Simon I. Eidelman

Семен Исаакович Эйдельман

1948 - 2021

Preambula

- Doubly charmed tetraquark T_{cc} and all related topics:
  - exotic hadrons
  - hypernuclei
  - future prospects
    → covered in depth at dedicated talks

M. Sarpis and others, today, 14:00, at **Exotic Hadrons** sessions

Plenary talks:
E. Spadaro Norella,
F.K. Guo,
A. Szczepaniak,
S. Prelovsek,
Y. Yamaguchi,
A. Polosa,
H. Tamura,
...

Exotic Hadrons sessions, Mon, Tue, Wed, Th, Fr,

Heavy baryon/meson sessions, Mon, Tue, Wed,

Hypernuclei sessions, Tue, Wed

Doubly charmed tetraquark T_{cc} and new roads it opens

** a personal view on selected keypoints*

Double-charmed tetraquark T_{cc} $[cc\bar{u}\bar{d}]$

- 2021: signal in $D^0D^0\pi^+$ just below D^0D^{*+} threshold

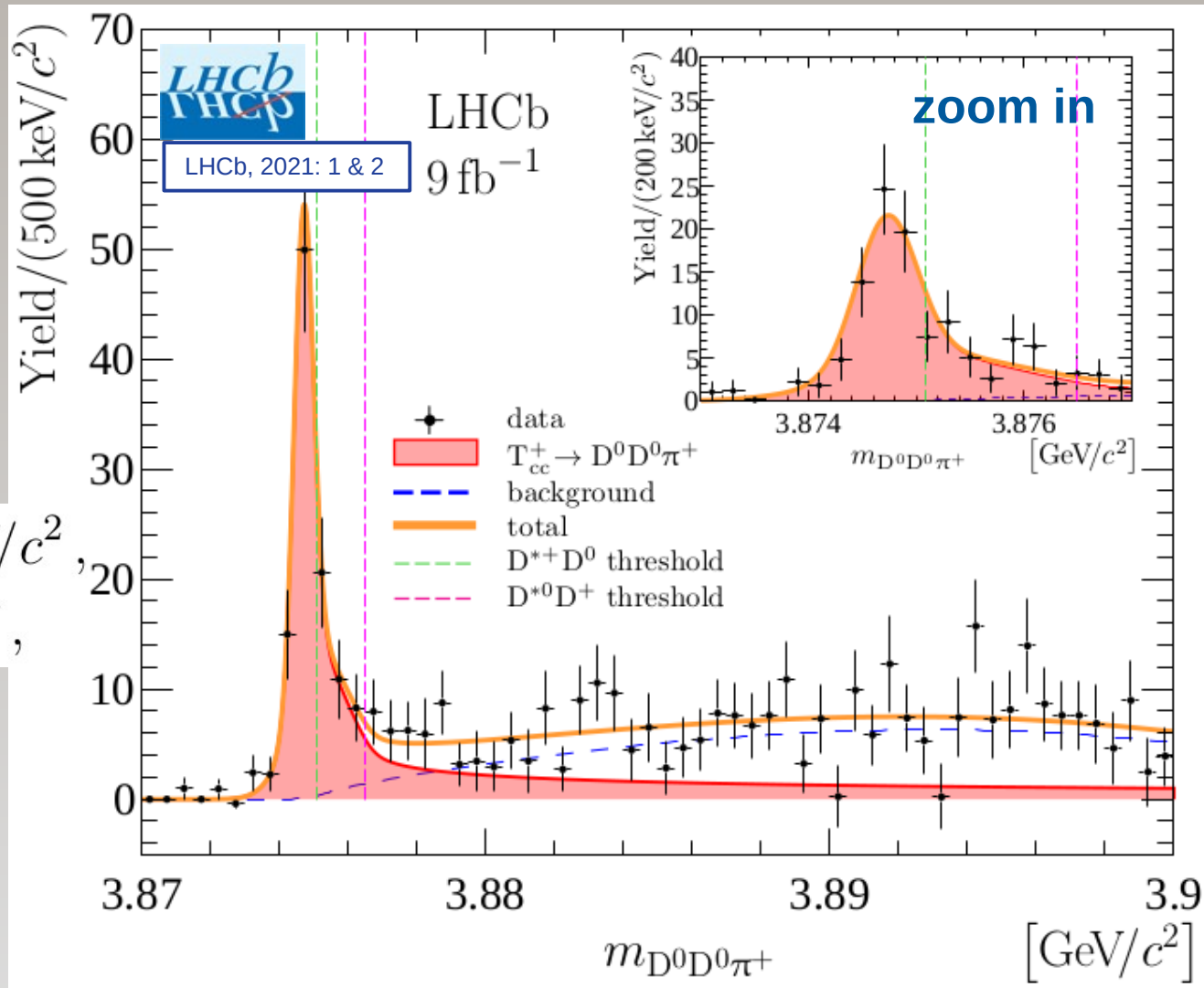
M. Sarpis, today, 14:00

- Model as $T_{cc}^+ \to D^0D^{*+}(\to D\pi)$ for $I(J^P)$ of T_{cc} as $0(1^+)$

  in this model width defined by $\Gamma(D^{*+})$ and δm

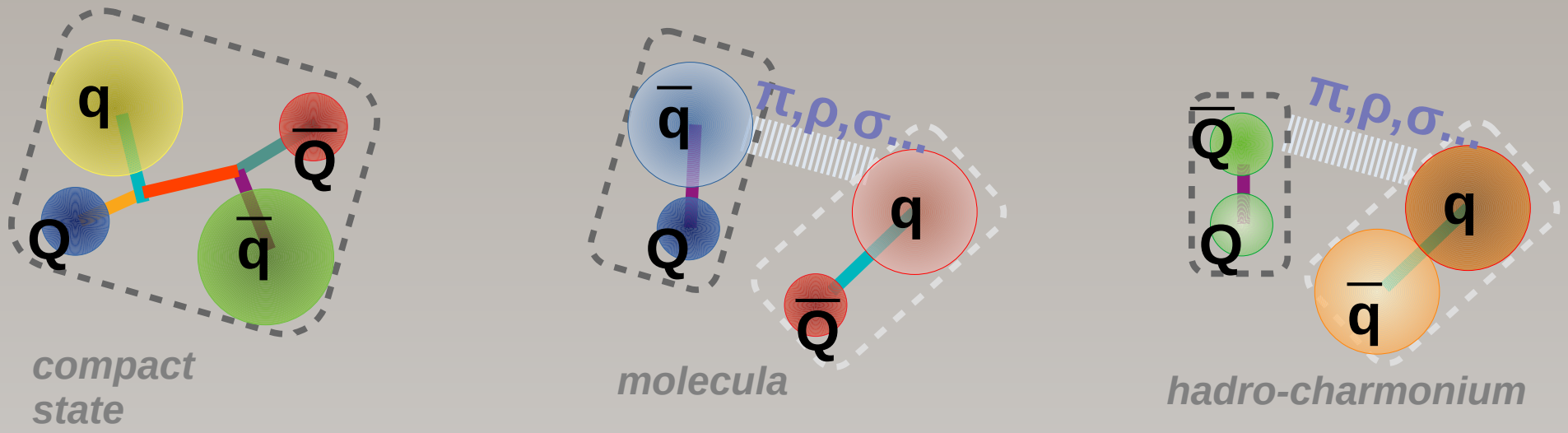
- Results:

$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\ \text{keV}/c^2,$$
$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}\ \text{keV},$$



Exotic hadron configurations

- $Q\bar{Q}q\bar{q}$ tetraquark as example



color of quarks

$$V(q_i q_j) \sim \frac{\lambda_i}{2}\frac{\lambda_j}{2} \quad \Rightarrow \quad V(qq)_{3^*} = \frac{1}{2} V(q\bar{q})_1$$

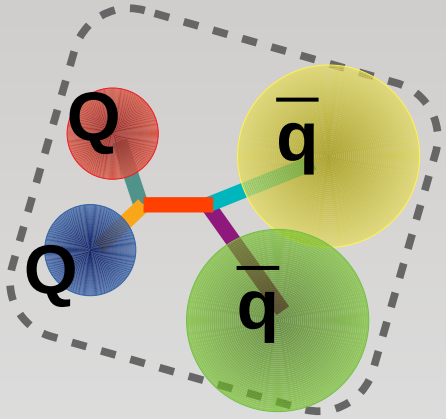
interaction between quarks

diquark

meson

- $QQ\bar{q}'\bar{q}''$ are prime candidates to be tightly bound having compact-state configuration

Adler, Richard, Taxil, 1982 | Ballot, Richard, 1983



Predictions for $cc\bar{u}\bar{d}$ mass

- No consensus if **c**-quark is heavy enough to ensure tightly bound state

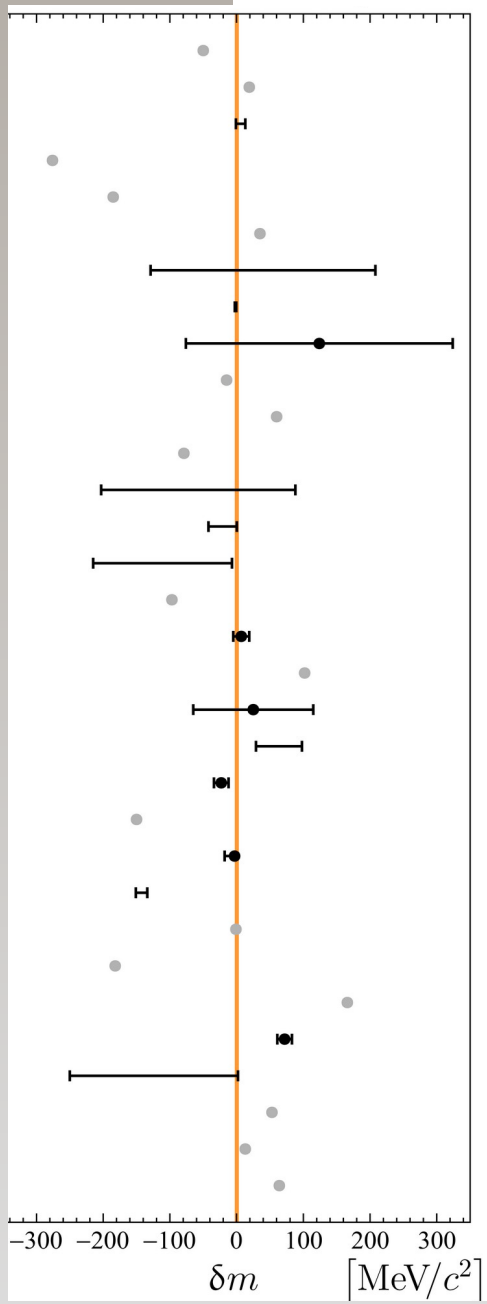
- Predictions for a ground $cc\bar{u}\bar{d}$ state (isoscalar with $J^P=1^+$) vary within ±250MeV wrt to D^0D^{*+} threshold

- The measured mass difference

$$\delta m_{\mathrm{U}} = -359 \pm 40^{+9}_{-6}\,\mathrm{keV}/c^2$$

is consistent with some of predictions

$$\delta m \equiv m_{\mathrm{T}^+_{\mathrm{cc}}} - (m_{\mathrm{D}^{*+}} + m_{\mathrm{D}^0})$$



J. Carlson *et al.*	1987
B. Silvestre-Brac and C. Semay	1993
C. Semay and B. Silvestre-Brac	1994
M. A. Moinester	1995
S. Pepin *et al.*	1996
B. A. Gelman and S. Nussinov	2003
J. Vijande *et al.*	2003
D. Janc and M. Rosina	2004
F. Navarra *et al.*	2007
J. Vijande *et al.*	2007
D. Ebert *et al.*	2007
S. H. Lee and S. Yasui	2009
Y. Yang *et al.*	2009
N. Li *et al.*	2012
G.-Q. Feng *et al.*	2013
S.-Q. Luo *et al.*	2017
M. Karliner and J. Rosner	2017
E. J. Eichten and C. Quigg	2017
Z. G. Wang	2017
W. Park *et al.*	2018
P. Junnarkar *et al.*	2018
C. Deng *et al.*	2018
M.-Z. Liu *et al.*	2019
L. Maiani *et al.*	2019
G. Yang *et al.*	2019
Y. Tan *et al.*	2020
Q.-F. Lü *et al.*	2020
E. Braaten *et al.*	2020
D. Gao *et al.*	2020
J.-B. Cheng *et al.*	2020
S. Noh *et al.*	2021
R. N. Faustov *et al.*	2021

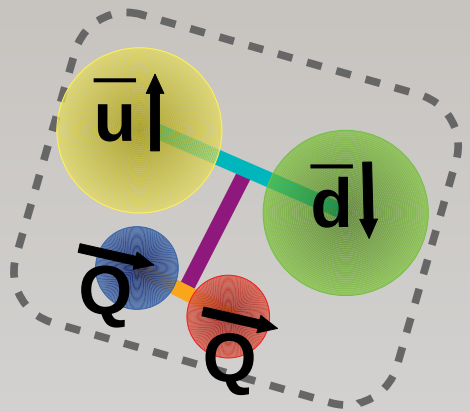
LHCb, 2021: 1 & 2

Notable match 1

- The measured mass difference

$$\delta m_{\mathrm{U}} = -359 \pm 40^{+9}_{-6}\,\mathrm{keV}/c^2$$

- Phenomenology model for compact tetraquark [cc]-[$\bar{u}\bar{d}$]
  - **1±12 MeV**
    - using measured Ξ_{cc} mass to calibrate cc binding
    (δm = 7±12 MeV → 1±12 MeV)
    Karliner, Rosner, 2017



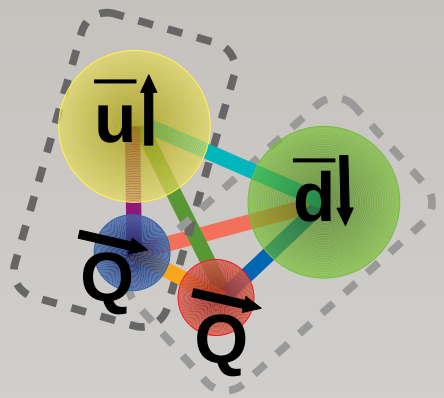
Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	−150.0
cc binding	−129.0
Total	3882.2 ± 12

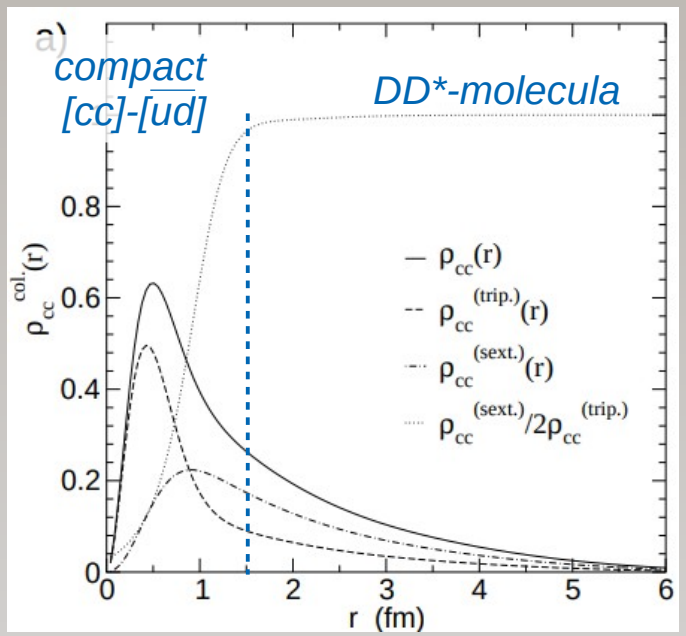
Notable match 2

- The measured mass difference

$$\delta m_{\mathrm{U}} = -359 \pm 40 \,^{+9}_{-6}\,\mathrm{keV}/c^2$$

- NR quark-quark potential model
  - **[-2.7,-0.6] MeV**
    with Bhaduri potential
  - gives insight into wave function: spatial & color configuration
    → dominated by DD* component
    Janc, Rosina, 2003

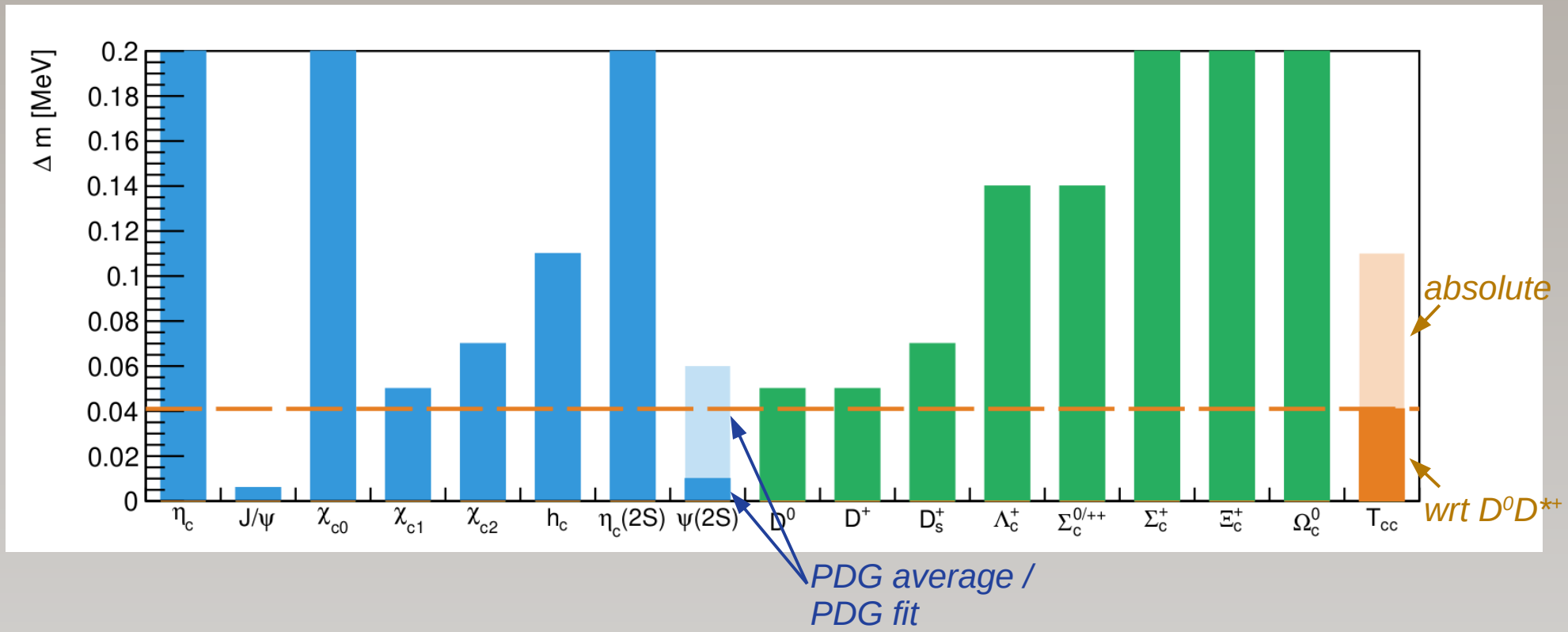




Would love to see a refined calculation

Measured mass precision

- T_{cc} measured mass has the best precision wrt threshold of all exotics
- Gives new input to tune the models



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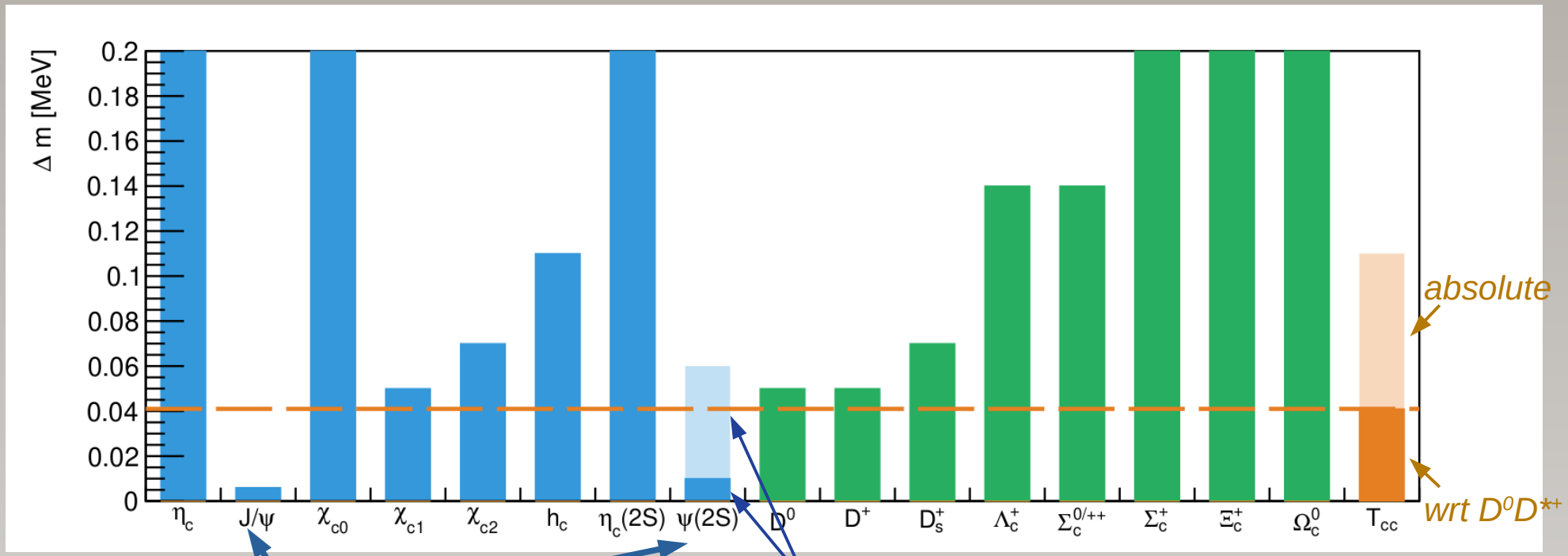
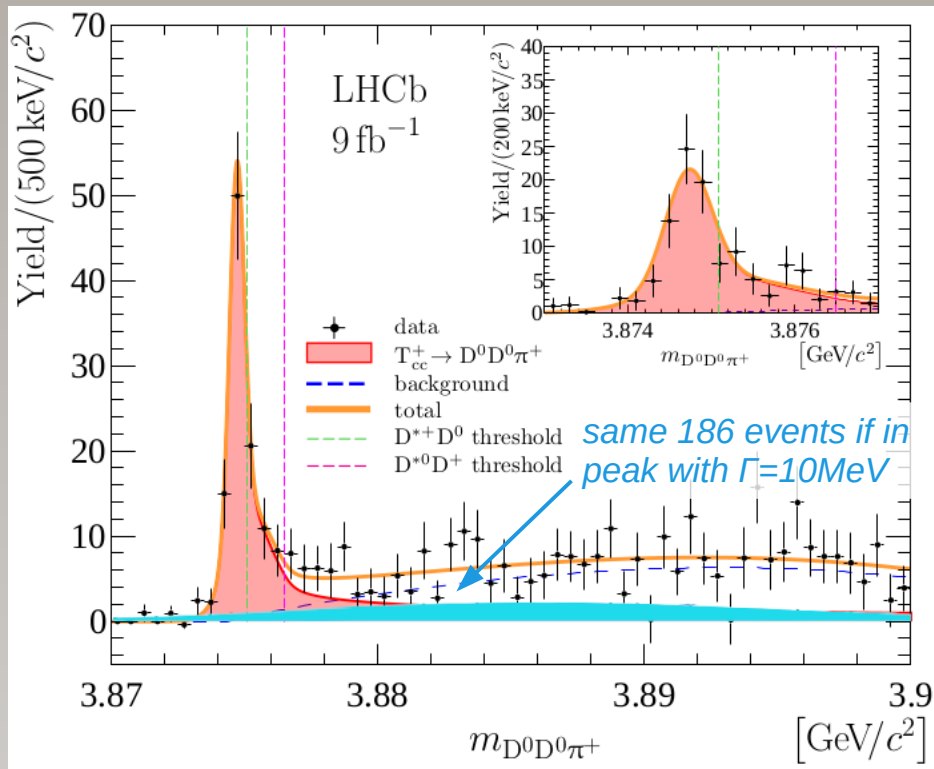


OLYA & KEDR
(1980-2005)
Resonance depolarization method.
With active participation of Simon Eidelman.

T_{cc} shape / width

- 10-100x more narrow than other exotic hadrons, thanks to being below D^0D^{*+} threshold!



- Model assumptions:
  - T_{cc} decays via only DD*
  - $J^P(T_{cc})=1^+$: DD* are in S-wave
  - T_{cc} is isoscalar: $|T_{cc}^+\rangle = \frac{1}{\sqrt{2}}\left(|D^{*+}D^0\rangle - |D^{*0}D^+\rangle\right)$
  - same coupling to D^0D^{*+}/D^+D^{*0}
  - preserve unitarity & analyticity

- Leads to width defined only by $\Gamma(D^{*+})$ and δm
  - our [LHCb] calculation: $\boldsymbol{\Gamma_{pole} = 48 \pm 2^{+0}_{-14}}$ **keV**
  - other theoretical calculations: 38-78 keV

  Lin, Cheng, Zhu | Ling et al. | Feijoo, Liang, Oset | Albaladejo | Du et al. | Ortega et al.

- Experimental probe on width is weak: **30 ≤ Γ ≤ 400 keV** *[unofficial estimation]*

Other doubly-heavy states, $[bb\bar{u}\bar{d}]$

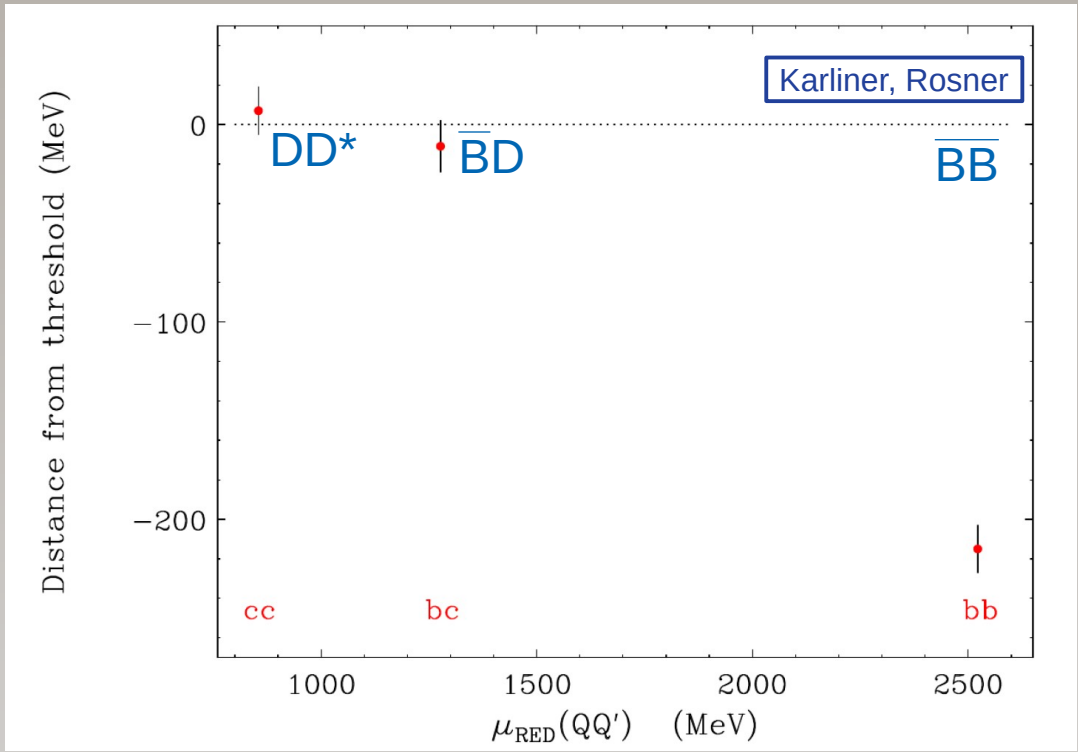
- The T_{cc} below DD* threshold supports predictions for long-lived T_{bb} ***[bb][ud]***

  Semay, SIlvestre-Brac, 1994
  Janc, Rosina, 2003
  Bicudo et al, 2015
  Karliner, Rosner, 2017
  Francis et al., 2017
  Junnarkar, Mathur, Padmanath, 2018

  … and many more

- Suppressed wrt to T_{cc} (150 events):
  - $b\bar{b}b\bar{b}$ production: 1.5%
  - BR($b \to D\pi/\mu$): $(0.1\text{-}1\%)^2$

  → expect yields of only ~10^{-4}



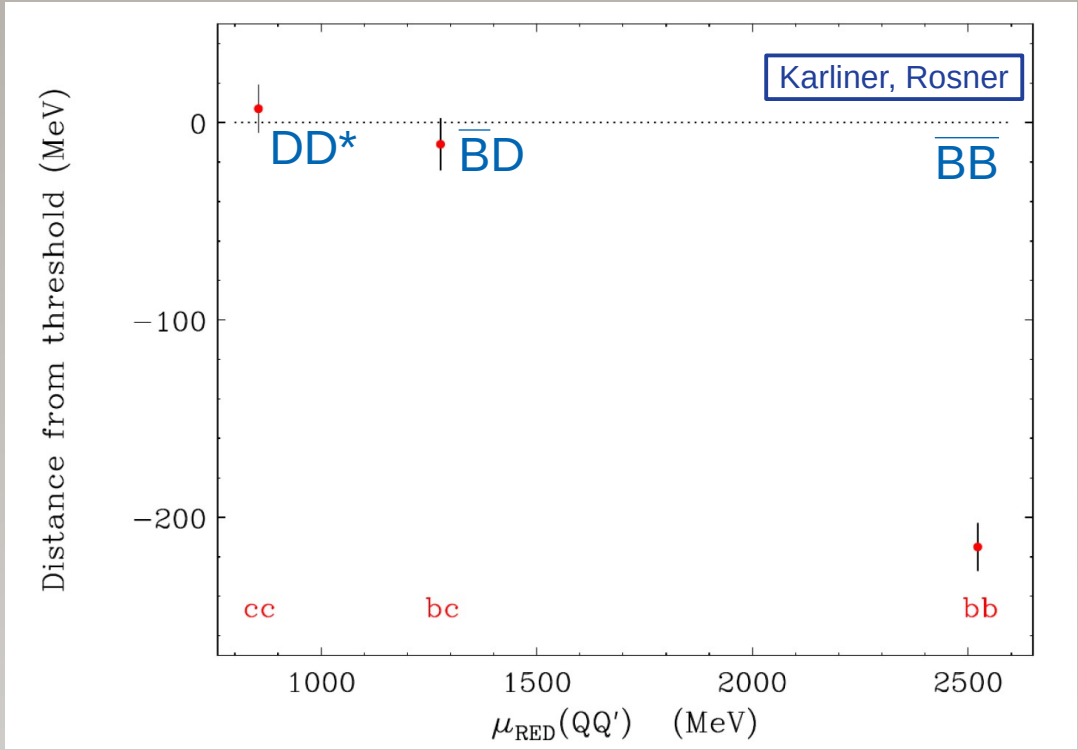
Other doubly-heavy states, $[bc\bar{u}\bar{d}]$

- T_{bc} ***[bc][ūd̄]*** may be below $\bar{B}D$ threshold by O(10) MeV

  Karliner, Rosner, 2017 | Semay, SIlvestre-Brac, 1994 | Liu et al., 2019 | Carames, Vijande, Valcarce, 2019 | Meng et al., 2021

  - Different expectations in some molecula models Li, Sun, Liu, Zhu, 2012 | Hudspith et al., 2020

what your model predicts?



- Prospects for searches at pp (LHC/LHCb) :

  1-10 events per mode in Run3.

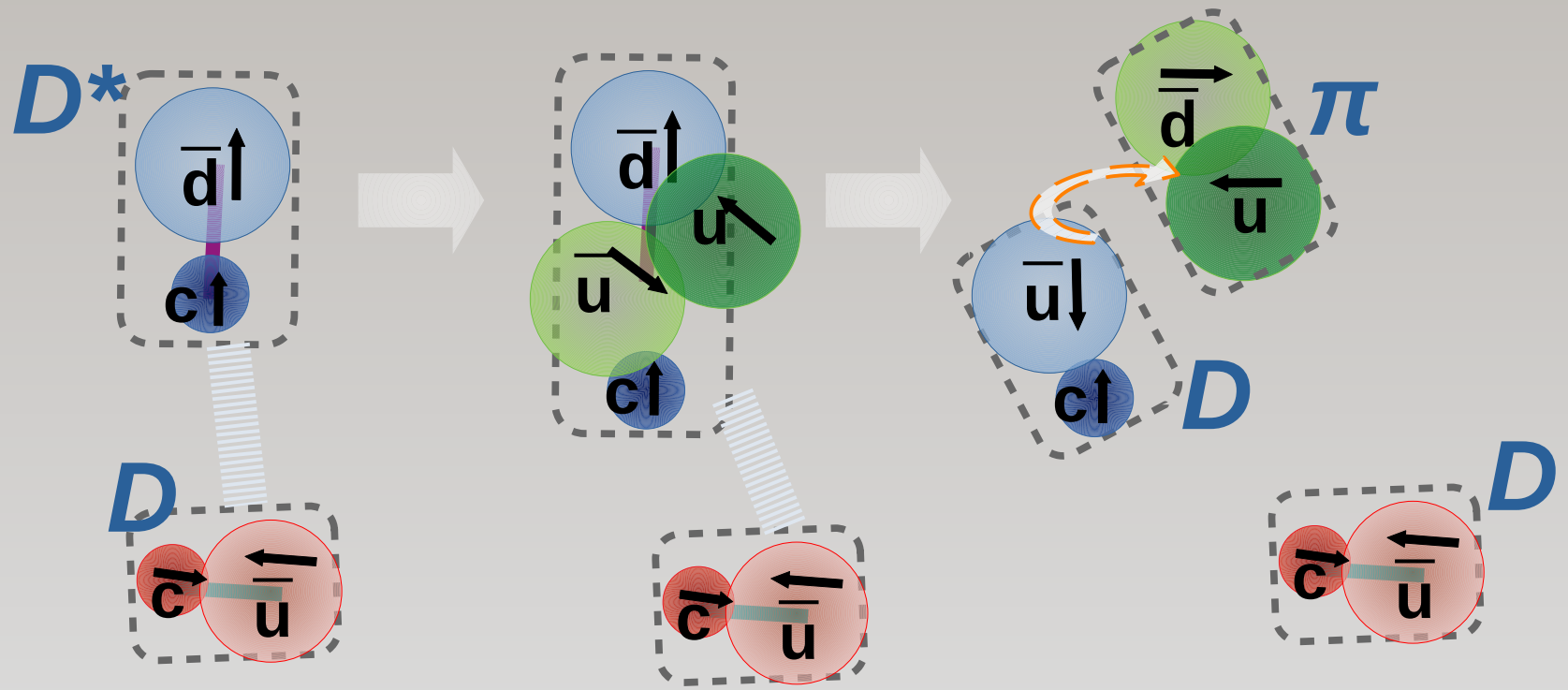
  real chances to find (if combining several modes)

Much more interesting!

Compact component

- T_{cc} looks to be perfectly compatible with molecula

- Can there be a compact-state admixture?
  How it would manifest itself?
  - effect on $T_{cc} \to D^0 D^0 \pi^+$ visible width/shape
  - presence of non-resonant decays $T_{cc} \to [DD]\pi/\gamma$



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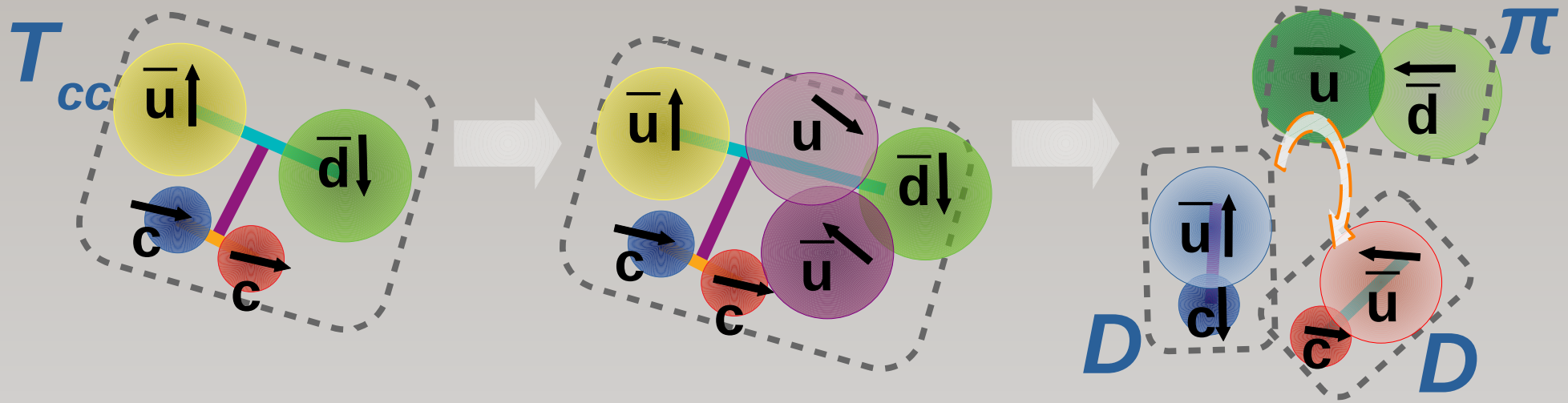


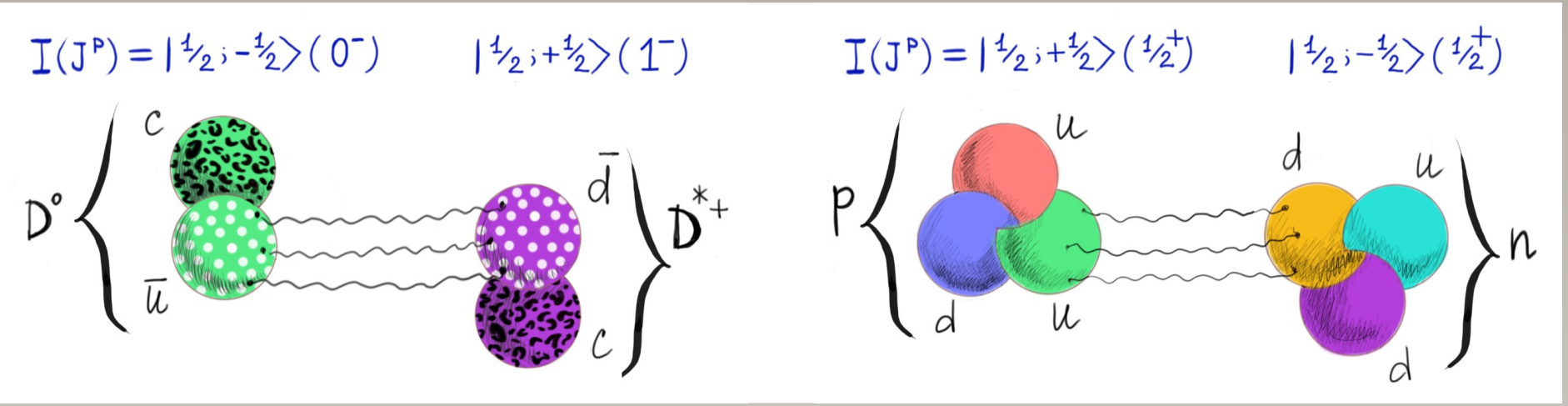
$$\frac{B(T_{cc} \to D D \pi, NR)}{B(T_{cc} \to D D^* [\to D \pi])} \sim P(compact)$$

or $\sim P(r < 1-2\,fm)$?

up to O(10%) for pure molecula

T_{cc} in molecula picture

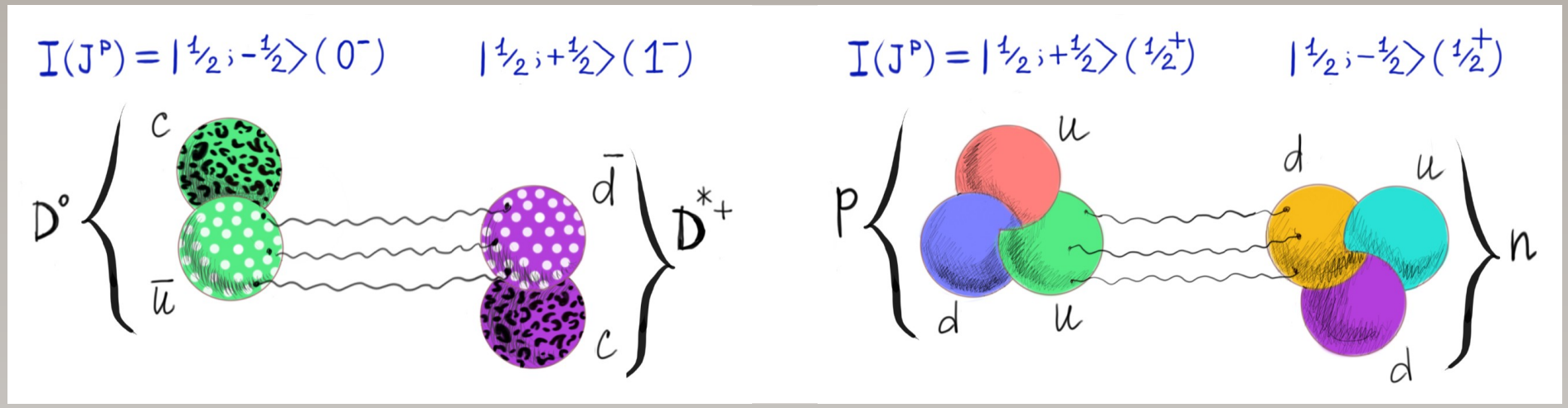
- Compare DD* molecula to deuteron (pn)



Maria Poliakova

T_{cc} in molecula picture

- Compare DD* molecula to deuteron (pn)



- Simplistic sphere-well model:

Maria Poliakova

$a(T_{cc}) = a(d)$

$V_{min}(T_{cc})/V_{min}(d) \sim 0.5$

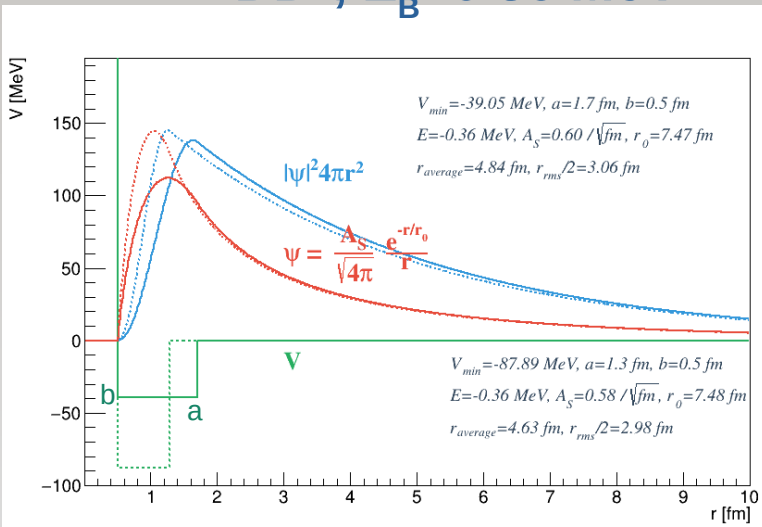
or

$a(T_{cc})/a(d) \sim 0.75$

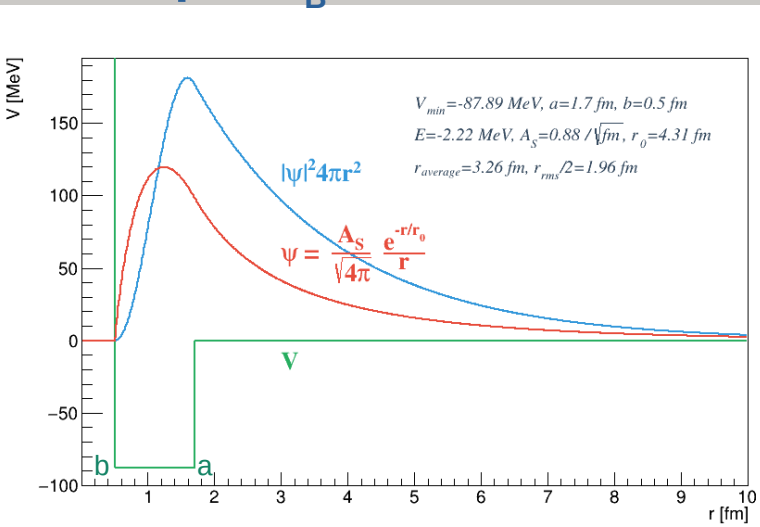
$V_{min}(T_{cc}) = V_{min}(d)$

$r(T_{cc})/r(d) \sim 1.5$

DD*, E_B=0.36 MeV

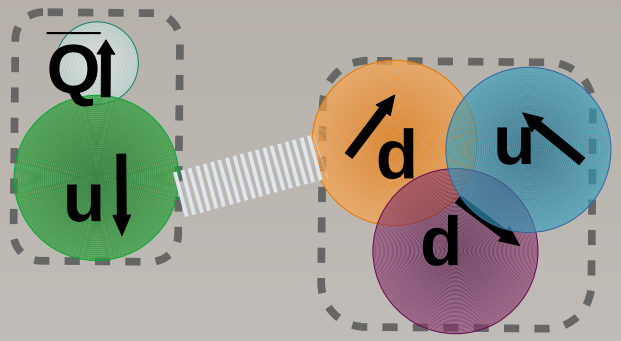


pn, E_B=2.22 MeV



Similar moleculas with heavy quark

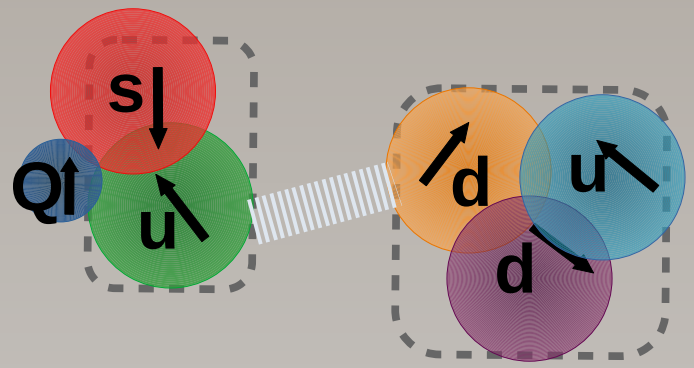
- Baryon-meson molecula with c/b-quark



candidates for stable compact multiquark

Gignoux, Silvestre-Brac, Richard, 1987 | Lipkin, 1987

- Di-baryon molecula with c/b-quark



Dover, Kahana, 1977

- No consensus in community.
  arguments for both ***instability*** and ***stability*** can be found

Pepin, Stancu, 1998 | Park, Park, Lee, 2015 | Vijande et al., 2016

Leandri, Silvestre-Brac, 1993, 1995 | Chow, 1995

Wang et al., 1995 | Stancu, 1999 | Huang, Ping, Wang, 2014 | Park, Cho, Lee, 2018 | Meng, Wang, Zhu, 2020

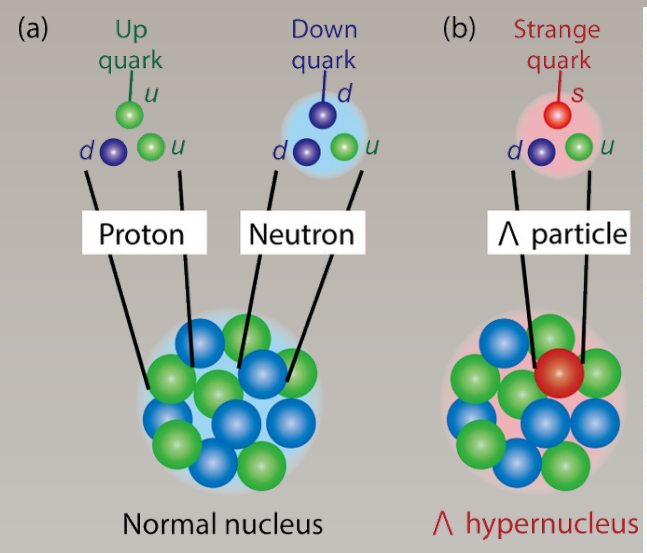
Instability of compact-state → short-range repulsion for molecula?

- Molecula configurations may give ~2-20 MeV binding

Yamaguchi et al., 2011 | Huang, Ping, Wang, 2014

Hypernuclei studies

- Hyper-nuclei with Λ(Σ/ΛΛ) are explored since 50's



Gal, Hungerford, Millener, 2016

Hypernucleus	Number of events	$B_\Lambda \pm \Delta B_\Lambda$ (MeV)
${}^{3}_{\Lambda}$H	204	0.13 ± 0.05
${}^{4}_{\Lambda}$H	155	2.04 ± 0.04
${}^{4}_{\Lambda}$He	279	2.39 ± 0.03
${}^{5}_{\Lambda}$He	1784	3.12 ± 0.02
${}^{6}_{\Lambda}$He	31	4.18 ± 0.10
${}^{7}_{\Lambda}$He	16	not averaged
${}^{7}_{\Lambda}$Li	226	5.58 ± 0.03
${}^{7}_{\Lambda}$Be	35	5.16 ± 0.08
${}^{8}_{\Lambda}$He	6	7.16 ± 0.70
${}^{8}_{\Lambda}$Li	787	6.80 ± 0.03
${}^{8}_{\Lambda}$Be	68	6.84 ± 0.05
${}^{9}_{\Lambda}$Li	8	8.50 ± 0.12
${}^{9}_{\Lambda}$Be	222	6.71 ± 0.04
${}^{9}_{\Lambda}$B	4	8.29 ± 0.18
${}^{10}_{\Lambda}$Be	3	9.11 ± 0.22
${}^{10}_{\Lambda}$B	10	8.89 ± 0.12
${}^{11}_{\Lambda}$B	73	10.24 ± 0.05
${}^{12}_{\Lambda}$B	87	11.37 ± 0.06
${}^{12}_{\Lambda}$C	6	10.76 ± 0.19
${}^{13}_{\Lambda}$C	6	11.69 ± 0.12
${}^{14}_{\Lambda}$C	3	12.17 ± 0.33

- ΛΛ in ${}^{6}_{\Lambda\Lambda}$He & ${}^{10}_{\Lambda\Lambda}$Be seem to provide extra binding (0.7-4.5 MeV)

H. Tamura, Plenary talk

- Stable ΛΛ di-baryon (***H-[uuddss]***) proposed by Jaffe

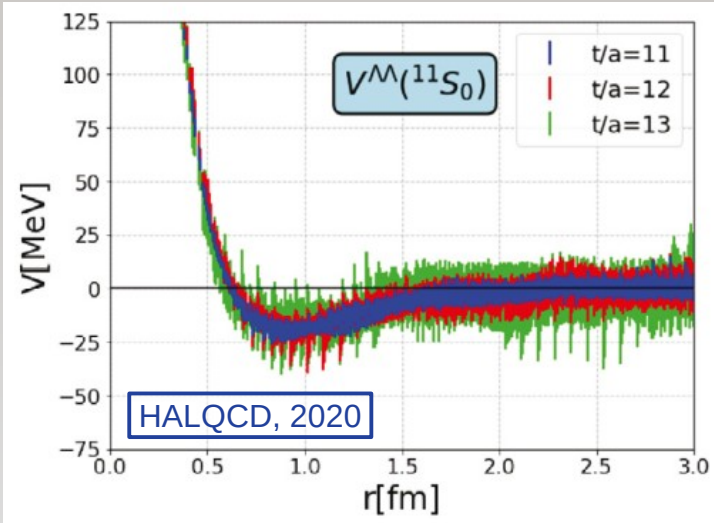
Jaffe, 1977

- Not found yet, but not excluded

Belle, 2013 Chrien, 1998 ALICE, 2015

- Is attraction between ΛΛ strong enough to make bound state?

B(ΛΛ) = 3.2±2.6 MeV ALICE, 2019



Hypernuclei sessions,
T. Nagae, K.Nakazawa, ...
Tue, Wed

Extention with heavy quark

- The $\Lambda_c\Lambda_c$ [uuddcc] bound state has more chances to exist due to ~100 MeV stronger binding between cc quarks * M. Karliner
- Various molecular systems with heavy quark:

lowest threshold

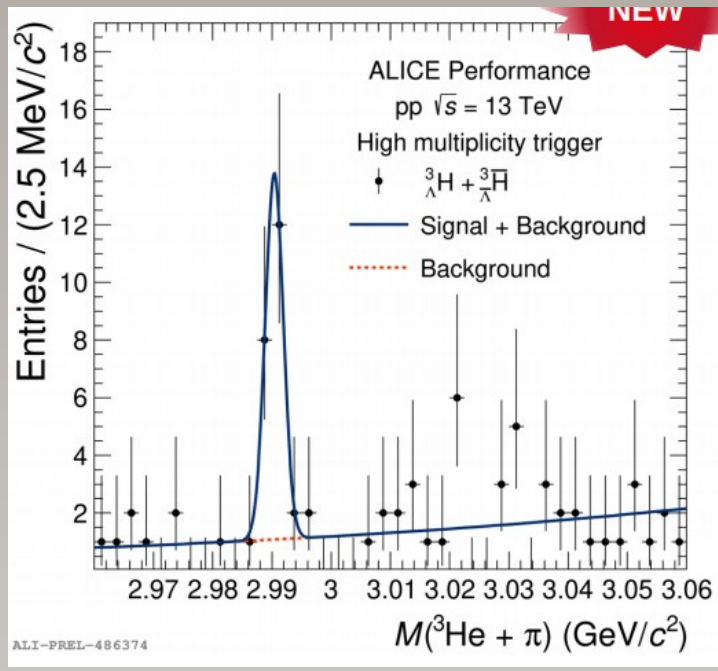
easier to produce

H_{ss} [ssuudd] :	$\Lambda\Lambda$ *2231 MeV*	$\Xi^0 n$ *2254 MeV*
H_{cs} [csuudd] :	$\Lambda_c\Lambda$ *3402 MeV*	$\Xi_c^+ n$ *3407 MeV*
H_{bs} [bsuudd] :	$\Lambda_b\Lambda$ *6735 MeV*	$\Xi_b^0 n$ *6732 MeV*
H_{cc} [ccuudd] :	$\Lambda_c\Lambda_c$ *4573 MeV*	$\Xi_{cc} N$ *4561 MeV*

harder to produce

Experimental feasibility

- ALICE observed hypertriton in both PbPb, pPb and pp collisions
  ALICE, 2021



- LHCb has x50-100 larger statistics of pp-collisions than ALICE

- LHCb has searched for long-lived ***[$\bar{b}$udud] & [$\bar{b}$sudu]*** in J/ψpKπ & J/ψpϕ channels
  σ*BR(pp→P_bX)/σ*BR(pp→Λ_b) < ~ 2 x 10^{-3} LHCb, 2018
  compare to $\sigma(d)/\sigma(p)$~2 x 10^{-3}

- Even more perspectives with charm / double-charm
  → my estimates for LHCb:
  O(10^5) candidates for $H_{c(s)}$, O(10^3-10^4) for $H_{b(s)}$ and O(10-100) for H_{cc}
  → O(10^4) H_c for ALICE J. Stachel, talk

Conclusion

- Double heavy tetraquarks provide new directions for spectroscopy studies
- T_{bc} ***[bc$\overline{u}\overline{d}$]*** likely be most important measurement of next 5-10 years in the field
- LHC gives opportunity to converge the studies of heavy tetra/penta/hexa-quarks and hypernuclei

nature physics

LETTERS

https://doi.org/10.1038/s41567-022-01614-y

Check for updates

OPEN

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

This Letter is dedicated to the memory of our dear colleague Simon Eidelman, whose friendship, deep physics insights and contributions to improving the quality of our papers were greatly appreciated and will be missed. We express our gratitude to our

Backup

T_{cc} low-range expansion

- Within model make expansion near pole and extract low-energy scattering parameters

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

A. Polosa, Wed

- scattering length: $a = \left[-(7.16 \pm 0.51) + i\,(1.85 \pm 0.28)\right]$ fm
- effective range: $0 \;\leq\; -r < 11.9\,(16.9)$ fm at $90\,(95)\%$ CL

- compositness (molecular component): $X = 1/\sqrt{1 + 2r/a}$

  - LHCb: **X > 0.48 at 90% CL**
  - re-calculation in same model: **0.44 < X < 0.91 at 90%CL** Mikhasenko

  - other models: **X = 0.84±0.06** Du et al. , **X = 0.83-0.90** Albaladejo

  - does any X != 1 indicates compact nature? Maiani

How much there is DD* in pure DD* molecula?

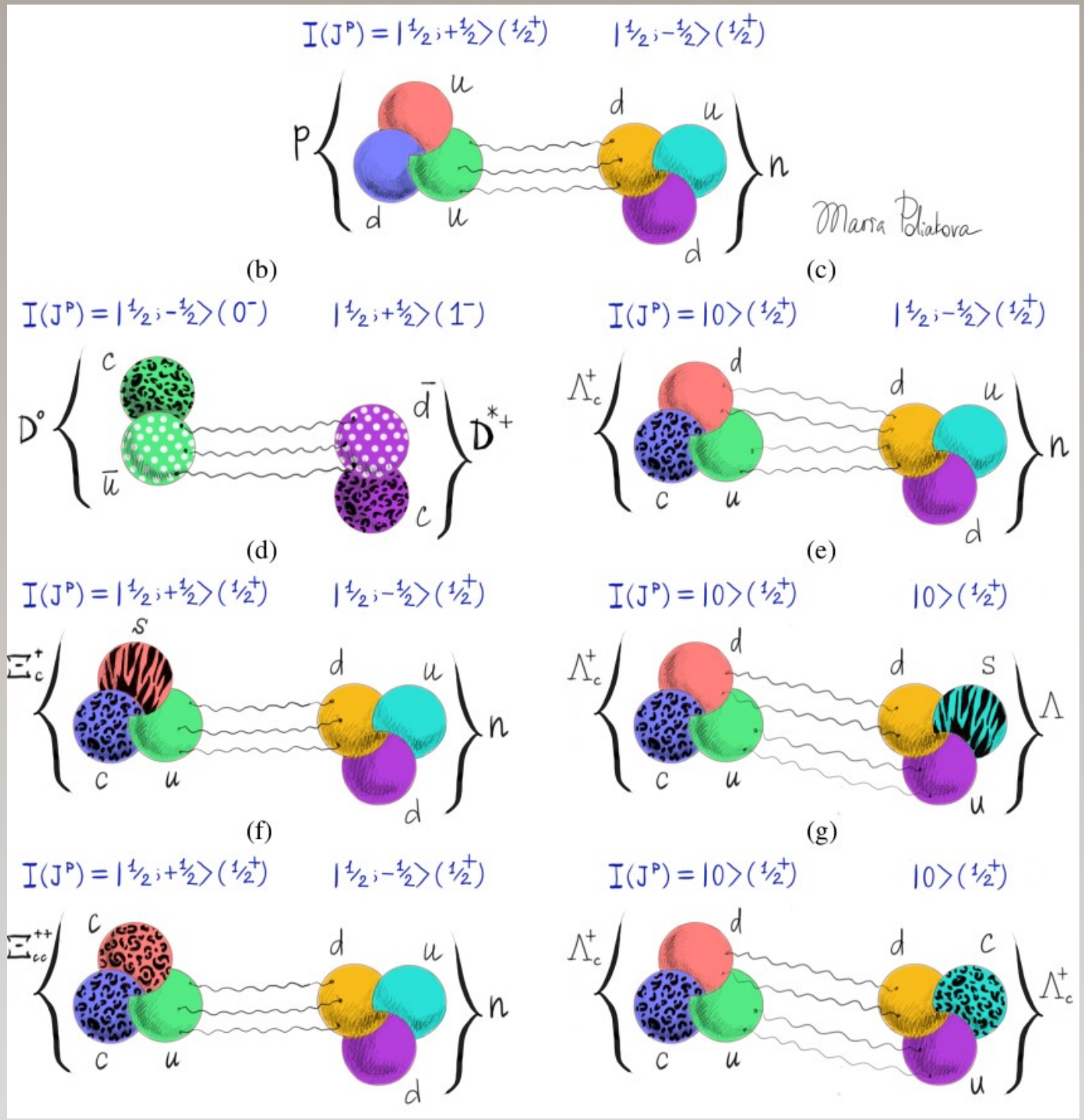
see more details in MITP Workshop, 2022

E. Oset / V. Baru, today, 14:30

L. Dai, today, 17:50

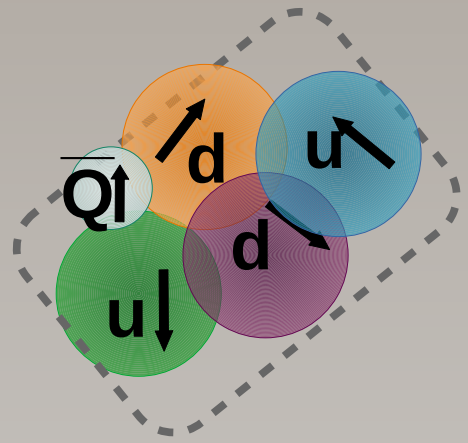
Various moleculas

- Note similarities in (iso)spin configurations

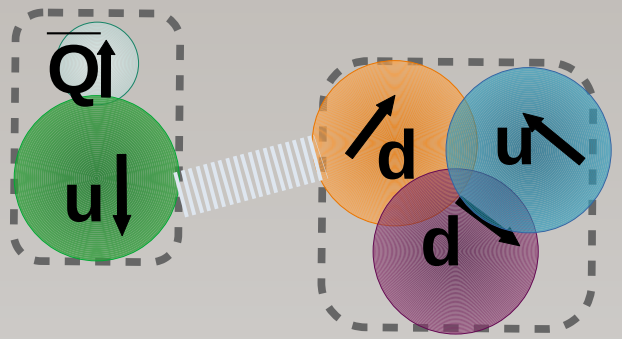


Pentaquark / Baryon-Meson

- **[$\bar{Q}$udud], [$\bar{Q}$sudu], Q=c/b**
  - candidates for stable compact pentaquark
  Gignoux, Silvestre-Brac, Richard, 1987 | Lipkin, 1987



- May be bound
  [$\bar{c}$udud], [$\bar{b}$udud] - repulsive
  [$\bar{c}$suud], [$\bar{c}$suud] - E_B~ 70-100 MeV
  ...or not...
  Park, Cho, Lee, 2018
  Vijande et al., 2016



- In molecula picture
  DN [$\bar{c}$u][dud], E_B~ 2 MeV
  BN [$\bar{b}$u][dud], E_B~ 20 MeV
  Yamaguchi et al., 2011

- LHCb has searched for long-lived ***[$\bar{b}$udud] & [$\bar{b}$sudu]***
  σ*BR(pp$\rightarrow P_b X$)/σ*BR(pp$\rightarrow \Lambda_b$) < ~ 2 x 10^{-3} LHCb, 2018

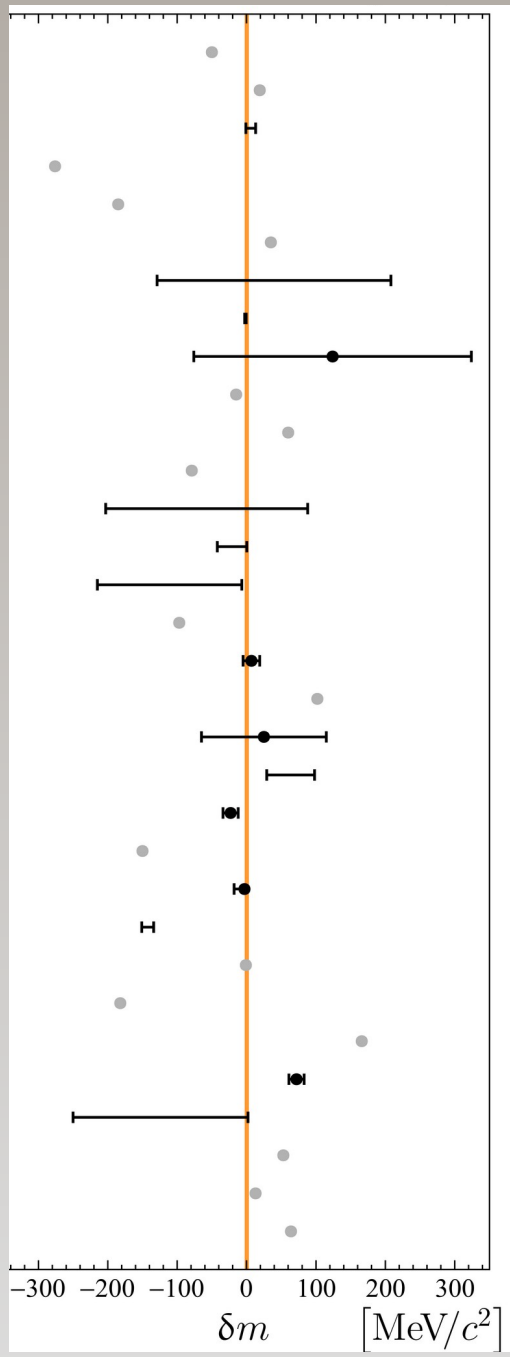
Measured mass, notable matches

- The measured mass difference

$$\delta m_{\mathrm{U}} = -359 \pm 40^{+9}_{-6}\,\mathrm{keV}/c^2$$

is consistent with some of predictions.

- Few notable matches for δm predictions:
  - **[-1,+13] MeV** Semay, SIlvestre-Brac, 1994
    (NR quark-quark potential model)
    false prediction (1993) for spin-0&1 $c\bar{c}q\bar{q}$ states with masses ~3300-3400 MeV
  - **[-2.7,-0.6] MeV** Janc, Rosina, 2003
    (NR quark-quark potential model)
    -0.6 MeV corresponds to Bhaduri potential
  - **[-42.1;+0.3] or [-18;+1] MeV**
    (OME exchange in DD molecula)*
    Li, Sun, Liu, Zhu, 2012 | Liu, Wu, Valderrama, Xie, Geng, 2019
  - **1±12 MeV** Karliner, Rosner, 2017
    (phenomenology model for compact tetraquark)
  - **-23±11 MeV** Junnarkar, Mathur, Padmanath, 2018
    (Lattice QCD)



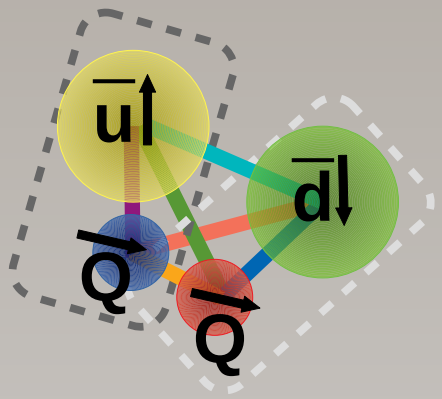
J. Carlson *et al.*	1987
B. Silvestre-Brac and C. Semay	1993
C. Semay and B. Silvestre-Brac	1994
M. A. Moinester	1995
S. Pepin *et al.*	1996
B. A. Gelman and S. Nussinov	2003
J. Vijande *et al.*	2003
D. Janc and M. Rosina	2004
F. Navarra *et al.*	2007
J. Vijande *et al.*	2007
D. Ebert *et al.*	2007
S. H. Lee and S. Yasui	2009
Y. Yang *et al.*	2009
N. Li *et al.*	2012
G.-Q. Feng *et al.*	2013
S.-Q. Luo *et al.*	2017
M. Karliner and J. Rosner	2017
E. J. Eichten and C. Quigg	2017
Z. G. Wang	2017
W. Park *et al.*	2018
P. Junnarkar *et al.*	2018
C. Deng *et al.*	2018
M.-Z. Liu *et al.*	2019
L. Maiani *et al.*	2019
G. Yang *et al.*	2019
Y. Tan *et al.*	2020
Q.-F. Lü *et al.*	2020
E. Braaten *et al.*	2020
D. Gao *et al.*	2020
J.-B. Cheng *et al.*	2020
S. Noh *et al.*	2021
R. N. Faustov *et al.*	2021

[see Refs. here]

Non-relativistic quark constituent model

- Solve Schrodinger equation considering interaction between every pair of quarks

$$H = \sum_i \left(m_i + \frac{\mathbf{p}_i^2}{2m_i} \right) - \frac{3}{16} \sum_{i<j} \tilde{\lambda}_i \tilde{\lambda}_j v_{ij}(r_{ij})$$



- Different variants for exact potential are used (modifications of Cornell potential)

$$V_{ij}^B = -\frac{\lambda_i^C}{2} \cdot \frac{\lambda_j^C}{2} \left(U_0 + \frac{\alpha}{r_{ij}} + \beta r_{ij} + \alpha \frac{\hbar^2}{m_i m_j c^2} \frac{e^{-r_{ij}/r_0}}{r_0^2 r_{ij}} \sigma_i \cdot \sigma_j \right),$$

$$r_{ij} = |\vec{r}_i - \vec{r}_j|;$$

color of quarks

one-gluon exchange ("Couloumb")

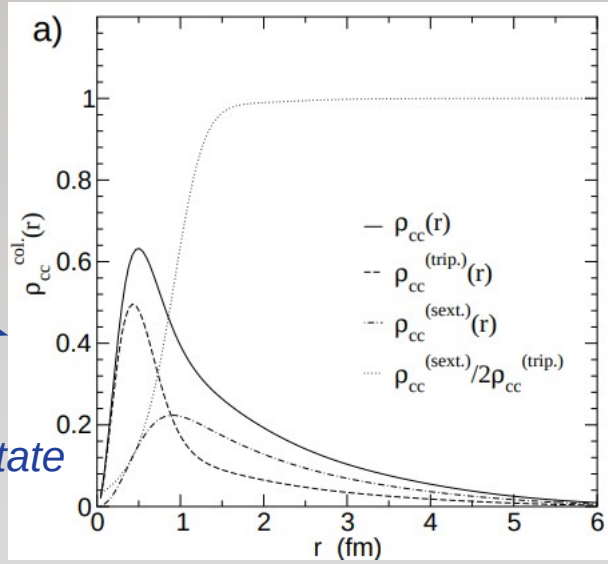
confinement

contact spin-spin interaction

- Results
  - → **δm = [-1;+13] MeV** Semay, SIlvestre-Brac, 1994
    δm = [-2.7;-0.6] MeV Janc, Rosina, 2003
    … + more within [-200;+100] MeV range

(choice of basic, parameters, ...)

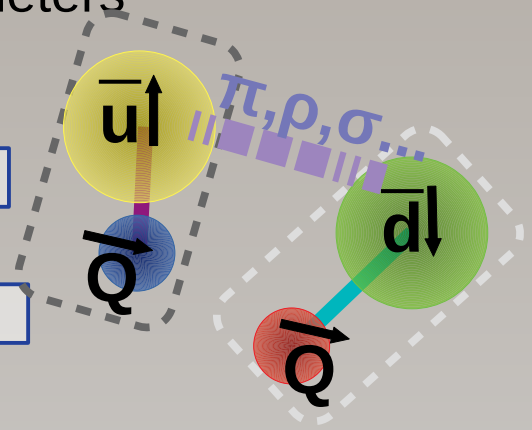
gives insight into wave-function: spatial & color configuration, fractions of molecula/compact state



Molecula object

- Consider one-boson-exchange between DD* forming a molecula
  - get (much stonger) binding depending on particular parameters (mainly cut-off value Λ~1GeV (0.2fm))

δm = [-332;-185] MeV Pepin, Stancu, Genovese, Richard, 1996
= [-42;0.3] MeV Li, Sun, Liu, Zhu, 2012
= [-18;+1] MeV Wu,Liu, Wu, Valderrama, Xie, Geng, 2019



- 2&3. Adding meson-exchange (π, ρ, K, σ, η, ...) terms to the potential in NR model (quark-quark interaction)
  - results vary a lot, indicate 100-200 MeV increase in binding wrt no-OBE,

δm = -129 MeV Vijande, Fernandez, Valcarce, Silvestre-Brac, 2003
= -15 MeV Vijande, Weissman, Valcarce, Barnea, 2007
= -203 MeV Yang, Deng, Ping, Goldman, 2009
= [-150;-1] MeV Yang, Ping, Segovia, 2019

(though do not agree with other calculations w/o OBE)

T_{cc}. Summary of Results

- A narrow peak in $D^0D^0\pi^+$ below D^0D^{*+} threshold is observed with S>20σ
- Naive BW parameters:

$$\begin{aligned} \delta m_{\rm BW} &= -273 \pm 61 \pm 5\,^{+11}_{-14}\,{\rm keV}/c^2\,, \\ \Gamma_{\rm BW} &= 410 \pm 165 \pm 43\,^{+18}_{-38}\,{\rm keV}\,, \end{aligned}$$

- Consistent with $[cc\bar{u}\bar{d}]$ isoscalar tetraquark T_{cc}^+ with $J^P=1^+$ for which

$$\delta' m_0 = -359 \pm 40\,^{+9}_{-6}\,{\rm keV}/c^2$$

  is determined using dedicated model

- A lower limit is set on $T_{cc}^+ \to DD^*$ coupling: $|g| > 5.1\,(4.3)\,{\rm GeV}$ at $90\,(95)\,\%$ CL

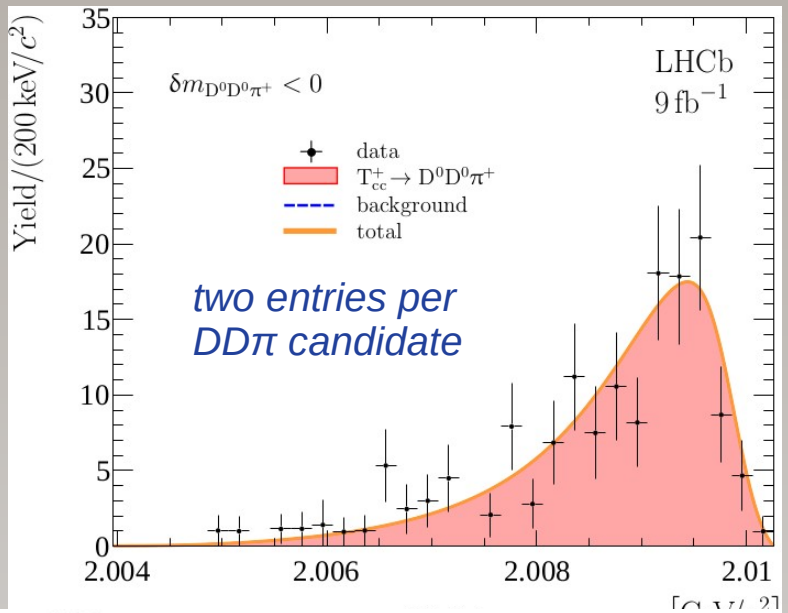
- Threshold structures observed in D^0D^0 and D^0D^+ are found to be consistent with $T_{cc}^+ \to D^0D^{0/+}\pi^{+/0}/\gamma$ decays via off-shell D* mesons
- Matching to low-energy DD* scattering amplitude we get

- Pole position:

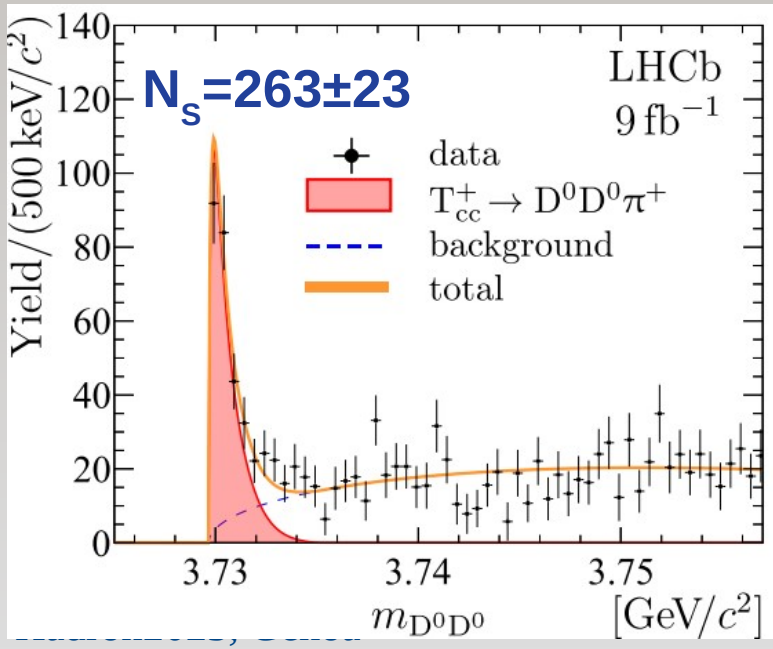
$$\begin{aligned} \delta' m_{\rm pole} &= -360 \pm 40\,^{+4}_{-0}\,{\rm keV}/c^2\,, \\ \Gamma_{\rm pole} &= 48 \pm 2\,^{+0}_{-14}\,{\rm keV}\,, \end{aligned}$$

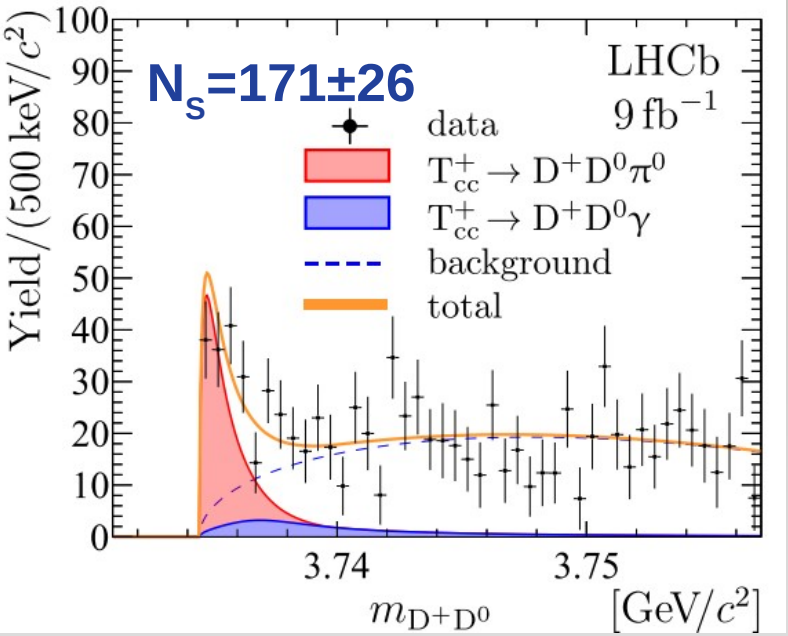
Confirm decay structure

- Integrate decay model over $D^0D^0\pi^+$ and $D^0D^0/D^0\pi/\gamma$ masses
  → obtain $D^0\pi^+$, D^0D^0 and D^0D^+ shapes



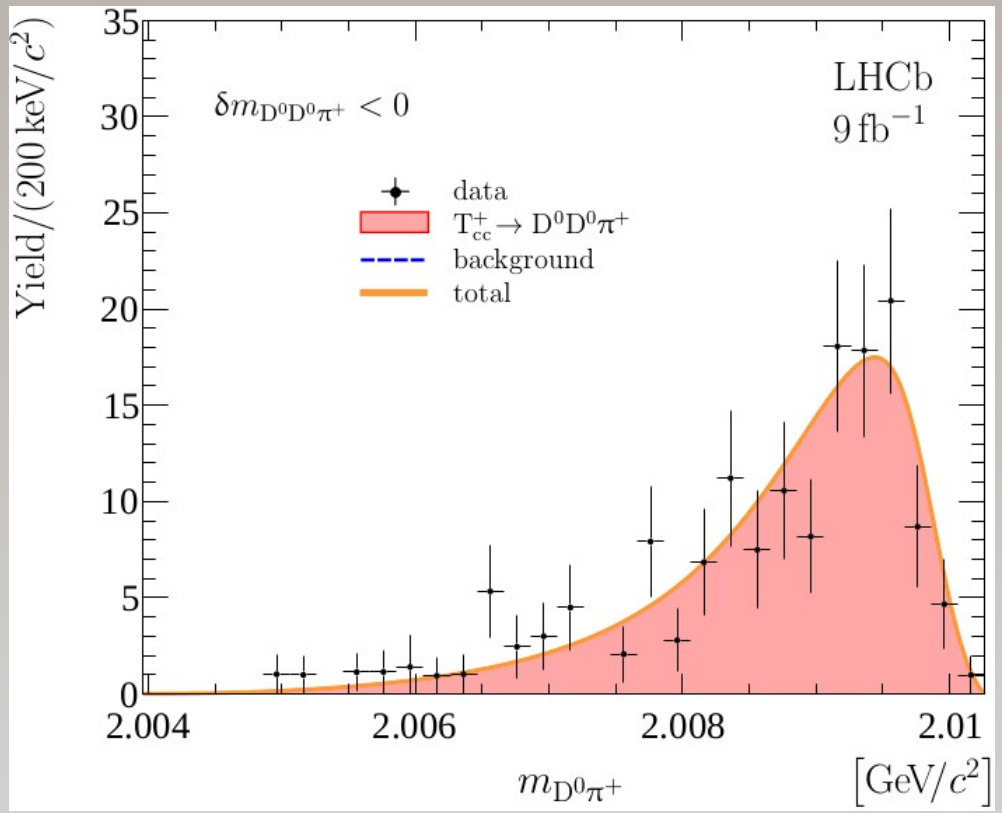
- Perfect agreement supports the assumptions:
  - $T_{cc} \to DD^*$ decaying via off-shell D^*
  - $J^P=1^+$ and I=0 assignement for T_{cc}

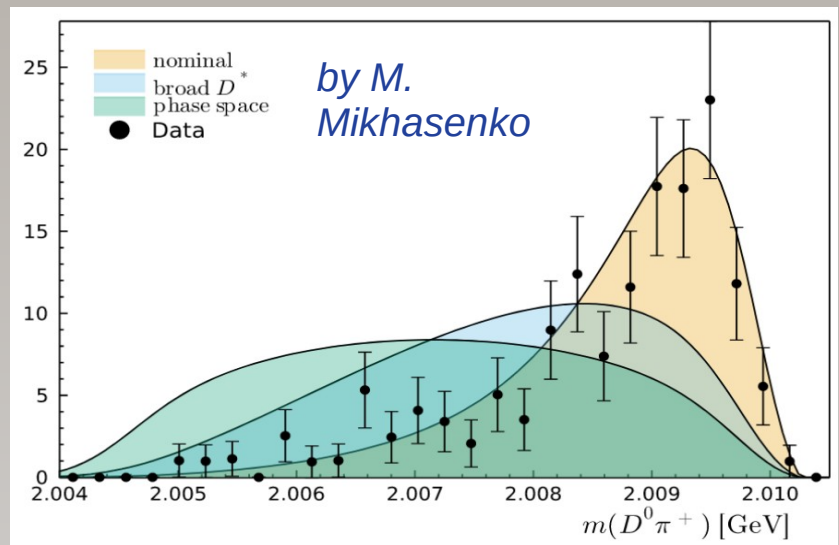


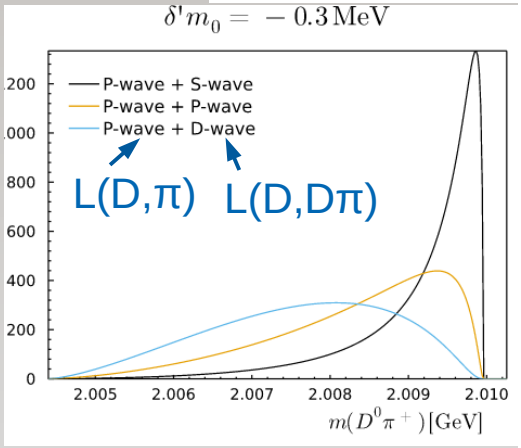


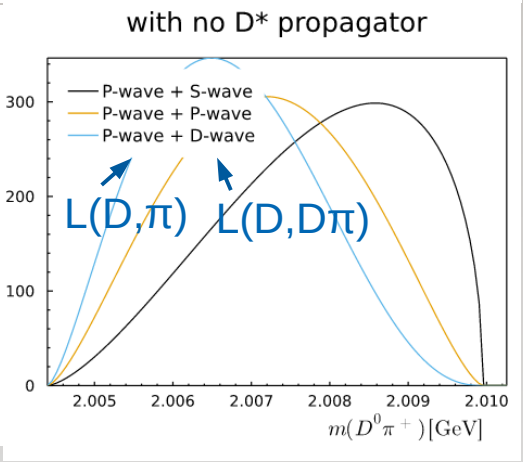
Offshell D*+

- Integrate unitarized model over $D^0D^0\pi^+$ and D^0D^0 masses
  → obtain $D^0\pi^+$ shape









Perfect agreement confirms

- $T_{cc} \to DD^*$ decaying via off-shell D*
- and the $J^P=1^+$ assignement for T_{cc}

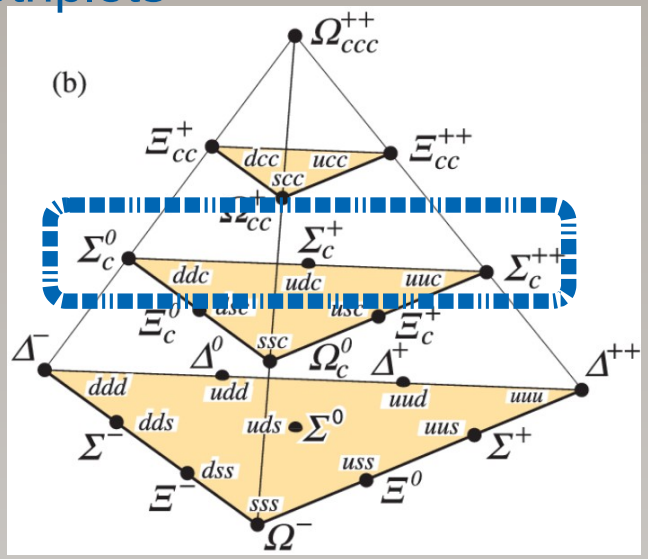
T_{cc} isospin

- If assume that $X \to D^0 D^0 \pi^+$ signal is part of an iso-triplet, then one can estimate masses of its partners to be:

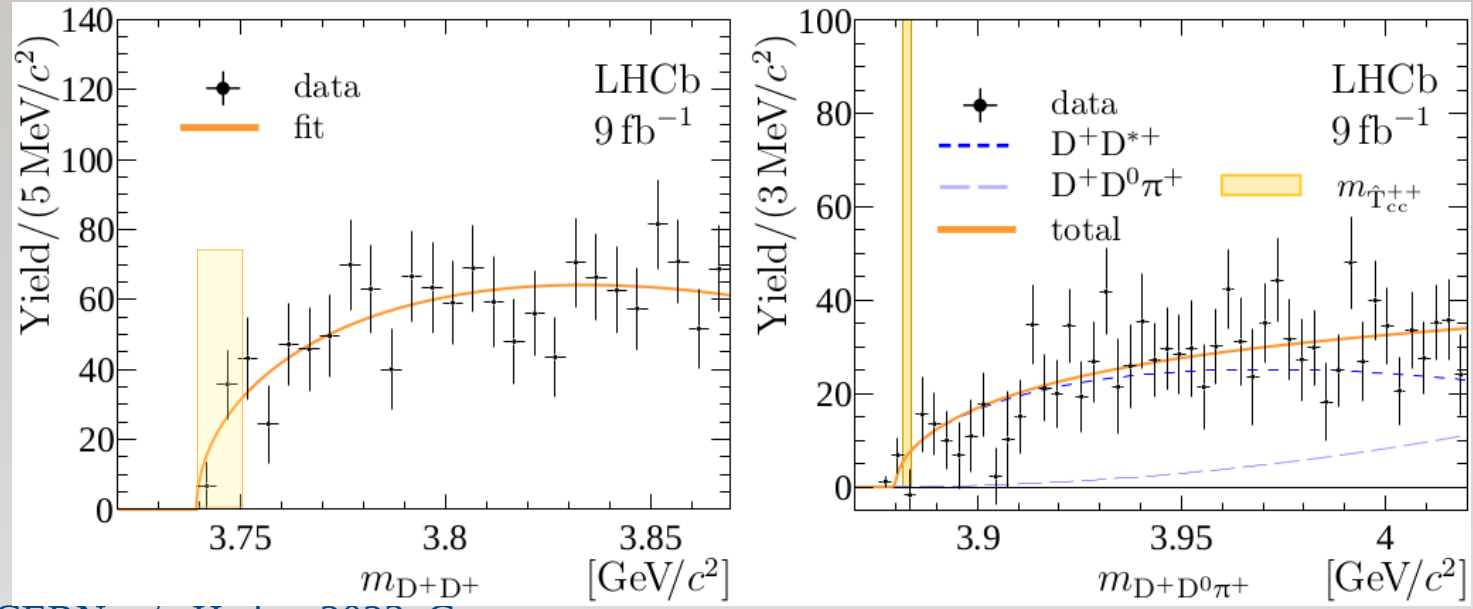
from Σ_b and Σ_c isotriplets

$$
\begin{aligned}
m_{\hat{T}^0_{cc}} &= m_{\hat{T}_{cc}} + m_u + m_u - a'\, q_{\bar{u}} q_{\bar{u}} - b'\, q_{cc}\,(q_{\bar{u}} + q_{\bar{u}}) \\
m_{\hat{T}^+_{cc}} &= m_{\hat{T}_{cc}} + m_u + m_d - a'\, q_{\bar{u}} q_{\bar{d}} - b'\, q_{cc}\,(q_{\bar{u}} + q_{\bar{d}}) \\
m_{\hat{T}^{++}_{cc}} &= m_{\hat{T}_{cc}} + m_d + m_d - a'\, q_{\bar{d}} q_{\bar{d}} - b'\, q_{cc}\,(q_{\bar{d}} + q_{\bar{d}})
\end{aligned}
$$

$$
\begin{aligned}
m_{\hat{T}^0_{cc}} - (m_{D^0} + m_{D^{*0}}) &= -2.8 \pm 1.5\ \mathrm{MeV}/c^2 \\
m_{\hat{T}^{++}_{cc}} - (m_{D^+} + m_{D^{*+}}) &= 2.7 \pm 1.3\ \mathrm{MeV}/c^2
\end{aligned}
$$



- Should therefore see a comparable peak from $T_{cc}^{++} \to D^+ D^{*+}$ decay (100-200 events) in D^+D^+ and $D^+D^0\pi^+$, no signal is seen



Production vs track multuplicity

- Can expect that T_{cc}^{+} has some propoerties similar to $\chi_{c1}(3872)$
- For $\chi_{c1}(3872)$ production a suppression wrt $\psi(2S)$ was observed at high track multiplicities
- Explained in comover model where $\chi_{c1}(3872)$ is broken by closely flying pions/gluons
- Therefore probing effective Qπ break-up cross-section:

$$\langle v\sigma_{\psi'} \rangle = 3.9 \pm 0.8 \text{ mb}$$

and fractions

$$\langle v\sigma_X \rangle = 2.6 \pm 0.7 \text{ mb}$$

of Q out of reach of comovers

$$f_{\text{out},\psi'} = 0.40 \pm 0.03 \text{ and } f_{\text{out},X} = 0.18 \pm 0.04$$

more details in Braaten et al., arXiv:2021.13499

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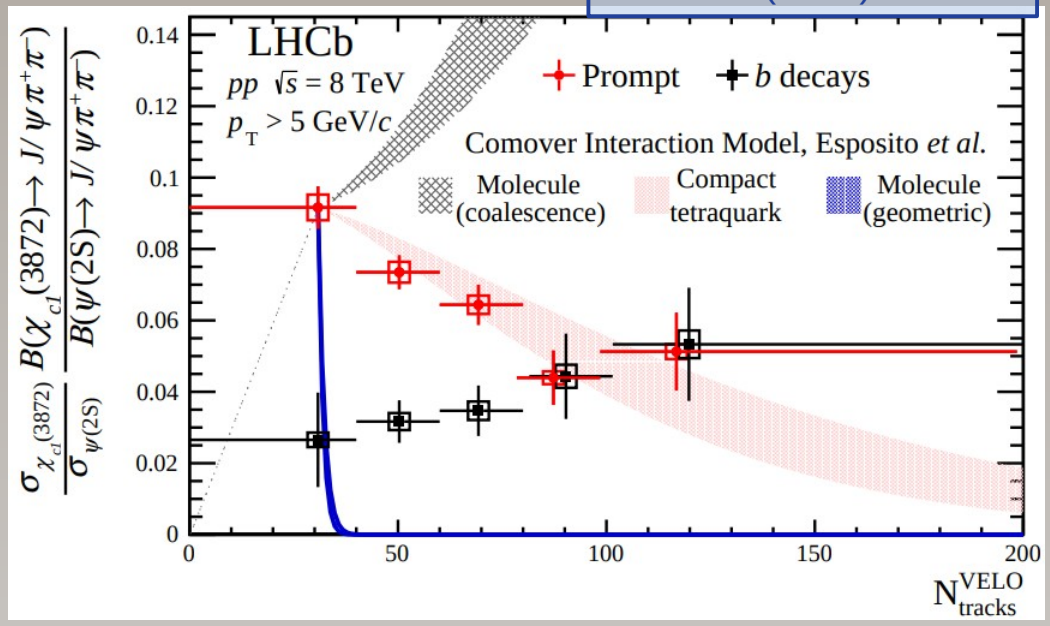
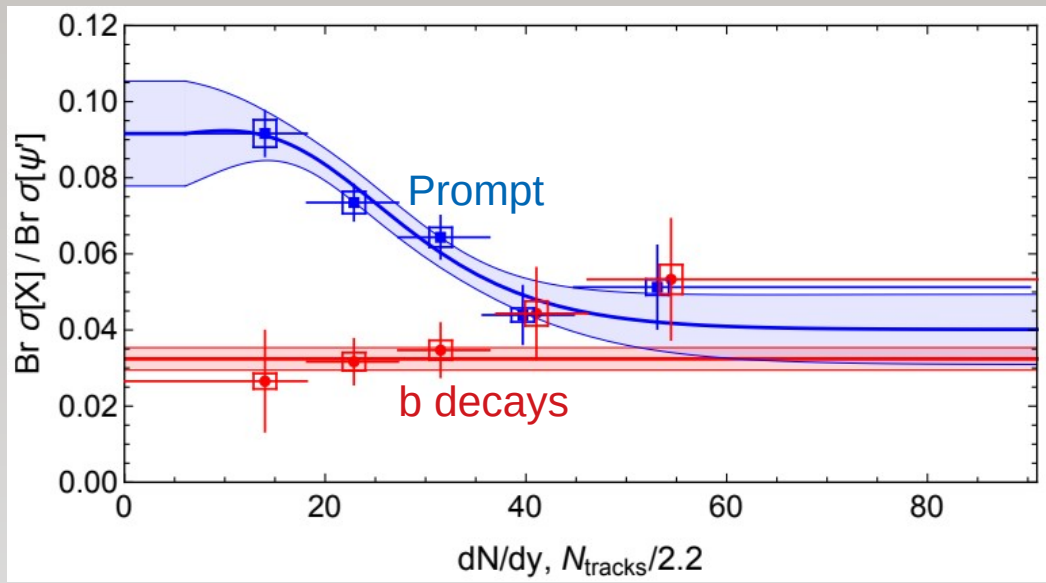
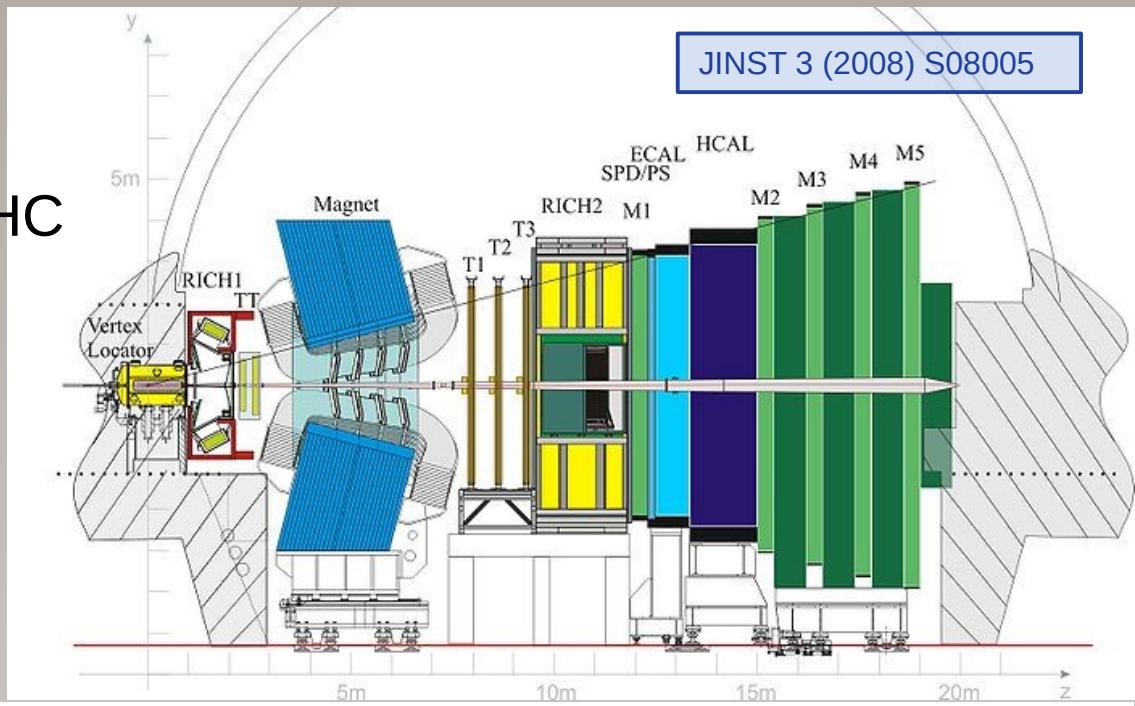




The LHCb detector

- LHCb - forward spectrometer at LHC with excellent
  - momenta/mass,
  - vertex/time resolution
  - particle identification (K/π/p/μ)



very powerful tool for heavy hadron spectroscopy → contribute to major part of hadrons discovered at LHC