Nuclei and Hadrons

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Variety of the hadronic states: conventional QM

QCD at low-energy regime:

- color interaction confined
- effective d.o.f. - **constituent** quarks (gluons?)

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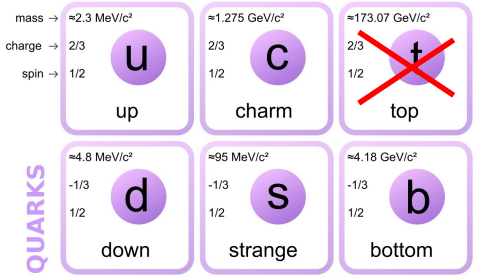

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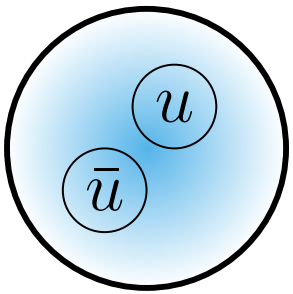
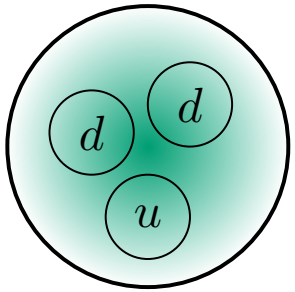
Ordinary matter:



meson



baryon

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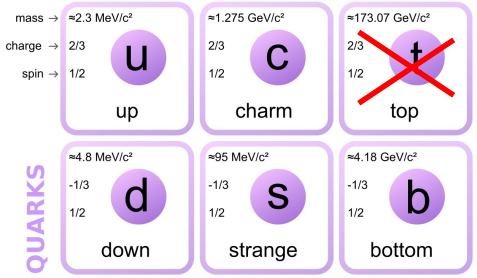

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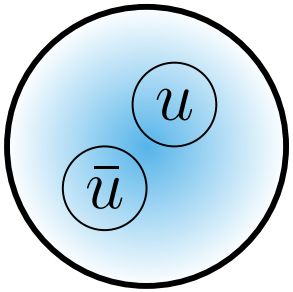

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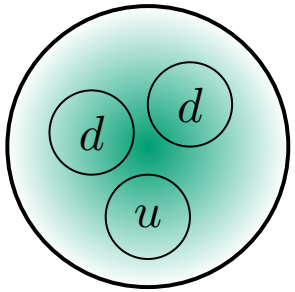
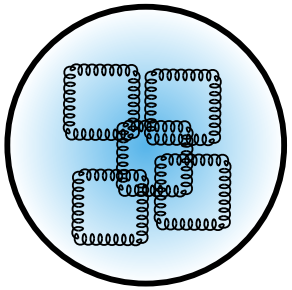
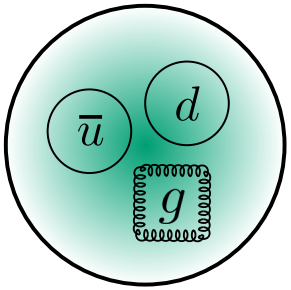


baryon

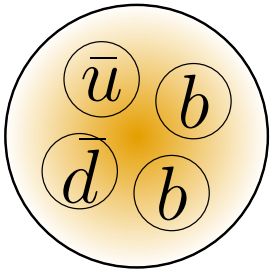
Exotic matter:



glueball



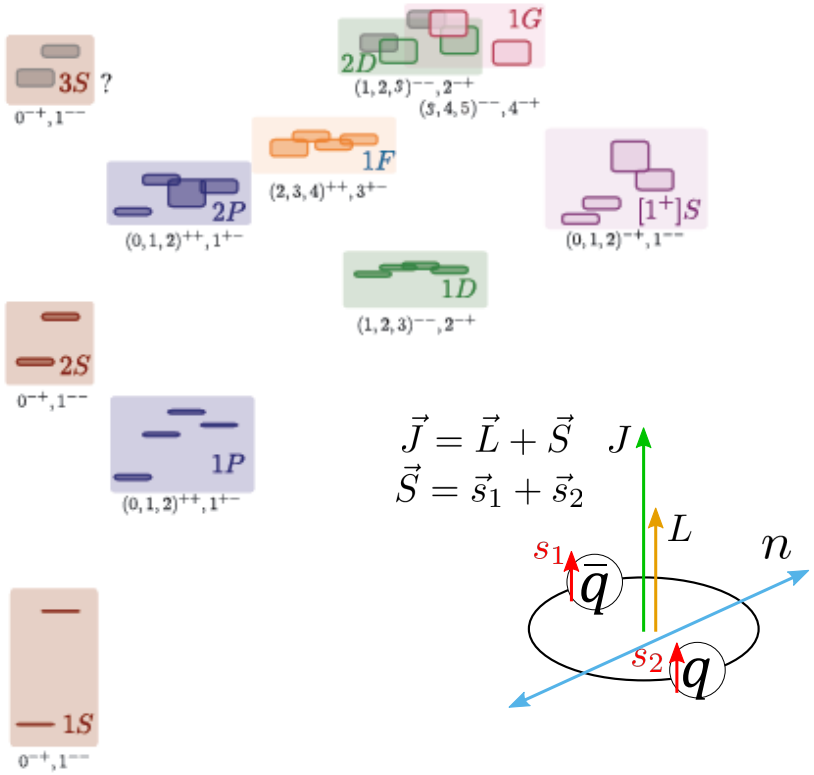
hybrid



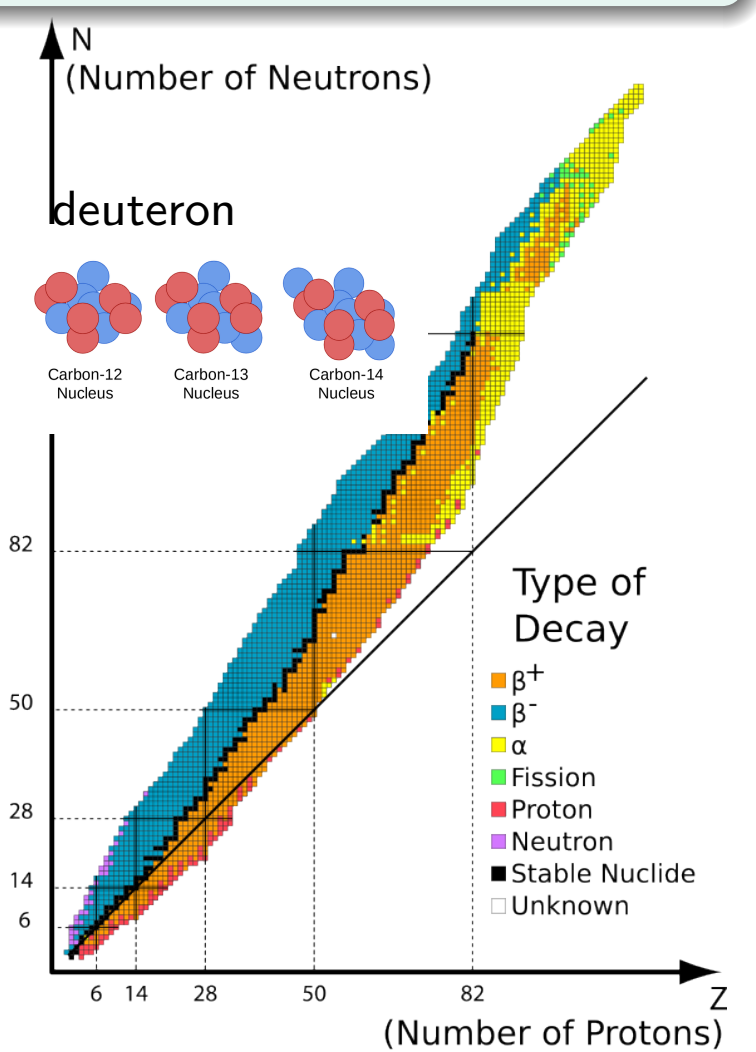
tetraquark

Two ways of building complexity

Hadron variety
(quark d.o.f.)



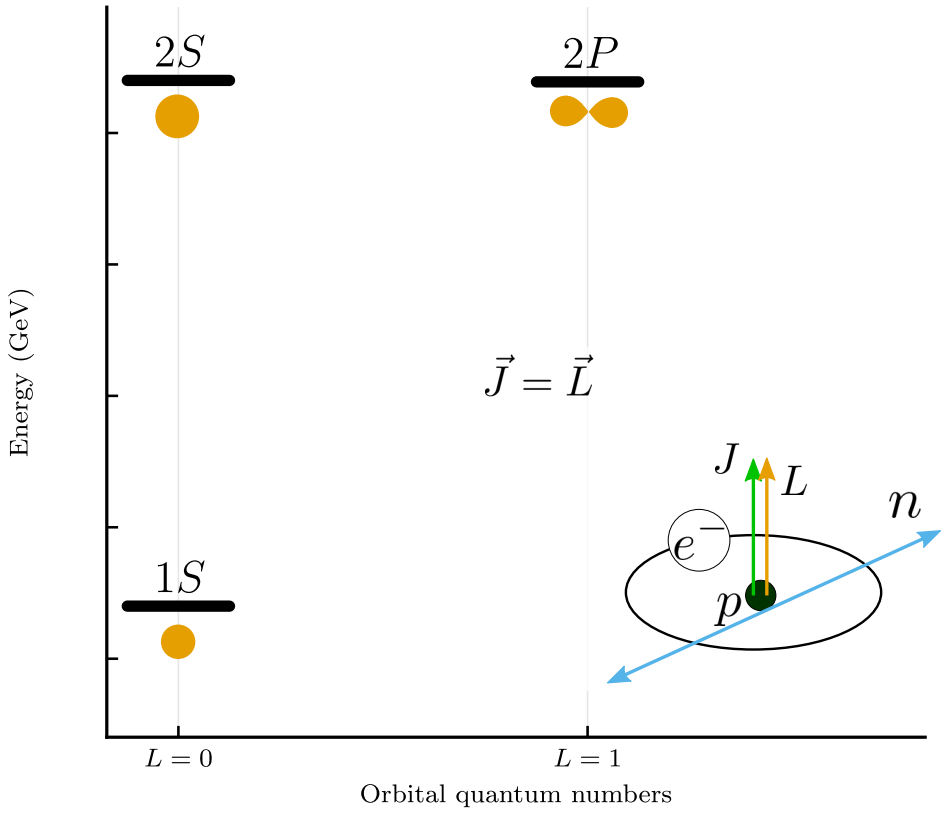
Atomic variety
(nucleon d.o.f.)



Meson spectrum in QM

Example: light mesons

QED



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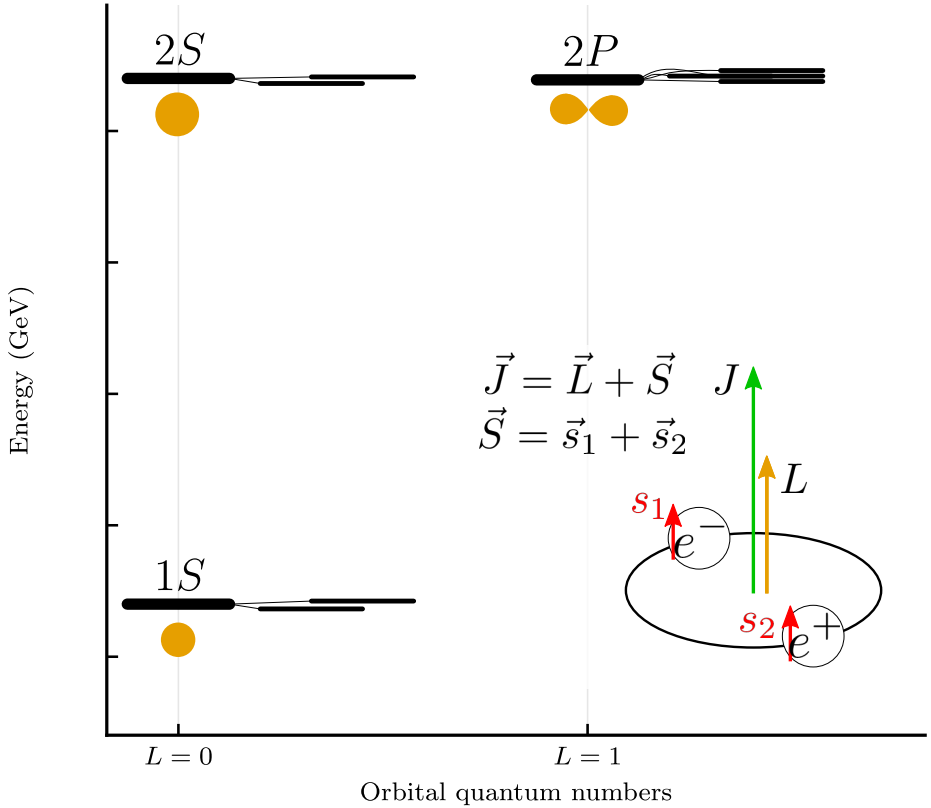

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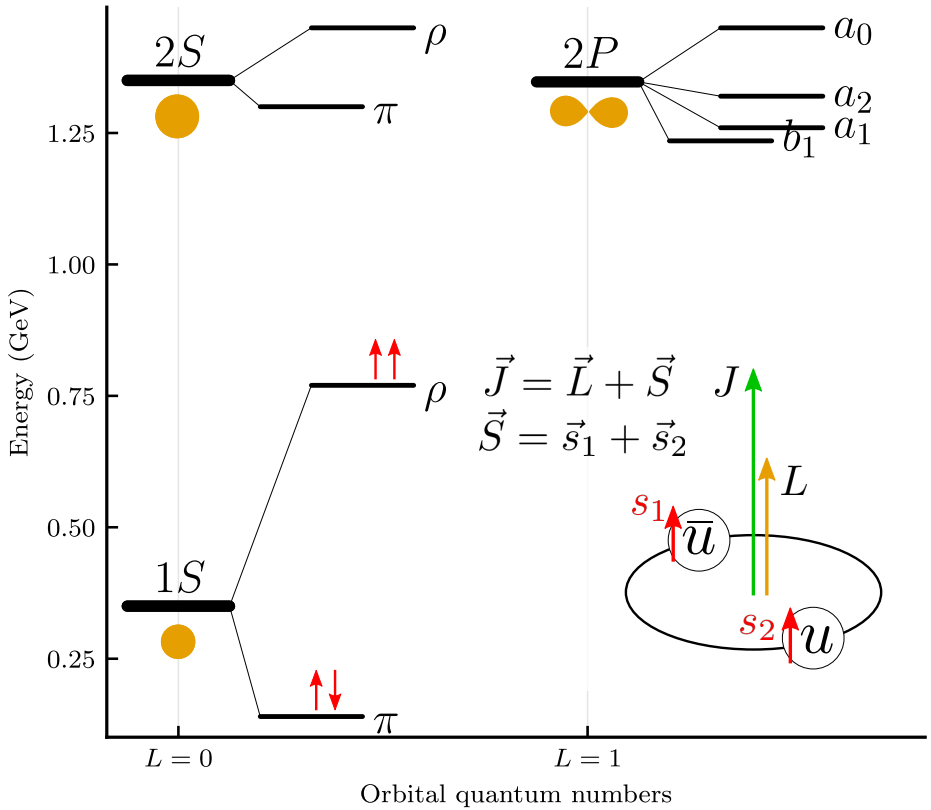

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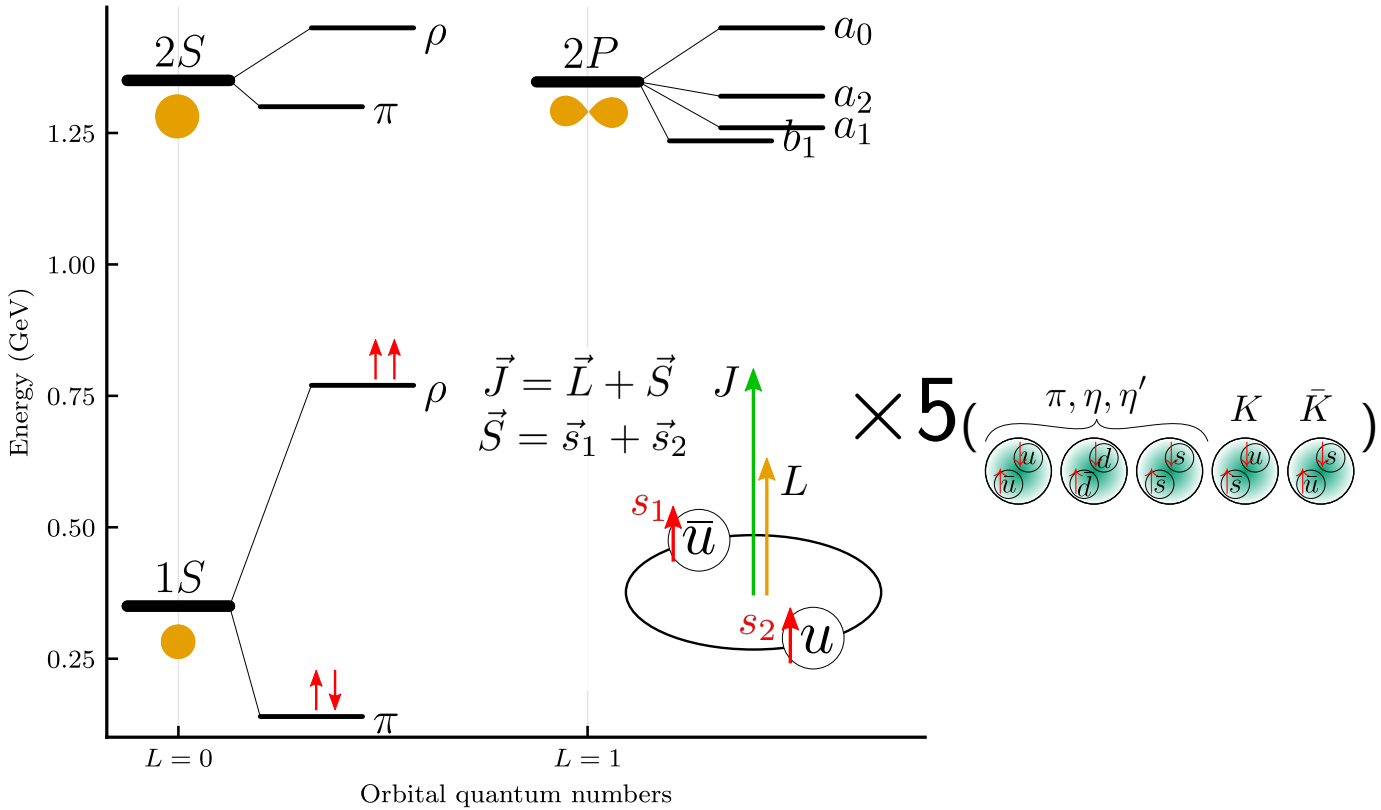

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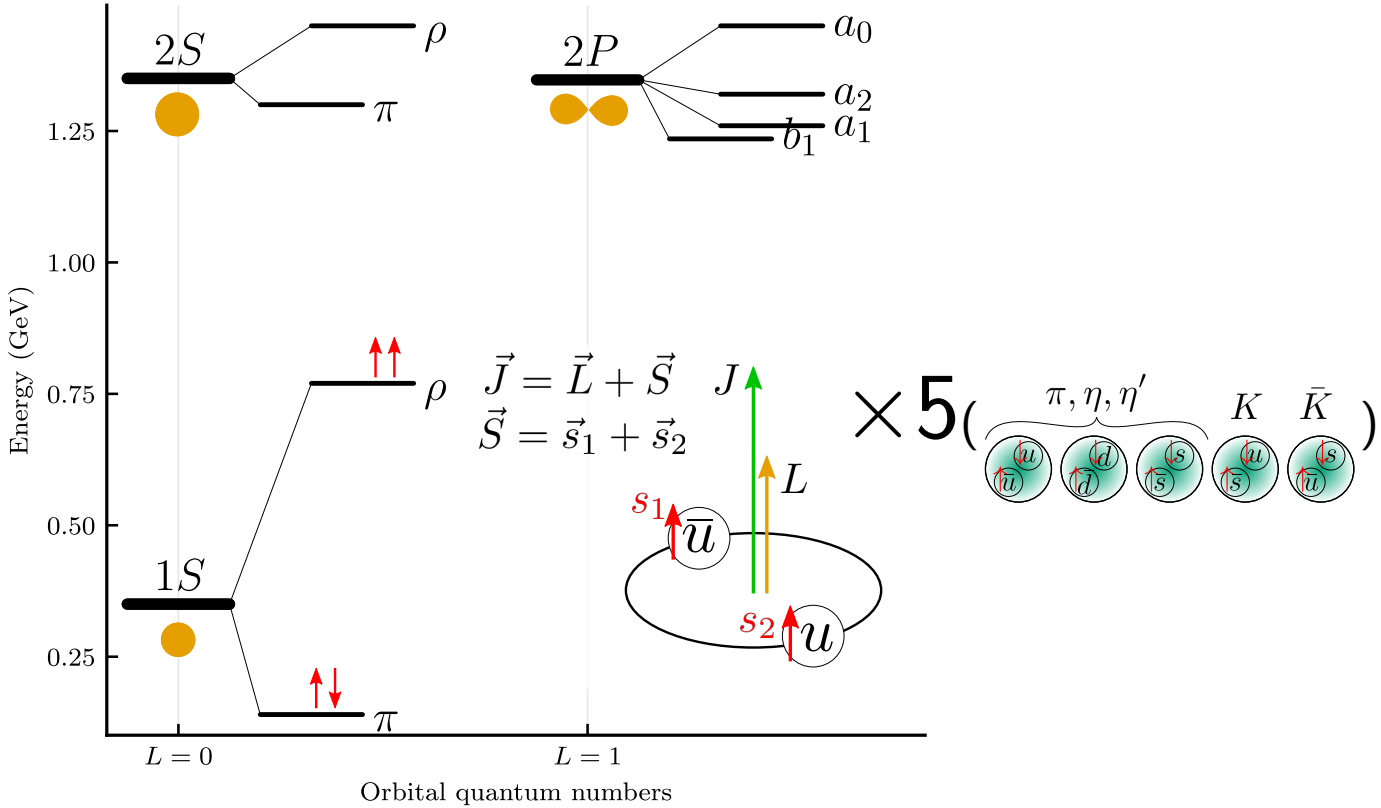
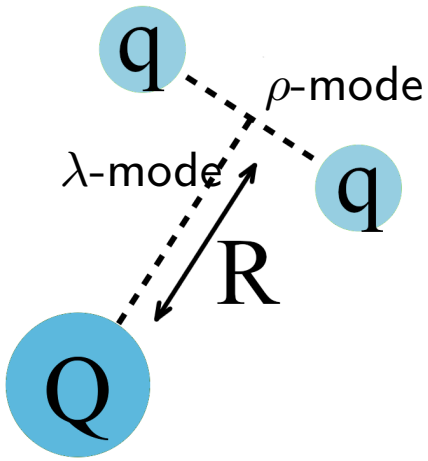


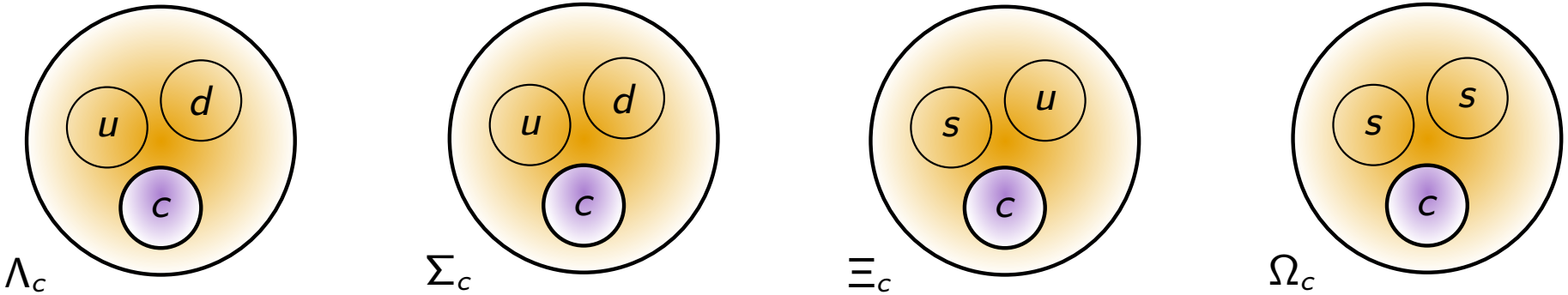
- (π, ρ), (K, K^*), $(\eta_c, J/\psi)$, ...
  are the lowest $1S$ states $(\downarrow\uparrow, \uparrow\uparrow)$ of the families.

Baryon spectrum

Example: charm baryons



- Heavy quark is **static** and **spinless** in the limit $m_Q \to \infty$.
- Excitations of Qqq are governed by the light diquark
- $q\uparrow^{(J^P=\frac{1}{2}^+)} \otimes q\uparrow^{(J^P=\frac{1}{2}^+)} \quad \Rightarrow \quad \underbrace{\uparrow\downarrow^{(J^P=0^+)}}_{\text{“good”}}$ and $\underbrace{\uparrow\uparrow^{(J^P=1^+)}}_{\text{“bad”}}$
- Excitation pattern is different for “good” and “bad” diquarks



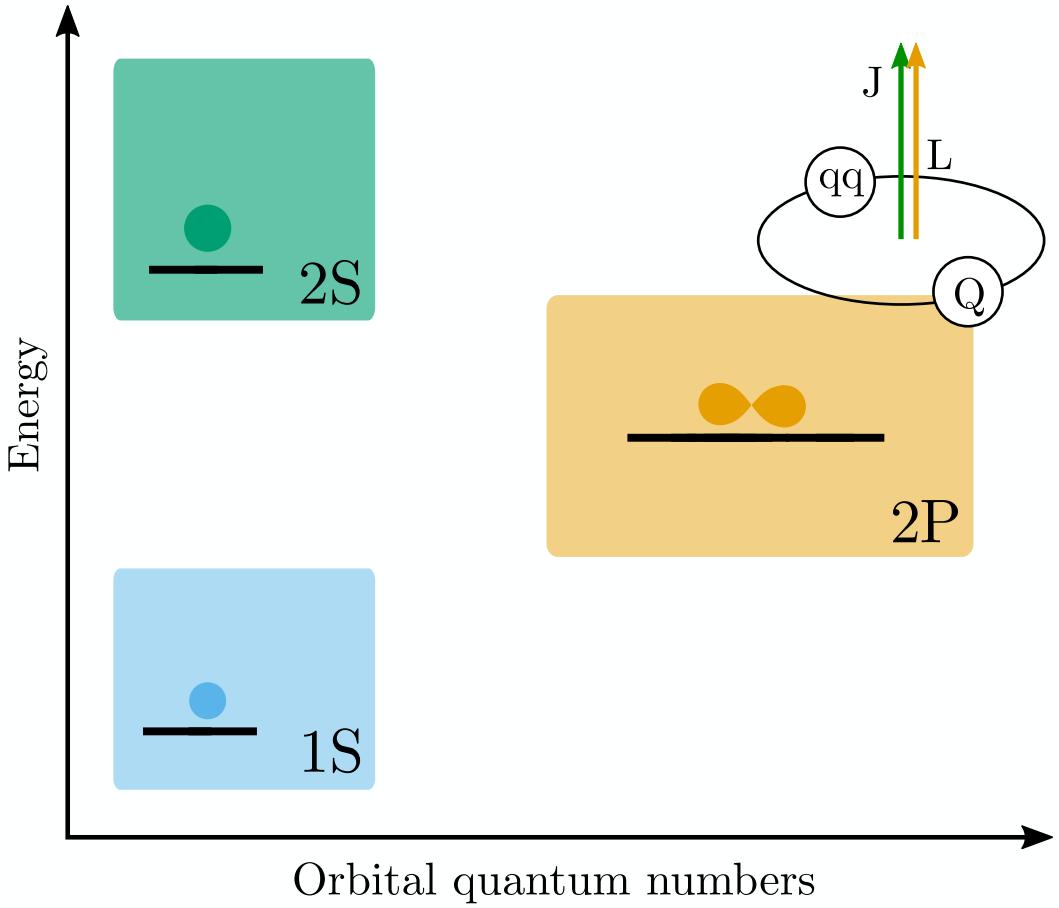
Λ_c “good”

Σ_c “bad” (isospin)

Ξ_c “good” + “bad”

Ω_c “bad” (identity)

Excitation spectrum of baryons with "bad" diquark



Structure:

- Radial and orbital excitations

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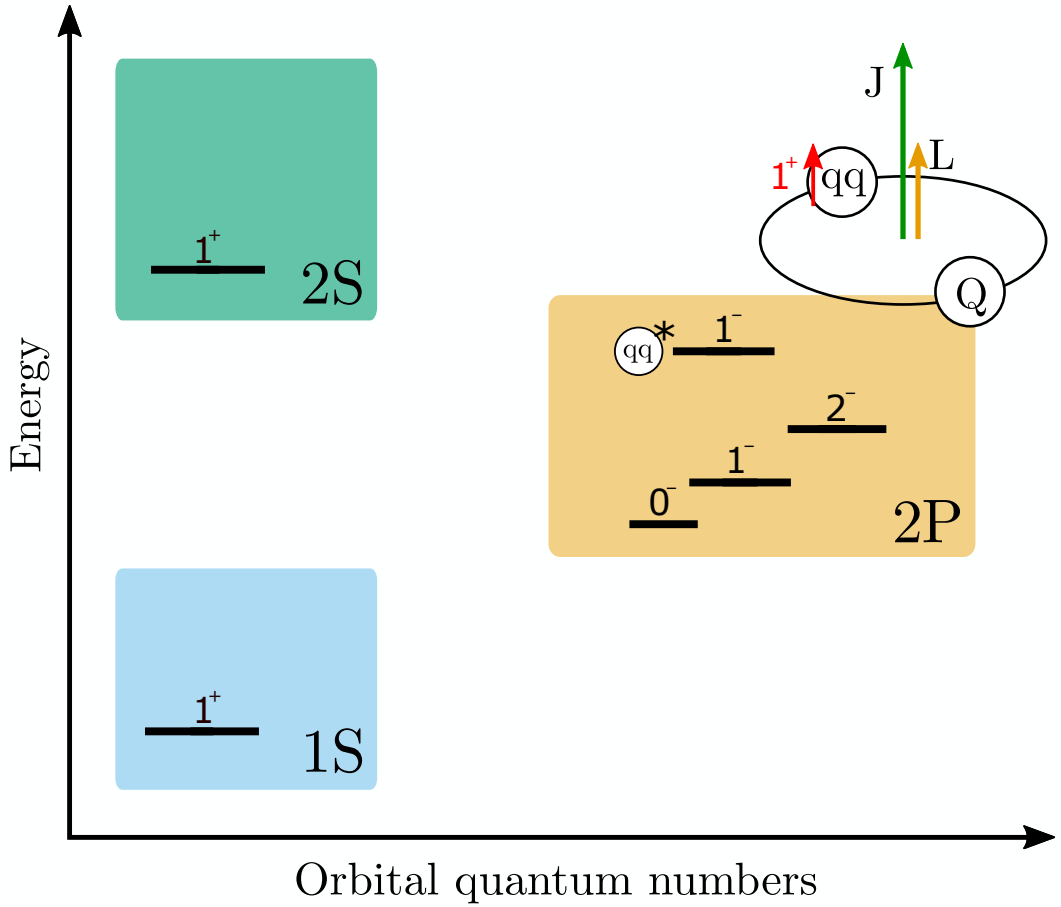

Structure:

- Radial and orbital excitations
- Light d.o.f.: Spin-Orbit splitting

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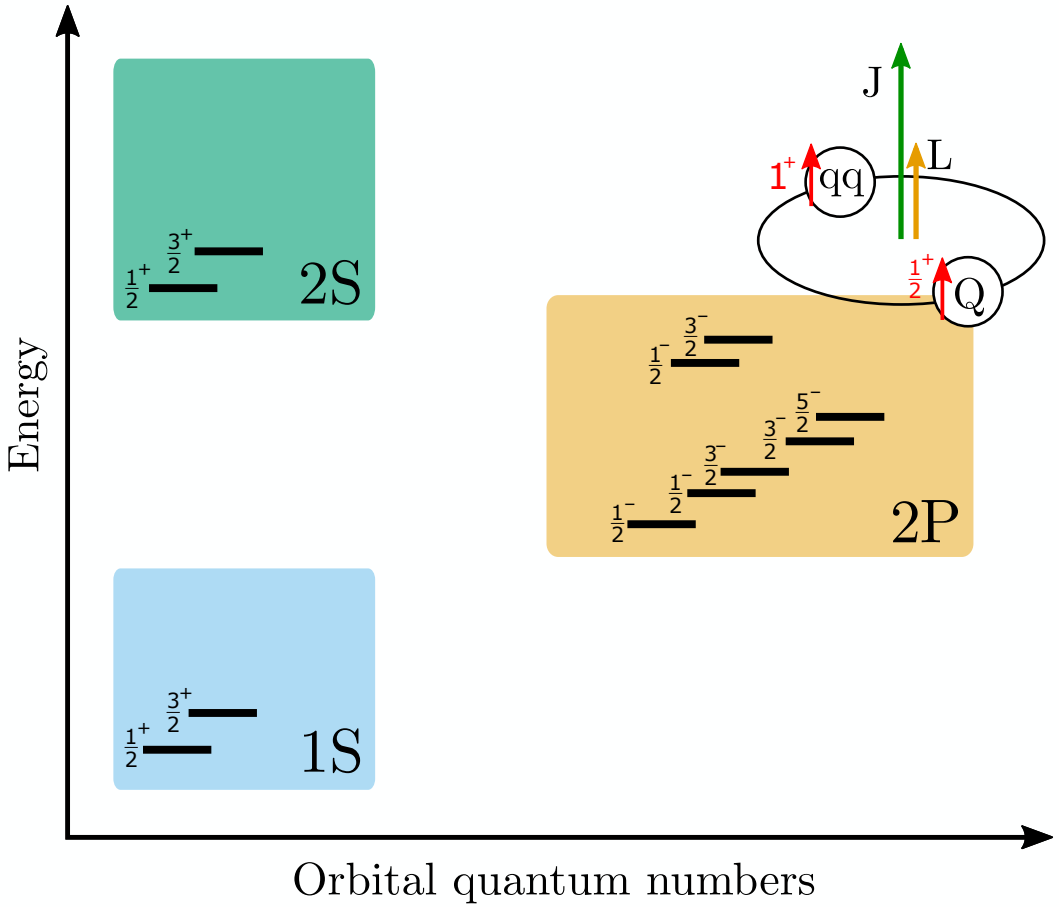

Structure:

- Radial and orbital excitations
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- "Hyperfine" doublets: heavy-quark spin

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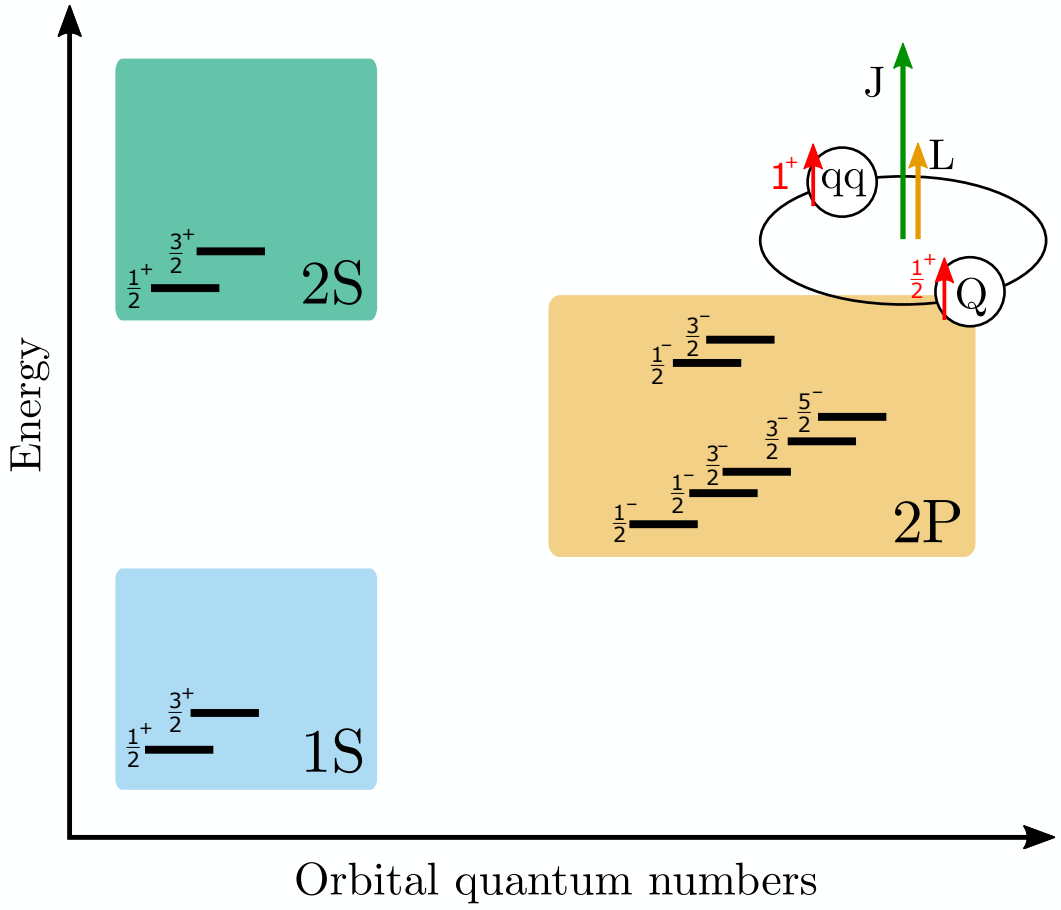


Structure:

- Radial and orbital excitations
- Light d.o.f.: Spin-Orbit splitting
- "Hyperfine" doublets: heavy-quark spin

Counting of states
– model independent
Size of splitting, the order
– differs from model to model

Hadronic molecules

- almost all hadrons pairs experience residual strong interaction
- large correlation function is an indication an under-threshold bound state

Deuteron

a bound state of pn

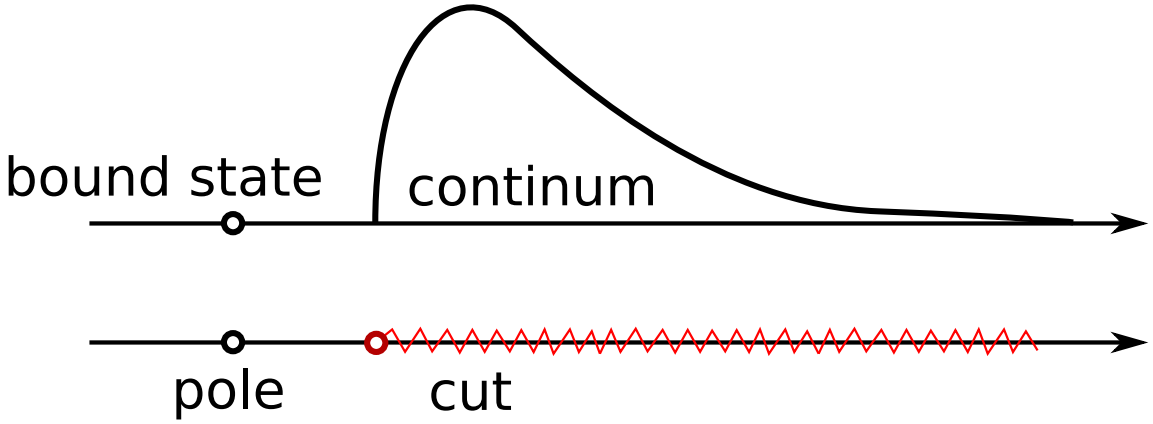
Hypertriton

a bound state of $p\Lambda$

Classical bound-state picture (hadronic molecule)

Complex energy plane

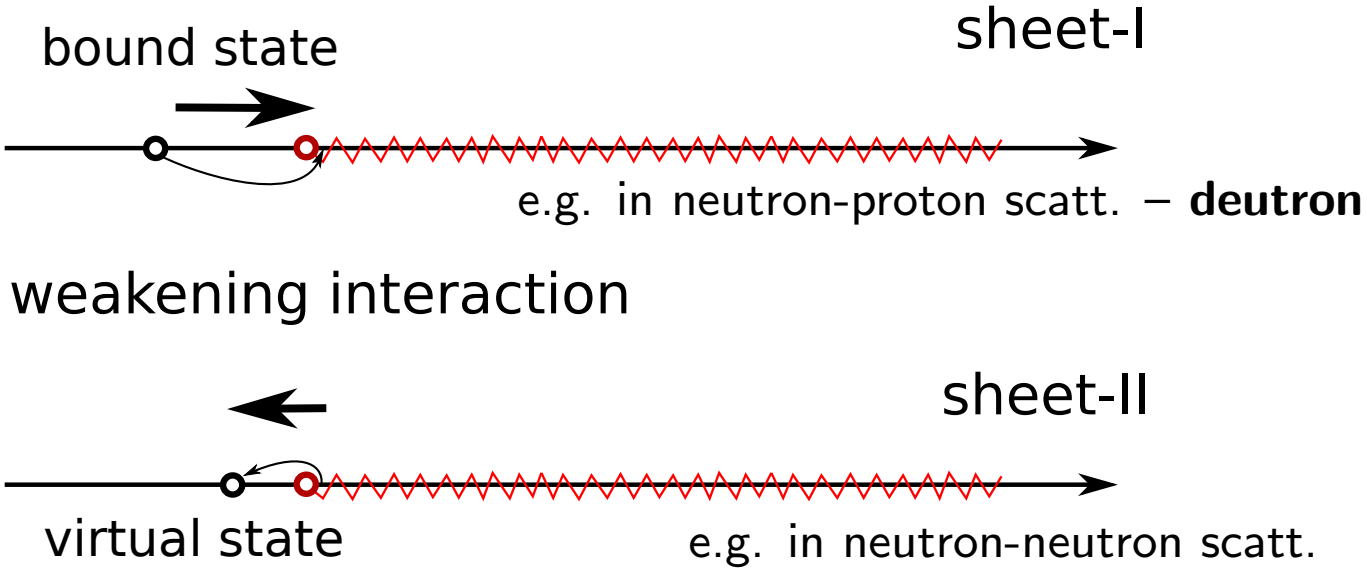
Structures of the complex scattering amplitude correspond to physical



- bound state - pole of the complex scattering amplitude
- continuum - free particles above elastic threshold (branching of the complex plane)

Strength of interaction

Molecular bound-state vs virtual state



- as weaker the binding as closer the pole to the threshold
- at some point moves to the unphysical sheet and leaves to $-\infty$.

Effect of continuum

What if a state (a resonance)

- appears close to hadronic threshold with an attraction (S-wave bound / virtual state), and
- has the same quantum numbers as the hadron-hadron interaction

?

- one could see both: hadronic molecule & resonance
- one can see only one of them
- is it a valid question (?)

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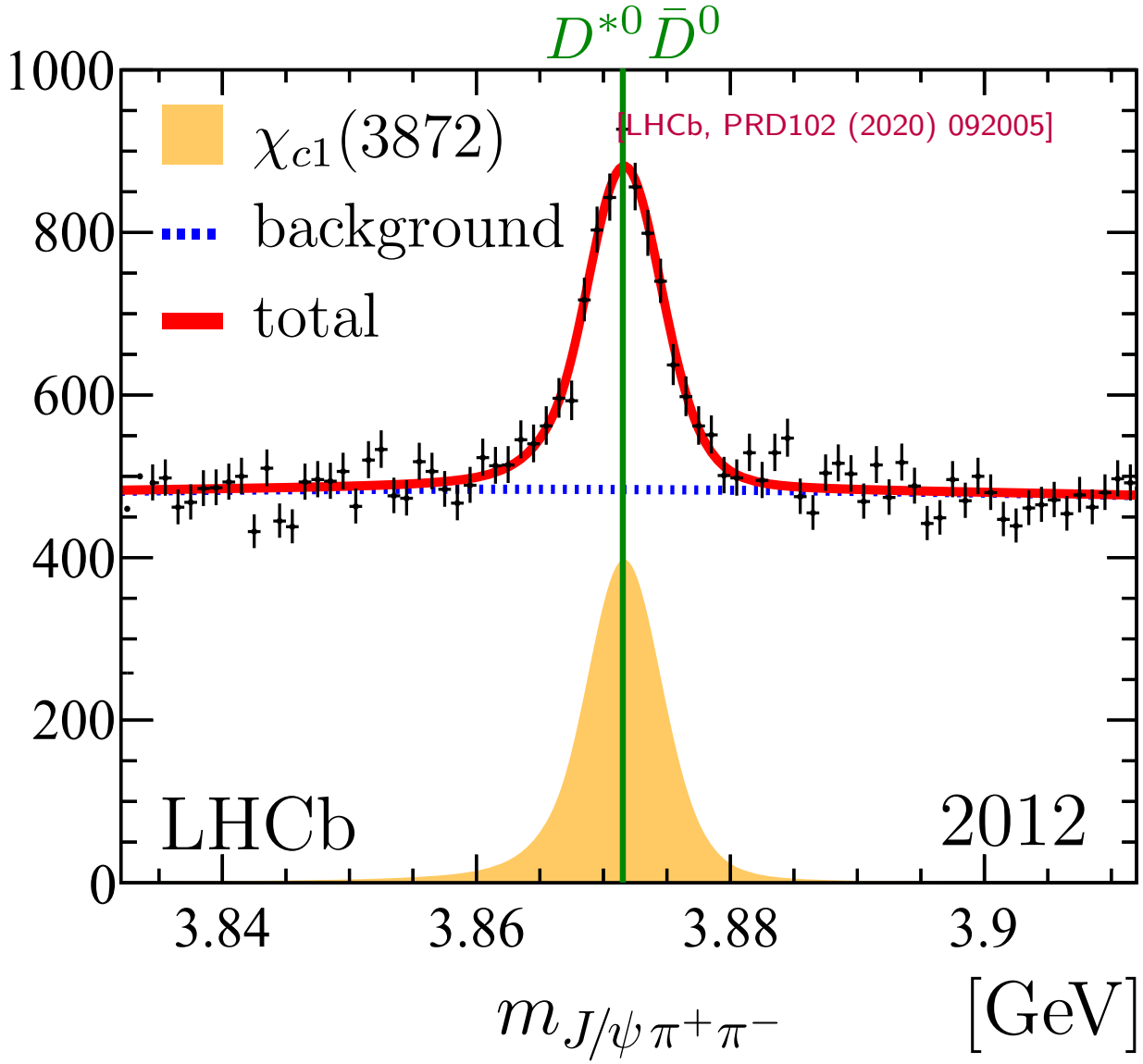
- Not very clear. There are many models. However, at least:
- QM implies that the phenomena mix
- resonance shifts mass/width parameters

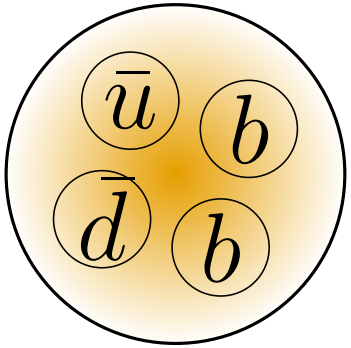
I. $\chi_{c1}(3872)$: charmonium state right at the $D^{*0}\bar{D}^0$ mass

Nature is highly debated from 2003 [Belle, PRL91 (2003), 262001]

- **Charmonium state** ($c\bar{c}$), $\chi_{c1}(2P)$ **is expected** 70 **MeV above**
- The peak right at the $D^{*0}\bar{D}^0$ threshold
- Large isospin violation in the strong decays to $J/\psi\pi^+\pi^-$ [LHCb 2022, 2204.12597]



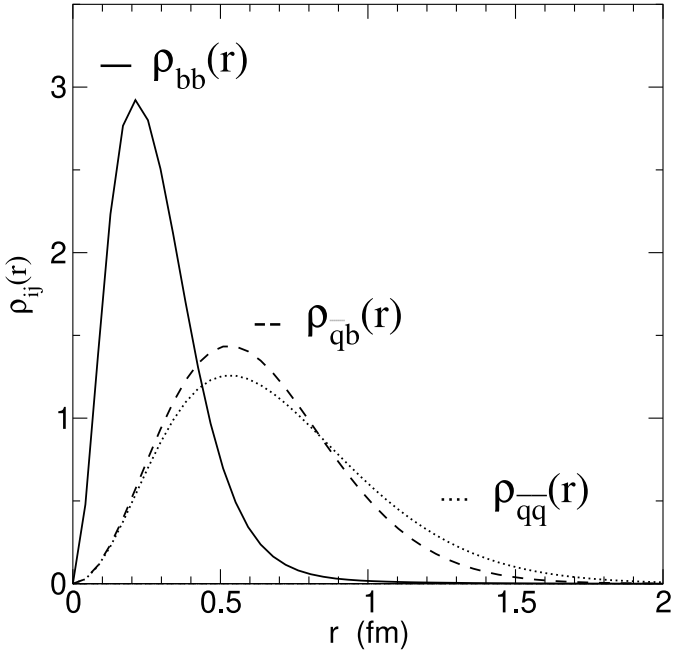
II. $T_{bb}^-[bb\bar{u}\bar{d}]$ stable tetraquark



- Firmly established in pheno/lattice calculations, e.g. [J.P. Ader et al., PRD 25, 2370 (1982)] / [Francis et al., PRL 118, 142001 (2017)];
- Not yet seem experimentally;
- Below open-flavor ($B^{*+}[\bar{b}u] + B^0[\bar{b}d]$) decay threshold – stable wrt strong, em. inteaction.
- **The distance to the open-flavor threshold get smaller with decreasing mass of heavy quark...**

T_{bb}^- is a "regular" QM hadron, similar to $\Lambda_b^0(bud)$: [Janc, Rosina (2004)]

- bb are close together, and
- are in color-anti-triplet, $3 \otimes 3 = \boxed{\bar{3}} \oplus 6$



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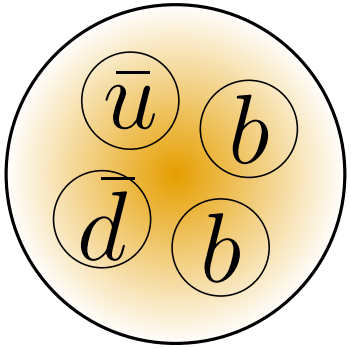

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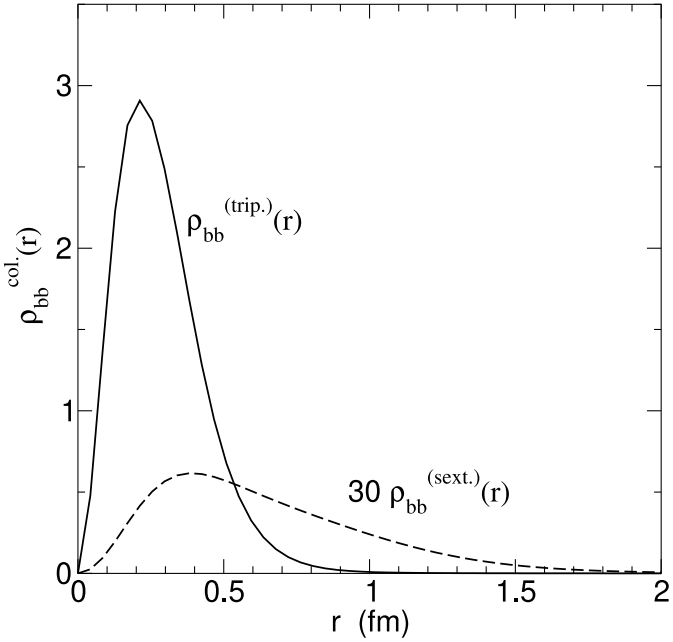


in 2021, we found T_{cc}^+:

The landmark of 2021: a signal in $D^0 D^0 \pi^+$

Breit-Wigner model

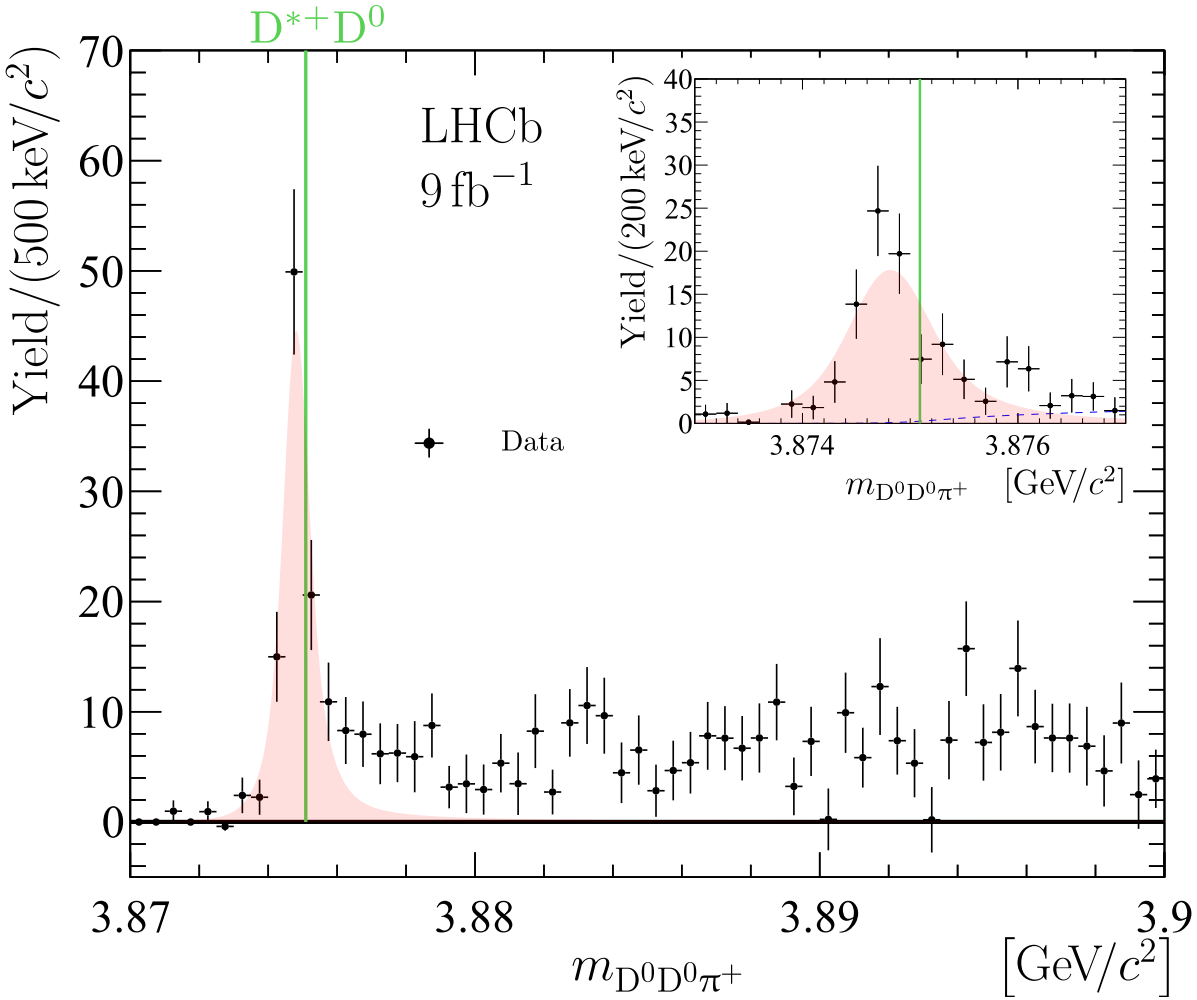
[LHCb, Nature Physics (2022)& Nature Communicatitions, 13, 3351]

Too naive model

BW signal [$(DD)_S$ π P-wave]
+ ph.sp. background

- significance $> 10\sigma$
- peak below (4.3σ)

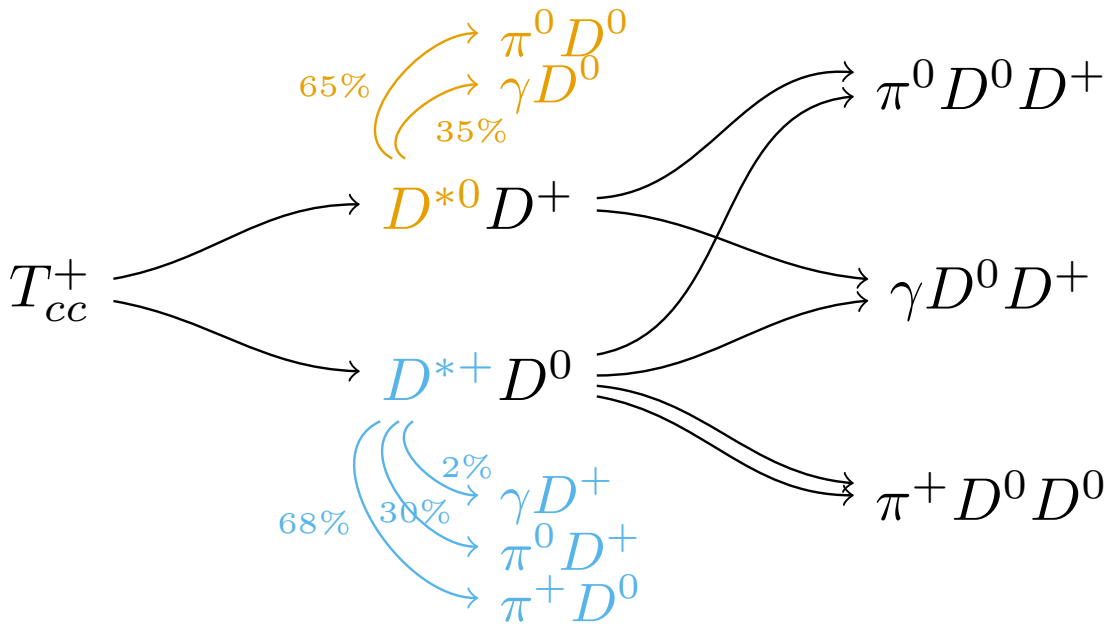
Parameter	Value
N	117 ± 16
δm_{BW}	-273 ± 61 keV/c^2
Γ_{BW}	410 ± 165 keV



Fundamental properties? Need better model ($D^* D$ threshold)

T_{cc}^+ decay amplitude

[LHCb, Nature Physics (2022)& Nature Communicatitions, 13, 3351]



Model assumptions:

- $J^P = 1^+$: S-wave decay to $D^* D$
- T_{cc}^+ is an isoscalar: $\left|T_{cc}^+\right\rangle_{I=0} = \left\{\left|D^{*0}D^+\right\rangle - \left|D^{*+}D^0\right\rangle\right\}/\sqrt{2}$
- No isospin violation in couplings to $D^{*+}D^0$ and $D^{*0}D^+$
- Unitary construction based on [MM et al. (JPAC), JHEP 08 (2019) 080]

Fit to the spectrum

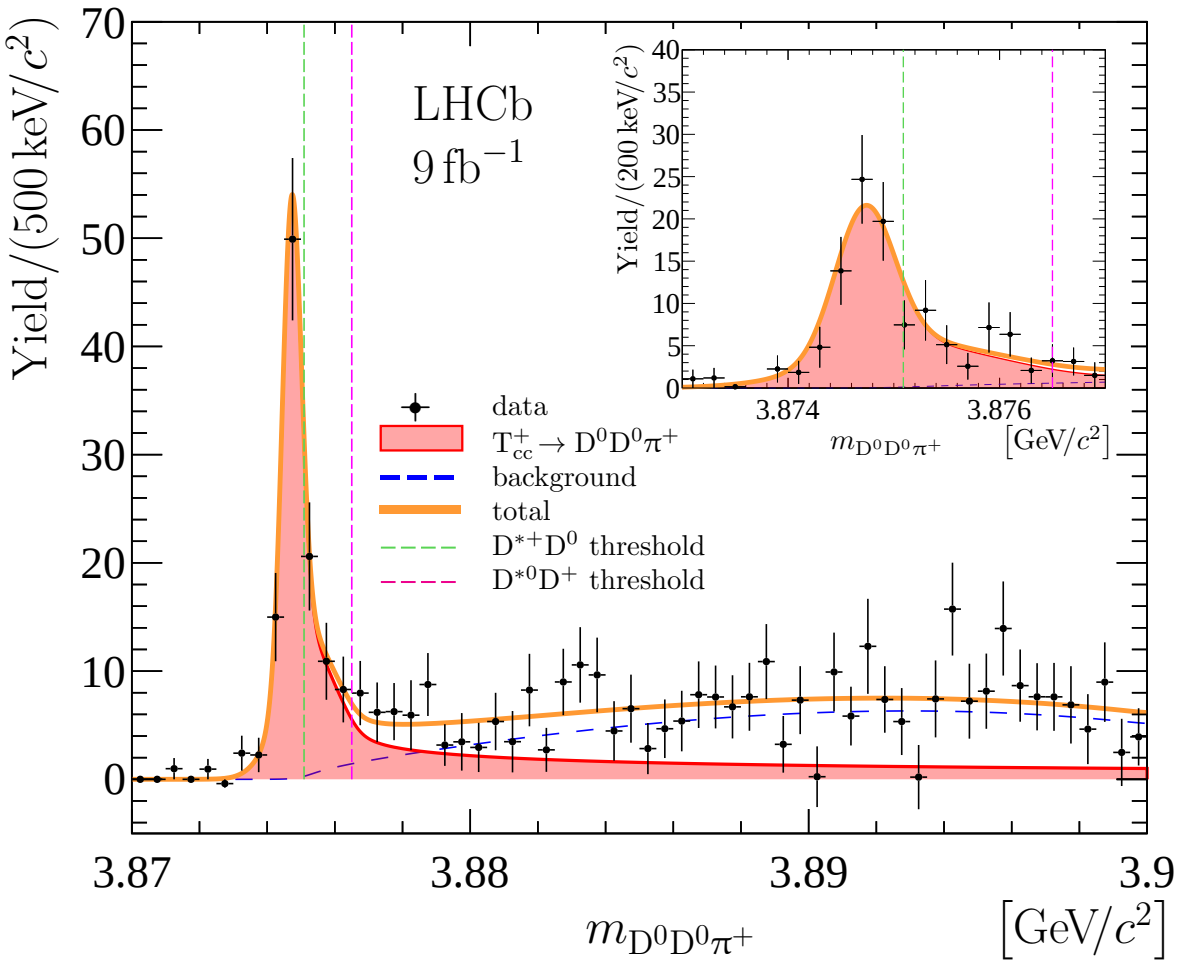
Unitarized model

[Nature Communicatitions, 13, 3351 (2022)]

Coupled-channel model has just 2 parameters

- **Peak position**: $-359 \pm 40\,\mathrm{keV}$
- **Coupling strength**: $|g| > 7.7(6.2)\,\mathrm{GeV}$ at 90(95)% CL

Parameter	Value
N	186 ± 24
δm_{U}	$-359 \pm 40\,\mathrm{keV}/c^2$
$\lvert g\rvert$	$3 \times 10^4\,\mathrm{GeV}$ (fixed)



Excellent agreement with the data. Reaction amplitude is fully fixed.

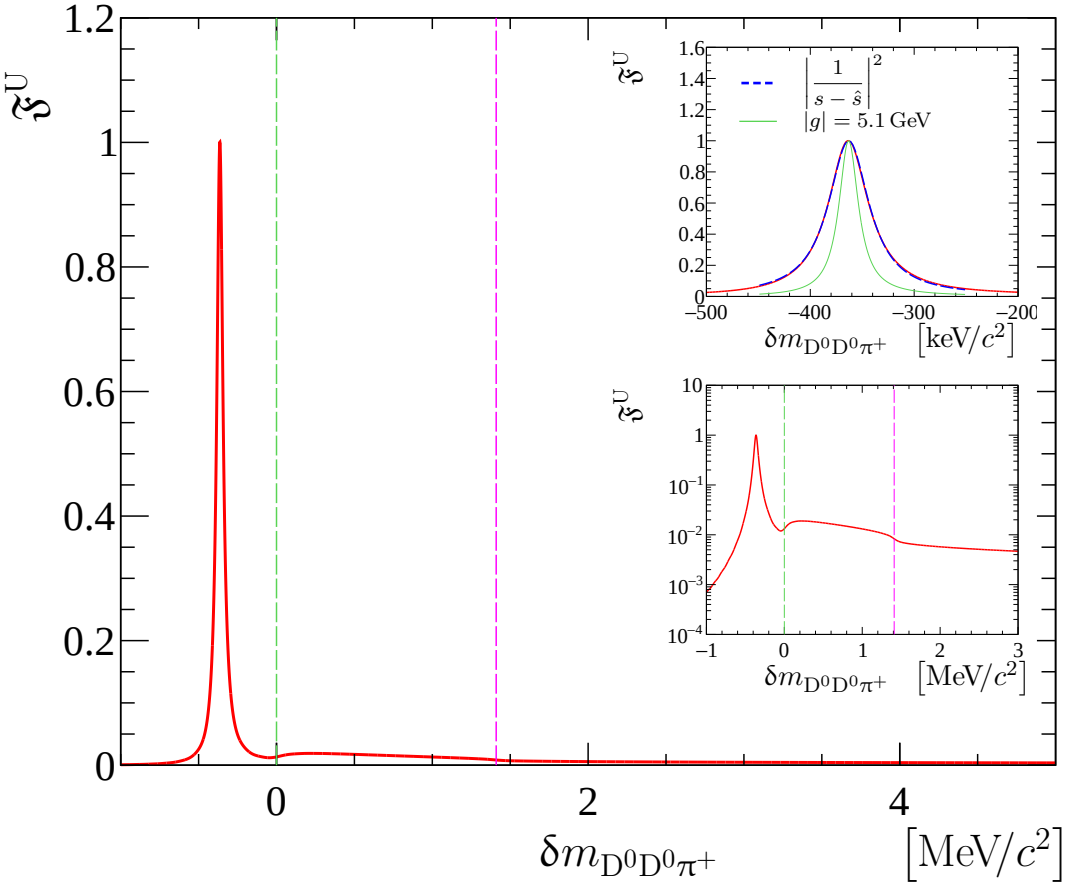
True mass spectrum

The resolution removed

[Nature Communicatitions, 13, 3351 (2022)]

Visible characteristics:

- Peak position: $-359 \pm 40\,\mathrm{keV}$
  (The most precise ever wrt to the threshold)
- FWHM: $47.8 \pm 1.9\,\mathrm{keV}$,
- Lifetime: $\tau \approx 10^{-20}\,s$.
  (Unprecedentedly large for exotic hadrons)



- Nearly-isolated resonance below the $D^{*+}D^0$ threshold
- Long tail with cusps at the $D^{*+}D^0$ and $D^{*0}D^+$ thresholds

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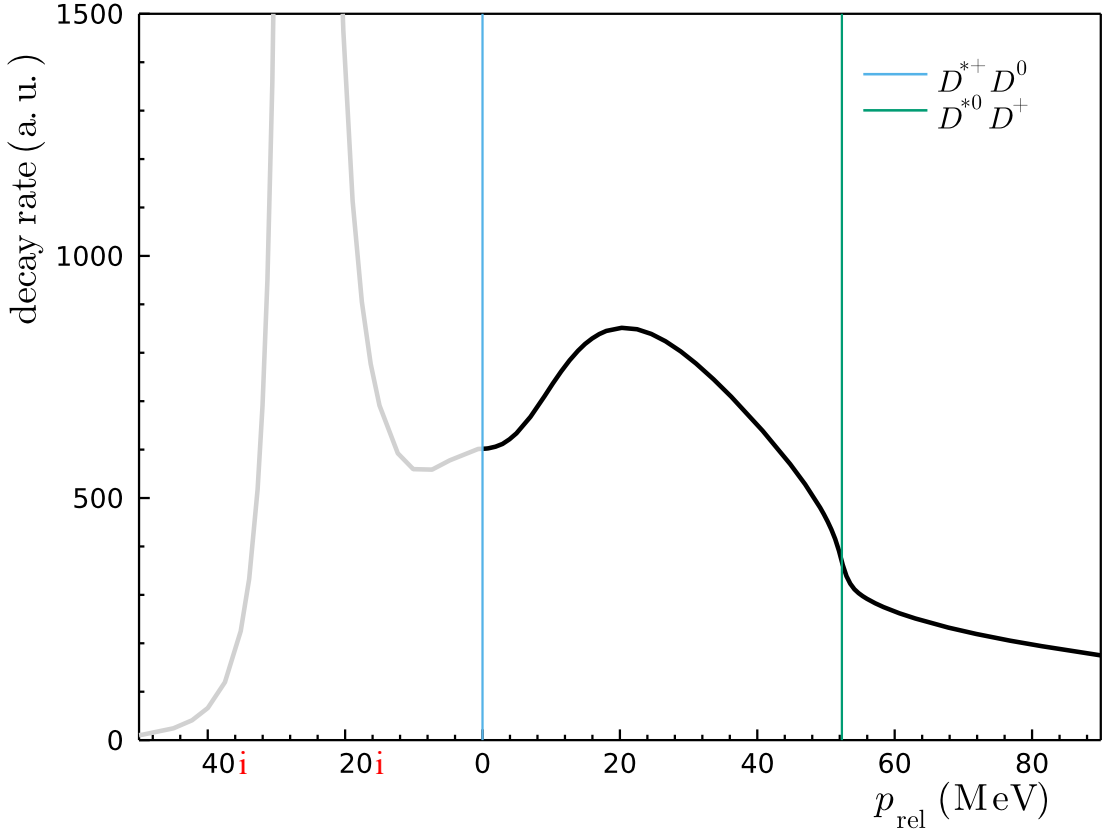

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Fundamental resonance parameters [interactive]

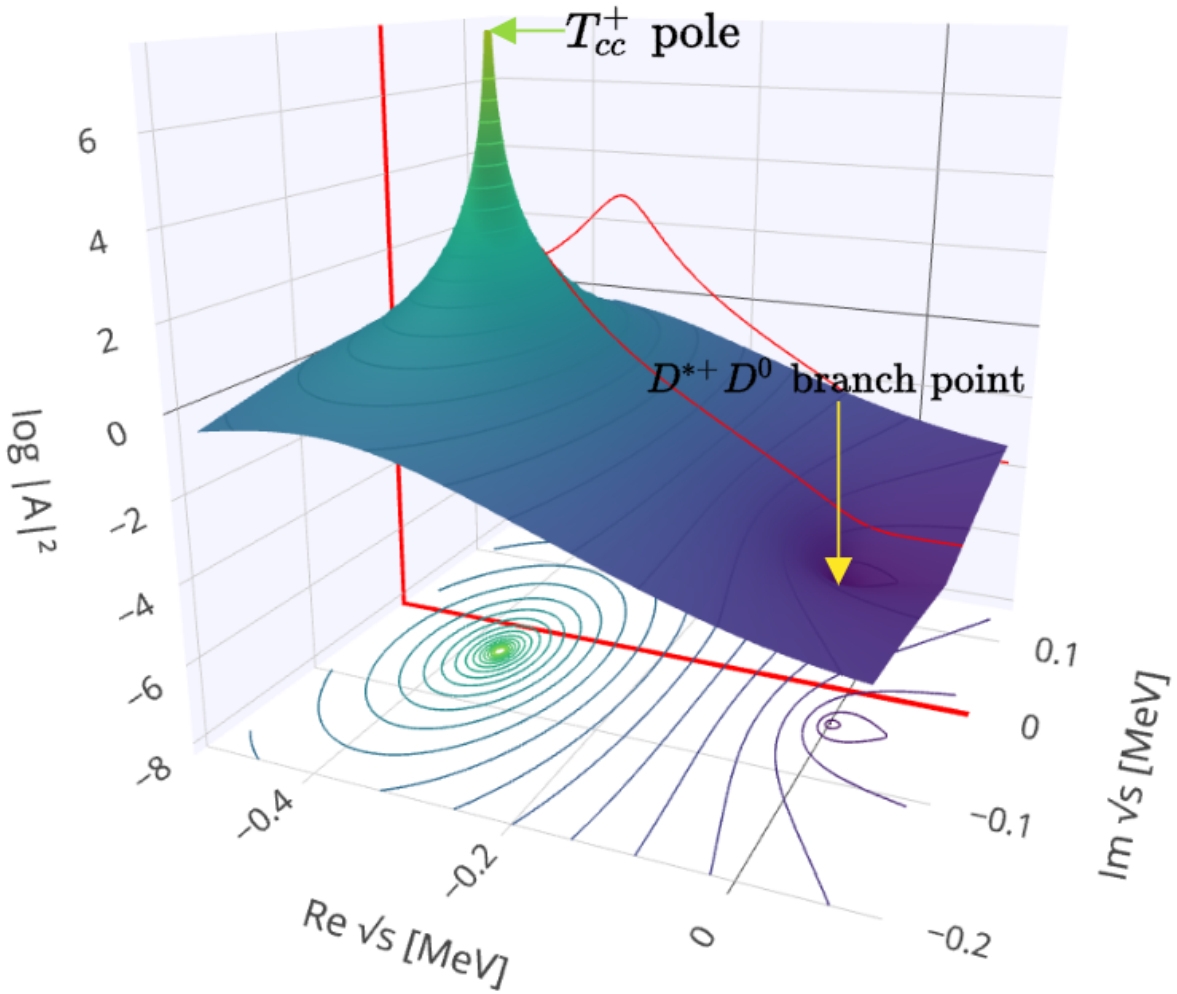
Mass and width – position of the complex pole of the reaction amplitude

- Analytic continuation is non-trivial due to three-body decays [MM et al. (JPAC), PRD 98 (2018) 096021]

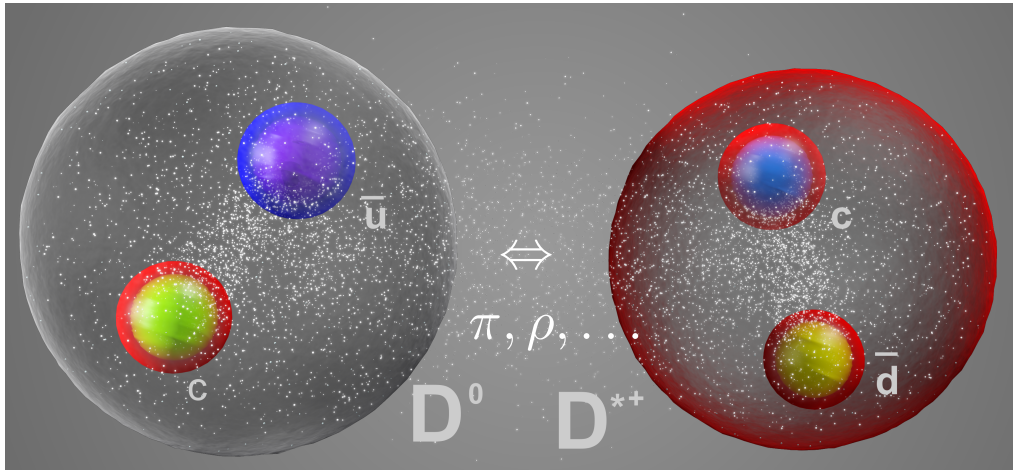
The pole parameters:

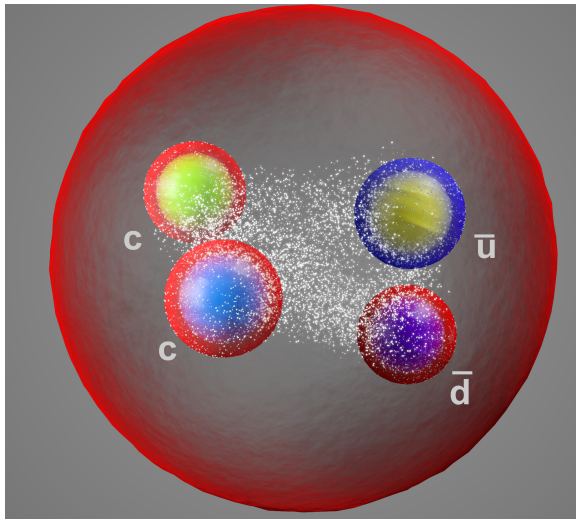
$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\,\text{keV}\,,$$

$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}\,\text{keV}\,.$$



T_{cc}^+ : Two extreme spatial configurations





Molecular configuration:

- two mesons are well separated,
- bound by forces similarly to el.mag. van der Waals,
- entirely coupled to $D^{*+}D^0$,
- lifetime is limited by D^{*+},

? spatially-extended object.

Compact configuration:

- genuine QCD state,
- compact (cc) core,
- there is no limit on lifetime, depends on how much it couples to continuum,

? typical hadronic size of 1 fm.

Effective range and Weinberg compositeness

Non-relativistic expansion near the threshold:

$$\mathcal{A}_{\rm NR}^{-1} = \frac{1}{a} + r\frac{k^2}{2} + O(k^4) - ik$$

Scattering length, a

- a characteristic size of the state
- $a > 0$: moderate interaction
- $a < 0$: strong attraction forming a bound state

Effective range, r

- is the second order correction
- ! always positive in potential scattering [Landau-Smorodinsky(1944), Esposito(2021)]

Weinberg compositeness: $X \equiv 1 - Z = \sqrt{\frac{1}{1+2r/a}}$

$X = 1$: composite (molecule) $\qquad X = 0$ elementary

According to the Weinberg's compositeness,

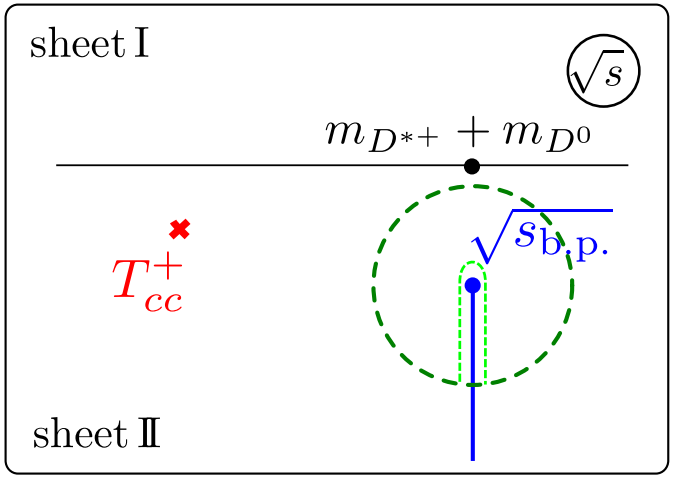
- Any state coupled to continuum (i.e. can decay) has a molecule component
- Non-zero effective range is an indication of the compact component

Scattering parameters for the $D^{*+}D^0$ system

[MM, 2203.04622]

$$\mathcal{A}^{-1}_{D^{*+}D^0\to D^{*+}D^0} = N\left(\frac{1}{a} + r\frac{k^2_{D^{*+}D^0}}{2} + O(k^4_{D^{*+}D^0}) - ik_{D^{*+}D^0}\right)$$

Finite width of D^* shifts the **expansion point** to the complex plane to match the analytic structure.



For the nominal model:

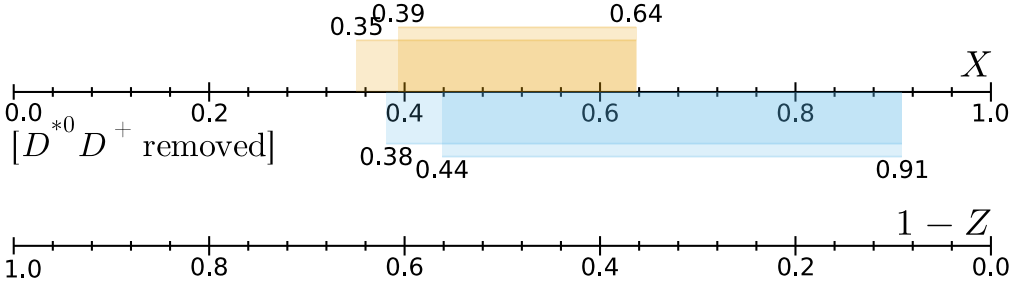
- Large scattering length, $\sim 6\,\text{fm}$,

$$1/a = (-33 \pm 2) + (2 \pm 0.1)i\,\text{MeV}\,,$$

- Negative CL for effective range:

$$-16.2(-21.2) < \text{Re}\, r < -4.3 \text{ at } 90(95)\%\text{ CL}\,.$$

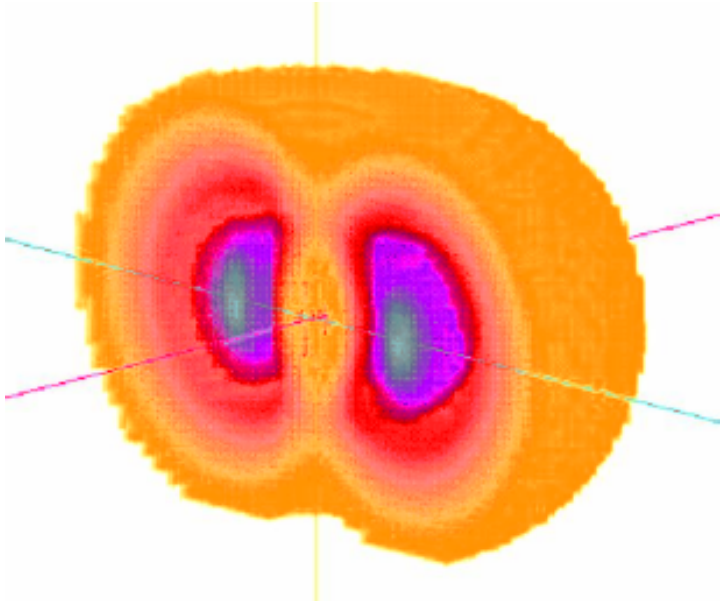
- Large compositeness



Compositeness compared to deuteron

[MM, 2203.04622]

Deuteron D^+ [Garcon, Van Orden(2001)]



- Presumably molecule
- Binding energy: 2.2 MeV
- $R_{\text{charge}} = 2.1\,\text{fm}$
- $R_{\text{matter}} = 1.9\,\text{fm}$
- scatt.len. $a = -5.42\,\text{fm}$
- eff.range $r = 1.75\,\text{fm}$

Tetraquark T_{cc}^+

[?]

- From the "compact" family
- Binding energy: 0.36 MeV
- $R_{\text{charge}} =$??
- $R_{\text{matter}} =$??
- $a = -5.54\,\text{fm}$
- $-16.2 < r < -4.3\,\text{fm}$ at 90% CL

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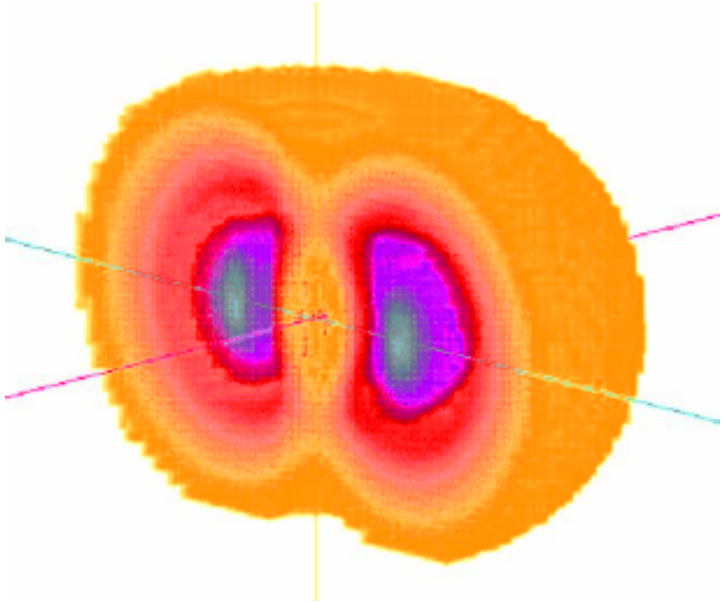

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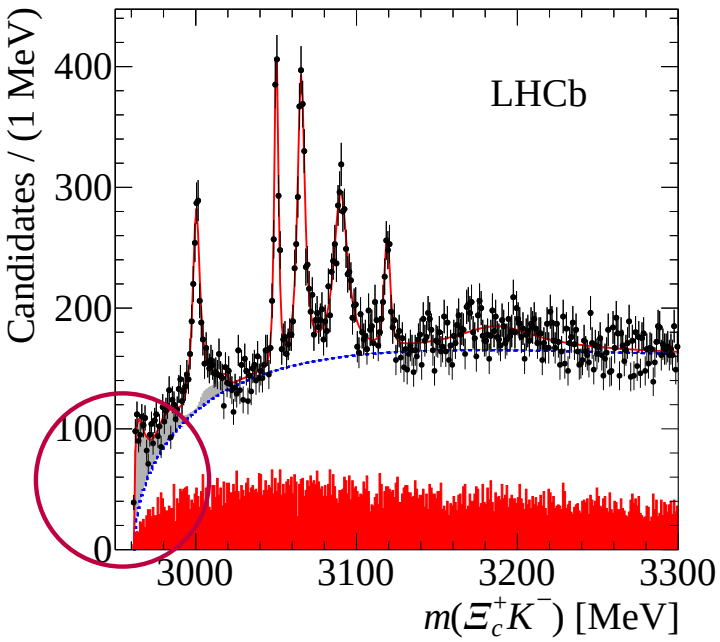
[?]

- From the "compact" family
- Binding energy: 0.36 MeV
- $R_{\text{charge}} =$??
- $R_{\text{matter}} =$??
- $a = -5.54\,\text{fm}$
- $-16.2 < r < -4.3\,\text{fm}$ at 90% CL
- $0.44 \leq X \leq 0.91$ at 90% CL

III. $\Xi_c^+ K^-$ threshold structure

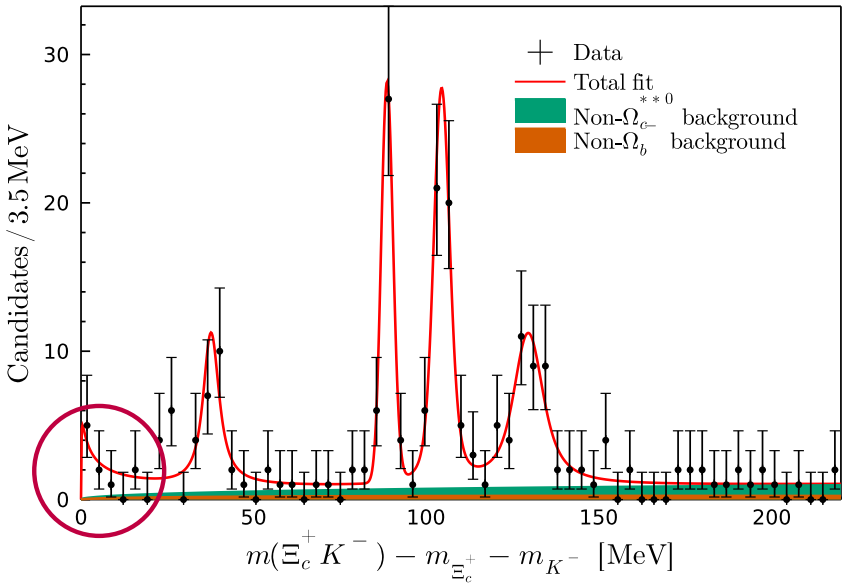
[LHCb, PRL 118, 182001 (2017)] and [LHCb, PRD 104 L091102 (2021)]

Inclusive



- Explained in the prompt analysis by the partially reconstructed $\Omega_c(3065)^+ \to \Xi_c'^+ K^-$ with anomalously large coupling.

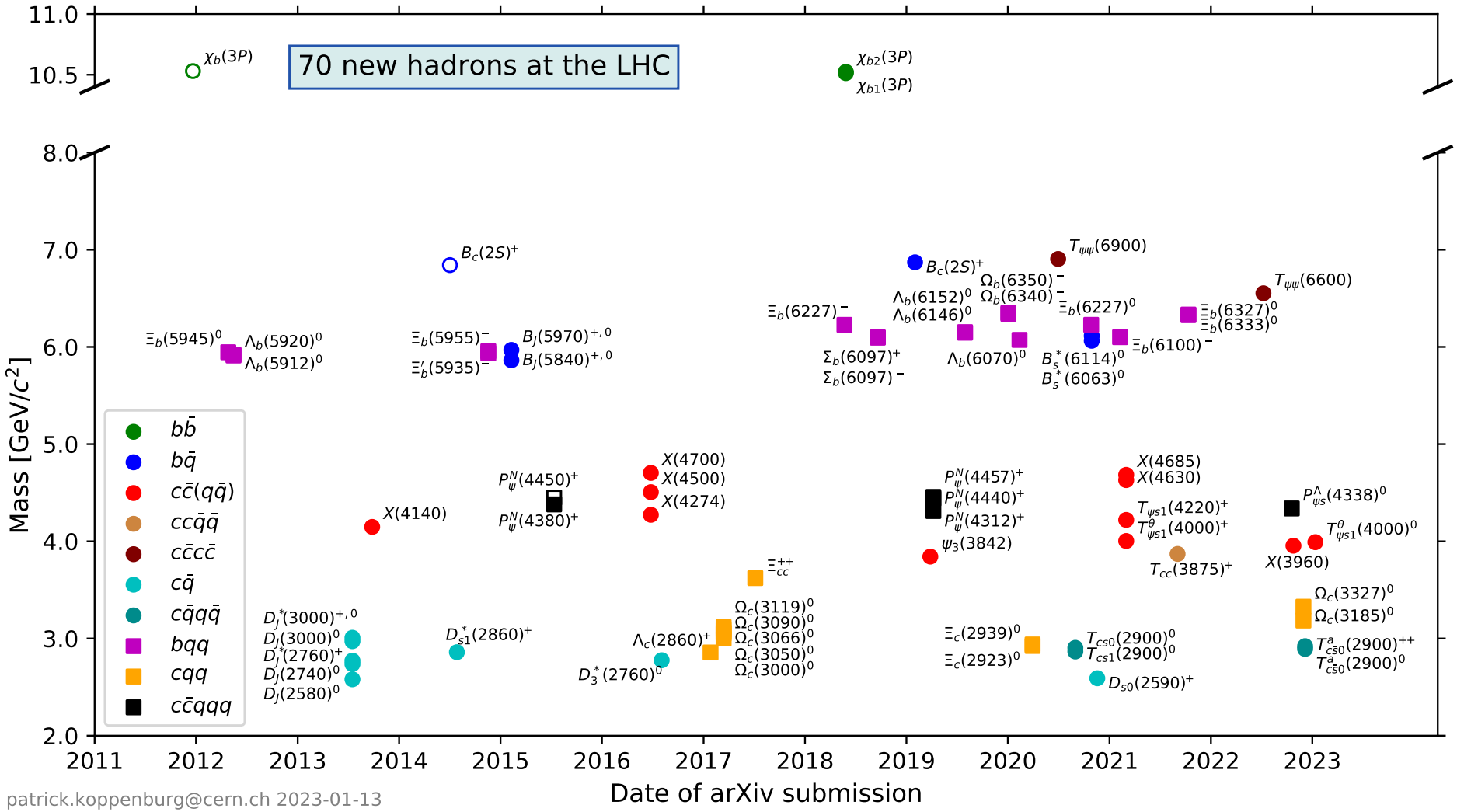
Exclusive



- Exclusive analysis: no feed down is possible
- Other non-physical sources are excluded
- Singinifance in the nominal fit is 5.3σ, 4.3σ including systematics
- No model sensitivity due to the low statistics

More puzzling exotic states

New hadronic states from LHC experiments



patrick.koppenburg@cern.ch 2023-01-13

Pentaquarks studies

(*) will be discussed today

$$\boxed{X_b \to (J/\psi p)\ldots}$$

$$\Lambda_b^0 \to (J/\psi p) K^- \quad (*)$$
$$\Lambda_b^0 \to (J/\psi p) \pi^-$$
$$B_s^0 \to (J/\psi p) \overline{p}$$

Thresholds: $\Sigma_c^{(*)+} \overline{D}^{(*)0}$ / $\Sigma_c^{(*)++} D^{(*)-}$

$$P_\psi^N:$$

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$$\Xi_{B^-} \to (J/\psi \Lambda) K^- \quad (*)$$
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$$P_{\psi s}^\Lambda:$$

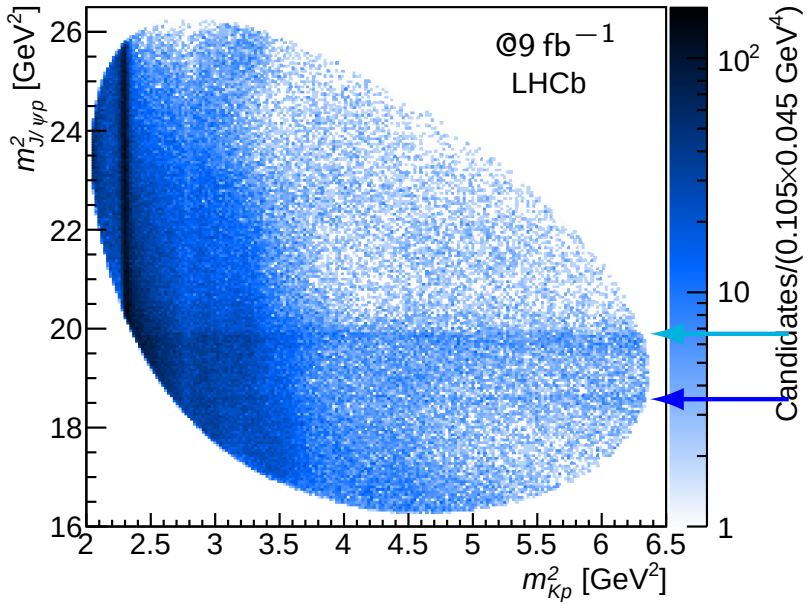
LHCb proposal for the new name convention of exotic hadrons [arXiv:2206.15233]

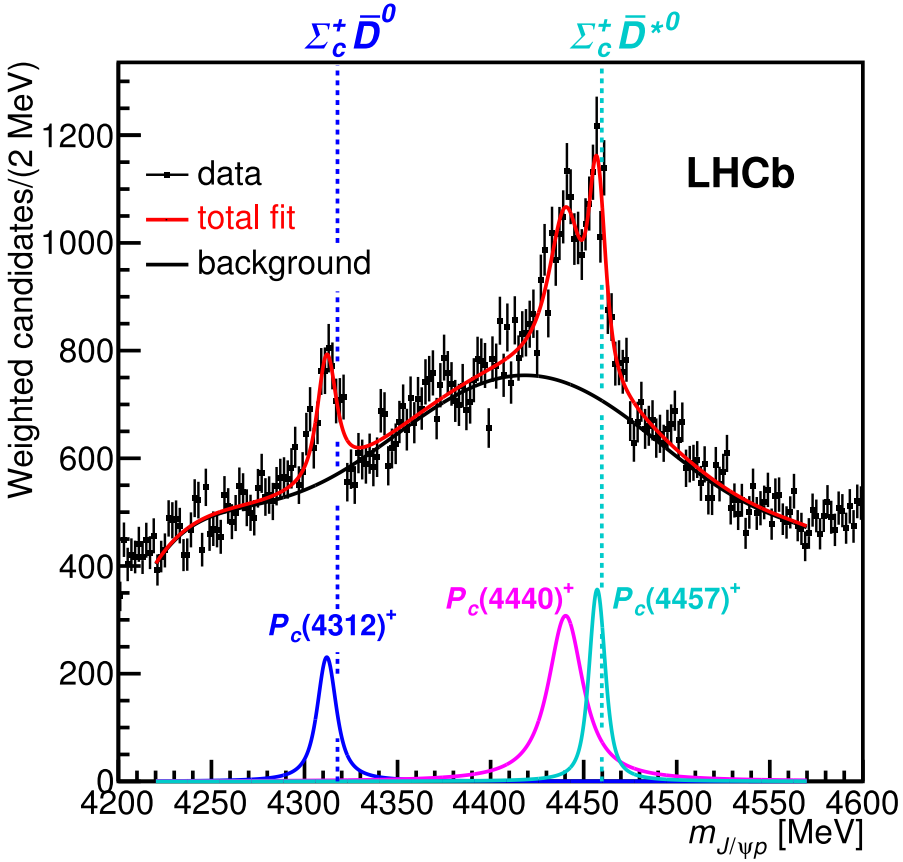
The first pentaquarks: $P^{\Lambda}_{\psi s}[uudc\bar{c}]$

[PRL 115 (2015), 072001; PRL 122 (2019) 22, 222001]

$$\Lambda_b^0 \to \underbrace{J/\psi p}_{P^N_\psi} K^-$$

- Close to the $\Sigma_c \bar{D}^{(*)}$ threshold,
- Multiplicity matches spin combination: $1/2 \otimes 1 = 1/2 \oplus 3/2$
- Narrow(!): 10, 20, and 5 MeV for Γ_{BW}





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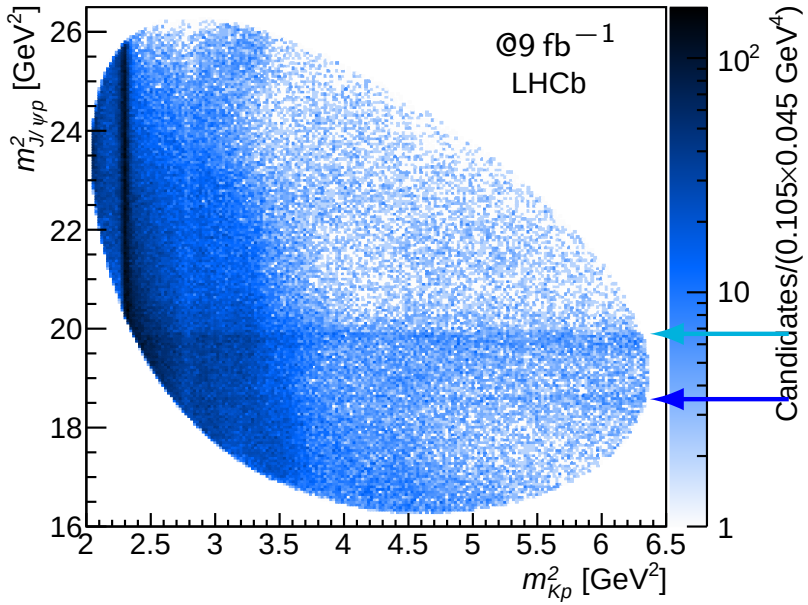

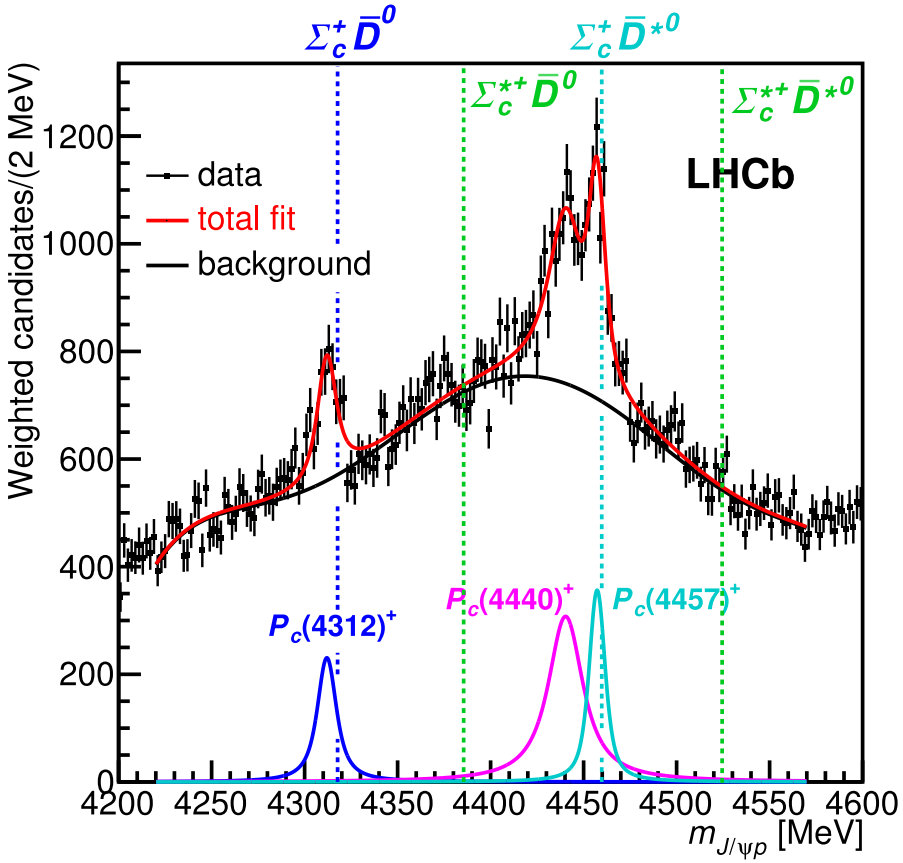

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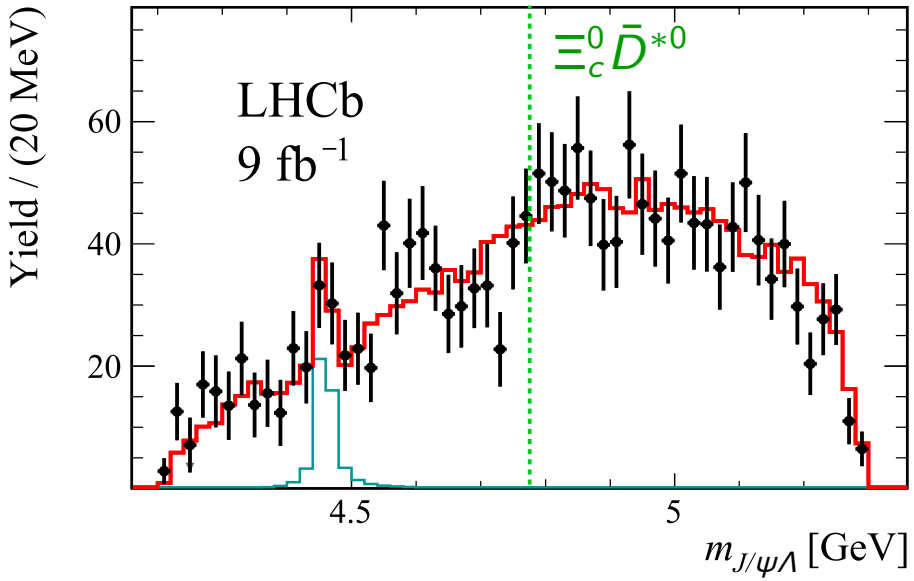
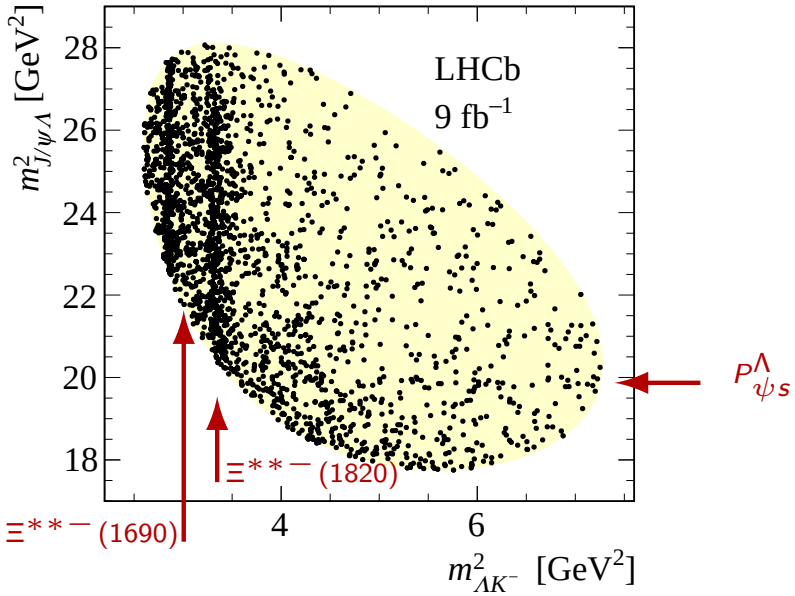
Hint for the strange partners: $P^{\Lambda}_{\psi s}[udsc\bar{c}]$

$\Xi_b^- \to J/\psi(\to \mu^+\mu^-)\Lambda(\to p\pi^-)K^-$ data sample [Sci.Bull. 66 (2021) 1278-1287]

$$\Xi_b^- \to \underbrace{J/\psi\Lambda}_{P^{\Lambda}_{\psi s}} K^-$$

- Full data sample 1750 signals with purity 80%.
- The decay is dominated by the Ξ resonances
- $P^{\Lambda}_{\psi s}(4459)$: $m = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV with 4.3σ significance





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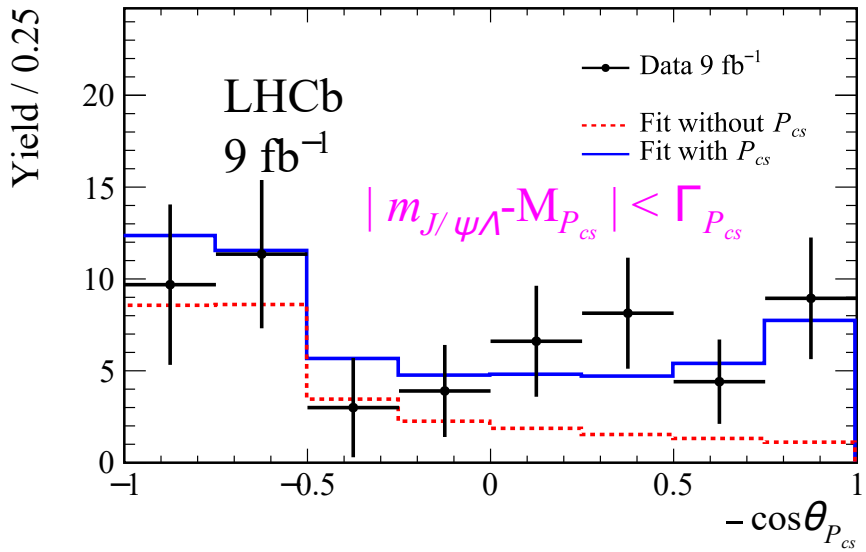
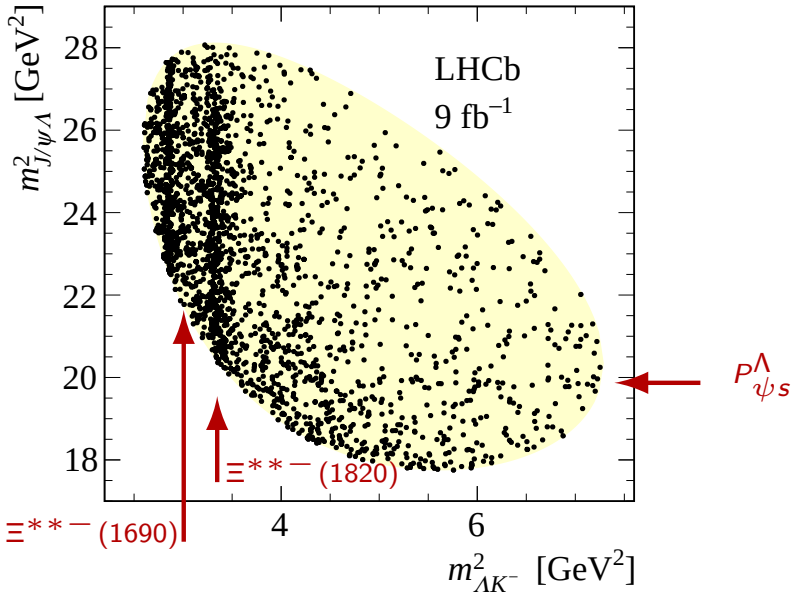


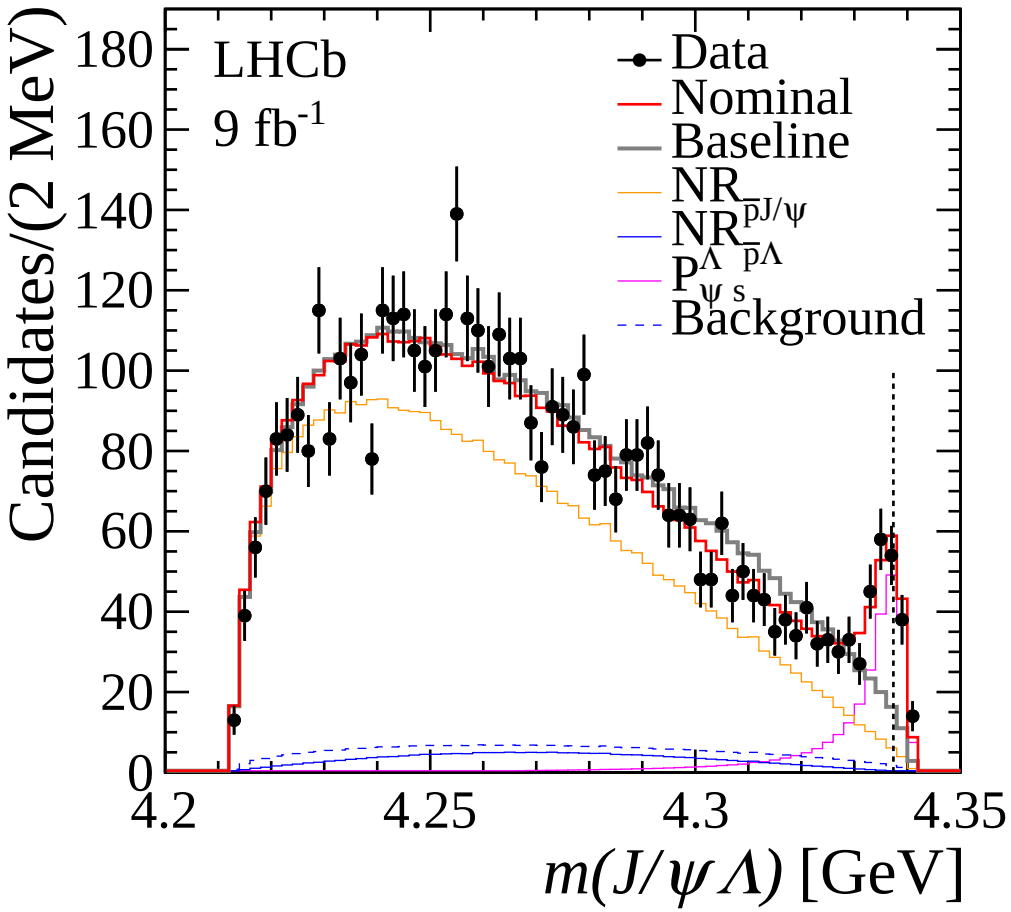


$B^- \to J/\psi(\to \mu^+\mu^-)\Lambda(\to p\pi)\overline{p}$

[LHCb, arXiv:2210.10346]

$$B^- \to \underbrace{J/\psi\Lambda}_{P^{\Lambda}_{\psi s}}\overline{p}$$

- Amplitudes:
  - NR($J/\psi p$), $84.0 \pm 2.2\%$
  - NR($\Lambda\overline{p}$), $11.3 \pm 1.3\%$
  - New $P^{\Lambda}_{\psi s}$, $12.5 \pm 0.7\%$,
- $J^P = 1/2^-$ is preferred
- BW mass is close to $\Xi_c\bar{D}$ thresholds:
  - $0.8\,\mathrm{MeV}$ above $\Xi_c^+ D^-$
  - $2.9\,\mathrm{MeV}$ above $\Xi_c^0\overline{D}^0$



Tetraquarks candidates

(*) will discussed today, some others are in the backup

$J/\psi\pi^+$

T^b_ψ (Z_c)

3900, 4430, ...

$J/\psi K^+$

$T^\theta_{\psi s}$ (Z_{cs})

4000, 4220

$J/\psi\phi$

X $(T_{\psi\phi})$

4140, 4274, 4500, ...

$J/\psi J/\psi$ (*)

$T_{\psi\psi}$ $(T_{cc\bar{c}\bar{c}})$

6900, ... (!)

$D^0 D^0 \pi^+$

T_{cc}

3874

$D^+ K^-$

T_{cs} (X)

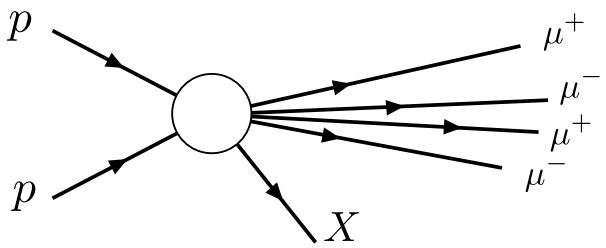
2900

$D_s^\pm \pi^+$

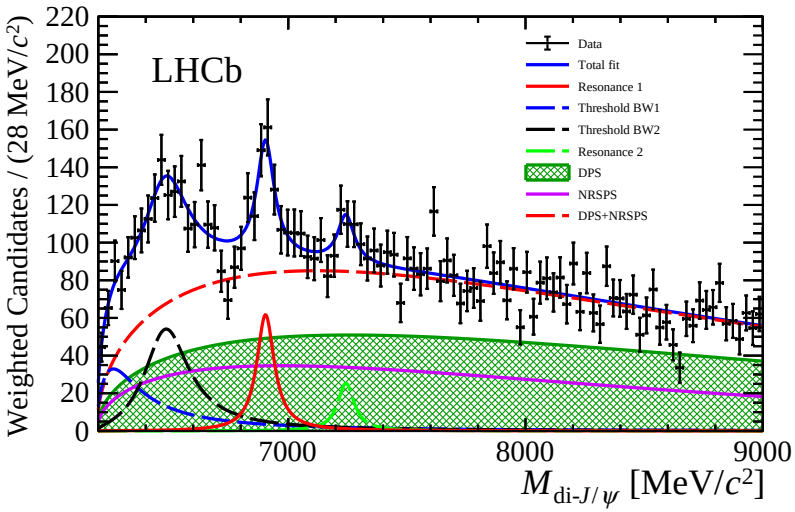
$T_{c\bar{s}}$ (X)

2900

$T_{\psi\psi} \to J/\psi J/\psi \to 4\ell$



- Tetraquarks in $J/\psi J/\psi$ spectrum seen by LHCb (2020), confirmed by CMS(2022)
- Peaking structure are hard to describe with naive models
- expects $\times 5$ more data by 2030



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

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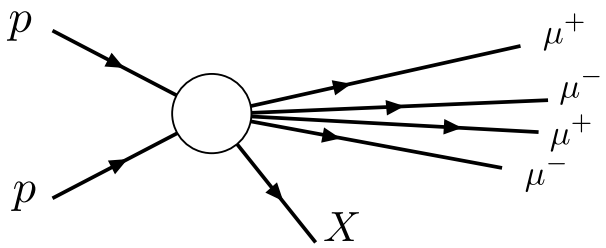

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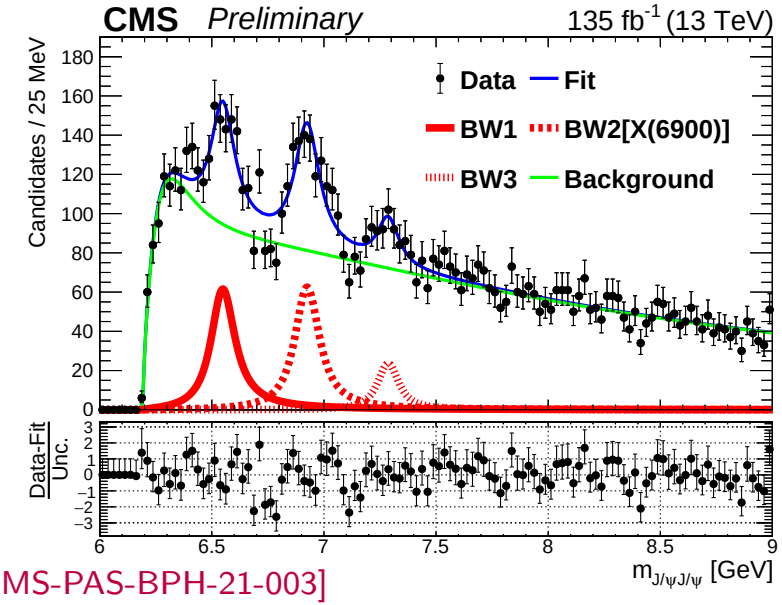

[CMS-PAS-BPH-21-003]

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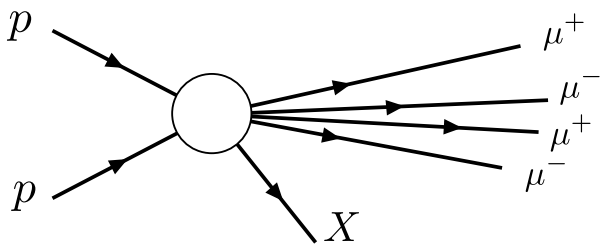

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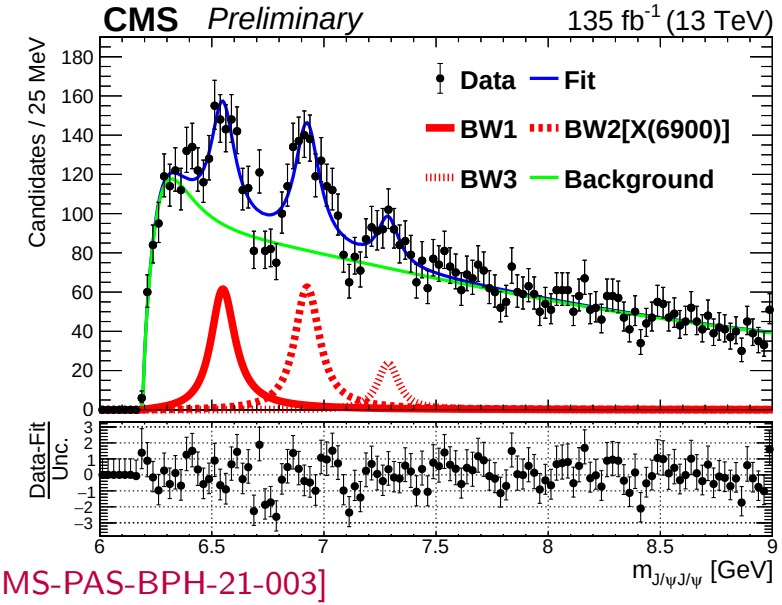

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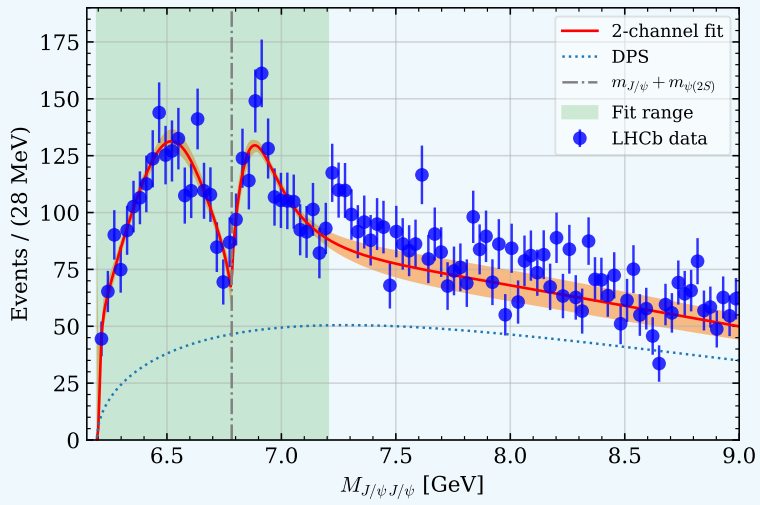

Accurate spectral analysis:

[X.-K. Dong et al., PRL 126 (2021) 13, 132001]

- Establish coupled-channel models
- Predict **near-threshold state**
  - $J^{PC} = 0^{++}$ or 2^{++}
  - Compositeness, $X \sim 0.3 - 0.95$
- Need angular analysis

[MM, L. An, R. McNulty, arXiv:2007.05501]

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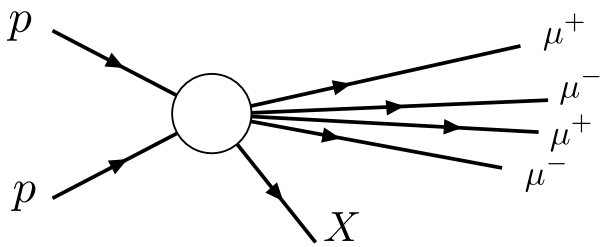

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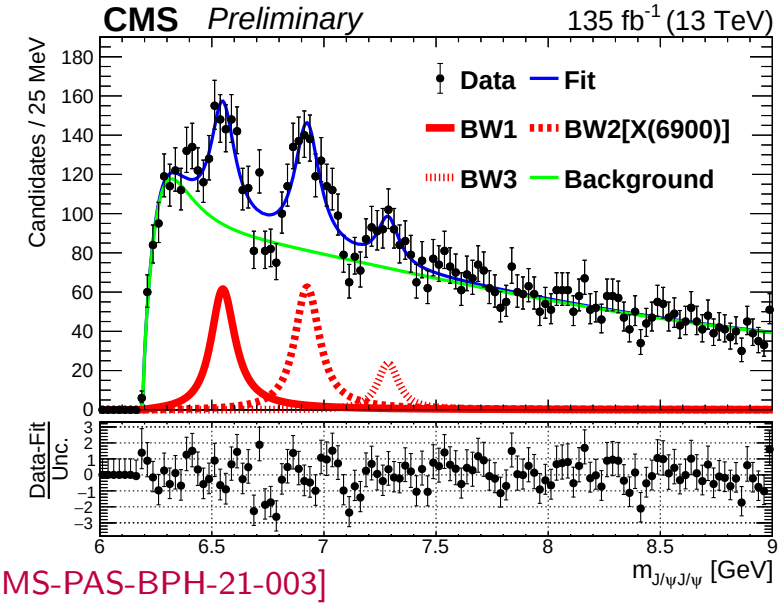

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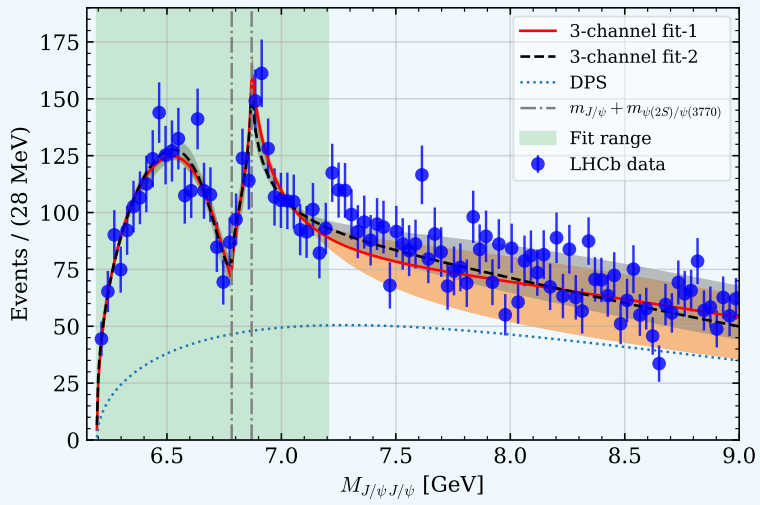

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Scattering parameters and compositeness

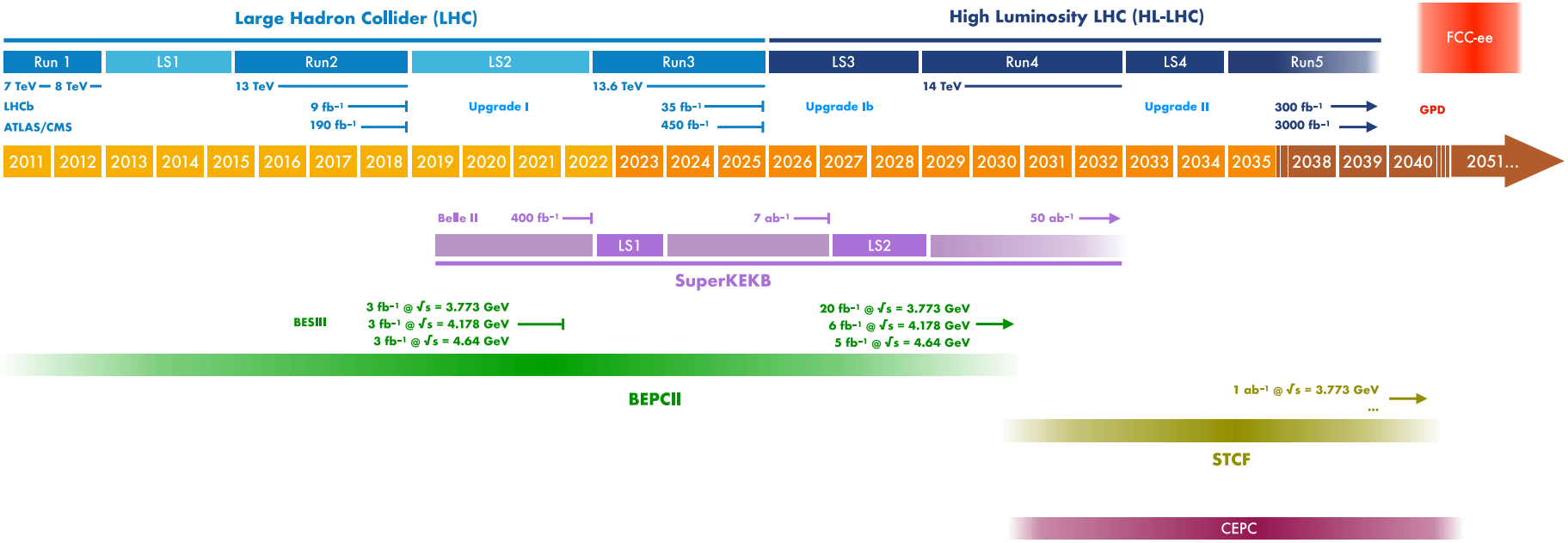
- a, r are fundamental parameters of hadronic interactions that can be measured.
- Weinberg compositeness is an attractive concept that gives an intuitive interpretation, however
- Misses rigorous validation e.g. using lattice QCD

Many new exotic states observed at LHCb, and other experiments:

- Some might turn out to be purely nuclei (hadronic molecules),
- Some clearly involve quark dynamics

Updated timeline for LHC

[W. Altmannshofer, F. Archilli, arXiv:2206.11331]



LHCb:

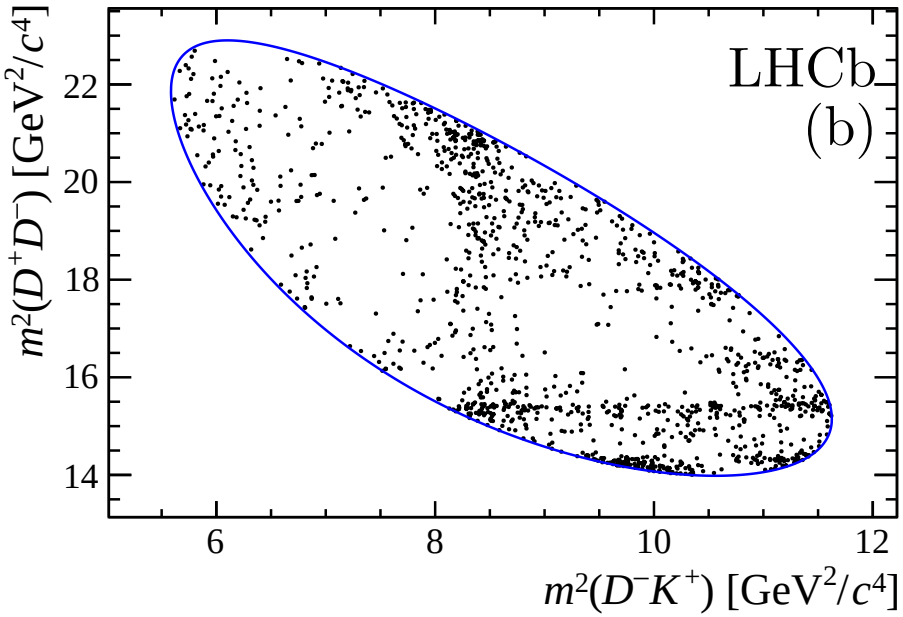
- ramping up after major Upgrade I
- $\times 5$ statistics in Run 3(2023-2025) @13.6 TeV + Run 4(2029-2032) @14 TeV

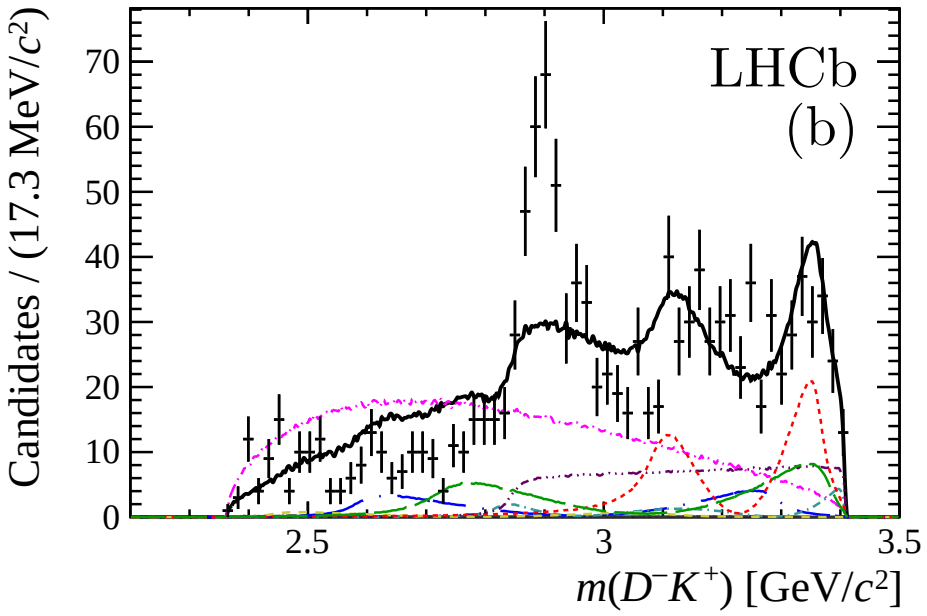
Backup

$$B^+ \to D^+ \underbrace{D^- K^+}_{T_{cs}}$$

Dalitz plot for $B^+ \to D^+D^-K^+$

[LHCb, PRD102 (2020) 112003]





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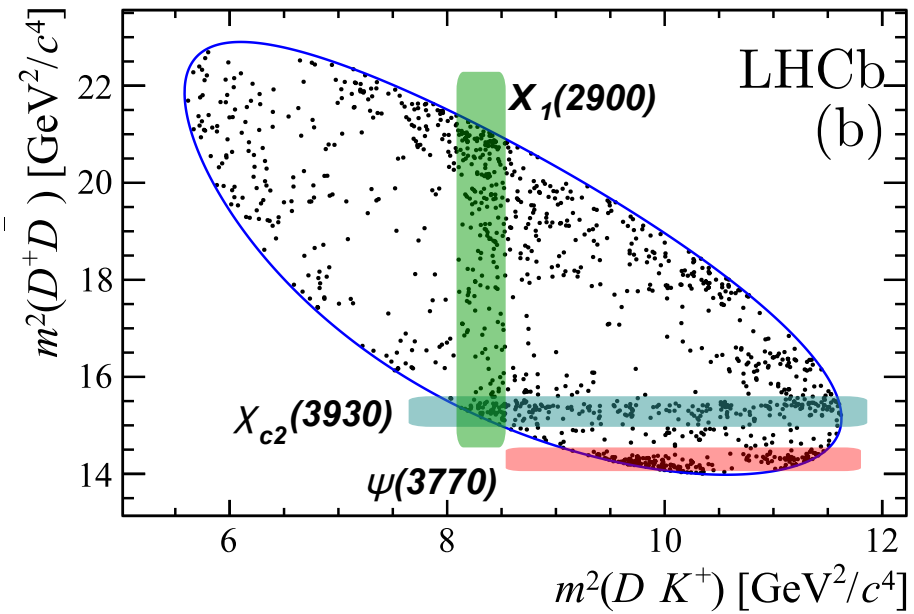
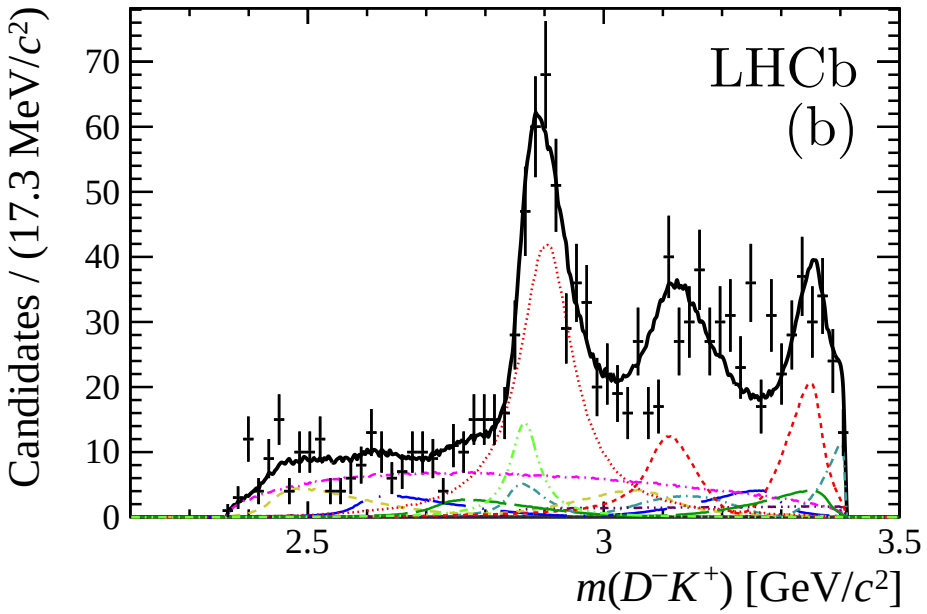
[LHCb, PRD102 (2020) 112003]





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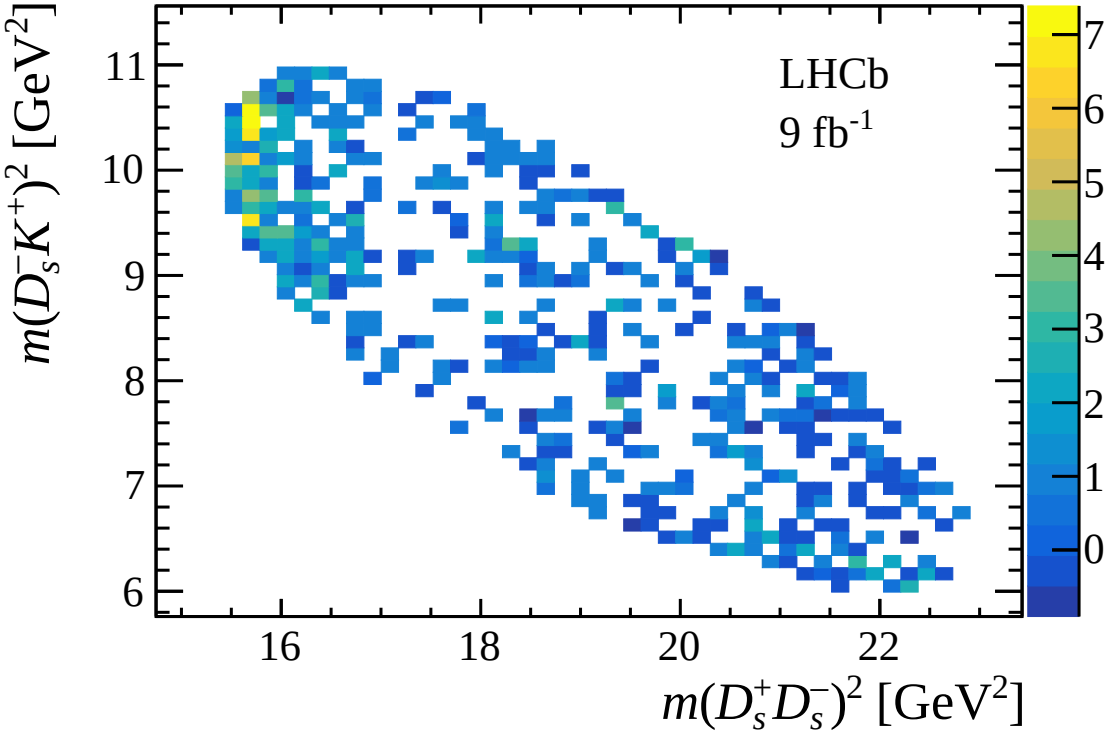
$$B^+ \to \underbrace{D_s^+ D_s^-}_{\chi_{c0}/T_{\psi\phi}} K^+$$

Threshold enhancement at $D_s^+ D_s^-$ in $B^+ \to D_s^+ D_s^- K^+$ decays [LHCb, arxiv:2211.05034, arXiv:2210.1515]



- $D_s^+ \to K^+ K^- \pi^+$
- Full data set, 9 fb^{-1}
- 360 signal candidates
- Purity of 84 %

$B^+ \to D_s^+ D_s^- K^+$ amplitude analysis

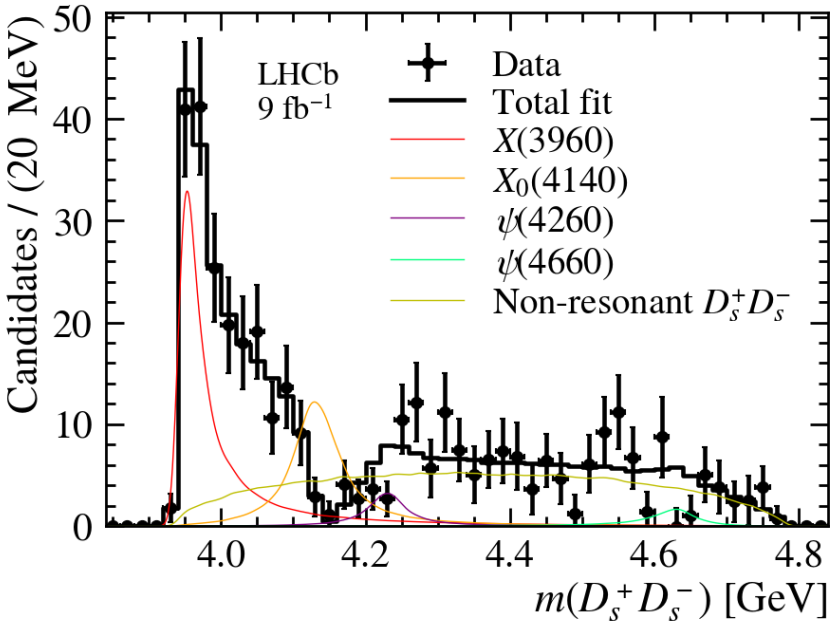
[LHCb, arxiv:2211.05034, arXiv:2210.1515]

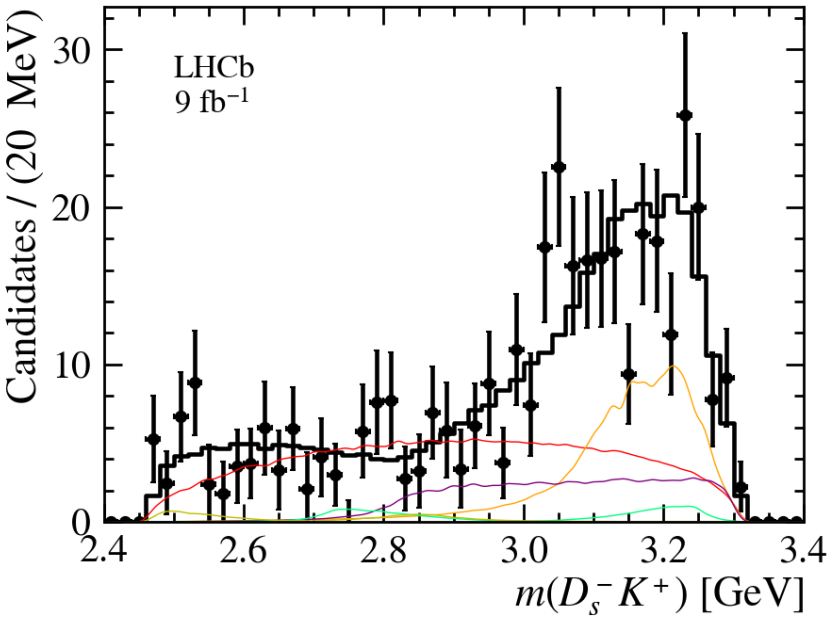
Main features of the data:

- Enhancement at the $D_s^+ D_s^-$ threshold
- Followed by a dip at 4.15 GeV.

Baseline model: $D_s^+ D_s^-$ resonances

- 1^{--}: $\psi(4260) \sim 4\,\%$, $\psi(4660) \sim 2\,\%$
- 0^{++}: $X(3960) \sim 24\%$, $X(4140) \sim 18\,\%$, NR$\sim 50\,\%$

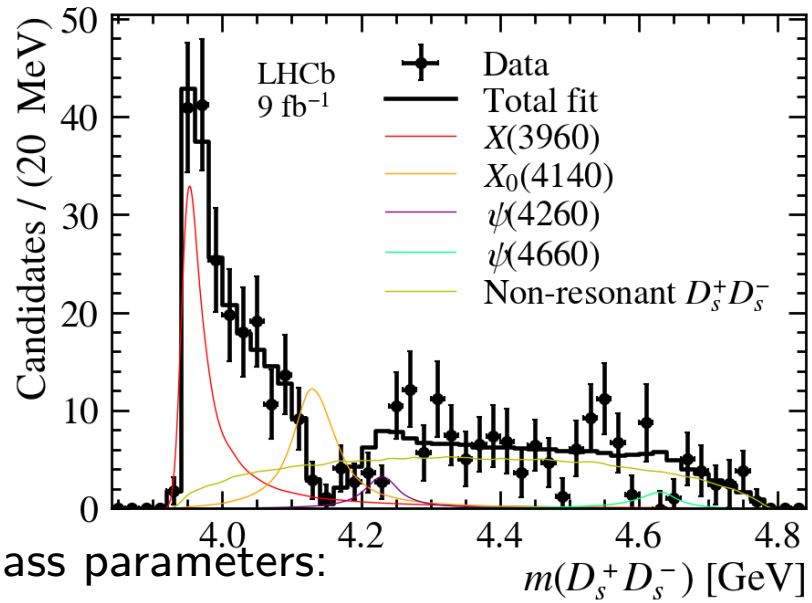


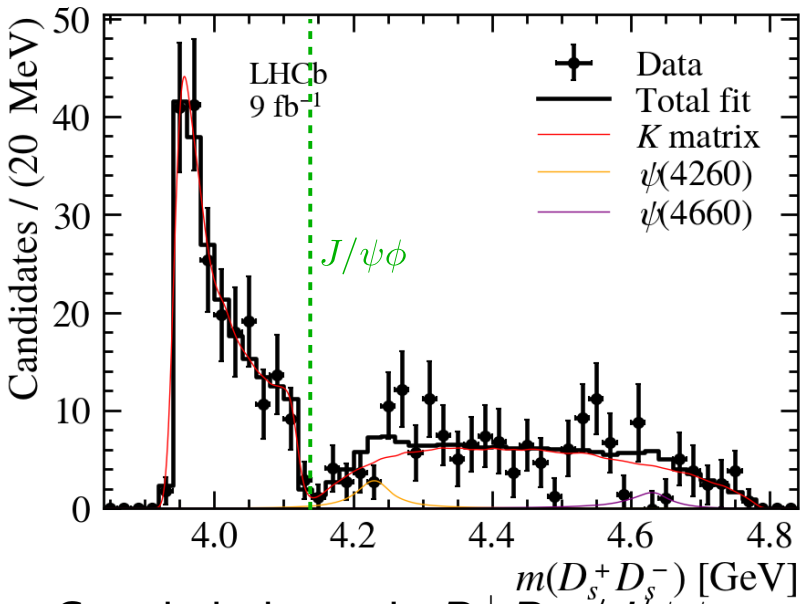


Alternative model using K-matrix

[LHCb, arxiv:2211.05034, arXiv:2210.1515]

Three interfering components in 0^{++} are replaced by the K-matrix.





Mass parameters:

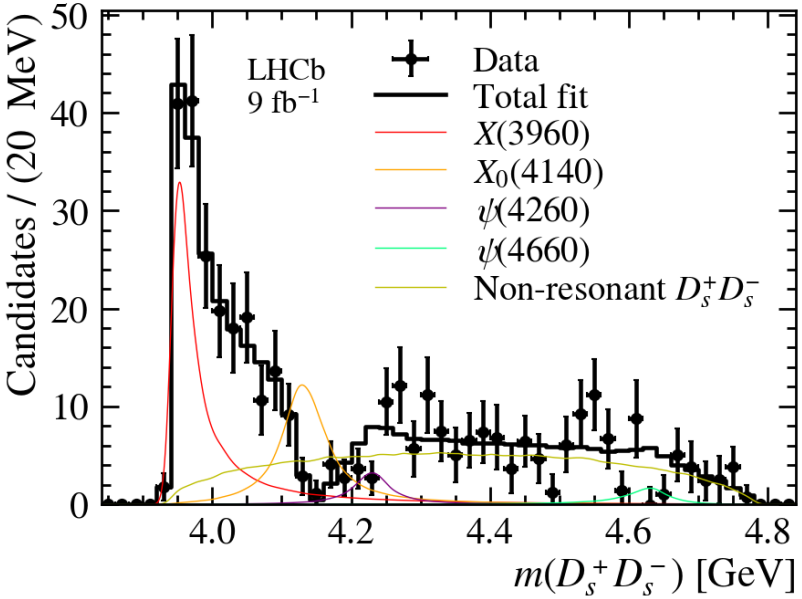
- 3960: $m = 3956 \pm 5 \pm 11\,\mathrm{MeV}$, $\Gamma = 43 \pm 13 \pm 8\,\mathrm{MeV}$
- 4140: $m = 4133 \pm 6 \pm 11\,\mathrm{MeV}$, $\Gamma = 67 \pm 17 \pm 7\,\mathrm{MeV}$

- Coupled channels $D_s^+ D_s^- / J/\psi\phi$
- One K-matrix pole + bgd term

Gives equally good fit

Is $X(3960)$ the same as $\chi_{c0}(3930)$ from D^+D^-?

$B^+ \to (D_s^+ D_s^-) K^+$ by LHCb:



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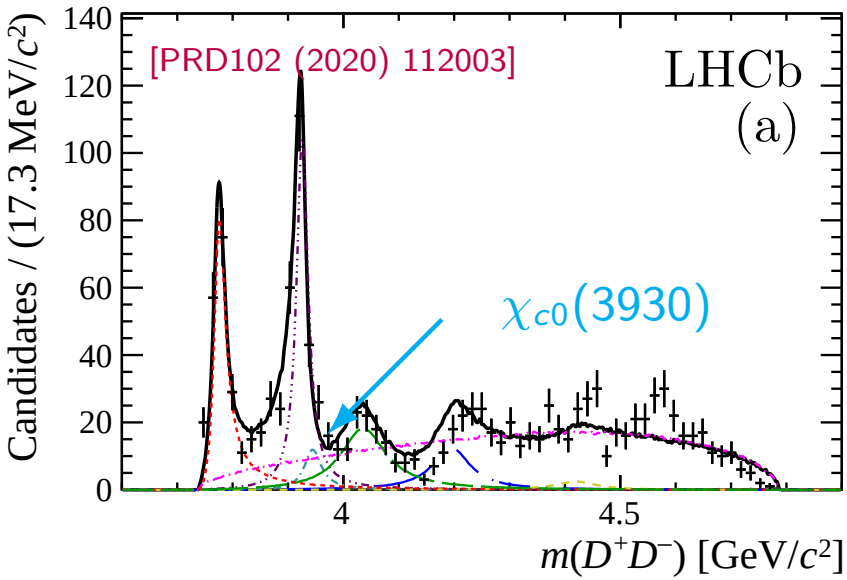
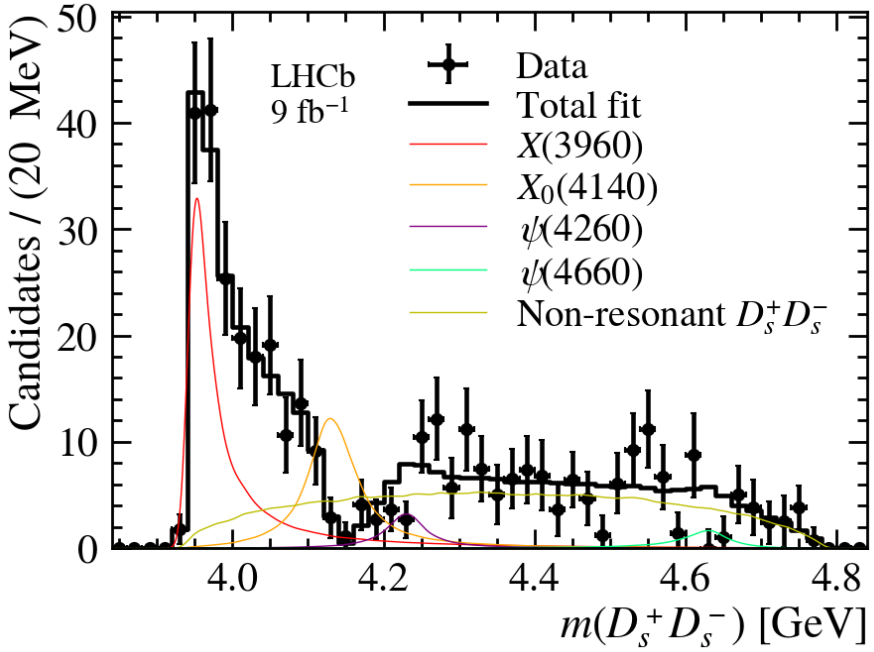


- Assuming to be the same, $\mathcal{B}(\chi_{c0} \to D^+D^-)/\mathcal{B}(\chi_{c0} \to D_s^+D_s^-) \sim 0.3$
  large molecular component, or large tetraquark component, $T_{\psi\phi}$
- [JHEP 06 (2021) 035] finds a state coupled to $D_s^+D_s^-$ on the lattice

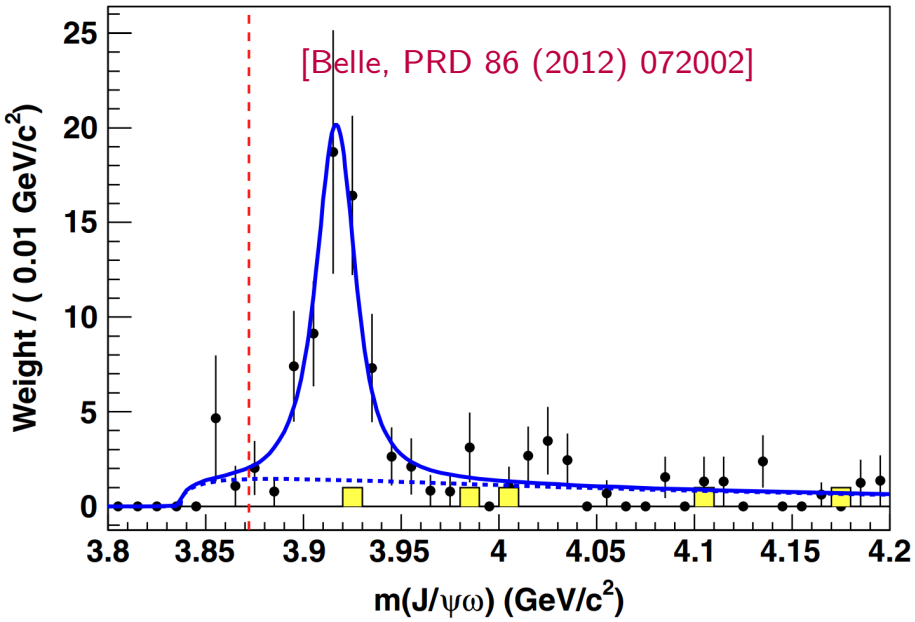
Is $X(3960)$ the same as $\chi_{c0}(3915)$?

[LHCb, arxiv:2211.05034, arXiv:2210.1515]

$B^+ \to (D_s^+ D_s^-) K^+$ by LHCb:



$\gamma\gamma \to J/\psi\omega$ by Belle:



- Belle sees a clean state in $J/\psi\omega$ with $J^P = 0^+$
- The $D_s^+ D_s^-$ signal might be a tail of the $\chi_{c0}(3915)$ state

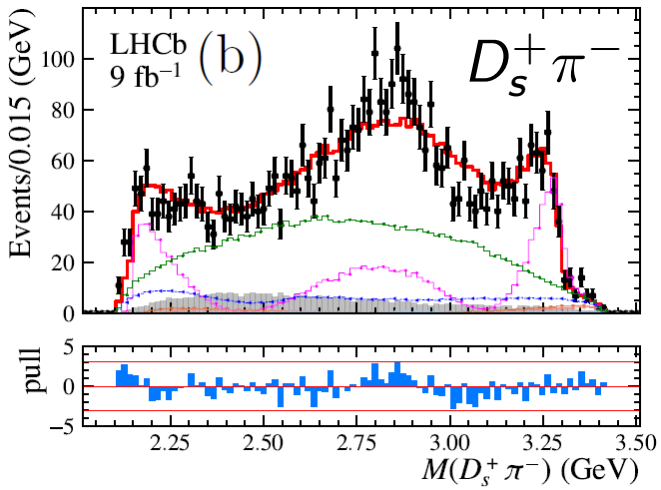
$$B^+ \to D^- \underbrace{D_s^+ \pi^+}_{T^a_{c\bar{s}}}$$

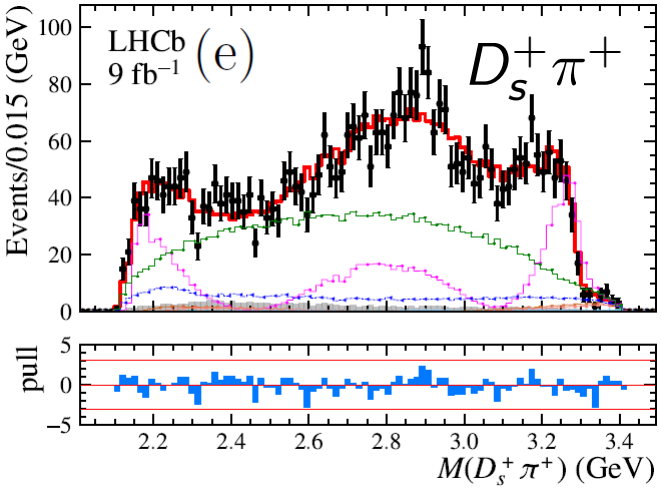
$$B^0 \to \bar{D}^0 \underbrace{D_s^+ \pi^-}_{T^a_{c\bar{s}}}$$

$T^a_{c\bar{s}}(2900)$ in the $D_s^\pm \pi^+$ system

[LHCb, arxiv:2212.02716]

- 4420 B^0 decays and 3940 B^- decays, including charge-conjugated reactions
- Simultaneous fit using the isospin symmetry
- Main components in B^0/B^+ model:
  - $D^* \sim 17/14\,\%$
  - $D_2^* \sim 22/23\,\%$
  - $D\pi$ S-wave$\sim 45/48\,\%$.
- $T^a_{cs} \sim 2\,\%$ needed ($> 5\sigma$), $J^P = 0^+$ is favored (7.5σ)
- Mass and width are close to these of $T^a_{cs}(2900)$
  - $T^{a0}_{c\bar{s}}$: $m = 2892 \pm 14 \pm 15\,\text{MeV}$, $\Gamma = 119 \pm 26 \pm 12\,\text{MeV}$;
  - $T^{a++}_{c\bar{s}}$: $m = 2921 \pm 17 \pm 19\,\text{MeV}$, $\Gamma = 137 \pm 32 \pm 14\,\text{MeV}$





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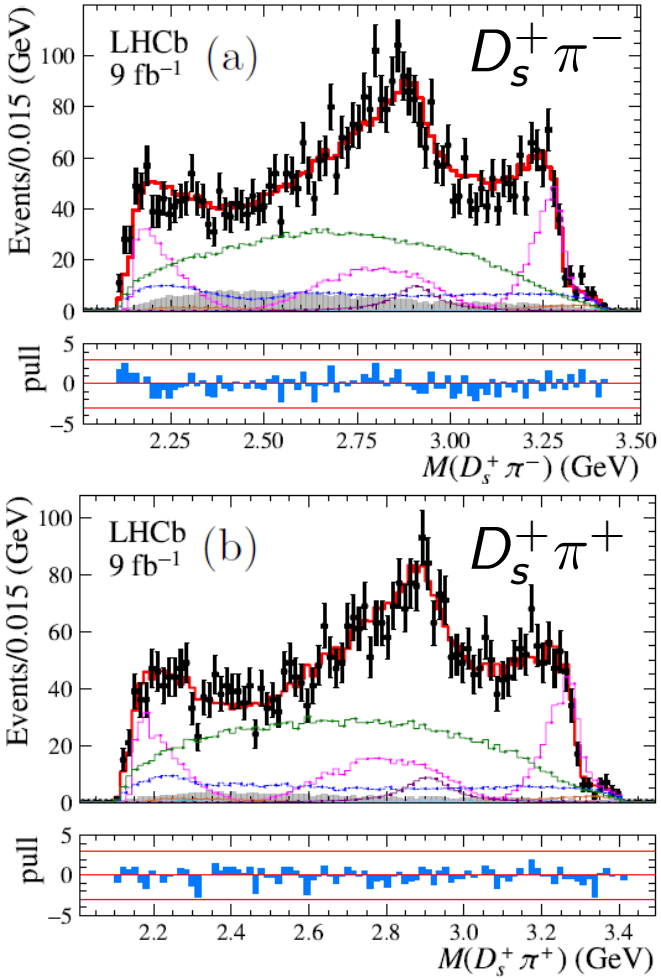


Polarimetry with Λ_c^+ three-body decays

Measuring polarization – general multibody decays?

→ Dalitz-Plot Decomposition (DPD) [MM et al. (JPAC), PRD 101 (2020) 3, 034033]

Factorization of variables describing dynamics and polarization:

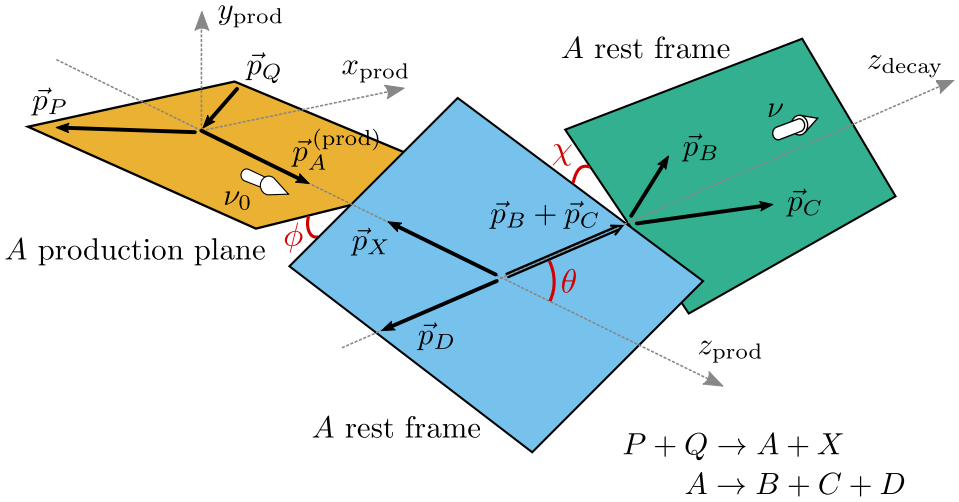
$$T_{\nu_0,\{\lambda\}}(\phi,\theta,\chi;\tau) = \sum_{\nu} D^{1/2}_{\nu_0,\nu}(\phi,\theta,\chi)\, A_{\nu,\{\lambda\}}(\tau)$$

Polarization d.o.f.

- Euler angles in active ZYZ convention
- rotation of the system as rigid body
- polarization affects angular distribution

Dynamic d.o.f.

- Mandelstam variables of the subsystems
- describes resonances in the decay



Polarimetry with $\Lambda_c^+ \to pK^-\pi^+$

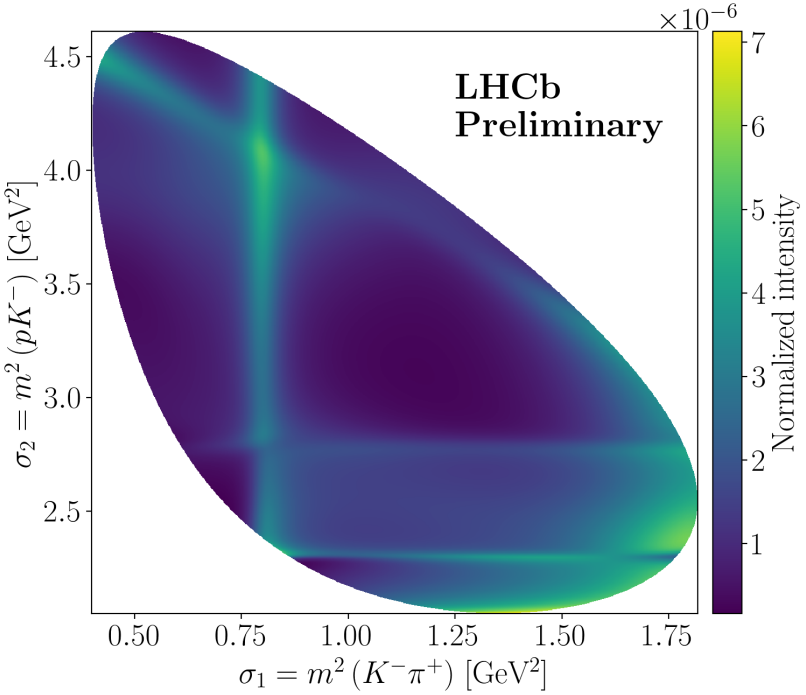
[LHCb, arxiv:2301.07010]

Aligned polarimeter vector field in Dalitz plot coordinates

Polarized decay rate:

$$|\mathcal{M}(\phi,\theta,\chi,\tau)|^2 = I_0(\tau)\left(1+\sum_{i,j=1}^{3} P_i R_{ij}(\phi,\theta,\chi)\alpha_j(\tau)\right)$$

intensity, $I_0(\tau)$



polarimetry field, $\alpha_j(\tau)$