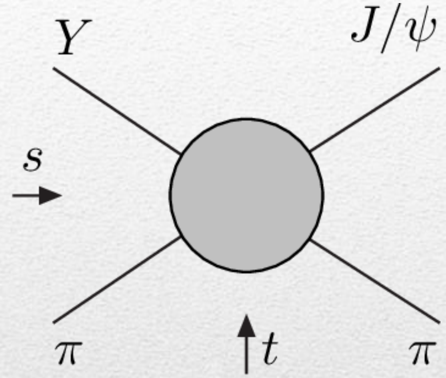
Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo, Meissner, Wang, Yang PRD92, 071502

Amplitude analysis for $Z_c(3900)$

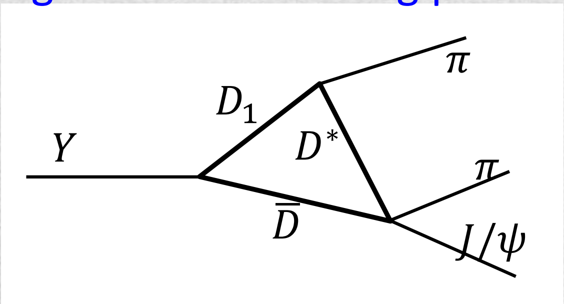
One can test different parametrizations of the amplitude, which correspond to
different singularities → different natures

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



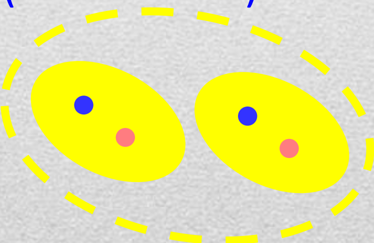


Triangle rescattering,
logarithmic branching point



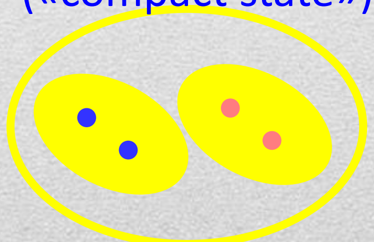
Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo *et al.* PRD92, 071502

(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

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~~

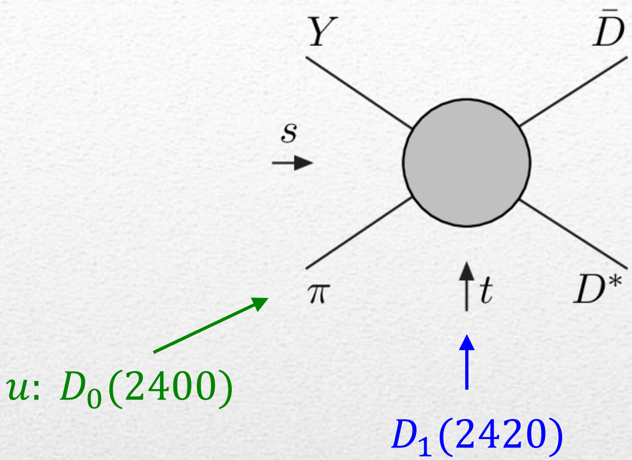
- Published data are not efficiency/acceptance corrected,
  → we are not able to give the absolute normalization of the amplitudes

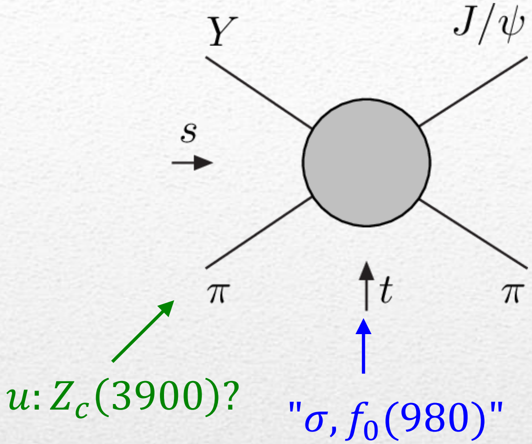
- No given dependence on E_{CM} is assumed – the couplings at different E_{CM} are independent parameters

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

Amplitude model





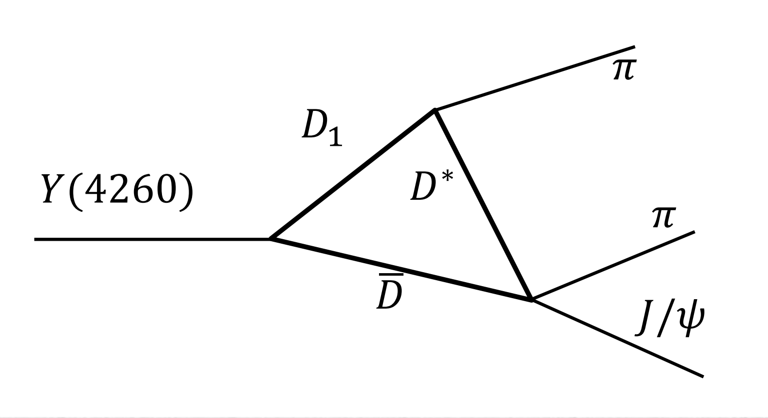
$$f_i(s,t,u) = 16\pi \sum_{l=0}^{L_{\max}} (2l+1)\left(a_{l,i}^{(s)}(s)P_l(z_s) + a_{l,i}^{(t)}(t)P_l(z_t) + a_{l,i}^{(u)}(u)P_l(z_u)\right)$$ Khuri-Treiman

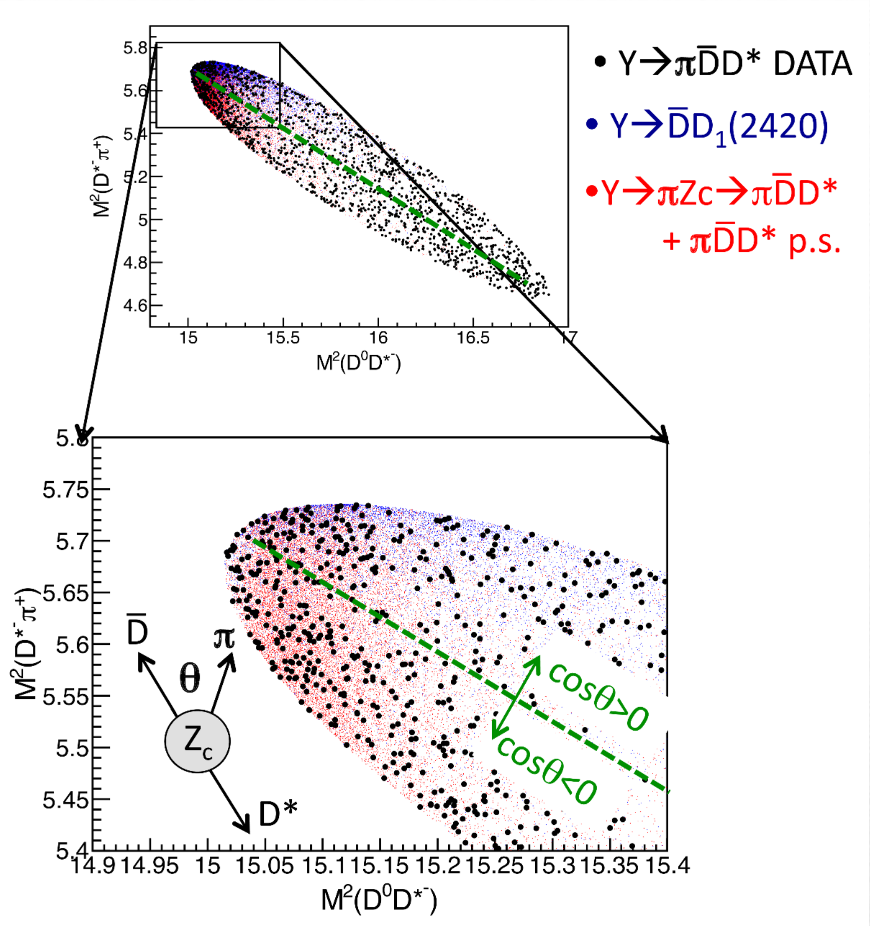
$$f_{0,i}(s) = \frac{1}{32\pi}\int_{-1}^{1} dz_s\, f_i\left(s, t(s,z_s), u(s,z_s)\right) = a_{0,i}^{(s)} + \frac{1}{32\pi}\int_{-1}^{1} dz_s \left(a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u)\right) \equiv a_{0,i}^{(s)} + b_{0,i}(s)$$

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

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

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

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

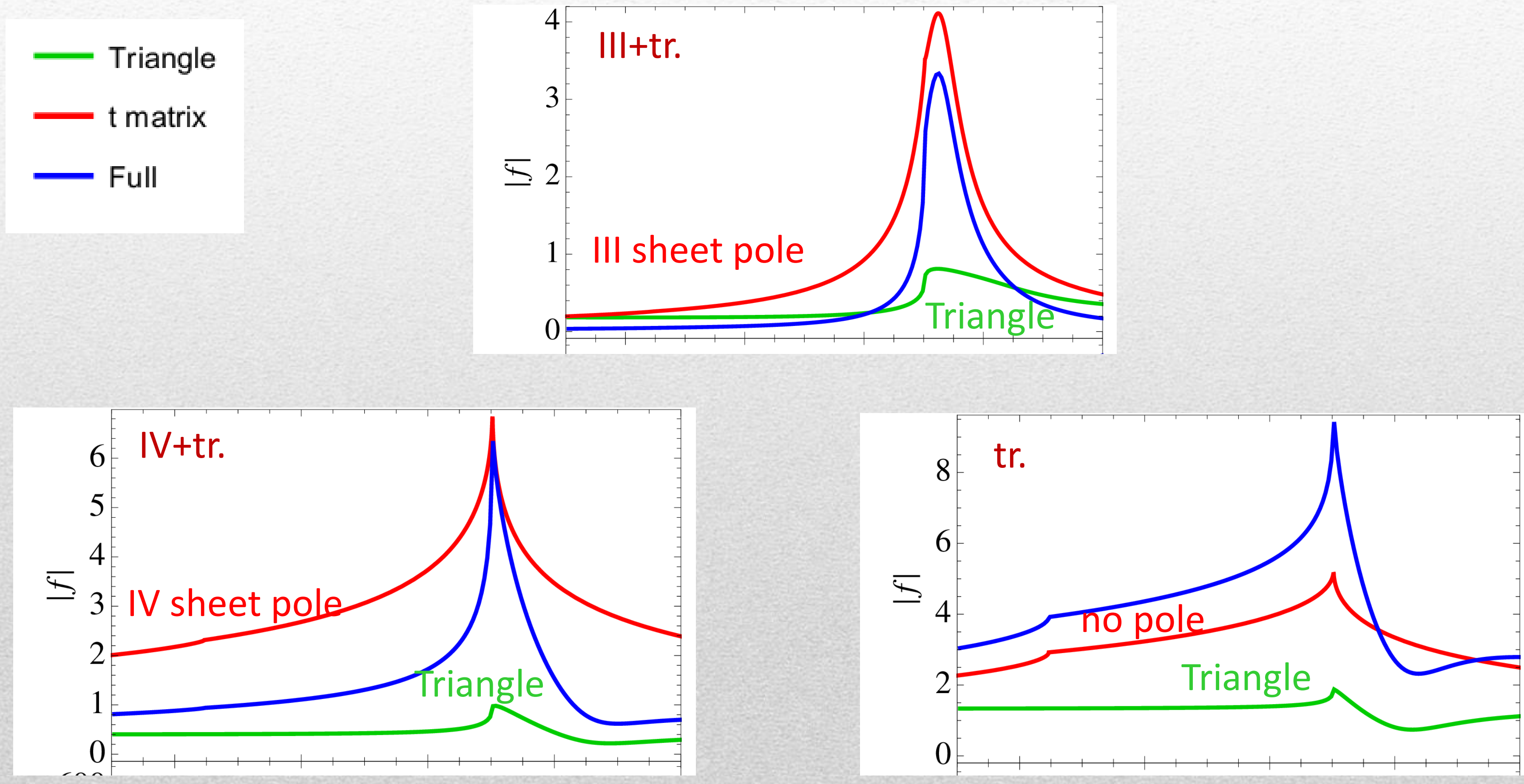
The scattering matrix is parametrized as $(t^{-1})_{ij} = K_{ij} - i\,\rho_i\,\delta_{ij}$

Four different scenarios considered:

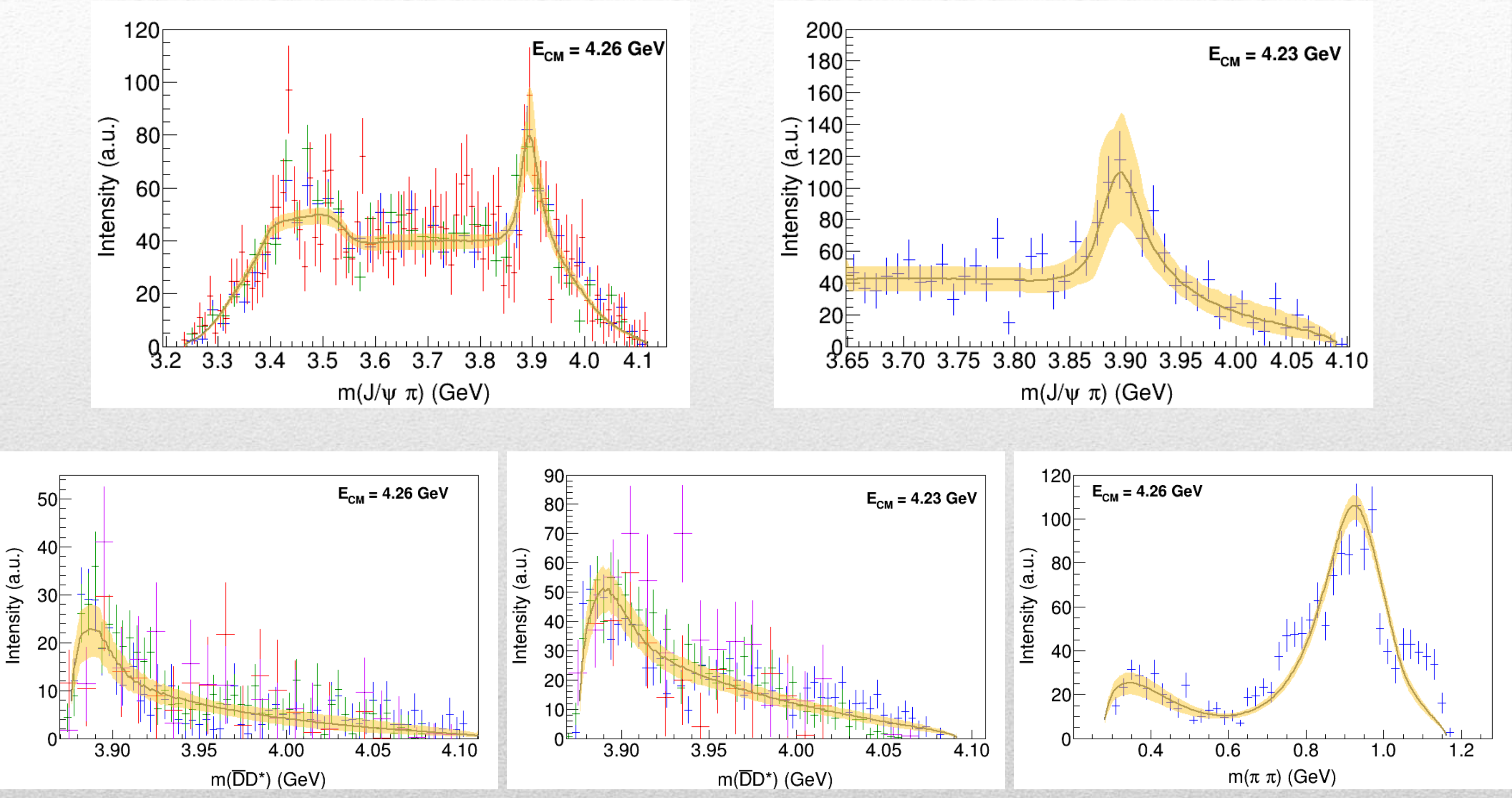
- «III»: the K matrix is $\frac{g_i\,g_j}{M^2 - s}$, this generates a pole in the closest unphysical sheet the rescattering integral is set to zero
- «III+tr.»: same, but with the correct value of the rescattering integral
- «IV+tr.»: the K matrix is constant, this generates a pole in the IV sheet
-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

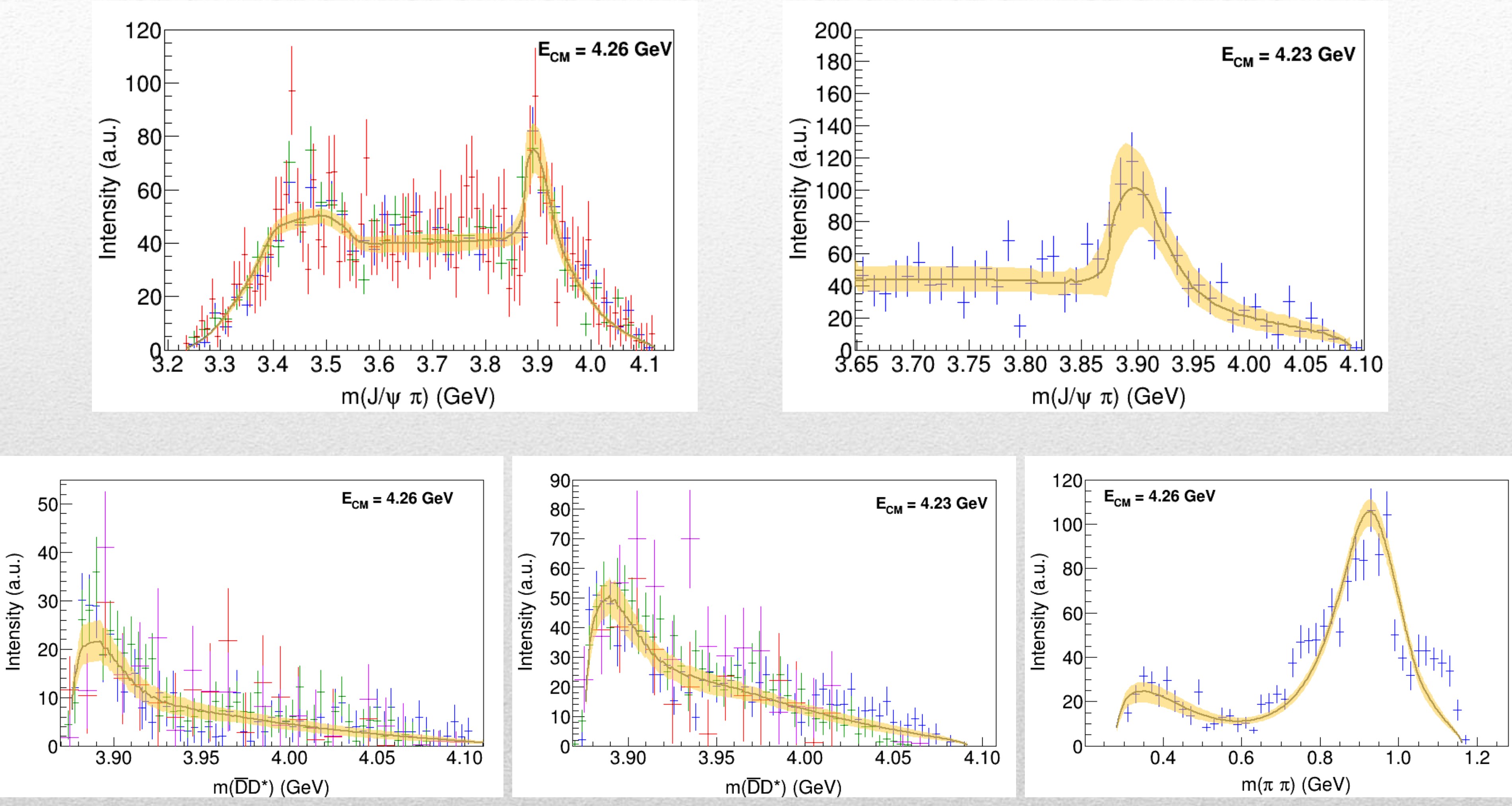


Fit: III



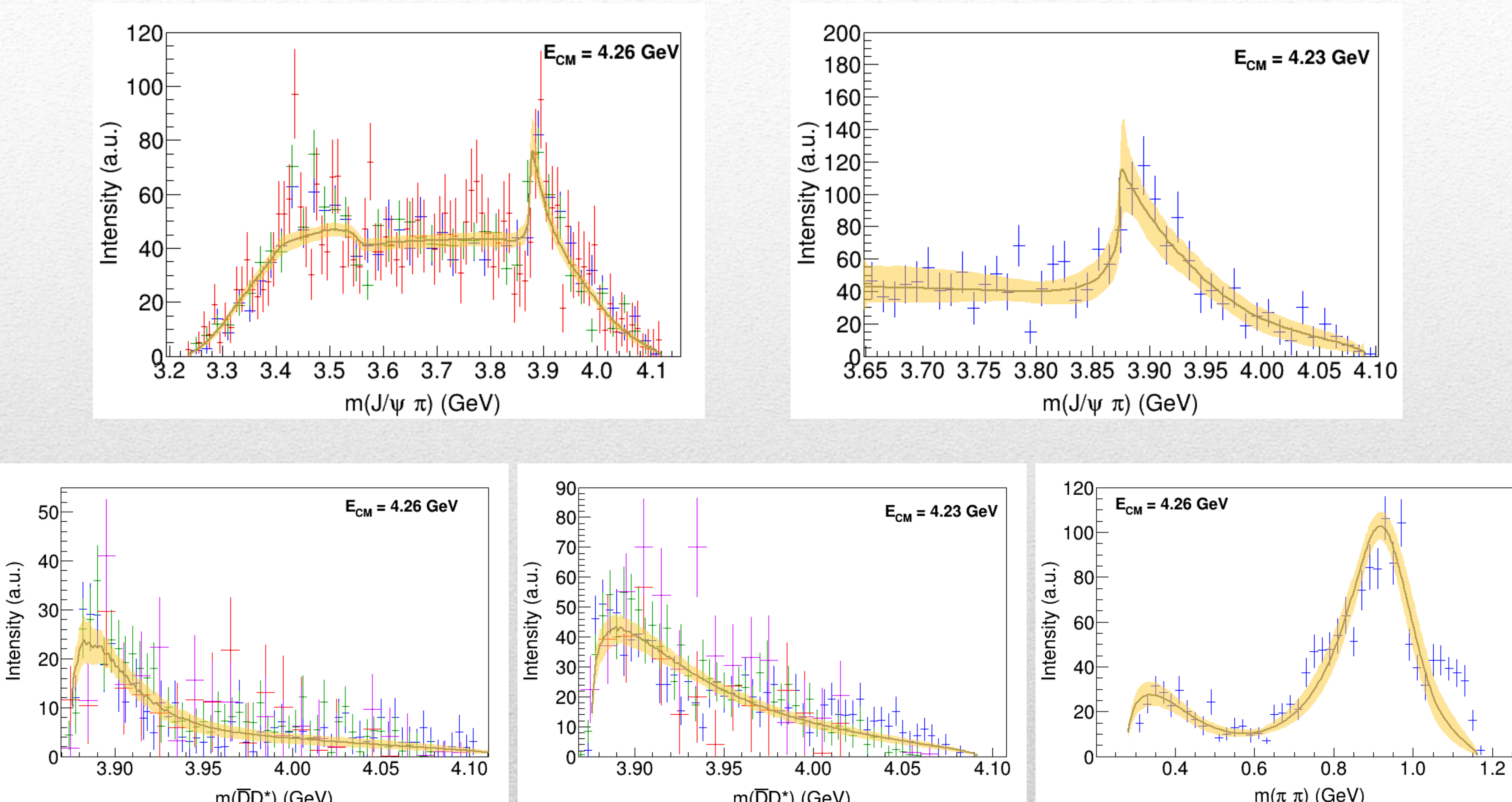
E_{CM} = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
E_{CM} = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
E_{CM} = 4.26 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)
E_{CM} = 4.23 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)
E_{CM} = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

Fit: III+tr.



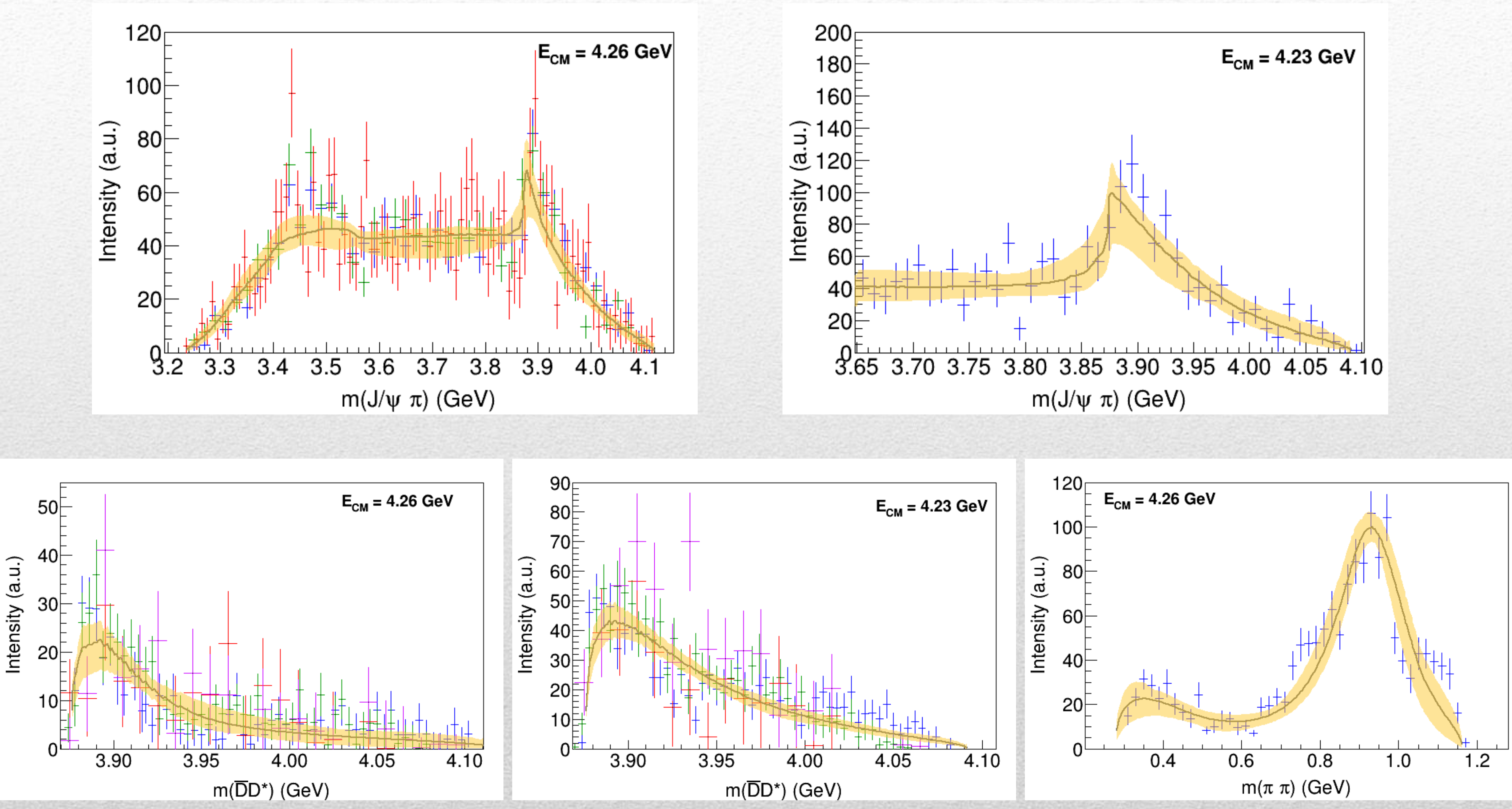
E_{CM} = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
E_{CM} = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
E_{CM} = 4.26 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)
E_{CM} = 4.23 GeV
Intensity (a.u.)
m($\bar{D}$D*) (GeV)
E_{CM} = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

Fit: IV+tr.



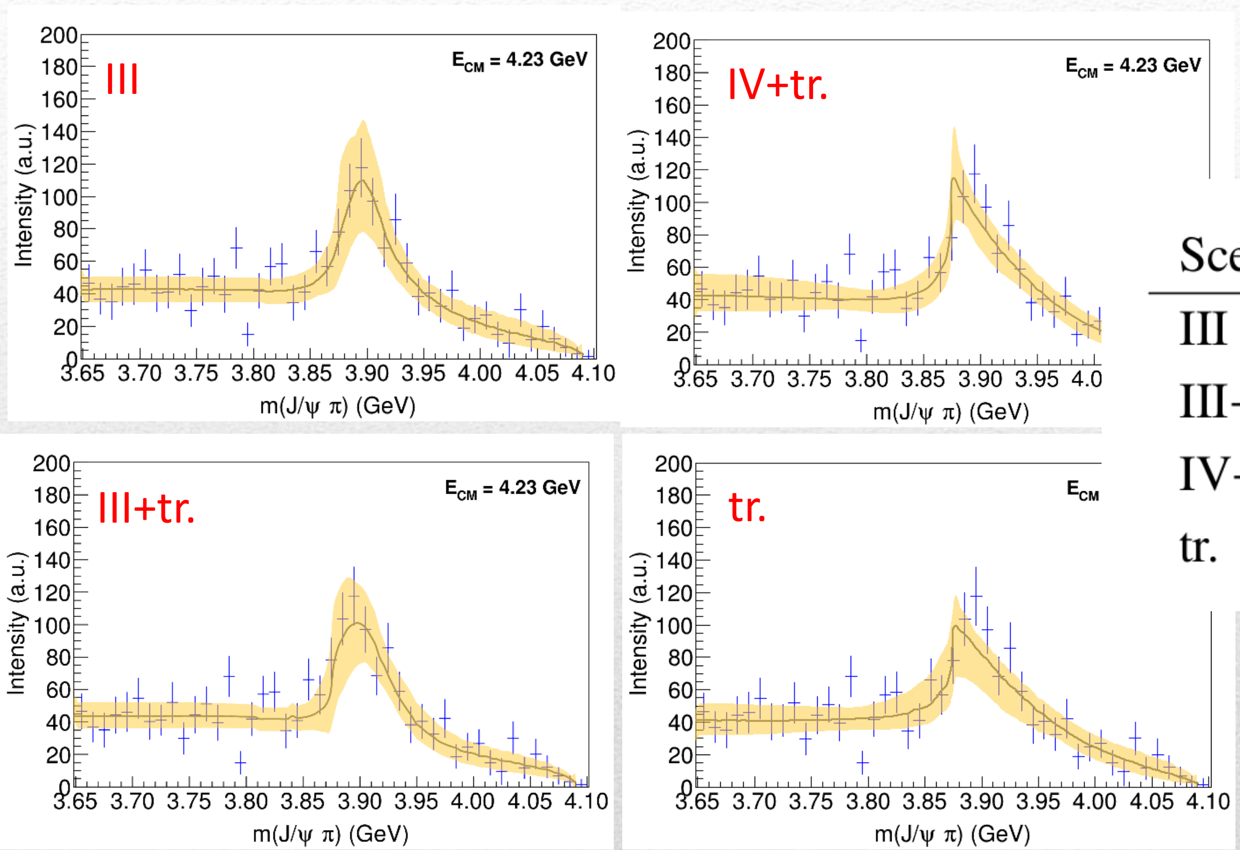
E_CM = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
E_CM = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)
E_CM = 4.26 GeV
Intensity (a.u.)
m(D̄D*) (GeV)
E_CM = 4.23 GeV
Intensity (a.u.)
m(D̄D*) (GeV)
E_CM = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

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(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)

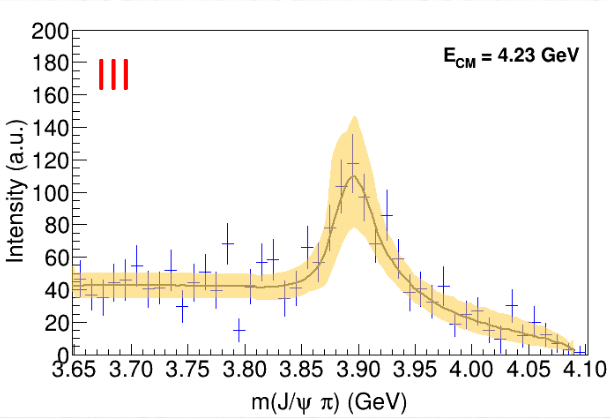
Fit summary

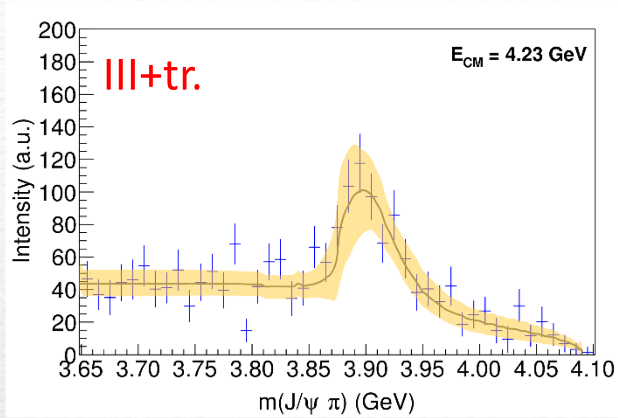


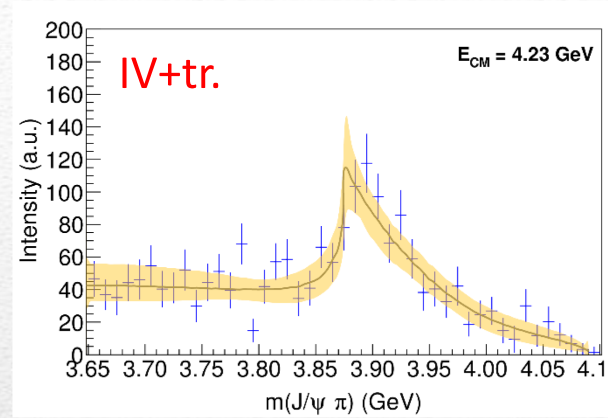
Scenario	χ^2	DOF	χ^2/DOF
III	644	532	1.21
III+tr.	642	532	1.21
IV+tr.	666	532	1.25
tr.	695	532	1.31

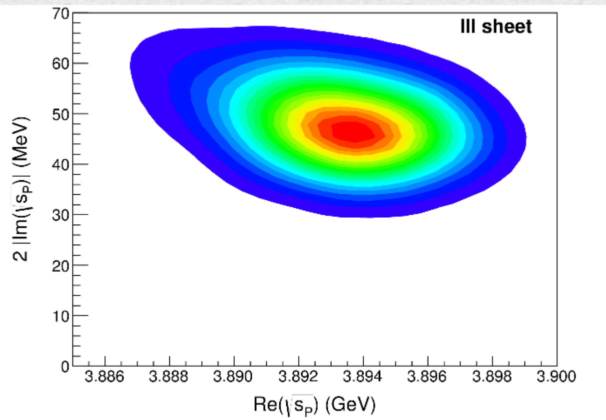
Naive loglikelihood ratio test give a $\sim 4\sigma$ significance of the scenario III+tr. over IV+tr., looking at plots it looks too much – better using some more solid test

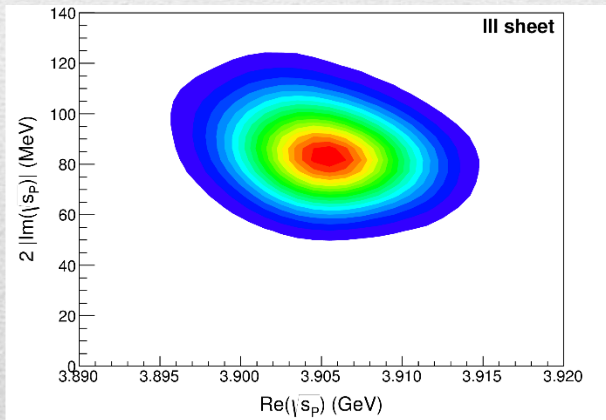
Pole extraction

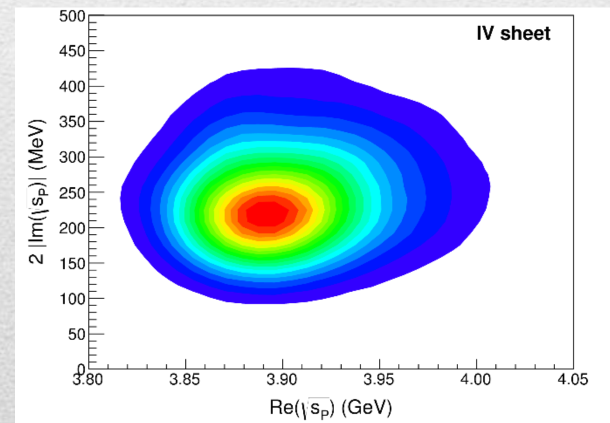






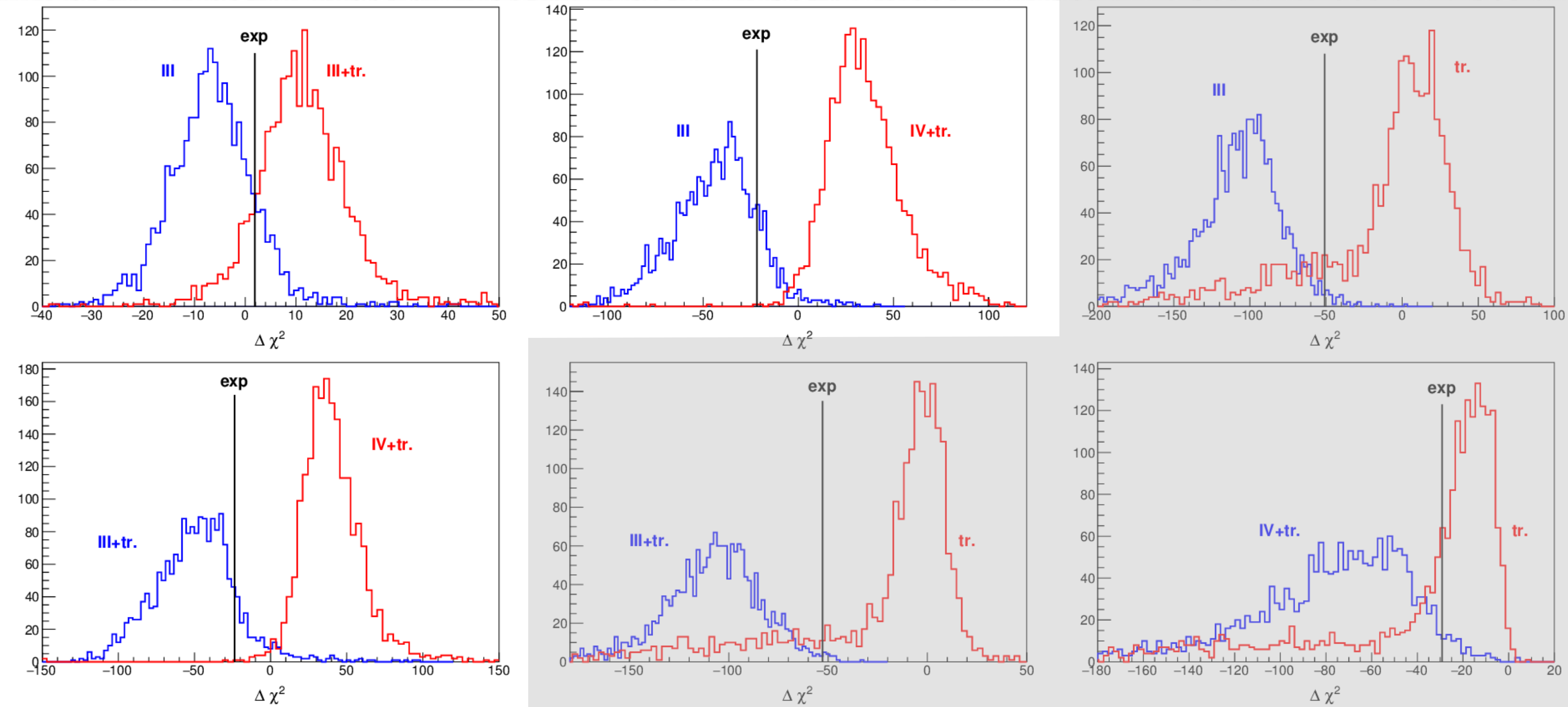






	III	III+tr.	IV+tr.
M (MeV)	$3893.2^{+5.5}_{-7.7}$	3905^{+11}_{-9}	3900^{+140}_{-90}
Γ (MeV)	48^{+19}_{-14}	85^{+45}_{-26}	240^{+230}_{-130}

Statistical analysis

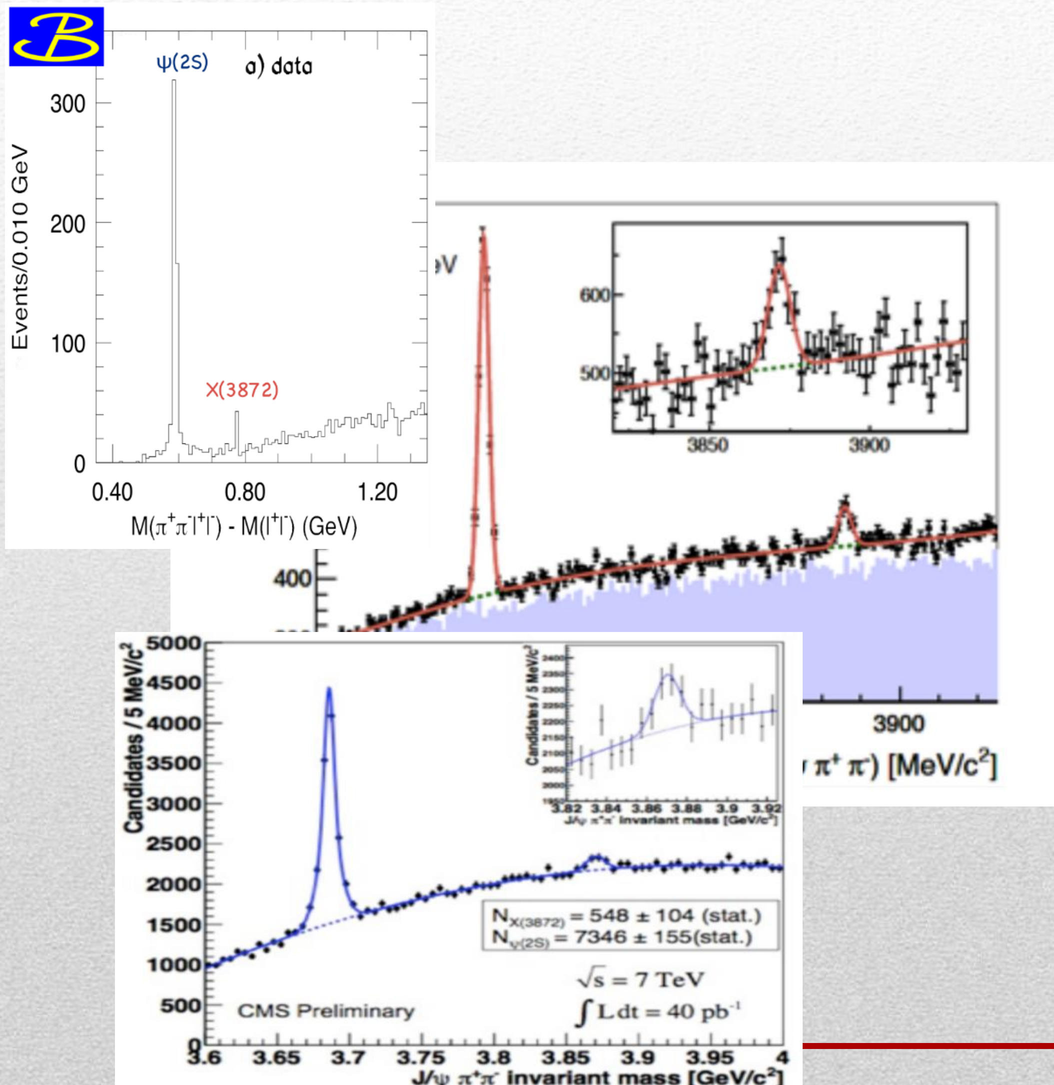


Toy experiments according to the different hypotheses, to estimate the relative rejection of various scenarios

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

$X(3872)$



- 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%

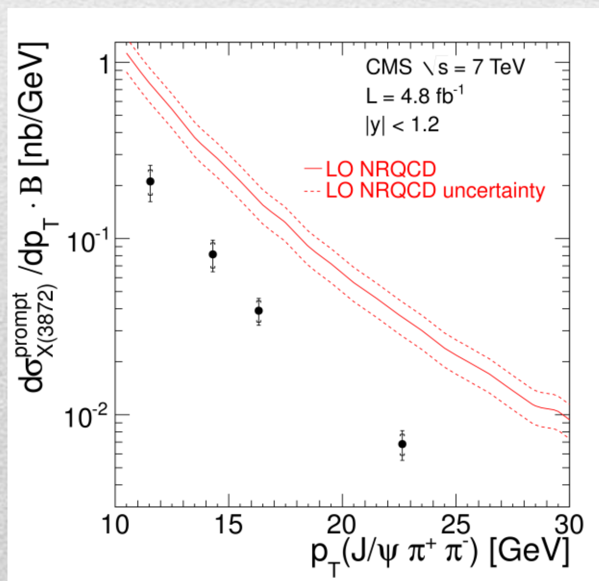
$X(3872)$

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 ($\times 10^5$)		$\mathcal{B}_{fit}$	R_{fit}
K^+X	$X \to \pi\pi J/\psi$	**0.86 ± 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	$X \to \pi\pi J/\psi$	**0.41 ± 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	$X \to D^{*0}\bar{D}^0$	**8.5 ± 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	$X \to D^{*0}\bar{D}^0$	**12 ± 4**	(BABAR,[38] Belle[37])		
		$22 \pm 10 \pm 4$	BABAR[38]		
		$9.7 \pm 4.6 \pm 1.3$	Belle[37]		
K^+X	$X \to \gamma J/\psi$	**0.202 ± 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	$X \to \gamma\psi(2S)$	**0.44 ± 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]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

Weinberg theorem

Resonant scattering amplitude

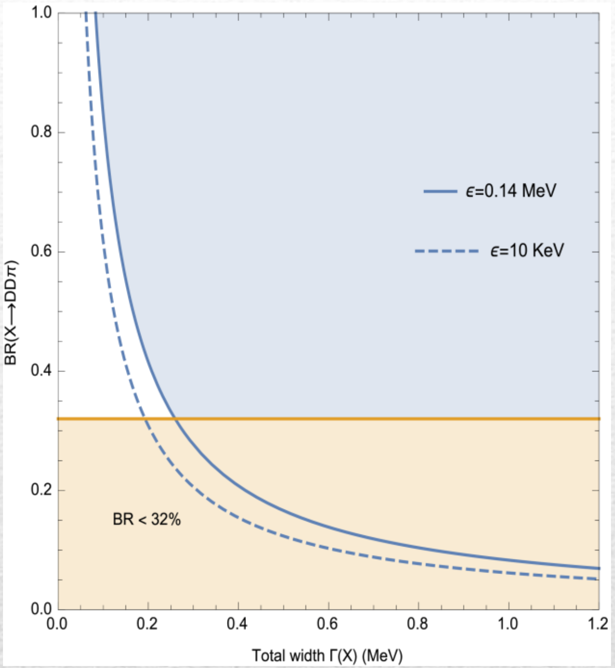
$$f(ab \to c \to ab) = -\frac{1}{8\pi\, E_{CM}} g^2 \frac{1}{(p_a + p_b)^2 - m_c^2}$$

with $m_c = m_a + m_b - B$, and $B, T \ll m_{a,b}$

$$f(ab \to c \to ab) = -\frac{1}{16\pi(m_a + m_b)^2} g^2 \frac{1}{B + T}$$

This has to be compared with the potential scattering for slow particles ($kR \ll 1$, being $R \sim 1/m_\pi$ the range of interaction) in an attractive potential U with a superficial level at $-B$

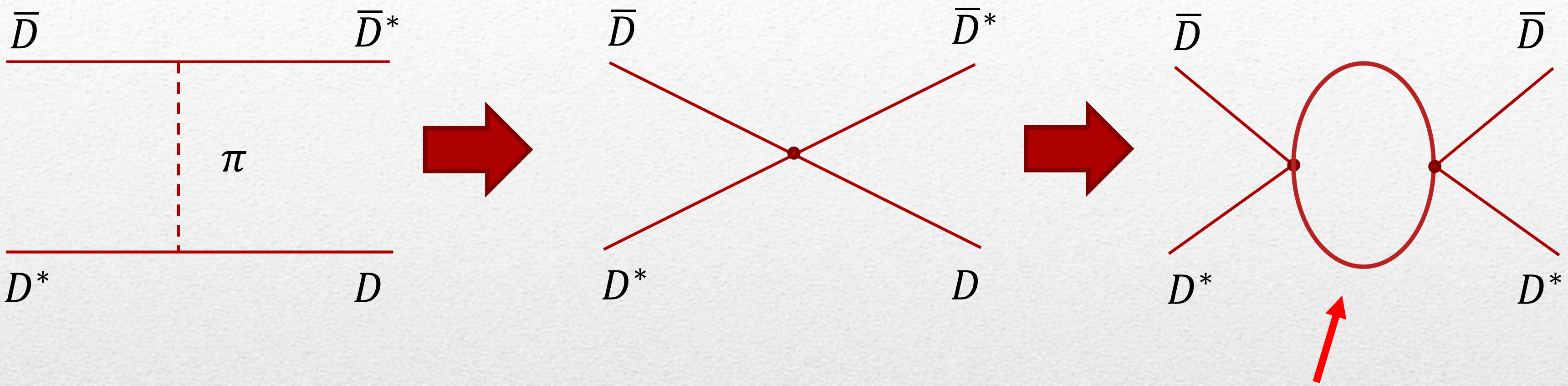
$$f(ab \to ab) = -\frac{1}{\sqrt{2\mu}} \frac{\sqrt{B} - i\sqrt{T}}{B + T}, B = \frac{g^4}{512\pi^2} \frac{\mu^5}{(m_a m_b)^2}$$



This corresponds to the pure molecular interpretation of the $X(3872)$

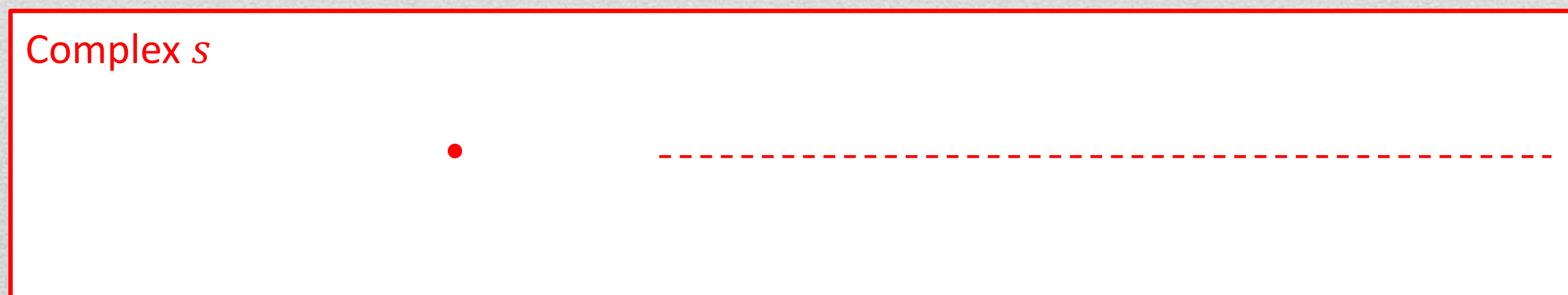
Weinberg, PR 130, 776
Weinberg, PR 137, B672
Polosa, PLB 746, 248

Weinberg and amplitudes



This means that IF you can consider the pion exchange as a contact interaction,
the amplitude is determined by the pole close to threshold

This loop is now divergent,
I need to renormalize the integral
I can put the pole where I want

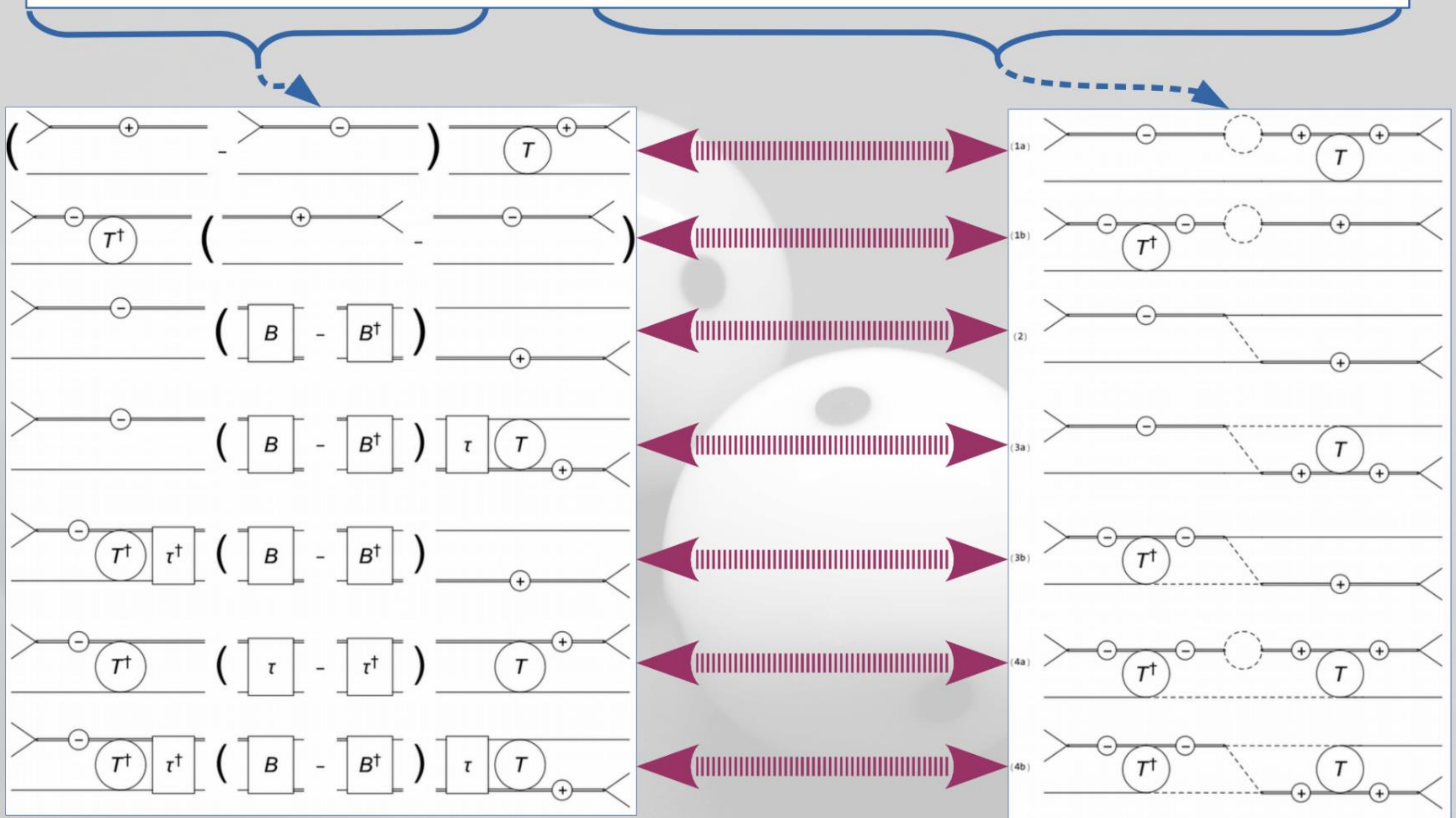


Three-Body Unitarity

Mai, Hu, Doring, AP, Szczepaniak, EPJA53, 9, 177
See talk by M. Doring tomorrow

3-body Unitarity (normalization condition ↔ phase space integral)

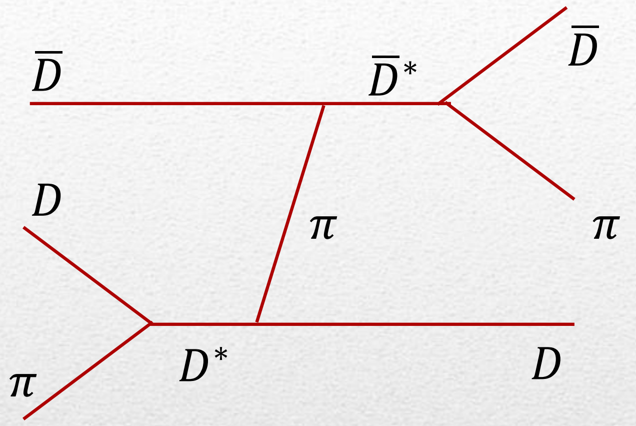
$$\langle q_1, q_2, q_3|(\hat{T}-\hat{T}^\dagger)|p_1, p_2, p_3\rangle = i\int_P \langle q_1, q_2, q_3|\hat{T}^\dagger|k_1, k_2, k_3\rangle\langle k_1, k_2, k_3|\hat{T}|p_1, p_2, p_3\rangle$$



M. Mai

Weinberg and amplitudes

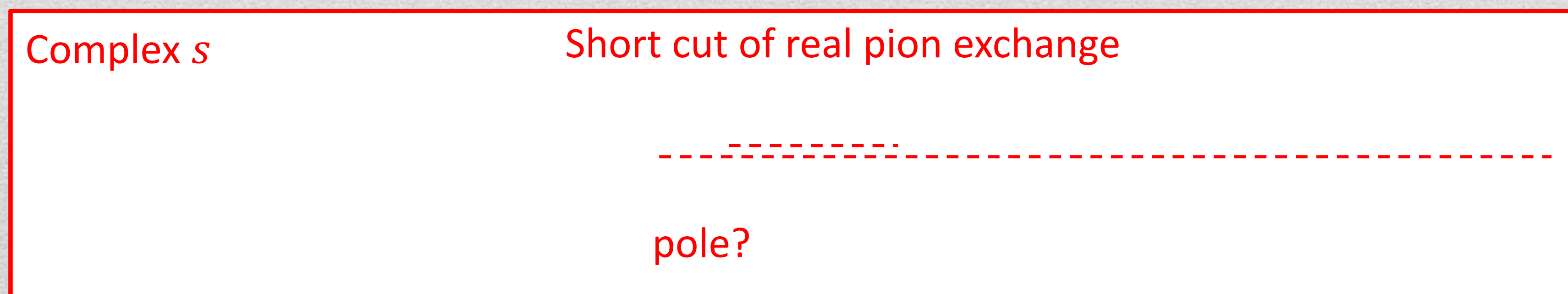
A. Jackura et al., in progress



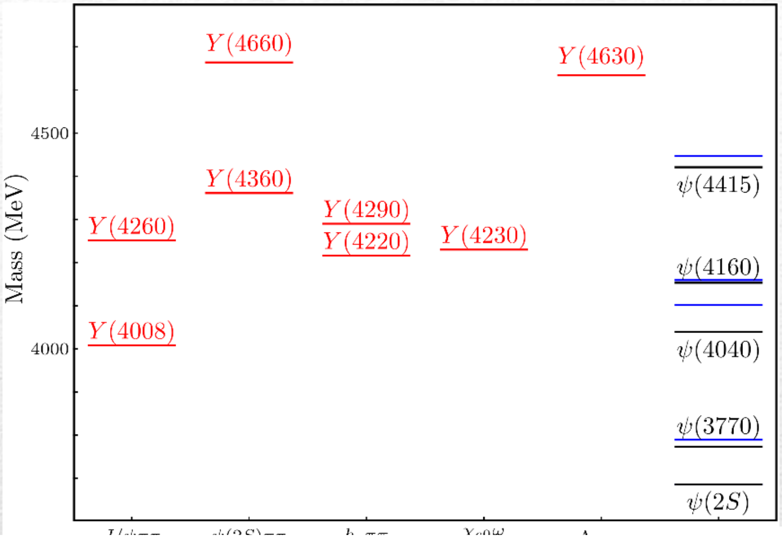
BUT the D^* actually decays into $D\pi$ and the system is constrained by 3-body unitarity

The position of the pole can be calculated given a model for the simple pion exchange

The simplest model leads to a convergent dispersion relation, the pole position is determined
One can check whether this purely molecular amplitude is consistent or not with data



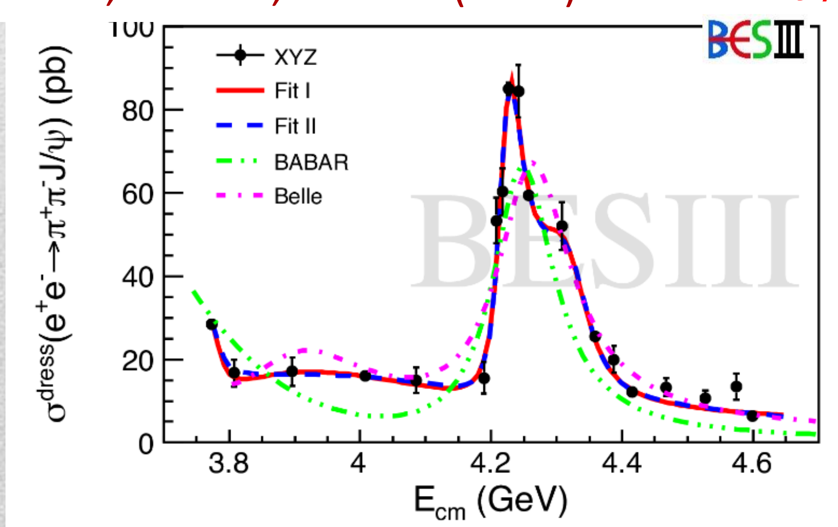
Vector Y states

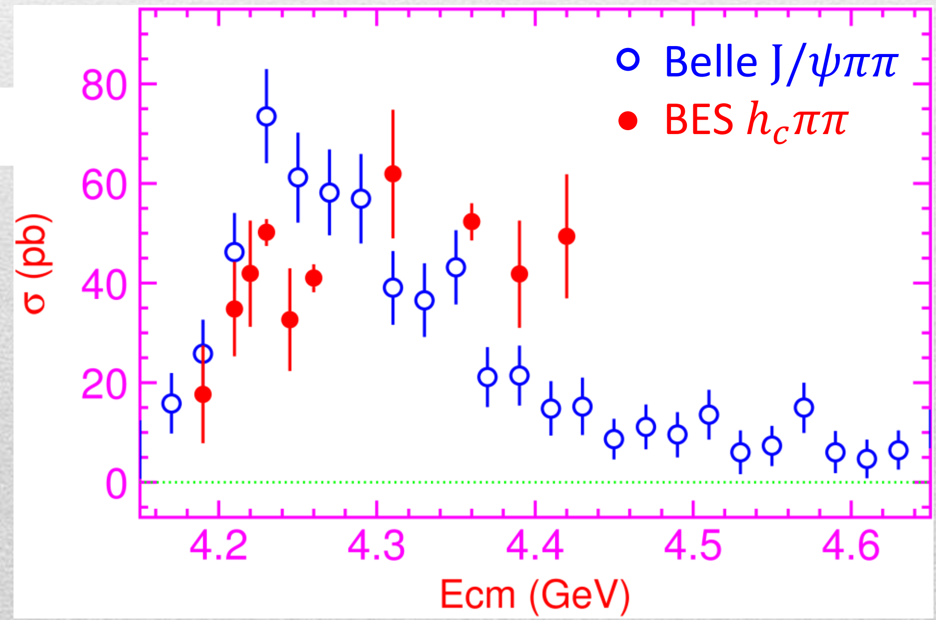


Lots of unexpected $J^{PC} = 1^{--}$ states
found in ISR/direct production (and nowhere else!)
Seen in few final states,
mostly $J/\psi\ \pi\pi$ and $\psi(2S)\ \pi\pi$

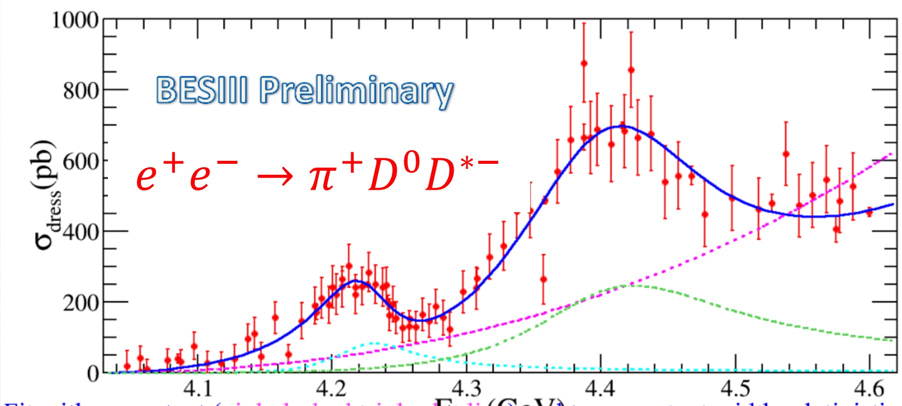
Not seen decaying into open charm pairs
Large HQSS violation

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





Vector Y states



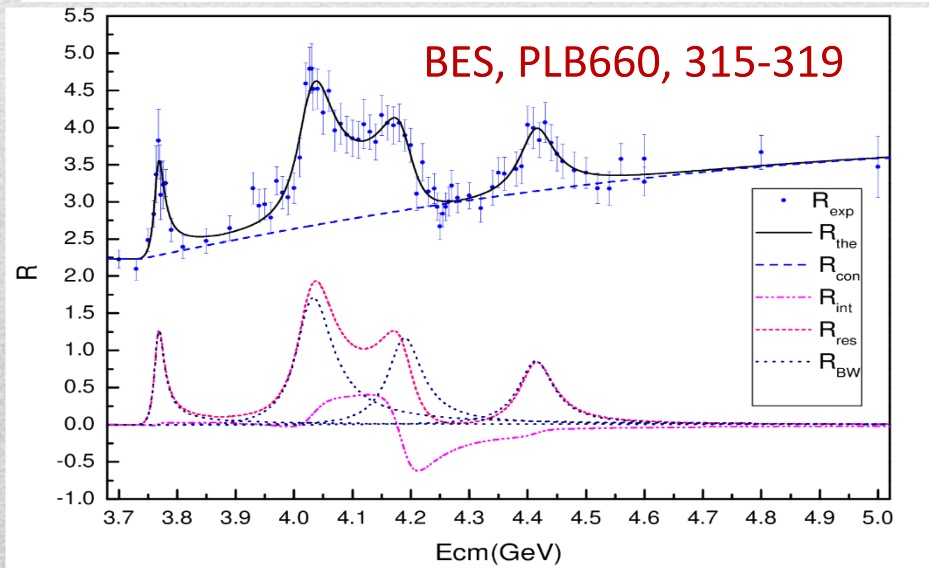
Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

$M(Y(4220)) = (4224.8 \pm 5.6 \pm 4.0)$ MeV/c^2, $\Gamma(Y(4220)) = (72.3 \pm 9.1 \pm 0.9)$ MeV.

$M(Y(4390)) = (4400.1 \pm 9.3 \pm 2.1)$ MeV/c^2, $\Gamma(Y(4220)) = (181.7 \pm 16.9 \pm 7.4)$ MeV.

6

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



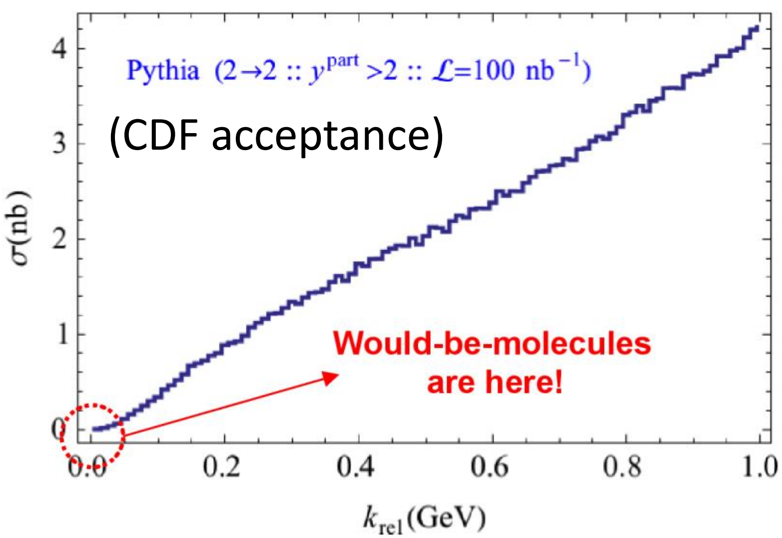
Most of the information about the ordinary charmonium comes from a BES fit to the R ratio

Times for a more refined analysis has come!

A. Amor, C. Fernandez-Ramirez, AP, U. Tamponi, in progress

Prompt production of $X(3872)$

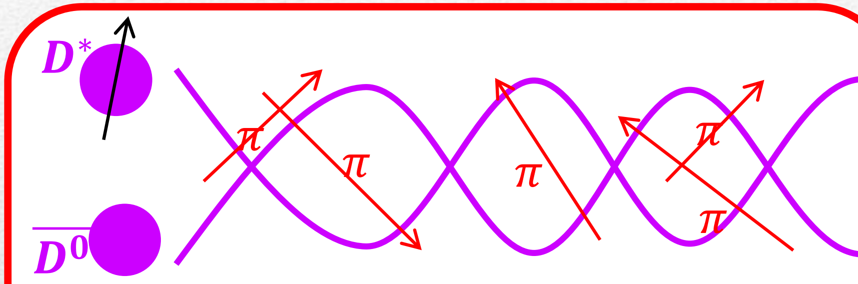
$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?) but it is copiously promptly produced at hadron colliders



$$\sigma_{MC}(p\bar{p} \to DD^*|k < k_{max}) \approx 0.1 \text{ nb}$$

$$\sigma_{exp}(p\bar{p} \to X(3872)) \approx 30 - 70 \text{ nb!!!}$$

Bignamini *et al.* PRL103 (2009) 162001



A solution can be FSI (rescattering of DD^*), which allow k_{max} to be as large as $5m_\pi$, $\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

However, the rescattering is flawed by the presence of pions that interfere with DD^* propagation. Estimating the effect of these pions increases σ, but not enough

Bignamini *et al.* PLB684, 228-230

Esposito, Piccinini, AP, Polosa, JMP 4, 1569

Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

Production of $Y(4260)$ and $P_c(4450)$

Given the new lineshape by BESIII, we need to rethink the binding energy of the $Y(4260)$

J. Nys and AP, to appear

	Constituents	Bind. Energy	Bind. Mom.	Mediator
$X(3872)$	$\bar{D}^0 D^{*0}$	$\sim$100 keV	$\sim$50 MeV	1π ($\sim$300 MeV)
$Y(4260)$	$\bar{D} D_1$	$\sim$70 MeV	$\sim$400 MeV	2π ($\sim$600 MeV)
$P_c(4450)$	$\bar{D}^* \Sigma_c$	$\sim$10 MeV	$\sim$150 MeV	1π ($\sim$300 MeV)

If the states are purely hadron molecule, all the properties depend on the position of the pole with respect to threshold – all the features are universal

What does the production of $X(3872)$ implies for the other states?

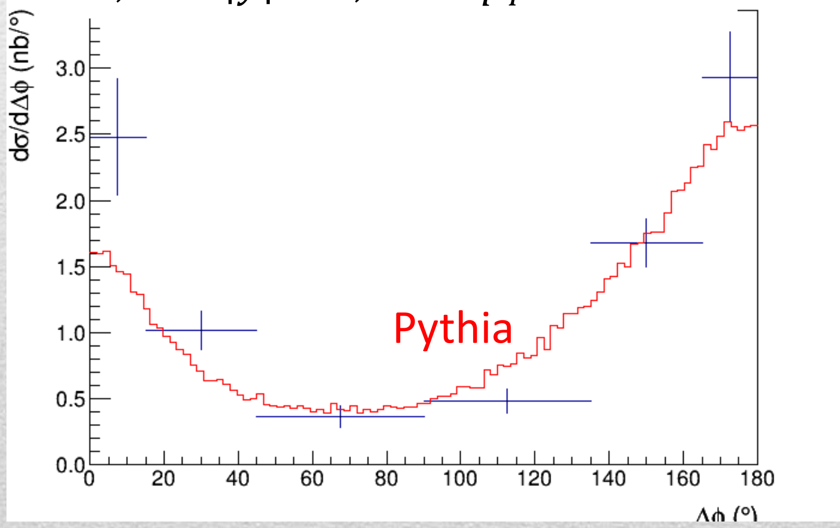
Production of $Y(4260)$ and $P_c(4450)$

We can use Pythia to simulate the production of event, and calculate the relative production of $Y(4260)$ and $P_c(4450)$ with respect to the $X(3872)$

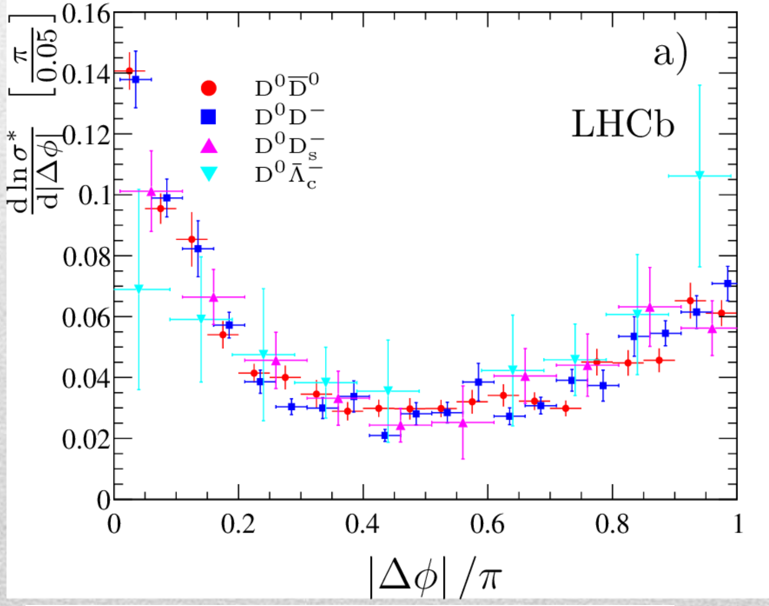
J. Nys and AP, to appear

We tune our MC on charm pair production

CDF data, $\sqrt{s} = 1.96$ TeV
D^0, D^{*-}: $|y| < 1, 5.5 < p_T < 20$ GeV



For baryons we can double check with LHCb data



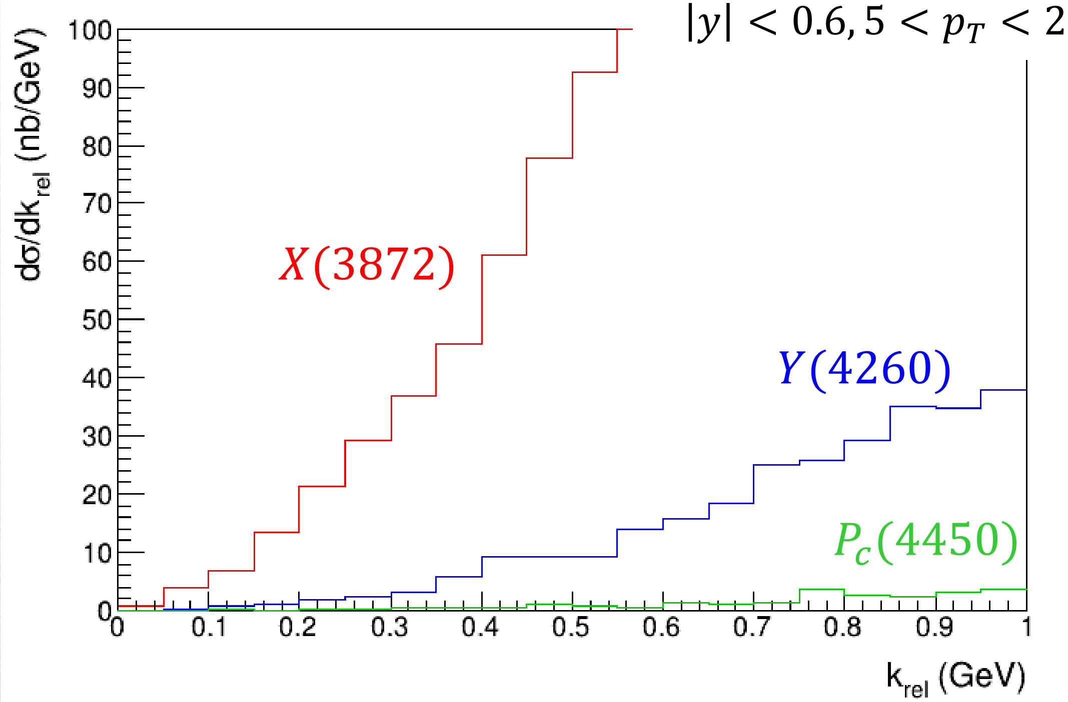
LHCb, $\sqrt{s} = 7$ TeV, JHEP 1206, 141
all: $2 < y < 4, 3 < p_T < 12$ GeV

Production of $Y(4260)$ and $P_c(4450)$

Naively, the fragmentation function of the D_1 is 1/10 of the D^*, but the cross section scales as k_{max}^3

J. Nys and AP, to appear

Pythia $p\bar{p}$, $\sqrt{s} = 1.96$ TeV
$|y| < 0.6, 5 < p_T < 20$ GeV



	No FSI	With FSI
$Y(4260)/X$	23	0.75
$P_c(4450)$/X	1.0	0.01

The production of $Y(4260)$ is expected to be at worse comparable with the $X(3872)$

Conclusions

- The discovery of exotic states has challenged the well established Charmonium framework
- Experiments are (too) prolific! Constant feedback on predictions
- Thorough amplitude analyses are requested to establish the existence of many of these states
- This also gives a guide to the interpretation of their microscopic nature

Thank you

BACKUP

Crossing symmetry in tensor formalisms

- The process $B \to \bar{D}\pi\pi$ is composed of scalar particles only

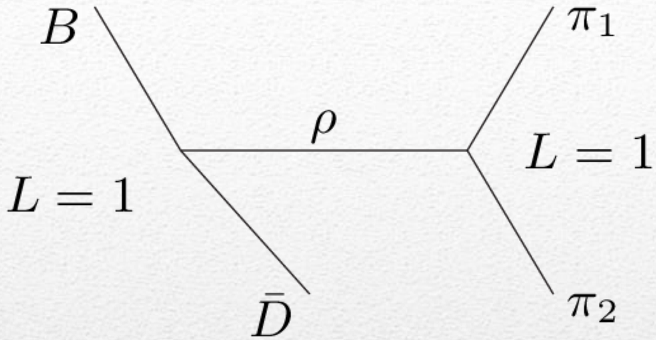
LHCb, PRD92, 032002 (2015)

- One defines the helicity angle in the isobar rest frame, then the amplitude is Lorentz Invariant
- Let's consider the ρ intermediate state, $B \to \bar{D}\rho(\to \pi\pi)$

$$A = \frac{m_B^2 + s - m_D^2}{2m_B^2} \cos\theta \times qp = \frac{E_\rho^{(B)}}{m_B} \cos\theta \times qp$$

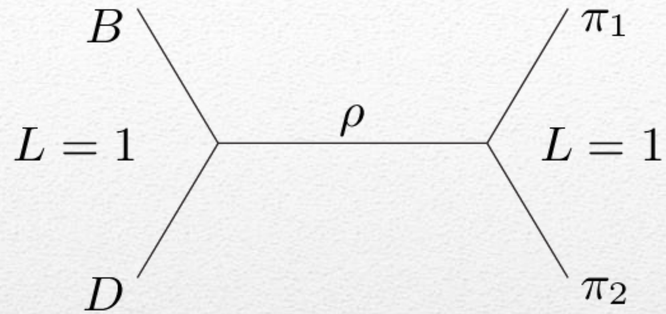
- The factors p and q are the $L = 1$ expected barrier factors. The additional factor is analytical in s, not a kinematical singularity. Why is it there?

Crossing symmetry in tensor formalisms



The tensor amplitude is given by $p_D^{(B)} \cdot p_\pi^{(\rho)}$, where $p_D^{(B)}$ is the breakup momentum in the B frame, and $p_\pi^{(\rho)}$ the decay momentum in the isobar frame

$$A = \frac{m_{B^0}^2 + s - m_{h_3}^2}{2m_{B^0}^2} pq\cos\theta$$



However, one can consider the scattering process just in the isobar rest frame.

$$A = pq\cos\theta$$

By crossing symmetry the amplitudes must be the same.

The usual implementation fails crossing symmetry

Note on $X(3872)$ production at hadron colliders and its molecular structure

Miguel Albaladejo,[1] Feng-Kun Guo,[2,3] Christoph Hanhart,[4]
Ulf-G. Meißner,[5,4] Juan Nieves,[6] Andreas Nogga,[4] and Zhi Yang[5]

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v:1709.09101v1 [hep-ph] 26 Sep 2017

The production of the $X(3872)$ as a hadronic molecule in hadron colliders is clarified. We show that the conclusion of Bignamini *et al.*, Phys. Rev. Lett. **103** (2009) 162001, that the production of the $X(3872)$ at high p_T implies a non-molecular structure, does not hold. In particular, using the well understood properties of the deuteron wave function as an example, we identify the relevant scales in the production process.

The argument is about the value of a nonnormalizable wave function.
Any argument about where the wave function is localized must be calculated for the modulus square

A widespread argument against the interpretation of the $X(3872)$ as a hadronic molecule is its copious production at hadron colliders. Based on the inequality[1]

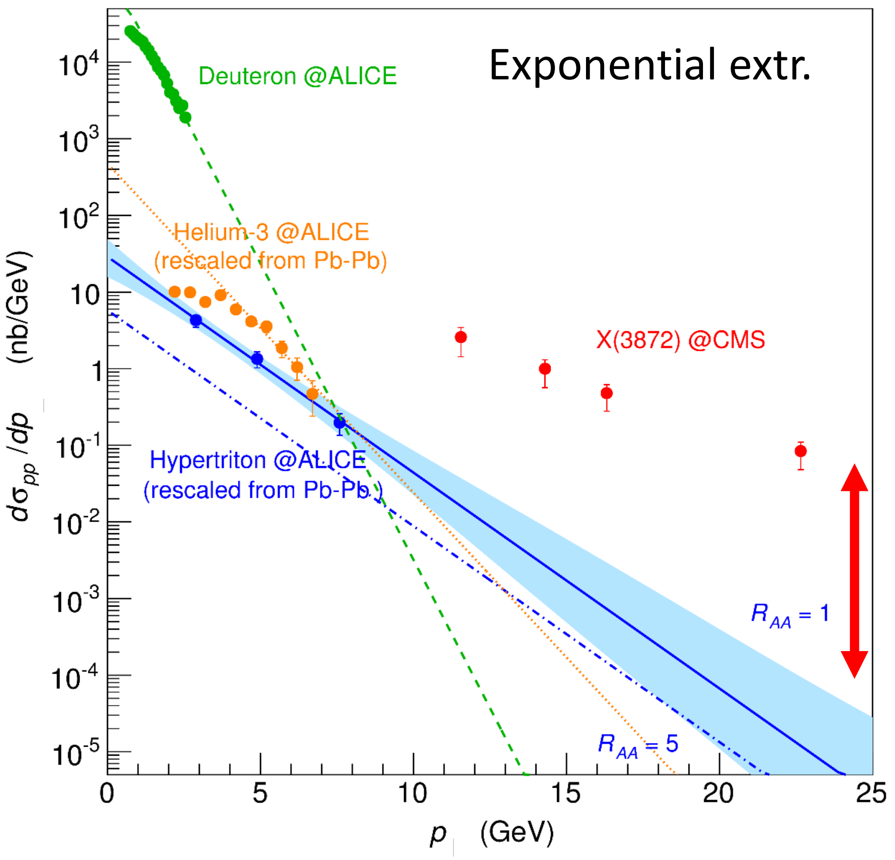
$$\sigma(\bar{p}p \to X) \sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$

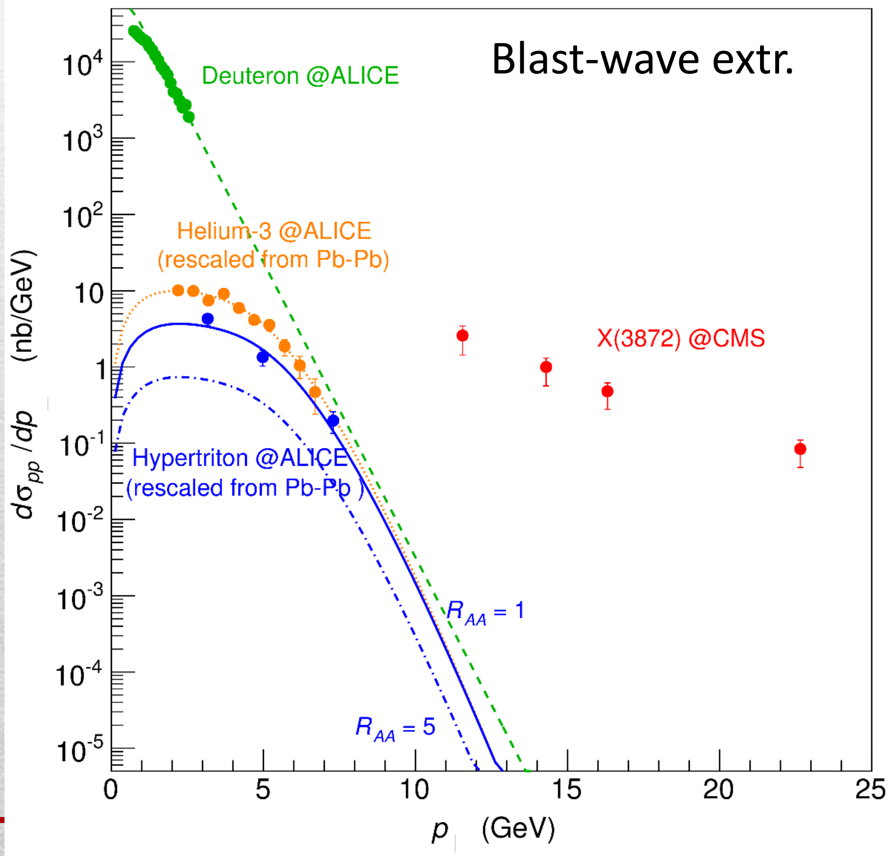
Light nuclei at ALICE vs. $X(3872)$

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp

The $X(3872)$ is way larger than the extrapolated cross section





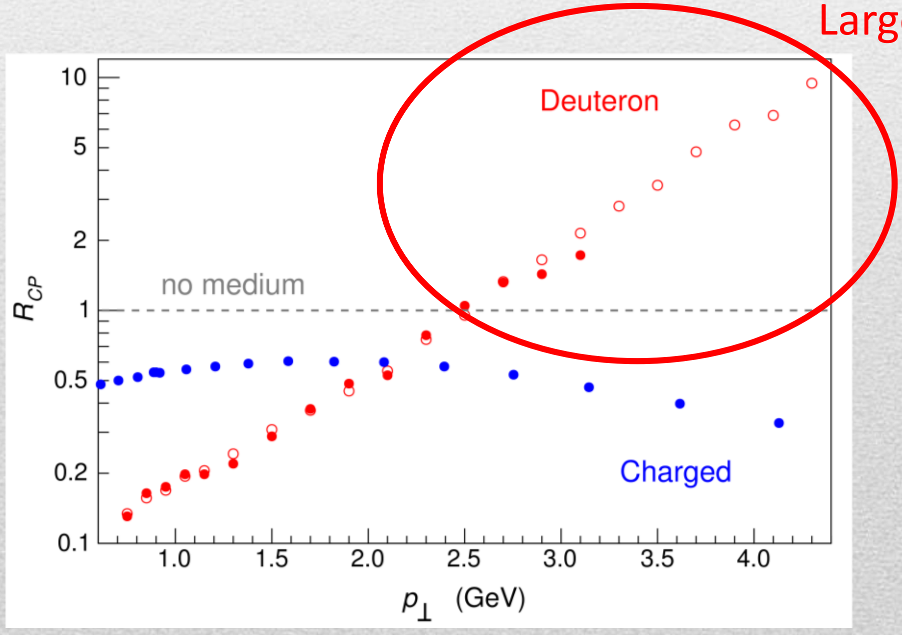
Nuclear modification factors

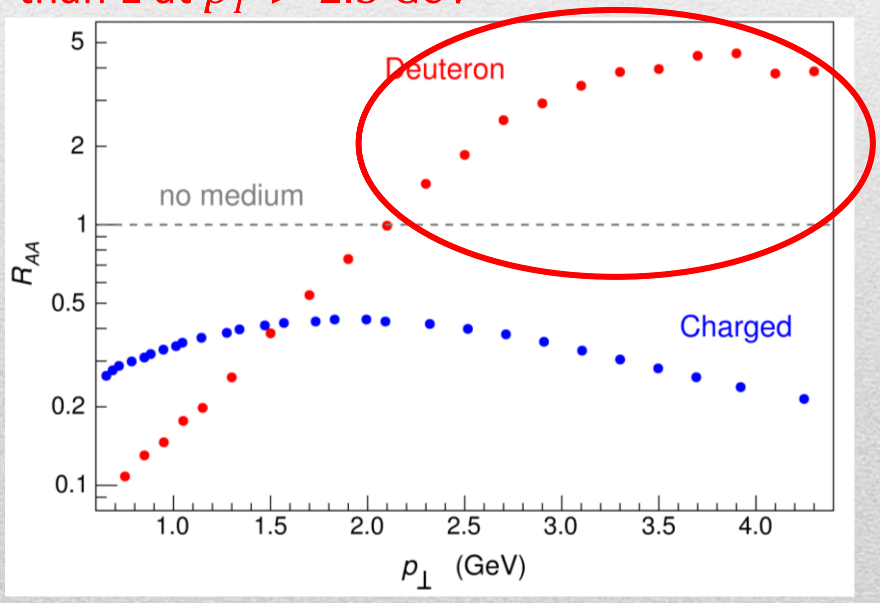
We can use deuteron data to extract the values of the nuclear modification factors (caveat: for RAA data have different $\sqrt{s}$)

$$R_{CP} = \frac{N_{coll}^{P}\left(\frac{dN}{dp_T}\right)_{\mathrm{C}}}{N_{coll}^{C}\left(\frac{dN}{dp_T}\right)_{P}}$$

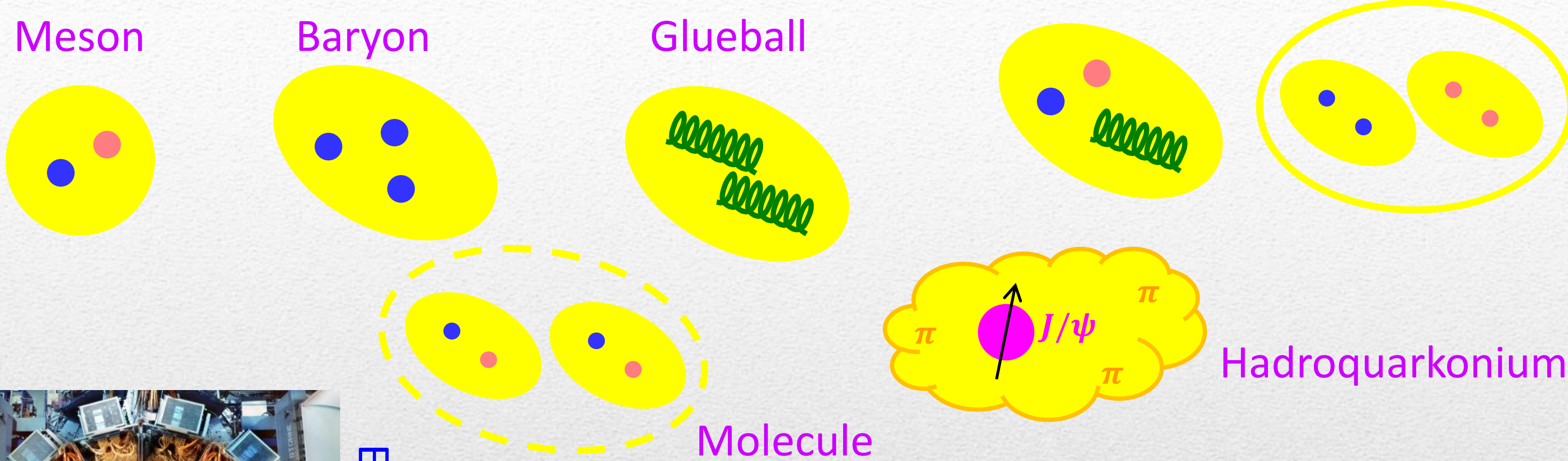
$$R_{AA} = \frac{\left(\frac{dN}{dp_T}\right)_{\mathrm{Pb-Pb}}}{N_{coll}\left(\frac{dN}{dp_T}\right)_{pp}}$$

Larger than 1 at $p_T > 2.5$ GeV

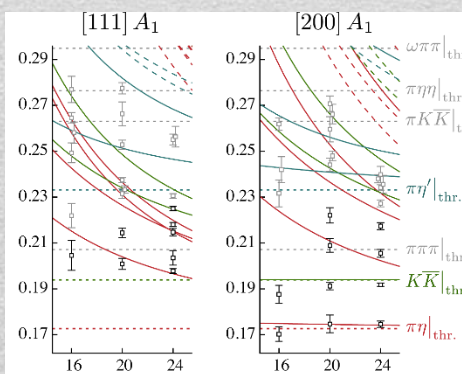




Hadron Spectroscopy



Experiment



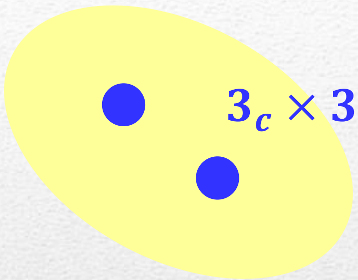
Lattice QCD

Data → Amplitude analysis (JPAC) → Properties, Model building

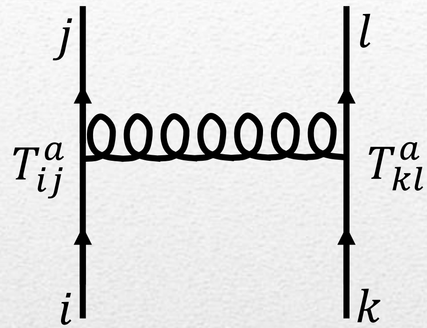
Interpretations on the spectrum leads to understanding fundamental laws of nature

Diquarks

Attraction and repulsion in 1-gluon exchange approximation is given by



$\mathbf{3}_c \times \mathbf{3}_c \in \bar{\mathbf{3}}_c$



$$R = \frac{1}{2}\left(C_2(R_{12}) - C_2(R_1) - C_2(R_2)\right)$$

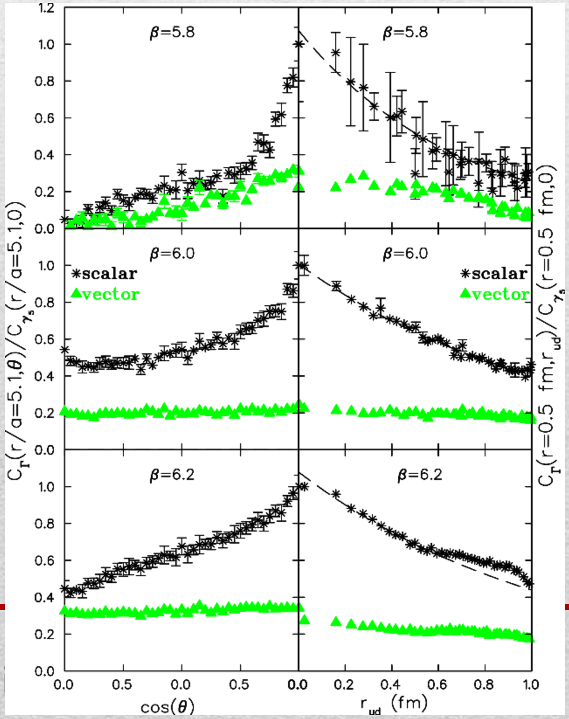
$$R_1 = -\frac{4}{3}, R_8 = +\frac{1}{6}$$

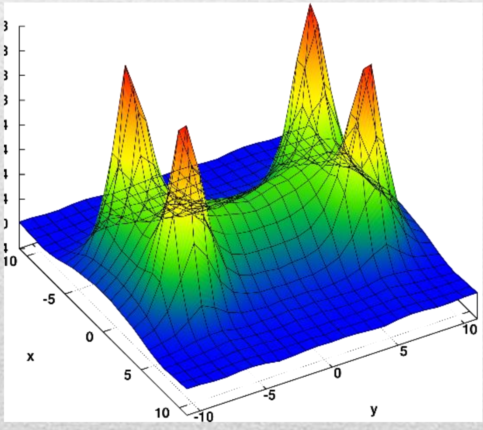
$$R_3 = -\frac{2}{3}, R_6 = +\frac{1}{3}$$

The singlet $\mathbf{1}_c$ is attractive

A diquark in $\bar{\mathbf{3}}_c$ is attractive

Evidence (?) of diquarks in LQCD, Alexandrou, de Forcrand, Lucini, PRL 97, 222002



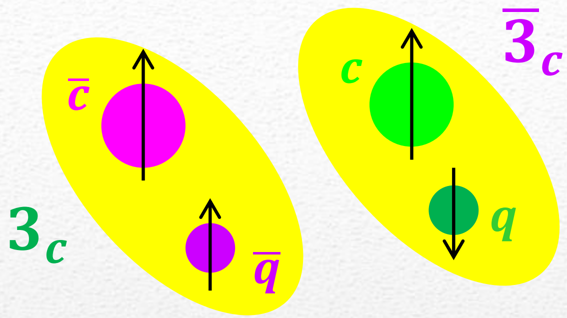


H-shape with a 4 quark system

Cardoso, Cardoso, Bicudo, PRD84, 054508

Tetraquark

In a constituent (di)quark model, we can think of a **diquark-antidiquark compact state**

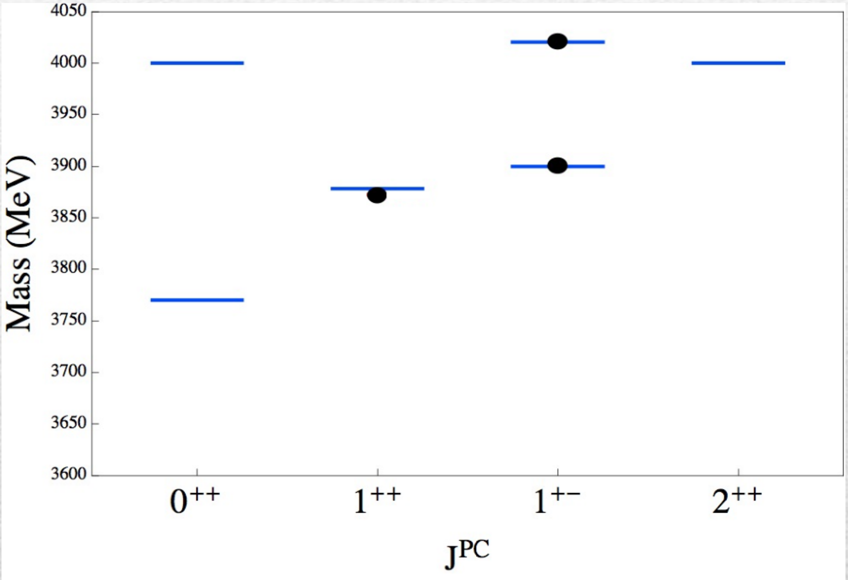


$$[cq]_{S=0}[\bar{c}\bar{q}]_{S=1} + h.c.$$

Maiani, Piccinini, Polosa, Riquer PRD71 014028
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 111102
Maiani, Piccinini, Polosa, Riquer PRD89 114010

Spectrum according to color-spin hamiltonian (all the terms of the Breit-Fermi hamiltonian are absorbed into a constant diquark mass):

$$H = \sum_{dq} m_{dq} + 2 \sum_{i<j} \kappa_{ij}\, \vec{S_i} \cdot \vec{S_j}\, \frac{\lambda_i^a}{2} \frac{\lambda_j^a}{2}$$



Decay pattern mostly driven by HQSS ✓
Fair understanding of existing spectrum ✓
A full nonet for each level is expected ✗

New ansatz: the diquarks are compact objects spacially separated from each other, only $\kappa_{cq} \neq 0$

Existing spectrum is fitted if $\kappa_{cq} = 67$ MeV

Tetraquark

Maiani, Piccinini, Polosa, Riquer PRD89 114010

J^{PC}	$cq\,\bar{c}\bar{q}$	$c\bar{c}\,q\bar{q}$	Resonance Assig.	Decays
0^{++}	$\|0,0\rangle$	$1/2\|0,0\rangle+\sqrt{3}/2\|1,1\rangle_0$	$X_0(\sim 3770\text{ MeV})$	$\eta_c, J/\psi$ + light mesons
0^{++}	$\|1,1\rangle_0$	$\sqrt{3}/2\|0,0\rangle-1/2\|1,1\rangle_0$	$X_0'(\sim 4000\text{ MeV})$	$\eta_c, J/\psi$ + light mesons
1^{++}	$1/\sqrt{2}(\|1,0\rangle+\|0,1\rangle)$	$\|1,1\rangle_1$	$X_1=X(3872)$	$J/\psi+\rho/\omega,\ DD^*$
1^{+-}	$1/\sqrt{2}(\|1,0\rangle-\|0,1\rangle)$	$1/\sqrt{2}(\|1,0\rangle-\|0,1\rangle)$	$Z=Z(3900)$	$J/\psi+\pi,\ h_c/\eta_c+\pi/\rho$
1^{+-}	$\|1,1\rangle_1$	$1/\sqrt{2}(\|1,0\rangle+\|0,1\rangle)$	$Z'=Z(4020)$	$J/\psi+\pi,\ h_c/\eta_c+\pi/\rho$
2^{++}	$\|1,1\rangle_2$	$\|1,1\rangle_2$	$X_2(\sim 4000\text{ MeV})$	J/ψ + light mesons

$$H_{\text{eff}} = 2m_Q + \frac{B_Q}{2}\boldsymbol{L}^2 - 3\kappa_{cq} + 2a_Y\,\boldsymbol{L}\cdot\boldsymbol{S} + b_Y\frac{\langle S_{12}\rangle}{4} + \kappa_{cq}\left[2(\boldsymbol{S_q}\cdot\boldsymbol{S_c}+\boldsymbol{S_{\bar{q}}}\cdot\boldsymbol{S_{\bar{c}}})+3\right]$$

Ali, Maiani, *et al.* arXiv:1708.04650

Label	$\|S_Q, S_{\bar{Q}}; S, L\rangle_J$
Y_1	$\|0,0;0,1\rangle_1$
Y_2	$(\|1,0;1,1\rangle_1+\|0,1;1,1\rangle_1)/\sqrt{2}$
Y_3	$\|1,1;0,1\rangle_1$
Y_4	$\|1,1;2,1\rangle_1$
Y_5	$\|1,1;2,3\rangle_1$

Two different mass scenarios

$$M_1 = 4008\pm 40^{+114}_{-28},\quad M_2 = 4230\pm 8,\quad M_3 = 4341\pm 8,\quad M_4 = 4643\pm 9.$$

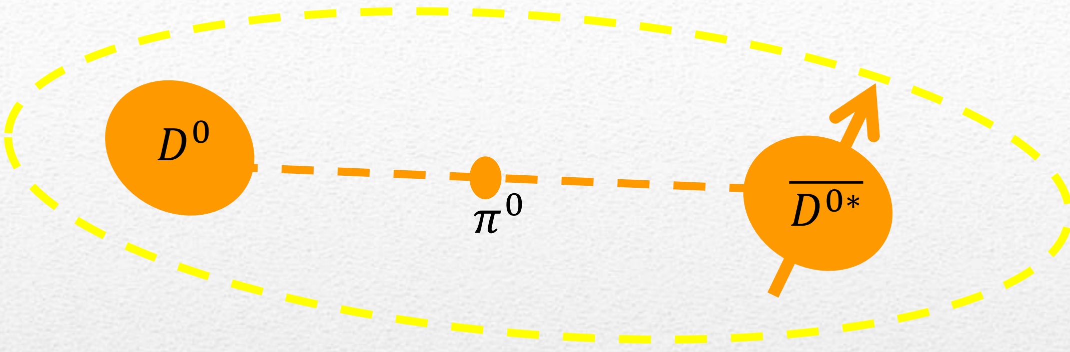
$$M_1 = 4219.6\pm 3.3\pm 5.1,\quad M_2 = 4333.2\pm 19.9,\quad M_3 = 4391.5\pm 6.3,\quad M_4 = 4643\pm 9,$$

Prediction for a high Y_5

$$M_5 = \begin{cases} 6539\text{ MeV} & \text{SI(c1)} \\ 6589\text{ MeV} & \text{SI(c2)} \\ 6862\text{ MeV} & \text{SII(c1)} \\ 6899\text{ MeV} & \text{SII(c2)} \end{cases}$$

Other models: Molecule

Tornqvist, Z.Phys. C61, 525
Braaten and Kusunoki, PRD69 074005
Swanson, Phys.Rept. 429 243-305



$X(3872) \sim \bar{D}^0 D^{*0}$
$Z_c(3900) \sim \bar{D}^0 D^{*+}$
$Z_c'(4020) \sim \bar{D}^{*0} D^{*+}$
$Y(4260) \sim \bar{D} D_1$

A deuteron-like meson pair, the interaction is mediated by the exchange of light mesons

- Some model-independent relations (Weinberg's theorem) ✓
- Good description of decay patterns (mostly to constituents) and $\mathrm{X}(3872)$ isospin violation ✓
- States appear close to thresholds ✓ (but $Z(4430)$ ✗)
- Lifetime of costituents has to be $\gg 1/m_\pi$
- Binding energy varies from -70 to -0.1 MeV, or even positive (repulsive interaction) ✗
- Unclear spectrum (a state for each threshold?) – depends on potential models ✗

$$V_\pi(r) = \frac{g_{\pi N}^2}{3} (\vec{\tau_1} \cdot \vec{\tau_2}) \left\{ [3(\vec{\sigma_1} \cdot \hat{r})(\vec{\sigma_2} \cdot \hat{r}) - (\vec{\sigma_1} \cdot \vec{\sigma_2})] \left(1 + \frac{3}{(m_\pi r)^2} + \frac{3}{m_\pi r} \right) + (\vec{\sigma_1} \cdot \vec{\sigma_2}) \right\} \frac{e^{-m_\pi r}}{r}$$

Needs regularization, cutoff dependence

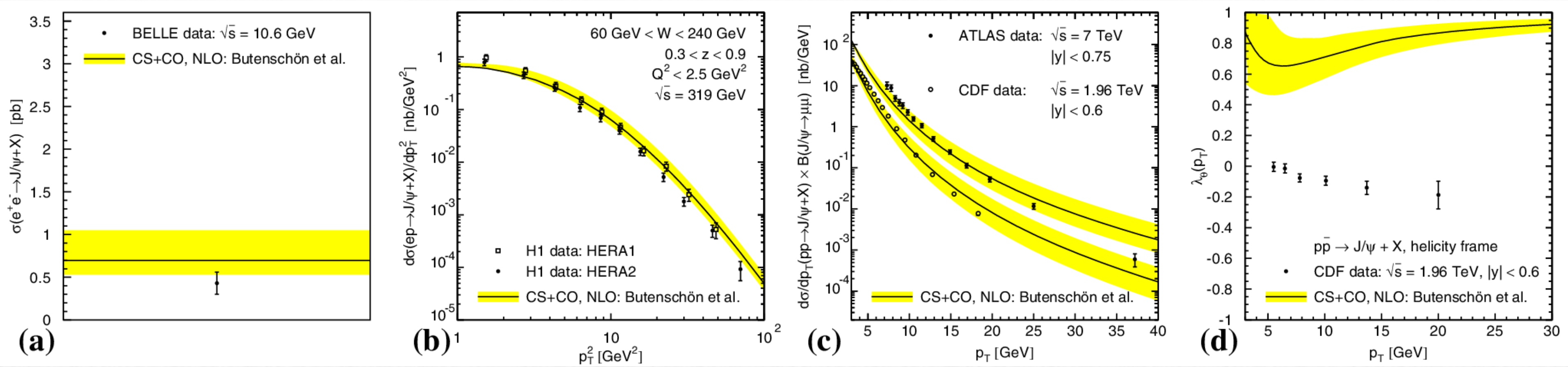
Multiscale system

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
$v_b^2 \sim 0.1, v_c^2 \sim 0.3$

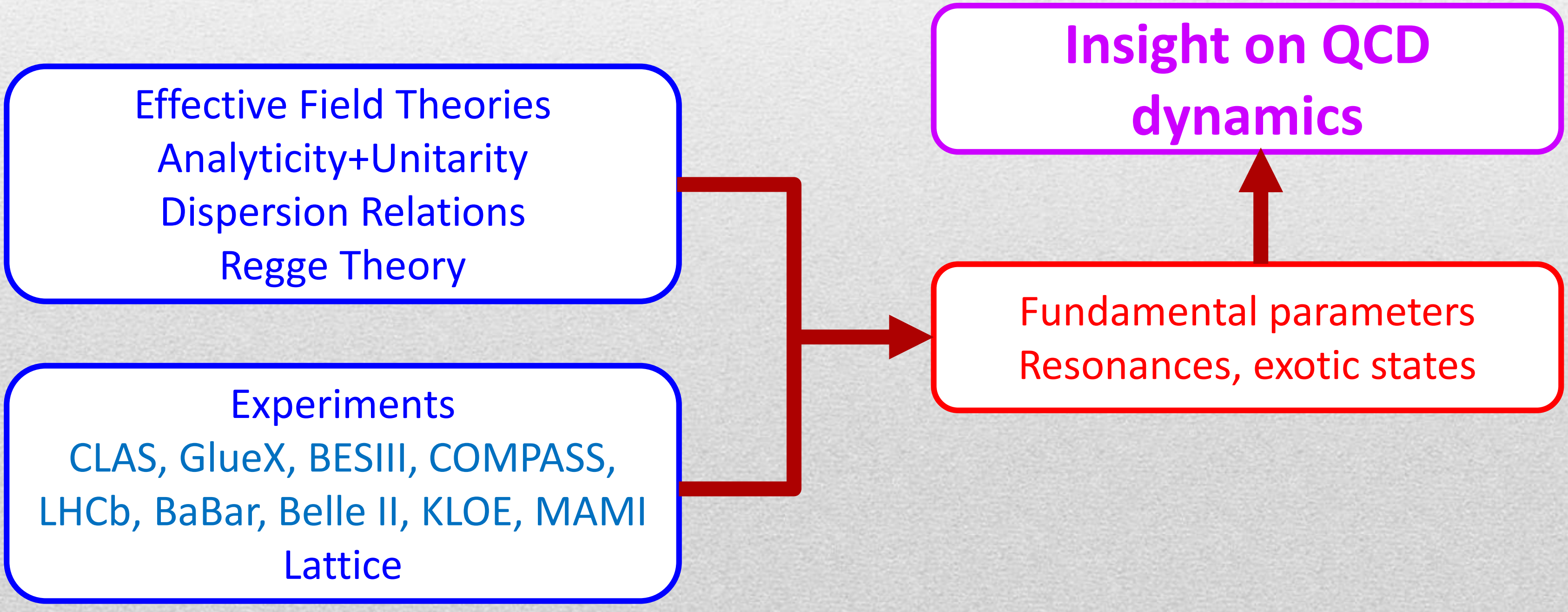


Factorization (to be proved) of universal LDMEs

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

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



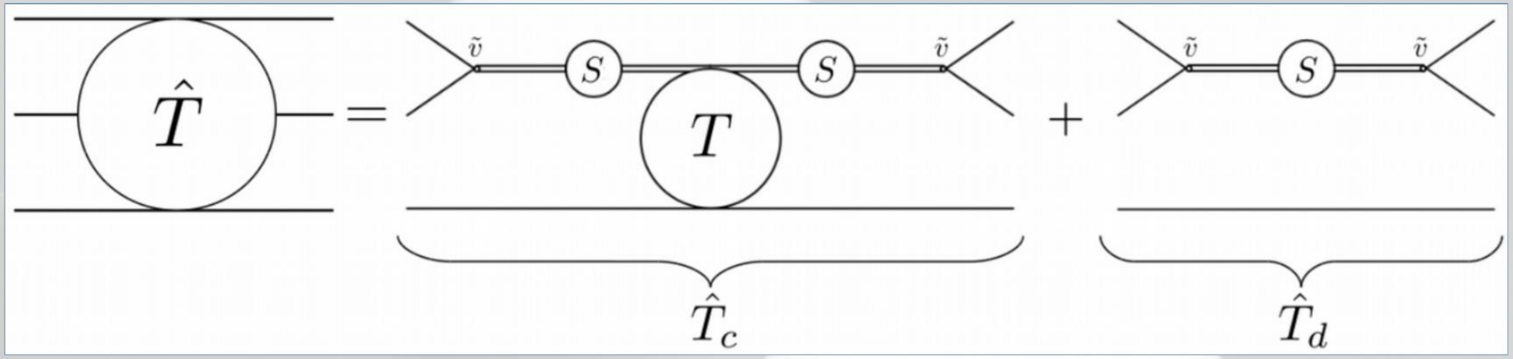
Three-Body Unitarity

Mai, Hu, Doring, AP, Szczepaniak, EPJA53, 9, 177

Original study by Amado/Aaron/Young **AAY(1968)**

- 3-dimensional integral equation from unitarity constraint & BSE ansatz
- valid below break-up energies ($E < 3m$)
- analyticity constraints unclear

One has to begin with asymptotic states



- v a general but cut-free (in the phys. region) function
- two-body interaction is parametrized by an *"isobar"*

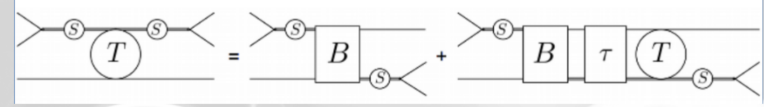
= has definite QN and correct r.h.-singularities w.r.t invariant mass

- **S and T are yet unknown functions**

M. Mai

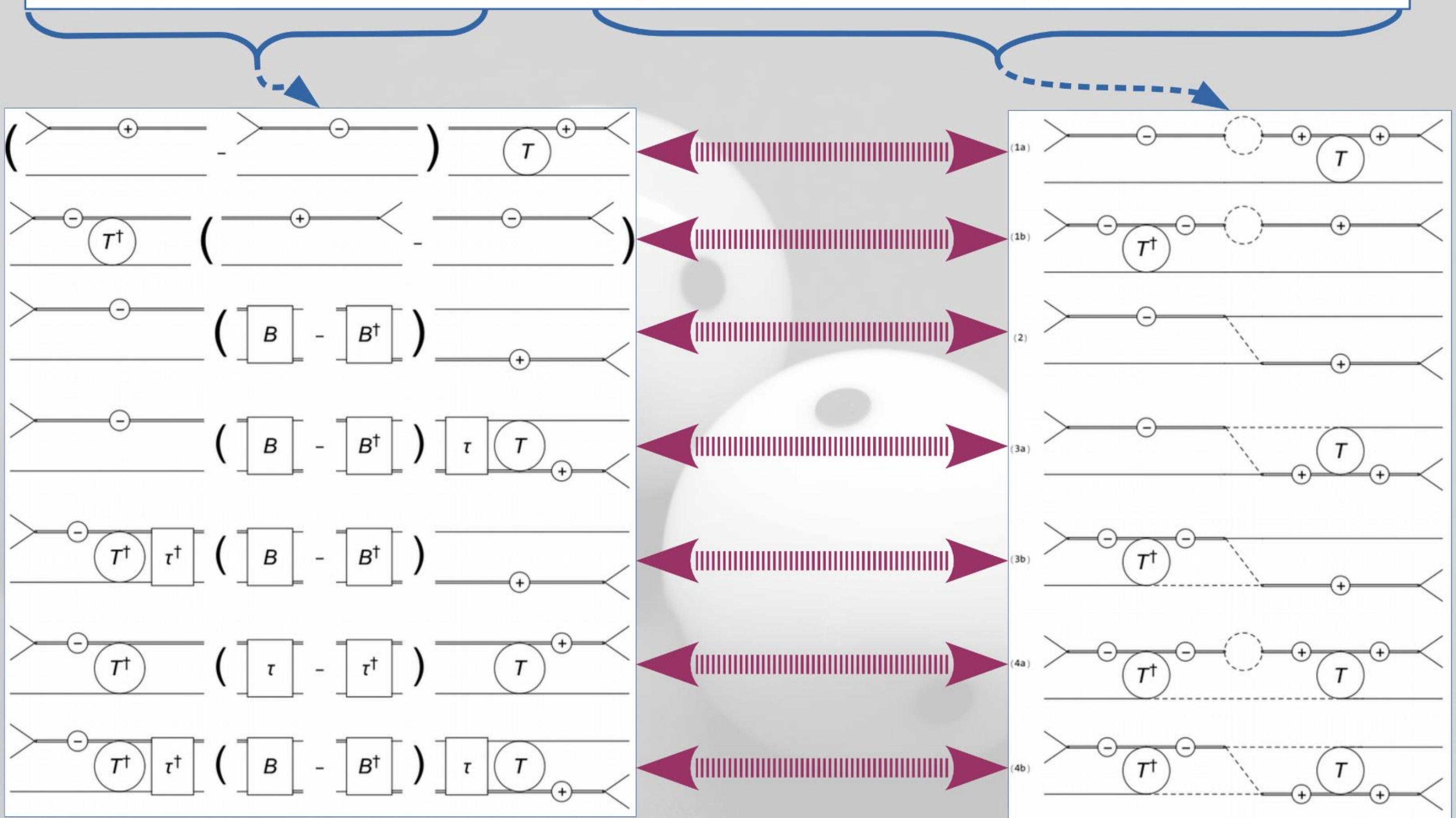
Three-Body Unitarity

A general ansatz for the Isobar-spectator interaction
→ B & τ are unknown!!!



3-body Unitarity (normalization condition ↔ phase space integral)

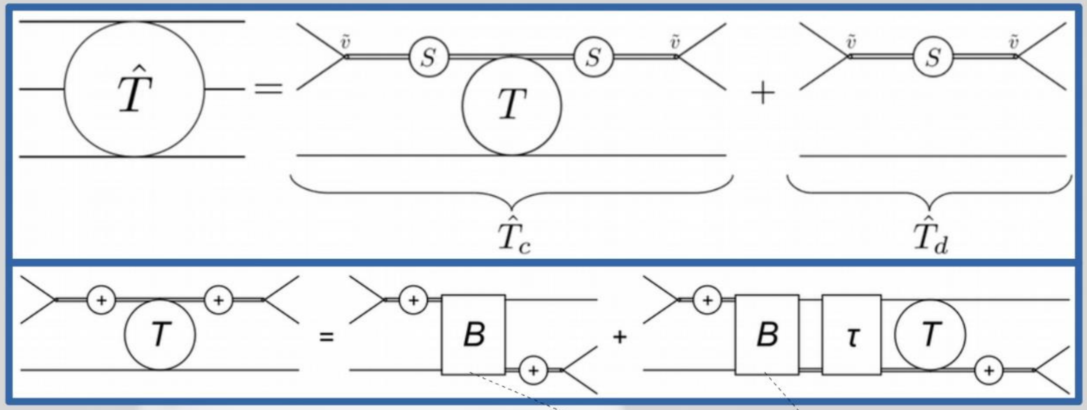
$$\langle q_1, q_2, q_3|(\hat{T}-\hat{T}^\dagger)|p_1, p_2, p_3\rangle = i\int_P \langle q_1, q_2, q_3|\hat{T}^\dagger|k_1, k_2, k_3\rangle\langle k_1, k_2, k_3|\hat{T}|p_1, p_2, p_3\rangle$$



M. Mai

SCATTERING AMPLITUDE

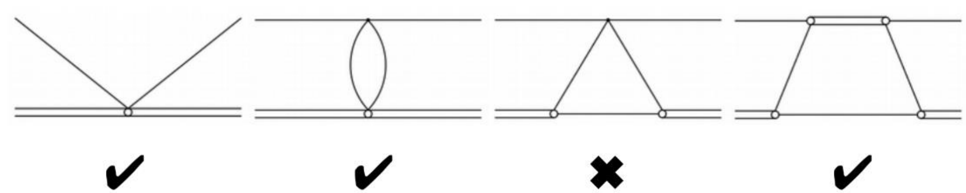
$3 \rightarrow 3$ scattering amplitude is a 3-dimensional integral equation



– Imaginary parts (***B, τ, S***) are fixed by **unitarity/matching**
For simplicity ***υ=λ*** (full relations available)

$$\langle q|B(s)|p\rangle = -\frac{\lambda^2}{2\sqrt{m^2+\mathbf{Q}^2}\left(E_Q-\sqrt{m^2+\mathbf{Q}^2}+i\epsilon\right)}$$

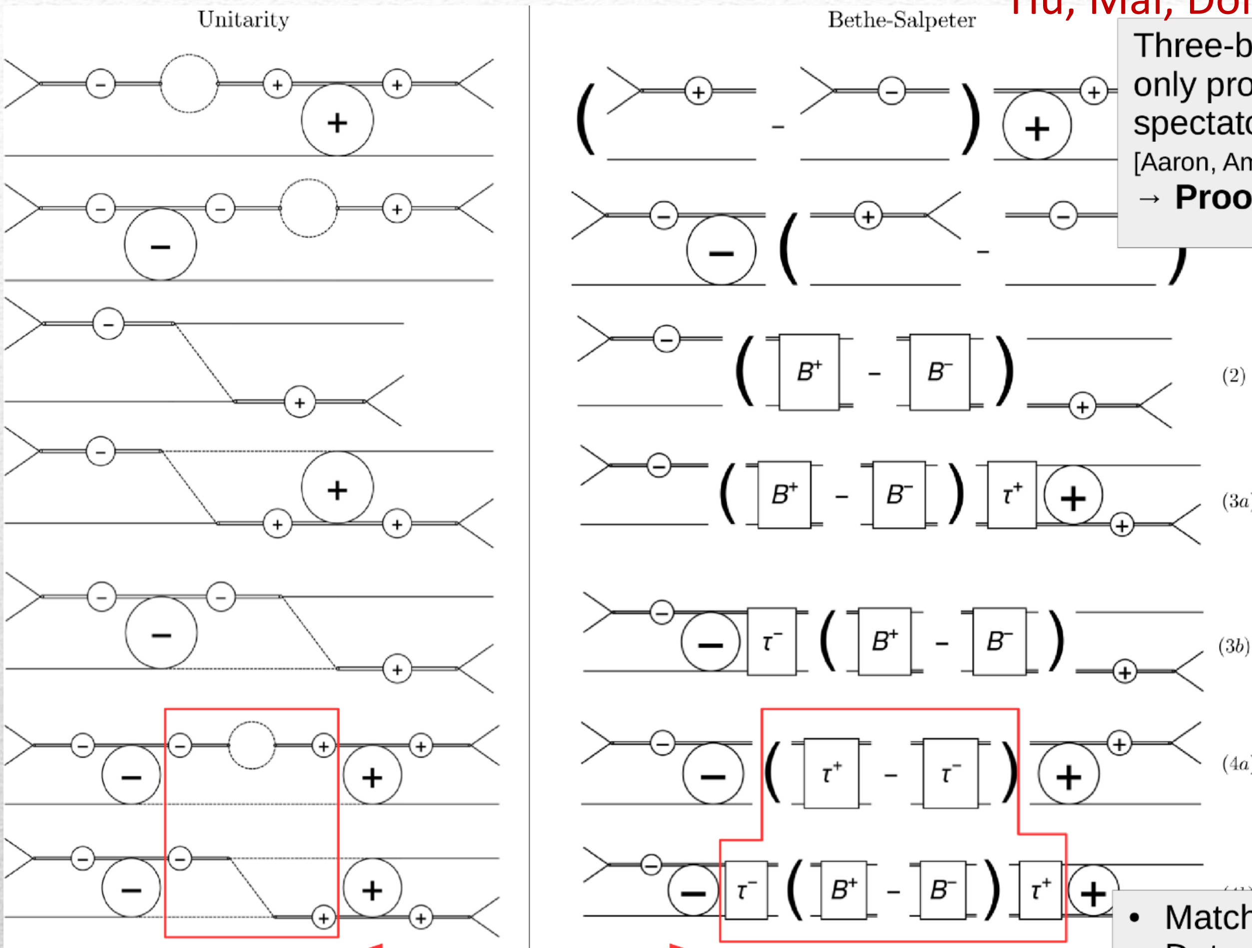
- un-subtracted dispersion relation
- one-π exchange in TOPT
- real contributions can be added to B



Three-Body Unitarity

Hu, Mai, Doring, AP, Szczepaniak, in prep.

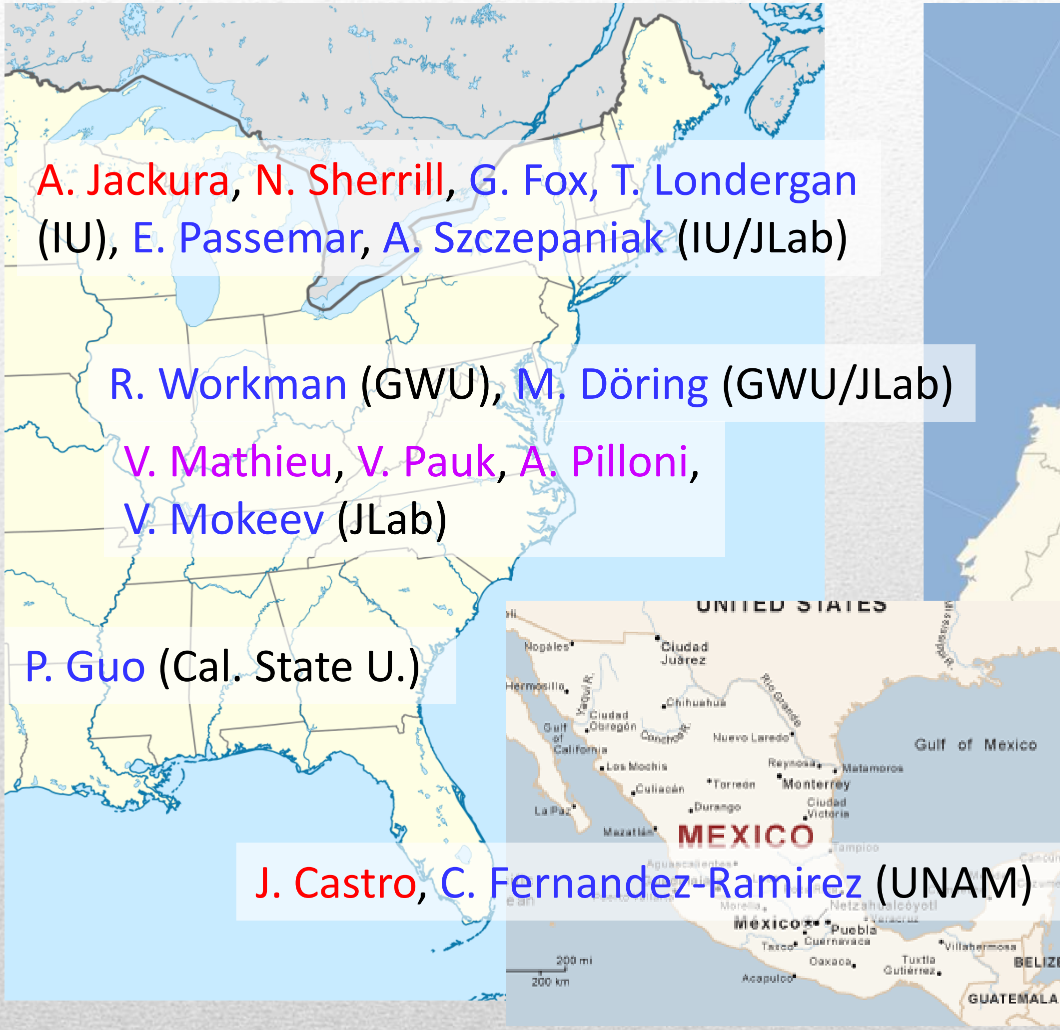
Three-body unitarity for isobars only proven for bound state-spectator scattering
[Aaron, Amamdo, Young, PR (1969)]
→ **Proof above breakup needed**!



Bound-state particle scattering requires only comparing these.

- Match Ansatz to unitarity
- Determine three-body amplitude
- Consistency of matching relations shown.
- Proof finished

Joint Physics Analysis Center



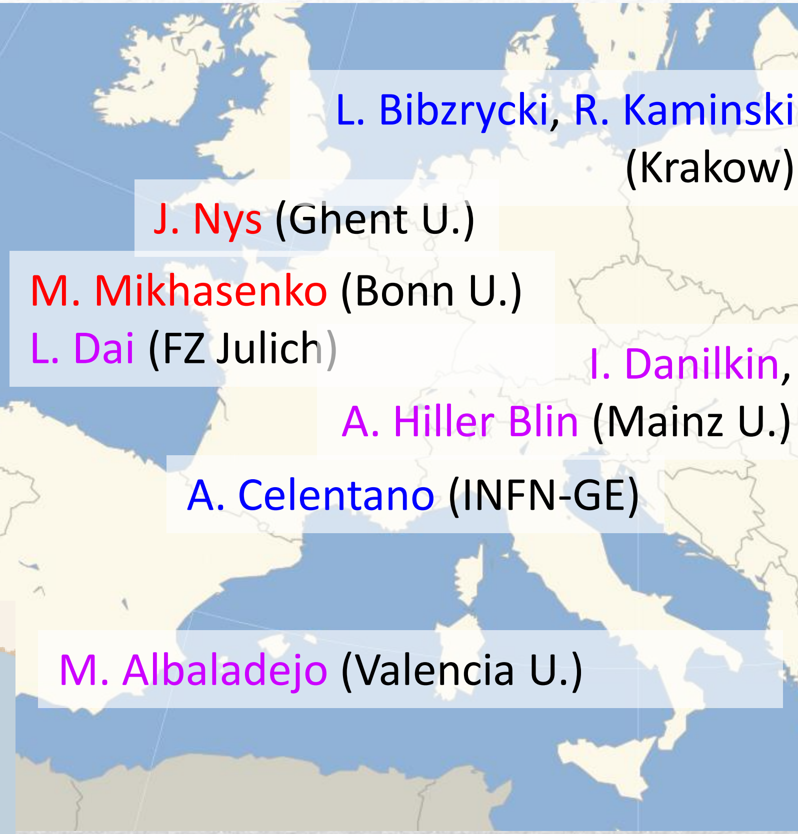
A. Jackura, N. Sherrill, G. Fox, T. Londergan (IU), E. Passemar, A. Szczepaniak (IU/JLab)

R. Workman (GWU), M. Döring (GWU/JLab)

V. Mathieu, V. Pauk, A. Pilloni, V. Mokeev (JLab)

P. Guo (Cal. State U.)

J. Castro, C. Fernandez-Ramirez (UNAM)



L. Bibzrycki, R. Kaminski (Krakow)

J. Nys (Ghent U.)

M. Mikhasenko (Bonn U.)
L. Dai (FZ Julich)

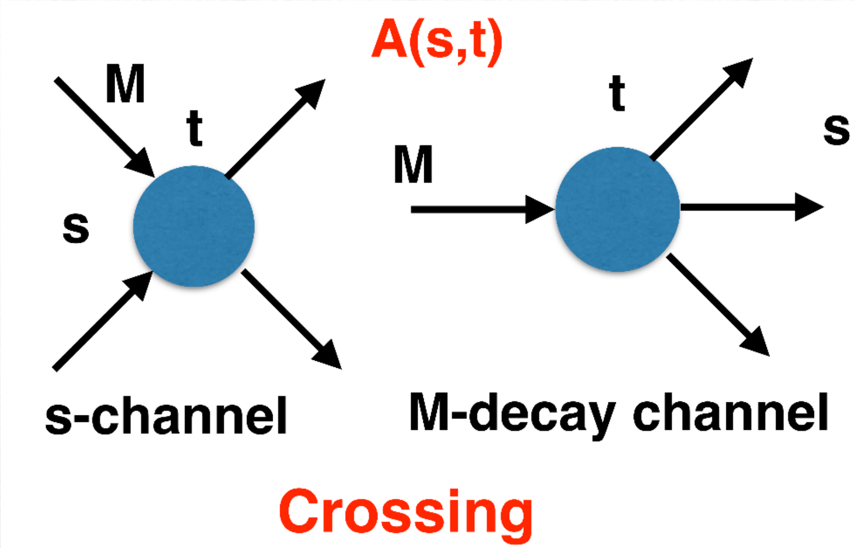
I. Danilkin, A. Hiller Blin (Mainz U.)

A. Celentano (INFN-GE)

M. Albaladejo (Valencia U.)

Students, Postdocs, Faculties

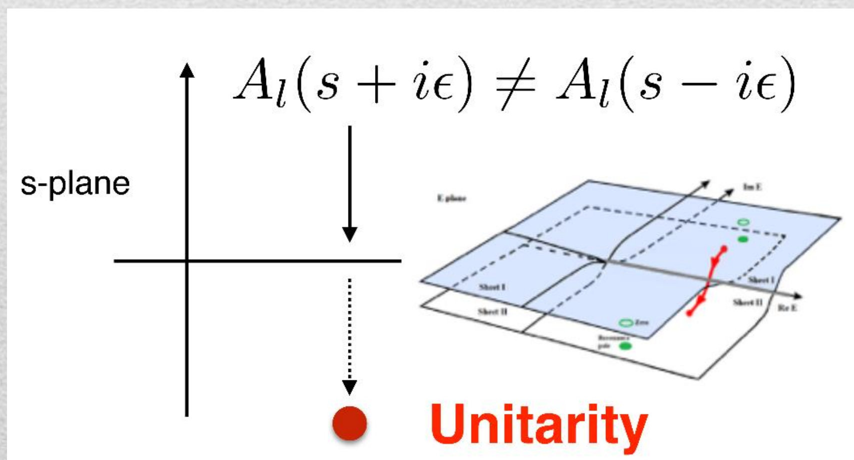
S-Matrix principles



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

Analyticity

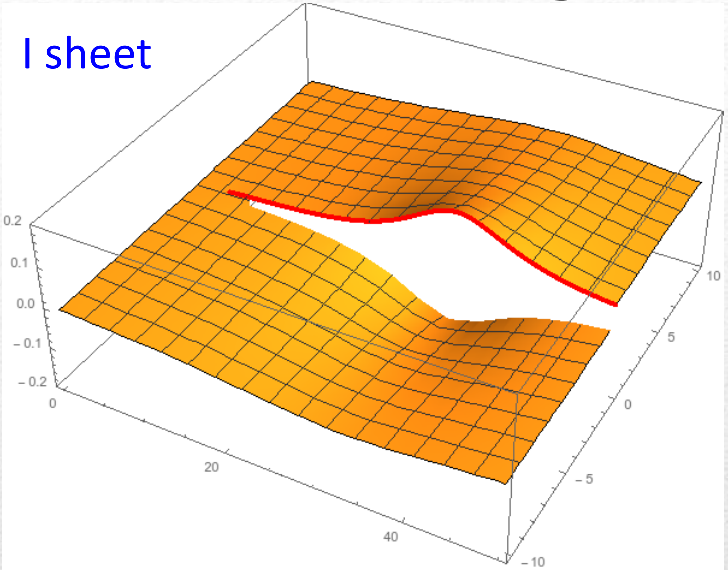
$$A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)$$

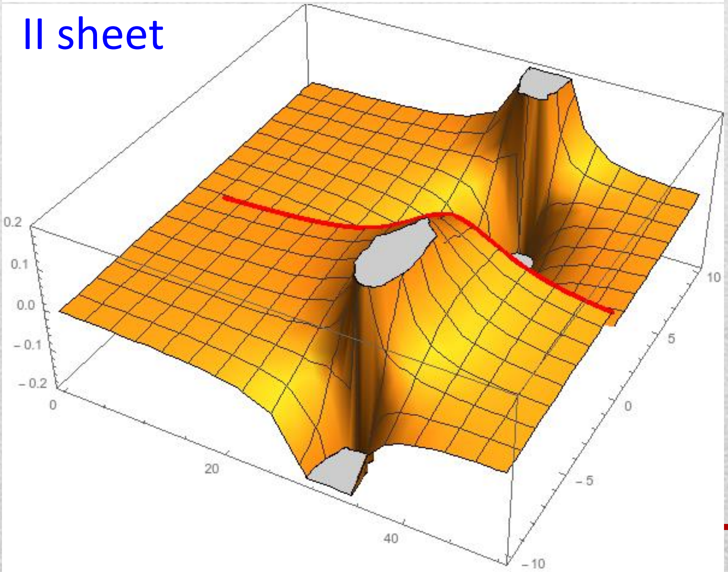


These are constraints the amplitudes have to satisfy, but do not fix the dynamics

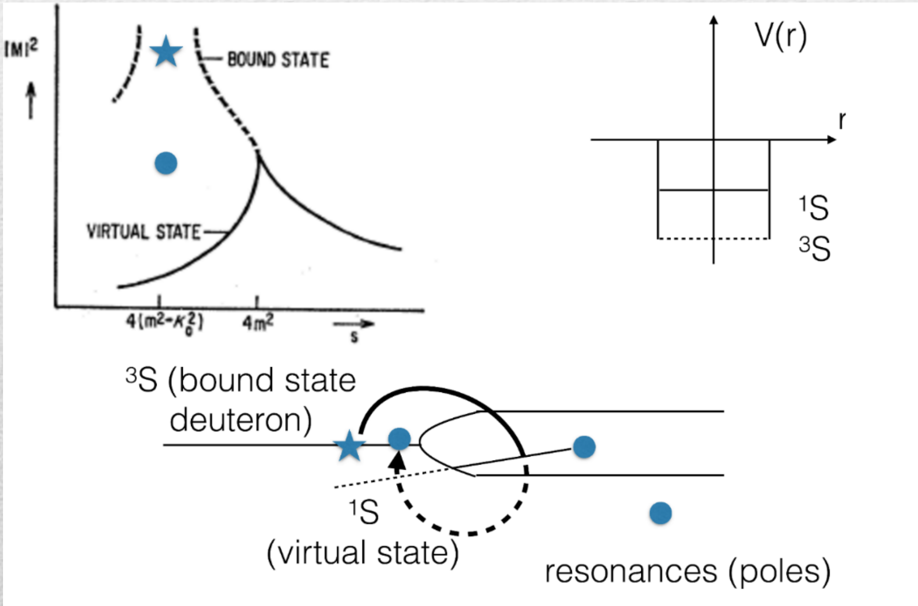
Resonances (QCD states) are poles in the unphysical Riemann sheets

Pole hunting

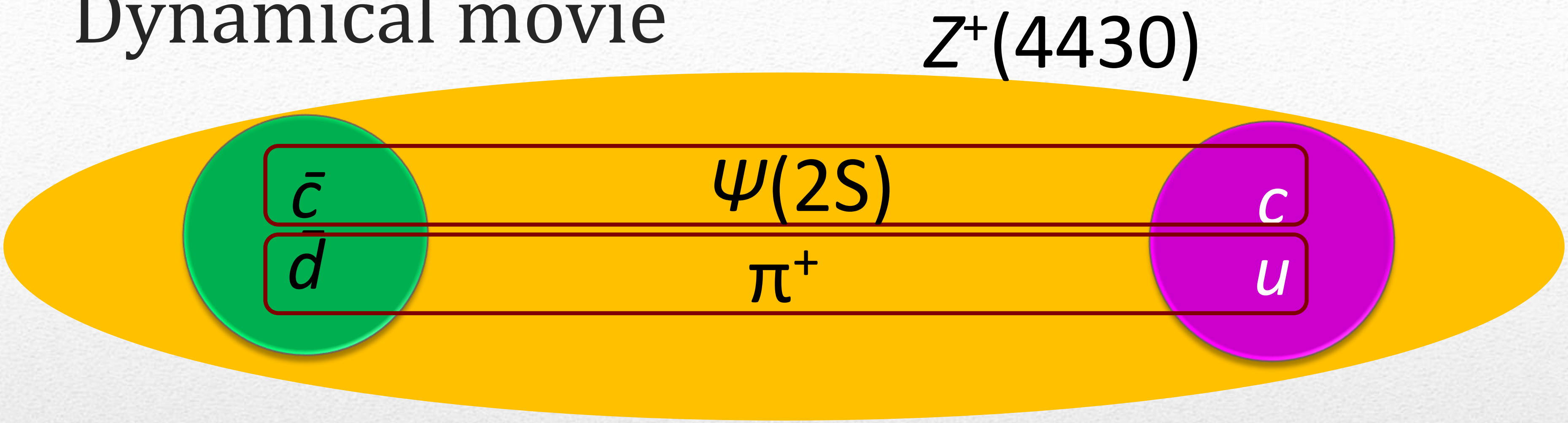




Bound states on the real axis 1st sheet
Not-so-bound (virtual) states on the real axis 2nd sheet



Dynamical movie



Brodsky, Hwang, Lebed PRL 113 112001

- Since this is still a $\mathbf{3} \leftrightarrow \bar{\mathbf{3}}$ 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 $\bar{B}^0 \longrightarrow K^- Z^+(4430)$ converts into potential energy until the diquarks come to rest
- Hadronization most effective at this point (WKB turning point)

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

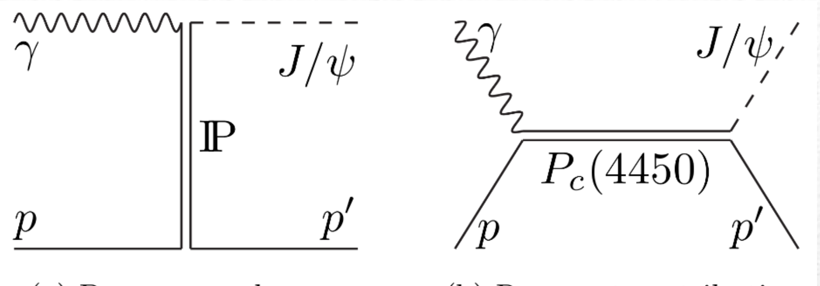
$$\frac{B(Z^+(4430)\to\psi(2S)\pi^+)}{B(Z^+(4430)\to J/\psi\,\pi^+)} \sim 72$$

$(> 10\text{ exp.})$

Pentaquark photoproduction

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

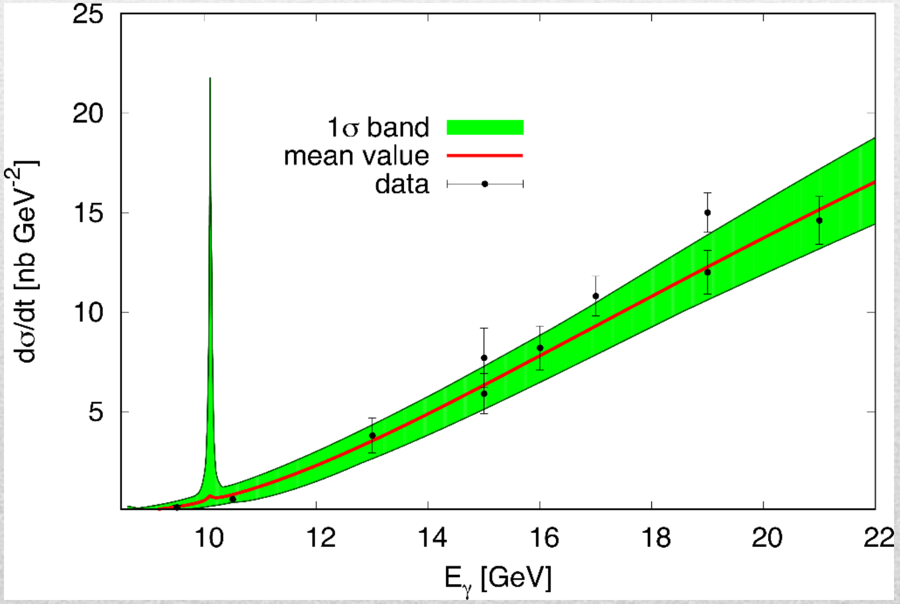
We use the (few) existing data and VMD + pomeron inspired bkg to estimate the cross section



(a) Pomeron exchange (b) Resonant contribution

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

σ_s (MeV)	0	60	120
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$	$0.157^{+0.037}_{-0.022}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$	$1.150^{+0.015}_{-0.023}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$	$0.111^{+0.038}_{-0.054}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$	$16.9^{+2.0}_{-1.1}$
b_0 (GeV^{-2})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$	$1.03^{+0.49}_{-0.31}$
$\mathcal{B}_{\psi p}$ (95% CL)	≤ 29 %	≤ 30 %	≤ 23 %



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

$Z_c(3900) \to \eta_c \rho$

Esposito, Guerrieri, AP, PLB 746, 194-201

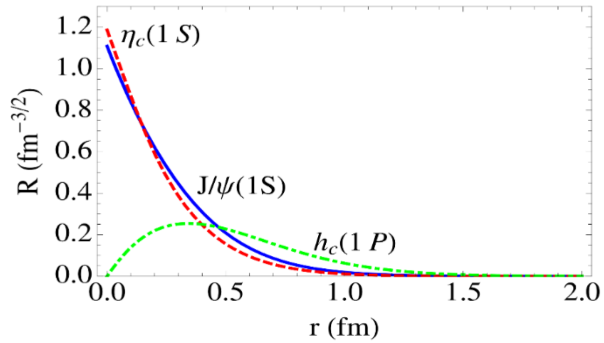
If tetraquark

Kinematics with HQSS, dynamics estimated according to Brodsky et al., PRL113, 112001

$$A = \langle \chi_{c\bar{c}} | \chi_c \otimes \chi_{\bar{c}} \rangle \langle \phi_{c\bar{c}} | \hat{T}_{\perp HQS} | \phi[cq][\bar{c}\bar{q}] \rangle + O\left(\frac{\Lambda_{QCD}}{m_c}\right)$$

Clebsch-Gordan

Uncertainty $\sim 25\%$



Reduced matrix element

- approximated as a constant
- or $\propto \psi_{c\bar{c}}(r_Z)$

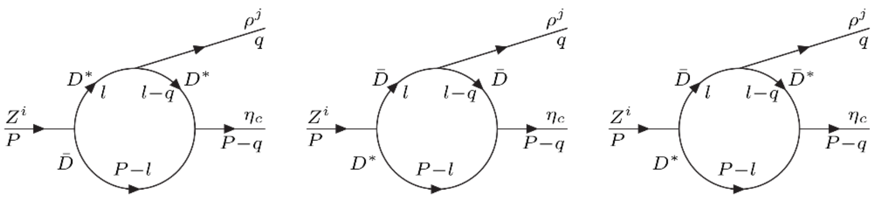
	Kinematics only		Dynamics included	
	type I	type II	type I	type II
$\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi \pi)}$	$(3.3^{+7.9}_{-1.4}) \times 10^2$	$0.41^{+0.96}_{-0.17}$	$(2.3^{+3.3}_{-1.4}) \times 10^2$	$0.27^{+0.40}_{-0.17}$
$\frac{\mathcal{BR}(Z'_c \to \eta_c \rho)}{\mathcal{BR}(Z'_c \to h_c \pi)}$	$(1.2^{+2.8}_{-0.5}) \times 10^2$		$6.6^{+56.8}_{-5.8}$	

$Z_c(3900) \to \eta_c \rho$

Esposito, Guerrieri, AP, PLB 746, 194-201

If molecule

Non-Relativistic Effective Theory, HQET+NRQCD and Hidden gauge Lagrangian
Uncertainty estimated with power counting at NLO



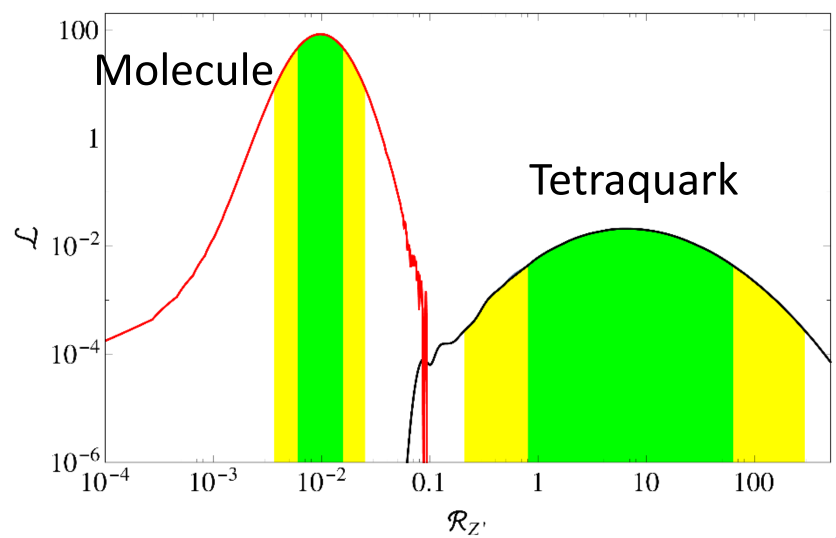
$$\mathcal{L}_{Z_c^{(\prime)}} = \frac{z^{(\prime)}}{2}\left\langle \mathcal{Z}^{(\prime)}_{\mu,ab}\bar{H}_{2b}\gamma^\mu \bar{H}_{1a}\right\rangle + h.c.,$$

$$\mathcal{L}_{c\bar{c}} = \frac{g_2}{2}\left\langle \bar{\Psi} H_{1a} \overleftrightarrow{\not{\partial}} H_{2a}\right\rangle + \frac{g_1}{2}\left\langle \bar{\chi}_\mu H_{1a}\gamma^\mu H_{2a}\right\rangle + h.c.,$$

$$\mathcal{L}_{\rho D D^*} = i\beta\left\langle H_{1b} v^\mu \left(\mathcal{V}_\mu - \rho_\mu\right)_{ba}\bar{H}_{1a}\right\rangle + i\lambda\left\langle H_{1b}\sigma^{\mu\nu}F_{\mu\nu}(\rho)_{ba}\bar{H}_{1a}\right\rangle + h.c.,$$

$$\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi\,\pi)} = \left(4.6^{+2.5}_{-1.7}\right)\times 10^{-2}\,; \quad \frac{\mathcal{BR}(Z_c' \to \eta_c \rho)}{\mathcal{BR}(Z_c' \to h_c\,\pi)} = \left(1.0^{+0.6}_{-0.4}\right)\times 10^{-2}\,.$$

$$\frac{\mathcal{BR}(Z_c \to h_c\,\pi)}{\mathcal{BR}(Z_c' \to h_c\,\pi)} = 0.34^{+0.21}_{-0.13}\,; \quad \frac{\mathcal{BR}(Z_c \to J/\psi\,\pi)}{\mathcal{BR}(Z_c' \to J/\psi\,\pi)} = 0.35^{+0.49}_{-0.21}$$



Prompt production of $X(3872)$

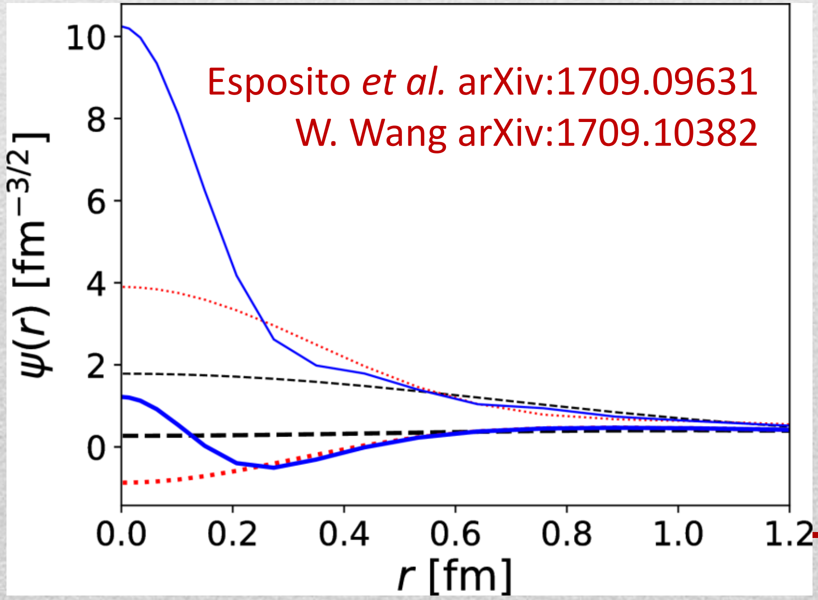
$$\sigma(\bar{p}p \to X) \sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$
$$\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$
$$\leq \int_{\mathcal{R}} d^3\mathbf{k} \, |\Psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k} \, |\langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle|^2$$
$$\leq \int_{\mathcal{R}} d^3\mathbf{k} \, |\langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle|^2$$

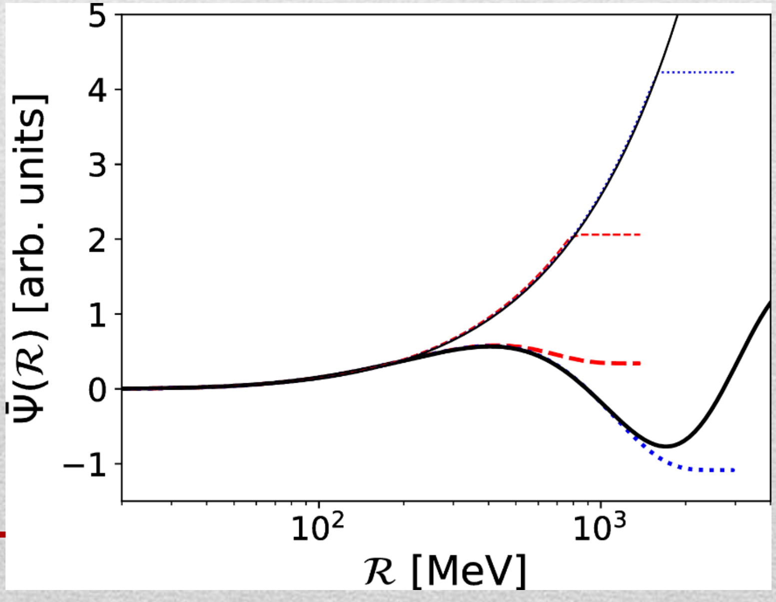
The estimate of the k_{max} has been brought back

Albaladejo *et al.* arXiv:1709.09101

The essence of the argument is that one has to look at the integral of the wave function

$$\int_R d^3\mathbf{k}\, \psi(\mathbf{k})$$





Towards hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

The absence of many of the predicted states might point to the need for selection rules

It is unlikely that the many close-by thresholds play no role whatsoever

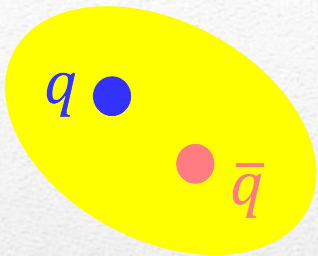
All the well assessed 4-quark resonances lie close and above some meson-meson thresholds:

We introduce a mechanism that might provide “dynamical selection rules” to explain the presence/absence of resc

	Thr.	δ (MeV)	$A\sqrt{\delta}$ (MeV)	Γ (MeV)
$X(3872)$	$\bar{D}^0 D^{*0}$	$0^\dagger$	$0^\dagger$	$0^\dagger$
$Z_c(3900)$	$\bar{D}^0 D^{*+}$	7.8	27.9	27.9
$Z_c'(4020)$	$\bar{D}^{*0} D^{*+}$	6.7	25.9	24.8¶
$X(4140)$	$J/\psi\,\phi$	*a*) 31.6	52.7	28.0
		b) 30.1	54.7	83.0
$Z_b(10610)$	$\bar{B}^0 B^{*+}$	2.7	16.6	18.4
$Z_b'(10650)$	$\bar{B}^{*0} B^{*+}$	1.8	13.4	11.5
$X(5568)$	$B_s^0\,\pi^+$	61.4	78.4	21.9
X_{bs}	$B^+ \bar{K}^0$	5.8	24.1	—

We introduce a mechanism that might provide “dynamical selection rules” to explain the presence/absence of resonances from the experimental data.

Dictionary – Quark model



L = orbital angular momentum
S = spin $q + \bar{q}$

J = total angular momentum
= exp. measured spin

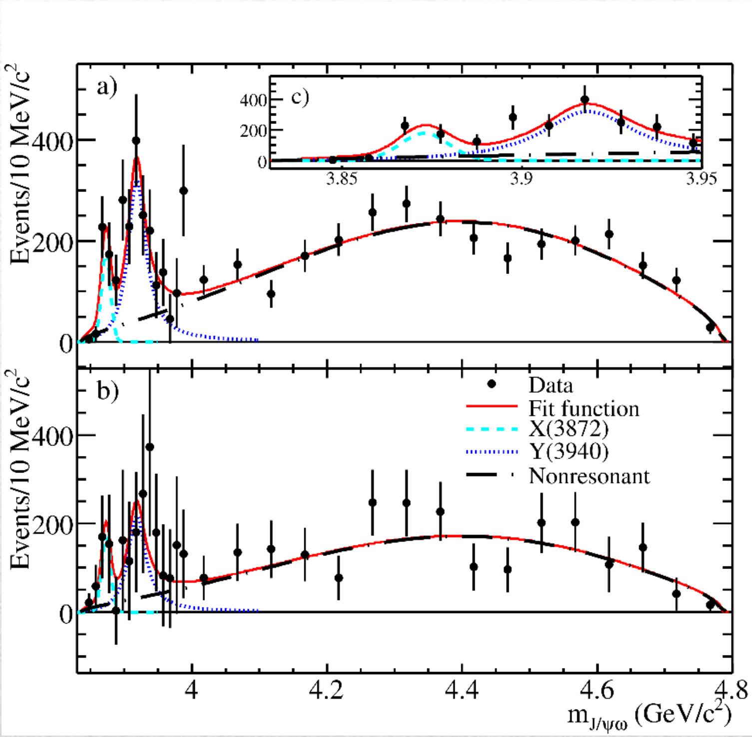
I = isospin = 0 for quarkonia

$$L - S \leq J \leq L + S$$
$$P = (-1)^{L+1}, C = (-1)^{L+S}$$
$$G = (-1)^{L+S+I}$$

J^{PC}	L	S	Charmonium ($c\bar{c}$)	Bottomonium ($b\bar{b}$)
0^{-+}	0 (S-wave)	0	$\eta_c(nS)$	$\eta_b(nS)$
1^{--}		1	$\psi(nS)$	$\Upsilon(nS)$
1^{+-}	1 (P-wave)	0	$h_c(nP)$	$h_b(nP)$
0^{++}		1	$\chi_{c0}(nP)$	$\chi_{b0}(nP)$
1^{++}		1	$\chi_{c1}(nP)$	$\chi_{b1}(nP)$
2^{++}		1	$\chi_{c2}(nP)$	$\chi_{b2}(nP)$

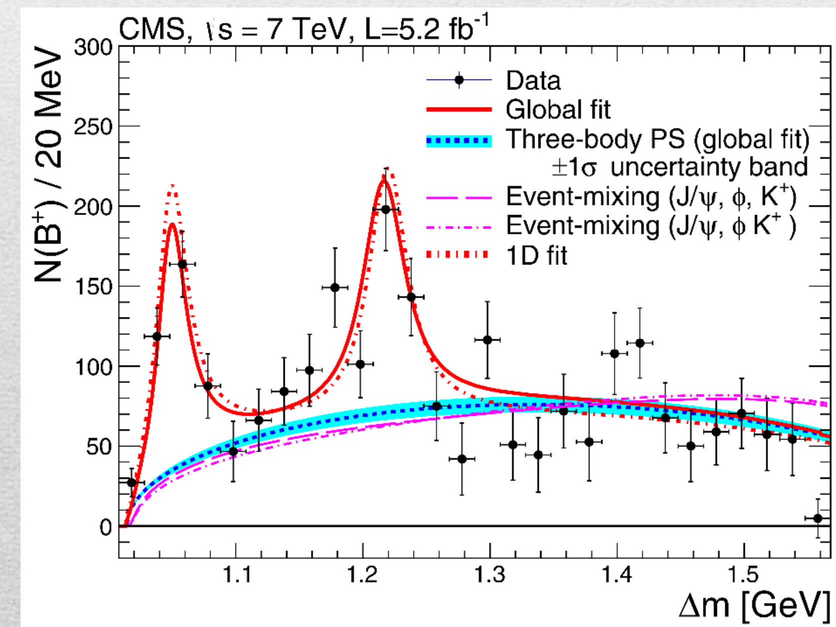
But $J/\psi = \psi(1S)$, $\psi' = \psi(2S)$

Other beasts



$X(3915)$, seen in $B \to X\,K \to J/\psi\,\omega$
and $\gamma\gamma \to X \to J/\psi\,\omega$
$J^{PC} = 0^{++}$, candidate for $\chi_{c0}(2P)$
But $X(3915) \not\to D\bar{D}$ as expected,
and the hyperfine splitting
$\mathrm{M}(2^{++}) - \mathrm{M}(0^{++})$ too small

One/two peaks seen in $B \to XK \to J/\psi\,\phi\,K$,
close to threshold



Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

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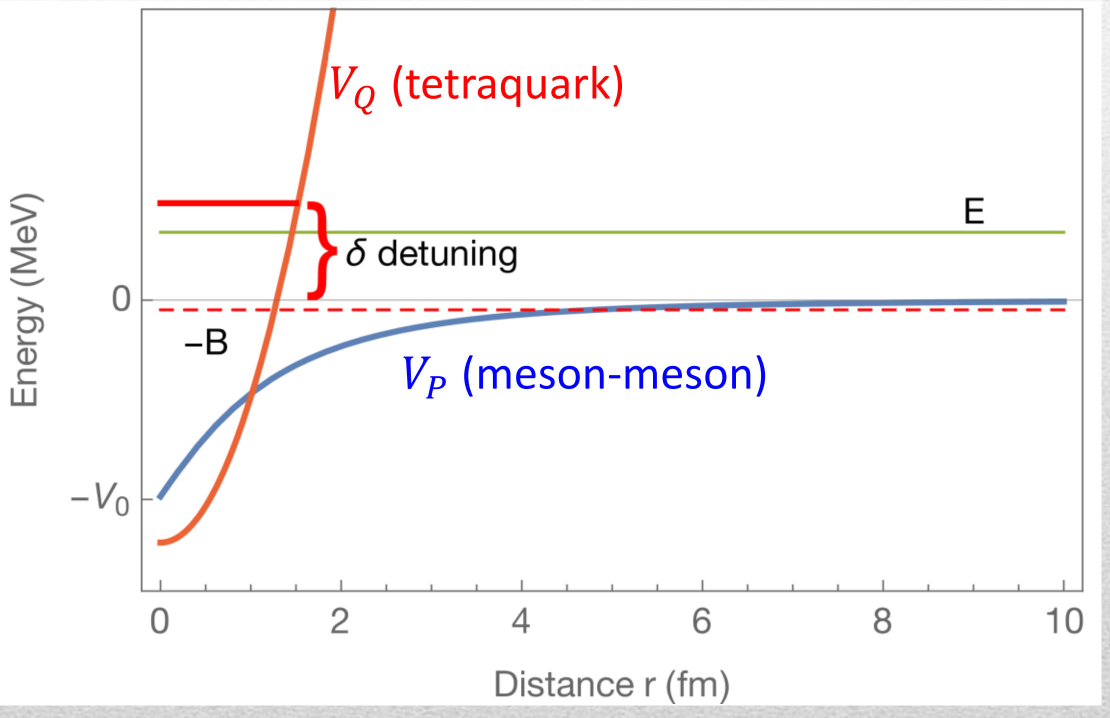


Let P and Q be orthogonal subspaces of the Hilbert space

$$H = H_{PP} + H_{QQ}$$

We have the (weak) scattering length a_P in the open channel.

We add an off-diagonal H_{QP} which connects the two subspaces

Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

$$\Gamma = -16\pi^3 \rho\, \Im(T) \sim 16\pi^4 \rho \left|H_{PQ}\right|^2 \delta\left(\frac{p_1^2}{2M} + \frac{p_2^2}{2M} - \delta\right)$$

The expected width is the average over momenta that allow for the existence of a tetraquark $p < \bar{p} = 50 \div 100 \text{ MeV}$

$$\Gamma \sim A\sqrt{\delta}$$

We therefore expect to see a level if:

- $\delta > 0$ the state lies above threshold
- $\delta < \frac{\bar{p}^2}{2M}$, only the closest threshold contributes
- The states ψ_Q and ψ_P are orthogonal

$X(3872)^+$ falls below threshold, $M(1^{++}) < M(D^{+*}\overline{D}^0)$

$\delta < 0$, so $a > 0 \rightarrow$ Repulsive interaction

No charged partners of the $X(3872)$!

Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

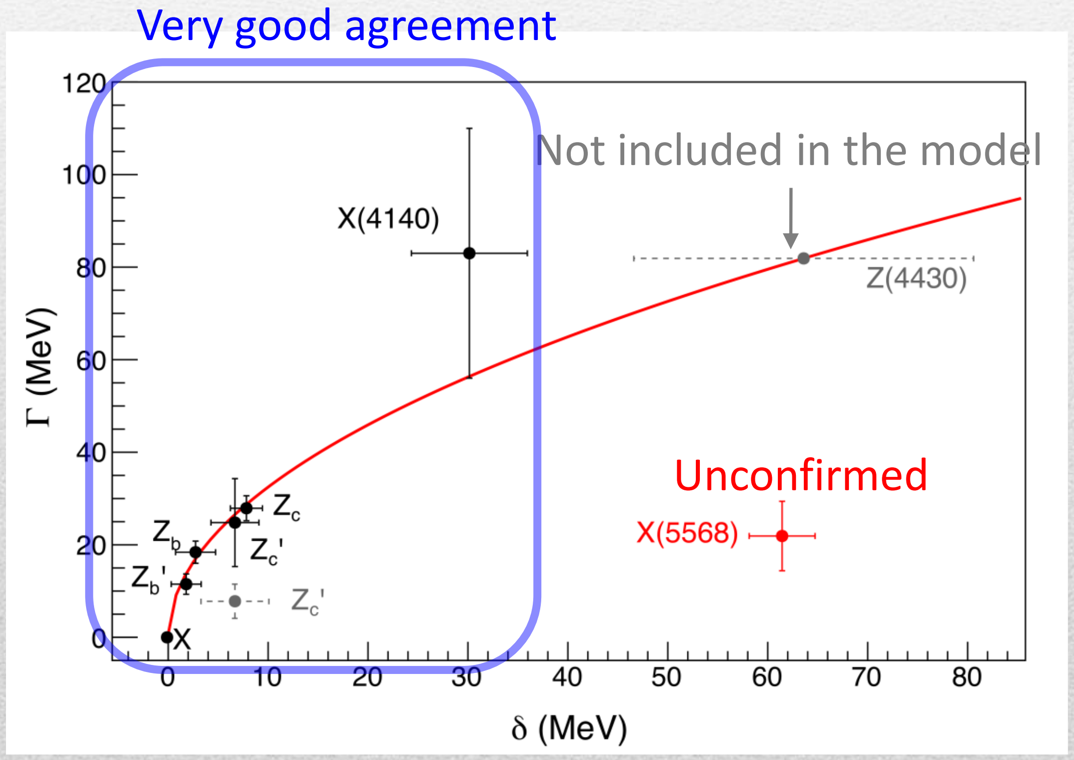
The model works only if no direct transition between closed channel levels can occur
This prevents the straightforward generalization to $L = 1$ and radially excited states (like the Ys or the $Z(4430)$)

In this picture, a $[bu][\bar{s}\bar{d}]$ state with resonance parameters of the $X(5568)$ observed by D0 is not likely

Also, one has to ensure the orthogonality between the two Hilbert subspaces P and Q.
This might affect the estimate for the X(4140)

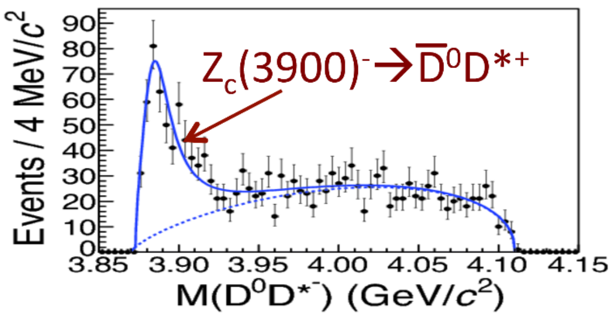
All the resonances can be fitted with

$$A = (10.3 \pm 1.3)\ \mathrm{MeV}^{1/2}$$
$$\chi^2/\mathrm{DOF} = 1.2/5$$



$Y(4260) \to \bar{D} D_1?$

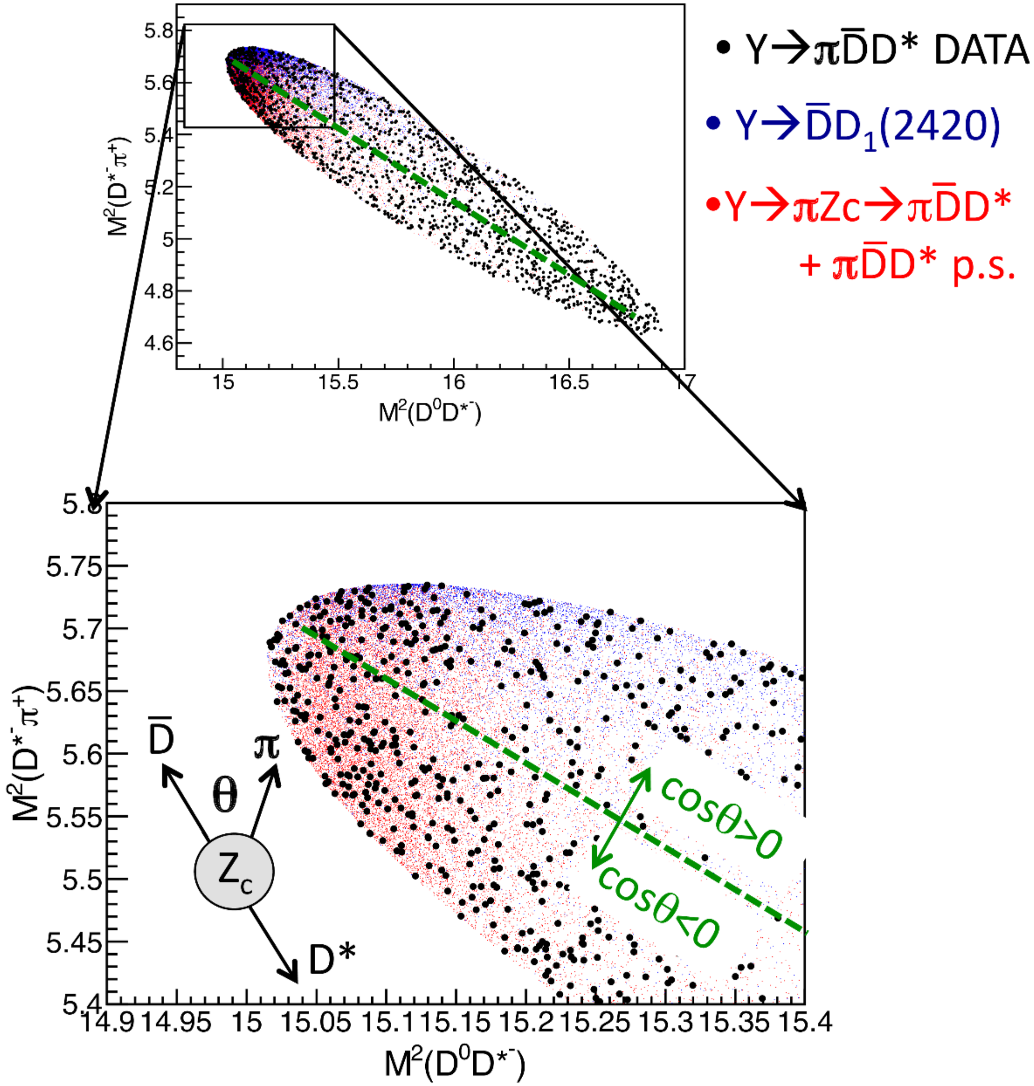
$e^+e^- \to Y(4260) \to \pi^- \bar{D}^0 D^{*+}$



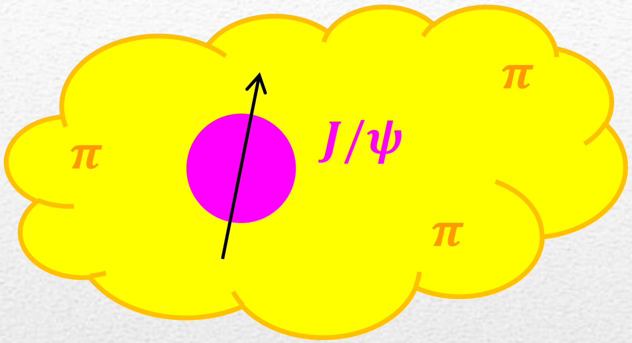
$$\mathcal{A} = \frac{N_{|cos\theta|>0.5} - N_{|cos\theta|<0.5}}{N_{|cos\theta|>0.5} + N_{|cos\theta|<0.5}}$$

	DD_1 MC	Z_c+ps MC	data
$\mathcal{A}$	0.43±0.04	0.02±0.02	0.12+0.06

Not a lot of room for $\bar{D}D_1(2410)$



Hadro-charmonium



Dubynskiy, Voloshin, PLB 666, 344
Dubynskiy, Voloshin, PLB 671, 82
Li, Voloshin, MPLA29, 1450060

Born in the context of QCD multipole expansion

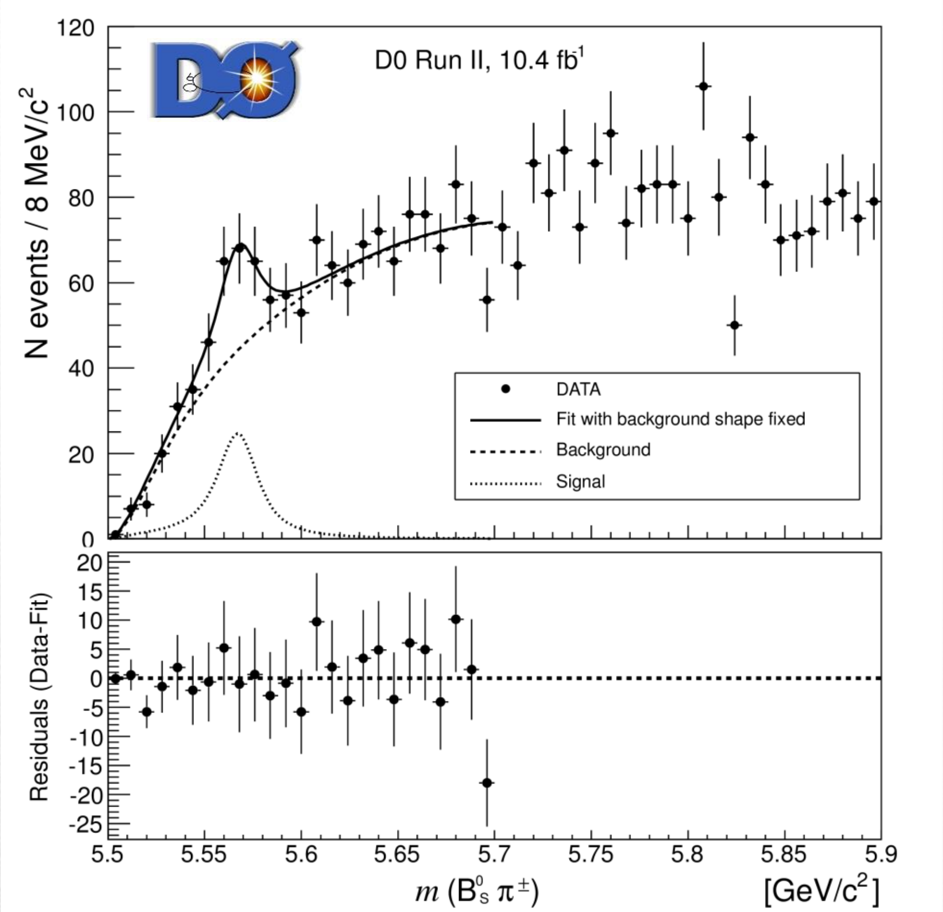
$$H_{eff} = -\frac{1}{2} a_\psi E_i^a E_i^a$$
$$a_\psi = \langle \psi | (t_c^a - t_{\bar{c}}^a) r_i \, G \, r_i (t_c^a - t_{\bar{c}}^a) | \psi \rangle$$

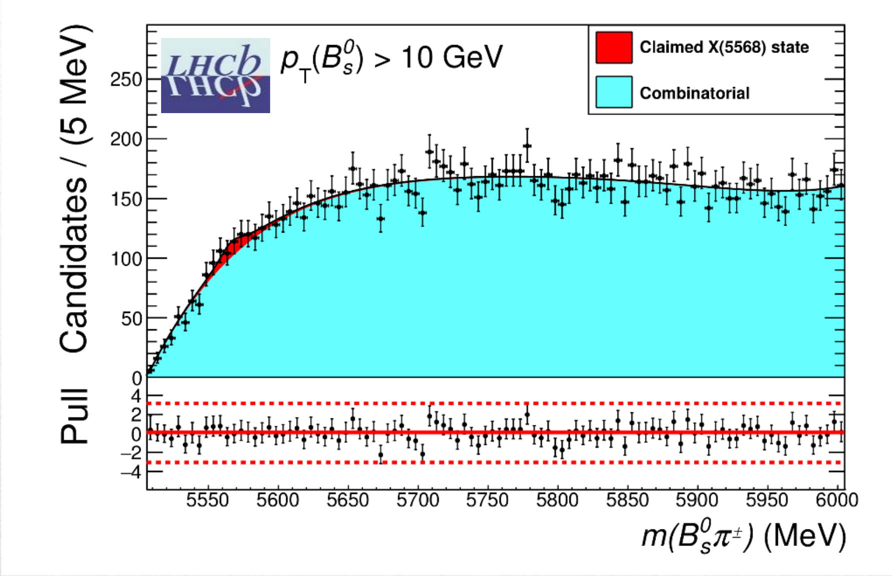
the chromoelectric field interacts with soft light matter (highly excited light hadrons)

A bound state can occur via Van der Waals-like interactions

Expected to decay into core charmonium + light hadrons,
Decay into open charm exponentially suppressed

Flavored $X(5568)$

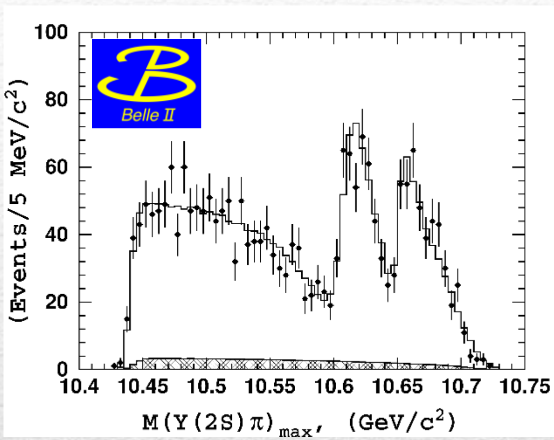


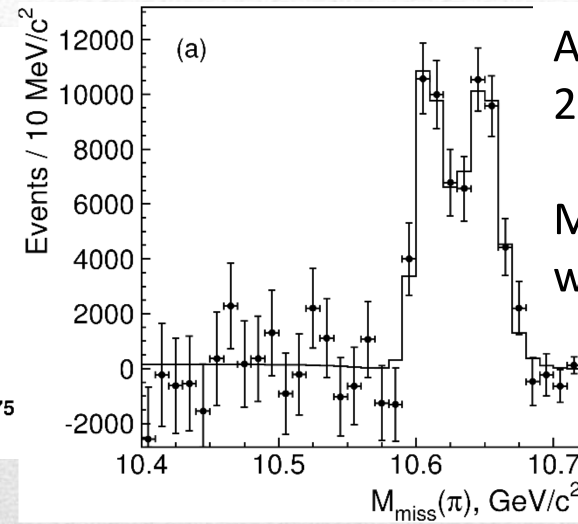


- A flavored state seen in $B_s^0\,\pi$ invariant mass by D0 (both $B_s^0 \to J/\psi\,\phi$ and $\to D_s\mu\nu$),
- not confermed by LHCb or CMS
- (different kinematics? Compare differential distributions)

Controversy to be solved

Charged Z states: $Z_b(106010), Z_b'(10650)$





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

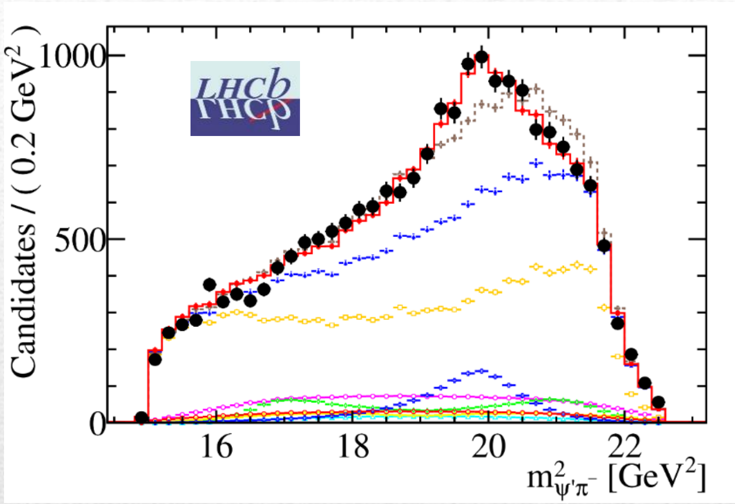
Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$
which violates HQSS

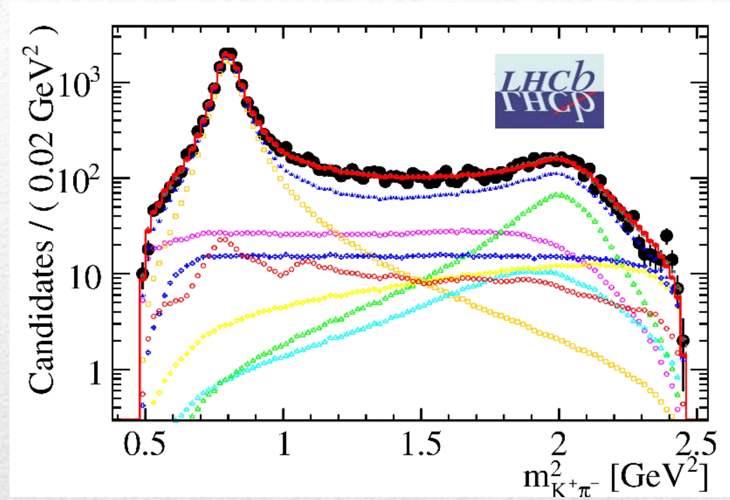
2 twin resonances!

$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
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

Charged Z states: $Z(4430)$

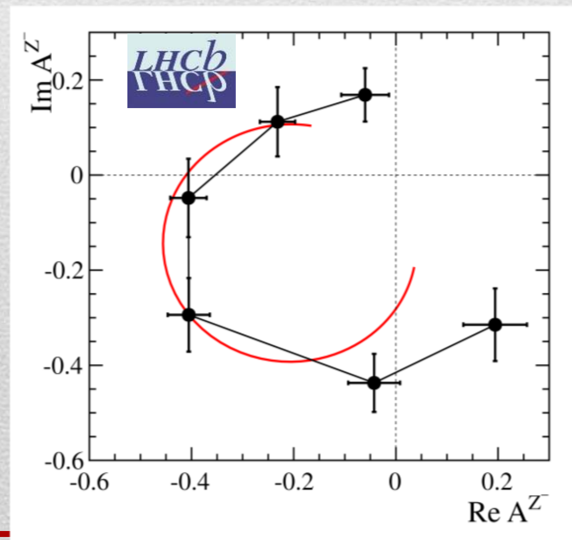




$Z(4430)^+ \to \psi(2S)\,\pi^+$
$I^G J^{PC} = 1^+ 1^{+-}$

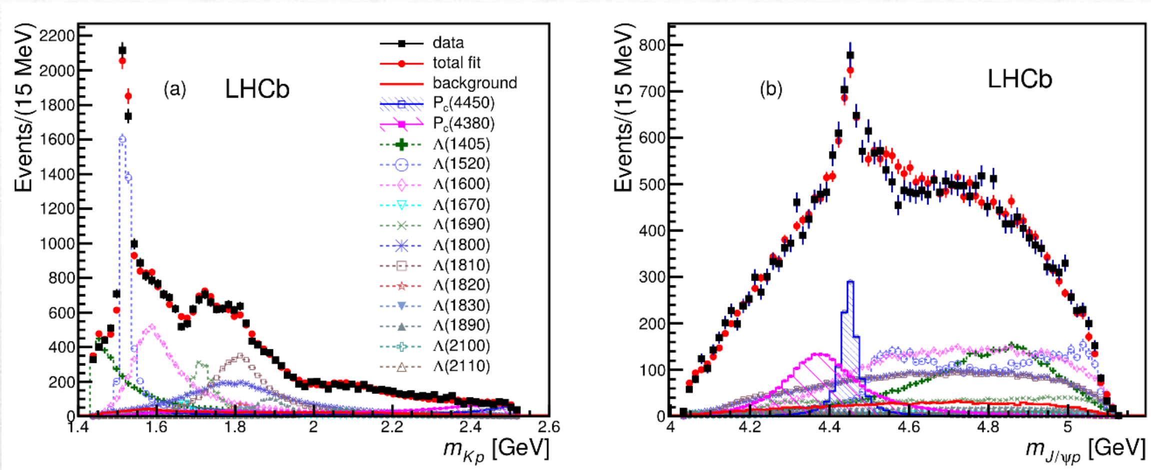
$M = 4475 \pm 7^{+15}_{-25}$ MeV
$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

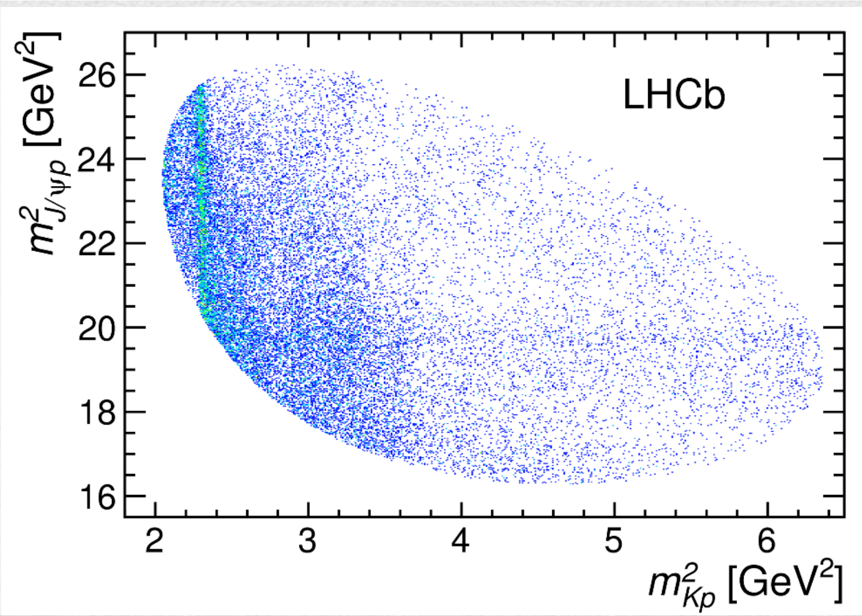
Far from open charm thresholds



If the amplitude is a free complex number, in each bin of $m^2_{\psi'\pi^-}$, the resonant behaviour appears as well

Pentaquarks!





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

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

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

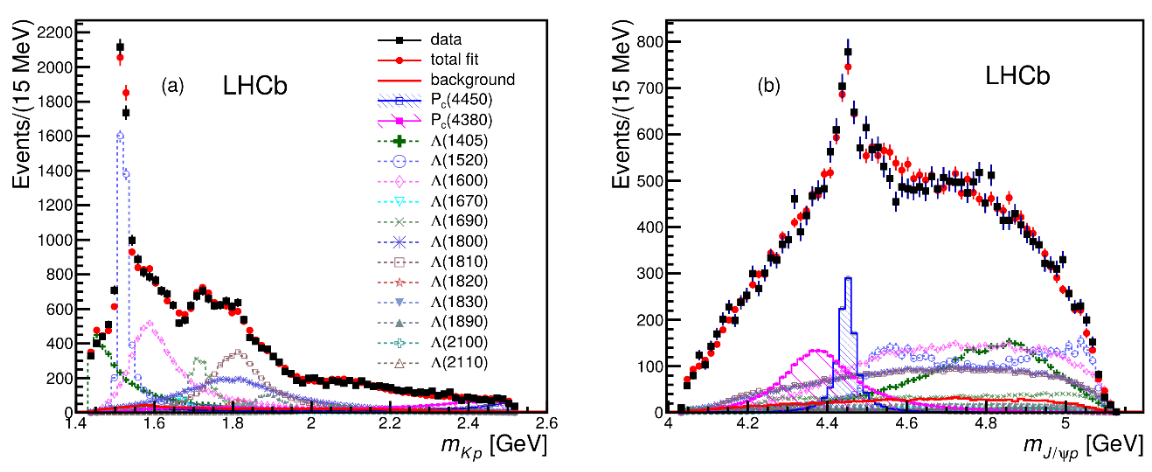
Quantum numbers

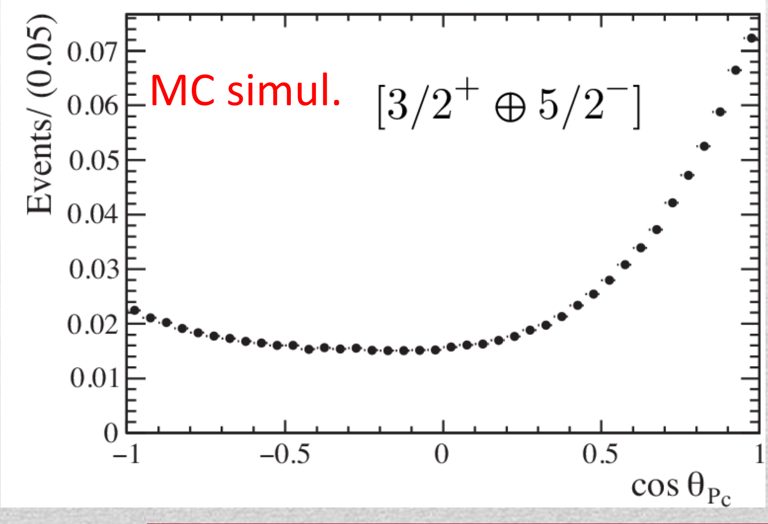
$$J^P = \left(\frac{3}{2}^-, \frac{5}{2}^+\right) \text{ or } \left(\frac{3}{2}^+, \frac{5}{2}^-\right) \text{ or } \left(\frac{5}{2}^+, \frac{3}{2}^-\right)$$

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

No obvious threshold nearby

Pentaquarks!





LHCb, PRL 115, 072001
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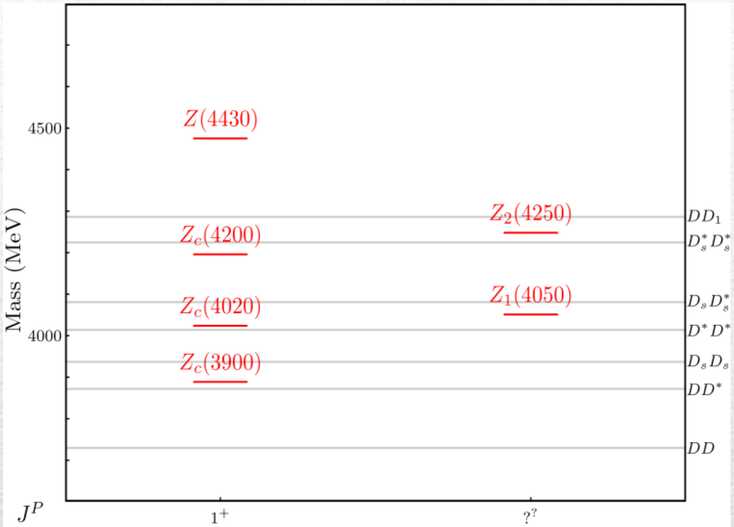
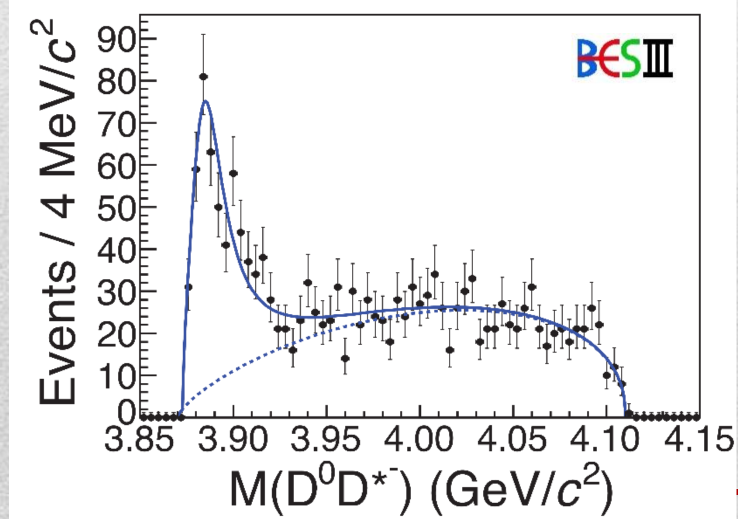
Opposite parities needed for the interference to correctly describe angular distributions, low mass region contaminated by Λ^* (model dependence?)

No obvious threshold nearby

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

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

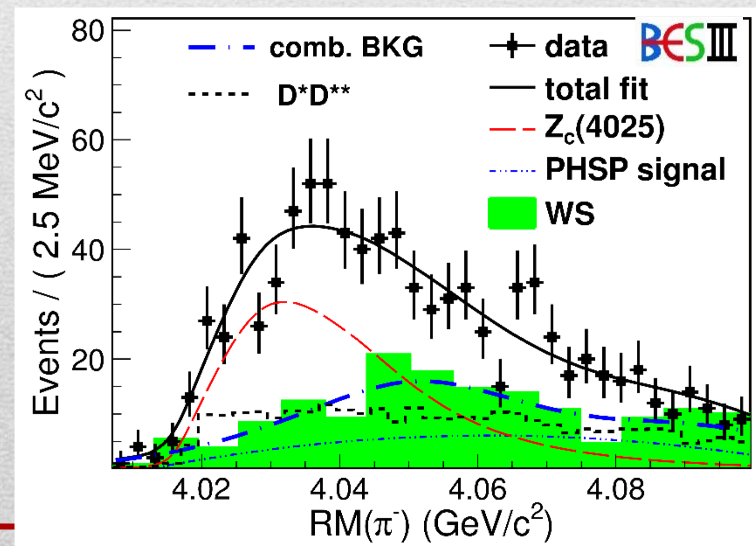




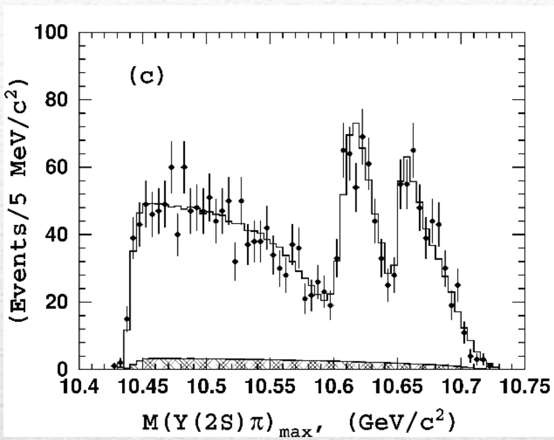
Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

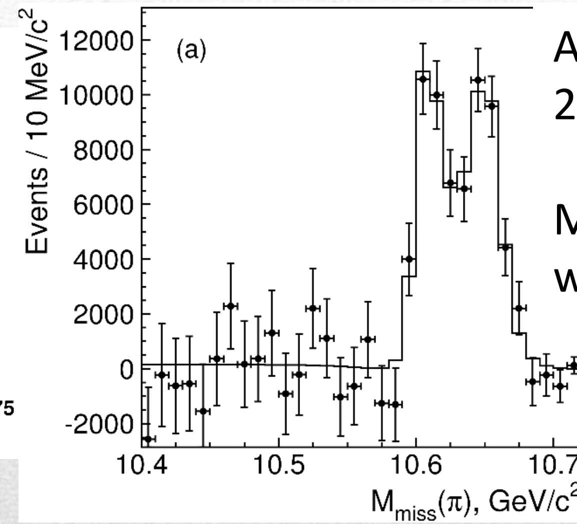
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

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



Charged Z states: $Z_b(106010), Z_b'(10650)$





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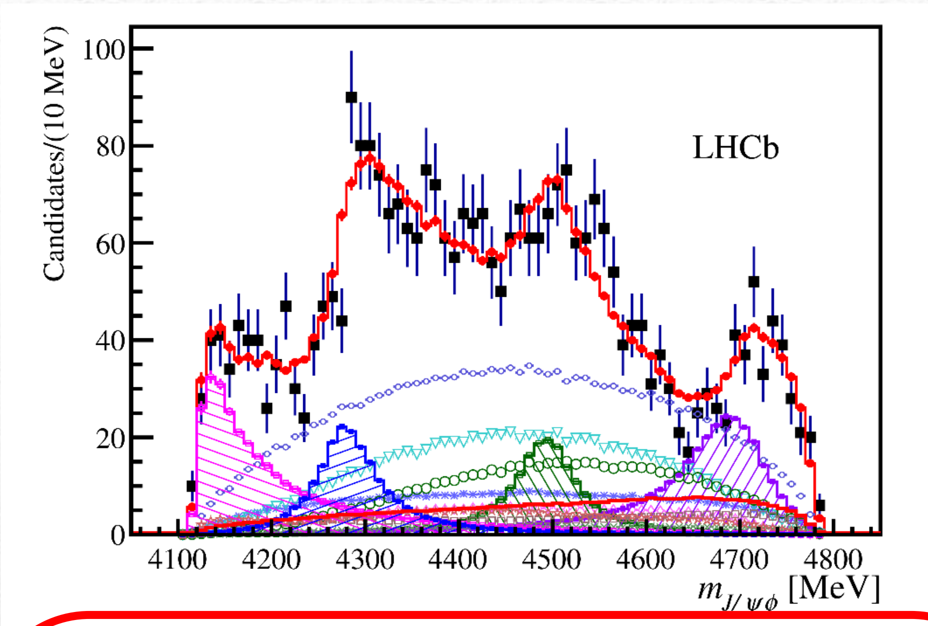
which violates HQSS

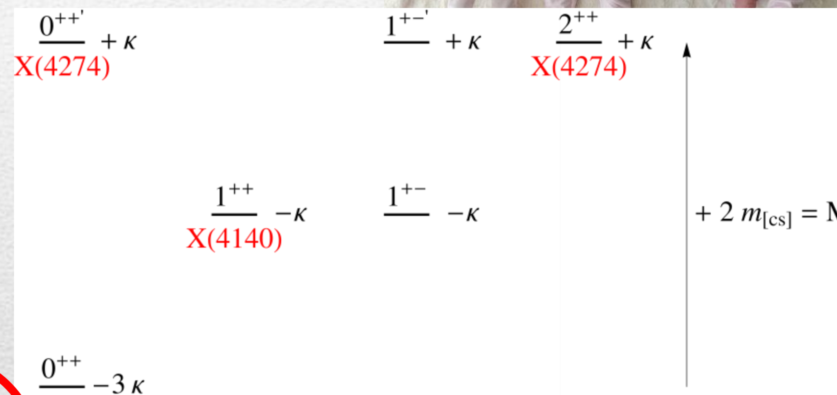
2 twin resonances!

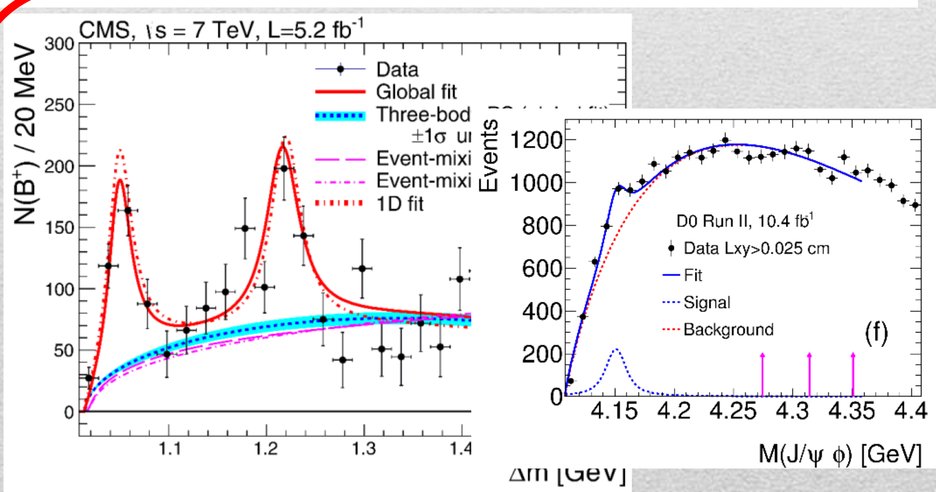
$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to (BB^*)^+\pi^-$
$M = 10607.2 \pm 2.0$ MeV, $\Gamma = 18.4 \pm 2.4$ MeV

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

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







Much narrower than LHCb! Look for prompt!

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

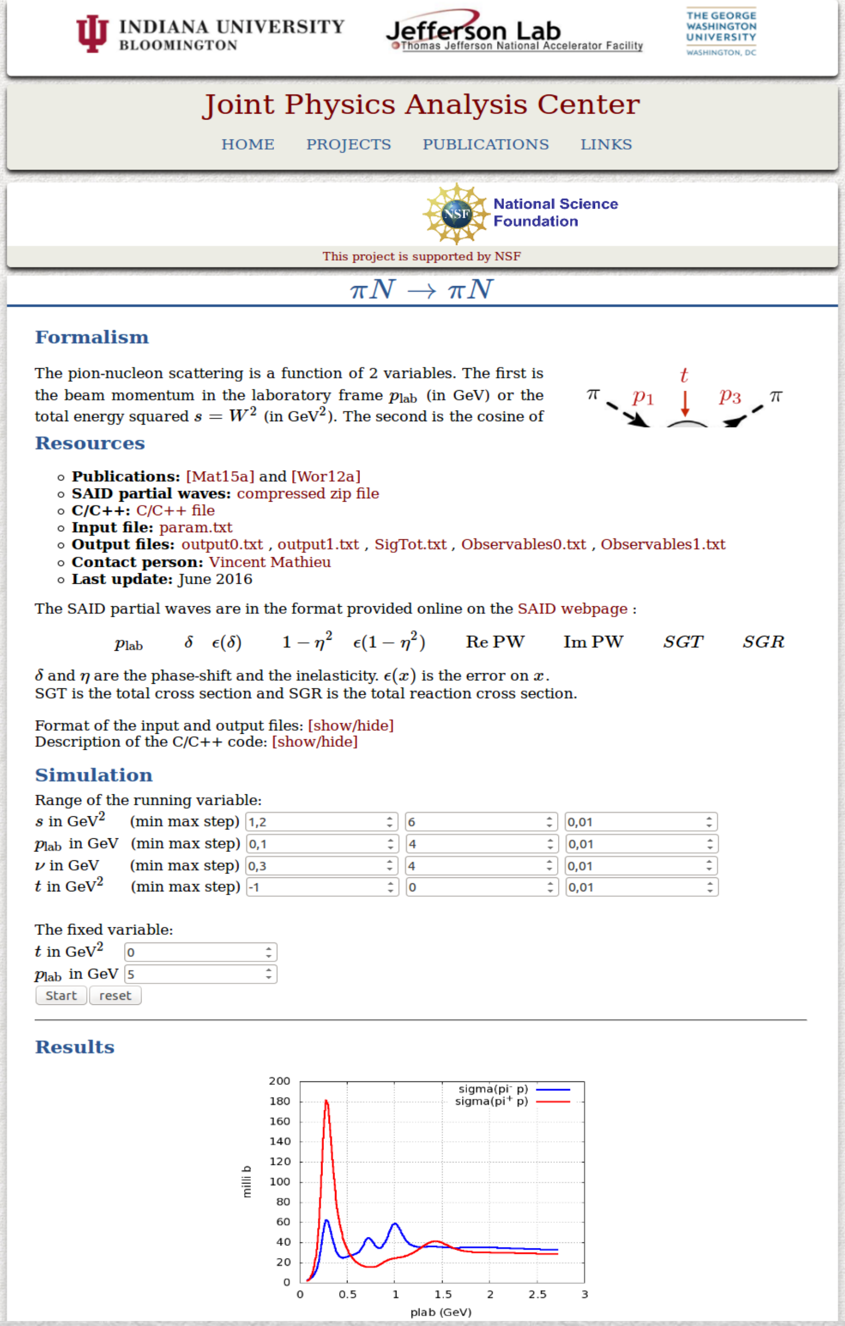
State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\chi_{c1}\gamma)$	Belle [23] (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [24,25] (>10), *BABAR* [26] (8.6)
				$p\bar{p} \to (\pi^+\pi^- J/\psi)$ ...	CDF [27,28] (11.6), D0 [29] (5.2)
				$pp \to (\pi^+\pi^- J/\psi)$ ...	LHCb [30,31] (np)
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [32] (4.3), *BABAR* [33] (4.0)
				$B \to K(\gamma J/\psi)$	Belle [34] (5.5), *BABAR* [35] (3.5)
					LHCb [36] (> 10)
				$B \to K(\gamma\psi(2S))$	*BABAR* [35] (3.6), Belle [34] (0.2)
					LHCb [36] (4.4)
				$B \to K(D\bar{D}^*)$	Belle [37] (6.4), *BABAR* [38] (4.9)
$Z_c(3900)^+$	3888.7 ± 3.4	35 ± 7	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [39] (np)
				$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [40] (8), Belle [41] (5.2)
					CLEO data [42] (>5)
$Z_c(4020)^+$	4023.9 ± 2.4	10 ± 6	1^{+-}	$Y(4260) \to \pi^-(\pi^+ h_c)$	BES III [43] (8.9)
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [44] (10)
$Y(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(\omega J/\psi)$	Belle [45] (8), *BABAR* [33,46] (19)
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [47] (7.7), *BABAR* [48] (7.6)
$Z(3930)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [49] (5.3), *BABAR* [50] (5.8)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [51,52] (6)
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [41,53] (7.4)
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [54] (5.0), *BABAR* [55] (1.1)
$Y(4140)$	4145.6 ± 3.6	14.3 ± 5.9	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [56,57] (5.0), Belle [58] (1.9),
					LHCb [59] (1.4), CMS [60] (>5)
					DØ [61] (3.1)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [52] (5.5)
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [62] (7.2)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$Y(4220)$	4196^{+35}_{-30}	39 ± 32	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data [63,64] (4.5)
$Y(4230)$	4230 ± 8	38 ± 12	1^{--}	$e^+e^- \to (\chi_{c0}\omega)$	BES III [65] (>9)
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [54] (5.0), *BABAR* [55] (2.0)
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	*BABAR* [66,67] (8), CLEO [68,69] (11)
					Belle [41,53] (15), BES III [40] (np)
				$e^+e^- \to (f_0(980) J/\psi)$	*BABAR* [67] (np), Belle [41] (np)
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [40] (8), Belle [41] (5.2)
				$e^+e^- \to (\gamma\,X(3872))$	BES III [70] (5.3)
$Y(4290)$	4293 ± 9	222 ± 67	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data [63,64] (np)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [58] (3.2)
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [71] (8), *BABAR* [72] (np)
$Z(4430)^+$	4478 ± 17	180 ± 31	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [73,74] (6.4), *BABAR* [75] (2.4)
					LHCb [76] (13.9)
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [62] (4.0)
$Y(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [77] (8.2)
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [71] (5.8), *BABAR* [72] (5)
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi(\pi\Upsilon(nS))$	Belle [78,79] (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle [78] (16)
				$\Upsilon(5S) \to \pi^-(B\bar{B}^*)^+$	Belle [80] (8)
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^-(\pi^+\Upsilon(nS))$	Belle [78] (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle [78] (16)
				$\Upsilon(5S) \to \pi^-(B^*\bar{B}^*)^+$	Belle [80] (6.8)

Guerrieri, AP, Piccinini, Polosa,
IJMPA 30, 1530002

Interactive tools

- Completed projects are fully documented on interactive portals
- These include description on physics, conventions, formalism, etc.
- The web pages contain source codes with detailed explanation how to use them. Users can run codes online, change parameters, display results.



http://www.indiana.edu/~jpac/

Lineshapes at 4230

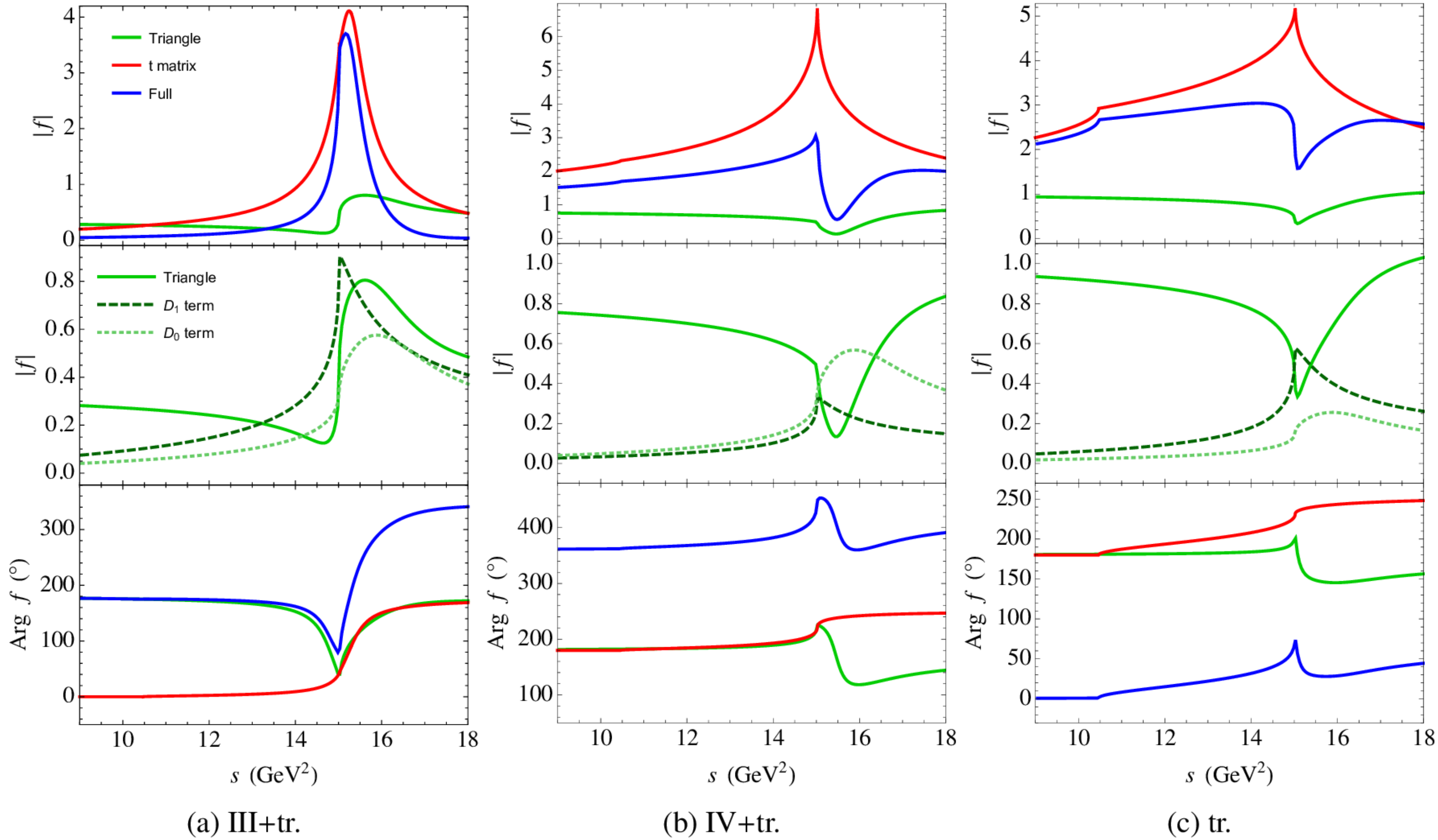


Figure 8: Same as Figure 7, but for $E_{CM} = 4.23$ GeV.

Counting rules

Brodsky, Lebed PRD91, 114025

- Exotic states can be produced in threshold regions in e^+e^-, electroproduction, hadronic beam facilities and are best characterized by cross section ratios
- Two examples:

1) $\frac{\sigma(e^+e^-\to Z_c^+\,\pi^-)}{\sigma(e^+e^-\to\mu^+\mu^-)} \propto \frac{1}{s^6}$ as $s\to\infty$

2) $\frac{\sigma(e^+e^-\to Z_c^+(\bar{c}c\bar{d}u)+\pi^-(\bar{u}d))}{\sigma(e^+e^-\to\Lambda_c(cud)+\bar{\Lambda}_c(\bar{c}\,\bar{u}\bar{d}))} \to const$ as $s\to\infty$

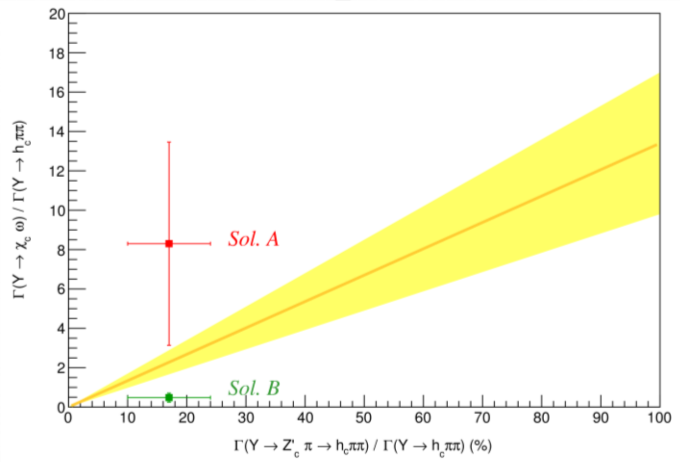
  - Ratio numerically smaller if Z_c behaves like weakly-bound dimeson molecule instead of diquark-antidiquark bound state due to weaker meson color van der Waals forces

Different estimates close to thesholds, and in presence of annihilating $q\,\bar{q}$

Guo, Meissner, Wang, Yang, 1607.04020

Voloshin PRD94, 074042

Tetraquark: the $Y(4220)$



$$\langle \chi_{c0}(p)\,\omega(\eta,q)|Y(\lambda,P)\rangle = g_\chi\,\eta\cdot\lambda,$$

$$\langle Z_c'(\eta,q)\,\pi(p)|Y(\lambda,P)\rangle = g_Z\,\eta\cdot\lambda\frac{P\cdot p}{f_\pi M_Y},$$

$$\langle h_c(\eta,q)\,\sigma(p)|Y(\lambda,P)\rangle = g_h\,\varepsilon_{\mu\nu\rho\sigma}\eta^\mu\lambda^\nu\frac{P^\rho q^\sigma}{P\cdot q},$$

$$\langle \pi(q)\pi(p)|\sigma(P)\rangle = \frac{P^2}{2f_\pi},$$

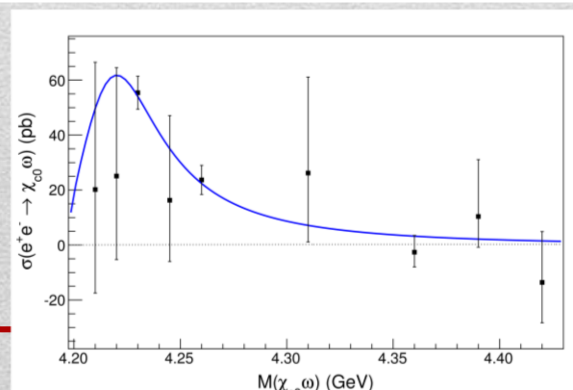
$$\frac{\Gamma\left(Y(4220)\to\chi_{c0}\omega\right)}{\Gamma(Y(4220)\to h_c\pi^+\pi^-)} = (13.4\pm 3.6)\times R_{YZ} = 2.3\pm 1.2.$$

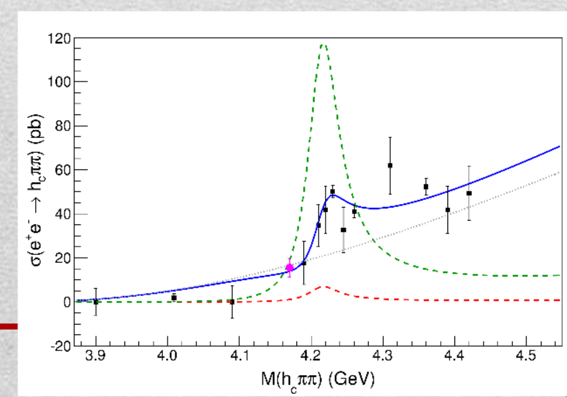
$$\frac{\Gamma\left(Y(4220)\to Z_c'^{\pm}\pi^{\mp}\to h_c\pi^+\pi^-\right)}{\Gamma\left(Y(4220)\to h_c\sigma\to h_c\pi^+\pi^-\right)} = 4.8\pm 3.5,$$

A state apparently breaking HQSS has been observed

Compatible to be the Y_3 state

Faccini, Filaci, Guerrieri, AP, Polosa, PRD 91, 117501





Tetraquark: the b sector

Ali, Maiani, Piccinini, Polosa, Riquer PRD91 017502

$$M(Z_b') - M(Z_b) = 2\kappa_b$$
$$M(Z_c') - M(Z_c) = 2\kappa_c \sim 120 \text{ MeV}$$
$$\kappa_b : \kappa_c = M_c : M_b \sim 0.30$$

$2\kappa_b \sim 36$ MeV, vs. 45 MeV (exp.)

$$Z_b = \frac{\alpha \left|1_{q\bar{q}} 0_{b\bar{b}}\right\rangle - \beta \left|0_{q\bar{q}} 1_{b\bar{b}}\right\rangle}{\sqrt{2}}$$
$$Z_b' = \frac{\alpha \left|1_{q\bar{q}} 0_{b\bar{b}}\right\rangle + \beta \left|0_{q\bar{q}} 1_{b\bar{b}}\right\rangle}{\sqrt{2}}$$

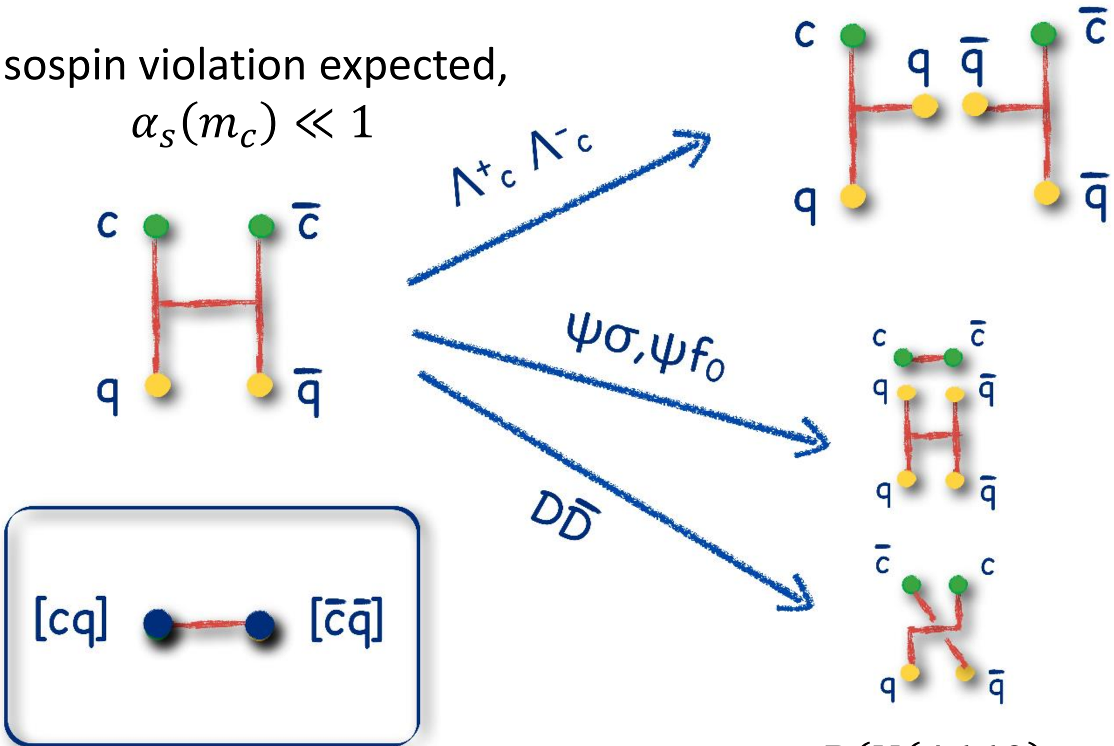
Data on $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ and $\Upsilon(5S) \to \mathrm{h_b}(nP)\pi\pi$ strongly favor $\alpha = \beta$

Baryonium

C. Sabelli

a structure $[cq][\bar{c}\bar{q}]$ can explain the dominance of baryon channel

Isospin violation expected, $\alpha_s(m_c) \ll 1$



Rossi, Veneziano, NPB 123, 507; Phys.Rept. 63, 149; PLB70, 255

$$\frac{B(Y(4660) \to \Lambda_c^+ \Lambda_c^-)}{B(Y(4660) \to \psi(2S)\pi\pi)} = 25 \pm 7$$

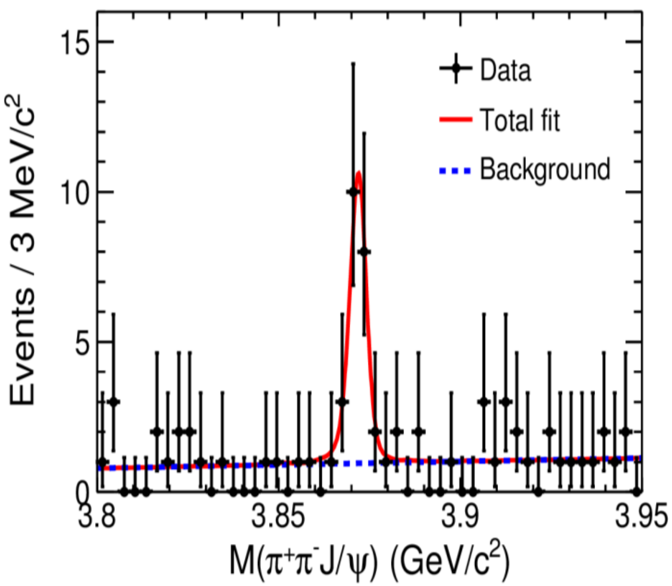
Cotugno, Faccini, Polosa, Sabelli, PRL 104, 132005

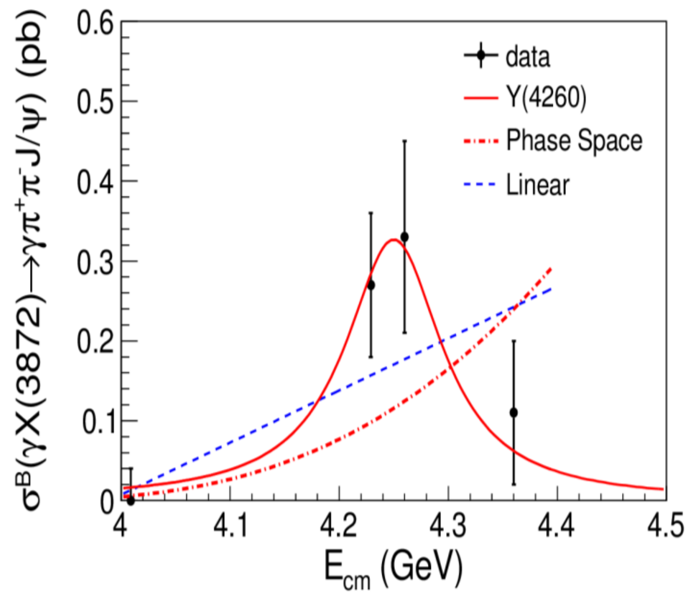
$Y(4260) \to \gamma X(3872)$

M. Ablikim et al., Phys. Rev. Lett. 112 (2014) 092001

F. Piccinini

BESIII: $e^+e^- \to Y(4260) \to X(3872)\gamma$





With $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] = 5\%$

$$\frac{\mathcal{B}[Y(4260) \to \gamma X(3872)]}{\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)} = 0.1$$

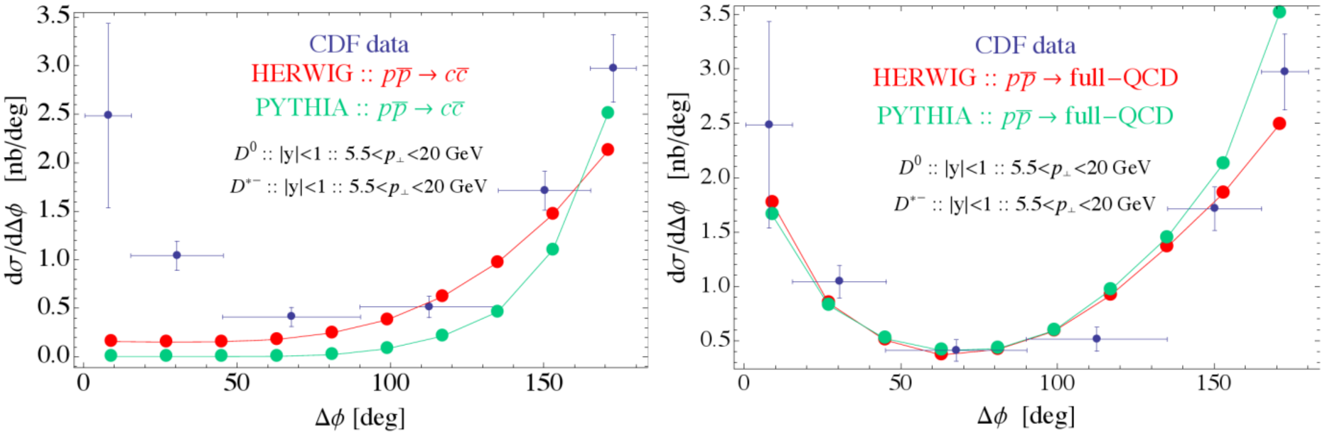
Strong indication that $Y(4260)$ and $X(3872)$ share a similar structure

Tuning of MC

Monte Carlo simulations

A. Esposito

- We compare the $D^0 D^{*-}$ pairs produced as a function of relative azimuthal angle with the results from CDF:



The c-cbar run understimate the low angles (low-k_0) region!

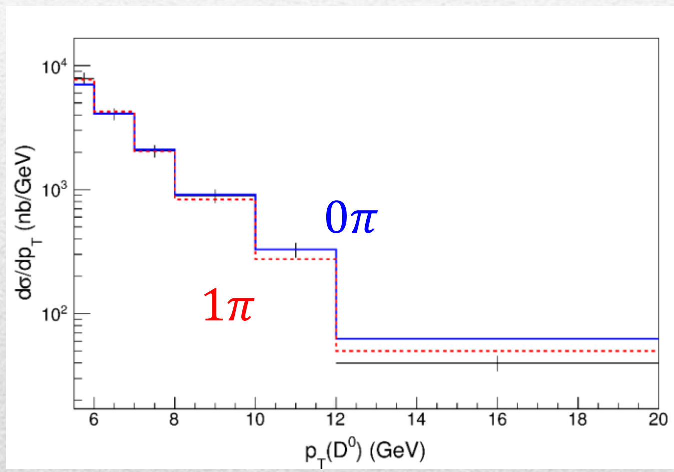
Such distributions of charm mesons are available at Tevatron
No distribution has been published (yet) at LHC

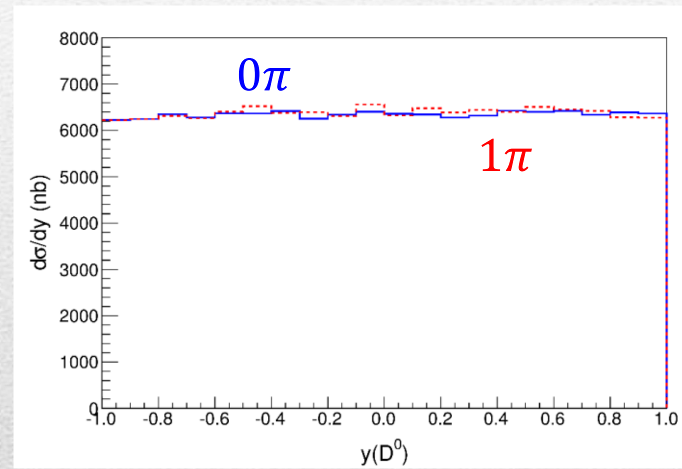
Tuning pions

This picture could spoil existing meson distributions used to tune MC
We verify this is not the case up to an overall K factor

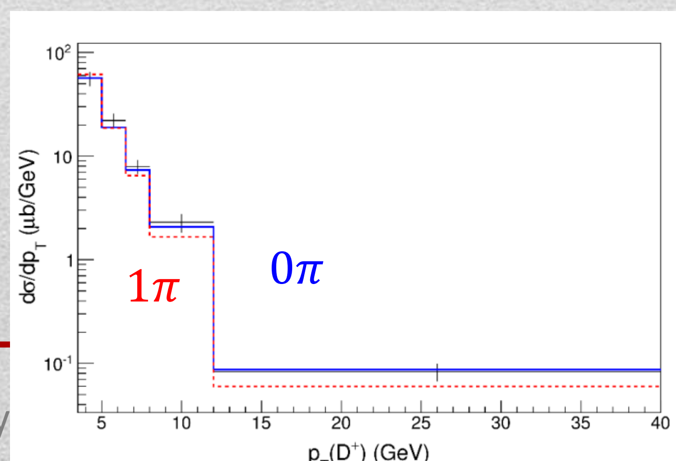
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

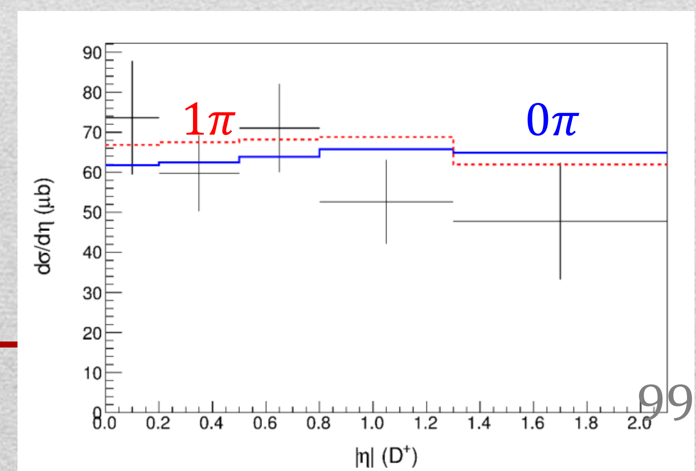
Neither at CDF...





...nor at ATLAS





$Z_c(3900)$

Physics
spotlighting exceptional research

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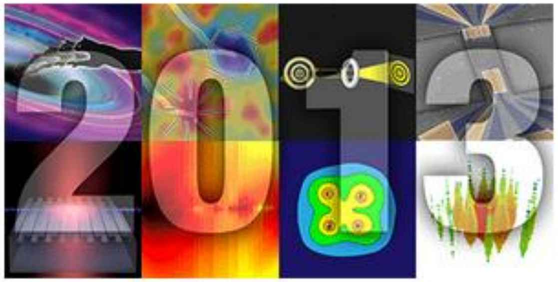
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas



Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

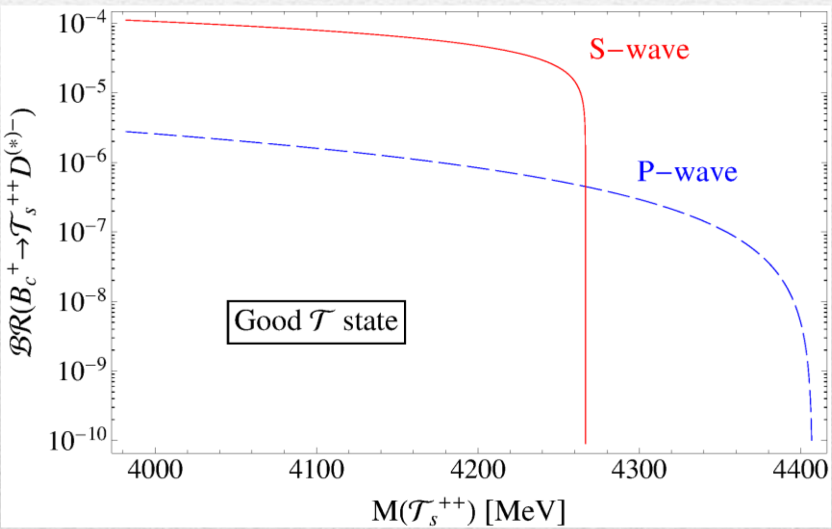
mysterious particle

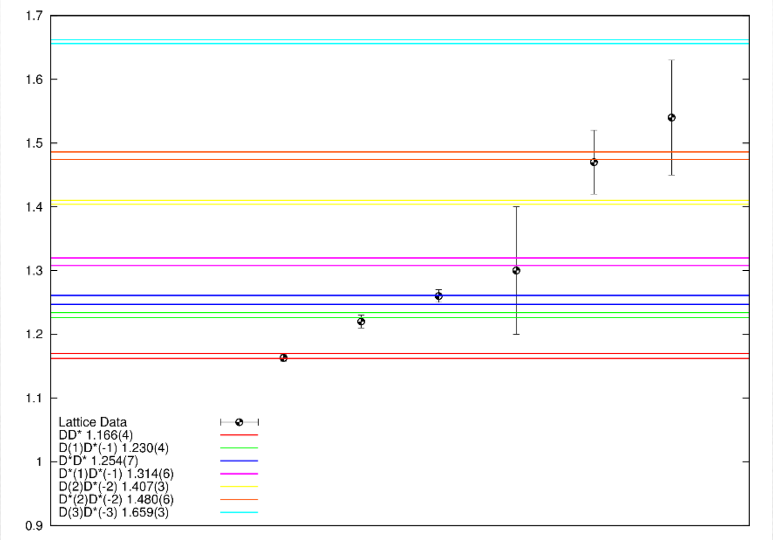
Doubly charmed states

For example, we proposed to look for doubly charmed states, which in tetraquark model are $[cc]_{S=1}[\bar{q}\bar{q}]_{S=0,1}$

These states could be observed in B_c decays @LHC and sought on the lattice

Esposito, Papinutto, AP, Polosa, Tantalo, PRD88 (2013) 054029

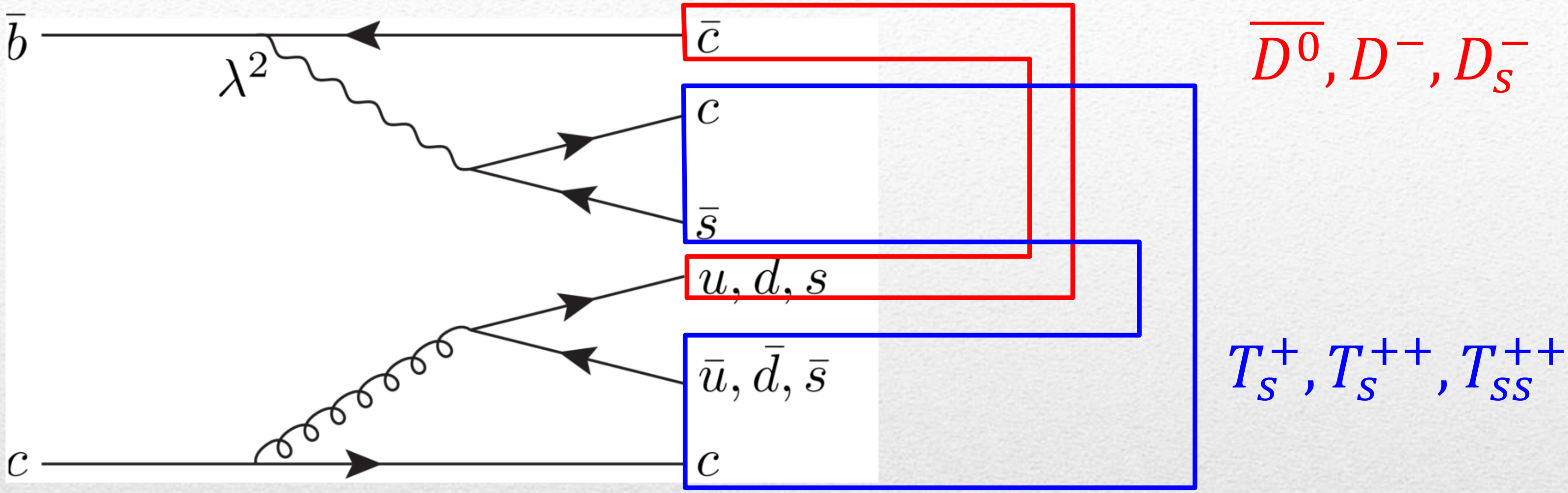


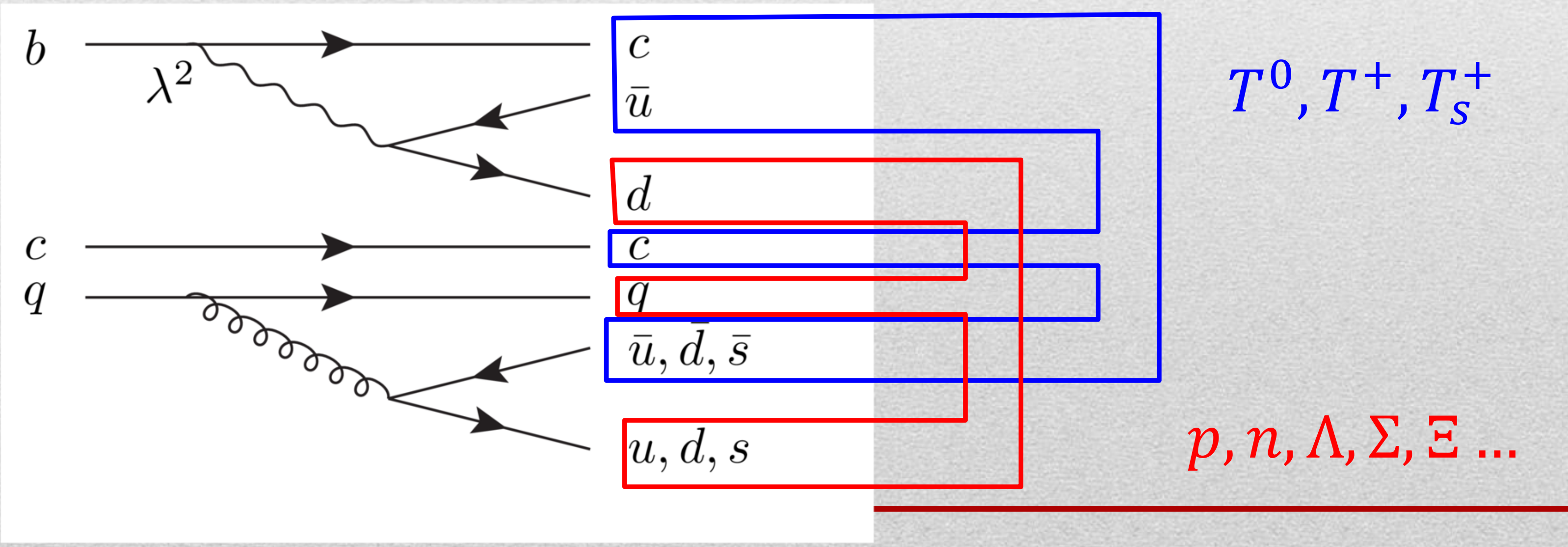


Preliminary results on spectrum for $m_\pi = 490$ MeV, $32^3 \times 64$ lattice, $a = 0.075$ fm

Guerrieri, Papinutto, AP, Polosa, Tantalo, PoS LATTICE2014 106

T states production



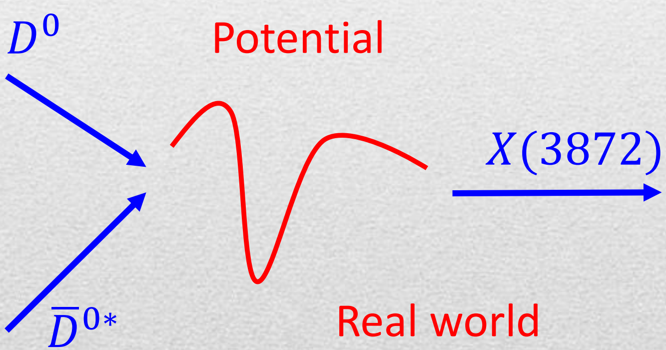


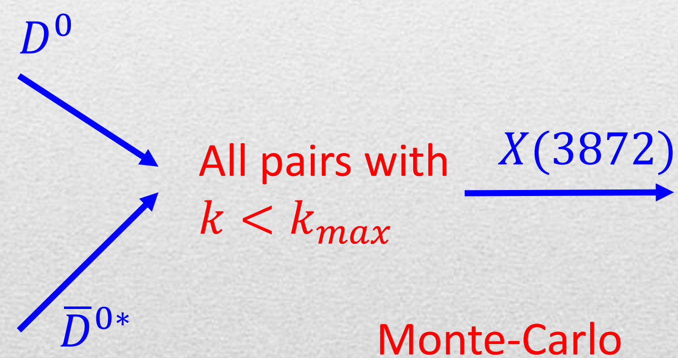
Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?)

We aim to evaluate prompt production cross section at hadron colliders via Monte-Carlo simulations

Q. What is a molecule in MC? **A.** «Coalescence» model



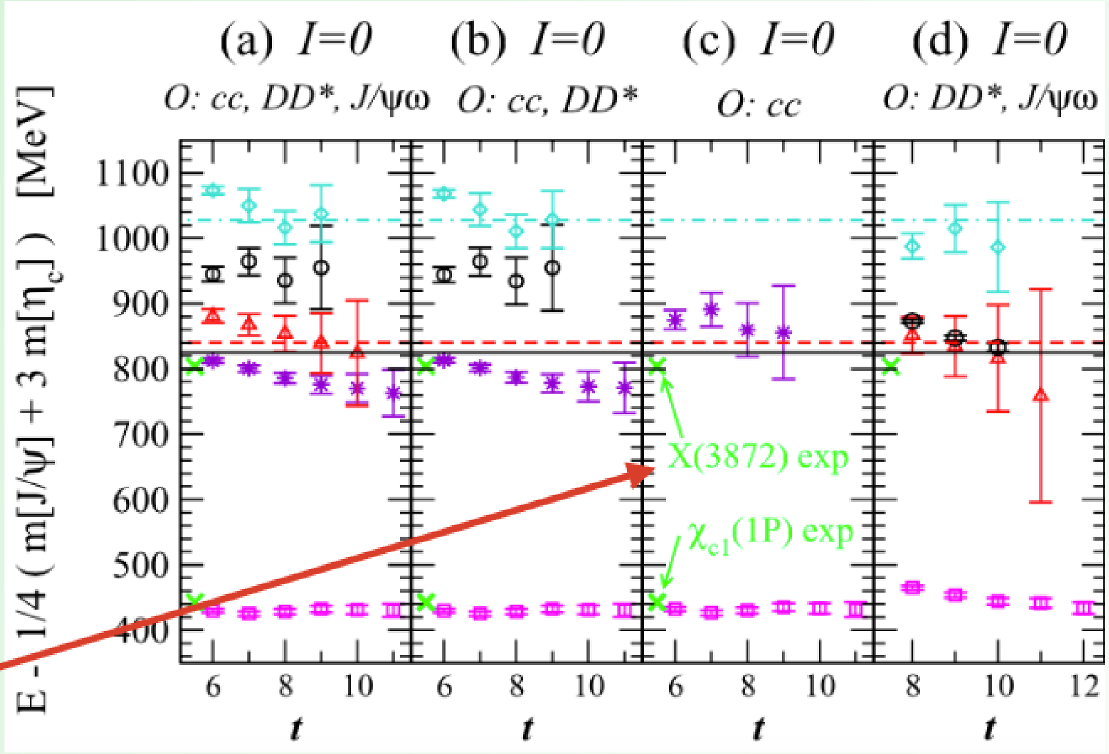


$$\sigma\big(p\bar{p} \to X(3872)\big) \sim \int d^3k\ |\langle X|D\bar{D}^*\rangle\langle D\bar{D}^*|p\bar{p}\rangle|^2 < \int_{k<k_{max}} d^3k\ |\langle D\bar{D}^*|p\bar{p}\rangle|^2$$

This should provide an upper bound for the cross section

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001
Kadastic, Raidan, Strumia PLB683 (2010) 248

X(3872) on the lattice: spectrum



Where is the $\chi_{c1}(2P)$?

$J^{PC} = 1^{++}\ I = 0$ channel

Caveats:

- Small lattices, large artifacts
- Three body dynamics may play a role
- Interpretation of the overlap coefficients is questionable

Status of other XYZ on the lattice is even less clear

Prelovsek *et al.* PRL 111 (2013) 192001 arXiv: 1307.5172

Estimating k_{max}

The binding energy is $E_B \approx -0.16 \pm 0.31$ MeV: very small!
In a simple square well model this corresponds to:

$$\sqrt{\langle k^2 \rangle} \approx 50 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 10 \text{ fm}$$

(binding energy reported in Kamal Seth's talk is $E_B \approx -0.013 \pm 0.192$ MeV:

$$\sqrt{\langle k^2 \rangle} \approx 30 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 30 \text{ fm}$$

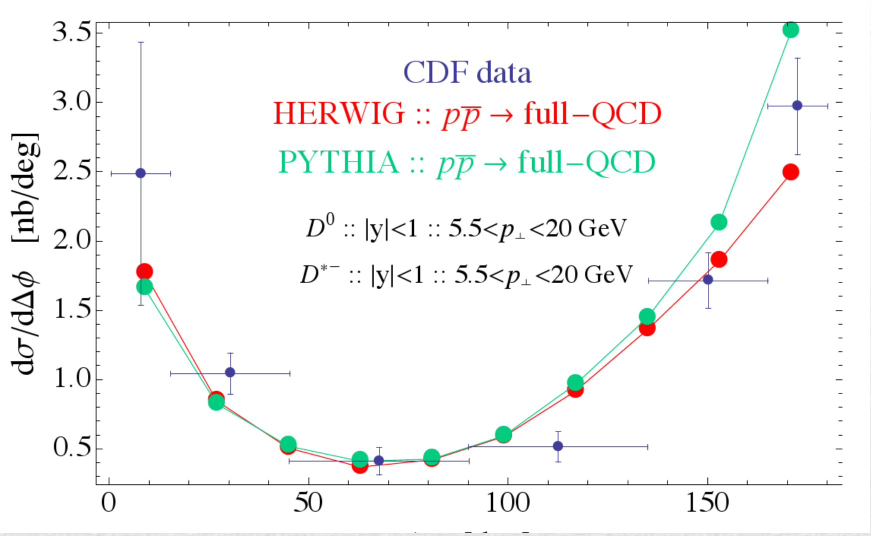
)

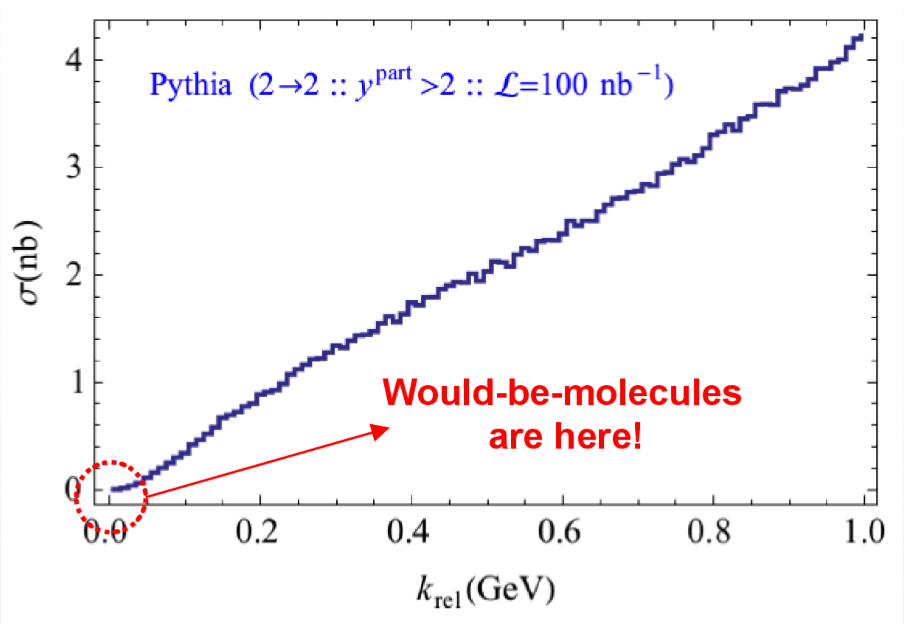
to compare with deuteron: $E_B = -2.2$ MeV

$$\sqrt{\langle k^2 \rangle} \approx 80 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 4 \text{ fm}$$

We assume $k_{max} \sim \sqrt{\langle k^2 \rangle} \approx 50$ MeV, some other choices are commented later

2009 results





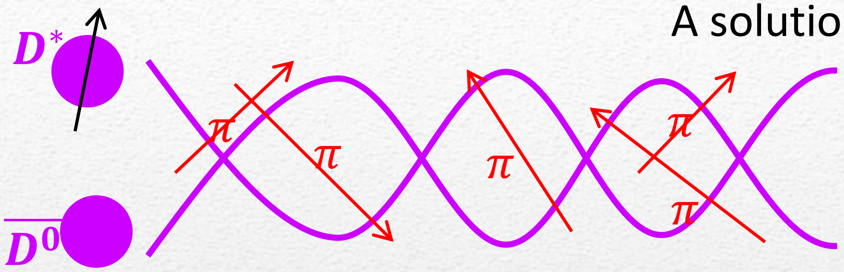
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$

We get $\sigma(p\bar{p} \to DD^* | k < k_{max}) \approx 0.1\text{ nb}$ @$\sqrt{s} = 1.96$ TeV

Experimentally $\sigma(p\bar{p} \to X(3872)) \approx 30 - 70\text{ nb!!!}$

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

Estimating k_{max}



A solution can be FSI (rescattering of DD^*) , which allow k_{max} to be as large as $5m_\pi \sim 700$ MeV

$\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

However, the applicability of Watson theorem is challenged by the presence of pions that interfere with DD^* propagation

Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, PLB684, 228-230

FSI saturate unitarity bound? Influence of pions small?

Artoisenet and Braaten, PRD83, 014019

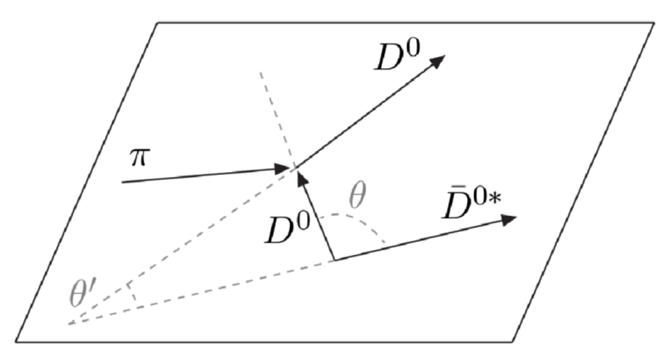
Guo, Meissner, Wang, Yang, JHEP 1405, 138; EPJC74 9, 3063; CTP 61 354
use $E_{max} = M_X + \Gamma_X$ for above-threshold unstable states

With different choices, 2 orders of magnitude uncertainty,
limits on predictive power

A new mechanism?

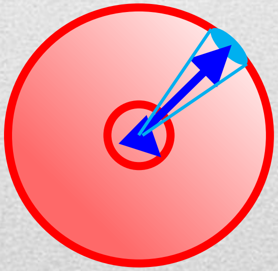
In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the pairs DD^*

Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

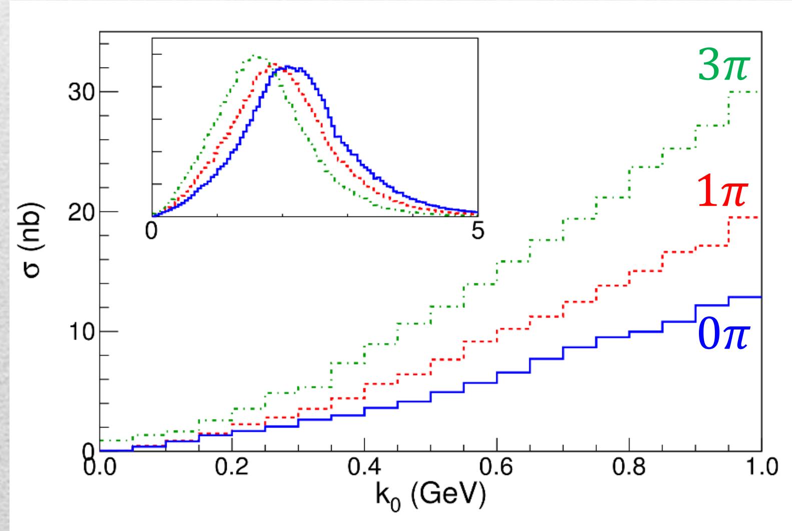


The mechanism also implies: D mesons actually "pushed" inside the potential well (the classical 3-body problem!)

$X(3872)$ is a real, negative energy bound state (stable)
It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100$ keV



By comparing hadronization times of heavy and light mesons, we estimate up to ~ 3 collisions can occur before the heavy pair to fly apart



We get $\sigma\big(p\bar{p} \to X(3872)\big) \sim 5$ nb, still not sufficient to explain all the experimental cross section

Hybridized tetraquarks – Selection rules

- Consider the down quark part of the *X(3872)* in the diquarkonium picture:

$$\Psi_{\mathbf{d}} = X_d = [cd]_0[\bar{c}\bar{d}]_1 + [cd]_1[\bar{c}\bar{d}]_0 \sim (D^{*-}D^{+} - D^{*+}D^{-}) + i(\psi \times \rho^0 - \psi \times \omega^0)$$

Fierz rearrangement

- The closest threshold from below is $\Psi_m \sim \bar{D}^0 D^{*0}$ ⟶ $\Psi_{\mathbf{d}} \perp \Psi_m$ ✓
- But if we consider the up quark part of the *X(3872)*:

$$\Psi_{\mathbf{d}} = X_u = [cu]_0[\bar{c}\bar{u}]_1 + [cu]_1[\bar{c}\bar{u}]_0 \sim (\bar{D}^{*0}D^0 - D^{*0}\bar{D}^0) - i(\psi \times \rho^0 + \psi \times \omega^0)$$

- But then ⟶ $\Psi_{\mathbf{d}} \not\perp \Psi_m$ ✗
- Only X_d is produced via this mechanism ⟶ isospin violation; ⟶ no hyperfine neutral doublet
- X_b (A) Diquark model predicts $M(X_b) \simeq M(Z_b) \simeq (10607 \pm 2)\ \text{MeV}$

  (B) The closest orthogonal threshold is $M(B^0 B^{*0}) = (10604.4 \pm 0.3)\ \text{MeV}$

  (C) This could either be above threshold (very narrow state) or below (no state at all)

  (D) Experimentally the diquark model overpredicts the mass of the *X*:

$$M(Z_c) - M(X) \simeq 32\ \text{MeV}$$

  (E) We favor the below threshold scenario ⟶ **no X_b should be seen**

A. Esposito

Production of hybridized tetraquarks

Going back to $pp(\bar{p})$ collisions, we can imagine hadronization to produce a state

$$|\psi\rangle = \alpha|[qQ][\bar{q}\bar{Q}]\rangle_C + \beta|(\bar{q}q)(\bar{Q}Q)\rangle_O + \gamma|(\bar{q}Q)(\bar{Q}q)\rangle_O$$

If $\beta,\gamma \gg \alpha$, an initial tetraquark state is not likely to be produced
The open channel mesons fly apart
(see MC simulations)

If hybridization mechanism is at work, an open state can resonate in a closed one

α expected to be small in Large N limit, Maiani, Polosa, Riquer JHEP 1606, 160

No prompt production without hybridization mechanism!

Note that only the $X(3872)$ has been observed promptly so far...

...and a narrow $X(4140)$ not compatible with the LHCb one → **needs confirmation**