Multiquarks and Molecular States

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Introduction

1.String breaking

2. Mixture with the threshold

3. Different Hadrons and Nuclei

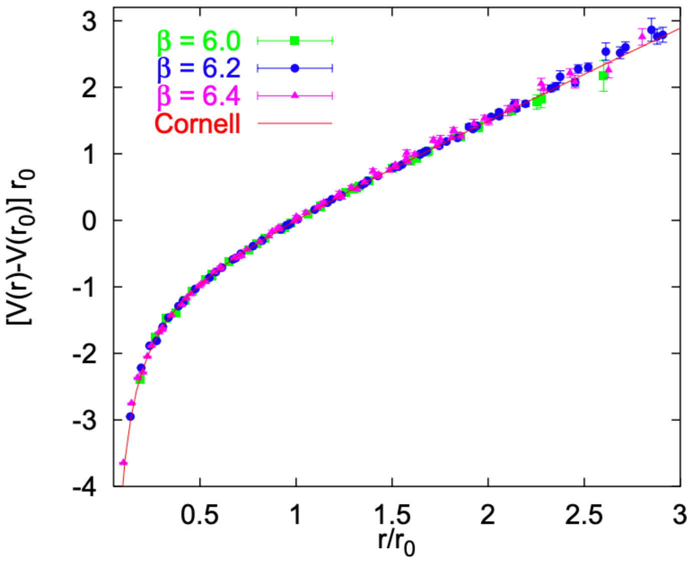
[G.S.Bali, PR 343 (2001) 1-136]

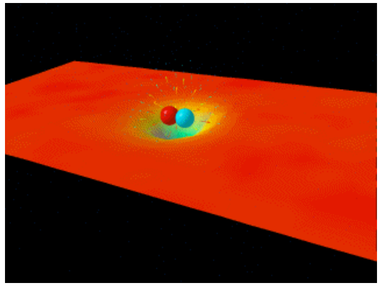
[D. Leinweber, CSSM, Adelaide]

[J. Bulava et al., PLB 793 (2019) 493-498]

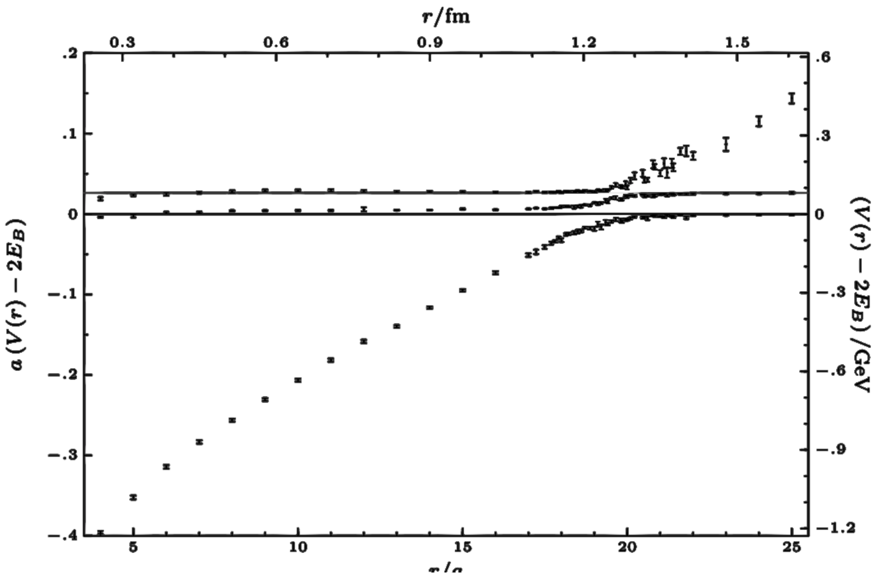
Effect of string breaking

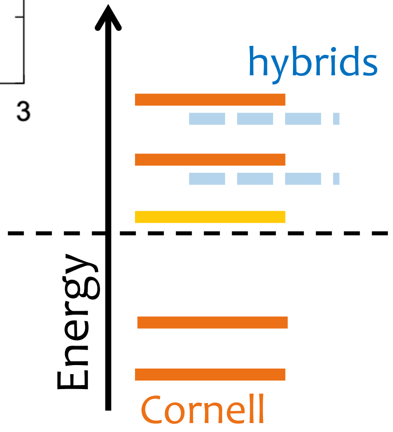
The quenched potential (no breaking)





The unquenched potential (breaking)





shifts “quenched” QCD states

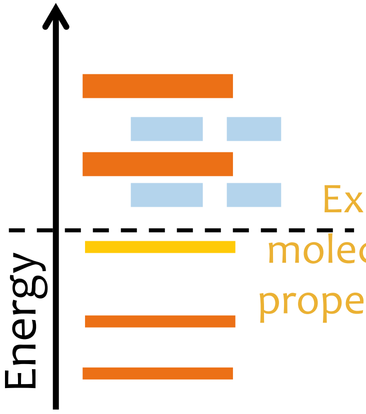
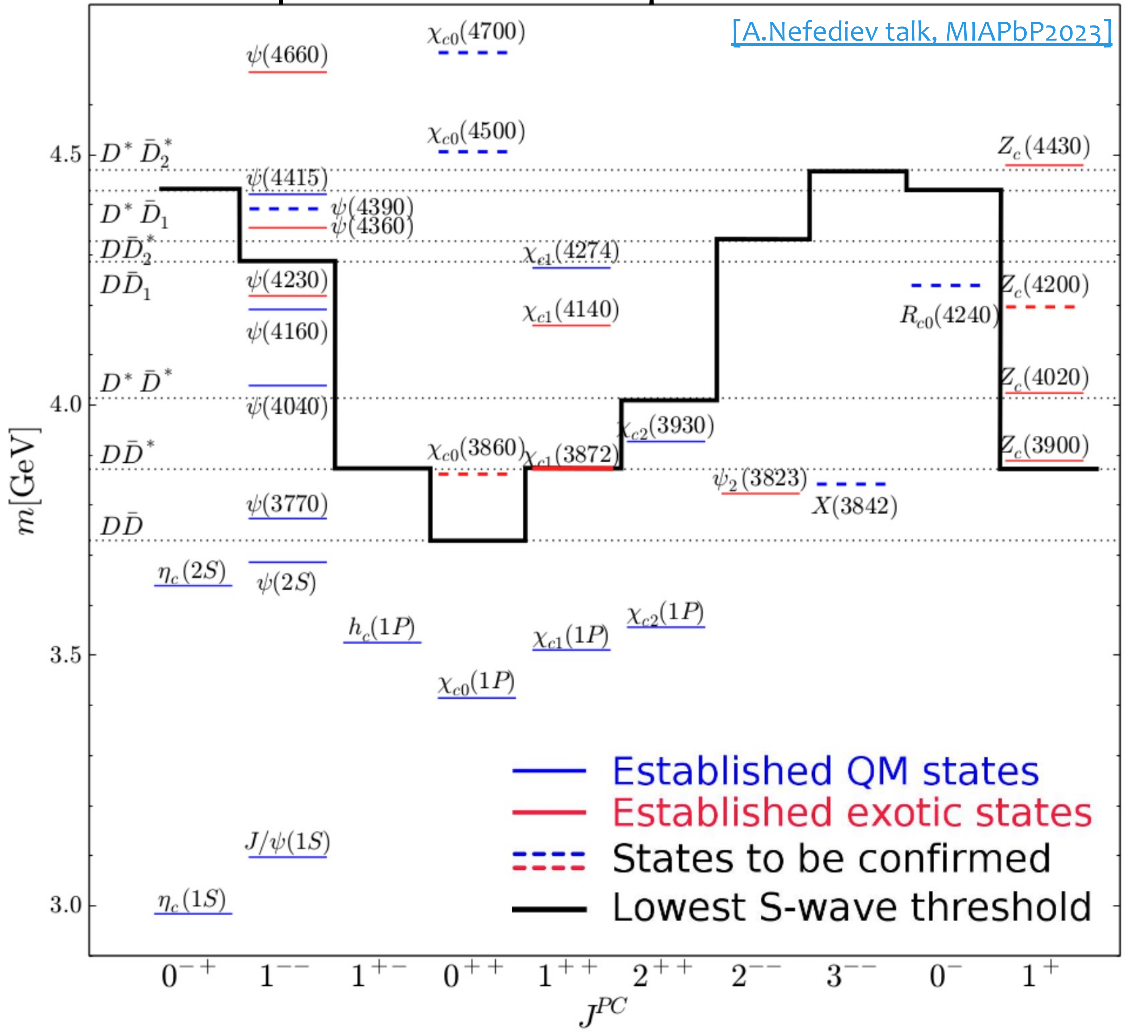


Exhibit molecular properties

QM states and thresholds

An example: charmonium spectrum



[A.Nefediev talk, MIAPbP2023]

Most of hadrons are not isolated:

near hadron-hadron threshold,

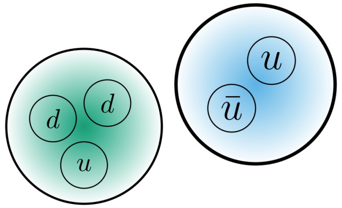
e.g. $q\bar{q} \rightarrow (q\bar{q})(q\bar{q})$**,**

hadronic states are coupled to hadron-hadron continuum

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

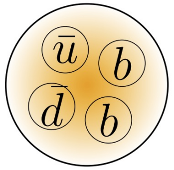
Misha Mikhasenko "Heavy flavour spectroscopy" January 18, 2024 4

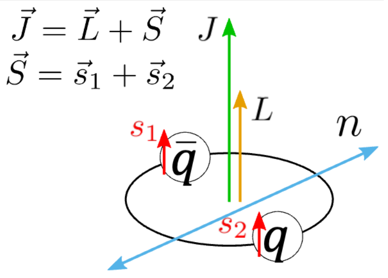
Possible configurations of hadrons



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

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



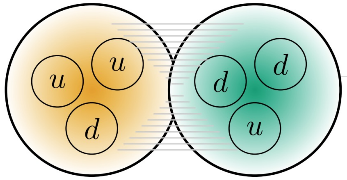


+ excitations

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

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

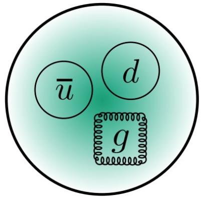
Admixed Molecules: $q\bar{q} \to (q\bar{q})(q\bar{q})$

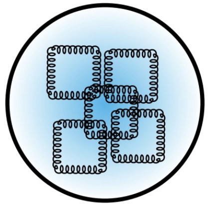


+ nuclei chart

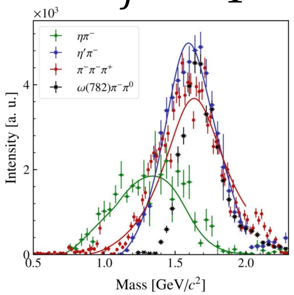
Hybrids: $q{\sim}g{\sim}\bar{q}$

Glueballs: $g{\sim}g$



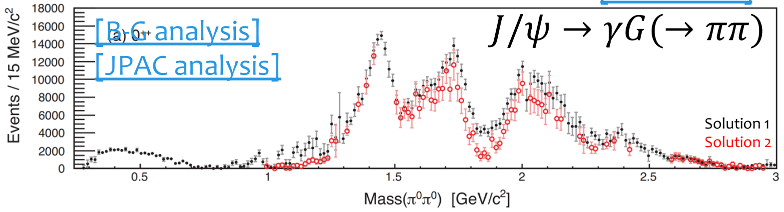


$J^{PC} = 1^{-+}$



[P.Haas, HADRON2023]

[BESIII data]



[B-G analysis]

[JPAC analysis]

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

Experimental techniques

1.Select clean data sample

2. Identify hadronic resonances

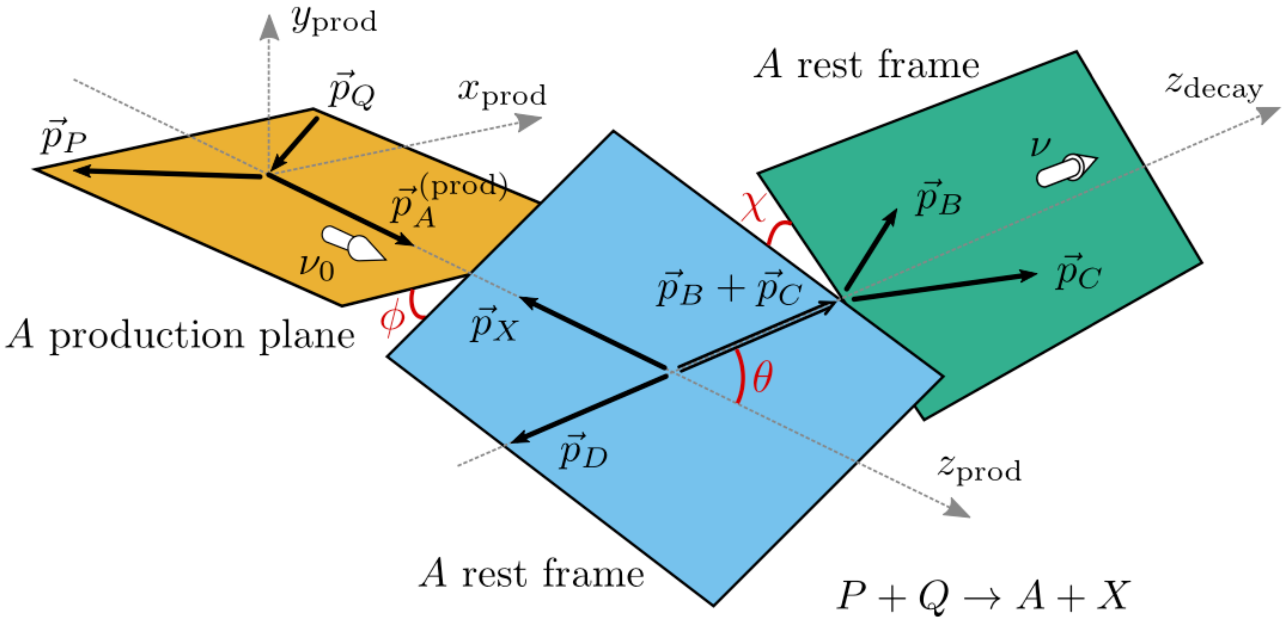
3. Pole mass and width
(reaction-theory analysis)

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: Clystal Ball, (PANDA)

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

Angular Analysis



$$P + Q \to A + X$$
$$A \to B + C + D$$

Correlations in angular distributions give access to particle spins

- model-independent rotational properties

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

- 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)]

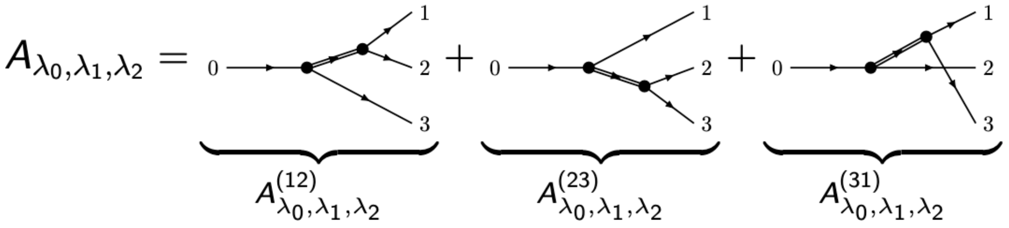
$$A_{\lambda_0,\lambda_1,\lambda_2} = \sum_{\nu} D^{1/2*}_{\lambda_0,\nu}(\alpha,\beta,\gamma)\, \underbrace{O^{\nu}_{\lambda_1,\lambda_2}(m_{12}^2, m_{23}^2)}_{O^{(12)}+O^{(23)}+O^{(31)}}$$

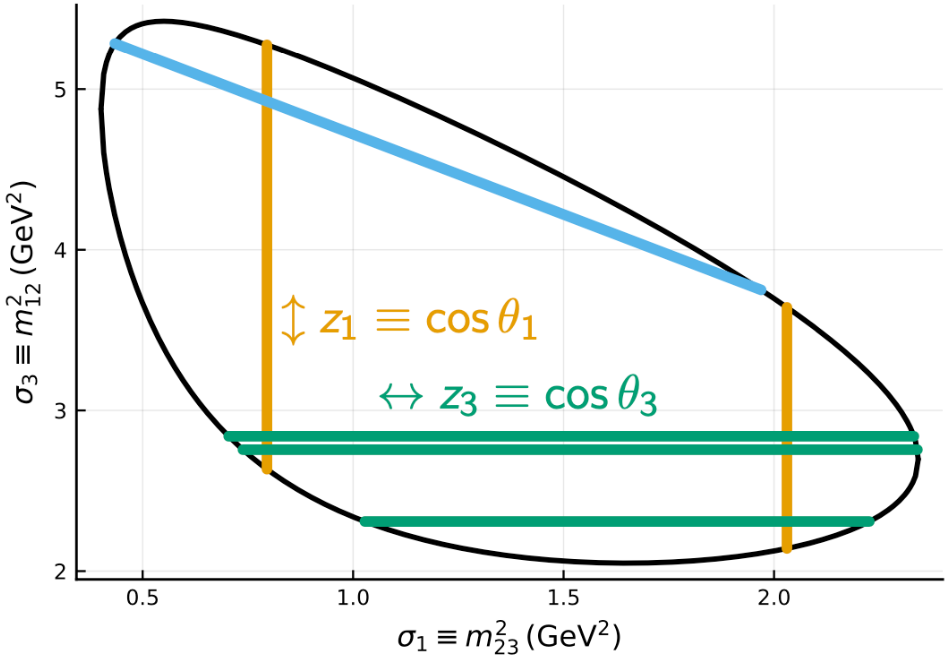
$$O^{(23)}_{\nu,\lambda_1,\lambda_2}(m_{12}^2, m_{23}^2) = \underbrace{\text{▨}}_{0\to X,1} \times \underbrace{\text{▨}}_{X\to 2,3} \times \underbrace{\text{▨}}_{\text{spin align.}}$$

- correct ϕ dependence by construction

Dynamic modeling

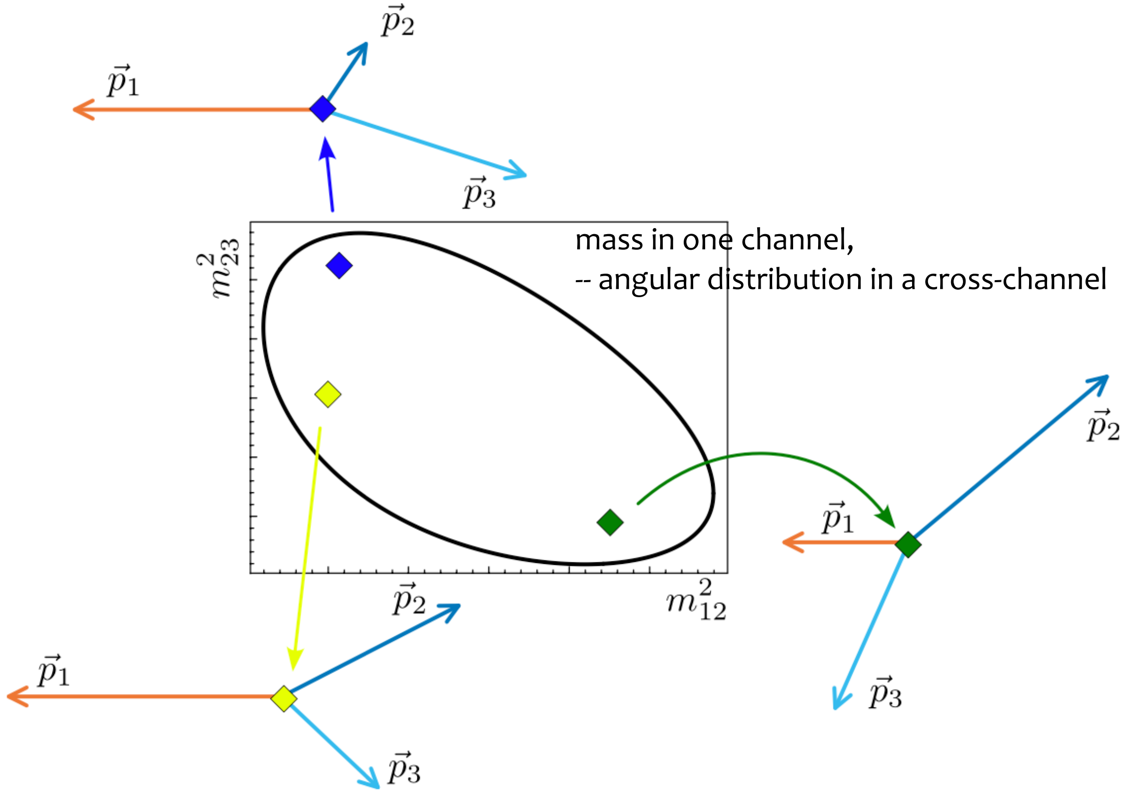
Cascade-reaction approach ("isobar model")





Due to cross channels

angular distributions and dynamic lineshapes are **mixed**



mass in one channel,
-- angular distribution in a cross-channel

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

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

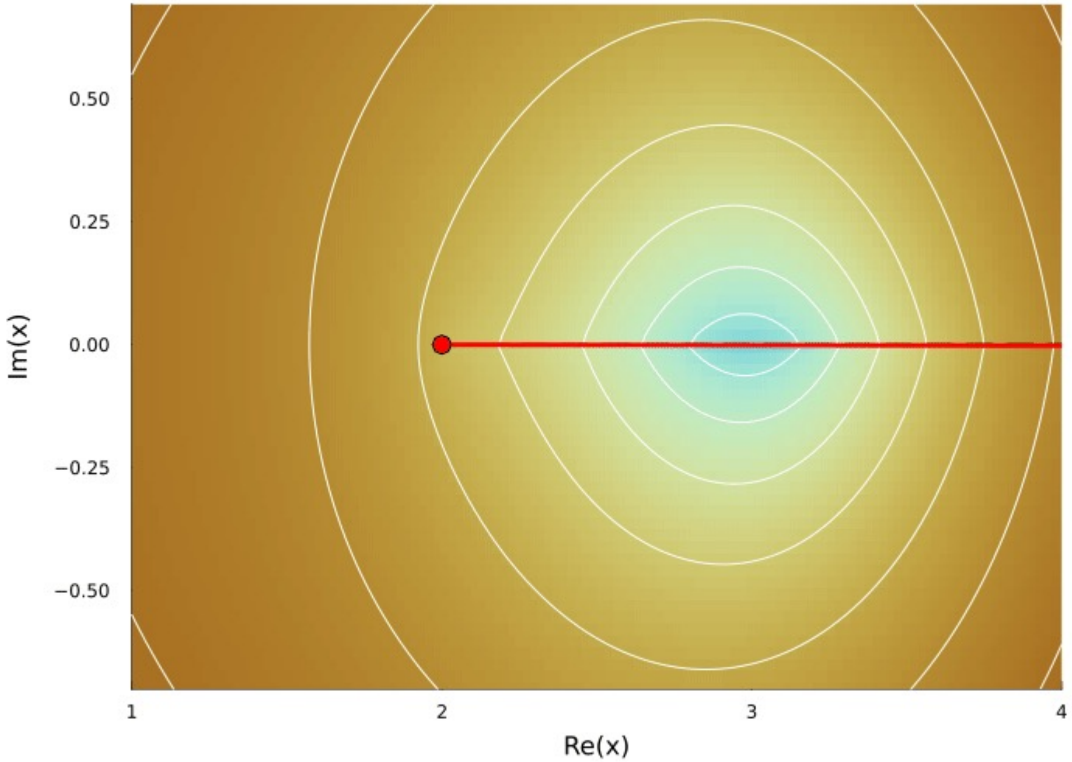
=Flatte=

4. Multiple channels, multiple resonances

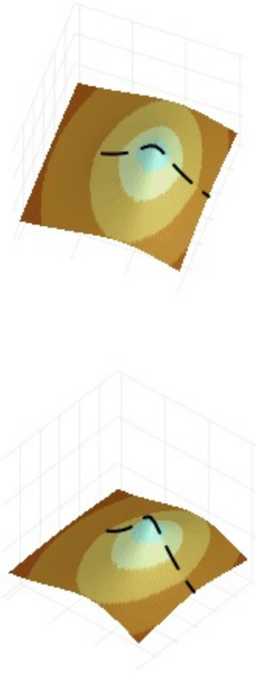
=K-matrix=

Analytic continuation – resonance poles

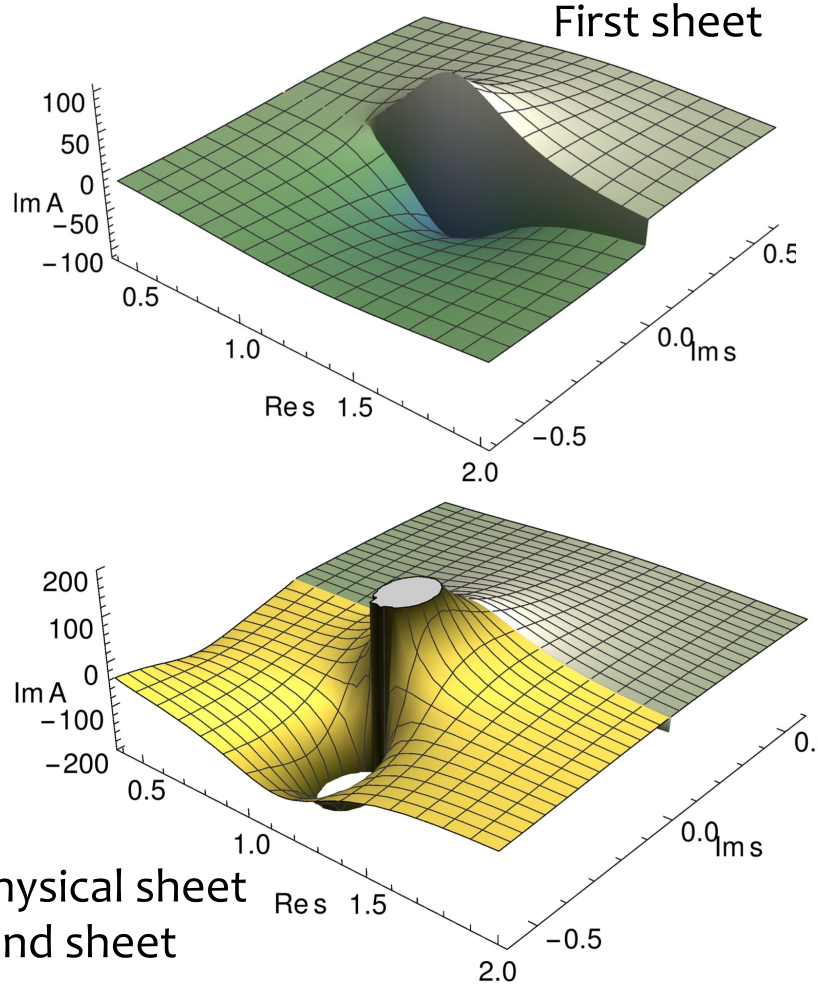
- Amplitude A is a complex function of E = x+iy
- Im(1/A) ~ phase sp. ~ sqrt(kin. energy)
- sqrt branch point – forms two sheets



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



Im A (x + iy)



Physical sheet
First sheet

Unphysical sheet
Second sheet

$\chi_{c1}(3872)$

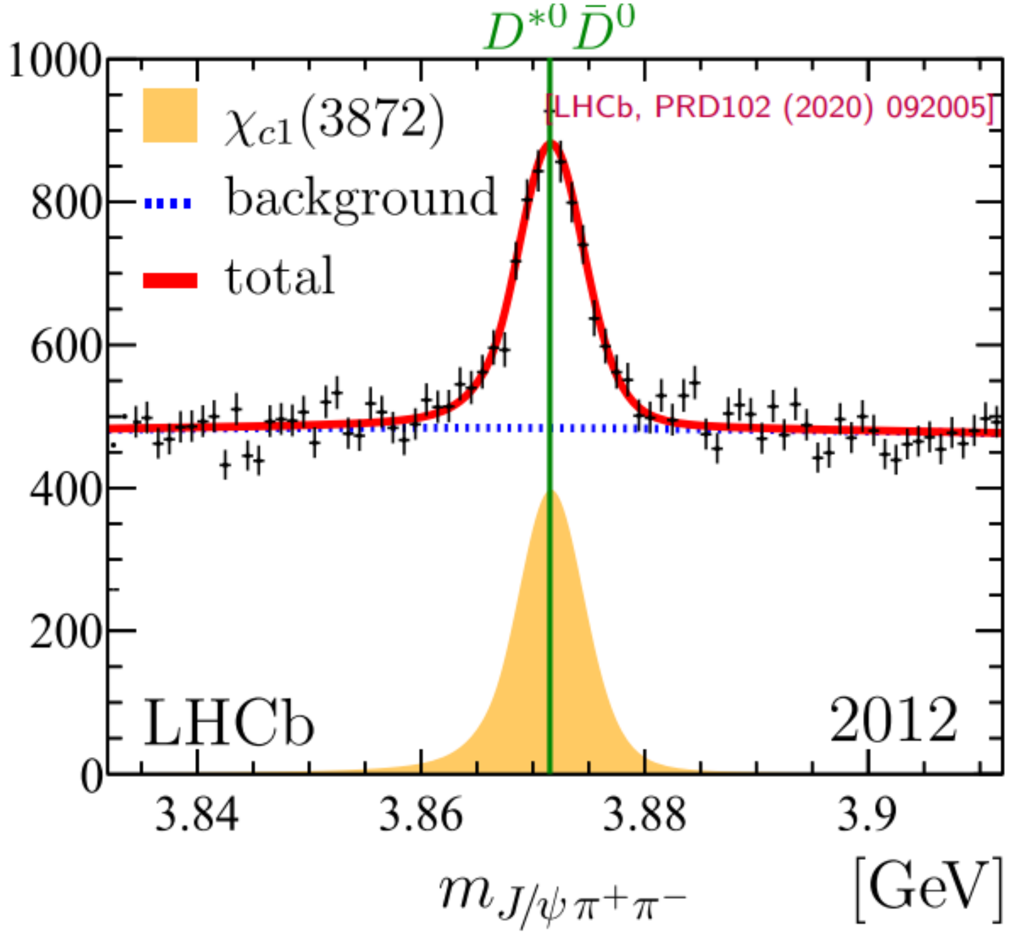
Consistent with the charmonium state that shows up next to **hadron-hadron threshold** exhibit molecular properties

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

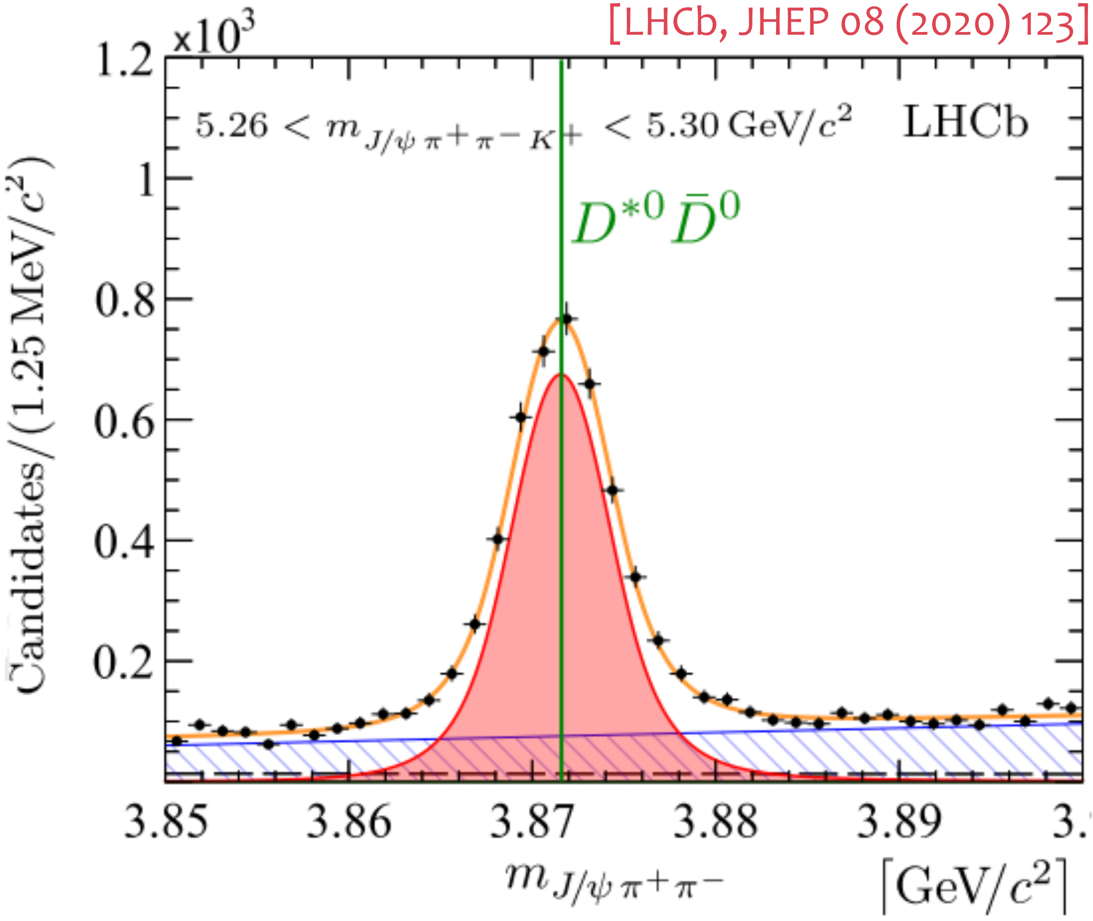
$\chi_{c1}(3872)$ is right at the $D^0 D^{*0}$ threshold

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

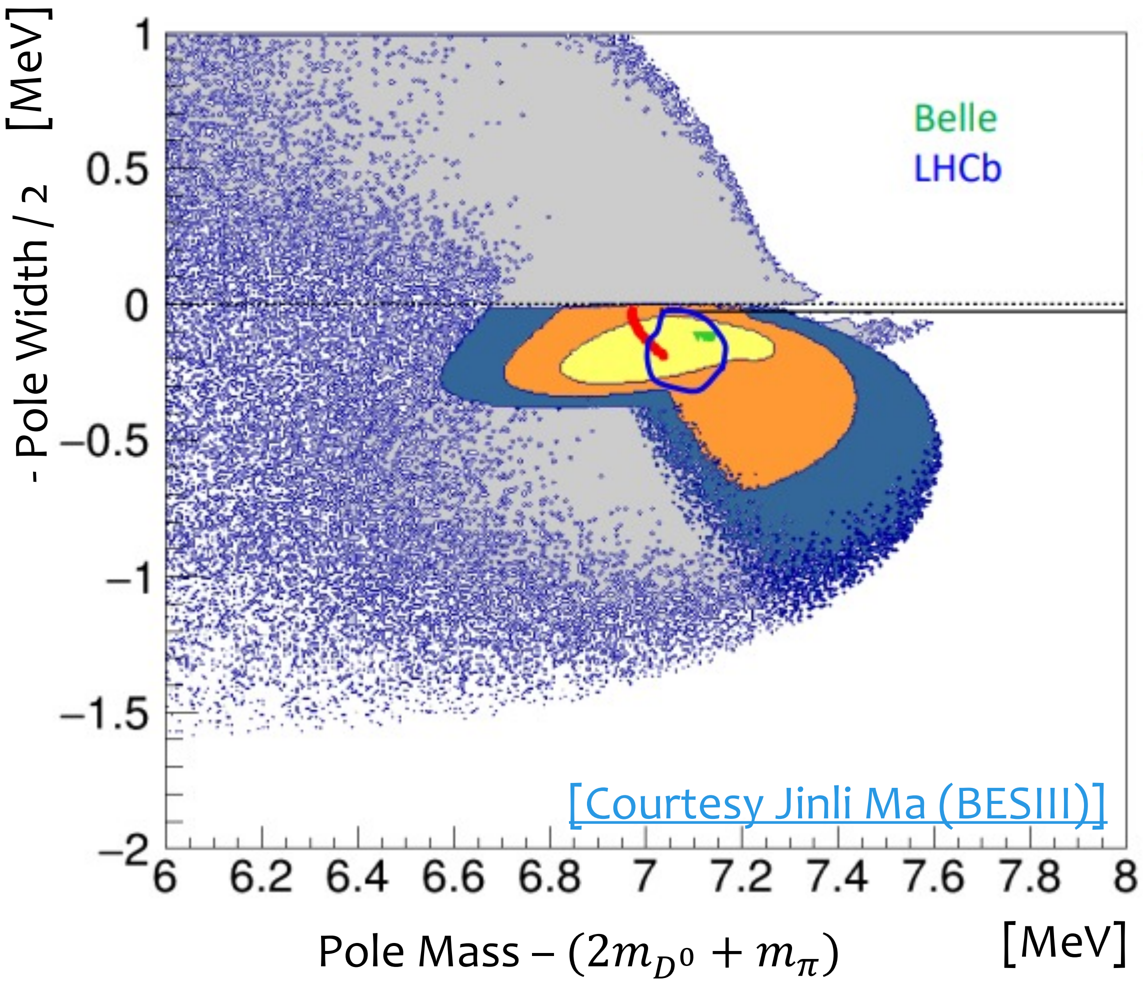
[PRD102 (2020) 092005]

- 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)]



[Courtesy Jinli Ma (BESIII)]

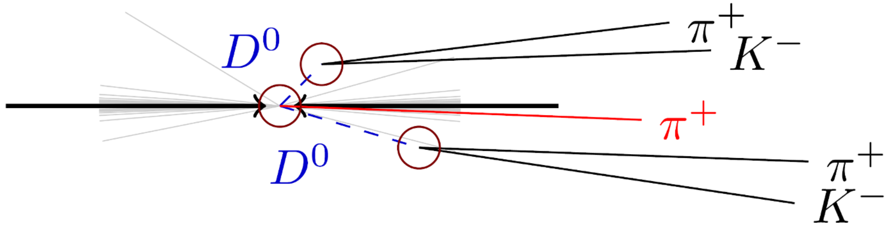
Tetraquark T_{cc}^{+}

Consistent with the QM-tetraquark state that shows up next to hadron-hadron threshold exhibit molecular properties

QM core, molecular appearance

Only seen in pp by LHCb

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



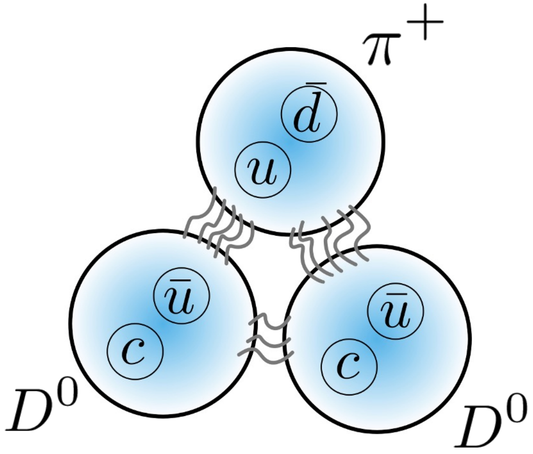
Peak in $D^0 D^0 \pi^+$ just below $D^{*+} D^0$ threshold

Extremely narrow, ~300keV

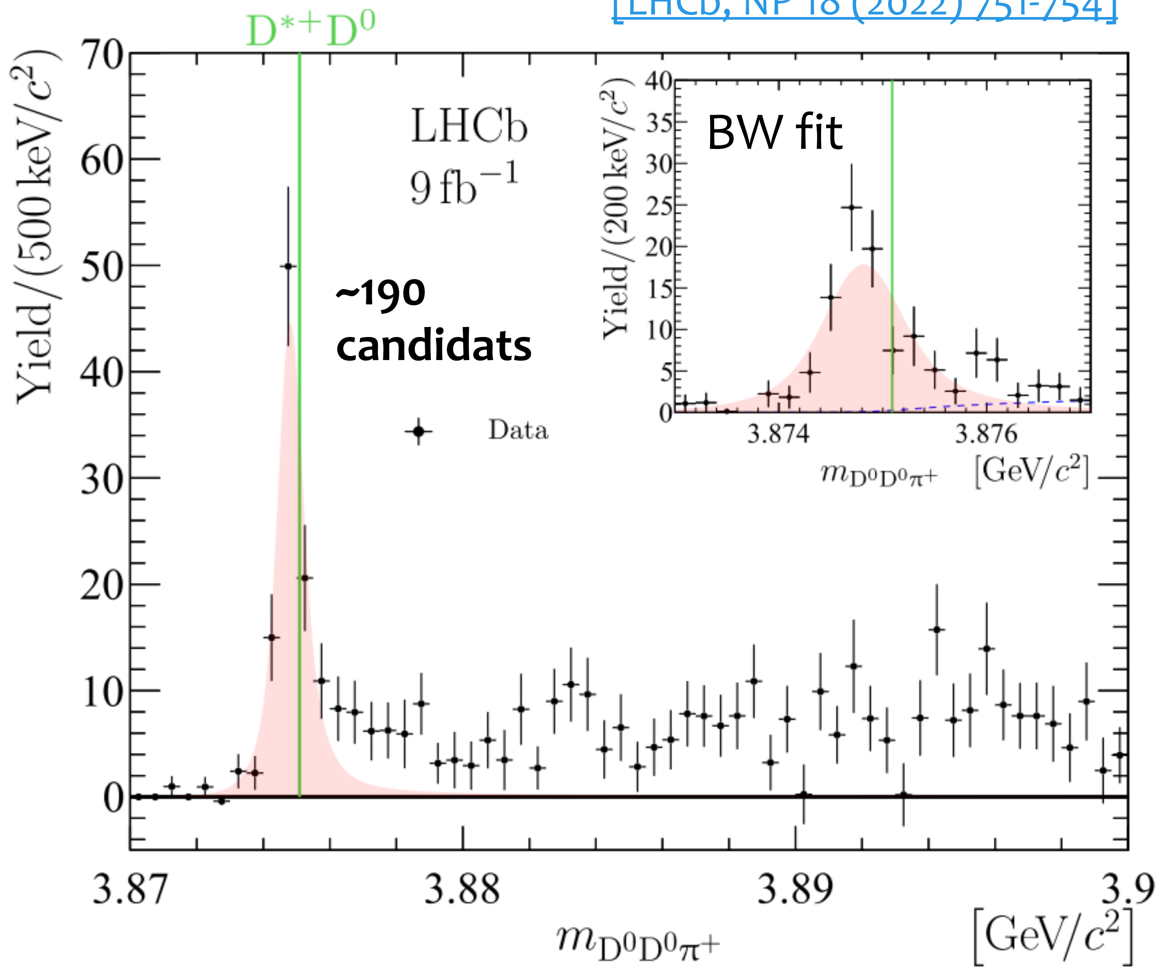
(resolution)

Needs to be treated as

three-body effect



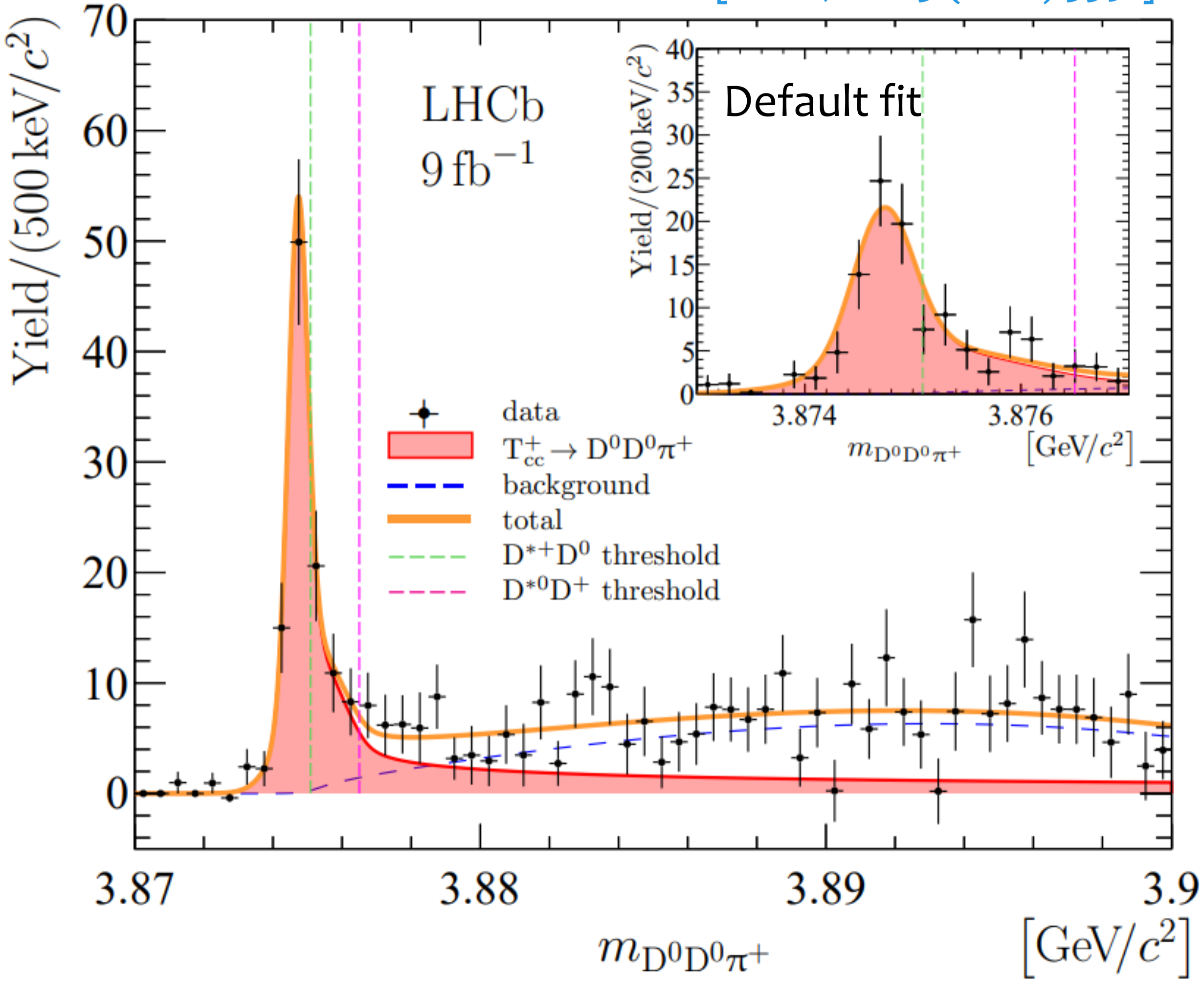
[LHCb, NP 18 (2022) 751-754]



~190 candidats

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

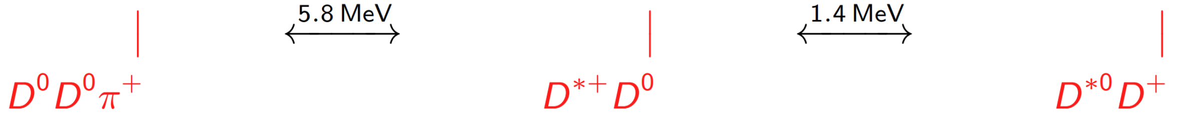
[LHCb, NC 13 (2022) 3351]



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

Coupled channel model

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



Yields good agreement with the data

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

Yields pole parameters:

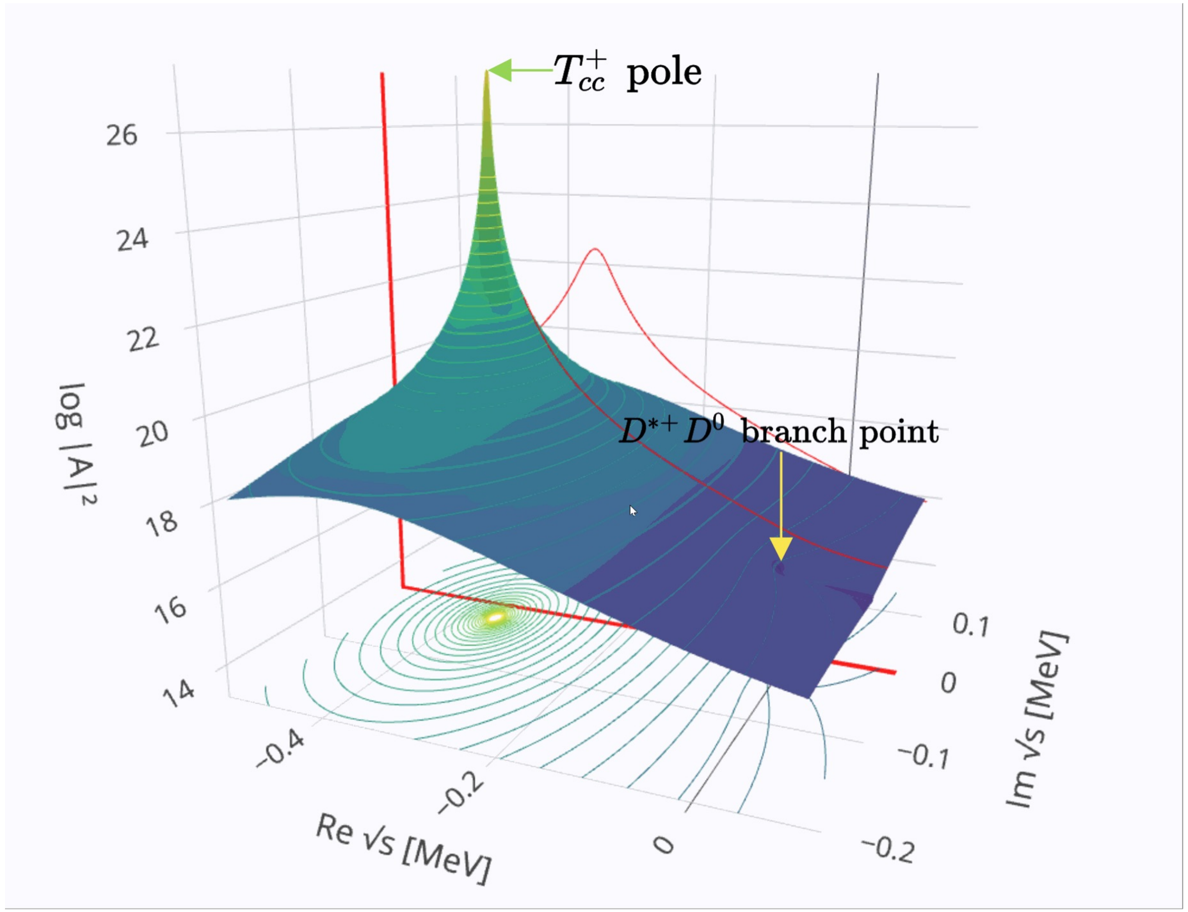
- ❖ Binding energy: $-360 \pm 40^{+4}_{-0}$ keV

(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,]



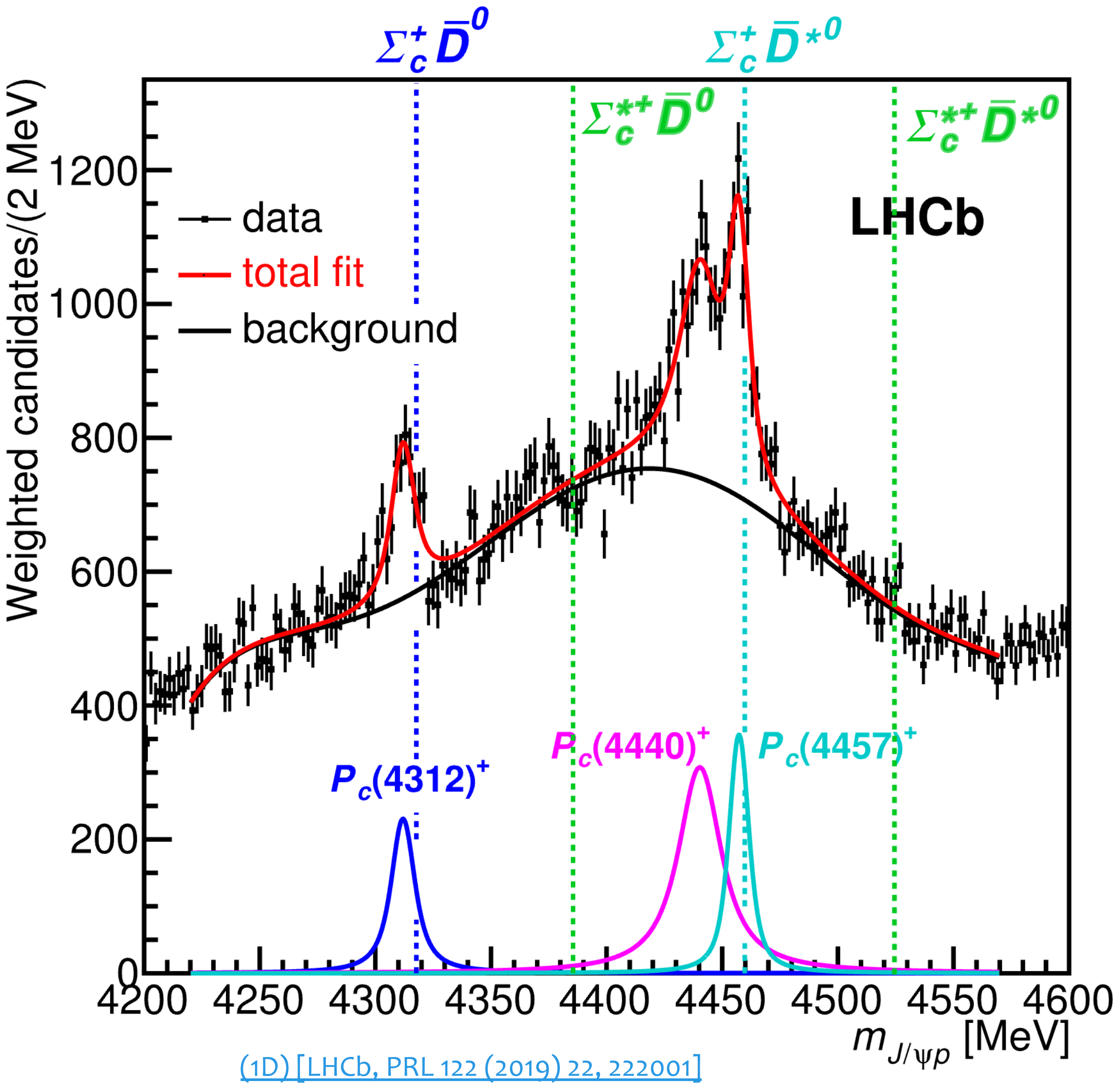
Pentaquarks $P_{c\bar{c}}^{+}$

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

QM core(?), molecular appearance(!)

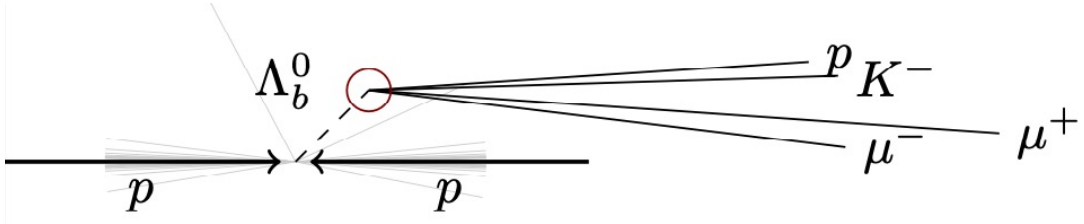
Only seem in b-decays by LHCb

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



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

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

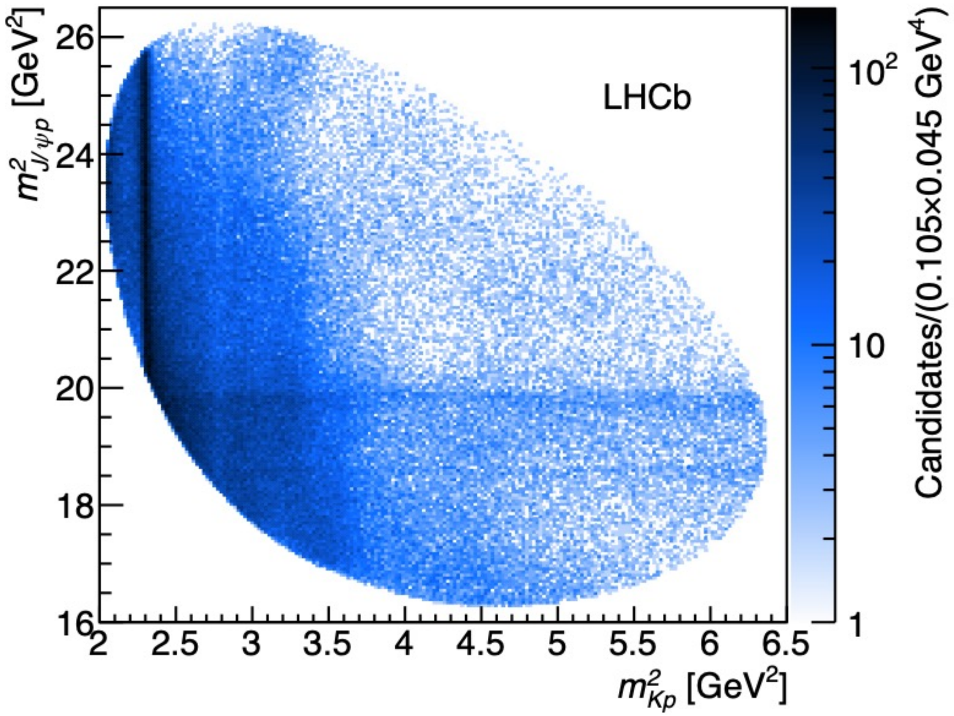


Narrow resonance states near threshold of $\Sigma_c^{+(*)}\bar{D}^{0(*)}$

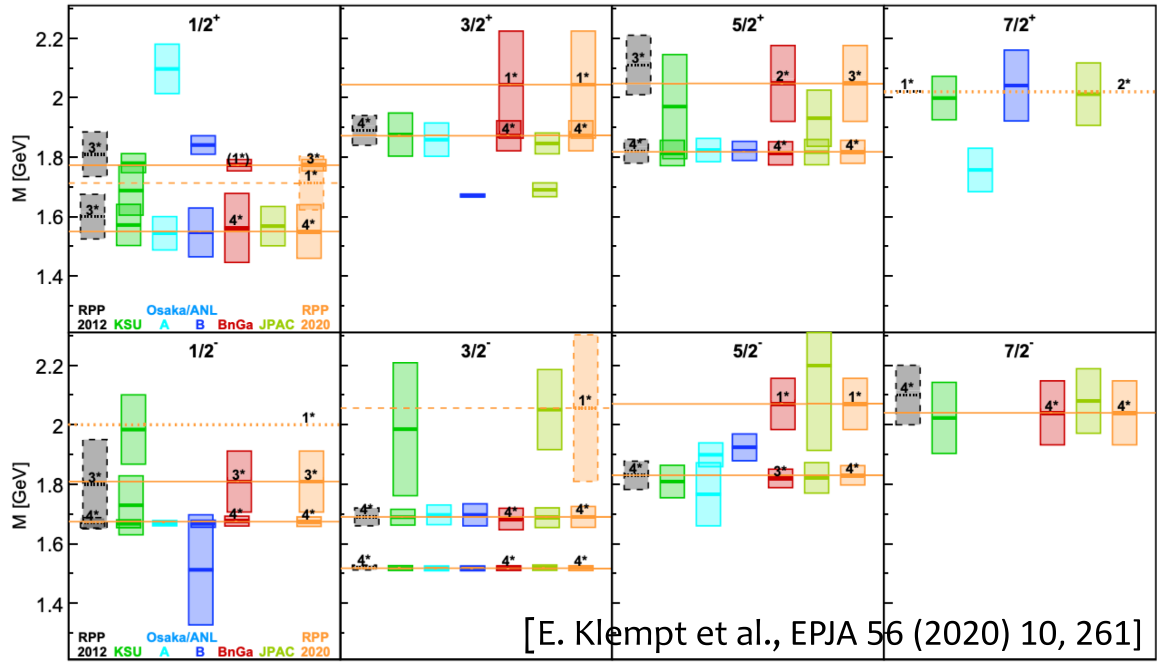
Large background from pK^- scattering –Λ resonances

Challenges for amplitude analysis (work in progress)

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



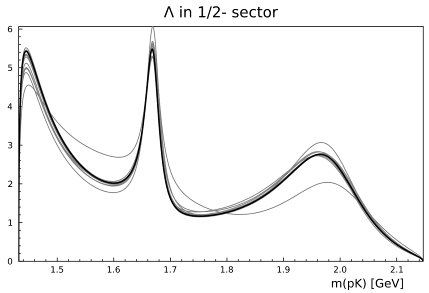
Might benefit from knowledge on Λ spectrum from $p\,K^-$ scattering data is needed

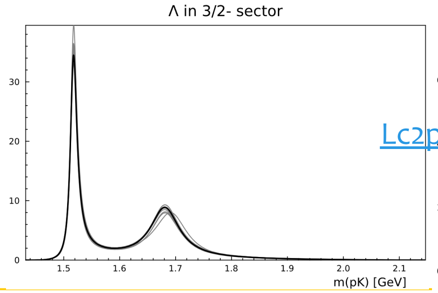


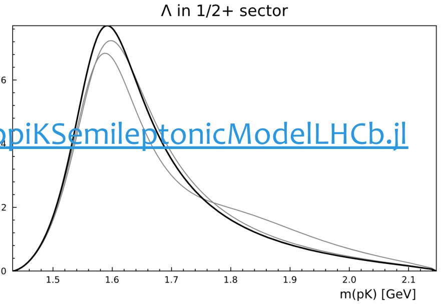
[E. Klempt et al., EPJA 56 (2020) 10, 261]

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

- Interfering background
- Largely unknown, now well constrained







Lc2ppiKSemileptonicModelLHCb.jl

Double J/psi resonances

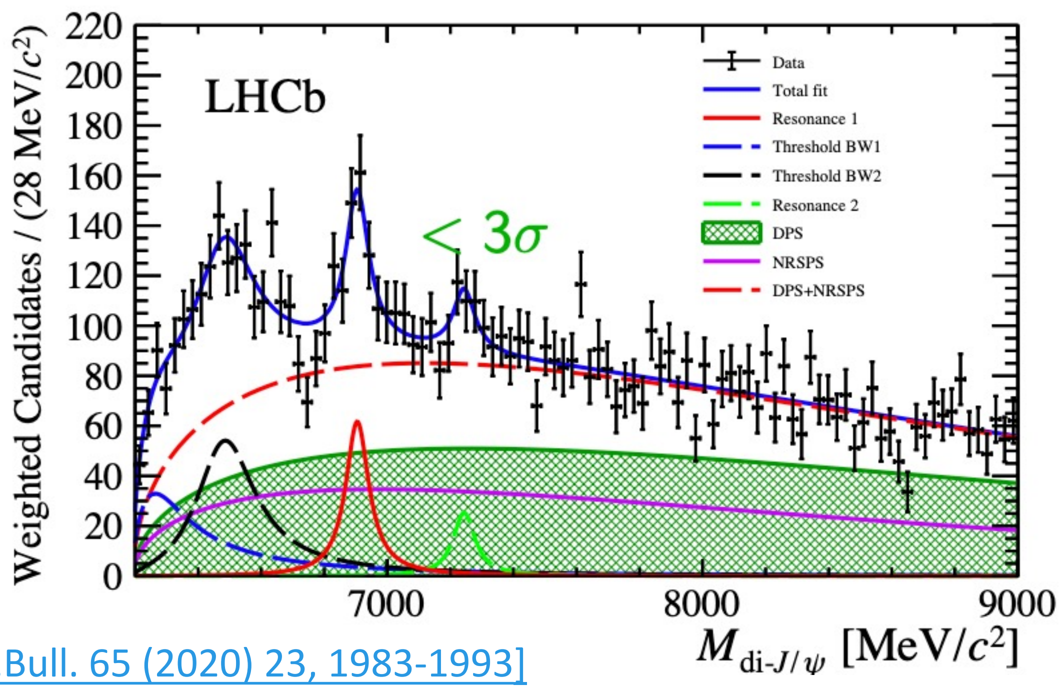
Unclear, many thresholds

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

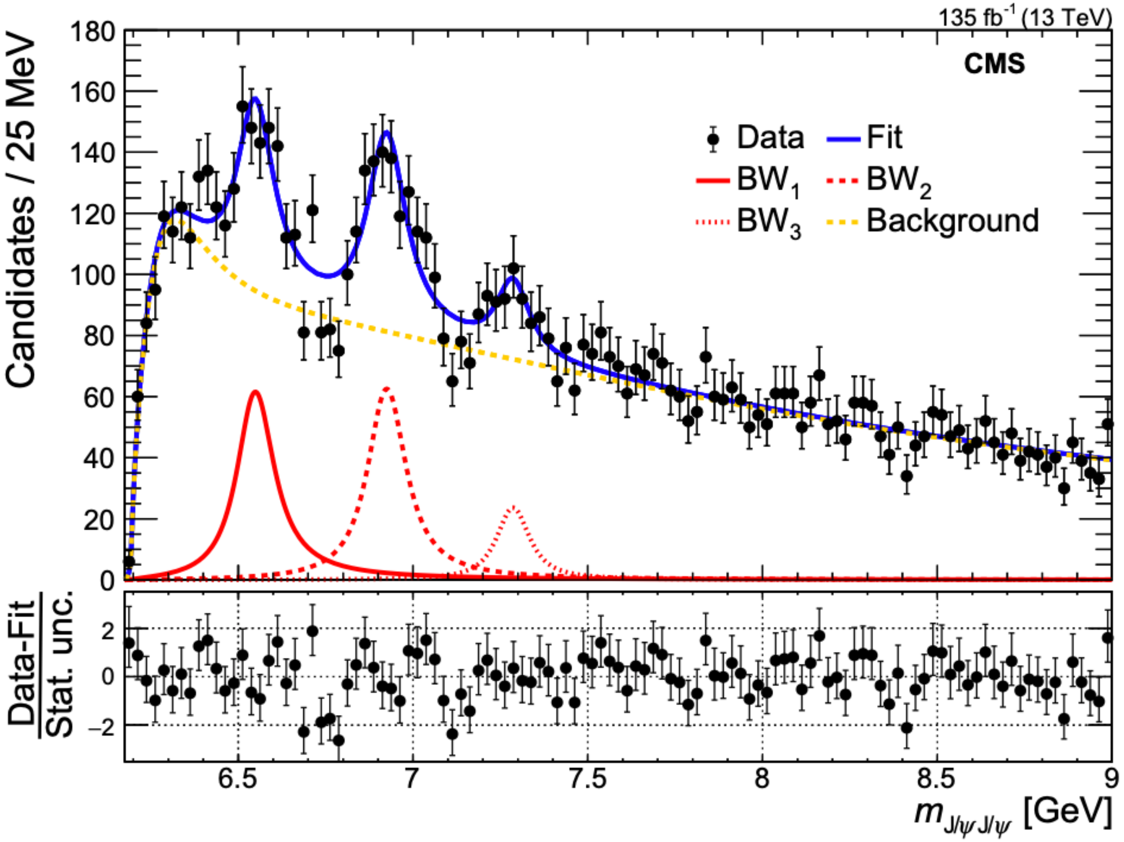
Seen in pp by LHCb, CMS, ATLAS

Double J/psi structures

[hep-ex: 2306.07164]

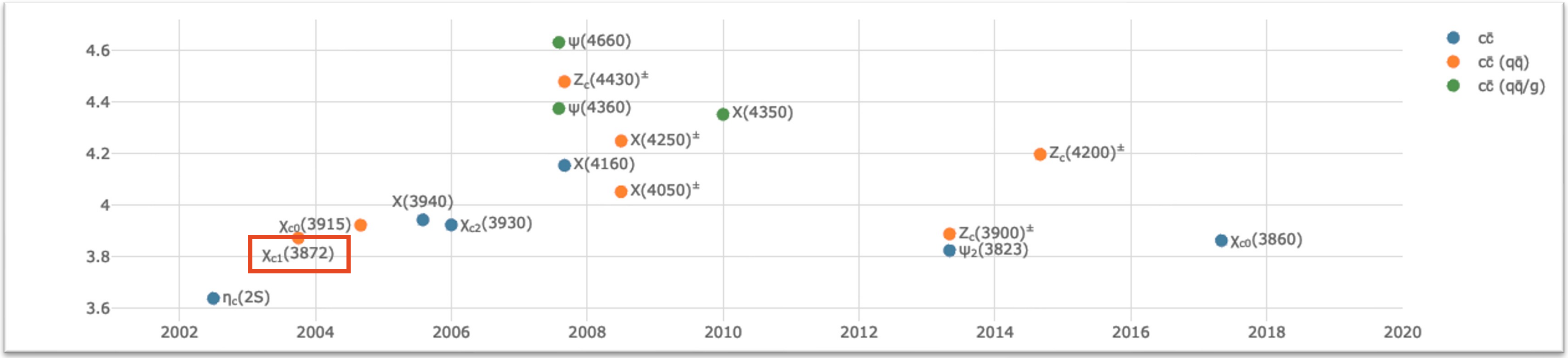


[Sci.Bull. 65 (2020) 23, 1983-1993]



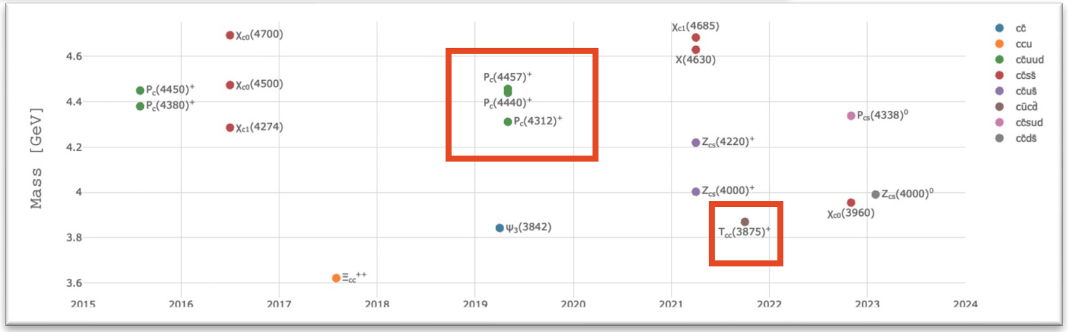
- Rapid **raise** at the threshold followed by the **three peaks.**
- Clear dips at 6.8 GeV, and 7.2 GeV
- Only simplistic modeling with unknown JP

Many exotic states. Particle zoo v2.0

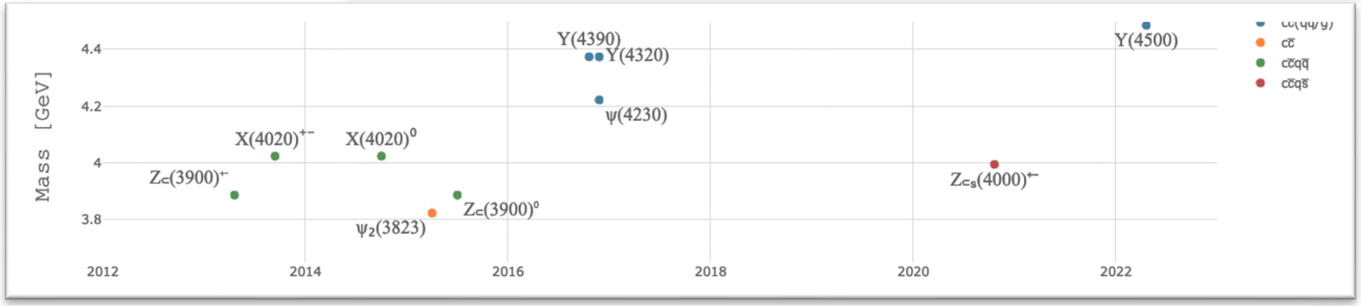


Belle

LHCb



BESIII



[QWG Exotics hub]

Open questions on exotic hadrons

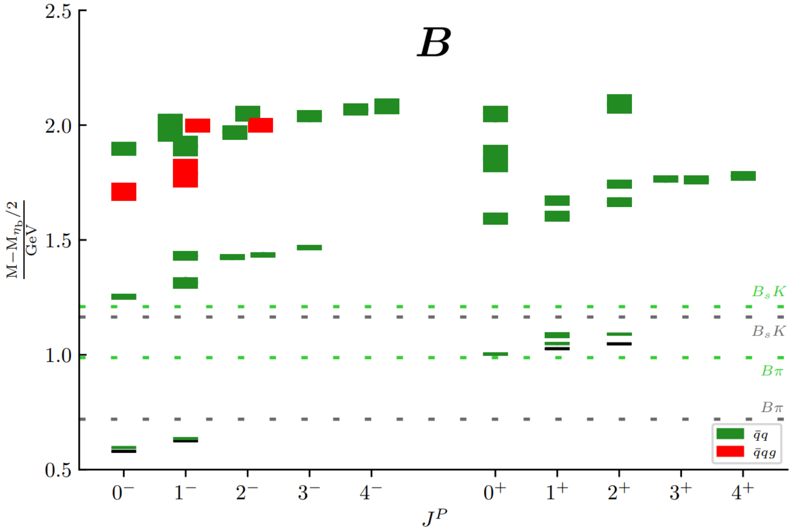
Having significant molecular contribution for hadronic state is fine.

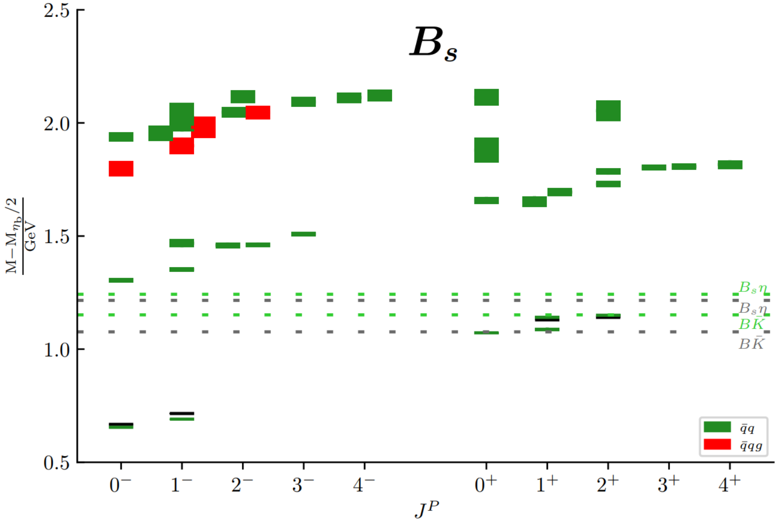
- We do not understand how the continuum acts.
  Why it sets some states right on the threshold? $[\chi_{c1}(3872) \to D^0 D^{*0}, T_{cc}^+ \to D^0 D^{*0}]$
- Does one always need a genuine QCD seed? – (extra numerous states wrt QM)
  From nuclear physics – “No” (plenty of atoms and isotops)
  $P_{c\bar{c}}^+$?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

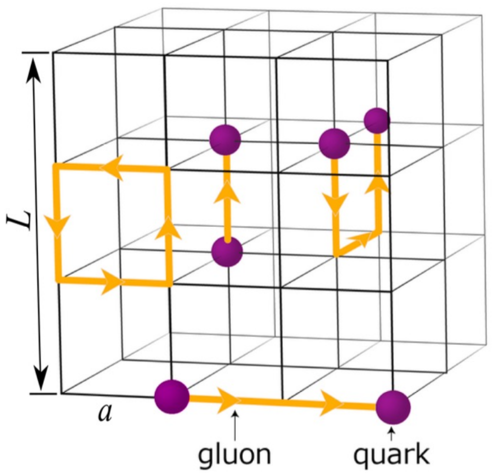
- Advanced amplitude analysis
- Collaboration of theory & experiment
- Synergy between different subfields

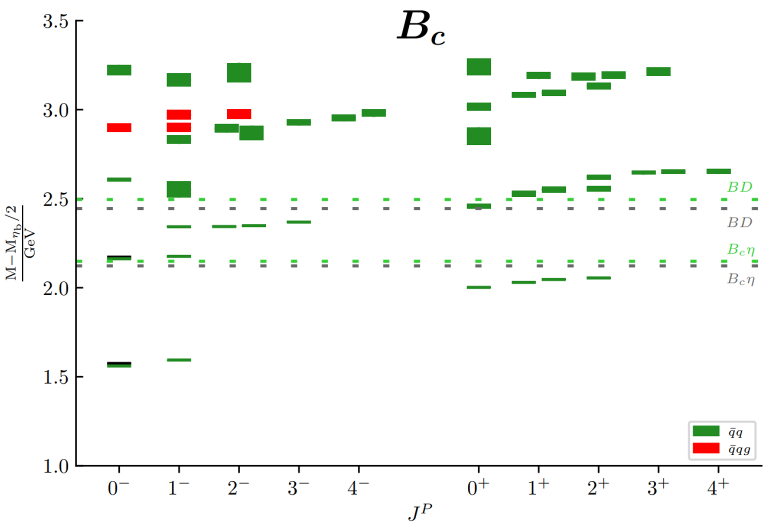
is critical to progress

Hybrids in meson spectrum





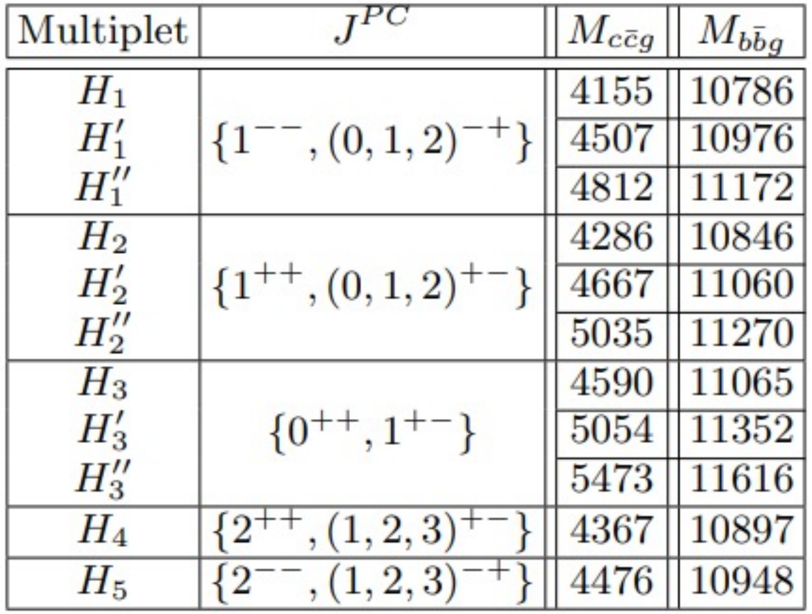




Hybrid states appear in all meson sectors consistently

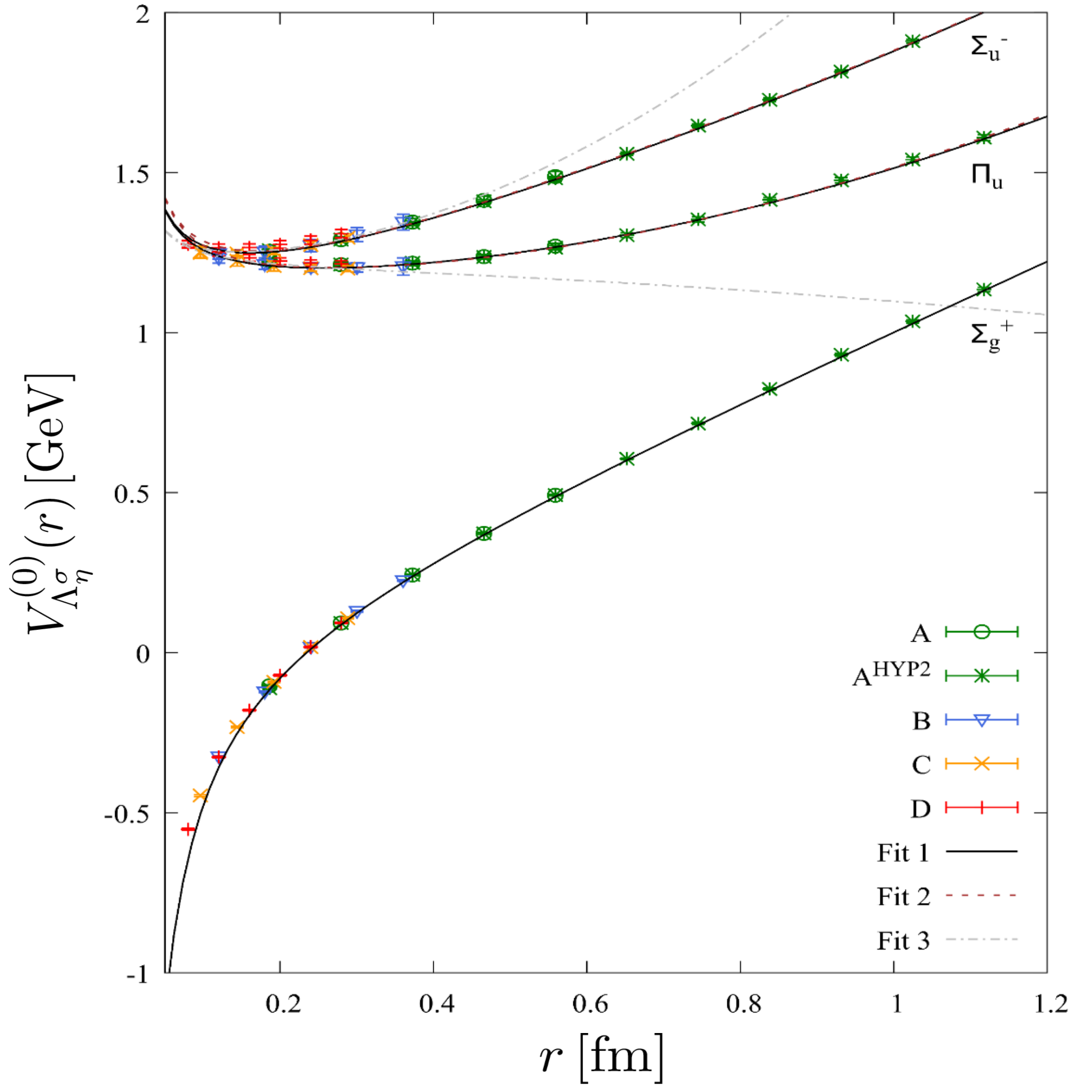
Hybrids

Are extra numerous states in charmonium spectrum

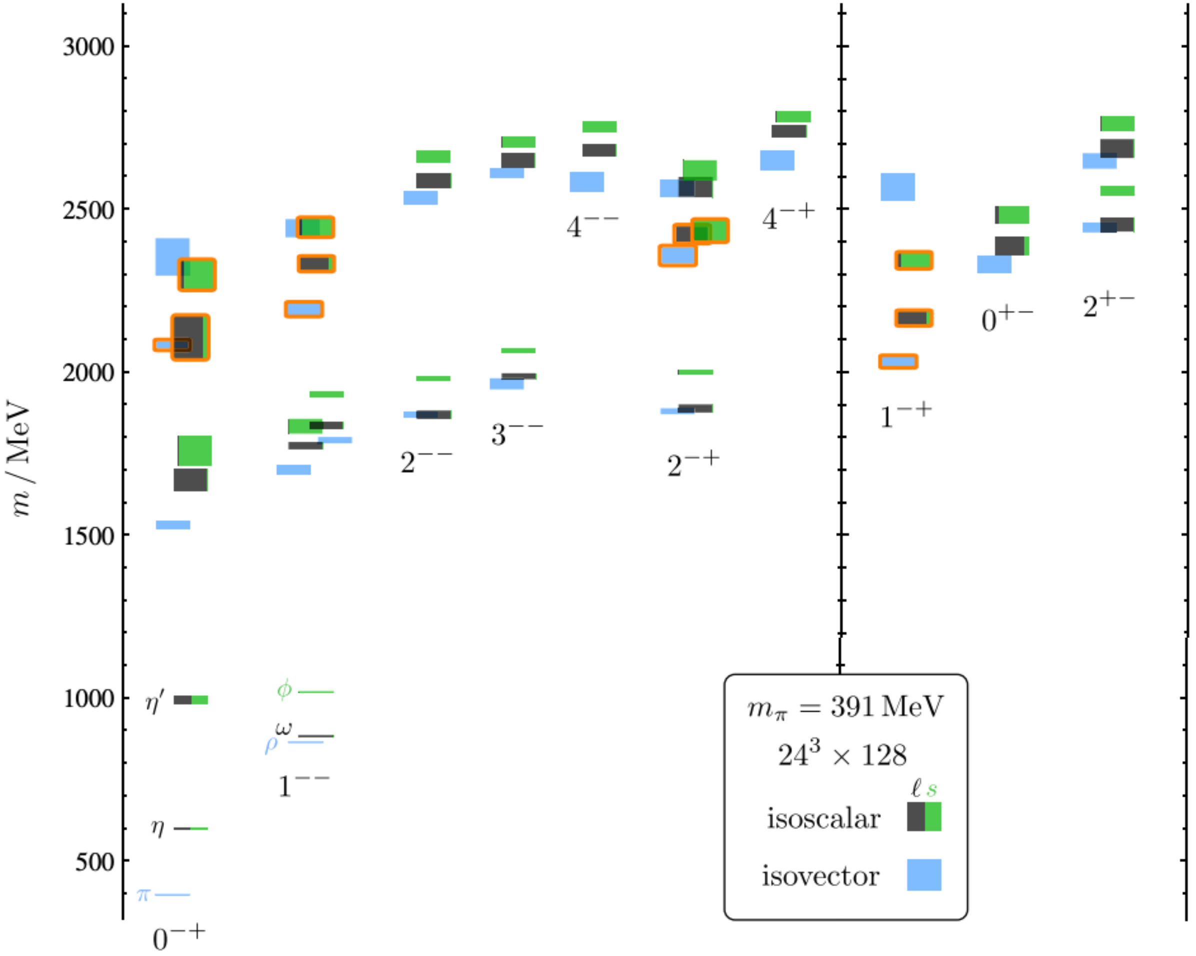


Multiplet	J^{PC}	$M_{c\bar{c}g}$	$M_{b\bar{b}g}$
H_1	$\{1^{--},(0,1,2)^{-+}\}$	4155	10786
H_1'		4507	10976
H_1''		4812	11172
H_2	$\{1^{++},(0,1,2)^{+-}\}$	4286	10846
H_2'		4667	11060
H_2''		5035	11270
H_3	$\{0^{++},1^{+-}\}$	4590	11065
H_3'		5054	11352
H_3''		5473	11616
H_4	$\{2^{++},(1,2,3)^{+-}\}$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

[Courtesy to Abhishek Mohapatra]



Hybrids in the light meson spectrum

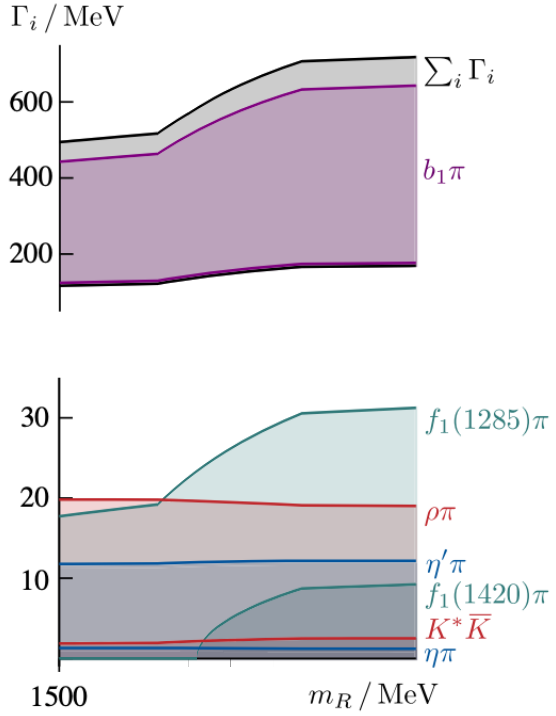


[Dudek et al., 2013]

Lattice QCD calculations for light meson sector are the most advanced

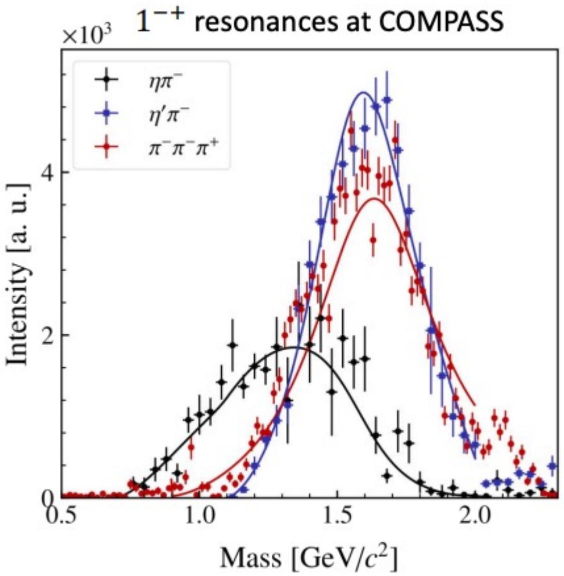
- Hybrid multiplets in GEVP calculations

- 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]