

# *Heavy Flavour Production Studies at CMS*

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ICHEP, Prague, July 19<sup>th</sup>, 2024

## This Talk

2024 CMS results on production/properties of open heavy flavour hadrons and quarkonia in  $pp$  collisions

- ◆ Observation of the  $\Xi_b^- \rightarrow \psi(2S)\Xi^-$  decay and studies of the  $\Xi_b(5945)^0$  baryon in proton-proton collisions at  $\sqrt{s} = 13$  TeV
- ◆ Measurement of the polarisations of prompt and non-prompt  $J/\psi$  and  $\psi(2S)$  mesons produced in  $pp$  collisions at  $\sqrt{s} = 13$  TeV
- ◆ Measurement of double-differential and total charm cross sections at  $\sqrt{s} = 7$  TeV

### References

[CMS-BPH-23-002](#)  
[CMS-BPH-22-009](#)  
[CMS-PAS-BPH-22-007](#)

### Further Talks

Lepton flavour violation studies at CMS

- [Chiara Ilaria Rovelli, 19th, Quark and Lepton Flavour Physics](#)

Rare and forbidden decays at CMS

- [Stefanos Leontsinis, 19th, Quark and Lepton Flavour Physics](#)

CMS results on flavour spectroscopy

- [Alexis Pompili, 20th, Quark and Lepton Flavour Physics](#)

CPV and lifetime measurements from CMS

- [Enrico Lusiani, 20th, Quark and Lepton Flavour Physics](#)

[arXiv:2402.17738](https://arxiv.org/abs/2402.17738), [Phys.Rev.D 110 \(2024\) 1, 012002](https://arxiv.org/abs/2402.17738)

Published in Jul

## Observation of the $\Xi_b^- \rightarrow \psi(2S)\Xi^-$ decay and studies of the $\Xi_b(5945)^0$ baryon in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

### Abstract

The first observation of the decay  $\Xi_b^- \rightarrow \psi(2S)\Xi^-$  and measurement of the branching ratio of  $\Xi_b^- \rightarrow \psi(2S)\Xi^-$  to  $\Xi_b^- \rightarrow J/\psi\Xi^-$  are presented. The  $J/\psi$  and  $\psi(2S)$  mesons are reconstructed using their dimuon decay modes. The results are based on proton-proton colliding beam data from the LHC collected by the CMS experiment at  $\sqrt{s} = 13$  TeV in 2016–2018, corresponding to an integrated luminosity of  $140 \text{ fb}^{-1}$ . The branching fraction ratio is measured to be  $\mathcal{B}(\Xi_b^- \rightarrow \psi(2S)\Xi^-) / \mathcal{B}(\Xi_b^- \rightarrow J/\psi\Xi^-) = 0.84^{+0.21}_{-0.19} (\text{stat}) \pm 0.10 (\text{syst}) \pm 0.02 (\mathcal{B})$ , where the last uncertainty comes from the uncertainties in the branching fractions of the charmonium states. New measurements of the  $\Xi_b(5945)^0$  baryon mass and natural width are also presented, using the  $\Xi_b^- \pi^+$  final state, where the  $\Xi_b^-$  baryon is reconstructed through the decays  $J/\psi\Xi^-$ ,  $\psi(2S)\Xi^-$ ,  $J/\psi\Lambda K^-$ , and  $J/\psi\Sigma^0 K^-$ . Finally, the fraction of  $\Xi_b^-$  baryons produced from  $\Xi_b(5945)^0$  decays is determined.

refer to further results for flavour spectra

- [Stefanos Leontsinis, 19th](#)
- [Alexis Pompili, 20th](#)



# ANALYSIS MOTIVATION

✓  $\Xi_b^-$  observed ~ 15 years ago, barely studied yet

PDG, Phys. Rev. D 110, 030001 (2024)



$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$I, J, P$  need confirmation.

$$m(\Xi_b^-) = 5797.0 \pm 0.6 \text{ MeV} \quad (S = 1.7)$$

$$m_{\Xi_b^-} - m_{\Lambda_b^0} = 177.46 \pm 0.31 \text{ MeV} \quad (S = 1.3)$$

$$m_{\Xi_b^-} - m_{\Xi_b^0} = 5.9 \pm 0.6 \text{ MeV}$$

$$\text{Mean life } \tau_{\Xi_b^-} = (1.572 \pm 0.040) \times 10^{-12} \text{ s}$$

CMS can contribute to b-baryon physics using dimuon decay

$\Xi_b^-$  DECAY MODES

$\Xi_b^-$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\Gamma$ (MeV/c)
$J/\psi \Xi^- \times B(b \rightarrow \Xi_b^-)$	$(1.02^{+0.26}_{-0.21}) \times 10^{-5}$		1782
$J/\psi \Lambda K^- \times B(b \rightarrow \Xi_b^-)$	$(2.5 \pm 0.4) \times 10^{-6}$		1631
$p K^- K^- \times B(b \rightarrow \Xi_b^-)$	$(3.7 \pm 0.8) \times 10^{-8}$		2731
$p K^- K^-$	seen		2731
$p K^- \pi^-$	seen		2783
$\Lambda_b^0 \pi^- \times B(b \rightarrow \Xi_b^-)/B(b \rightarrow \Lambda_b^0)$	$(7.0 \pm 0.9) \times 10^{-4}$		99
$\Xi_c^0 \pi^-$	seen		2367
$\Sigma(1385) K^-$	$(2.6 \pm 2.3) \times 10^{-7}$		2707
$\Lambda(1405) K^-$	$(1.9 \pm 1.2) \times 10^{-7}$		2702
$\Lambda(1520) K^-$	$(7.6 \pm 3.2) \times 10^{-7}$		2673
$\Lambda(1670) K^-$	$(4.5 \pm 2.3) \times 10^{-7}$		2629
$\Sigma(1775) K^-$	$(2.2 \pm 1.5) \times 10^{-7}$		2599
$\Sigma(1915) K^-$	$(2.6 \pm 2.5) \times 10^{-7}$		2553
$\Xi^- \gamma$	$< 1.3 \times 10^{-4}$	95%	-

CMS-BPH-12-001

- $\Xi_b(5945)^0$  observed in 2012
  - only a few measurements of mass and width

**Mass** PDG Live

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
<b>5952.3 ± 0.6</b>	<b>OUR AVERAGE</b>		<b>Currently a few LHCb and CMS only</b>
5952.35 ± 0.02 ± 0.58	<sup>1,2</sup> AAJ	<b>2023AU</b> LHCb	pp at 7, 8, 13 TeV
5952.3 ± 0.1 ± 0.6	<sup>3</sup> AAJ	2016AE LHCb	pp at 7, 8 TeV
5951.4 ± 0.8 ± 0.6	<sup>4</sup> CHATRCHYAN	2012S CMS	pp at 7 TeV, 5.3 fb <sup>-1</sup>

**Width** PDG Live

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
0.87 ± 0.06 ± 0.05	<sup>1</sup> AAJ	<b>2023AU</b> LHCb	pp at 7, 8, 13 TeV

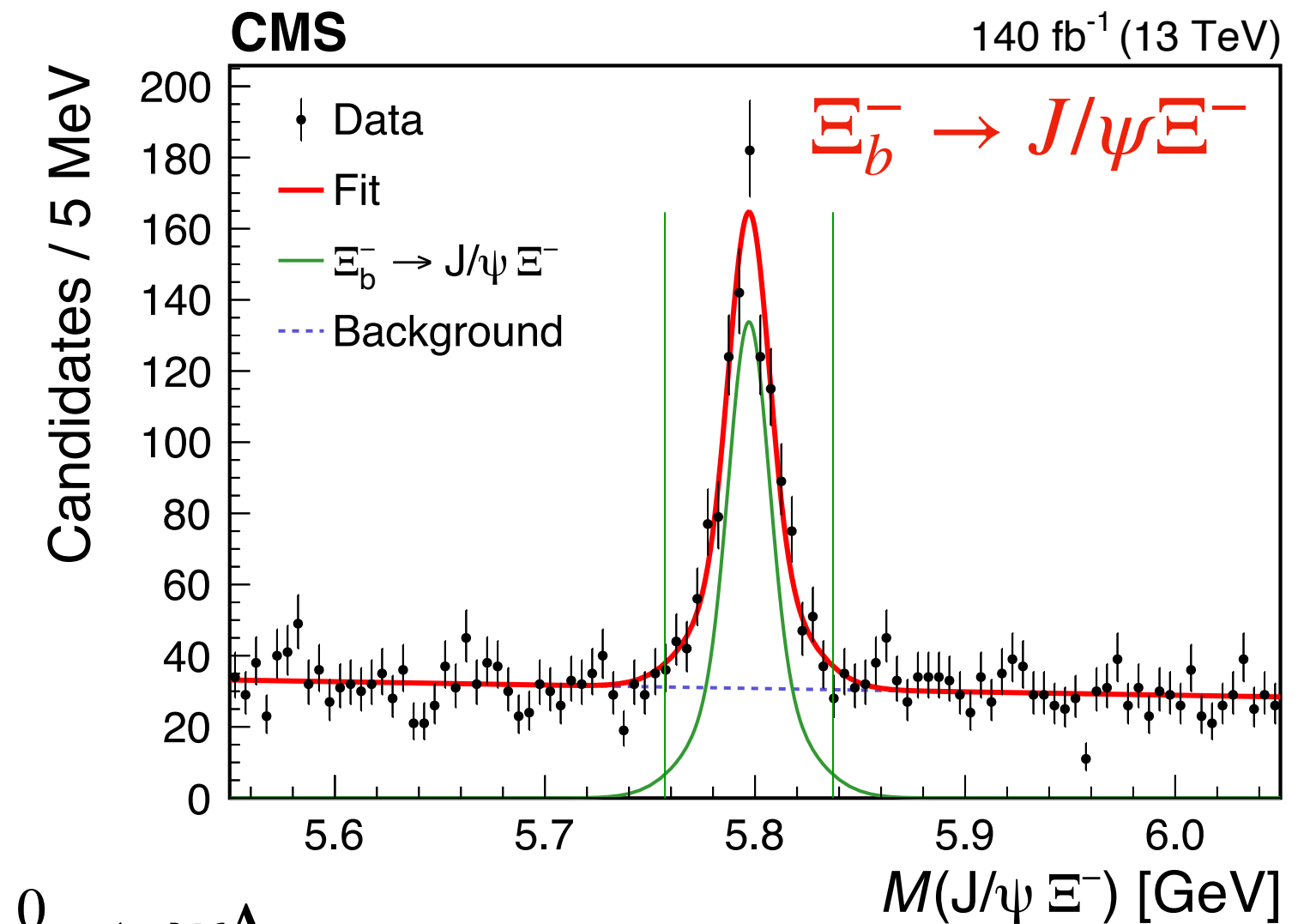
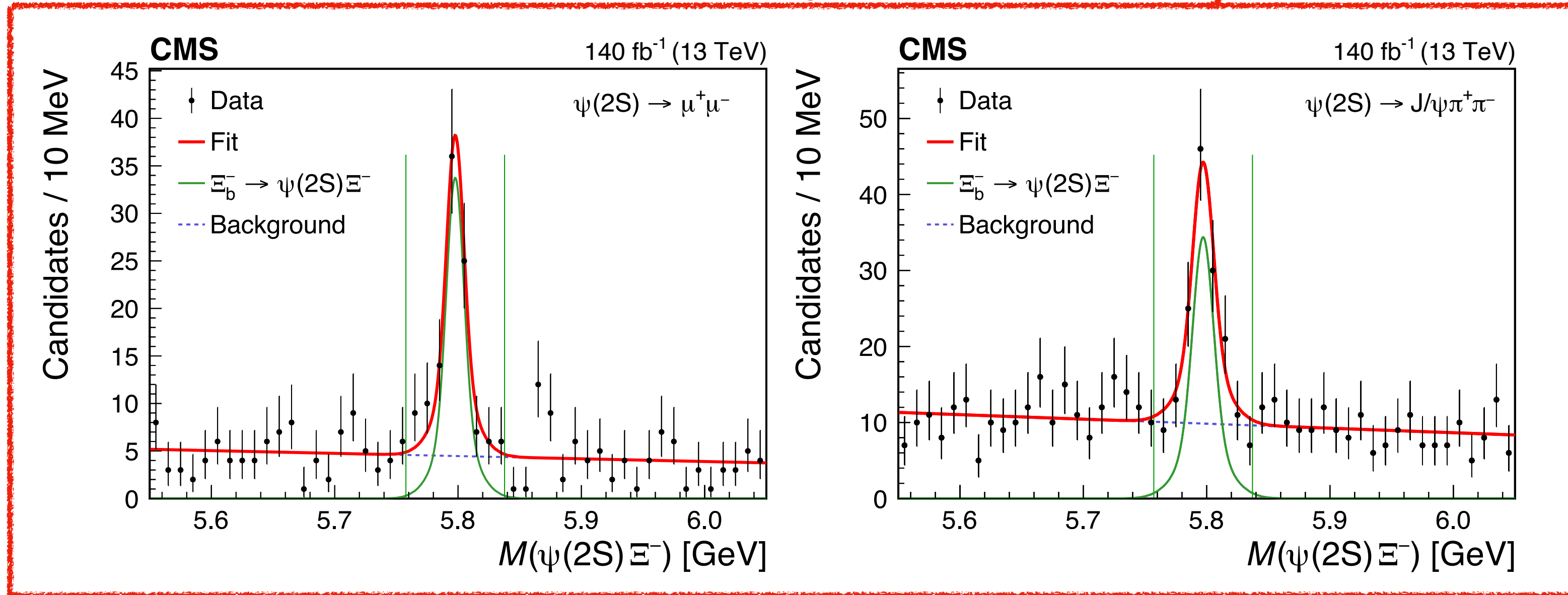
**Currently only one used**

No observation of  $\Xi_b^- \rightarrow \psi(2S)\Xi^-$  !

# MEASUREMENT OF $\Xi_b^- \rightarrow \psi(2S)\Xi^-$ DECAY AND BRANCHING FRACTION RATIO

✓  $\Xi_b^- \rightarrow \psi\Xi^-$  measured with  $\psi \rightarrow \mu^+\mu^-$  decay ( $\psi$  refers to  $J/\psi$  or  $\psi(2S)$ )

First observation of  $\Xi_b^- \rightarrow \psi(2S)\Xi^-$  decay



$$R = \frac{B(\Xi_b^- \rightarrow \psi(2S)\Xi^-)}{B(\Xi_b^- \rightarrow J/\psi\Xi^-)} = 0.84^{+0.21}_{-0.19}(\text{stat}) \pm 0.10(\text{syst}) \pm 0.02(\text{B})$$

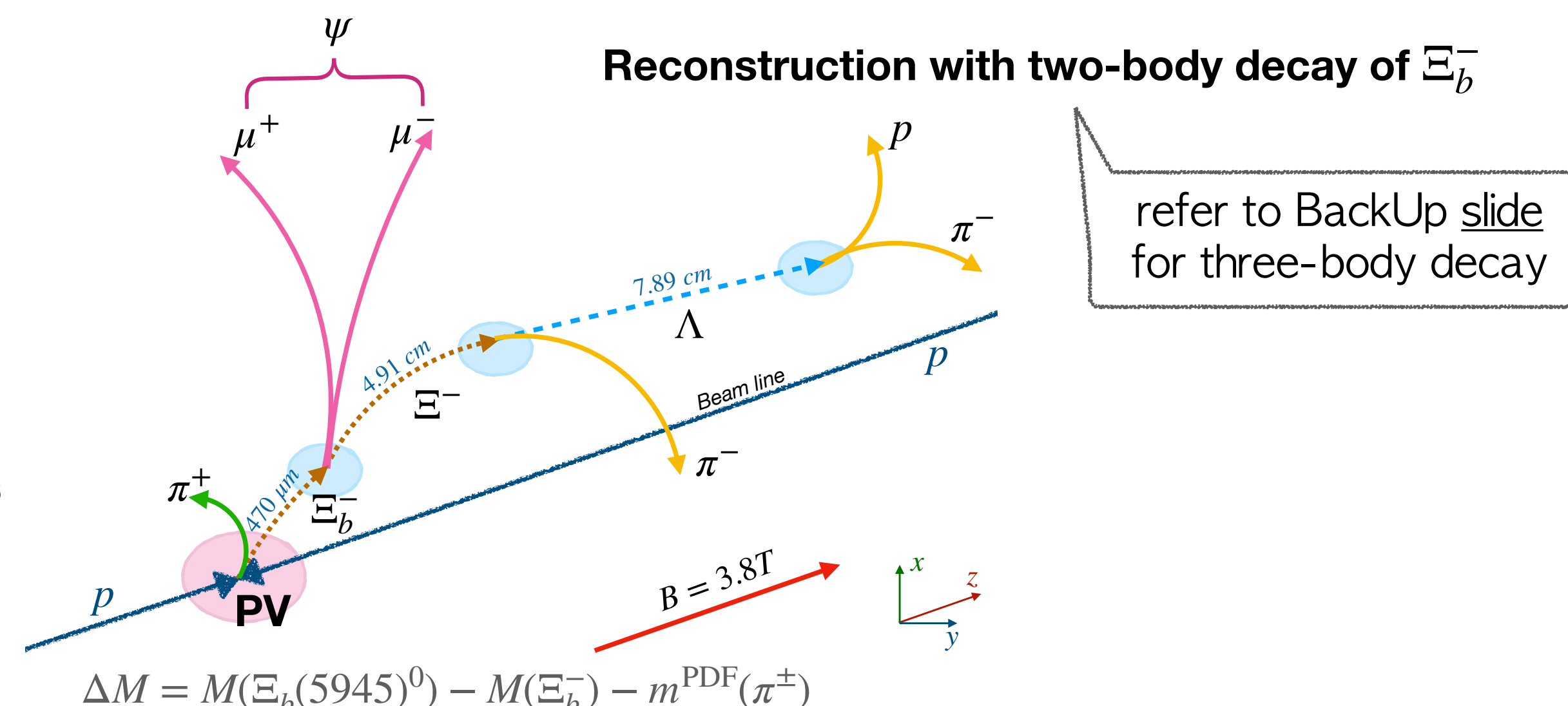
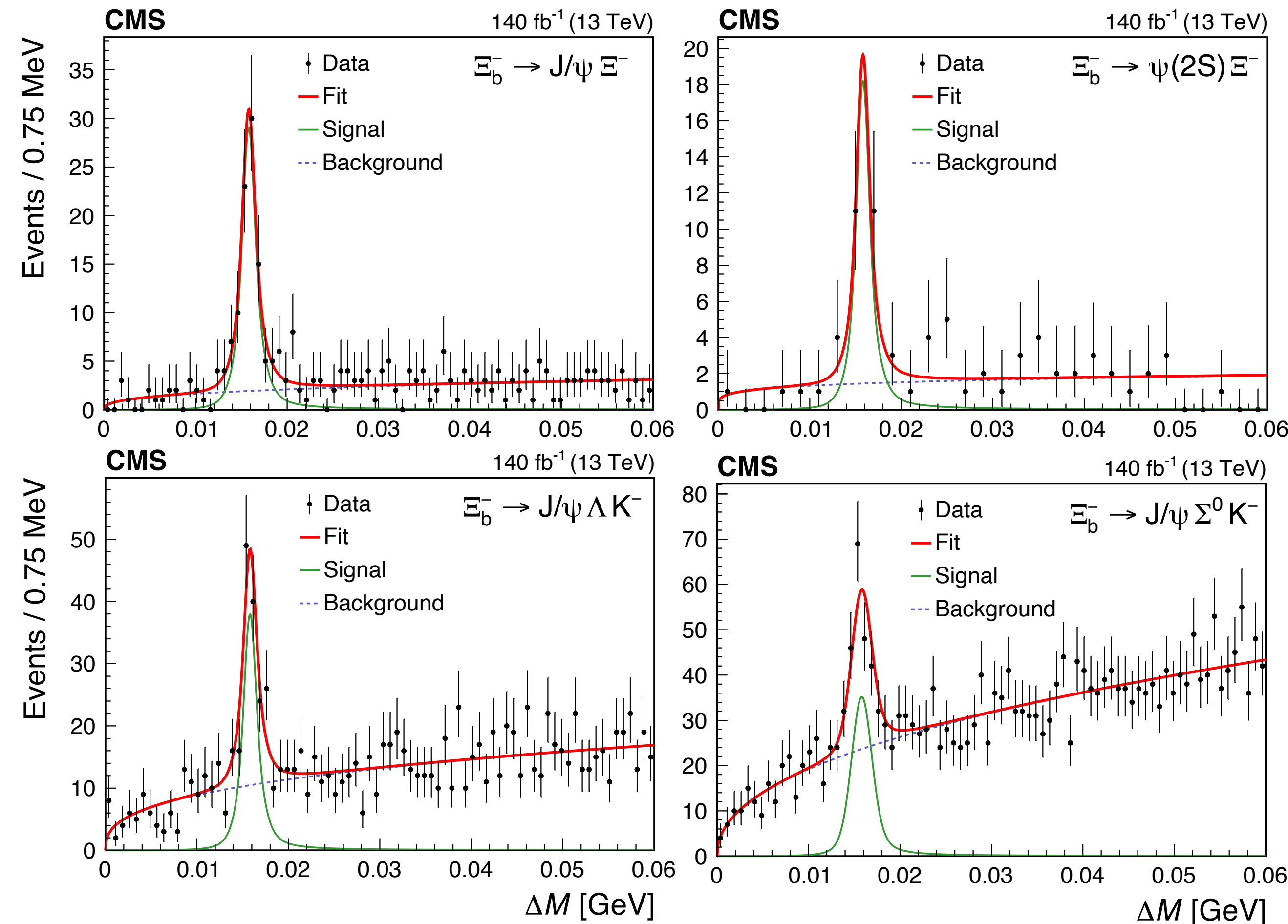
• consistent with analogous measured ratios of  $B^+ \rightarrow \psi K^+$ ,  $B^0 \rightarrow \psi K_s^0$ ,  $B_s^0 \rightarrow \psi\phi$  and  $\Lambda_b^0 \rightarrow \psi\Lambda$

✓ No clear pattern for the branching fraction ratios



# MEASUREMENTS AND STUDIES OF $\Xi_b(5945)^0$

$\sqrt{\Xi_b(5945)^0 \rightarrow \Xi_b^- \pi^+}$  reconstructed through decays of  $\Xi_b^- \rightarrow J/\psi \Xi^-$ ,  $\Xi_b^- \rightarrow \psi(2S) \Xi^-$ ,  $\Xi_b^- \rightarrow J/\psi \Lambda K^-$  and  $\Xi_b^- \rightarrow J/\psi \Sigma^0 K^-$



- $M(\Xi_b(5945)^0) = 5952.4 \pm 0.1(\text{stat} + \text{syst}) \pm 0.6(m_{\Xi_b^-}) \text{ MeV}$
- $\Gamma(\Xi_b(5945)^0) = 0.87_{-0.20}^{+0.22}(\text{stat}) \pm 0.16(\text{syst}) \text{ MeV}$

better precision than the previous CMS results in agreement with results from LHCb

✓ About a third of  $\Xi_b^-$  produced from  $\Xi_b(5945)^0$  decays

[arXiv:2406.14409](https://arxiv.org/abs/2406.14409)

Public since Jun

## Measurement of the polarizations of prompt and non-prompt $J/\psi$ and $\psi(2S)$ mesons produced in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

### Abstract

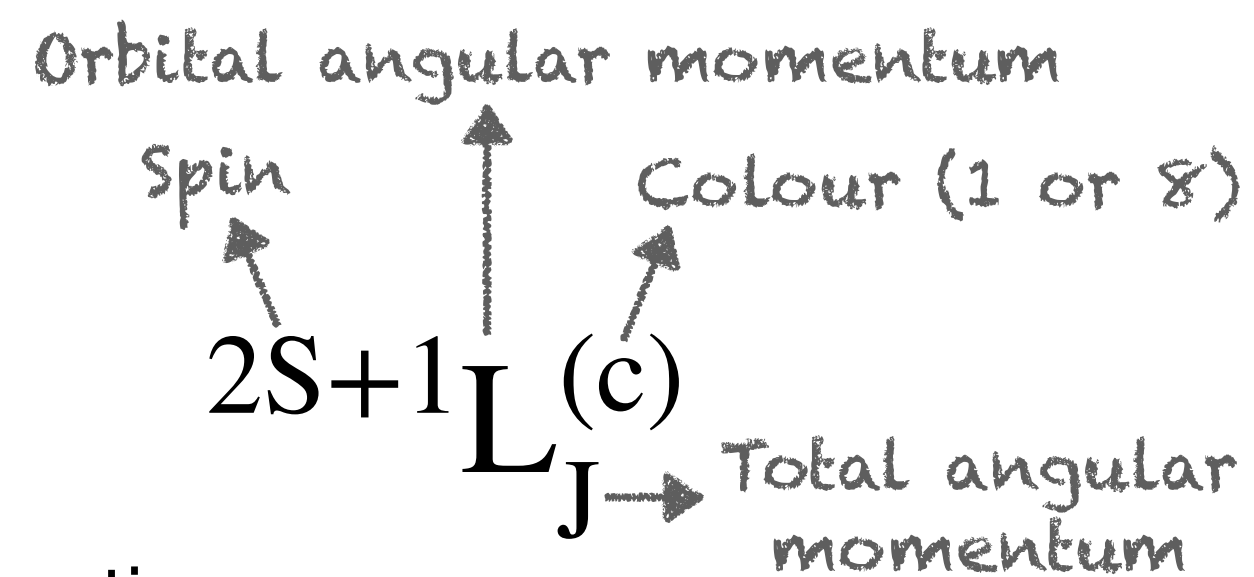
The polarizations of prompt and non-prompt  $J/\psi$  and  $\psi(2S)$  mesons are measured in proton-proton collisions at  $\sqrt{s} = 13$  TeV, using data samples collected by the CMS experiment in 2017 and 2018, corresponding to a total integrated luminosity of  $103.3 \text{ fb}^{-1}$ . Based on the analysis of the dimuon decay angular distributions in the helicity frame, the polar anisotropy,  $\lambda_\theta$ , is measured as a function of the transverse momentum,  $p_T$ , of the charmonium states, in the 25–120 and 20–100 GeV ranges for the  $J/\psi$  and  $\psi(2S)$ , respectively. The non-prompt polarizations agree with predictions based on the hypothesis that, for  $p_T \gtrsim 25$  GeV, the non-prompt  $J/\psi$  and  $\psi(2S)$  are predominantly produced in two-body B meson decays. The prompt results clearly exclude strong transverse polarizations, even for  $p_T$  exceeding 30 times the  $J/\psi$  mass, where  $\lambda_\theta$  tends to an asymptotic value around 0.3. Taken together with previous measurements, by CMS and LHCb at  $\sqrt{s} = 7$  TeV, the prompt polarizations show a significant variation with  $p_T$ , at low  $p_T$ .



# ANALYSIS MOTIVATION

✓ Quarkonia provide an ideal study for the understanding of hadron formation in QCD

- polarisation measurements provide straightforward information for hadronization models
  - polarisation of quarkonium is observable that most directly reflects the mixture of S, L, J, c configurations



## "Short-distance coefficients (SDCs)"

• **quark production** and **quarkonium formation** well separated processes within non-relativistic QCD (**NRQCD**) framework

## "Long-distance matrix elements (LDMEs)"

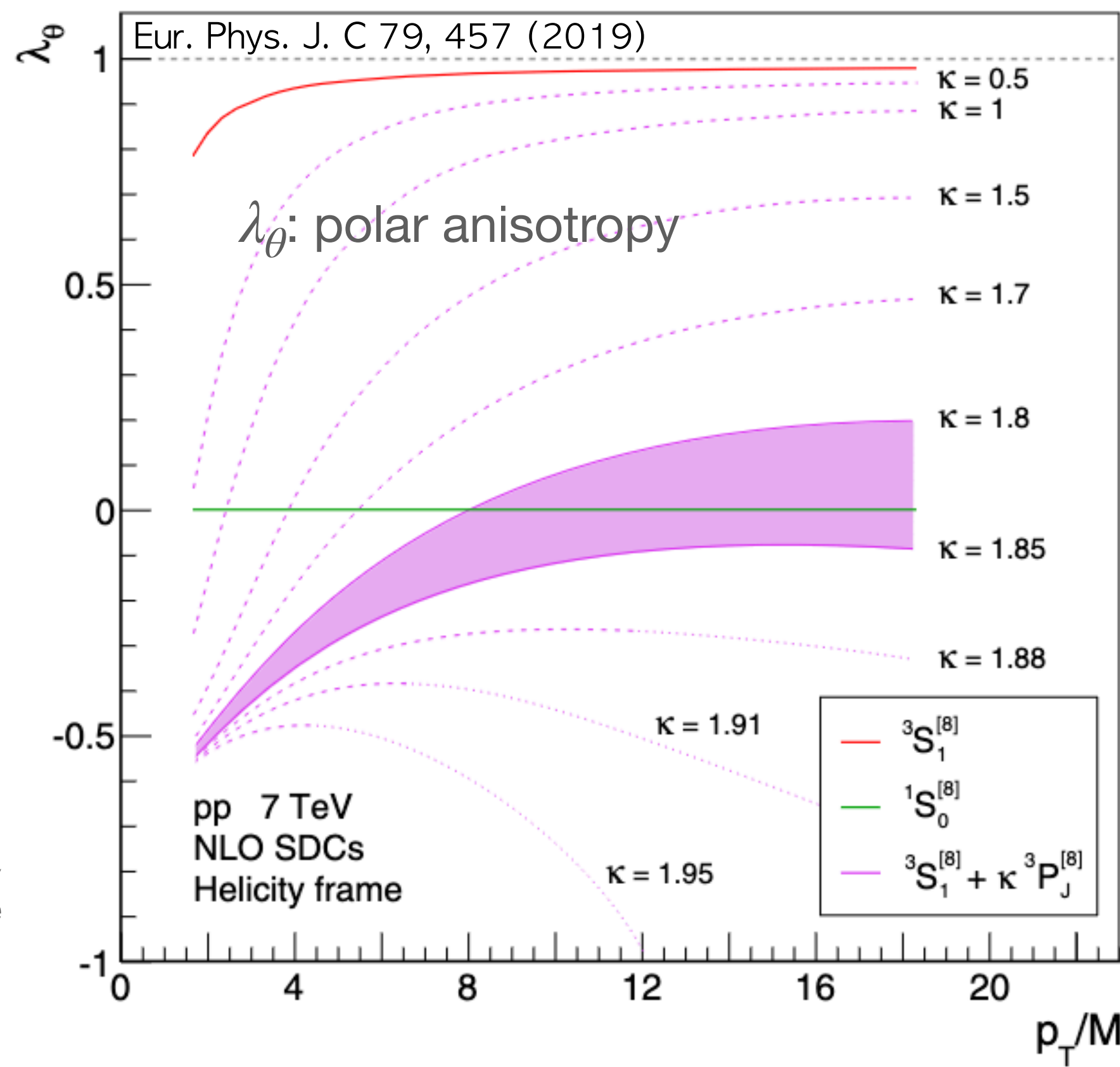
- only a small number of leading and sub-leading terms is quantitatively important
- NRQCD foresees all possible S, L, J, c configuration of  $Q\bar{Q}$

unpolarised,  $p_T$  independent

- two distinct physical polarisation terms  $^1S_0^{[8]}$  and  $^3S_1^{[8]} + \kappa^3P_{0|1|2}^{[8]}$

polarised,  $p_T$  dependent

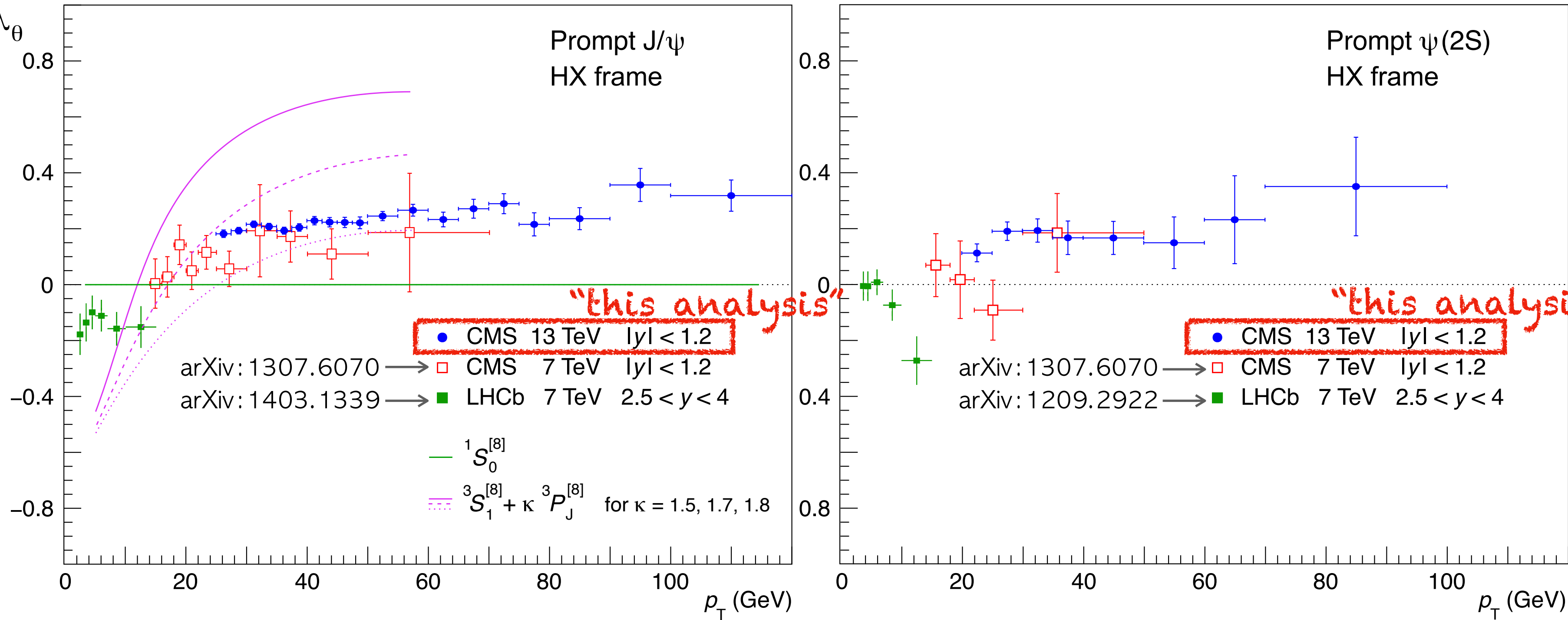
S-wave quarkonia mainly produced through a superposition of  $^1S_0^{[8]}$ ,  $^3S_1^{[8]}$  and  $^3P_{0|1|2}^{[8]}$   
 Possible singlet contribution negligible  
 P-wave term alone is unphysical ( $\lambda_\theta > 1$ )





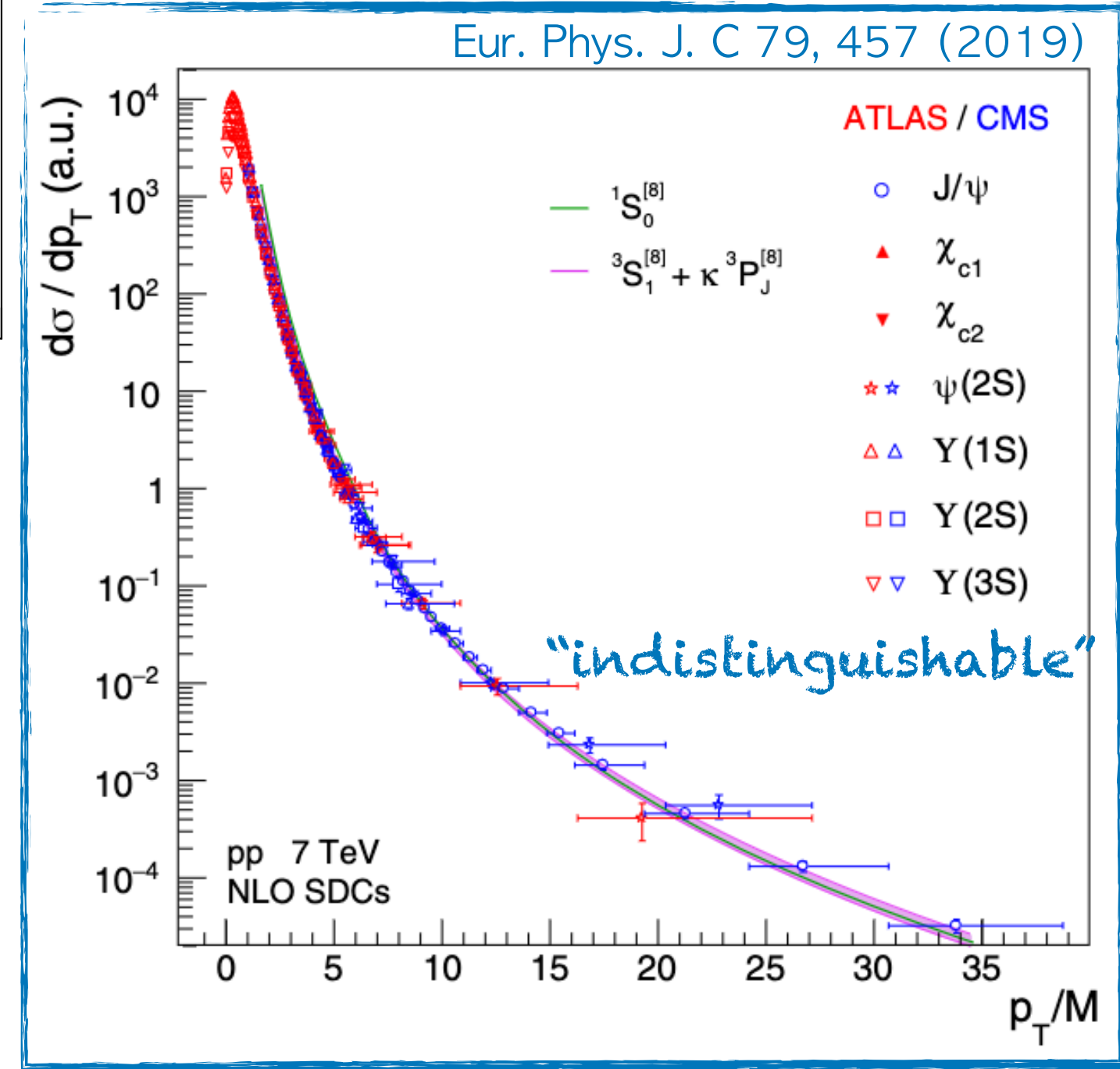
# PROMPT $J/\psi$ AND $\psi(2S)$ MEASUREMENTS

$\sqrt{\lambda_\theta}$  measured as a function of  $p_T$  based on dimuon decay angular distributions in helicity (HX) frame



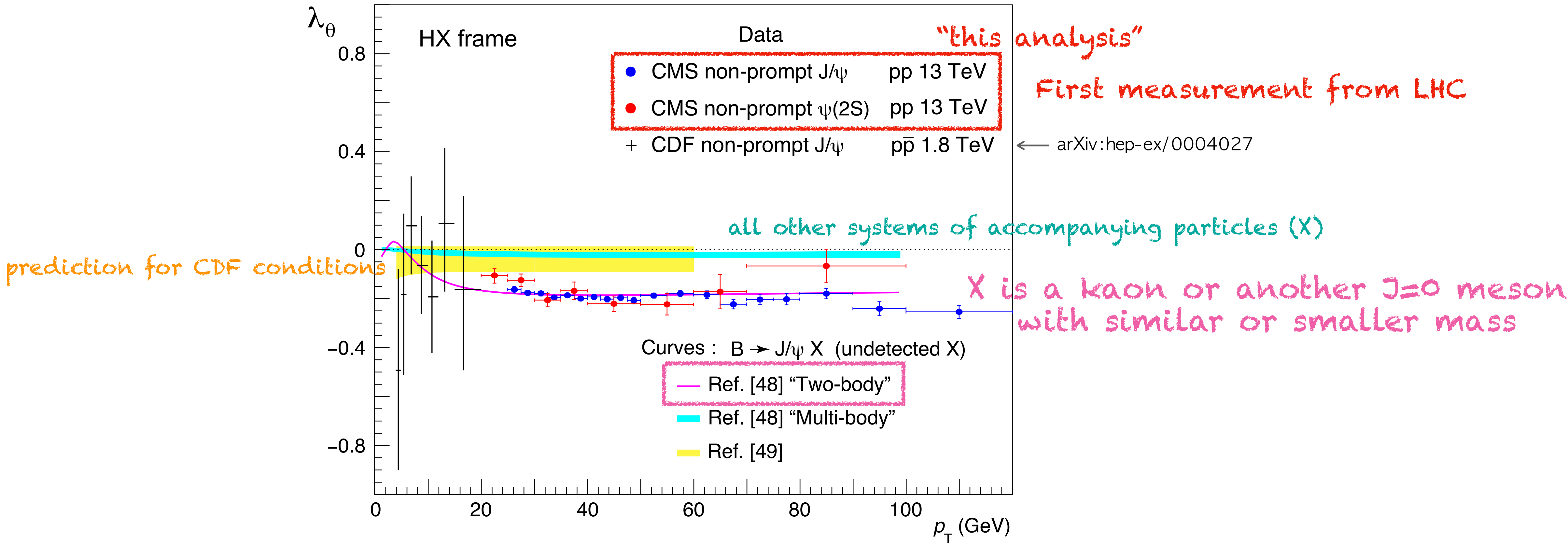
$\lambda_\theta \sim +0.3$

- significant  $p_T$  dependence of polarisation including CMS and LHCb data (7 TeV)
- $\lambda_\theta \sim 0.3$  at high  $p_T$ : no strong transverse polarisation
- significant constraints on phenomenological analyses of charmonium production, which mostly based on  $p_T$ -differential cross section measurements



# NON-PROMPT $J/\psi$ AND $\psi(2S)$ MEASUREMENTS

✓  $\lambda_\theta$  measured as a function of  $p_T$  based on dimuon decay angular distributions in helicity (HX) frame



- both  $J/\psi$  and  $\psi(2S)$  results are consistent
- $\lambda_\theta \sim -0.2$  at high  $p_T$
- measurement consistent with hypothesis that charmonium produced by **two-body B decays** through colour-singlet processes

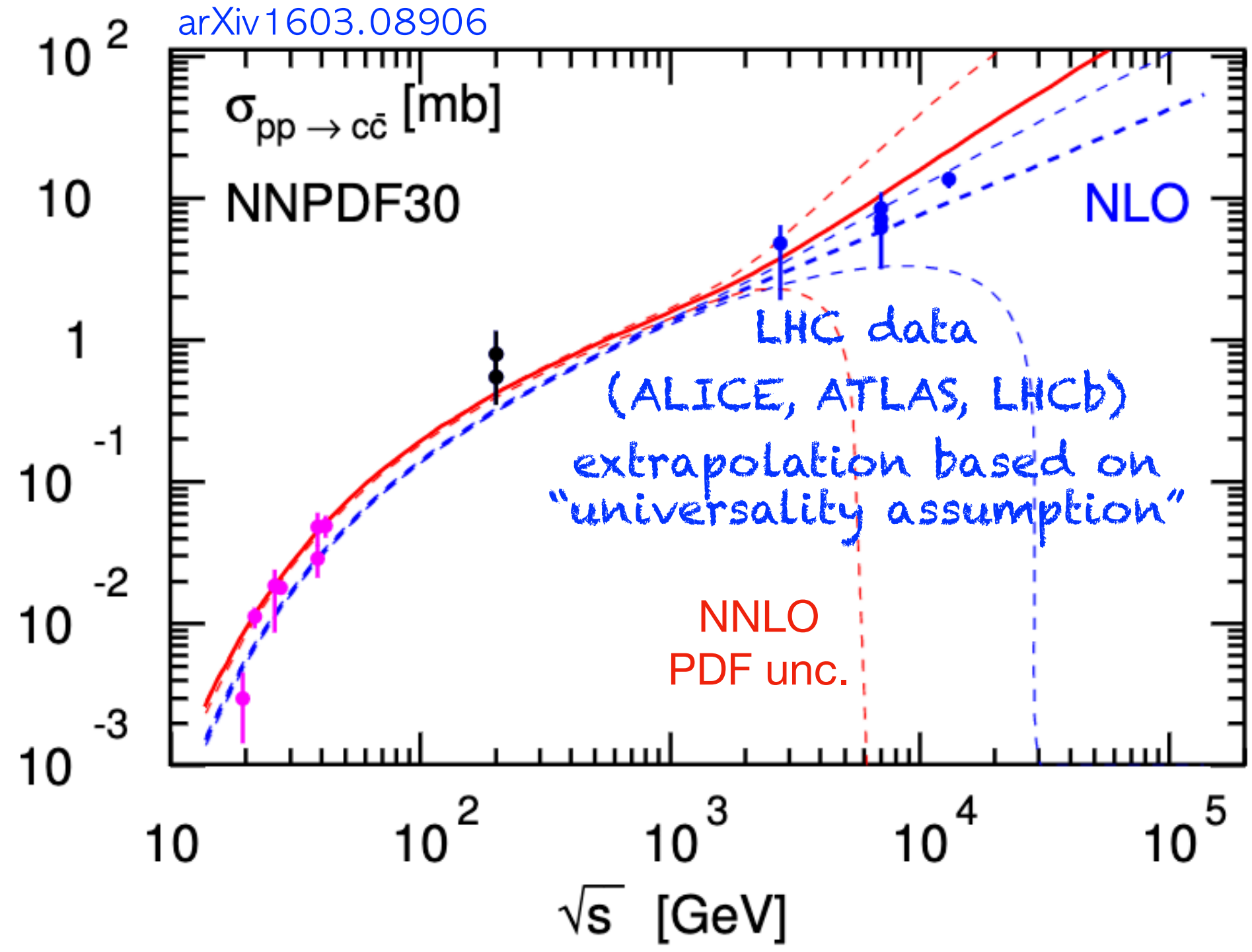
Public since Jul

# Measurement of double-differential and total charm cross sections at 7 TeV



# ANALYSIS MOTIVATION

- ✓ **Charm production measurements** provide important test of QCD
  - charm, beauty and top have mass scale larger than  $\Lambda_{\text{QCD}}$ ;  $\alpha_s$  small enough for perturbative theory
  - any interactions involving quark encounter non-perturbative QCD; requires a strong interplay btw. experiment and theory
  - charm mass scale close to  $\Lambda_{\text{QCD}}$ ; transition region of pert. and non-pert. regimes
    - challenging perturbative calculation: NLO+NLL (FONLL) known for differential cross section, while NNLO for total cross section
  - total cross section measurements can be compared with NNLO
    - fiducial cross section extrapolated
      - so far based on *fragmentation universality assumption*
      - recent LHC data: **charm fragmentation non-universal!**



28 July 2021, CERN COURIER

STRONG INTERACTIONS | NEWS

## Charm breaks fragmentation universality

28 July 2021

A report from the ALICE experiment

The study of heavy-flavour hadron production is an important test for quantum chromodynamics. Hadron production is usually computed via the convolution of the parton distribution functions, the partonic cross section and the fragmentation of charm quarks into charm hadrons. The latest measurements performed in  $e^+e^-$  or ep collisions show that the fragmentation of charm quarks into charm hadrons is not independent of the colliding systems.

arXiv: 2308.04877

ALICE, pp  $|y| < 0.5$

■  $\sqrt{s} = 13$  TeV

■  $\sqrt{s} = 5.02$  TeV

◆ B factories,  $e^+e^-$ ,  $\sqrt{s} = 10.5$  GeV

◆ LEP,  $e^+e^-$ ,  $\sqrt{s} = m_Z$

◆ HERA, ep, DIS

○ HERA, ep, photoproduction

$\sim 5\sigma$

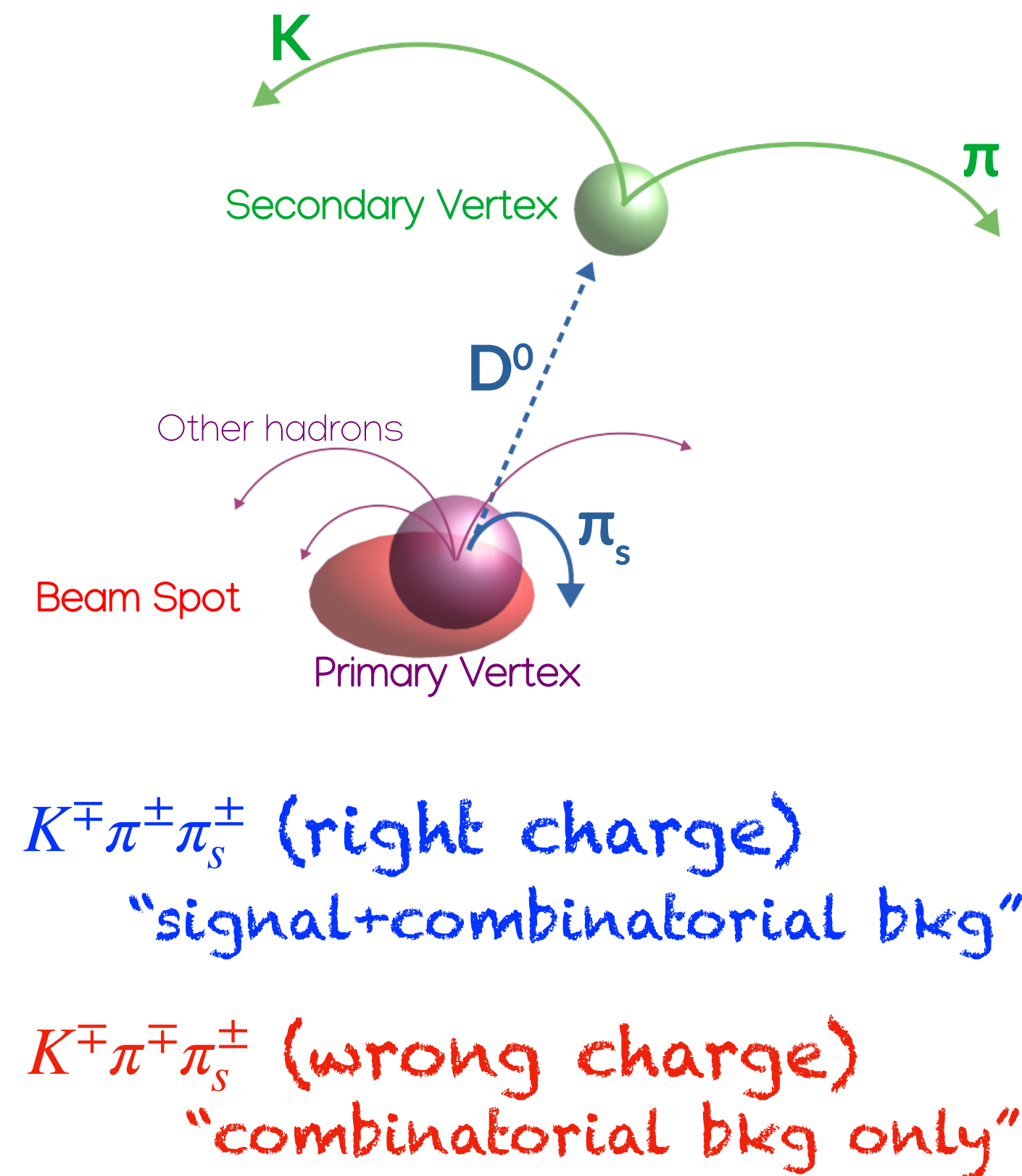
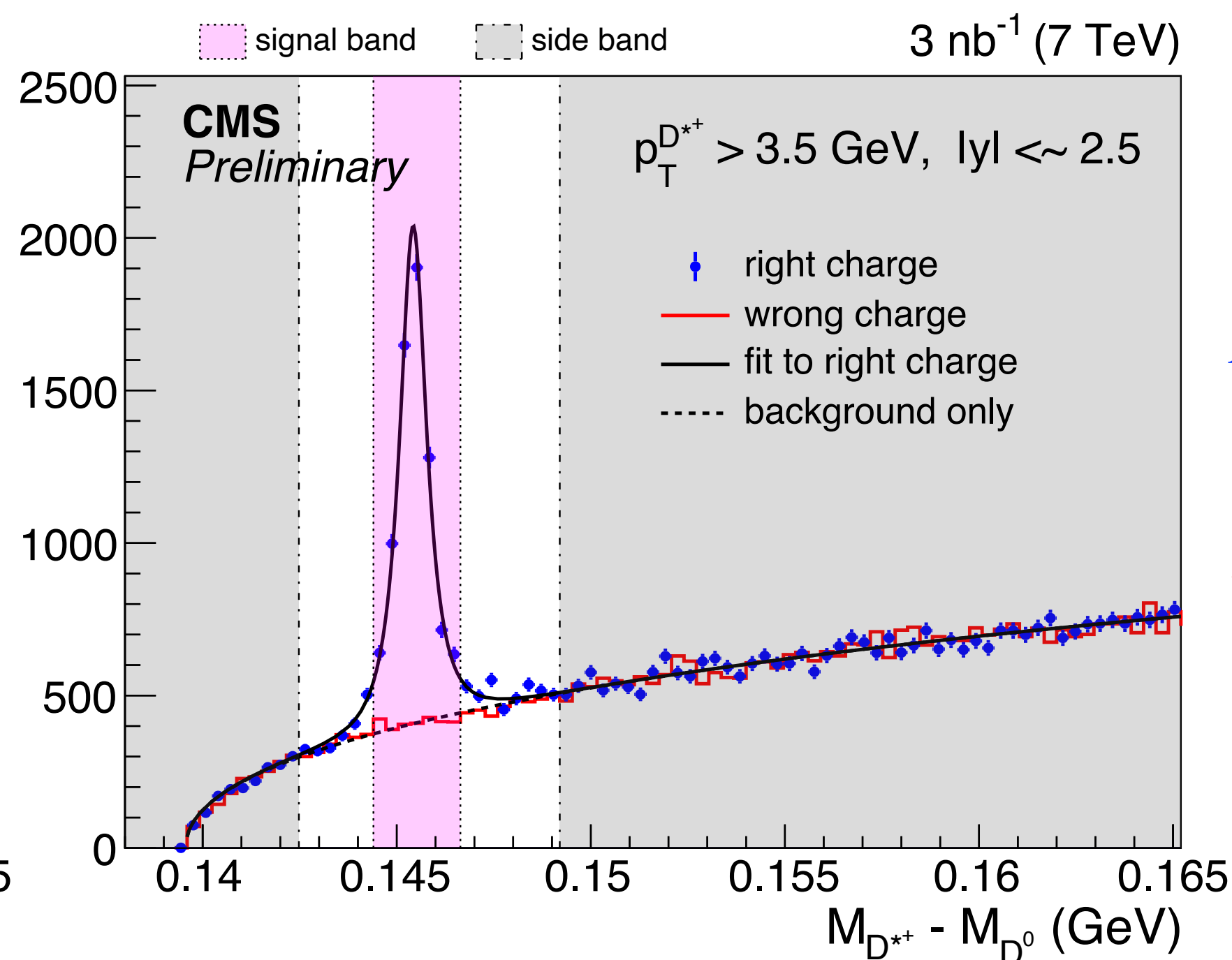
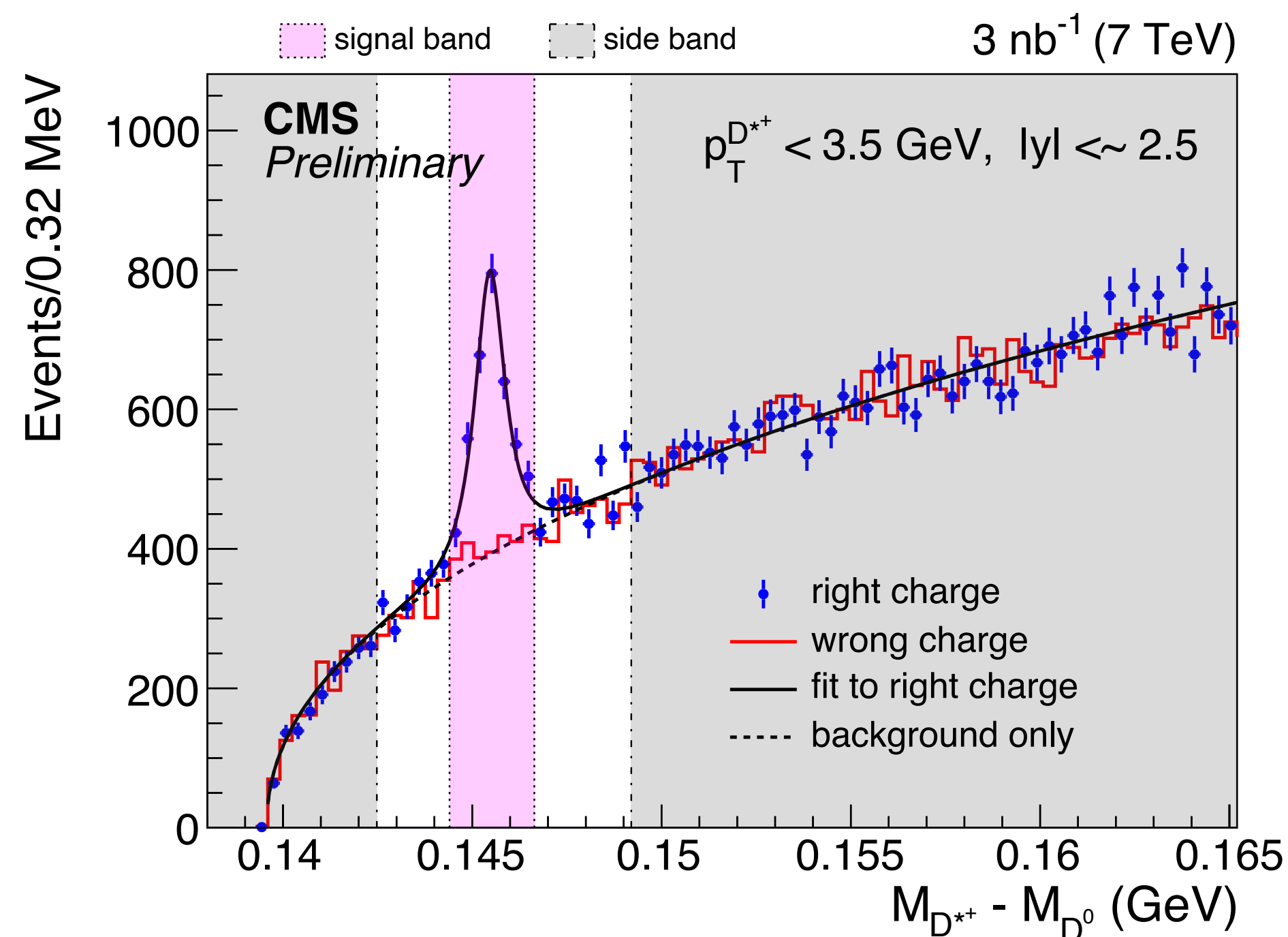
$\times 20$

The assumption that charm-to-hadron fragmentation is universal is not valid

Further in another talk, Y. Yang

# $D^{*+}$ RECONSTRUCTION

- ✓  $D^{*+}$  has the best signal to background ratio for a broad phase space coverage
- ✓  $D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow K^- \pi^+ \pi_s^+$  (the most probable) measured
  - **lower momentum (slow)** of  $\pi_s^+$  compared to  $D^{*+}$  and  $D^0$ ;  $K^-$  and  $\pi^+$  distinguished
  - strongly suppressed combinatorial background with good resolution of  $M_{D^{*+}} - M_{D^0}$



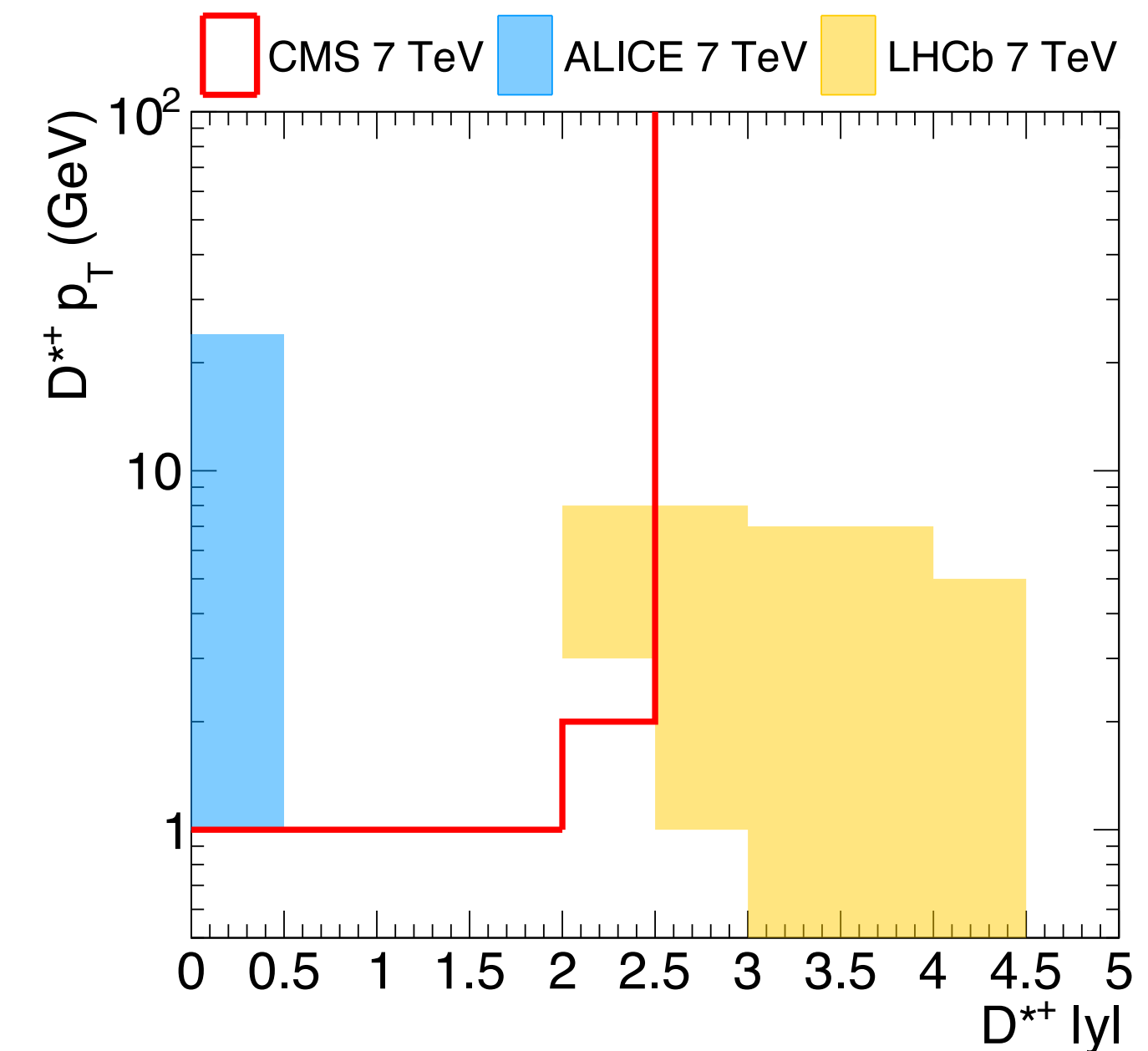
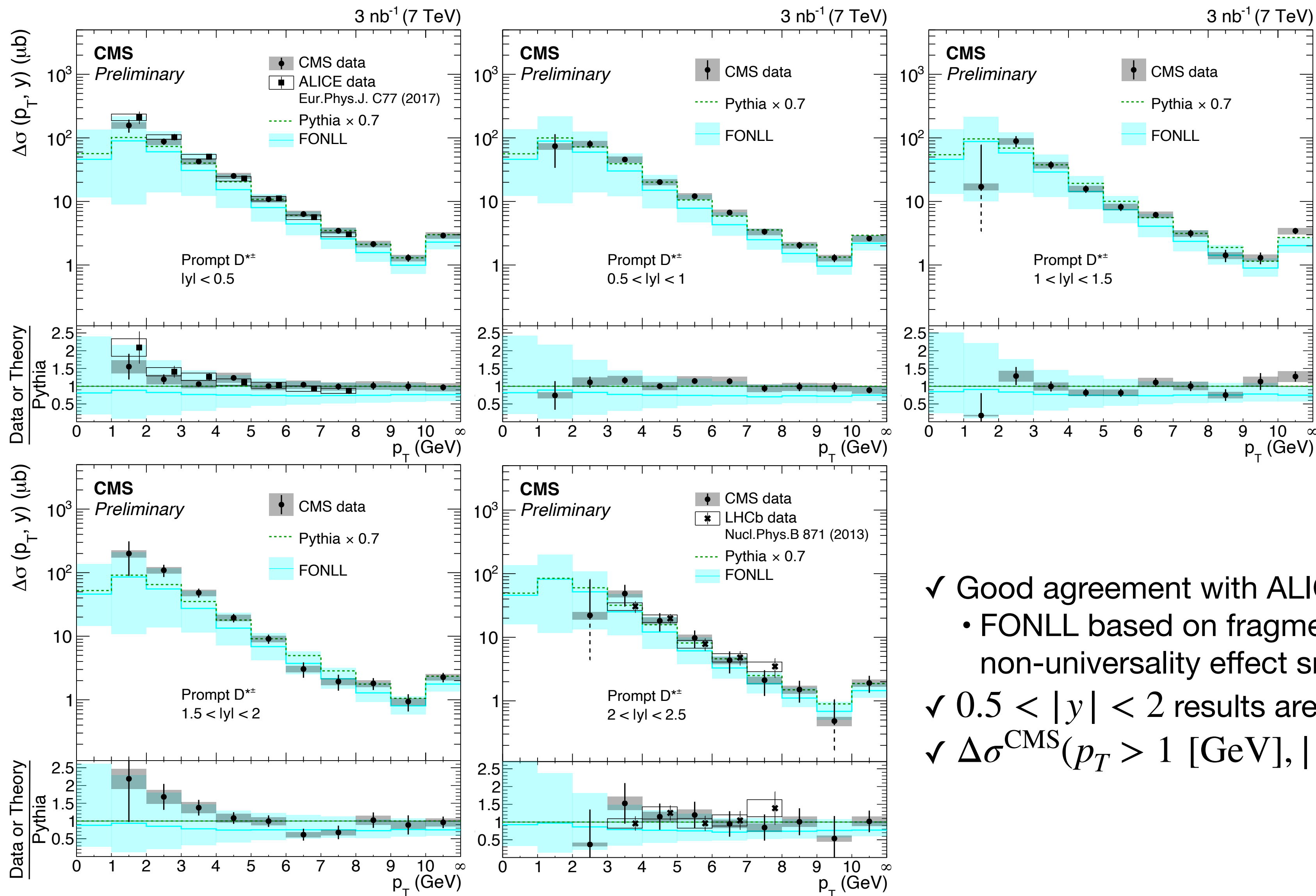
- signal extracted with background subtraction
  - **wrong charge** normalised to **right charge** in **side band** and subtracted in **signal band**
  - fit used to evaluate for systematics of **signal band** definition



# DOUBLE-DIFFERENTIAL PROMPT $D^{*+}$ CROSS SECTION MEASUREMENTS

✓ Prompt  $D^{*+}$  measured in  $p_T > 1$  GeV &  $|y| \lesssim 2.5$  (the largest coverage in LHC)

✓ **CMS+LHCb**: almost full phase space  
 • **minimal theory/model dependence!**



- ✓ Good agreement with ALICE/LHCb data, and Pythia/FONLL predictions
  - FONLL based on fragmentation universality assumption, while non-universality effect smaller than theory unc.
- ✓  $0.5 < |y| < 2$  results are new in LHC
- ✓  $\Delta\sigma^{\text{CMS}}(p_T > 1 \text{ [GeV]}, |y| < 2.5) = 1.28 \pm 0.22 \text{ mb}$



# TOTAL CHARM CROSS SECTION MEASUREMENTS

refer to BackUp slide

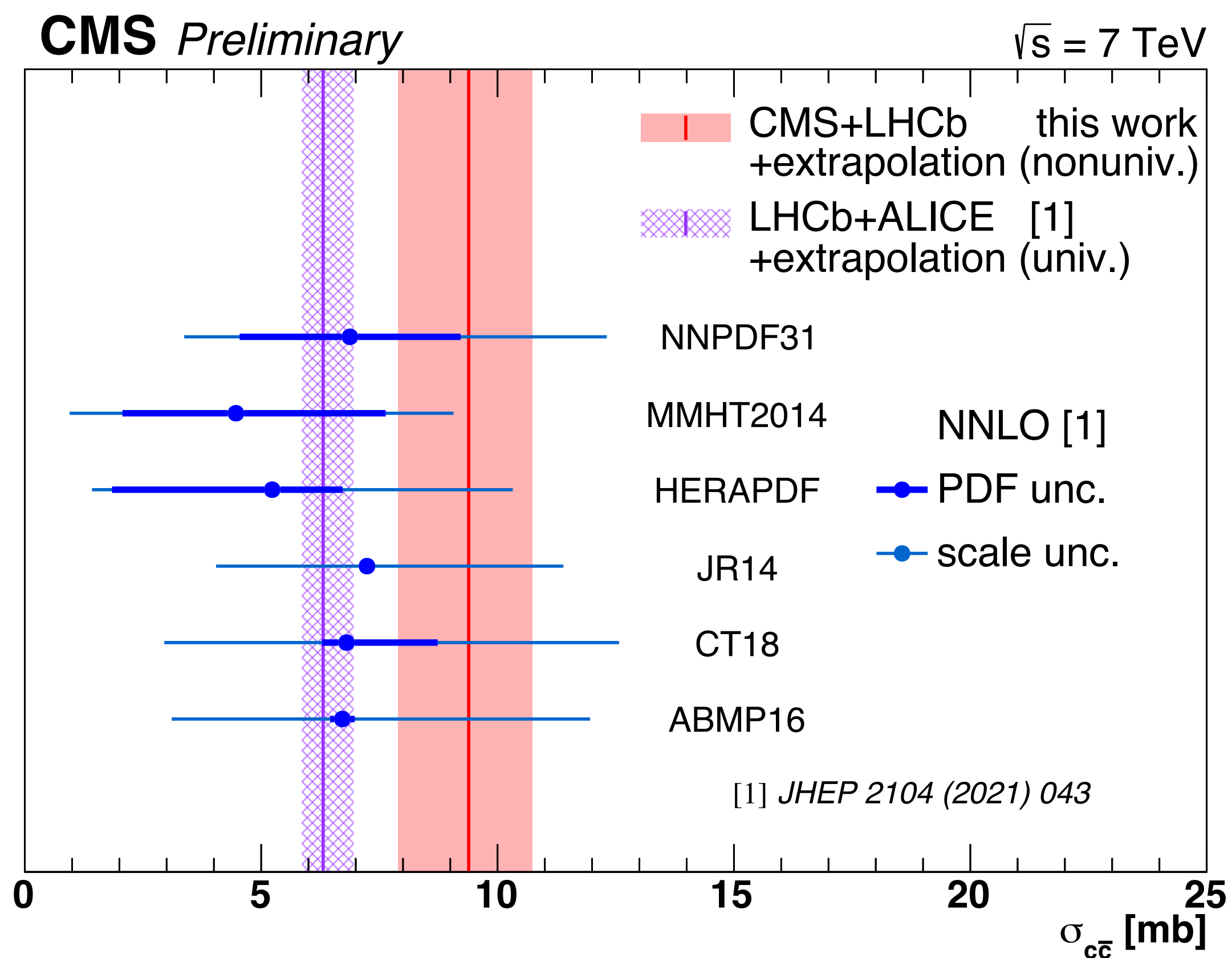
✓ Measured fiducial cross section (including larger rapidity measurements from LHCb) extrapolated to full phase space

- **data-driven FONLL (ddFONLL)** parametrisation used for extrapolation

*“a theory-inspired extrapolation function which is constrained by various published LHC data without the need to assume any particular non-universal fragmentation model”*

refer to [a talk ‘Charm total cross section measurements at the LHC and beyond’](#) later today

✓ Total charm cross section measured accounting for non-universal charm fragmentation



$D^*$  fragmentation fraction in  $pp$  collisions

$$\begin{aligned} \sigma_{c\bar{c}} &= 9.39^{+0.74}_{-0.74}(\text{data})^{+0.77}_{-0.73}(\text{ddFONLL})^{+0.83}_{-1.07}(f^{pp}) \text{ [mb]} \\ &= 9.39^{+1.35}_{-1.49}(\text{total}) \text{ [mb]} \end{aligned}$$

refer to BackUp slide

- with **the smallest extrapolation factor** ever for charm in LHC
- consistent with upper edge of uncertainty band of NNLO
- increased significantly compared to measurements based on universality assumption

# SUMMARY

## CMS-BPH-23-002

✓  $\Xi_b^- \rightarrow \psi(2S)\Xi^-$  decay observed for the first time

- branching fraction measured relative to  $\Xi_b^- \rightarrow J/\psi\Xi^-$ , resulting in  $R = \frac{B(\Xi_b^- \rightarrow \psi(2S)\Xi^-)}{B(\Xi_b^- \rightarrow J/\psi\Xi^-)} = 0.84_{-0.19}^{+0.21}(\text{stat}) \pm 0.10(\text{syst}) \pm 0.02(\text{B})$

✓  $\Xi_b(5945)^0$  mass and width measured using  $\Xi_b^- \pi^+$  final state

- about a third of  $\Xi_b^-$  produced from  $\Xi_b(5945)^0$  decays

## CMS-BPH-22-009

✓ The polar anisotropy measured as a function of  $p_T$  for prompt and non-prompt  $J/\psi$  and  $\psi(2S)$

- the prompt results exclude strong transverse polarisations
- the non-prompt results show agreement with predictions of two-body B meson decay production

## CMS-PAS-BPH-22-007

✓ Double-differential prompt  $D^{*+}$  cross sections measured at 7 TeV in  $p_T > 1$  GeV &  $|y| \lesssim 2.5$

- results show agreement with ALICE and LHCb

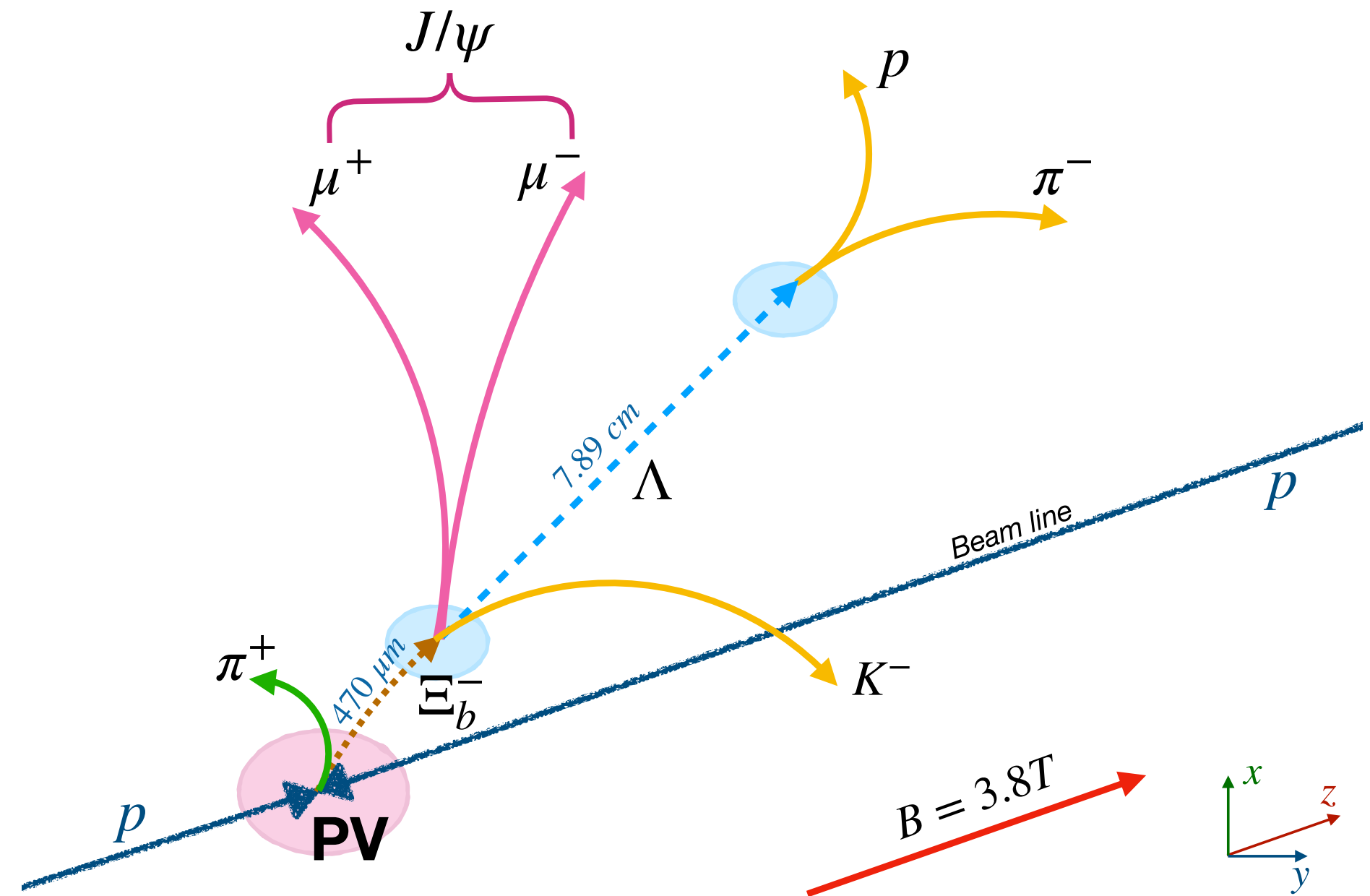
✓ Total charm cross section measured accounting for non-universal charm fragmentation

- with the smallest extrapolation factor ever for charm in LHC, including LHCb measurements for  $2.5 < |y| < 4.5$
- resulting in  $\sigma_{c\bar{c}} = 9.39_{-1.49}^{+1.35}(\text{total})$  [mb], which is consistent with NNLO QCD theory prediction

*Thanks for your attention!*

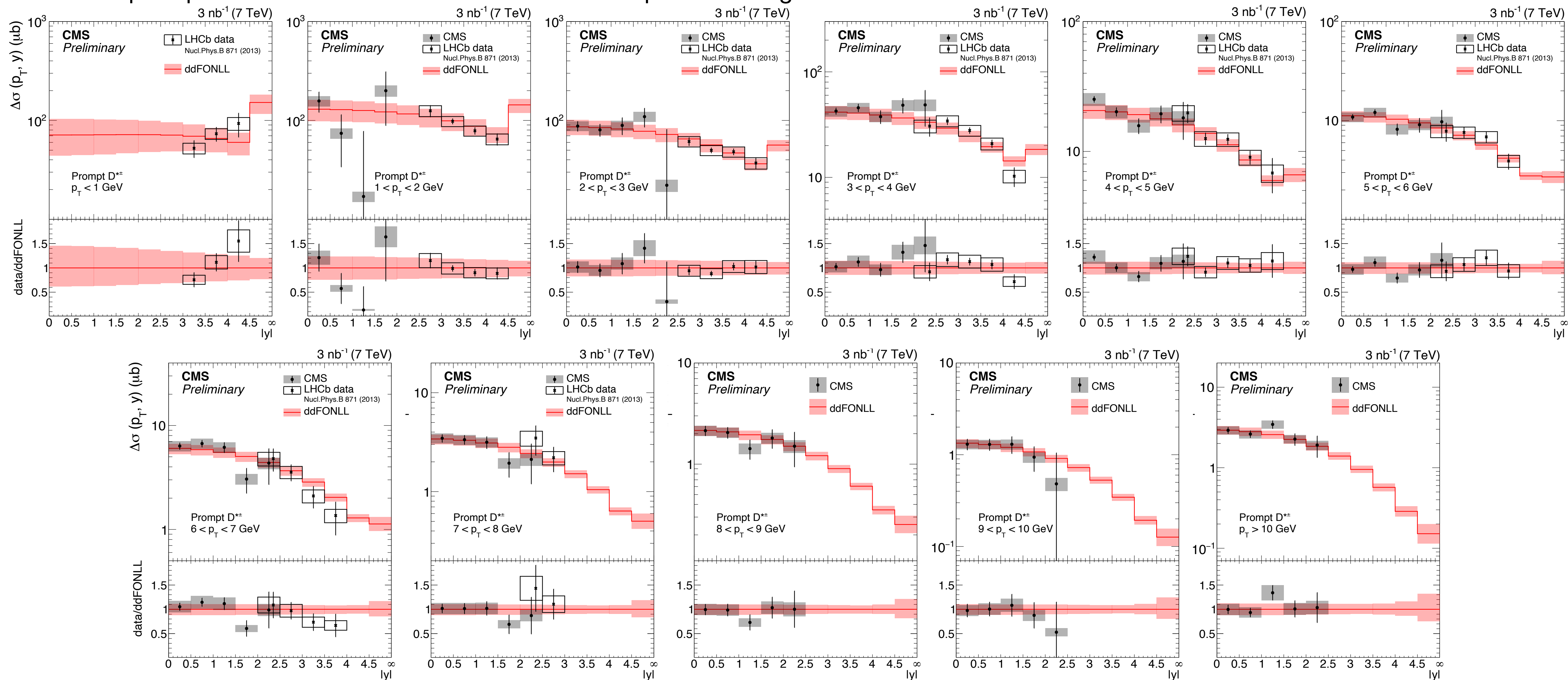
BACKUP





# TOTAL $D^{*+}$ CROSS SECTION

✓ 7 TeV prompt  $D^{*+}$  data from CMS and LHCb extrapolated using **ddFONLL**



► **ddFONLL** gives good descriptions for **data** overall in full kinematic range

$$\checkmark \sigma_{D^{*+}} = \Delta\sigma_{D^{*+}}^{\text{data}}(\text{measured phase space}) + \Delta\sigma_{D^{*+}}^{\text{ddFONLL}}(\text{unmeasured phase space})$$

$$\sqrt{\sigma_{c\bar{c}}} = \frac{\sigma_{D^{*+}}}{f_{D^{*+}}^{pp}} = \frac{\Delta\sigma_{D^{*+}}^{\text{data}}(\text{measured phase space}) + \Delta\sigma_{D^{*+}}^{\text{ddFONLL}}(\text{unmeasured phase space})}{f_{D^{*+}}^{pp}}$$

$2.22^{+0.25}_{-0.25}$  [mb]       $0.94^{+0.10}_{-0.11}(\tilde{f})^{+0.21}_{-0.17}(\text{PDF})^{+0.10}_{-0.14}(\mu_f, \mu_r, m_c, \alpha_K)$  [mb]

$0.168^{+0.015}_{-0.019}$

$$EF = \frac{\Delta\sigma_{D^{*+}}^{\text{data}} + \Delta\sigma_{D^{*+}}^{\text{ddFONLL}}}{\Delta\sigma_{D^{*+}}^{\text{data}}}$$

**EF = 1.4,**  
 "the smallest ever for charm in LHC"