Exotic Hadrons

Experimental and Theoretical overview

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Hadronic physics and heavy quarks on the lattice

Hamilton Mathematics Institute, Ireland, 06/06/202

Introduction

1.String breaking

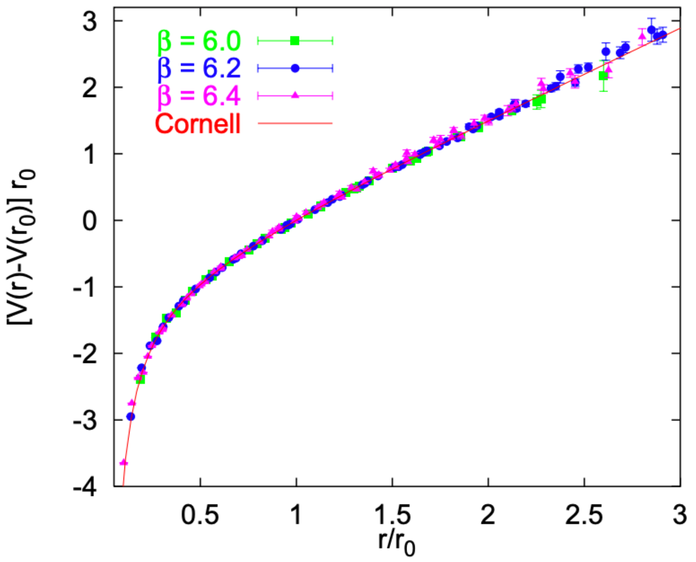
2. Mixture with the threshold

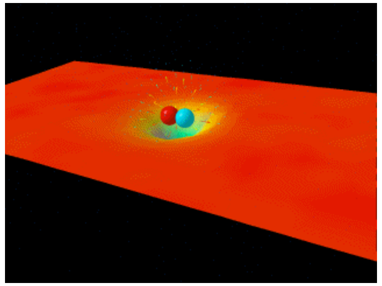
3. Different Hadrons and Nuclei

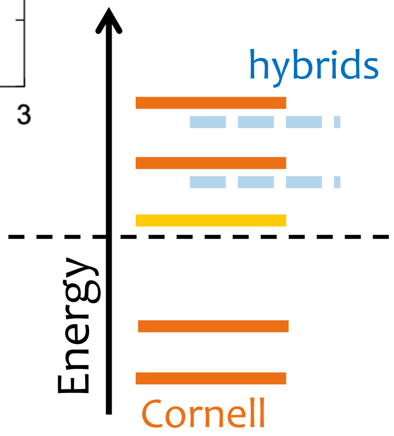
[G.S.Bali, PR 343 (2001) 1-136]
[D. Leinweber, CSSM, Adelaide]
[J. Bulava et al., PLB 793 (2019) 493-498]

Effect of string breaking

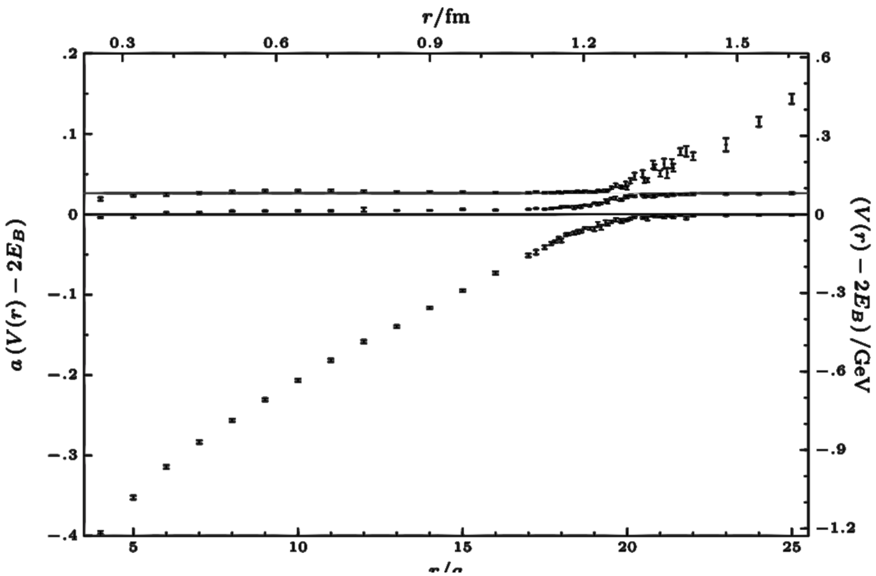
The quenched potential (no breaking)







The unquenched potential (breaking)



shifts “quenched” QCD states

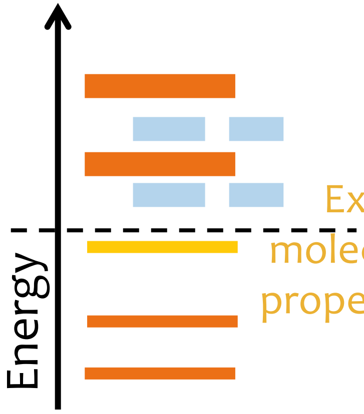
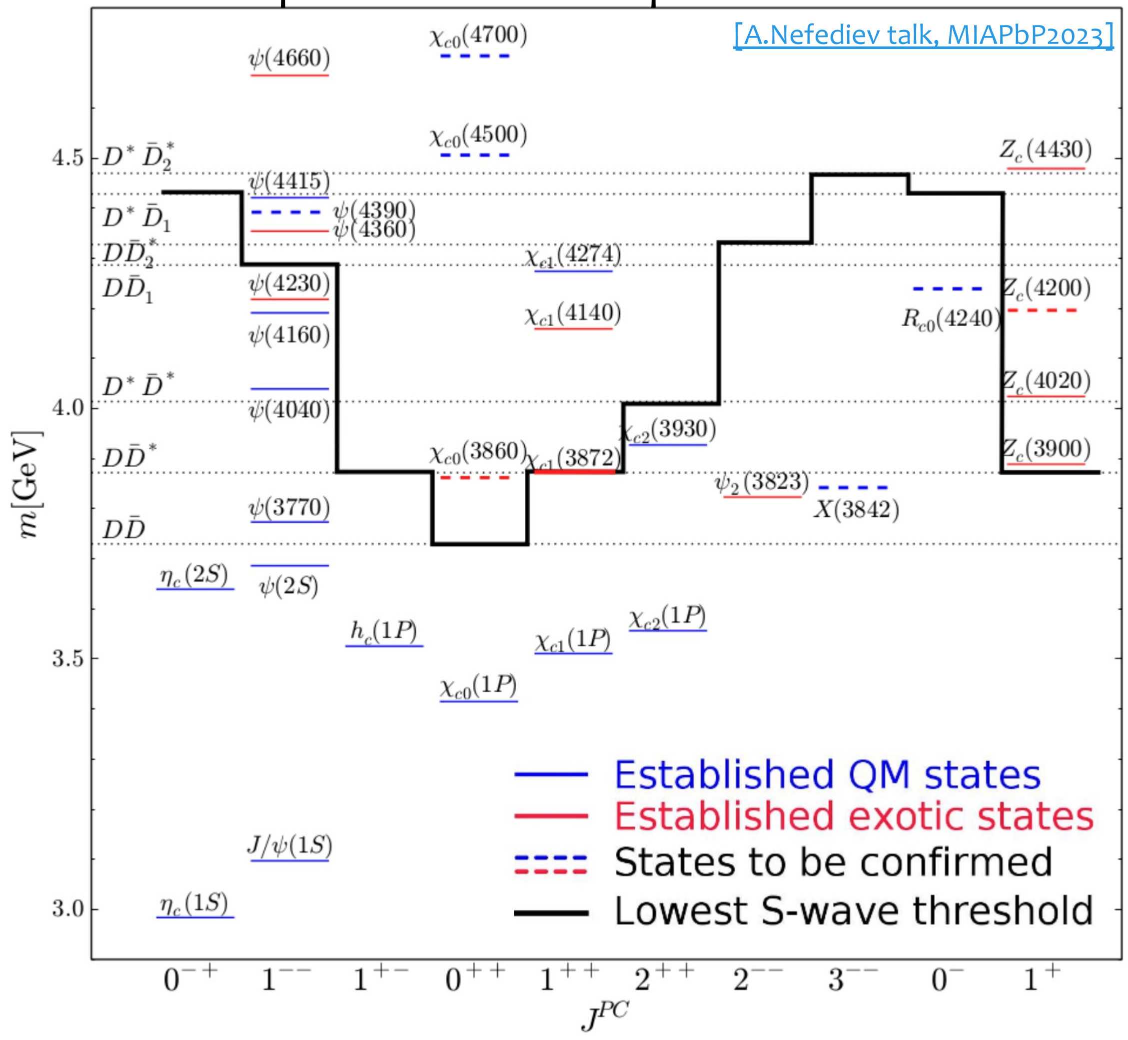


Exhibit molecular properties

An example: charmonium spectrum



QM states and thresholds

Most of hadrons are not isolated:

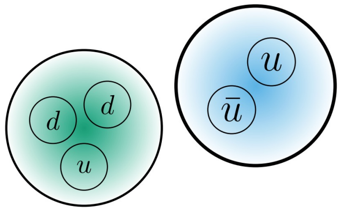
near hadron-hadron threshold,

e.g. $q\bar{q} \to (q\bar{q})(q\bar{q})$**,**

hadronic states are coupled to hadron-hadron continuum

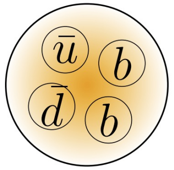
Molecule component:
a part of the state wave function is $(q\bar{q})(q\bar{q})$

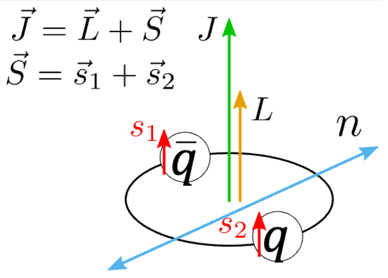
Possible configurations of hadrons



Conventional Quark Model: $(q\bar{q}, qqq)$

Bigger Quark Model $(q\bar{q}q\bar{q}, qqqq\bar{q}, \ldots)$



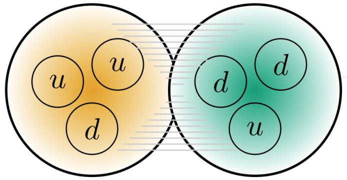


+ excitations

Conventional Hadronic Molecules = Nuclei: $(qqq)(qqq)$

Heavy-Flavor Hadronic Molecules: $(Qqq)(Qqq)$, $(Q\bar{q})(Qqq)$, …

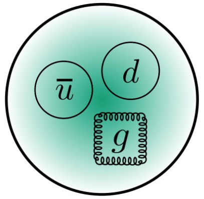
Admixed Molecules: $q\bar{q} \to (q\bar{q})(q\bar{q})$

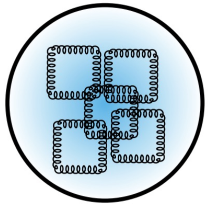


+ nuclei chart

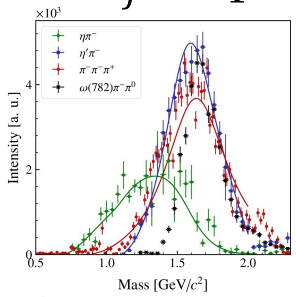
Hybrids: $q{\sim}g{\sim}\bar{q}$

Glueballs: $g{\sim}g$





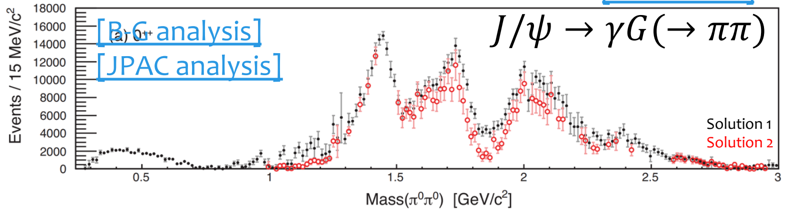
$J^{PC} = 1^{-+}$



[P.Haas, HADRON2023]

[BESIII data]

$J/\psi \to \gamma G(\to \pi\pi)$



[B-G analysis]

[JPAC analysis]

Experimental techniques

1.Select clean data sample

2. Identify hadronic resonances

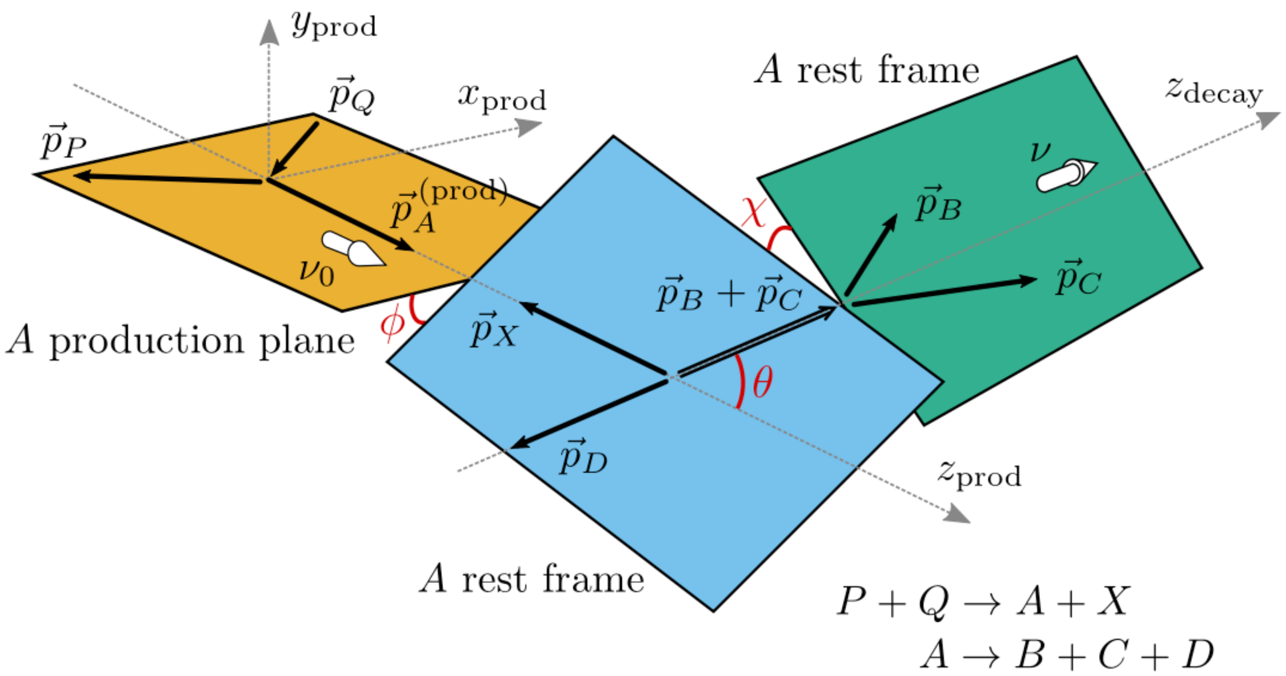
3. Pole mass and width
(reaction-theory analysis)

3. Spin and parity
(angular analysis)

e^+e^- machines: Belle, BESIII, BaBar
pp production: LHCb , ALICE, CMS, ATLAS
b-decays: LHCb, BaBar
pip and leptoproduction: COMPASS
photoproduction: GlueX, Crystal Barrel
$p\bar{p}$ annihilation: Crystal Ball, (PANDA)

[Jacob-Wick] [Chung]
[Chen and Ping, 2017]
[Wang *et al.*, 2020]
[Mikhasenko *et al.*, 2020]
[Lie et al, 2022]

Angular Analysis



Correlations in angular distributions give access to particle spins

- model-independent rotational properties

$$A^{(23)}_{\lambda_0,\lambda_1,\lambda_2} = \underbrace{\boxtimes(\phi_i,\theta_i)}_{0\to X,1} \times \underbrace{\boxtimes(\phi_i',\theta_i')}_{X\to 2,3} \times \underbrace{\square(\phi_i'',\theta_i'')}_{\text{spin align.}}$$

- unphysical inhomogenity
- spin 1/2: $A(\pi) \neq A(-\pi)$
- range of ϕ matters $[-\pi,\pi]$ vs $[0,2\pi]$

Recent simplification of amplitude construction approach

[JPAC, PRD 101, 034033 (2020)]

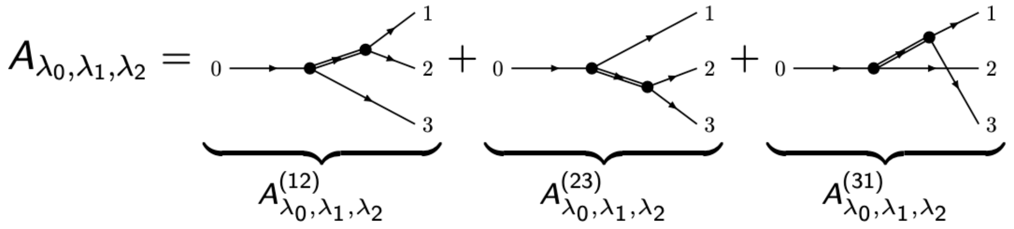
$$A_{\lambda_0,\lambda_1,\lambda_2} = \sum_\nu D^{1/2*}_{\lambda_0,\nu}(\alpha,\beta,\gamma)\,\underbrace{O^\nu_{\lambda_1,\lambda_2}(m_{12}^2,m_{23}^2)}_{O^{(12)}+O^{(23)}+O^{(31)}}$$

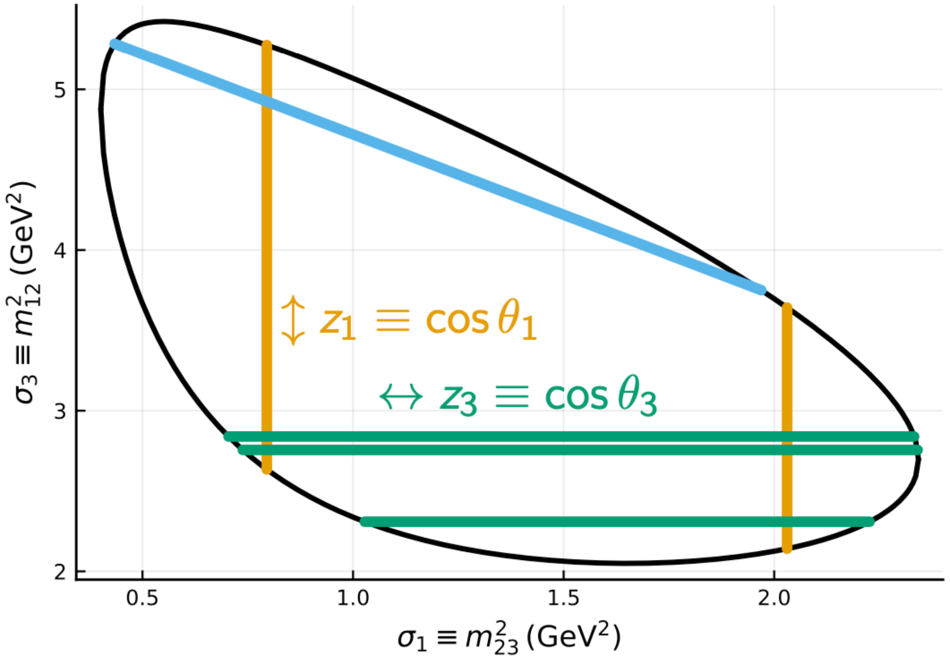
$$O^{(23)}_{\nu,\lambda_1,\lambda_2}(m_{12}^2,m_{23}^2) = \underbrace{\boxtimes}_{0\to X,1} \times \underbrace{\boxtimes}_{X\to 2,3} \times \underbrace{\square}_{\text{spin align.}}$$

- correct ϕ dependence by construction

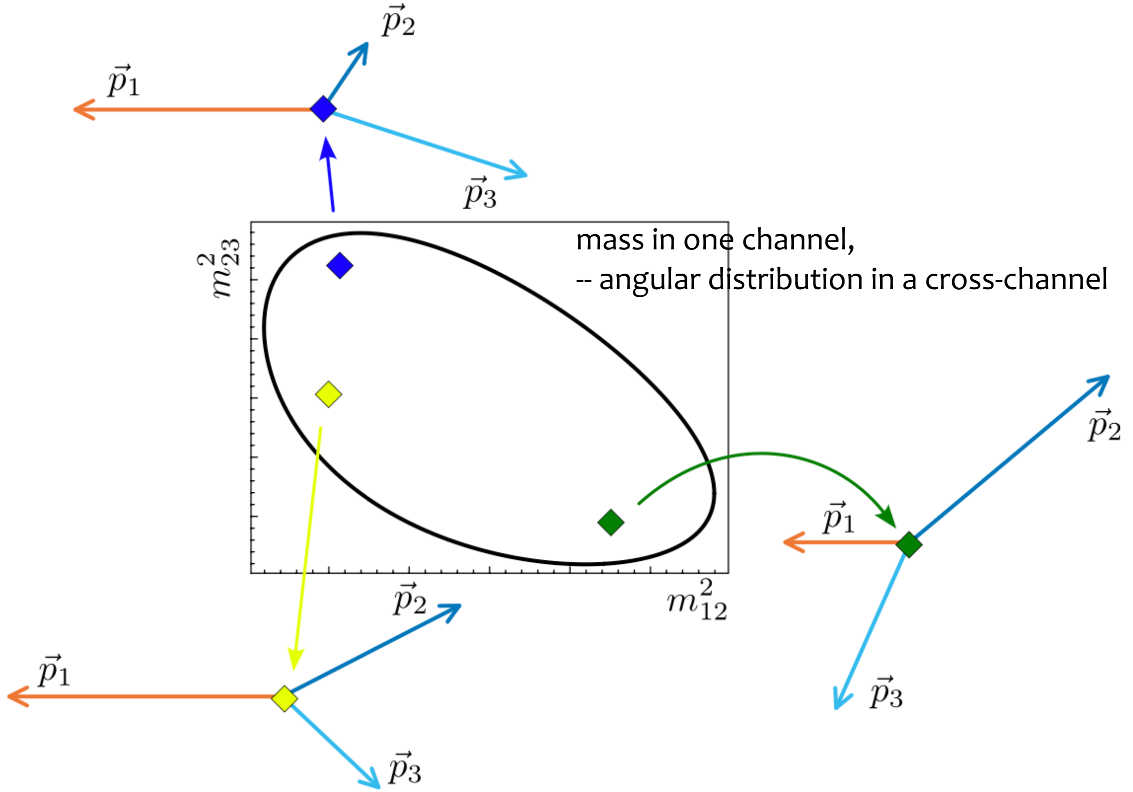
Dynamic modeling

Cascade-reaction approach ("isobar model")





Due to cross channels
angular distributions and dynamic lineshapes are **mixed**



Hadronic amplitude

Probability density function is a square of amplitude summed over spin projections

$$I(s) \;=\; \sum_{\text{spin}} |A(s)|^2$$

$A(s)$ is a complex function of energy, $s = E^2$

Example of a resonance amplitude

$$A(s) = \frac{N(s)}{m^2 - s - ig^2\rho(s)}$$

$N(s)$ is reaction dependent (B-decays / e+e-), denominator is universal

Imaginary part is something we control well:

1. Decay threshold is far away / unknown

$ig^2\rho(s) = m\Gamma$ (const)

2. The only relevant continuum to consider

$ig^2\rho(s)$

=Breit-Wigner=

3. there are multiple channels to consider

$i(g_1^2\rho_1 + g_2^2\rho_2 + \cdots)$

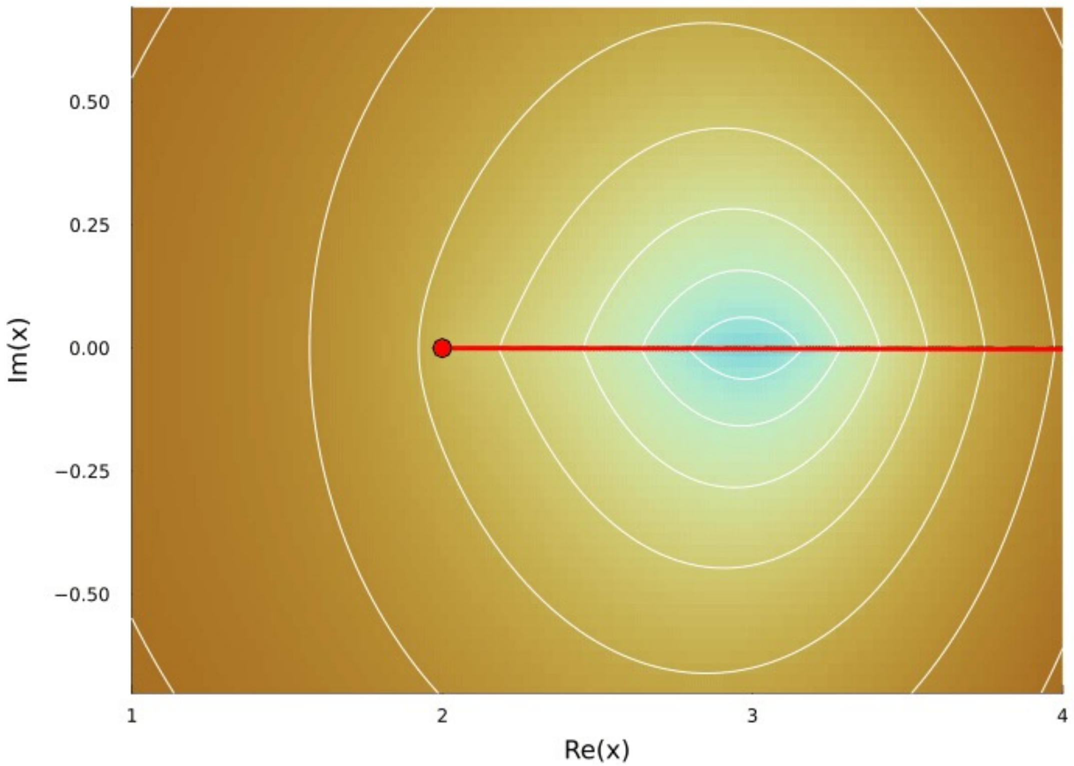
=Flatte=

4. Multiple channels, multiple resonances

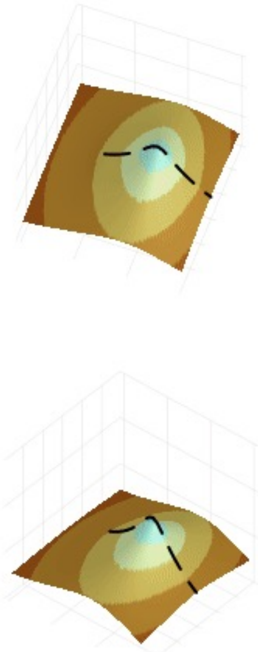
=K-matrix=

Analytic continuation – resonance poles

- Amplitude A is a complex function of E = x+iy
- Im(1/A) ~ phase sp. ~ sqrt(kin. energy)
- sqrt branch point – forms two sheets

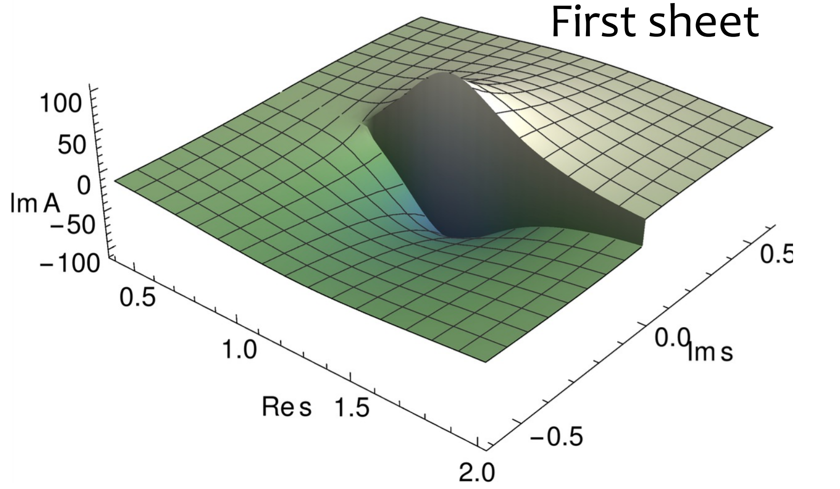


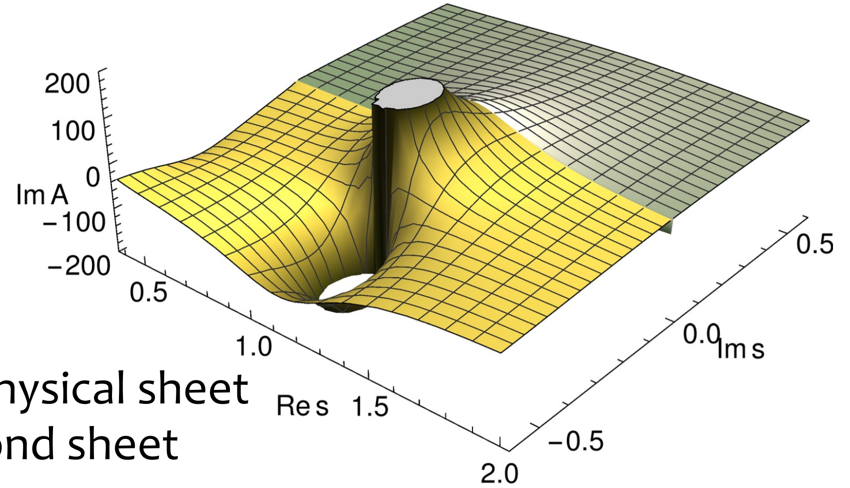
$|A(x+iy)|^2$



Im A (x + iy)

Physical sheet
First sheet





Unphysical sheet
Second sheet

$\chi_{c1}(3872)$

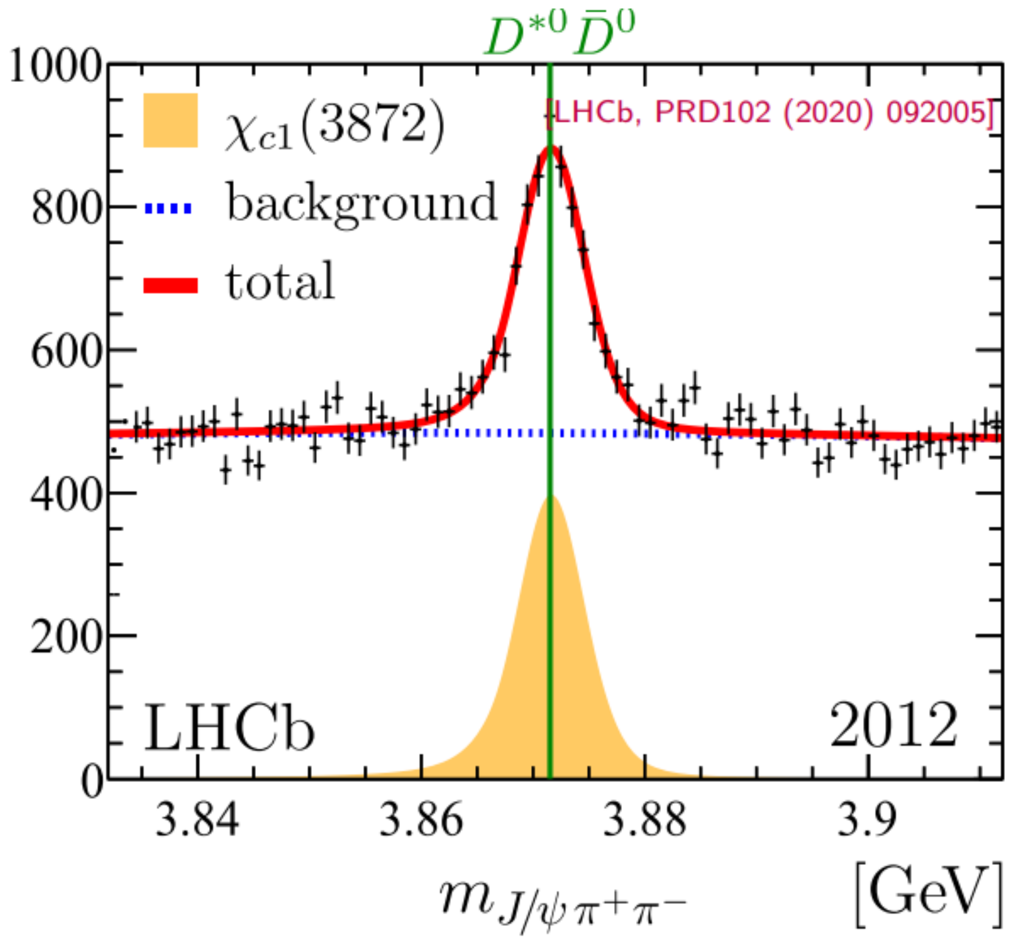
Consistent with the charmonium state that shows up next to **hadron-hadron threshold**
exhibit molecular properties

QM core, molecular appearance

Seen in e+e- by Belle, BESIII, BaBar
Seen in pp by LHCb, CMS, ALICE.
Seem in b-decays by LHCb, BaBar,
Might be seen in leptoproduction by COMPASS

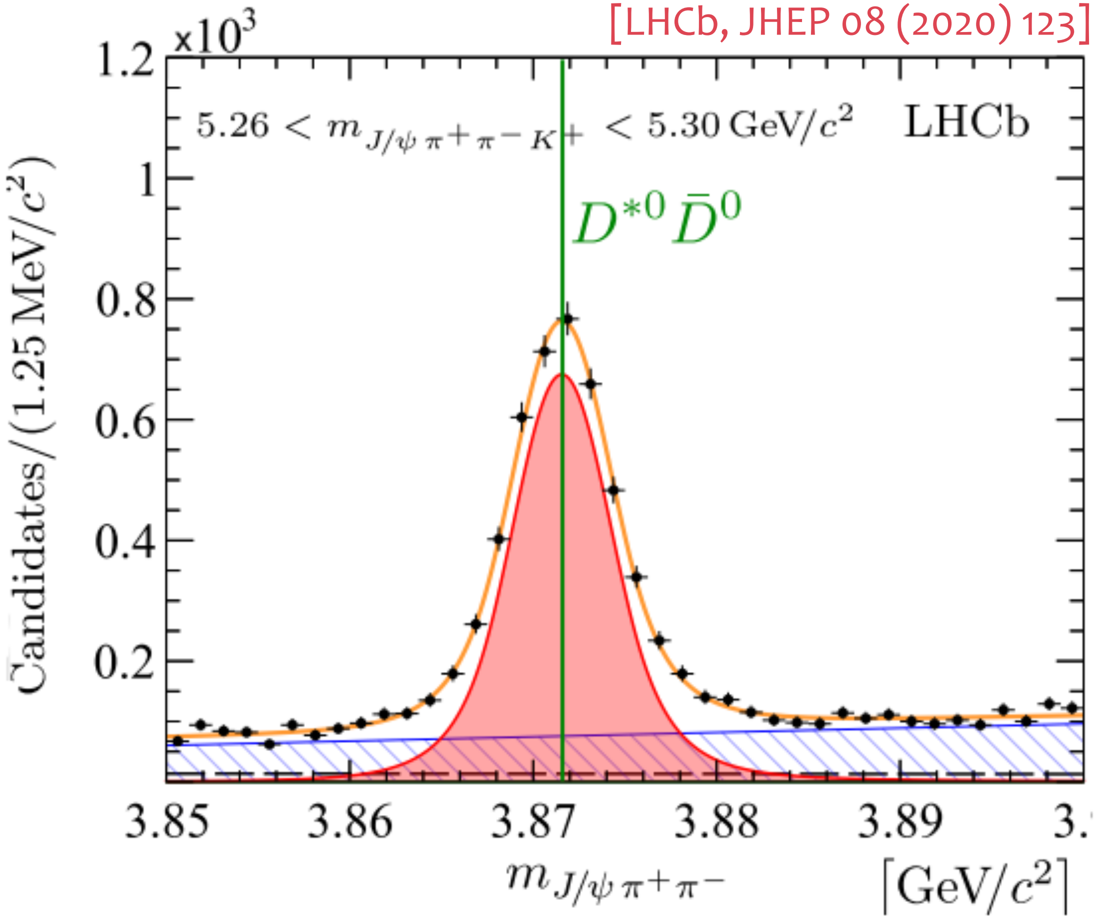
$\chi_{c1}(3872)$ is right at the $D^0 D^{*0}$ threshold

Prompt production ($pp \to \chi_{c1}\, X$)



From B-decays ($B^+ \to \chi_{c1} K^+$)

[LHCb, JHEP 08 (2020) 123]



$\chi_{c1}(3872)$ lineshape and parameters

Flatte lineshape

$$A(s) = \frac{1}{m^2 - s - ig^2\rho_{D^*\bar{D}} - im\Gamma_0}$$

General agreement on the pole parameters between BESIII, Belle, LHCb:

- Analysis of $J/\psi\,\pi^+\pi^-$ by LHCb

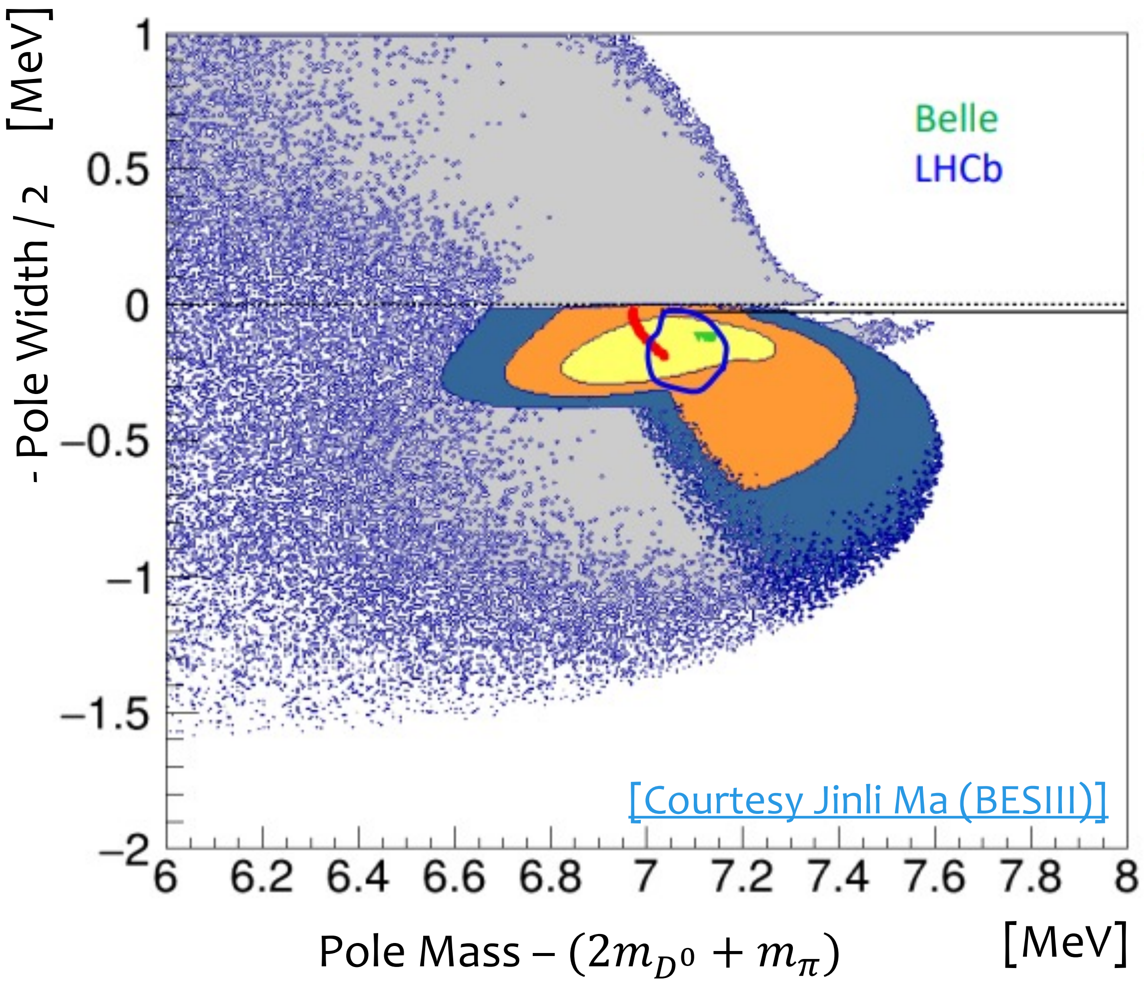
[PRD102 (2020) 092005]

- BESIII combined analysis of $J/\psi\,\pi^+\pi^-$ & $D^{0*}\bar{D}^0$

[hep-ex: 2309.01502]

$\Gamma_{\text{known}}/\Gamma_{\pi^+\pi^-J/\psi}$	β	2.8
$\Gamma_{\text{unknown}}/\Gamma_{\pi^+\pi^-J/\psi}$	α	8

[C. Li and C.-Z. Yuan, PRD 100, 094003 (2019)]



Doubly heavy tetraquark T_{QQ}

Look like regular QM-tetraquark state similar to Λ_b^0 baryon

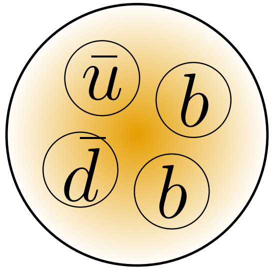
T_{cc}^+ : shows up next to hadron-hadron threshold
exhibit molecular properties

T_{bb}^- : decays weakly, can flies meters

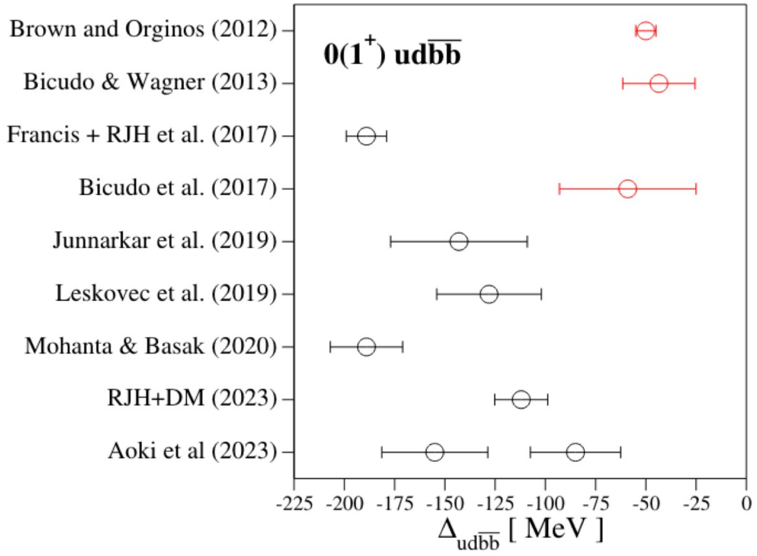
Only seen in pp by LHCb

T_{cb}^0 : likely to exist

Tetraquark T_{bb}^{-}



[courtesy Renwick Hudspith]



Firmly established in pheno, e.g.

[Ader, Richard, PRD 25, 2370 (1982)]

lattice calculations, e.g.

[Francis et al., PRL 118, 142001 (2017)]

Below open-flavor threshold

Stable wrt strong interaction

Similar to a "regular" QM hadron

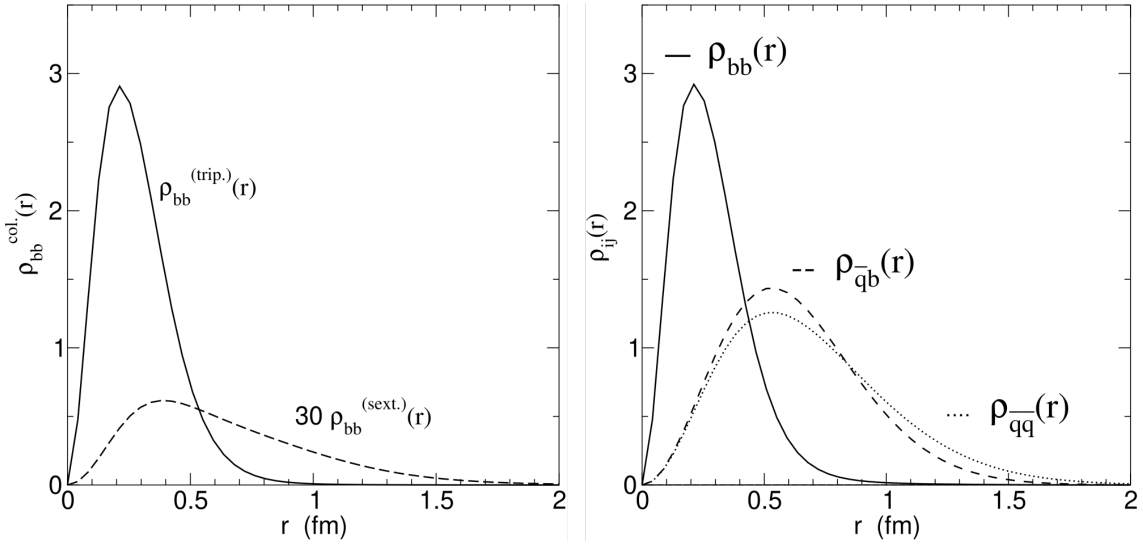
bb are close together, and

are in color-anti-triplet

Not yet seem experimentally; won't be soon

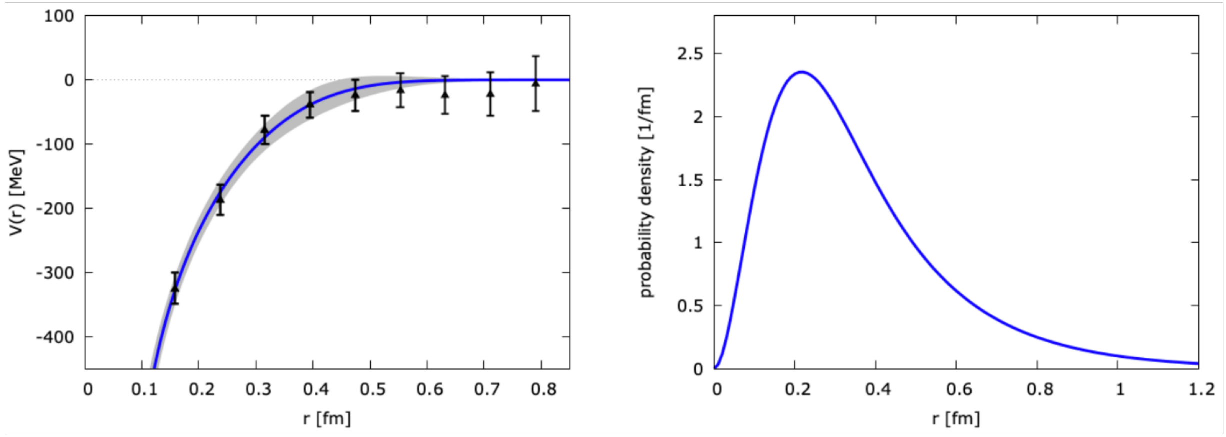
Anticipated for 50y

[Janc, Rosina, FBS35 (2004) 175-196]



Continuum for T_{bb}^{-}

[Bicudo et al., PRD103, 114506 (2021)]

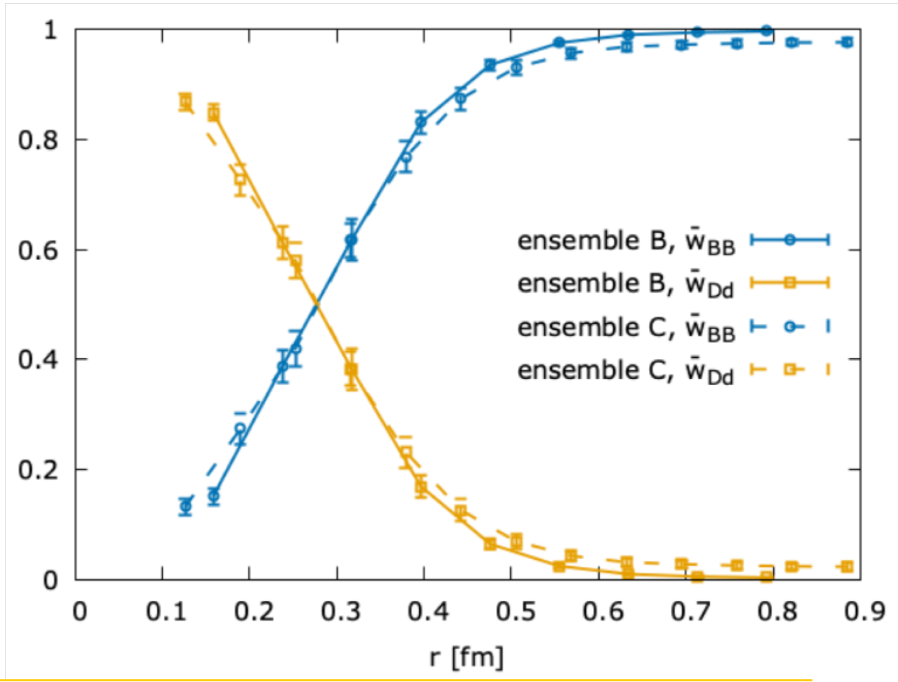


Born-Oppenheimer approach with a lattice potential

$$\mathcal{O}_{BB,\Gamma} = 2N_{BB}(\mathcal{C}\Gamma)_{AB}(\mathcal{C}\tilde{\Gamma})_{CD}\left(\bar{Q}_C^a(\mathbf{r}_1)\psi_A^{(f)a}(\mathbf{r}_1)\right)\left(\bar{Q}_D^b(\mathbf{r}_2)\psi_B^{(f')b}(\mathbf{r}_2)\right)$$

$$\mathcal{O}_{Dd,\Gamma} = -N_{Dd}\epsilon^{abc}\left(\psi_A^{(f)b}(\mathbf{z})(\mathcal{C}\Gamma)_{AB}\psi_B^{(f')c}(\mathbf{z})\right)\epsilon^{ade}\left(\bar{Q}_C^f(\mathbf{r}_1)U^{fd}(\mathbf{r}_1;\mathbf{z})(\mathcal{C}\tilde{\Gamma})_{CD}\bar{Q}_D^g(\mathbf{r}_2)U^{ge}(\mathbf{r}_2;\mathbf{z})\right)$$

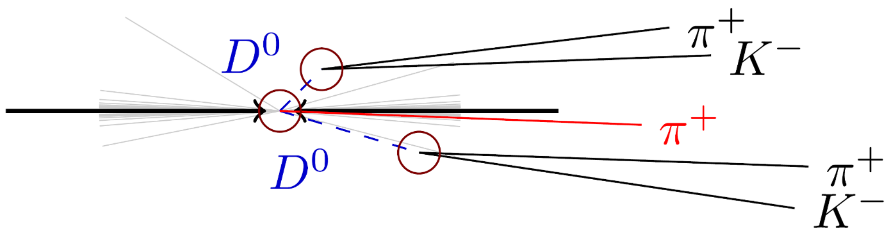
Diquark-diquark configuration vs meson-meson configurations



Tetraquark component dominants at smaller r, while at the high r tails, the molecular component is present.

meson-meson is surprisingly important

Doubly-charm tetraquark T_{cc}^+ right at the $D^0 D^{*+}$ threshold



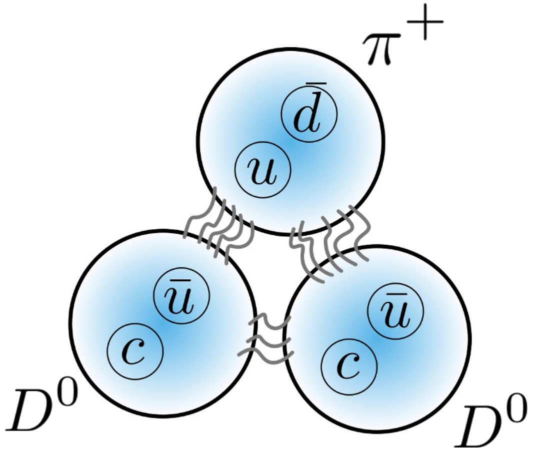
Peak in $D^0 D^0 \pi^+$ just below $D^{*+} D^0$ threshold

Extremely narrow, ~300keV

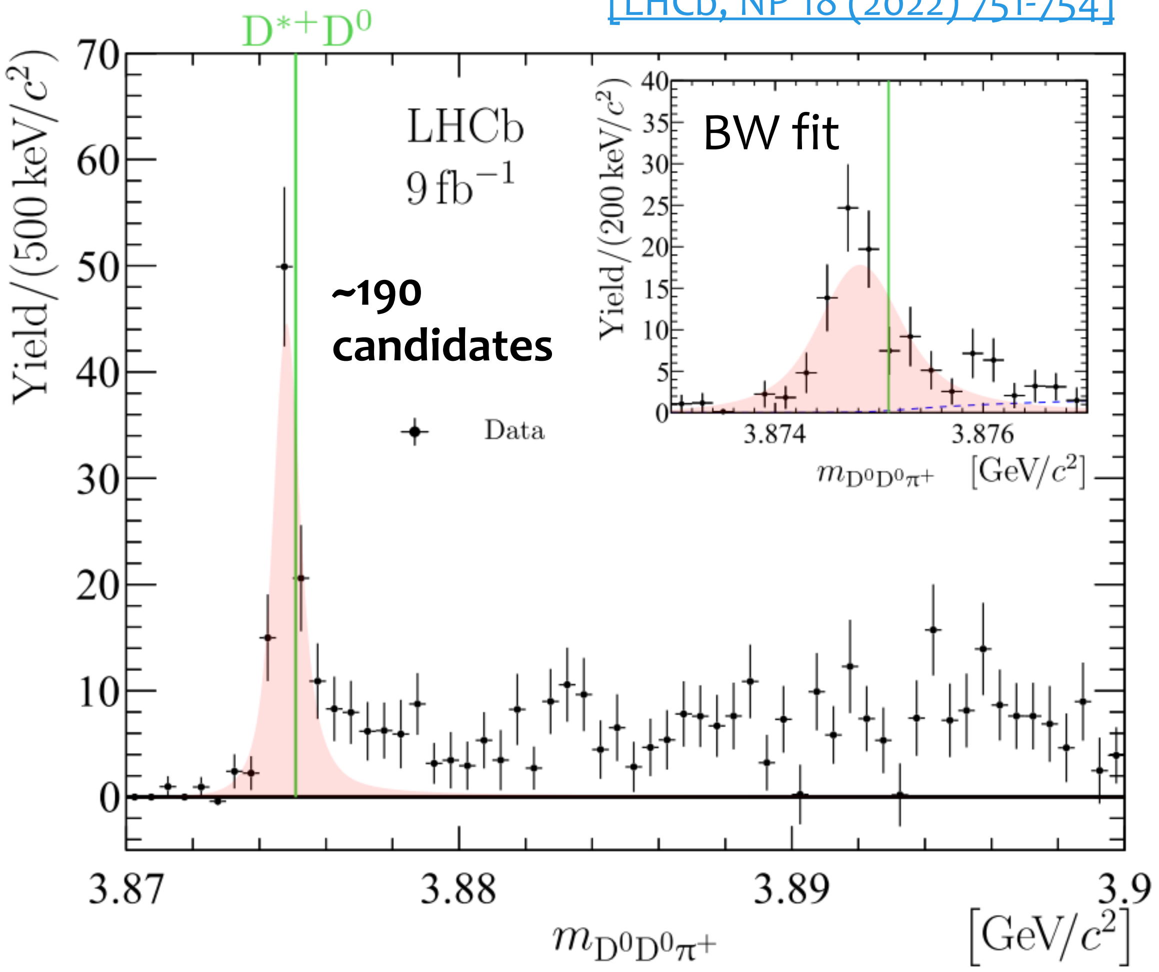
(resolution)

Needs to be treated as

three-body effect

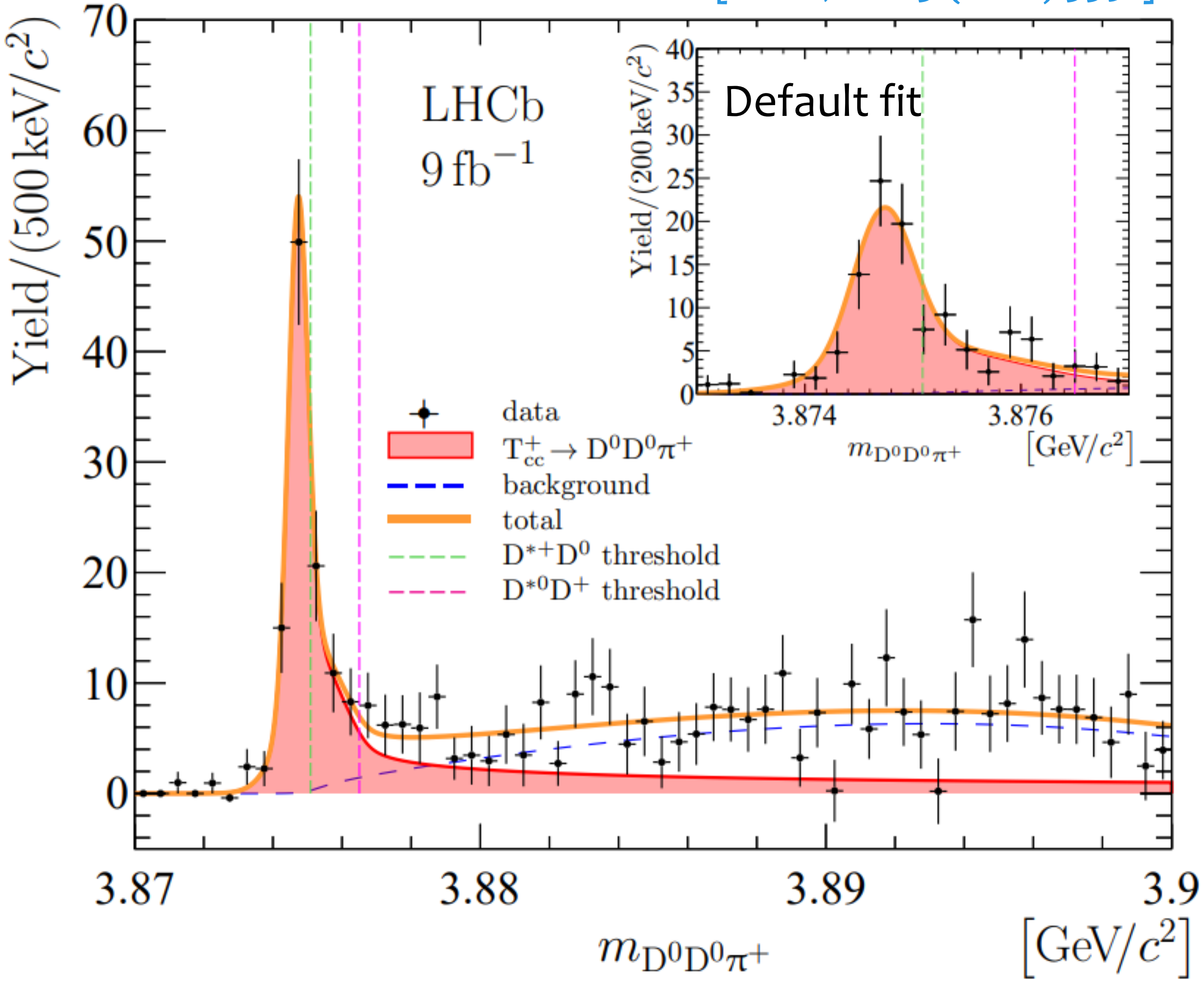


[LHCb, NP 18 (2022) 751-754]



Studies of the doubly-charm tetraquark T_{cc}^{+}

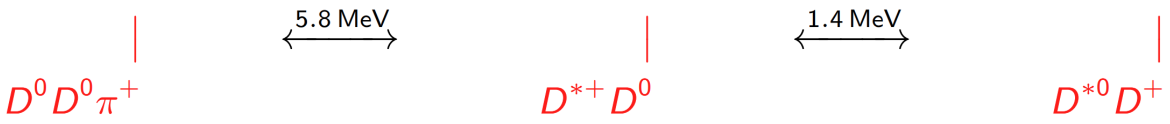
[LHCb, NC 13 (2022) 3351]



QN: isoscalar ($I = 0$), axial ($J^{PC} = 1^{++}$)

Coupled channel model

$$D^{*+}D^0 + D^{*0}D^+$$
$$\to \{D^0D^0\pi^+, D^0D^+\pi^0, D^0D^+\gamma\}$$



Yields good agreement with the data

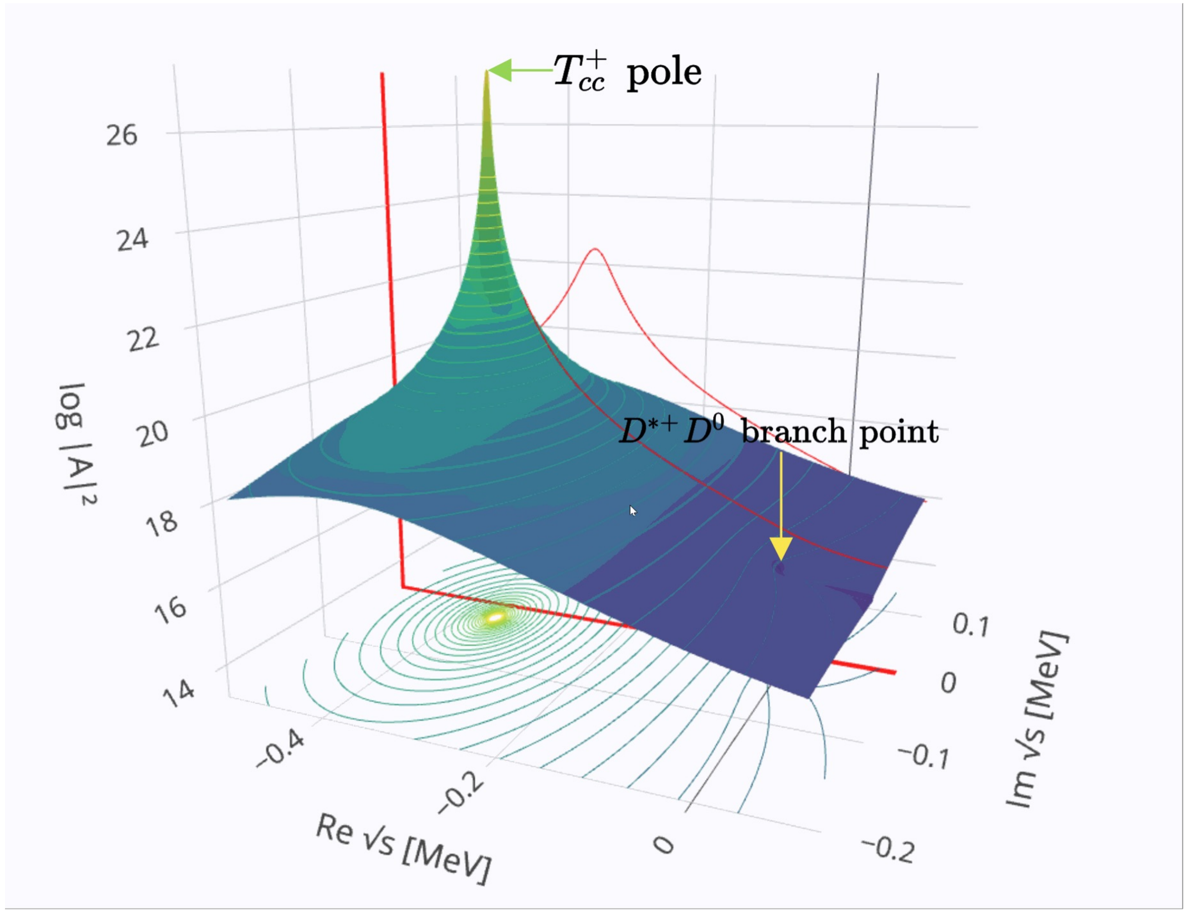
Analytic continuation and T_{cc}^{+} pole parameters

Yields pole parameters:

❖ Binding energy: $-360 \pm 40^{+4}_{-0}$ keV
(well determined by the data)

❖ Width: $48 \pm 2^{+0}_{-14}$ keV
(driven by the model: D^{*+} width, pion-exchange)

[Baru et al.,]
[MM, Effective range, hep-ph:]
[QWG talk,]
[Albaladejo,]



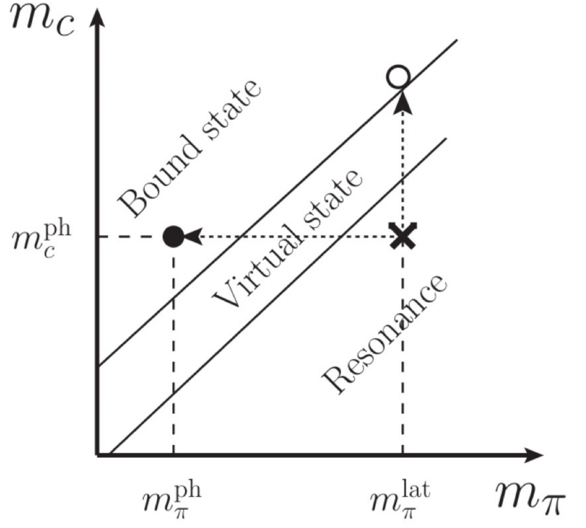
T_{cc}^{+} on lattice

Seen on lattice by several groups

[Yan Lyu et al., PRL131, 161901 (2023)]

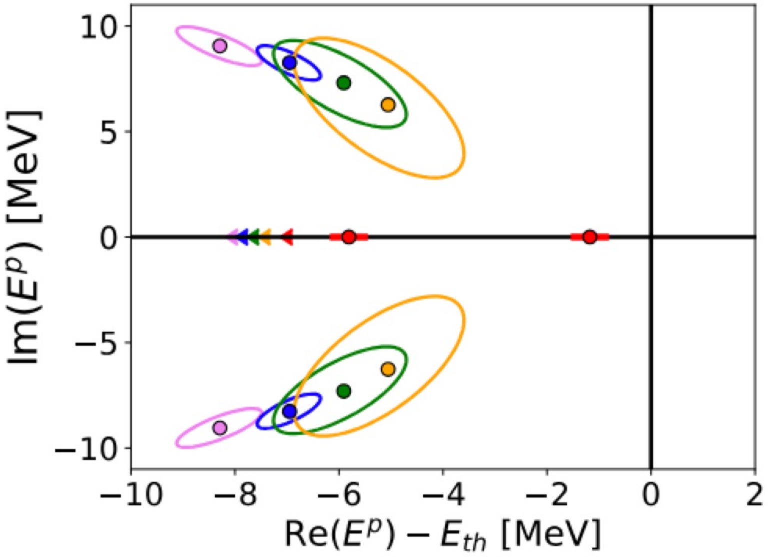
[Padmanath-Prelovsek, PRL129, 032002 (2022)]

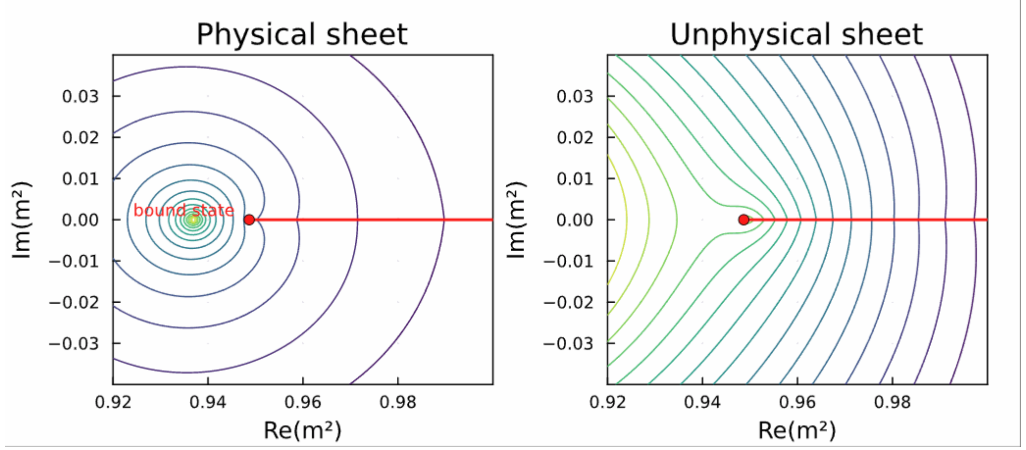
[S. Chen et al., PLB833, 137391 (2022)]



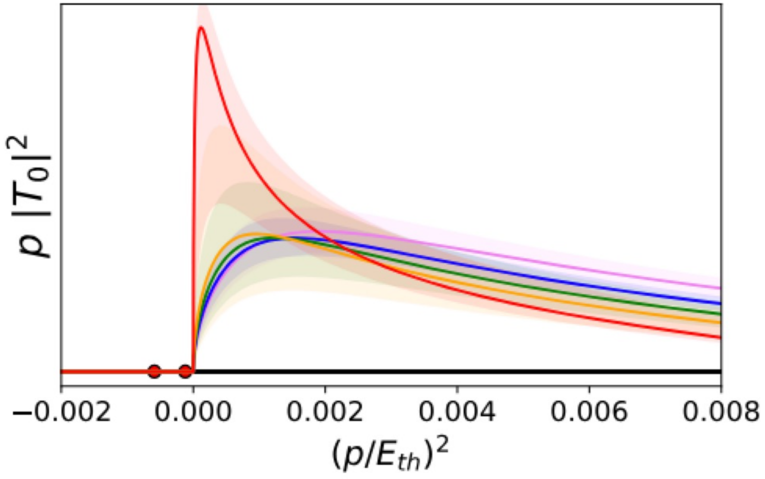
[courtesy Sasa Prelovsek]

[Collins et al., PRD109 (2024) 9, 094509]





[mmikhasenko@github]



Transition: **bound state** → **virtual state** → **resonance.**

No fundamental difference.The state is mostly **molecular** in vicinity of the threshold

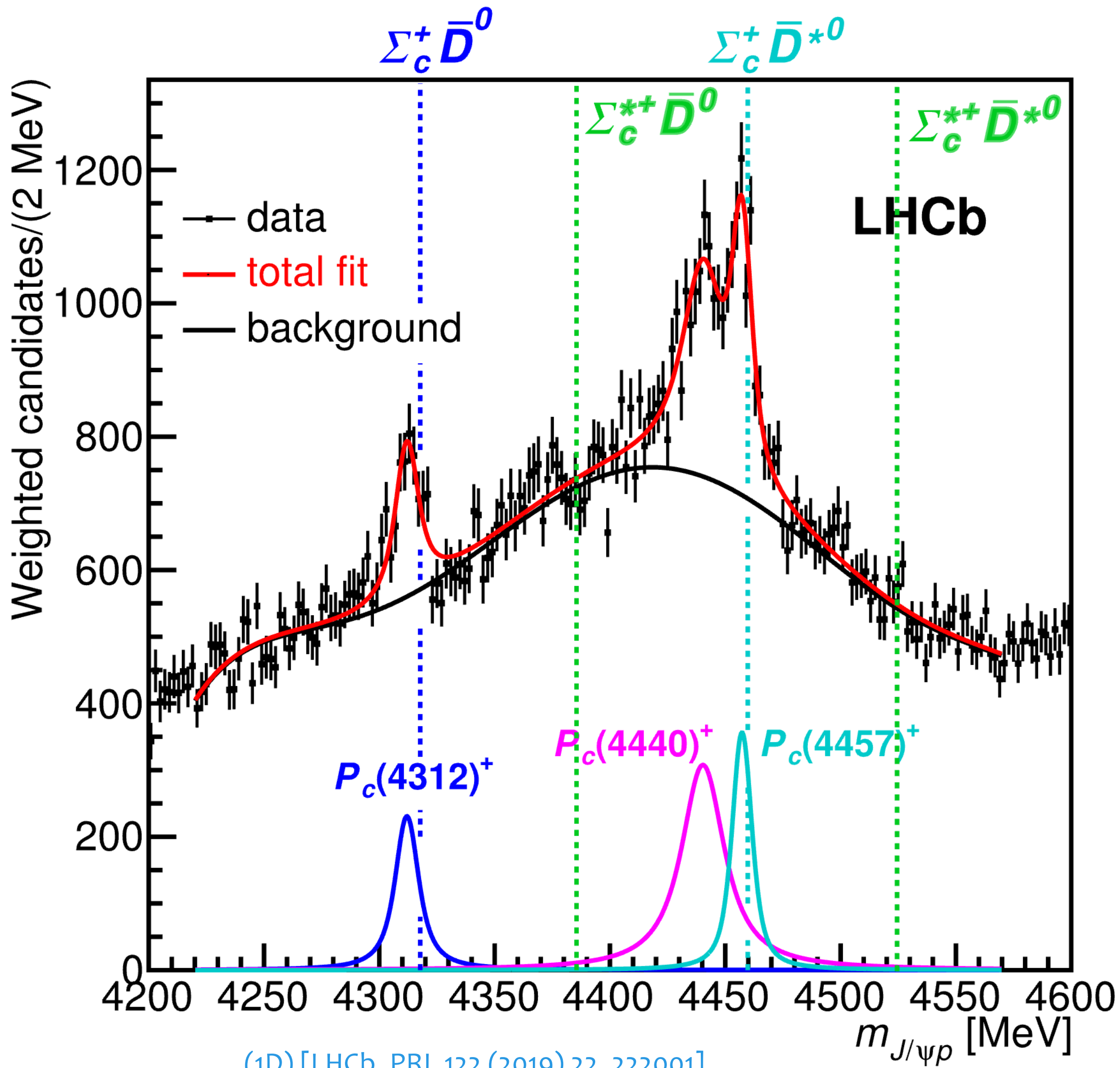
Pentaquarks $P_{c\bar{c}}^{+}$

Show up next to hadron-hadron threshold
unclear if consistent with the QM-tetraquark state that

QM core(?), molecular appearance(!)

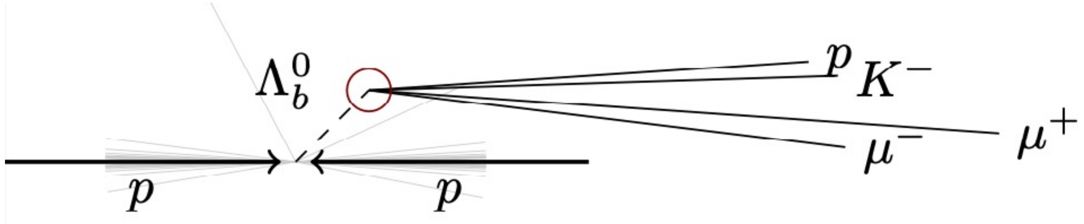
Only seem in b-decays by LHCb

Pentaquarks $P_{c\bar{c}}^{+}$



(1D) [LHCb, PRL 122 (2019) 22, 222001]

(AmAn) [LHCb, PRL 115 (2015), 072001]

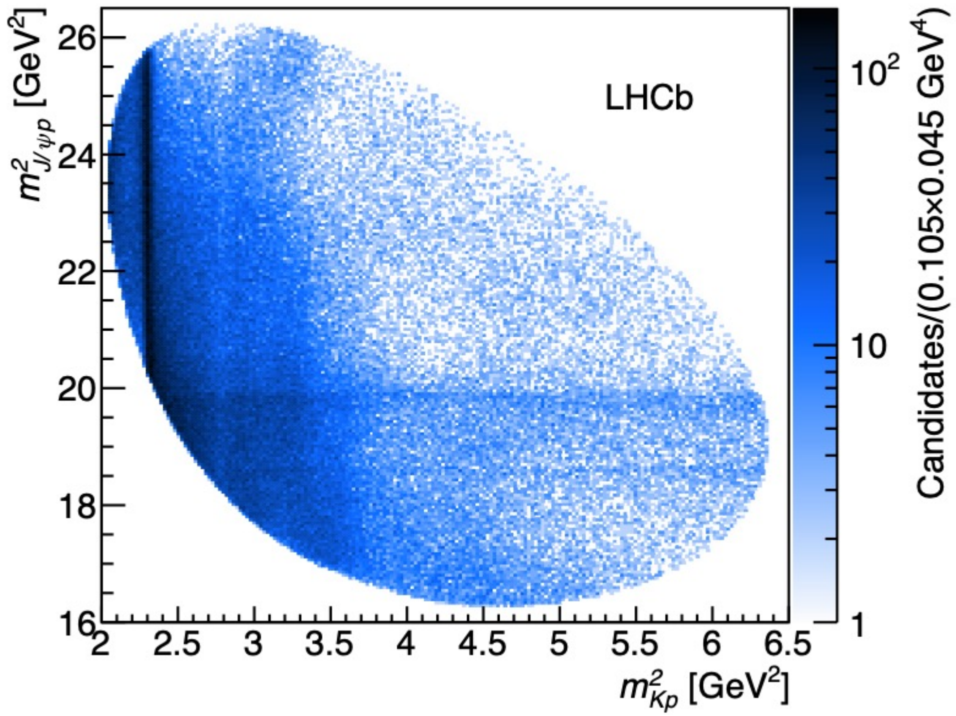


Narrow resonance states near threshold of $\Sigma_c^{+(*)}\bar{D}^{0(*)}$

Large background from pK^- scattering – Λ resonances

Challenges for amplitude analysis (work in progress)

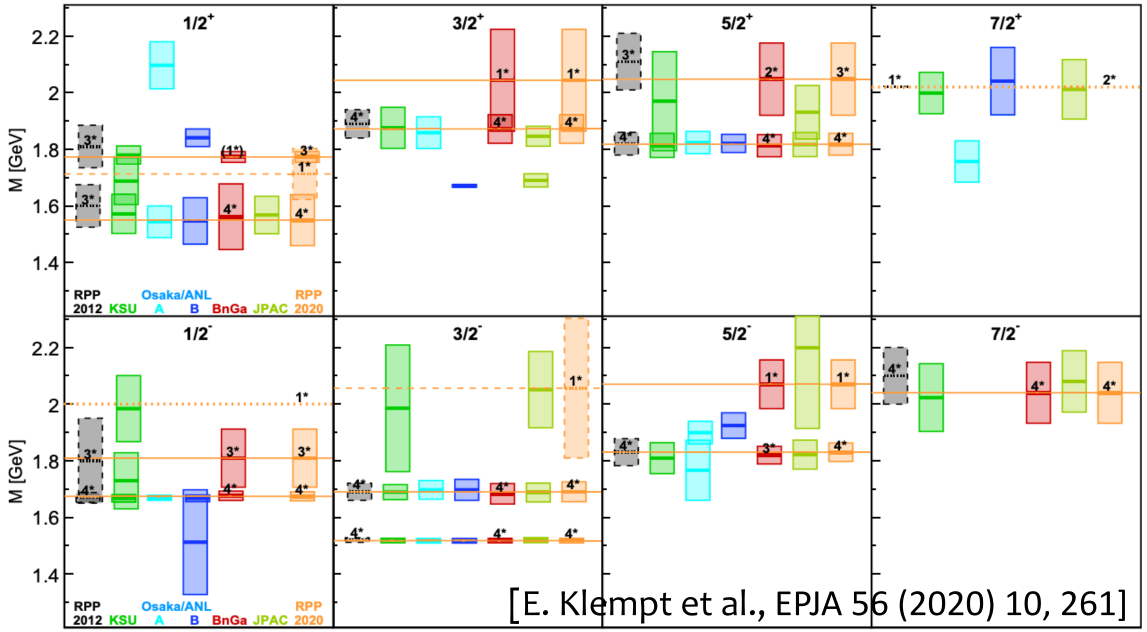
$\Lambda_b^0 \to K^- p\, J/\psi$ [LHCb, PRL 122 (2019) 22, 222001]



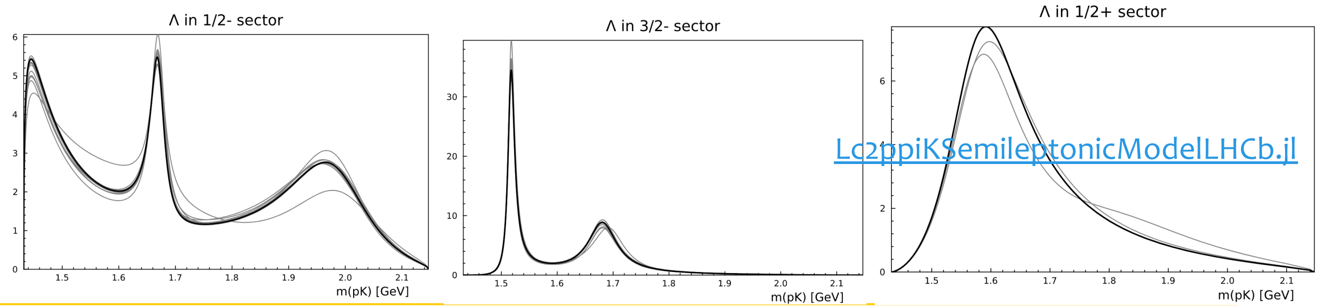
Phase space is dominated by resonances in $p\,K^-$

- Interfering background
- Largely unknown, now well constrained

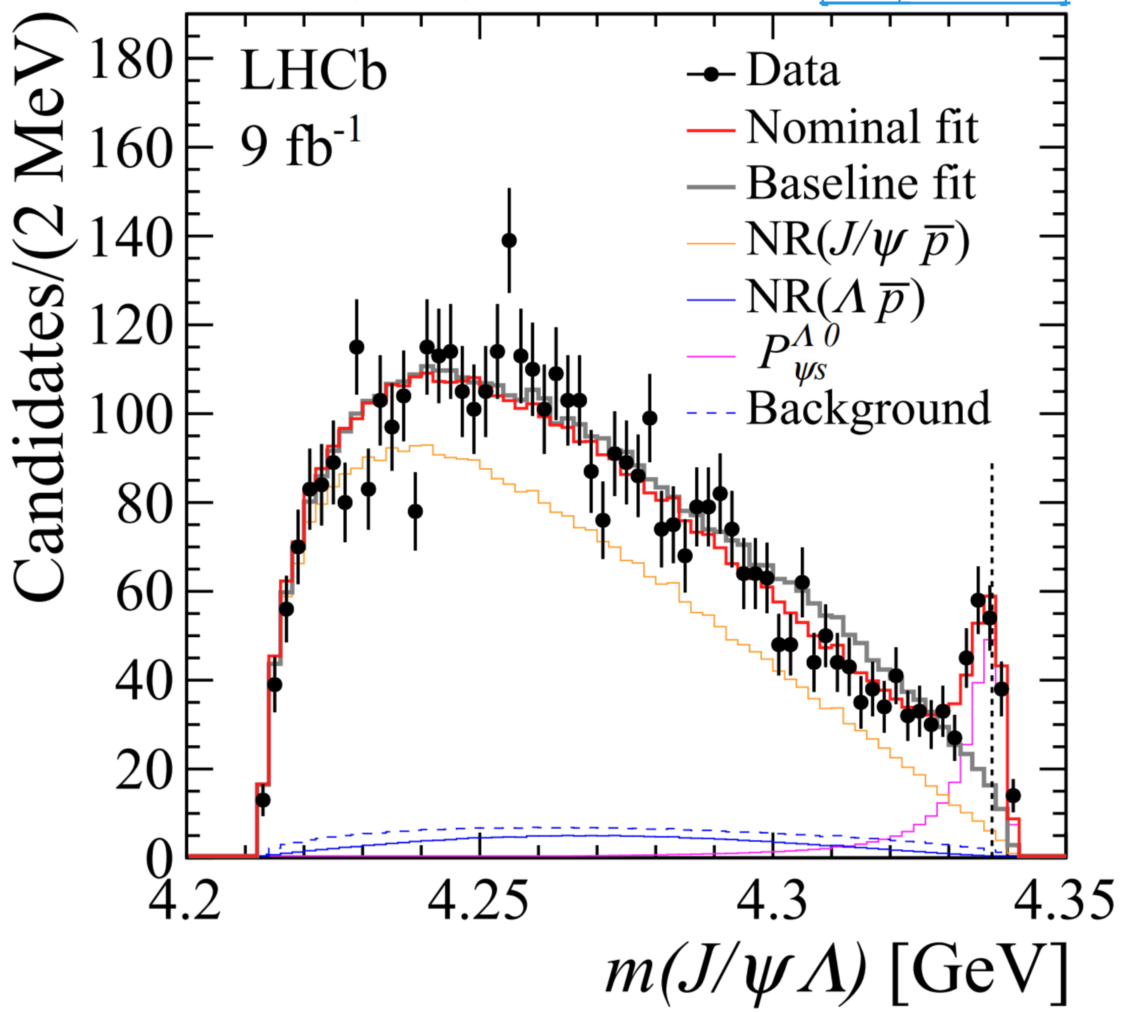
Might benefit from knowledge on Λ spectrum from $p\,K^-$ scattering data is needed



[E. Klempt et al., EPJA 56 (2020) 10, 261]



Lc2ppiKSemileptonicModelLHCb.jl



Strange Partner*

Prominent peak near $\Xi_c\bar{D}$ threshold

- **0.8±0.7 MeV above $\Xi_c^+D^-$**
- **2.9±0.7 MeV above $\Xi_c^0\bar{D}^0$**

$J^P = 1/2^-$ **is preferred**

Aligned with $\Xi_c^+D^-$ molecule

Fully heavy tetraquarks, $QQ\bar{Q}\bar{Q}$

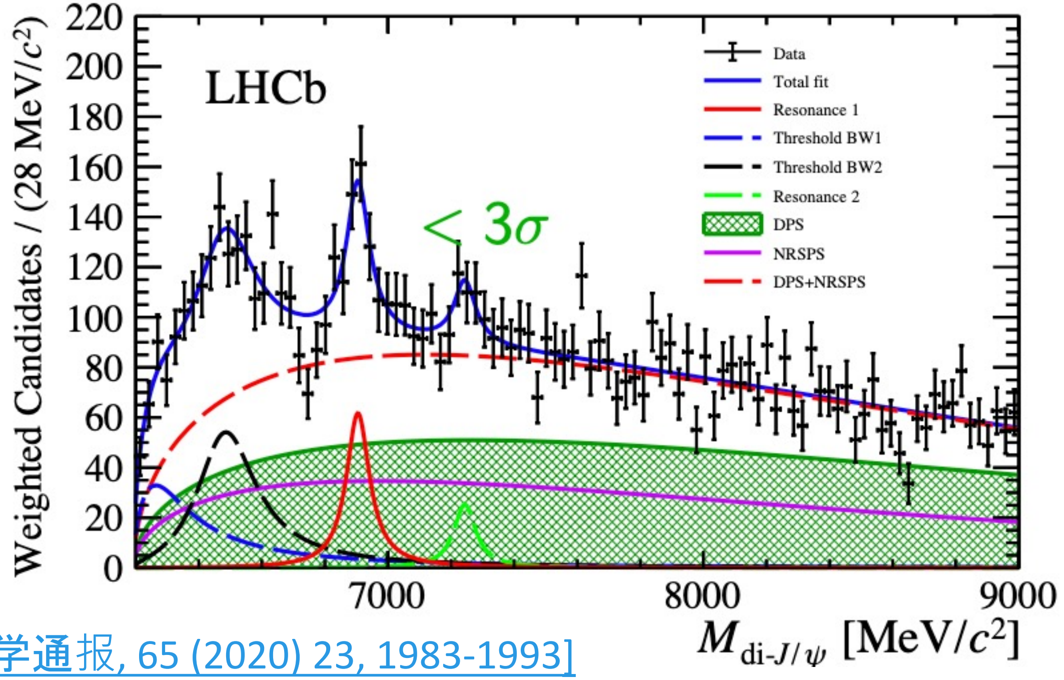
Unclear, many thresholds

Lattice QCD, pheno:
no hints for binding for $b\bar{b}b\bar{b}$

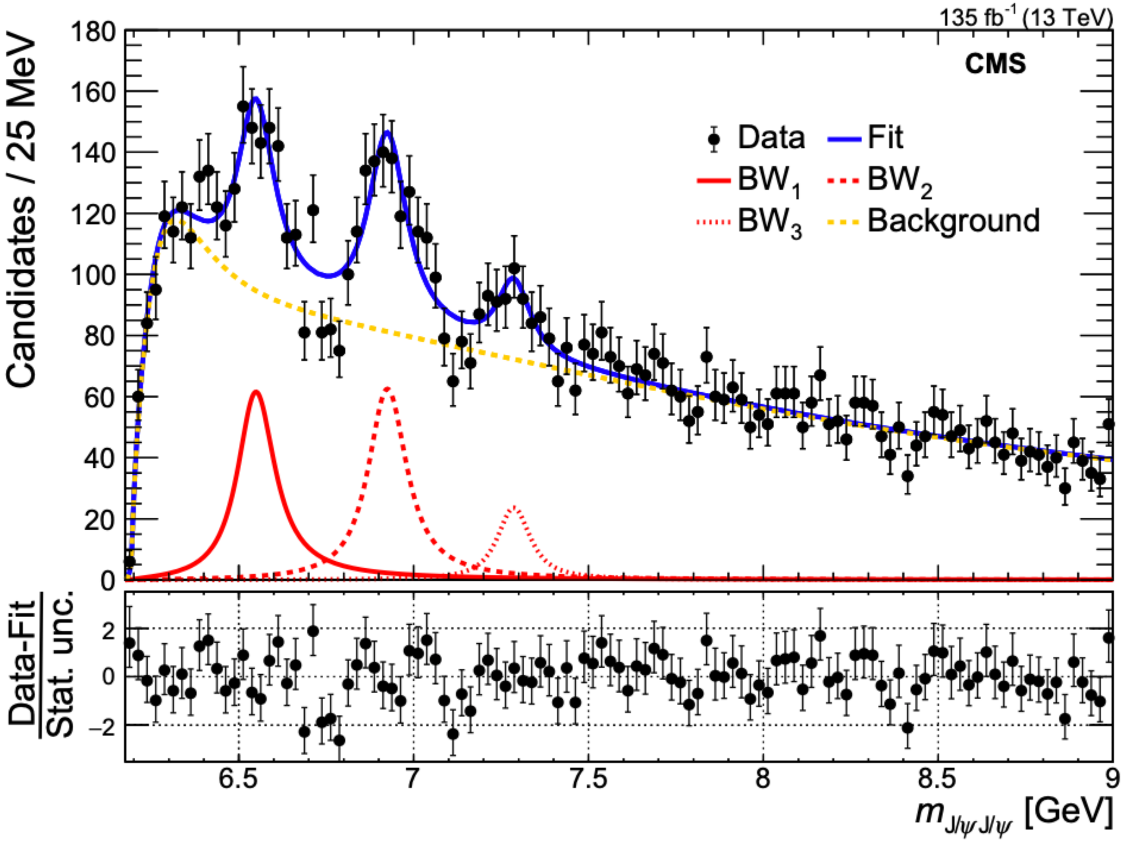
Seen in pp by LHCb, CMS, ATLAS

$cc\bar{c}\bar{c}$ from double J/ψ structures

[PRL 132 (2024) 11, 111901]



[科学通报, 65 (2020) 23, 1983-1993]



- Rapid **raise** at the threshold followed by the **three peaks.**
- Clear dips at 6.8 GeV, and 7.2 GeV
- Only simplistic modeling with unknown JP

$bb\bar{b}\bar{b}$ from ATLAS

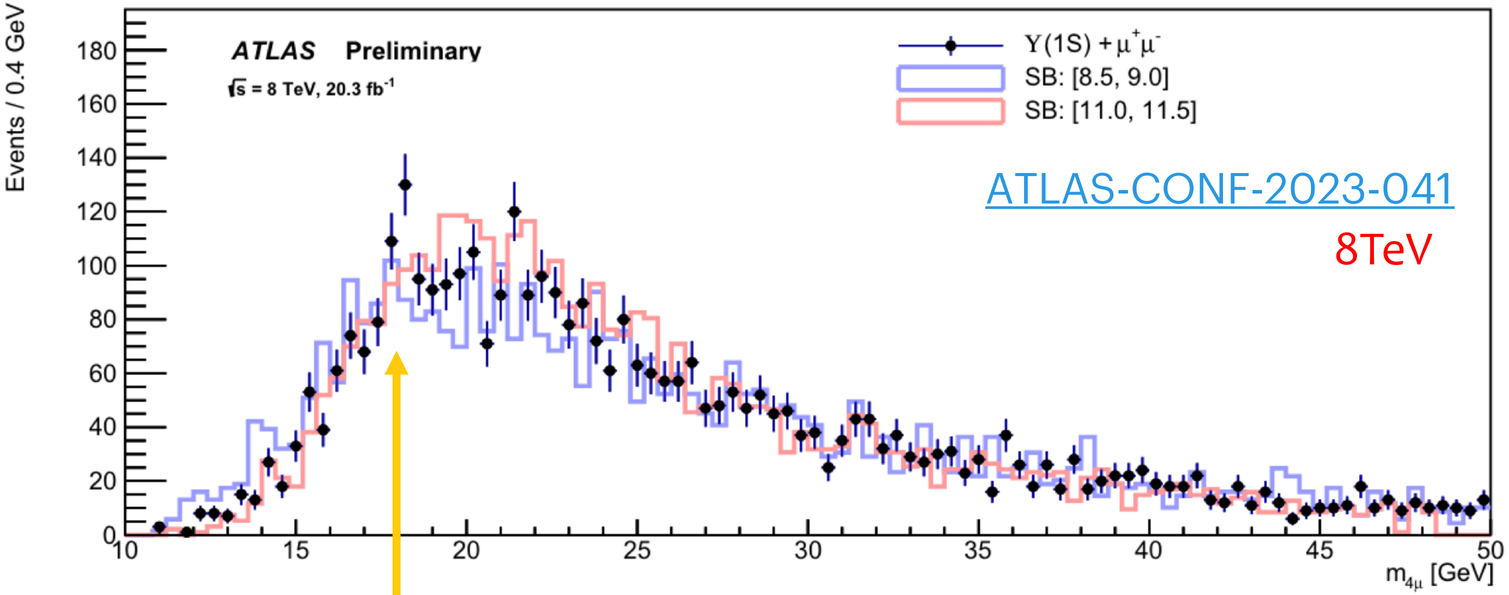
ATLAS observed a signal in $\Upsilon\mu^+\mu^-$

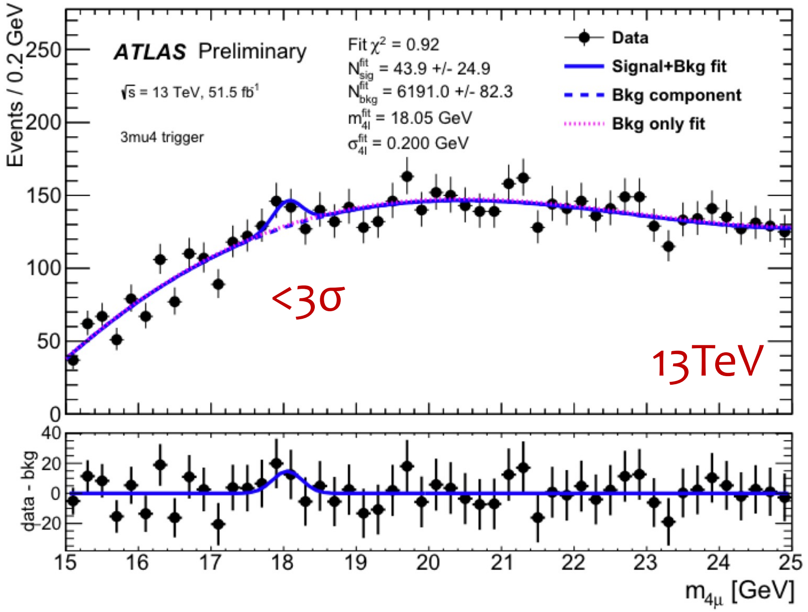
Local significance >5σ

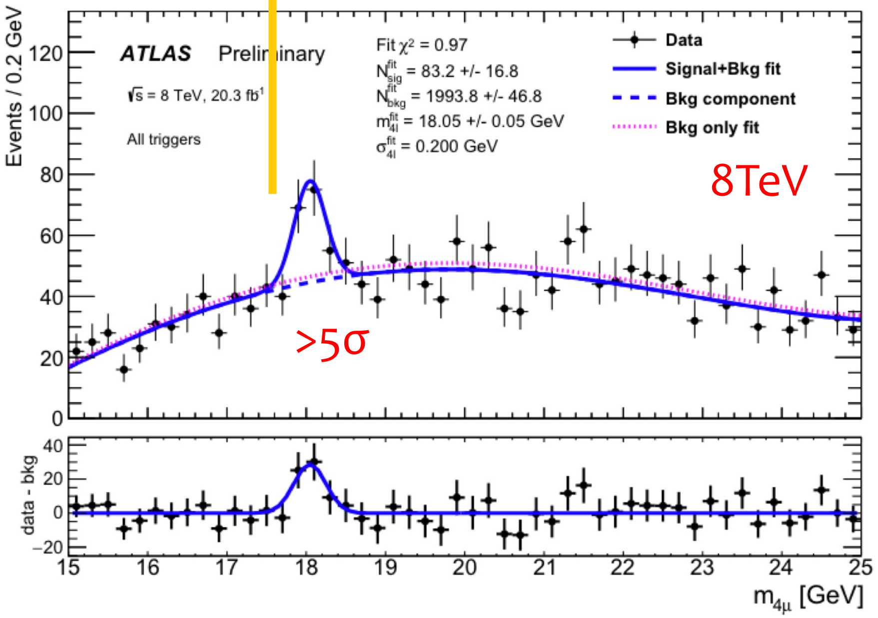
Mass is about 18 GeV

Stable with respect to modifications of cuts trigger conditions.

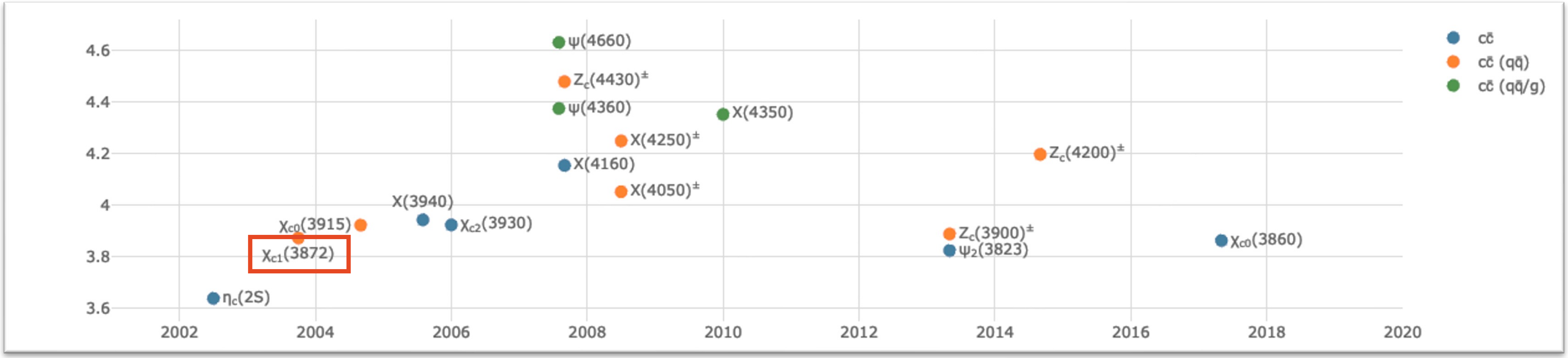
Disappears with 13TeV data (sadly)





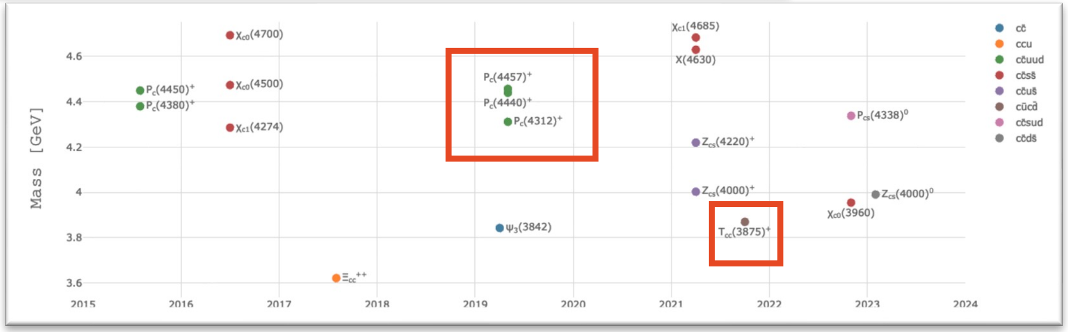


Many exotic states. Particle zoo v2.0

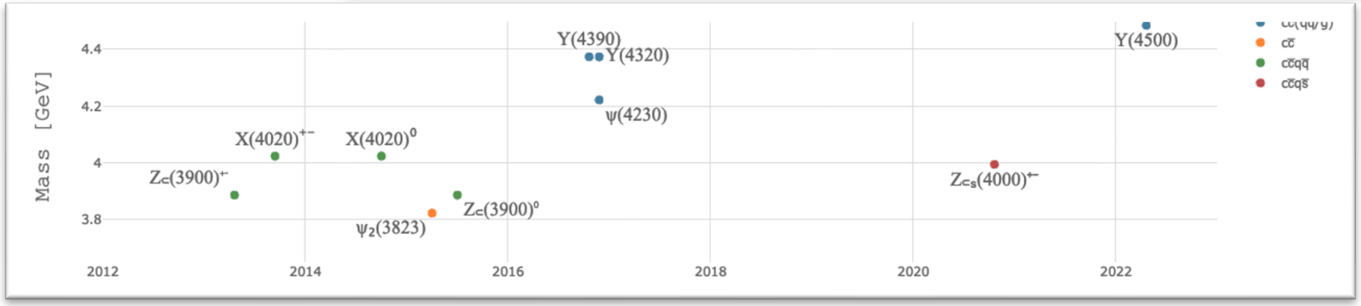


Belle

LHCb



BESIII



[QWG Exotics hub]

Open questions on exotic hadrons

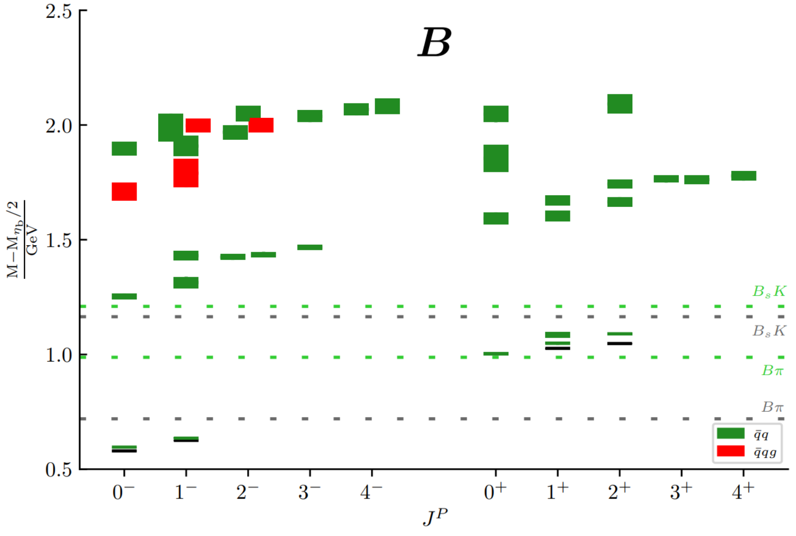
Having significant molecular contribution for hadronic state is fine.

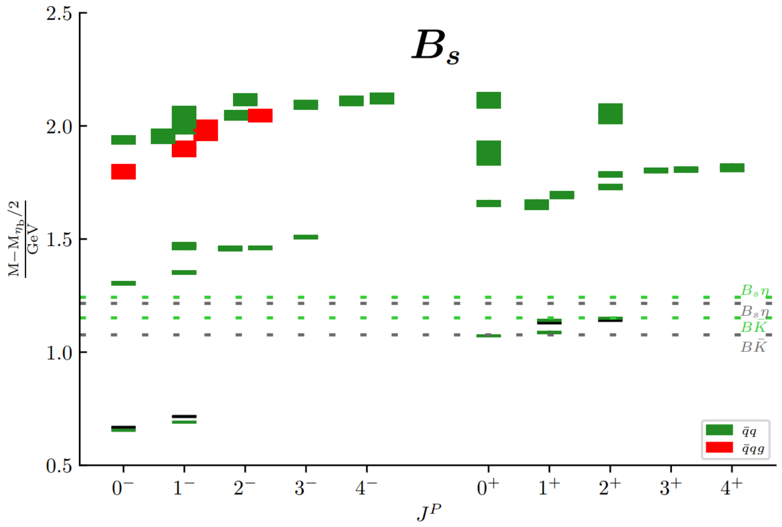
- We do not understand how the continuum acts.
  Why it sets some states right on the threshold? $[\chi_{c1}(3872) \to D^0 D^{*0}, T_{cc}^+ \to D^0 D^{*0}]$
- Does one always need a genuine QCD seed? – (extra numerous states wrt QM)
  From nuclear physics – "No" (plenty of atoms and isotops)
  $P_{c\bar{c}}^+, T_{cc\bar{c}\bar{c}}^0$?
- Extra-numerous states: hybrids, glueballs?

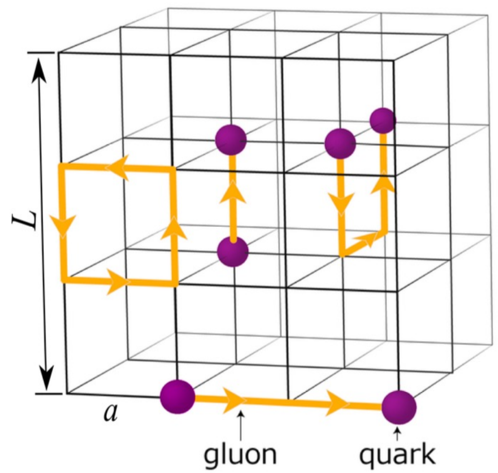
- Advanced amplitude analysis
- Collaboration of theory & experiment
- Synergy between different subfields

is critical to progress

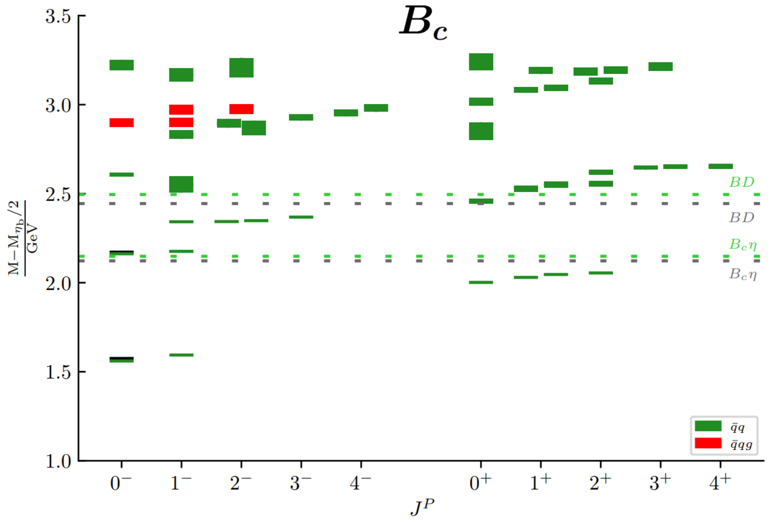
Hybrids in meson spectrum







[S. Ryan et al., JHEP 02 (2021) 214]



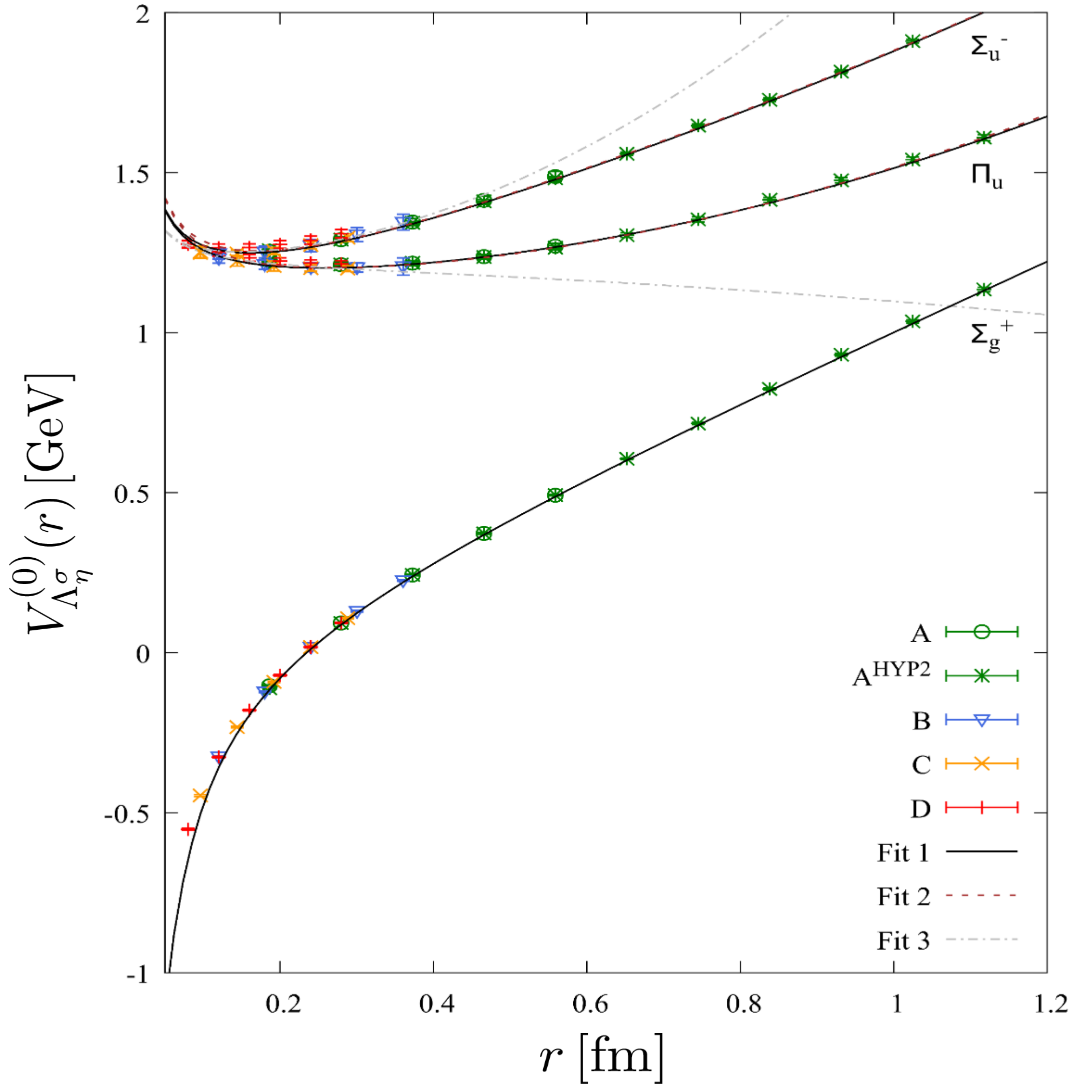
Hybrid states appear in all meson sectors consistently

Hybrids

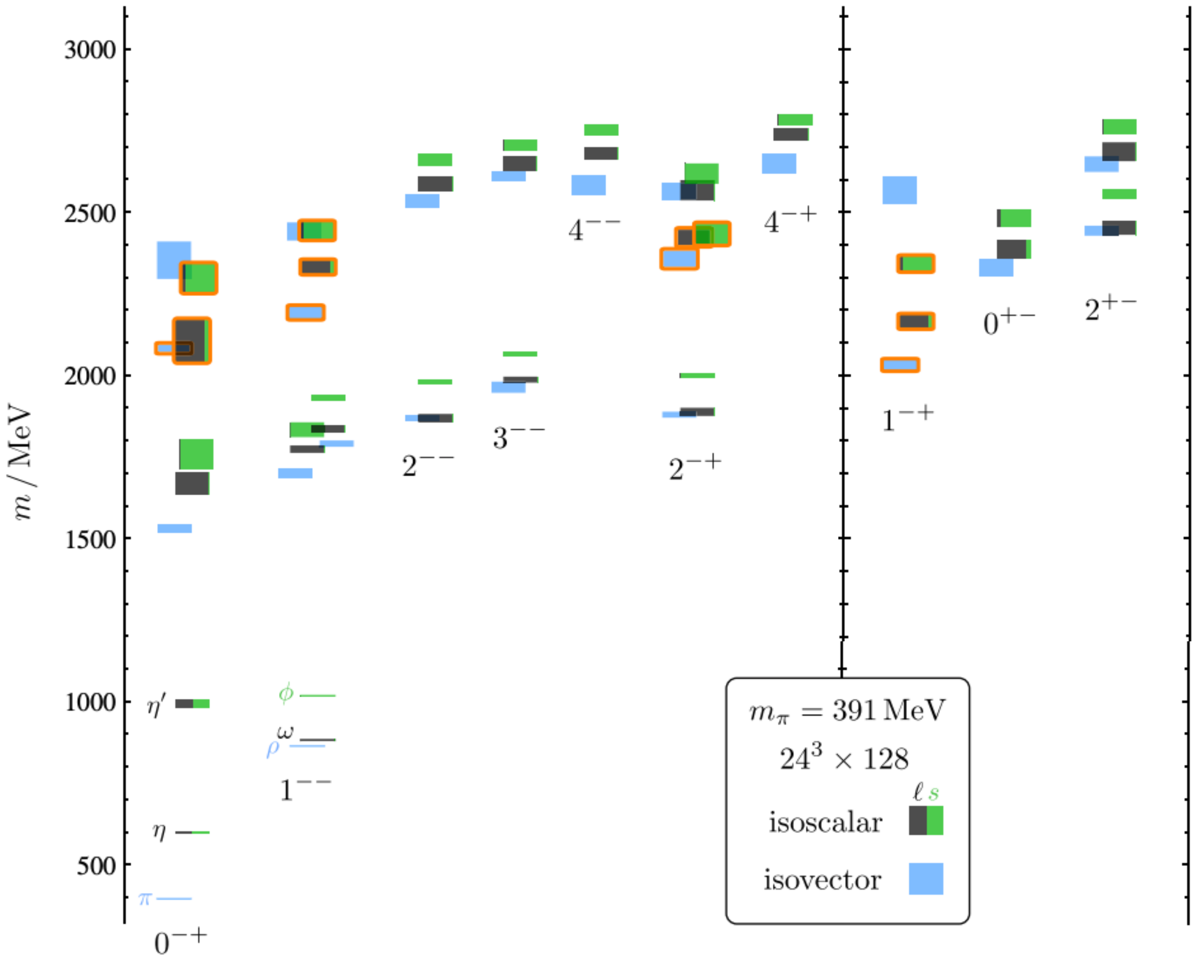
[Courtesy to Abhishek Mohapatra]

are extra numerous states in charmonium spectrum?

Multiplet	J^{PC}	$M_{c\bar{c}g}$	$M_{b\bar{b}g}$
H_1	$\{1^{--}, (0,1,2)^{-+}\}$	4155	10786
H_1'		4507	10976
H_1''		4812	11172
H_2	$\{1^{++}, (0,1,2)^{+-}\}$	4286	10846
H_2'		4667	11060
H_2''		5035	11270
H_3	$\{0^{++}, 1^{+-}\}$	4590	11065
H_3'		5054	11352
H_3''		5473	11616
H_4	$\{2^{++}, (1,2,3)^{+-}\}$	4367	10897
H_5	$\{2^{--}, (1,2,3)^{-+}\}$	4476	10948



Hybrids in the light meson spectrum

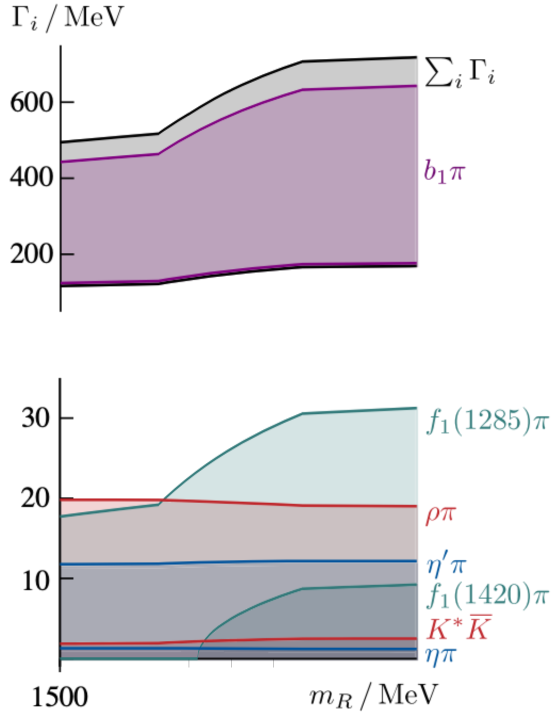


[Dudek et al., 2013]

Lattice QCD calculations for light meson sector are the most advanced

- Hybrid multiplets in GEVP calculations

- properties of the lightest hybrid meson using scattering amplitudes



[Woss et.al., 2020]

Hybrid mesons from COMPASS

Exotic pi1(1600) with JPC = 1-+

- Established in eta'pi

- Consistently described in eta pi

- Found in rho pi [sophisticated 3pi PWA]

- is being discovered in b1 pi [sophisticated 2piomega PWA]