Doubly charmed tetraquark at LHCb and future prospects

Picture:S. Velasco,
Quanta Magazine

Ivan Polyakov

Birmingham University Seminar,
30 March 2022

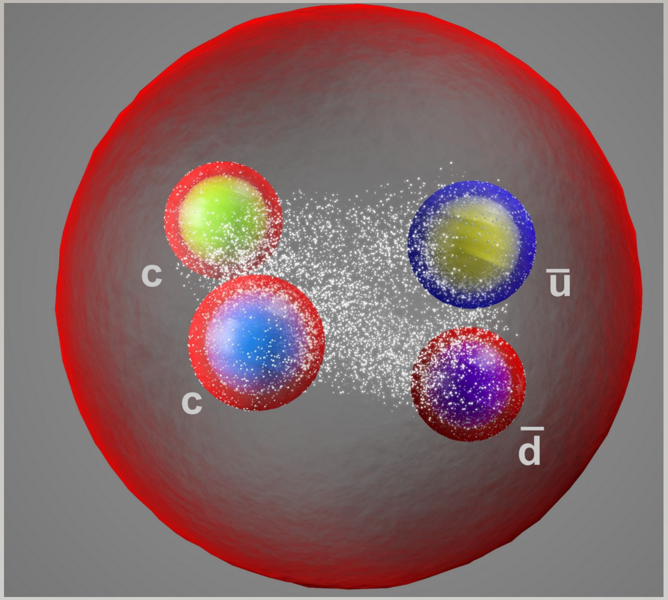
Outlook

- Introduction (mini-review)
  - QCD & hadron spectroscopy
    theory and experiment, exotic hadrons
  - predictions for $QQ\overline{qq'}$
- The T_{cc}^{+} tetraquark
  - LHCb detector & Selection
  - Observation of the signal
  - Study with unitarized model
  - Interpretations
  - Production properties

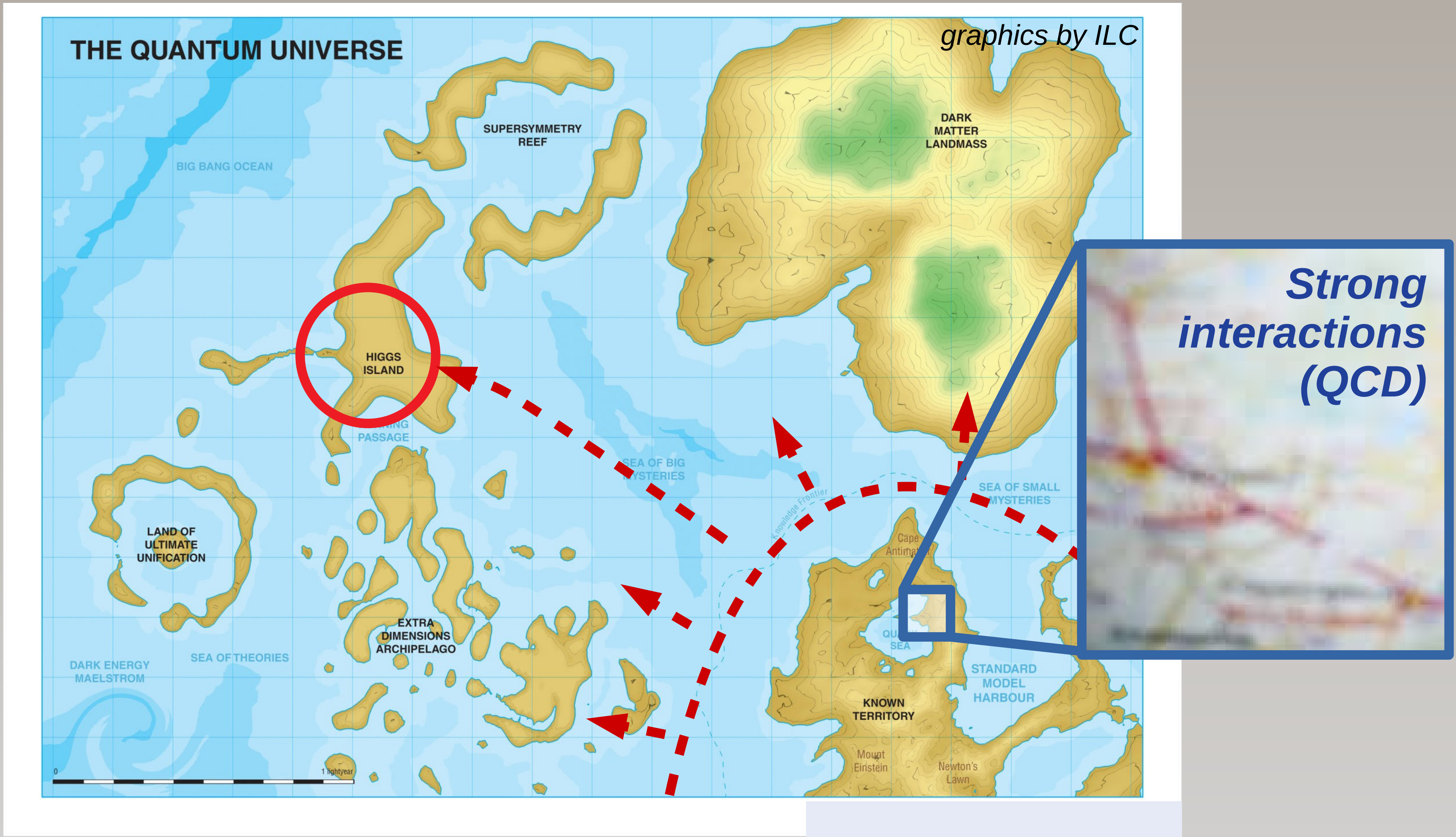
arXiv:2109.01038

arXiv:2109.01056

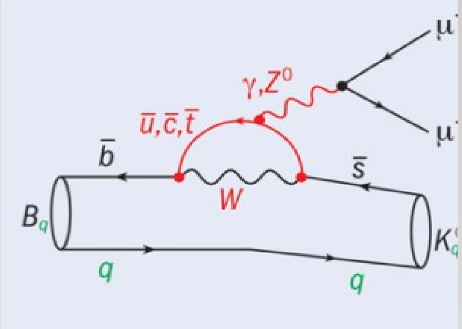
- Discussion
  - Reflection on the results
  - Open questions
- Future possibilities
  - Doubly heavy tetraquarks
  - Hexaquarks

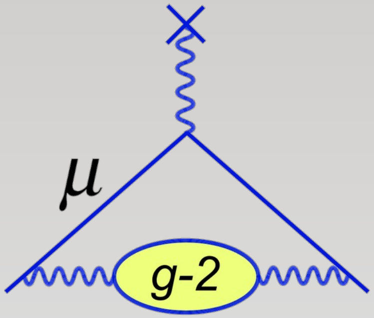


High Energy Physics frontiers


graphics by ILC

- The known QCD is not that well known
- And it’s understanding also limits the hunt for non-direct signs of NP: B-decays, g-2 of μ, ...





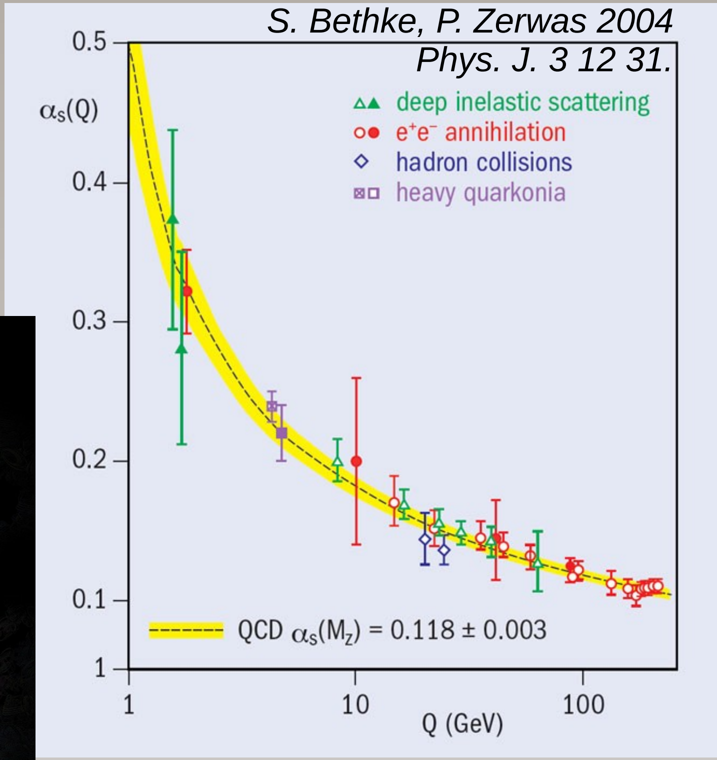
QCD vs. Hadron Spectorscopy

- QCD is successful theory giving in precise predictions at high energies

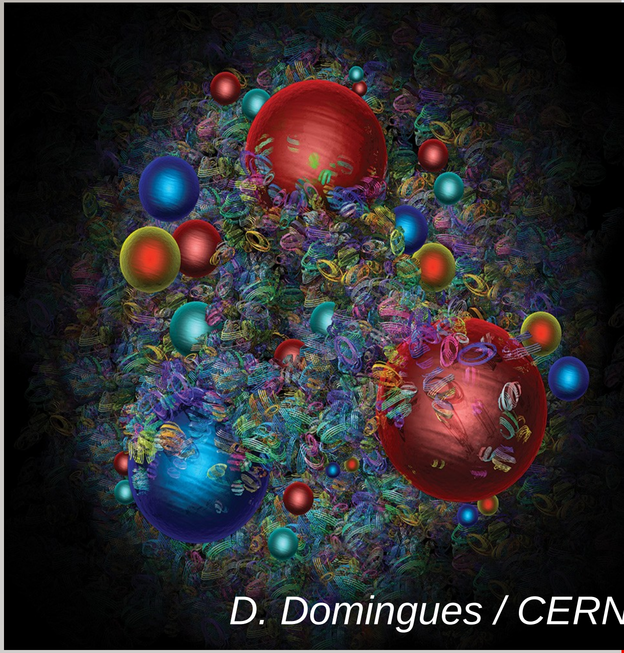
- However is higly non-perturbative at hadron/nuclei energy scale

- Therefore for hadron spectroscopy (semi-)phenomenological approaches have to be used

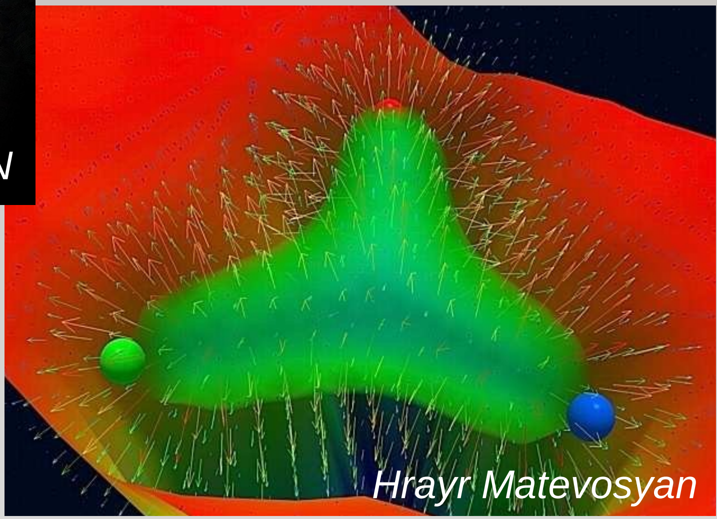
  mini-review in the following (oversimplified & incomplete)



S. Bethke, P. Zerwas 2004 Phys. J. 3 12 31.



D. Domingues / CERN



Hrayr Matevosyan

Theory approaches, 1

- Effective approach for compact hadrons (“bag” model)

  extracting effective parameters from measured hadron masses
  - may involve assumptions about diquarks, string, …

  - Heavy Quank Symmetry – expansion in 1/m_Q + kin. Corrections

see in

Brambilla, Vairo, Rösch, 2005

…

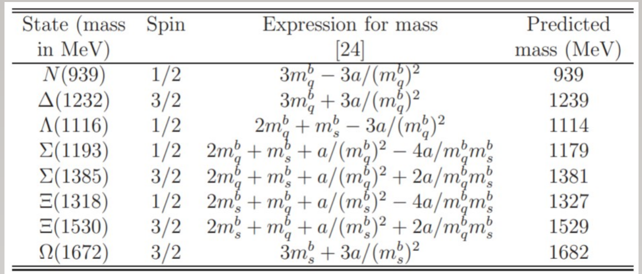
Eichten, Quigg, 2017

Braaten, He, Mohapatra, 2020

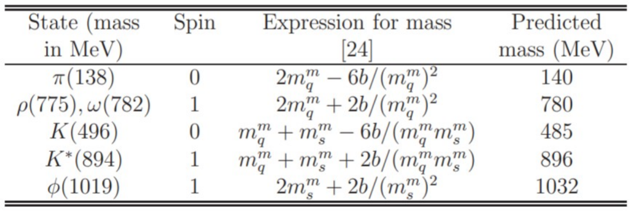
… and much more ...

  - Sum of quark masses, binding, hyperfine interaction

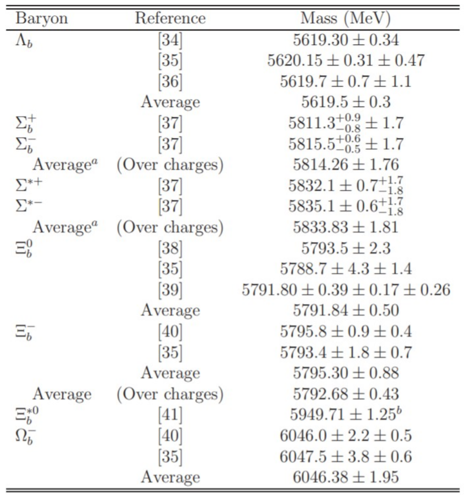
    -> reproduces masses of (ground) hadron states within ~10 MeV



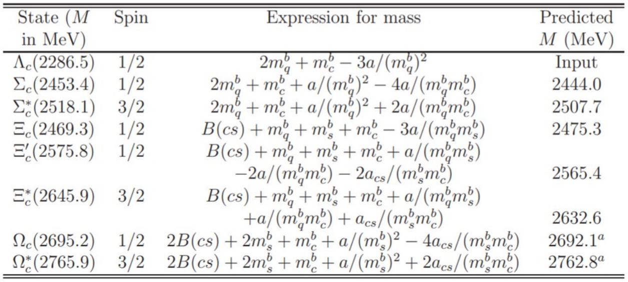
State (mass in MeV)	Spin	Expression for mass [24]	Predicted mass (MeV)
$N(939)$	1/2	$3m_q^b - 3a/(m_q^b)^2$	939
$\Delta(1232)$	3/2	$3m_q^b + 3a/(m_q^b)^2$	1239
$\Lambda(1116)$	1/2	$2m_q^b + m_s^b - 3a/(m_q^b)^2$	1114
$\Sigma(1193)$	1/2	$2m_q^b + m_s^b + a/(m_q^b)^2 - 4a/m_q^b m_s^b$	1179
$\Sigma(1385)$	3/2	$2m_q^b + m_s^b + a/(m_q^b)^2 + 2a/m_q^b m_s^b$	1381
$\Xi(1318)$	1/2	$2m_s^b + m_q^b + a/(m_s^b)^2 - 4a/m_q^b m_s^b$	1327
$\Xi(1530)$	3/2	$2m_s^b + m_q^b + a/(m_s^b)^2 + 2a/m_q^b m_s^b$	1529
$\Omega(1672)$	3/2	$3m_s^b + 3a/(m_s^b)^2$	1682



State (mass in MeV)	Spin	Expression for mass [24]	Predicted mass (MeV)
$\pi(138)$	0	$2m_q^m - 6b/(m_q^m)^2$	140
$\rho(775), \omega(782)$	1	$2m_q^m + 2b/(m_q^m)^2$	780
$K(496)$	0	$m_q^m + m_s^m - 6b/(m_q^m m_s^m)$	485
$K^*(894)$	1	$m_q^m + m_s^m + 2b/(m_q^m m_s^m)$	896
$\phi(1019)$	1	$2m_s^m + 2b/(m_s^m)^2$	1032



Baryon	Reference	Mass (MeV)
Λ_b	[34]	5619.30 ± 0.34
	[35]	$5620.15 \pm 0.31 \pm 0.47$
	[36]	$5619.7 \pm 0.7 \pm 1.1$
	Average	5619.5 ± 0.3
Σ_b^+	[37]	$5811.3^{+0.9}_{-0.8} \pm 1.7$
Σ_b^-	[37]	$5815.5^{+0.6}_{-0.5} \pm 1.7$
Average[a]	(Over charges)	5814.26 ± 1.76
Σ^{*+}	[37]	$5832.1 \pm 0.7^{+1.7}_{-1.8}$
Σ^{*-}	[37]	$5835.1 \pm 0.6^{+1.7}_{-1.8}$
Average[a]	(Over charges)	5833.83 ± 1.81
Ξ_b^0	[38]	5793.5 ± 2.3
	[35]	$5788.7 \pm 4.3 \pm 1.4$
	[39]	$5791.80 \pm 0.39 \pm 0.17 \pm 0.26$
	Average	5791.84 ± 0.50
Ξ_b^-	[40]	$5795.8 \pm 0.9 \pm 0.4$
	[35]	$5793.4 \pm 1.8 \pm 0.7$
	Average	5795.30 ± 0.88
Average	(Over charges)	5792.68 ± 0.43
Ξ_b^{*0}	[41]	5949.71 ± 1.25^b
Ω_b^-	[40]	$6046.0 \pm 2.2 \pm 0.5$
	[35]	$6047.5 \pm 3.8 \pm 0.6$
	Average	6046.38 ± 1.95



State (M in MeV)	Spin	Expression for mass	Predicted M (MeV)
$\Lambda_c(2286.5)$	1/2	$2m_q^b + m_c^b - 3a/(m_q^b)^2$	Input
$\Sigma_c(2453.4)$	1/2	$2m_q^b + m_c^b + a/(m_q^b)^2 - 4a/(m_q^b m_c^b)$	2444.0
$\Sigma_c^*(2518.1)$	3/2	$2m_q^b + m_c^b + a/(m_q^b)^2 + 2a/(m_q^b m_c^b)$	2507.7
$\Xi_c(2469.3)$	1/2	$B(cs) + m_q^b + m_s^b + m_c^b - 3a/(m_q^b m_s^b)$	2475.3
$\Xi_c'(2575.8)$	1/2	$B(cs) + m_q^b + m_s^b + m_c^b + a/(m_q^b m_s^b)$ $-2a/(m_q^b m_c^b) - 2a_{cs}/(m_s^b m_c^b)$	2565.4
$\Xi_c^*(2645.9)$	3/2	$B(cs) + m_q^b + m_s^b + m_c^b + a/(m_q^b m_s^b)$ $+a/(m_q^b m_c^b) + a_{cs}/(m_s^b m_c^b)$	2632.6
$\Omega_c(2695.2)$	1/2	$2B(cs) + 2m_s^b + m_c^b + a/(m_s^b)^2 - 4a_{cs}/(m_s^b m_c^b)$	2692.1[a]
$\Omega_c^*(2765.9)$	3/2	$2B(cs) + 2m_s^b + m_c^b + a/(m_s^b)^2 + 2a_{cs}/(m_s^b m_c^b)$	2762.8[a]

Gasiorowicz, Rosner, 1981

Karliner, Rosner, 2017

+ successful predictions of Ξ_{cc} and T_{cc} masses!

  - …

Theory approaches, 2

- Effective approach for compact hadrons (“bag” model)
  - Heavy Quank Symmetry – explansion in $1/m_Q$ + kin. corrections
  - Sum of quark masses, binding, hyperfine interaction
  - …

  extracting effective parameters from measured hadron masses
  - may involve assumptions about diquarks, string, …

see in

Brambilla, Vairo, Rösch, 2005

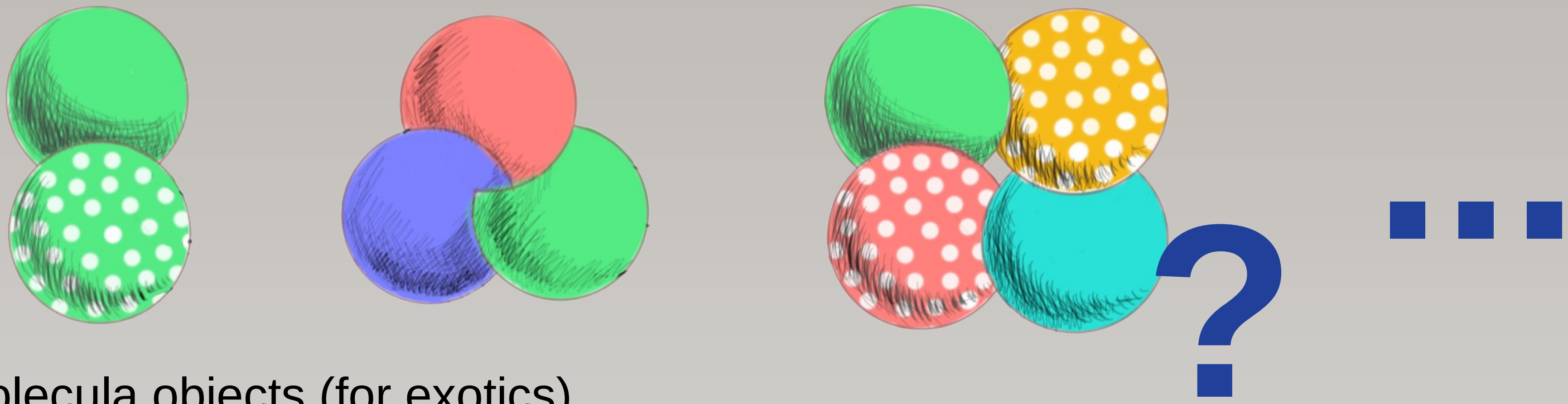
… Eichten, Quigg, 2017

Braaten, He, Mohapatra, 2020

Gasiorowicz, Rosner, 1981

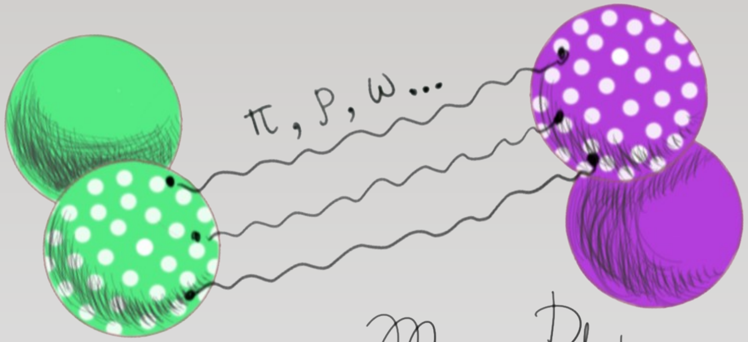
Karliner, Rosner, 2017

… and much more ...



- Molecula objects (for exotics)

  corresponding form-factors
  and cut-offs
  not well controlled
  → *uncertainties up*
  to O(100 MeV)



Maria Poliakova

Tornquist, 1991 & 2003

Voloshin, Okun, 1976 …

Pepin, Stancu, Genovese, Richard, 1996

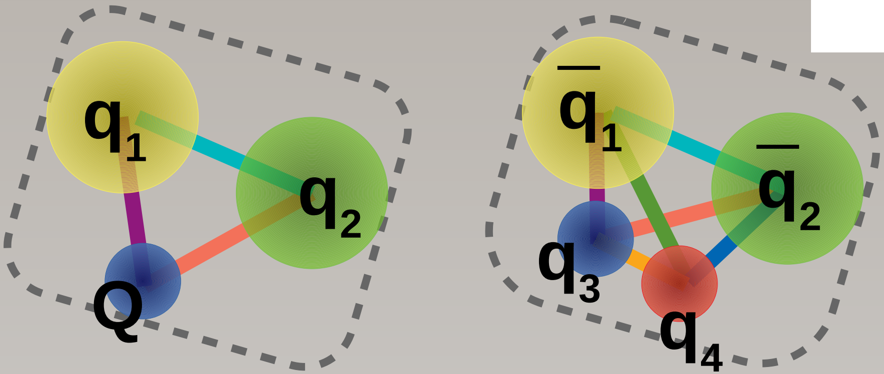
Li, Sun, Liu, Zhu, 2012

Wu,Liu, Wu, Valderrama, Xie, Geng, 2019

… and much more ...

Theory approaches, 3

- NR quark constituent model
  with semi-phenomenological
  quark-quark interaction potential



color of quarks

$$V_{ij} = -\frac{3}{16}\lambda_i^C\lambda_j^C\left[V_{OGE}+V_{CONF}+V_{SS}\right]$$

one-gluon exchange (“Couloumb”)

$$V_{OGE} = \frac{\alpha}{r_{ij}}\,, \quad V_{CONF} = V_0+\beta r_{ij}\,, \quad V_{SS} = \alpha\frac{\hbar^2}{m_i m_j c^2}\frac{e^{-r_{ij}/r_0}}{r_0^2 r_{ij}}\sigma_i\sigma_j$$

confinement

contact spin-spin interaction

$$H = \sum_i\left(m_i+\frac{p_i^2}{2m_i}\right)+\sum_{i<j}V_{ij}(r_{ij})$$

Bhaduri, Cohler, Yogami, 1981

Semay, SIlvestre-Brac, 1994

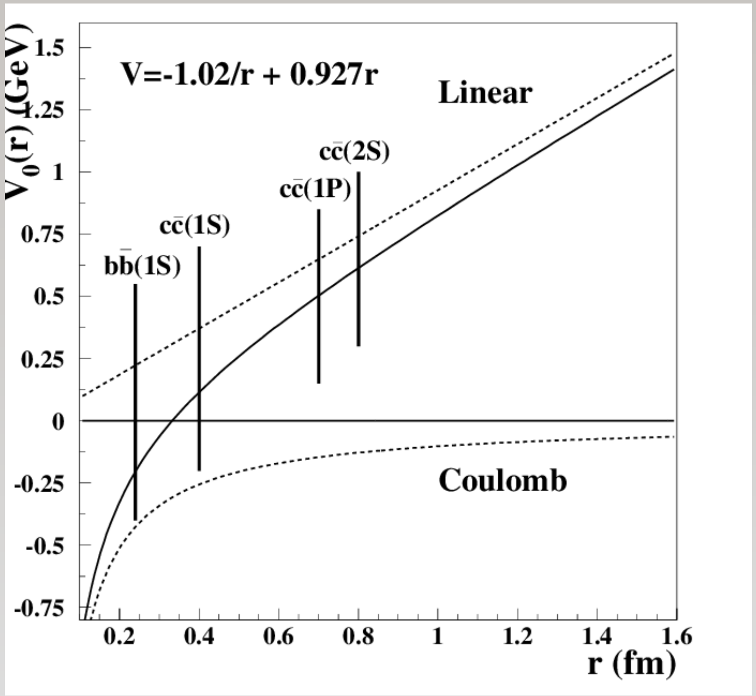
Silvestre-Brac, 1996

Janc, Rosina, 2003

… and more ...

- Can also take boson exchange (molecular binding) into account

Vijande, Fernandez, Valcarce, Silvestre-Brac, 2004



- Heavy quark allows to probe shorter range where OGE dominates

- Understanding is limited by the quark configurations to consider

Theory approaches, 4

- Lattice QCD
  hard to simultaneously work with heavy and light quarks
  (small lattice step and large lattice)

Hashimoto, Onogi, 2004

Prelovsek, 2017

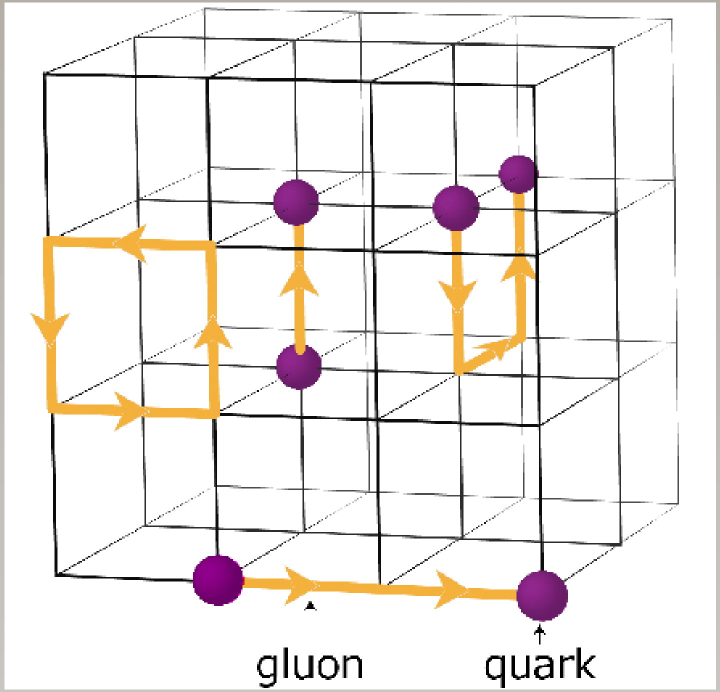
Hashimoto, Laiho, Sharpe, 2020 (PDG)

...

Follana et al, 2007

Donald et al., 2012

10.1051/epjconf/202024509008



- QCD sum rules *typically give >100 MeV uncertainty*

** please tell me if not the case*

Navarra, Nielsen, Lee, 2007

Wang, 2018

Understanding is limited by the quark configurations to consider

Experimental studies

- Hadrons beyond conventional ($q_1\bar{q}_2$ and $q_1q_2q_3$) were anticipated since 60's

- First candidates for tetraquarks in 90's: f_0(500), K^*_0(800), a_0(980) and f_0(980) later D^*_{sJ} (2317), D_{sJ}(2460) and D_{sJ}(2632)

  no clear conclusion reached due to large widths & theoretical ambiguities

Fazio, 2004

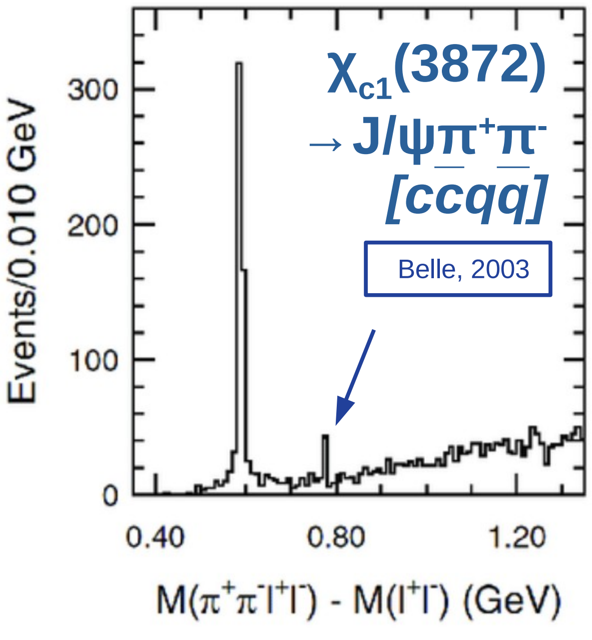
Eidelman, Gutsche, Hanhart, Mitchell, Spanier, 2020 (PDG)

- Θ^+ [$uudd\bar{s}$] claimed in 2003 later shown to be false

Trilling, 2006 (PDG)

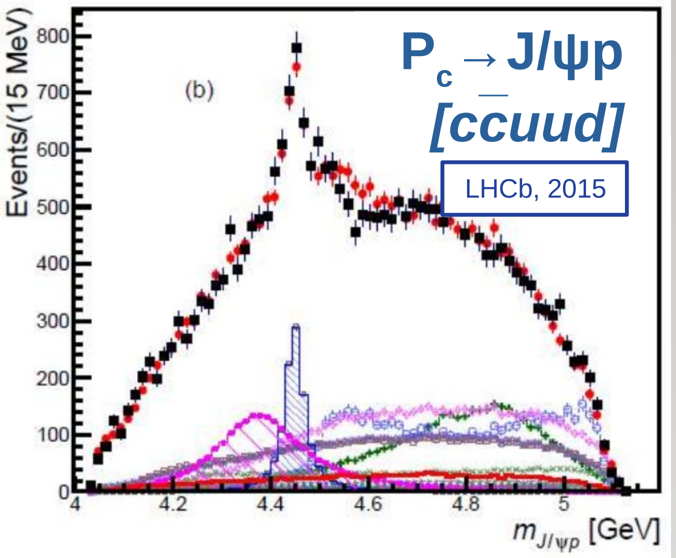
- First ones uniquely identified as exotic were χ_{c1}(3872) and P_c discovered in heavy sector

much smaller widths and clearer understanding of $c\bar{c}$ allowed to exclude conventional interpretations



χ_{c1}(3872) $\rightarrow J/\psi\pi^+\pi^-$ [$c\bar{c}q\bar{q}$]

Belle, 2003

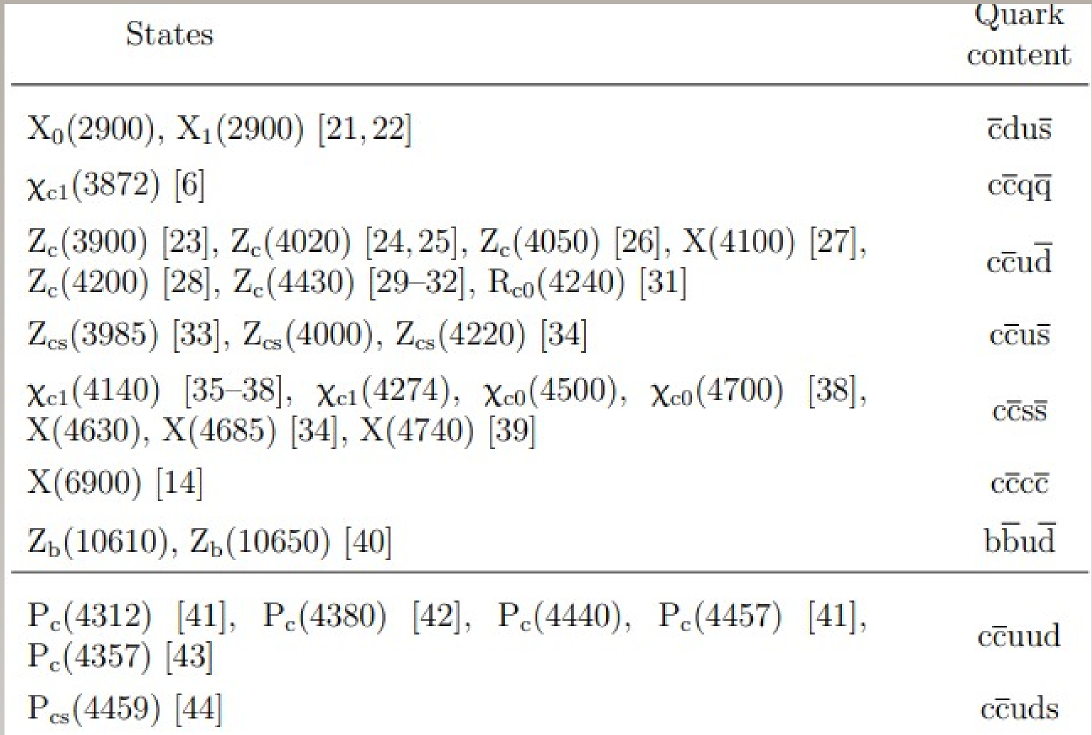


$P_c \rightarrow J/\psi p$ [$\bar{c}cuud$]

LHCb, 2015

Exotic hadrons

- Exotic hadrons: $c\bar{c}q_1\bar{q}_2$ and $c\bar{c}q_1q_2q_3$
  ~30 tetra/pentaquarks candidates discovered since then
  - *most have $Q\bar{Q}$ pair and large width,*
  - *interpretations are still unclear - molecula/compact*
  - *and even resonance nature is questioned*



States	Quark content
$X_0(2900)$, $X_1(2900)$ [21, 22]	$\bar{c}du\bar{s}$
$\chi_{c1}(3872)$ [6]	$c\bar{c}q\bar{q}$
$Z_c(3900)$ [23], $Z_c(4020)$ [24, 25], $Z_c(4050)$ [26], $X(4100)$ [27], $Z_c(4200)$ [28], $Z_c(4430)$ [29–32], $R_{c0}(4240)$ [31]	$c\bar{c}u\bar{d}$
$Z_{cs}(3985)$ [33], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [34]	$c\bar{c}u\bar{s}$
$\chi_{c1}(4140)$ [35–38], $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ [38], $X(4630)$, $X(4685)$ [34], $X(4740)$ [39]	$c\bar{c}s\bar{s}$
$X(6900)$ [14]	$c\bar{c}c\bar{c}$
$Z_b(10610)$, $Z_b(10650)$ [40]	$b\bar{b}u\bar{d}$
$P_c(4312)$ [41], $P_c(4380)$ [42], $P_c(4440)$, $P_c(4457)$ [41], $P_c(4357)$ [43]	$c\bar{c}uud$
$P_{cs}(4459)$ [44]	$c\bar{c}uds$

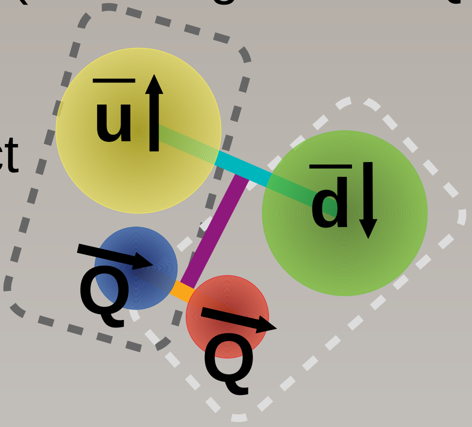
- $QQ\bar{q}'\bar{q}''$ are prime candidates to be bound and therefore long-lived
  - first estimates *(based on $V_{qq'}(r) \sim r^{0.1}$ approximation)* stated that should happen for $m_Q/m_q > 6\text{-}8$ *(compare to $m_b/m_u \sim 15$, $m_c/m_u \sim 5\text{-}6$)*

Adler, Richard, Taxil, 1982

Ballot, Richard, 1983

Predictions for $cc\overline{ud}$ mass

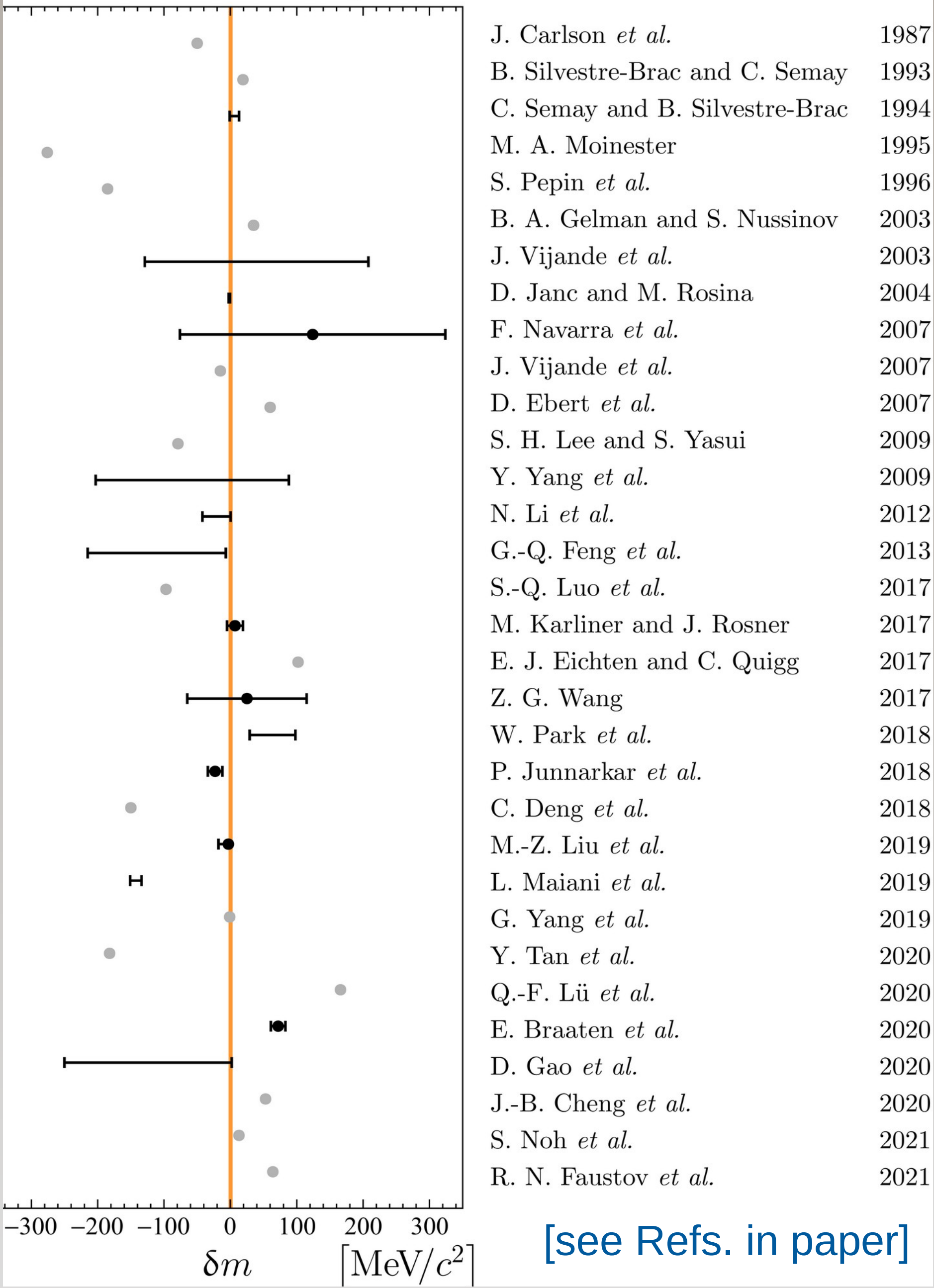
- More recent calculations (including Lattice QCD) all agree that it should be true for $[bb][\overline{ud}]$ with QQ forming compact color anti-triplet and resulting binding of ~150MeV



- However not clear for $[bc][\overline{ud}]$ and $[cc][\overline{ud}]$

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

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



[see Refs. in paper]

”Observation of an exotic narrow doubly charmed tetraquark”

arXiv:2109.01038

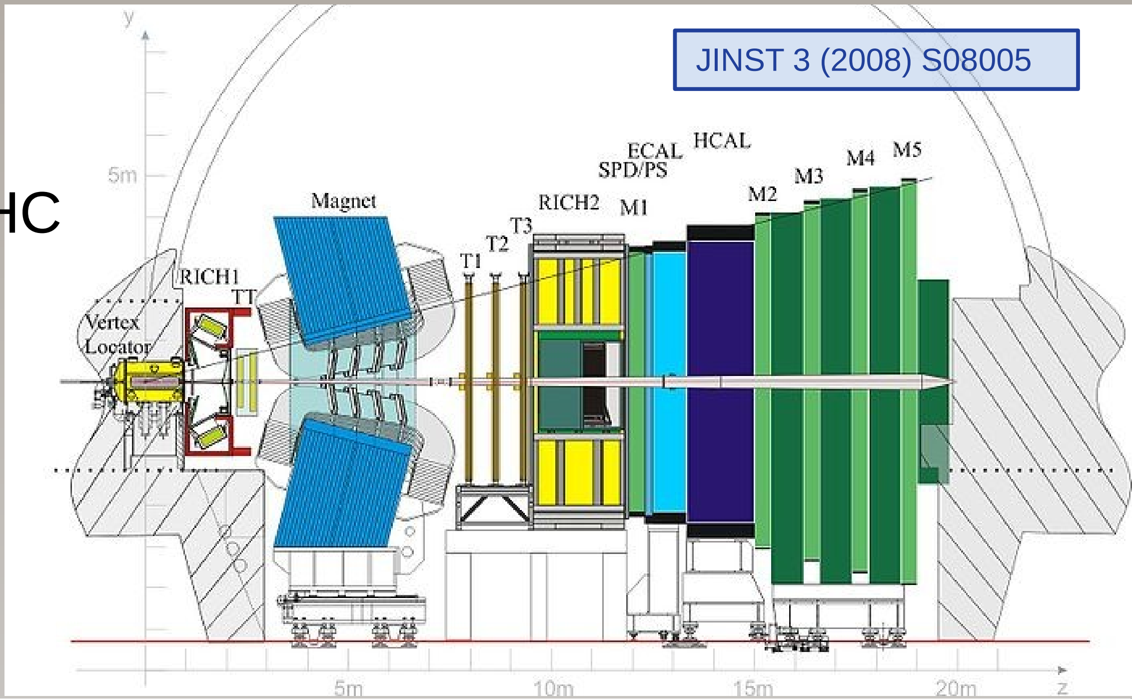
&

”Study of the doubly charmed tetraquark T_{cc}^{+}”

arXiv:2109.01056

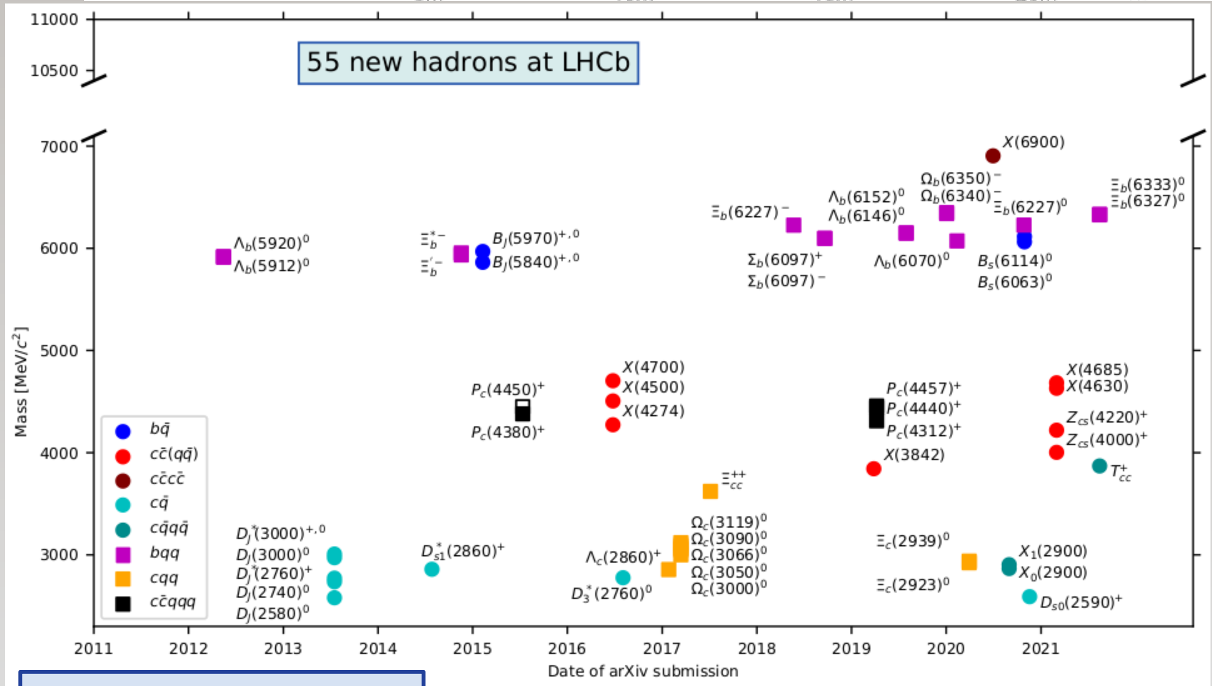
The LHCb detector

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



JINST 3 (2008) S08005

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

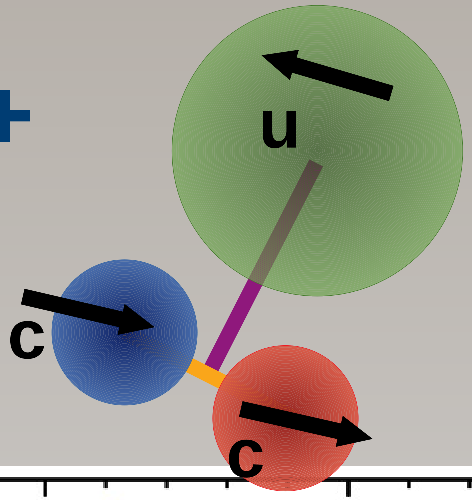


LHCb-FIGURE-2021-001

Previous hadrons with two c-quarks

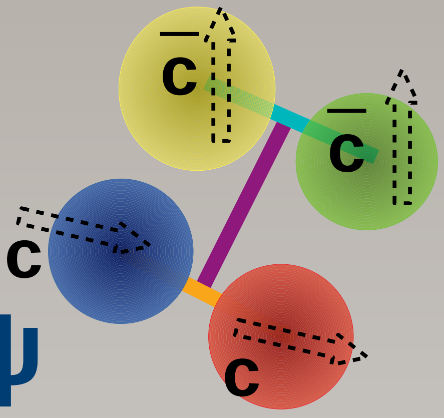
- The observations of Ξ_{cc}^{++} [ccu] and X[$cc\bar{c}\bar{c}$] → J/ψJ/ψ indicate that if the [$cc\bar{u}\bar{d}$] exists it should be accessible at LHCb in $DD^{(*)}$ final states

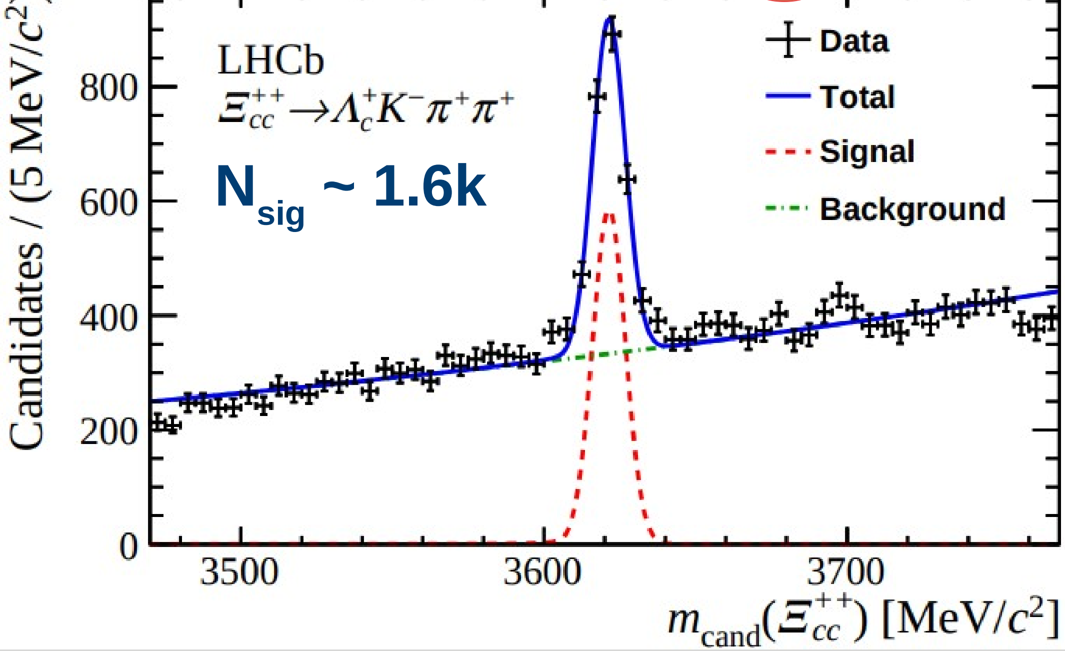
Ξ_{cc}^{++}



$X_{cc\bar{c}\bar{c}}$

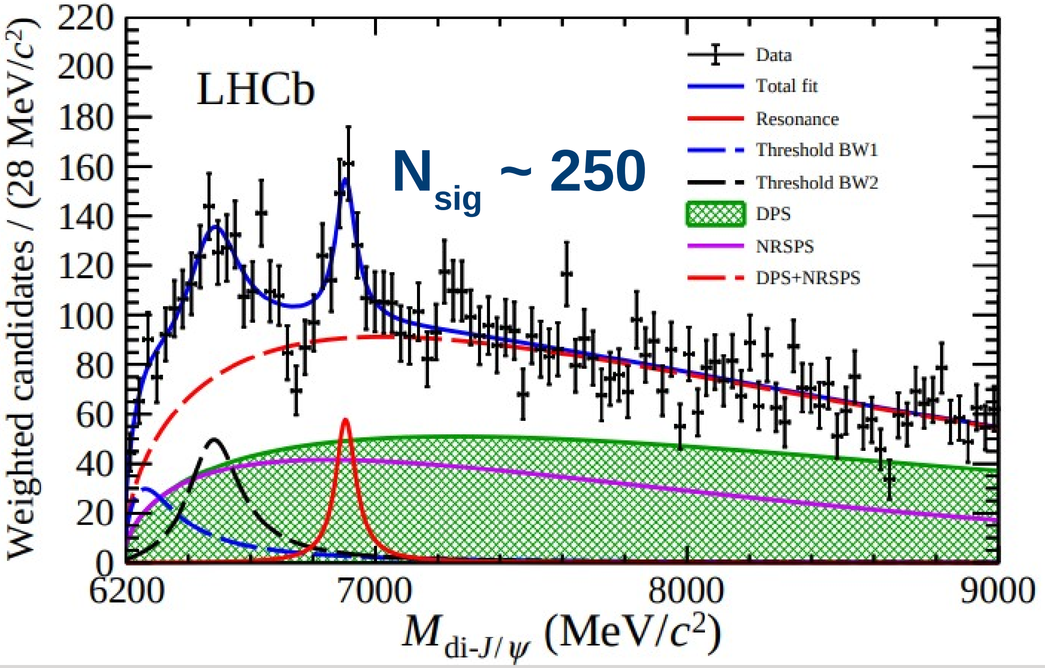
→ J/ψJ/ψ





N_{sig} ~ 1.6k

JHEP 02 (2020) 049

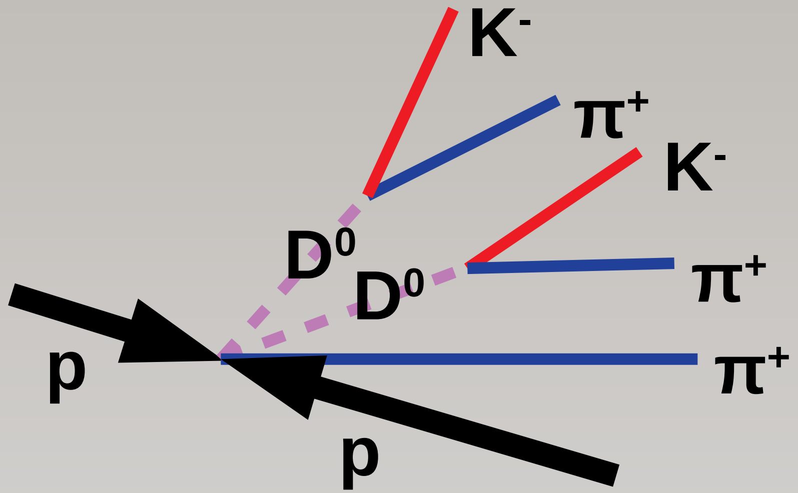


N_{sig} ~ 250

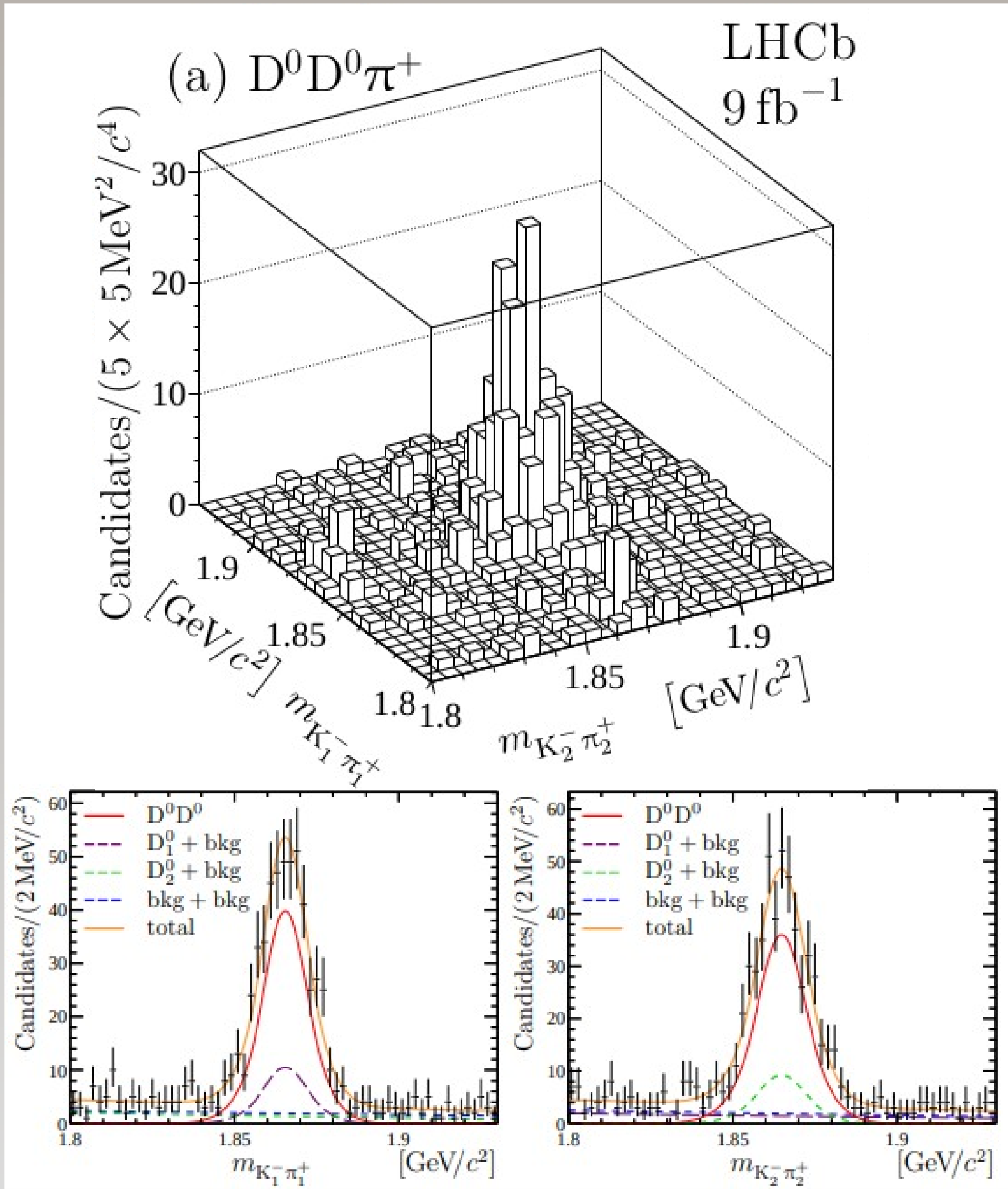
Sci. Bul. 65 (2020) 1983

Selection of $D^0D^0\pi^+$

- Select prompt $D^0D^0\pi^+$ candidates via $D^0 \to K^-\pi^+$
- Require non-prompt K^- & π^+ with high p_T
- Require good quality of track, vertexes & particle identification
- Ensure no K/π candidates belong to one track (clones)
  or duplicates or reflections via mis-ID

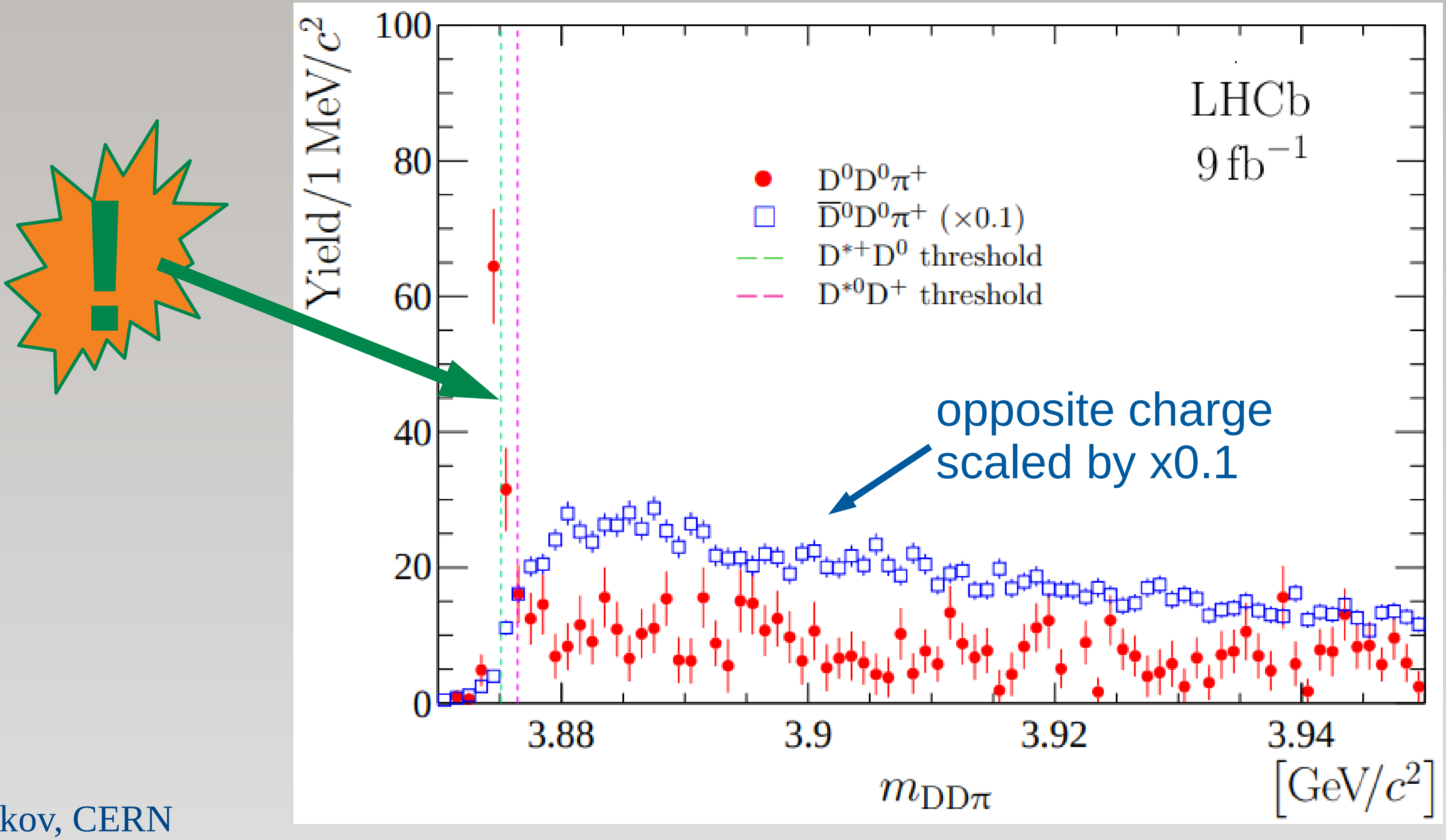


- Subtract fake-D background using 2D fit to $(m_{K\pi}, m_{K\pi})$



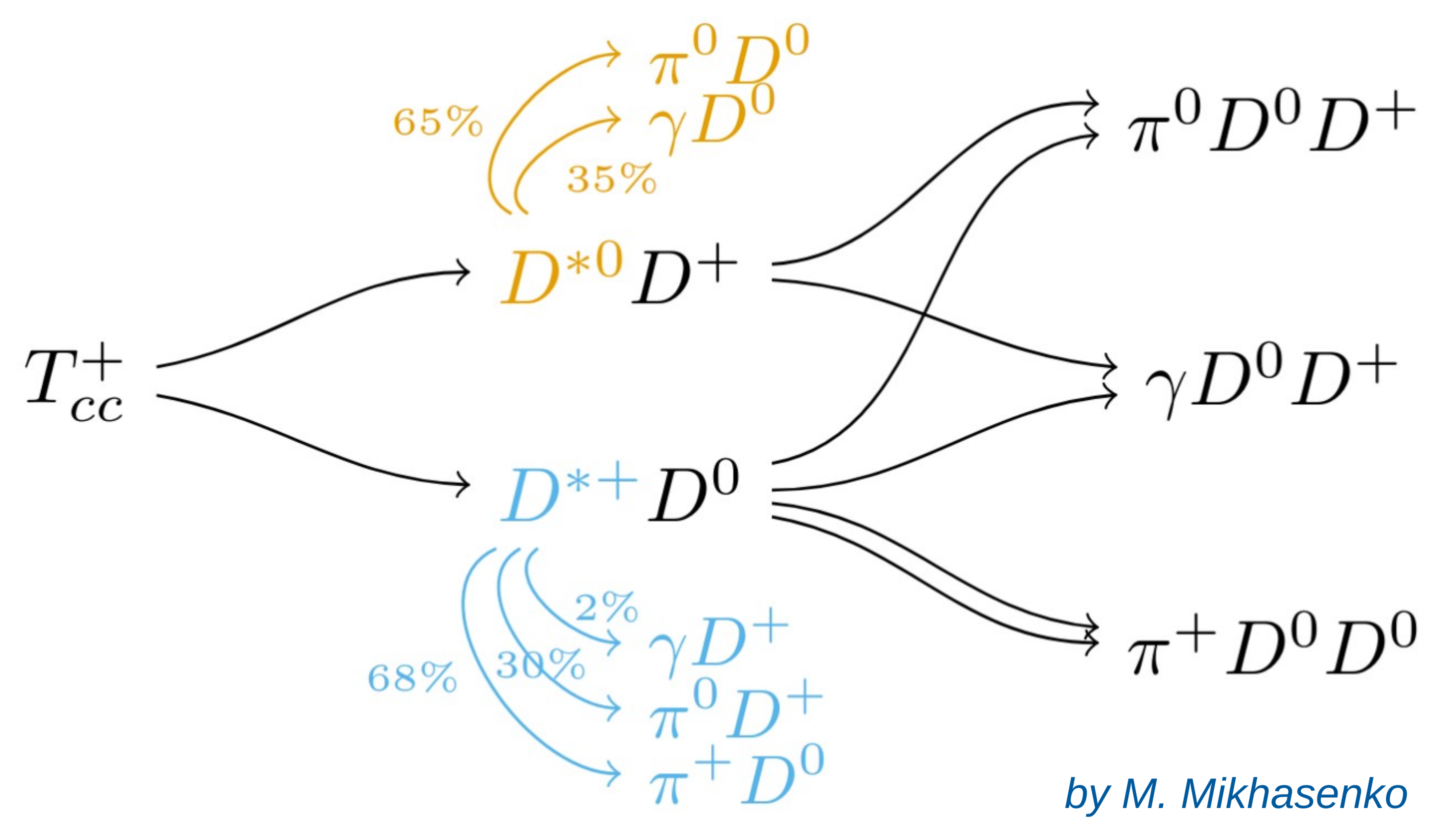
Signal

- A narrow peak near DD* threshold is seen
- No peaking structures in sidebands or opposite-sign mode (can’t be explained by DCS decay $D^0 \to K^+\pi^-$)
- The structure is present in all different data taking condition subsamples, ensured by various cross-checks



opposite charge scaled by x0.1

Decay amplitude



by M. Mikhasenko

- Model assumptions:
  - $J^{P}=1^{+}$: decays to $D^{0}D^{*+}/D^{+}D^{*0}$ in S-wave
  - T_{cc}^{+} is isoscalar:

$$\left|T_{cc}^{+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D^{*+}D^{0}\right\rangle - \left|D^{*0}D^{+}\right\rangle\right)$$

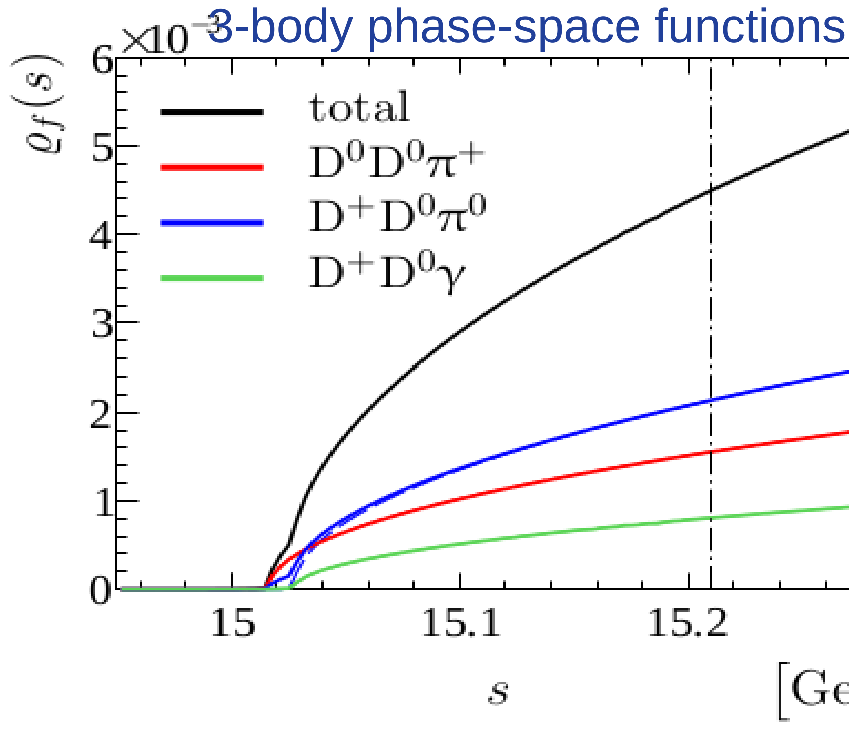
  - Decays to $D^{0}D^{*+}/D^{+}D^{*0}$ with same couplings

Unitarized 3-body BW model

- Constructed 3-body Breit-Wigner model as

$$\mathcal{A}_{\mathrm{U}}(s) = \frac{1}{m_{\mathrm{U}}^2 - s - i m_{\mathrm{U}} \hat{\Gamma}(s)}$$

$$\varrho_f(s) = \frac{1}{(2\pi)^5} \frac{\pi^2}{4s} \iint ds_{12} ds_{23} \frac{\left|\mathfrak{M}_f(s, s_{12}, s_{23})\right|^2}{|g|^2}$$


3-body phase-space functions

  - where complex width is derived as

$$i m_{\mathrm{U}} \hat{\Gamma}(s) \equiv |g|^2 \Sigma(s)$$

Imaginary part for unitarity (optical theorem)

$$\begin{aligned} \Im\, \Sigma(s)\big|_{\Im s = 0^+} &= \frac{1}{2} \varrho_{\mathrm{tot}}(s)\,, \\ \varrho_{\mathrm{tot}}(s) &\equiv \sum_f \varrho_f(s) \end{aligned}$$

Real part for analyticity (Kramers-Kronig relations)

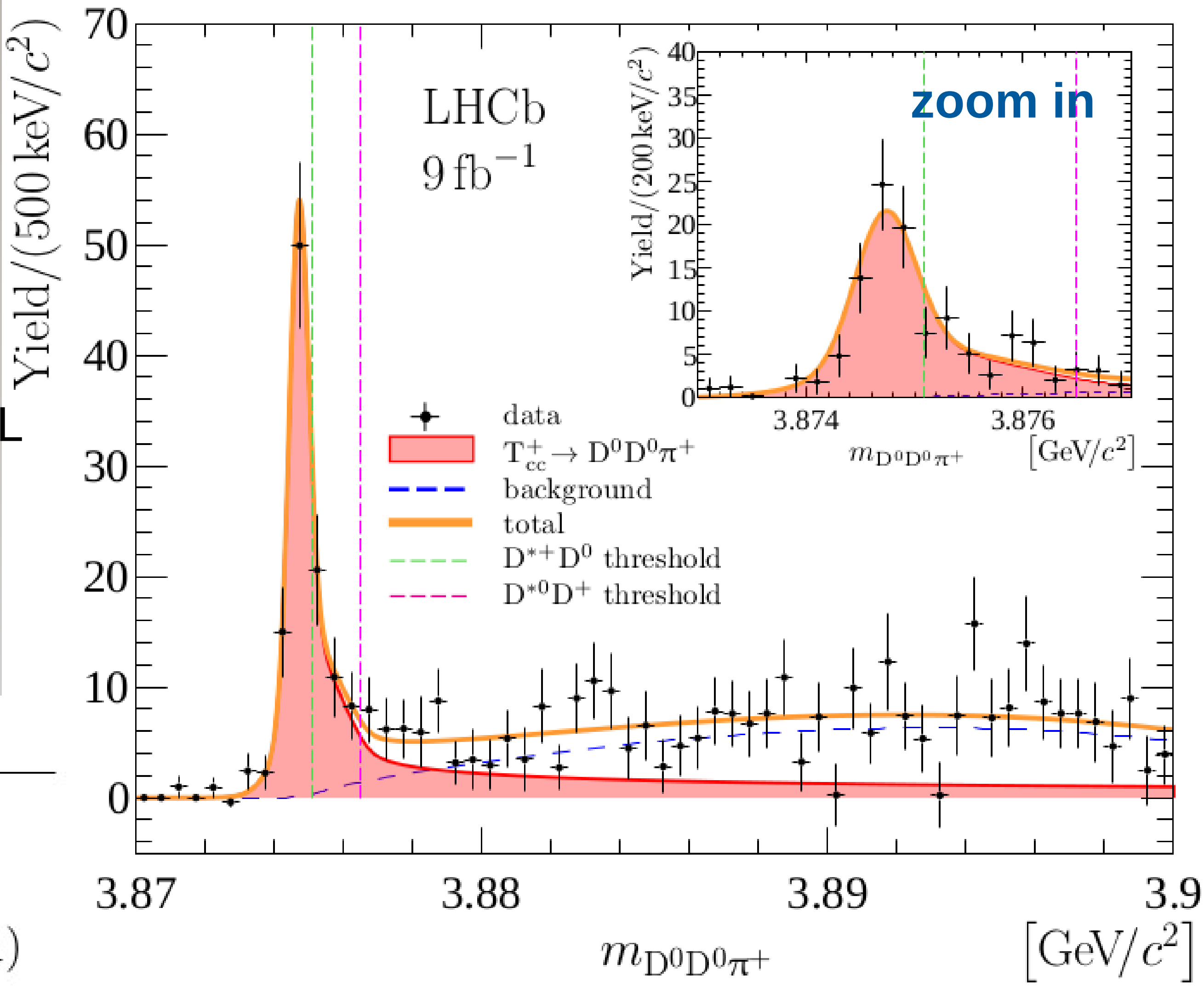
$$\begin{aligned} \Re\, \Sigma(s)\big|_{\Im s = 0^+} &= \xi(s) - \xi(m_{\mathrm{U}}^2)\,, \\ \xi(s) &= \frac{s}{2\pi}\, \mathrm{p.v.} \int_{s_{\mathrm{th}}^*}^{+\infty} \frac{\varrho_{\mathrm{tot}}(s')}{s'(s'-s)} ds' \end{aligned}$$

Fit with unitarized model

- Fit to same data, use same model as before except for the signal function
- Peak position below D^0D^{*+} threshold with **~9σ** significance!
- Peak shape does not depend on $T_{cc} \rightarrow DD^*$ coupling $|g|$ for large values

  → get limit
  $|g|>7.7(6.2)$ GeV at 90(95)% CL
- Results:

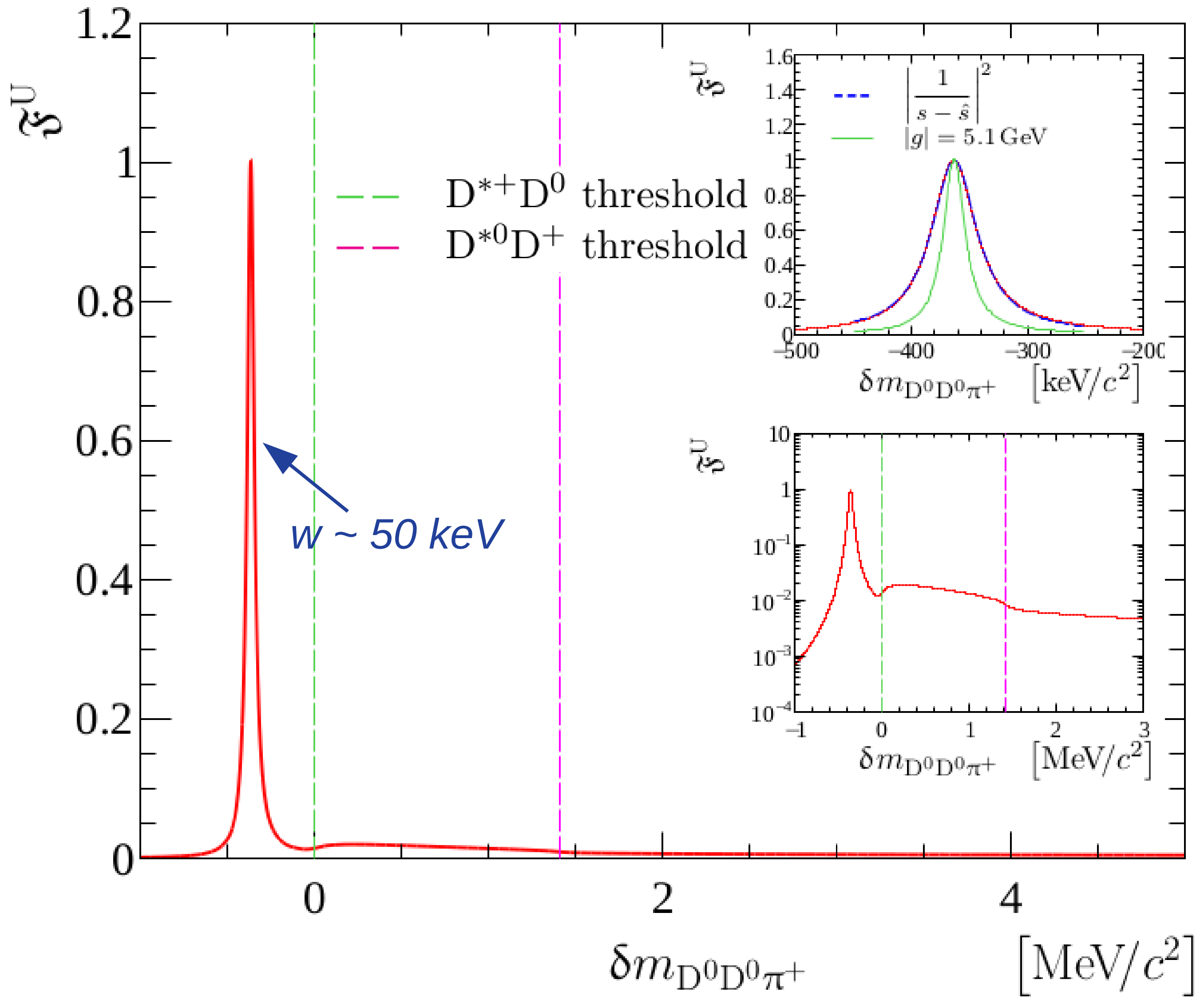
Parameter	Value
N	186 ± 24
δm_{U}	$-359 \pm 40\,\mathrm{keV}/c^2$
$\lvert g \rvert$	$3 \times 10^4\,\mathrm{GeV}$ (fixed)



Mass shape in unitarized model

- Fit result (before smearing with resolution)

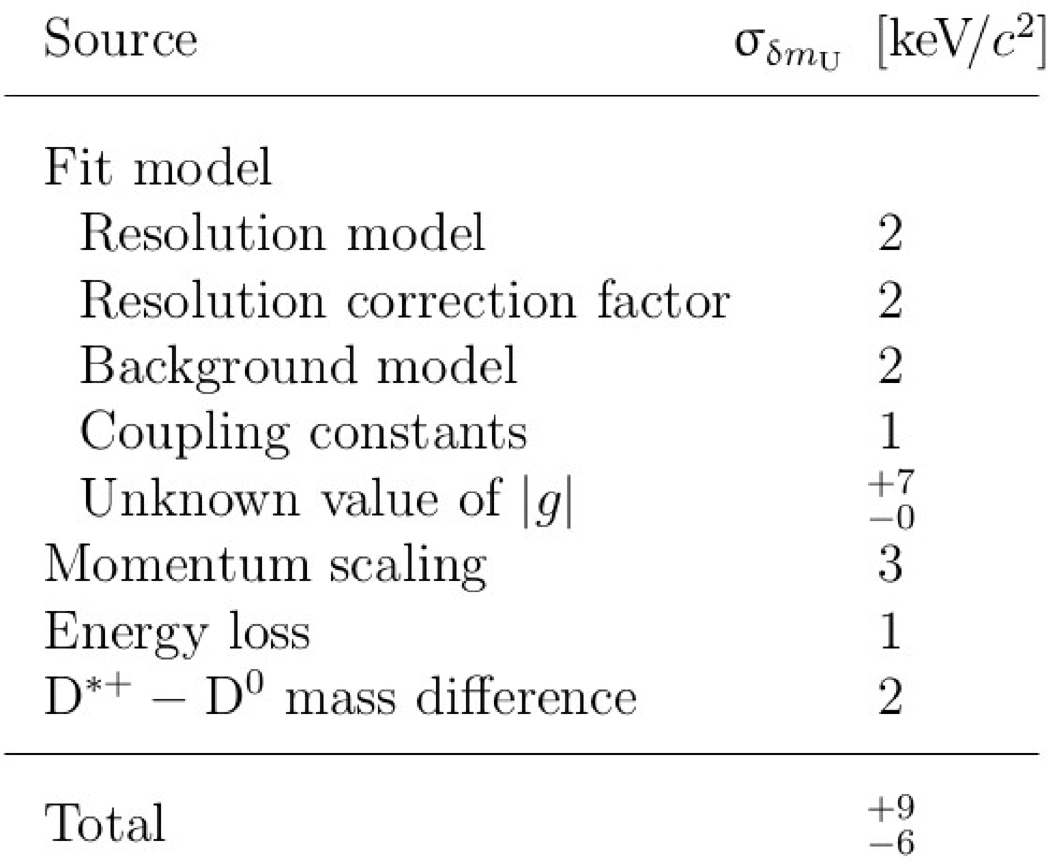
- Close to Breit-Wigner in proximity to peak maximum
- Large tail above DD* thresholds



w ~ 50 keV

Systematic uncertainties

- Systematic uncertainties found to be negligibly small
  (thanks to closeness to threshold)



Source	$\sigma_{\delta m_{\mathrm{U}}}$ [keV/c^2]
Fit model	
Resolution model	2
Resolution correction factor	2
Background model	2
Coupling constants	1
Unknown value of $\lvert g \rvert$	${}^{+7}_{-0}$
Momentum scaling	3
Energy loss	1
$\mathrm{D}^{*+} - \mathrm{D}^0$ mass difference	2
Total	${}^{+9}_{-6}$

- Measured mass wrt threshold:

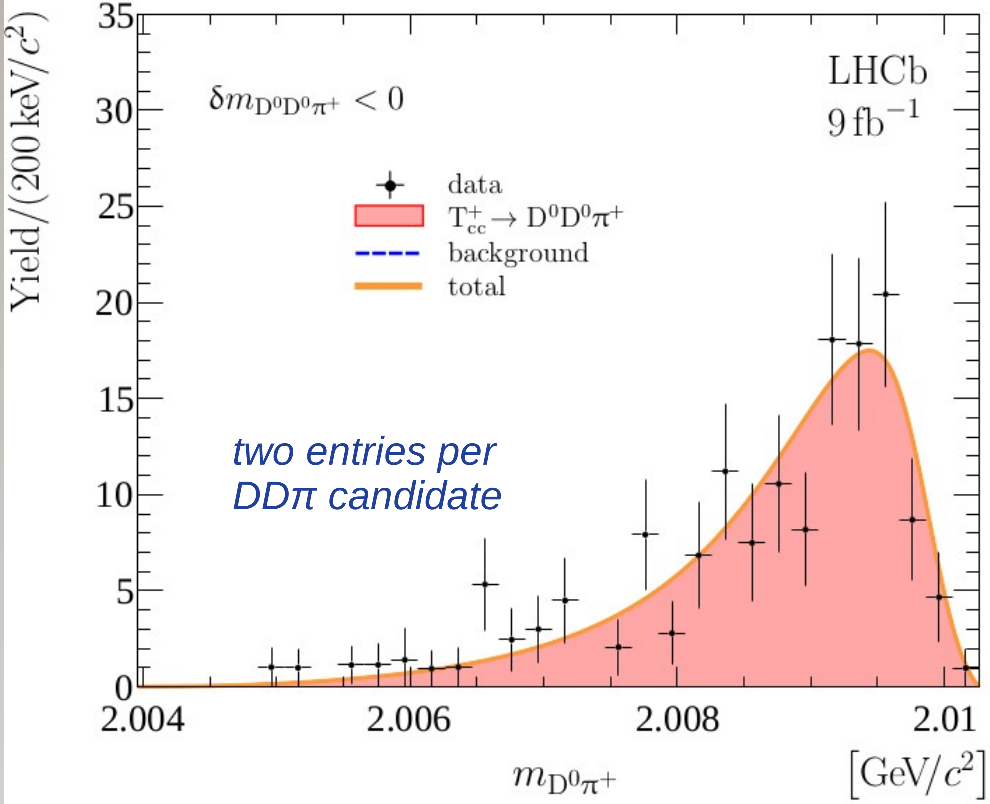
$$\delta' m_0 = -359 \pm 40\,{}^{+9}_{-6}\,\mathrm{keV}/c^2$$

- Fit model systematics considered for the lower limit of |g| changing it to

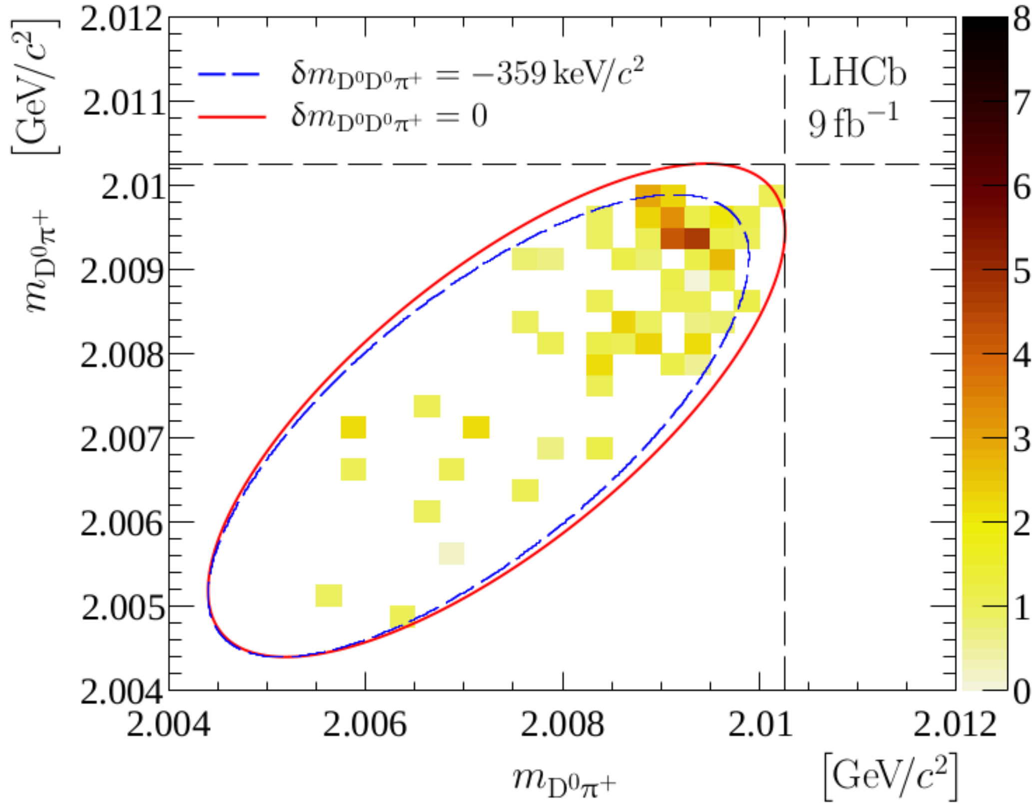
$$\lvert g \rvert > 5.1\,(4.3)\,\mathrm{GeV}\ \text{at}\ 90\,(95)\,\%\ \mathrm{CL}$$

Offshell D^{*+}

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



two entries per DDπ candidate

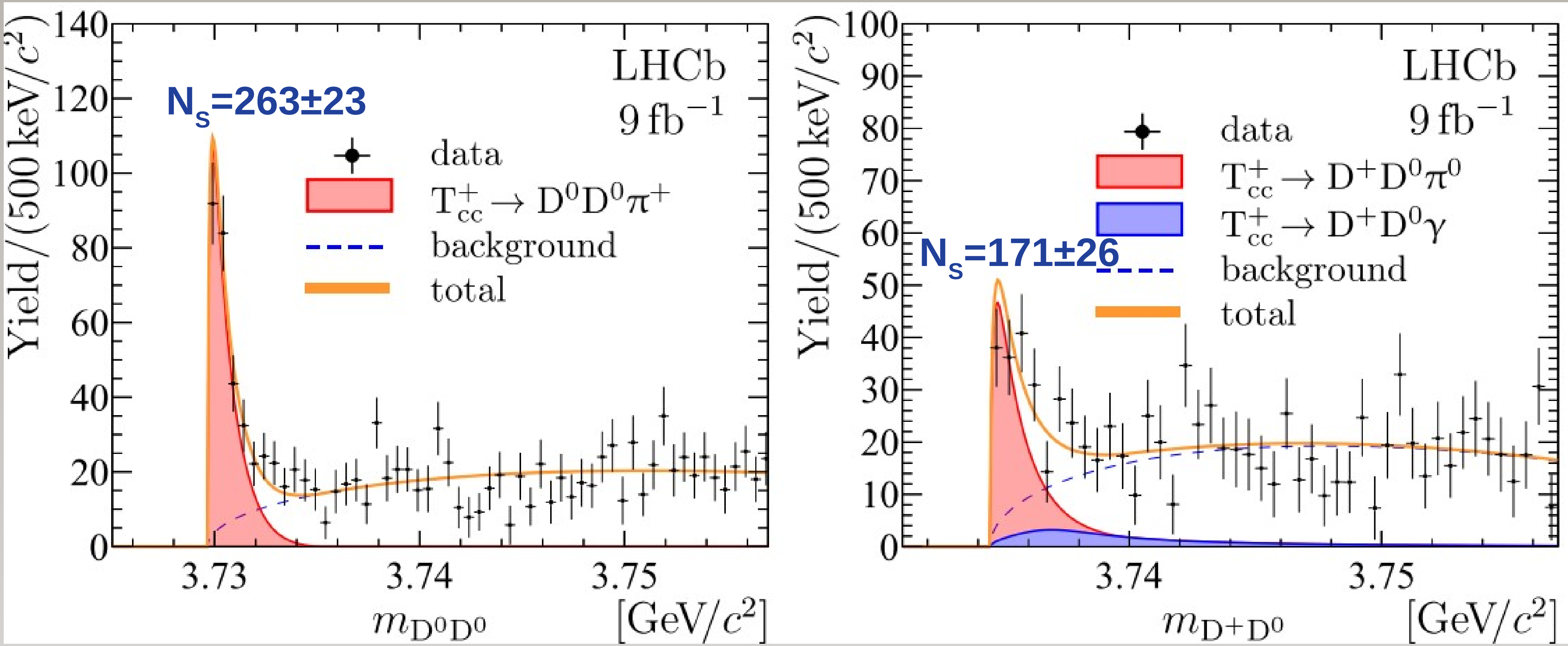


Perfect agreement supports the assumptions:

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

Partially reconstructed $T_{cc} \to D^0 D^{0/+} X$

- Obtain D^0D^0 mass shape from $T_{cc} \to D^0 D^{*+} (\to D^0\pi^+)$ and D^0D^+ mass shape from $T_{cc} \to D^0 D^{*+} (\to D^+\pi^0)$ and $T_{cc} \to D^+ D^{*0} (\to D^0\pi^0/\gamma)$ in the same way as for $D^0\pi^+$



- Relative yields are in agreement with model expectations for isoscalar T_{cc} with $J^P=1^+$ and $D^{0/+}$ reconstruction efficiencies

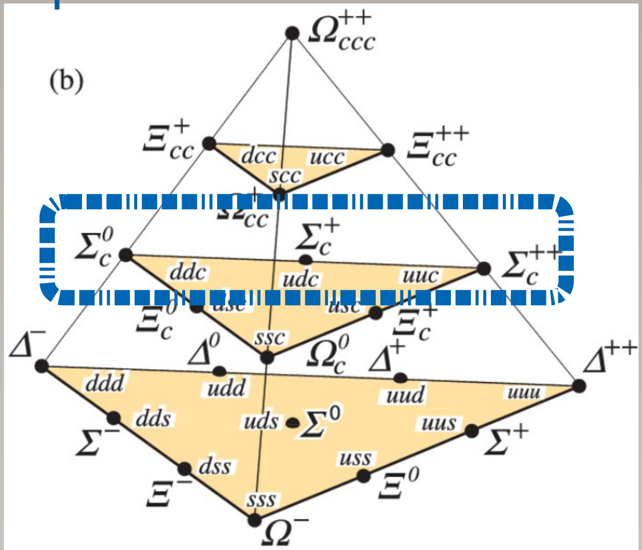
T_{cc} isospin

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

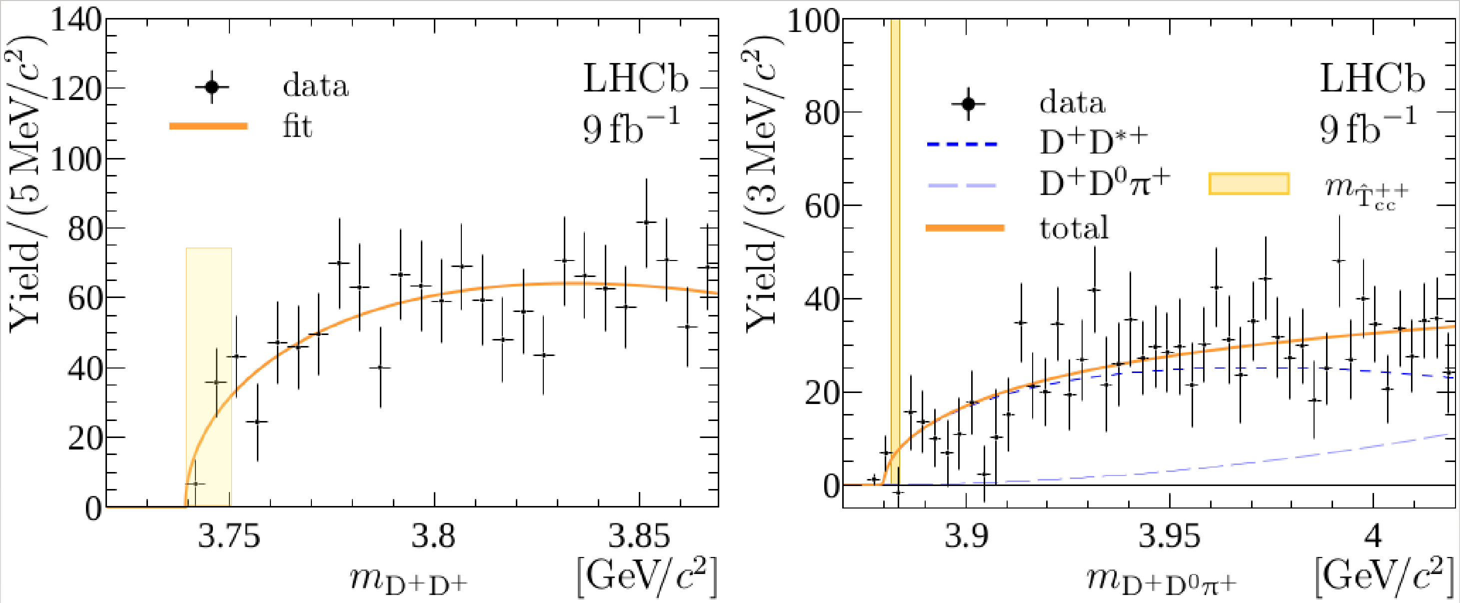
$$\begin{aligned}
m_{\hat{T}^0_{cc}} &= m_{\hat{T}_{cc}} + m_u + m_u - a'\, q_{\bar{u}}q_{\bar{u}} - b'\, q_{cc}\left(q_{\bar{u}} + q_{\bar{u}}\right)\\
m_{\hat{T}^+_{cc}} &= m_{\hat{T}_{cc}} + m_u + m_d - a'\, q_{\bar{u}}q_{\bar{d}} - b'\, q_{cc}\left(q_{\bar{u}} + q_{\bar{d}}\right)\\
m_{\hat{T}^{++}_{cc}}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

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

from Σ_b and Σ_c isotriplets



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



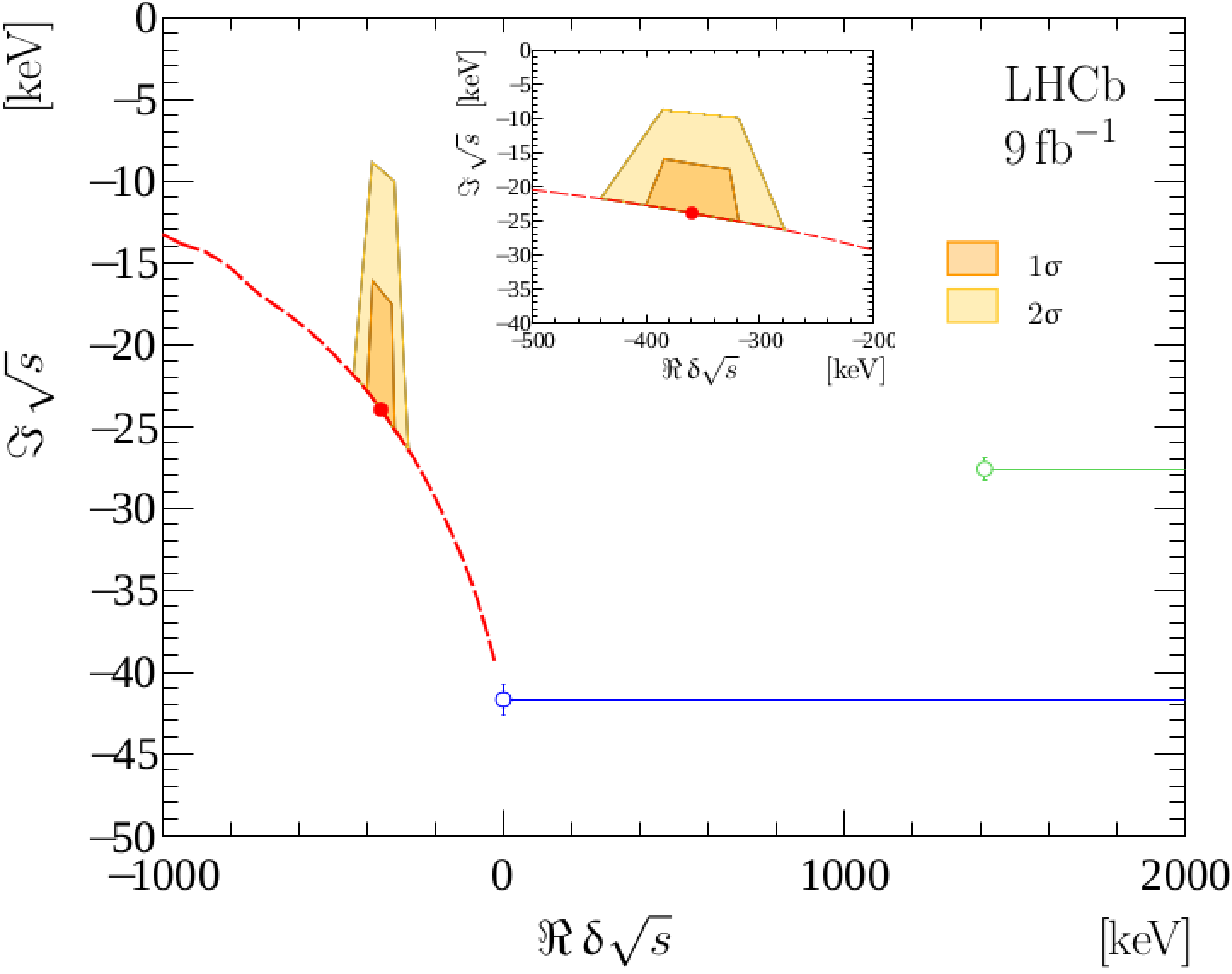
Pole position

- Within the advanced decay model (with dominant role of DD* decay mode) find pole position as solution

$$\frac{1}{\mathcal{A}_{\mathrm{U}}^{II}(\hat{s})} = 0$$

$$\sqrt{\hat{s}} \equiv m_{\mathrm{pole}} - \frac{i}{2}\Gamma_{\mathrm{pole}}$$

$$\delta\sqrt{s} \equiv \sqrt{s} - (m_{\mathrm{D}^{*+}} + m_{\mathrm{D}^0})$$



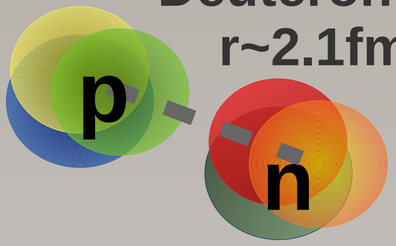
- Result

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

Low-energy expansion

- From expansion near pole can extract low-energy scattering parameters

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

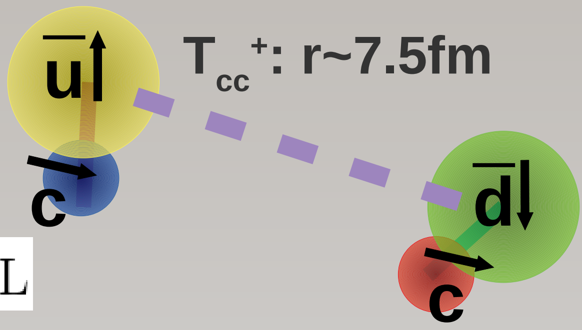


Deuteron: r~2.1fm

- scattering length: $a = \left[-(7.16 \pm 0.51) + i\,(1.85 \pm 0.28)\right]\,\mathrm{fm}$
- characteristic size: $R_a \equiv -\Re\, a = 7.16 \pm 0.51\,\mathrm{fm}$
- effective range: $0 \;\leq\; -r < 11.9\,(16.9)\,\mathrm{fm}$ at $90\,(95)\%$ CL
- Weinberg compositness: $Z < 0.52\,(0.58)$ at $90\,(95)\%$ CL

see more discussions in

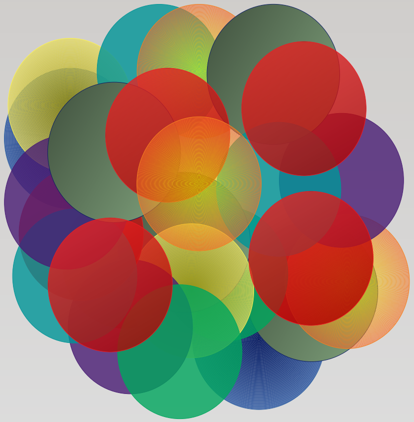
MITP Workshop, 2022 | Mikhasenko, 2022



T_{cc}^{+}: r~7.5fm

- size in case of D^0D^{*+} molecula: $R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4\,\mathrm{fm}$

^{238}U: r~5.8fm



Production vs track multiplicity

- Based on characteristic size one can expect that T_{cc}^{+} has some properties 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

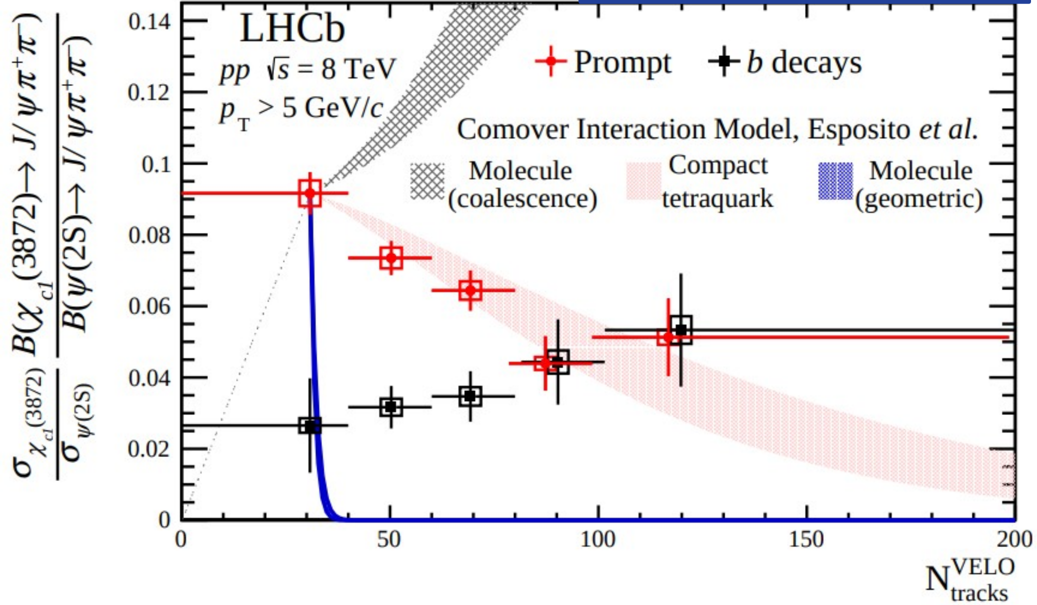
- Therefore probing effective Qπ break-up cross-section:

$$\langle v\sigma_{\psi'}\rangle = 3.9 \pm 0.8 \text{ mb}$$
$$\langle v\sigma_{X}\rangle = 2.6 \pm 0.7 \text{ mb}$$

and fractions of Q out of reach of comovers

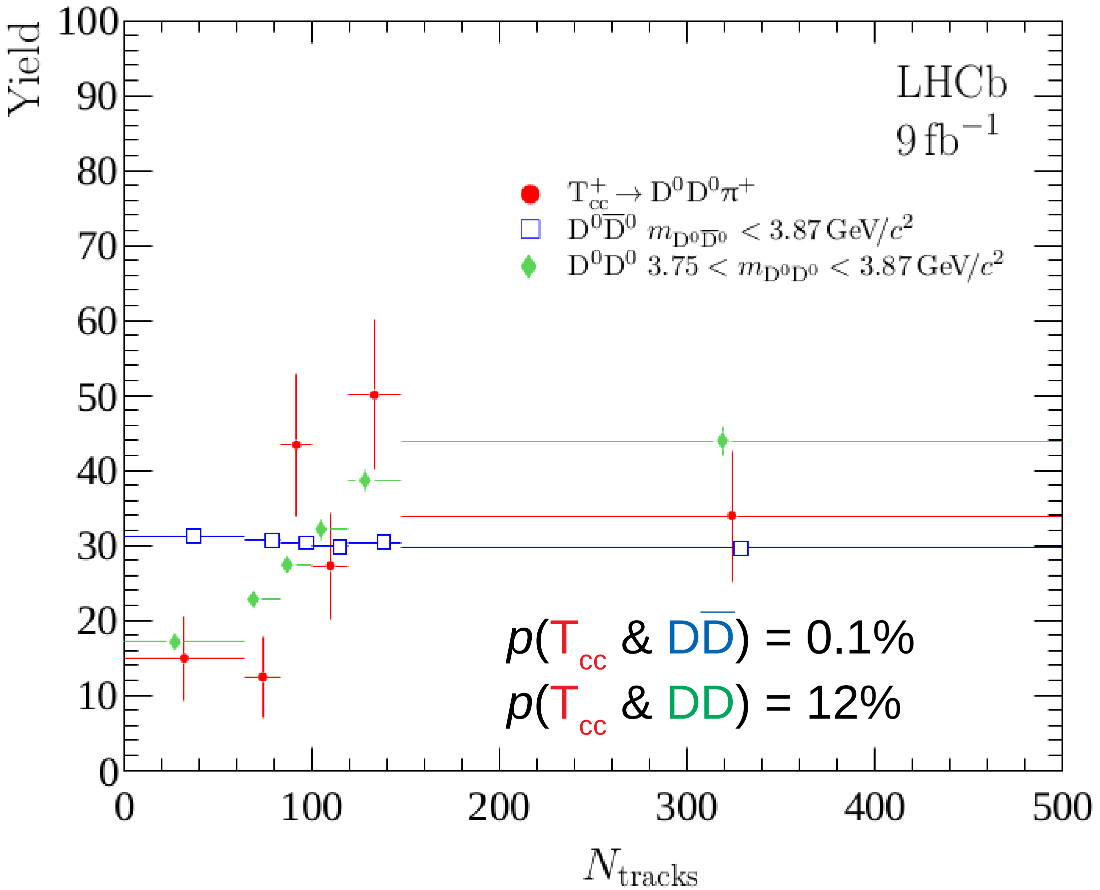
more details in Braaten et al., arXiv:2021.13499

PRL 126 (2021) 092001



T_{cc} multiplicity distribution

- Compare **$T_{cc}^{+} \to D^0D^0X$ signal** distributions with
  - **D^0D^0 in $3.75<m_{DD}<3.87$ GeV region** (presumably dominated by double-parton scattering)
  - **$D^0\bar{D}^0$ in $m_{DD}<3.87$ GeV region** (mainly single $pp \to D\bar{D}$ production)



$p(T_{cc}$ & $D\bar{D}) = 0.1\%$

$p(T_{cc}$ & $DD) = 12\%$

- No suppression of T_{cc}^{+} wrt $D\bar{D}$ (and also to DD) at high multiplicities in contrast to X(3872) wrt ψ(2S)
- Intriguing similarity with $c\bar{c}+c\bar{c}$

Discussions

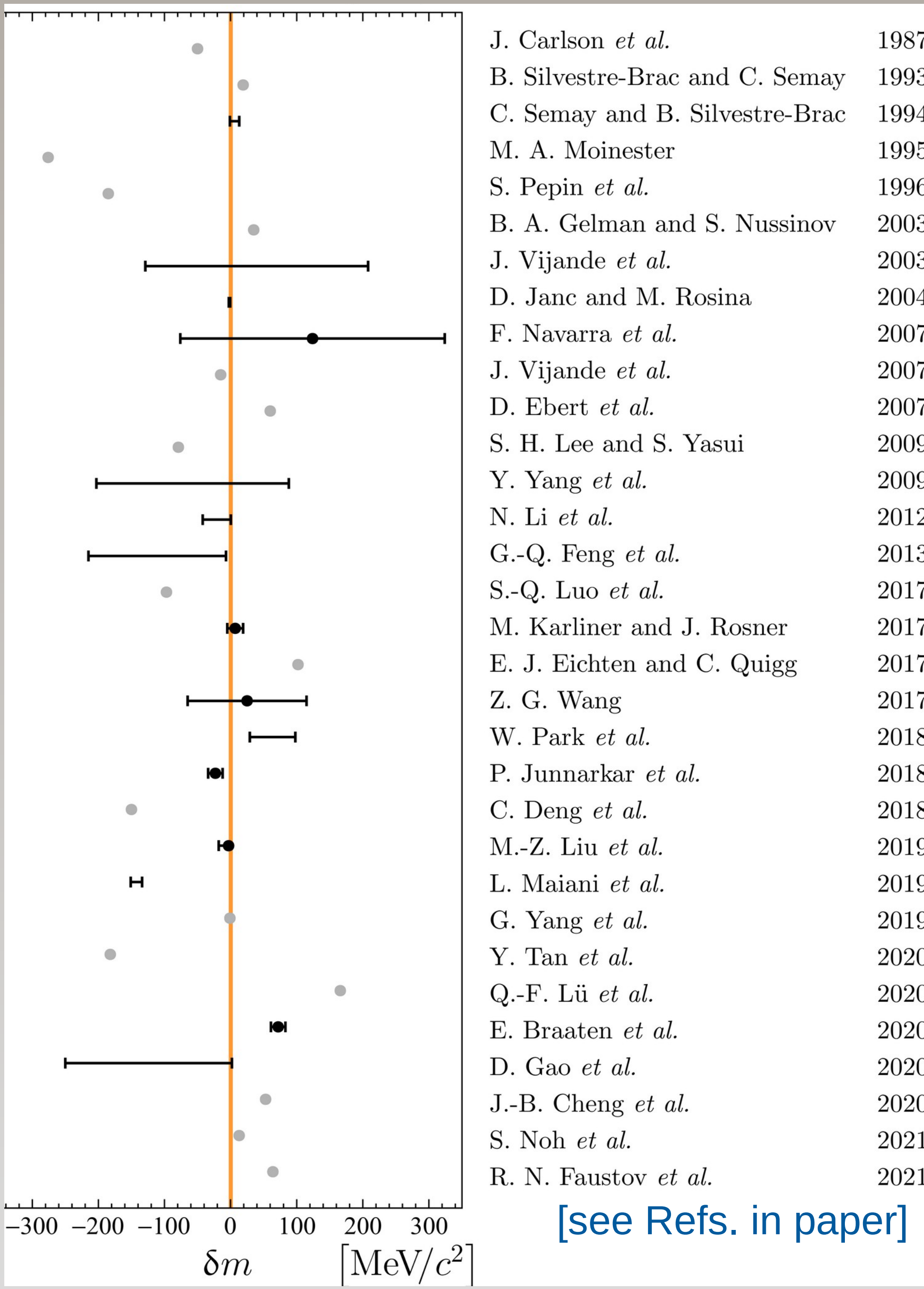
Reflections on measured mass, 1

- 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)



[see Refs. in paper]

Two of the notable matches

- The measured mass difference

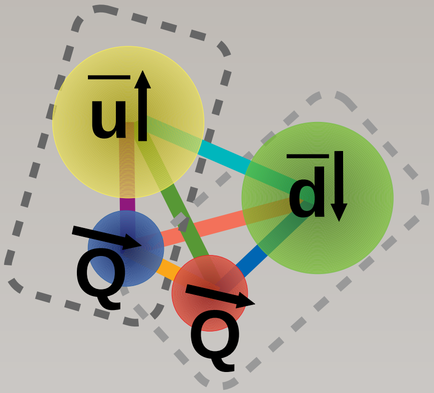
$$\delta m_{\mathrm{U}} = -359 \pm 40\,^{+\,9}_{-\,6}\,\mathrm{keV}/c^2$$

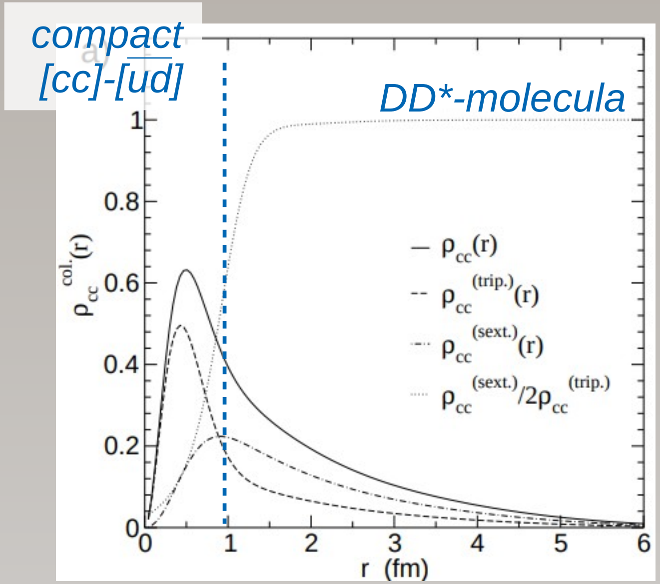
- NR quark-quark potential model
  - **[-2.7,-0.6] MeV**

    -0.6 MeV corresponds to Bhaduri potential

    gives insight into wave function:
    spatial & color configuration
    → dominated by DD component*

    Janc, Rosina, 2003



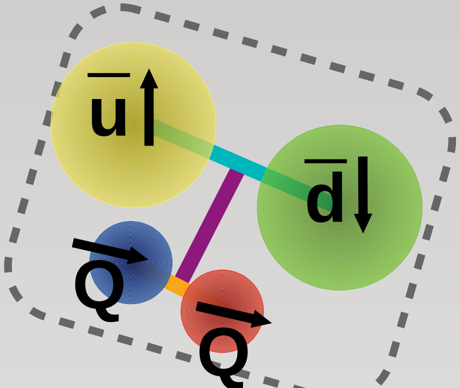


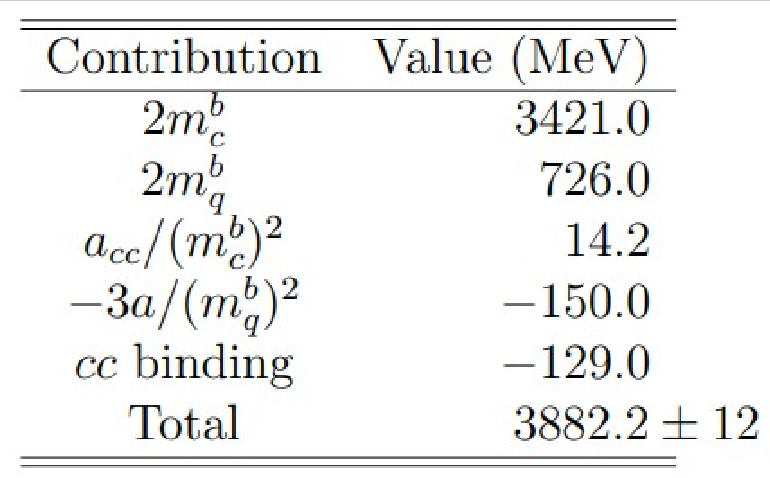
- Phenomenology model for compact tetraquark $[cc]$-$[\overline{ud}]$
  - **1±12 MeV**

    - 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

Reflections on measured mass, 2

- The measured mass difference

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

has the best precision wrt threshold of all exotics

- Demands better theory estimates

→ can start from accounting for isospin splitting

note $m_{th}(D^+D^{*0})-m_{th}(D^0D^{*+})=1.3$ *MeV*

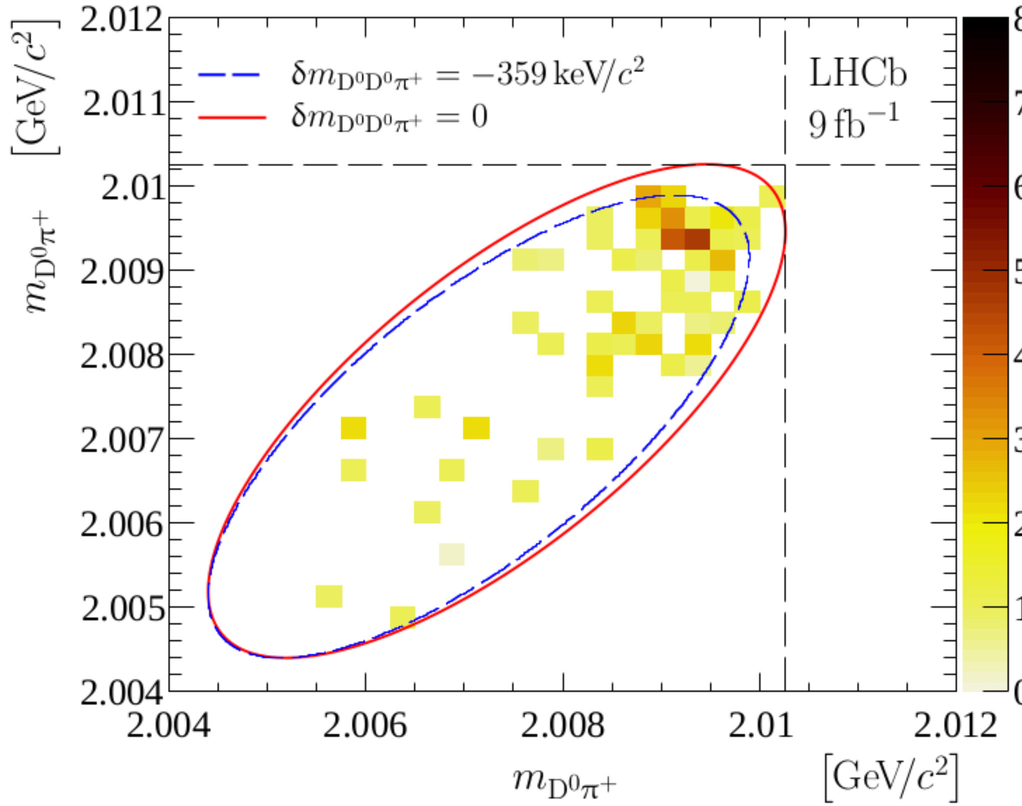
- Using known D^0 and D^{*+} mass can derive

$$\begin{aligned} \mathbf{m(T_{cc}^{+})} &\mathbf{= 3874.75 \pm 0.04(exp) \pm 2x0.05(D^0)\ MeV} \\ &\mathbf{= 3874.75 \pm 0.11\ MeV} \end{aligned}$$

which is better than precision for
Λ_c(0.14 MeV), Σ_c(0.14MeV), Ξ_{cc}^{++}(0.4MeV) and η_c(0.4MeV)
→ new input to tune the models

Future prospects for T_{cc}^+

- Analysis of the $T_{cc}^+ \rightarrow D^0D^0\pi^+$ Dalitz-plot analysis to confirm $J^P=1^+$ spin assignment and probe for isovector component



- Dedicated measurement on D^0D^0X and D^0D^+X relative yields to probe iso-spin violation

- Production cross-section and multiplicity / momentum spectra

- Inclusion of $D^0 \rightarrow K\pi\pi\pi$ can give ~50% gain in statistics

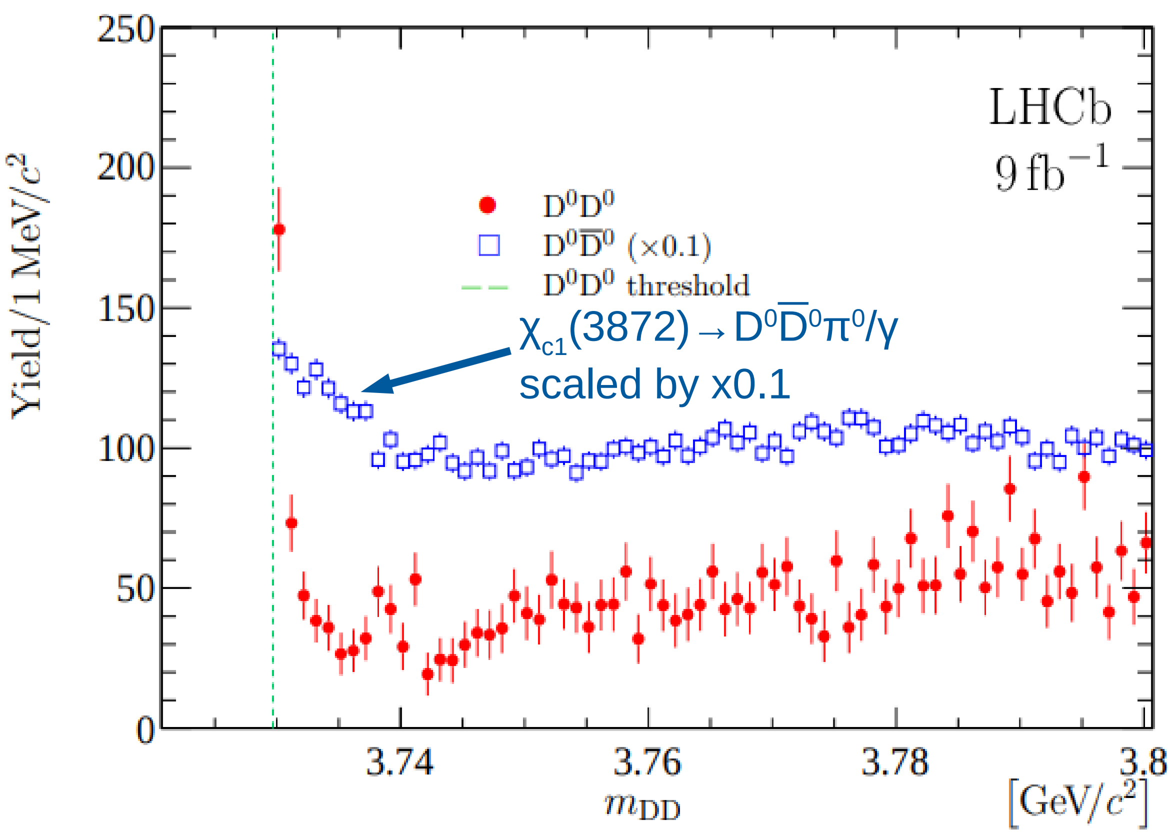
- Data of Run3 (x5 gain in statistics) will be especially important

Production estimation

- One can estimate yields wrt $\chi_{c1}(3872)$ using D^0D^0 and $D^0\overline{D}^0$ spectra:

$$\frac{N(T_{cc}^{+} \rightarrow D^0D^0\pi^+)}{N(\chi_{c1}(3872) \rightarrow D^0\overline{D}^0\pi^0)} \sim 1/20$$

- In future with better understanding of $\chi_{c1}(3872) \rightarrow D^0\overline{D}^0X$ shape a dedicated measurement can be done



$\chi_{c1}(3872) \rightarrow D^0\overline{D}^0\pi^0/\gamma$
scaled by x0.1

- Interesting to determine $\sigma(T_{cc}^{+})/\sigma(\Xi_{cc}^{++})$, either closer to

  $\sigma(\Lambda_c^{+})/\sigma(D) \sim 0.1\text{-}0.2$ or $\sigma(\Lambda_b^{0})/\sigma(B) \sim 1/2$ (in pp at 13 TeV) or less?

  will be limited by knowledge of $Br(\Xi_{cc}^{++} \rightarrow \Lambda_c^{+}K\pi\pi) \sim 5\text{-}20\%$,
  $Br(\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+}) \sim 1.3\text{-}4\%$,
  $Br(\Xi_c^{+} \rightarrow pK\pi) \sim (6.2\pm3.0)\times10^{-3}$

Other doubly-heavy states

- The T_{cc} below DD* threshold supports predictions for stable T_{bb}
- Interestingly, binding for ***[bc][$\overline{ud}$]*** wrt $\overline{B}D$ threshold is expected to be ~10 MeV higher than for T_{cc}^{+} wrt DD*

  Karliner, Rosner, 2017 | Semay, SIlvestre-Brac, 1994

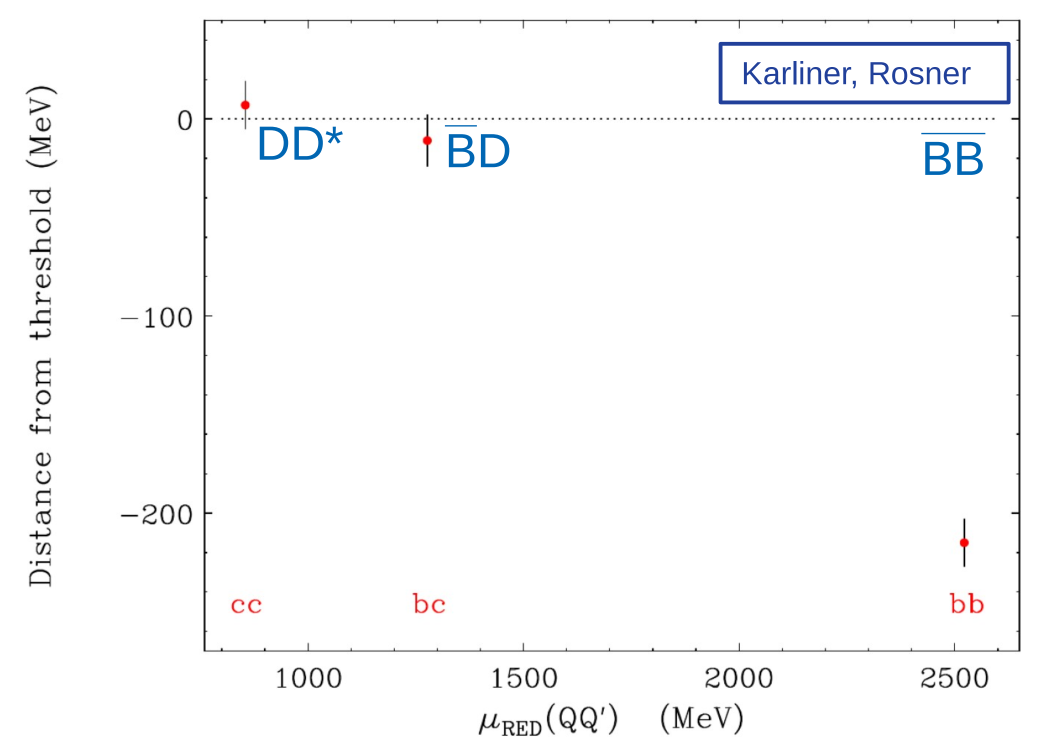
  → Giving stable T_{bc}?

  - Different expectations in molecula models

    Li, Sun, Liu, Zhu, 2012

    Liu, Wu, Valderrama, Xie, Geng, 2019

  - Good test for models



Karliner, Rosner

- From naive phenomenology (HQS-like) estimates one can expect that
  - ***[cc][$\overline{sq}$]*** and ***[cc][$\overline{sq}$]*** are above corresponding thresholds.
  - ***[cc][ud]$\bar{q}$*** can decay to Ξ_{cc} + hadrons

Upgrade and Future searches for $T_{bb/c}$

see talk by Steve Blusk
[the Tcc mini-workshop]

- **Cons**
  - O(2-20) supression with every c → b substitution
    compare with $\sigma(\Xi_{cc}) : \sigma(\Xi_{bc}) : \sigma(\Xi_{bb}) \sim 1 : 0.4 : 0.015$ *at 14TeV in pp*
  - Br($b \rightarrow c + \pi/\mu/X$) are 0.1-1%

Zhang, Wu, Zhong, Yu, Fang, 2011

- **Pros**
  - x5 gain in integrated luminosty in Run3 (2022-2024)
  - gain in trigger and reconstruction efficiencies (x2?) from Upgraded LHCb
  - larger trigger efficiency for final states with high-p_T muon

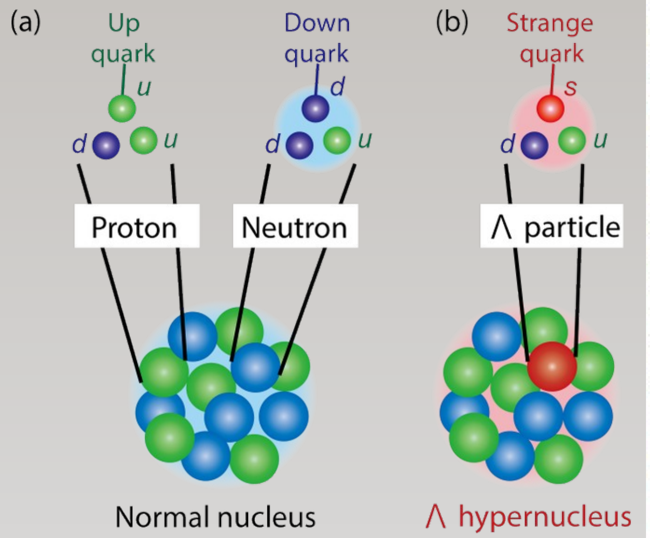
- Comparing to ~150 events of $T_{cc} \rightarrow D^0 D^0 \pi^+$ one can expect in Run3
  - T_{bc} *- real chances to find (if combining several modes)*
    - long-lived: ~ O(1-10) events in modes $D^0 D^+ \pi^-$, $\bar{B}^0 K^- \pi^+$, $D^0 D^+ \mu\nu$, $\Xi_{cc}^+ \bar{p}$, $T_{cc}^+ \pi^-$, ...
    - promptly-decaying: ~ O(10) events in modes $B^- D^+$, $\bar{B}^0 D^0$
  - $T_{bb} \rightarrow BD + X$ ~ O(0.01) *- not much hope yet*

Hadron physics meets Nuclear

- In hadron spectroscopy advances of the theory is limited by the quark configurations to consider ($q_1\bar{q}_2$ & $q_1q_2q_3$, $c\bar{c}q_1\bar{q}_2$ & $c\bar{c}q_1q_2q_3$)
  - *problems with interpretation in most cases (except for the T_{cc}^{+}!)*
  - *In general presence of heavy quark helps*

- In nuclear physics systems with only light quarks are usually considered
  - where non-perturbative effects are at its maximum

- Hyper-nuclei with Λ are explored since 50's



- Inclusion on b/c-quark will simplify the system and bring such a unique tool to new level

Gal, Hungerford, Millener, 2016

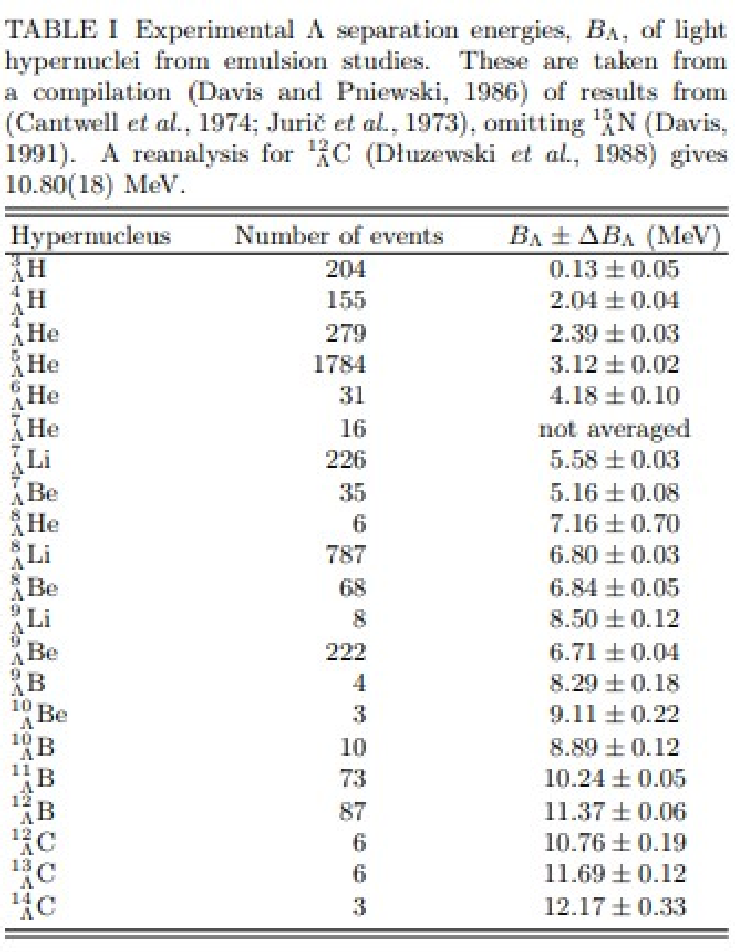
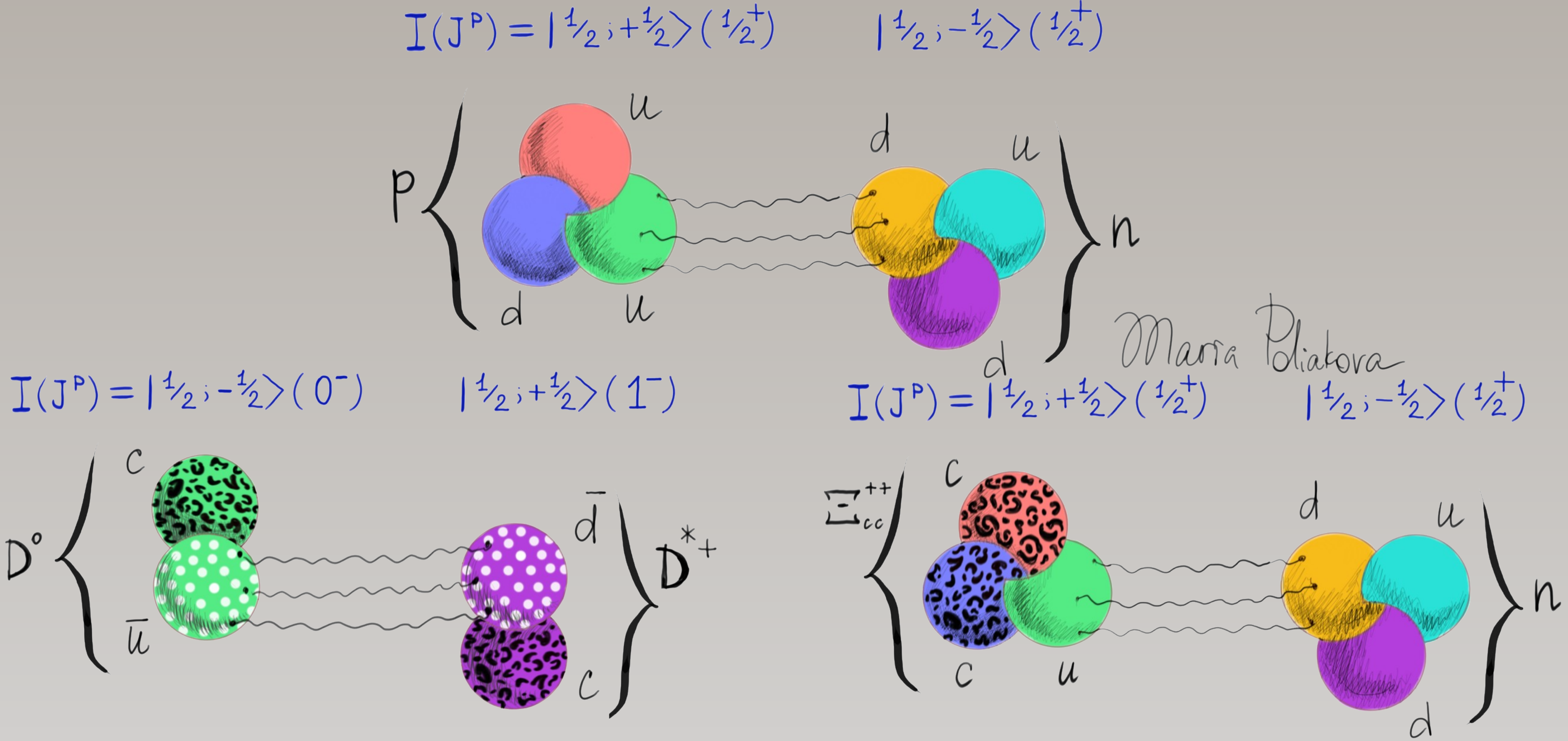


TABLE I Experimental Λ separation energies, B_Λ, of light hypernuclei from emulsion studies. These are taken from a compilation (Davis and Pniewski, 1986) of results from (Cantwell *et al.*, 1974; Jurič *et al.*, 1973), omitting ${}^{15}_{\Lambda}\mathrm{N}$ (Davis, 1991). A reanalysis for ${}^{12}_{\Lambda}\mathrm{C}$ (Dłuzewski *et al.*, 1988) gives 10.80(18) MeV.

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

Similarities in binding

- Note same spin-isospin structure in following examples



- No consensus in predictions for masses of the heavy hexaquarks/dibaryons
- Arguments for both ***instability*** and ***stability*** can be found

Pepin, Stancu, 1998

Park, Park, Lee, 2015

Vijande, Valcarce, Richard, Sorba, 2016

Leandri, Silvestre-Brac, 1993, 1995

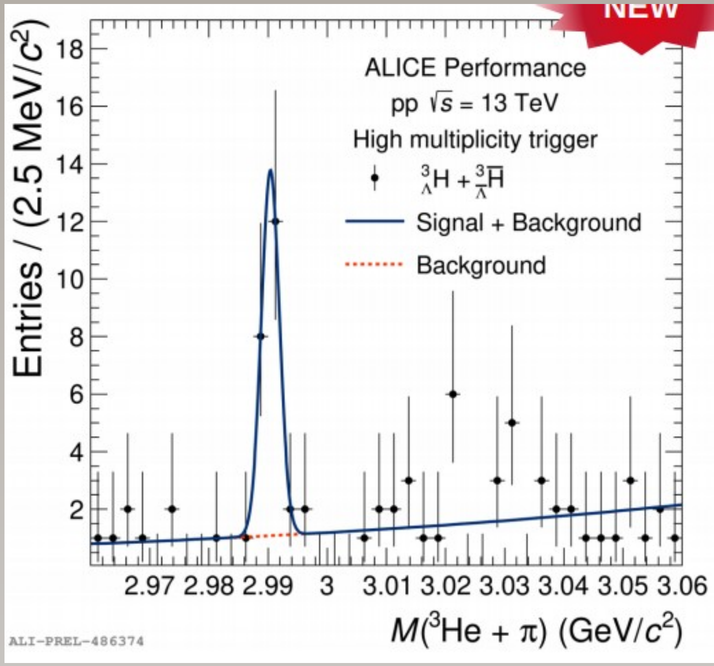
Chow, 1995

Wang, Ping, Wu, Teng, Goldman, 1995

Stancu, 1999

Huang, Ping, Wang, 2014

Hyper-nuclei at LHC



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

  ALICE, 2107.10627

- Searches for ΛΛ di-baryon (uuddss) are ongoing, – no success yet

  ALICE, 1506.07499 ALICE, 1905.07209

- The [uuddcc] has more chances to exist due to ~100 MeV stronger binding between cc quarks *

  ** M. Karliner*

- LHCb has x50-100 larger statistics of pp-collisions than ALICE,
  - perfectly suited for reconstructing c-hadron decays (τ~O(ps)),
  - $c\bar{c}$ produced in ~5% of pp collisions

  LHCb, 1205.0975

- Possible modes for searches:
  - H_c [*cuduud*] → $ppK^-\pi^+(\pi^-)$ / $p\Lambda_c$
  - H_{cs} [*csudud*] → $ppK^-K^-\pi^+$
  - H_{cc} [*ccuudd*] → $\Lambda_c pK^-\pi^+$, .../ $\Lambda_c\Lambda_c$
  - H_{ss} [*ssuudd*] → $ppK^-\pi^+$
  - ...

Deuteron ID & TORCH

- Hypernuclei decays with deuterons (d) and possibly tritons (t, ^{3}H) / ^{3}He
  - H_{ss} [*ssuudd*] → dK^-
  - H_c [*cuduud*] → $dK^-\pi^+(\pi^+)$ / dD^+
  - H_{cs} [*csudud*] → $dK^-K^-\pi^+\pi^+$ / dD^0K^-
  - H_{cc} [*ccuudd*] → dD^0, $dD^+\pi^-$ / dD^0D^+
  - $^3H_\Lambda$ → $^3He\,\pi^-$, $dp\pi^-$
  - $^3He_\Lambda$ → $^3He\,\pi^+\pi^-$, dp
  - $^3H_{\Lambda c}$ → $tK^-\pi^+$, dpK^-, $^3He\,K^-$
  - $^3He_{\Lambda c}$ → $^3He\,K^-\pi^+$, $dpK^-\pi^+$, tK^-
  - ...

- Currently no deuteron ID at LHCb above 30 GeV/c

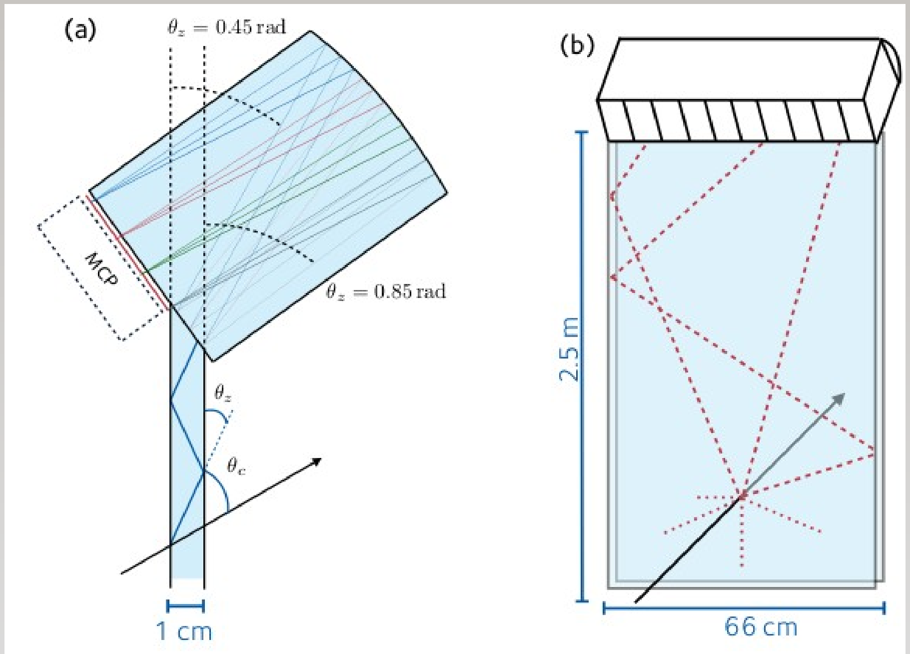
- Time-of-flight detector prepared for LHCb Upgrade II

N. Harnew et al., arXiv:1810.06658

T.H. Hancock et al., NIM A 958 (2020) 162060

- Aiming to provide p/K/π identification in 2-10 GeV/c range where present RICH detectors are not efficient

- Will also provide identification for deuteron and triton up to 25-30 GeV/c, thus enriching potential for hyper-nuclei searches



Conclusions

- A novel class of hadrons observed – [$cc\overline{ud}$],
  just below D^0D^{*+} threshold, consistent with predicted T_{cc}^+ with $J^P=1^+$
- $D^0D^0\pi^+$, $D^0\pi^+$, D^0D^0, D^0D^+ spectra described
- Intriguing production properties

arXiv:2109.01038

arXiv:2109.01056

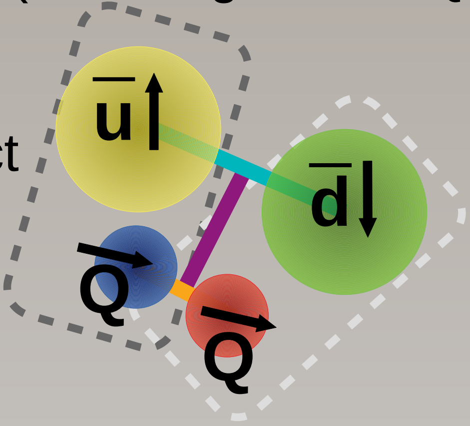

opens insight into the new area
more to see and explore

- Run3 (2022-2024) and Upgraded LHCb will bring a lot of possibilities for further studies - T_{cc}, T_{bc}, H_c, H_{cc}, ...

Backup

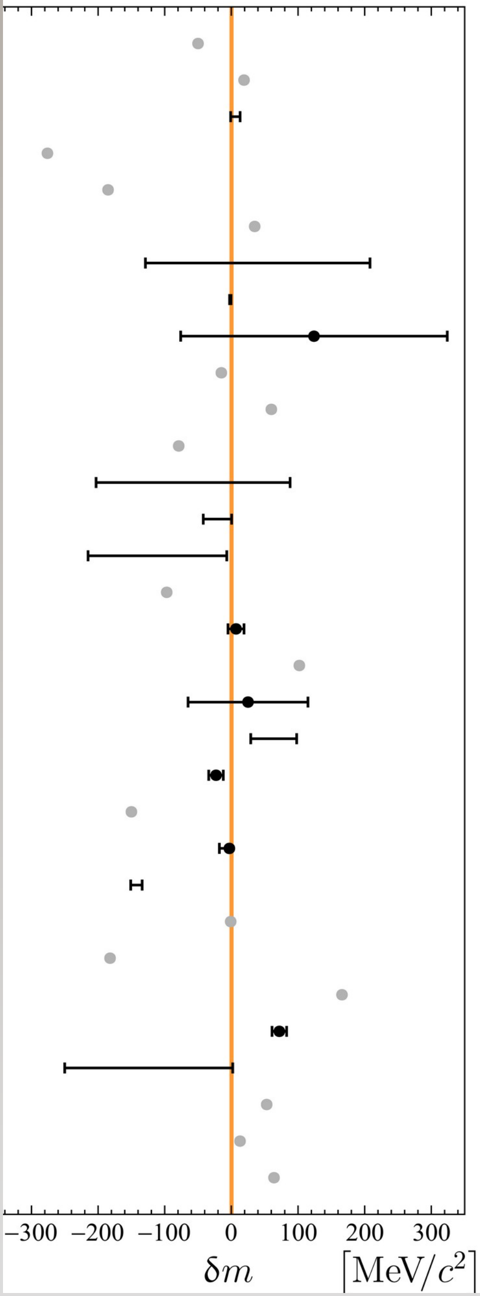
Predictions for $cc\overline{ud}$ mass

- More recent calculations (including Lattice QCD) all agree that it should be true for $[bb][\overline{ud}]$ with QQ forming compact color anti-triplet and resulting binding of ~150MeV



- However not clear for $[bc][\overline{ud}]$ and $[cc][\overline{ud}]$
- Predictions for a ground $cc\overline{ud}$ state (isoscalar with $J^P=1^+$) vary within ±250MeV wrt to D^0D^{*+} threshold
- Review few selected in the following
  Neither full, nor objective, and oversimplified → see Ref. List in papers for an overview

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



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

[see Refs. in paper]

Selected theory approaches

- Few selected approaches discussed in following
  - Phenomenological approach for compact hadrons
  - Non-relativistic quark constituent model
  - Molecula object
  - Hydrogen bond in QCD
  - Lattice QCD
  - … others

Neither full, nor objective, and oversimplified →
see Ref. List in papers for an overview

Phenomenology approach for compact hadrons

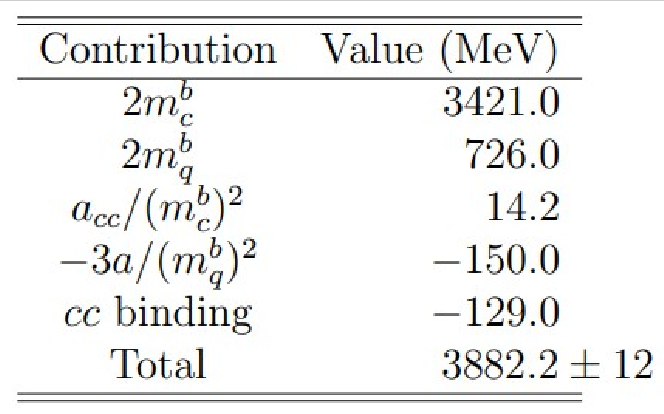
- Extracting effective quark masses and binding or hyperfine interaction terms from measured hadron masses and assuming cc are in anti-triplet color configuration
  - 1a. Heavy Quark Symmetry
    - $m(cc\bar{u}\bar{d}) = m(\Xi_{cc}) + 315\ \mathrm{MeV} \sim m(\Xi_{cc}) + [m(\Lambda_c)-m(D^0)]$ + *kinematic correction*

      → δm = +102 MeV $\longrightarrow$ **δm = +65 MeV** *(~ 3 MeV)*

      using measured Ξ_{cc} mass

      Eichten, Quigg, 2017
  - 1b. More detailed calculation with estimation of uncertainties

    → **δm = 72±11 MeV** Braaten, He, Mohapatra, 2020
  - 1c. Different treatment of meson/baryon quark masses & splitting parameters



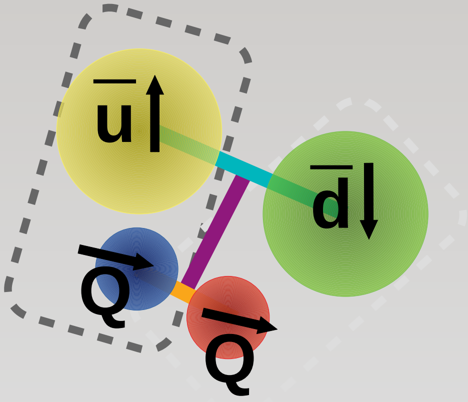
Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	−150.0
cc binding	−129.0
Total	3882.2 ± 12

→ δm = 7±12 MeV

$\downarrow$ *using measured Ξ_{cc} mass*

δm = 1±12 MeV

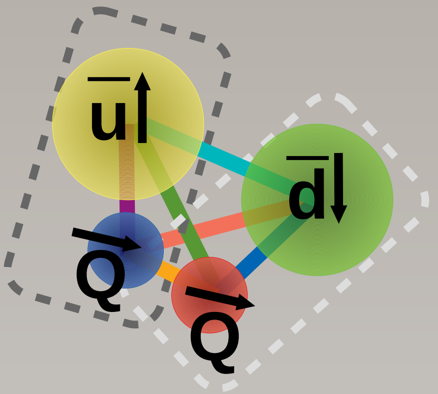
Karliner, Rosner, 2017



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

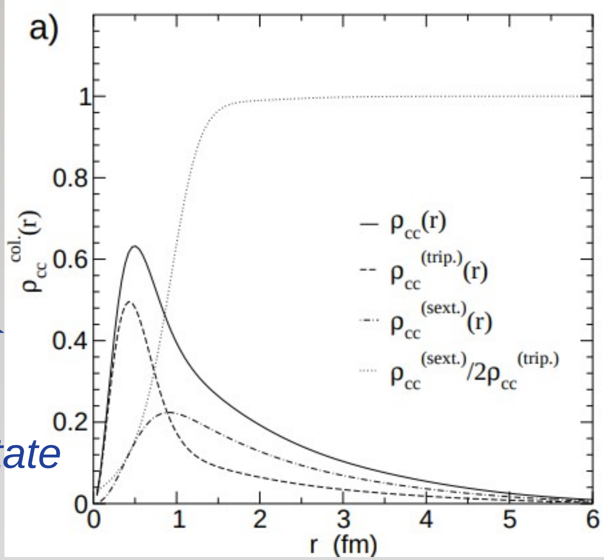
→ **δm = [-1;+13] MeV** Semay, SIlvestre-Brac, 1994

δm = [-2.7;-0.6] MeV Janc, Rosina, 2003

… + more within [-200;+100] MeV range

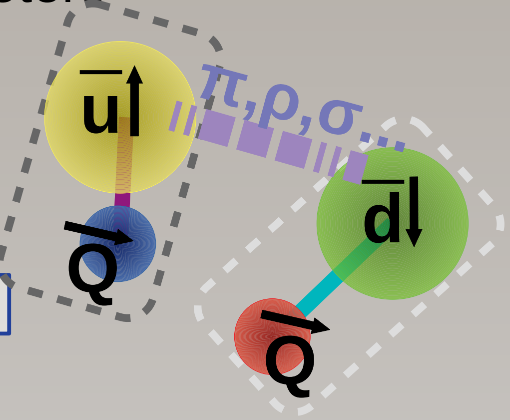
(choice of basic, parameters, ...)

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)

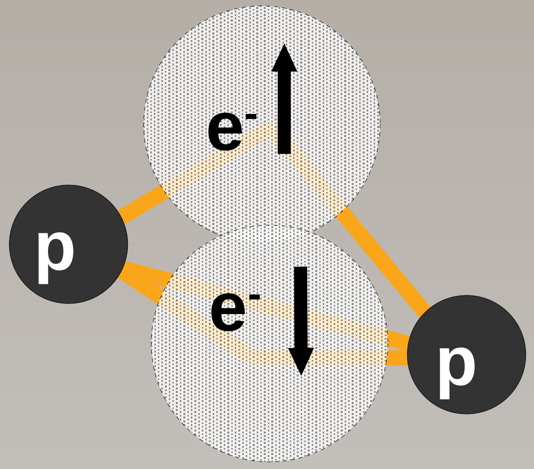
Hydrogen bond of QCD

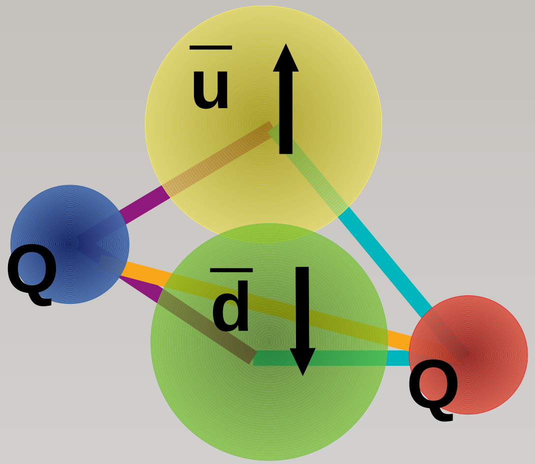
- Consider interaction between two D-mesons by solving Schrodinger equation for light quarks (q) given fixed distance between the heavy ones (Q)
  → get effective interaction between QQ

$$H = \frac{1}{2M}\sum_{\text{heavy}} P_i^2 + \frac{1}{2m}\sum_{\text{light}} p_i^2 + V(\boldsymbol{x}_A,\boldsymbol{x}_B) + V_I(\boldsymbol{x}_A,\boldsymbol{x}_B,\boldsymbol{x}_1,\boldsymbol{x}_2)$$

Q-Q interaction

Q-q and q-q interaction





→ get **O(MeV)** binding between D mesons:
and thus **δm ~ -135 MeV** Maiani, Polosa, Riquer, 2019

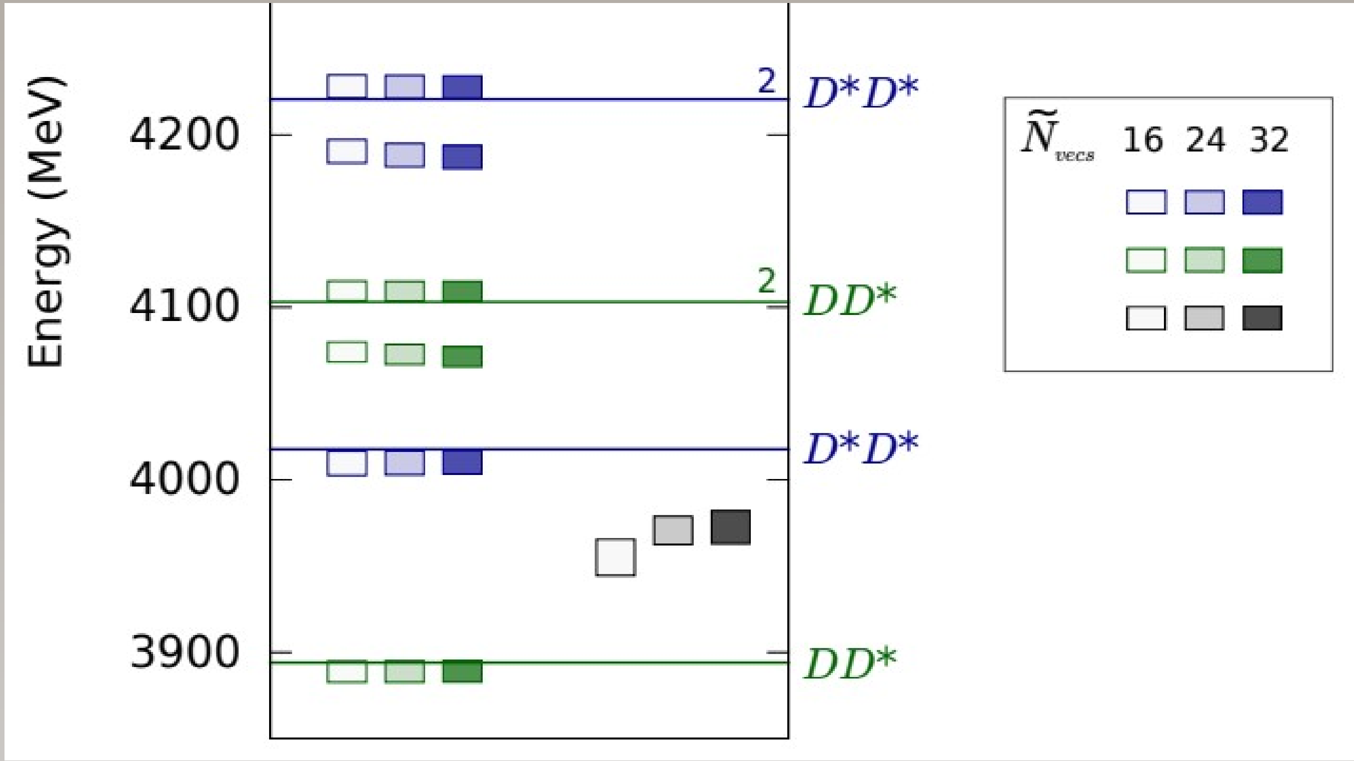
is it analogous to quark consituent model with OGE?
should it be re-considered for DD interaction?*

Lattice QCD

- Inconclusive
  - **no binding**

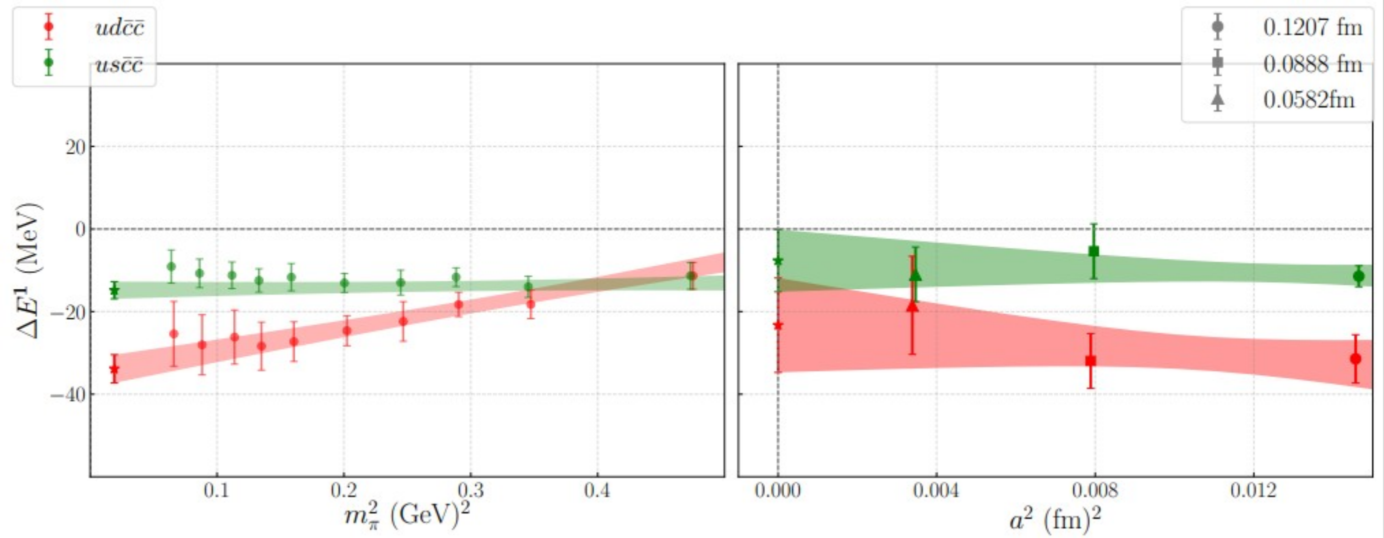
HAL QCD Collaboration, 2014

Hadron Spectrum Collaboration, 2017



- **δm ~ -23±11 MeV**

Junnarkar, Mathur, Padmanath, 2018



Summary of Results

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

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

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

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

  is determined using dedicated model

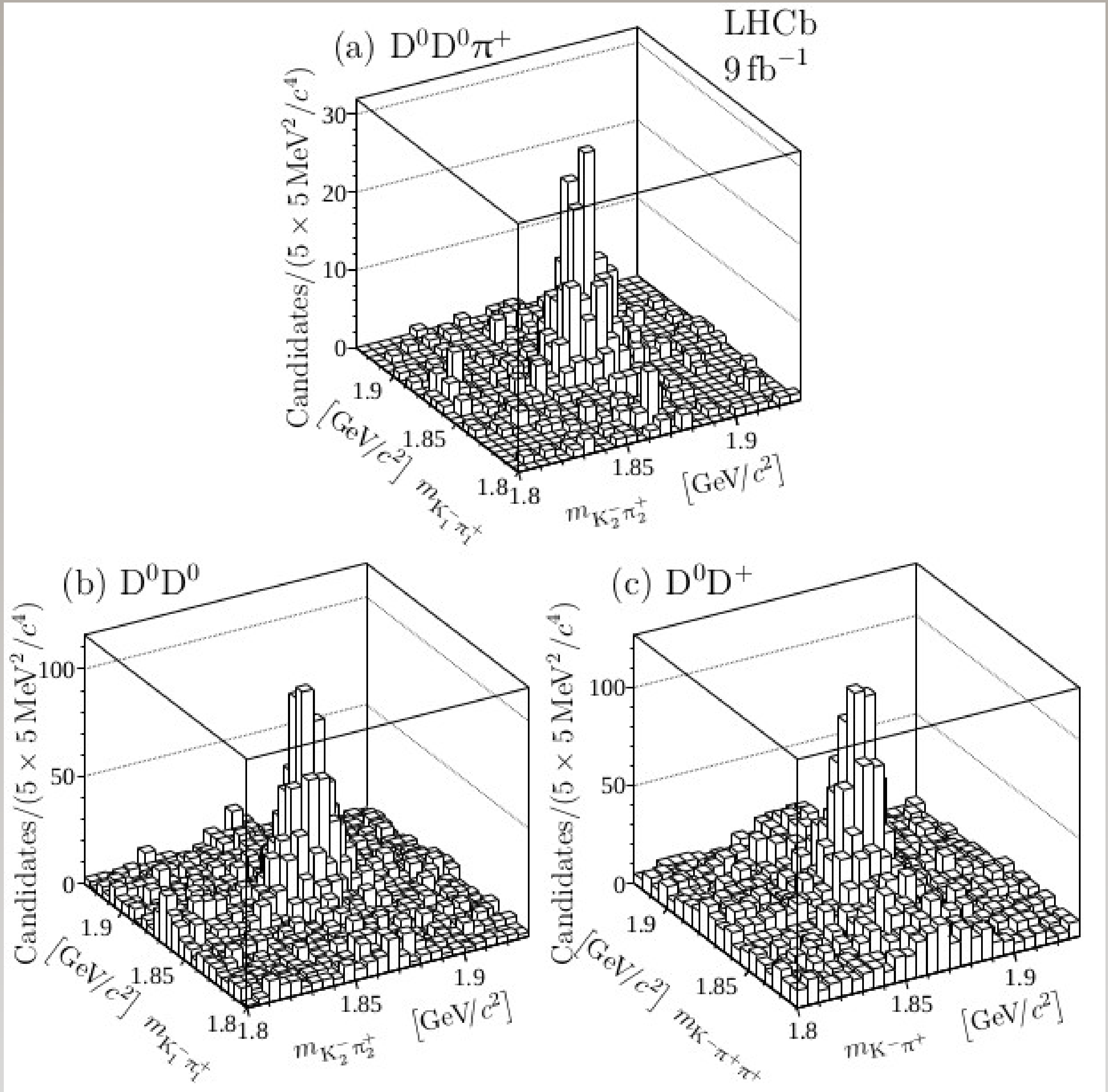
- A lower limit is set on $T_{cc}^+ \rightarrow DD^*$ coupling: $|g| > 5.1\,(4.3)\,\mathrm{GeV}$ at $90\,(95)\,\%$ CL

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

- Pole position:

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

2D LEGO Plots



Resolution model

- Sum of two gaussian functions, where widths and relative fractions are determined from simulation:

  σ_1 = 263 keV x 1.05

  σ_2 = 2.413 x σ_1

  f_1 = 0.778

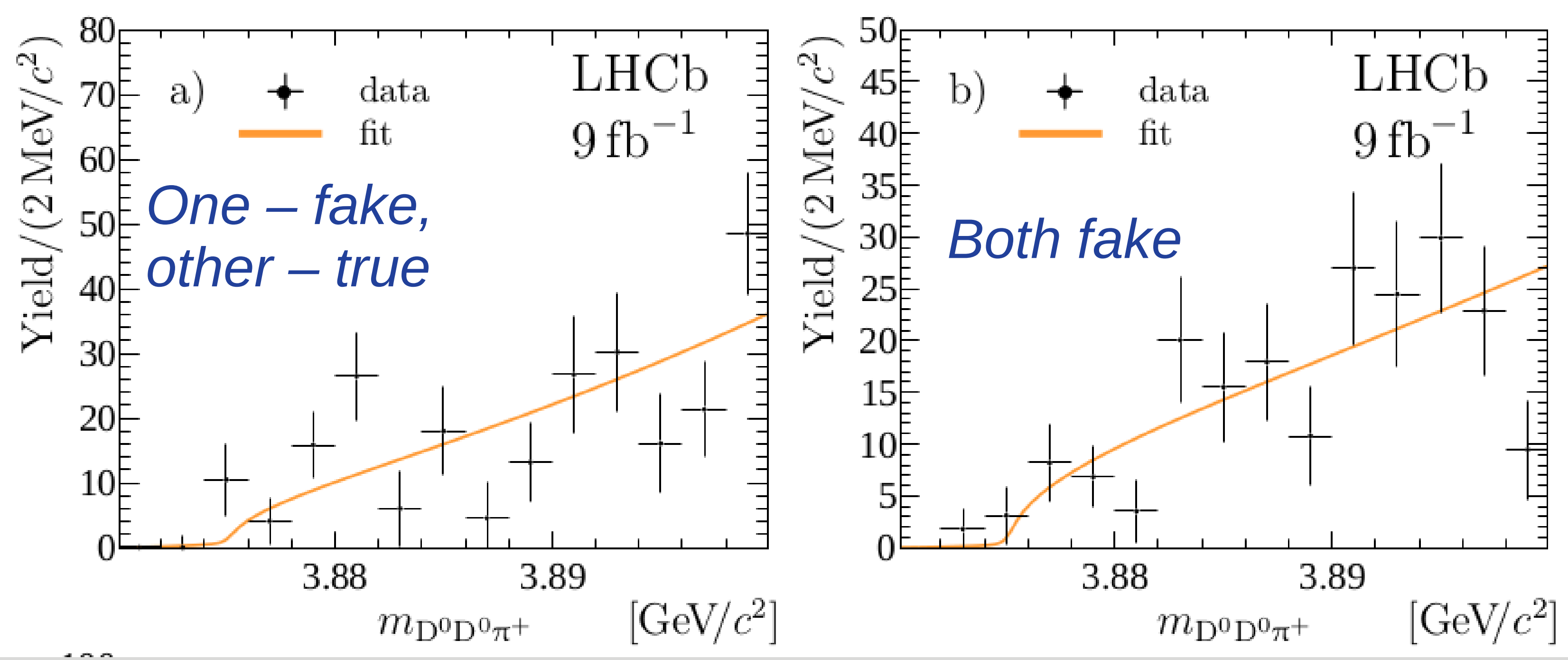
  a 1.05 correction motivated by data-simulation comparison in various decay channels

- For systematics :
  - correction factor varied within 1.0-1.1
  - many alternative parametrisations tried:
    Apolonios, CrystalBall, Student-t, Jphnson-U, Novosibirsk

Cross-checks

- Different years, data taking conditions
- Exclude double-counting, ensure no duplicated tracks
- No reflections from mis-identification
- Ensure peaks produced by true D^0 candidates

Mass distributions with fake D^0's



One – fake, other – true

Both fake

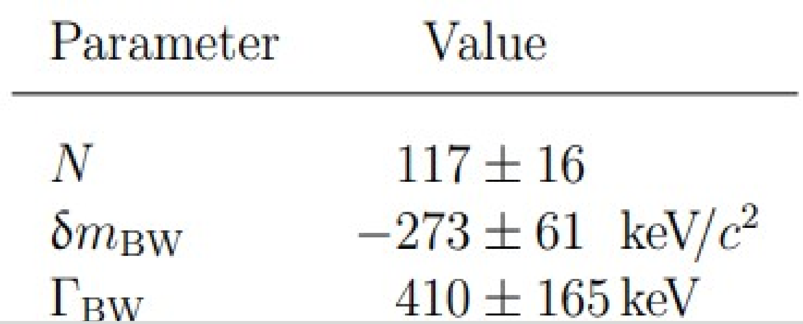
Fit with Breit-Wigner function

- The distribution is fit with a sum of
  - P-wave relativistic Breit-Wigner
  - $D^{*+}D^0$ phase space x pol_1

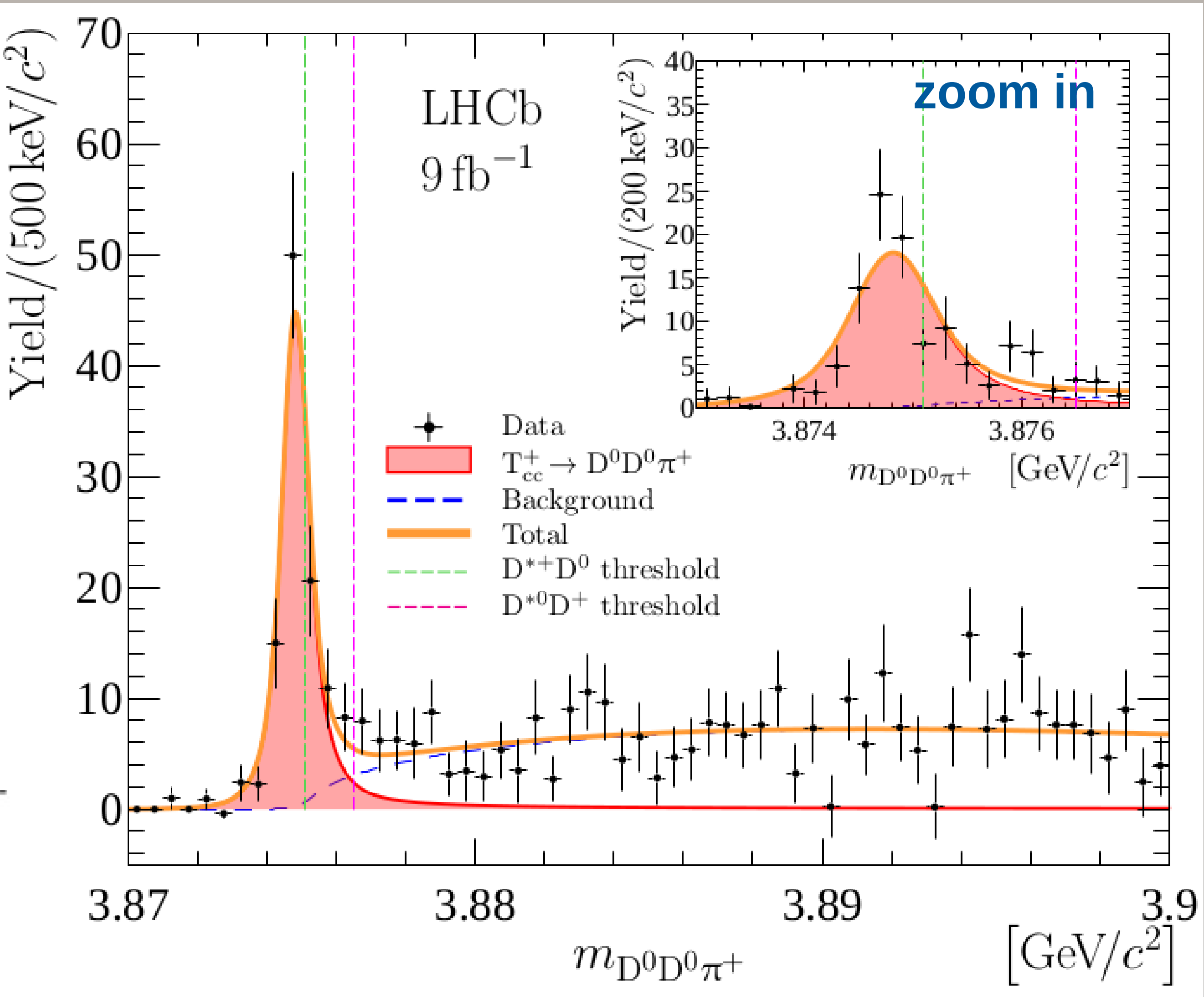
  both convolved with resolution of ~400keV

- Found to be below the $D^{*+}D^0$ threshold (with 4.3σ significance for "*below $D^{*+}D^0$*")

- Results:

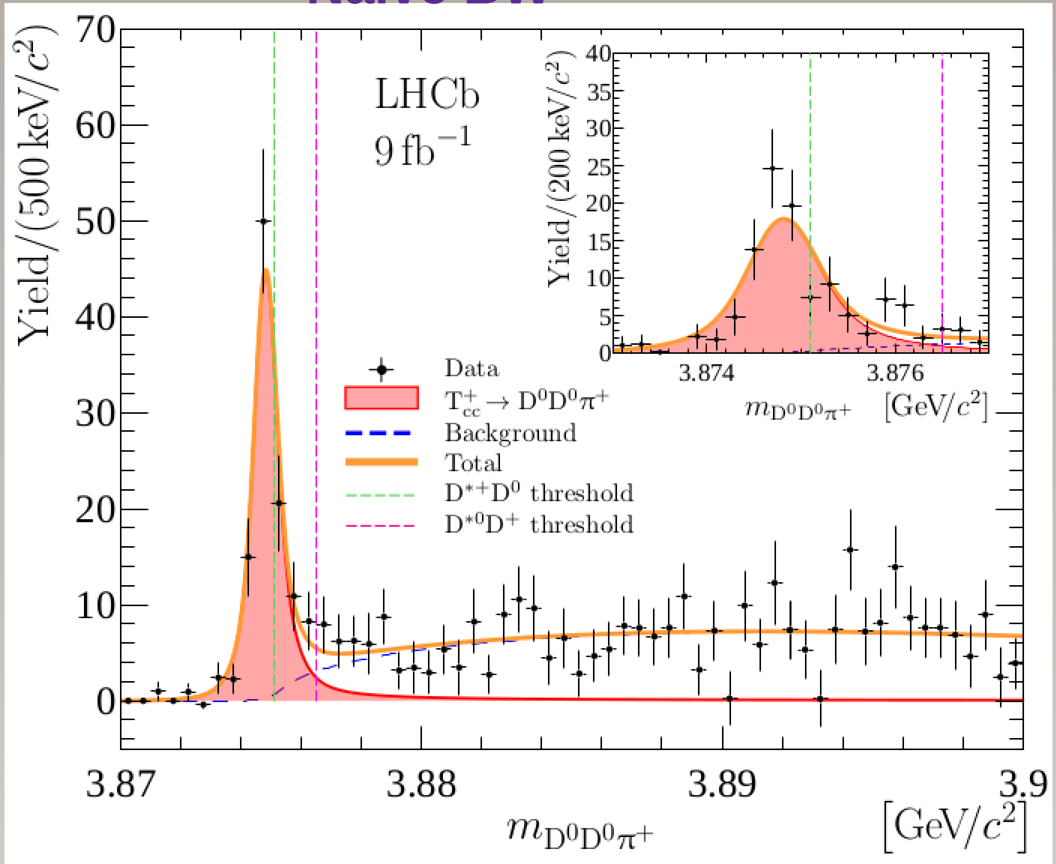


Parameter	Value
N	117 ± 16
$\delta m_{\rm BW}$	$-273 \pm 61 \ \ \text{keV}/c^2$
$\Gamma_{\rm BW}$	$410 \pm 165\,\text{keV}$

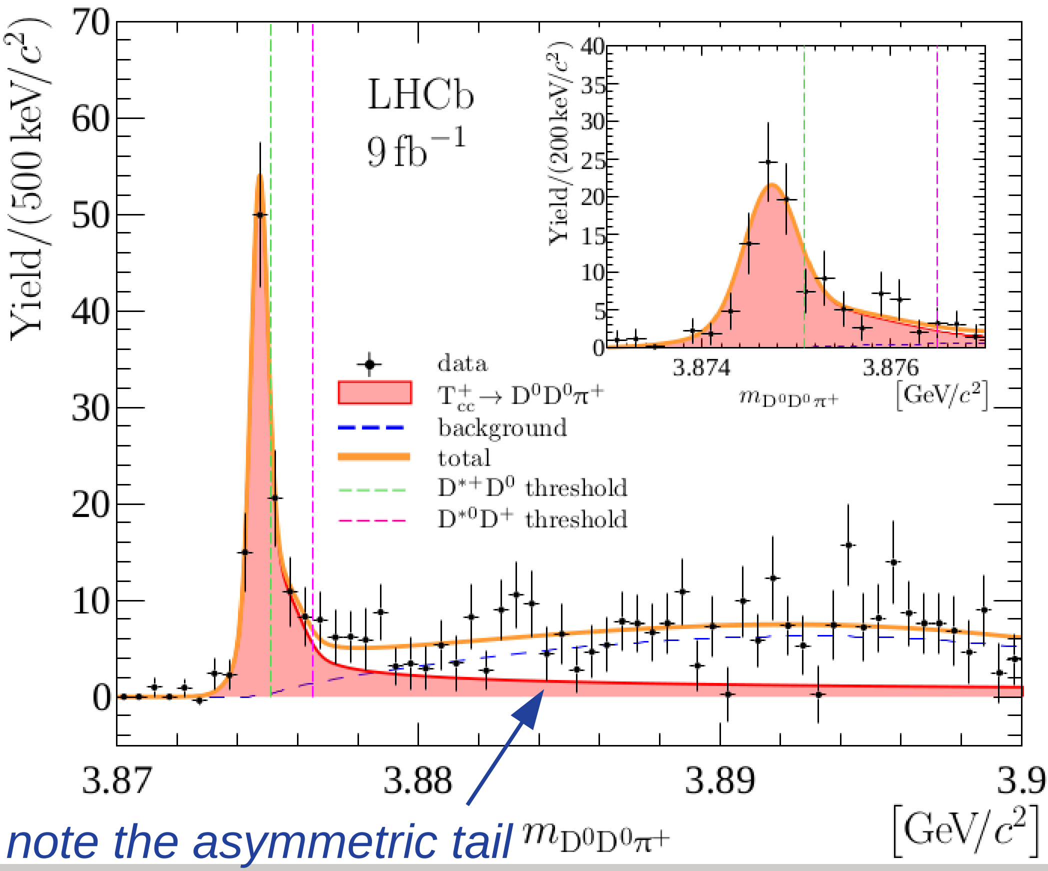


Fits with Naive and Unitarized models

Naive BW



Unitarized



note the asymmetric tail

- Compare position of peak maximum and FWHM (before convolving with resolution)

too naive →

	$\delta\mathfrak{m}$ [keV/c^2]	$\mathfrak{w}$ [keV/c^2]
$\mathfrak{F}^{\mathrm{BW}}$	-279 ± 59	409 ± 163
$\mathfrak{F}^{\mathrm{U}}$	-361 ± 40	47.8 ± 1.9

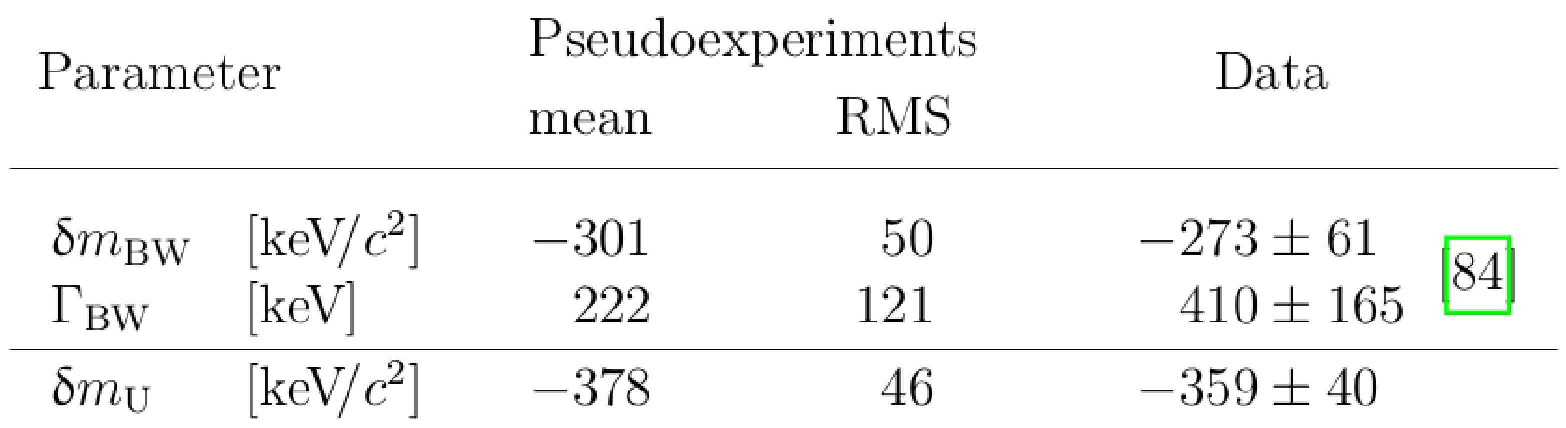
- Both consistent with data

Consistency of Naive and Unitarized

- Generate 25k pseudoexperiments using unitarized BW model,
  fit them with naive BW model.
  Get δ’m_{BW} and Γ_{BW} consistent with values obtained from data

- Generate 4k pseudoexperiments using naive BW model,
  fit them with unitarized BW model.
  Get δ’m_0 consistent with values obtained from data

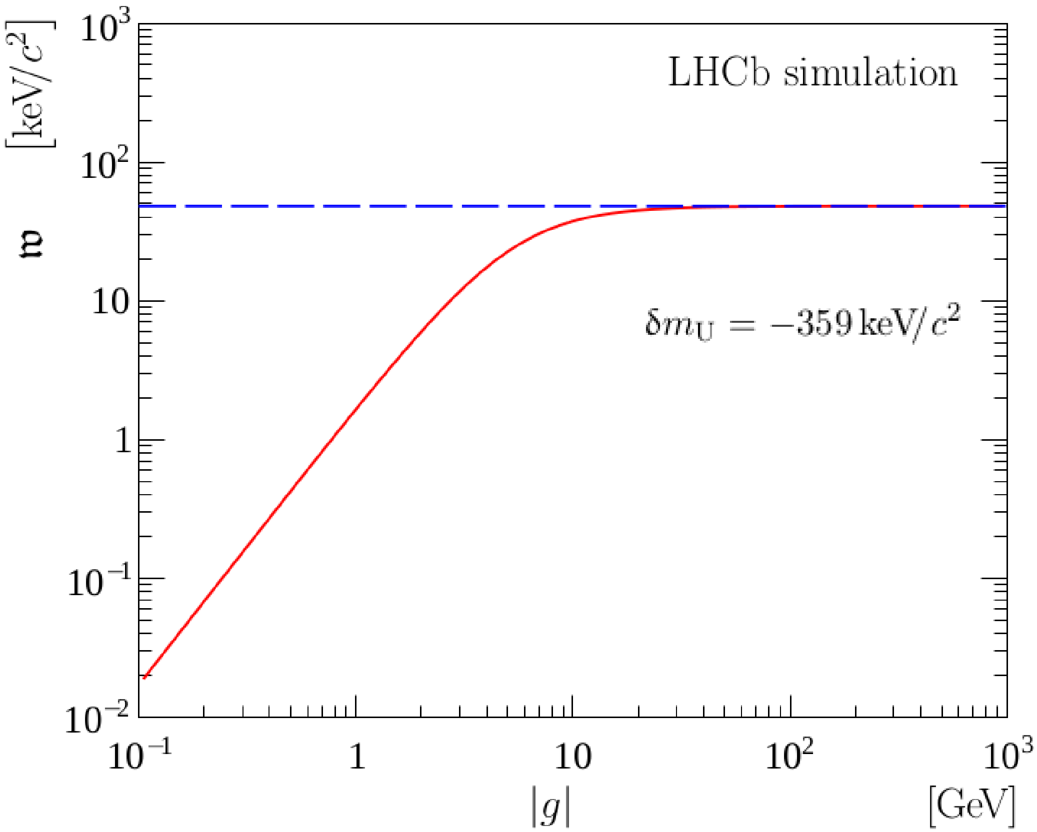
- Consistent considering current statistics, mass resolution and background

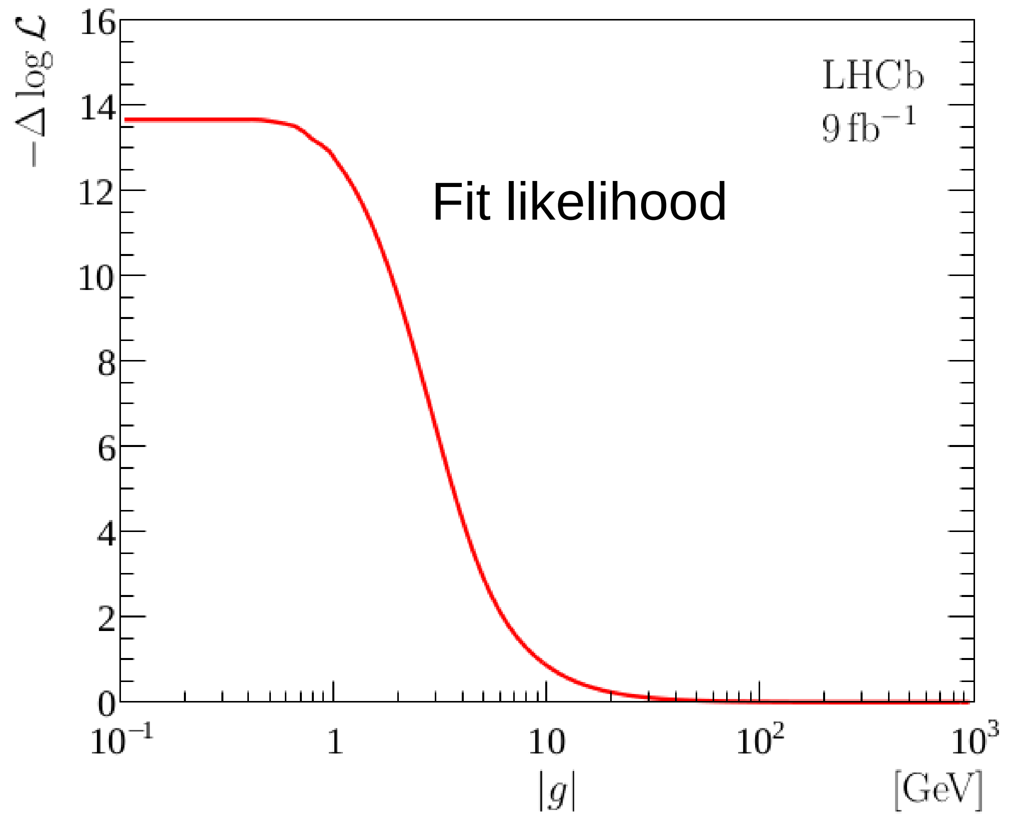


Parameter		Pseudoexperiments		Data	
		mean	RMS		
δm_{BW}	$[\mathrm{keV}/c^2]$	-301	50	-273 ± 61	[84]
Γ_{BW}	$[\mathrm{keV}]$	222	121	410 ± 165	
δm_{U}	$[\mathrm{keV}/c^2]$	-378	46	-359 ± 40	

Scaling in unitarized model

- For large values of |g| a scaling of overall shape is in place and visible width depends only on mass and Γ(D*+)

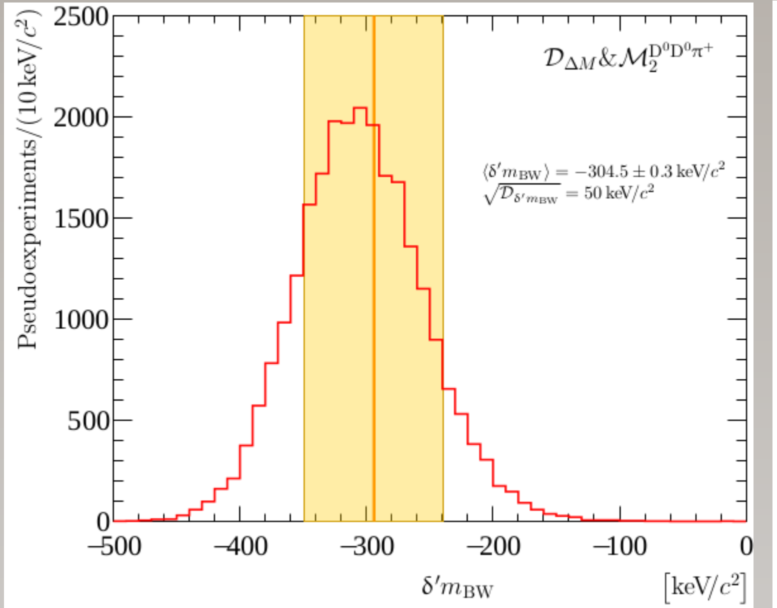


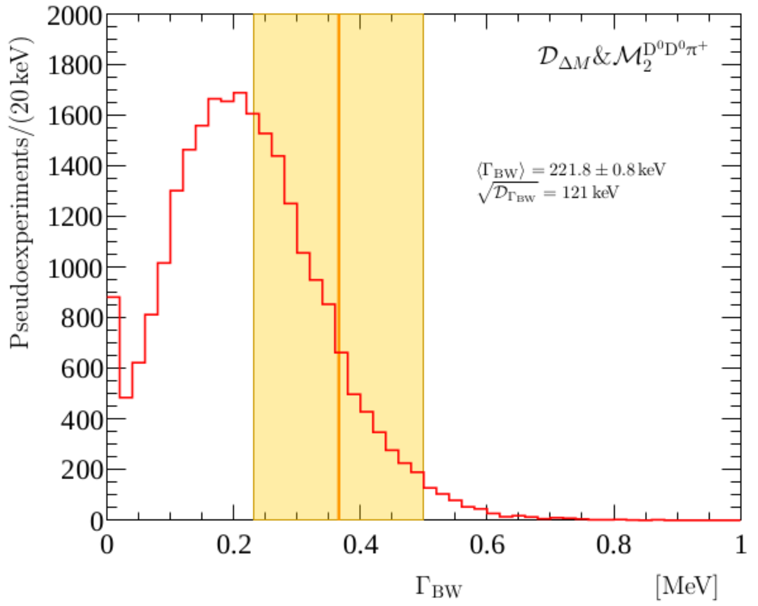


Fit likelihood

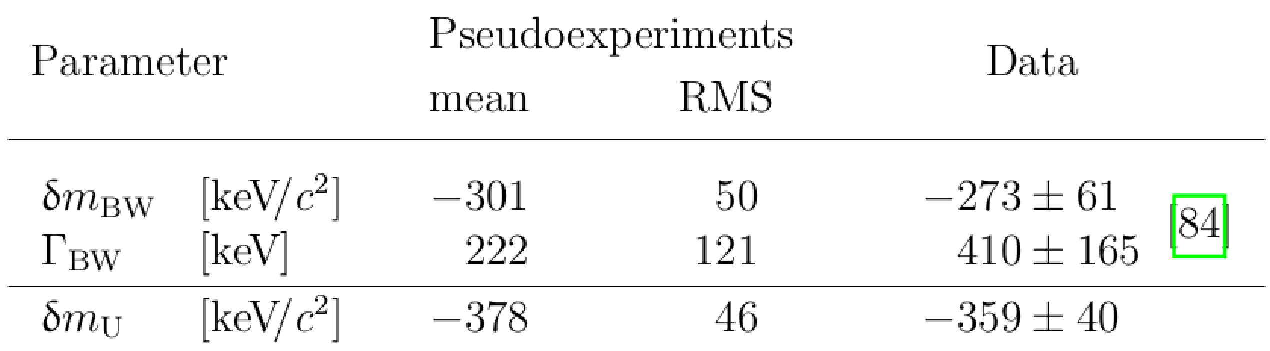
Consistency of Naive and Advanced

- Generate 25k pseudoexperiments using advanced BW model,
  fit them with naive BW model.
  Get δ'm_{BW} and Γ_{BW} consistent with values obtained from data

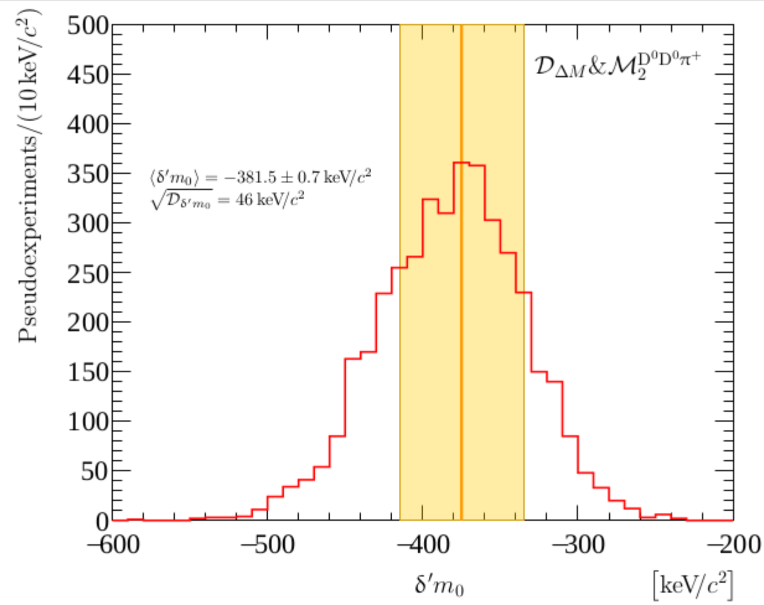




- Generate 4k pseudoexperiments using naive BW model,
  fit them with advanced BW model.
  Get δ'm_0 consistent with values obtained from data



Parameter		Pseudoexperiments mean	 RMS	Data	
δm_{BW}	[keV/c^2]	−301	50	−273 ± 61	[84]
Γ_{BW}	[keV]	222	121	410 ± 165	
δm_U	[keV/c^2]	−378	46	−359 ± 40	



Decay amplitude

- 3 key assumptions:
  - T_{cc}^{+} is isoscalar
  - $J^P=1^+$
  - It decays to D^0D^{*+}/D^+D^{*0} with same couplings

$$\left|\mathrm{T}_{\mathrm{cc}}^{+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\mathrm{D}^{*+}\mathrm{D}^{0}\right\rangle - \left|\mathrm{D}^{*0}\mathrm{D}^{+}\right\rangle\right)$$

- Derive amplitudes for **X → DD*** *(as $1^+\to0^-1^-$ in S-wave)* and **D* → Dπ/γ** (*as $1^-\to0^-0^-/1^-$*): (parameters ***f, h, μ*** – from known BR)

$$\begin{aligned}
\mathcal{A}_{\mathrm{D}^{*+}\to\mathrm{D}^0\pi^+} &= f\epsilon^{\alpha}_{\mathrm{D}^*}p_{\mathrm{D}\alpha}\\
\mathcal{A}_{\mathrm{D}^{*+}\to\mathrm{D}^+\pi^0} &= -\frac{f}{\sqrt{2}}\epsilon^{\alpha}_{\mathrm{D}^*}p_{\mathrm{D}\alpha}\\
\mathcal{A}_{\mathrm{D}^{*0}\to\mathrm{D}^0\pi^0} &= +\frac{f}{\sqrt{2}}\epsilon^{\alpha}_{\mathrm{D}^*}p_{\mathrm{D}\alpha}\,,
\end{aligned}$$

$$\mathcal{A}_{\mathrm{D}^*\to\gamma\mathrm{D}} = i\mu h\epsilon_{\alpha\beta\eta\xi}\epsilon^{\alpha}_{\mathrm{D}^*}p^{\beta}_{\mathrm{D}^*}\epsilon^{*\eta}_{\gamma}p^{\xi}_{\gamma}$$

$$\begin{aligned}
\mathcal{A}^{\mathrm{S-wave}}_{\mathrm{T}_{\mathrm{cc}}^{+}\to\mathrm{D}^{*+}\mathrm{D}^0} &= +\frac{g}{\sqrt{2}}\epsilon_{\mathrm{T}_{\mathrm{cc}}^{+}\mu}\epsilon^{*\mu}_{\mathrm{D}^*}\\
\mathcal{A}^{\mathrm{S-wave}}_{\mathrm{T}_{\mathrm{cc}}^{+}\to\mathrm{D}^{*0}\mathrm{D}^+} &= -\frac{g}{\sqrt{2}}\epsilon_{\mathrm{T}_{\mathrm{cc}}^{+}\mu}\epsilon^{*\mu}_{\mathrm{D}^*}
\end{aligned}$$

and combine them to together

$$\begin{aligned}
\mathcal{A}_{\pi^+\mathrm{D}^0\mathrm{D}^0} &= \frac{fg}{\sqrt{2}}\epsilon_{\mathrm{T}_{\mathrm{cc}}^{+}\nu}\left[\mathfrak{F}_+(s_{12})\times\left(-p_2^{\nu}+\frac{(p_2p_{12})p_{12}^{\nu}}{s_{12}}\right)+(p_2\leftrightarrow p_3)\right]\,,\\
\mathcal{A}_{\pi^0\mathrm{D}^+\mathrm{D}^0} &= -\frac{fg}{2}\epsilon_{\mathrm{T}_{\mathrm{cc}}^{+}\nu}\left[\mathfrak{F}_+(s_{12})\times\left(-p_2^{\nu}+\frac{(p_2p_{12})p_{12}^{\nu}}{s_{12}}\right)+\left(\begin{array}{c}p_2\leftrightarrow p_3\\ \mathfrak{F}_+\leftrightarrow\mathfrak{F}_0\end{array}\right)\right]\\
\mathcal{A}_{\gamma\mathrm{D}^+\mathrm{D}^0} &= i\frac{hg}{\sqrt{2}}\epsilon_{\alpha\beta\eta\xi}\epsilon^{\beta}_{\mathrm{T}_{\mathrm{cc}}^{+}}\epsilon^{\eta}_{\gamma}p^{\xi}_{\gamma}\left[\mu_+\mathfrak{F}_+(s_{12})p_{12}^{\alpha}-\mu_0\mathfrak{F}_0(s_{13})p_{13}^{\alpha}\right]
\end{aligned}$$

$$\mathfrak{F}(s) = \frac{1}{m^2_{\mathrm{D}^*}-s-im_{\mathrm{D}^*}\Gamma_{\mathrm{D}^*}}$$

Low-energy scattering approximation

- Relation between unitarized amplitude and low-energy expansion

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

$$\frac{2}{|g|^2}\mathcal{A}_{\mathrm{U}}^{-1} = -\left[\xi(s) - \xi(m_{\mathrm{U}}^2)\right] + 2\frac{m_{\mathrm{U}}^2 - s}{|g|^2} - i\varrho_{\mathrm{tot}}(s)$$

- Proportionality factor

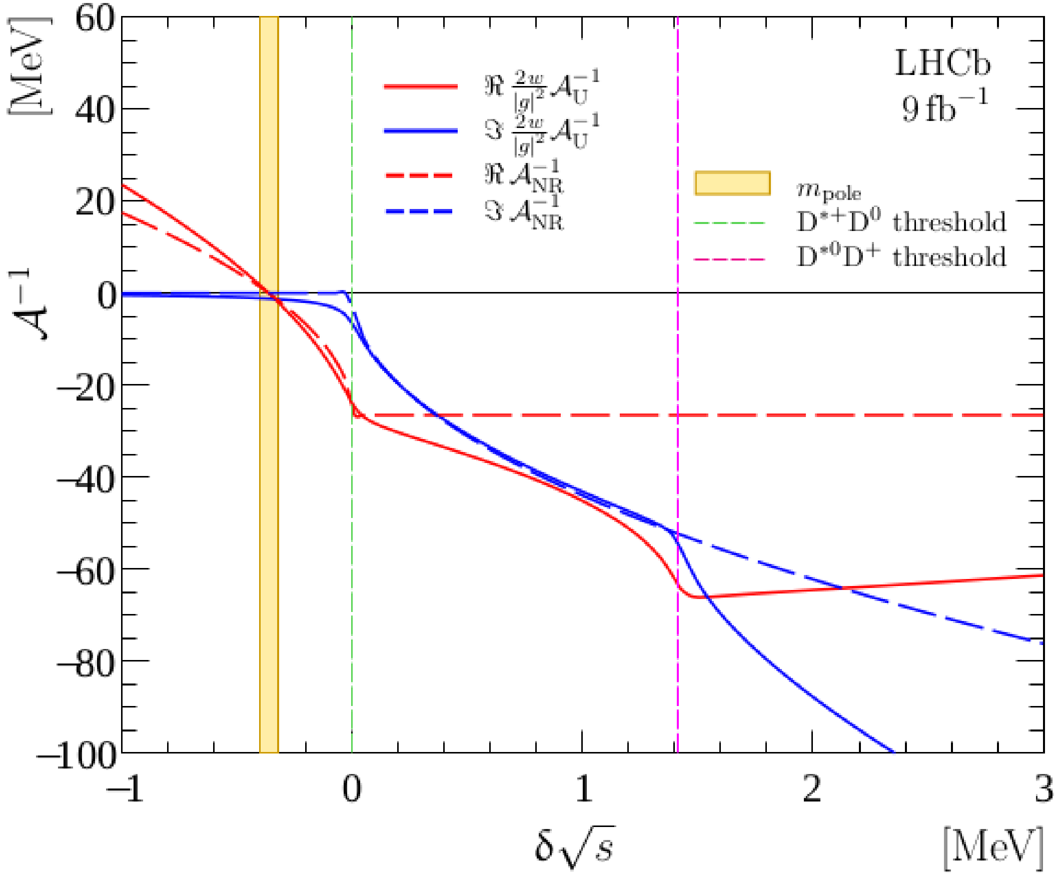
$$w = \frac{24\pi}{m_{\mathrm{D}^{*+}} + m_{\mathrm{D}^0}}\frac{1}{c_1}$$

- Inverse scattering length

$$\frac{1}{a} = -\frac{1}{w}\left\{\left[\xi(s_{\mathrm{th}}) - \xi(m_{\mathrm{U}}^2)\right] + i\varrho_{\mathrm{tot}}(s_{\mathrm{th}})\right\}$$

- Slope of linear term

$$r = -\frac{1}{w}\frac{16}{|g|^2}$$



Extended Data Fig. 9: Comparison of the $\mathcal{A}_{\mathrm{U}}$ and $\mathcal{A}_{\mathrm{NR}}$ amplitudes. The real and imaginary parts of the inverse $\mathcal{A}_{\mathrm{U}}$ and $\mathcal{A}_{\mathrm{NR}}$ amplitudes. The yellow band correspond to the pole position and vertical dashed lines show the $\mathrm{D}^{*+}\mathrm{D}^0$ and $\mathrm{D}^{*0}\mathrm{D}^+$ mass thresholds.

Analytic continuation

- To study poles analytic continuation of amplitude and hence complex width and phase-space functions onto complex plane is required

$$\Sigma\left(s\right)=\frac{s}{2\pi}\int\limits_{s^*_{\mathrm{th}}}^{+\infty}\frac{\varrho_{\mathrm{tot}}\left(s'\right)}{s'\left(s'-s\right)}\,ds'-\xi\left(m^2_{\mathrm{U}}\right)\ ,$$

$$\frac{1}{\mathcal{A}^{II}_{\mathrm{U}}\left(s\right)}=m^2_{\mathrm{U}}-s-\left|g\right|^2\Sigma(s)+i\left|g\right|^2\varrho_{\mathrm{tot}}(s)$$

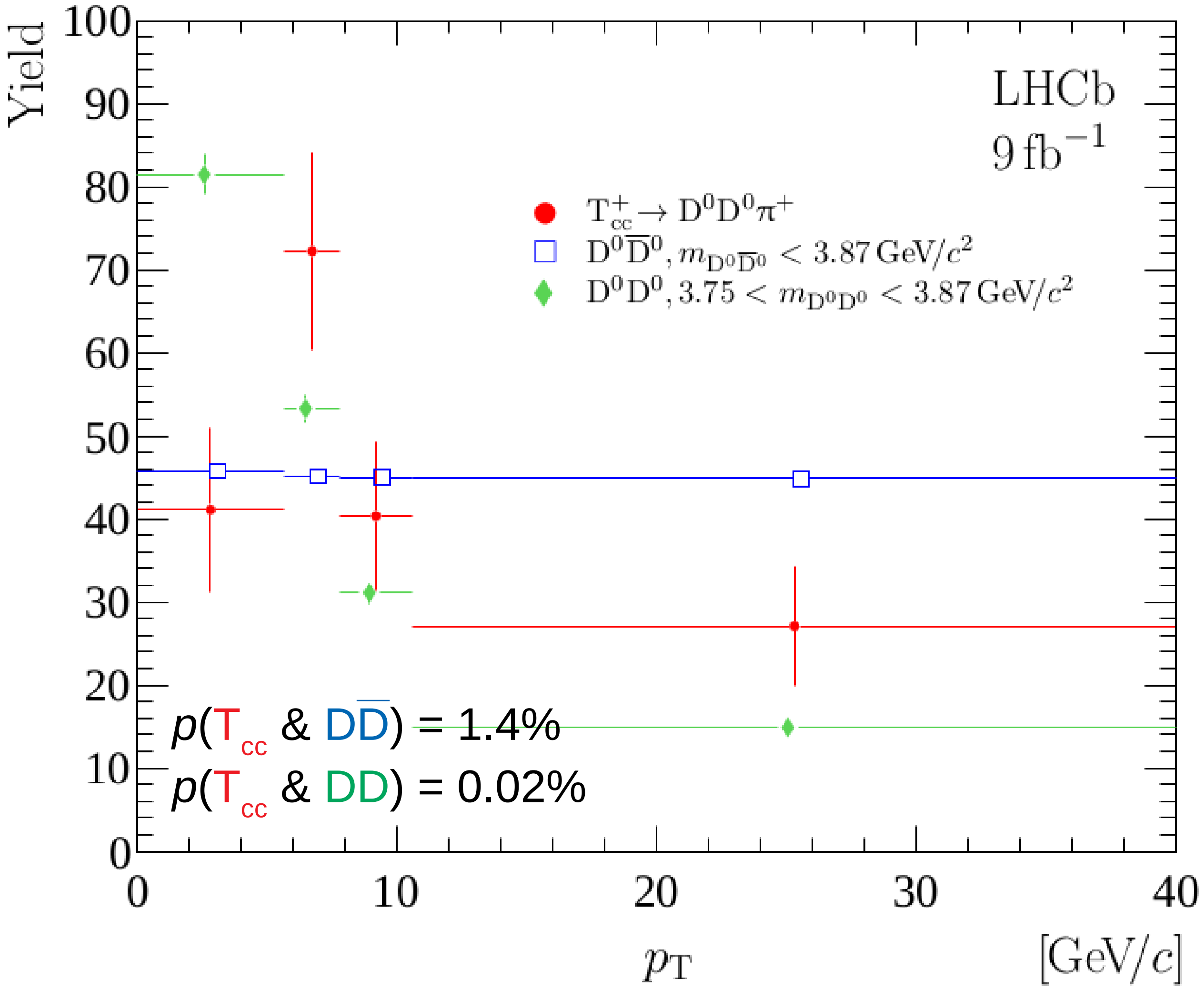
- For ρ functors

$$\int\limits_{\mathcal{D}}\left|\mathfrak{M}\right|^2\,d\Phi_3=\frac{1}{2\pi(8\pi)^2 s}\int\limits_{(m_2+m_3)^2}^{(\sqrt{s}-m_1)^2}ds_{23}\int\limits_{s^-_{12}(s,s_{23})}^{s^+_{12}(s,s_{23})}\left|\mathfrak{M}\right|^2\,ds_{12}$$

$$\begin{aligned}s^{\pm}_{12}\left(s,s_{23}\right)=m_1^2+m_2^2&-\frac{\left(s_{23}-s+m_1^2\right)\left(s_{23}+m^2+m_3^2\right)}{2s_{23}}\\&\pm\frac{\lambda^{1/2}\left(s_{23},s,m_1^2\right)\lambda^{1/2}\left(s_{23},m_2^2,m_3^2\right)}{2s_{23}}\end{aligned}$$

Transverse momenta spectra

- Compare **$T_{cc}^{+} \to D^0D^0X$ signal** distributions with
  - **D^0D^0 in $3.75<m_{DD}<3.87$ GeV region** (presumably dominated by double-parton scattering)
  - **$D^0\bar{D}^0$ in $m_{DD}<3.87$ GeV region** (mainly single $pp \to D\bar{D}$ production)

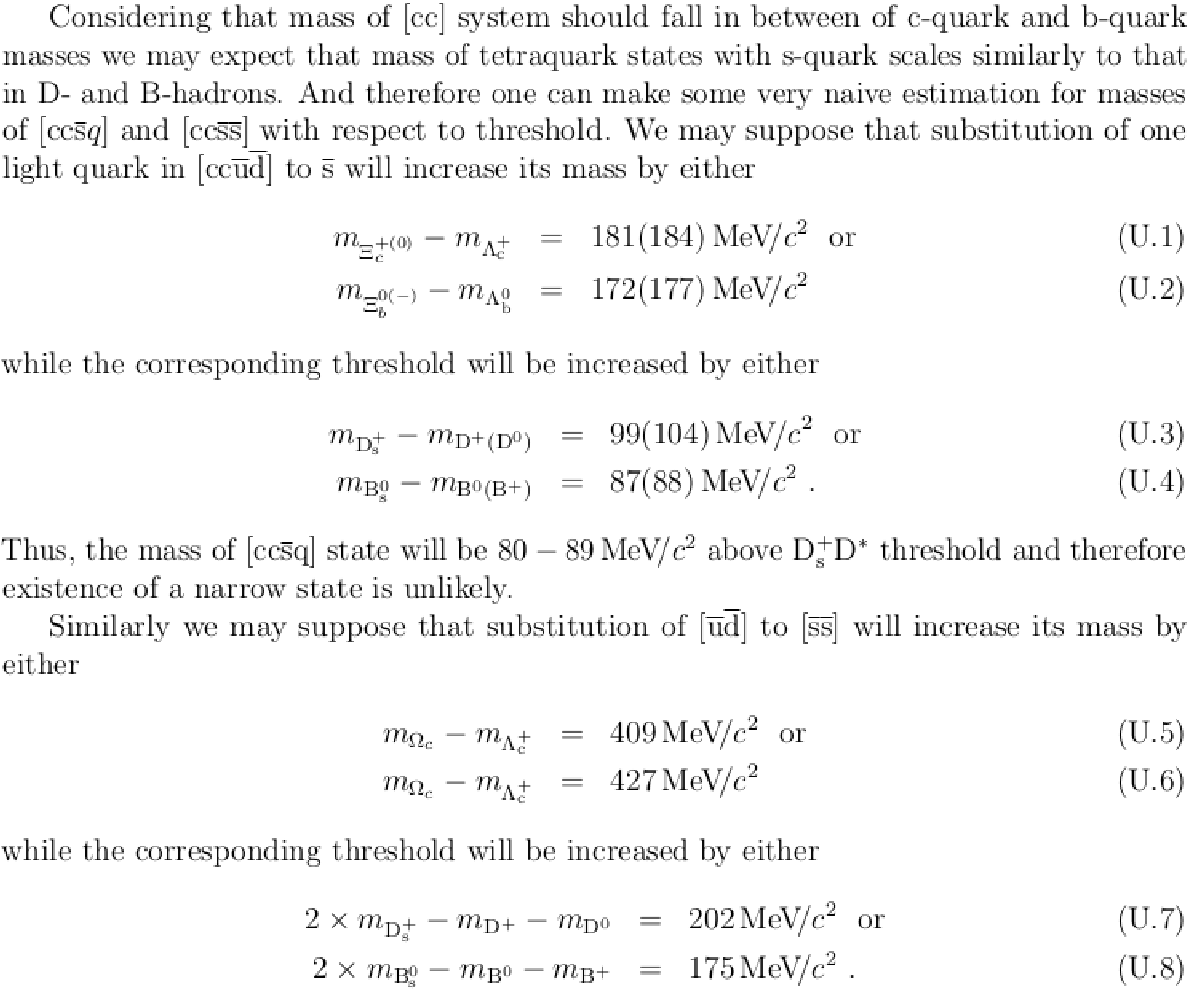


$p(T_{cc}$ & $D\bar{D}) = 1.4\%$

$p(T_{cc}$ & $DD) = 0.02\%$

- Intriguing similarity with $c\bar{c}+c\bar{c}$

ccsq tetraquarks



Considering that mass of [cc] system should fall in between of c-quark and b-quark masses we may expect that mass of tetraquark states with s-quark scales similarly to that in D- and B-hadrons. And therefore one can make some very naive estimation for masses of $[\mathrm{cc\bar{s}}q]$ and $[\mathrm{cc\bar{s}\bar{s}}]$ with respect to threshold. We may suppose that substitution of one light quark in $[\mathrm{cc\bar{u}\bar{d}}]$ to $\bar{\mathrm{s}}$ will increase its mass by either

$$m_{\Xi_c^{+(0)}} - m_{\Lambda_c^+} = 181(184)\,\mathrm{MeV}/c^2 \quad \text{or} \qquad (\mathrm{U.1})$$
$$m_{\Xi_b^{0(-)}} - m_{\Lambda_b^0} = 172(177)\,\mathrm{MeV}/c^2 \qquad (\mathrm{U.2})$$

while the corresponding threshold will be increased by either

$$m_{\mathrm{D_s^+}} - m_{\mathrm{D^+(D^0)}} = 99(104)\,\mathrm{MeV}/c^2 \quad \text{or} \qquad (\mathrm{U.3})$$
$$m_{\mathrm{B_s^0}} - m_{\mathrm{B^0(B^+)}} = 87(88)\,\mathrm{MeV}/c^2\ . \qquad (\mathrm{U.4})$$

Thus, the mass of $[\mathrm{cc\bar{s}q}]$ state will be $80 - 89\,\mathrm{MeV}/c^2$ above $\mathrm{D_s^+D^*}$ threshold and therefore existence of a narrow state is unlikely.

Similarly we may suppose that substitution of $[\mathrm{\bar{u}\bar{d}}]$ to $[\mathrm{\bar{s}\bar{s}}]$ will increase its mass by either

$$m_{\Omega_c} - m_{\Lambda_c^+} = 409\,\mathrm{MeV}/c^2 \quad \text{or} \qquad (\mathrm{U.5})$$
$$m_{\Omega_c} - m_{\Lambda_c^+} = 427\,\mathrm{MeV}/c^2 \qquad (\mathrm{U.6})$$

while the corresponding threshold will be increased by either

$$2 \times m_{\mathrm{D_s^+}} - m_{\mathrm{D^+}} - m_{\mathrm{D^0}} = 202\,\mathrm{MeV}/c^2 \quad \text{or} \qquad (\mathrm{U.7})$$
$$2 \times m_{\mathrm{B_s^0}} - m_{\mathrm{B^0}} - m_{\mathrm{B^+}} = 175\,\mathrm{MeV}/c^2\ . \qquad (\mathrm{U.8})$$

Production vs track multiplicity

- Can expect that T_{cc}^{+} has some propoerties similar to $\chi_{c1}(3872)$

- For $\chi_{c1}(3872)$ production a suppression wrt ψ(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:

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

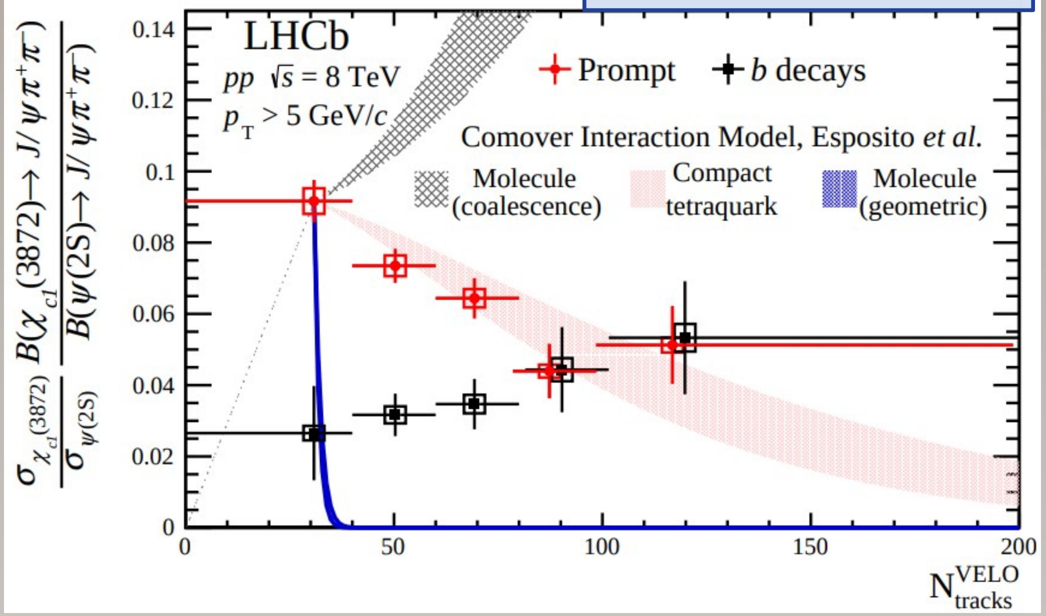
$$\langle v\sigma_{X}\rangle = 2.6 \pm 0.7 \text{ mb}$$

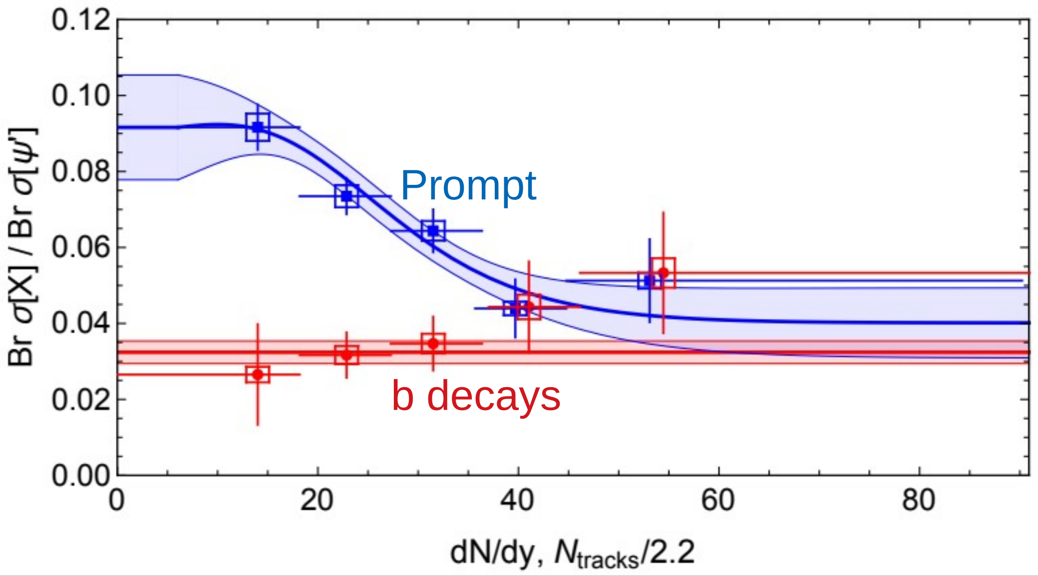
and fractions of Q out of reach of comovers

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

more details in Braaten et al., arXiv:2021.13499

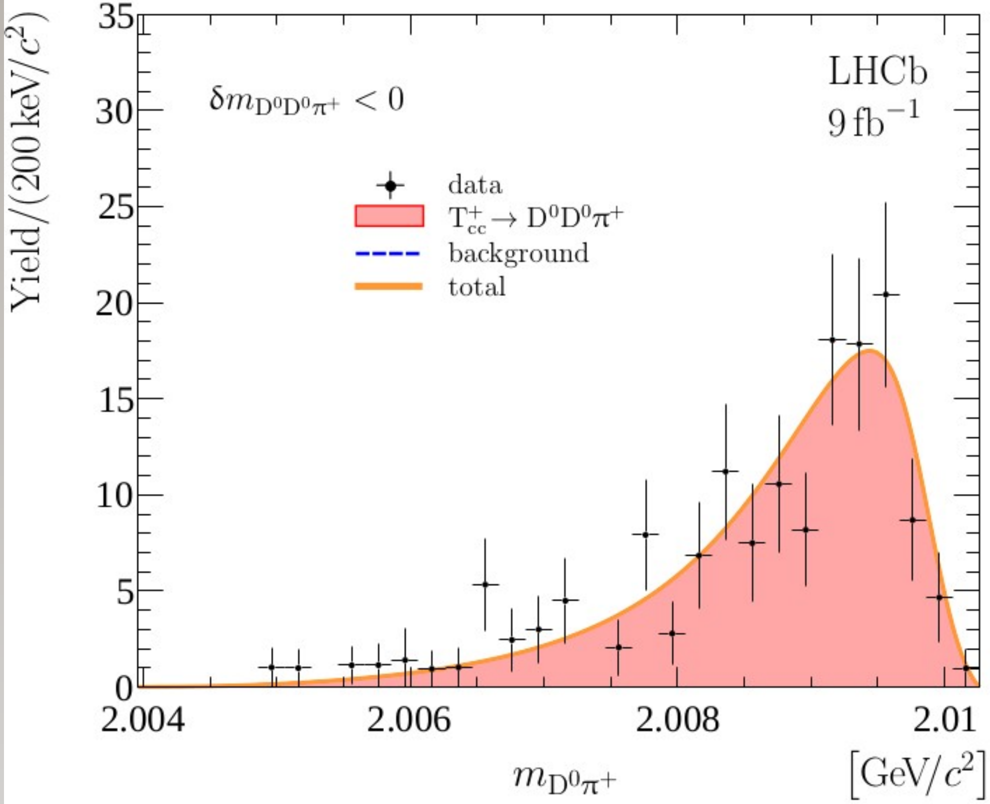
PRL 126 (2021) 092001

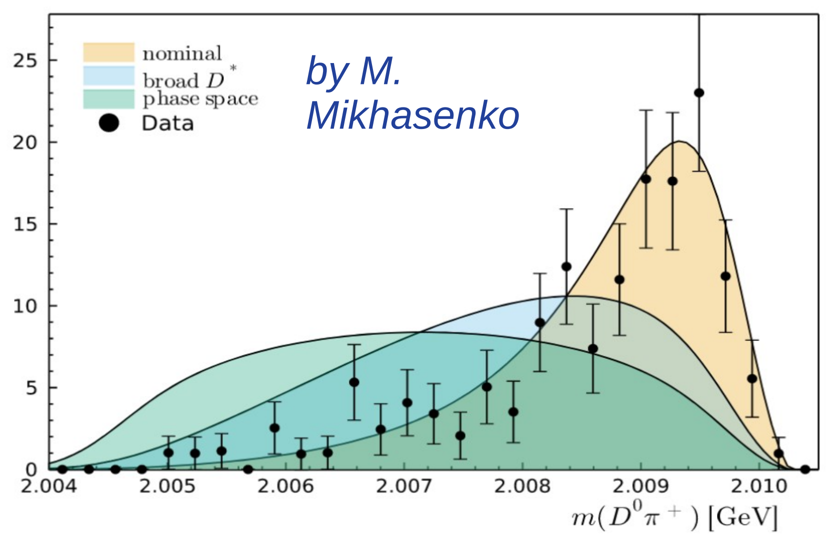


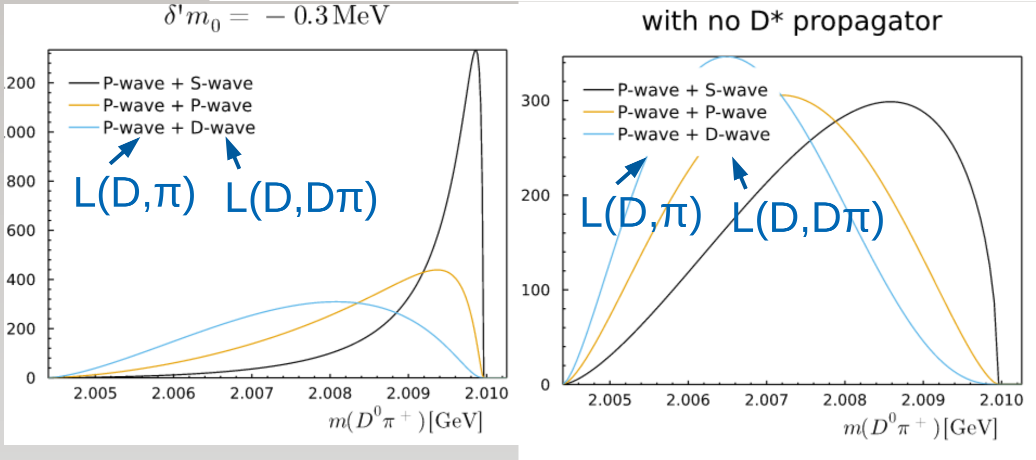


Offshell D^{*+}

- 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}