Observation of the doubly charmed tetraquark T_{cc}^{+} in the LHCb experiment

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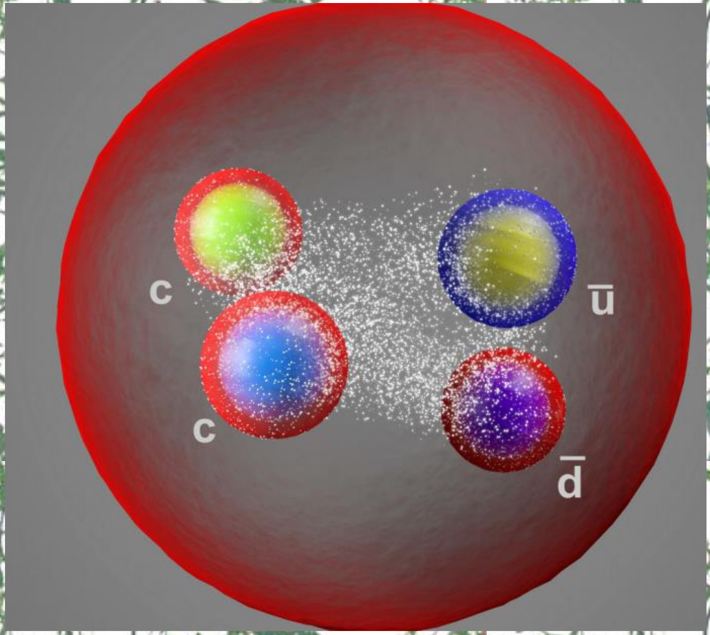


Hadrons

- Mesons:
  - Quark + antiquark
- Baryons
  - Three quarks

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

- Everything else, aka *"exotics"*
  - Glueballs
  - Hybrids,
  - Pentaquarks,
  - Tetraquarks,
  - Hexaquarks, …

30 "*exotic*" heavy flavor hadrons

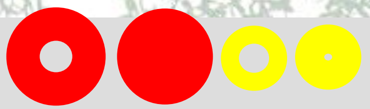
24 tetraquark candidates

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]	$c\bar{c}uds$

6 pentaquark candidates

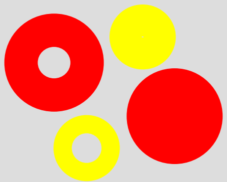
(24-2) tetraquark candidates

- All are "quarkonium-like"

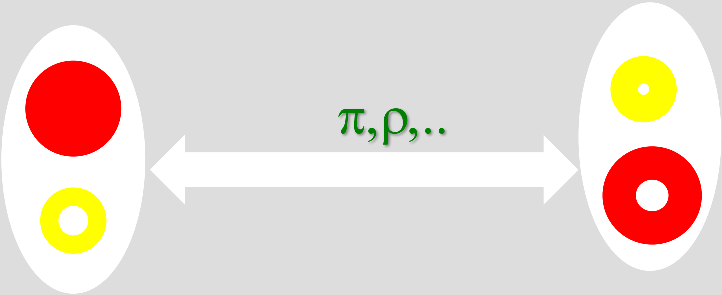


What is the internal structure?

- Compact tetraquark

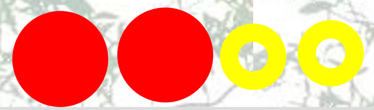


- Molecula



- … something else

$QQ\bar{q}\bar{q}$



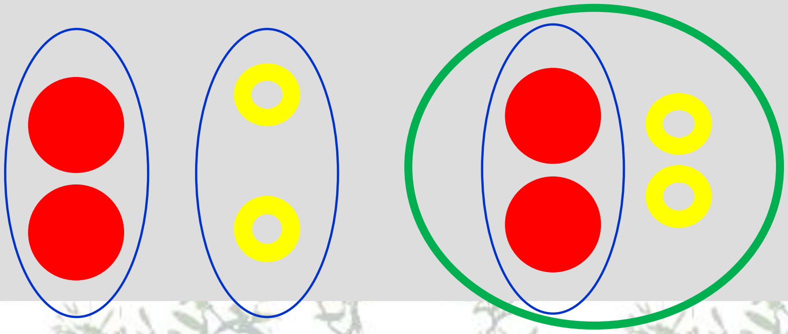
- Discussed from the end of 70s

Jaffe 1977, Jaffe 1978, Lipkin 1987,…

- For large m_Q could be bound and “stable

Adler, Richard & Taxil 1982,
Ballot &Richard 1983,
Zouzou,Silvestre-Brac, Gignous&Richard 1986,
Lipkin 1986,
Heller&Tijon 1987,
Manohar &Wise 1993

- QQ attraction in color antitriplet state
  - half of those in $Q\bar{Q}$ in color-singlet state
  - Binding energy: $\alpha_s^2 m_Q$ large for *sufficiently* heavy Q
- Diquark-antidiquark or diquark + two antiquarks (“antibaryon”) picture



$bb\overline{qq}$ $bc\overline{qq}$ $cc\overline{qq}$

- $bb\overline{qq}$: Theory & Lattice QCQ consensus
  - Exists & "stable"

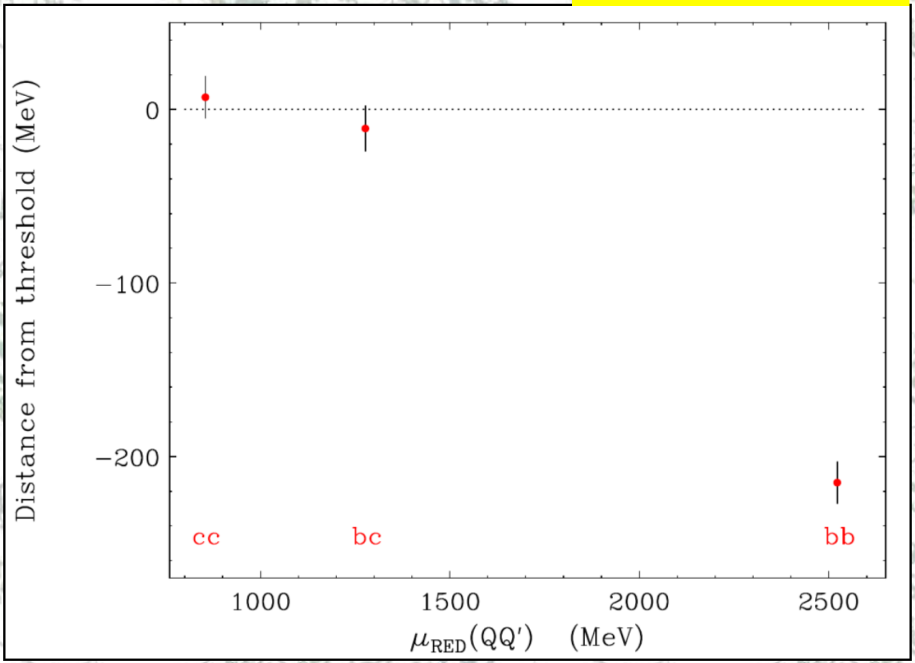
  mass << m(B) + m(B*)

- $bc\overline{qq}$: *likely* exists and may be almost stable

  mass close to m(B) + m(D)

- $cc\overline{qq}$: no consensus

Karliner&Risner, 2017



$cc\bar{u}\bar{d}$: ±250 MeV near DD^* threshold

color antitriplet

- S = 1

light "good" scalar isoscalar diquark

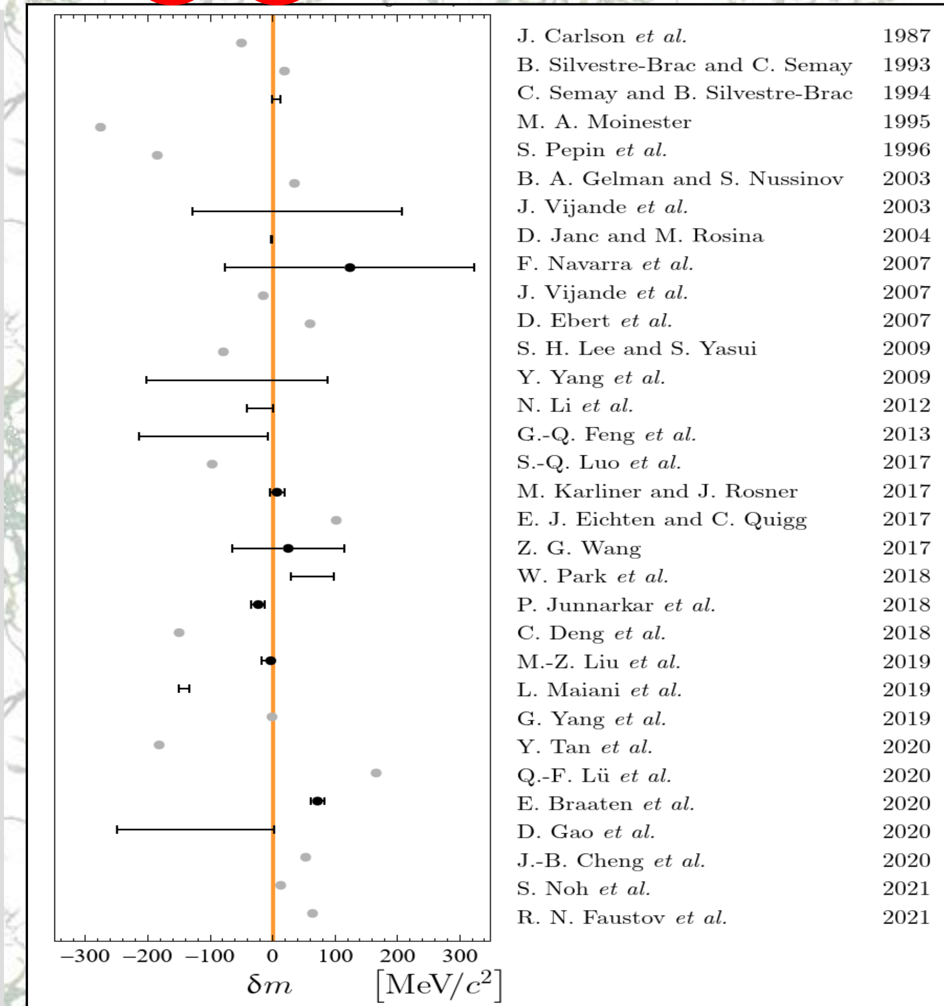
- S = 0

- In S-wave it fixes quantum numbers:

  $I(J^P) = 0(1^+)$

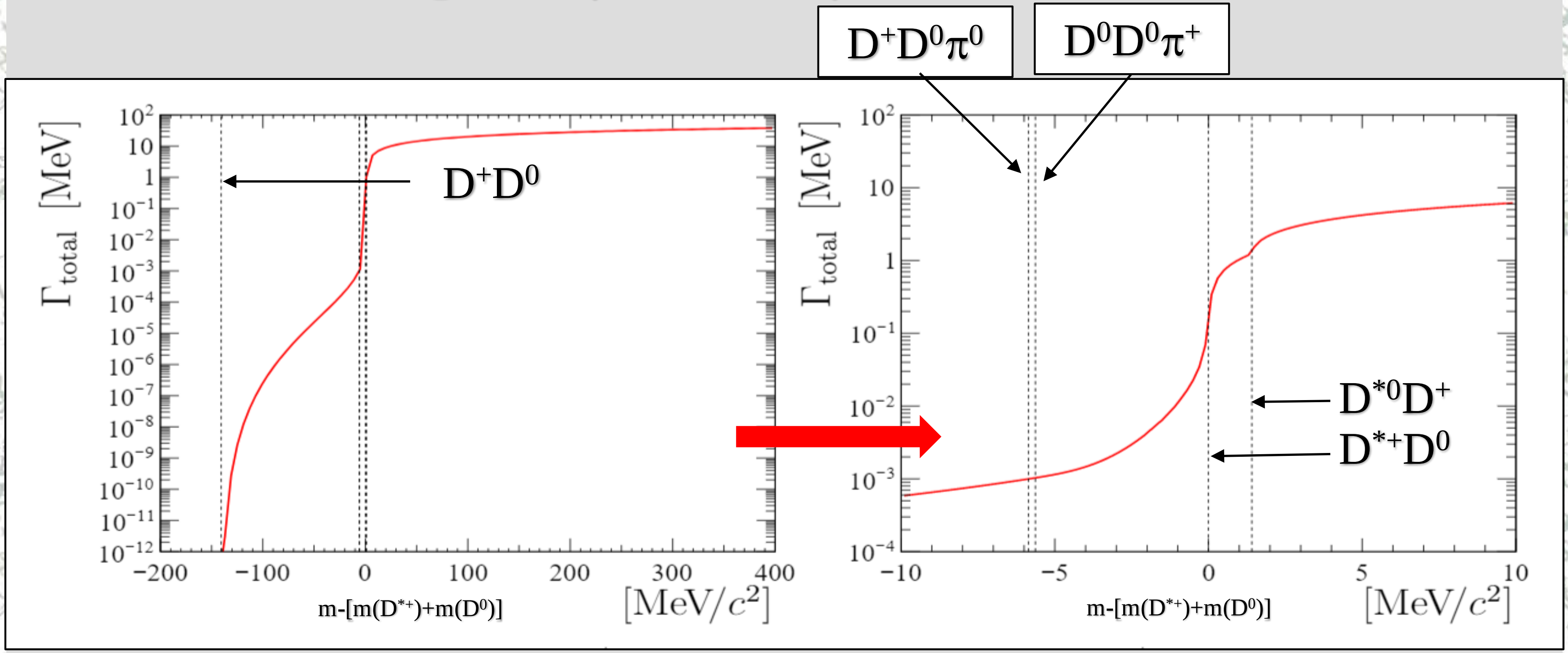
- Direct relation to Ξ_{cc}^{++} ccu

Karliner&Risner, 2017

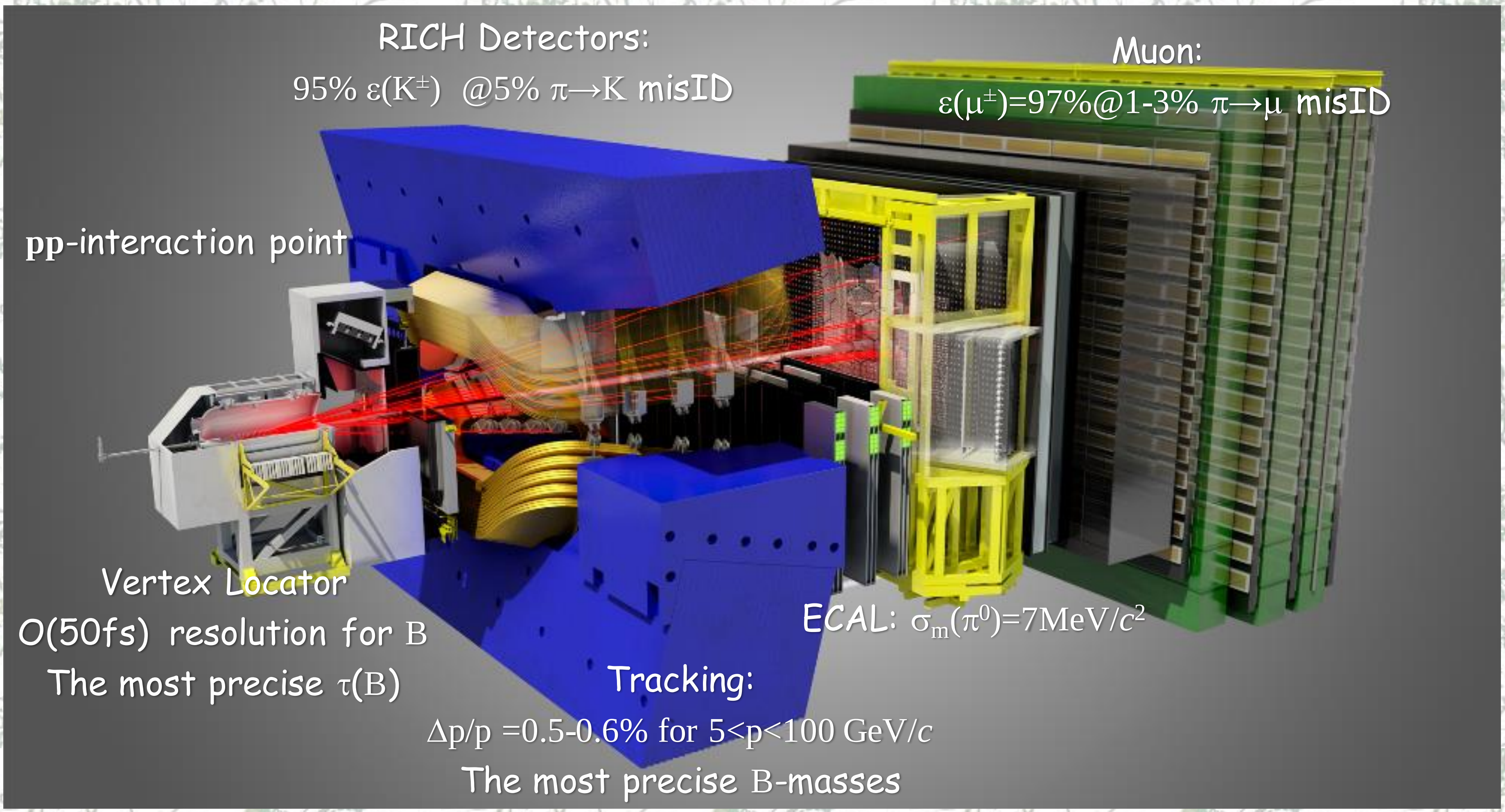


T_{cc}^{+} basic properties

Huge dependency on the mass



~40% of heavy quarks in $<4\%$ of 4π

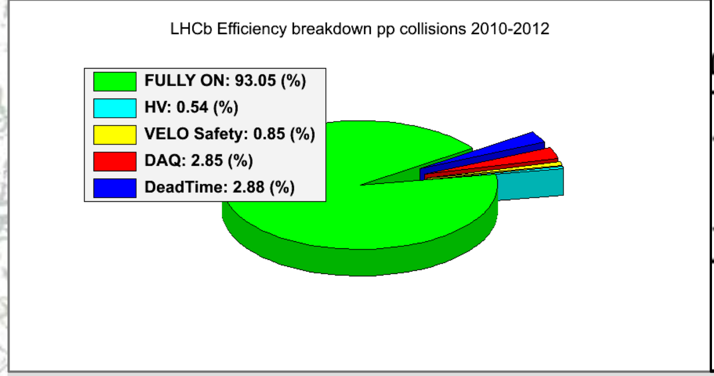


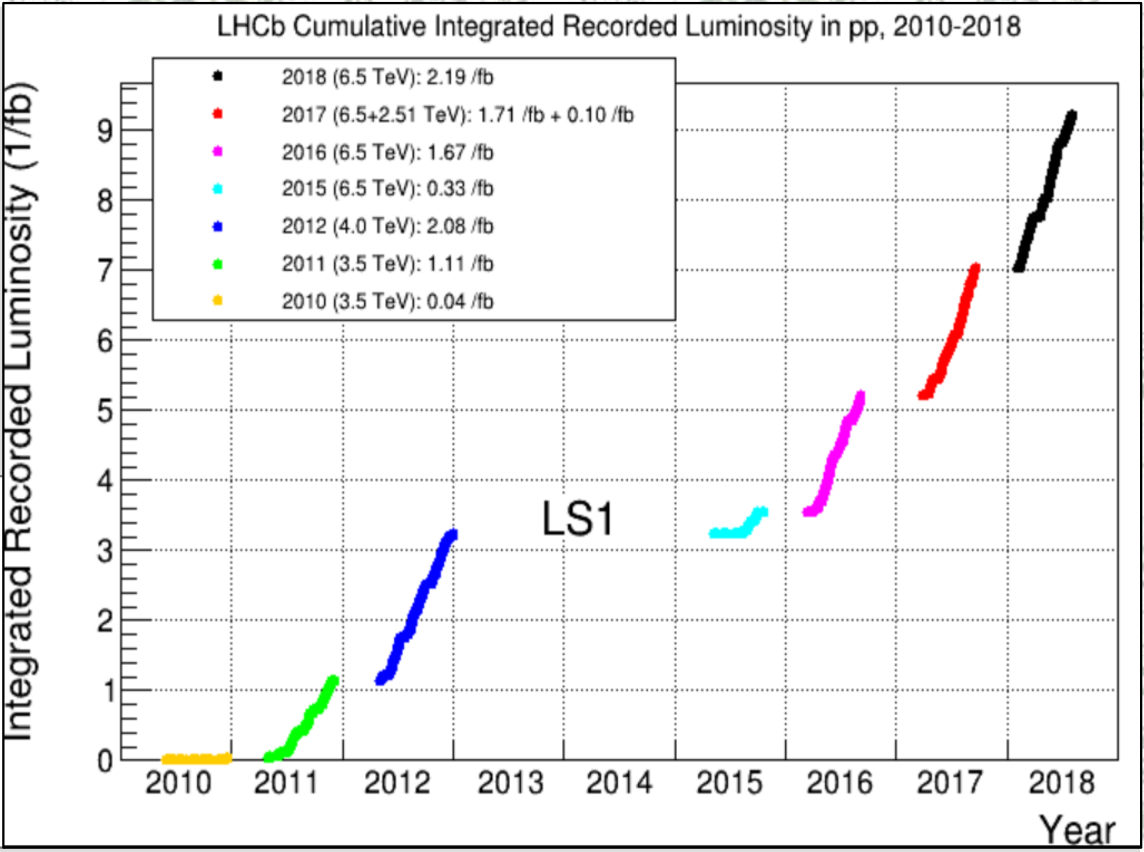
Run I+II

$1 fb^{-1}$@7TeV

$2 fb^{-1}$@8TeV

$8 fb^{-1}$ @13TeV





Thanks to LHC accelerator team for the excellent performance of machine

LHCb is very good for DD and D$\bar{\text{D}}$

JHEP 06 (2012) 141

Observation of double charm production involving open charm in pp collisions at $\sqrt{s} = 7$ TeV

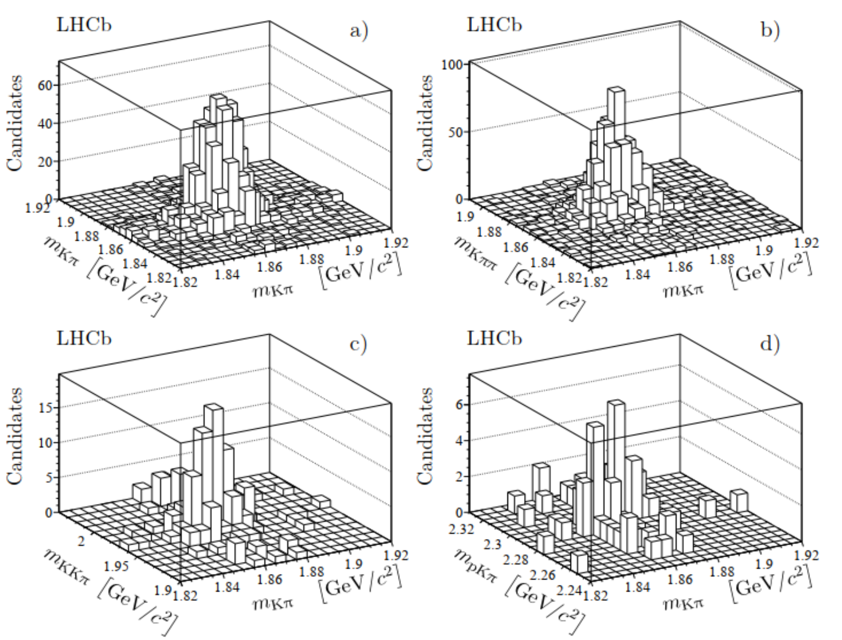


Figure 5: Invariant mass distributions for D^0C candidates: a) D^0D^0, b) D^0D^+, c) $D^0D_s^+$ and d) $D^0\Lambda_c^+$.

JHEP 07 (2019) 035

Near-threshold D$\bar{\text{D}}$ spectroscopy and observation of a new charmonium state $\psi_3(1D)$

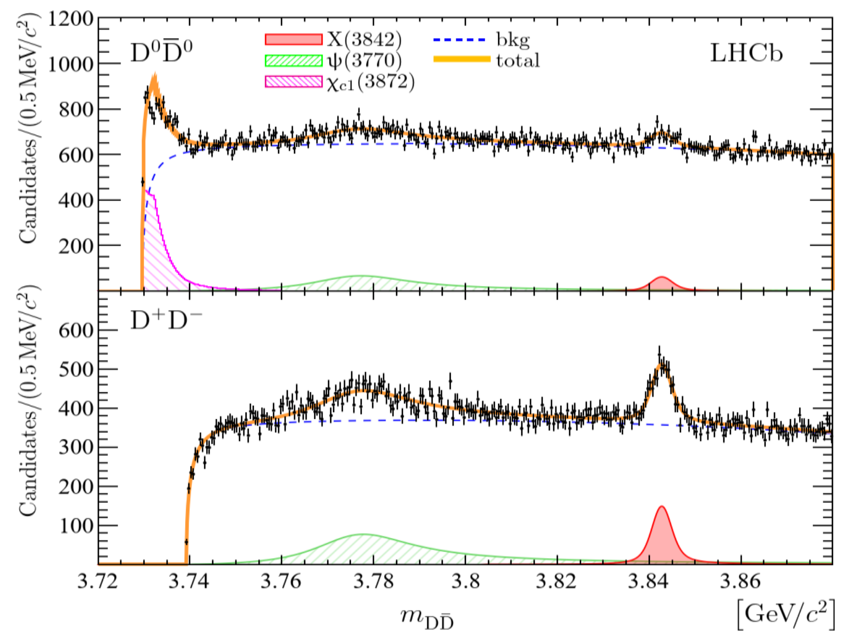
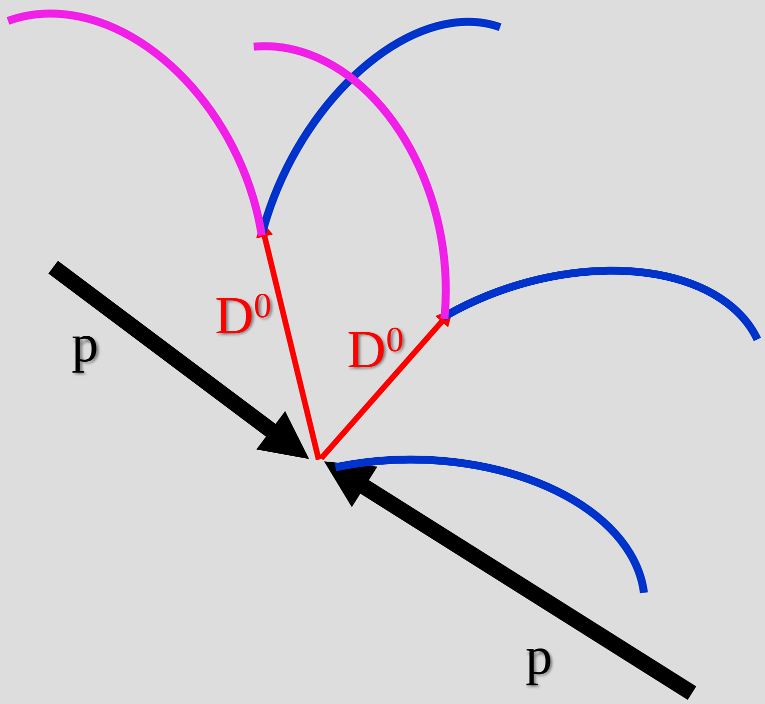


Figure 5: Mass spectra of (top) $D^0\bar{D}^0$ and (bottom) D^+D^- candidates in the near-threshold $m_{D\bar{D}} < 3.88\,\text{GeV}/c^2$ region. The result of the simultaneous fit described in the text is superimposed.

$D^0D^0\pi^+$: Reconstruction & selection

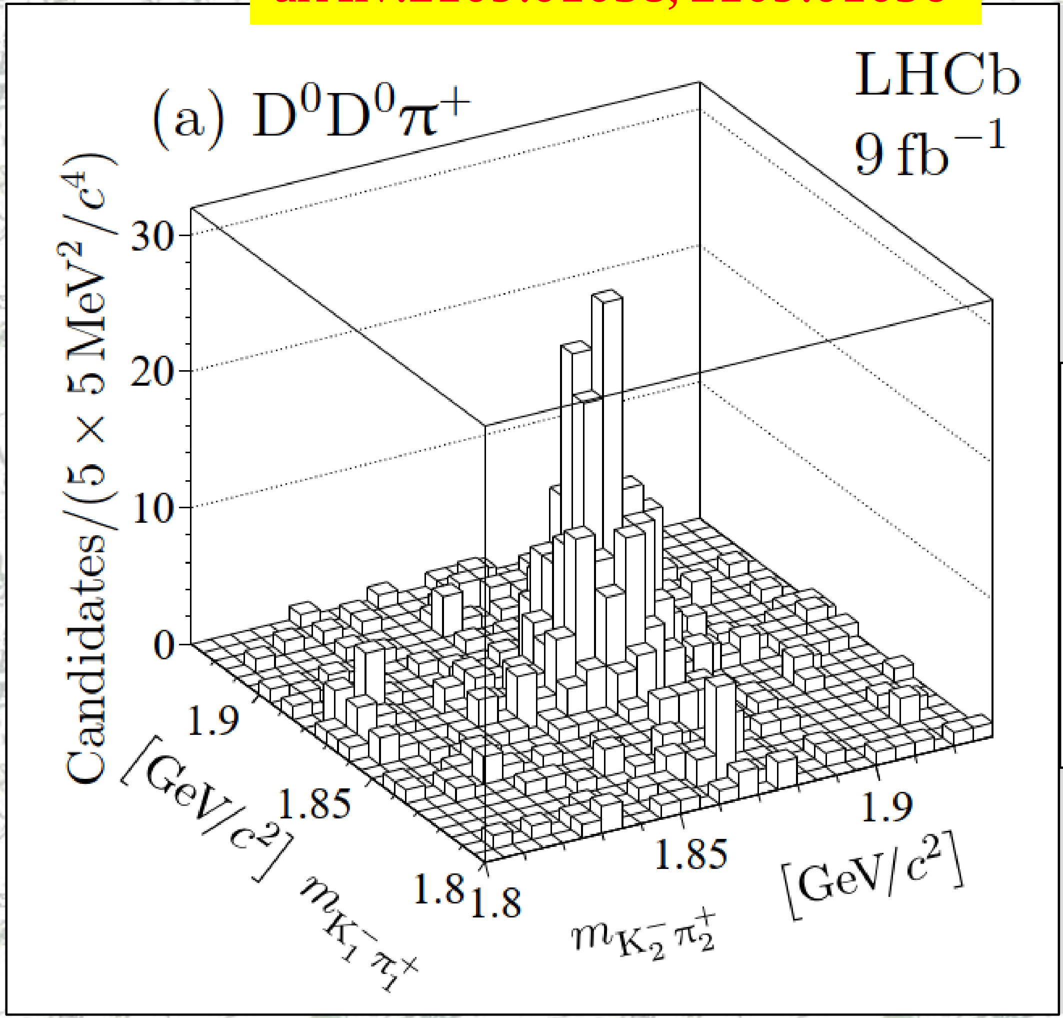
$(D^0 \to K^-\pi^+)\ (D^0 \to K^-\pi^+)\ \pi^+$



- 5 hadron final state
  - 3 pions + 2 kaons
- PID is important (RICH)
- Efficient charm trigger
- Good quality tracks, vertices & PID
- No duplicated tracks
- Finite D^0 lifetime

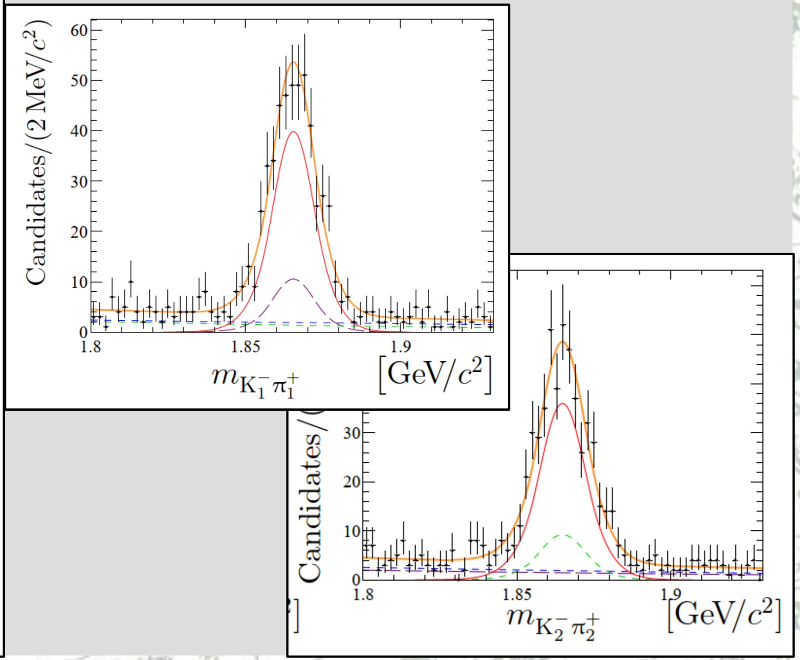
Selected $D^0D^0\pi^+$

arXiv:2109:01038, 2109:01056



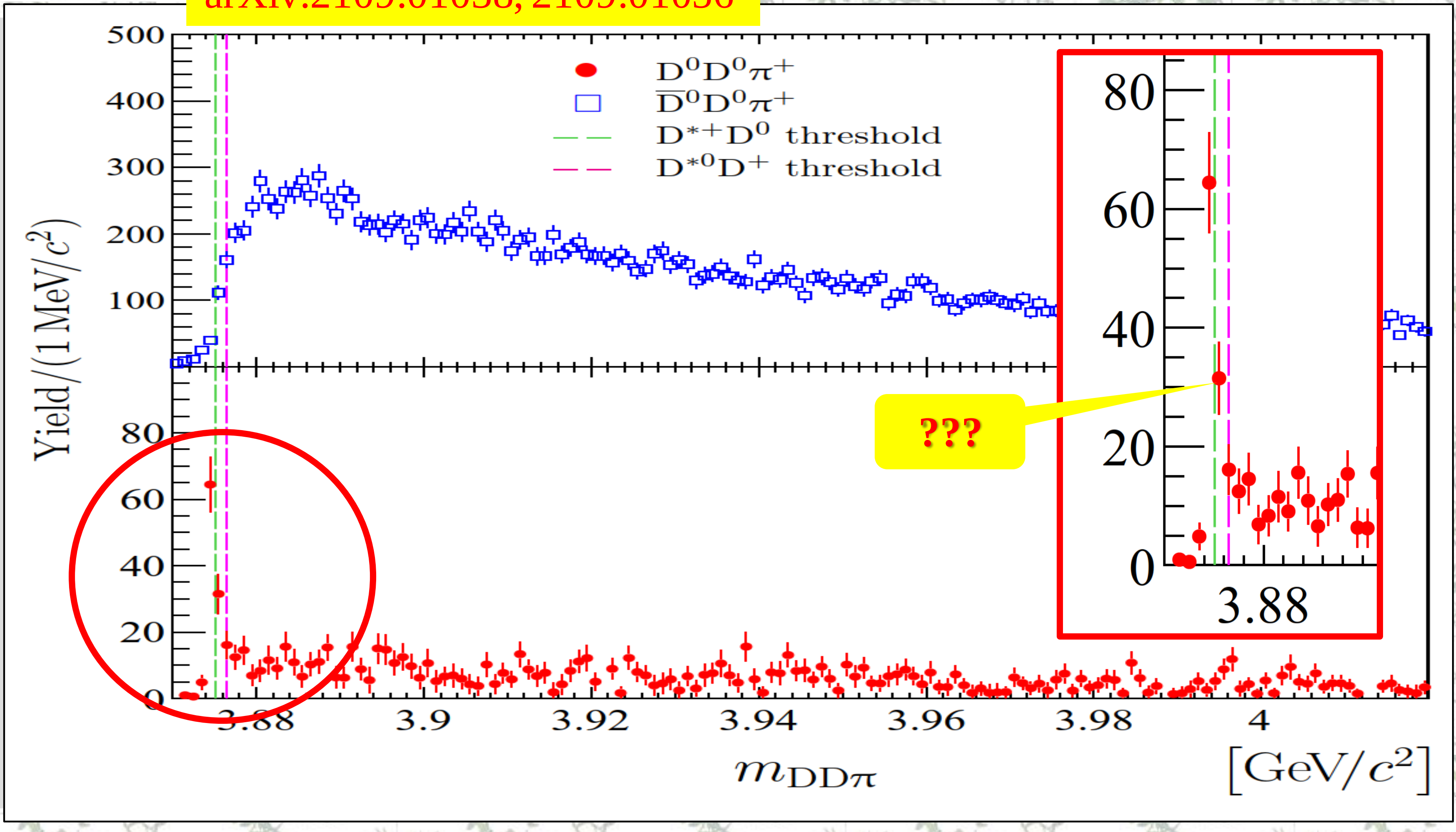
Non D^0 background is small

statistically subtracted using sPlot



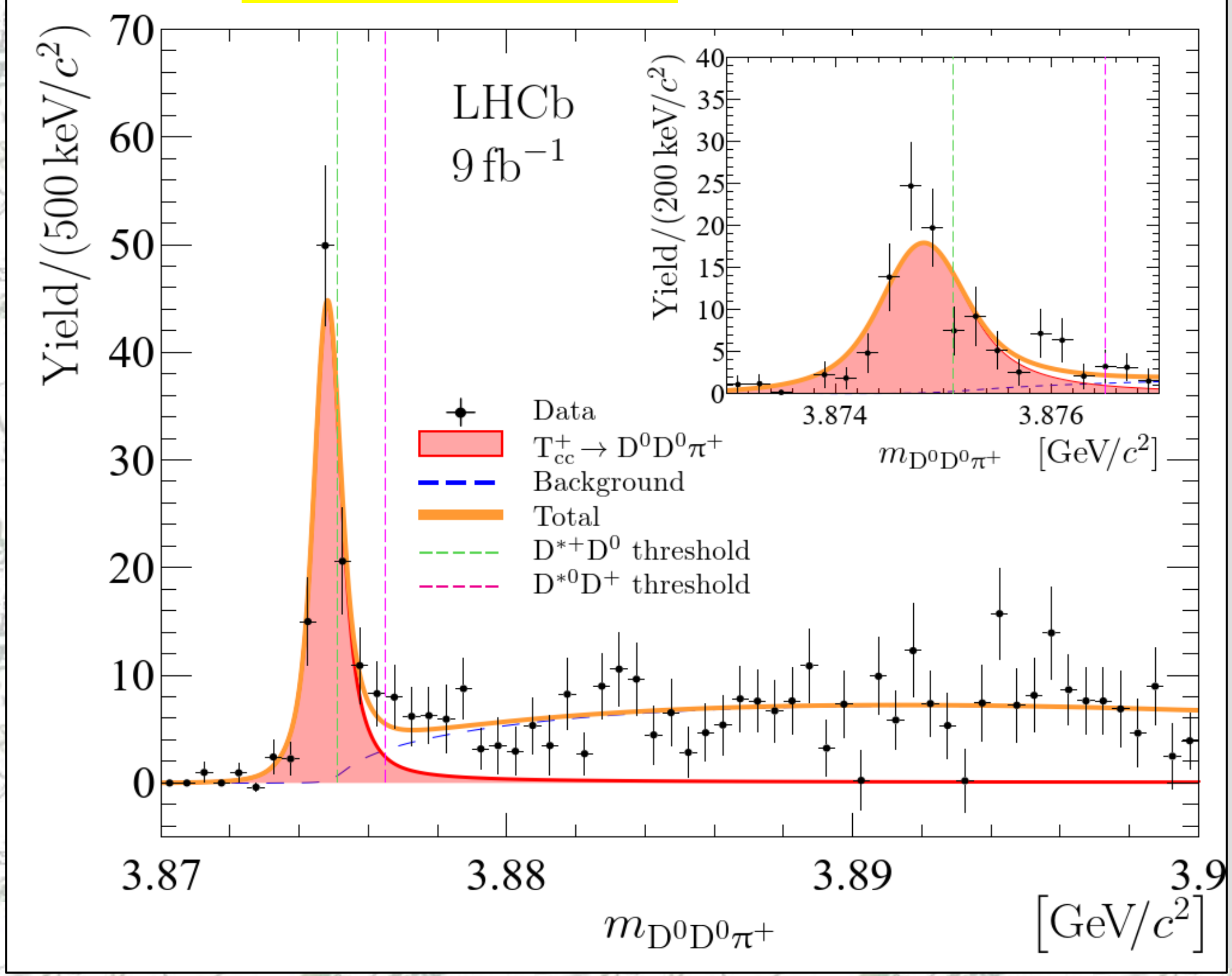
Selected $D^0D^0\pi^+$ vs $D^0\overline{D}^0\pi^+$

arXiv:2109:01038, 2109:01056



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

arXiv:2109:01038



Peak is stable

- Data taking periods
- Data taking conditions
- Dipole magnet polarity
- Charge

~~Reflections~~

~~Fake D^0~~

~~Duplicates~~

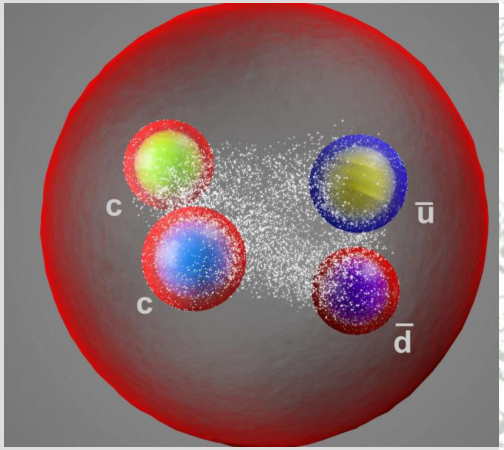
Breit-Wigner fit

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

- Significance 22σ
- $m_{\rm BW}$ below $D^{*+}D^0$ threshold 4.3σ

T_{cc}^{+}

- Narrow, just below $D^{+*}D^{0}$ threshold
  - The most long lived exotics so far
  - Very close to threshold like X(3872)
    - Is it a coincidence?
- Minimal quark content $\mathbf{cc\overline{ud}}$
- Good match to expected T_{cc}^{+}



- To get more information a *physics motivated model* is required instead of Breit-Wigner

Unitarized 3-body Breit-Wigner

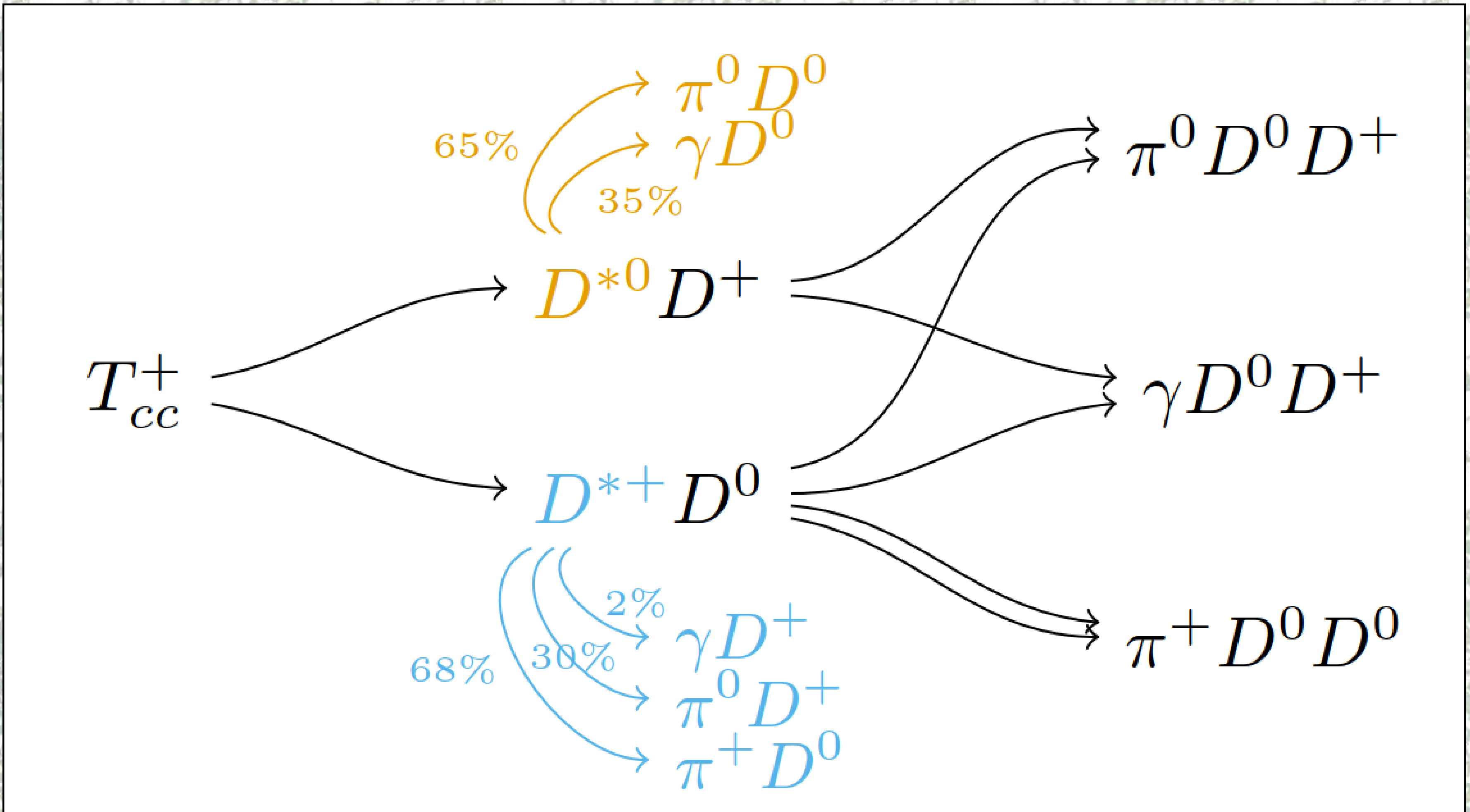
- Build the amplitude $T_{cc}^{+} \rightarrow D^{*}D \rightarrow DD\pi$ or $DD\gamma$
  - T_{cc}^{+} $I(J^{P}) = 0(1^{+})$ $\left|T_{cc}^{+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D^{*+}D^{0}\right\rangle - \left|D^{*0}D^{+}\right\rangle\right)$
  - Isospin coupling to $D^{*}D$ (both $D^{*+}D^{0}$ and $D^{*0}D^{+}$)
  - In vicinity of threshold keep only S-wave $1^{+} \rightarrow 1^{-} + 0^{-}$
  - $D^{*} \rightarrow D\pi$ or $D\gamma$

$$\mathcal{A}^{\mathrm{S-wave}}_{\mathrm{T_{cc}^{+}\rightarrow D^{*+}D^{0}}} = +\frac{g}{\sqrt{2}}\epsilon_{\mathrm{T_{cc}^{+}}\mu}\epsilon^{*\mu}_{\mathrm{D^{*}}}$$
$$\mathcal{A}^{\mathrm{S-wave}}_{\mathrm{T_{cc}^{+}\rightarrow D^{*0}D^{+}}} = -\frac{g}{\sqrt{2}}\epsilon_{\mathrm{T_{cc}^{+}}\mu}\epsilon^{*\mu}_{\mathrm{D^{*}}}$$

- *All constants and parameters are taken from D^{*} decay widths*
- *Unknowns: the mass and $|g|$*

- *Calculate $T_{cc}^{+} \rightarrow D^{*}D \rightarrow DD\pi$ or $DD\gamma$ decay widths as functions of mass*
  - 3-body phase space functions ρ

Model



Actual branchings are functions of T_{cc}^+ mass (and shape)

Amplitude

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

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

- Self energy

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

Unitarity

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

Analiticity

Causality

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

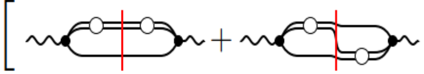
2 parameters

mass $\mathrm{m_U}$

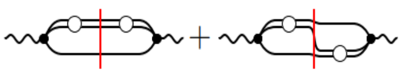
coupling $|\mathrm{g}|$

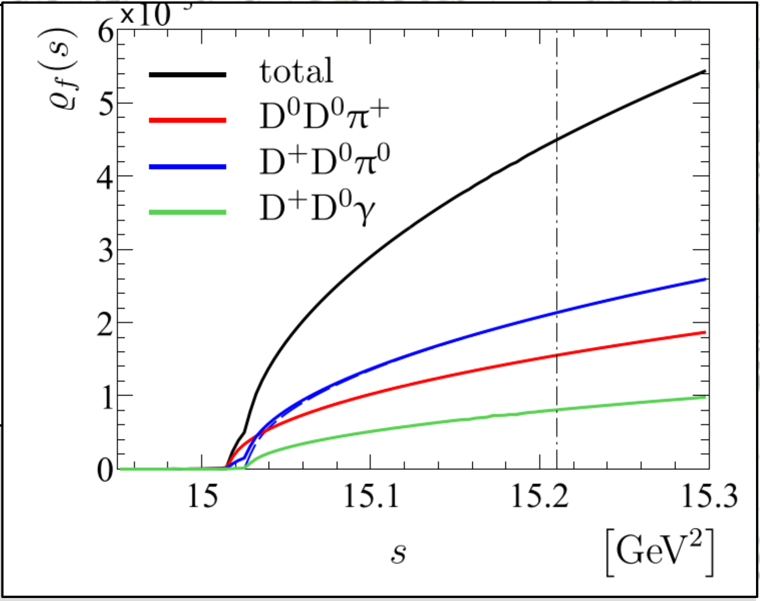
Amplitude

$$A(s) = \frac{|g|^2}{m^2 - s - i|g|^2/2\left[\ \ \right]}$$



$$\mathrm{Im}\left[\ \ \right] = \varrho_{\mathrm{tot}}.$$





Unitarity

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

$$\varrho_{\mathrm{tot}}\ (s) \equiv \sum_f \varrho_f\ (s)\ .$$

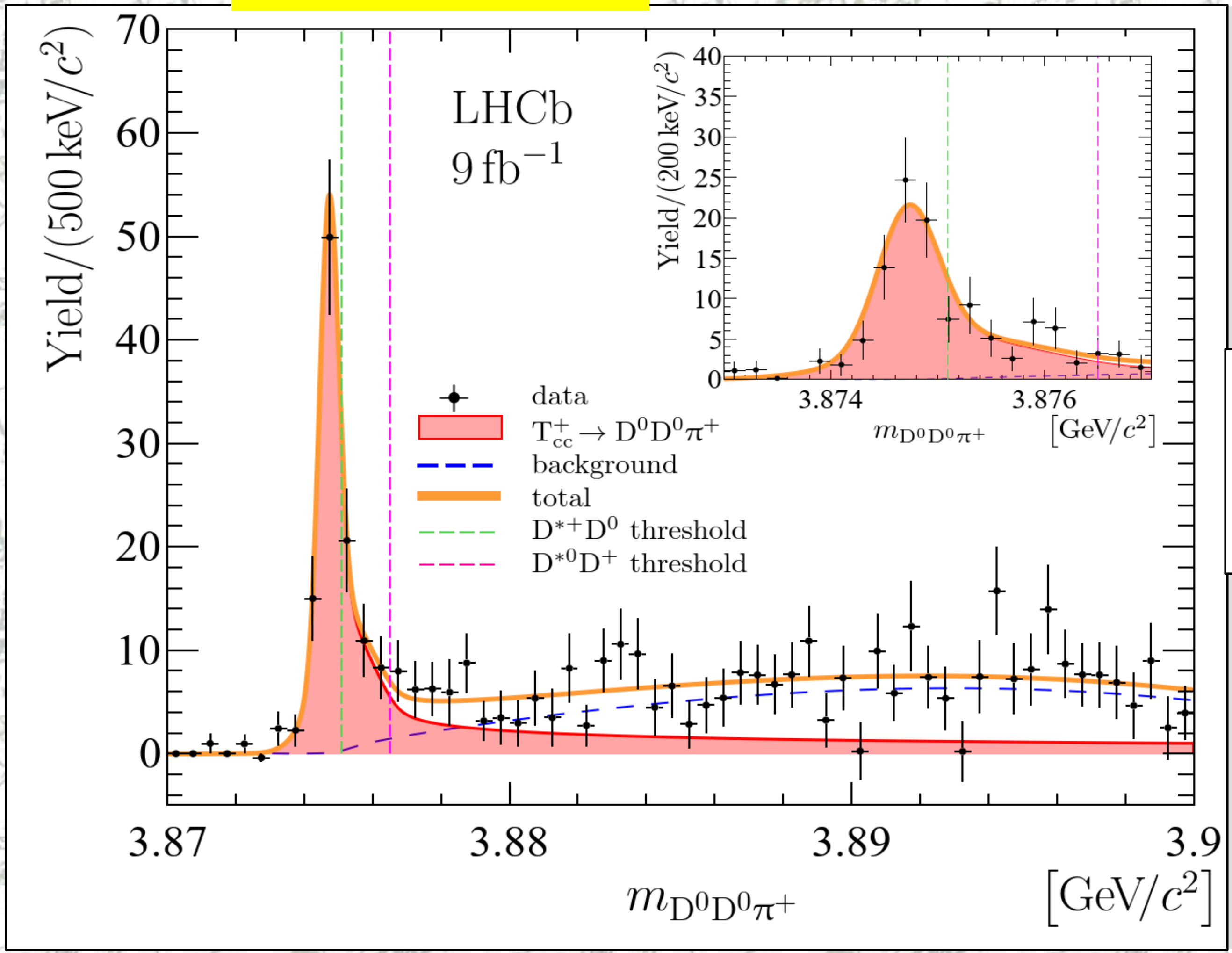
Casuality

$$\Re\,\Sigma(s)|_{\Im s=0^+} = \xi(s) - \xi(m_{\mathrm{U}}^2)\ ,$$

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

Fit with advanced model

arXiv:2109:01056



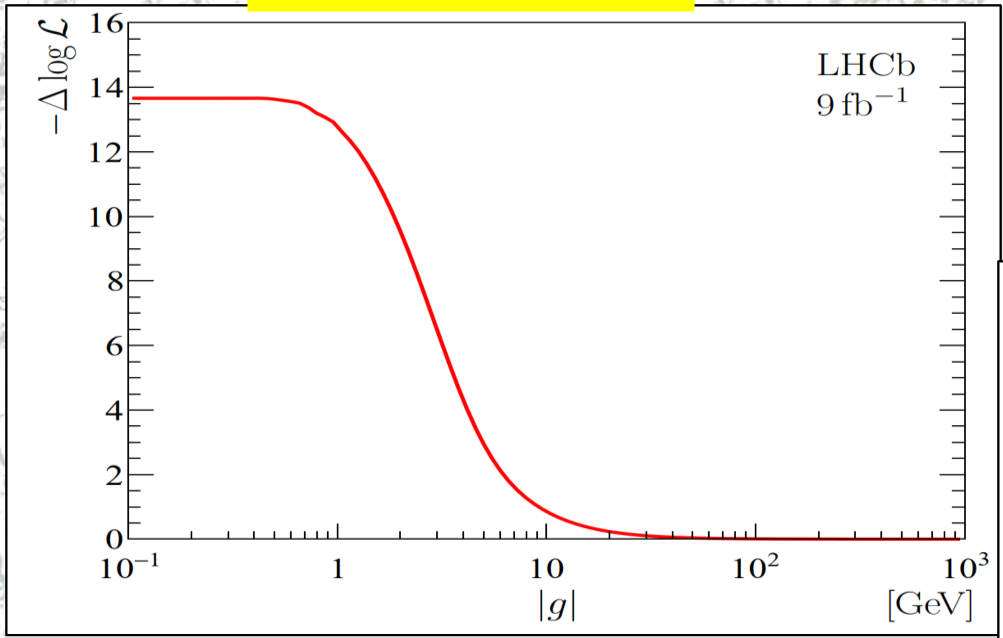
- *Better description*
- *Asymmetric shape*
- Heavy tail

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

- Significance 22σ
- m_U below $D^{*+}D^0$ threshold 9σ

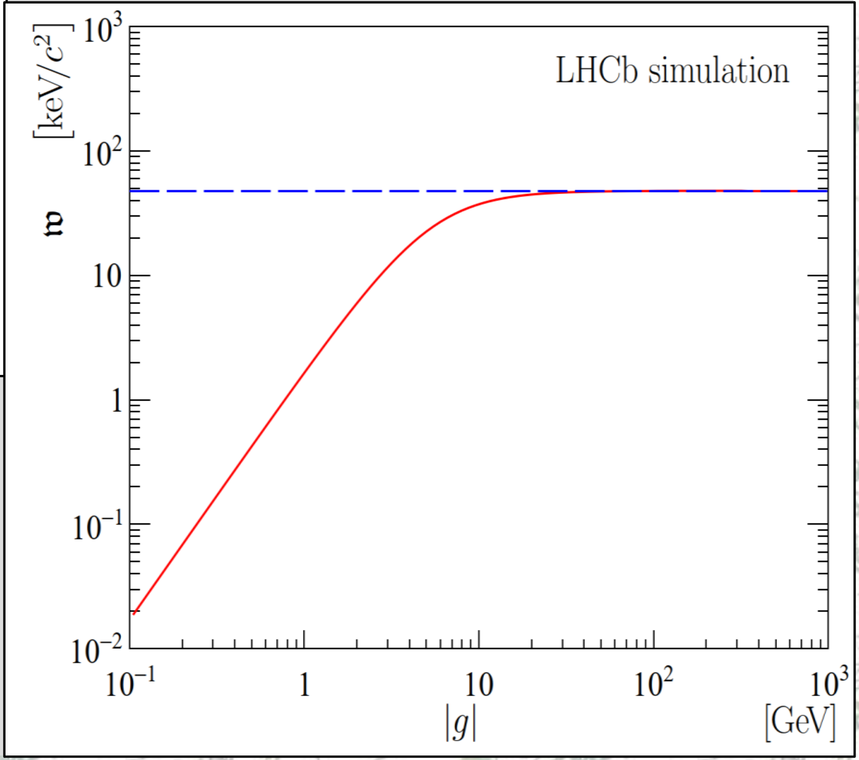
What about |g| ?

arXiv:2109:01056



Fit claims |g| is not small

$$|g| > 7.7\ (6.2)\ \text{GeV}$$

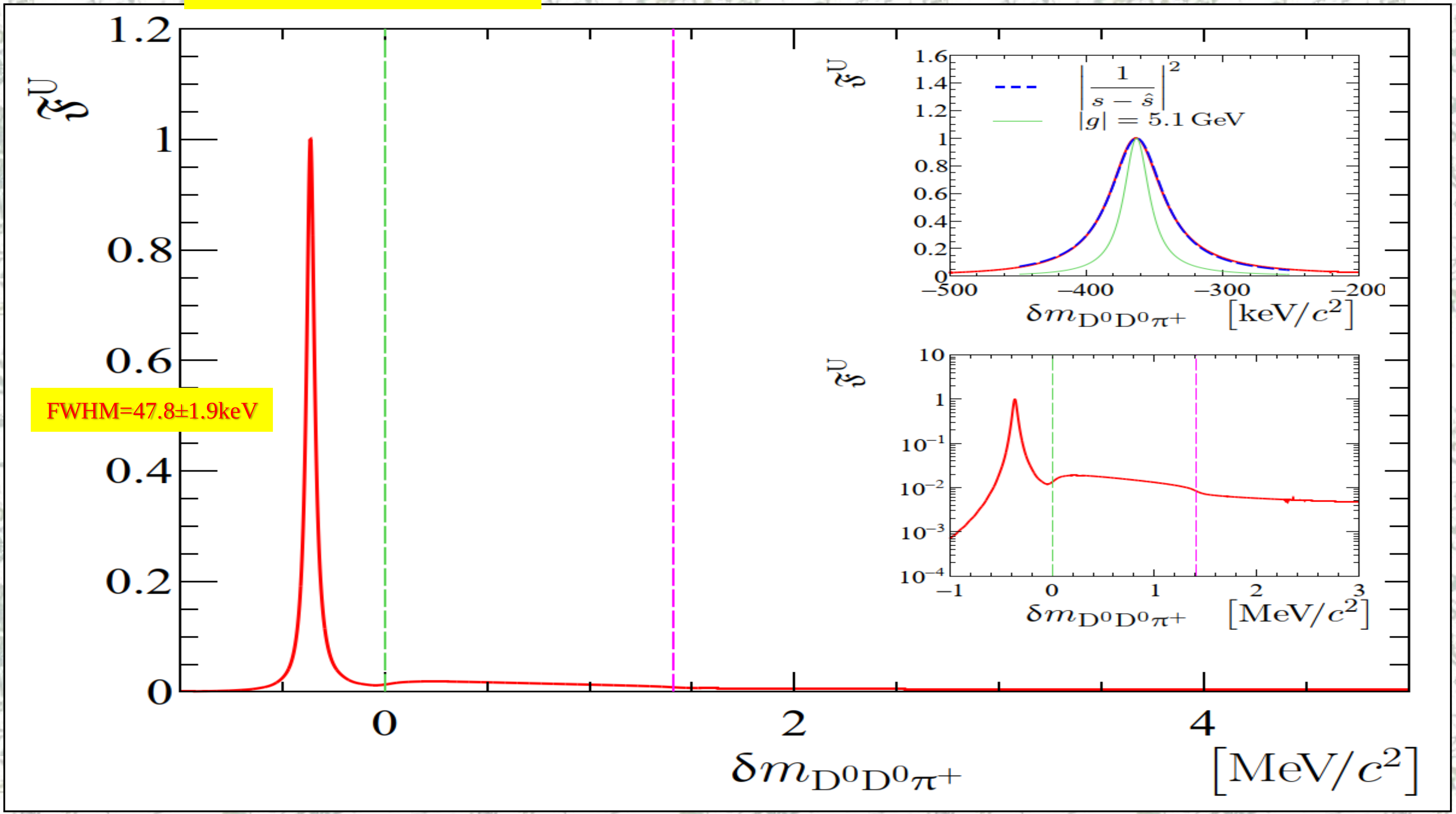


The model exhibits *Flatte-like* scaling: for large |g| visible widths/FWHM is in saturation

FWHM=47.8±1.9keV

Mass shape (remove resolution)

arXiv:2109:01056



Systematic for mass parameter

arXiv:2109:01056

- Vary resolution
- Vary correction factor
- Alternative background
- Coupling constants
  - D^* parameters
- Smaller values of |g|
- Momentum scale
- Energy loss
  - Amount of material

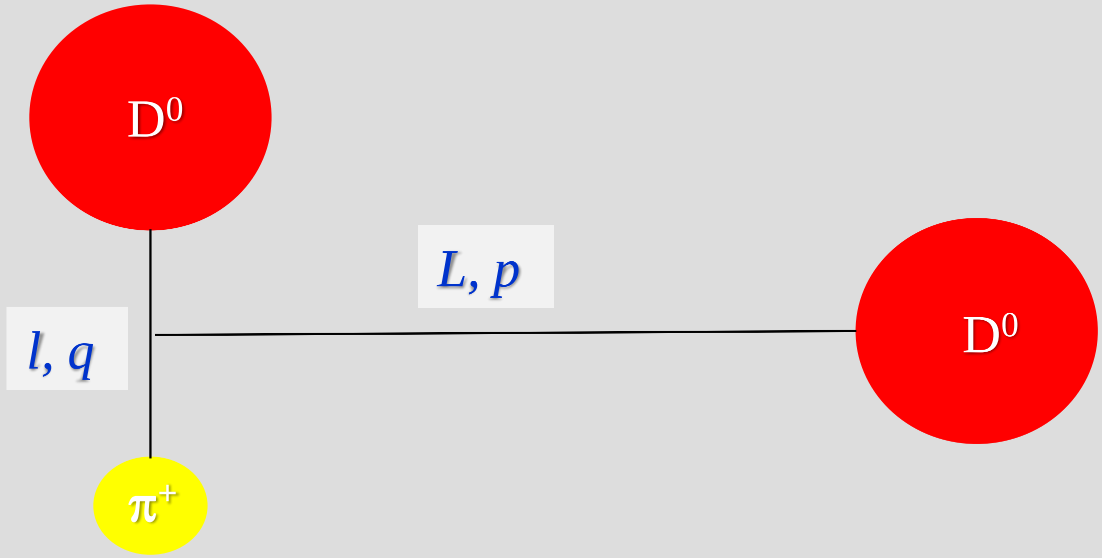
$$\delta m_{\mathrm{U}} = -359 \pm 40\,^{+\,9}_{-\,6}\,\mathrm{keV}/c^2$$

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

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

What else can we say about T_{cc}^{+} ?

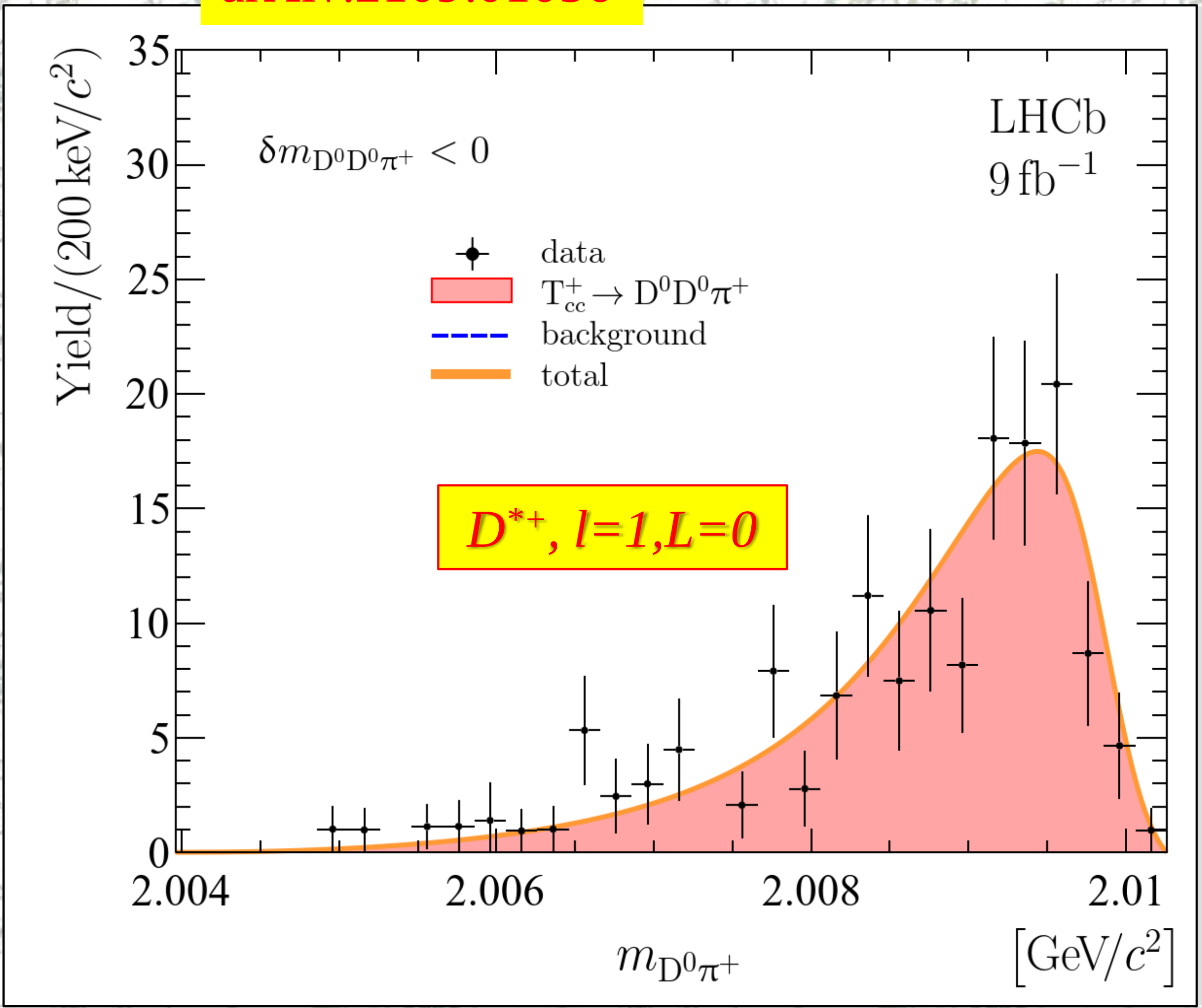
- Three body final state $D^0D^0\pi^+$



- l and L define J^P quantum numbers
- Can we measure them?

$D^0\pi^+$ mass spectrum

arXiv:2109:01056



$D^0D^0\pi^+$ below $D^{*+}D^0$ threshold

$D^0\pi^+$ mass spectrum depends on the decay dynamic.

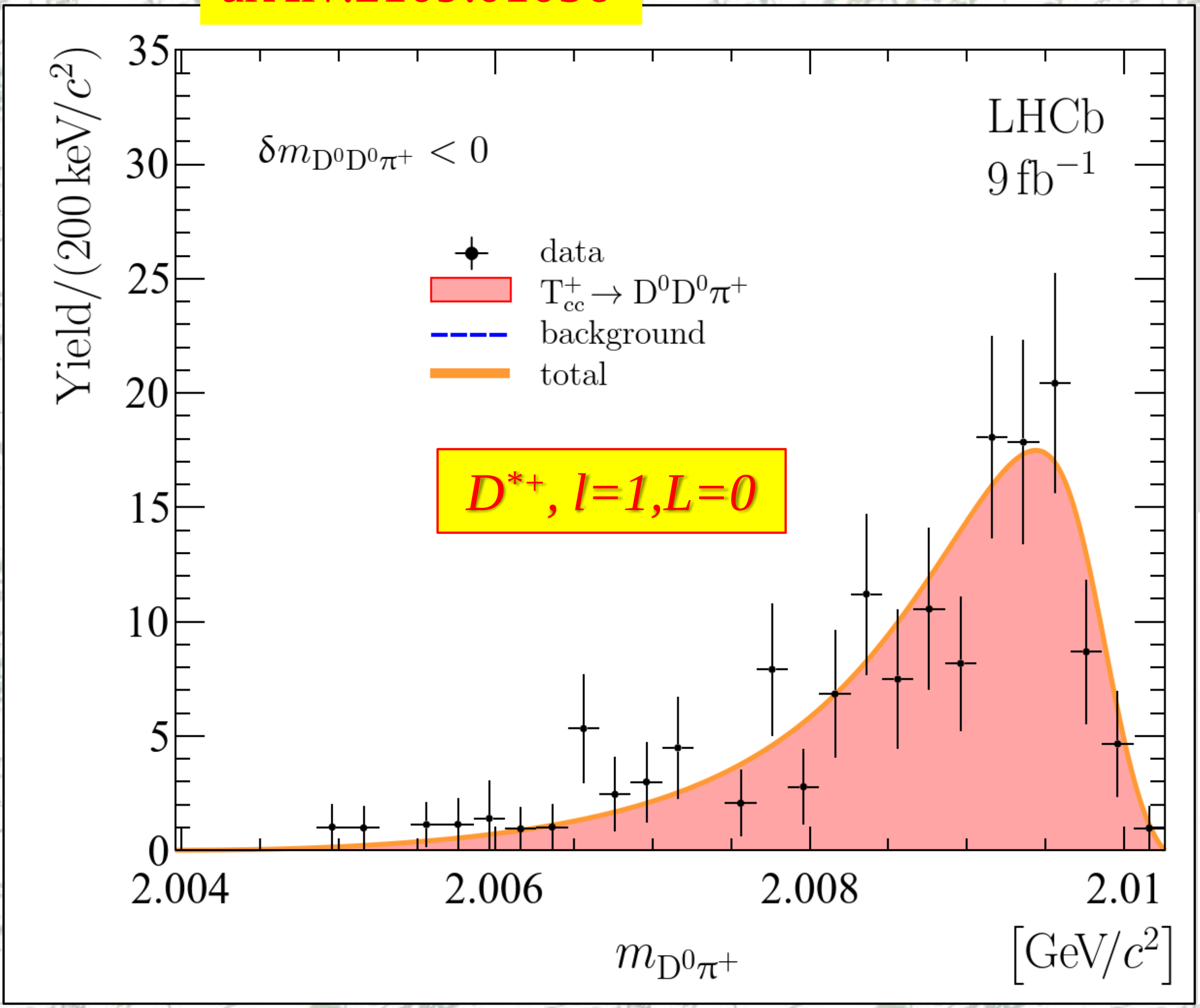
Perfect agreement with our model

3 main features

- D^{*+} propagator
- q^{2l+1} at left edge
- p^{2L+1} at right edge
- … + resolution

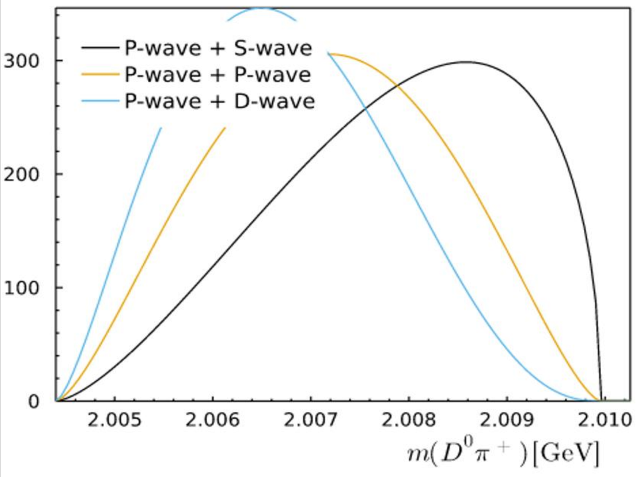
$D^0\pi^+$ mass spectrum: D^{*+} and *l*

arXiv:2109:01056



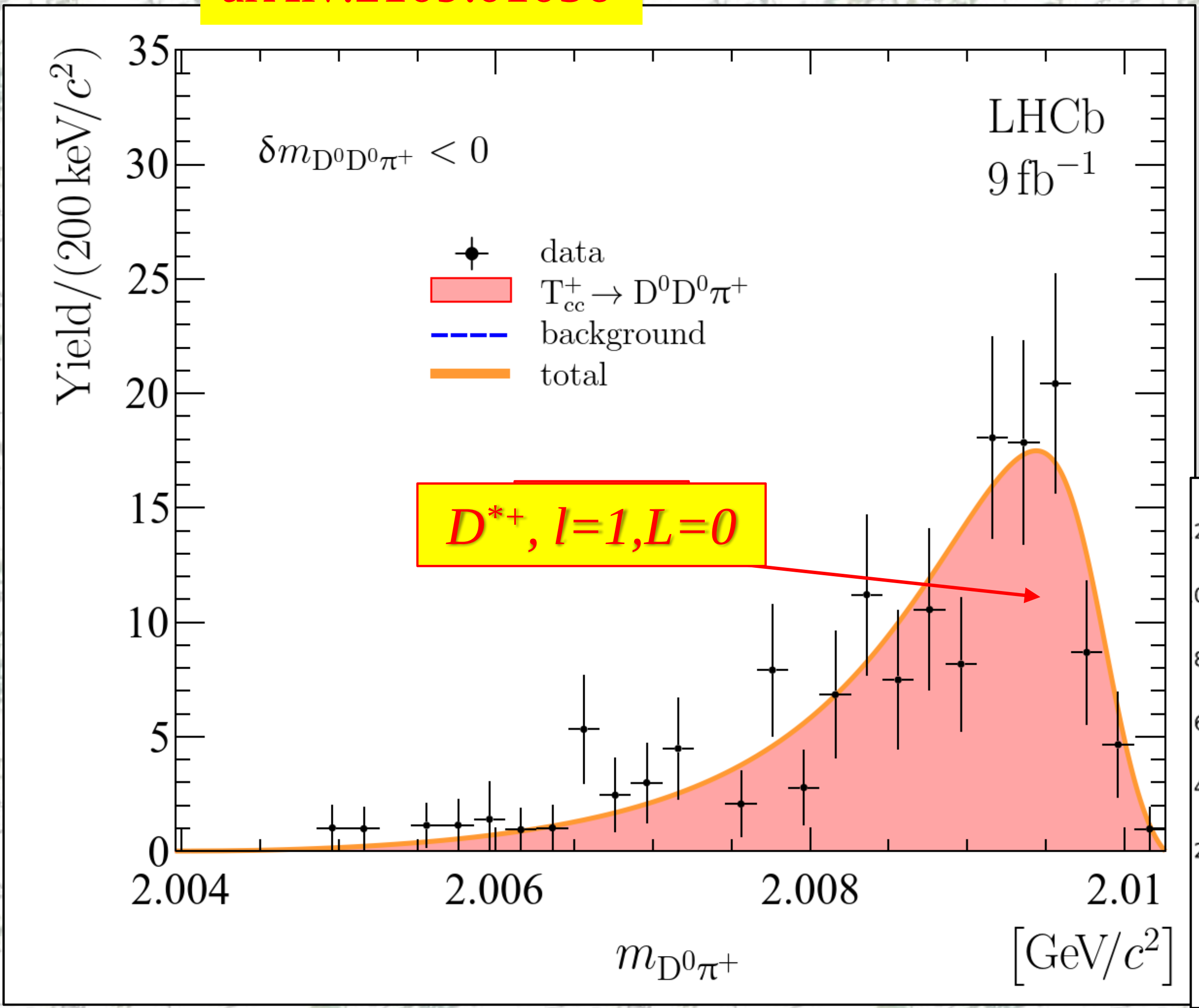
3 main features

- ***D^{*+} propagator***
- q^{2l+1} at left edge
- p^{2L+1} at right edge
- … + resolution
- … + interference



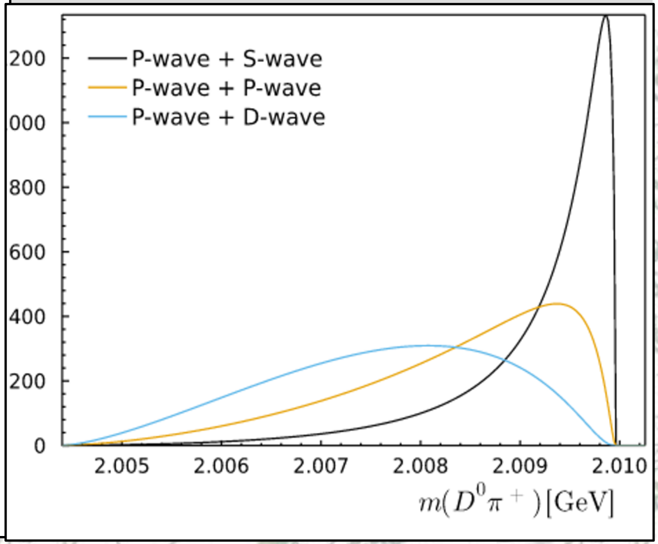
$D^0\pi^+$ mass spectrum: *L*

arXiv:2109:01056



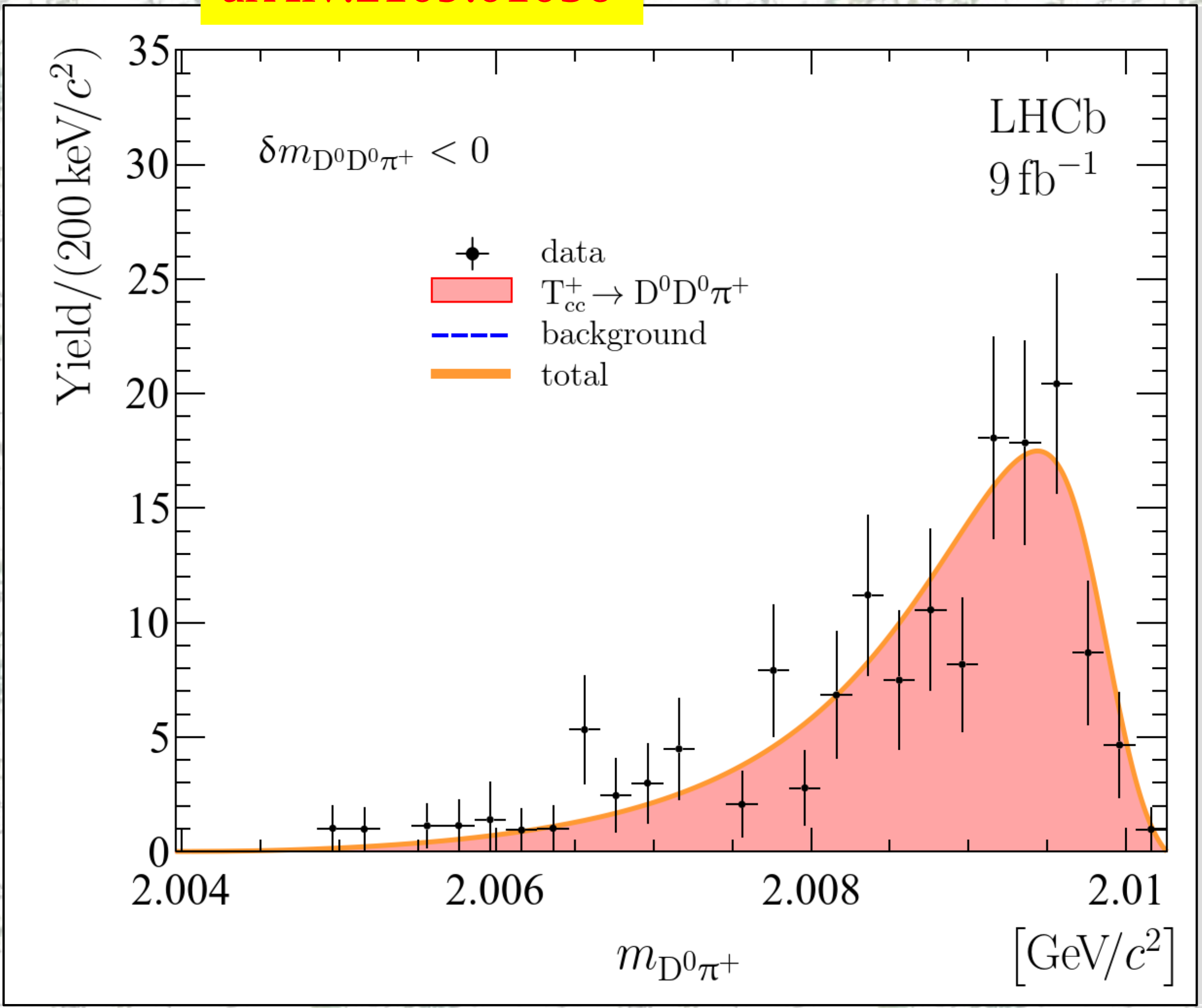
3 main features

- ***D^{*+} propagator***
- q^{2l+1} at left edge
- p^{2L+1} at right edge
- … + *resolution*
- … + *interference*



$D^0\pi^+$ mass spectrum: quantum numbers

arXiv:2109:01056



- T_{cc}^+ decays via intermediate *off-shell* D^{*+} meson

  ***l* = 1**

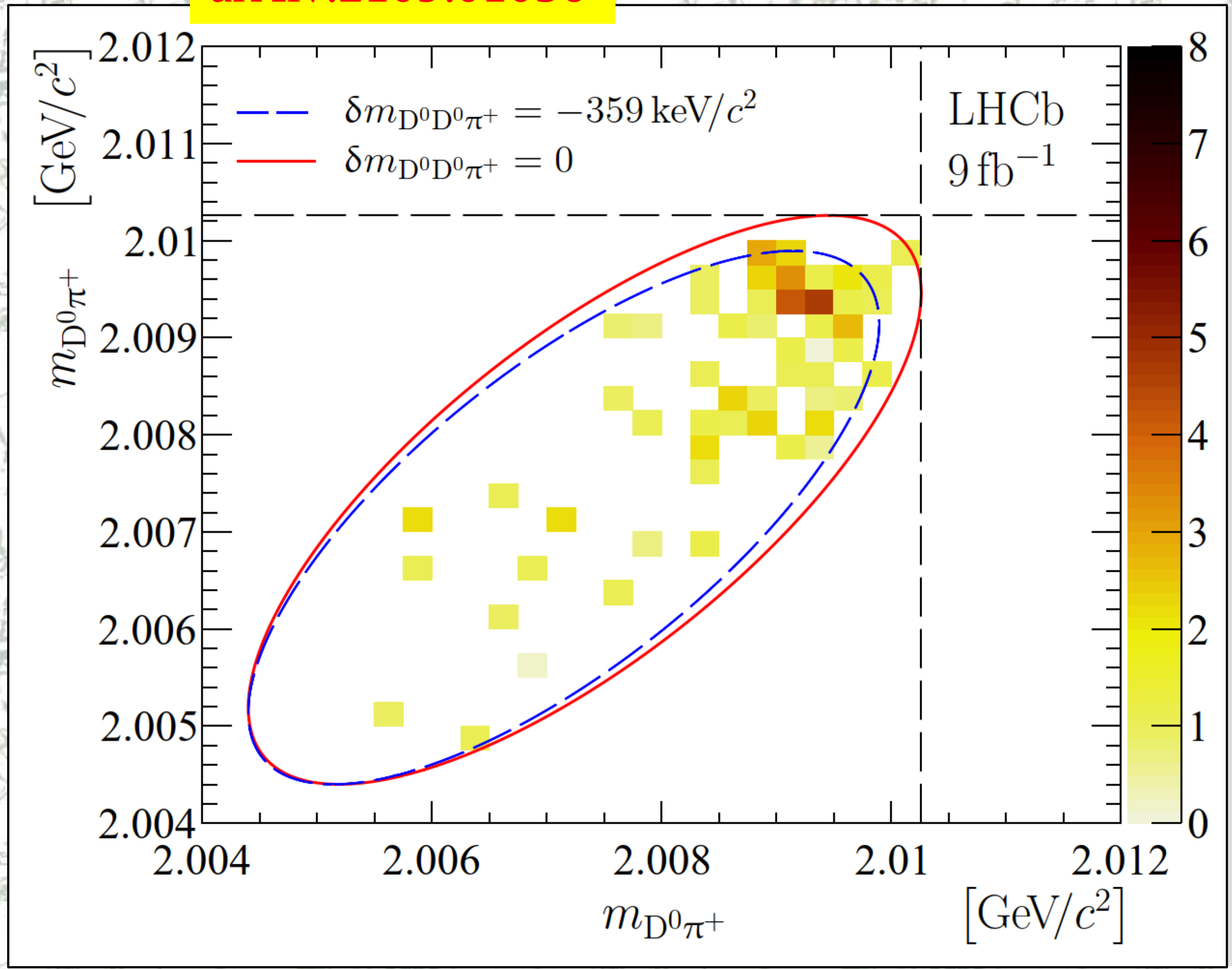
- ***L*=0** is largely favored

J^P = 1+

- Spectrum is in perfect agreement with our model for $I(J^P)=0(1^+)$ $T_{cc}^+ \to D^*D$ decays.

$D^0D^0\pi^+$ Dalitz plot

arXiv:2109:01056



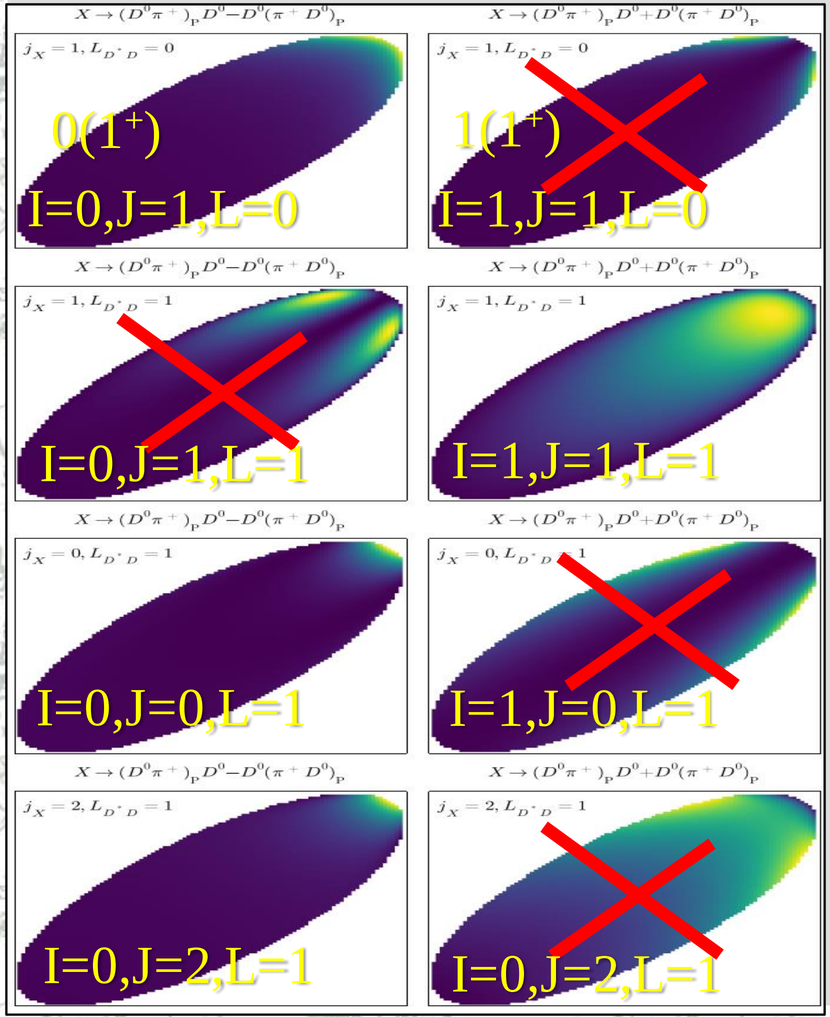
$D^0D^0\pi^+$ below $D^{*+}D^0$ threshold

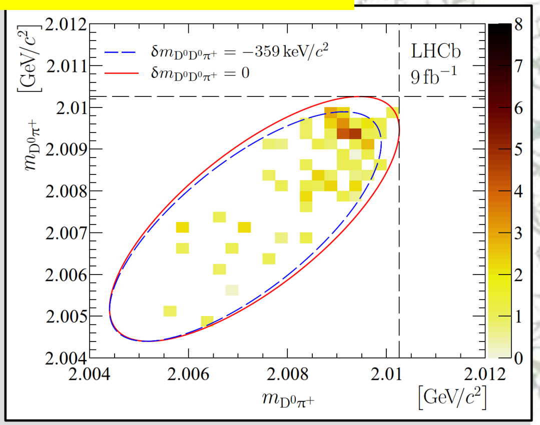
All quantum numbers can be determined from Dalitz plot analysis

- For future
- ☹ Treatment of resolution is not trivial

$D^0D^0\pi^+$ Dalitz plot

arXiv:2109:01056

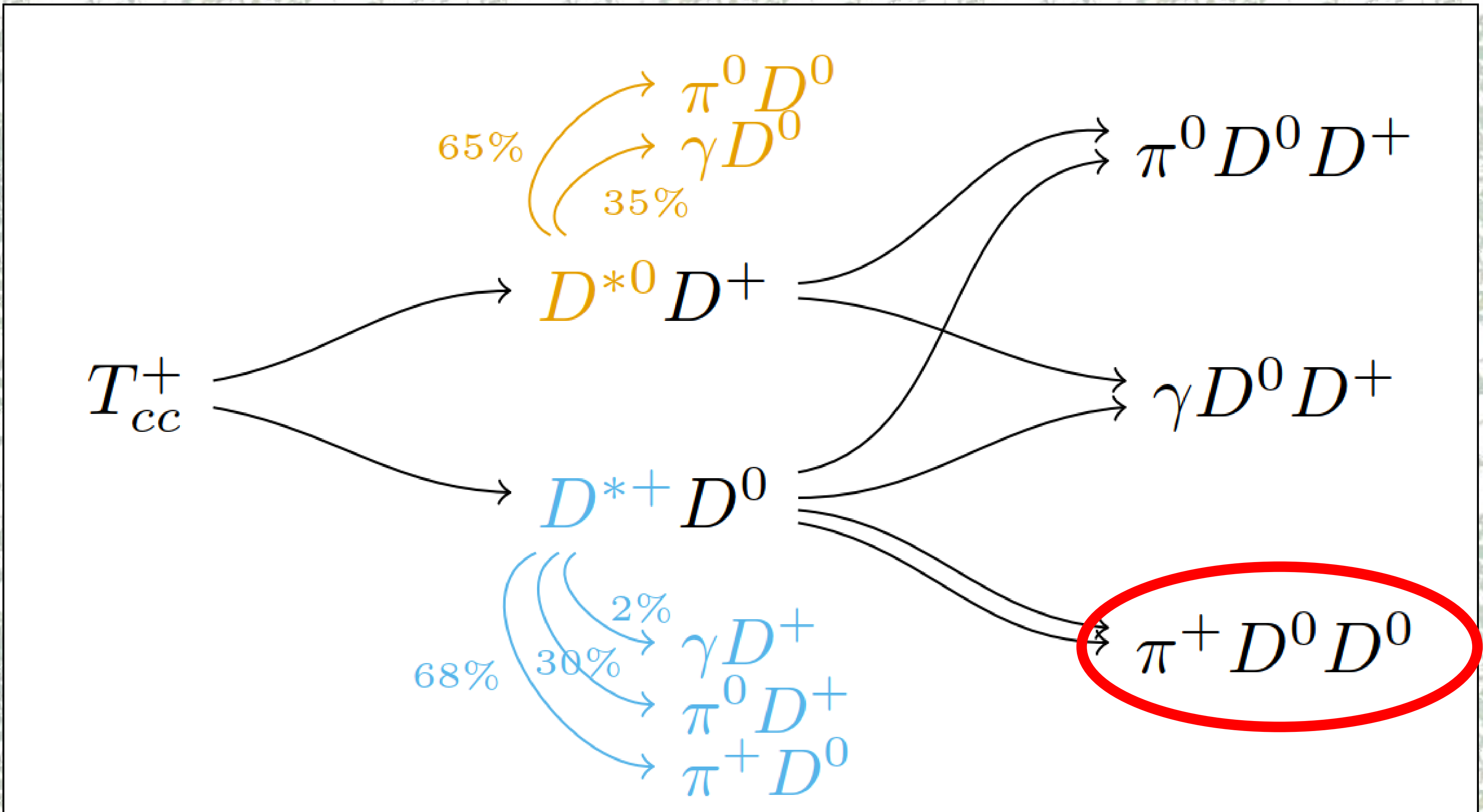




- Complete Dalitz plot analysis for future
  - Need more events
  - Treatment of resolution is not trivial

- However some variants (including isospin) can be excluded already now

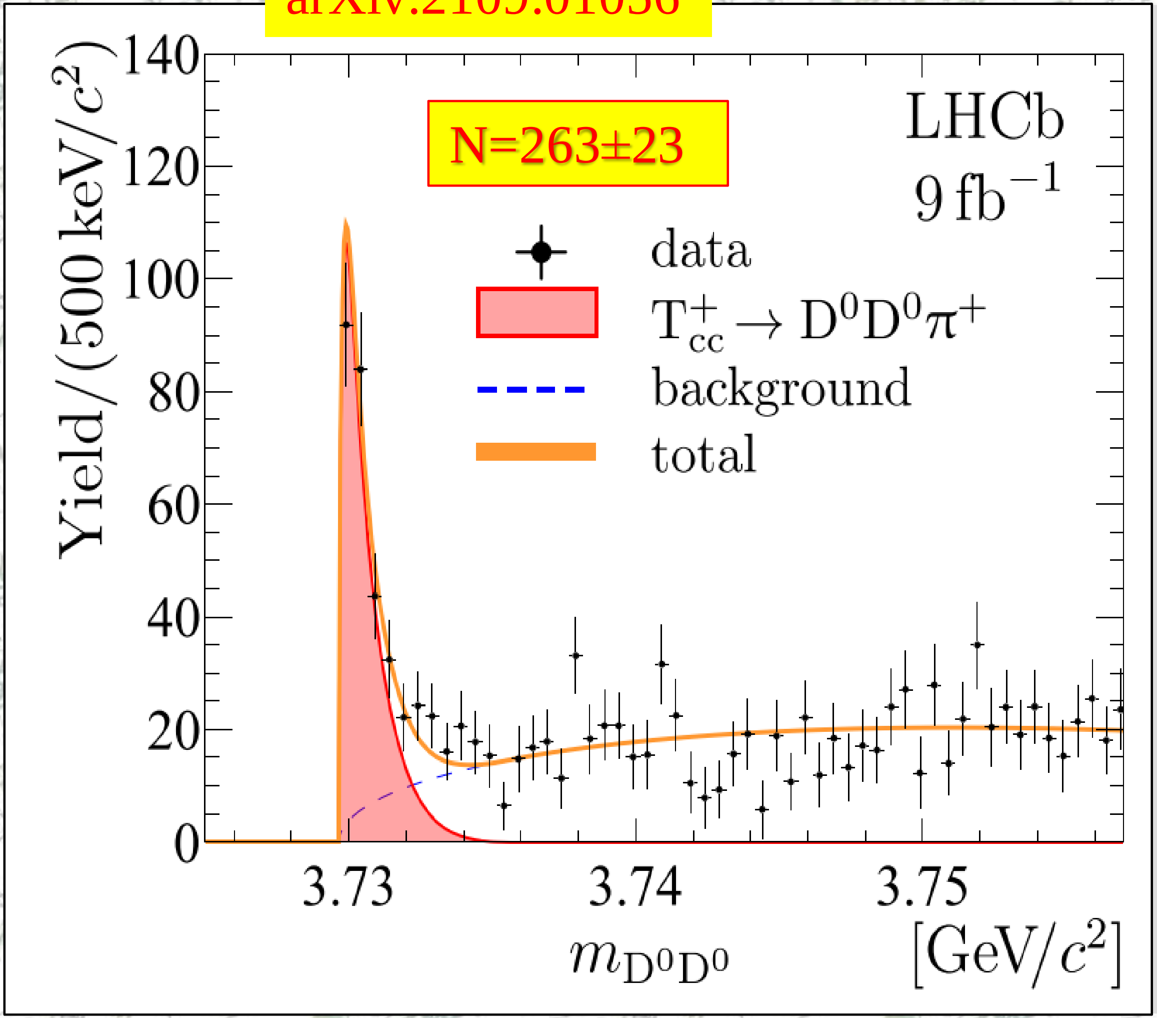
Model



Actual branchings are functions of T_{cc}^{+} mass (and shape)

D^0D^0 from $T_{cc}^+ \to D^*D$

arXiv:2109:01056

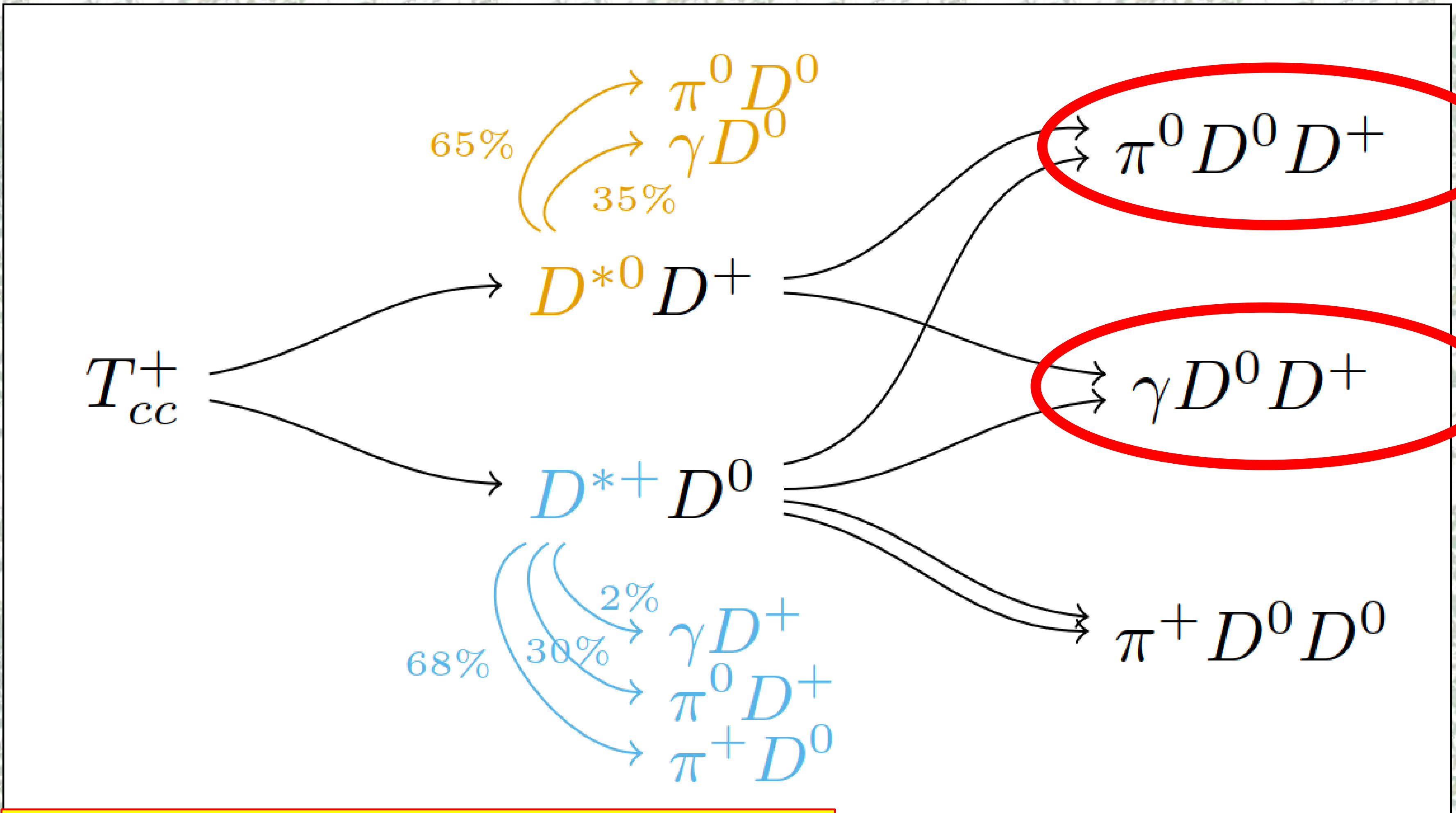


- Energy release in $D^{*+} \to D^0\pi^+$ is very small
- D^0D^0 from $T_{cc}^+ \to D^*D$ form a narrow near-threshold peak
- Exact shape depend on the $T_{cc}^+ \to D^*D$ decay dynamics

Select inclusive prompt D^0D^0

- Excellent agreement with our 0(1+) T_{cc}^+ decay model
  - in shape
  - in number
- Significance >20σ

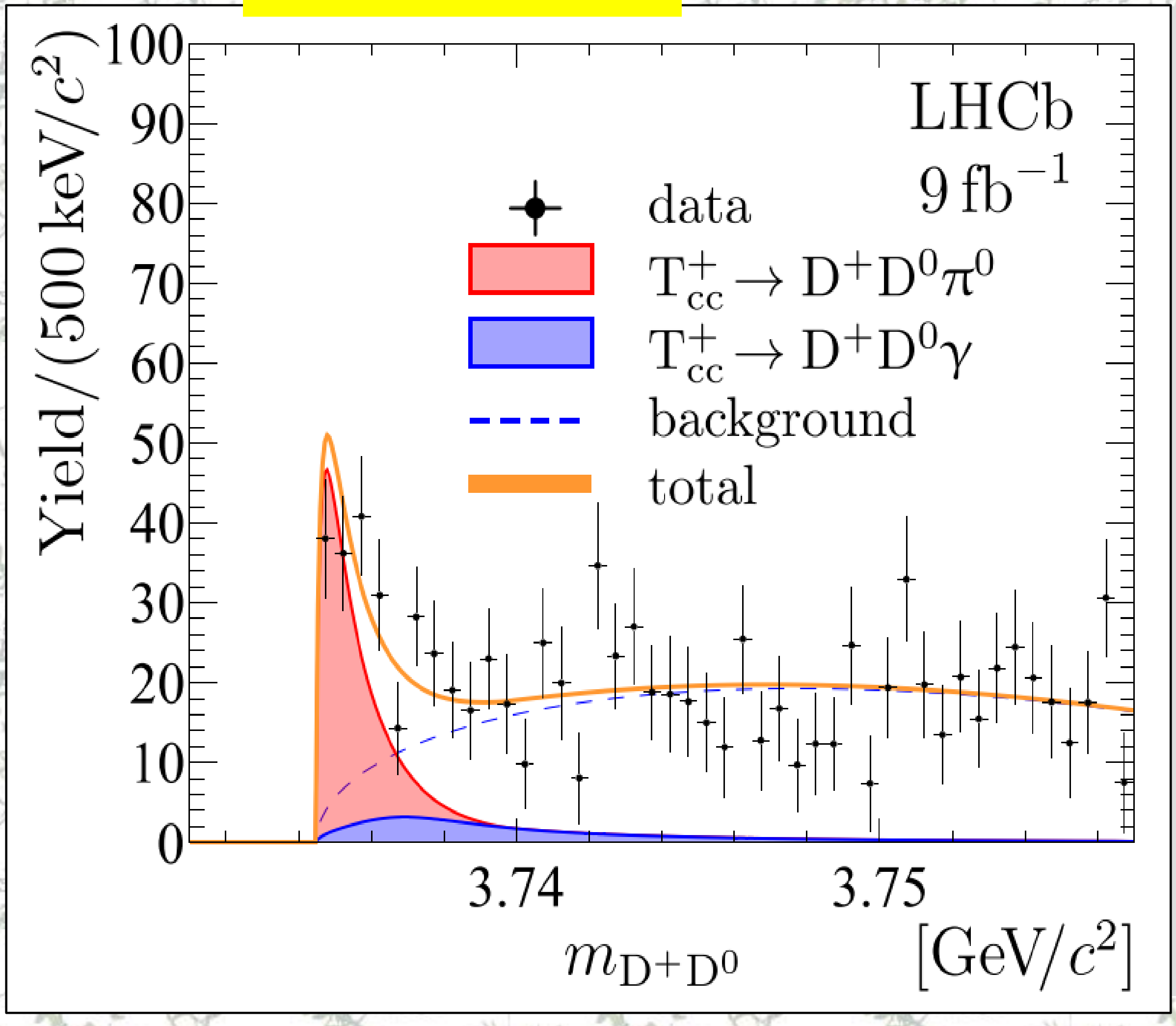
Model



Actual branchings are functions of T_{cc}^+ mass (and shape)

D^+D^0 from $T_{cc}^+ \to D^*D$

arXiv:2109:01056



- For $T_{cc}^+ \to D^{*+}D^0$ and $T_{cc}^+ \to D^{*0}D^+$: 3 final states:

  $T_{cc}^+ \to D^0D^0\pi^+$

  $T_{cc}^+ \to D^+D^0\pi^0$

  $T_{cc}^+ \to D^+D^0\gamma$

Select inclusive prompt D^+D^0

- Excellent agreement with our $0(1^+)$ T_{cc}^+ decay model
  - in shape
  - in number
- Significance $>10\sigma$

I=1 (isovector) nature?

arXiv:2109:01056

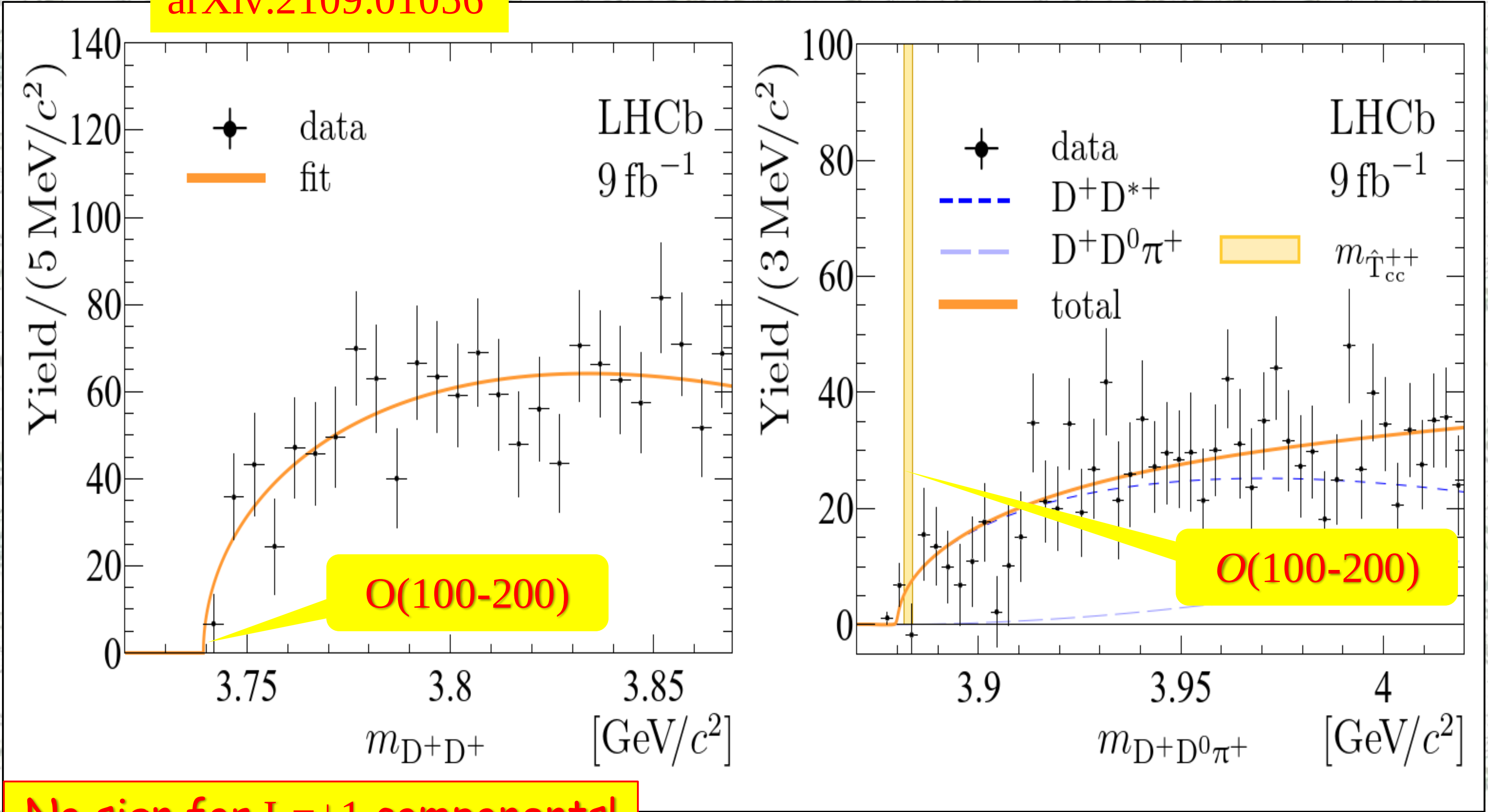
- Many arguments in favor of I=0 isocalar, but it could be $I_3=0$ component of I=1 isotriplet T^0_{cc} T^+_{cc} T^{++}_{cc}
  - Light antiquarks in isovector state, similar to Σ_c, Σ_b baryons
- Interpreting the observed peak as $I_3=0$ component, from Σc and Σ_b mass splitting the masses of $I_3=\pm1$ components are

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

- T^0_{cc} just below $D^{*0}D^0$ threshold (very narrow)
  - $T^0_{cc} \rightarrow D^{*0}D^0 \rightarrow D^0D^0\pi^0$ and $D^0D^0\gamma$
- T^{++}_{cc} slightly above $D^{*+}D^+$ threshold (can be up to few MeV)
  - $T^{++}_{cc} \rightarrow D^{*+}D^+ \rightarrow D^+D^+\pi^0$, $D^+D^+\gamma$, $D^+D^0\pi^+$
- There MUST be signals D^+D^+ and $D^+D^0\pi^+$ spectra!
- There MUST be much larger signal in D^0D^0 spectrum!

I=1 (isovector) nature?

arXiv:2109:01056

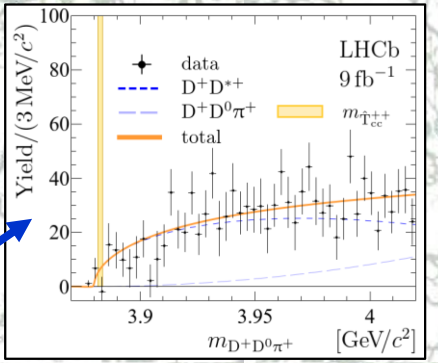


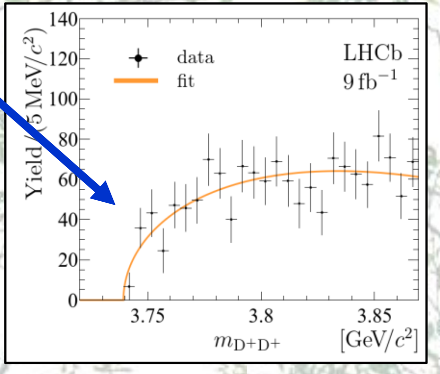
No sign for $I_3=\pm1$ components!

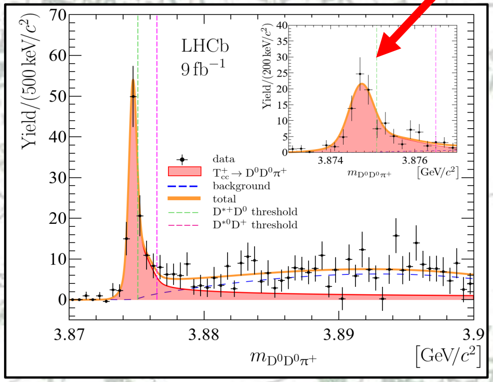
~~I=1 (isovector) nature?~~

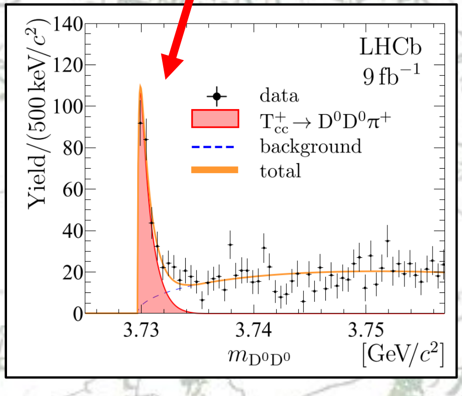
Expected relative yields (*very* approximate)

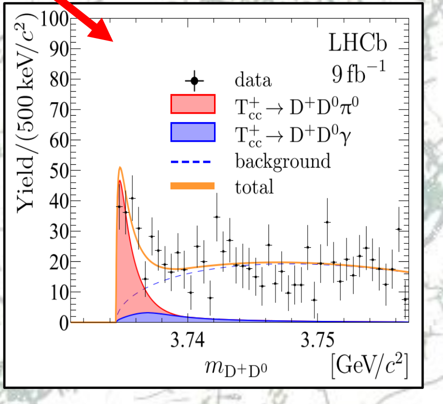
I	I_3		$D^0D^0\pi^+$	D^0D^0X	D^+D^0X	$D^+D^0\pi^+$	D^+D^+
1	+1	T_{cc}^{++}	-	-	2/3	2/3	1/3
1	0	T_{cc}^{+}	2/3	2/3	1/3	-	-
1	-1	T_{cc}^{0}	-	1	-	-	-
1		**Σ**	**2/3**	**5/3**	**1**	**2/3**	**1/3**
0	**0**	T_{cc}^{+}	**2/3**	**2/3**	**1/3**	**-**	**-**







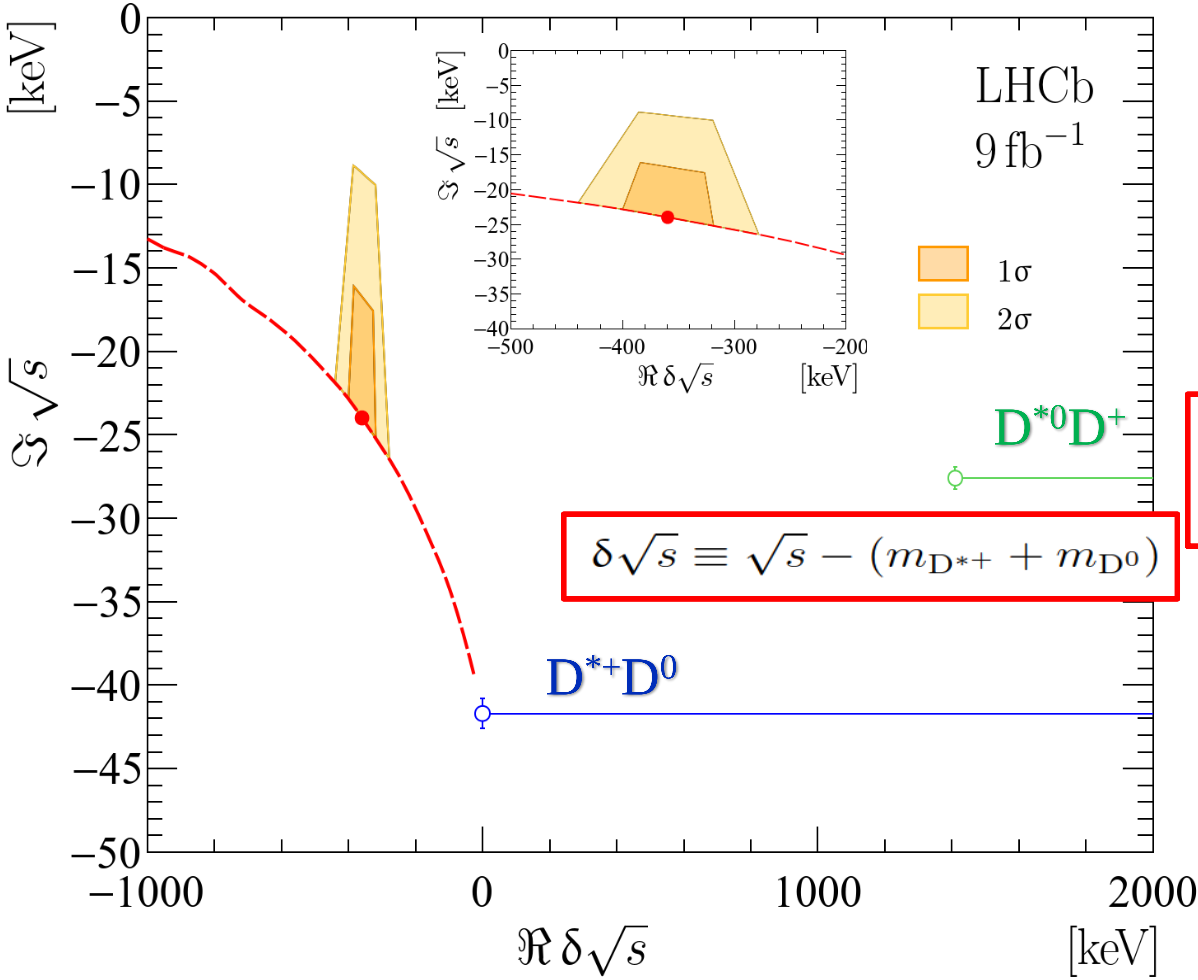




~~I=1~~

Amplitude pole

arXiv:2109:01056



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

Analytic continuation of the amplitude to the second Riemann sheet

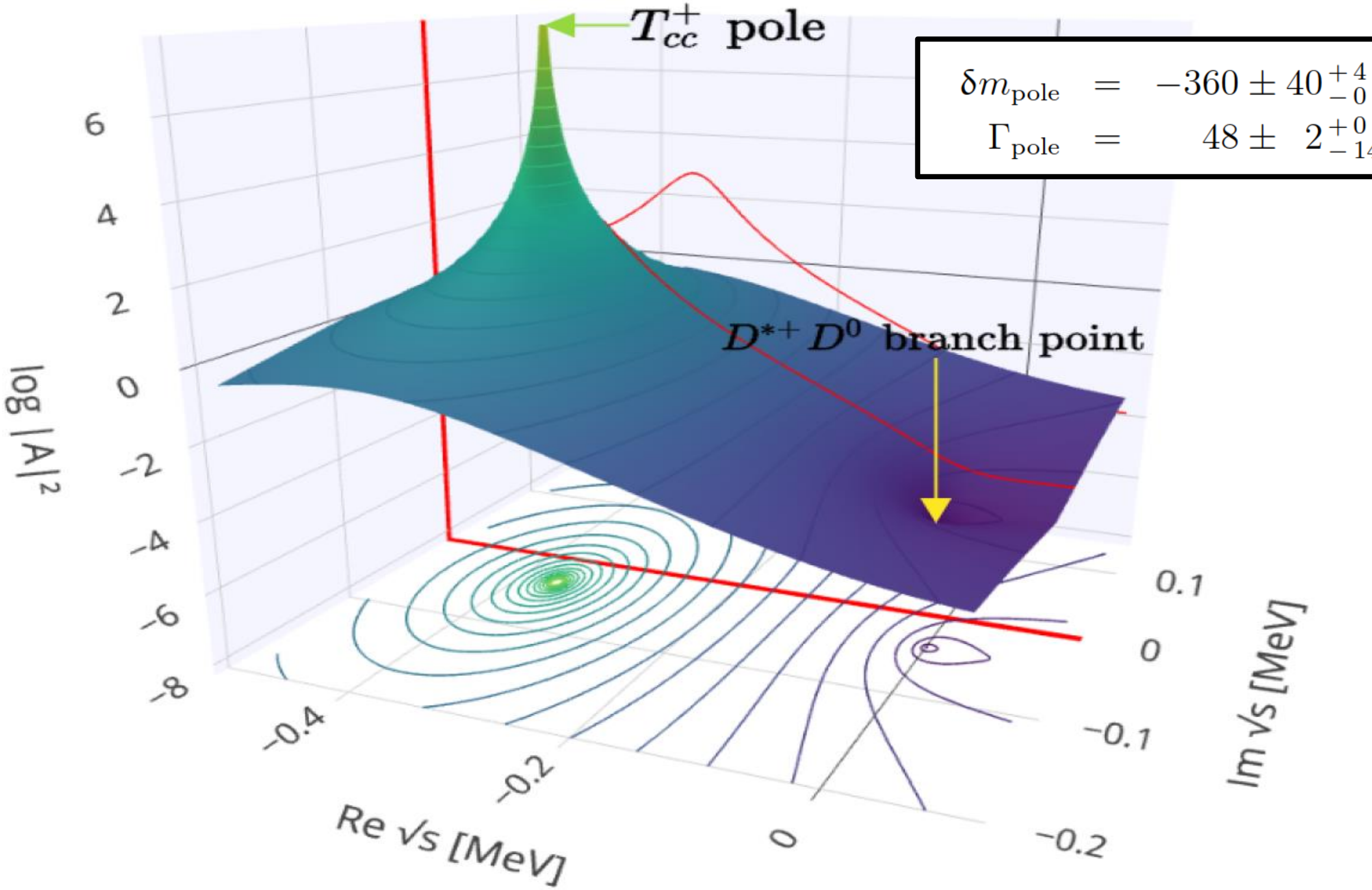
$$\sqrt{\hat{s}} \equiv m_{pole} - \frac{i}{2}\Gamma_{pole}$$

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

$m_{pole} \approx m_U$

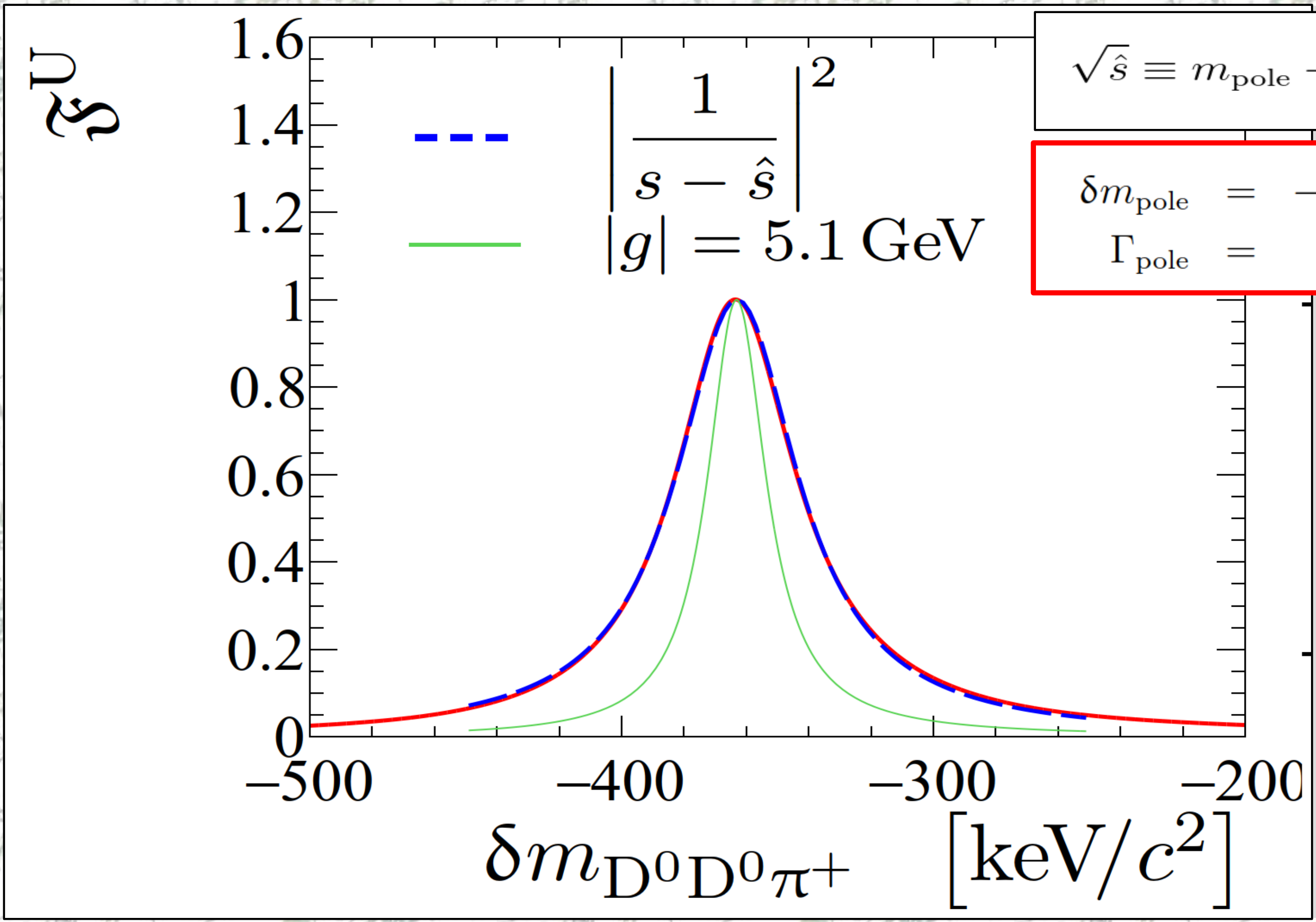
$\Gamma_{pole} \approx$ FWHM

Amplitude pole



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

Amplitude pole



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

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

Low energy scattering parameters

- Scattering length a

  $\mathrm{Re}\, a < 0$: attractive potential

  $-\mathrm{Re}\, a$: characteristic size

- Effective range r

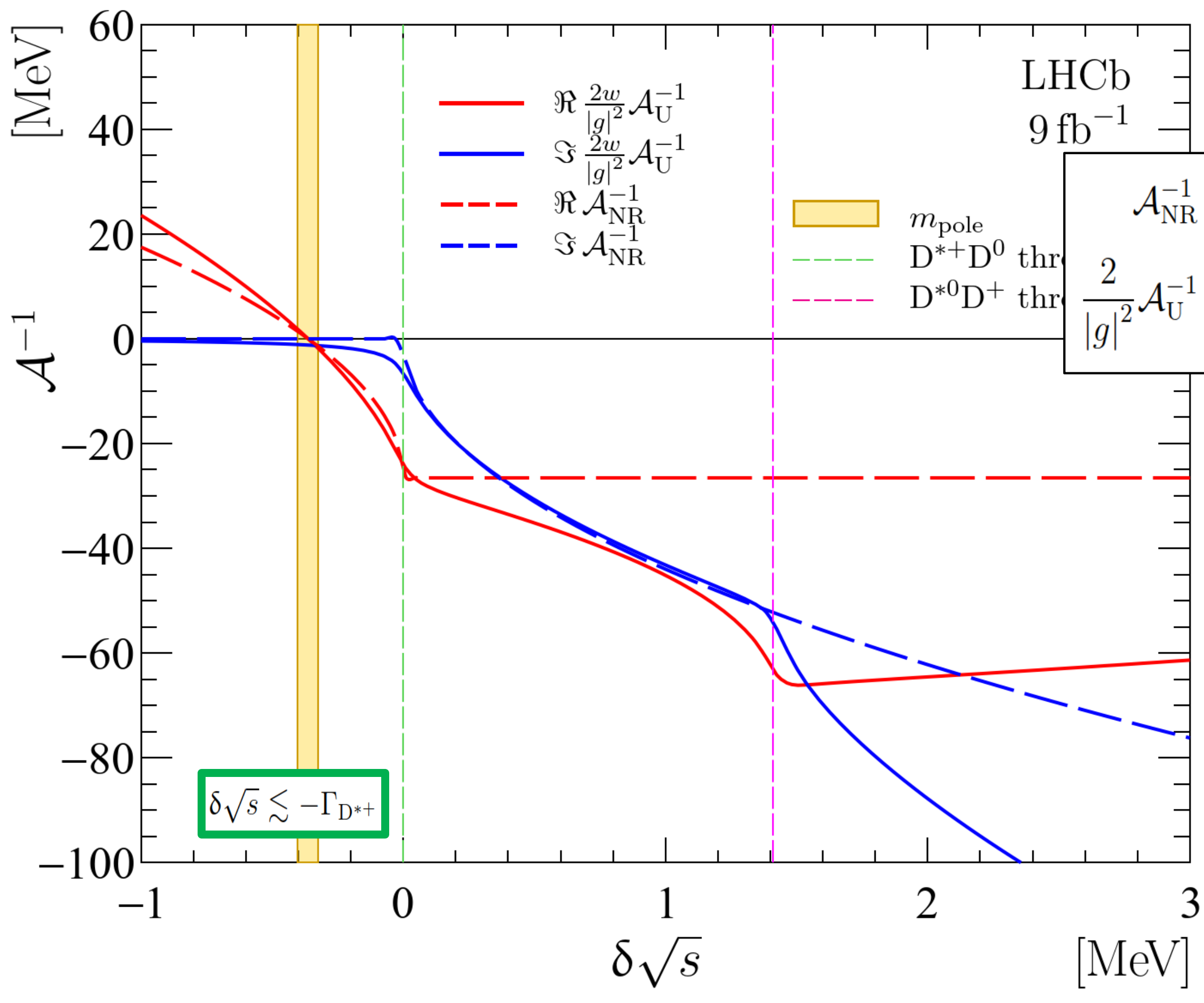
$$\mathcal{A}_{\mathrm{NR}}^{-1} = \frac{1}{a} + r\frac{k^2}{2} - ik + \mathcal{O}(k^4)\,,$$

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

$k = 4\pi\sqrt{s}\,\rho_{\mathrm{tot}}(s)$

Low energy scattering parameters

arXiv:2109:01056



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

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

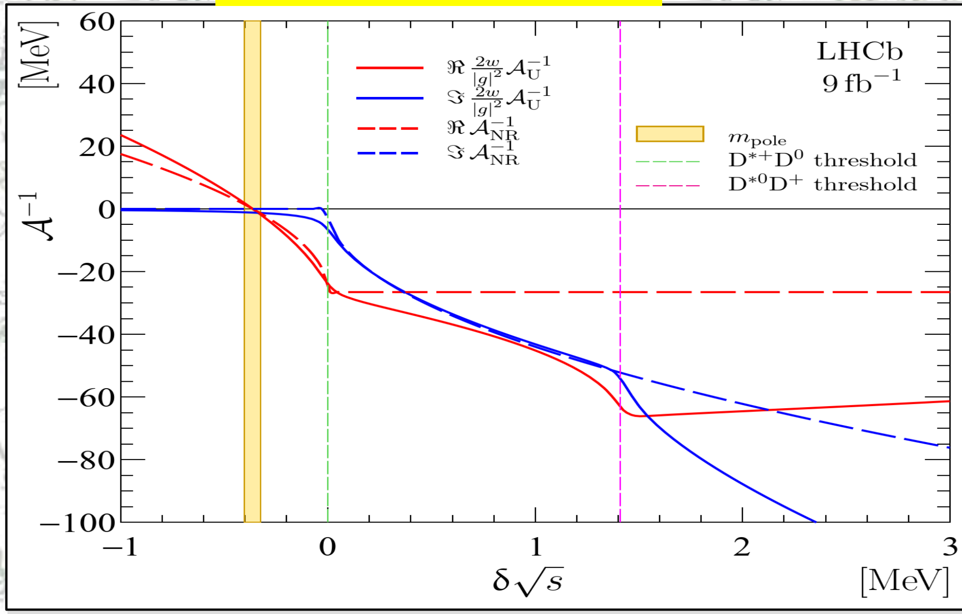
- Match to low energy scattering amplitude

- Good match for scaled amplitude

$$\delta\sqrt{s} \lesssim -\Gamma_{D^{*+}}$$

Low energy scattering parameters

arXiv:2109:01056



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

- Scattering length

$$a = \left[-(7.16 \pm 0.51) + i\,(1.85 \pm 0.28)\right] \text{fm}$$

- Real part is negative
  - → attraction

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

$$0 \leq -r < 11.9\,(16.9)\ \text{fm at } 90\,(95)\%\ \text{CL}$$

Non-positive ← "feature" of our model

- Compositness $Z = 1 - \sqrt{\frac{1}{1+2\,|r/\Re\, a|}}$

$$Z \propto |g|^{-2}$$

$$Z < 0.52\,(0.58)\ \text{at } 90\,(95)\%\ \text{CL}$$

Weinberg 1965,
Matuschek,Baru,Guo&Hanhart 2021

Effective size

arXiv:2109:01056

- Effective size from the scattering length

$$R_a \equiv -\Re\, a = 7.16 \pm 0.51\,\mathrm{fm}$$

- Effective size from the binding energy $\Delta E = -\delta m_{\mathrm{U}}$

Guo, Hanhart, Meissner, Wang,Zhao&Zou 2018

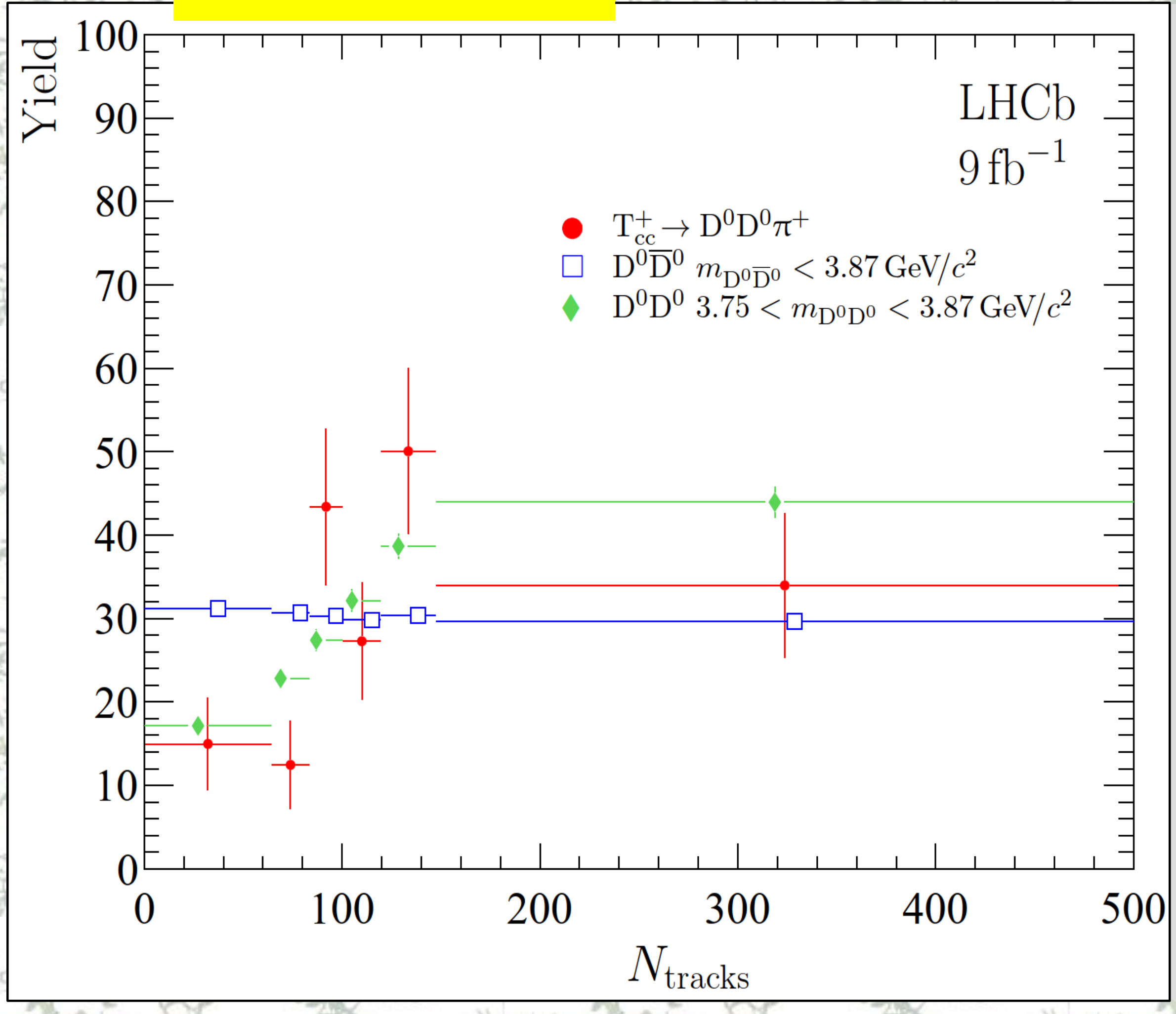
$$\gamma = \sqrt{2\mu\Delta E} = 26.4 \pm 1.5\,\mathrm{MeV}/c\,,\quad R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4\,\mathrm{fm}$$

- The object is really large
  - … around Radium or Uranium nuclear $R = r_0 A^{1/3}$
  - Top three: X(3872), T_{cc}^{+} and *deuteron* (+other nuclei…)

Large size ***should*** have effect on production properties

Event activity/Track multiplicity

arXiv:2109:01056



- Track multiplicity
- low-mass $D\overline{D}$ and DD

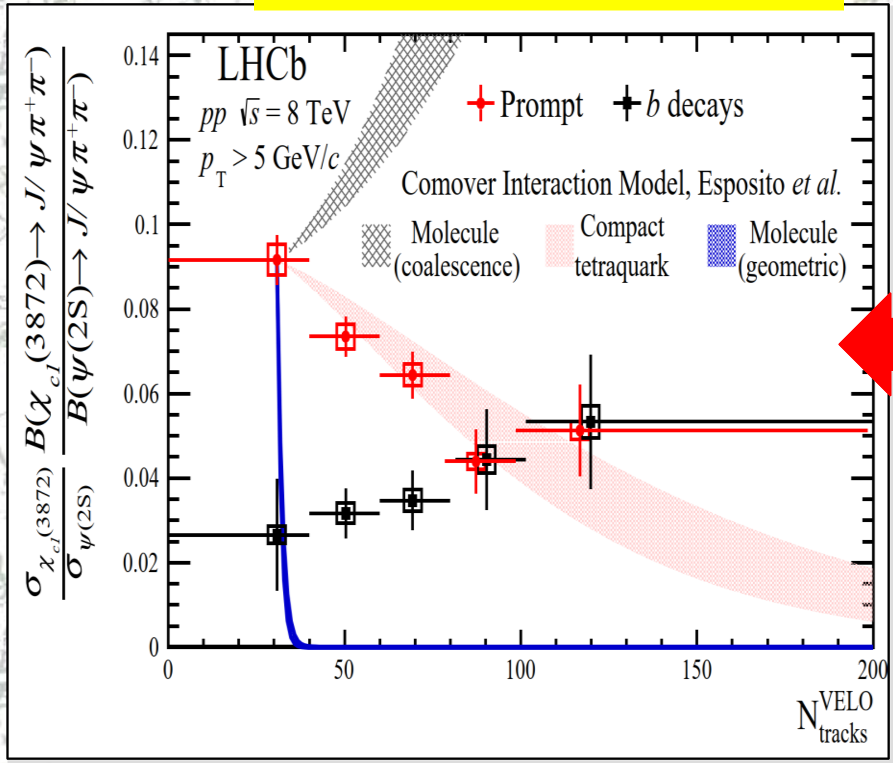
p-value: T_{cc}^+ vs $D\overline{D}$ = 0.1%
p-value: T_{cc}^+ vs DD = 12%

- Similar to DD
  - DPS process
  - … unexpected
- Different from $D\overline{D}$
  - Expected ***but*** ***totally different***!

Track multiplicity for X(3872)

PRL 126 (2021) 092001

arXiv:2109:01056

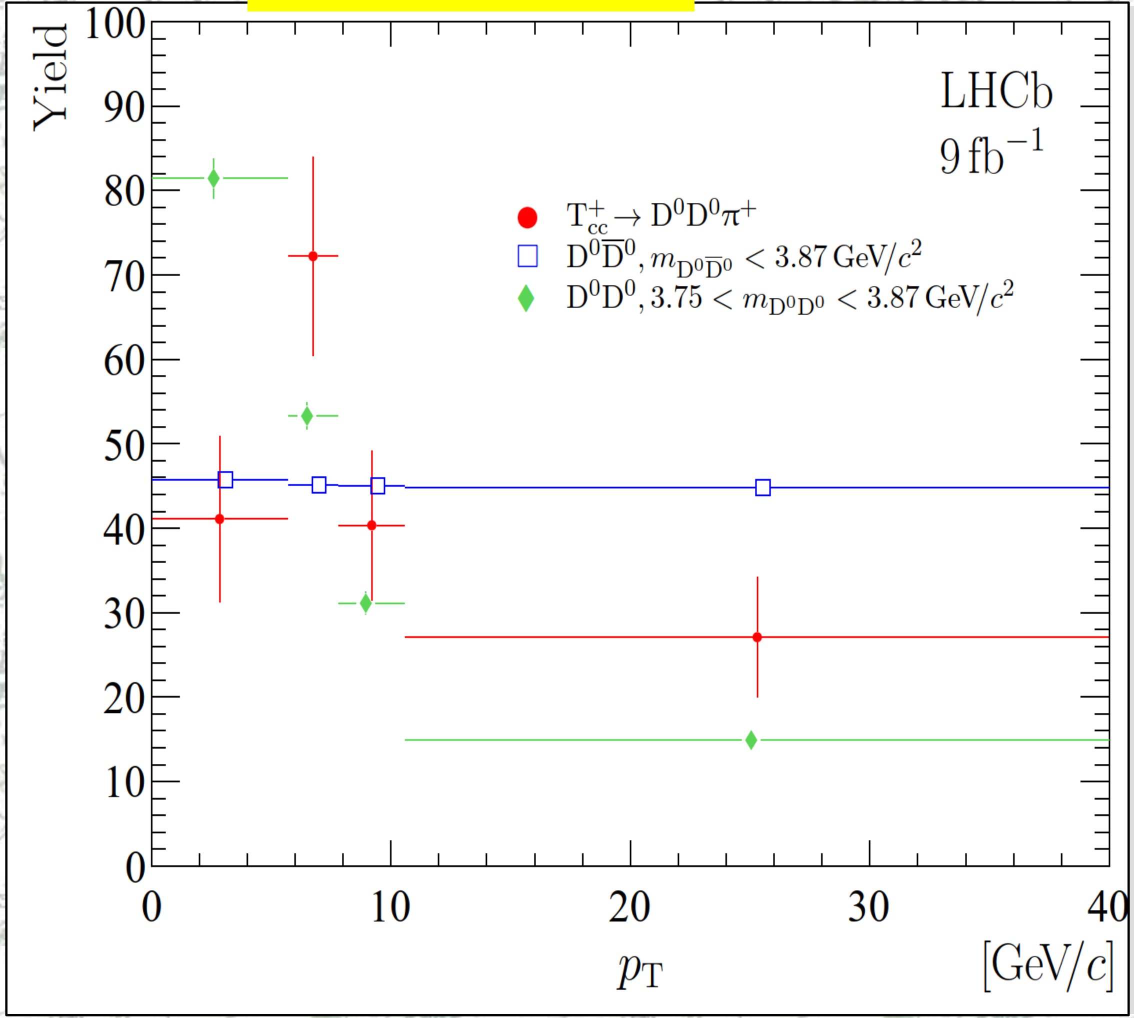


- Both states are "large", some similarity could be expected
- X(3872) clear suppression for large multiplicity
- T_{cc}^+ *no suppression!!! One sees enhancement!!!*

- Both states are "large", some similarity could be expected
- X(3872) clear suppression for large multiplicity
- T_{cc}^+ *no suppression!!! One sees enhancement!!!*

p_T spectrum

arXiv:2109:01056



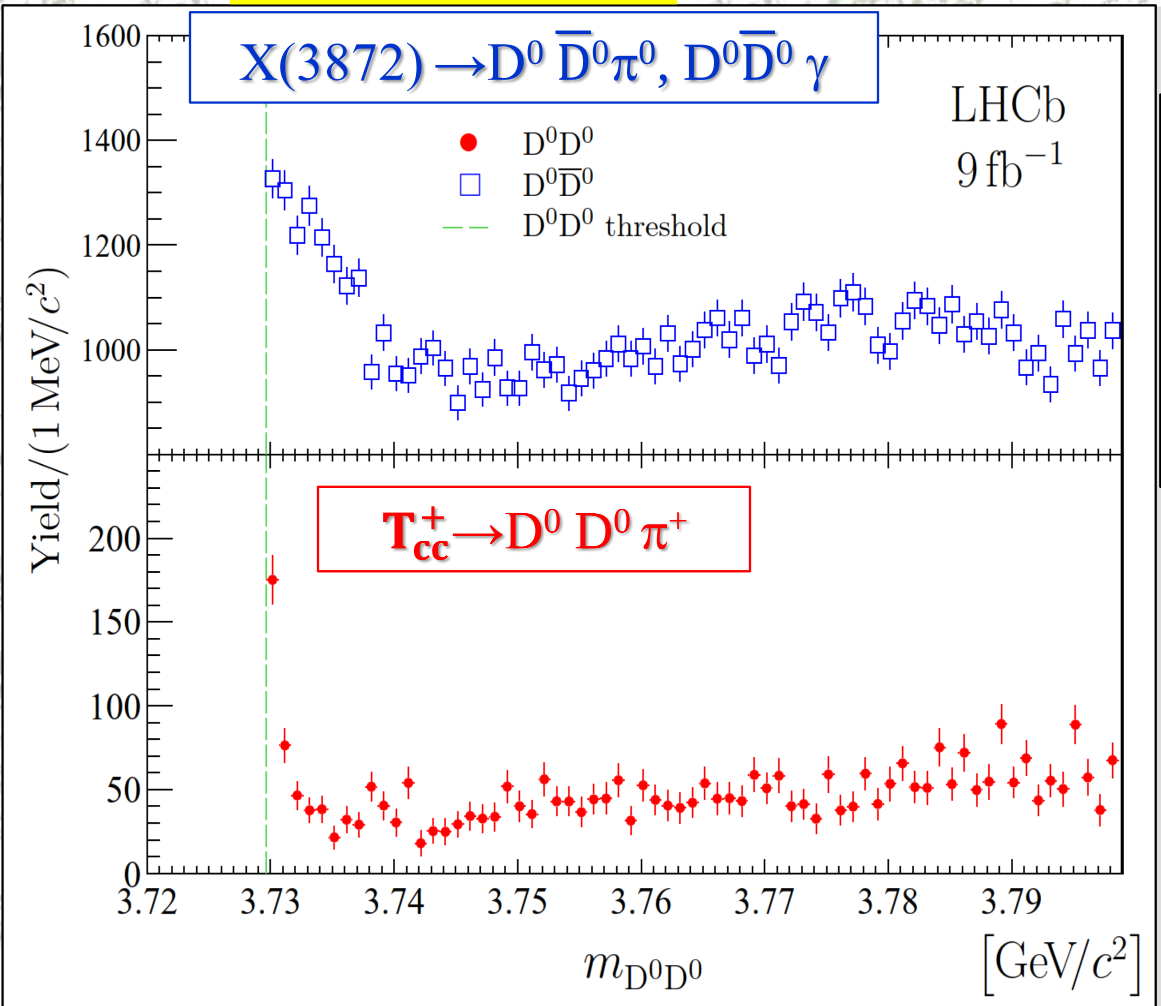
p-value: T_{cc}^{+} vs $D\overline{D}$ = 1.4%

p-value: T_{cc}^{+} vs DD = 0.02%

- A bit inconclusive
- More data is needed

Production estimate

arXiv:2109:01056



- Huge X(3872) signal

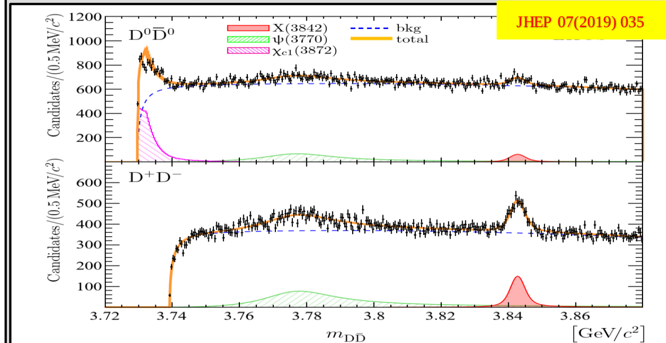


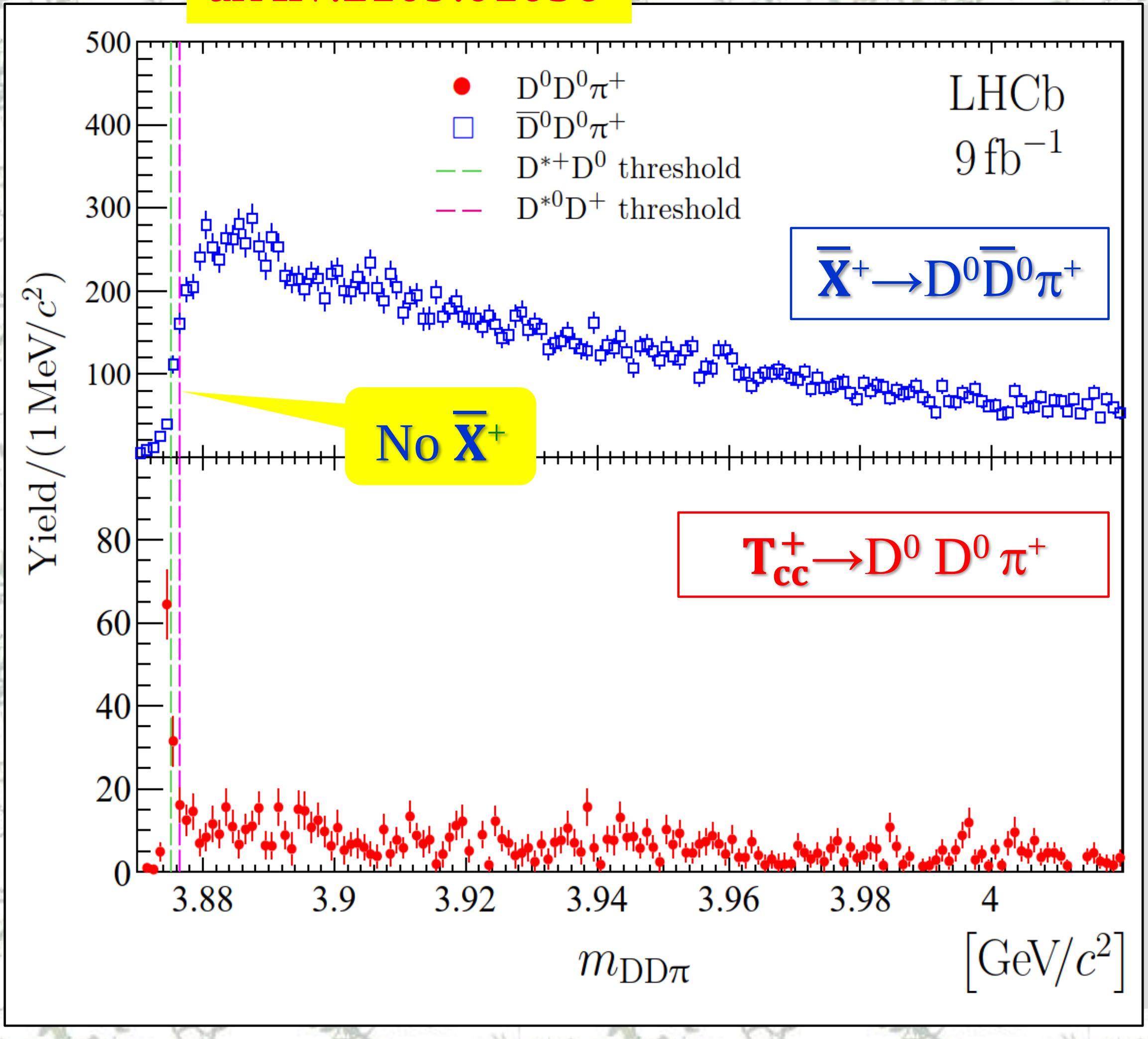
Figure 5: Mass spectra of (top) $D^0\bar{D}^0$ and (bottom) D^+D^- candidates in the near-threshold $m_{D\bar{D}} < 3.88\,\mathrm{GeV}/c^2$ region. The result of the simultaneous fit described in the text is superimposed.

$N(T_{cc}^{+})/N(X(3872)) \sim 1/20$

- Large uncertainty (>30%) due to X(3872) shape and background
  Larger than T_{cc}^{+} statistics
- Better understanding of X(3872) is needed

Production estimate: $\bar{X}^+$

arXiv:2109:01056



For compact tetraquark interpretation of X(3872) *there is charged partner* $\bar{X}^+$

- *close to* $D^{*+}\bar{D}^0$ *threshold*

Maiani, Piccinini,Polosa&Riquer 2005,2014
Maiani, Polosa&Riquer 2018,2020

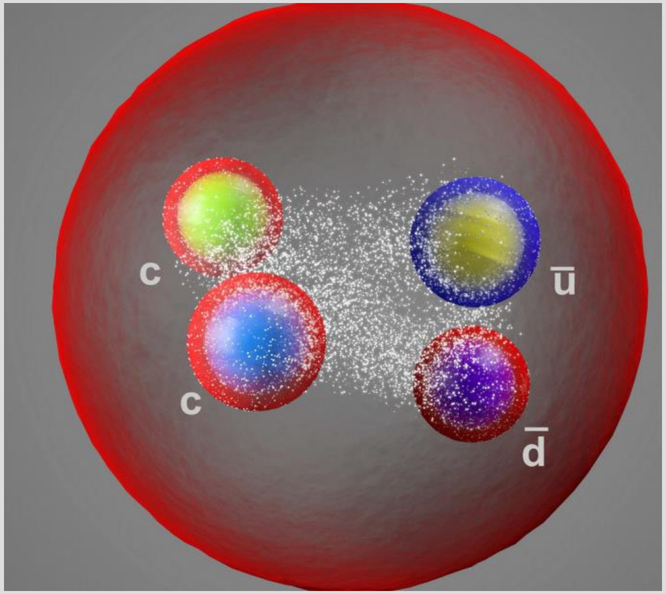
No $\bar{X}^+$ signal is observed

$\bar{X}^+$	:	T_{cc}^+	:	X(3872)
<0.1	:	1	:	~20

Summary I/V

arXiv:2109:01038

- Manifestly exotic state near $D^{*+}D^0$ threshold is observed with overwhelming significance
  - New class of hadronic matter
  - Narrow
  - Just below threshold
  - Minimal quark content $cc\overline{ud}$
  - Long awaited T_{cc}^{+}



- Breit-Wigner mass and width

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

Summary II/V

arXiv:2109:01056

- Decay proceed via an intermediate off-shell D^{*+}
  - Strong argument in favor of $J^P=1^+$
- Using dedicated unitarized 3-body model

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

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

- Pole position

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

- Study of D^0D^0 and D^+D^0 spectra support isoscalar nature
- Study of D^+D^+ and $D^+D^0\pi^+$ spectra rejects isovector nature

Summary III/V

arXiv:2109:01056

- Scattering length
- Effective range
- Compositness
- Effective size

$$a = \left[-(7.16 \pm 0.51) + i\,(1.85 \pm 0.28) \right] \text{fm}$$

$$0 \le -r < 11.9\,(16.9)\,\text{fm at } 90\,(95)\%\ \text{CL}$$

$$Z < 0.52\,(0.58) \text{ at } 90\,(95)\%\ \text{CL}$$

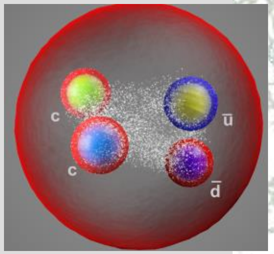
$$R_a \equiv -\Re\, a = 7.16 \pm 0.51\,\text{fm}$$

$$R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4\,\text{fm}$$

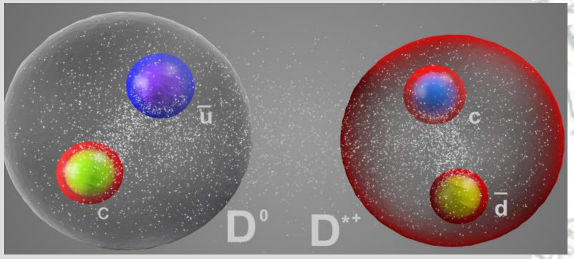
- No suppression of production at large multiplicities
  - Enhancement is seen
- Suprising similarity with D^0D^0 (DPS) production

Summary IV/V

- We already know a lot about T_{cc}^{+} now
  - Is it enough to answer the main questions?
  - What ia missing?



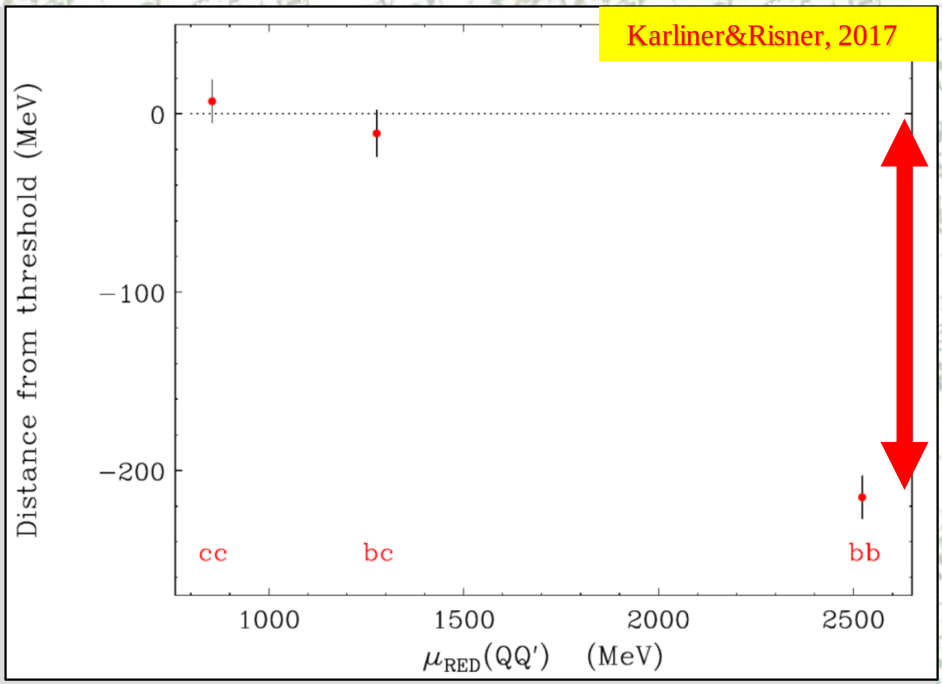
- What is the nature of
  - Compact tetraquark? Binding is expected. Closeness to threshold is “accidental”.
  - Molecula? Closeness to threshold is “natural”



- (Nearby) future
  - Amplitude analysis of Dalitz plot
  - Production measurements
    - Relative to $X(3872)\to D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$, “ψ” $\to D^0\bar{D}^0$, Ξ_{cc}^{++}
  - Add new decay channels of $D^0\to K^-\pi^+\pi^+\pi^-$
- More data in Run 3

Summary V

- T_{cc}^{+} *is almost stable*
- T_{bc}^{0} *can be stable*
- T_{bb}^{-} *should be stable*
  - Theory consensus
  - Lattice QCD
  - Only weak decays!
  - Macroscopic lifetime!



arXiv:2109:01038

arXiv:2109:01056

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2021-165
LHCb-PAPER-2021-031
September 2, 2021

arXiv:2109.01038v2 [hep-ex] 3 Sep 2021

Observation of an exotic narrow doubly charmed tetraquark

LHCb collaborati

Abstract

Conventional hadronic matter consists of baryons
and quark-antiquark pairs, respectively. The obse
state, a doubly charmed tetraquark containing t
an anti-d quark, is reported using data collect
the Large Hadron Collider. This exotic state w
manifests itself as a narrow peak in the mass spect
the $D^{*+}D^0$ mass threshold. The near-threshold
narrow width reveals the resonance nature of the

†Authors are listed at the end of this Letter.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2021-169
LHCb-PAPER-2021-032
September 2, 2021

p 2021

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

tion†

ectrum just below the $D^{*+}D^0$ mass
nding to an integrated luminosity
n proton-proton collisions at cen-
tate is consistent with the ground
of $cc\bar{u}\bar{d}$ and spin-parity quantum
pectra disfavours interpretation of
structure via intermediate off-shell
ribution. The mass of the resonance
d. Resonance parameters including
ge and compositeness are measured
re of the T_{cc}^+ state. In addition, an
on track multiplicity is observed.

Simon Eidelman 1948 - 2021

Our distinguished colleague, beloved member of LHCb and whole hadron physics community has passed away.

His contribution to the field will have a lasting impact in future generations.

We dedicate the oncoming papers on the observation of the T_{cc}^+ to his memory.

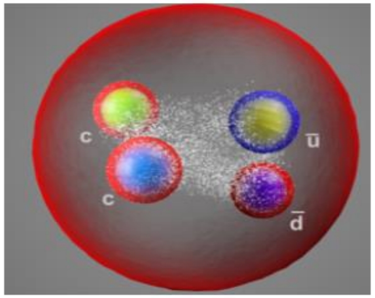
https://indico.cern.ch/e/TccWorkshop

Mini-workshop on "T_{cc}^{+} and beyond", Online

14 September 2021
Europe/Zurich timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- My Conference
  - My Contributions
- Participant List
- Videoconference

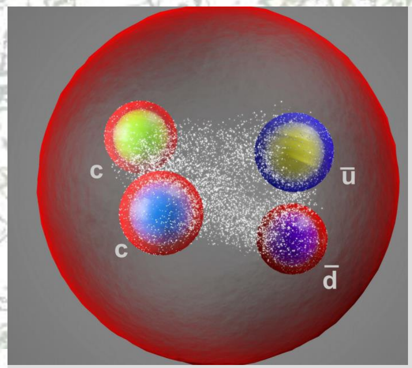


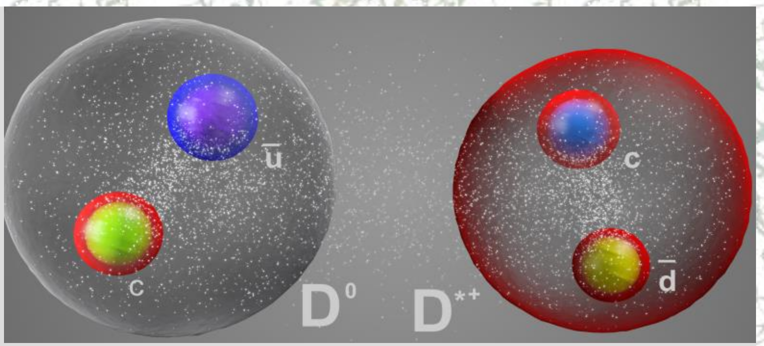
The workshop is dedicated to discussion on the recent observation of the exotic doubly charmed tetraquark T_{cc}^{+}. The main purpose of the workshop is to summarize our current knowledge, both experimental and theoretical, on double heavy tetraquark system, including the properties of the T_{cc}^{+} tetraquark and discuss the next steps.

1. LHCb-PAPER-2021-031, arXiv:2109.01038
2. LHCb-PAPER-2021-032, arXiv:2109.01056

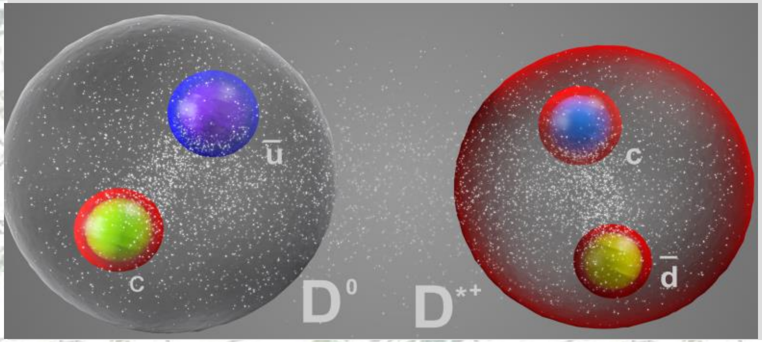
The workshop is scheduled at the same date after the CERN LHC seminar, where the observation of the T_{cc}^{+} tetraquark and measurement of its properties is reported.

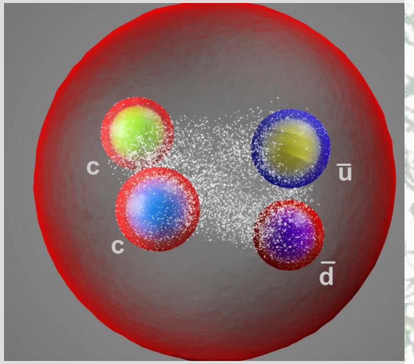
Due to COVID-19, workshop is purely virtual, on-line only

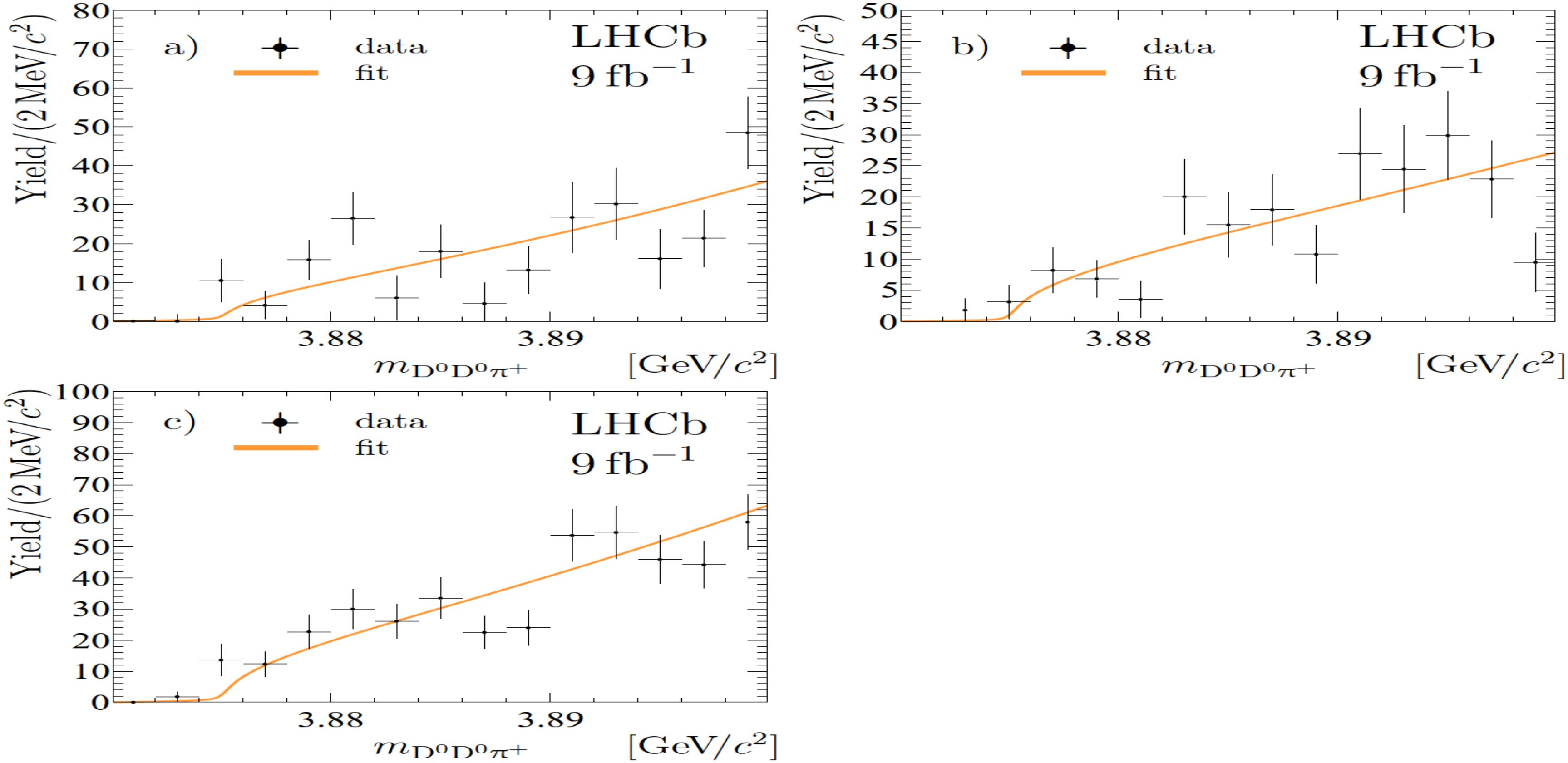




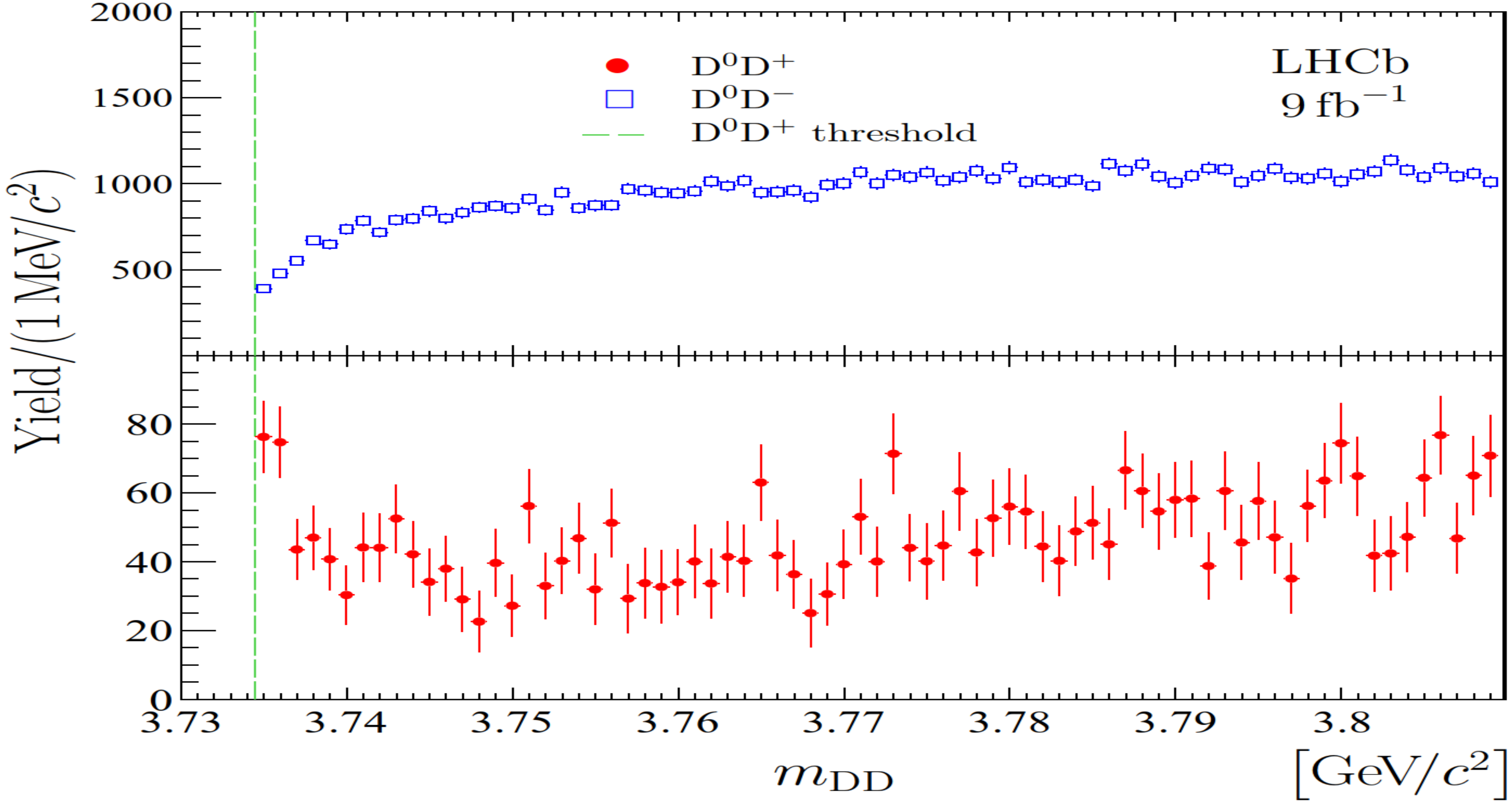
Thank you!



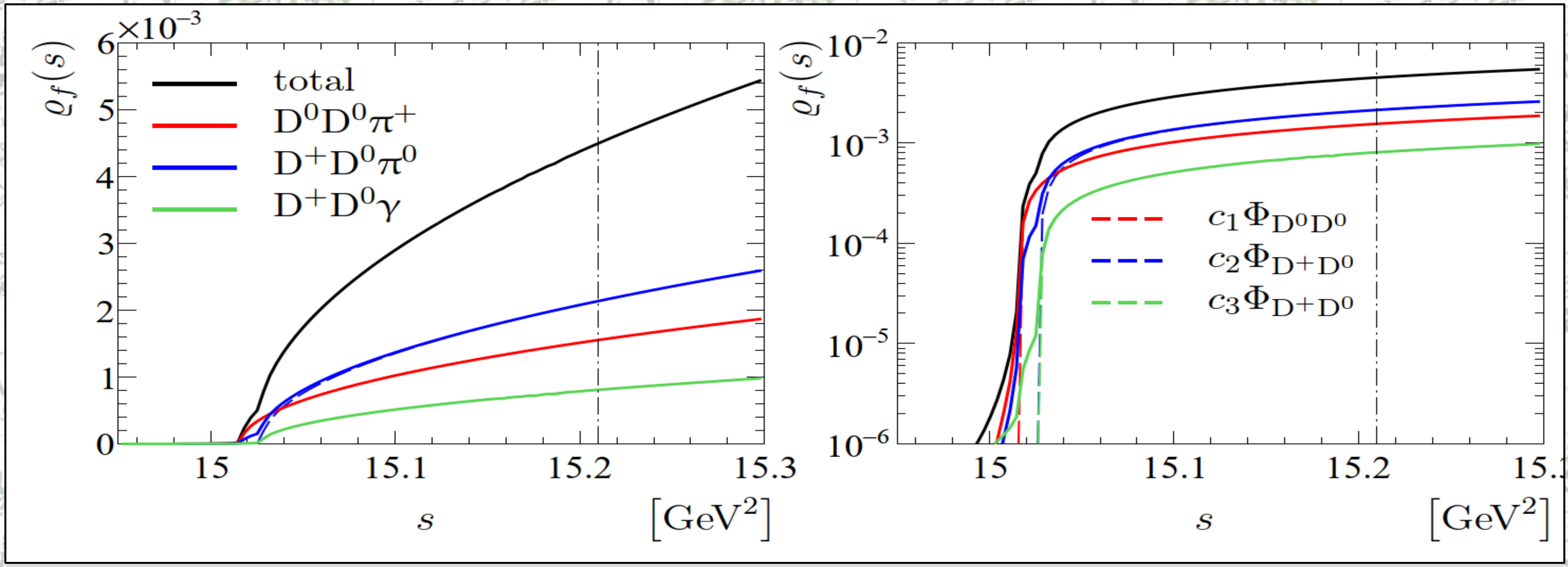




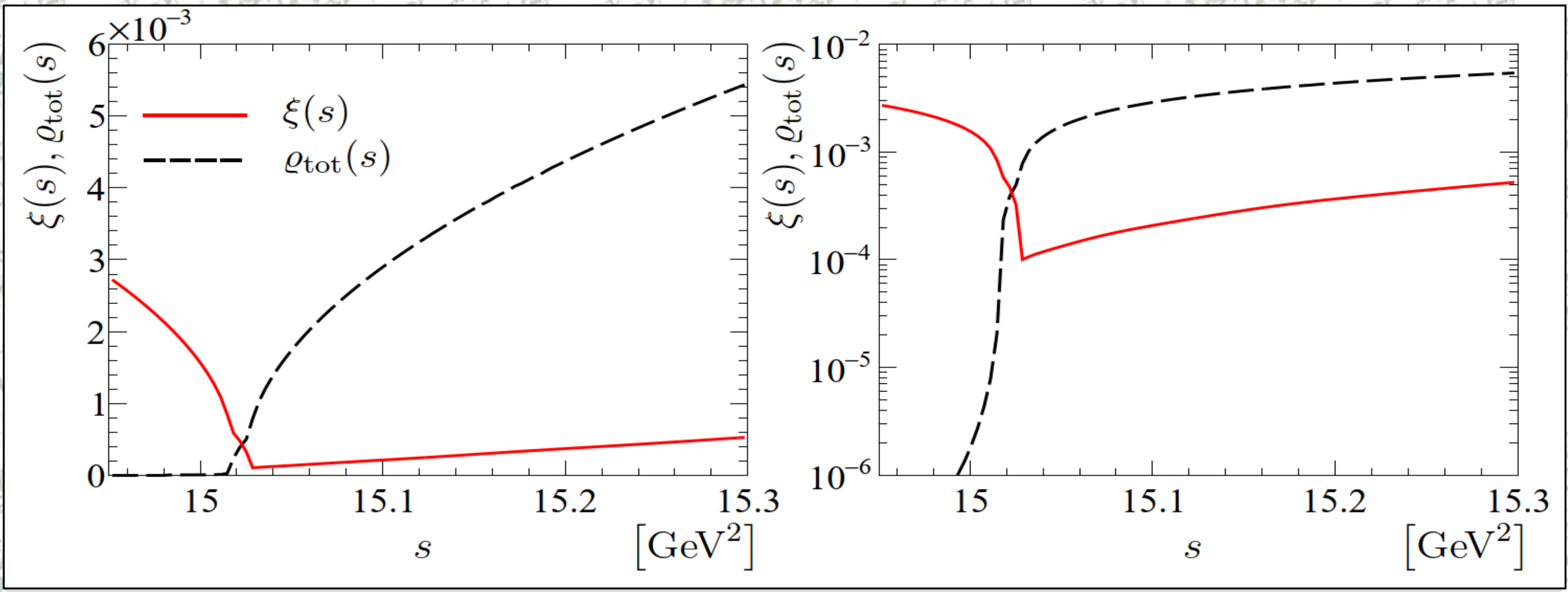
Extended Data Fig. 2: Mass distributions for $D^0D^0\pi^+$ combinations with fake D^0 candidates. Mass distributions for $D^0D^0\pi^+$ combinations with (a) one true and one fake D^0 candidate, (b) two fake D^0 candidates and (c) at least one fake D^0 candidate. Results of the fits with background-only functions are overlaid.



Extended Data Fig. 4: Mass distributions for D^0D^+ and D^0D^- candidates. Background-subtracted D^0D^+ and D^0D^- mass distributions.



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



$$\xi(s) = \frac{s}{2\pi}\,\mathrm{p.v.}\int\limits_{s^*_{\rm th}}^{+\infty} \frac{\varrho_{\rm tot}(s')}{s'\,(s'-s)}\,ds'\,,$$

Mass splitting for isovector

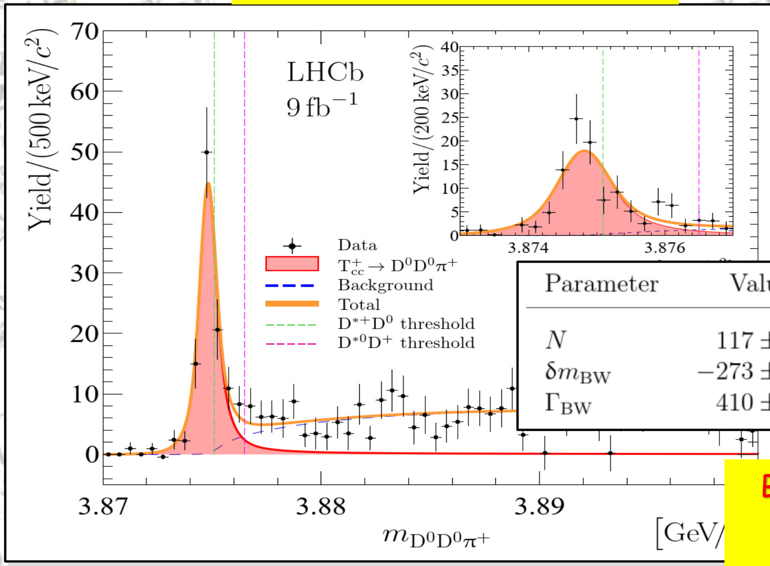
$$
\begin{aligned}
m_{\Sigma_c^{++}} &= m_{\Sigma} + m_{\mathrm{u}} + m_{\mathrm{u}} - a\, q_{\mathrm{u}} q_{\mathrm{u}} - b\, q_{\mathrm{c}} \left(q_{\mathrm{u}} + q_{\mathrm{u}}\right) \\
m_{\Sigma_c^{+}} &= m_{\Sigma} + m_{\mathrm{u}} + m_{\mathrm{d}} - a\, q_{\mathrm{u}} q_{\mathrm{d}} - b\, q_{\mathrm{c}} \left(q_{\mathrm{u}} + q_{\mathrm{d}}\right) \\
m_{\Sigma_c^{0}} &= m_{\Sigma} + m_{\mathrm{d}} + m_{\mathrm{d}} - a\, q_{\mathrm{d}} q_{\mathrm{d}} - b\, q_{\mathrm{c}} \left(q_{\mathrm{d}} + q_{\mathrm{d}}\right)
\end{aligned}
$$

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

$$
\begin{aligned}
m_{\hat{\mathrm{T}}_{\mathrm{cc}}^{0}} - m_{\hat{\mathrm{T}}_{\mathrm{cc}}^{+}} &= -5.9 \pm 1.5\,\mathrm{MeV}/c^2\,, \\
m_{\hat{\mathrm{T}}_{\mathrm{cc}}^{++}} - m_{\hat{\mathrm{T}}_{\mathrm{cc}}^{+}} &= 7.9 \pm 1.3\,\mathrm{MeV}/c^2\,.
\end{aligned}
$$

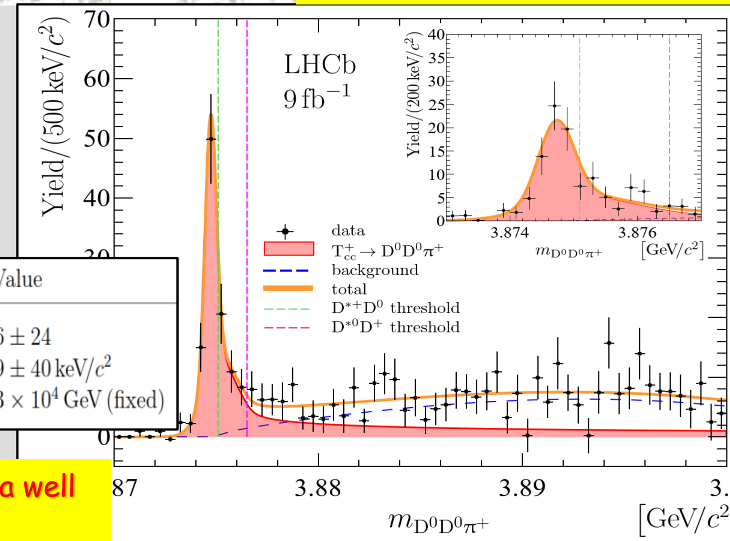
Consistency of two models

arXiv:2109:01038



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

arXiv:2109:01056



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

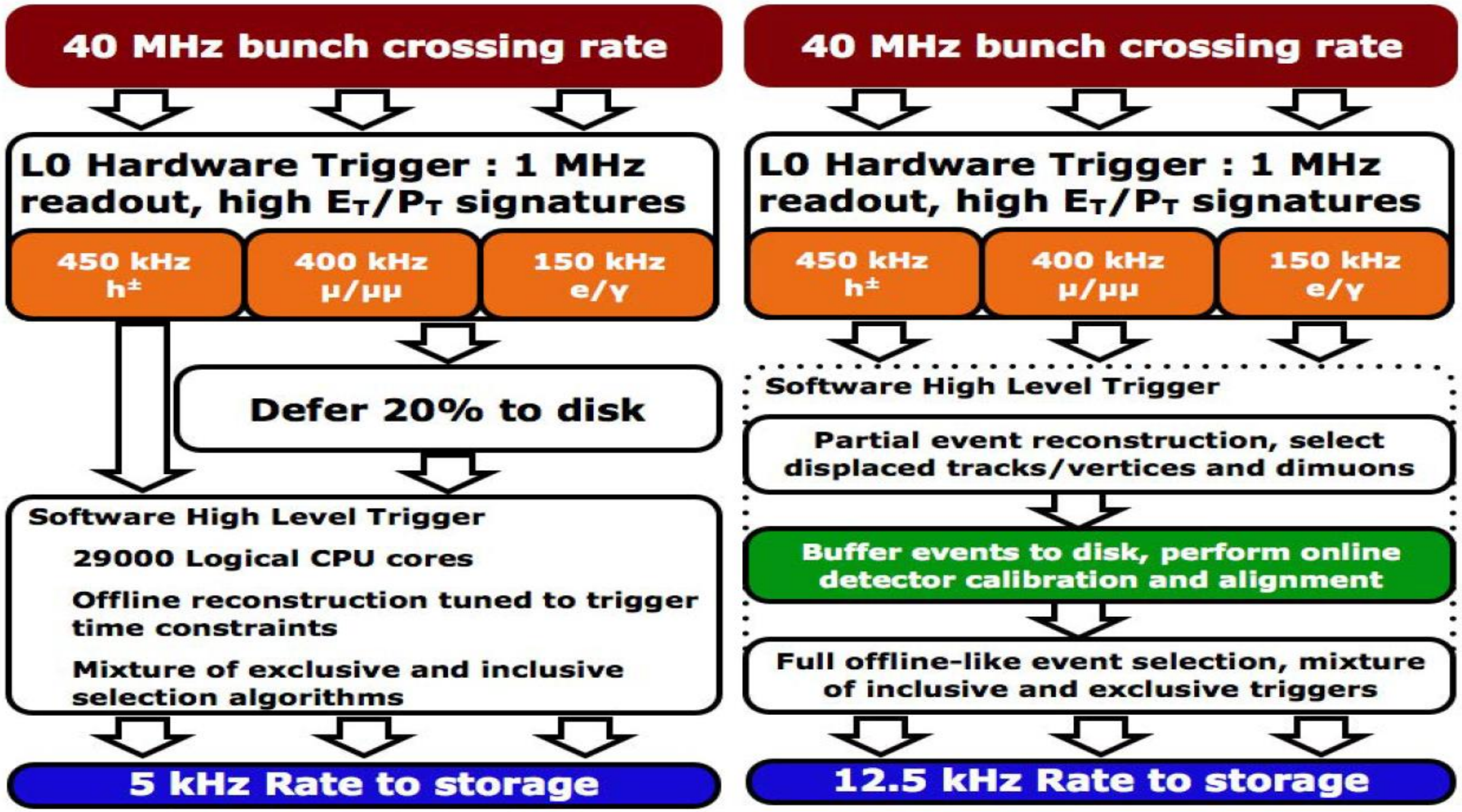
Both models describe data well
Resolution
backrgound

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

- Cross-check with pseudoexpriments

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

Trigger



40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHz readout, high ET/PT signatures
450 kHz h±
400 kHz μ/μμ
150 kHz e/γ
Defer 20% to disk
Software High Level Trigger
29000 Logical CPU cores
Offline reconstruction tuned to trigger time constraints
Mixture of exclusive and inclusive selection algorithms
5 kHz Rate to storage
40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHz readout, high ET/PT signatures
450 kHz h±
400 kHz μ/μμ
150 kHz e/γ
Software High Level Trigger
Partial event reconstruction, select displaced tracks/vertices and dimuons
Buffer events to disk, perform online detector calibration and alignment
Full offline-like event selection, mixture of inclusive and exclusive triggers
12.5 kHz Rate to storage