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Recent results in production of open-charm and charmonium states at LHCb

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On behalf of the LHCb collaboration

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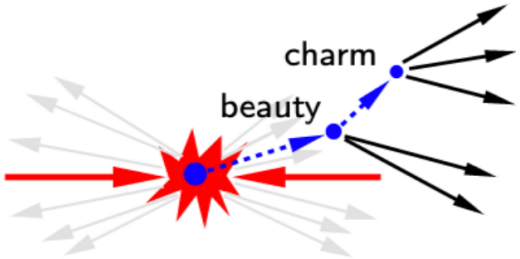
Introduction

- **Charm** meson spectroscopy is of great interest, theoretically and experimentally, as a testing ground for quark-models predictions in the Standard Model.

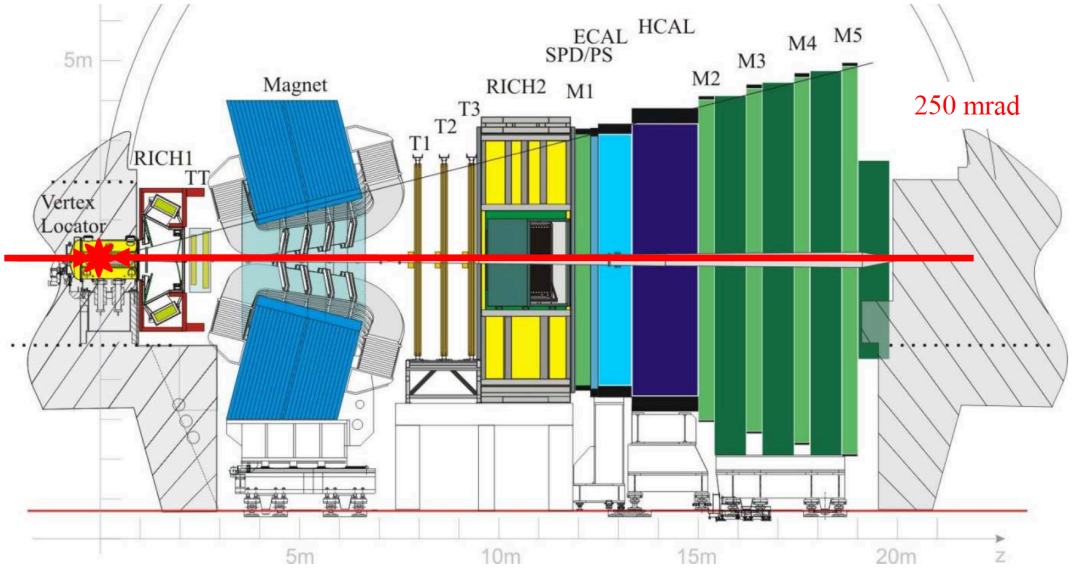


- Production of conventional and exotic charm states from B-decays.

- Study the heavy **quarkonium** production can provide important information to probe the theory of strong interaction.

- The nature of **charmonium-like state** $\chi_{c1}(3872)$ is still not clear. By including the LHCb data recorded during Run1 and Run2, it is possible to measure the double-differential cross-section of $\chi_{c1}(3872)$ for the first time.

LHCb detector



Int. J. Mod. Phys A 30, 1530022 (2015)

- Designed for precision measurements in b, c flavor sectors.
- It covers a pseudo-rapidity range of $2 < \eta < 5$.
- Run1: $\mathcal{L} = 3.0$ fb^{-1} from pp collision at 7 TeV (2011) and 8 TeV (2012) in the center-of-mass-energy.
- Run2: $\mathcal{L} = 6.0$ fb^{-1} from pp collision at 13 TeV (2015-2018) in the center-of-mass-energy.

Outline

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

  Phys. Rev. D102 (2020) 112003

- Observation of a new excited D_s^+ meson in $B^0 \to D^-D^+K^+\pi^-$ decays

  Phys. Rev. Lett. 126 (2021) 122002

- Measurement of the J/ψ production cross-section in pp collisions at $\sqrt{s} = 5$ TeV

  LHCb-PAPER-2021-020, in preparation

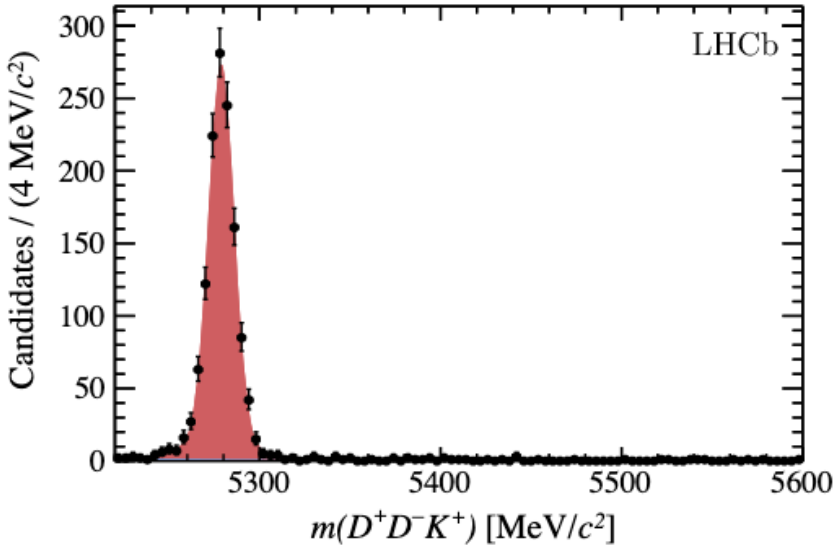
- Measurement of $\chi_{c1}(3872)$ production in pp collision at $\sqrt{s} =$ 8 and 13 TeV

  LHCb-PAPER-2021-026, in preparation

$B^+ \to D^+D^-K^+$

Phys. Rev. D102 (2020) 112003

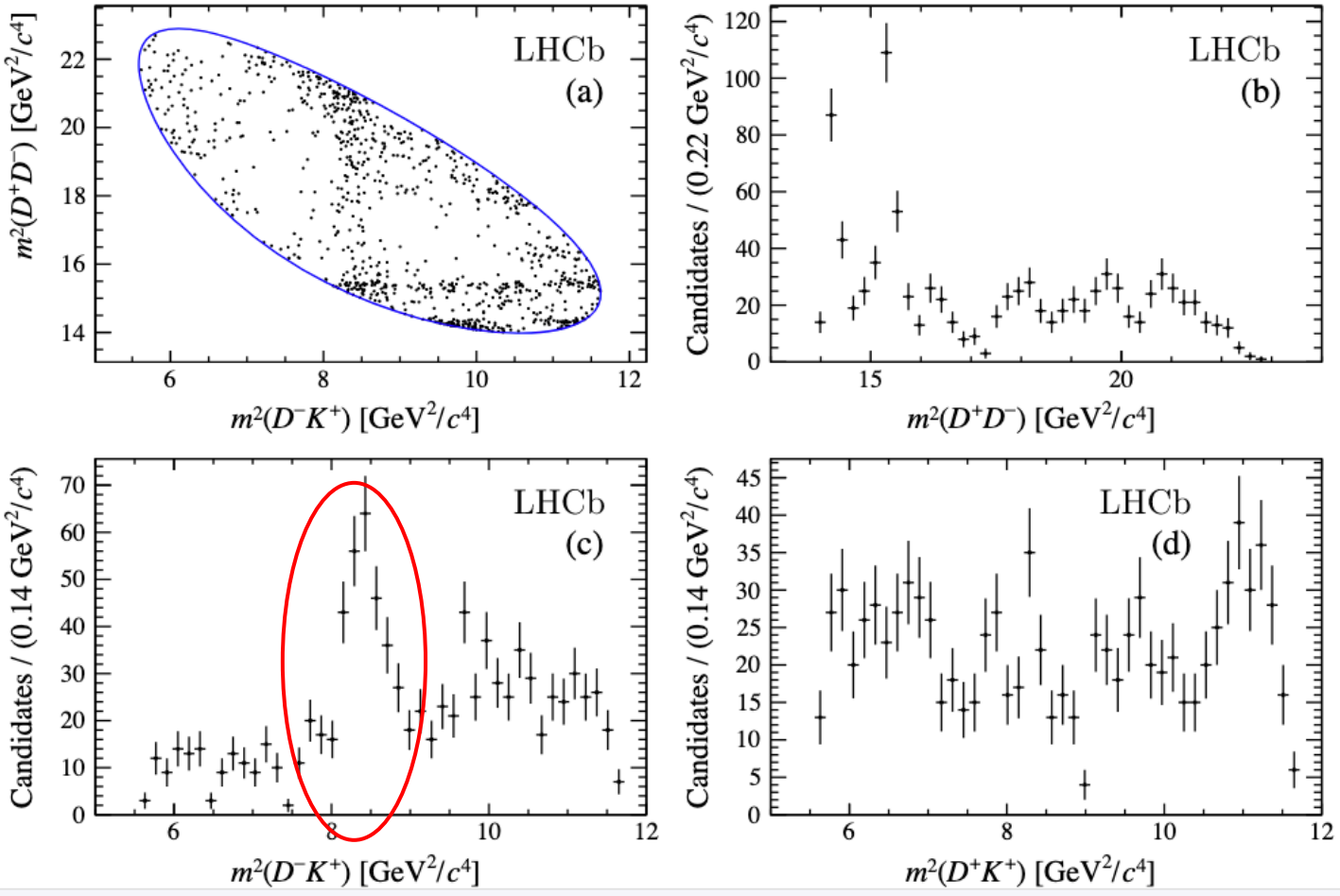
- The $B^+ \to D^{(*)+}D^{(*)-}K^+$ family of decays offers a good laboratory to study charmonium states.
- With unprecedented pure sample obtained by LHCb, the first $B^+ \to D^+D^-K^+$ amplitude analysis is presented
- Resonances in the D^-K^+ system would indicate exotic contribution.



1260 candidates,
purity > 99.5%

$B^+ \to D^+D^-K^+$

Phys. Rev. D102 (2020) 112003



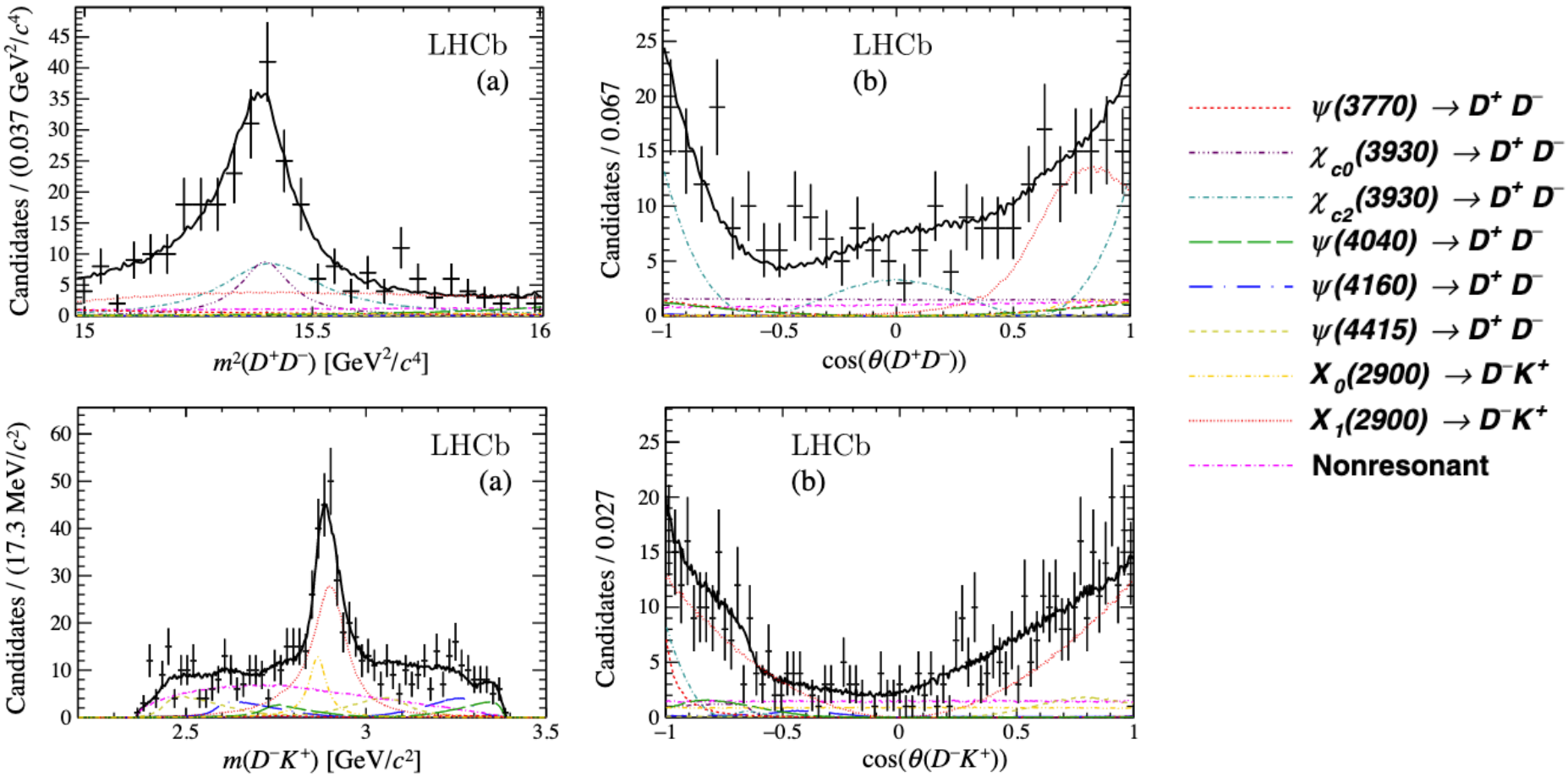
- The projection of candidates in Dalitz plot (run II data)
- Clear excess at 8.25 GeV^2/c^4 (also observed for run 1 data) in D^-K^+.

$B^+ \to D^+D^-K^+$

Phys. Rev. D102 (2020) 112003

- The spin-0 and spin-2 states is necessary for $\chi_{cj}(3930)$
- Good data description by including new spin-0 and spin-1 resonance in the D^-K^+ system

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



$B^0 \to D^- D^+ K^+ \pi^-$

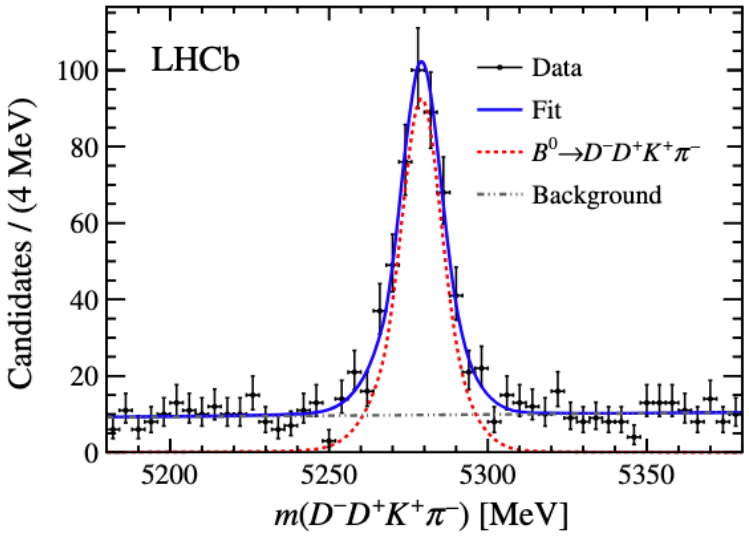
Phys. Rev. Lett. 126 (2021) 122002

- The study of the charm-strange spectrum is rich in structures ⇒ interesting place for testing theories.
  - Some states are already experimentally well established
  - But some predicted states are still not observed
- D_s state have been observed in $B \to D\bar{D}K$ decays

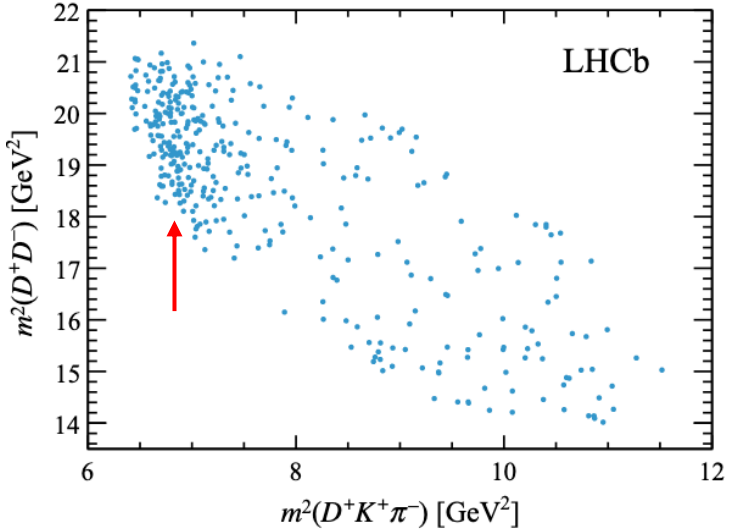
  Phys.Rev.Lett.100(2008)092001
- Most studies has been focused in excited D_s^+ decaying into DK
  - Only sensitive to D_s^+ natural spin-parity states.
- The $D^+K^+\pi^-$ allows to access all spin-parity D_s states in a large mass range

$B^0 \to D^- D^+ K^+ \pi^-$

Phys. Rev. Lett. 126 (2021) 122002



- Fit to the B^0 spectrum
- 444 ± 27 signal candidates

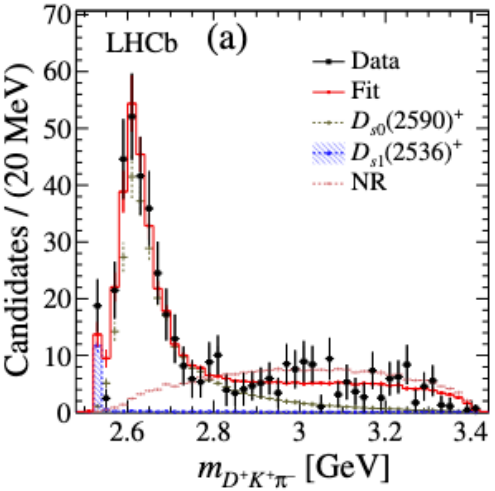


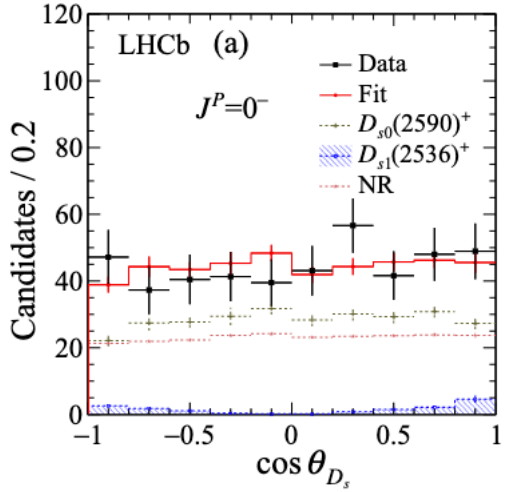
Dalitz plot in the square mass of $D^- D^+$ vs $D^+ K^+ \pi^-$

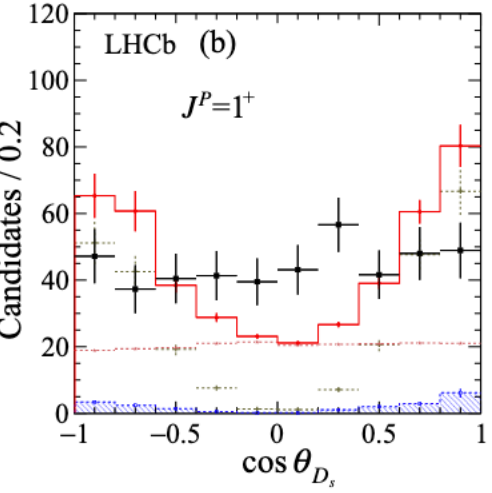
- For candidates with masses within 20 MeV of the B^0 mass.
- Clear cluster of candidates observed in $D^+ K^+ \pi^-$ mass around 2.6 GeV.

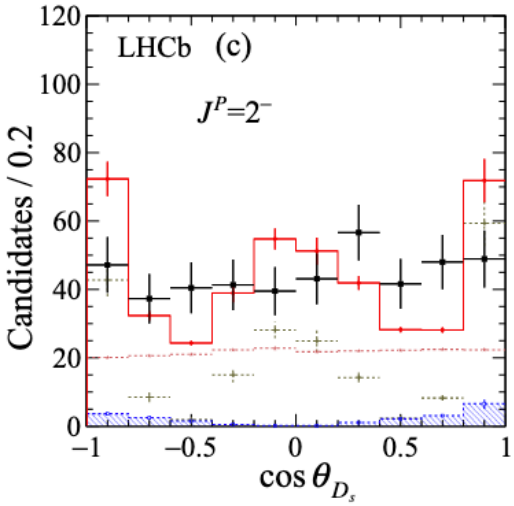
$B^0 \to D^- D^+ K^+ \pi^-$

Phys. Rev. Lett. 126 (2021) 122002









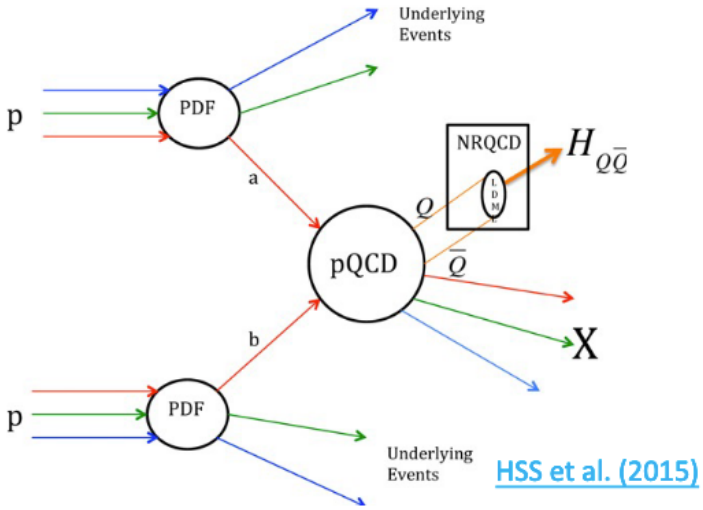
	Fit fraction ($\times 10^{-2}$)
$D_{s0}(2590)^+$	$63 \pm 9(\text{stat}) \pm 9(\text{syst})$
$D_{s1}(2536)^+$	$3.9 \pm 1.4(\text{stat}) \pm 0.8(\text{syst})$
NR	$51 \pm 11(\text{stat}) \pm 19(\text{syst})$
D_{s0}^+–NR	$-18 \pm 18(\text{stat}) \pm 24(\text{syst})$
D_{s1}^+/D_{s0}^+	$6.1 \pm 2.4(\text{stat}) \pm 1.4(\text{syst})$

- Mass = $2591 \pm 6 \pm 7$ MeV
- $\Gamma = 89 \pm 16 \pm 12$ MeV
- Best fit with $J^P = 0^-$

J/ψ production

LHCb-PAPER-2021-020

- Prompt J/ψ
  - Probe J/ψ production mechanism
  - $c\bar{c}$ pair production: perturbative QCD
  - Hadronisation: non-perturbative QCD

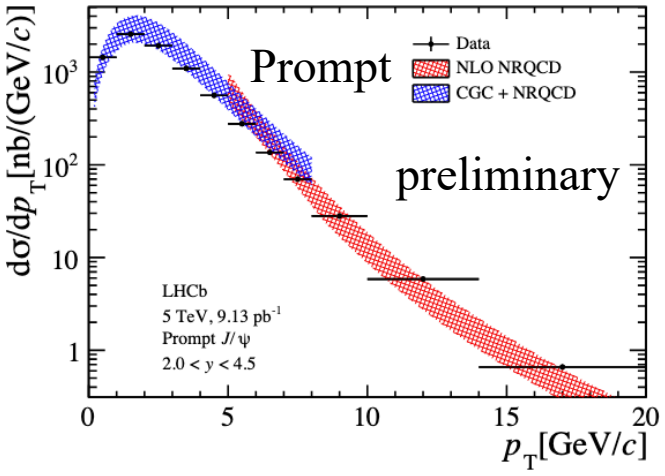


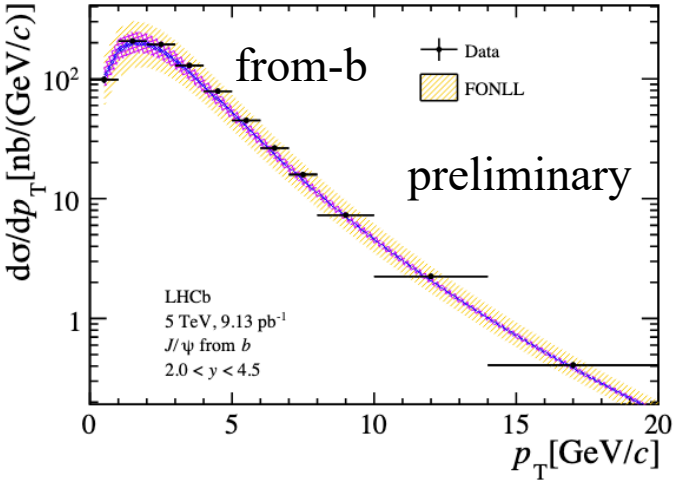
- J/ψ from b
  - Probe b-hadron production mechanism
  - Theory model: Fixed Order plus Next-to-Leading Logarithms(FONLL).

J/ψ production

LHCb-PAPER-2021-020

- Integrated cross-sections ($p_T < 20$ GeV/c, $2.0 < y < 4.5$) assuming zero polarisation
  - $\sigma_{\text{prompt}} = 8.154 \pm 0.010\,(\text{stat.}) \pm 0.283\,(\text{syst.})$ μb
  - $\sigma_{\text{from}-b} = 0.820 \pm 0.002\,(\text{stat.}) \pm 0.034\,(\text{syst.})$ μb





NLO NRQCD: Phys. ReV Lett. 106, 042002
Color Glass Condensate (CGC): Phys. Rev. Lett. 113,192301

FONLL: JHEP 10 (2012) 137
EPJC 75 (2015) 610

- The inclusion of CGC effects achieves a reasonable agreement between data and theory for prompt J/ψ at low p_T.
- Good agreement with predictions both for prompt J/ψ and J/ψ from-b.

$\chi_{c1}(3872)$ production

LHCb-PAPER-2021-026

- $\chi_{c1}(3872)$ is an exotic meson discovered in 2003 by Belle

  Phys.Rev.Lett. 91 (2003) 262001

- $J^{PC} = 1^{++}$ determined by LHCb

  Phys.Rev. D 92 (2015) 011102

- The nature of $\chi_{c1}(3872)$ still not clear.

- ATLAS measurement consistent with NLO NRQCD prediction for $\boldsymbol{\chi_{c1}(2P) - D^0\overline{D^{*0}}}$

  JHEP 01 (2017) 117

- Recently LHCb measured the multiplicity dependent prompt $\chi_{c1}(3872)$ production consistent with a compact tetraquark.

  Phys.Rev.Lett. 126 (2021) 092001

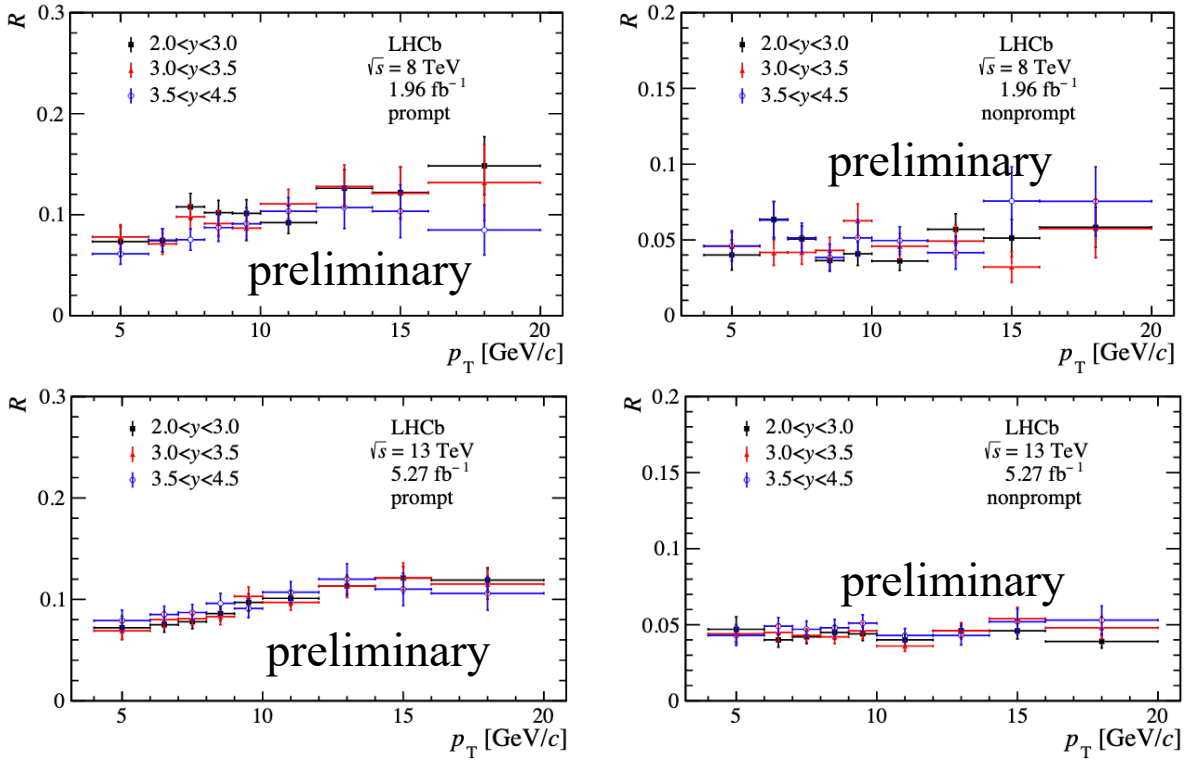
$\chi_{c1}(3872)$ production

LHCb-PAPER-2021-026

The double-differential cross-section of $\chi_{c1}(3872)$ relative to $\psi(2S)$ are measured for 2012 (8TeV), and 2016, 2017 and 2018 (13TeV).

2012 (8 TeV)

2016+2017+2018 (13 TeV)

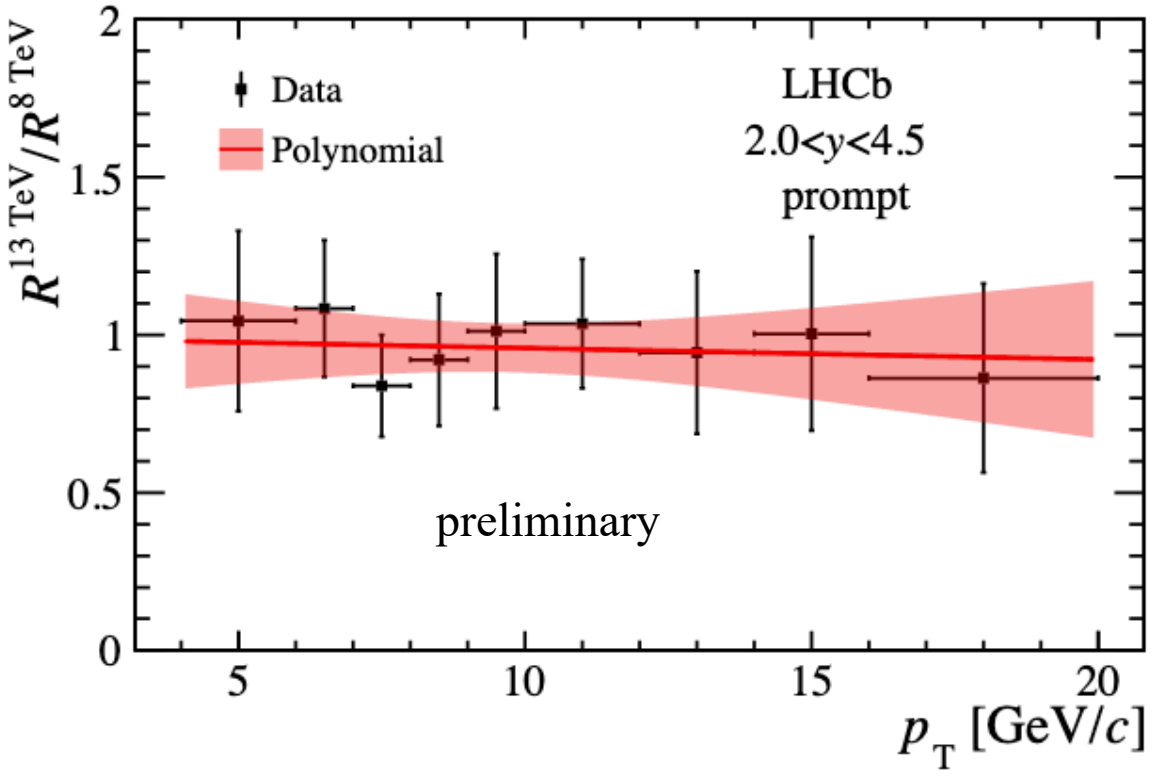


- The prompt ratio increase as a function of p_T, showing that $\chi_{c1}(3872)$ production is enhanced relative to prompt $\psi(2S)$ in higher p_T region.
- This flat behavior of the non-prompt ratio is set by the b-decay branching ratios.

$\chi_{c1}(3872)$ production

LHCb-PAPER-2021-026

The double ratio cross-section of $\chi_{c1}(3872)$ relative to $\psi(2S)$ between 13 TeV and 8 TeV as a function of p_T integrated over 2.0 < y < 4.5.



- A first-order polynomial is used to fit the double ratio.
- The central value is consistent with one, the slope is consistent with zero.
- Have no dependence on p_T and center-of-mass energy.

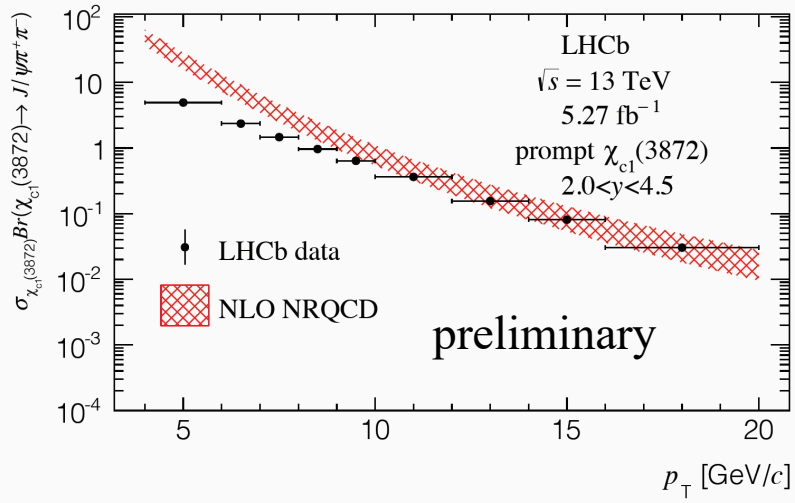
$\chi_{c1}(3872)$ production

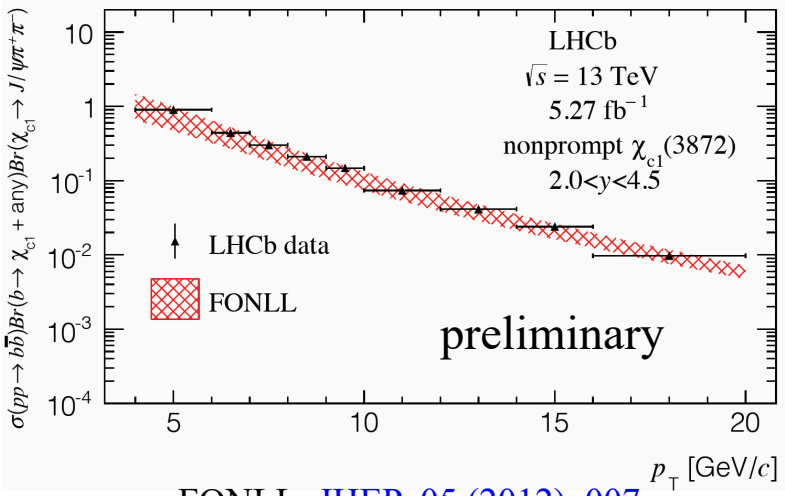
LHCb-PAPER-2021-026

Take the cross-section of $\psi(2S)(\rightarrow \mu^+\mu^-)$ as input. LHCb, EPJC 80(2020) 185

The measured cross-section times branching fractions as a function of p_T for

- prompt $\chi_{c1}(3872)$ compared to NLO NRQCD predictions,
- b-decay $\chi_{c1}(3872)$ compared to FONLL predictions.





FONLL: JHEP 05 (2012) 007
EPJC 75 (2015) 610

NRQCD prediction: PRD 96 (2017) 074014

$$\frac{d\sigma}{dp_T} = k \cdot \mathcal{O} <^3 P_1^{[1]} > (d\sigma(^3P_1^{[1]}) + r \cdot d\sigma(^3S_1^{[8]}))/m_c^2$$

- Include color-singlet and color-octet contribution.
- $k = 0.014$ and $r = 0.26$ are extracted by fitting the CMS data.

- The prompt production is consistent with NLO NRQCD in the p_T > 10 GeV/c region.
- Might be $\boldsymbol{\chi_{c1}(2P) - D^0\overline{D^{*0}}}$, produced through $\boldsymbol{\chi_{c1}(2P)}$ component.

Summary

- Many results in open-charm and charmonium states in pp collisions at LHCb
- Recent results are reported in this talk

  Open-charm
  - Amplitude analysis of $B^+ \to D^+ D^- K^+$ decays
  - Observation of a new excited D_s^+ meson in $B^0 \to D^- D^+ K^+ \pi^-$ decays

  Charmonium
  - Measurement of the J/ψ production cross-section in pp collisions at $\sqrt{s}$ = 5 TeV

  Charmonium-like
  - Measurement of $\chi_{c1}(3872)$ production in pp collision at $\sqrt{s}$ = 8 and 13 TeV

- These results provide tests of the predictions from QCD models.

Thanks!