# Hot Topics in Spectroscopy at LHCb

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On behalf of the LHCb collaboration

HQL2021 - The XV International Conference on Heavy Quarks and Leptons
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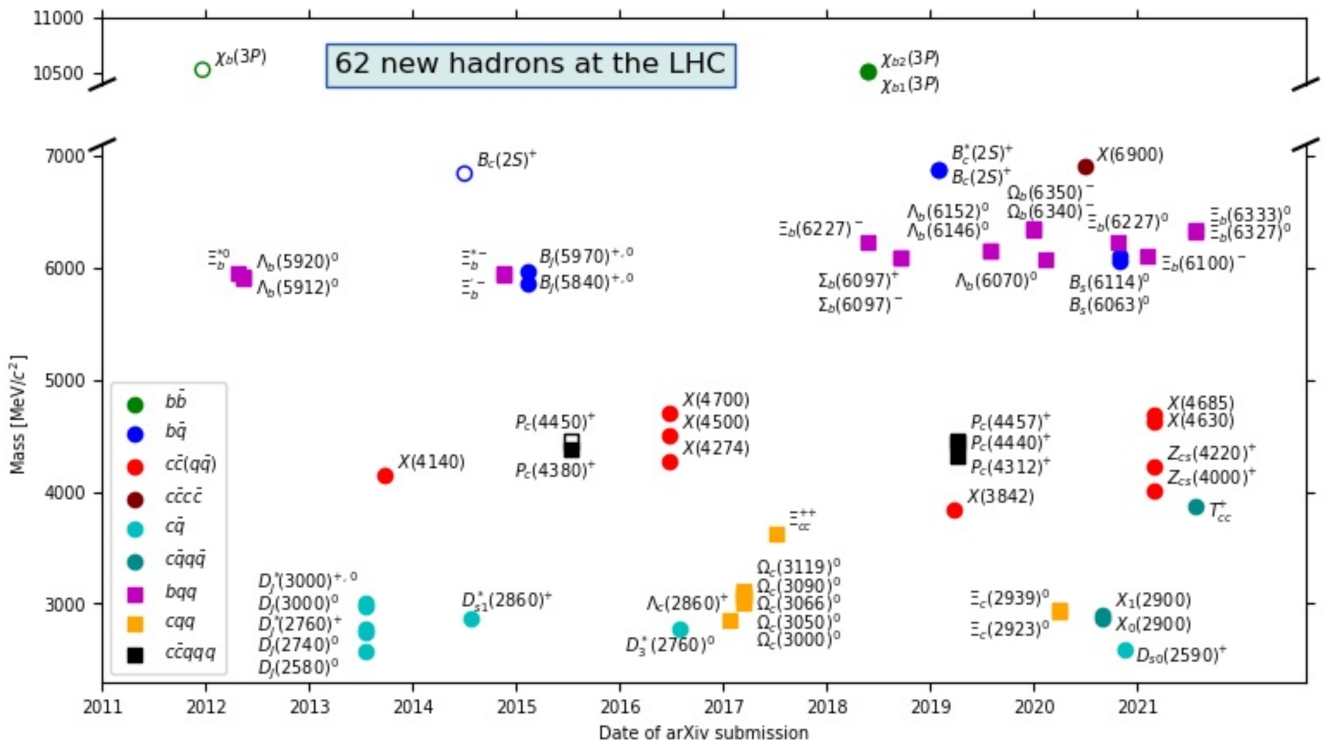
Warwick

# Outline

The LHC is a heavy flavour factory that has led to a new Golden Age for Heavy Spectroscopy. A deluge of recent results. In this talk I focus on:

- Introduction
- Pentaquarks in $B_s \to J/\psi p\bar{p}$
- Amplitude analysis of $B^+ \to D^+D^-K^-$
- Doubly charmed tetraquark $T_{cc}^+$

For more results on LHCb spectroscopy see talk by M. Stahl on Tuesday afternoon



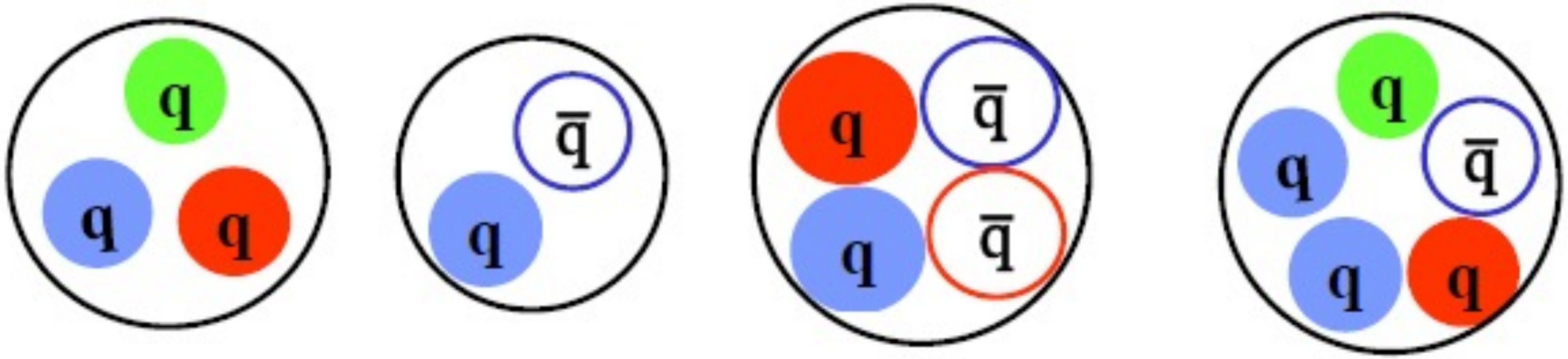

https://www.nikhef.nl/~pkoppenb/particles.html

# Introduction

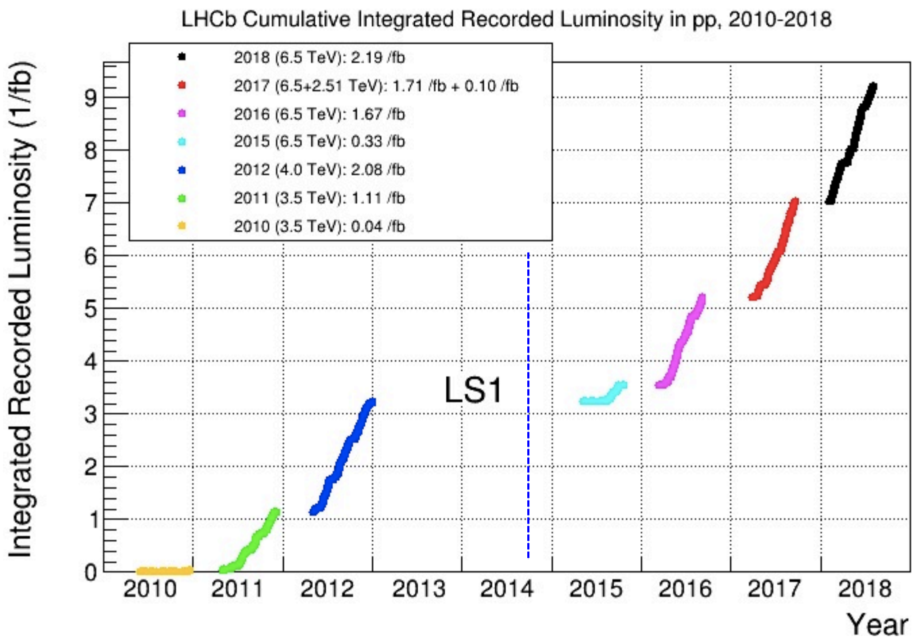
Studies of hadronic resonances tests predictions allow us to probe the quark model and QCD

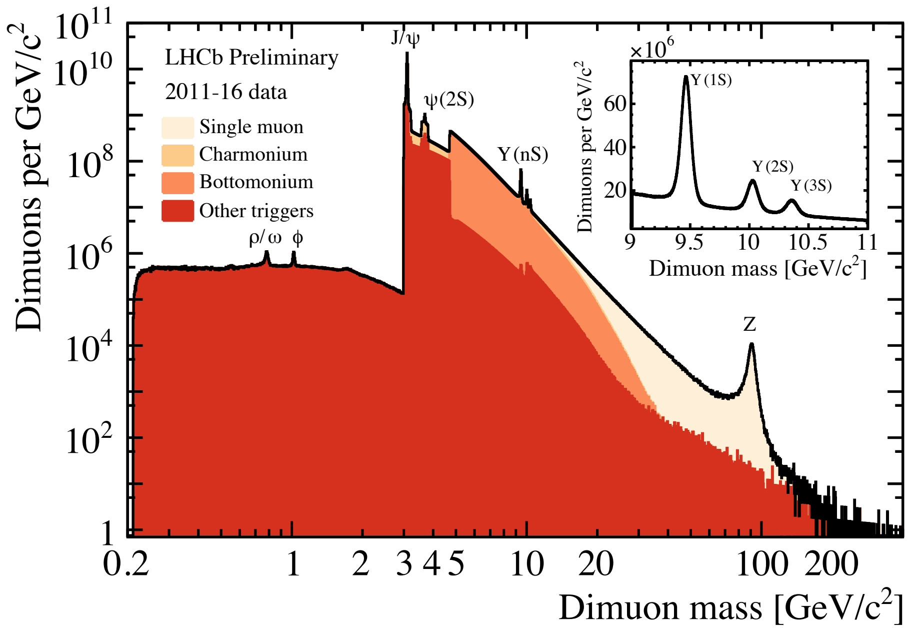
- Map out conventional states with two or three quarks

- Look for exotic states with more than 3 quarks: tetraquarks, pentaquarks
  - Study dynamics of exotic states : diquarks, molecules



# Dataset

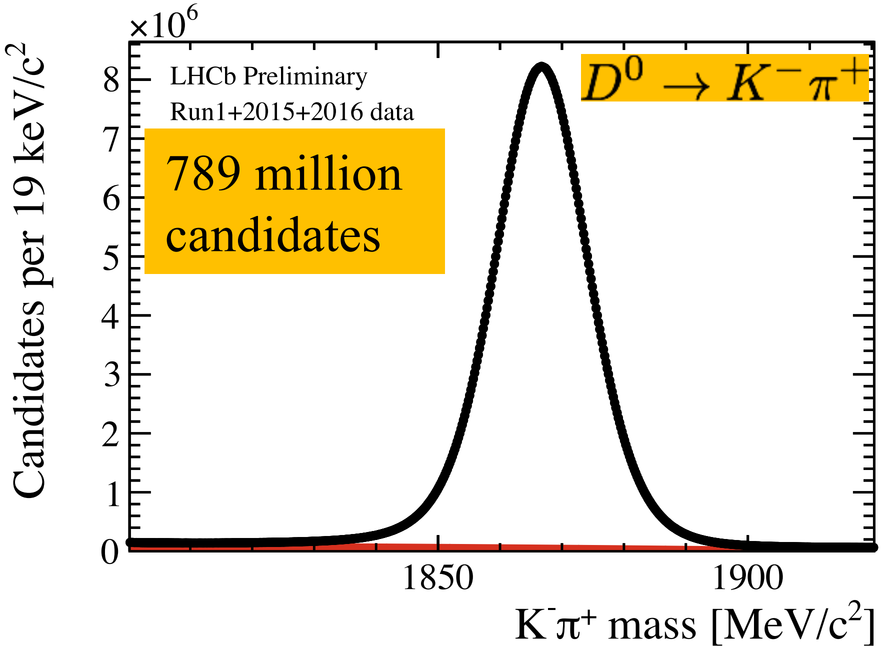



World largest heavy flavour dataset
(9 fb$^{-1}$) collected during Run1+Run2

- Precision tracking
- Excellent PID using RICH
- Trigger for fully hadronic decays

Int.J.Mod.Phys. A30 (2015) no.07, 1530022

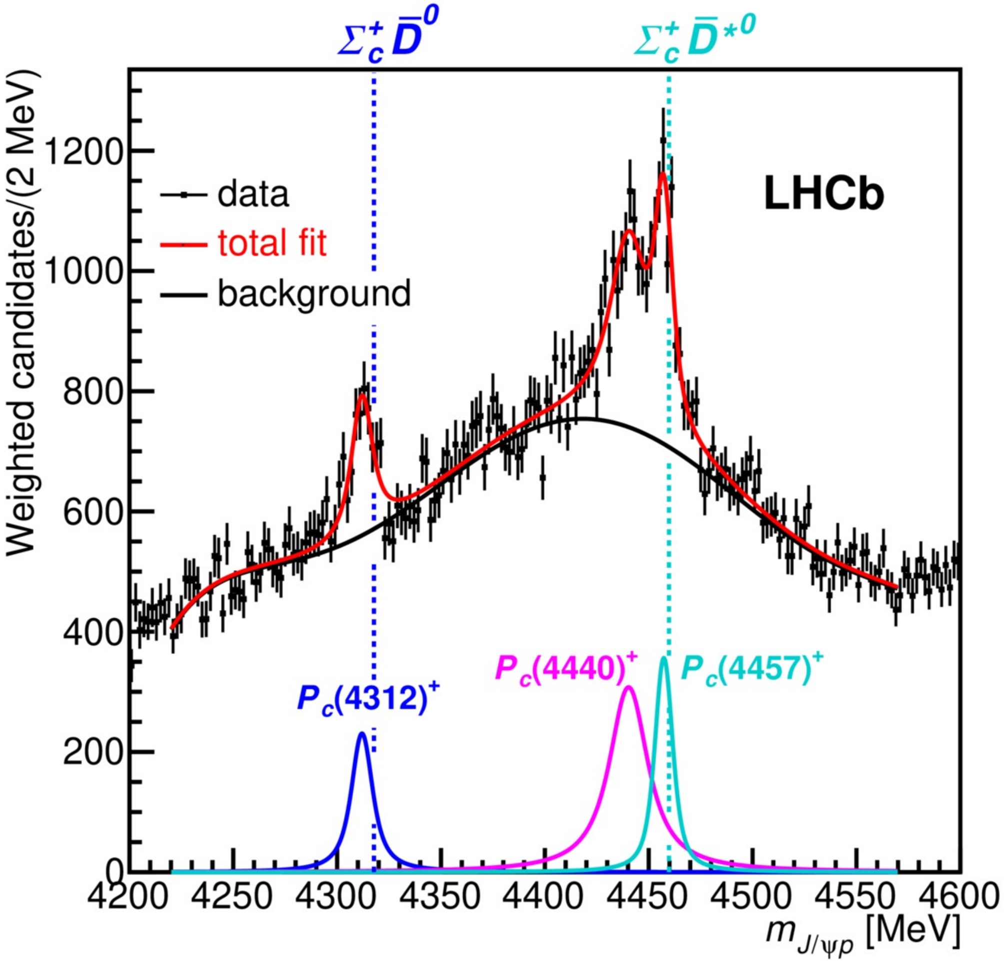


# State of the Art

- Full amplitude analyses of complex and diverse decay chains, exploiting the power of modern computing
- Coupled channel approach for states near threshold (moving beyond the simple Breit Wigner) and pole searches, e.g. for X(3872)
  - e.g for X(3872) see PRD 102, 092005
- Report information about the production environment
  - e.g event multiplicity for X(3872), PRL. 126, 092001

# Pentaquarks in $B_s \to J/\psi p\bar{p}$

# Recap: Pentaquarks in $\Lambda_b \to J/\psi p K^-$




PRL. 122 (2019) 222001

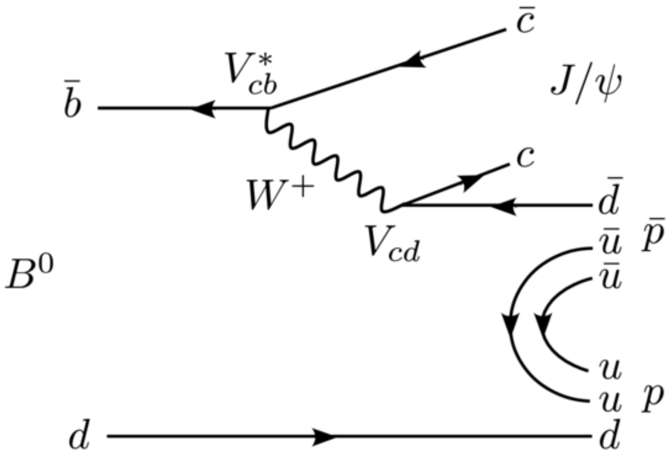
2019 study of $\Lambda_b \to J/\psi p K^-$ mode with the full LHCb dataset (9 fb$^{-1}$) finds 3 narrow pentaquark candidates

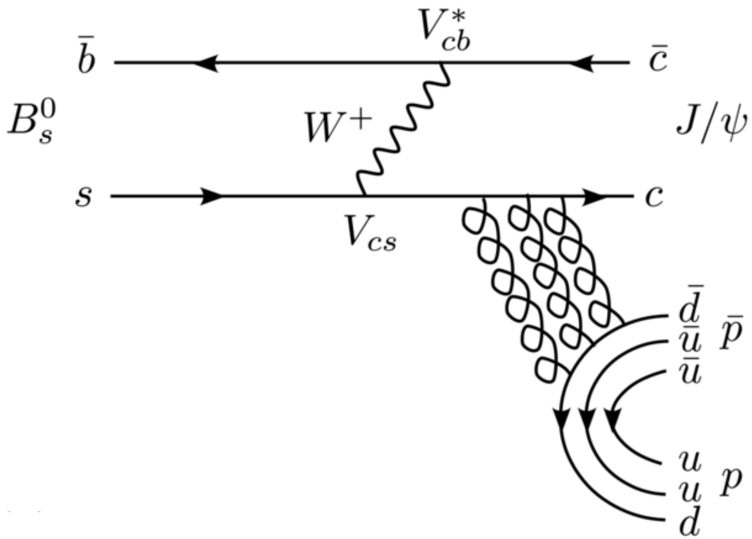
| State | $M$ [MeV] | $\Gamma$ [MeV] |
|---|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+3.7}_{-4.5}$ |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 4.9^{+8.7}_{-10.1}$ |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+5.7}_{-1.9}$ |

# The decays $B_{s,d} \rightarrow J/\psi p\bar{p}$

**Observed by LHCb using data up to 2016, 5.3 fb$^{-1}$ (PRL.122 (2019) 191804)**

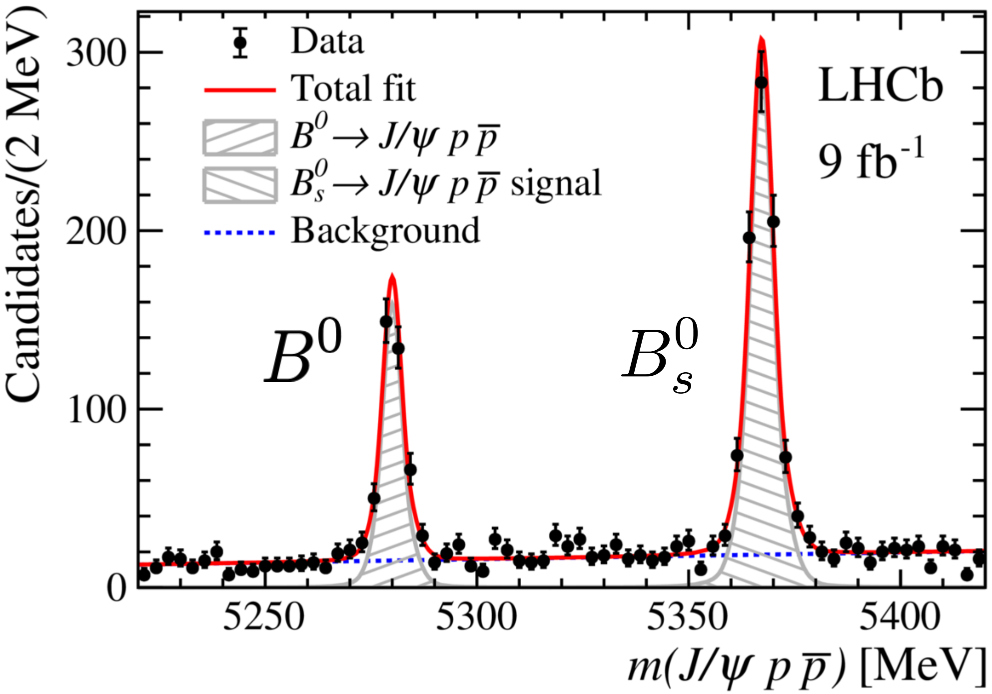
- The decay $B_d \rightarrow J/\psi p\bar{p}$ is Cabbibo suppressed whilst $B_s \rightarrow J/\psi p\bar{p}$ is OZI suppressed
- Suggested as good channels to look for exotics (Pentaquarks, glueball, $f_J(2300)$) - see EJPC C75 (2015) 101
- Production of $P_c(4312)^+$ kinematically allowed



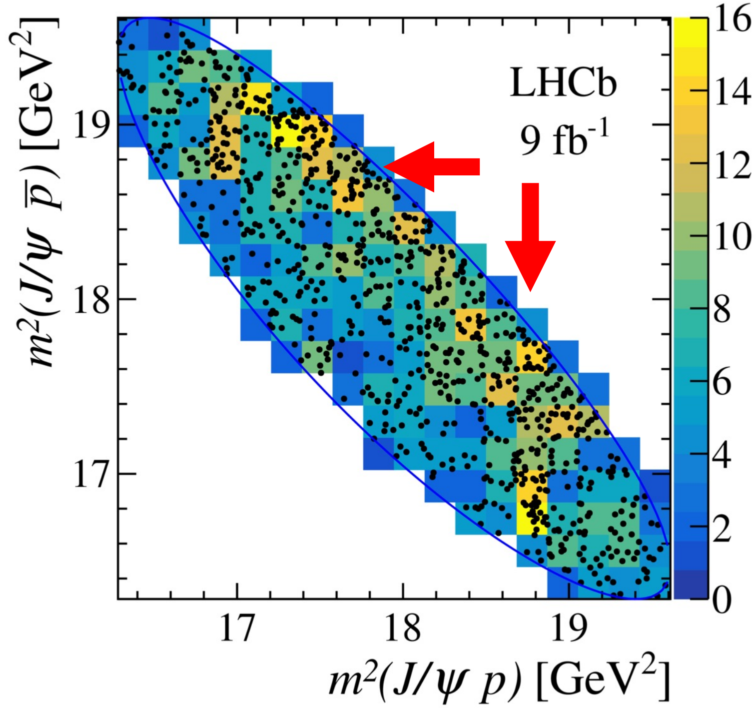



# The decays $B_{s,d} \to J/\psi p\bar{p}$

- New analysis using full Run 1+2 dataset 9 fb$^{-1}$
- Gives a sample of $797 \pm 31$ $B_s \to J/\psi p\bar{p}$ decays
- First full amplitude analysis of $B_s \to J/\psi p\bar{p}$



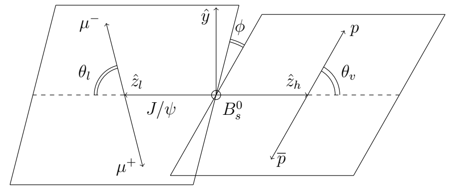

arXiv: 2108.04720



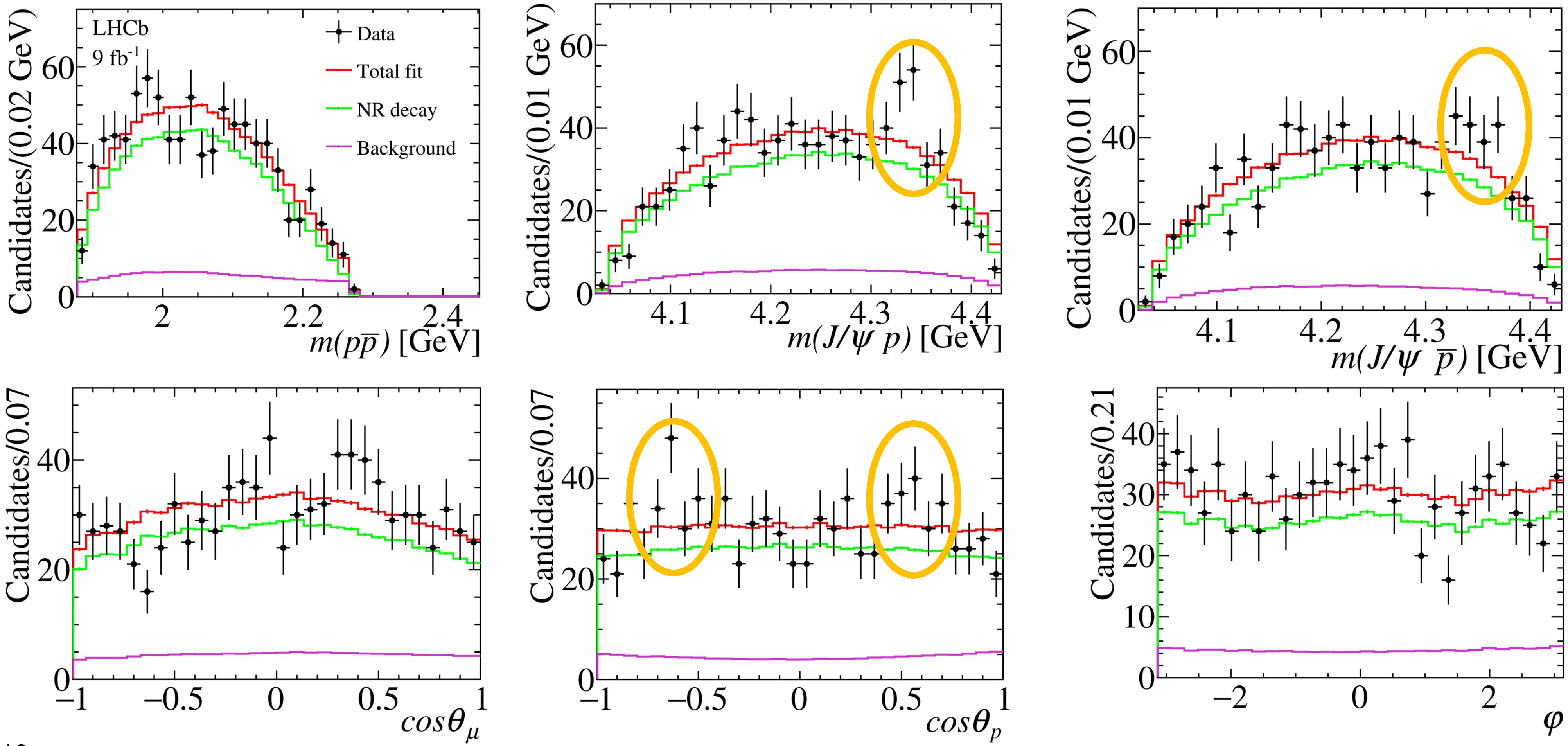

$B_s$ signal region

# $B_s \to J/\psi p\bar{p}$ amplitude analysis

- 4-D amplitude using helicity formalism, to untagged data assuming CP conservation



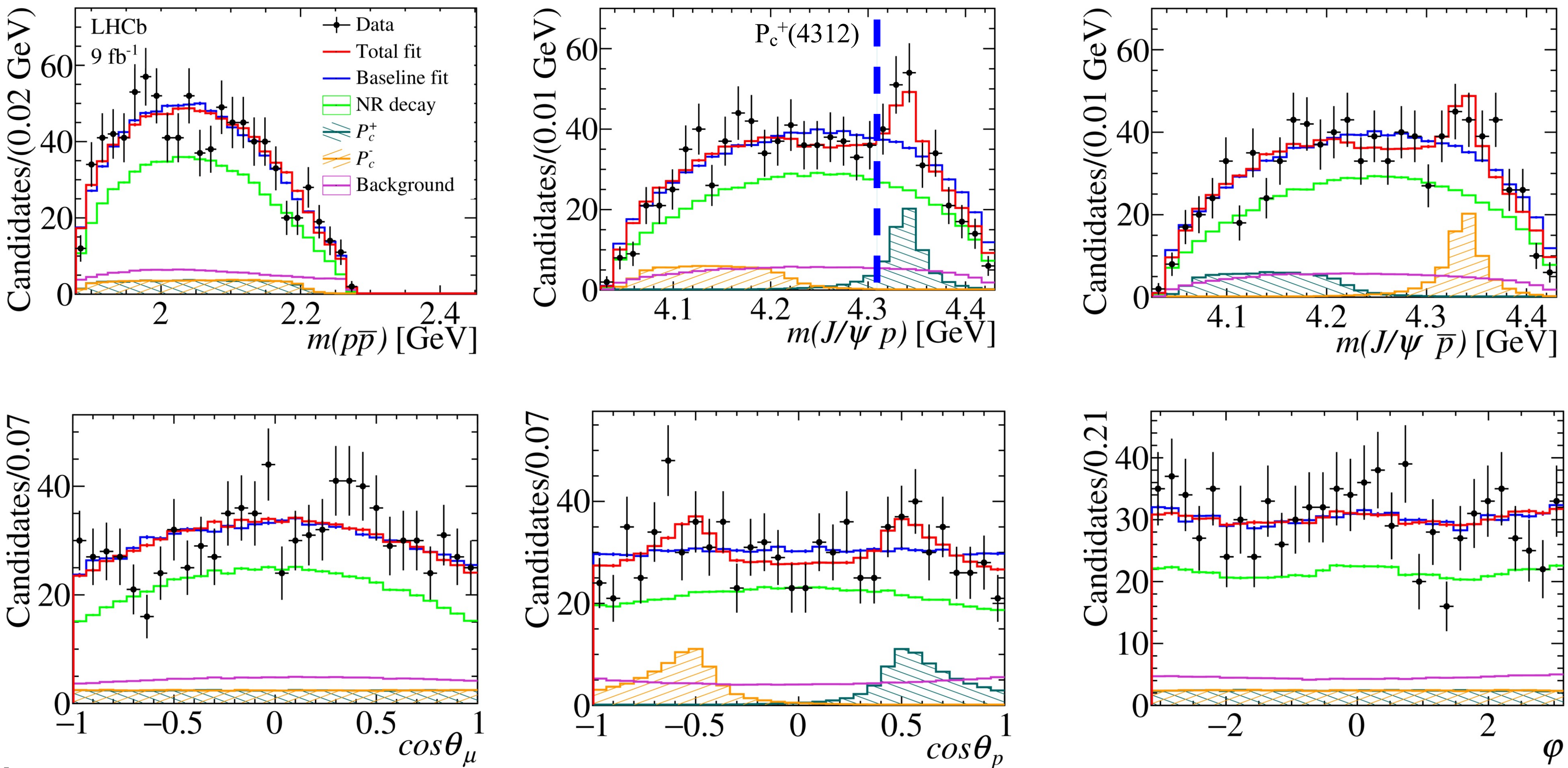

- Phase space model does not describe data well



# $B_s \to J/\psi p\bar{p}$ amplitude analysis

- Add $P_c^+$ and $P_c^-$ with same mass and width (floating)

- Improves mass and helicity distribution



# $B_s \to J/\psi p\bar{p}$ amplitude analysis

- Evidence for new pentaquark state
- Significance $3.7\sigma$ ($3.1\ \sigma$ ) for $J^P = {}^1/_2$ (${}^3/_2$)

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV}$$

$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV}$$

- Current dataset insufficient to determine $J^P$
- Fit not improved adding contributions from either $P_c(4312)^+$ or $f_J(2300)$
- No enhancement at threshold (as seen in other baryonic decays)

arXiv: 2108.04720

# Amplitude analysis of $B^+ \to D^+D^-K^-$

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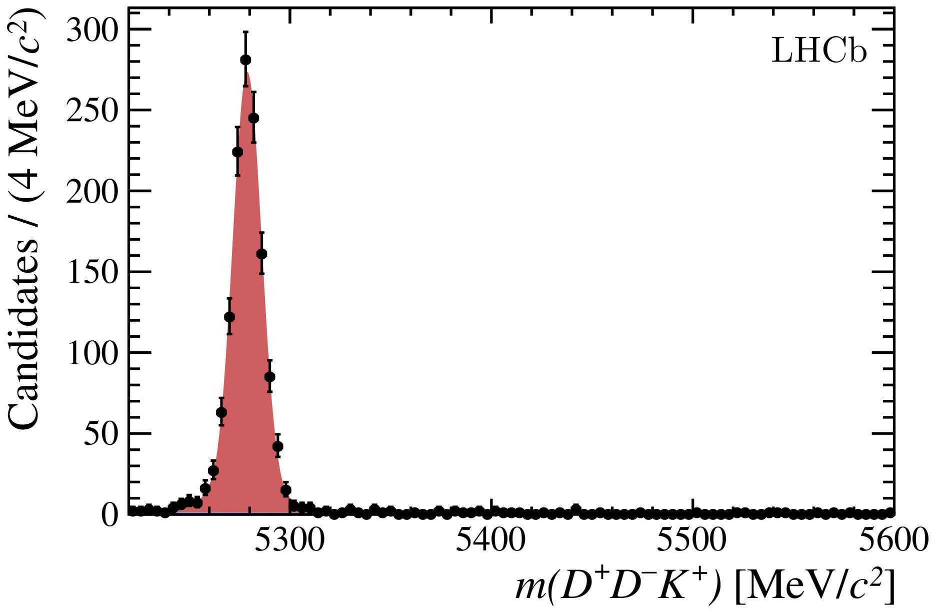
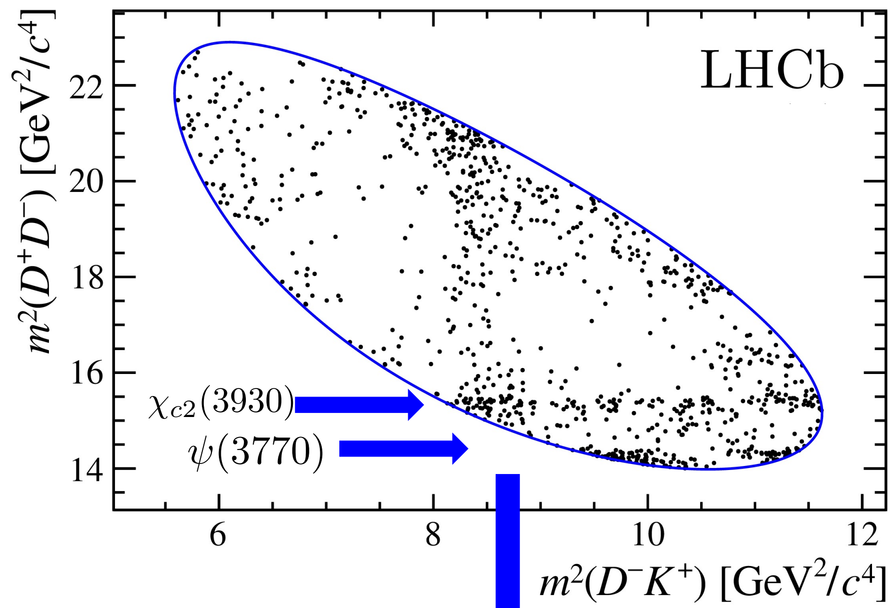
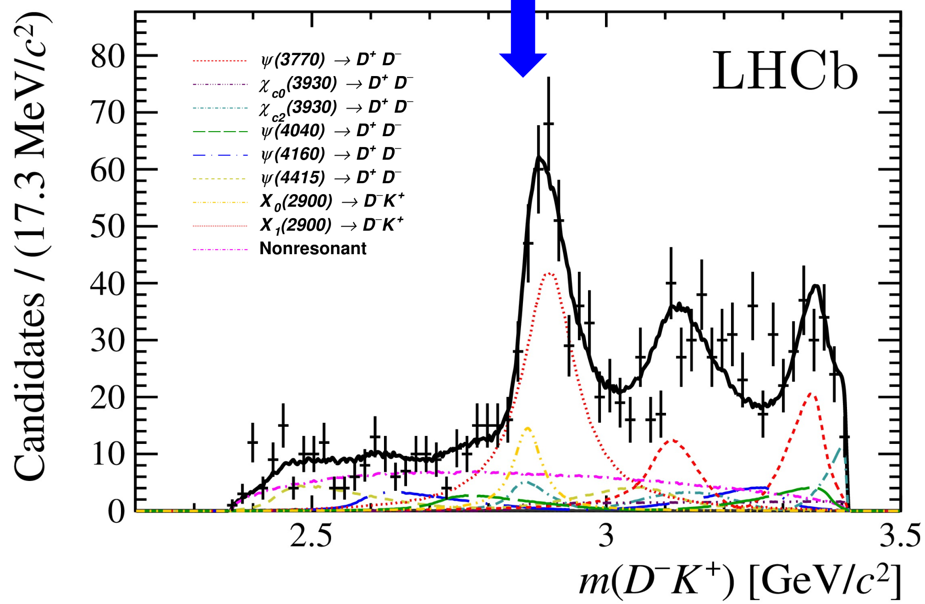
PRD 102 (2020) 242001



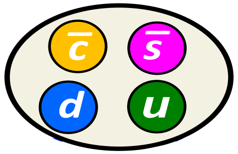

Around 1300 candidates selected in full Run 1+2 dataset

Full amplitude analysis performed

Significant enhancement seen in $m(D^-K^+)$ around ~ 2900 MeV

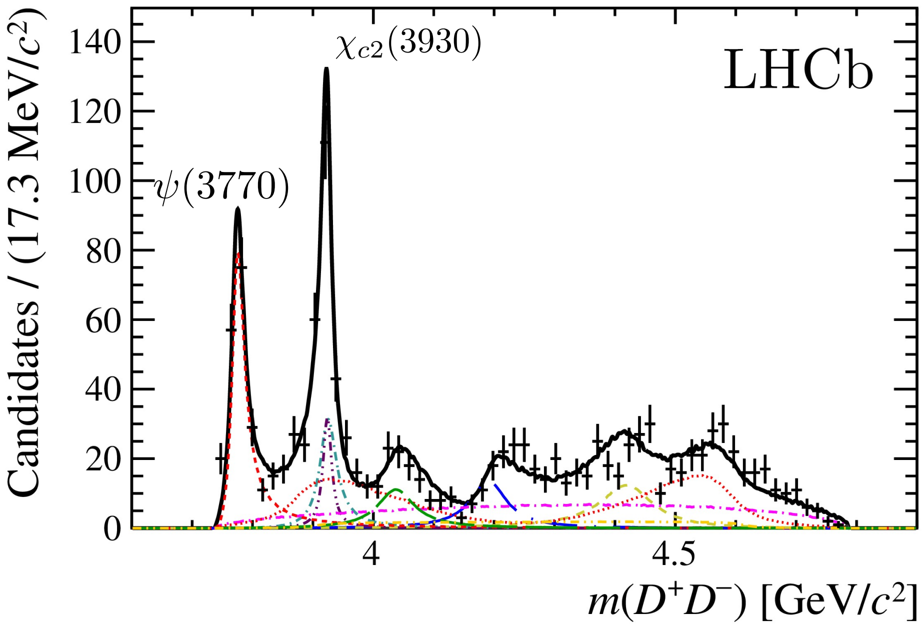
# Amplitude analysis of $B^+ \to D^+D^-K^+$

Data well described by two states $X_0(2900)$ and $X_1(2900)$ with high significance




Conclusion supported by model independent analysis
PRL 125 (2020) 242001)

| Resonance | Mass (GeV/$c^2$) | Width (MeV) |
|---|---|---|
| $\chi_{c0}(3930)$ | $3.9238 \pm 0.0015 \pm 0.0004$ | $17.4 \pm 5.1 \pm 0.8$ |
| $\chi_{c2}(3930)$ | $3.9268 \pm 0.0024 \pm 0.0008$ | $34.2 \pm 6.6 \pm 1.1$ |
| $X_0(2900)$ | $2.866 \pm 0.007 \pm 0.002$ | $57 \pm 12 \pm 4$ |
| $X_1(2900)$ | $2.904 \pm 0.005 \pm 0.001$ | $110 \pm 11 \pm 4$ |




Amplitudes analysis also requires both a spin 0 and spin 2 state decaying to $D^+D^-$ in the mass region around 3930MeV

Deepens puzzle of what states are present in this region

# Observation of a doubly charmed tetraquark, $T_{cc}^{+}$

# Doubly charmed tetraquark

LHCb has seen

- Doubly charmed baryon, $\Xi_{cc}^{++}$ (ccu) PRL 119 (2017) 112001
- ud$\bar{c}\bar{s}$ tetraquark candidates, $X_{0,1}(2900)$ (Science Bullitin 65 (2020) 1983)
- cc$\bar{c}\bar{c}$ tetraquark candidate, X(6900) (PRD 102 (2020) 242001)

What about tetraquark with double charm content ? cc$\bar{u}\bar{d}$

For a system $QQ\bar{u}\bar{d}$, in limit $m_Q \rightarrow \infty$ system should give a bound and stable state

Likely to be true for bb$\bar{u}\bar{d}$, not clear for cc$\bar{u}\bar{d}$

Predictions for mass of cc$\bar{u}\bar{d}$ ground state (isoscalar with $J^P = 1^+$) vary within $\pm$250 MeV compared to $DD^{*+}$ threshold

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

Use full Run 1+ Run 2 dataset

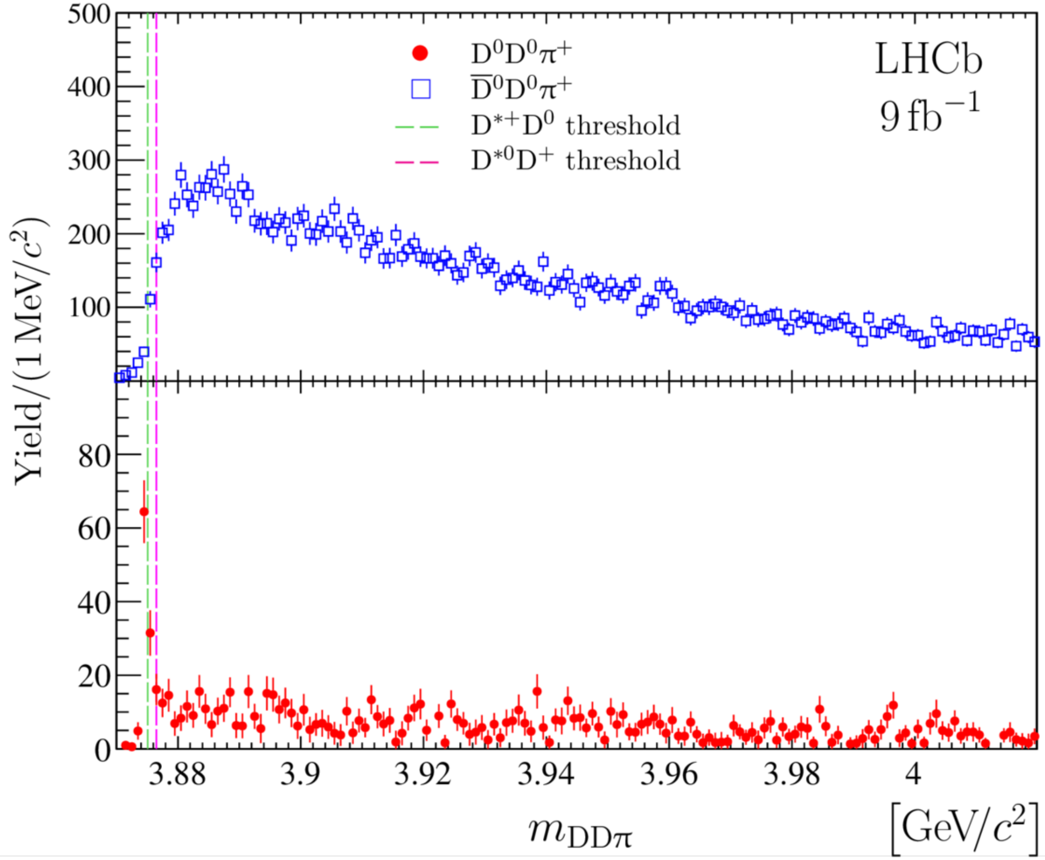
Select well identified $K/\pi$ candidates displaced with high transverse momentum

Combine to make $D^0 \to K^- \pi^+$ candidates

Make $D^0 D^0 \pi^+$ candidates

Ensure no candidates are duplicates or clones

Fake D background subtracted using 2D fit to $(m_{K\pi}, m_{K\pi})$

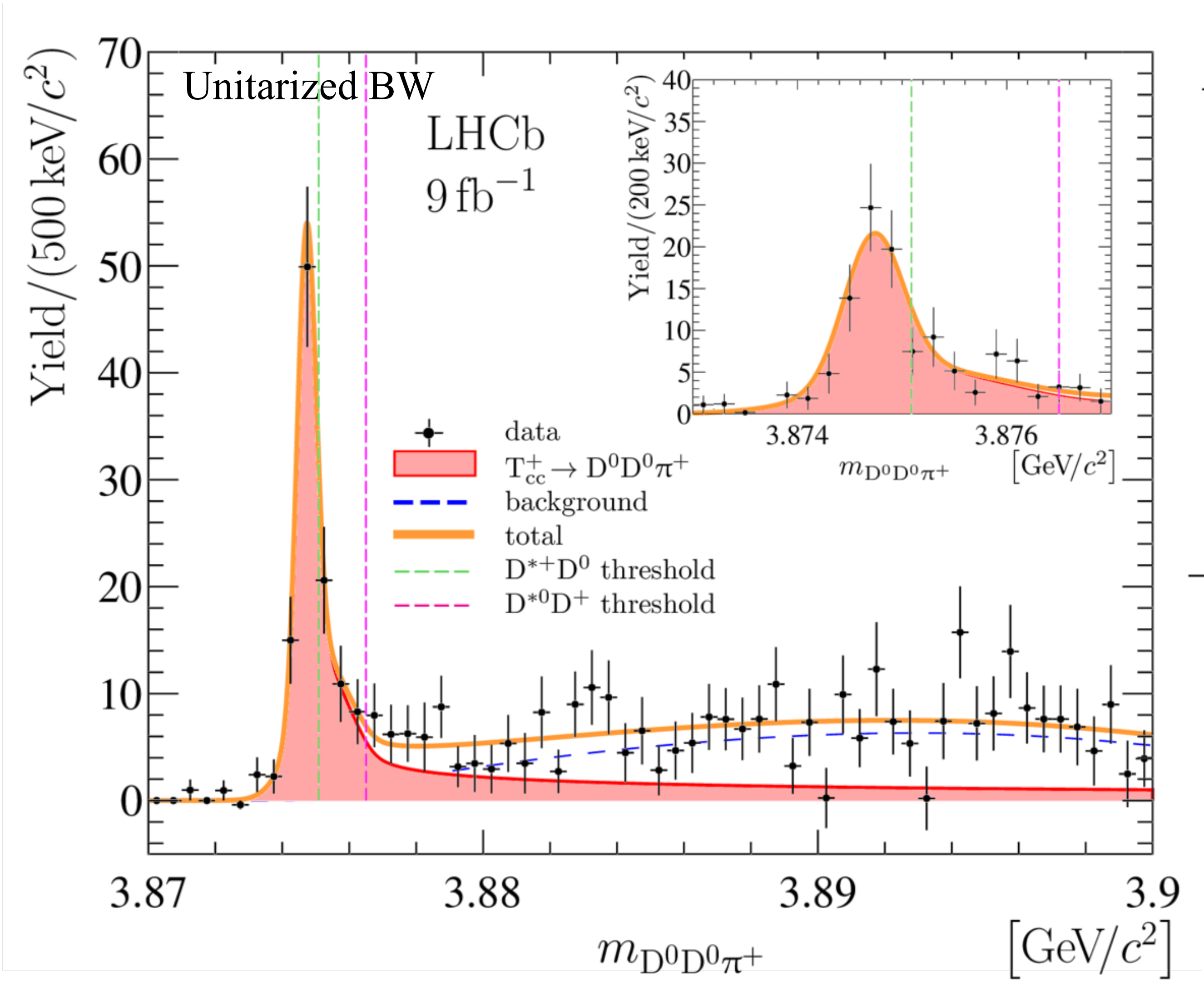



Significant narrow peak just below DD* threshold

arXiv: 2109.01038
arXiv: 2109.01056

# Mass fit for $D^0 D^0 \pi^+$

Fits made with relativistic P-wave Breit Wigner and a unitarized Breit-Wigner form that is more appropriate for a state close to threshold




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

Fixed by $D^{0*}$ width

## Mode and FWHM

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

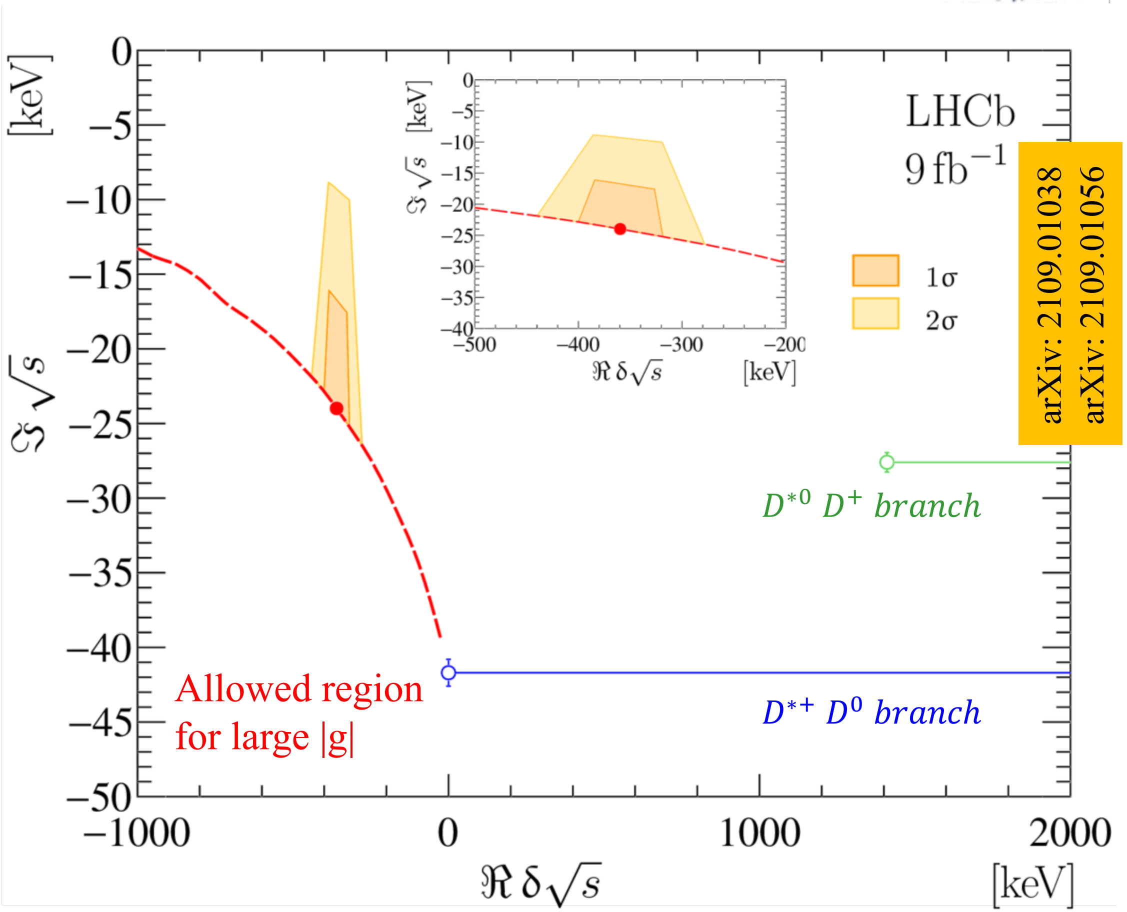
Narrow peak below $D^{*+}D^0$, threshold: $T_{cc}^+$

# $D^0 D^0 \pi^+$ pole search

Pole on second Riemann sheet

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

$$\Gamma_{\text{pole}} = 48 \pm 2\,^{+0}_{-14}\ \text{keV}$$




Extract the scattering length

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

Effective range $\quad -r < 11.9\,(16.9)\ \text{fm at}\ 90\,(95)\%\ \text{CL}$

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

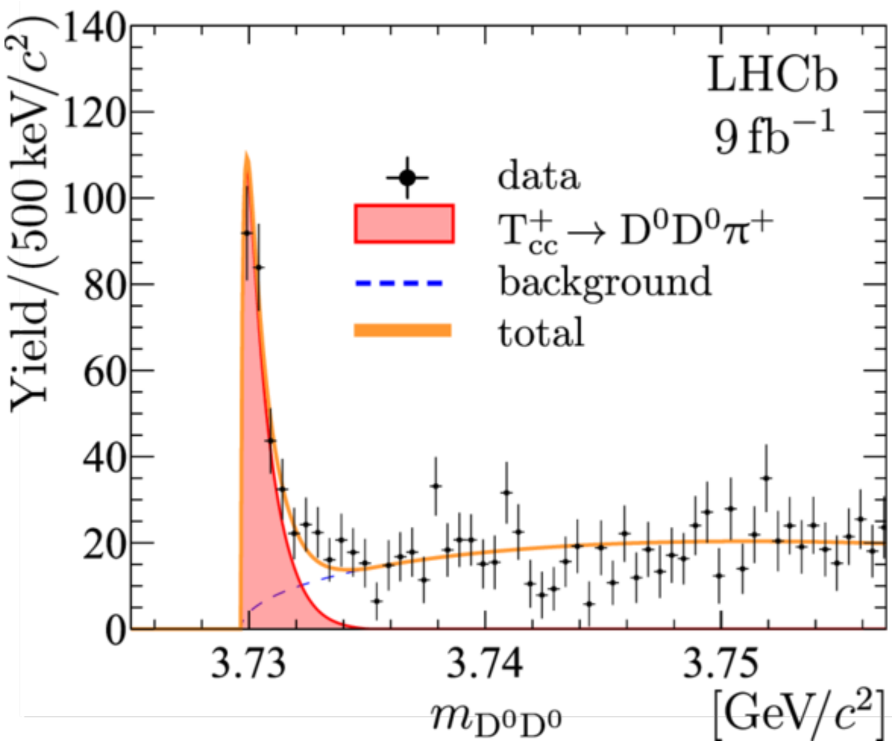
# Is the $T_{cc}^{+}$ an isosinglet ?

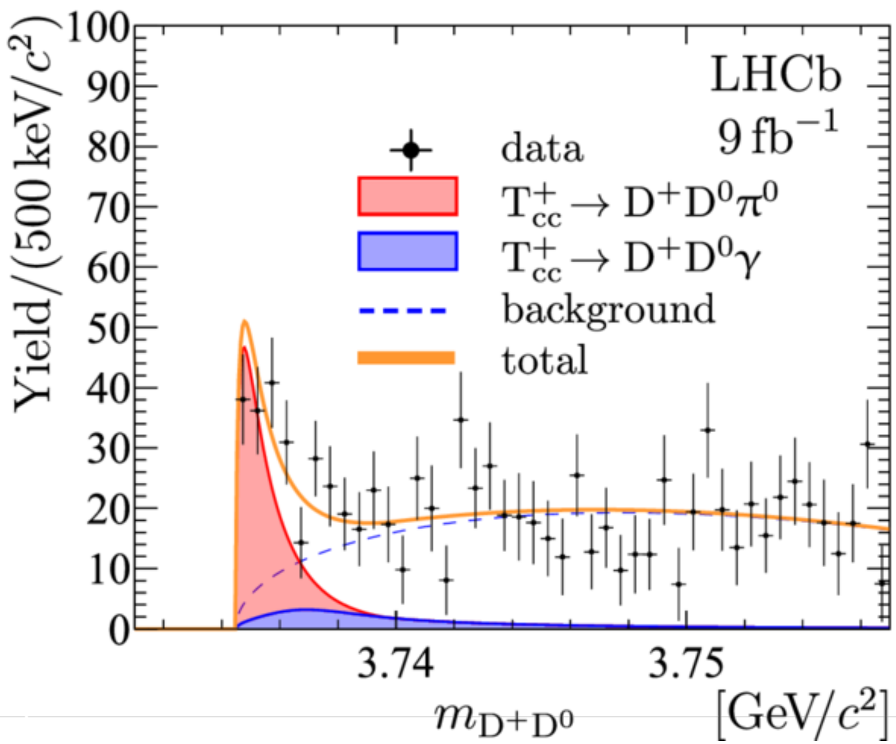
Study also mass $D^0D^0$ and $D^0D^+$ mass distributions

Observed shape is consistent with expectations for partially reconstructed $T_{cc}^{+}$

No evidence for further narrow peaks: supports hypothesis that the the $T_{cc}^{+}$ is an isoscalar state rather than member of isotriplet

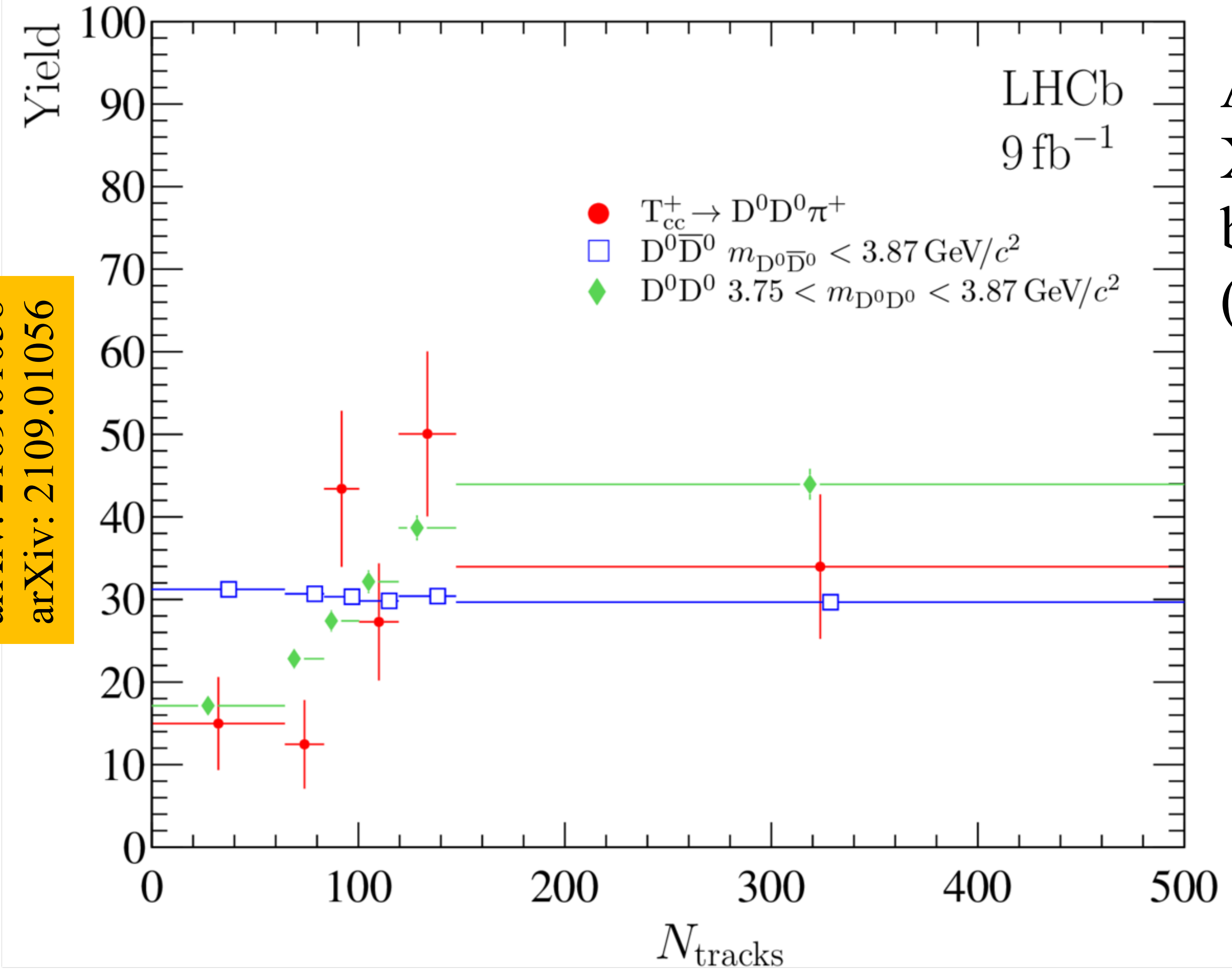
arXiv: 2109.01038
arXiv: 2109.01056



# Multiplicity dependence

arXiv: 2109.01038
arXiv: 2109.01056

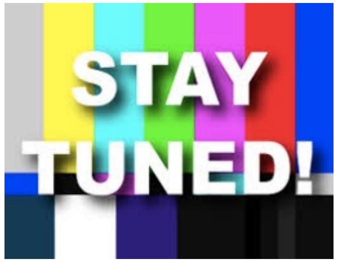



As recently done for X(3872) production bin in track multiplicity (cf PRL. 126, 092001)

- Contrary to X(3872) no suppression at high multiplicity
- Dependence is surprising close to $D^0D^0$(which is dominated by Double Parton Scattering)

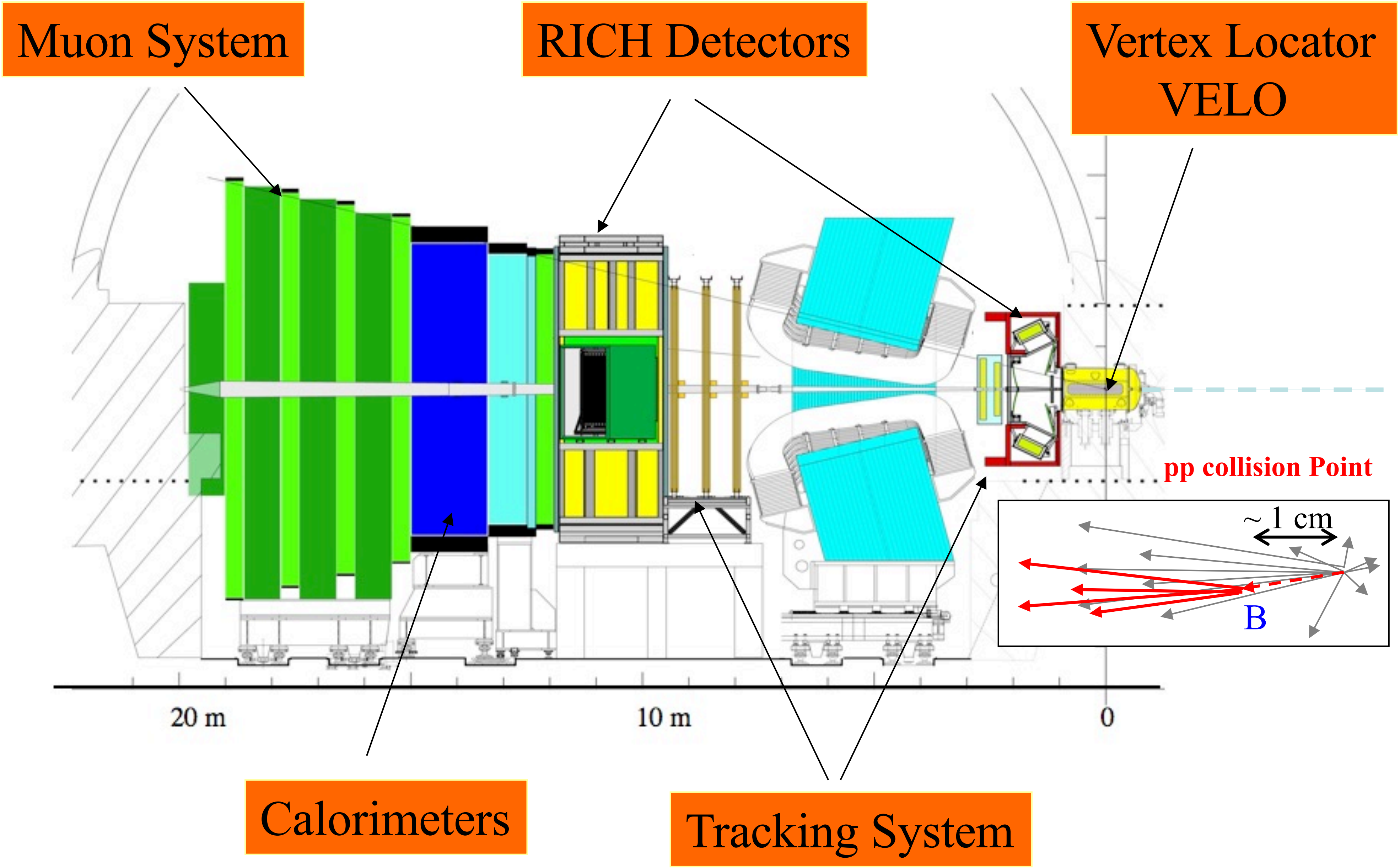
# Summary

- Many important LHCb results in spectroscopy over the last months
  - New pentaquark candidates in $B_s \rightarrow J/\psi p\bar{p}$ mode
  - Candidate tetraquarks with quark content $\bar{c}\bar{s}ud$ in $B^+ \rightarrow D^+D^-K^-$
  - Prompt production of a doubly charmed tetraquark ($T_{cc}^+$)
- Still more to come from Run 1+2 dataset over the next couple of years
- From 2022 LHCb upgrade will increase dataset by factor 5-10 depending on mode

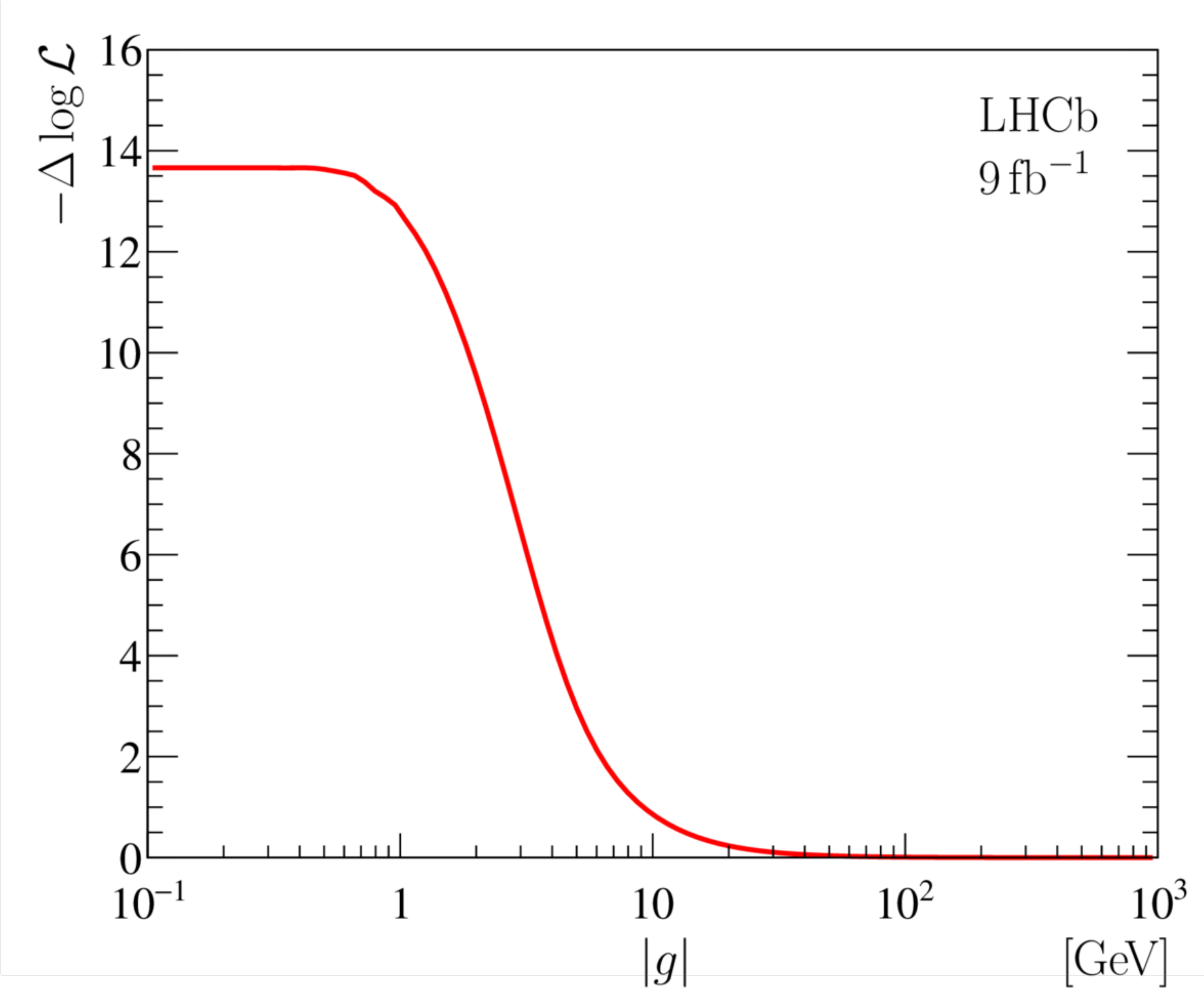


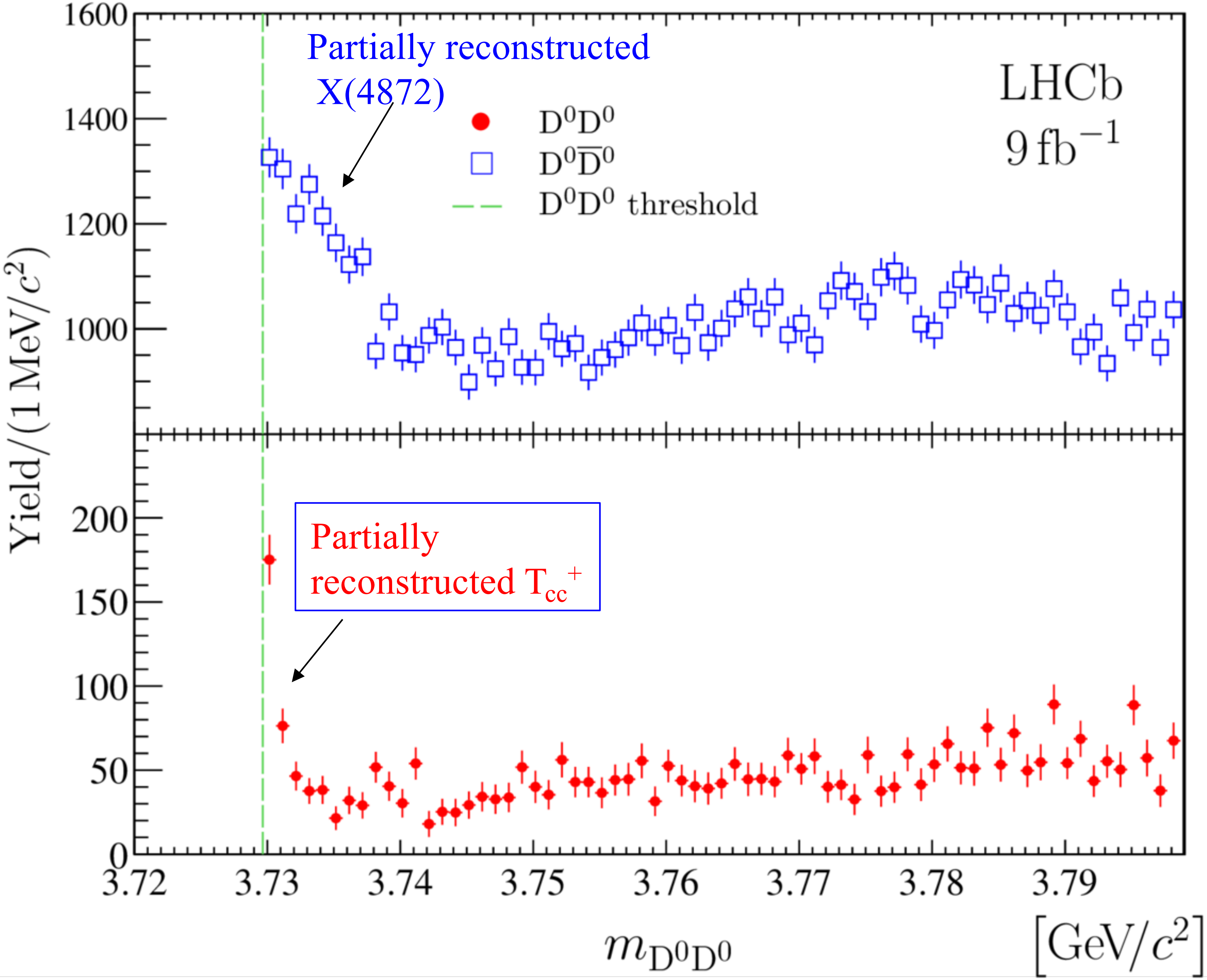
# Backup

# The LHCb Detector



# $T_{cc}^{+}$ g-coupling




Partially reconstructed
X(4872)
LHCb
9 fb$^{-1}$
$D^0D^0$
$D^0\bar{D}^0$
$D^0D^0$ threshold
Partially
reconstructed $T_{cc}^+$
Yield/(1 MeV/$c^2$)
$m_{D^0D^0}$ [GeV/$c^2$]
1600
1400
1200
1000
200
150
100
50
0
3.72
3.73
3.74
3.75
3.76
3.77
3.78
3.79