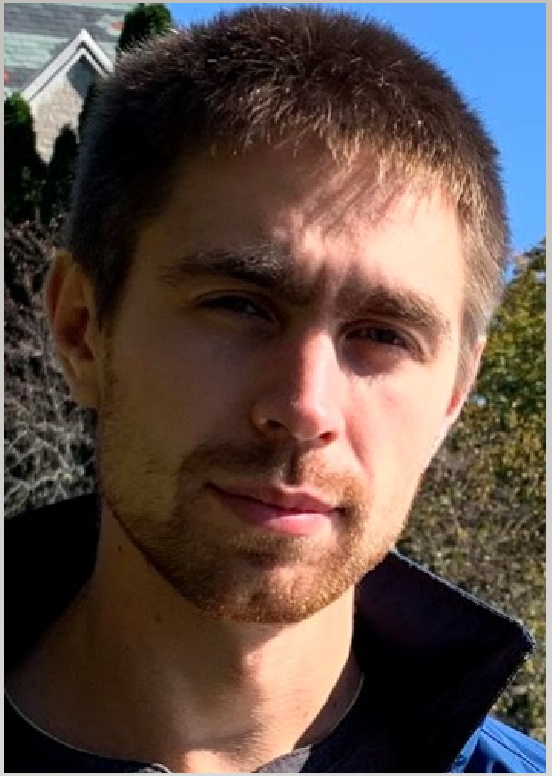
Observation and study of the doubly charmed T_{cc}^{+} tetraquark at LHCb

arXiv:2109.01038 arXiv:2109.01056

Ivan Polyakov
Syracuse University

on behalf of LHCb collaboration



14 September 2021

Outlook

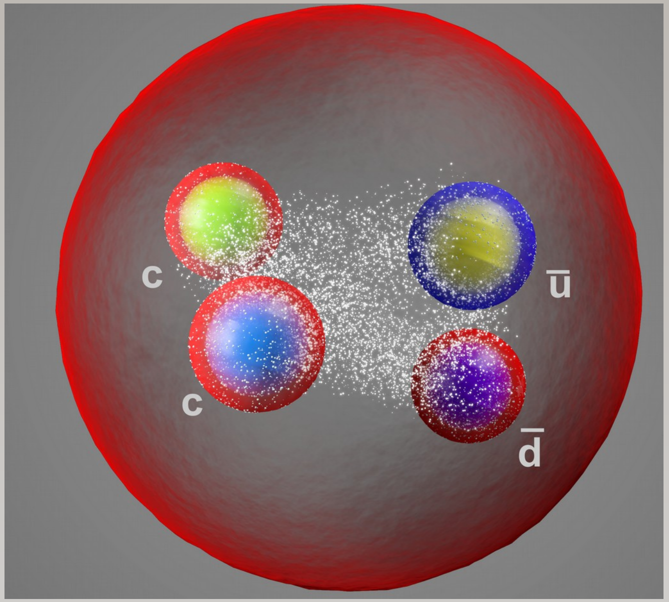
- Motivation and theory predictions for $QQ\overline{qq}'$

- LHCb detector & Selection
- Observation of the signal
- Study with unitarized model
- Interpretations
- Production properties

Measurements

arXiv:2109.01038

arXiv:2109.01056



- Discussions. Open questions. Future measurements

Introduction

Exotic hadrons

- Unconventional hadrons (alternative to $q_1q_2q_3$ or $q_1\bar{q}_2$) were discussed since the birth of Quark Model [Gell-Mann, Zweig, 1964] [Jaffe, 1977]

- Interest revived after observation of $\chi_{c1}(3872)$ by Belle in 2003 and ~30 more tetra/pentaquarks candidates since then
  - *most have $Q\bar{Q}$ pair and large width,*
  - *interpretations are still unclear - molecula/compact*
  - *and even resonance nature is questioned*

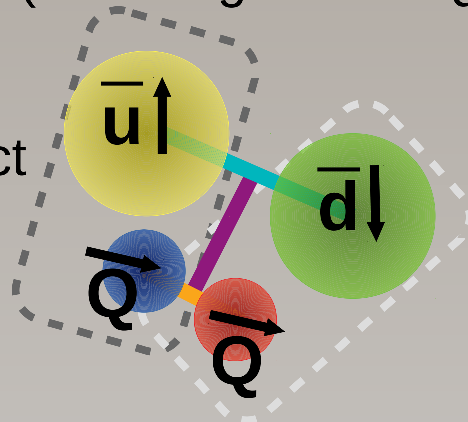
States	Quark content
$X_0(2900)$, $X_1(2900)$ [21, 22]	$\bar{c}d u\bar{s}$
$\chi_{c1}(3872)$ [6]	$c\bar{c}q\bar{q}$
$Z_c(3900)$ [23], $Z_c(4020)$ [24, 25], $Z_c(4050)$ [26], $X(4100)$ [27], $Z_c(4200)$ [28], $Z_c(4430)$ [29–32], $R_{c0}(4240)$ [31]	$c\bar{c}u\bar{d}$
$Z_{cs}(3985)$ [33], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [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 $m_b/m_u\sim15$, $m_c/m_u\sim5\text{-}6$)*

[Adler, Richard, Taxil, 1982] [Ballot, Richard, 1983]

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

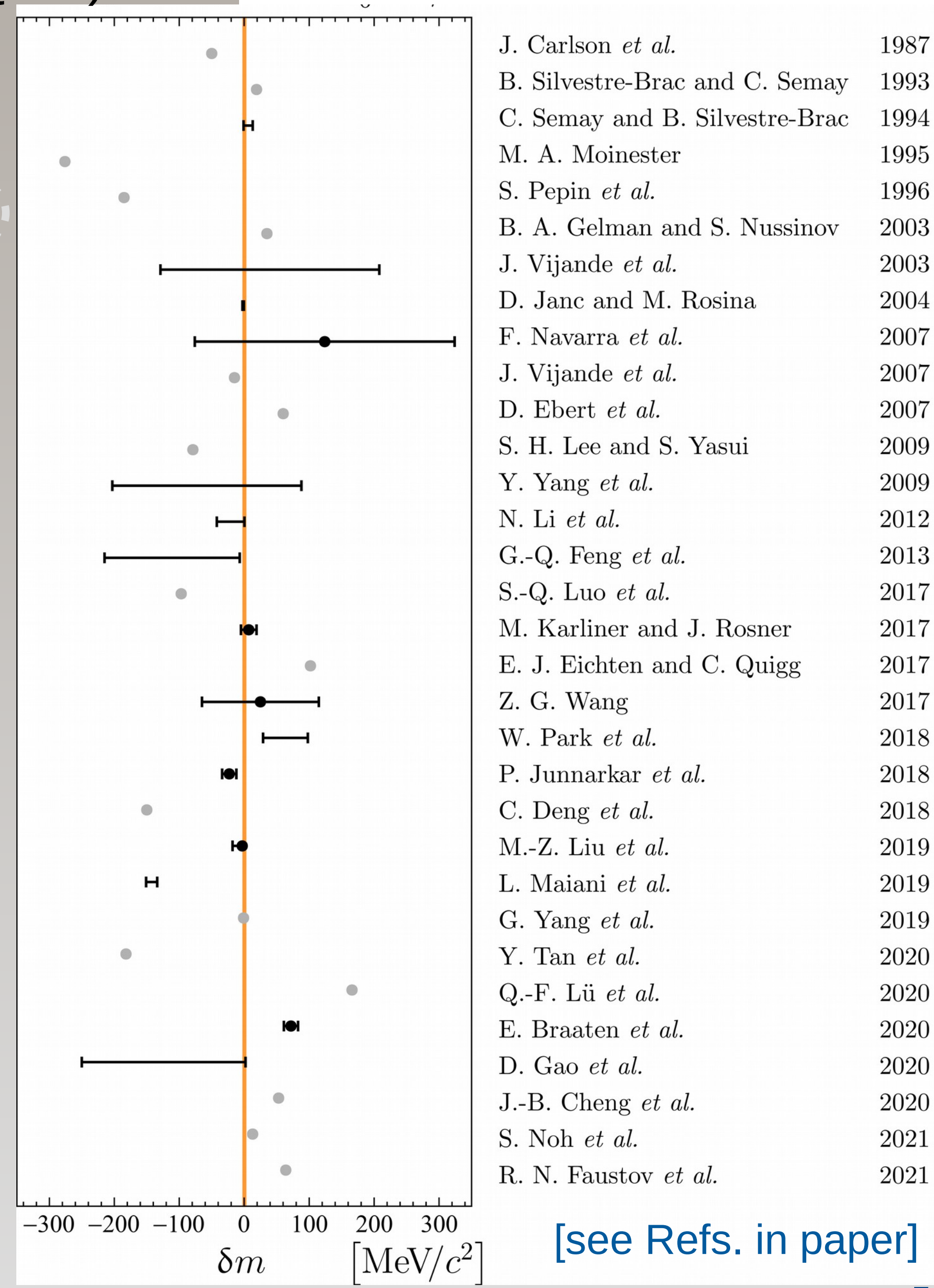
- More recent calculations (including Lattice QCD) all agree that it should be true for $[bb][\bar{u}\bar{d}]$ with QQ forming compact color anti-triplet and resulting binding of ~150MeV



- However not clear for $[bc][\bar{u}\bar{d}]$ and $[cc][\bar{u}\bar{d}]$

- Predictions for a ground $cc\bar{u}\bar{d}$ 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]

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
    - *$m(cc\bar{u}\bar{d}) = m(\Xi_{cc}) + 315\ \mathrm{MeV} \sim m(\Xi_{cc}) + [m(\Lambda_c)\text{-}m(D^0)]$ + kinematic correction*

    → δm = +102 MeV $\xrightarrow{\text{using measured } \Xi_{cc} \text{ mass}}$ **δm = +65 MeV** *(~ 3 MeV)*

    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

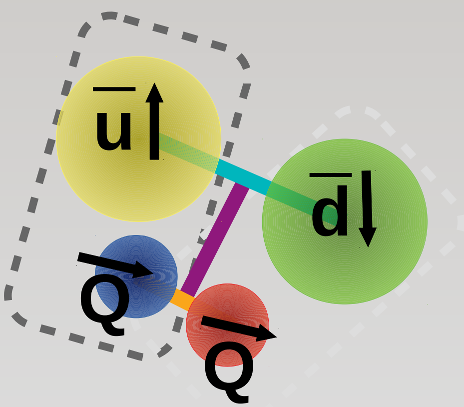
Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	−150.0
cc binding	−129.0
Total	3882.2 ± 12

→ δm = 7±12 MeV

↓ *using measured Ξ_{cc} mass*

δm = 1±12 MeV

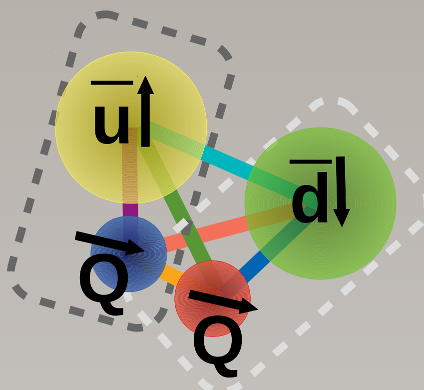
Karliner, Rosner, 2017



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

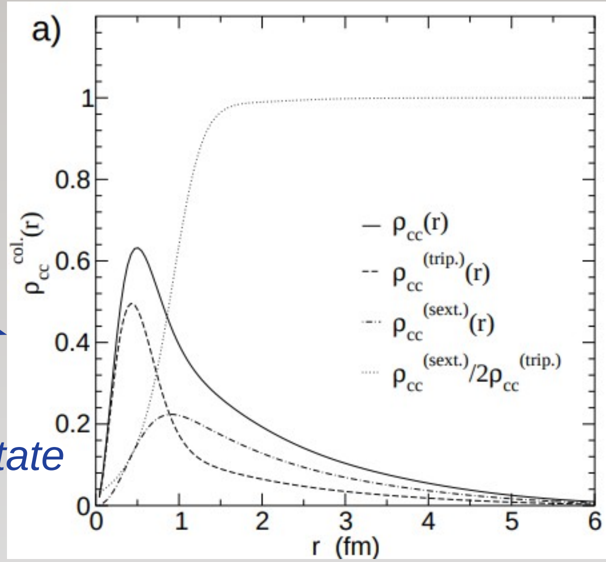
→ **δm = [-1;+13] MeV** Semay, SIlvestre-Brac, 1994

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

… + more within [-200;+100] MeV range

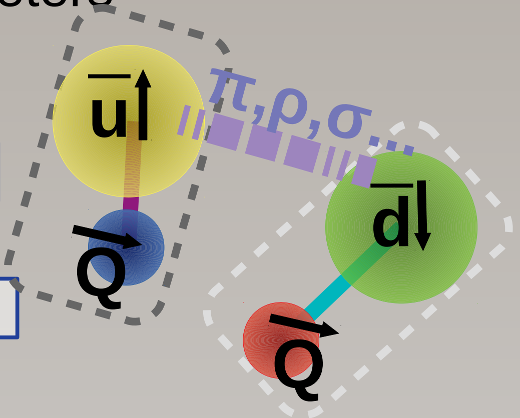
(choice of basic, parameters, ...)

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

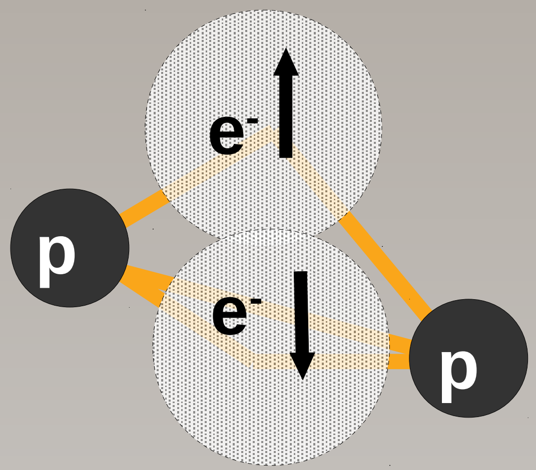
- 2&3. Adding meson-exchange (π, ρ, K, σ, η, ...) terms to the potential in NR model (quark-quark interaction)
  - results vary a lot, indicate 100-200 MeV increase in binding wrt no-OBE,

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

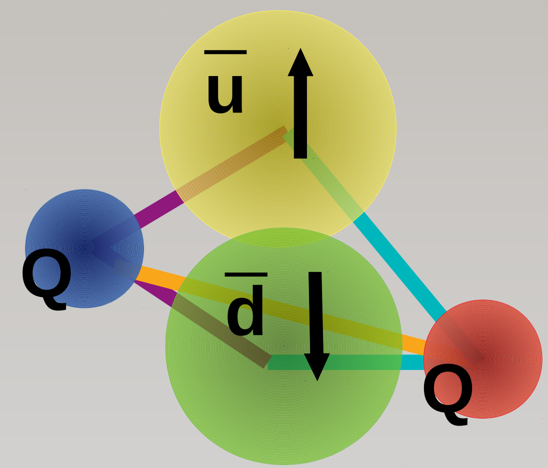
- Consider interaction between two D-mesons by solving Schrodinger equation for light quarks (q) given fixed distance between the heavy ones (Q) → get effective interaction between QQ



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

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

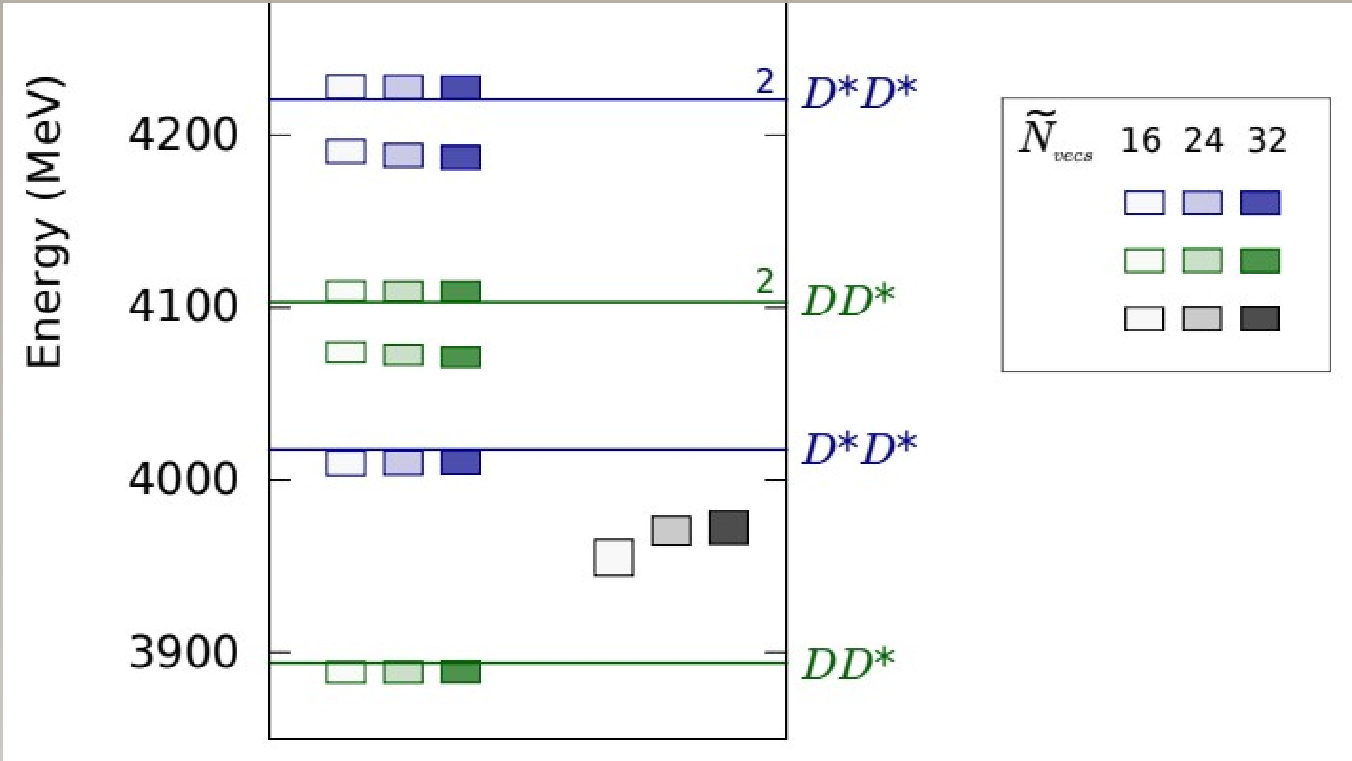
is it analogous to quark consituent model with OGE?
should it be re-considered for DD interaction?*

Lattice QCD

- Inconclusive
  - **no binding**

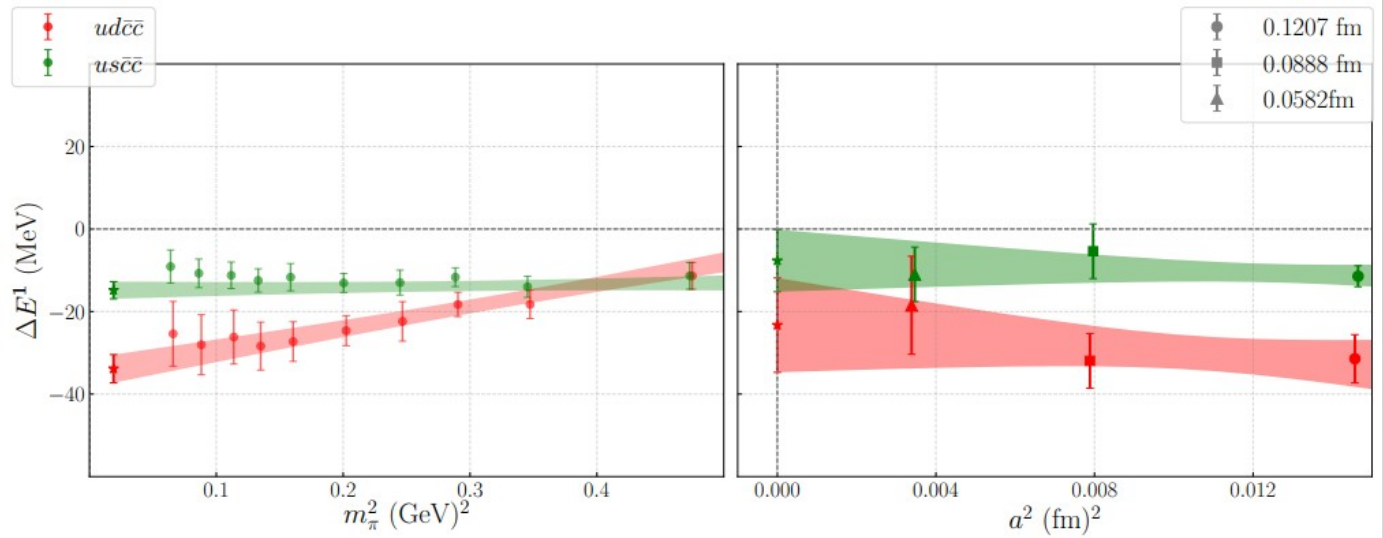
HAL QCD Collaboration, 2014

Hadron Spectrum Collaboration, 2017



  - **δm ~ -23±11 MeV**

Junnarkar, Mathur, Padmanath, 2018



”Observation of an exotic narrow doubly charmed tetraquark”

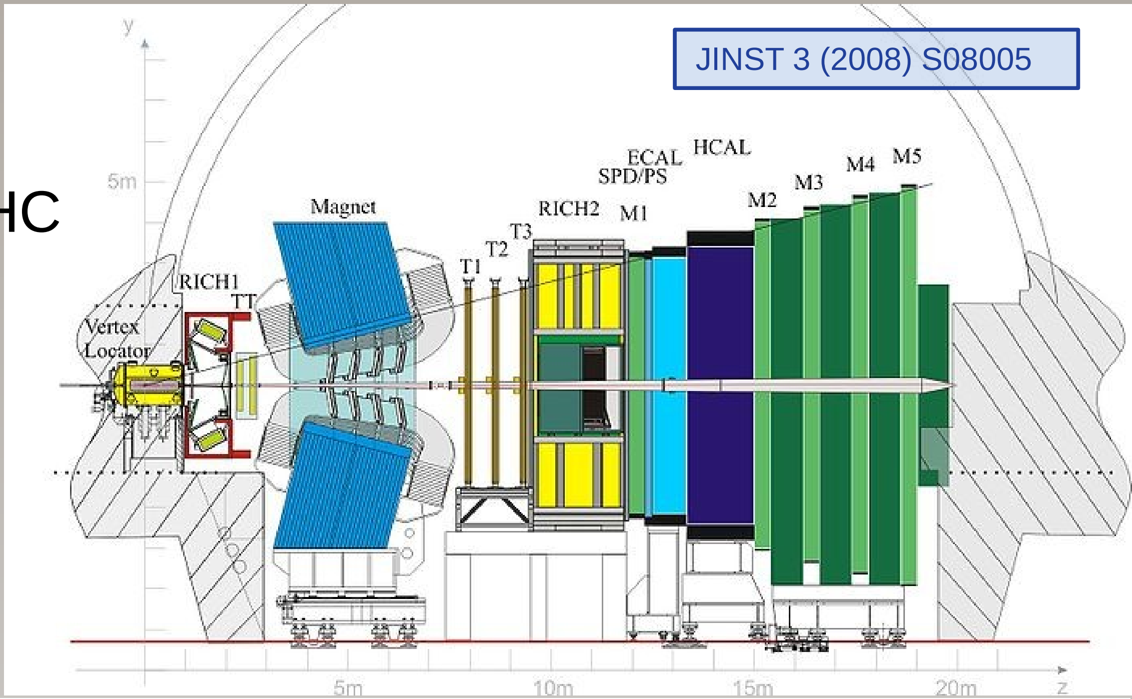
arXiv:2109.01038

&

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

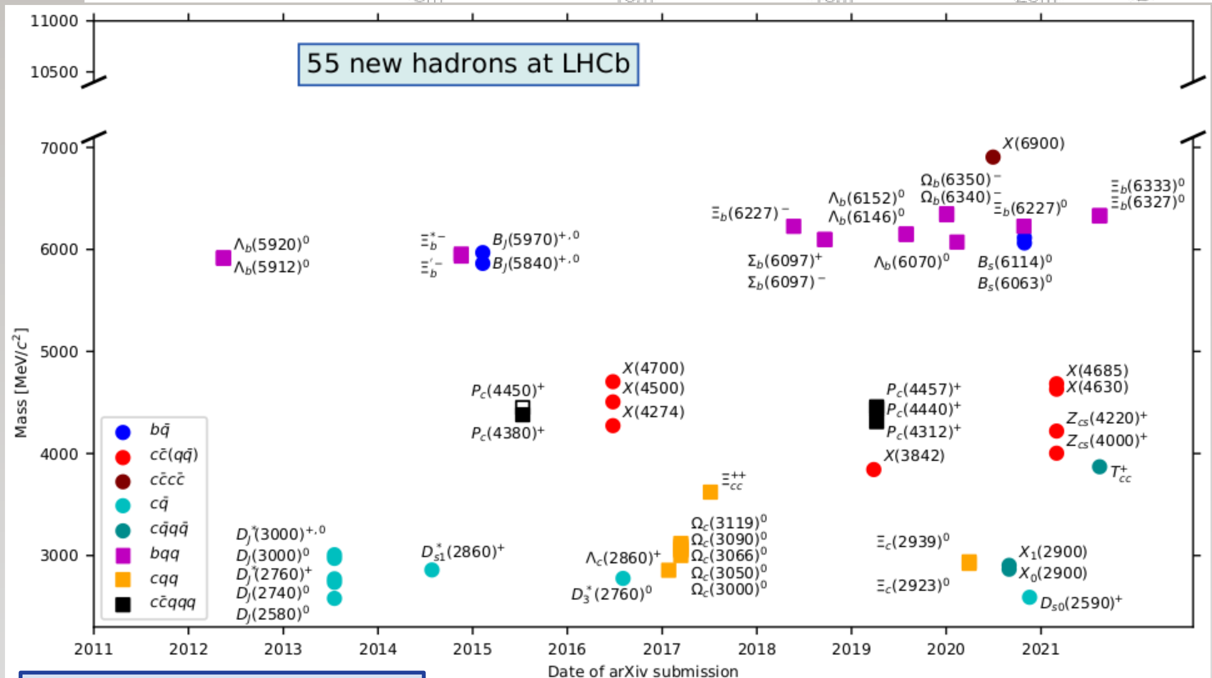
arXiv:2109.01056

The LHCb detector



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

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

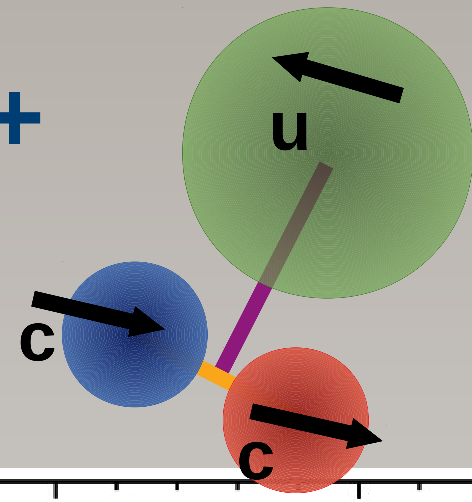


LHCb-FIGURE-2021-001

Previous hadrons with two c-quarks

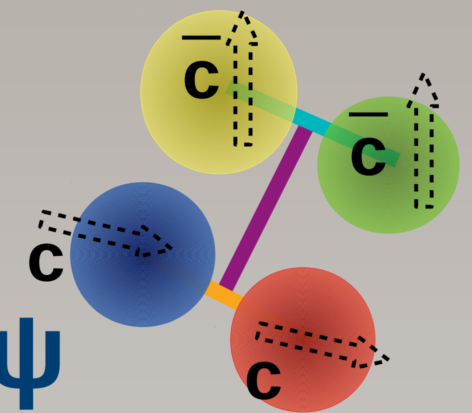
- The observations of Ξ_{cc}^{++} [ccu] and $X[cc\bar{c}\bar{c}] \rightarrow J/\psi J/\psi$ indicate that if the $[cc\bar{u}\bar{d}]$ exists it should be accessible at LHCb in $DD^{(*)}$ final states

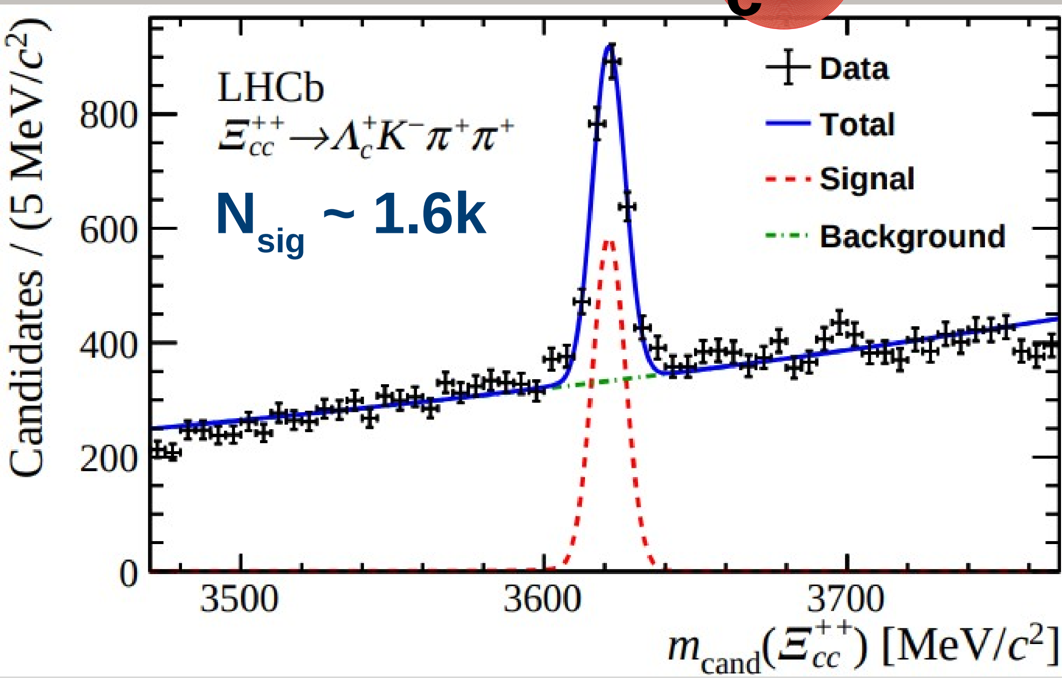
Ξ_{cc}^{++}



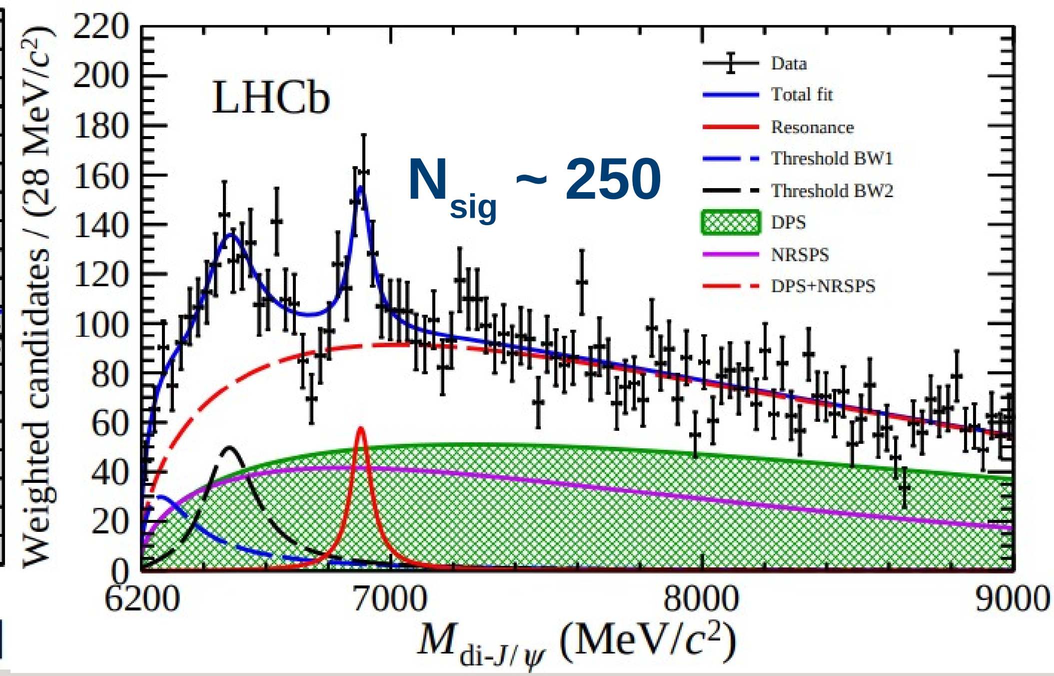
$X_{cc\bar{c}\bar{c}}$

$\rightarrow J/\psi J/\psi$





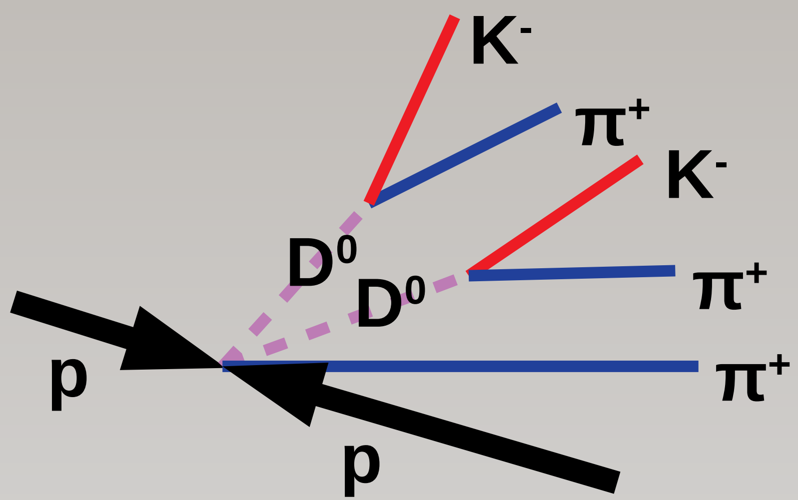
JHEP 02 (2020) 049

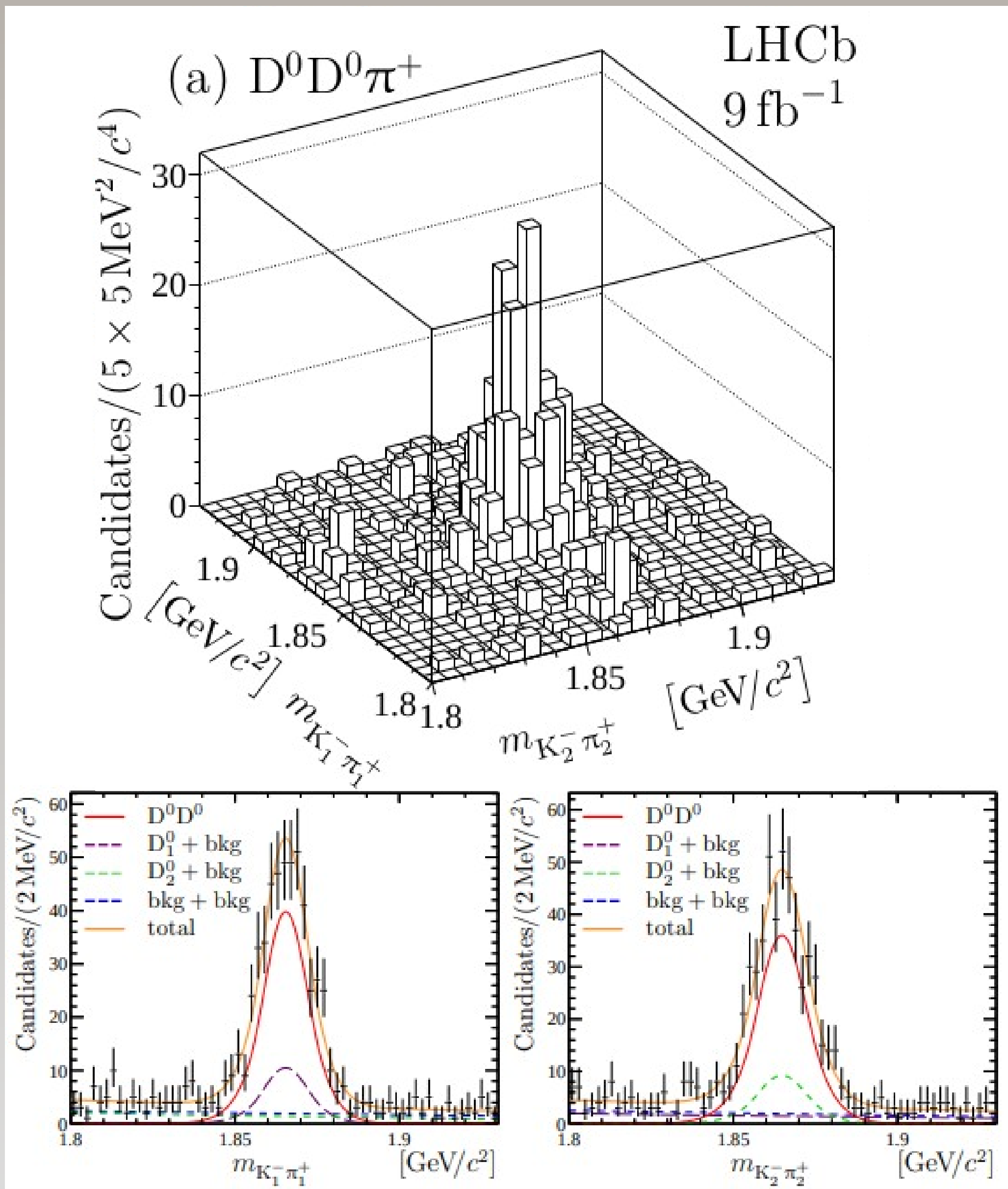


Sci. Bul. 65 (2020) 1983

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

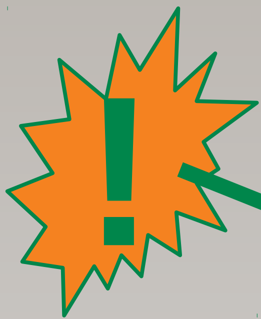


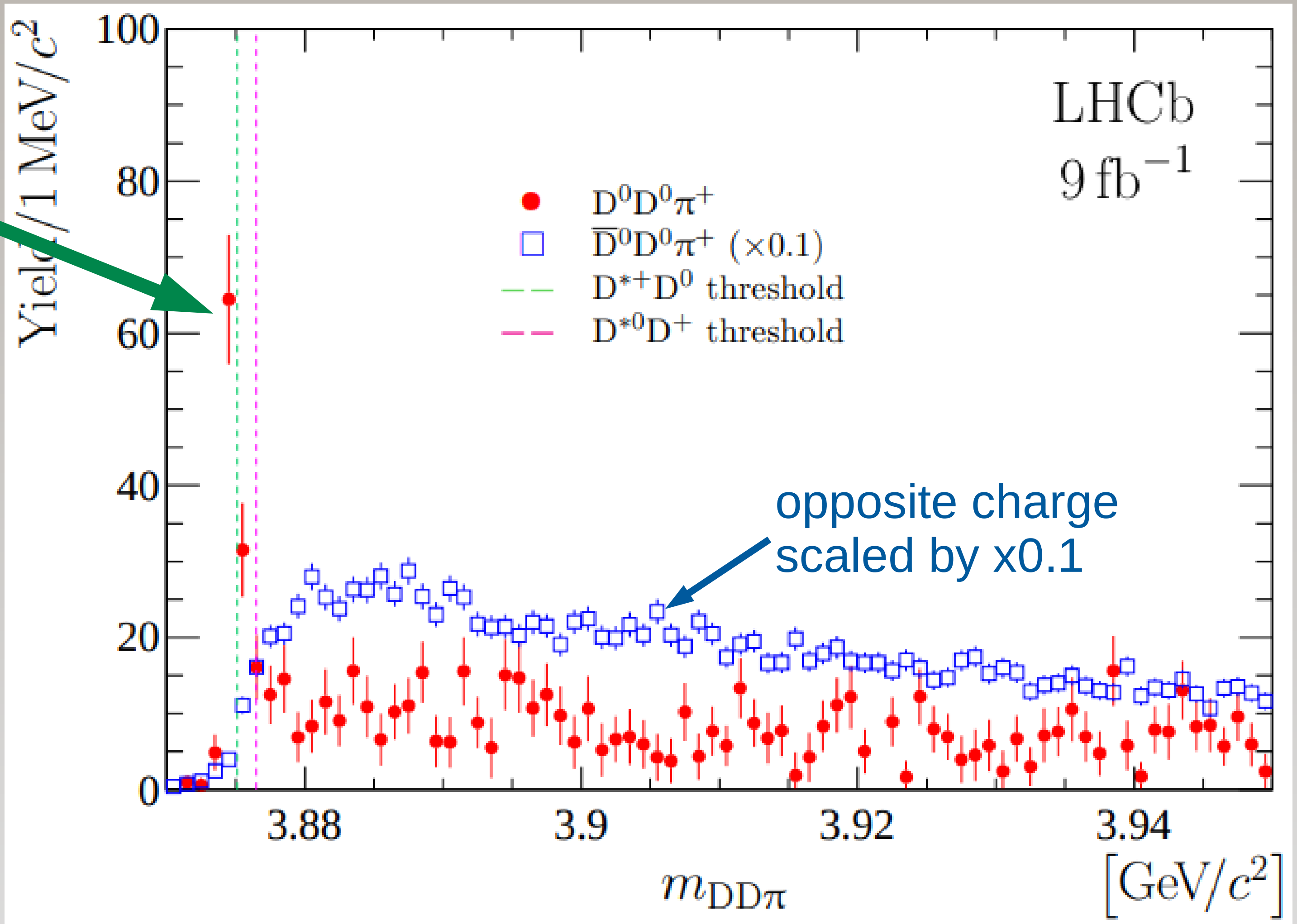


- Subtract fake-D background using 2D fit to ($m_{K\pi}$,$m_{K\pi}$)

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

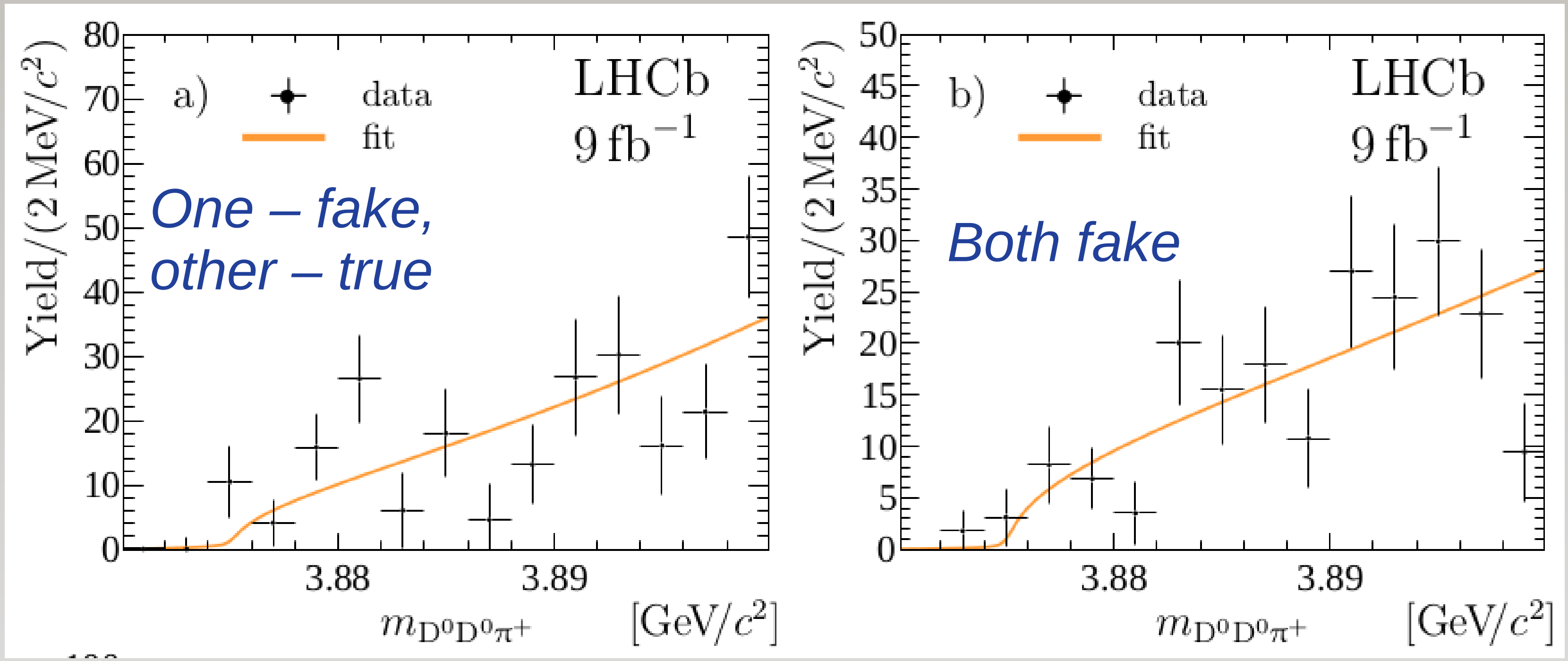




Cross-checks

- 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



Fit with Breit-Wigner function

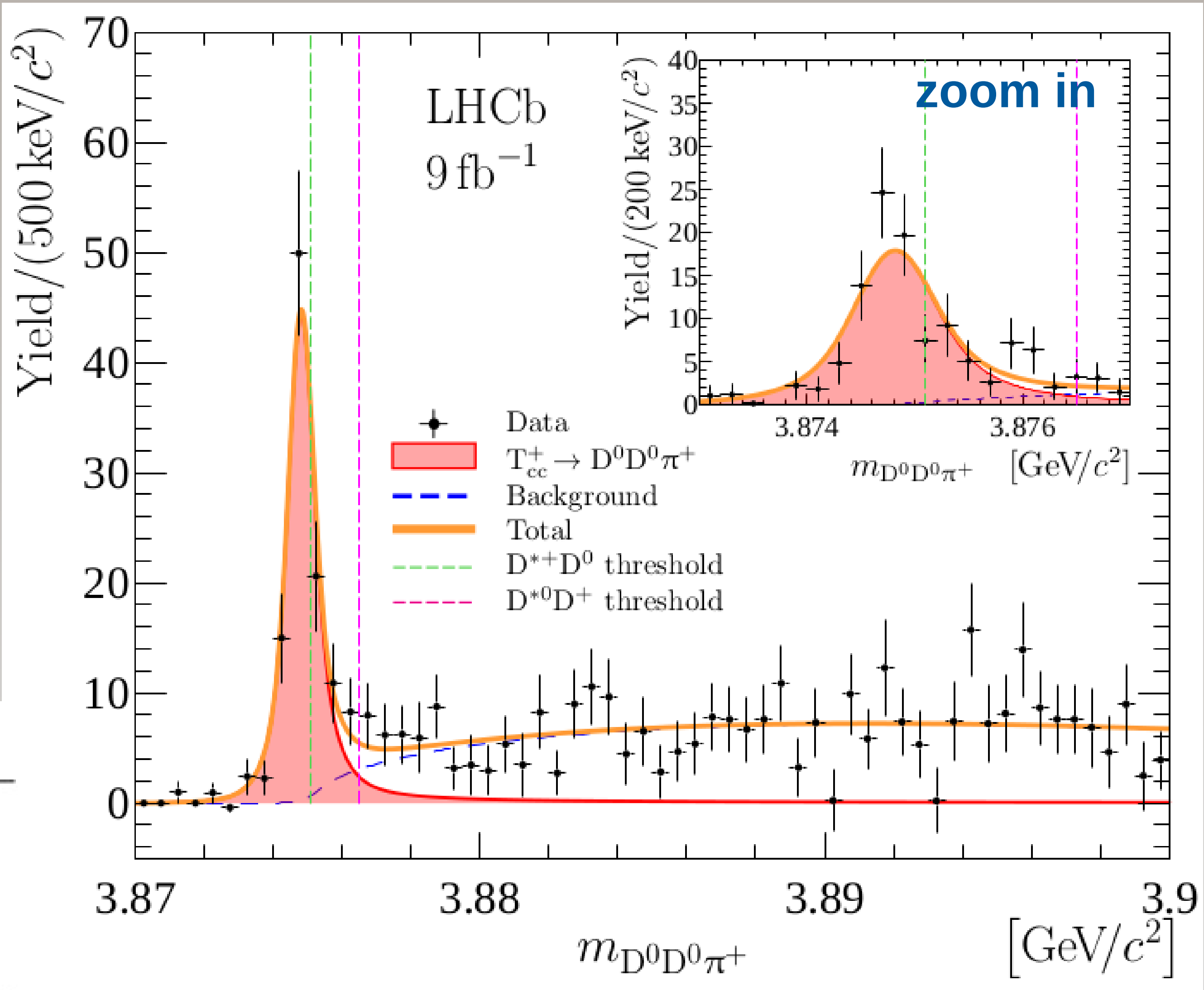
- The distribution is fit with a sum of
  - P-wave relativistic Breit-Wigner
  - $D^{*+}D^0$ phase space x pol_1

  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
δm_{BW}	$-273 \pm 61 \quad \mathrm{keV}/c^2$
Γ_{BW}	$410 \pm 165\,\mathrm{keV}$



Decay amplitude

- Construct an advanced model assuming
  - T_{cc}^{+} is isoscalar
  - $J^P=1^+$
  - Same coupling for decays to DD*

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

- 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)

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

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

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

and combine them to together

$$\begin{aligned}
\mathcal{A}_{\pi^{+}\mathrm{D}^{0}\mathrm{D}^{0}} &= \frac{fg}{\sqrt{2}}\epsilon_{\mathrm{T}_{\mathrm{cc}}^{+}\nu}\left[\mathfrak{F}_{+}(s_{12})\times\left(-p_{2}^{\nu}+\frac{(p_{2}p_{12})p_{12}^{\nu}}{s_{12}}\right)+(p_{2}\leftrightarrow p_{3})\right]\,,\\
\mathcal{A}_{\pi^{0}\mathrm{D}^{+}\mathrm{D}^{0}} &= -\frac{fg}{2}\epsilon_{\mathrm{T}_{\mathrm{cc}}^{+}\nu}\left[\mathfrak{F}_{+}(s_{12})\times\left(-p_{2}^{\nu}+\frac{(p_{2}p_{12})p_{12}^{\nu}}{s_{12}}\right)+\left(\begin{array}{c}p_{2}\leftrightarrow p_{3}\\ \mathfrak{F}_{+}\leftrightarrow\mathfrak{F}_{0}\end{array}\right)\right]\\
\mathcal{A}_{\gamma\mathrm{D}^{+}\mathrm{D}^{0}} &= i\frac{hg}{\sqrt{2}}\epsilon_{\alpha\beta\eta\xi}\epsilon^{\beta}_{\mathrm{T}_{\mathrm{cc}}^{+}}\epsilon^{\eta}_{\gamma}p^{\xi}_{\gamma}\left[\mu_{+}\mathfrak{F}_{+}(s_{12})p_{12}^{\alpha}-\mu_{0}\mathfrak{F}_{0}(s_{13})p_{13}^{\alpha}\right]
\end{aligned}$$

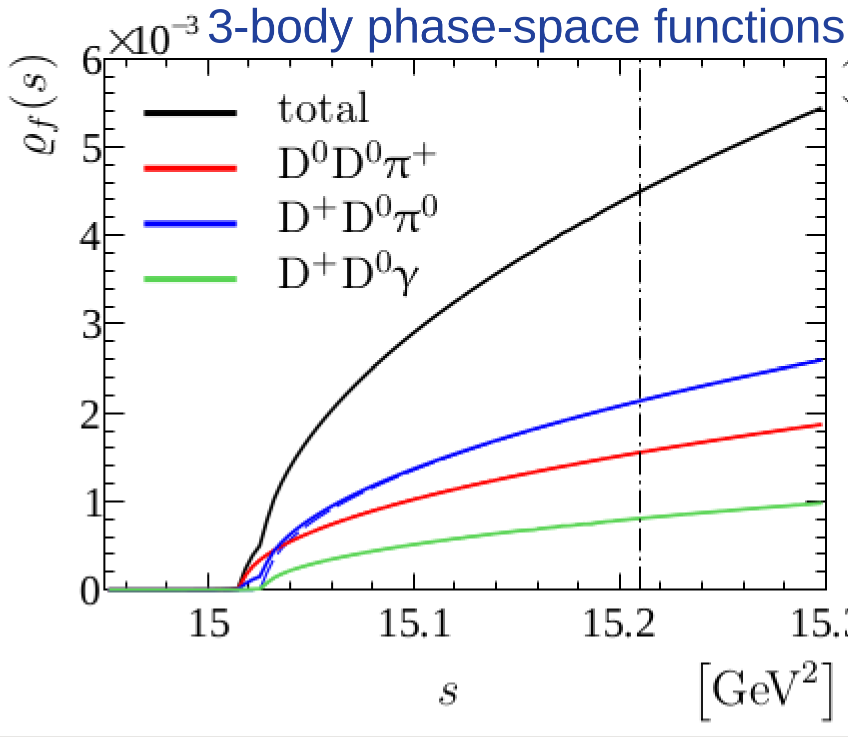
$$\mathfrak{F}(s) = \frac{1}{m^{2}_{\mathrm{D}^{*}}-s-im_{\mathrm{D}^{*}}\Gamma_{\mathrm{D}^{*}}}$$

Unitarized 3-body BW model

- Constructed advanced 3-body Breit-Wigner model where
  - 3-body phase-space is calculated via integral of X→DD*[→Dπ/γ] matrix element over $D^0D^{0/+}\pi^+/\gamma$ Dalitz plot

$$\mathfrak{F}_f^{\mathrm{U}}(s) = \varrho_f(s)\left|\mathcal{A}_{\mathrm{U}}(s)\right|^2 ,$$
$$\mathcal{A}_{\mathrm{U}}(s) = \frac{1}{m_{\mathrm{U}}^2 - s - i m_{\mathrm{U}}\hat{\Gamma}(s)}$$

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



- and where complex width is derived as

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

Imaginary part for unitarity (optical theorem)

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

Real part for analyticity (Kramers-Kronig relations)

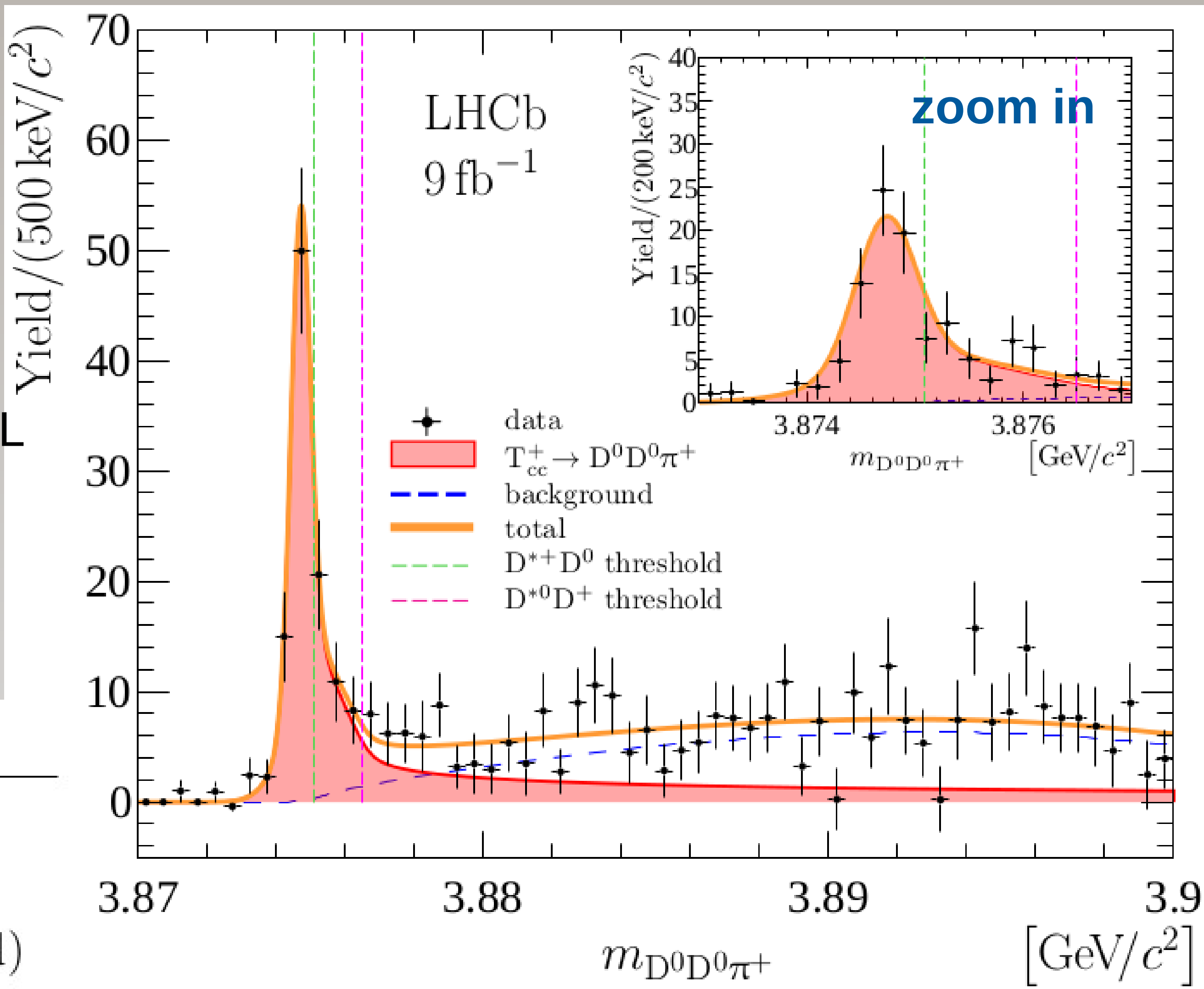
$$\Re\,\Sigma(s)|_{\Im s=0^+} = \xi(s) - \xi(m_{\mathrm{U}}^2) ,$$
$$\xi(s) = \frac{s}{2\pi}\,\mathrm{p.v.}\int_{s^*_{\mathrm{th}}}^{+\infty}\frac{\varrho_{\mathrm{tot}}(s')}{s'(s'-s)}ds'$$

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:

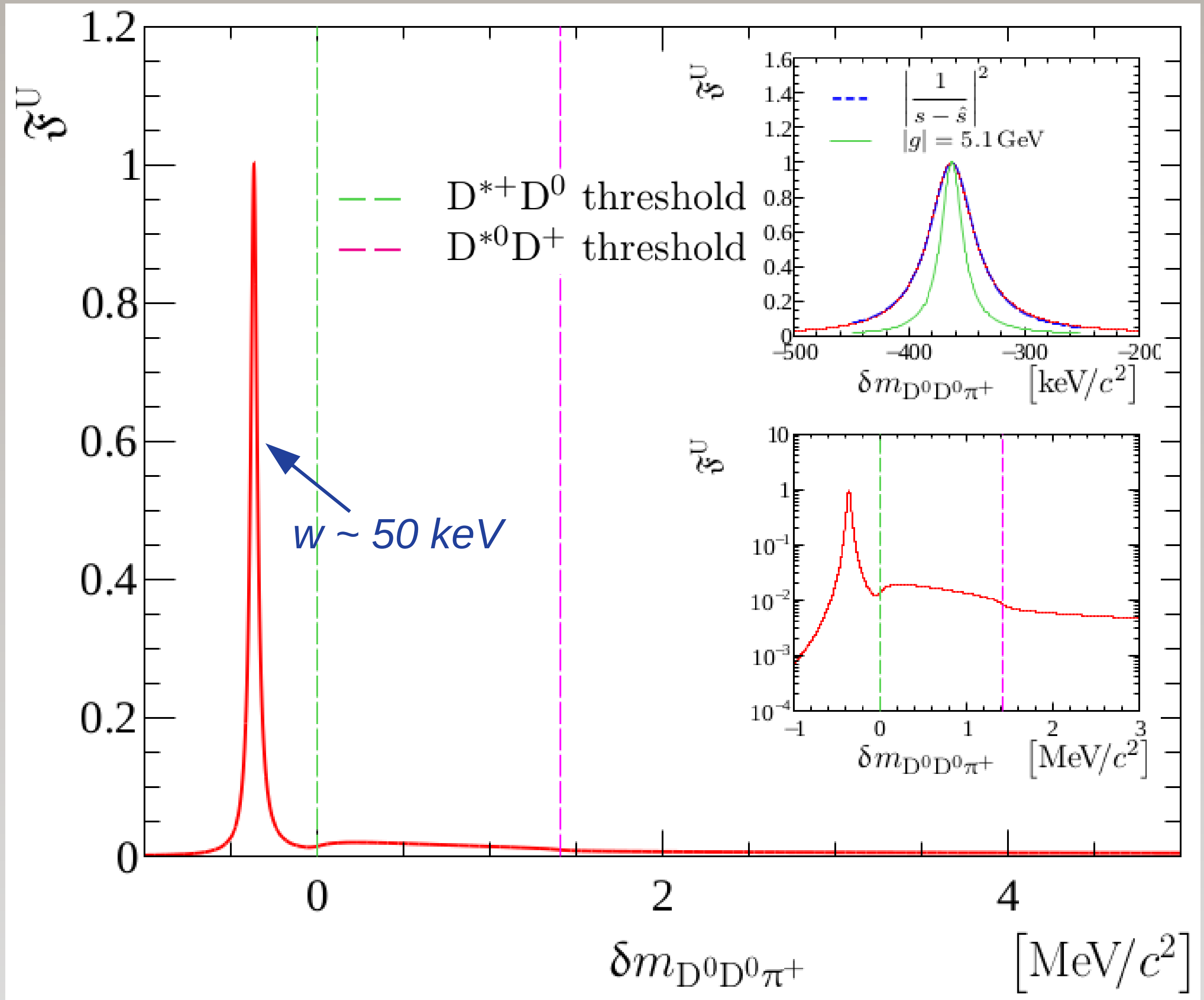
Parameter	Value
N	186 ± 24
δm_{U}	$-359 \pm 40\,\mathrm{keV}/c^2$
$\lvert g \rvert$	3×10^4 GeV (fixed)



Mass shape in unitarized model

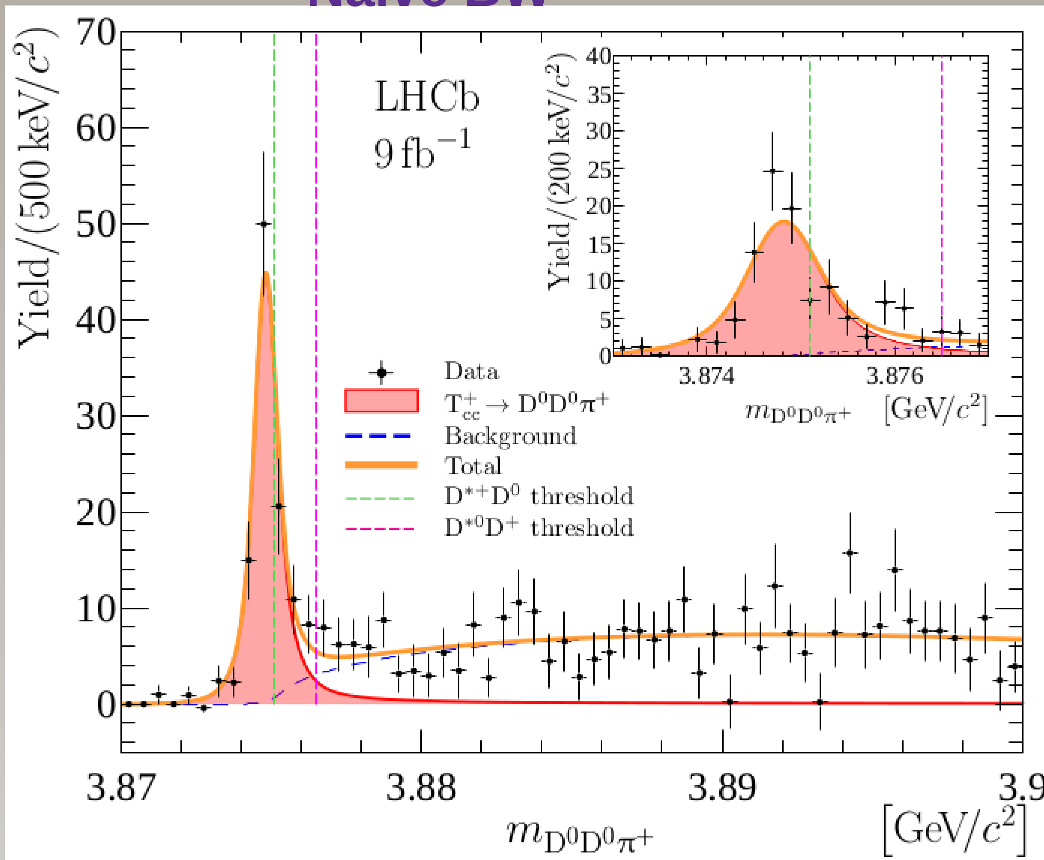
- Fit result (before smearing with resolution)

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

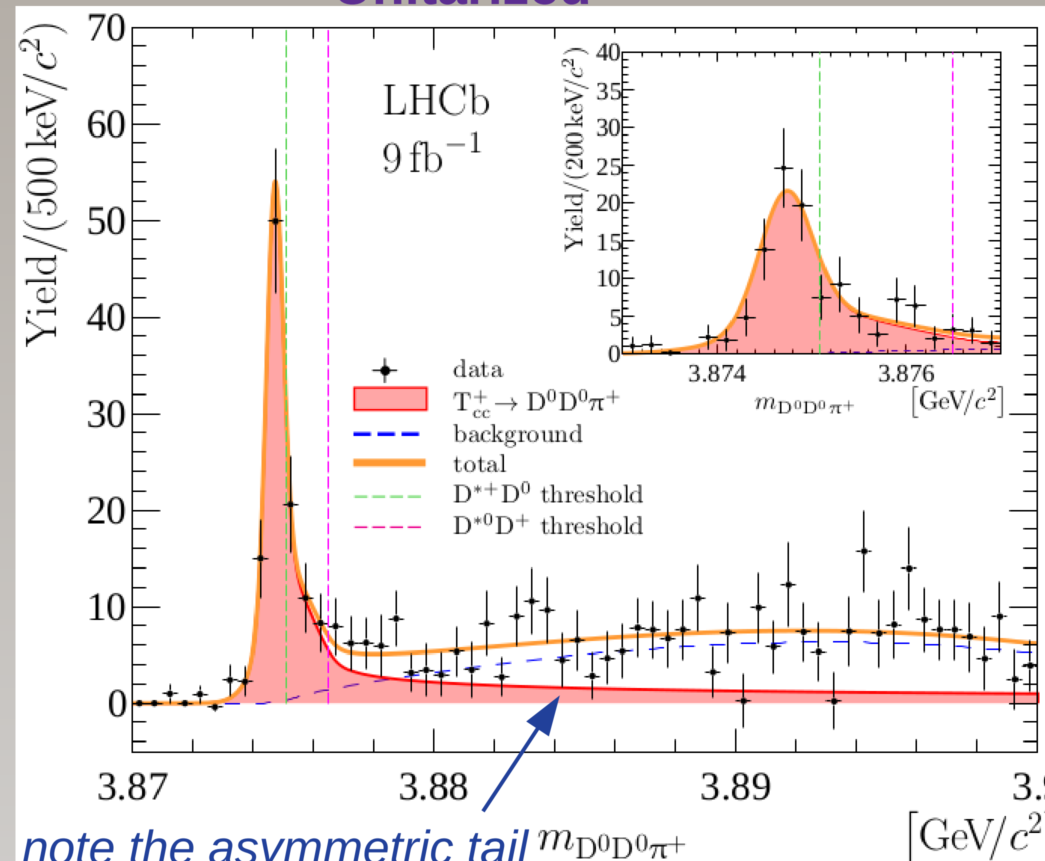


Fits with Naive and Unitarized models

Naive BW



Unitarized



- 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 $\delta' m_{BW}$ and Γ_{BW} consistent with values obtained from data

- Generate 4k pseudoexperiments using naive BW model, fit them with unitarized BW model. Get $\delta' m_0$ consistent with values obtained from data

Parameter		Pseudoexperiments mean	Pseudoexperiments RMS	Data	
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	

Systematic uncertainties (unitarized model)

- Fit model
  - try alternative resolution functions
  - apply ±5% correction for resolution scale
  - try alternative background models
  - vary coupling constants f,h,μ within related uncertainties from BR(D*→Dπ/γ) and Γ(D*)
  - try smaller value for |g|
- Vary momentum scale by ±0.03%
- Vary energy loss correction by ±10%
- Uncertainty on D^0 mass cancels out in difference, while account for uncertainty on $m(D^{*+})-m(D^0)$

Source	$\sigma_{\delta m_U}$ [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
$D^{*+} - D^0$ mass difference	2
Total	$^{+9}_{-6}$

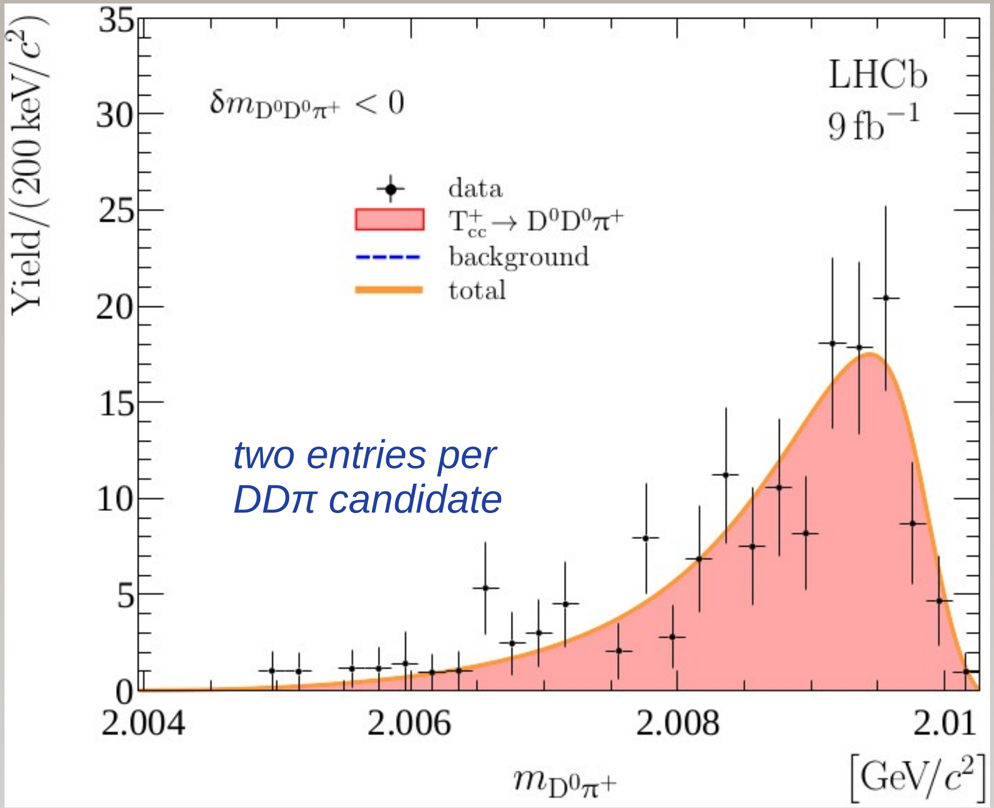
- Fit model systematics considered for the lower limit of |g| changing it to

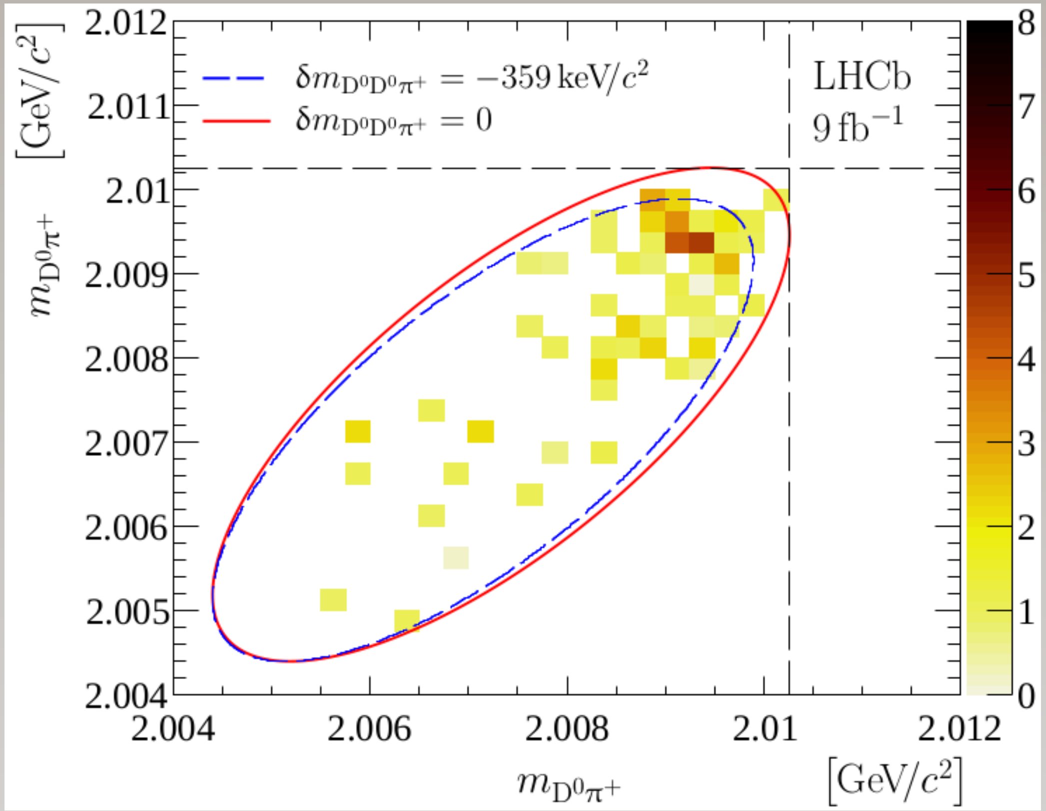
$$|g| > 5.1\,(4.3)\ \text{GeV at } 90\,(95)\,\%\ \text{CL}$$

Additional Studies

Offshell D*+

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



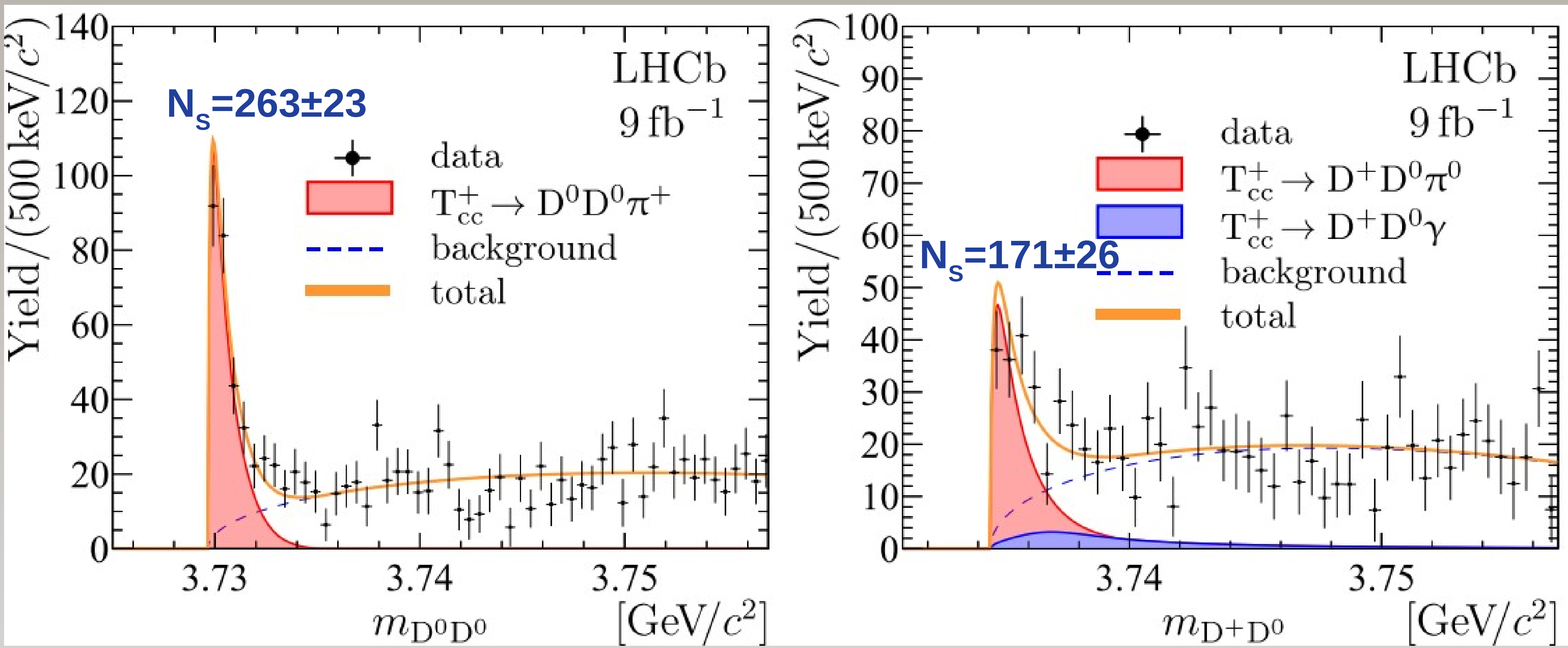


Perfect agreement confirms

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

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

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



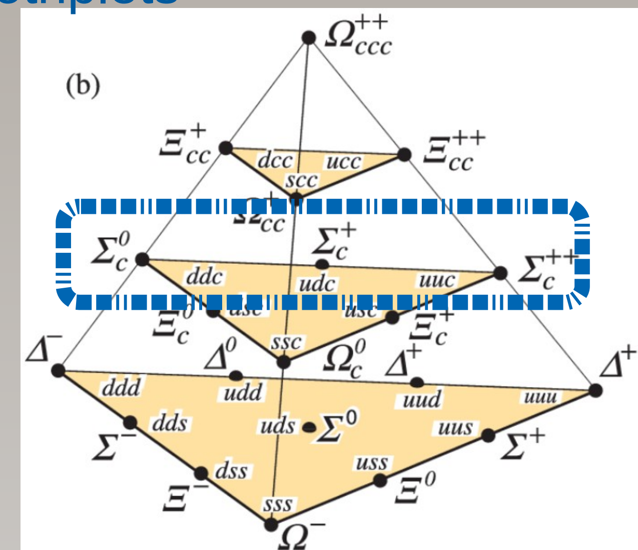
- Relative yields are in agreement with model expectations for isoscalar T_{cc} with $J^P=1^+$ and $D^{0/+}$ reconstruction efficiencies

T_{cc} isospin

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

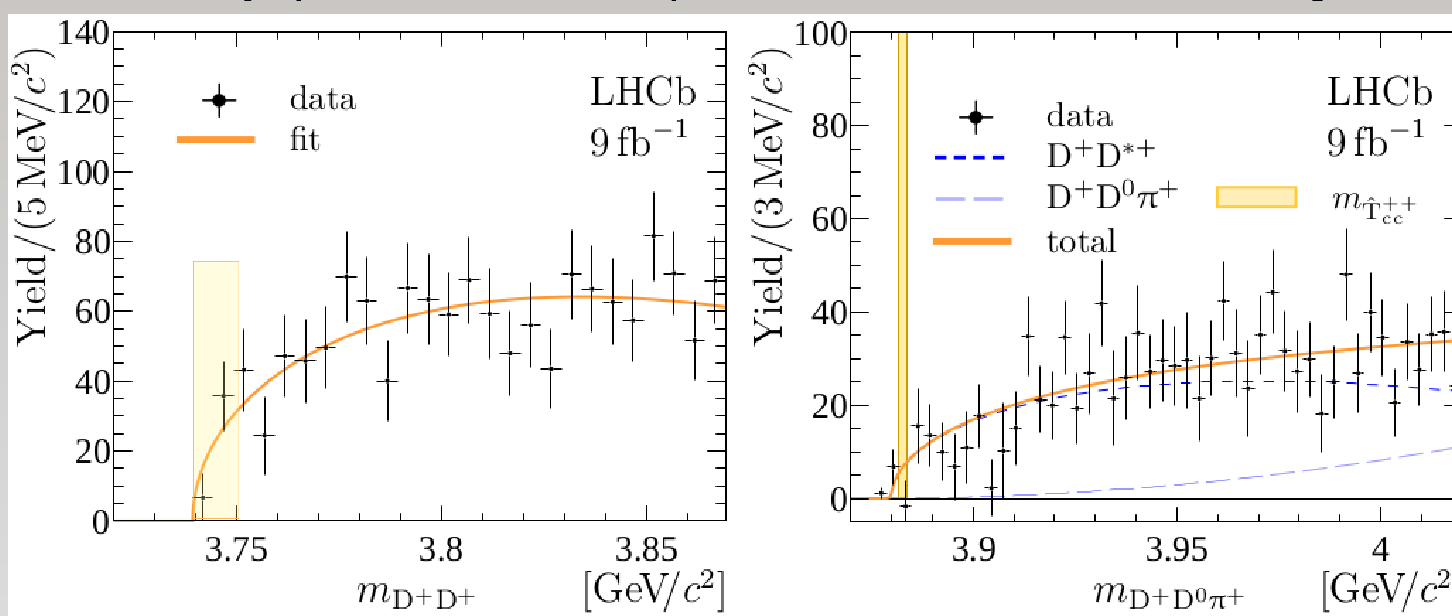
$$
\begin{aligned}
m_{\hat{T}^0_{cc}} &= m_{\hat{T}_{cc}} + m_u + m_u - a' q_{\bar{u}} q_{\bar{u}} - b' q_{cc} (q_{\bar{u}} + q_{\bar{u}}) \\
m_{\hat{T}^+_{cc}} &= m_{\hat{T}_{cc}} + m_u + m_d - a' q_{\bar{u}} q_{\bar{d}} - b' q_{cc} (q_{\bar{u}} + q_{\bar{d}}) \\
m_{\hat{T}^{++}_{cc}} &= m_{\hat{T}_{cc}}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

from Σ_b and Σ_c isotriplets



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

- 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



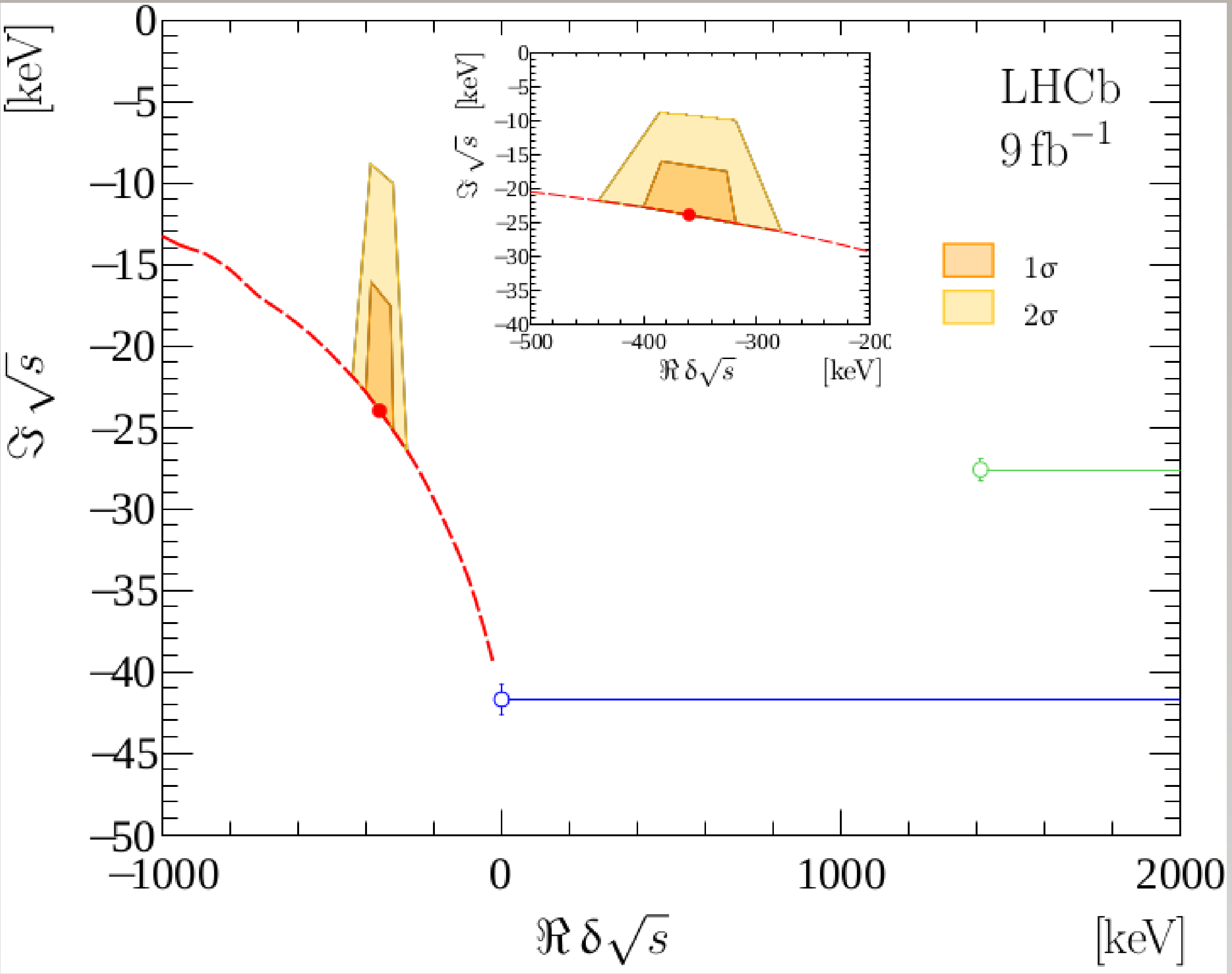
Pole position

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

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

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

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



- 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

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

  - 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: $0 \;\leq\; -r < 11.9\,(16.9)\,\mathrm{fm\ at\ }90\,(95)\%\ \mathrm{CL}$
  - Weinberg compositness: $Z < 0.52\,(0.58)\ \mathrm{at}\ 90\,(95)\%\ \mathrm{CL}$

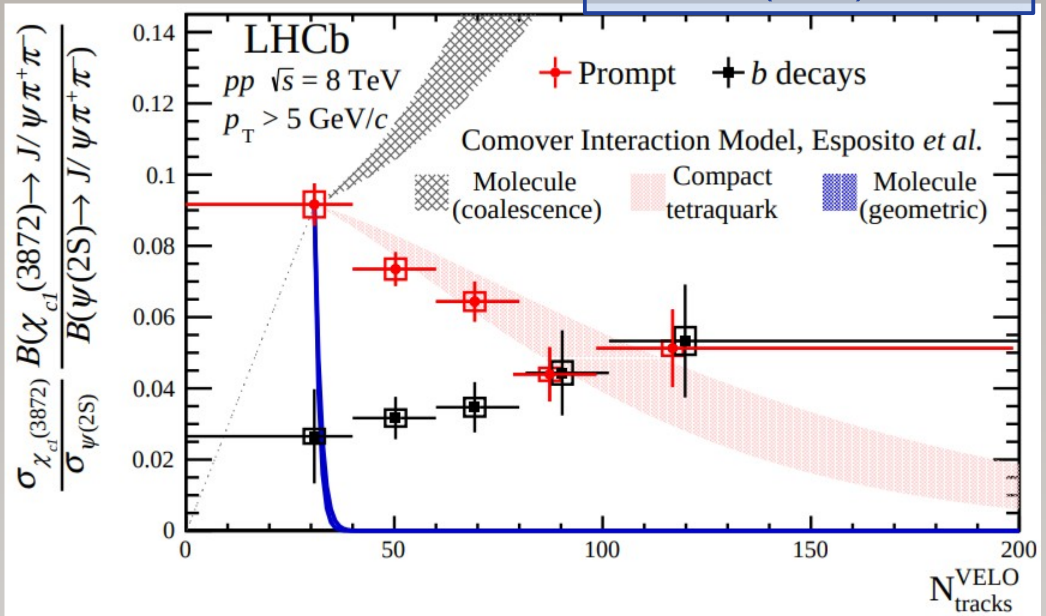
- size in case of D^0D^{*+} molecula: $R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4\,\mathrm{fm}$

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

PRL 126 (2021) 092001



- Explained in comover model where $\chi_{c1}(3872)$ is broken by closely flying pions/gluons

- Therefore probing effective $Q\pi$ break-up cross-section:

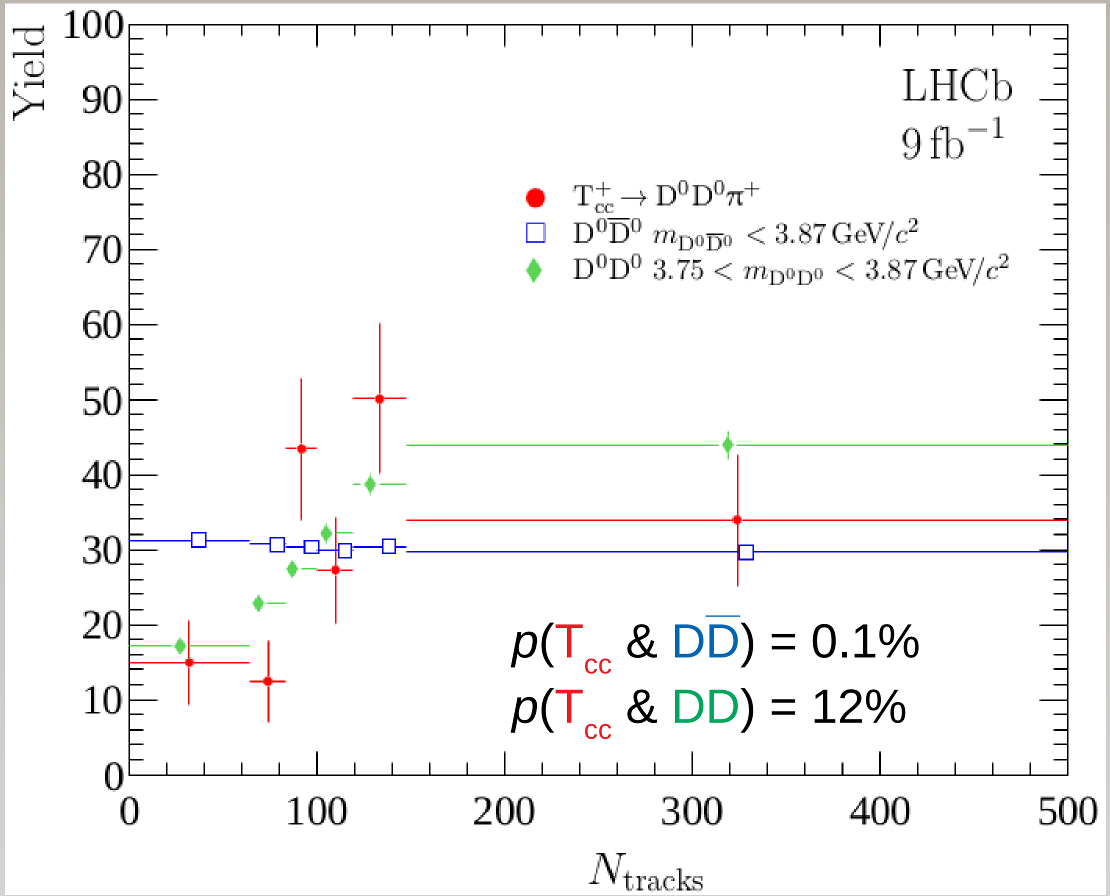
$$\langle v\sigma_{\psi'}\rangle = 3.9 \pm 0.8 \text{ mb}$$
$$\langle v\sigma_{X}\rangle = 2.6 \pm 0.7 \text{ mb}$$

and fractions of Q out of reach of comovers

more details in Braaten et al., arXiv:2021.13499

T_{cc} multiplicity distribution

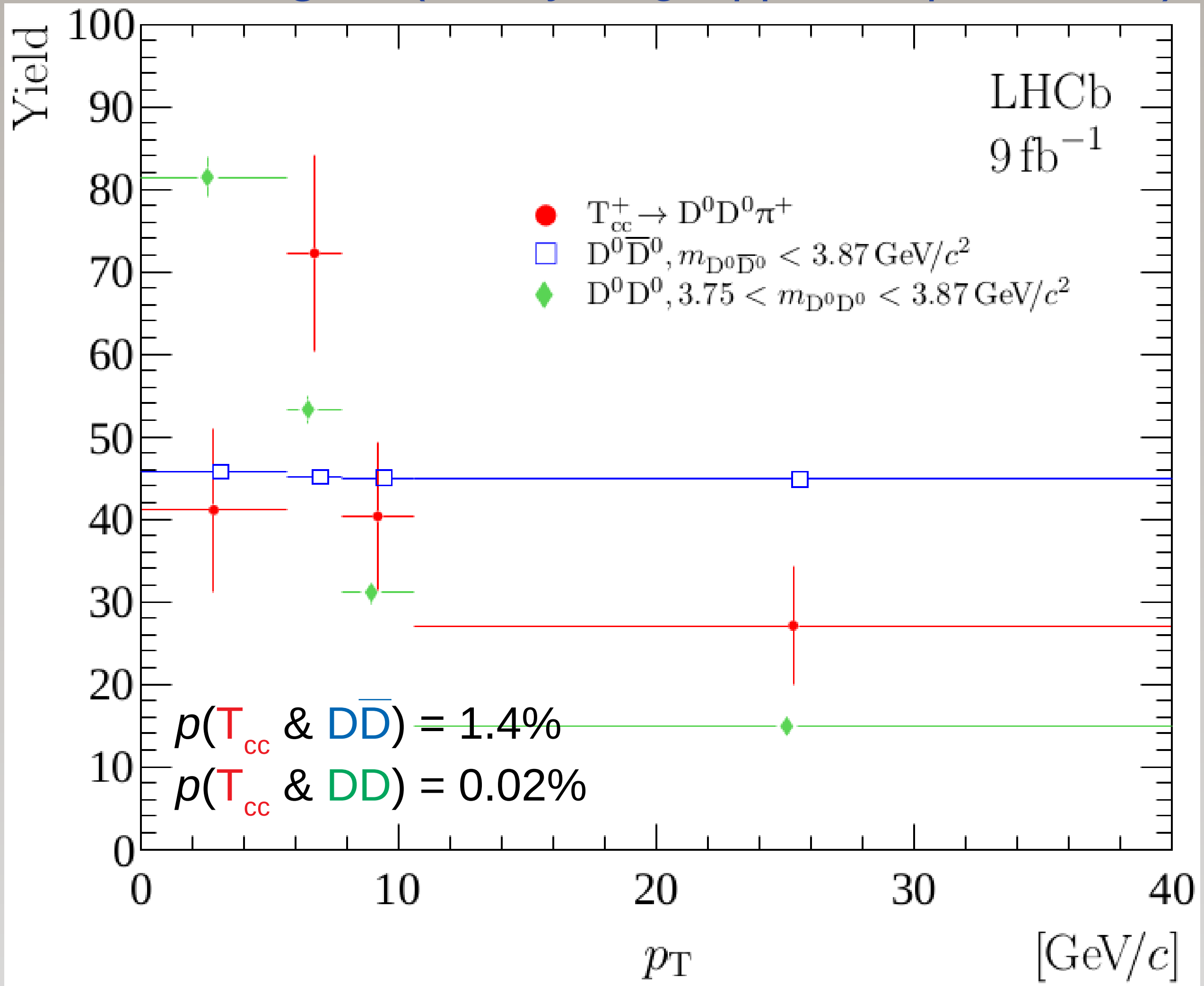
- Compare $T_{cc}^{+} \rightarrow D^0D^0X$ **signal** distributions with
  - **D^0D^0 in $3.75<m_{DD}<3.87$ GeV region** (presumably dominated by double-parton scattering)
  - **$D^0\bar{D}^0$ in $m_{DD}<3.87$ GeV region** (mainly single $pp \rightarrow D\bar{D}$ production)



- 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 $c\bar{c}+c\bar{c}$

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)
  - **$D^0\overline{D}^0$ in $m_{DD}<3.87$ GeV region** (mainly single $pp \to D\overline{D}$ production)



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

Discussions

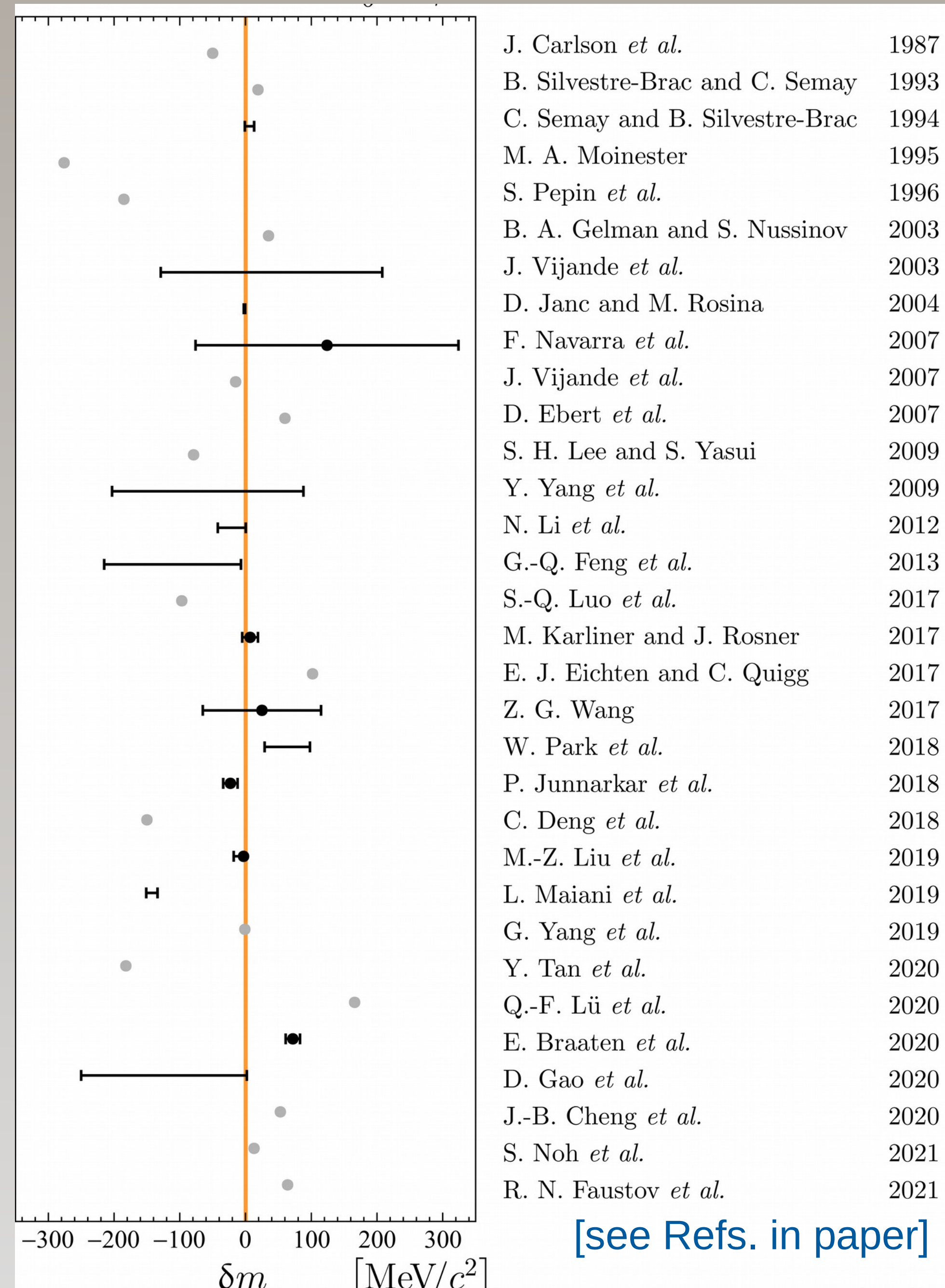
Reflections on measured mass, 1

- 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]

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

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

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

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

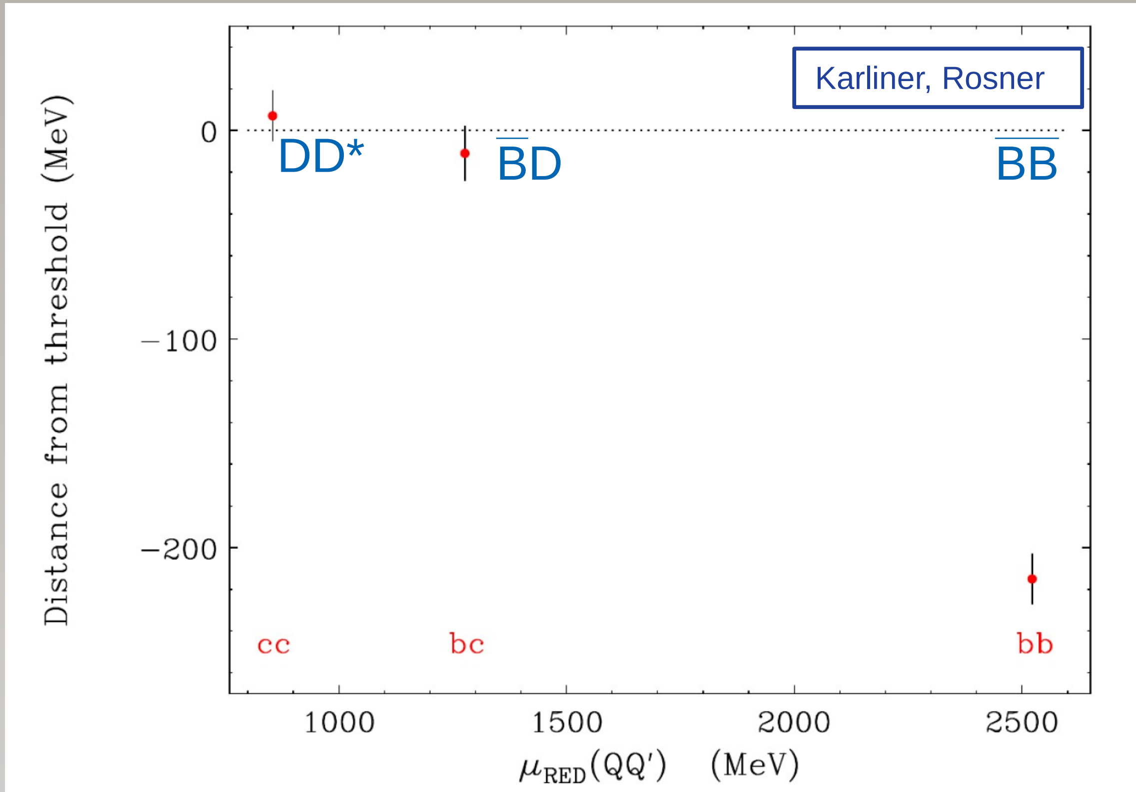
  → Giving stable T_{bc}?

  - Opposite expectations in molecula models

    Li, Sun, Liu, Zhu, 2012

    Liu, Wu, Valderrama, Xie, Geng, 2019

  - Good test for models



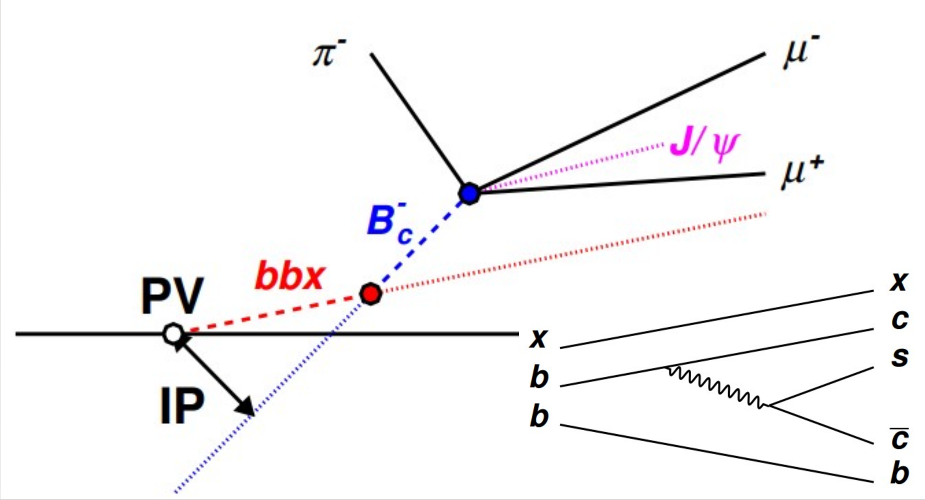
- From naive phenomenology (HQS-like) estimates one can expect that
  - **[cc][$\overline{sq}$]** and **[cc][$\overline{sq}$]** are above corresponding thresholds.
  - **[cc][ud]$\overline{q}$** can decay to Ξ_{cc} + hadrons

- What about **[ccuudd]** hexa-quark? Decays to $H_{cc} \rightarrow \Lambda_c\Lambda_c$, $H_{cc} \rightarrow \Xi_{cc}N$, $H_{cc} \rightarrow \Lambda_c pK\pi$?

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

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

- **Cons**
  - O(2-20) supression with every $c \to b$ substitution
    compare with $\sigma(\Xi_{cc}) : \sigma(\Xi_{bc}) : \sigma(\Xi_{bb})$ ~ 1 : 0.4 : 0.015 at 14TeV in pp
    Zhang, Wu, Zhong, Yu, Fang, 2011
  - $Br(b \to c + \pi/\mu/X)$ are 1-10% or less
- **Pros**
  - larger trigger efficiency for final states with high-p_T muon
- Comparing to ~100 events of $T_{cc} \to D^0D^0\pi^+$ can look for
  - $T_{bc} \to D^0D^+\pi^-$, $\overline{B}^0K^-\pi^+$, $D^0D^+\mu\nu$ ~ O(1-10)
  - $T_{bb} \to BD + X$ ~ O(0.1)
  - …
- Option to search via detached B_c mesons
  - can also look for detached T_{cc}^+
  Gershon, Poluektov, 2019
- Exploit higher statistics of Run3&4 data
  expect linear gain in statistics with luminosity

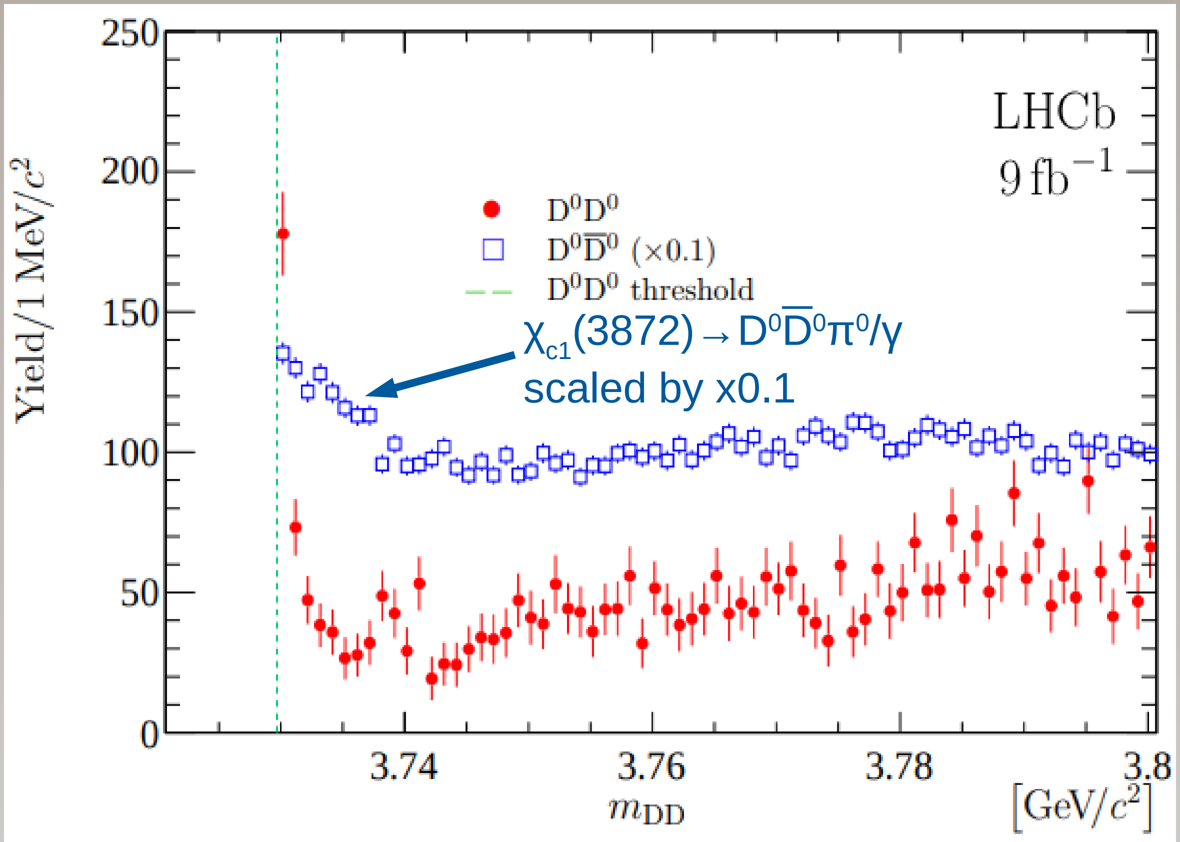


Production estimation

- 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



- 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 $Br(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K\pi\pi) \sim 5\text{-}20\%$,
  $Br(\Xi_{cc}^{++} \rightarrow \Xi_c^+\pi^+) \sim 1.3\text{-}4\%$,
  $Br(\Xi_c^+ \rightarrow pK\pi) \sim (6.2\pm3.0)\text{x}10^{-3}$

Open questions / Future measurements

- *Is the measured mass and description of various spectra enough to answer the question on T_{cc} nature?*

- *Can any lessons be learned for other exotics, in particular $\chi_{c1}(3872)$? What about applying same models for describing nuclei, i.e. deuteron?*

- Dalitz analysis of $T_{cc}^{+} \to D^0 D^0 \pi^+$ (& joint $D^0 D^+$?) to confirm $J^P = 1^+$
  - *Are non-resonant decays $T_{cc}^{+} \to DD\pi/\gamma$ significant?*

- Production measurements
  - cross-section, multiplicity and p_T dependence
  reference channels: $\chi_{c1}(3872)$, non-resonant $D^0 D^0$, $D^0 \overline{D}^0$, …
  - *What quantities are of the most importance?*

- Searches for T_{bc} and T_{bb} and other QQ-states
  - *What's their production x-section and BRs?*
  - *Is T_{bc} long-lived? What about cc-hexaquark?*

- Will we have a chance to see the T_{cc}^{+} in ion collisions, $e^- e^+$ (Belle II), *bc*-hadron decays, …?

Conclusions

- A novel class of hadrons observed – $[cc\bar{u}\bar{d}]$, 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

- We invite you to join the mini-workshop "T_{cc} and beyond" in the afternoon (13:00-18:00 CET) for detailed discussion: indico.cern.ch/event/1065494/

Backup

Summary of Results

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

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

- 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

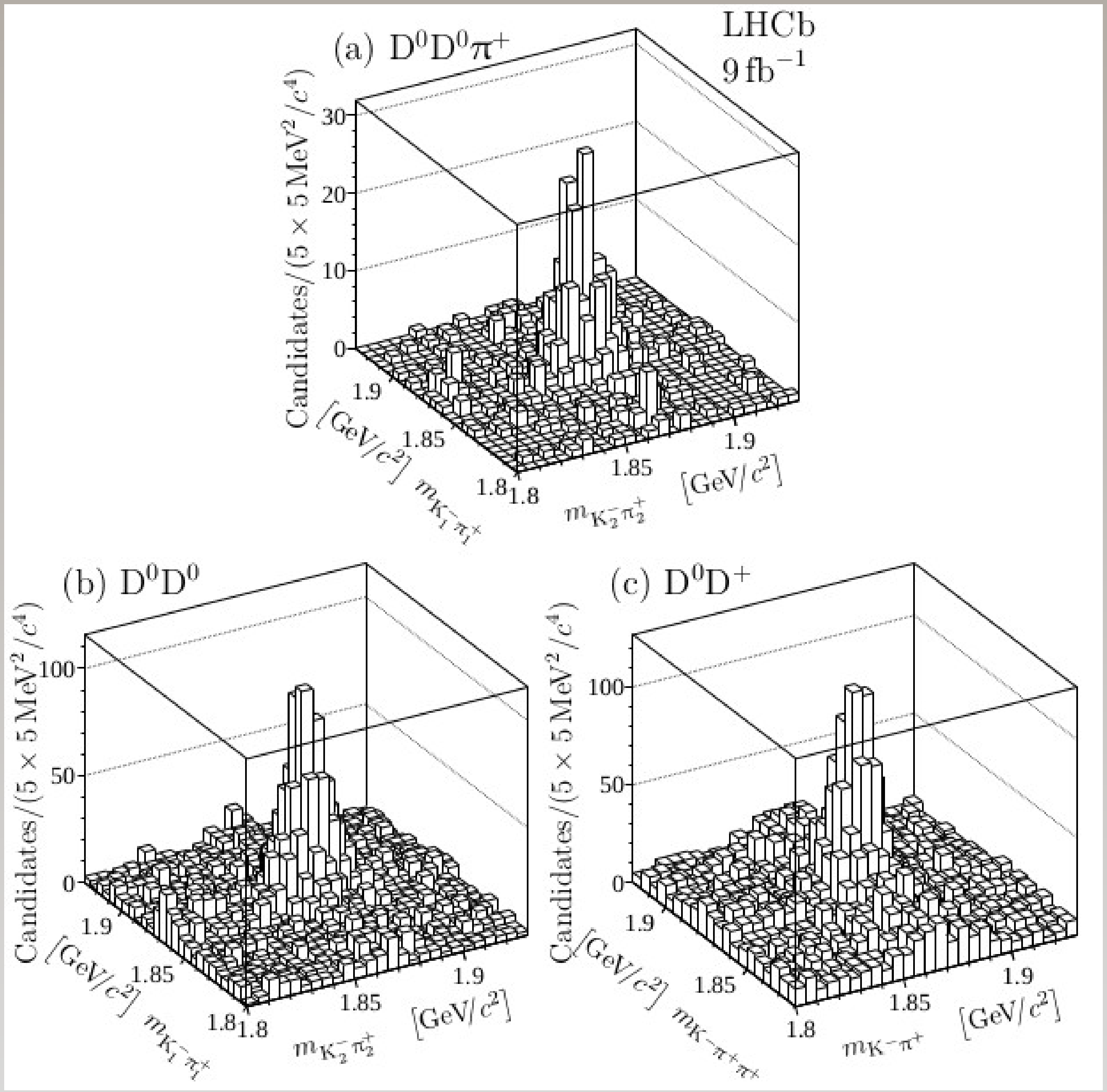
- A lower limit is set on $T_{cc}^+ \to DD^*$ coupling: $|g| > 5.1\,(4.3)\,\mathrm{GeV}$ at $90\,(95)\,\%$ CL

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

- Pole position:

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

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

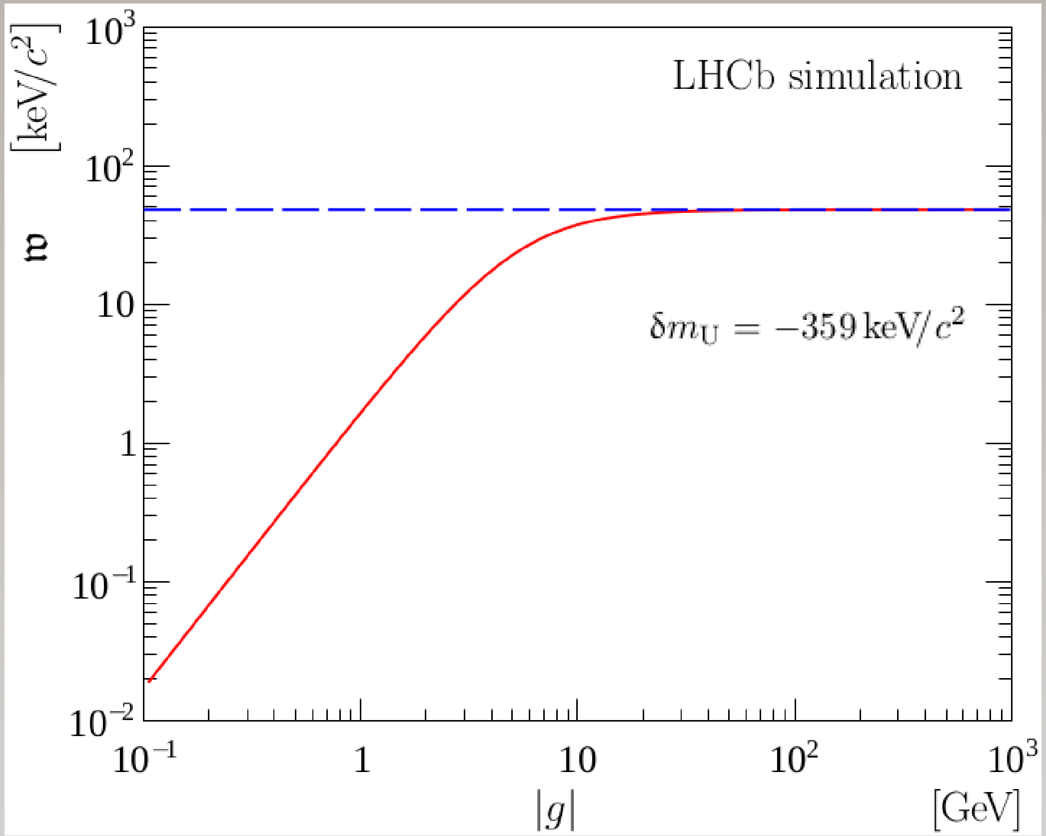
  f_1 = 0.778

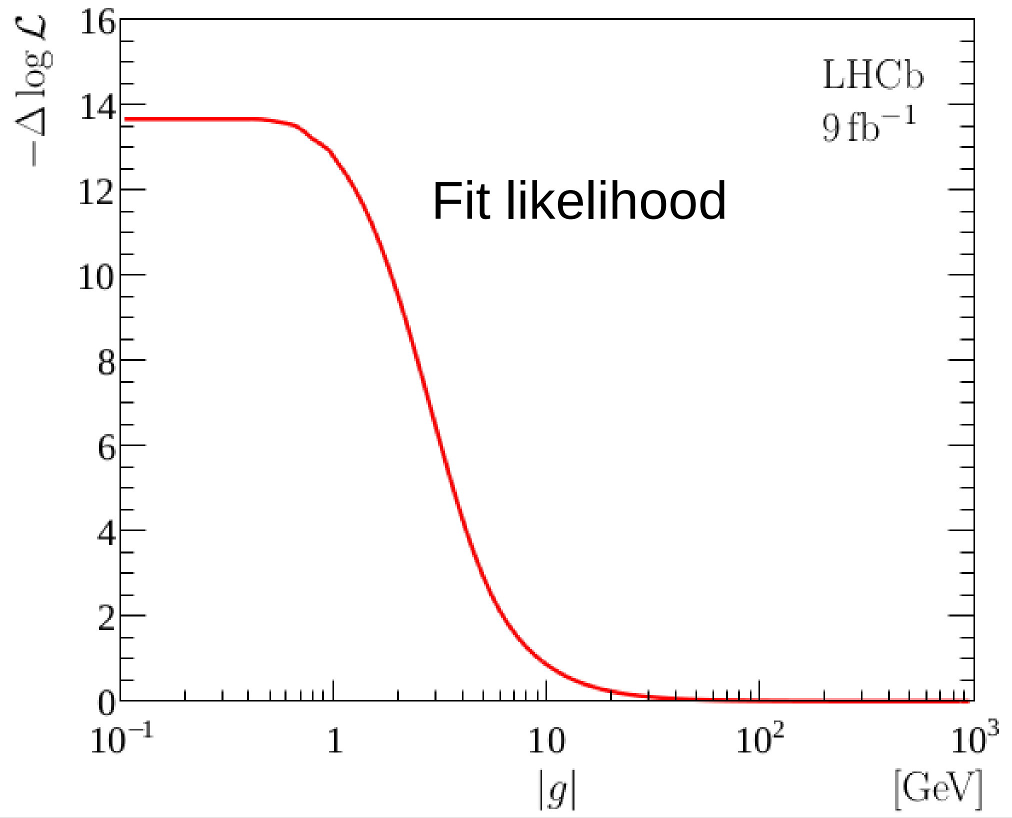
  a 1.05 correction motivated by data-simulation comparison in various decay channels

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

Scaling in unitarized model

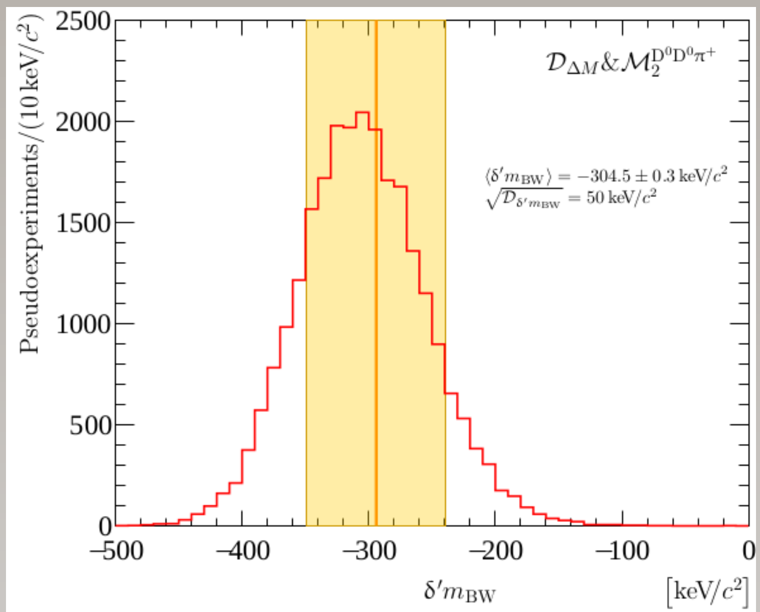
- For large values of |g| a scaling of overall shape is in place and visible width depends only on mass and Γ(D*+)

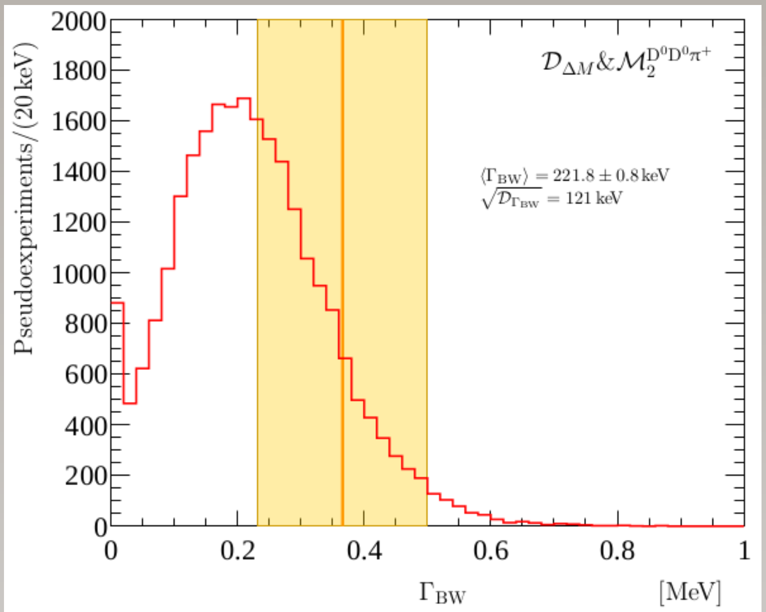




Consistency of Naive and Advanced

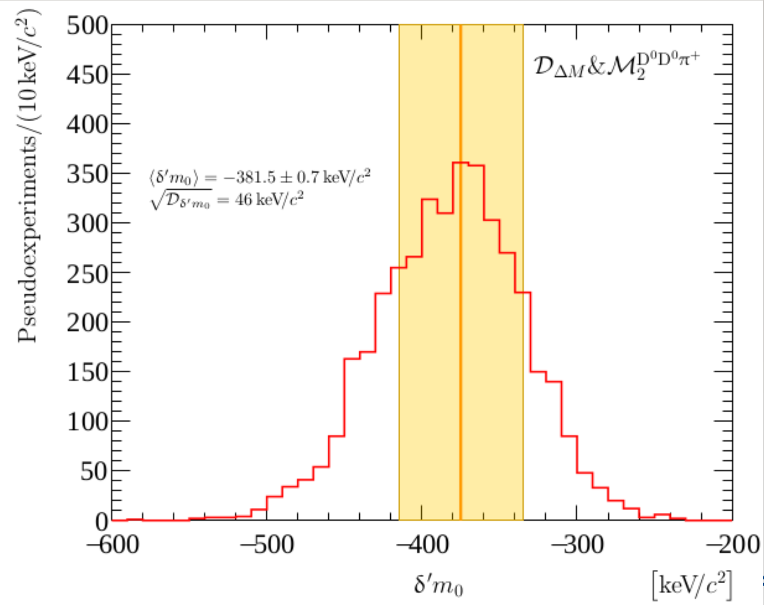
- Generate 25k pseudoexperiments using advanced BW model, fit them with naive BW model. Get $\delta' m_{BW}$ and Γ_{BW} consistent with values obtained from data





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

Parameter		Pseudoexperiments mean	Pseudoexperiments 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	



Low-energy scattering approximation

- Relation between unitarized amplitude and low-energy expansion

$$\begin{aligned}\mathcal{A}_{\mathrm{NR}}^{-1} &= \frac{1}{a} + r\frac{k^2}{2} - ik + \mathcal{O}(k^4)\,, \\ \frac{2}{|g|^2}\mathcal{A}_{\mathrm{U}}^{-1} &= -\left[\xi(s) - \xi(m_{\mathrm{U}}^2)\right] + 2\frac{m_{\mathrm{U}}^2 - s}{|g|^2} - i\varrho_{\mathrm{tot}}(s)\end{aligned}$$

- Proportionality factor

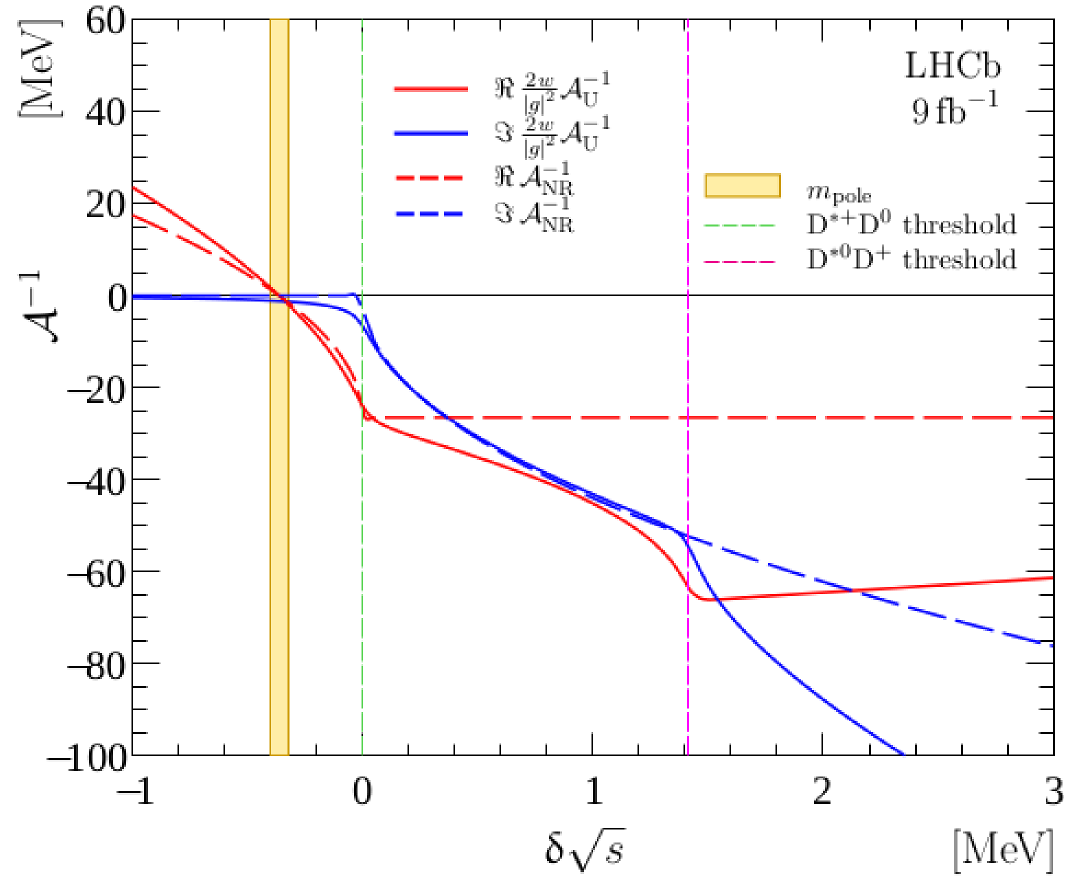
$$w = \frac{24\pi}{m_{\mathrm{D}^{*+}} + m_{\mathrm{D}^0}}\frac{1}{c_1}$$

- 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

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

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

- For ρ functors

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

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

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 $[cc\bar{s}q]$ and $[cc\bar{s}\bar{s}]$ with respect to threshold. We may suppose that substitution of one light quark in $[cc\bar{u}\bar{d}]$ to $\bar{s}$ will increase its mass by either

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

$$m_{\Xi_b^{0(-)}} - m_{\Lambda_b^0} = 172(177)\,\mathrm{MeV}/c^2 \tag{U.2}$$

while the corresponding threshold will be increased by either

$$m_{\mathrm{D}_s^+} - m_{\mathrm{D}^+(\mathrm{D}^0)} = 99(104)\,\mathrm{MeV}/c^2 \quad \text{or} \tag{U.3}$$

$$m_{\mathrm{B}_s^0} - m_{\mathrm{B}^0(\mathrm{B}^+)} = 87(88)\,\mathrm{MeV}/c^2\ . \tag{U.4}$$

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

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

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

$$m_{\Omega_c} - m_{\Lambda_c^+} = 427\,\mathrm{MeV}/c^2 \tag{U.6}$$

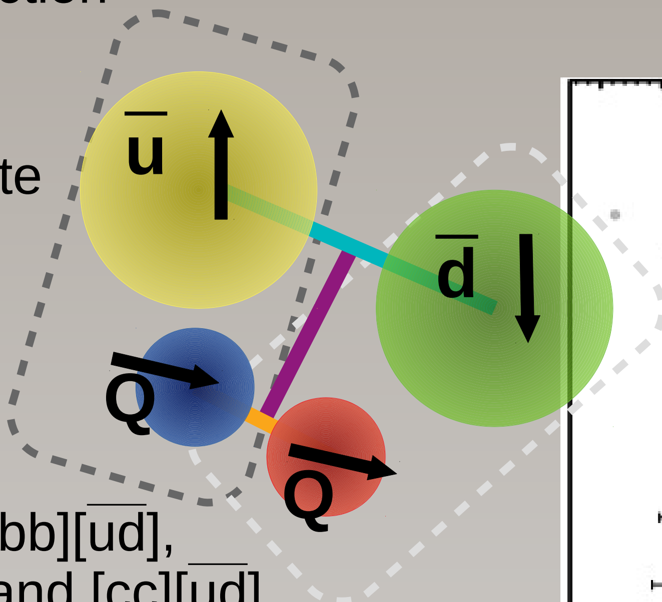
while the corresponding threshold will be increased by either

$$2 \times m_{\mathrm{D}_s^+} - m_{\mathrm{D}^+} - m_{\mathrm{D}^0} = 202\,\mathrm{MeV}/c^2 \quad \text{or} \tag{U.7}$$

$$2 \times m_{\mathrm{B}_s^0} - m_{\mathrm{B}^0} - m_{\mathrm{B}^+} = 175\,\mathrm{MeV}/c^2\ . \tag{U.8}$$

Doubly charmed tetraquark

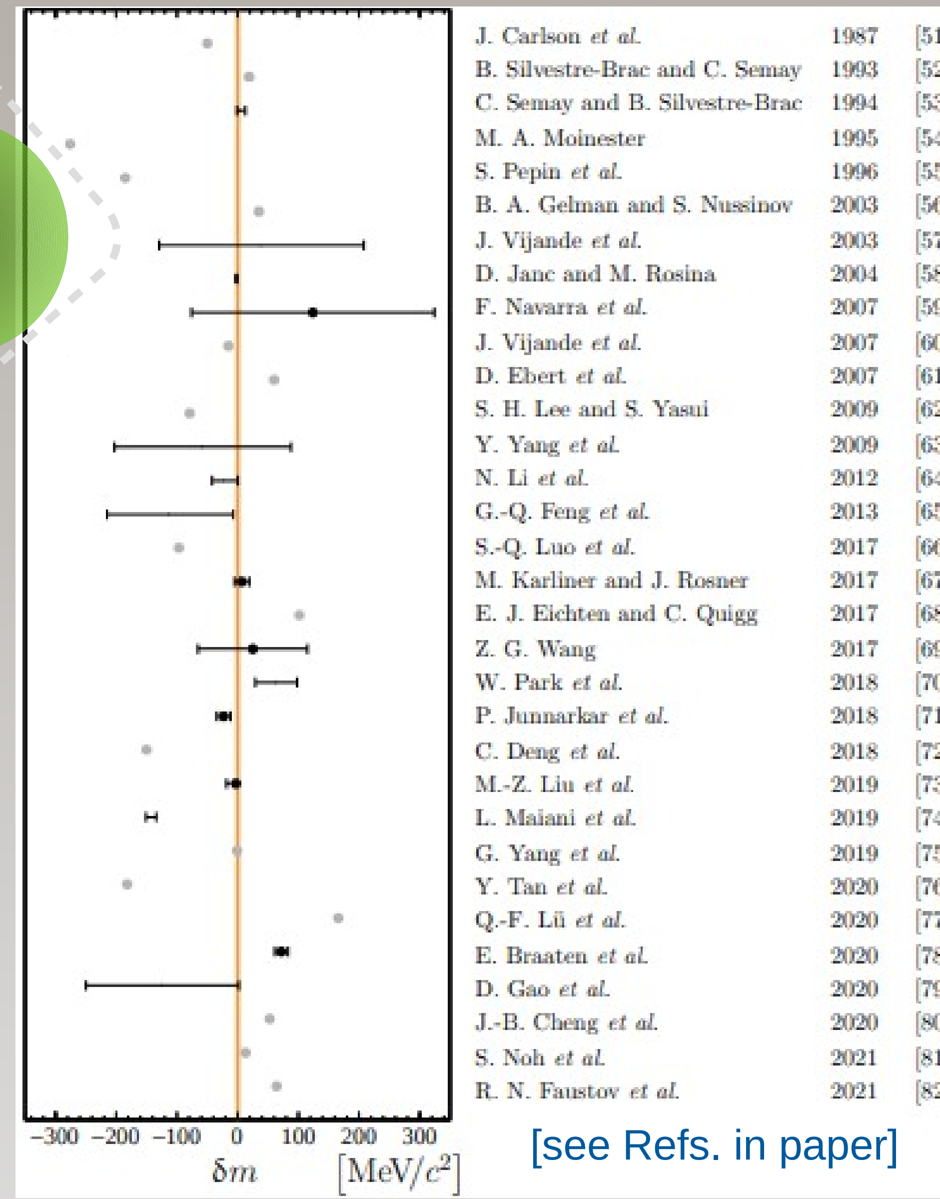
- In $m_Q \to +\infty$ limit attraction in $[QQ][\overline{ud}]$ system should give bound (and thus stable) state



Likely to be true for $[bb][\overline{ud}]$, no 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

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



Selected theory approaches - 1

- 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
    - $m(cc\overline{ud}) = m(\Xi_{cc}) + 315\ \mathrm{MeV} \sim m(\Xi_{cc}) + [m(\Lambda_c) - m(D^0)] + \text{kinematic correction}$ *(~ 3 MeV)*

    → δm = +102 MeV → **δm = +65 MeV**

    using updated $m(\Xi_{cc})$ measurement

    Eichten, Quigg, 2017

  - 1b. More detailed calculation with estimation of uncertainties

$$H_\ell^Q = m_Q + \mathcal{E}_\ell + \frac{\mathcal{K}_\ell}{2m_Q} + \frac{\mathcal{S}_\ell}{2m_Q}\boldsymbol{S}\cdot\boldsymbol{j}_\ell \qquad H_\ell^{Q_1Q_2} = (m_{Q_1} + m_{Q_2}) + \mathcal{E}_{\ell,Q_1Q_2} + \frac{\mathcal{S}_{\ell,Q_1Q_2}}{8\mu_{Q_1Q_2}}\boldsymbol{S}\cdot\boldsymbol{j}_\ell$$

    → **δm = 72±11 MeV**

    Braaten, He, Mohapatra, 2020

  - 1c. Different treatment of meson/baryon quark masses & splitting parameters

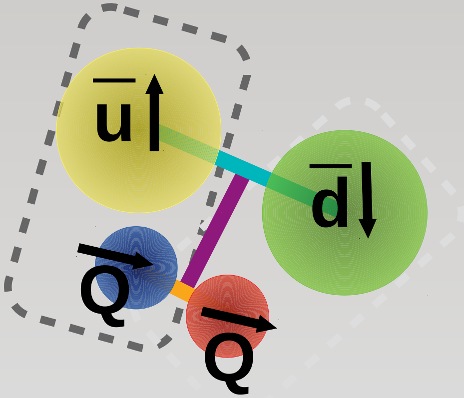
Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	-150.0
cc binding	-129.0
Total	3882.2 ± 12

→ δm = 7±12 MeV

using updated $m(\Xi_{cc})$ measurement

δm = 1±12 MeV

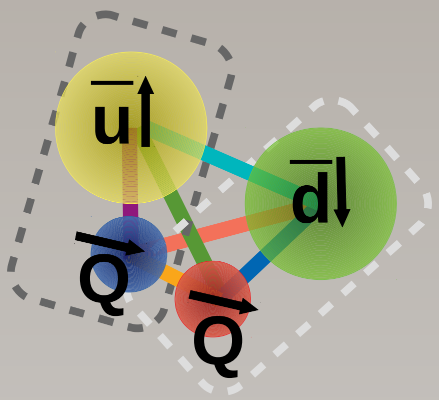
Karliner, Rosner, 2017



Selected theory approaches - 2

- Non-relativistic consituent quark model.
  Solve Heisenberg equation assuming total interaction is the sum of two-quark potentials

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



- Quark-quark potential describing
  - confinement part
  - one gluon exchange (OGE)
  with different variants for OGE term:
  Bhaduri/AL1(2)/AP1(2)

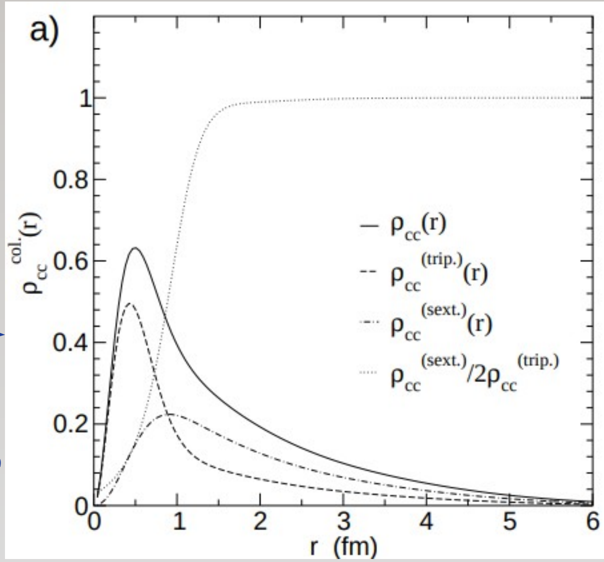
$$V_{ij}^{B} = -\frac{\lambda_i^C}{2} \cdot \frac{\lambda_j^C}{2} \left(U_0 + \frac{\alpha}{r_{ij}} + \beta r_{ij} + \alpha \frac{\hbar^2}{m_i m_j c^2} \frac{e^{-r_{ij}/r_0}}{r_0^2 r_{ij}} \sigma_i \cdot \sigma_j \right),$$
$$r_{ij} = |\vec{r}_i - \vec{r}_j|;$$

one-gluon exchange ("Couloumb") *confinement* *contact spin-spin interaction*

$$V_{ij}^{AL1} = -\frac{\lambda_i^C}{2} \cdot \frac{\lambda_j^C}{2} \left(U_0 + \frac{\alpha}{r_{ij}} + \beta r_{ij} + \tilde{\alpha} \frac{2\pi\hbar^2}{3 m_i m_j c^2} \frac{e^{-r_{ij}^2/r_0^2}}{\pi^{3/2} r_0^3} \sigma_i \cdot \sigma_j \right),$$
$$r_0(m_i, m_j) = A \left(\frac{m_i + m_j}{2 m_i m_j} \right)^B, \qquad r_{ij} = |\vec{r}_i - \vec{r}_j|;$$

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

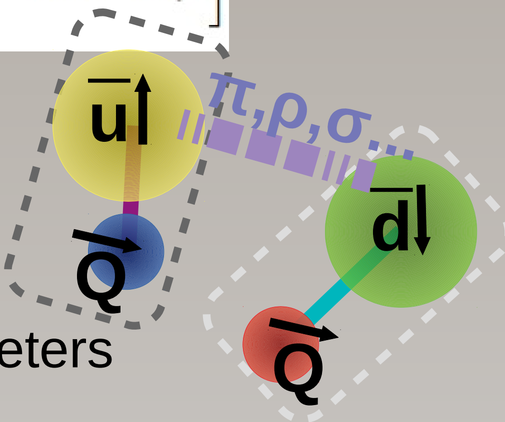
  gives insight into wave-function: spatial & color configuration, fractions of molecula/compact state



(choice of basic, parameters, ...)

Selected theory approaches - 3

- 3. Consider one-boson-exchange between DD* forming a molecula with exchange potential of style
$$\sum_{i<j} \vec{\tau}_i \cdot \vec{\tau}_j \, \vec{\sigma}_i \cdot \vec{\sigma}_j \frac{g^2}{4\pi} \frac{1}{4m^2} \left[\mu^2 \frac{\exp(-\mu r_{ij})}{r_{ij}} - 4\pi \delta^{(3)}(r_{ij}) \right]$$
with form-factor dependence on cut-off parameter Λ~1GeV (0.2fm)
$$V_M(\vec{q}, \Lambda) = V_M(\vec{q}) \, F^2(q, m, \Lambda)$$
$$F(q, m, \Lambda) = \left(\frac{\Lambda^2 - m^2}{\Lambda^2 - q^2} \right)^n$$



  - get (much stonger) binding depending on particular parameters (mainly cut-off value)

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, *(though do not agree with other calculations w/o 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

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 $\psi(2S)$ was observed at high track multiplicities
- Explained in comover model where $\chi_{c1}(3872)$ is broken by closely flying pions/gluons
- Therefore probing effective $Q\pi$ break-up cross-section:

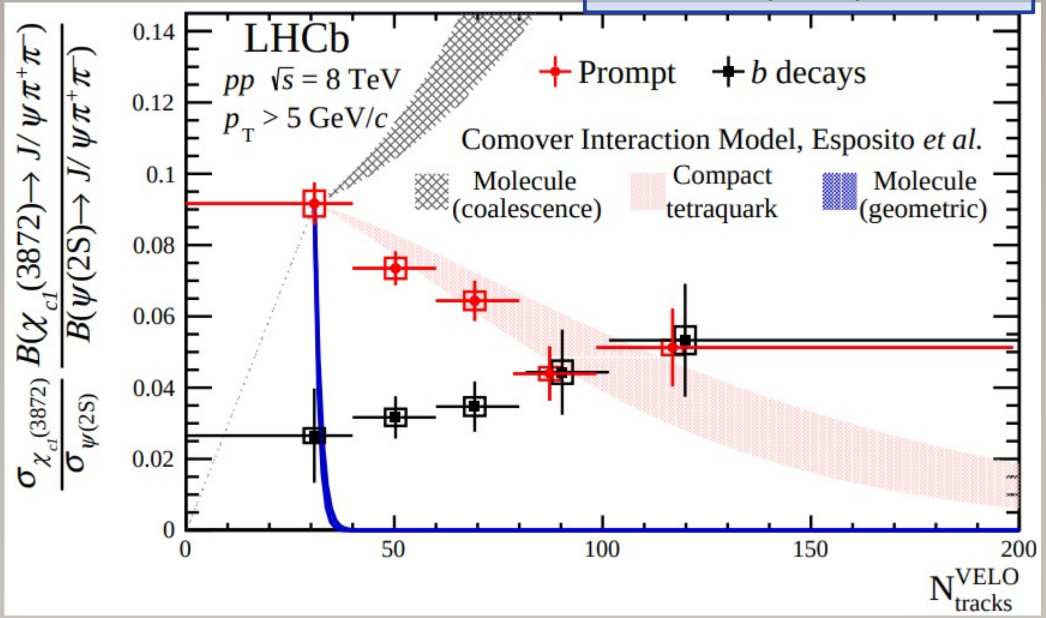
$$\langle v\sigma_{\psi'}\rangle = 3.9 \pm 0.8 \text{ mb}$$
$$\langle v\sigma_{X}\rangle = 2.6 \pm 0.7 \text{ mb}$$

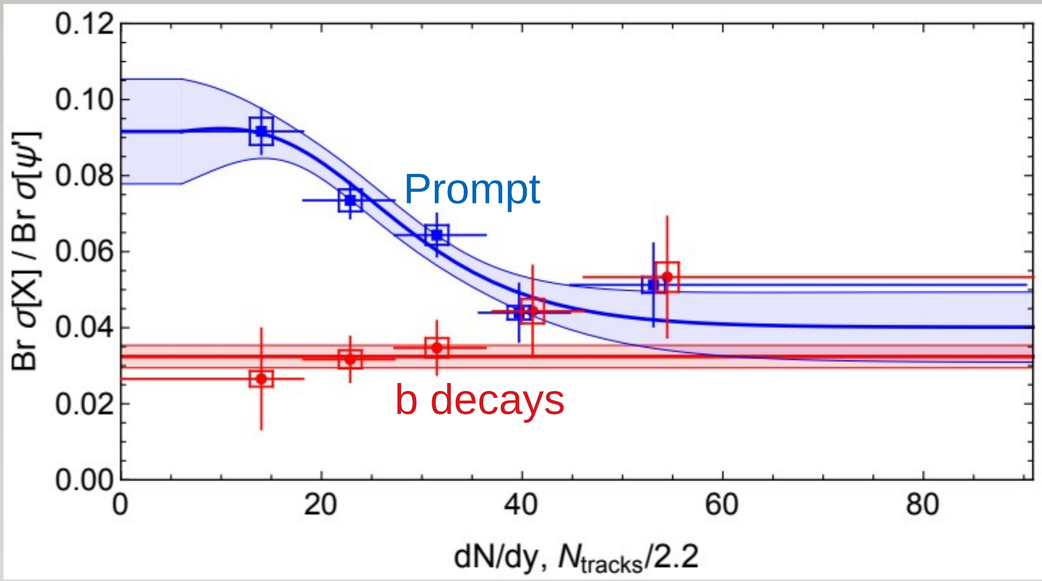
and fractions of Q out of reach of comovers

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

more details in Braaten et al., arXiv:2021.13499

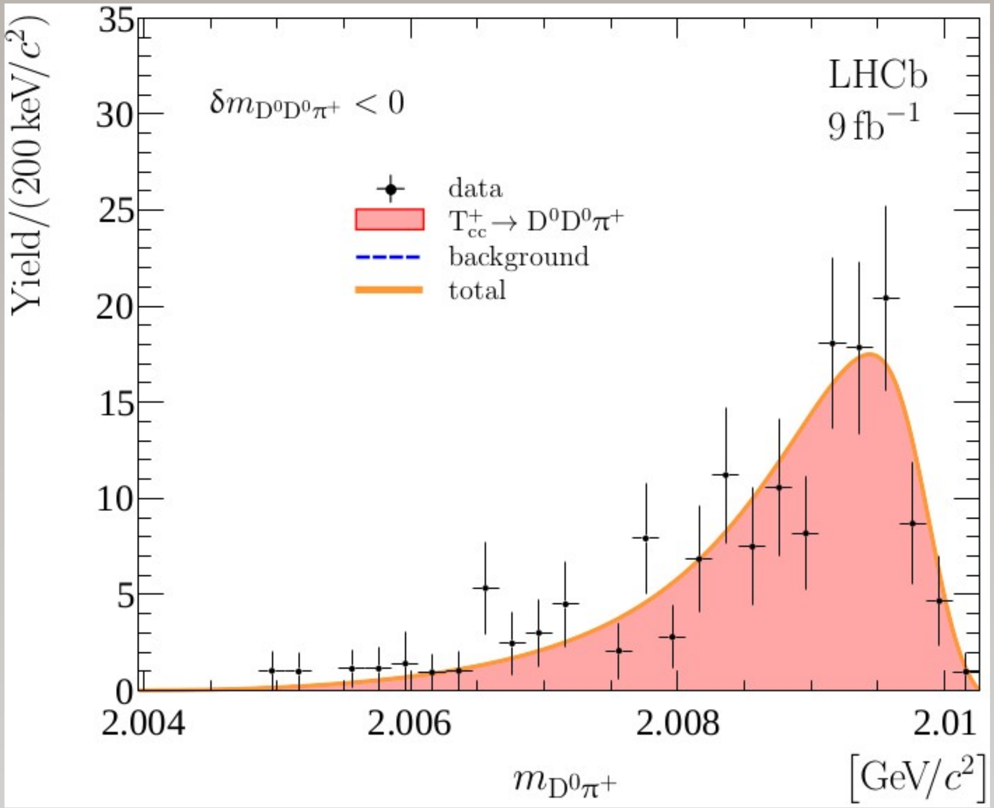
PRL 126 (2021) 092001

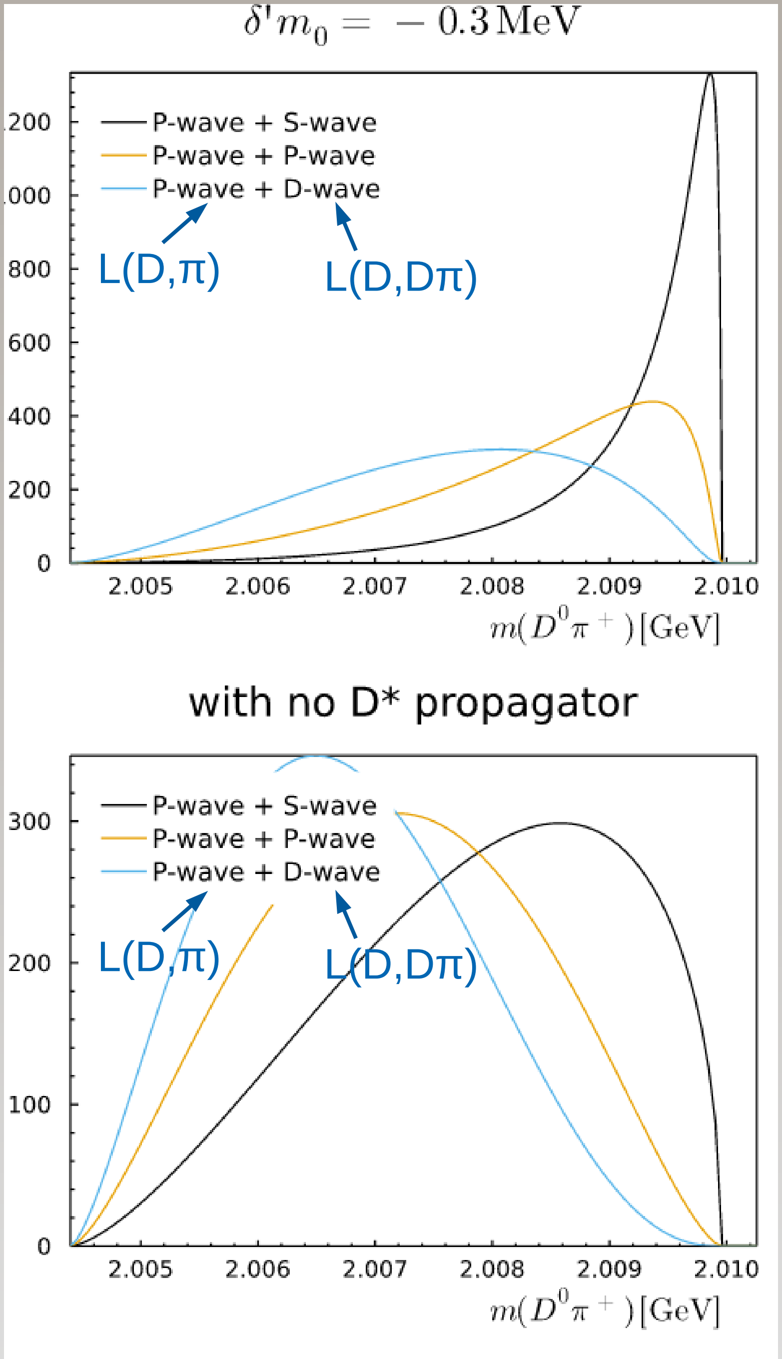




Offshell D^{*+}

- 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}