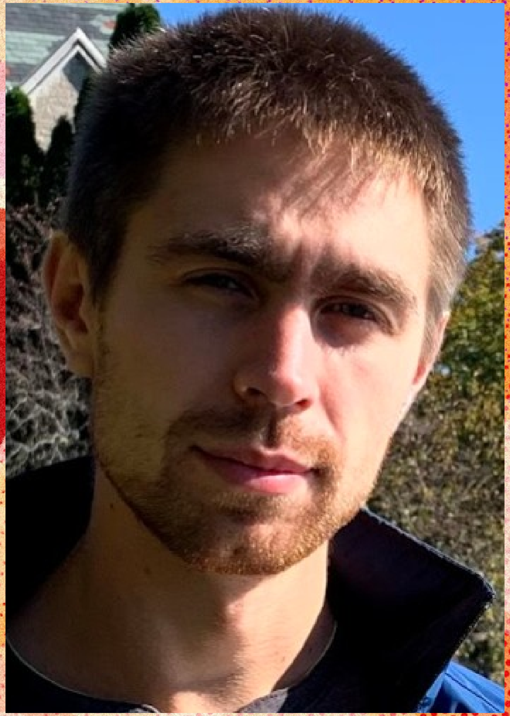
Doubly charmed tetraquark at LHCb and future prospects



Ivan Polyakov

LPHE EPFL Seminar,
29 November 2021

Picture:S. Velasco,
Quanta Magazine

Outlook

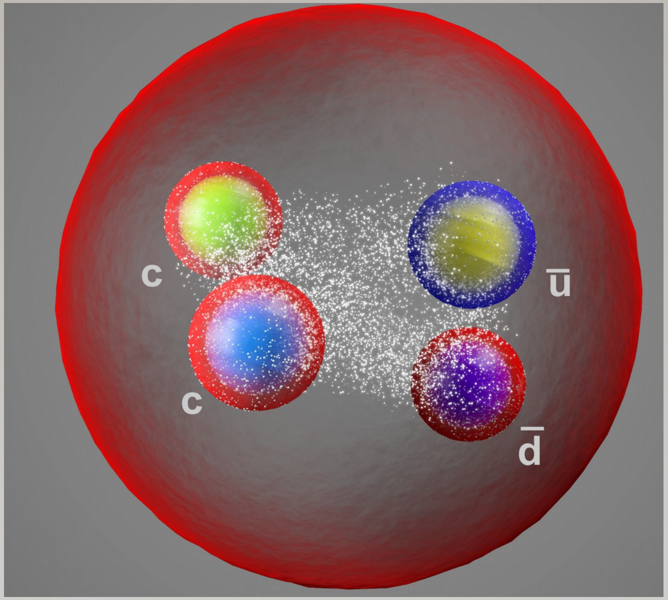
- Introduction -
  QCD, hadron spectroscopy theory and predictions for $QQ\overline{qq}'$

- The T_{cc}^{+} tetraquark:
  - LHCb detector & Selection
  - Observation of the signal
  - Study with unitarized model
  - Interpretations
  - Production properties

Measurements

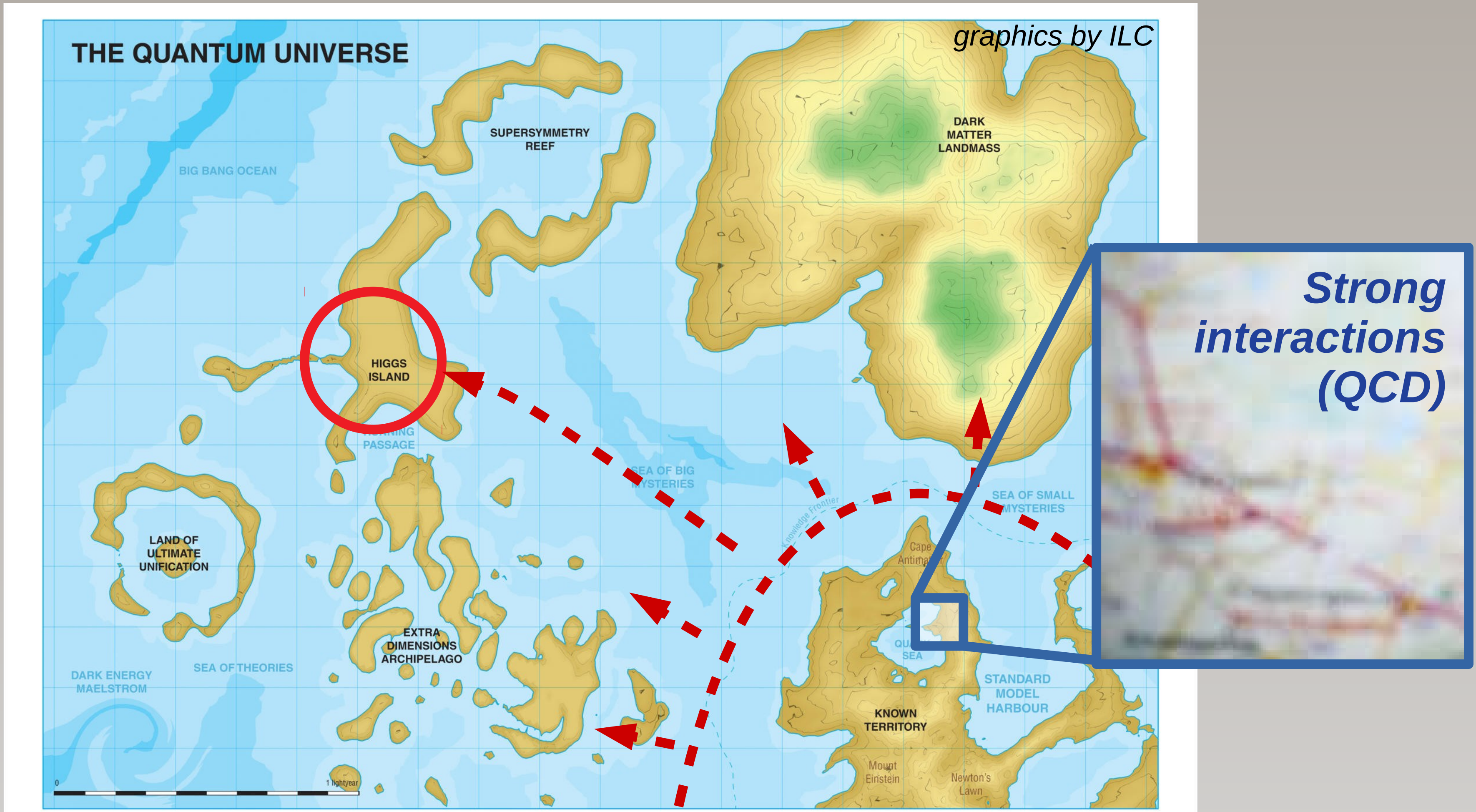
arXiv:2109.01038

arXiv:2109.01056



- Discussion
  - Reflection on the results
  - Open questions
  - Future possibilities

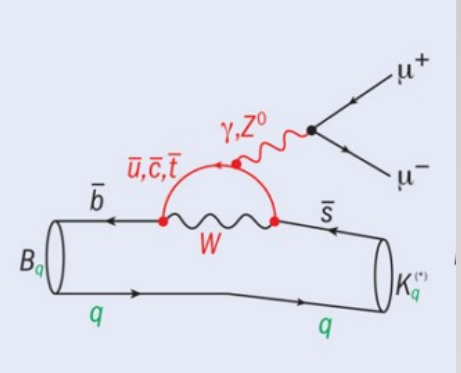
High Energy Physics frontiers

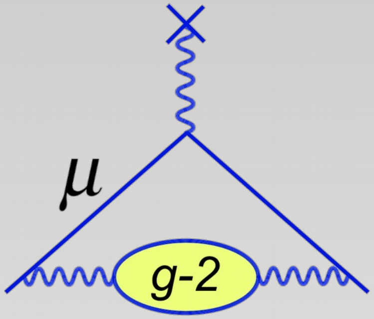


graphics by ILC

Strong interactions (QCD)

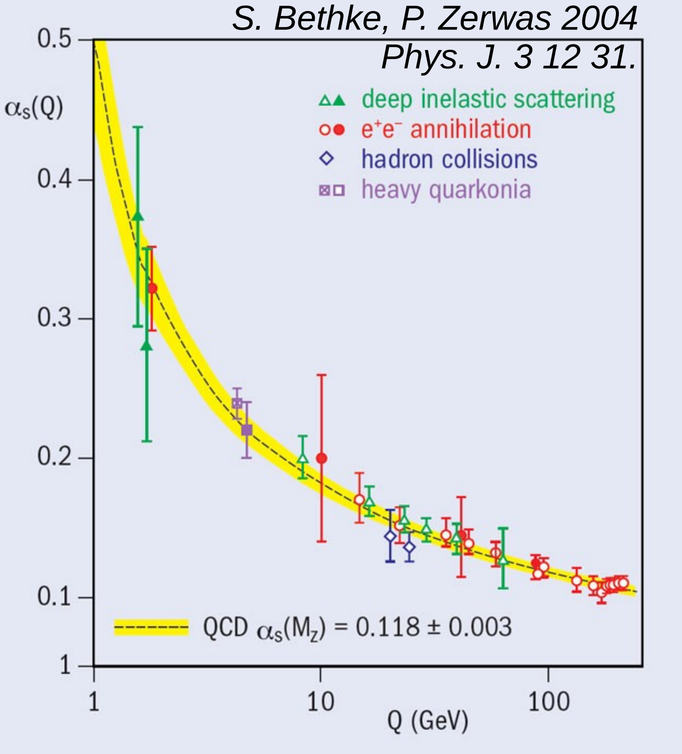
- The known QCD is not that well known
- And it’s understanding also limits the hunt for non-direct signs of NP: B-decays, g-2 of μ, ...



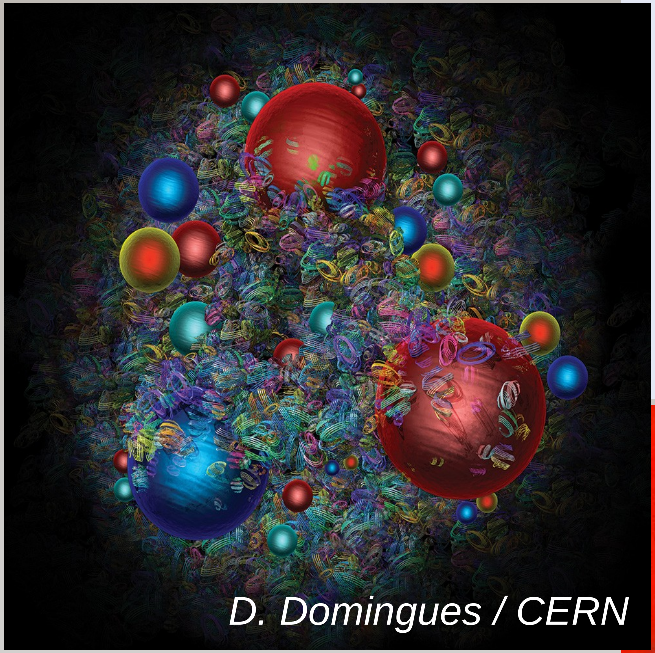


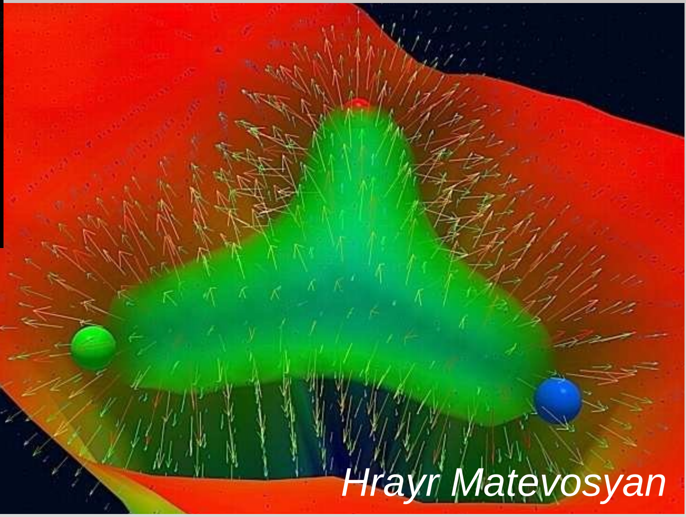
QCD vs. Hadron Spectorscopy

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


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

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


D. Domingues / CERN


Hrayr Matevosyan

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

  mini-review in the following
  (oversimplified & incomplete)

Theory approaches, 1

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

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

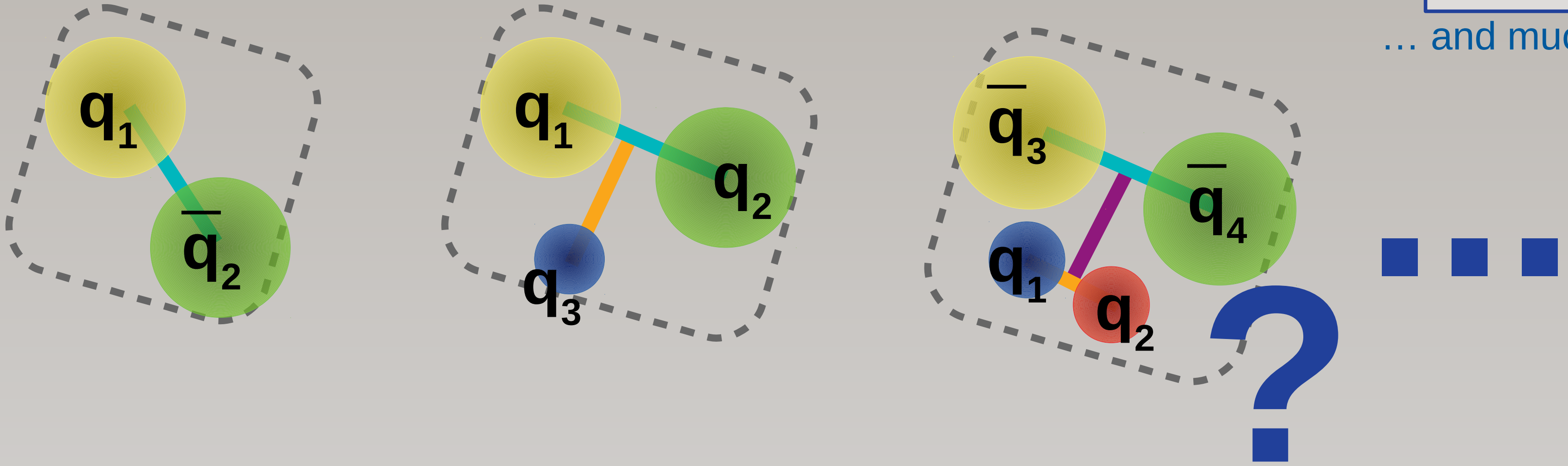
see in predictions for T_{cc}^+:

Eichten, Quigg, 2017

Braaten, He, Mohapatra, 2020

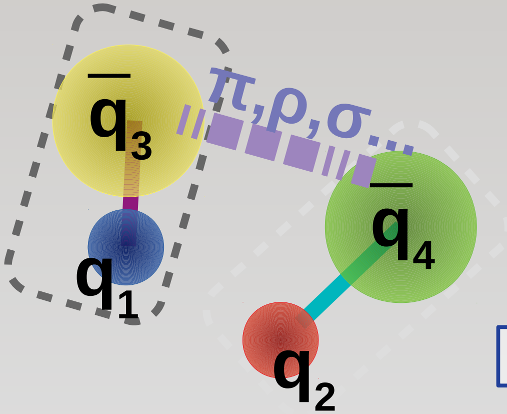
Karliner, Rosner, 2017

… and much more ...



- Molecula objects (for exotics)

    corresponding form-fators
    and cut-offs not well controlled



see in predictions for T_{cc}^+:

Pepin, Stancu, Genovese, Richard, 1996

Li, Sun, Liu, Zhu, 2012

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

… and much more ...

Theory approaches, 2

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

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

color of quarks

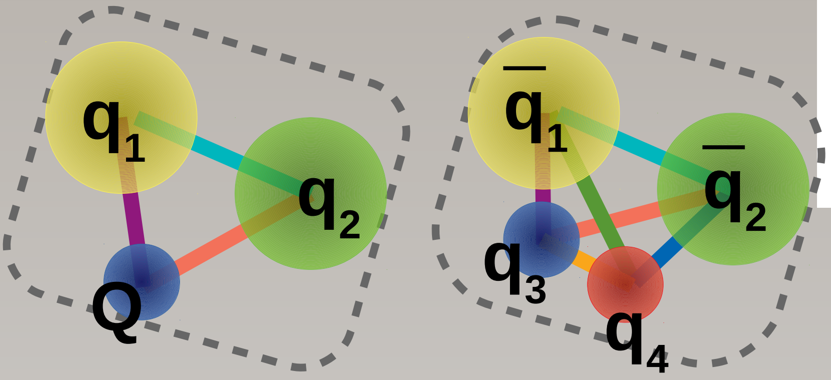
$$V_{ij}^B=-\frac{\lambda_i^C}{2}\cdot\frac{\lambda_j^C}{2}\left(U_0+\frac{\alpha}{r_{ij}}+\beta r_{ij}+\alpha\frac{\hbar^2}{m_i m_j c^2}\frac{e^{-r_{ij}/r_0}}{r_0^2 r_{ij}}\sigma_i\cdot\sigma_j\right),$$

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

one-gluon exchange (“Couloumb”)

confinement

contact spin-spin interaction



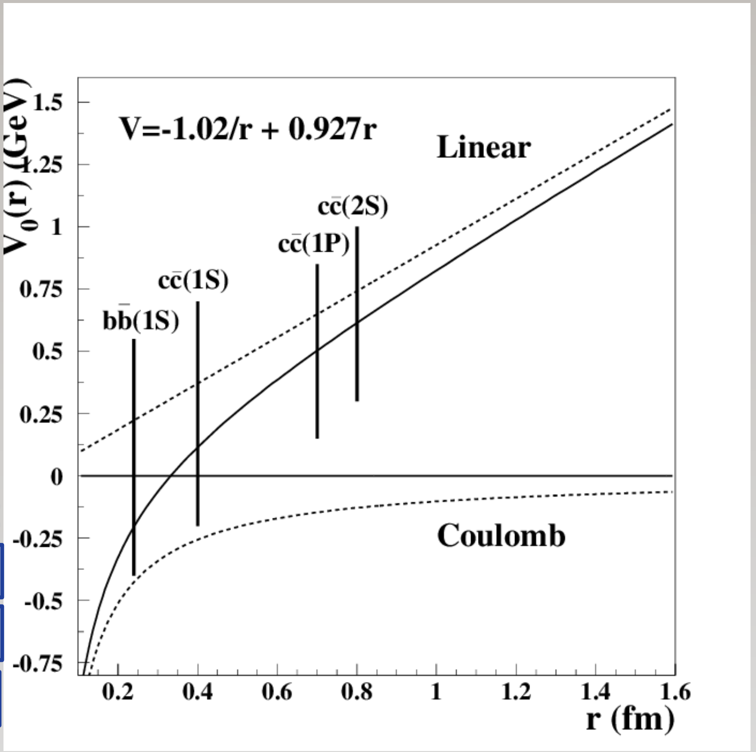
can also take boson exchange (molecular binding) into account

Semay, SIlvestre-Brac, 1994

Janc, Rosina, 2003

… and more ...

- Heavy quark allows to probe shorter range where OGE dominates



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

predictions for T_{cc}^+:

HAL QCD Collaboration, 2014

Hadron Spectrum Collaboration, 2017

Junnarkar, Mathur, Padmanath, 2018

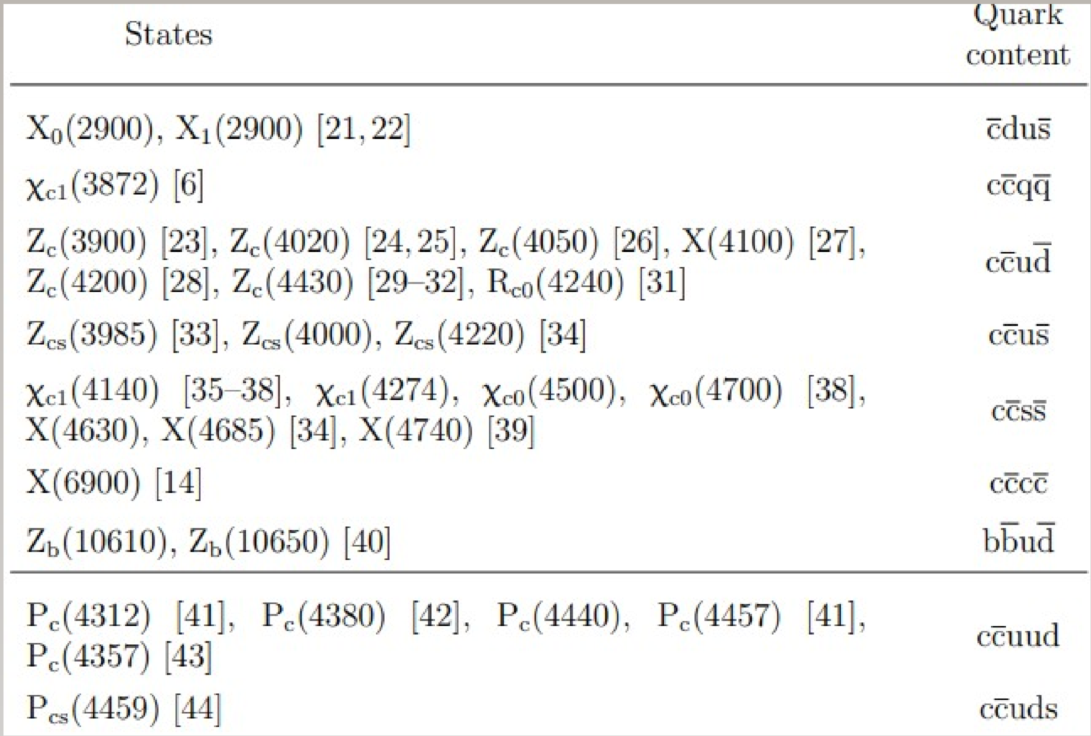
- QCD sum rules *typically give >100 MeV uncertainty*

[see Refs. in predictions for T_{cc}^+]

Exotic hadrons

Understanding is limited by the quark configurations to consider

- Conventional hadrons: $q_1\bar{q}_2$ and $q_1q_2q_3$
- Exotic hadrons: $c\bar{c}q_1\bar{q}_2$ and $c\bar{c}q_1q_2q_3$
  ~30 tetra/pentaquarks candidates discovered since observation of $\chi_{c1}(3872)$ by Belle in 2003
  - *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]	$c\bar{c}uds$

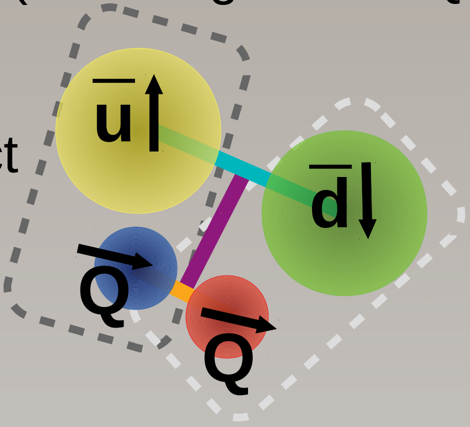
- $QQ\bar{q}'\bar{q}''$ are prime candidates to be bound and therefore long-lived
  - first estimates *(based on $V_{qq'}(r)\sim r^{0.1}$ approximation)*
    stated that should happen for $m_Q/m_q>6$-8 *(compare to $m_b/m_u\sim15$, $m_c/m_u\sim5$-6)*

Adler, Richard, Taxil, 1982

Ballot, Richard, 1983

Predictions for cc$\overline{\text{ud}}$ mass

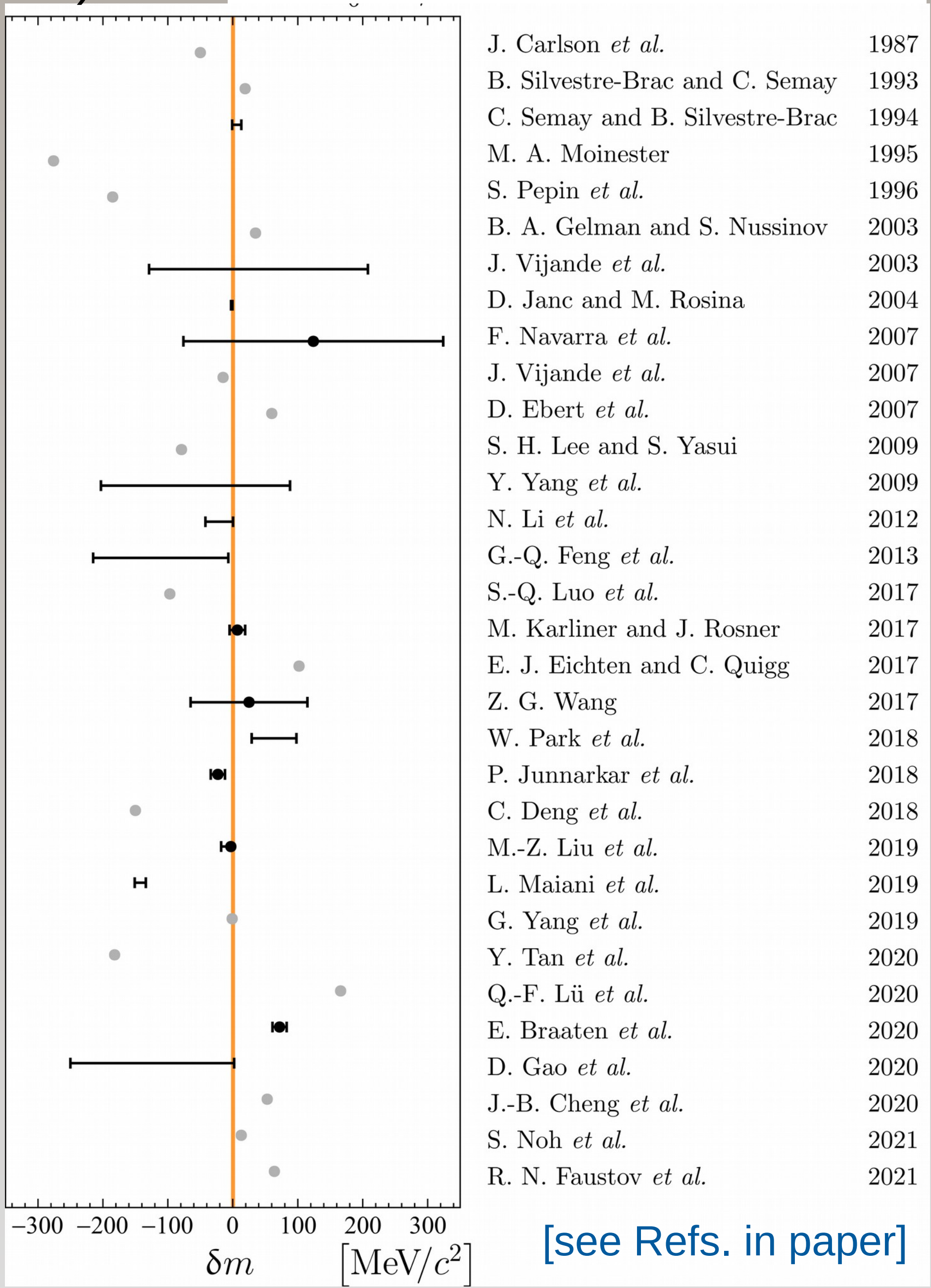
- More recent calculations (including Lattice QCD) all agree that it should be true for [bb][$\overline{\text{ud}}$] with QQ forming compact color anti-triplet and resulting binding of ~150MeV



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

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

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



[see Refs. in paper]

”Observation of an exotic narrow doubly charmed tetraquark”

arXiv:2109.01038

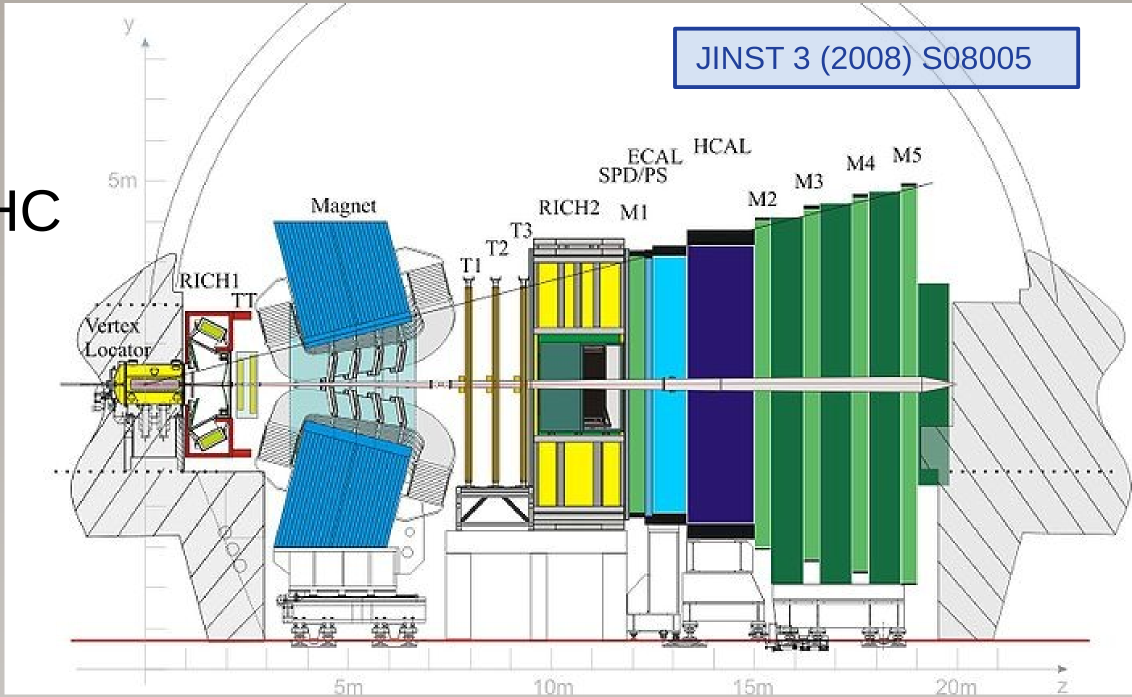
&

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

arXiv:2109.01056

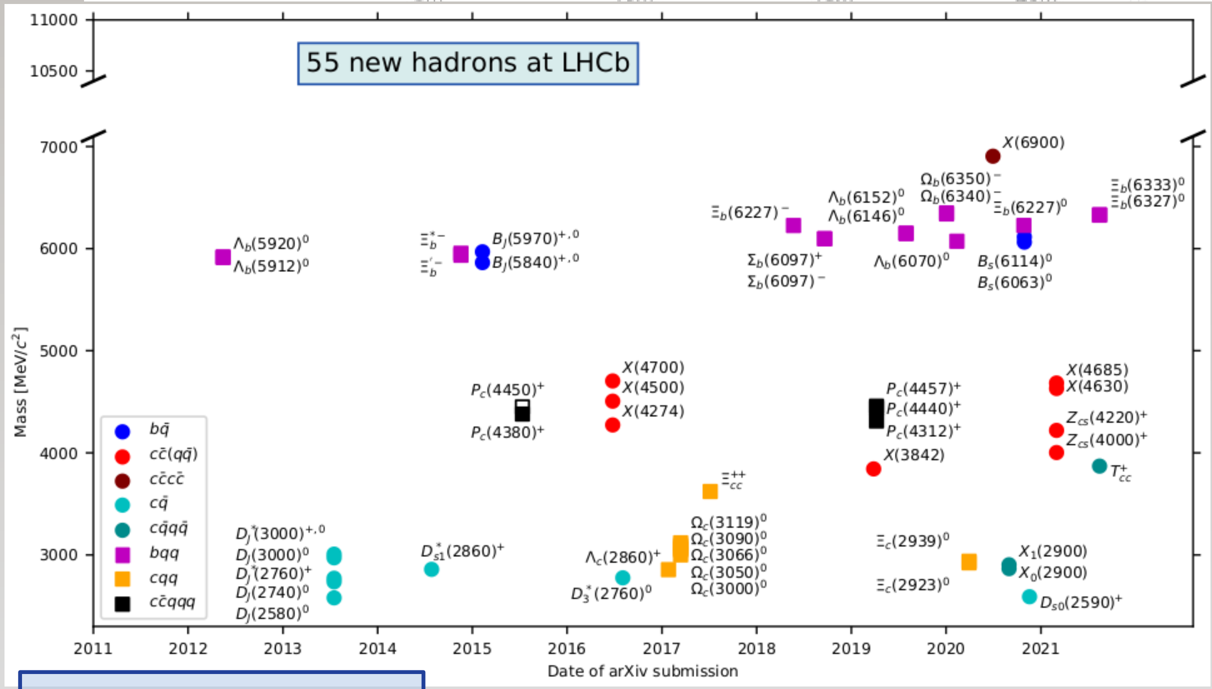
The LHCb detector

- 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

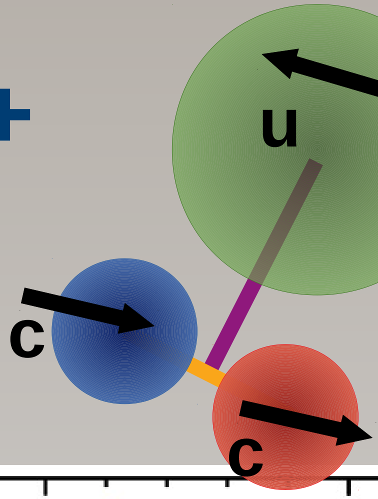


LHCb-FIGURE-2021-001

Previous hadrons with two c-quarks

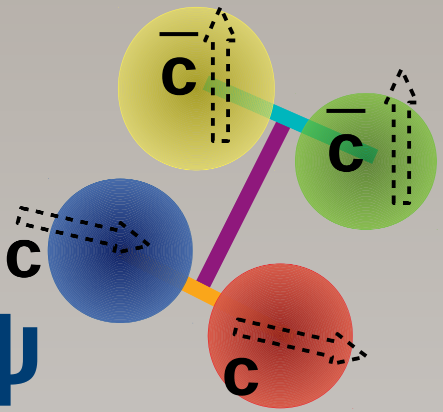
- The observations of Ξ_{cc}^{++} [ccu] and $X[cc\bar{c}\bar{c}] \rightarrow J/\psi J/\psi$ indicate that if the $[cc\bar{u}\bar{d}]$ exists it should be accessible at LHCb in $DD^{(*)}$ final states

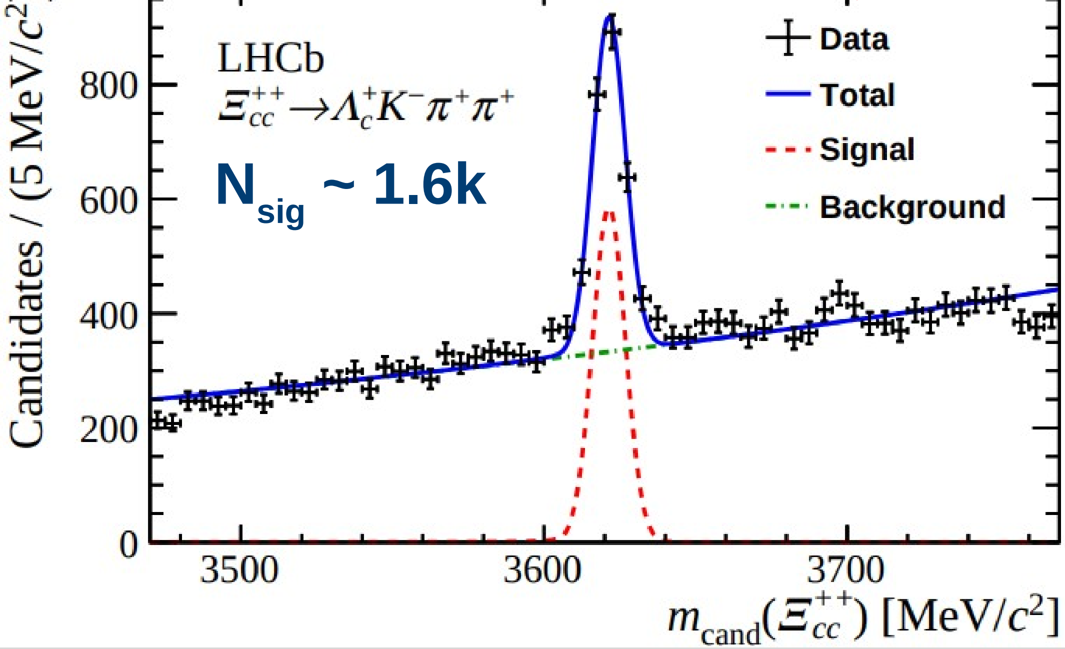
Ξ_{cc}^{++}



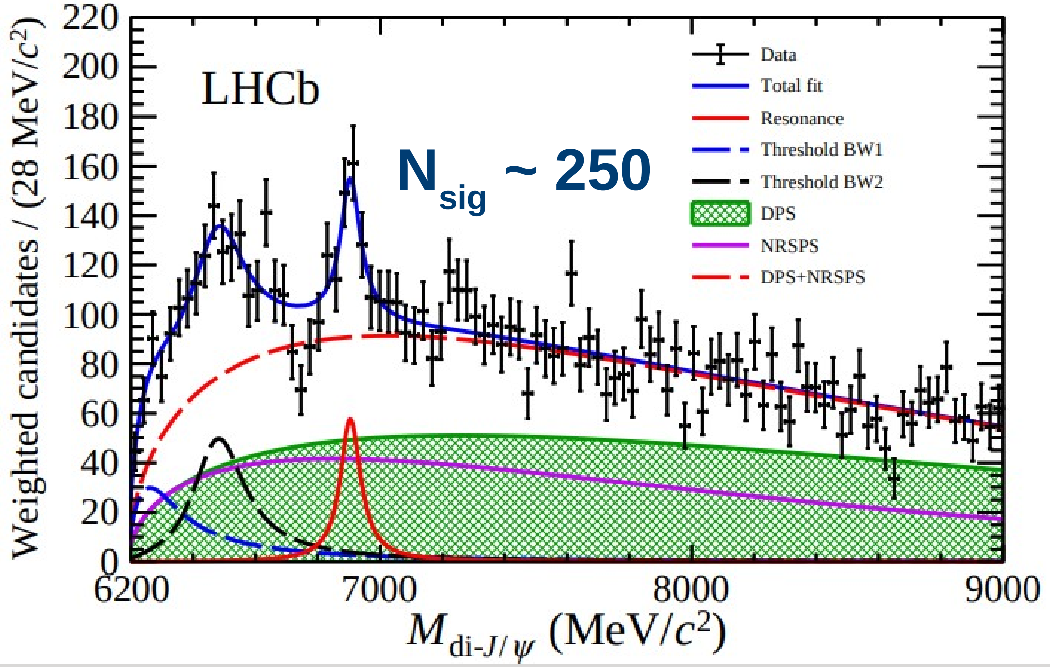
$X_{cc\bar{c}\bar{c}}$

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





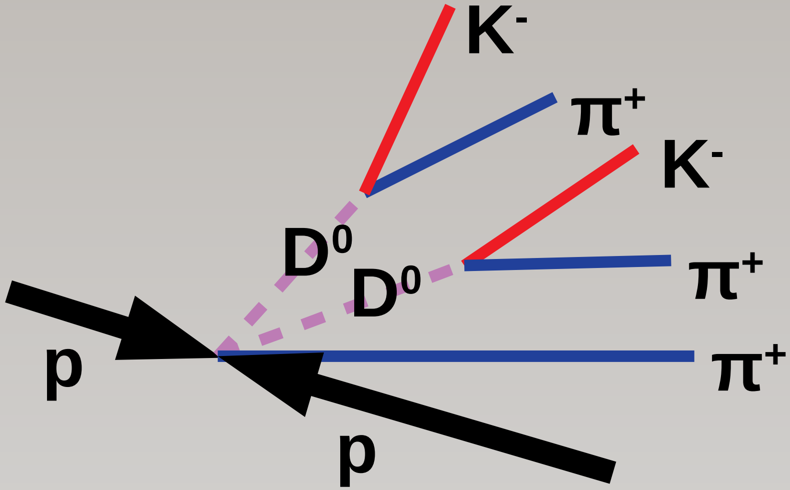
JHEP 02 (2020) 049



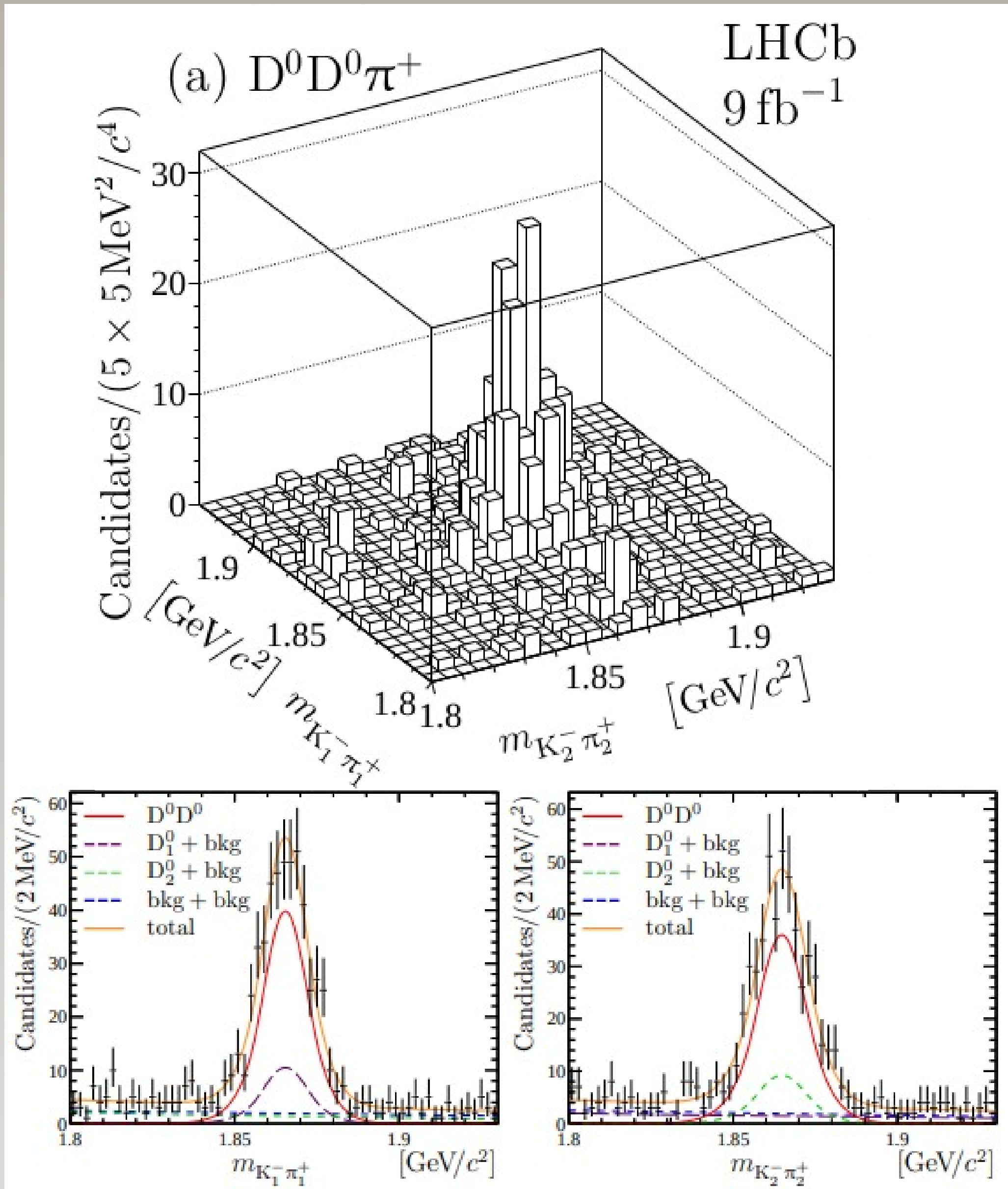
Sci. Bul. 65 (2020) 1983

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

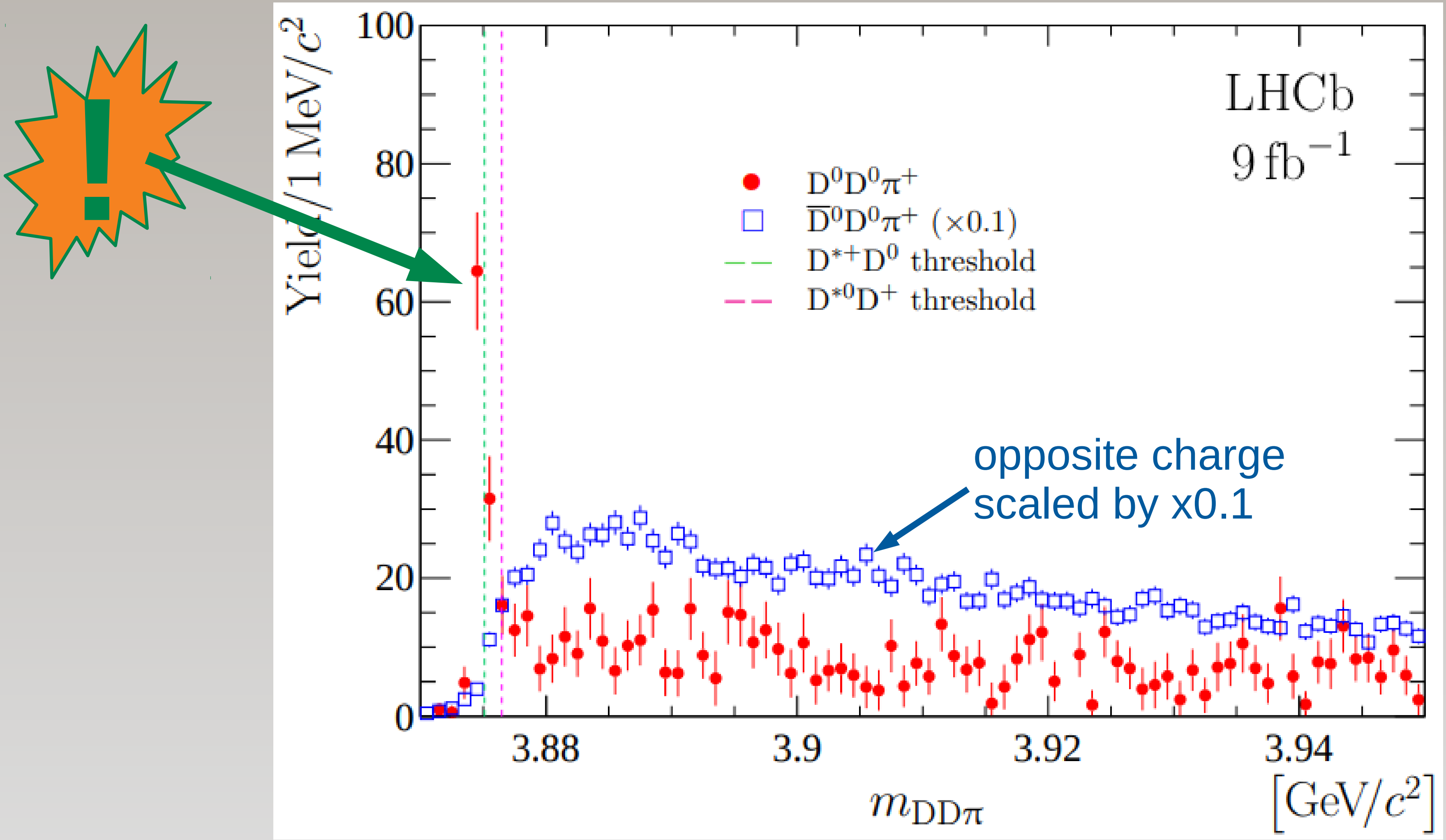


- Subtract fake-D background using 2D fit to $(m_{K\pi}, m_{K\pi})$



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

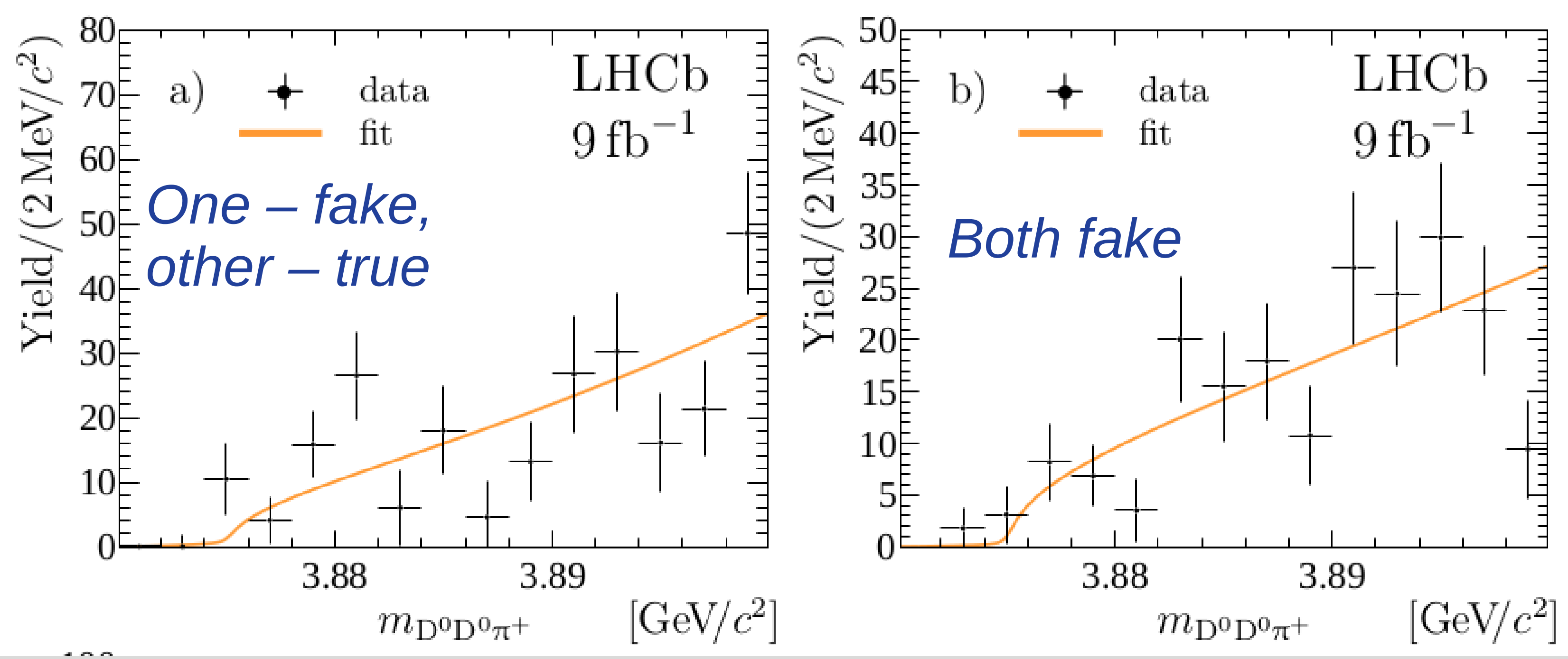


opposite charge scaled by x0.1

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

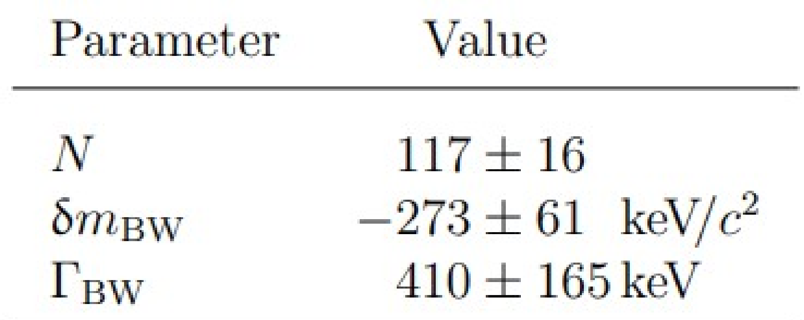
Fit with Breit-Wigner function

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

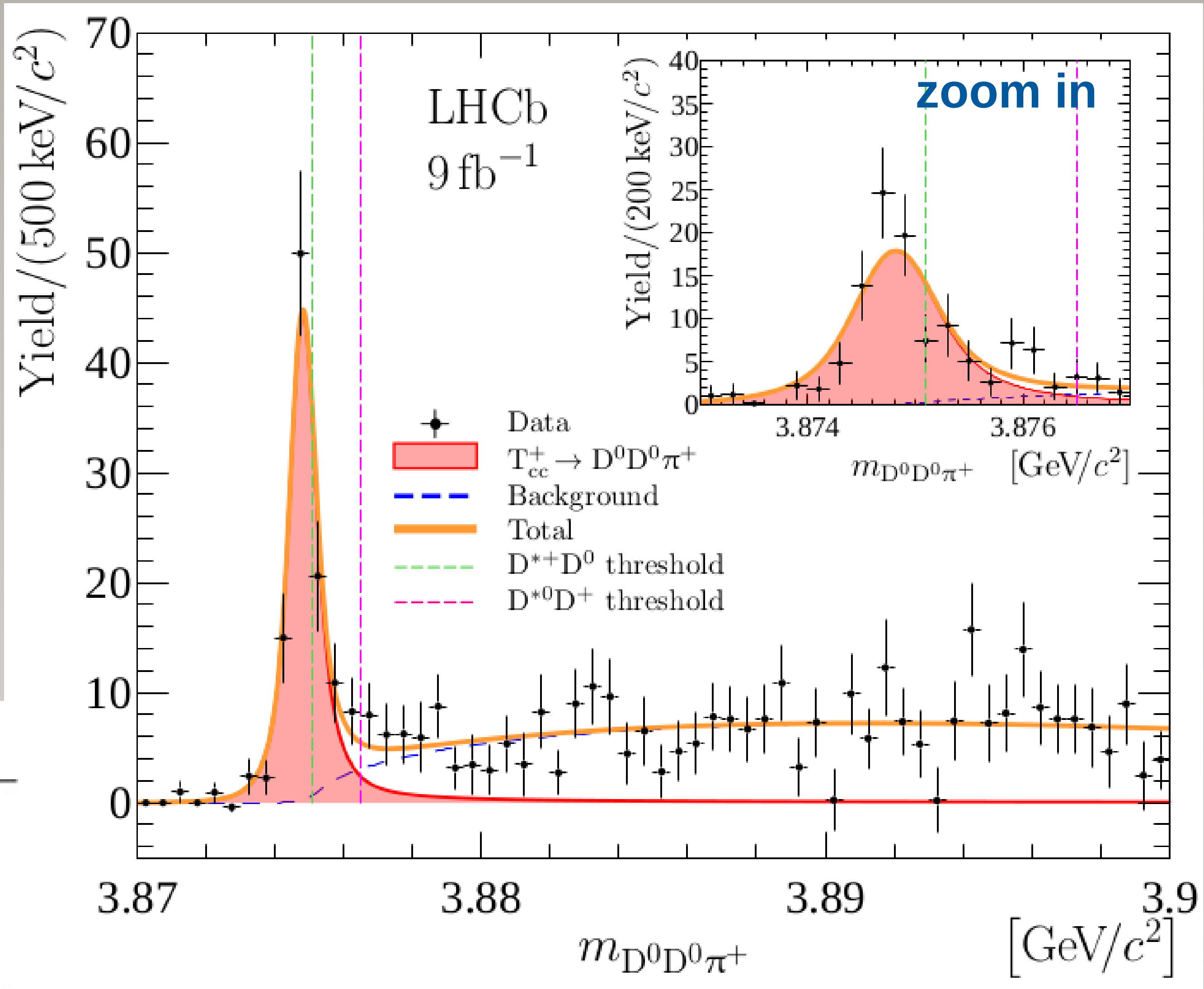
  both convolved with resolution of ~400keV

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

- Results:



Parameter	Value
N	117 ± 16
δm_{BW}	$-273 \pm 61 \ \mathrm{keV}/c^2$
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)

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

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

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

and combine them to together

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

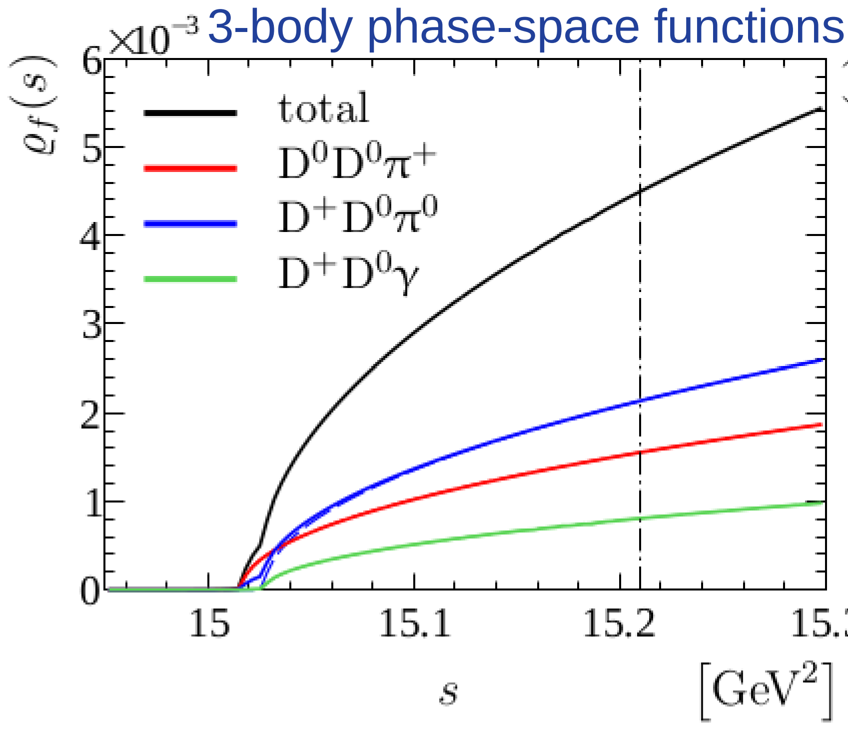
$$\mathfrak{F}(s) = \frac{1}{m^{2}_{\mathrm{D}^{*}} - s - im_{\mathrm{D}^{*}}\Gamma_{\mathrm{D}^{*}}}$$

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

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

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


3-body phase-space functions

- 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)

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

Real part for analyticity (Kramers-Kronig relations)

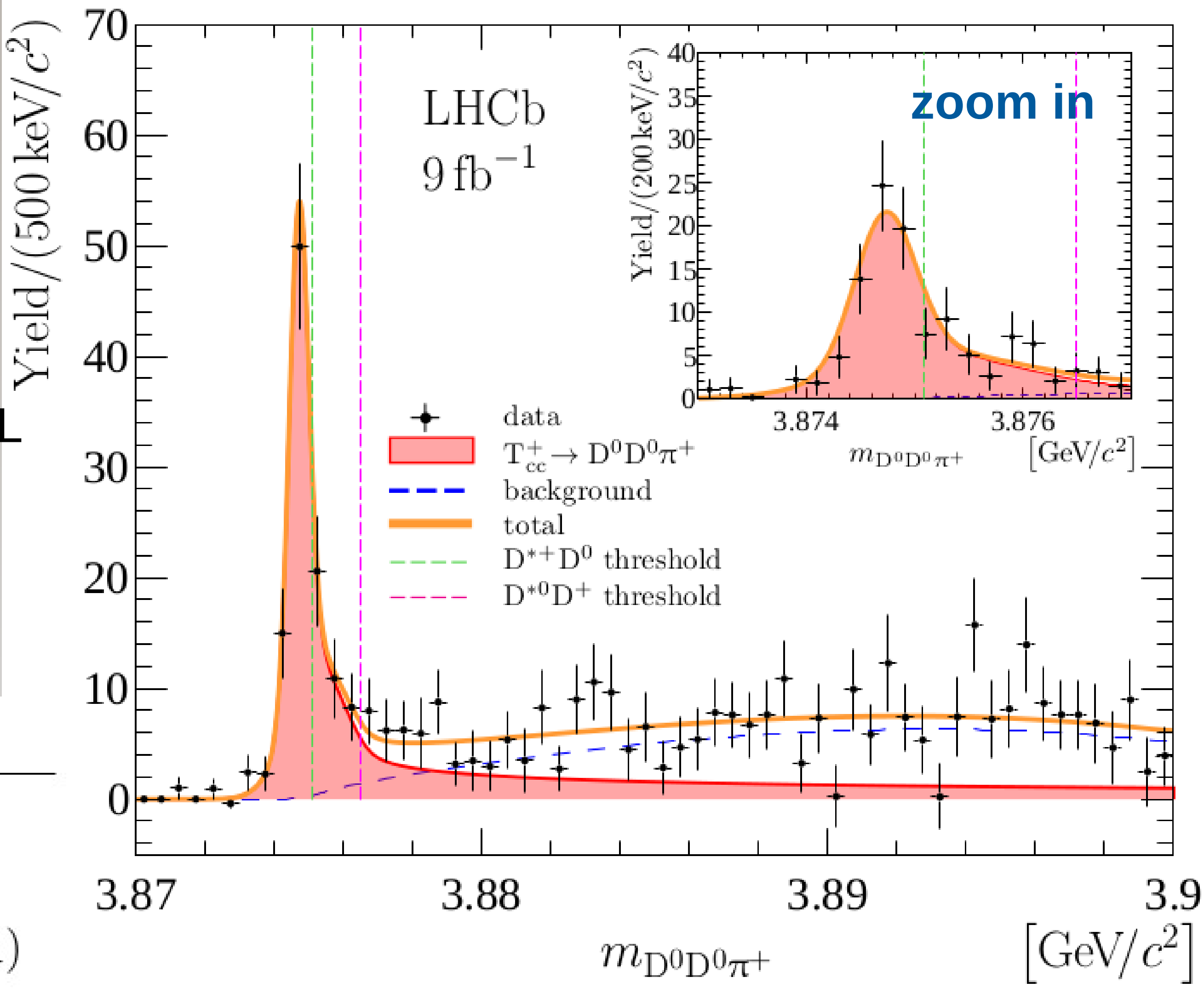
$$\begin{aligned}\Re\,\Sigma(s)\big|_{\Im s=0^+} &= \xi(s) - \xi(m_{\mathrm{U}}^2), \\ \xi(s) &= \frac{s}{2\pi}\,\mathrm{p.v.}\!\int_{s^*_{\mathrm{th}}}^{+\infty}\frac{\varrho_{\mathrm{tot}}(s')}{s'(s'-s)}\,ds'\end{aligned}$$

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)

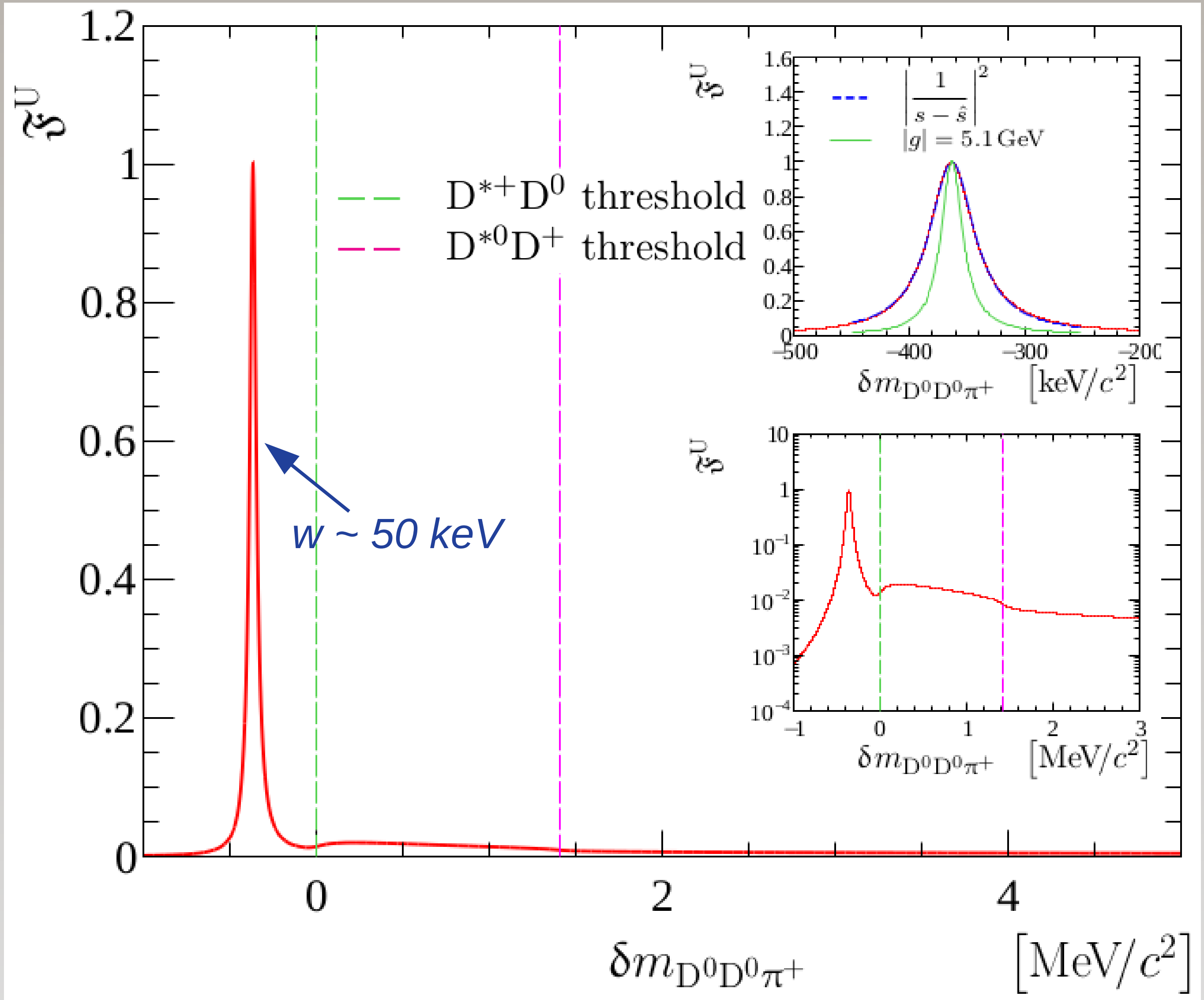


zoom in

Mass shape in unitarized model

- Fit result (before smearing with resolution)

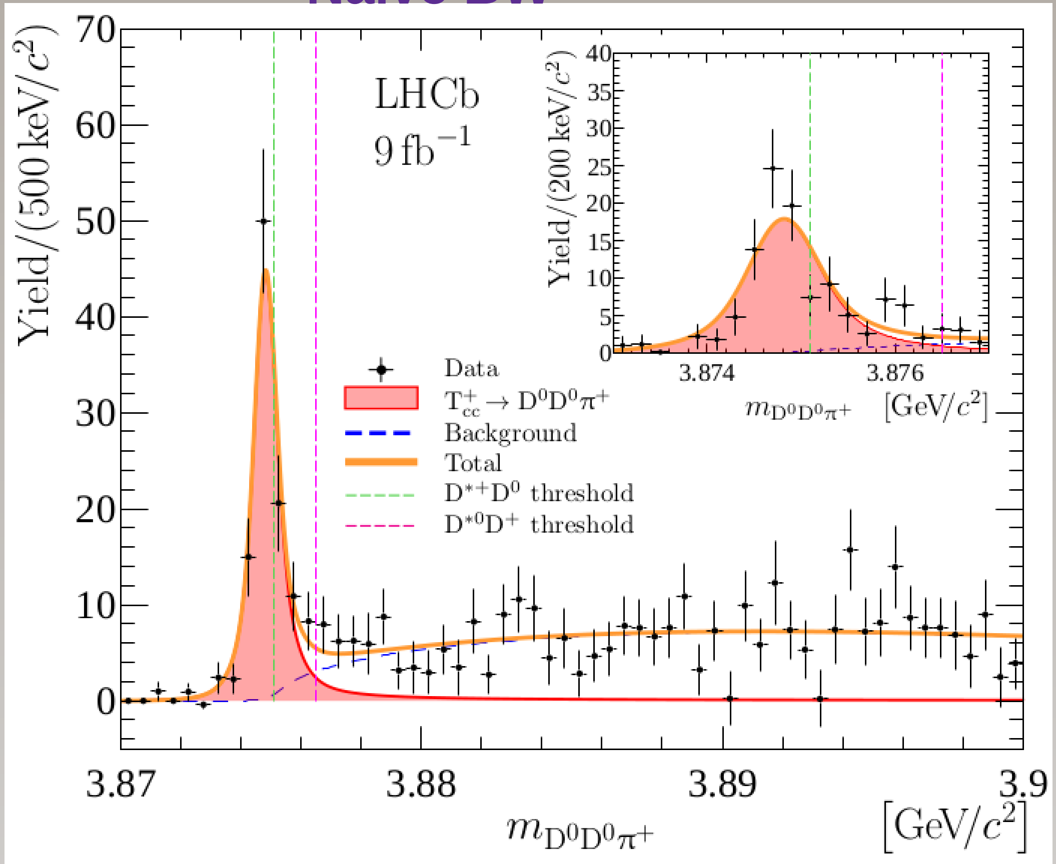
- Close to Breit-Wigner in proximity to peak maximum
- Large tail above DD* thresholds



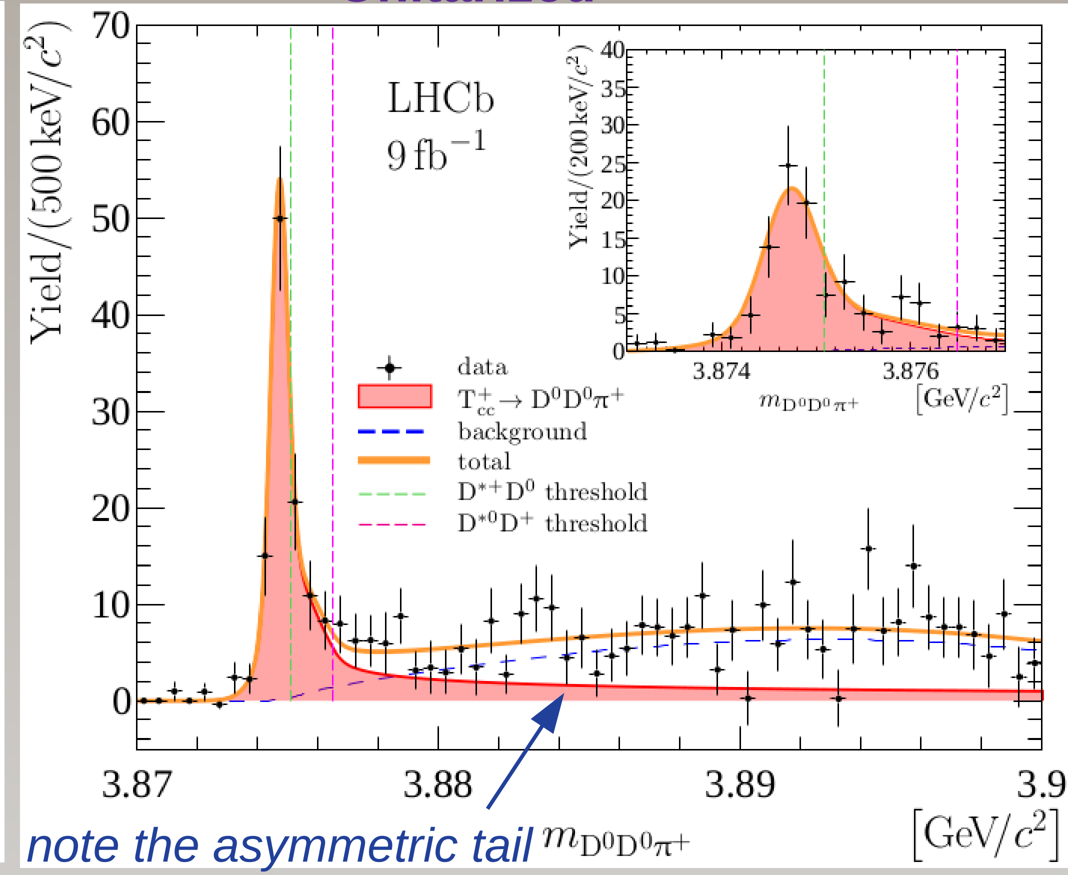
w ~ 50 keV

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

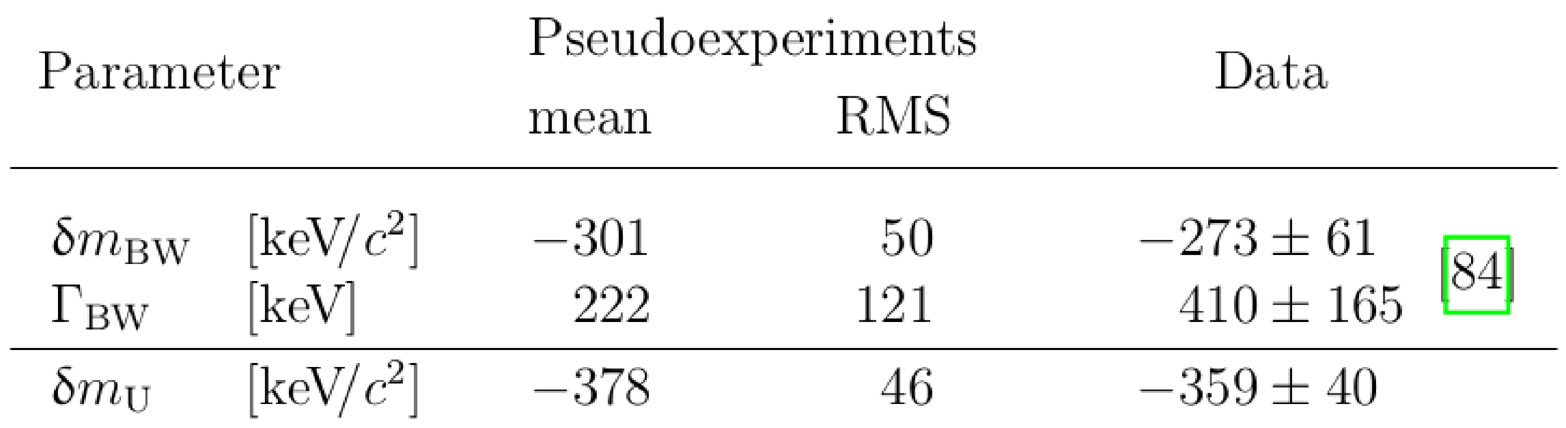
- Both consistent with data

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		
$\delta m_{\rm BW}$	[keV/c^2]	−301	50	−273 ± 61	[84]
$\Gamma_{\rm BW}$	[keV]	222	121	410 ± 165	
$\delta m_{\rm U}$	[keV/c^2]	−378	46	−359 ± 40	

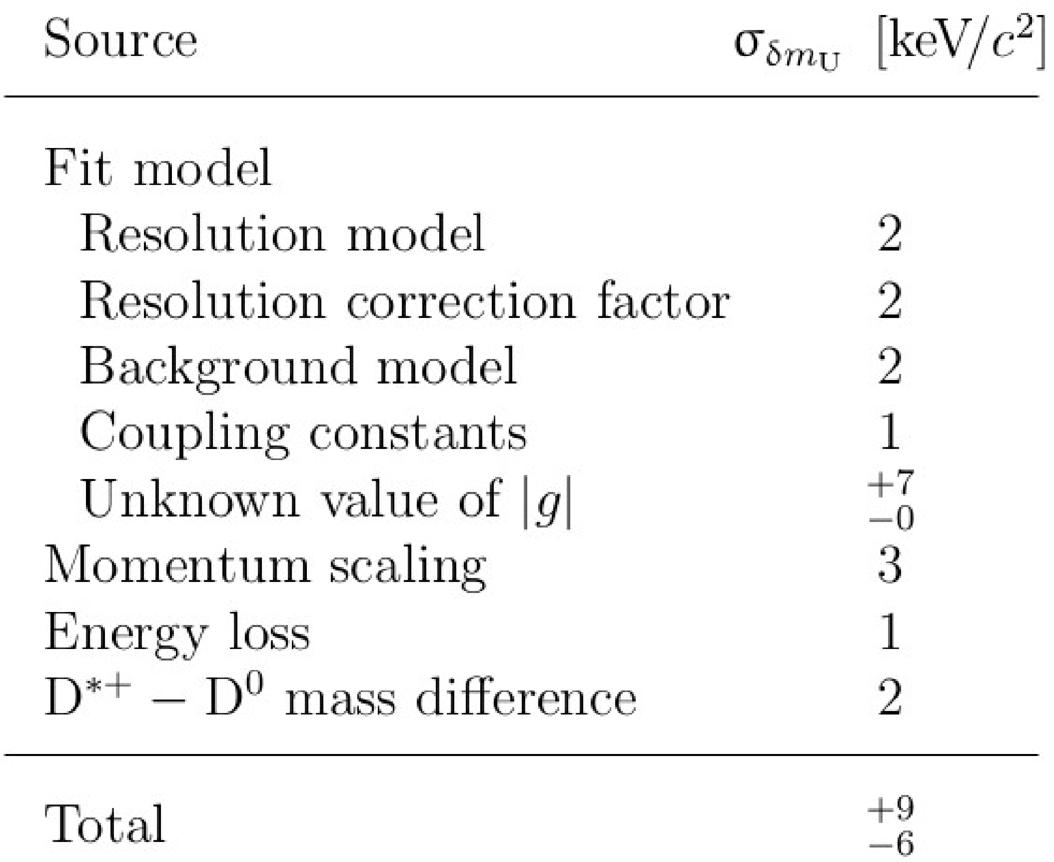
Systematic uncertainties (unitarized model)

- 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($D^* \rightarrow D\pi/\gamma$) 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	$^{+9}_{-6}$

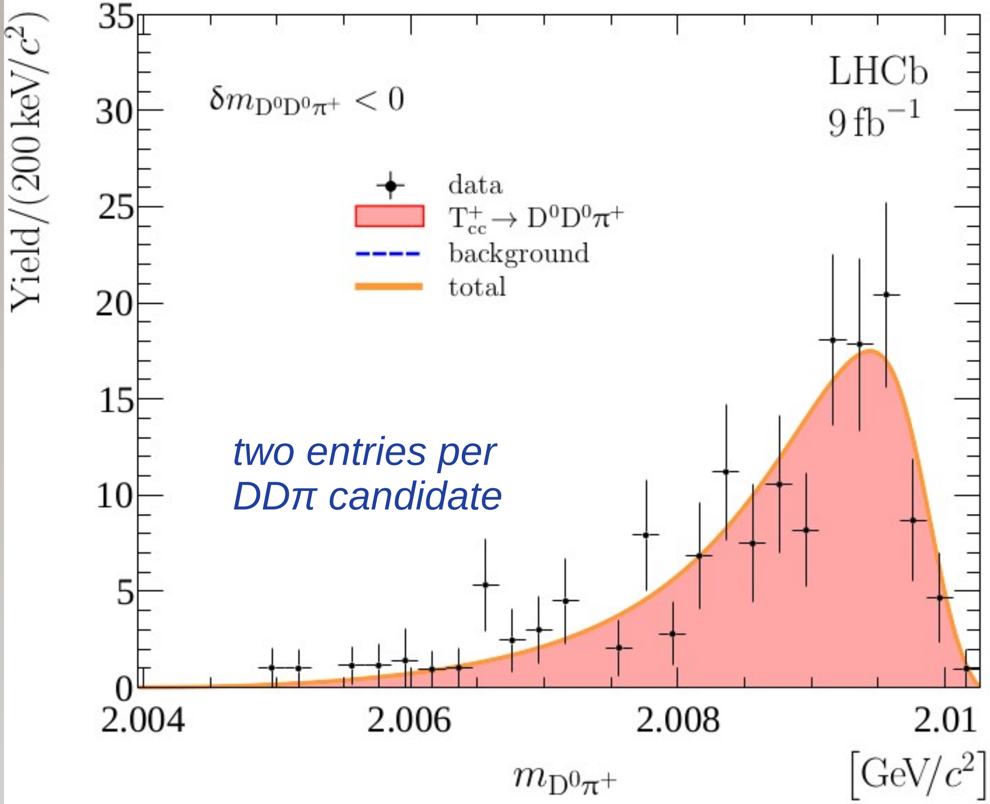
- Fit model systematics considered for the lower limit of |g| changing it to

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

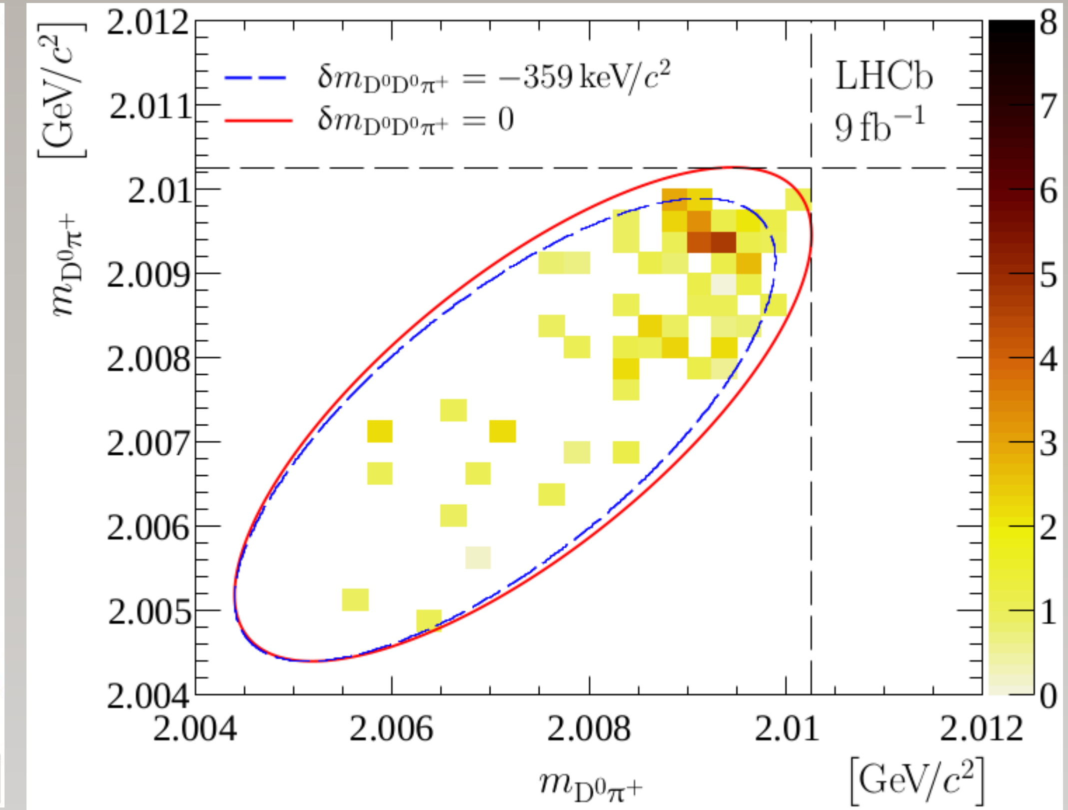
Additional Studies

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

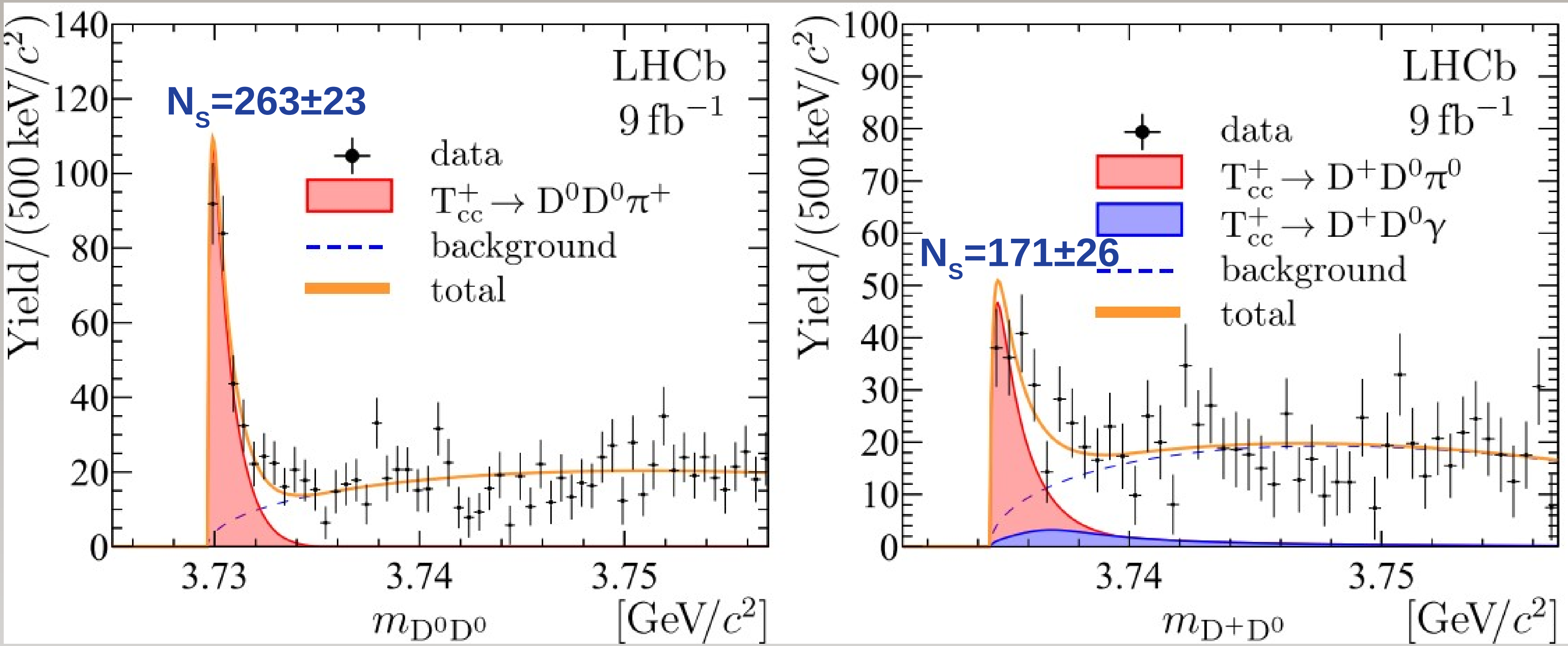


Perfect agreement supports the assumptions:

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

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

- Obtain D^0D^0 mass shape from $T_{cc}\rightarrow D^0D^{*+}(\rightarrow D^0\pi^+)$ and D^0D^+ mass shape from $T_{cc}\rightarrow D^0D^{*+}(\rightarrow D^+\pi^0)$ and $T_{cc}\rightarrow D^+D^{*0}(\rightarrow D^0\pi^0/\gamma)$ 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

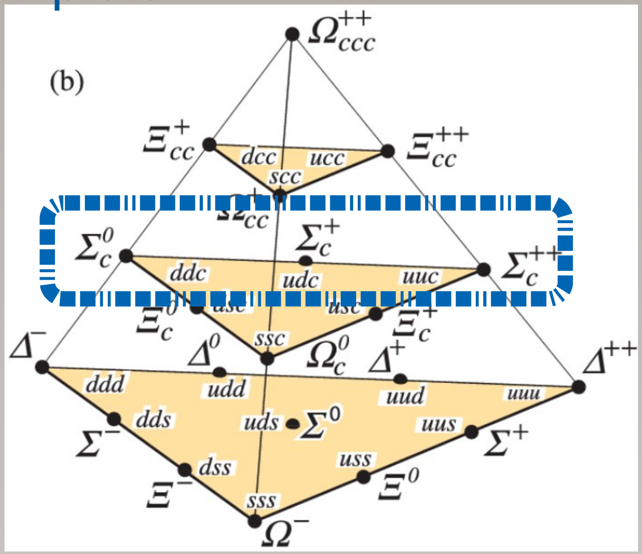
T_{cc} isospin

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

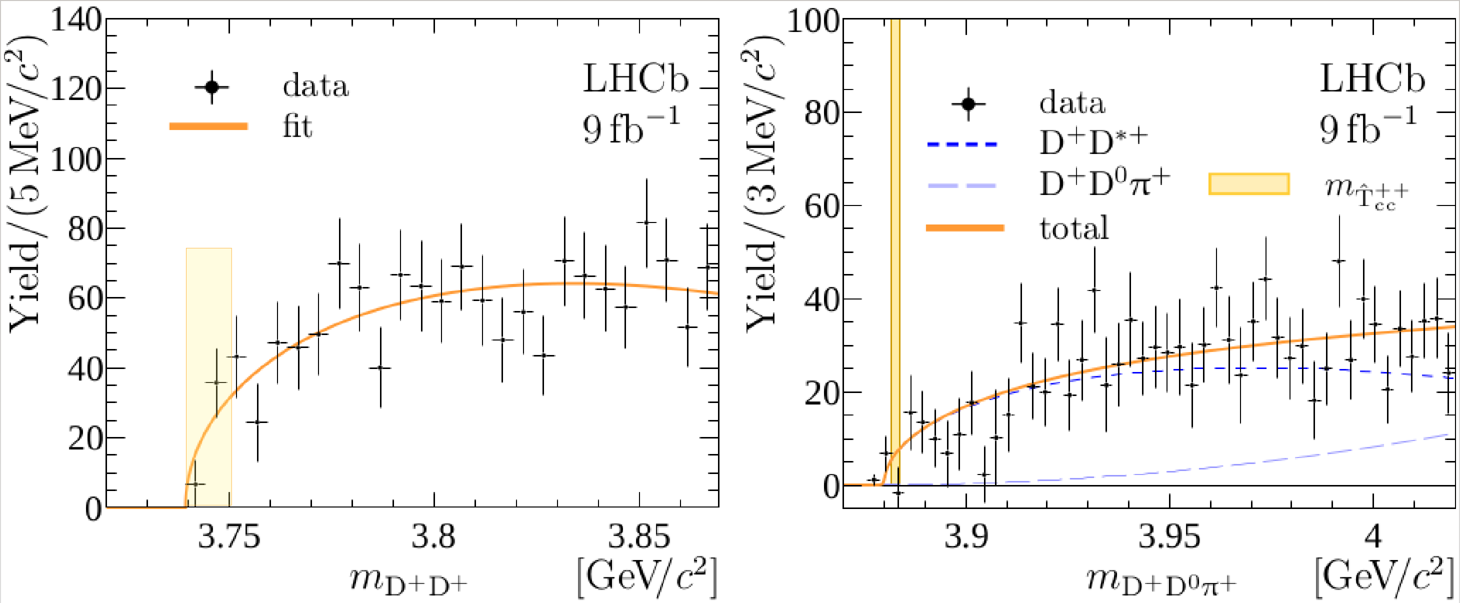
$$
\begin{aligned}
m_{\hat{T}^0_{cc}} &= m_{\hat{T}_{cc}} + m_u + m_u - a'\, q_{\bar{u}} q_{\bar{u}} - b'\, q_{cc}\left(q_{\bar{u}} + q_{\bar{u}}\right) \\
m_{\hat{T}^+_{cc}} &= m_{\hat{T}_{cc}} + m_u + m_d - a'\, q_{\bar{u}} q_{\bar{d}} - b'\, q_{cc}\left(q_{\bar{u}} + q_{\bar{d}}\right) \\
m_{\hat{T}^{++}_{cc}}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

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

from Σ_b and Σ_c isotriplets



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



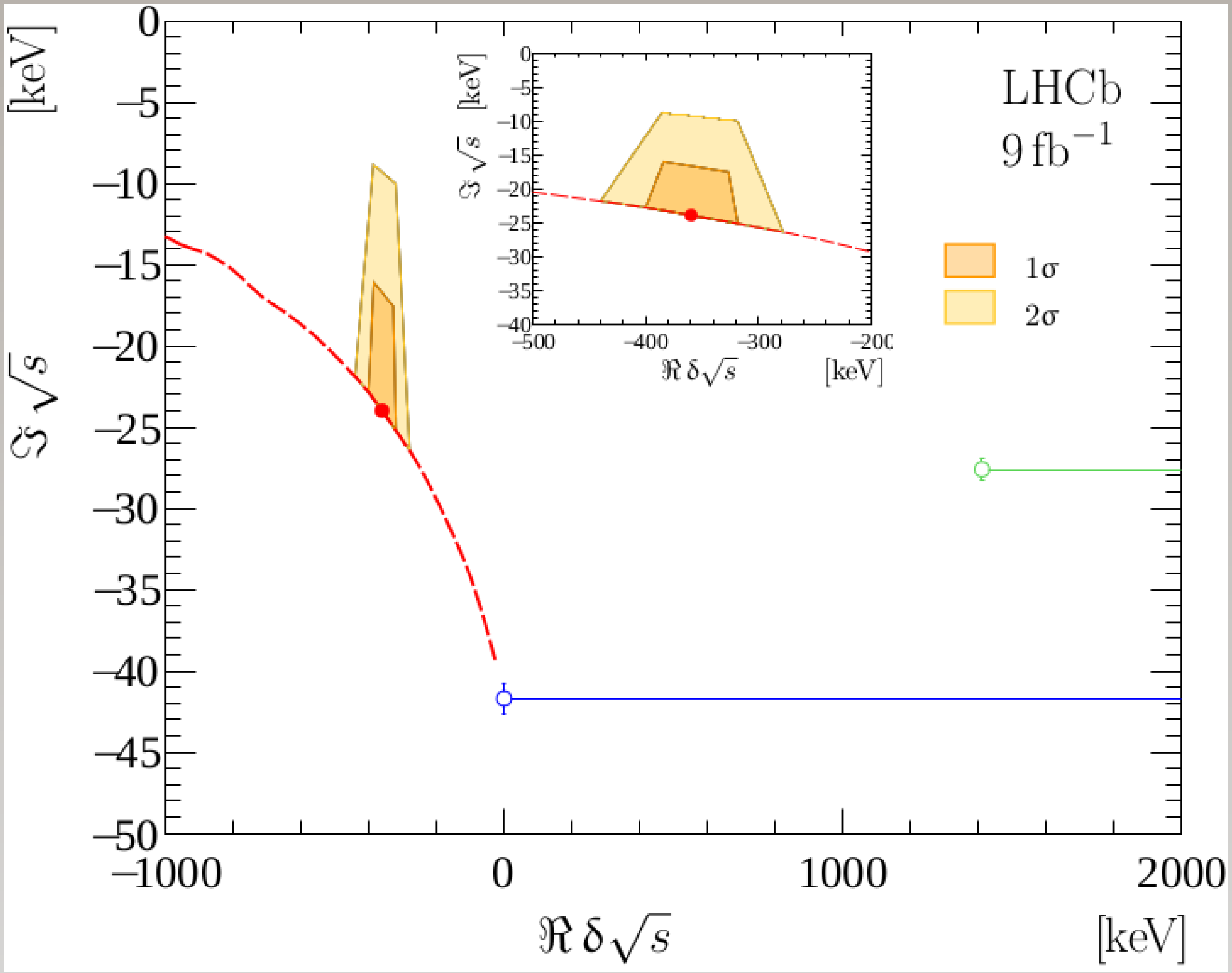
Pole position

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

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

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

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



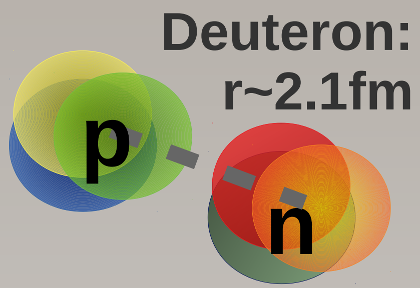
- Result

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

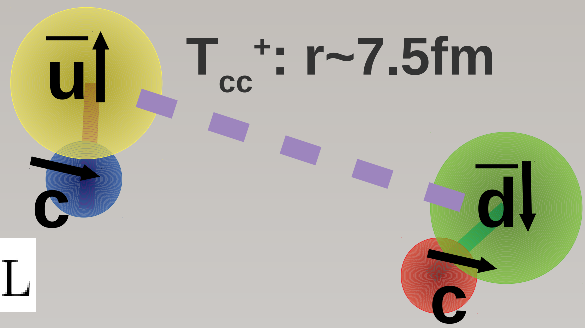
Low-energy expansion

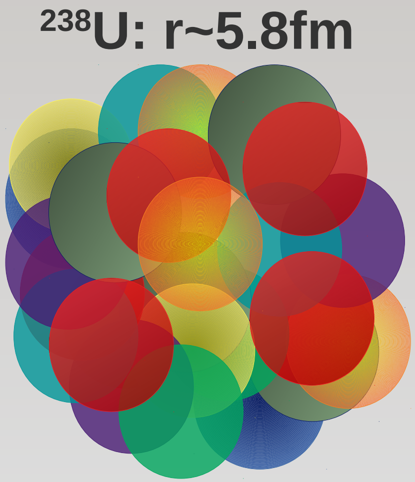
- From expansion near pole can extract low-energy scattering parameters

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



  - 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: $0 \ \leq \ -r < 11.9\,(16.9)\,\mathrm{fm\ at\ 90\,(95)\%\ CL}$
  - 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 ψ(2S) was observed at high track multiplicities

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

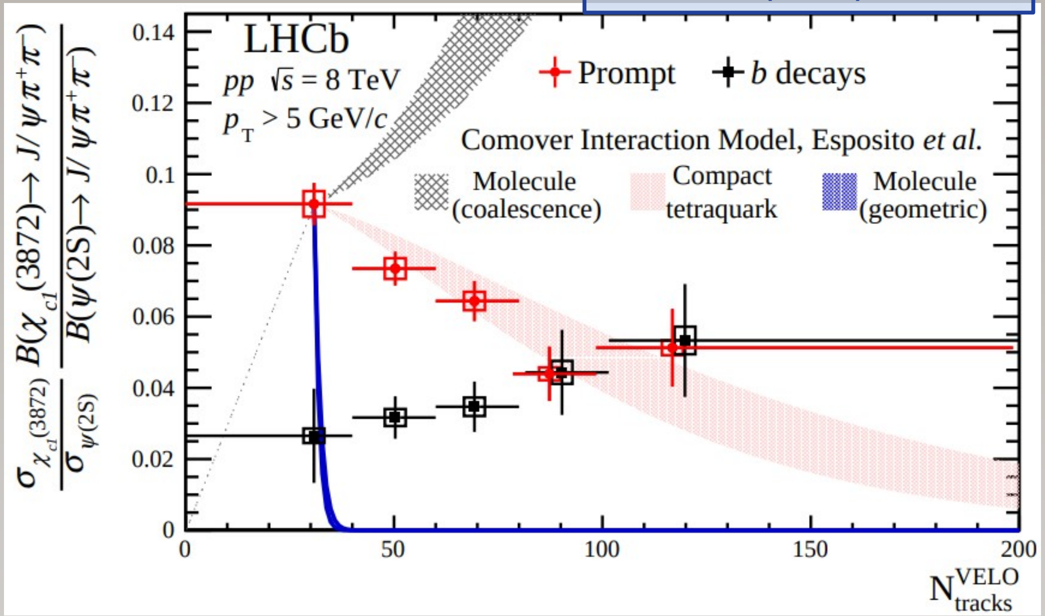
- Therefore probing effective Qπ break-up cross-section:

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

and fractions of Q out of reach of comovers

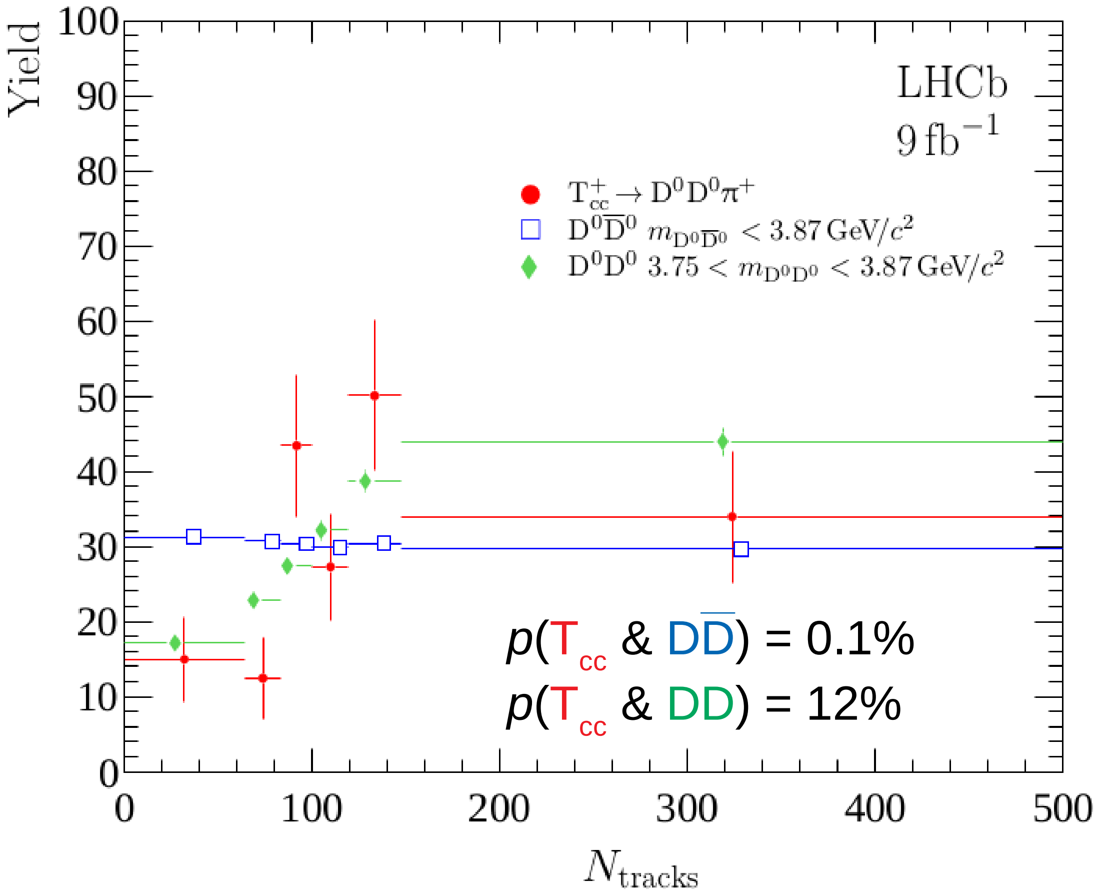
more details in Braaten et al., arXiv:2021.13499

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



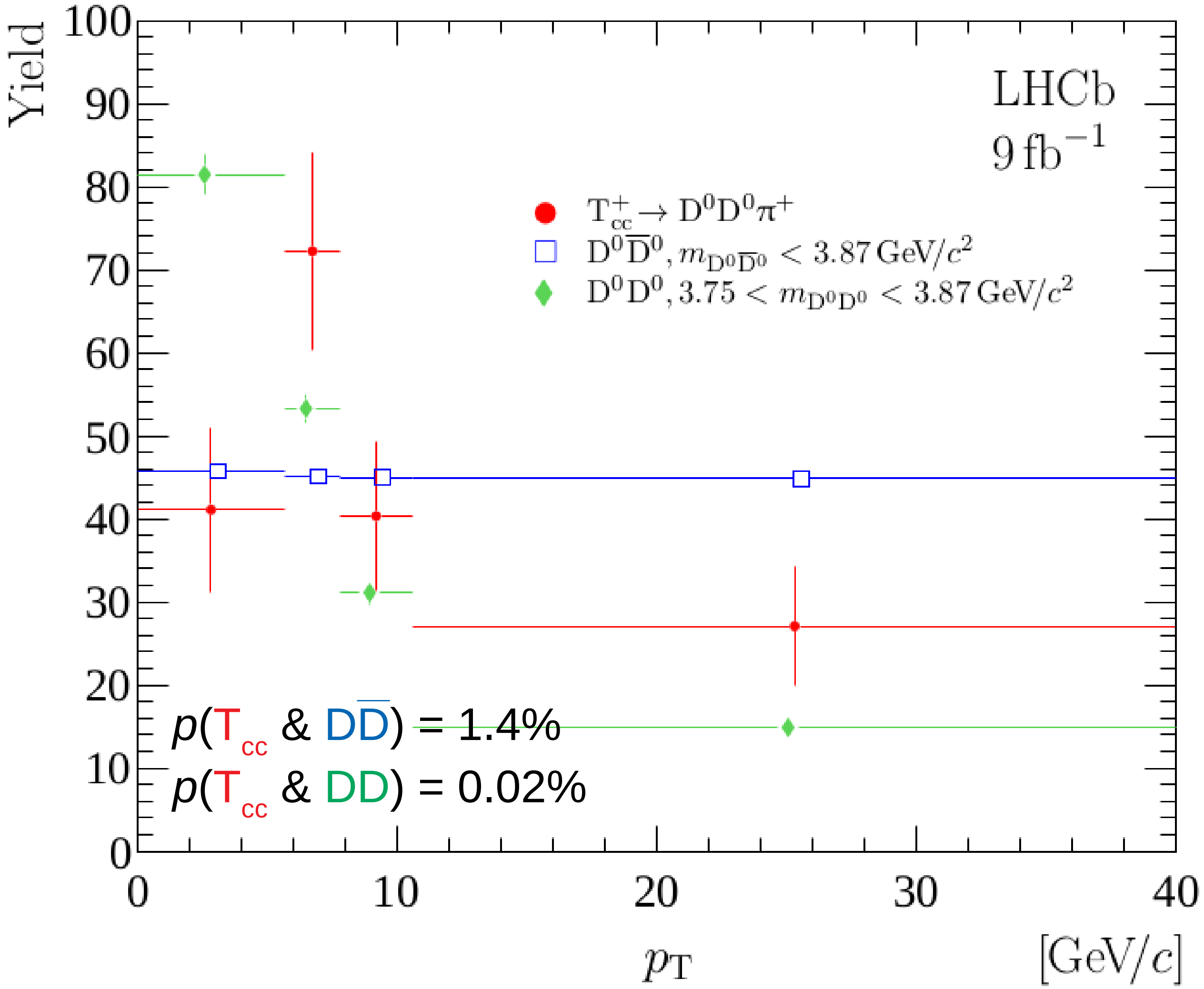
$p(T_{cc}\ \&\ D\overline{D}) = 0.1\%$

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

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

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



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

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

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

Discussions

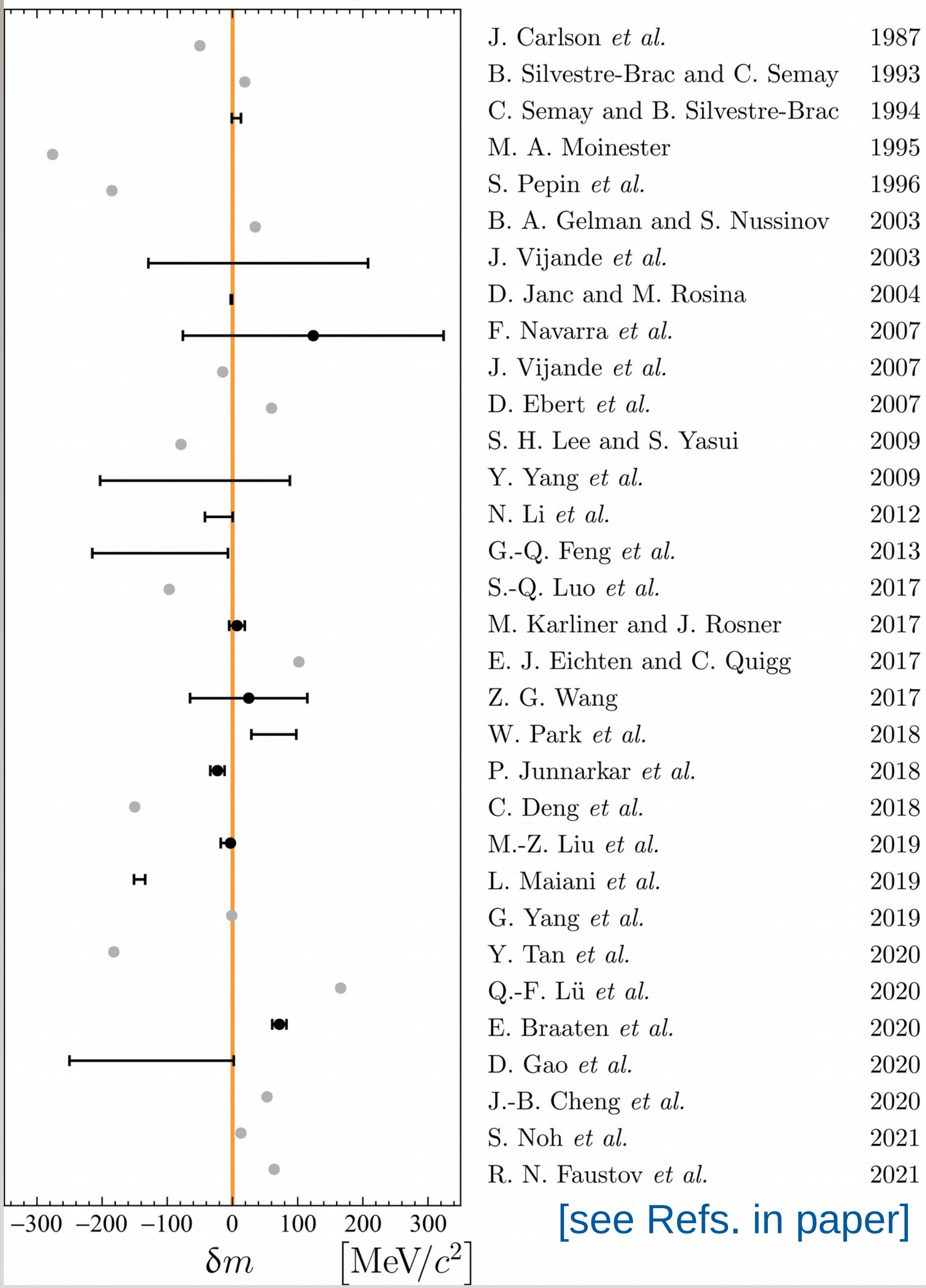
Reflections on measured mass, 1

- 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 $cc\bar{q}\bar{q}$ 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

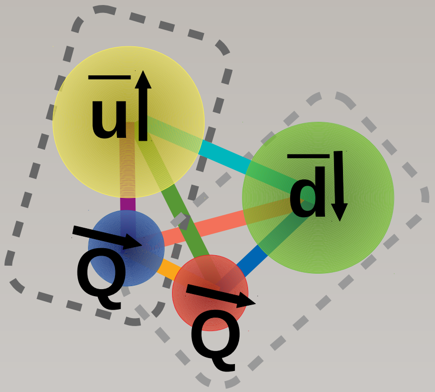
$$\delta m_{\mathrm{U}} = -359 \pm 40\,^{+\,9}_{-\,6}\,\mathrm{keV}/c^2$$

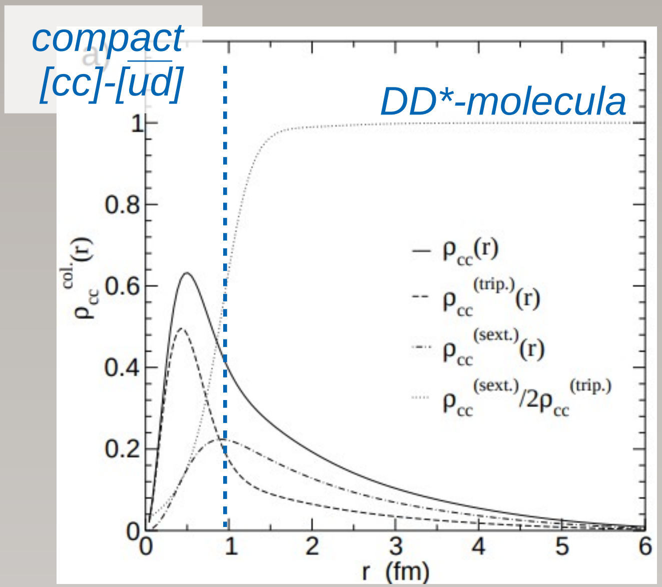
- NR quark-quark potential model
  - **[-2.7,-0.6] MeV**

    -0.6 MeV corresponds to Bhaduri potential

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

    Janc, Rosina, 2003




compact [cc]-[$\overline{ud}$]

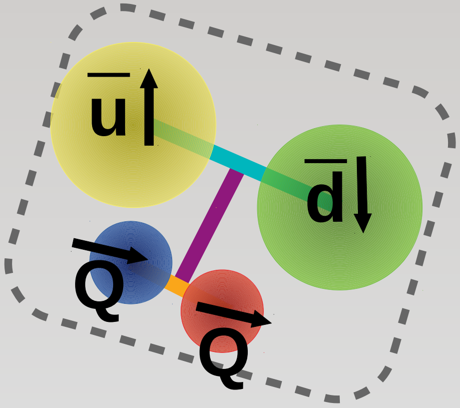
DD-molecula*

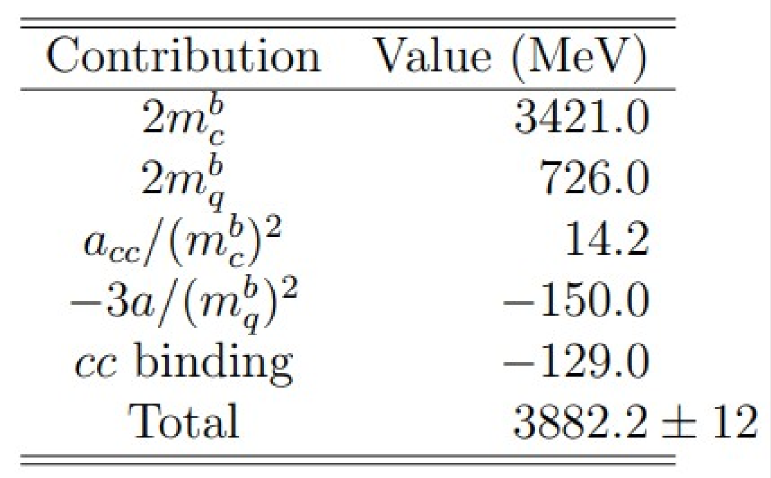
- Phenomenology model for compact tetraquark [cc]-[$\overline{ud}$]
  - **1±12 MeV**

    - 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*

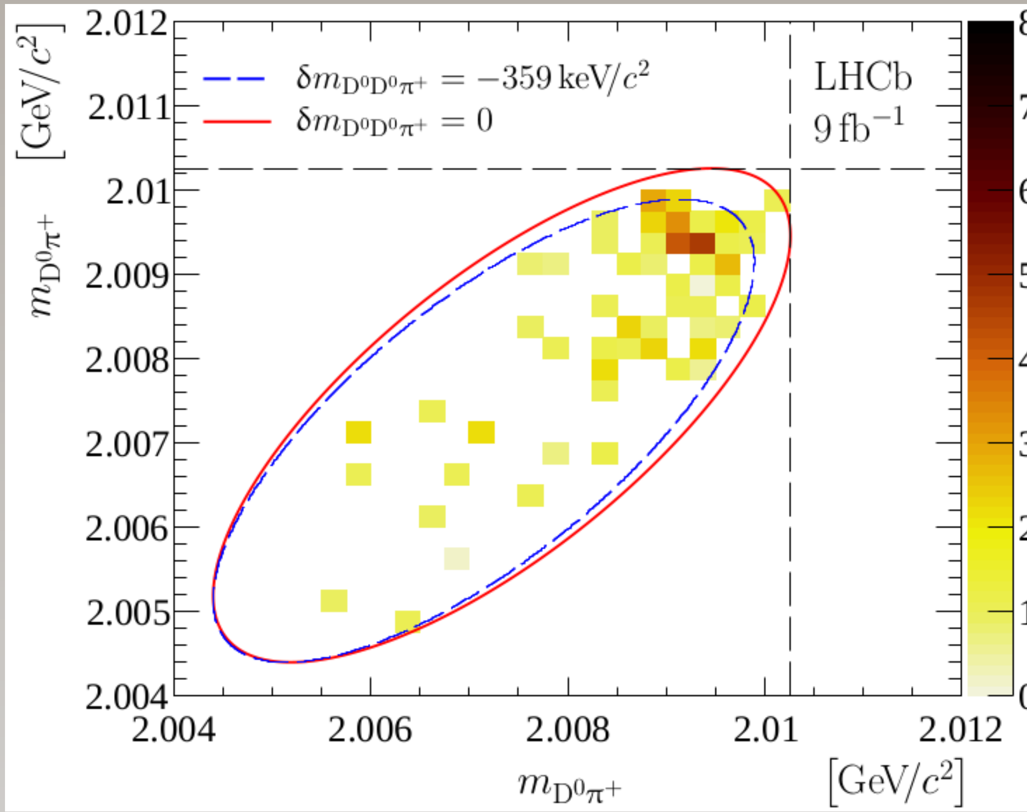
- Using known D^0 and D^{*+} mass can derive

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

  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

Future prospects for T_{cc}^+

- Analysis of the $T_{cc}^+ \rightarrow D^0 D^0 \pi^+$ 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

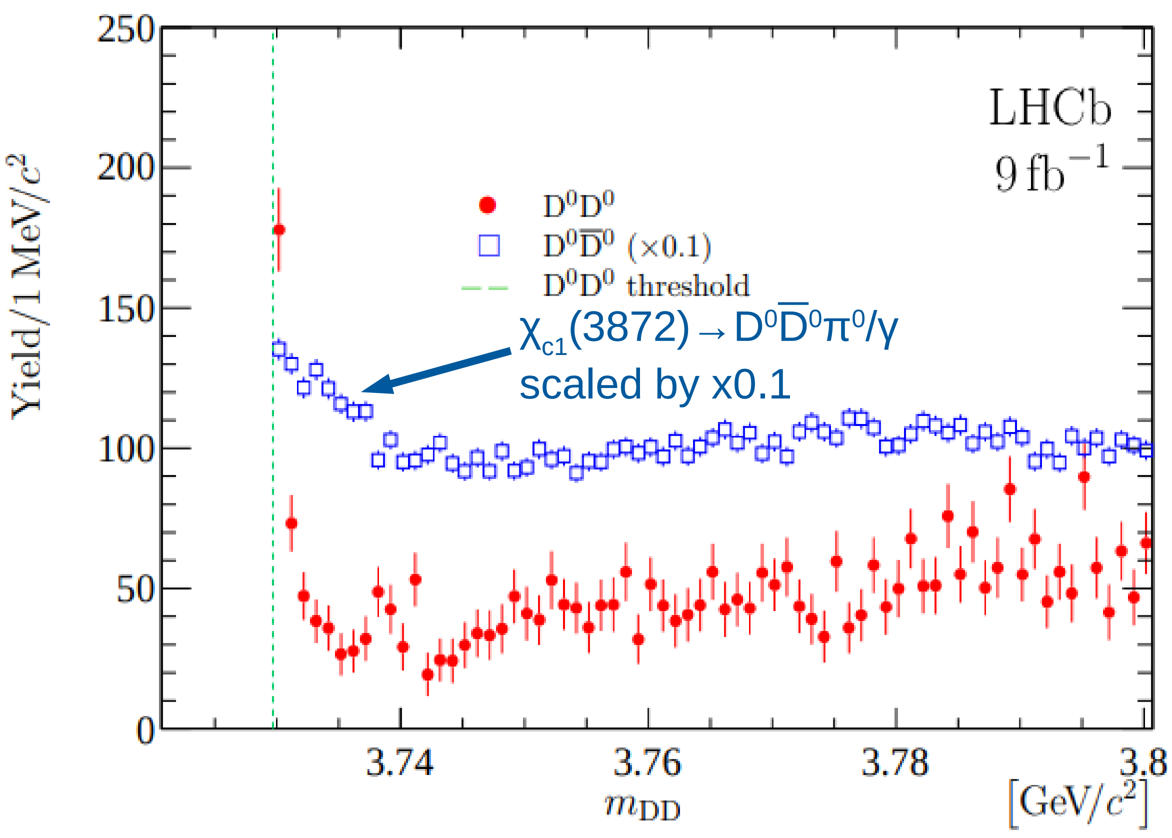
- Data of Run3 (x5 gain in statistics, possibly x2 in efficiency) will be especially important

Production estimation

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

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

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



$\chi_{c1}(3872)\to D^0\overline{D}^0\pi^0/\gamma$
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 $Br(\Xi_{cc}^{++}\to\Lambda_c^{+}K\pi\pi) \sim 5\text{-}20\%$,
  $Br(\Xi_{cc}^{++}\to\Xi_c^{+}\pi^+) \sim 1.3\text{-}4\%$,
  $Br(\Xi_c^{+}\to pK\pi) \sim (6.2\pm3.0)\times10^{-3}$

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

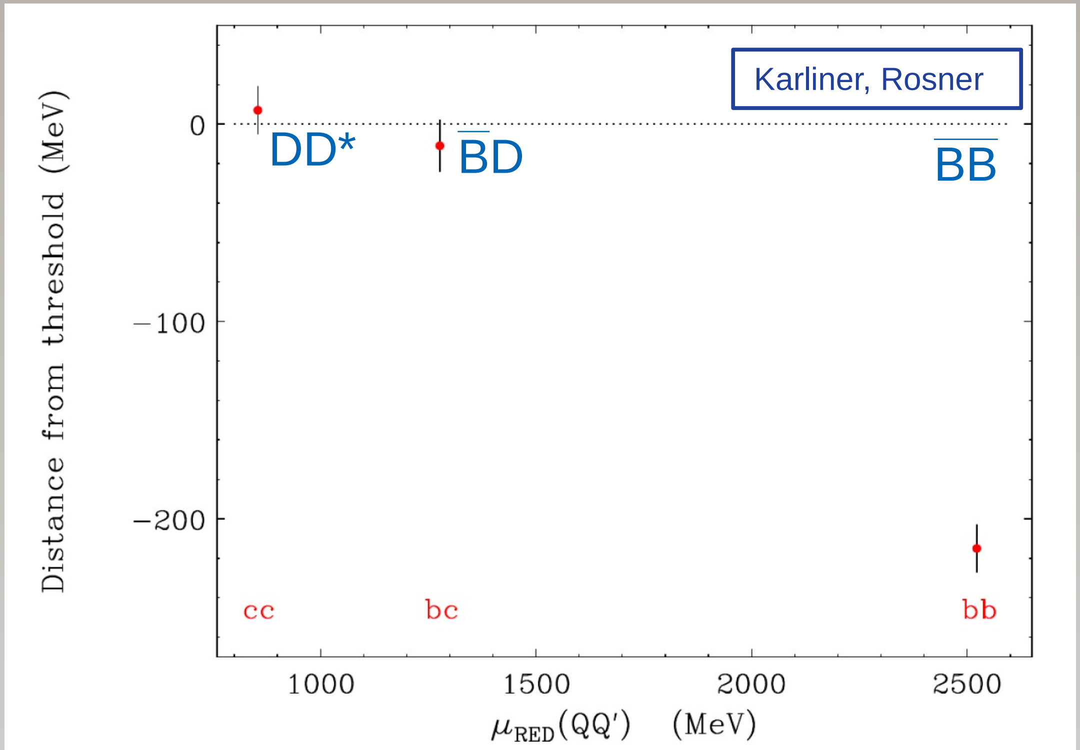
→ Giving stable T_{bc}?

- Different expectations in molecula models

Li, Sun, Liu, Zhu, 2012

Liu, Wu, Valderrama, Xie, Geng, 2019

- Good test for models



- 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

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

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

- **Cons**
  - O(2-20) supression with every $c \rightarrow b$ 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

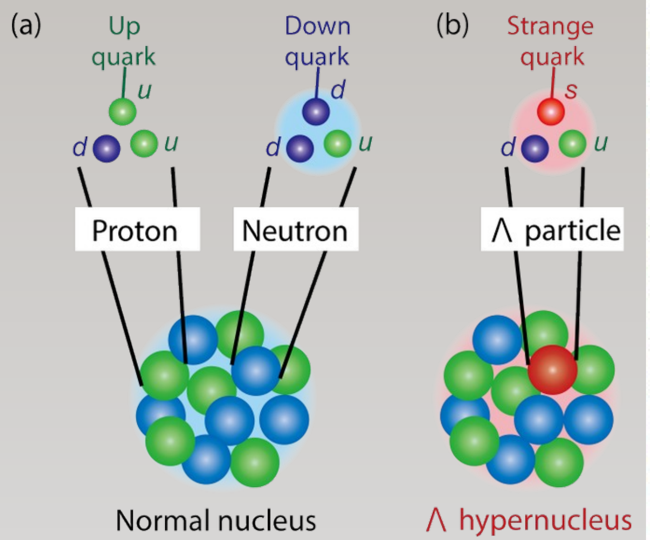
- **Pros**
  - x5 gain in integrated luminosty in Run3 (2022-2024)
  - gain in trigger and reconstruction efficiencies (x2?) from Upgraded LHCb
  - larger trigger efficiency for final states with high-p_T muon

- Comparing to ~150 events of $T_{cc} \rightarrow D^0D^0\pi^+$ one can expect in Run3
  - long-lived T_{bc} : $T_{bc} \rightarrow D^0D^+\pi^-$, $\overline{B}^0K^-\pi^+$, $D^0D^+\mu\nu$, $\Xi_{cc}^+\bar{p}$, $T_{cc}^+\pi^-$ ~ O(1-10)
  - promptly-decaying T_{bc} : $T_{bc} \rightarrow B^-D^+$, $\overline{B}^0D^0$ ~ O(10)
  - $T_{bb} \rightarrow BD + X$ ~ O(0.01)
  - …

- Real chances to find T_{bc}
  - especially if combining several modes
  - can further gain from using partially reconstructed semi-leptonic B/T_{bc} decays
  not much hope for T_{bb} yet

Hadron physics meets Nuclear

- In hadron spectroscopy advances of the theory is limited by the quark configurations to consider
  - conventional hadrons: $q_1\bar{q}_2$ and $q_1q_2q_3$
  - exotic hadrons: $c\bar{c}q_1\bar{q}_2$ and $c\bar{c}q_1q_2q_3$ →
    - *problems with interpretation in most cases (except for the T_{cc}^{+}!)*
    - *In general presence of heavy quark helps (m_c~1.5 GeV, m_b~5 GeV while Λ_{QCD}~0.3 GeV)*
- In nuclear physics systems with only light quarks are usually considered
  - where non-perturbative regime is at its maximum
- Hyper-nuclei with Λ are explored since 50's giving valuable insight into nuclei physics



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

Gal, Hungerford, Millener, 2016

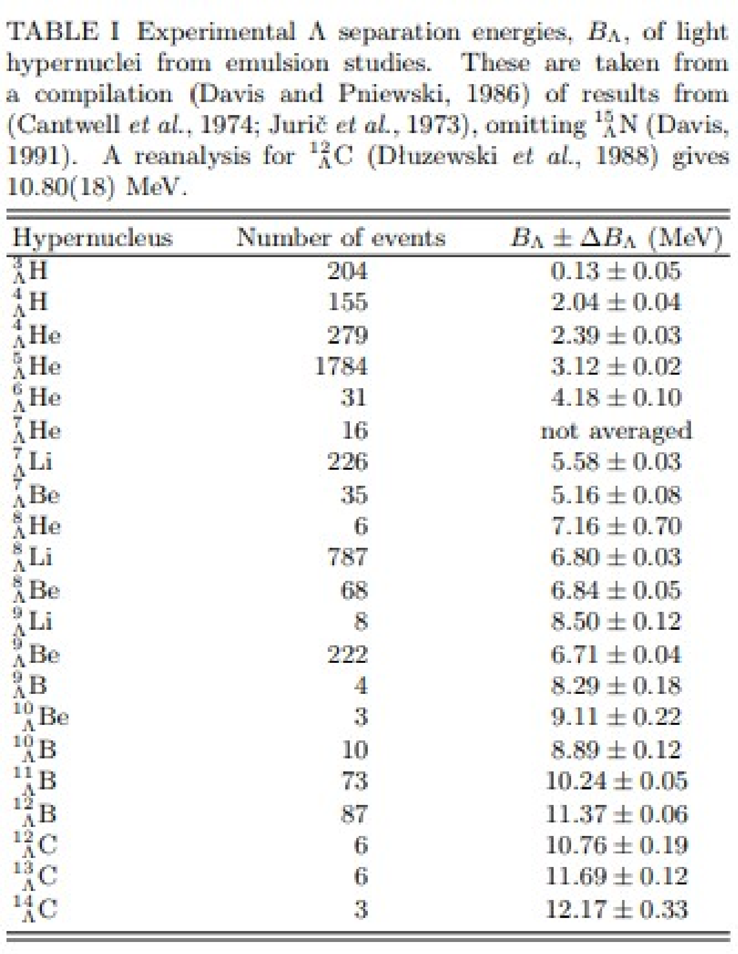
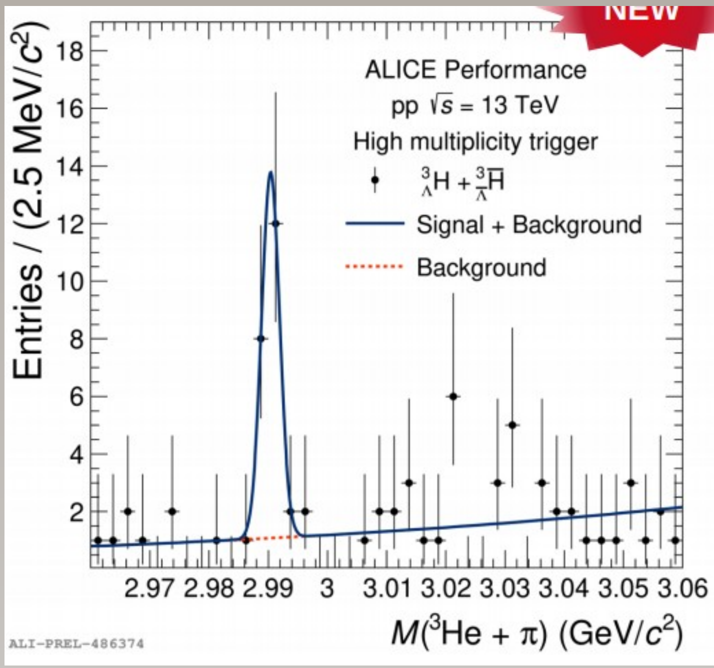


TABLE I Experimental Λ separation energies, B_Λ, of light hypernuclei from emulsion studies. These are taken from a compilation (Davis and Pniewski, 1986) of results from (Cantwell *et al.*, 1974; Jurič *et al.*, 1973), omitting ${}^{15}_{\Lambda}$N (Davis, 1991). A reanalysis for ${}^{12}_{\Lambda}$C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

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

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, 1905.07209
  ALICE, 1506.07499

- 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)),
  - cc produced in ~5% of pp collisions LHCb, 1205.0975

  possible modes for searches:
  - H_c [cuduud] → $ppK^-\pi^+$ / $p\Lambda_c$
  - H_{cc} [ccuudd] → $\Lambda_c pK^-\pi^+$ / $\Lambda_c\Lambda_c$
  - and also H_s, H_b, ...

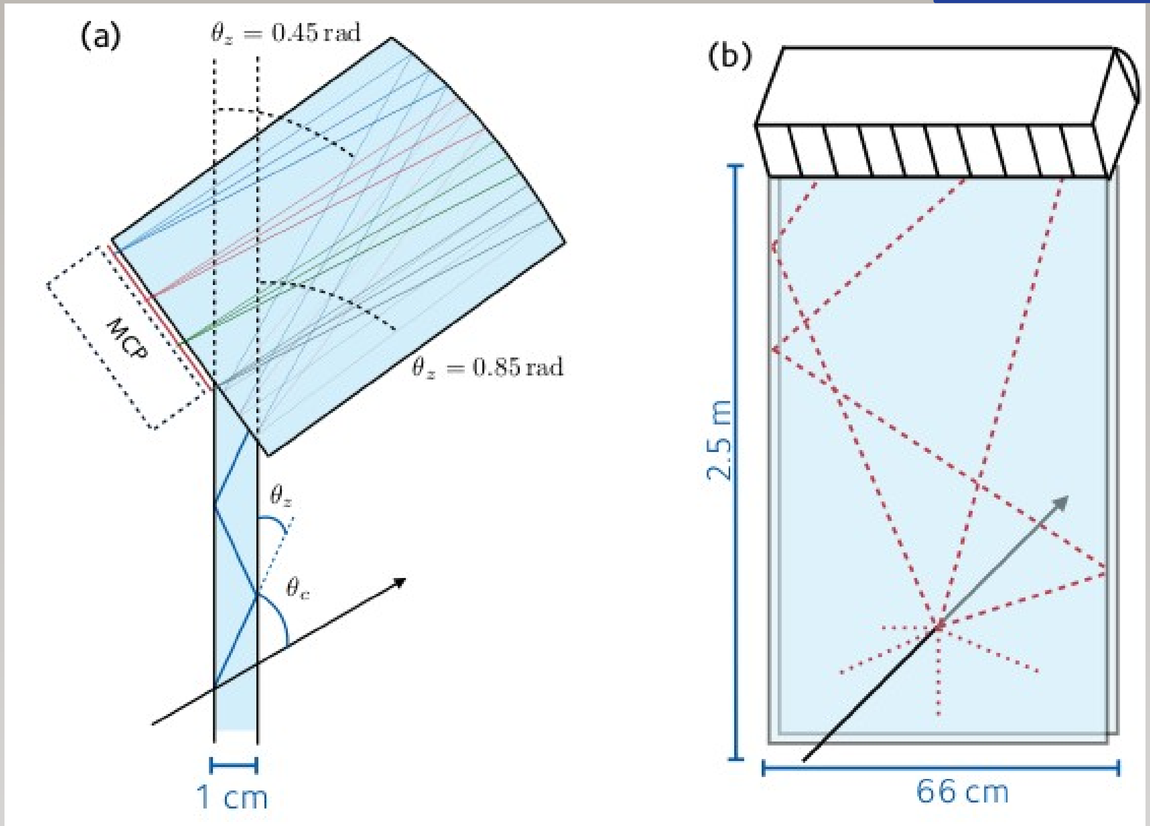
The TORCH sub-detector

- Time-of-flight detector prepared for LHCb Upgrade II (and in some part in Ib?)

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

N. Harnew et al., arXiv:1810.06658

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



- 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 – $[cc\bar{u}\bar{d}]$, 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

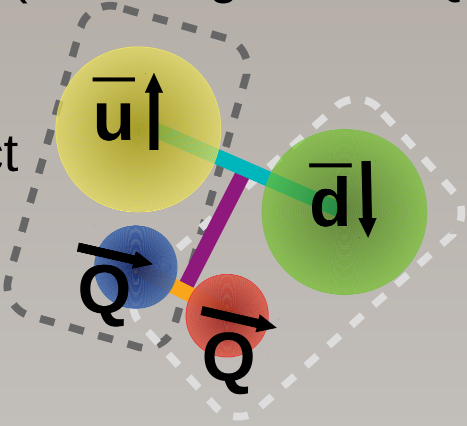
opens insight into the new area
more to see and explore

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

Backup

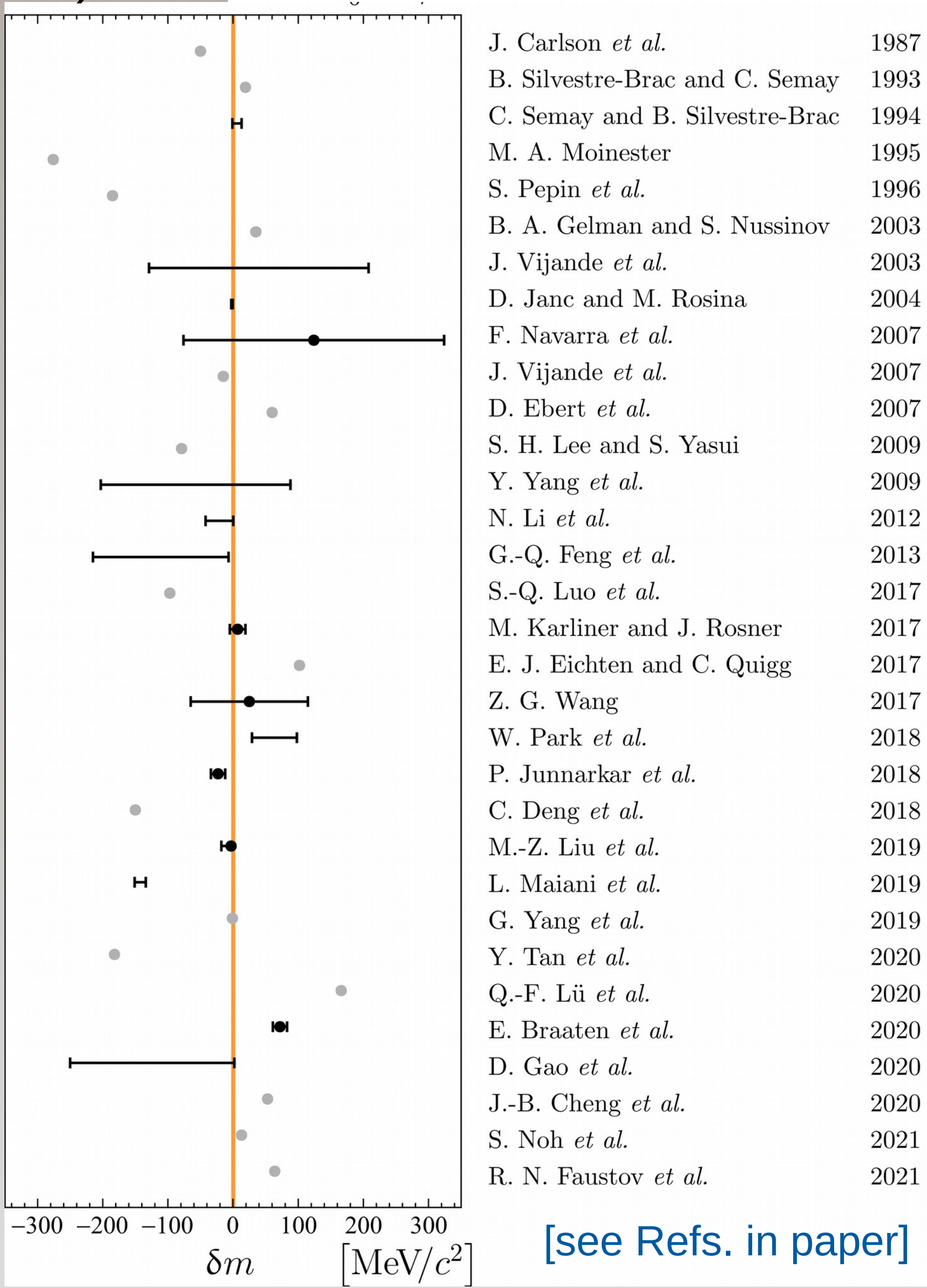
Predictions for $cc\overline{ud}$ mass

- 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

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



[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

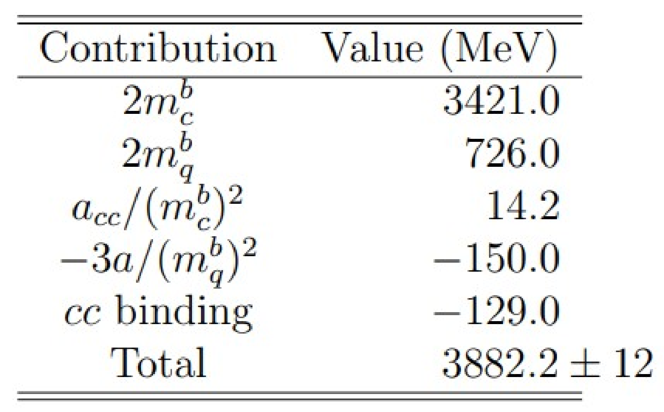
Phenomenology approach for compact hadrons

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

      → 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



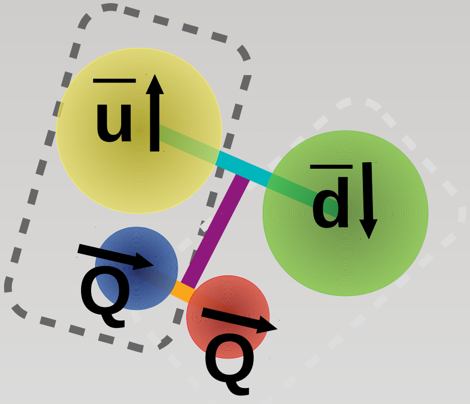
Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	−150.0
cc binding	−129.0
Total	3882.2 ± 12

→ δm = 7±12 MeV

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

δm = 1±12 MeV

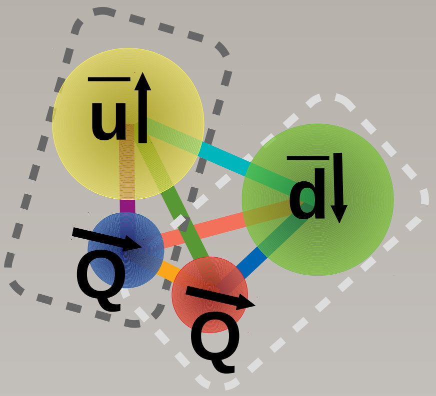
Karliner, Rosner, 2017



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

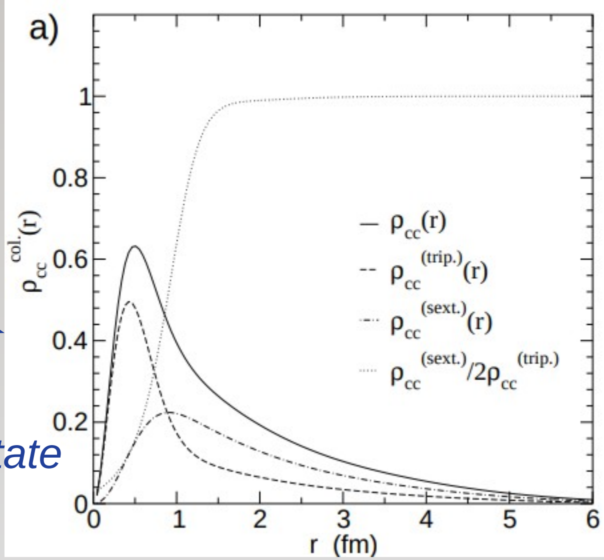
→ **δm = [-1;+13] MeV** Semay, SIlvestre-Brac, 1994

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

… + more within [-200;+100] MeV range

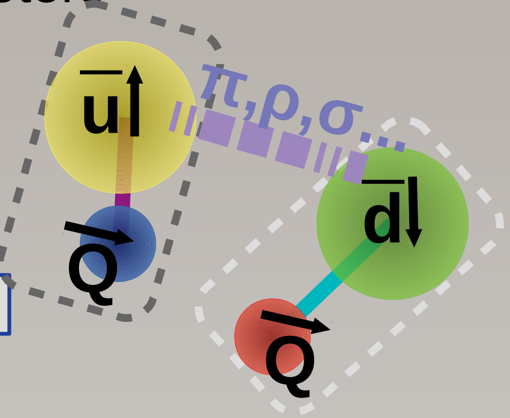
(choice of basic, parameters, ...)

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

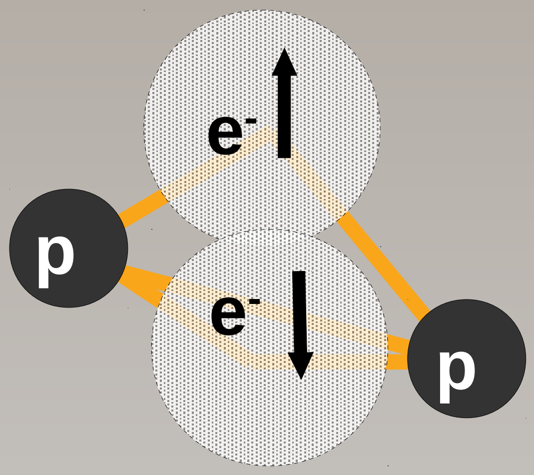
= -203 MeV Yang, Deng, Ping, Goldman, 2009

= [-150;-1] MeV Yang, Ping, Segovia, 2019

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

Hydrogen bond of QCD

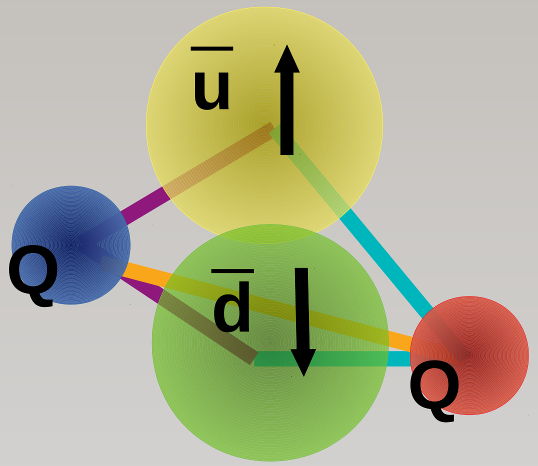
- Consider interaction between two D-mesons by solving Schrodinger equation for light quarks (q) given fixed distance between the heavy ones (Q)
  → get effective interaction between QQ



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

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

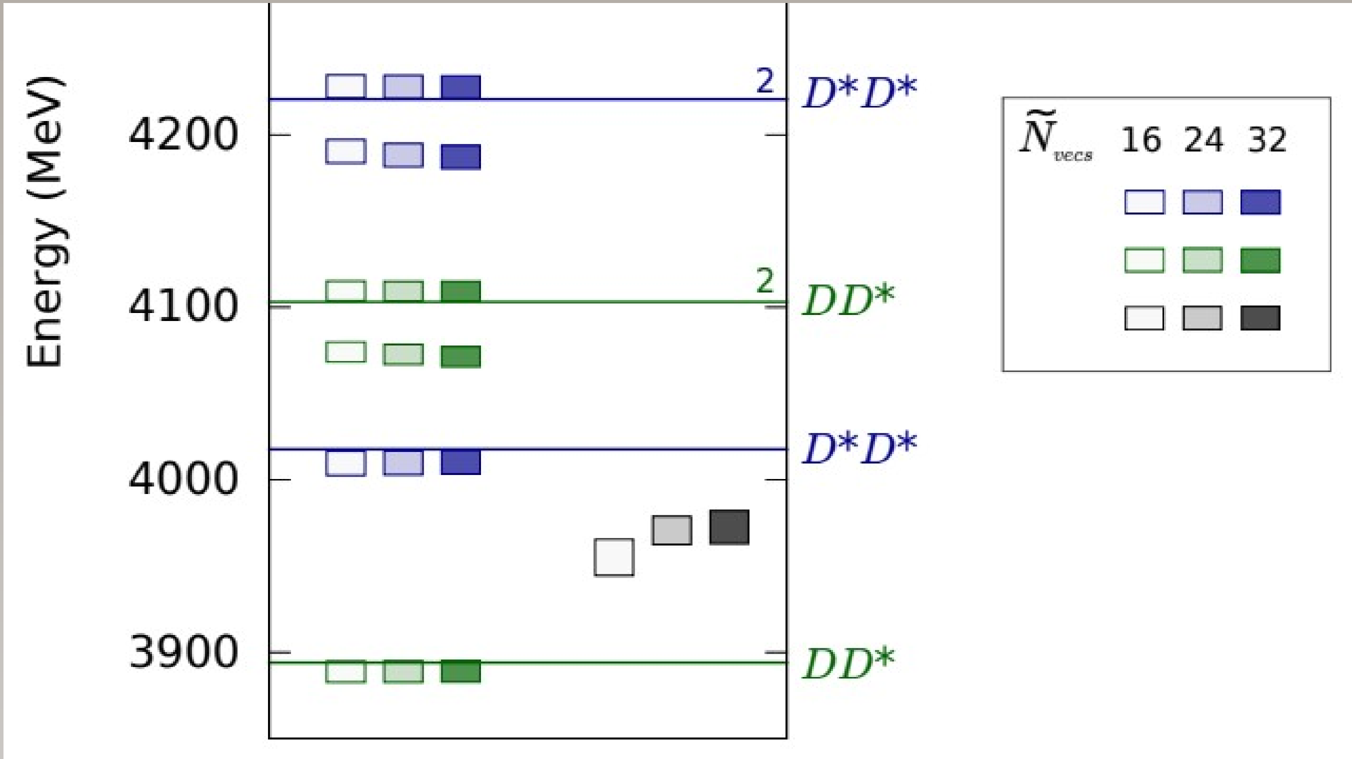
is it analogous to quark consituent model with OGE?
should it be re-considered for DD interaction?*

Lattice QCD

- Inconclusive
    - **no binding**

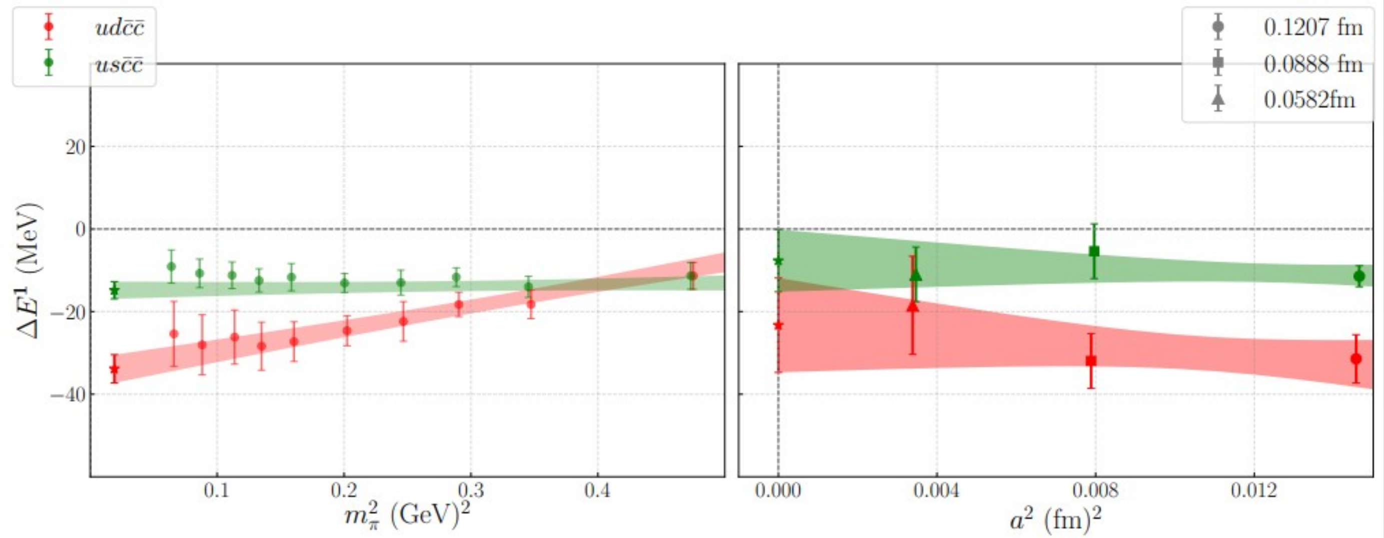
HAL QCD Collaboration, 2014

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 $S>20\sigma$
- Naive BW parameters:

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

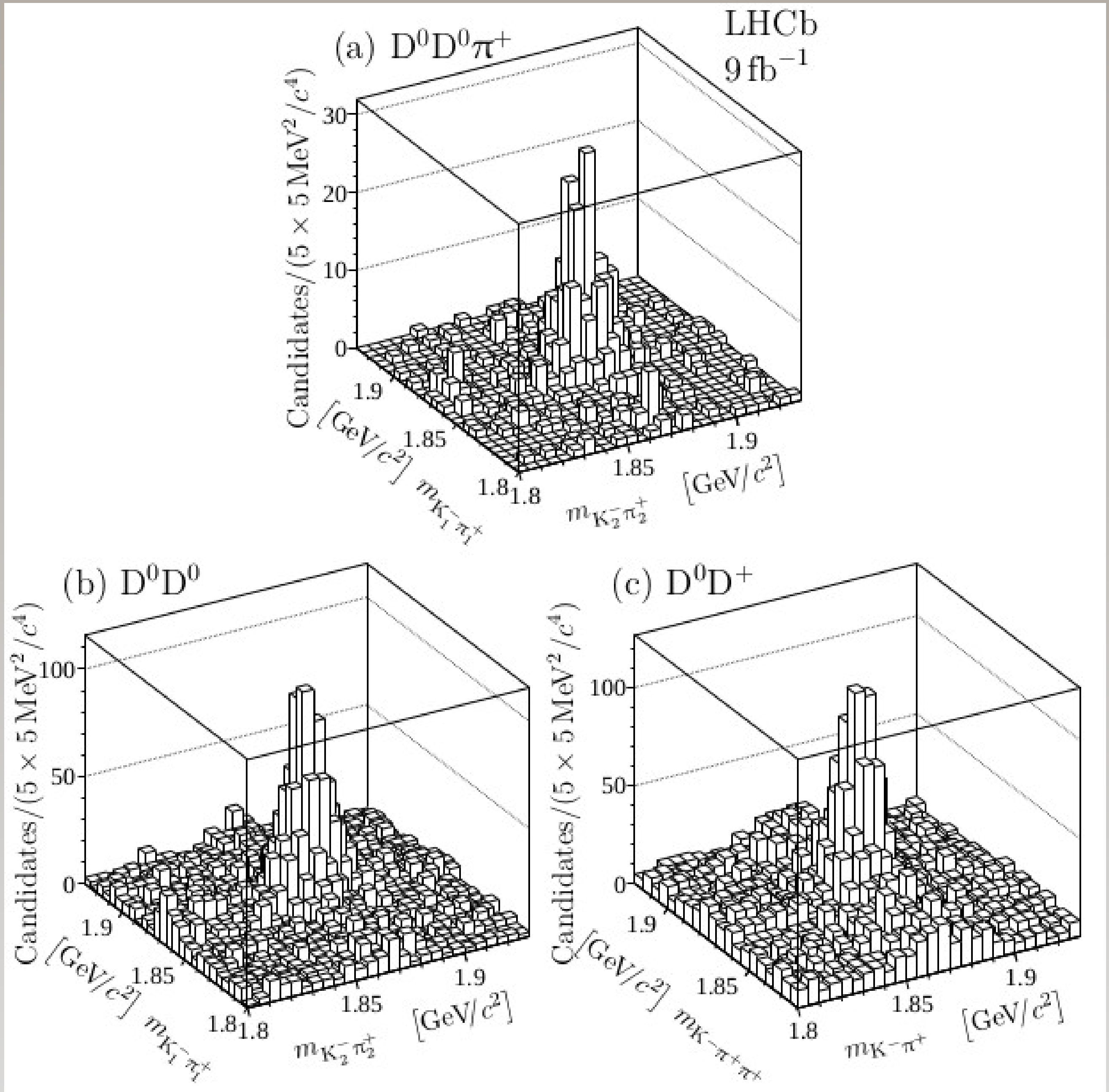
- Consistent with $[cc\bar{u}\bar{d}]$ isoscalar tetraquark T_{cc}^+ with $J^P=1^+$ for which

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

  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:

  $\sigma_1 = 263$ keV x 1.05

  $\sigma_2 = 2.413 \times \sigma_1$

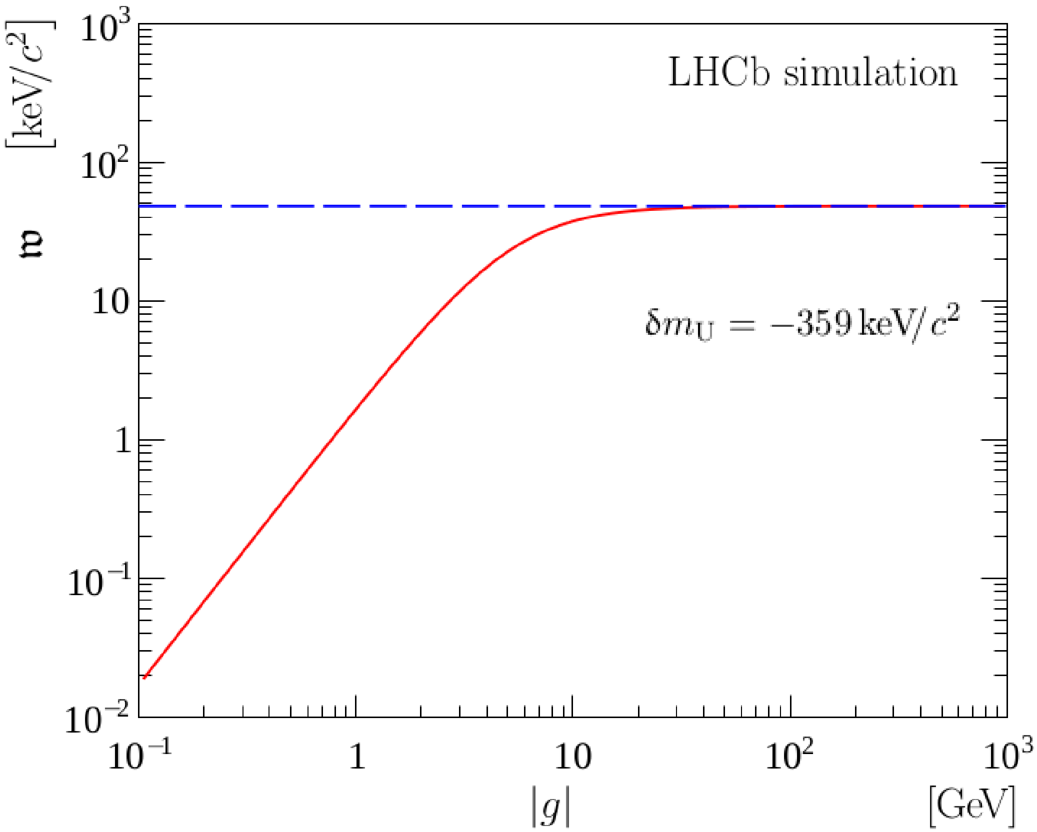
  $f_1 = 0.778$

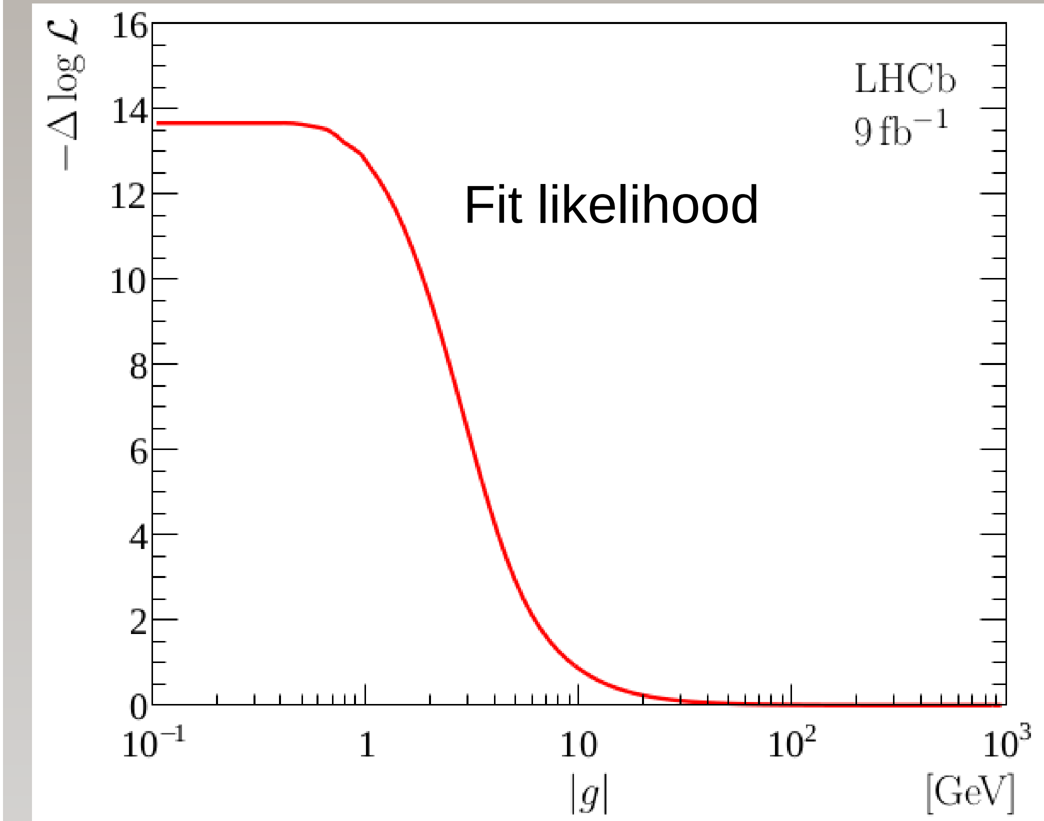
  a 1.05 correction motivated by data-simulation comparison in various decay channels

- 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*⁺)

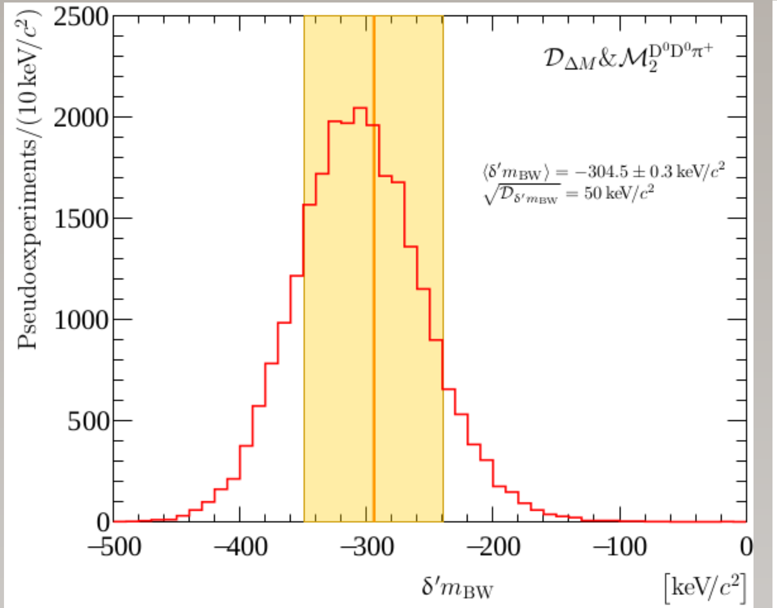


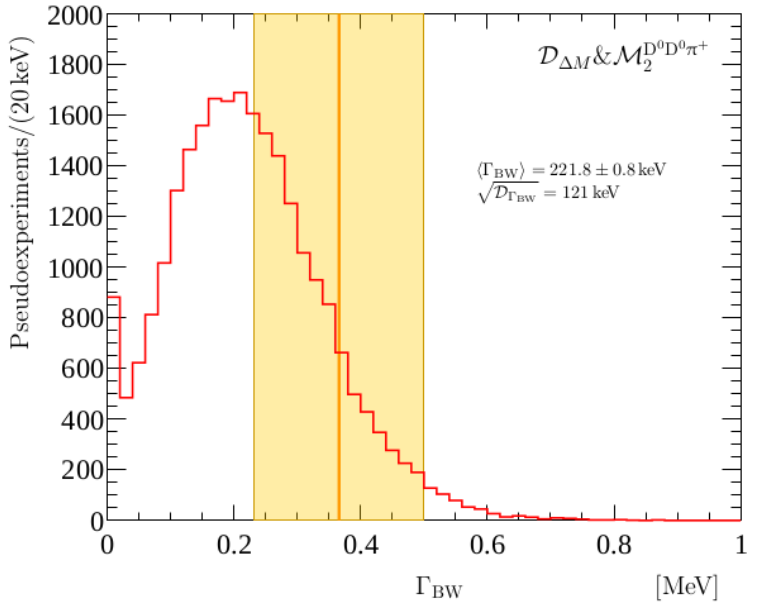


Fit likelihood

Consistency of Naive and Advanced

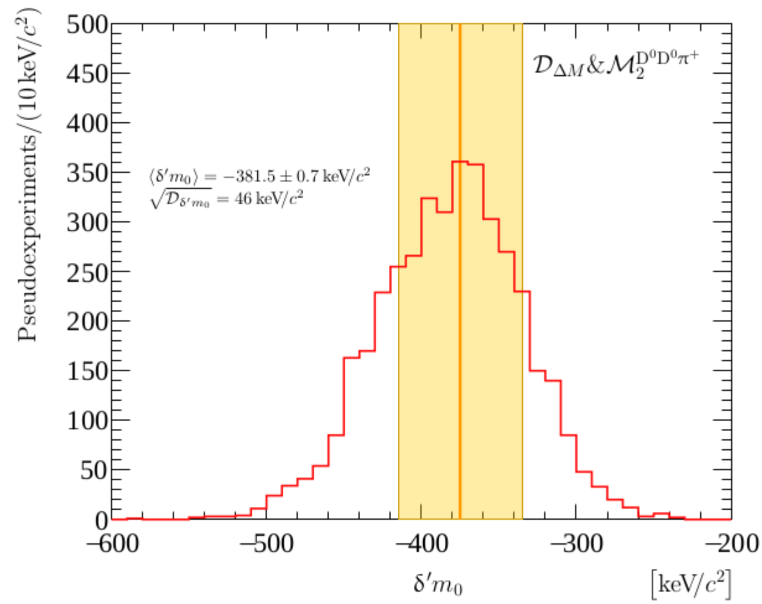
- Generate 25k pseudoexperiments using advanced BW model, fit them with naive BW model.
  Get δ'm_{BW} and Γ_{BW} consistent with values obtained from data





- 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		Data	
		mean	RMS		
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

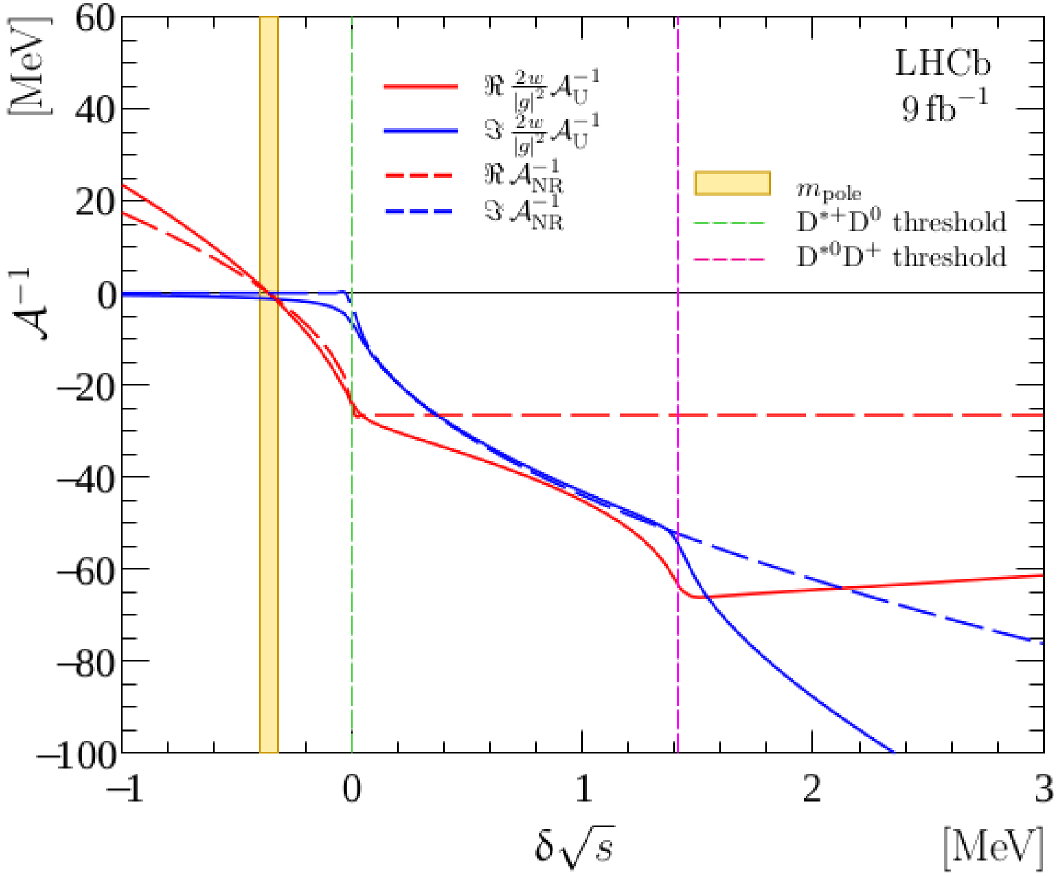
$$w = \frac{24\pi}{m_{\mathrm{D^{*+}}} + m_{\mathrm{D^0}}}\frac{1}{c_1}$$

- 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 $\mathrm{D^{*+}D^0}$ and $\mathrm{D^{*0}D^+}$ mass thresholds.

Analytic continuation

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

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

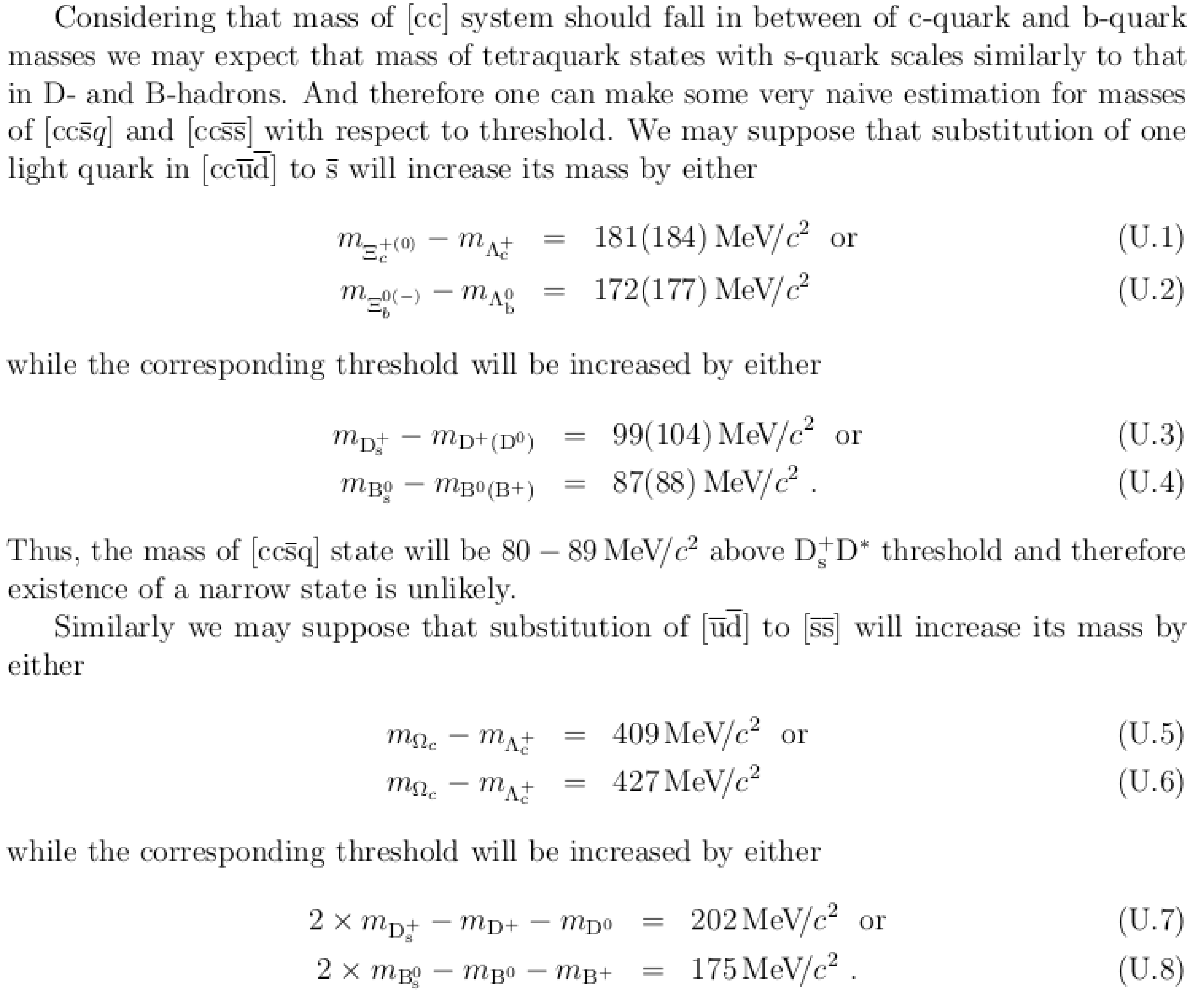
$$\frac{1}{\mathcal{A}_{\mathrm{U}}^{II}\left(s\right)}=m_{\mathrm{U}}^{2}-s-\left|g\right|^{2}\Sigma(s)+i\left|g\right|^{2}\varrho_{\mathrm{tot}}(s)$$

- For ρ functors

$$\int\limits_{\mathcal{D}}\left|\mathfrak{M}\right|^{2}\,d\Phi_{3}=\frac{1}{2\pi(8\pi)^{2}s}\int\limits_{(m_{2}+m_{3})^{2}}^{(\sqrt{s}-m_{1})^{2}}ds_{23}\int\limits_{s_{12}^{-}(s,s_{23})}^{s_{12}^{+}(s,s_{23})}\left|\mathfrak{M}\right|^{2}\,ds_{12}$$

$$\begin{aligned}s_{12}^{\pm}\left(s,s_{23}\right)=m_{1}^{2}+m_{2}^{2}&-\frac{\left(s_{23}-s+m_{1}^{2}\right)\left(s_{23}+m^{2}+m_{3}^{2}\right)}{2s_{23}}\\&\pm\frac{\lambda^{1/2}\left(s_{23},s,m_{1}^{2}\right)\lambda^{1/2}\left(s_{23},m_{2}^{2},m_{3}^{2}\right)}{2s_{23}}\end{aligned}$$

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

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

while the corresponding threshold will be increased by either

$$\begin{aligned} m_{\mathrm{D}_s^+} - m_{\mathrm{D}^+(\mathrm{D}^0)} &= 99(104)\,\mathrm{MeV}/c^2 \quad \text{or} && \text{(U.3)} \\ m_{\mathrm{B}_s^0} - m_{\mathrm{B}^0(\mathrm{B}^+)} &= 87(88)\,\mathrm{MeV}/c^2\ . && \text{(U.4)} \end{aligned}$$

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

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

while the corresponding threshold will be increased by either

$$\begin{aligned} 2 \times m_{\mathrm{D}_s^+} - m_{\mathrm{D}^+} - m_{\mathrm{D}^0} &= 202\,\mathrm{MeV}/c^2 \quad \text{or} && \text{(U.7)} \\ 2 \times m_{\mathrm{B}_s^0} - m_{\mathrm{B}^0} - m_{\mathrm{B}^+} &= 175\,\mathrm{MeV}/c^2\ . && \text{(U.8)} \end{aligned}$$

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

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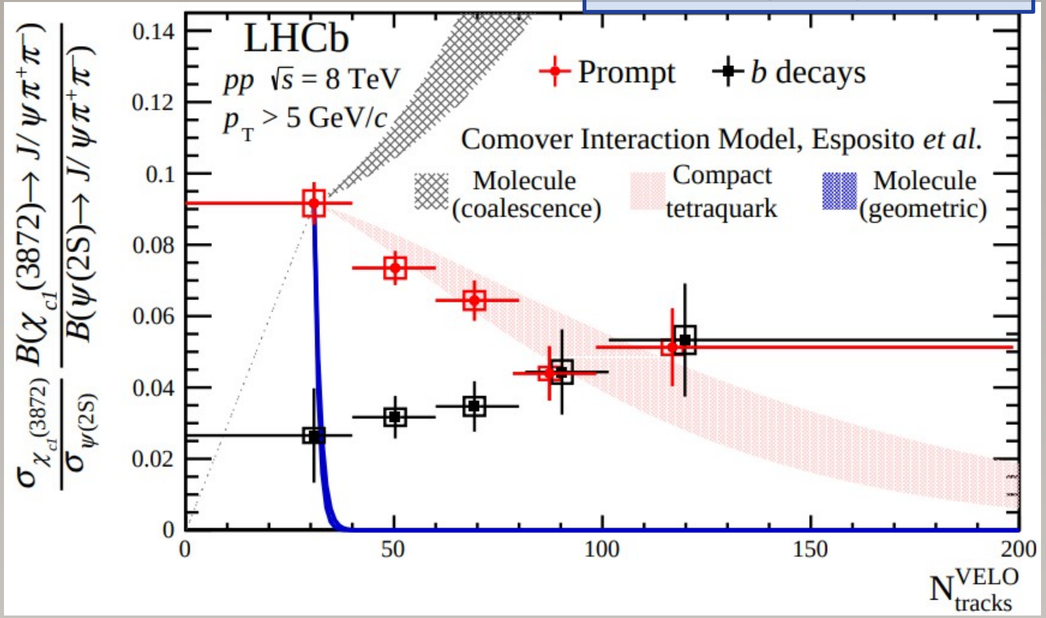
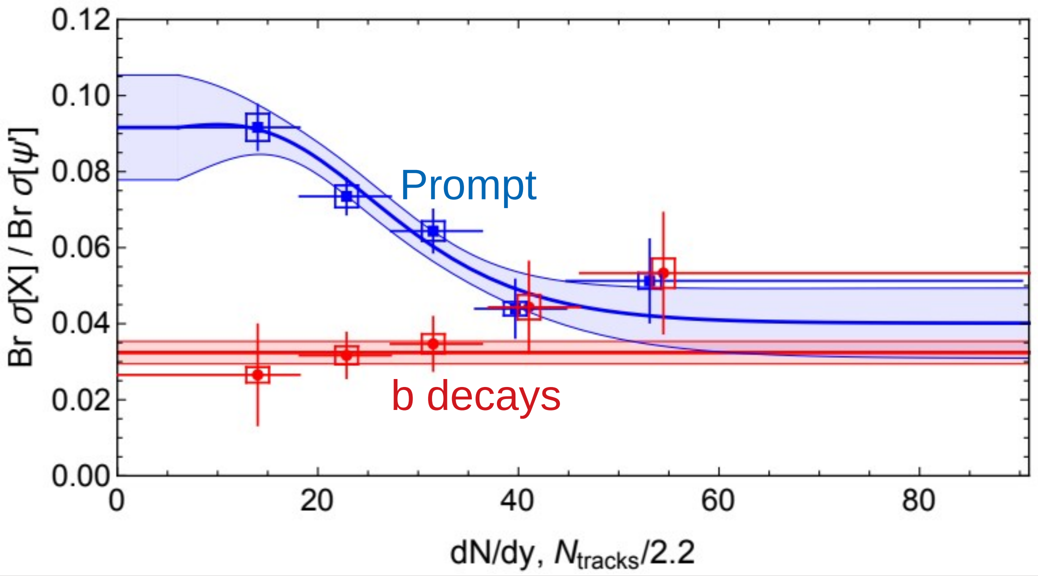
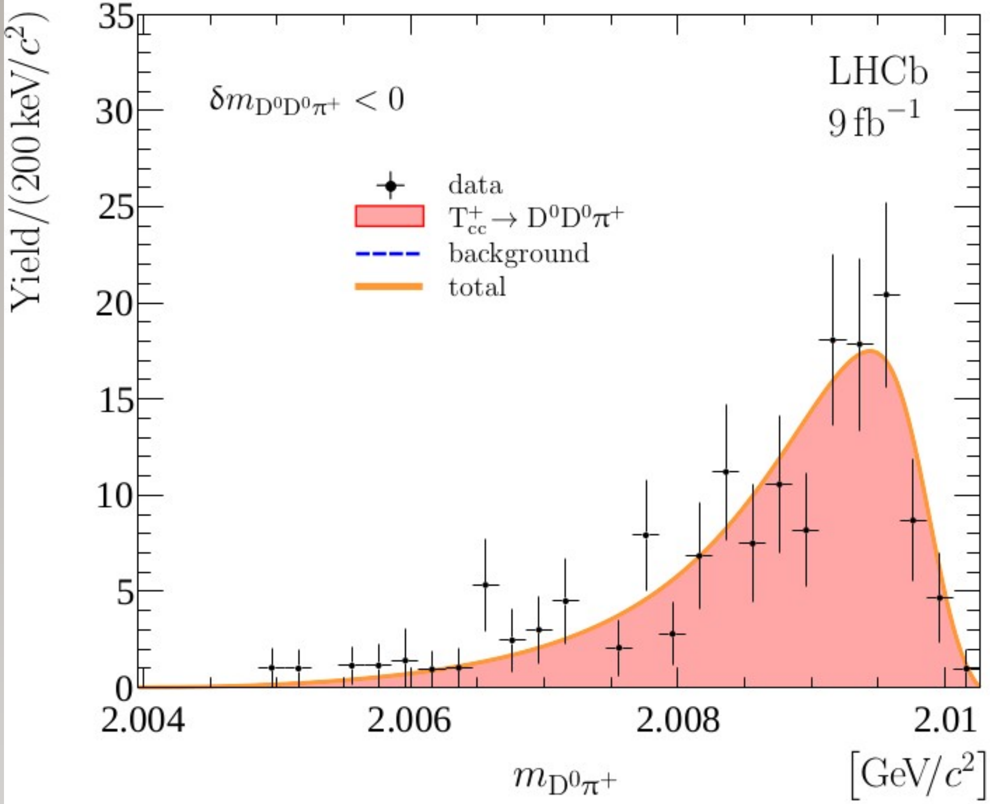
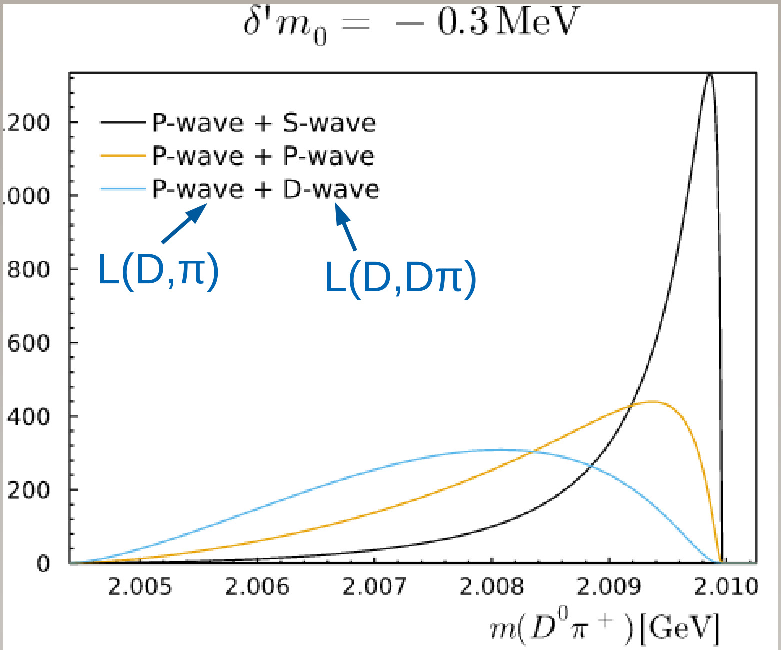




Offshell D^{*+}

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

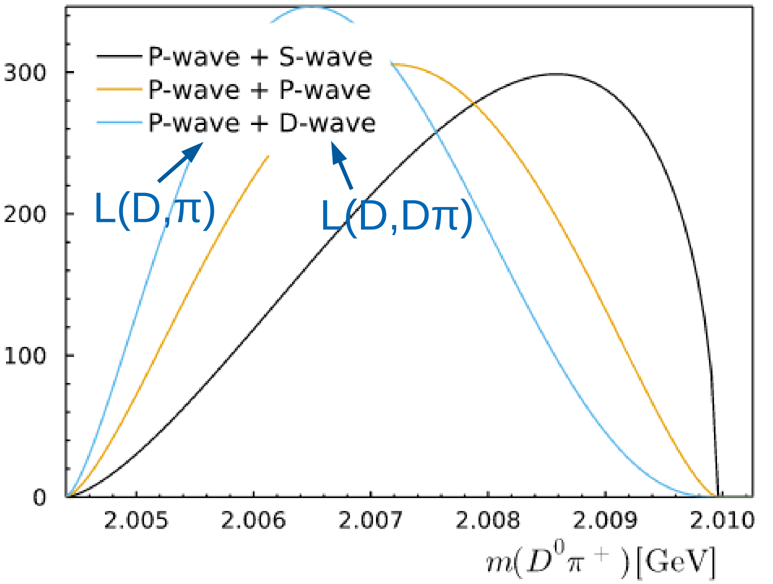




L(D,π)

L(D,Dπ)

with no D* propagator



L(D,π)

L(D,Dπ)

Perfect agreement confirms

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