Hadron Physics

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Plan for the lecture

1. **Quantum Chromodynamics**
   - Gluons
   - Quarks

2. **Hadronic excitation ladder:**
   - Level counting
   - Quark model
   - Lattice QCD

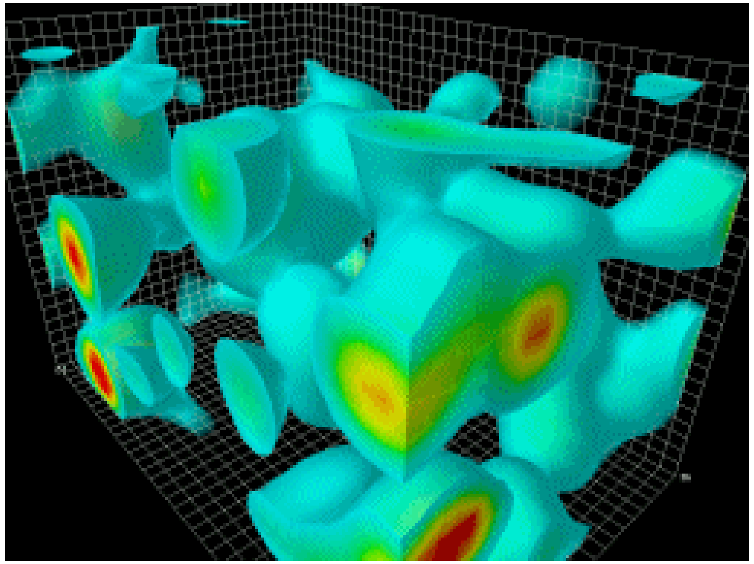
3. **Hadron scattering**

Understanding Quantum Chromodynamics

[Midjourney 2023, MM]
Oil pointing, depths of the quantum realm, entangled particles dance gracefully in a cosmic ballet, their movements dictated by the complex interplay of forces and probabilities. Through delicate strokes and swirling colors, capture the particles' intricate choreography, where their trajectories converge and diverge, manifesting the enigmatic beauty of the quantum world.

QCD vacuum

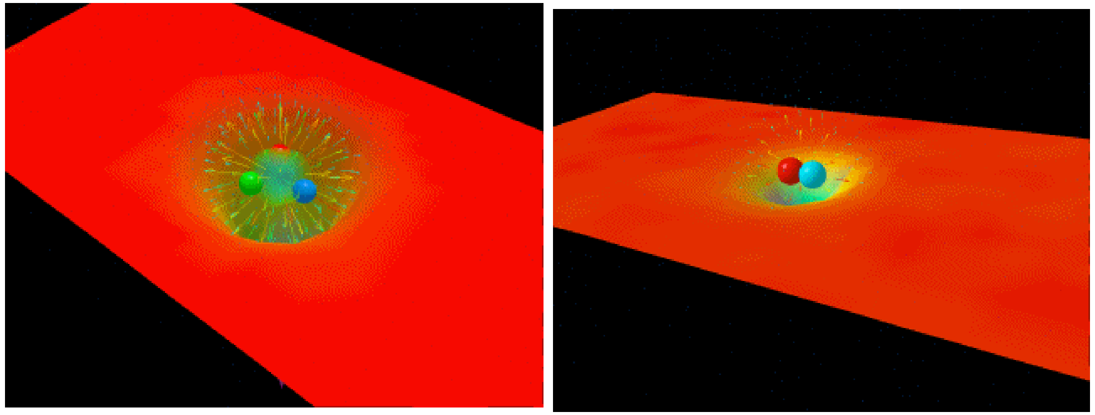
- Vacuum is not empty,
  filled with fluctuating gluonic fields.
- Physical quarks appear to move in a gluon mean field
  they gain mass
- This is transition from
  SM massless quarks -> constituent qurks

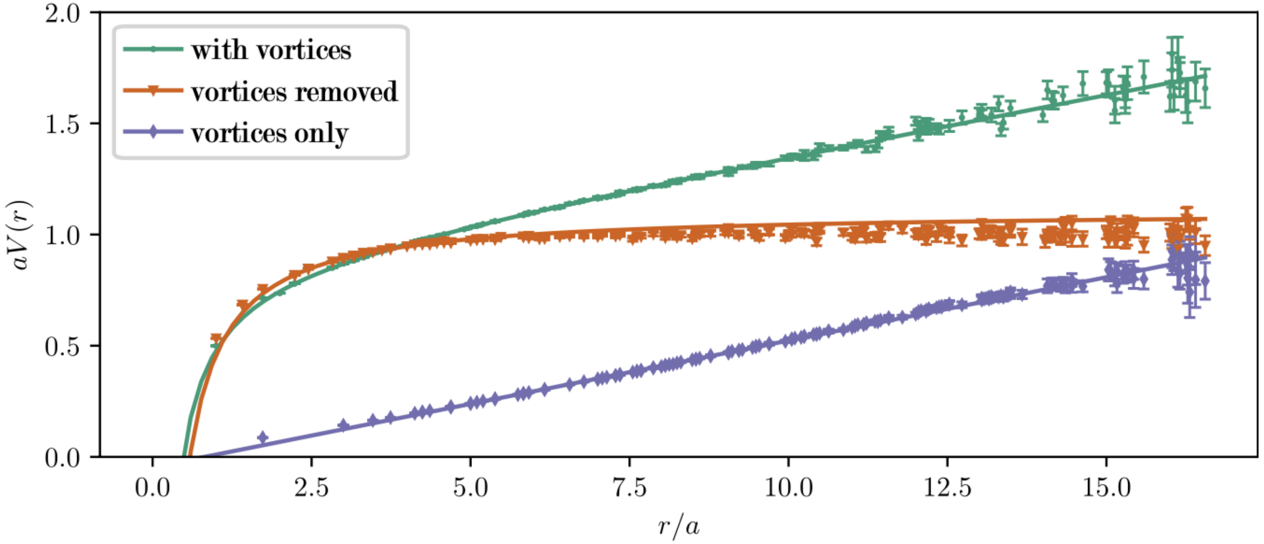


The animations illustrate the typical four-dimensional structure of gluon-field configurations averaged over in describing the vacuum properties of QCD. The volume of the box is 2.4 by 2.4 by 3.6 fm, big enough to hold a couple of protons. Contrary to the concept of an empty vacuum, QCD induces chromo-electric and chromo-magnetic fields throughout space-time in its lowest energy state. After a few sweeps of smoothing the gluon field (50 sweeps of APE smearing), a lumpy structure reminiscent of a lava lamp is revealed. This is the QCD Lava Lamp. The action density, which is similar to an energy density, is displayed.

Confinement

- **Gluon self-interaction**
- **Flux tube**
- **Energy increases with distance**
- **Many strictures in QCD vacuum fields:** instantons, merons, abelian monopoles, centre vortices

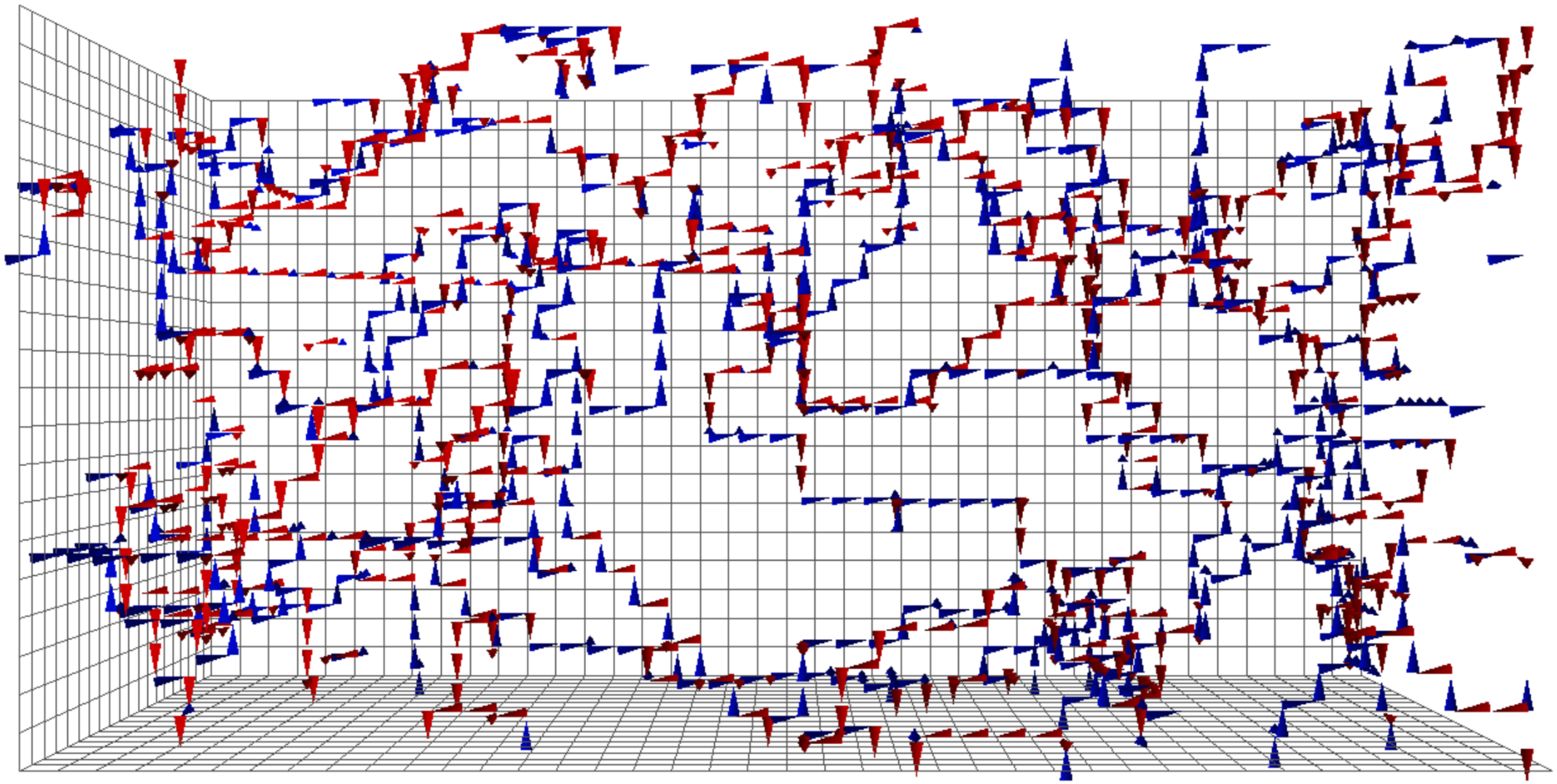




This animation shows the suppression of the QCD vacuum from the region between a quark-antiquark pair illustrated by the colored spheres. The separation of the quarks varies from 0.125 fm to 2.25 fm, the latter being about 1.3 times the diameter of a proton. The surface plot illustrates the reduction of the vacuum action density in a plane passing through the centers of the quark-antiquark pair. The vector field illustrates the gradient of this reduction. The tube joining the two quarks reveals the positions in space where the vacuum action is maximally expelled and corresponds to the famous "flux tube" of QCD. As the separation between the quarks changes the tube gets longer but the diameter remains approximately constant. As it costs energy to expel the vacuum field fluctuations, a linear confinement potential is felt between quarks.

QCD Vortices

Penetrate vacuum and cause the confinement



SM and QCD Lagrangian

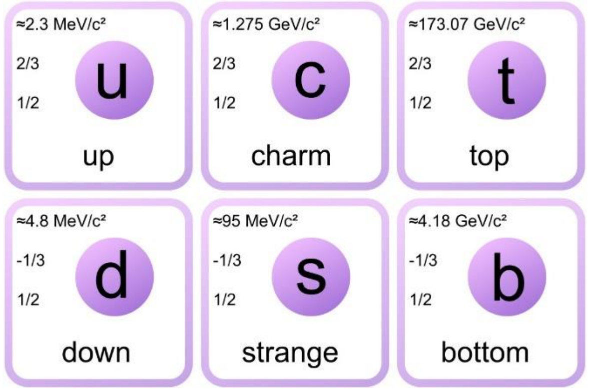
Gluons! – reason of the confinement

Light quarks: u,d,s

- massless(!)
- cheap
- mixed

Heavy quarks: c,b,t

- massive
- expensive
- conserved



$$\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).
\end{gathered}$$

[Diagrammatica, Lecture Notes, M. Veltman]

Every family gets own energy range

Family is determined by QM

- quark content
- isospin

Example 1:

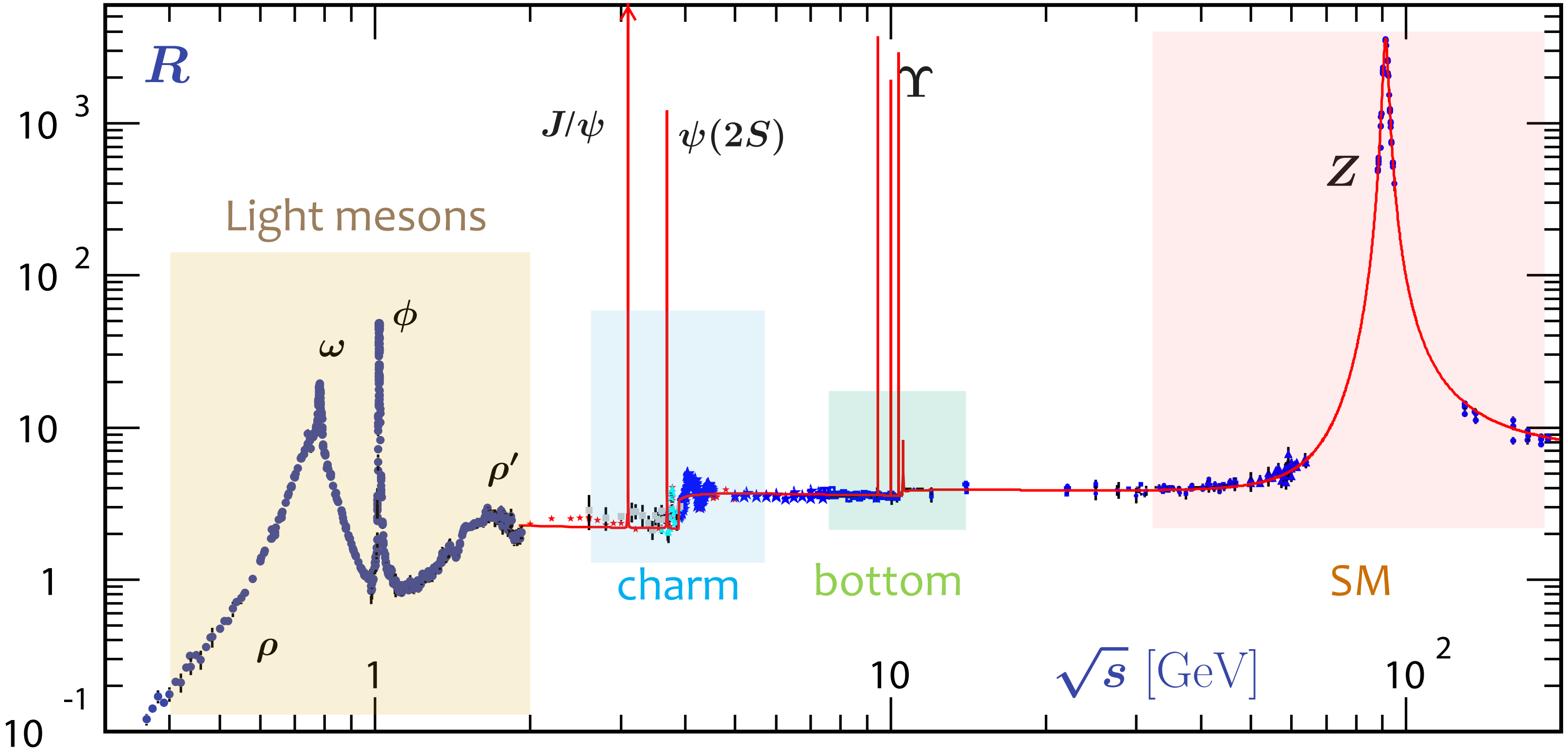
udc with I=0 => Λ_c^+

udc with I=1 => Σ_c^+

Example 2:

uud - proton, ~ 1GeV

$uudc\bar{c}$ - pentaquark, ~4.3GeV



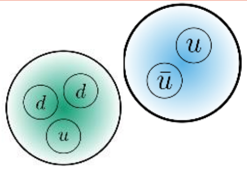
$$R = \frac{\sigma^{(0)}(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Hadronic Excitations

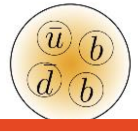
[Midjourney 2023, MM] Highly defined macrophotography of a weird unseen quantum world + images

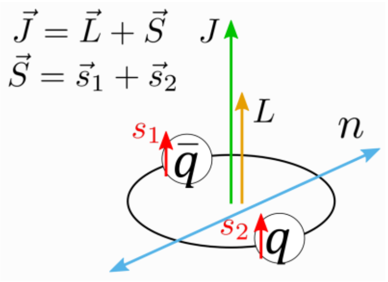
Possible configurations of hadrons

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



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



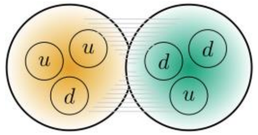


+ excitations

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

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

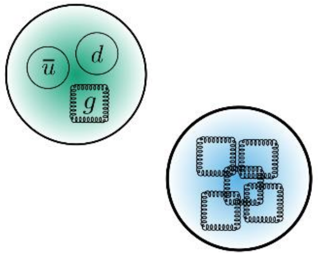
Admixed Molecules: $q\bar{q} \to (q\bar{q})(q\bar{q})$



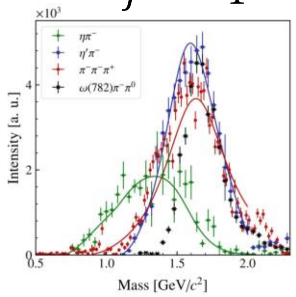
+ nuclei chart

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

Glueballs: $g{\sim}g$

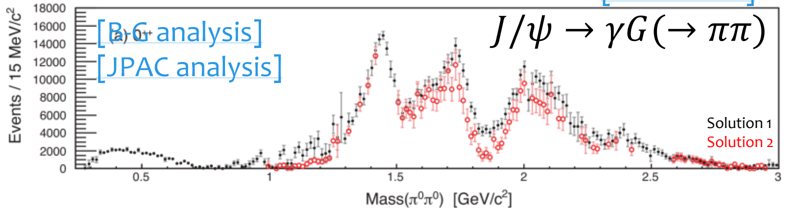


$J^{PC} = 1^{-+}$



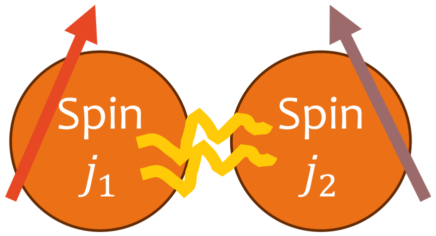
[P.Haas, HADRON2023]

[BESIII data]



Reminder on spin algebra

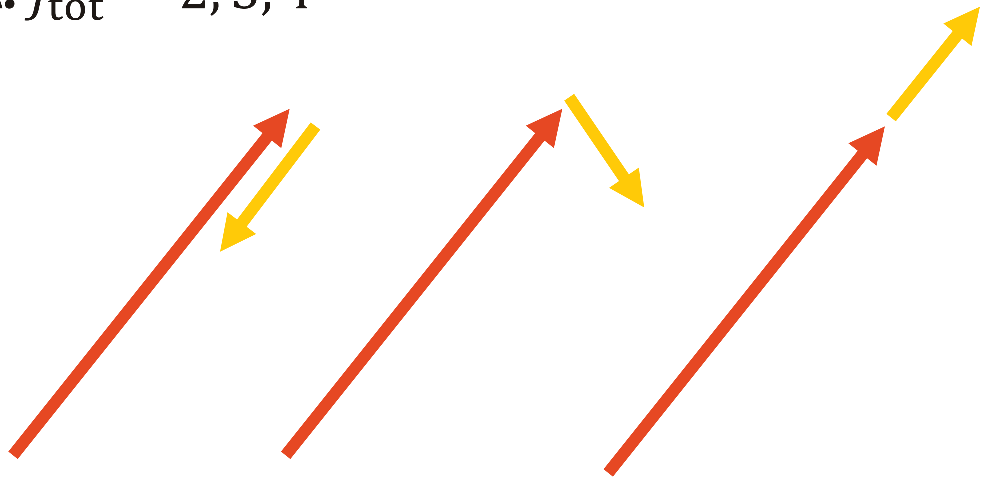
Consider an interacting system of spins



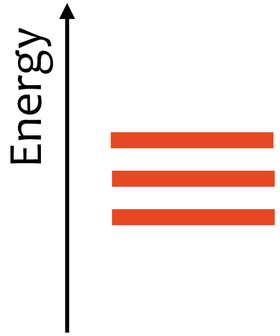
Q: what is an energy spectrum?

Say, $j_1 = 1$ and $j_1 = 3$

A: $j_{\mathrm{tot}} = 2, 3, 4$

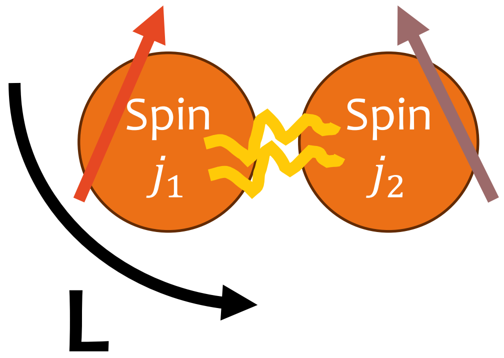


=> three energy levels



Adding orbital excitation

The system can be excited radially

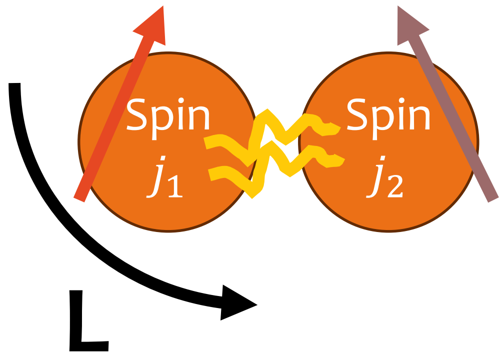


j1	x	j2	
3/2	x	1/2	1 2 [S-wave]
			(0 1 2) (1 2 3) [P]
			(1 2 3) (0 1 2 3 4) [D]
			(2 3 4) (1 2 3 4 5) [F]

Q: what are multiplicities of L-wave multiplets?

Add parity

Interaction conserves parity



j1	x	j2	
3/2+	x	1/2-	1- 2- [S-wave]
			(0+ 1+ 2+) (1+ 2+ 3+) [P]
			(1- 2- 3-) (0- 1- 2- 3- 4-) [D]
			(2+ 3+ 4+) (1- 2- 3- 4- 5-) [F]

Q: what are parities of different configurations?

Say, 3/2+ x 1/2-

Radial excitations and orbital excitations

Hydrogen atom:

n – principle quantum number

l – orbital quantum number

(l<n)

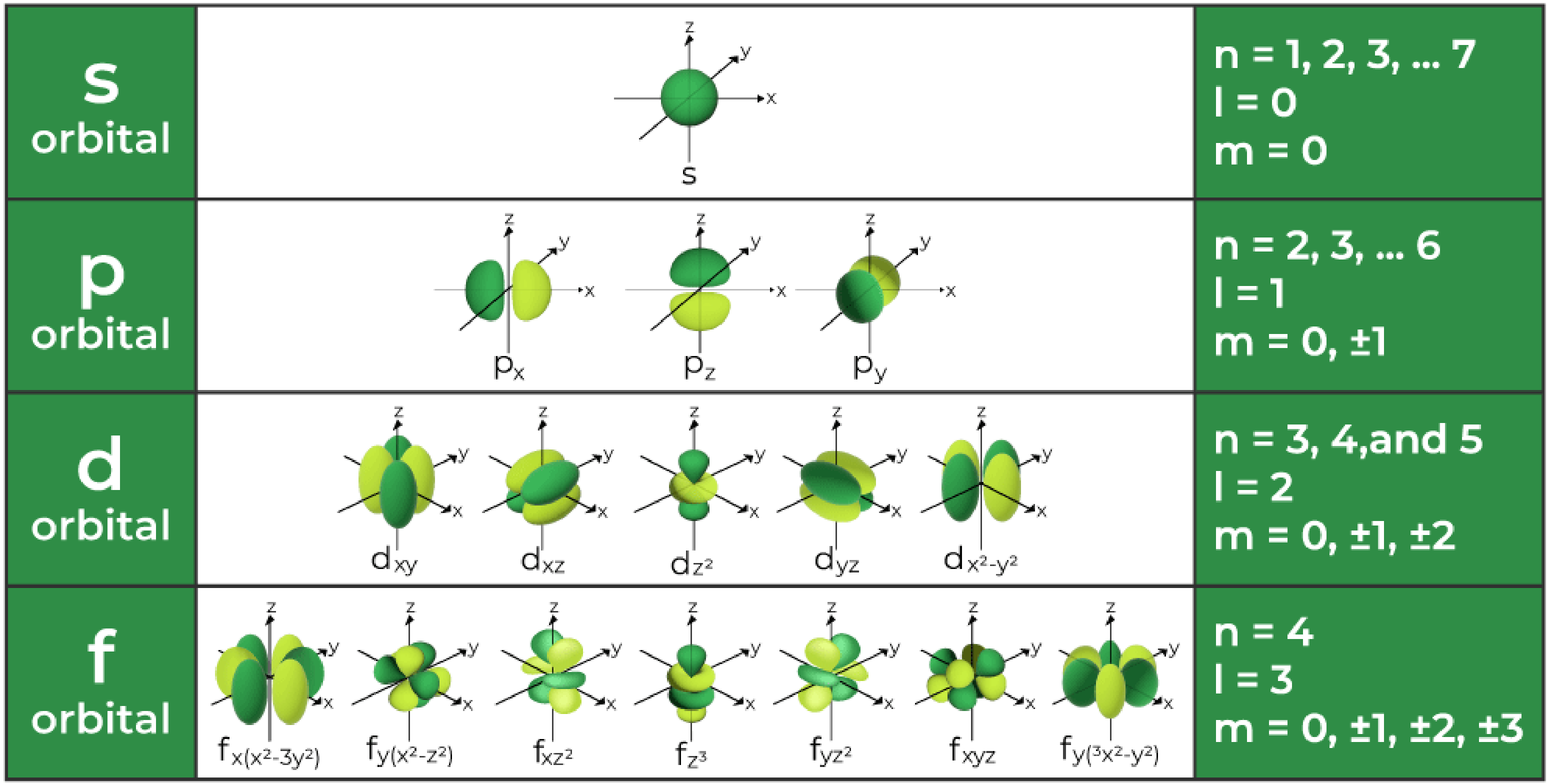
The spectrum is

. . .

1S

2S 1P

3S 2P 1D



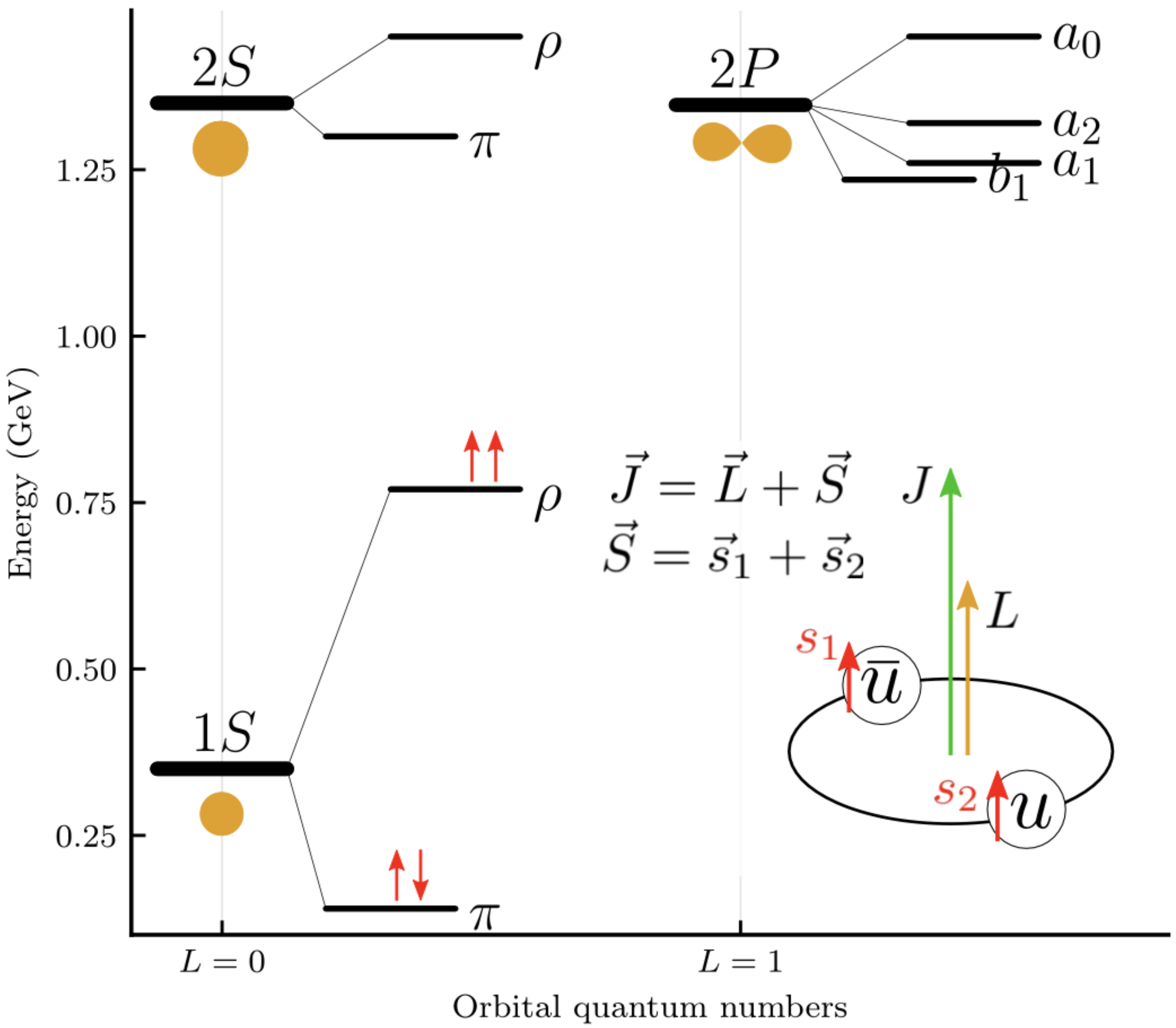
[https://www.geeksforgeeks.org/quantum-numbers]

Meson excitations

Same for all conventional mesons, $q\bar{q}$

1/2+ x 1/2- | 0- 1- [S-wave]

=> doublets(nS), and
quadruplets (nP, nD, nF…: 3+1)



Exercise 2: baryon spectrum

Determine spin and parity of the excited states

Λ_c^+ (Λ_b^0) spectrum:

Q 1/2+ x [ll] 0+

Ω_c^0 (Ω_b^- or $\Sigma_{c/b}$) spectrum:

Q 1/2+ x [ll] 1+

Charmonium in Quark model

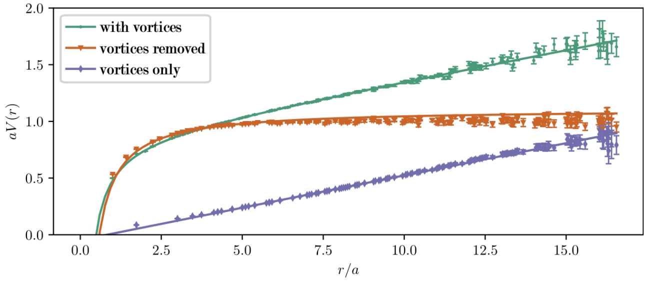
Relativistic Quark Model

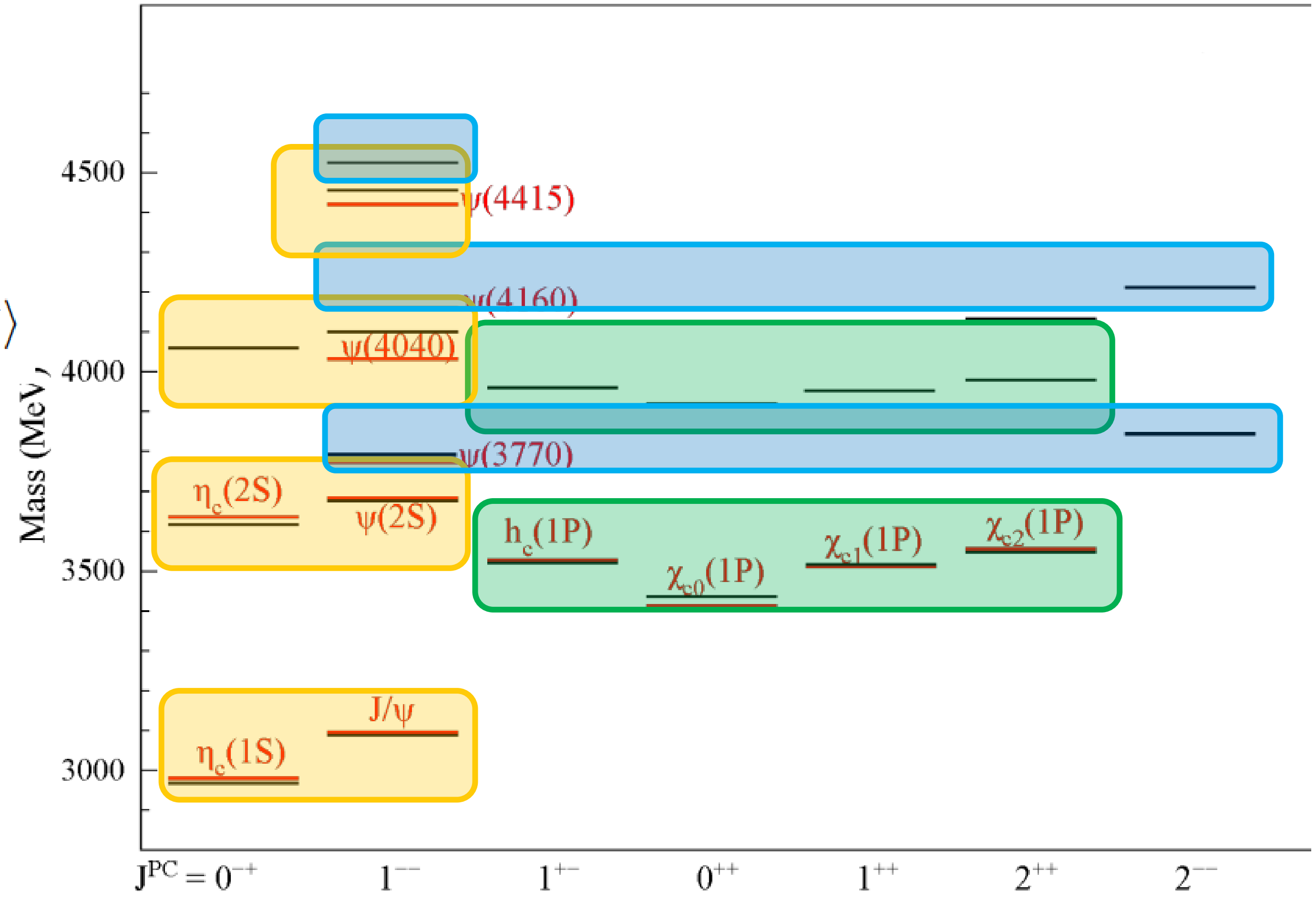
[Gotfrey-Isgur, PRD32, 1985]

$$\left(\sqrt{m_1^2+p^2}+\sqrt{m_2^2+p^2}+V\right)|\Psi\rangle = E|\Psi\rangle$$

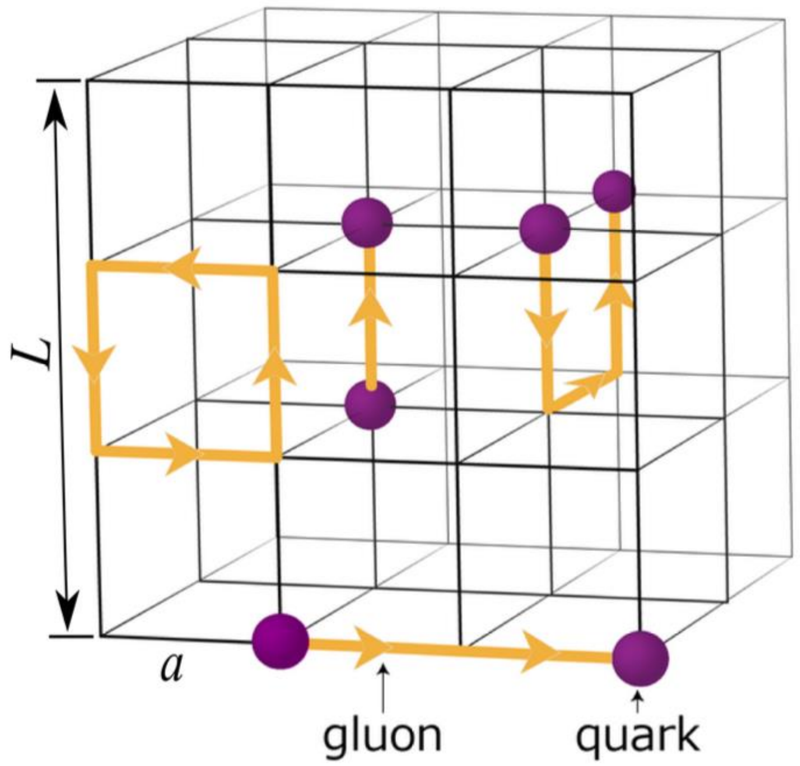
potential V:

One-gluon exchange +
linear confinement +
relativistic effects





Lattice QCD



First-principle computation tool

- start from **QCD Lagrangian**

$$\mathcal{L} = \bar{\psi}\left(i\gamma^\mu D_\mu - m\right)\psi - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- compute **expectation value** for an operator

$$\langle\mathcal{O}\rangle = \frac{1}{Z}\int \mathcal{D}U\mathcal{D}\Psi\mathcal{D}\bar{\Psi}\mathcal{O}e^{-S_{QCD}}$$

- integrate **fermion fields** analytically**, gluon** numerically (importance sampling, average over ensemble)

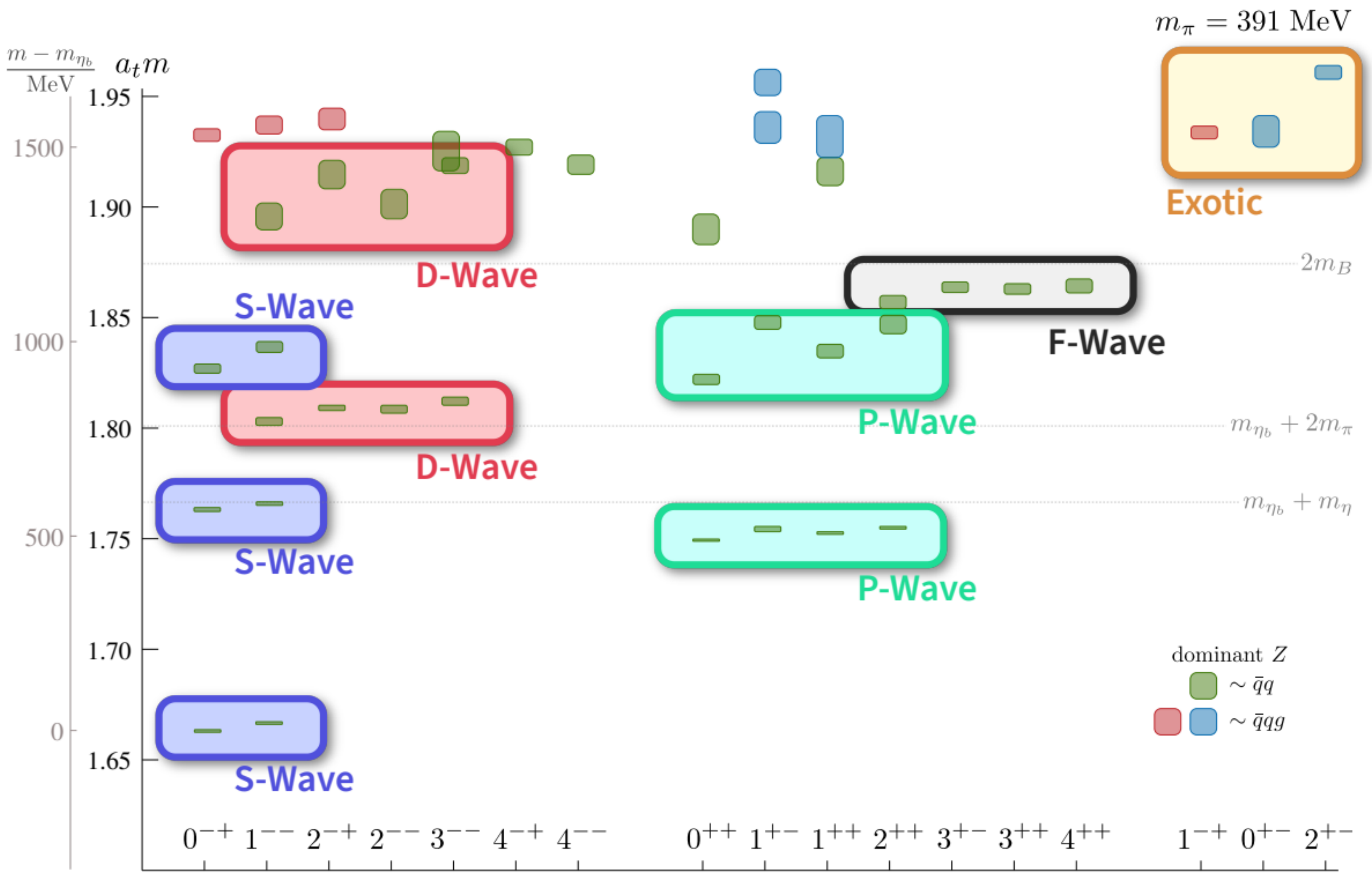
- using Euclidian time find energy, E_0

$$e^{iE_0 t} \to e^{-E_0 T}$$

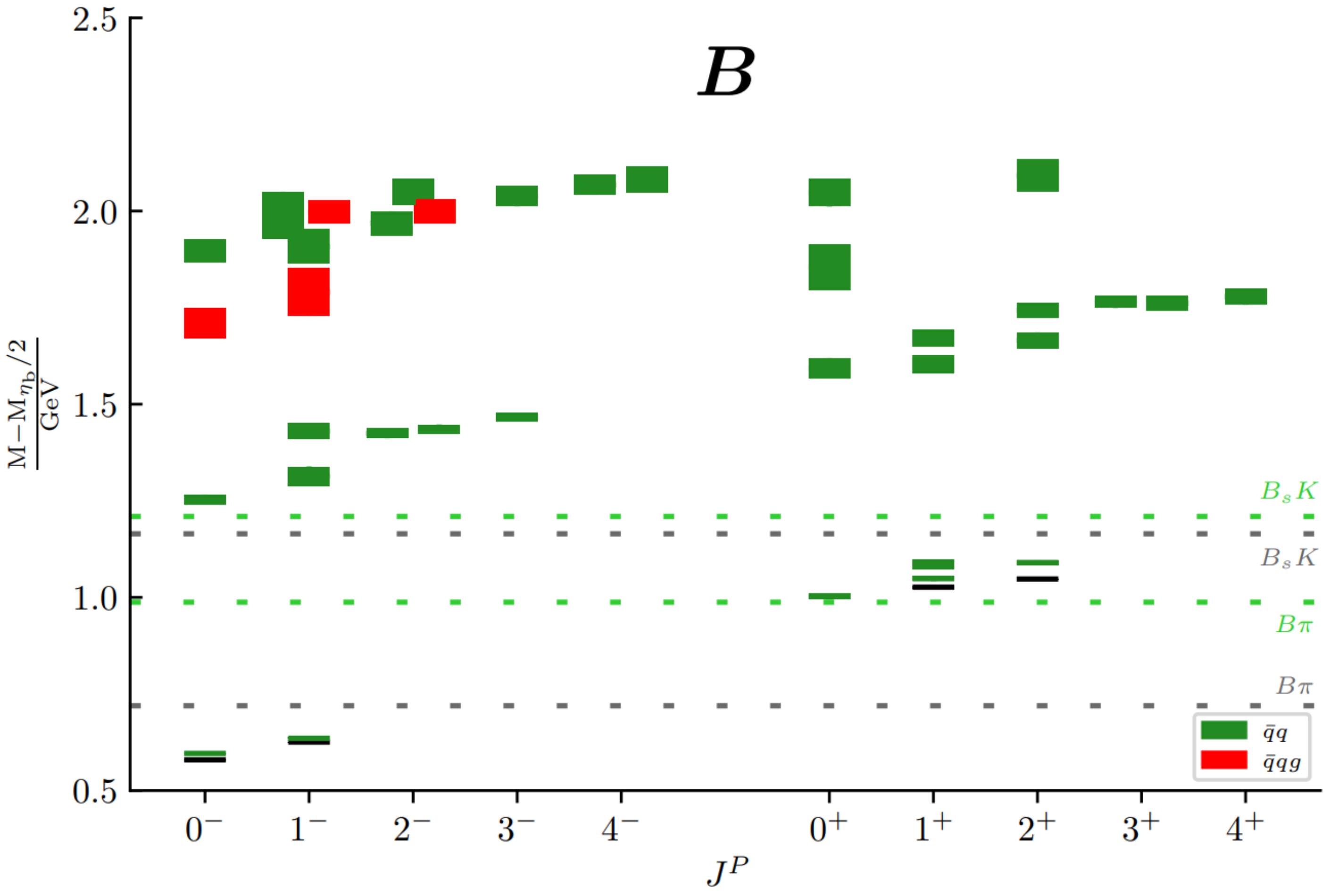
Bottomonium spectrum

[HadSpec, JHEP 02 (2021) 214]

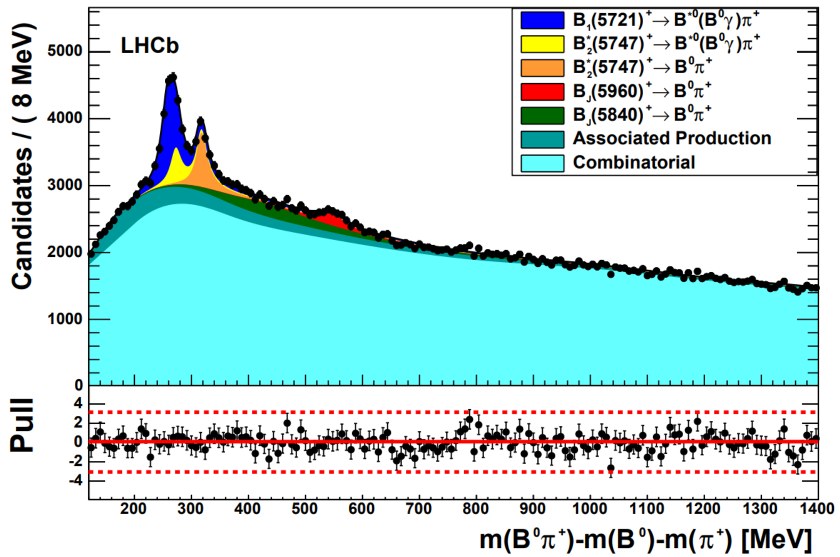
Always same pattern



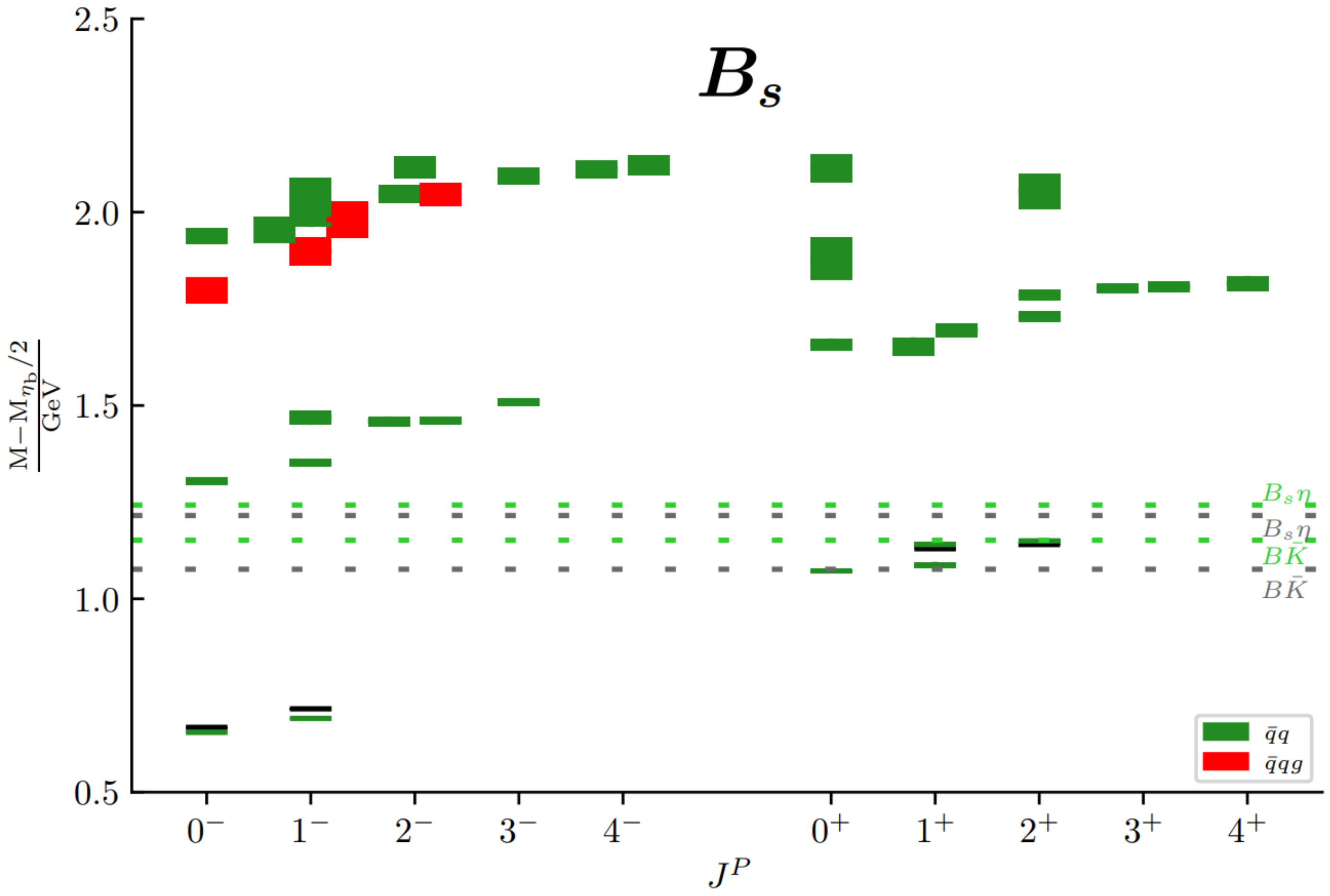
Excitations spectrum of B mesons



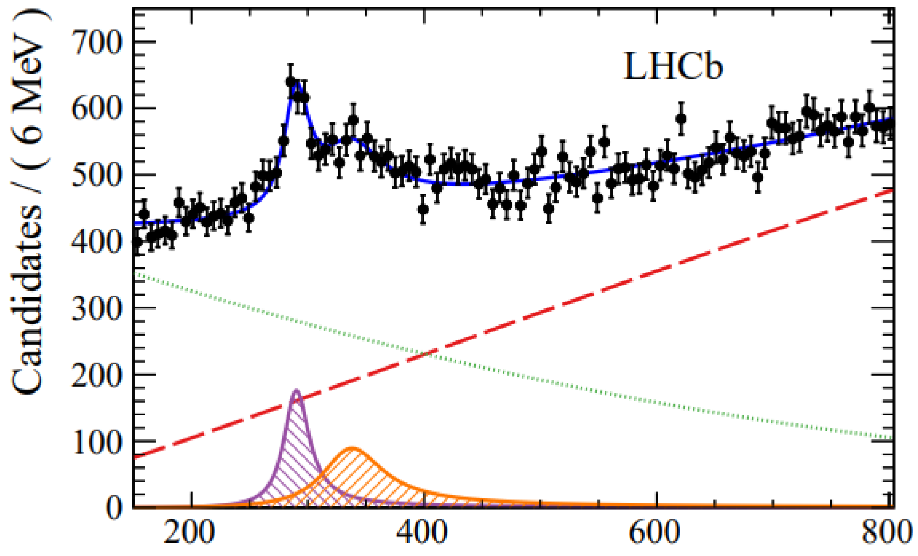
[LHCb, JHEP 1504 (2015) 024]



Excitations spectrum of Bs mesons

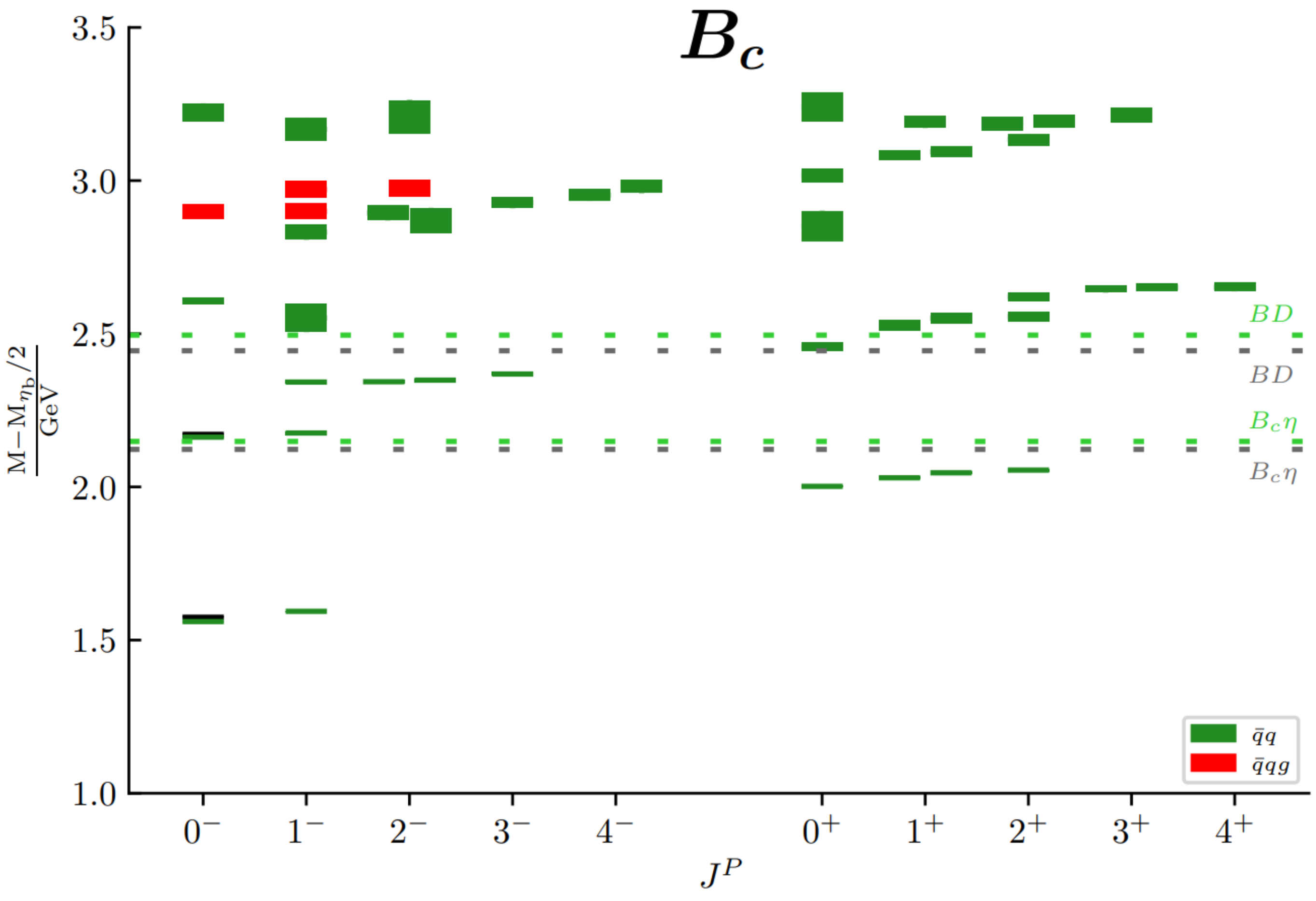


[LHCb, Eur. Phys. J. C81 (2021) 601]

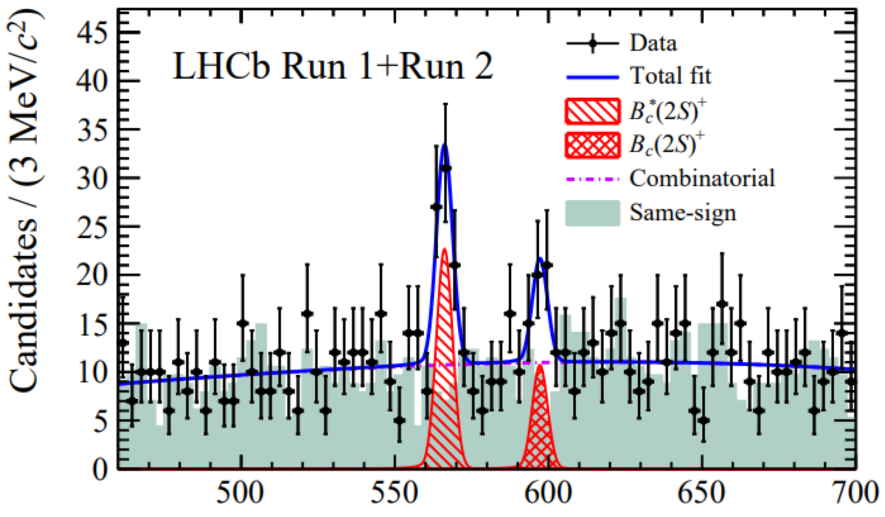


m(B+K-)-m(B+)-m(K-) [MeV]

Excitations spectrum of Bc mesons

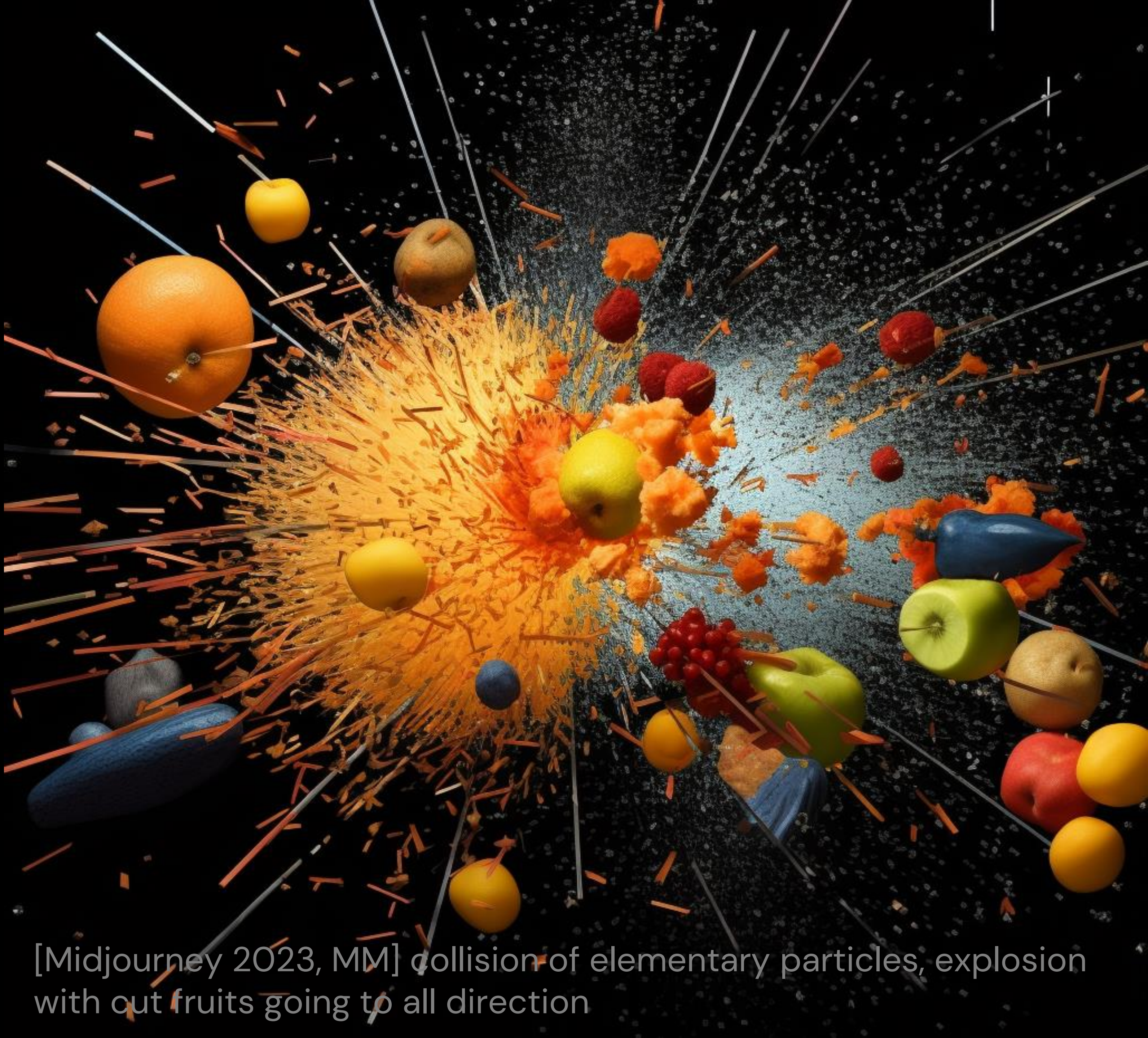


[LHCb, Phys.Rev.Lett. 122 (2019) 23, 232001]



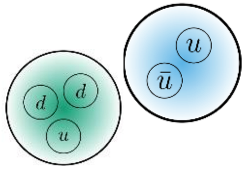
m(Bc+π+π-)-m(B+)-2m(π-) [MeV]

Hadron scattering



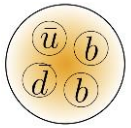
[Midjourney 2023, MM] collision of elementary particles, explosion with cut fruits going to all direction

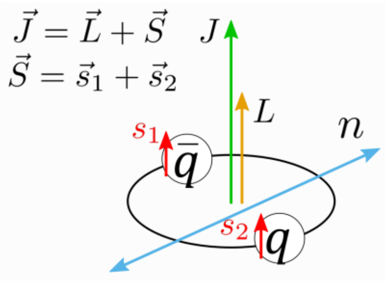
Possible configurations of hadrons



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

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



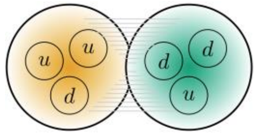


+ excitations

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

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

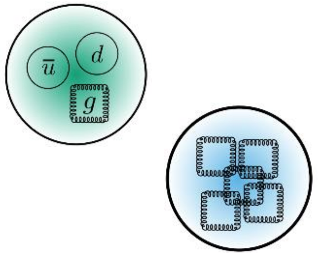
Admixed Molecules: $q\bar{q} \to (q\bar{q})(q\bar{q})$



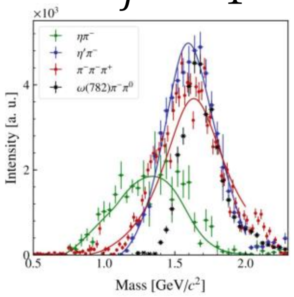
+ nuclei chart

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

Glueballs: $g{\sim}g$



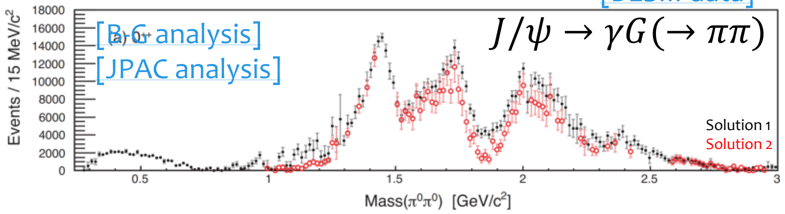
$J^{PC} = 1^{-+}$



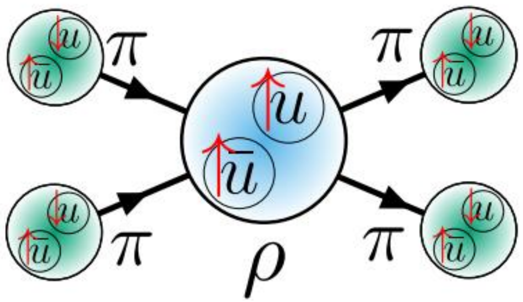
[P.Haas, HADRON2023]

[BESIII data]

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



QCD states as resonances



Most of hadrons can decay P0->P1,P2

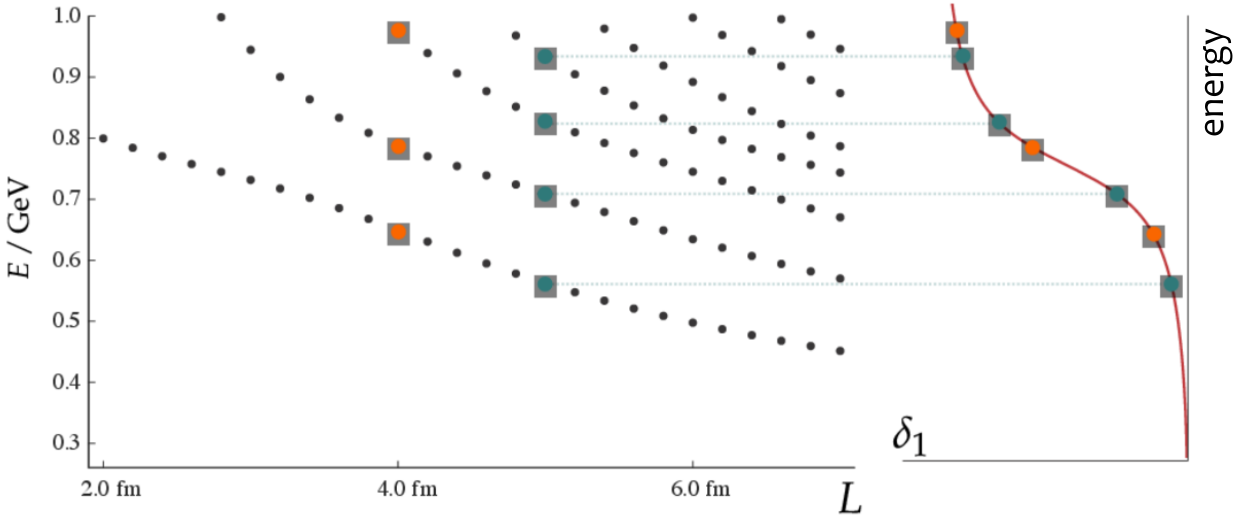
- ”particle” – a genuine QCD states

- ”continuum” – spectrum of P1,P2

- **No rest energy for the “particle” – continuum spectrum**
- **width ~ 1/lifetime**
- **One can compute the same on lattice:**

  < pi pi > correlation

<- Lüscher formalism (1991) ->



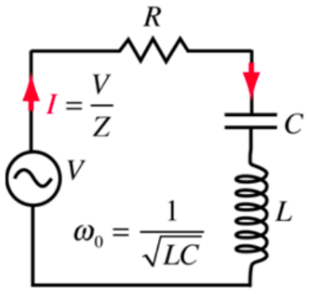
Resonances

A resonance is a common phenomenon across fields (peak, phase motion, pole)

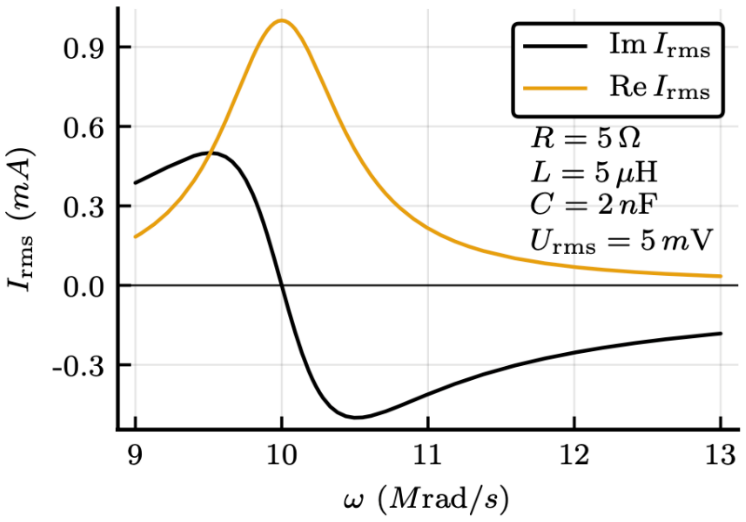
QCD excited states appear as resonances in scattering / decays

Hence often called ”resonances”

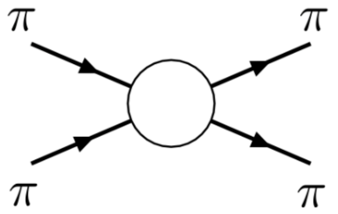
Electric resonance



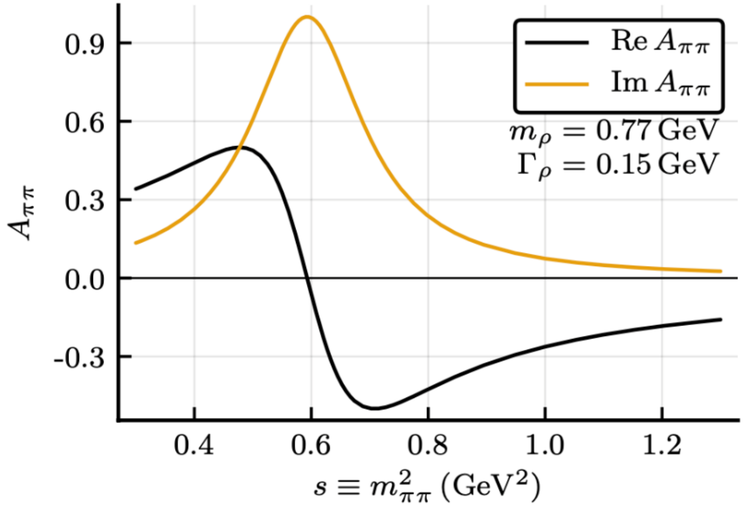
$$I_{\rm rms} = \frac{U}{R + iL\omega - \frac{i}{C\omega}}$$



Hadronic resonance



$$A_{\pi\pi} = \frac{m\Gamma}{m^2 - s - im\Gamma}$$



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. I do not know how this thing decays / decay threshold is far away

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

2. The only relevant continuum channel is the one I consider

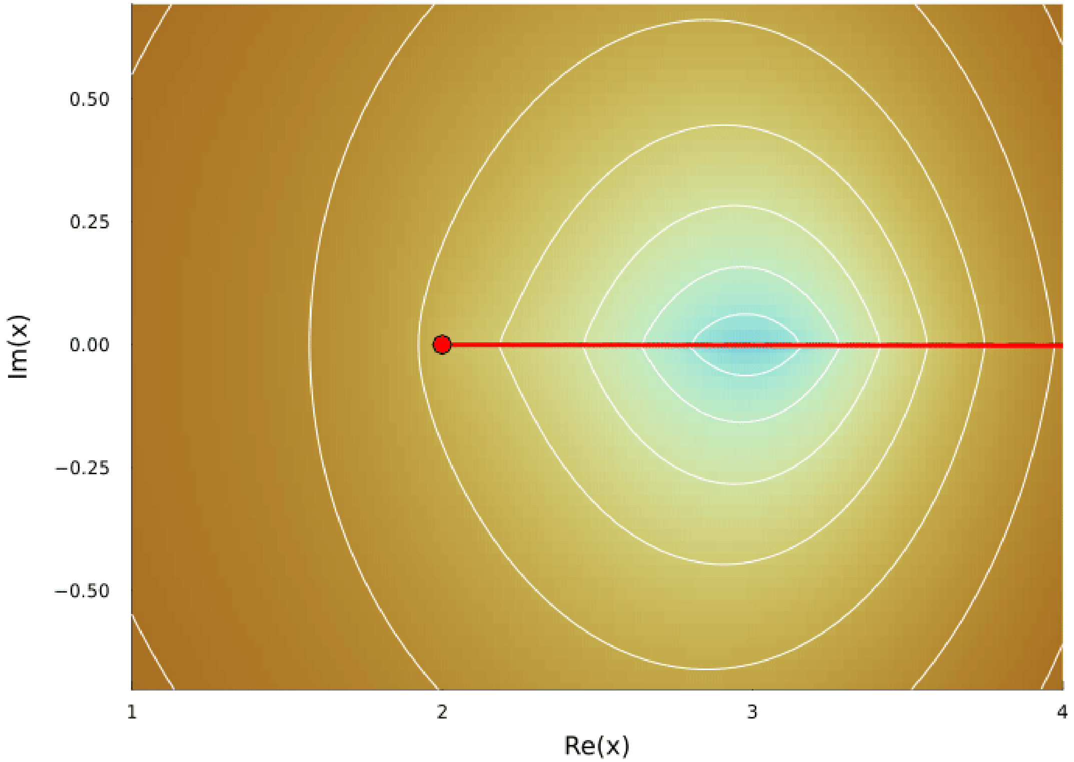
$ig^2\rho(s)$

3. there are multiple channels to consider

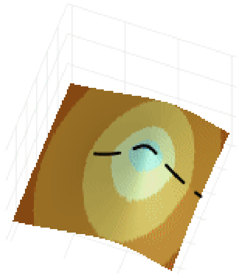
$i(g_1^2\rho_1 + g_2^2\rho_2 + \cdots)$

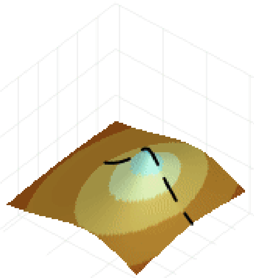
First and second Riemann sheets

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



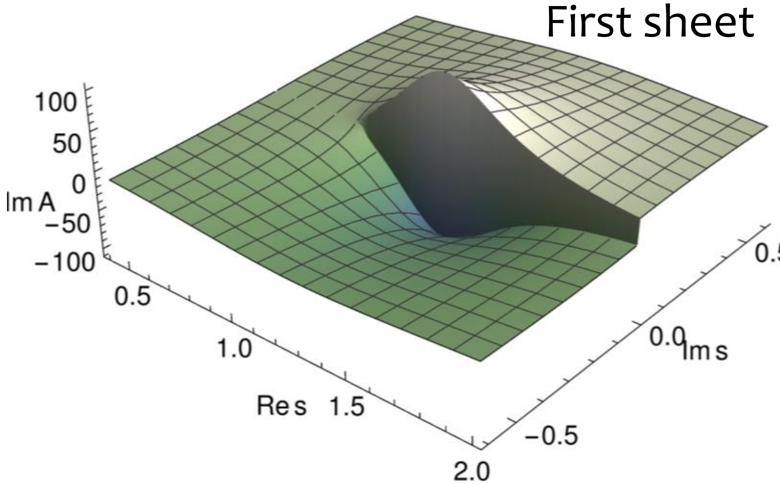
| A (x + iy) |^2

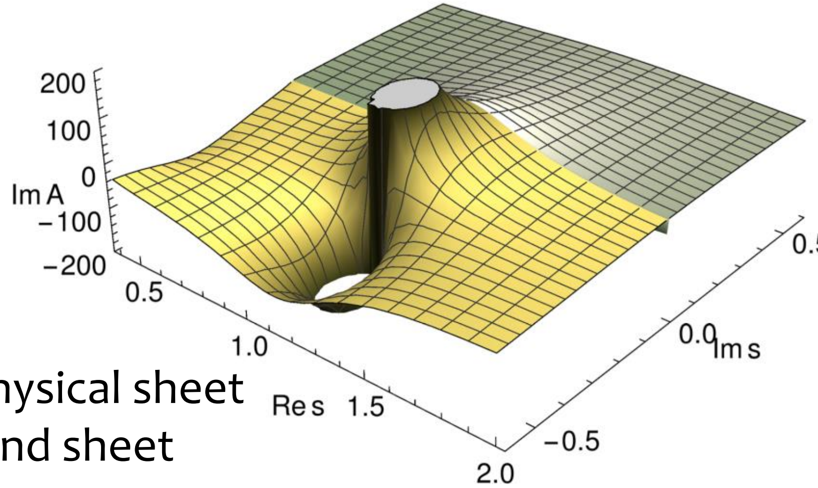




Im A (x + iy)

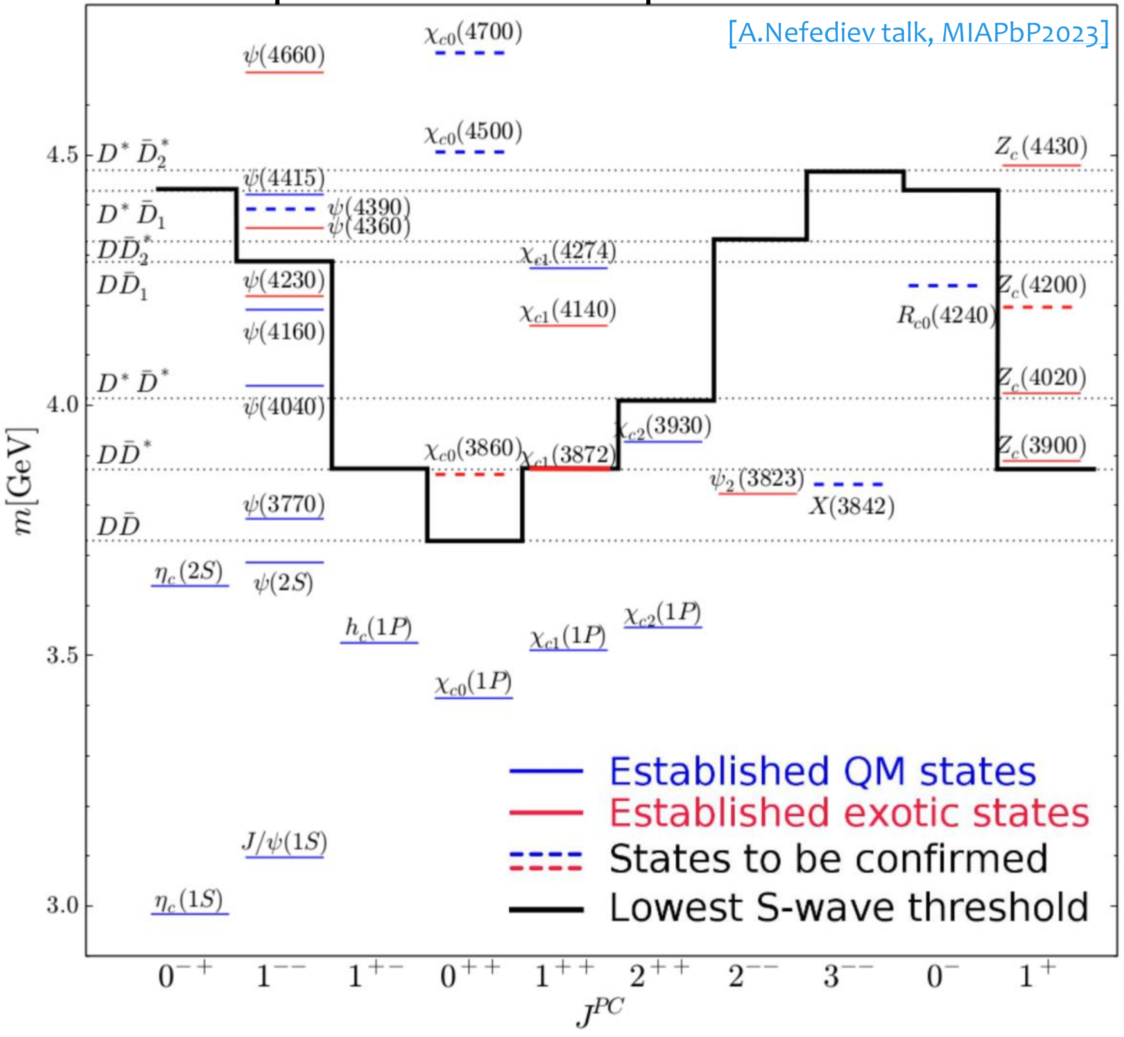
Physical sheet
First sheet





Unphysical sheet
Second sheet

An example: charmonium spectrum



QM states and thresholds

Most of hadrons are not isolated:

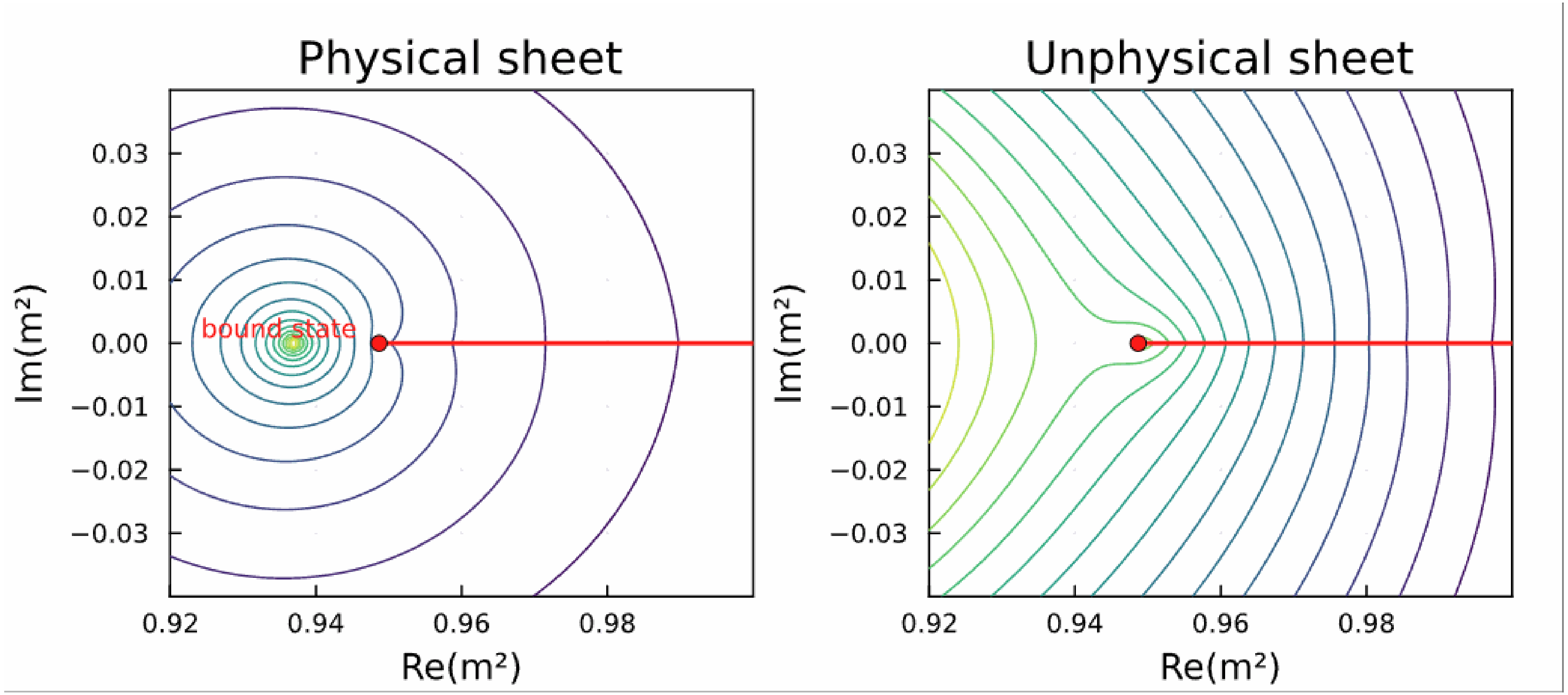
near hadron-hadron threshold,

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 $(q\bar{q})(q\bar{q})$

How molecule is often a good model



Transition: **bound state → virtual state → resonance**. No fundamental difference

The state is mostly **molecular** in vicinity of the threshold

[GitHub/mmikhasenko]

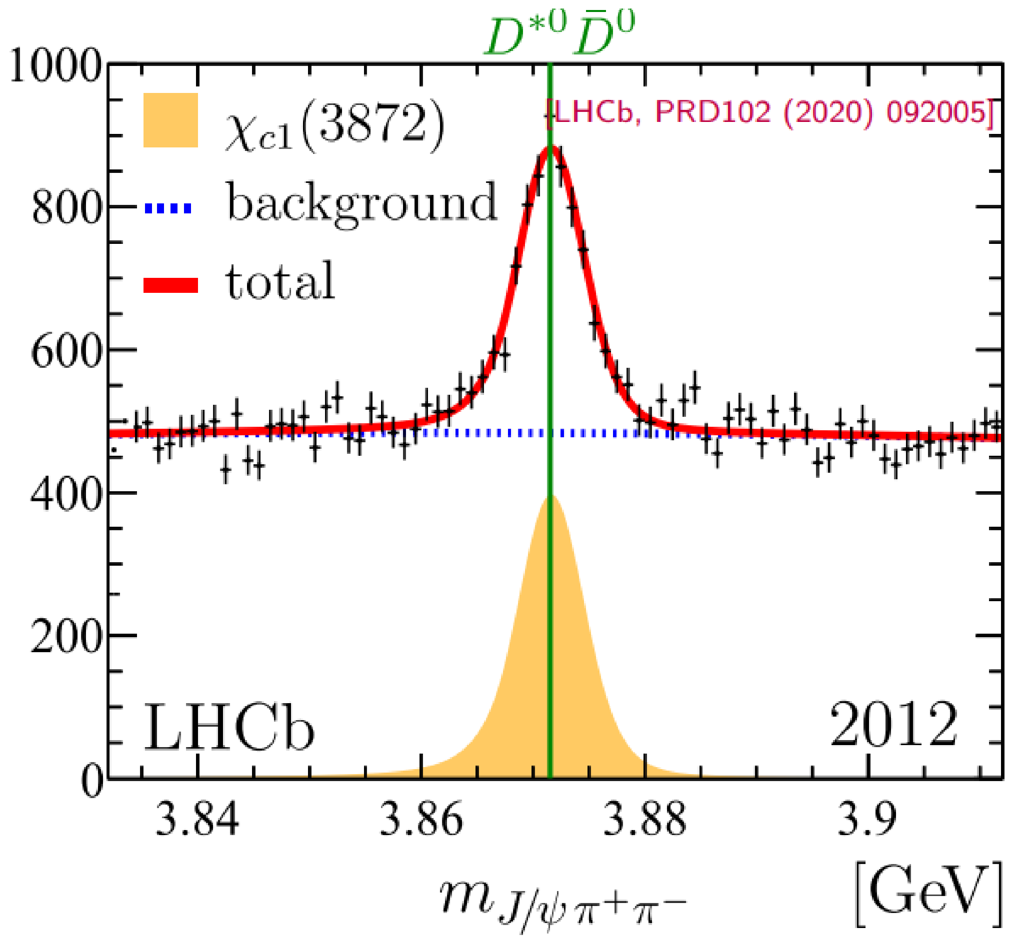
Experimental stand

[Midjourney 2023, MM]

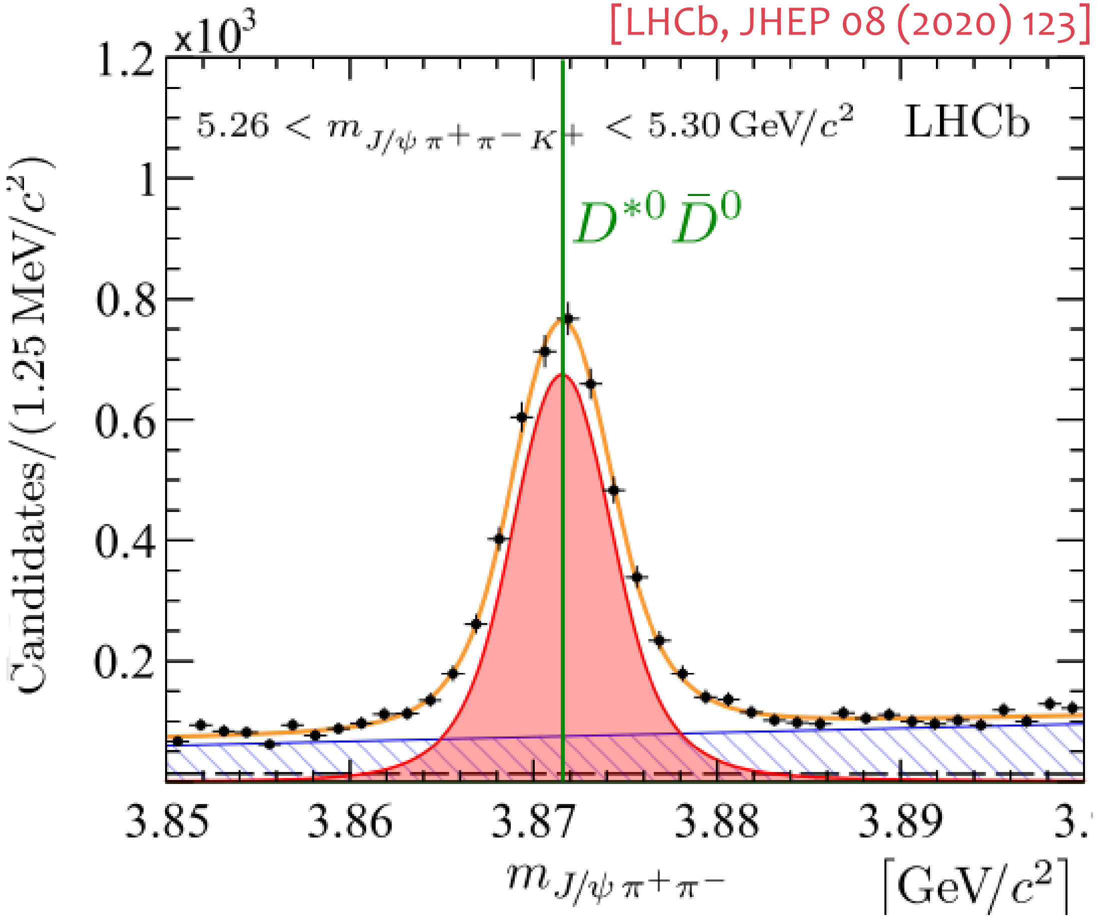
[Midjourney 2023, MM] 19th century photograph of happy smiling children playing with a **collider**

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

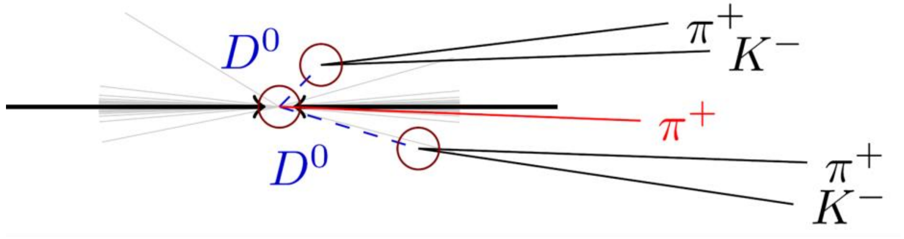
Prompt production ($pp \to \chi_{c1}\ X$)



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



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



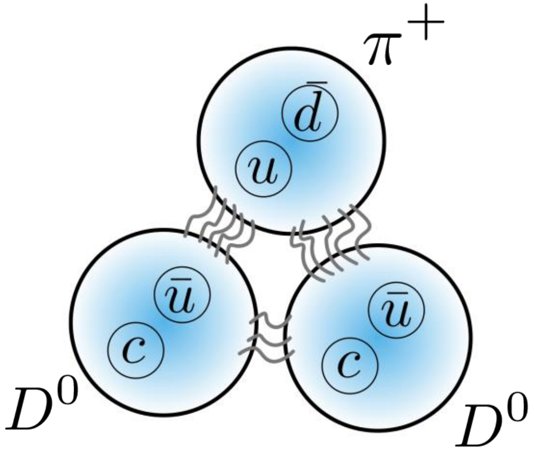
Peak in $D^0D^0\pi^+$ just below $D^{*+}D^0$ threshold

Extremely narrow, ~300keV

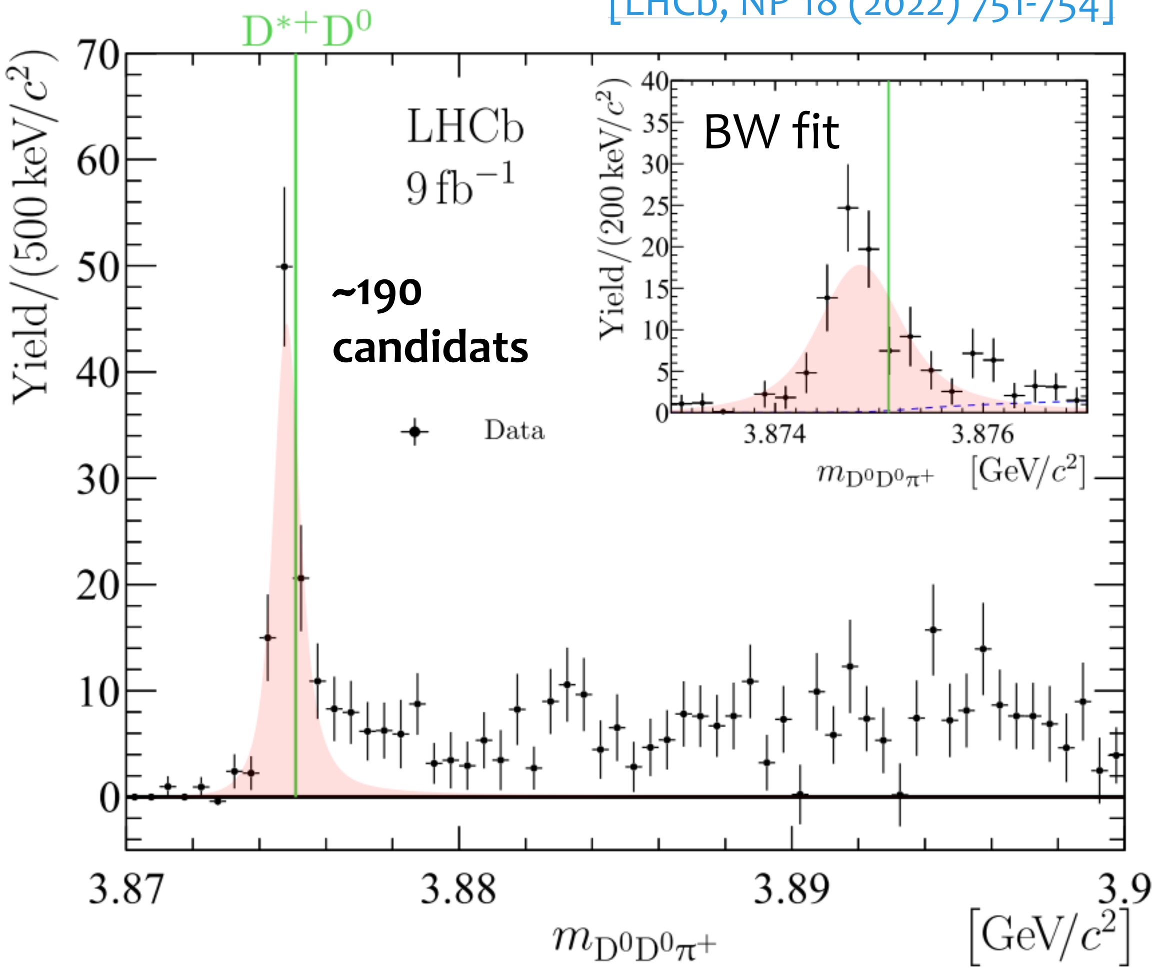
(resolution)

Needs to be treated as

three-body effect

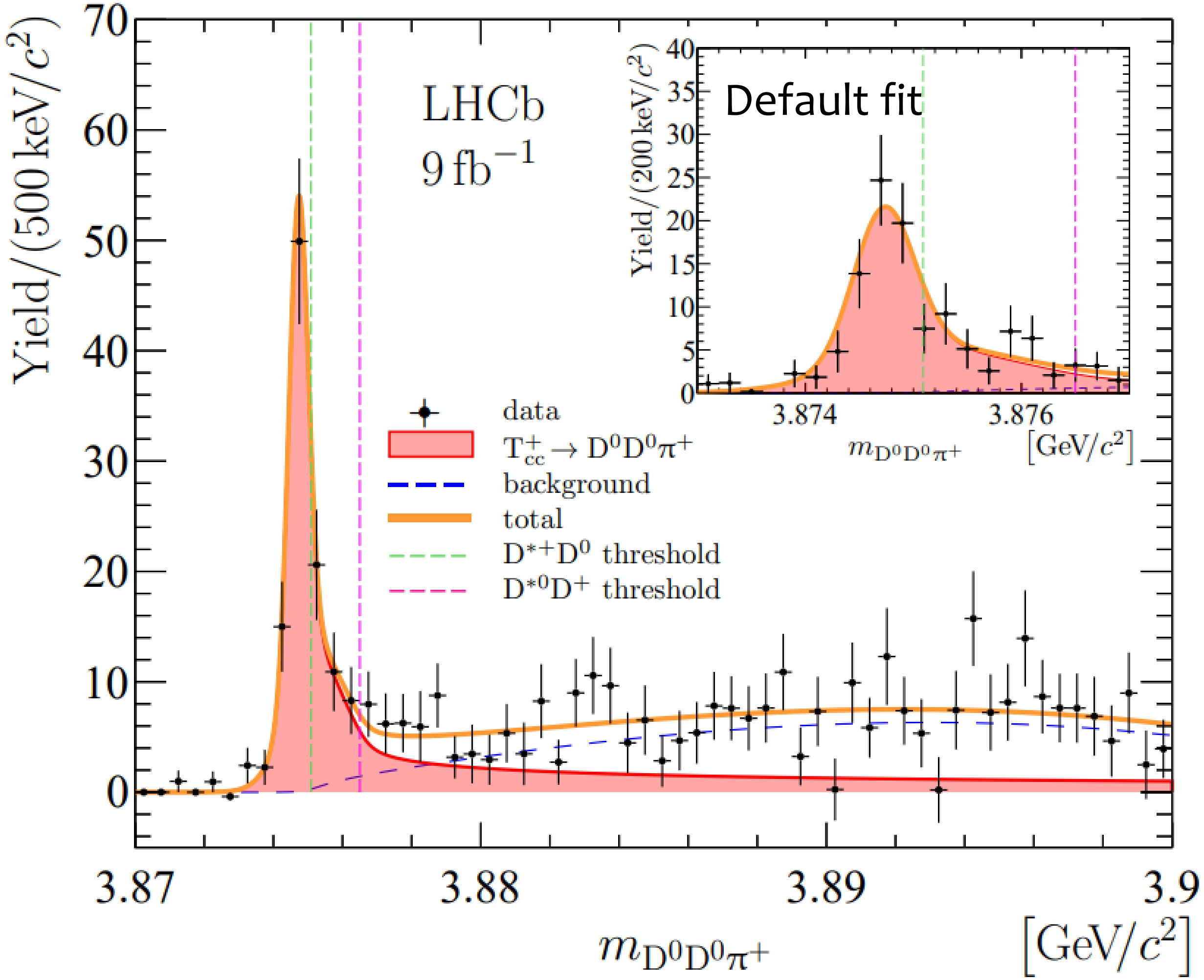


[LHCb, NP 18 (2022) 751-754]



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

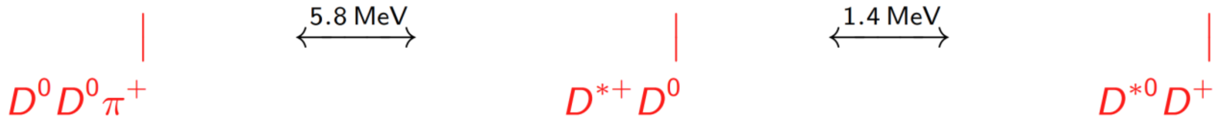
[LHCb, NC 13 (2022) 3351]



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

Coupled channel model

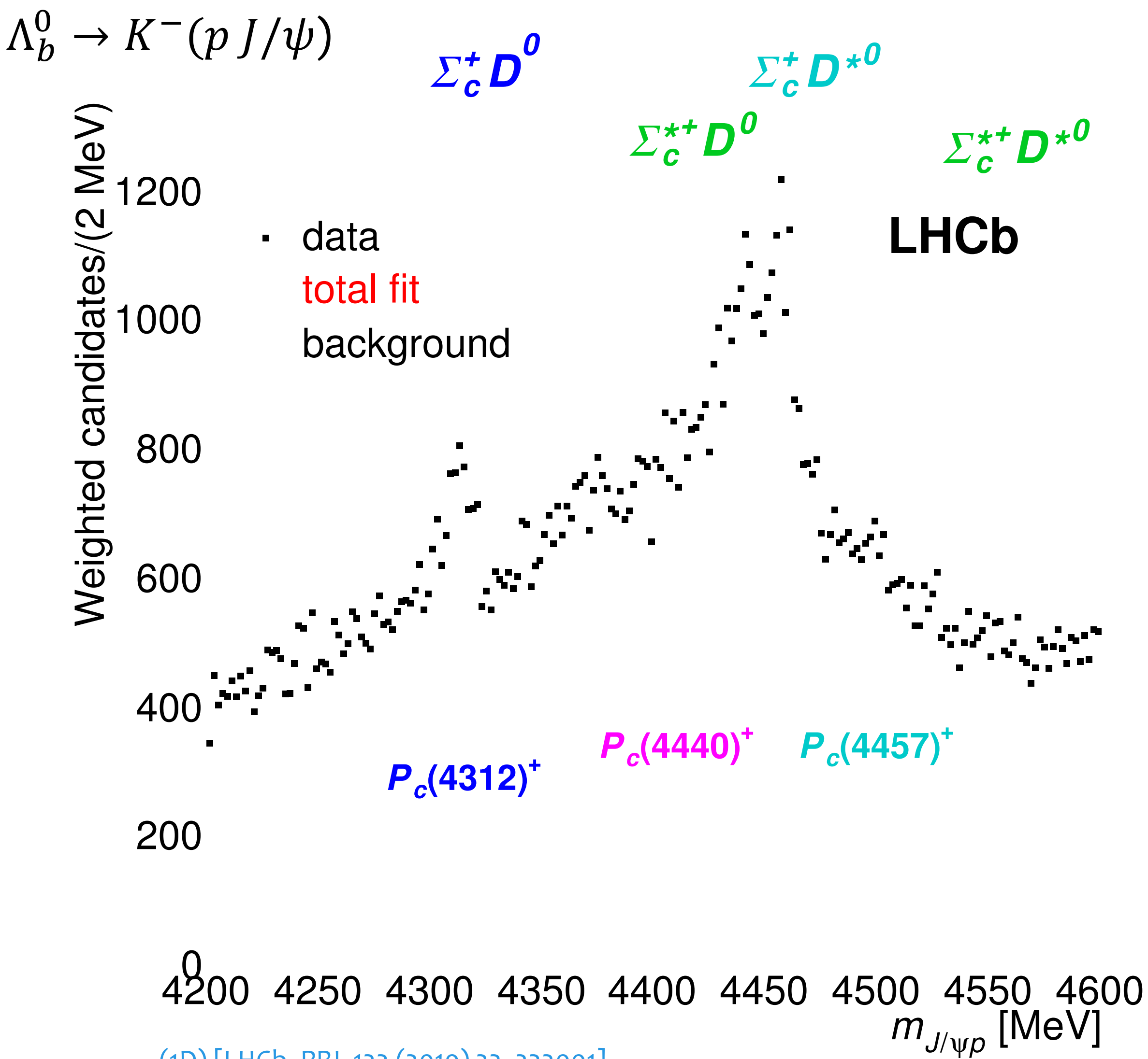
$$D^{*+}D^0 + D^{*0}D^+$$
$$\to \{D^0D^0\pi^+, D^0D^+\pi^0, D^0D^+\gamma\}$$



Yields pole parameters:

- **Binding energy:** $-360 \pm 40^{+4}_{-0}$ **keV**
- **Width:** $48 \pm 2^{+0}_{-14}$ **keV**

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



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

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

Near threshold

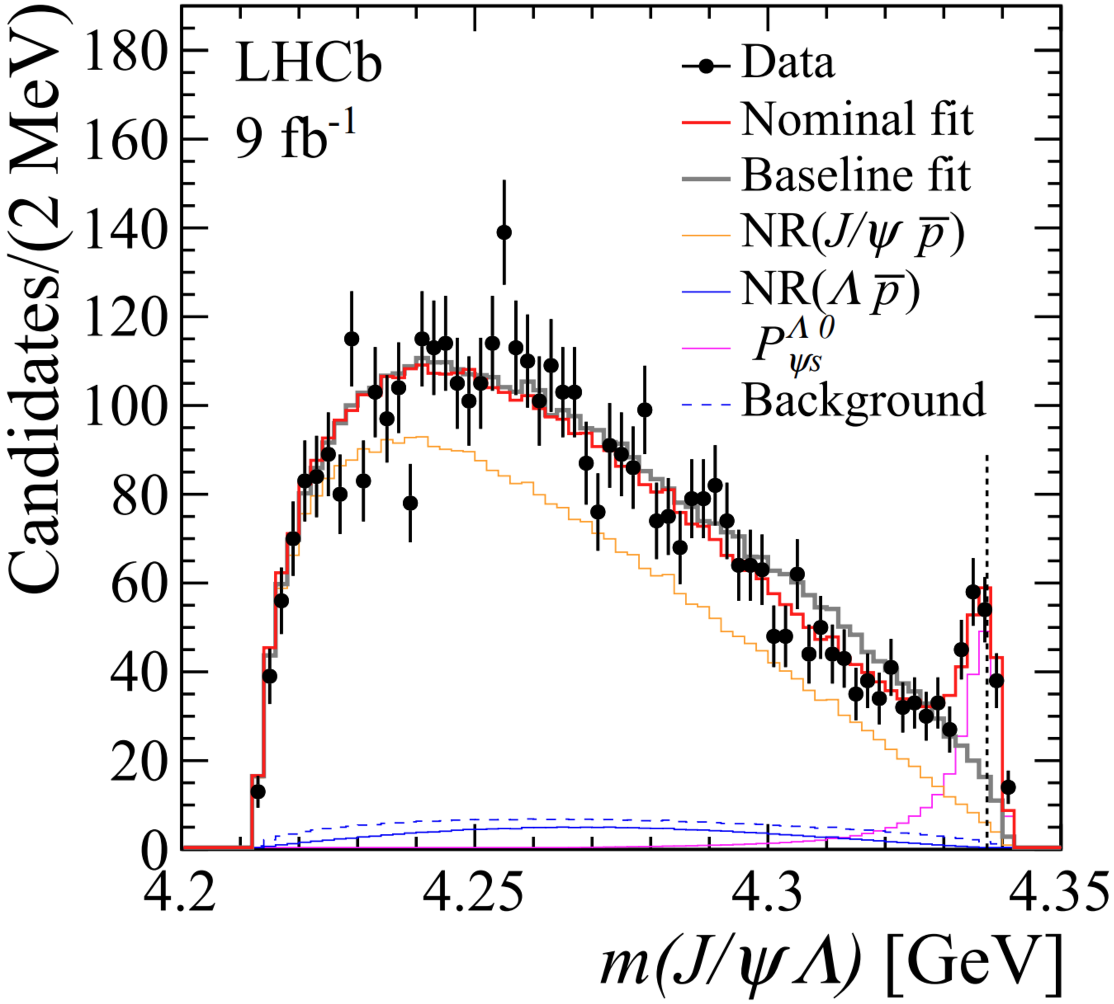
Multiplicity matches threshold spin algebra

QM states are complex and unknown

Strange Pentaquark $P_{c\bar{c}s}^{+}$

$B^- \to (J/\psi\Lambda)\bar{p}$

[LHCb, 2210.10346]



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

Challenges for near future

1. Observation of T^0_{cb} (Run-III / IV), T^-_{bb} (future) ~ 1 phdaway
2. Continuum effects for open-flavor mesons (DJ, DsJ, BJ, BsJ) ~ 1 phdaway
3. Charm/bottom baryons: diquark excitations, continuum ~ few phdaway
4. Genuine QCD pentaquarks, seed for hadronic molecules? ~ few phdaway
5. Double - J/ψ spectrum ~ 1 phdaway
6. Light hybrids / glueballs with LHCb ~ 1 phdaway
7. Observing three-body hadronic effects: triangle singularity ~ 1 phdaway
8. ….

Open questions on exotic hadrons

Having significant molecular contribution for hadronic state is fine.

- **We do not understand effect how the continuum acts.**
  Why it sets some states right to the threshold? $[\chi_{c1}(3872) \to \boldsymbol{D^0 D^{*0}}, \boldsymbol{T_{cc}^{+}} \to \boldsymbol{D^0 D^{*0}}]$

- **Does one always need a genuine QCD seed? – (extra numerous states wrt QM)**
  From nuclear physics – "No" (plenty of atoms and isotops)
  $\boldsymbol{P_{c\bar{c}}^{+}}$ **?**

- **Other configurations: hybrids, glueballs?**

Join pentaquarks and tetraquarks investigation