Sergey Barsuk, LAL Orsay
on behalf of Alice, Atlas, CDF, CMS and LHCb collaborations

Production of heavy hadrons at hadronic colliders

Selected results since HADRON 2017

Production of quarkonia and open flavour hadrons in pp and heavy ion collisions at LHC (and Tevatron)

- Experimental review of baryons with two heavy quarks, Liming ZHANG
- Status of quarkonium production, Hee Sok CHUNG
- Associated quarkonium production at ATLAS, Tamar ZAKAREISHVILI
- Central exclusive meson production in proton-proton collisions in ALICE at the LHC, Rainer SCHICKER

pp collisions

- Fate of Heavy Quark Bound States inside Quark-Gluon Plasma, Xiaojun YAO
- Quarkonia production in heavy ion collisions at LHCb, Zhenwei YANG
- Production of open heavy flavour hadrons in pPb and fixed-target collisions LHCb, Jiayin SUN

Heavy-ion collisions, pA and AA

- *In this talk: production studies as a probe of underlying mechanisms*
- *Spectroscopy is addressed by other speakers*

- Study of **heavy flavour production** provides powerful QCD tests

- Comprehension of **heavy flavour production mechanism**, predictive model robust against experimental verifications and yielding simultaneous description of
  - Hadroproduction (and production in b-decays)
  - Different quarkonia and open flavour hadrons
  - Production (and polarization) in the entire p_T and rapidity range

- Two scales of production:
  hard process of **$Q\bar{Q}$ formation** and **hadronization of $Q\bar{Q}$** at softer scales
- **Factorization**:

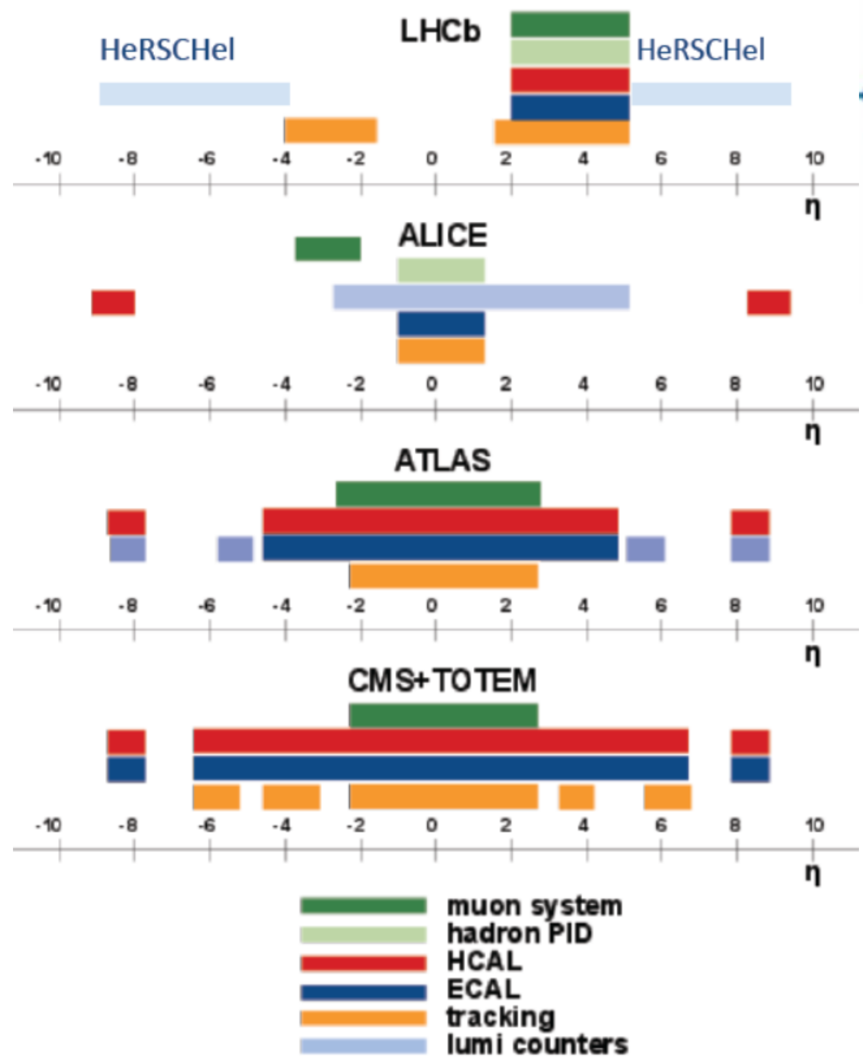
$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle \mathcal{O}^H(n) \rangle$$

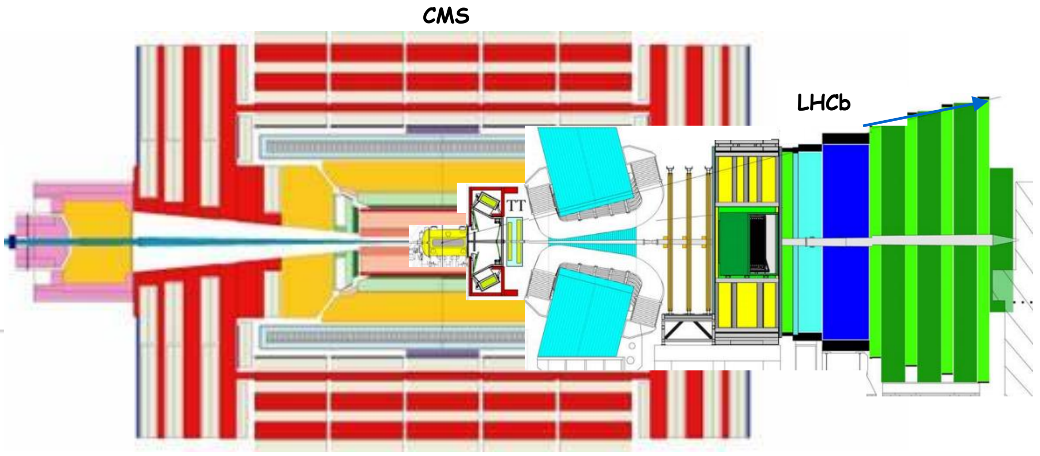
Short distance: perturbative cross-sections + pdf for the production of a $Q\bar{Q}$ pair

Long distance matrix elements (LDME), non-perturbative part

- Colour-singlet model: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} quantum numbers as the final-state quarkonium
- NRQCD: all viable colours and J^{PC} allowed for the intermediate $Q\bar{Q}$ state, they are adjusted in the long-distance part with a given probability.
  Long-Distance Matrix Elements (LDME) from experimental data
- **Universality**: *same LDME for prompt production and production in b-decays*
- Heavy-Quark **Spin-Symmetry** (HQSS): links between colour-singlet (CS) and colour-octet (CO) LDME of different quarkonium states

❑ **Complementary cross-section measurements** and overlap in rapidity





❑ Key detector systems for production measurements: **vertex reconstruction, particle identification (Muon detector, charged hadron ID), Trigger**

Quarkonia production in pp collisions

Dedicated talks at HADRON 2019

- Status of quarkonium production, Hee Sok CHUNG
- Quarkonium production at ATLAS, Tamar ZAKAREISHVILI

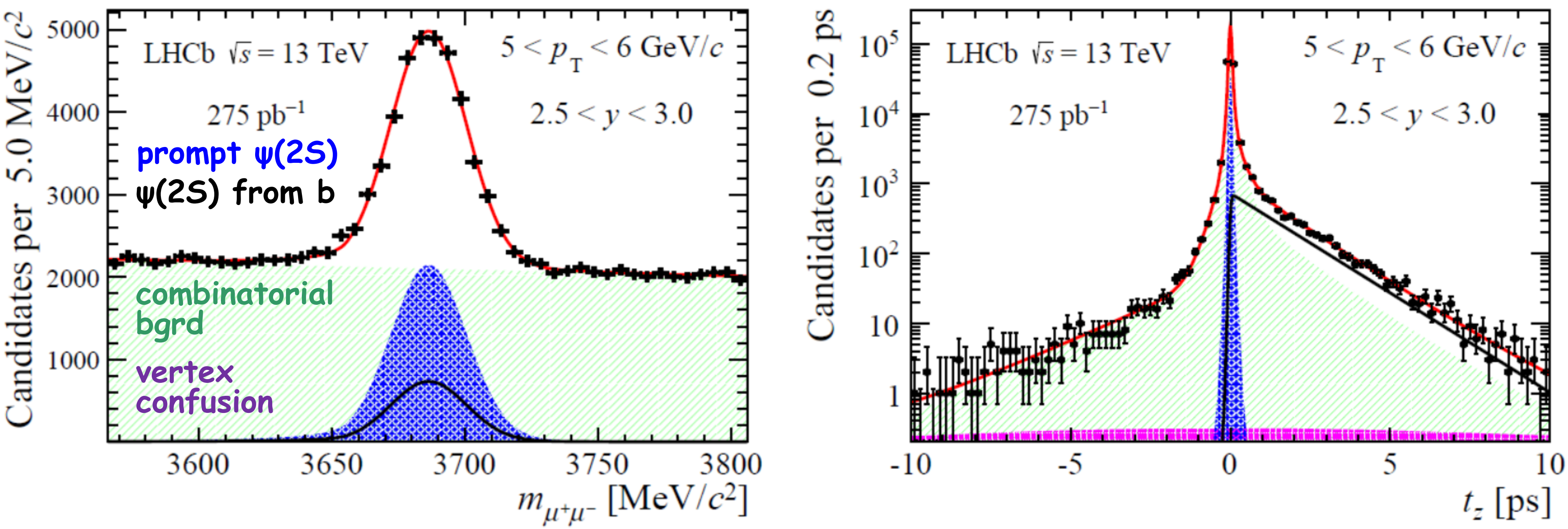
ψ(2S) production at 7 and 13 TeV

arXiv:1908.03099

$\sqrt{s}$ = 7, 13 TeV, $\int L dt$ ~ 614, 275 pb^{-1}

- Negligible feed-down compared to J/ψ
- **Prompt** (pp collision vertex) **ψ(2S) production** and **production in b-decays**
- Double differential cross-sections from two-dimensional fit in bins of p_T and y
- Prompt and b-decay components are extracted from the fit to pseudo-lifetime distribution

$$t_z = \frac{\left(z_{\psi(2S)} - z_{\rm PV}\right) \times M_{\psi(2S)}}{p_z}$$



- **Integral** cross sections:

$$\sigma(\text{prompt } \psi(2S), 7\,\text{TeV}) = 0.471 \pm 0.001\,(\text{stat}) \pm 0.025\,(\text{syst})\,\mu\text{b},$$
$$\sigma(\psi(2S)\text{-from-}b, 7\,\text{TeV}) = 0.126 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst})\,\mu\text{b}.$$

$$\sigma(\text{prompt } \psi(2S), 13\,\text{TeV}) = 1.430 \pm 0.005\,(\text{stat}) \pm 0.099\,(\text{syst})\,\mu\text{b},$$
$$\sigma(\psi(2S)\text{-from-}b, 13\,\text{TeV}) = 0.426 \pm 0.002\,(\text{stat}) \pm 0.030\,(\text{syst})\,\mu\text{b}.$$

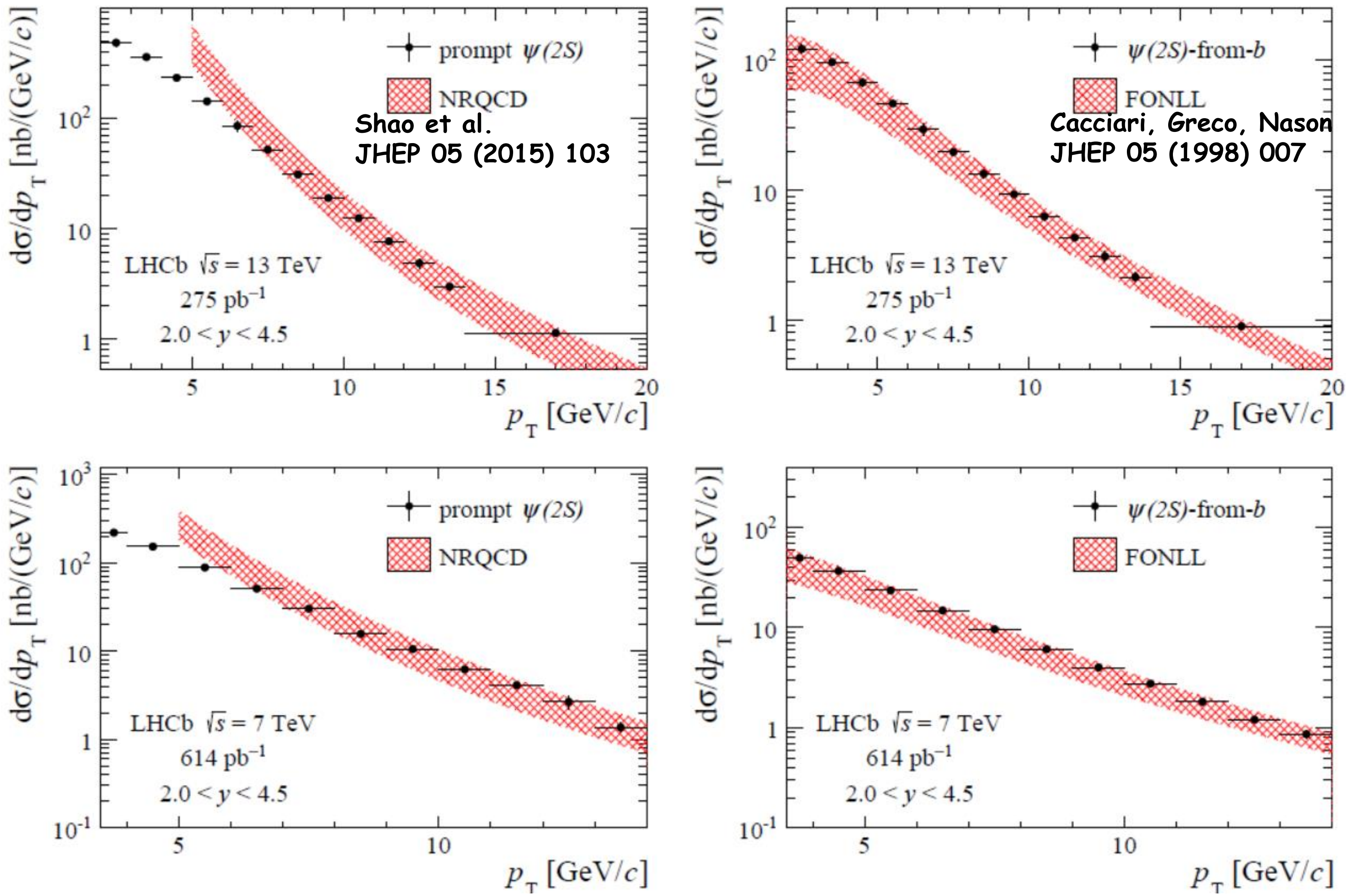
ψ(2S) production at 7 and 13 TeV

- **Prompt ψ(2S) production** and **production in b-hadron decays**

arXiv:1908.03099

$\sqrt{s}$ = 7, 13 TeV, $\int L dt$ ~ 614, 275 pb^{-1}

- **Differential** cross sections

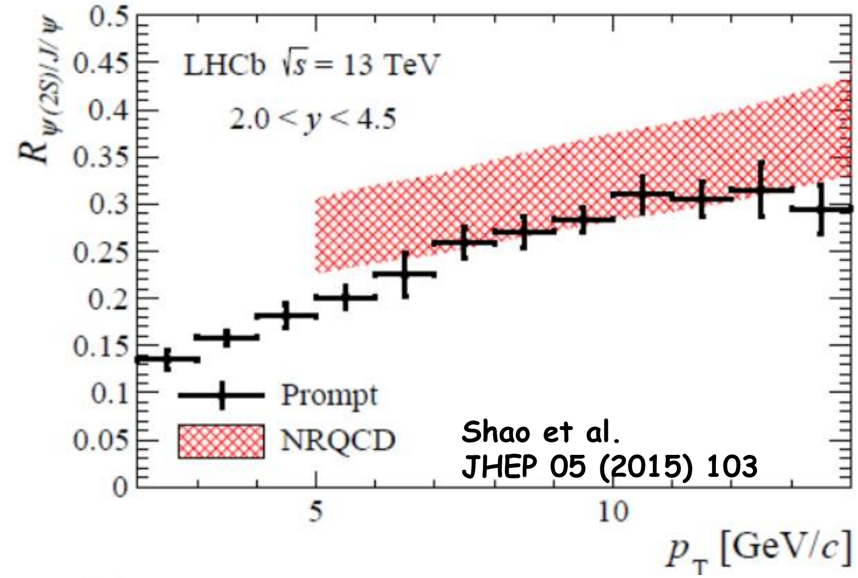


- Overall **good agreement with predictions, with deviation at low p_T** for prompt ψ(2S)
- New measurement at 7 TeV supersedes earlier result based on smaller event sample

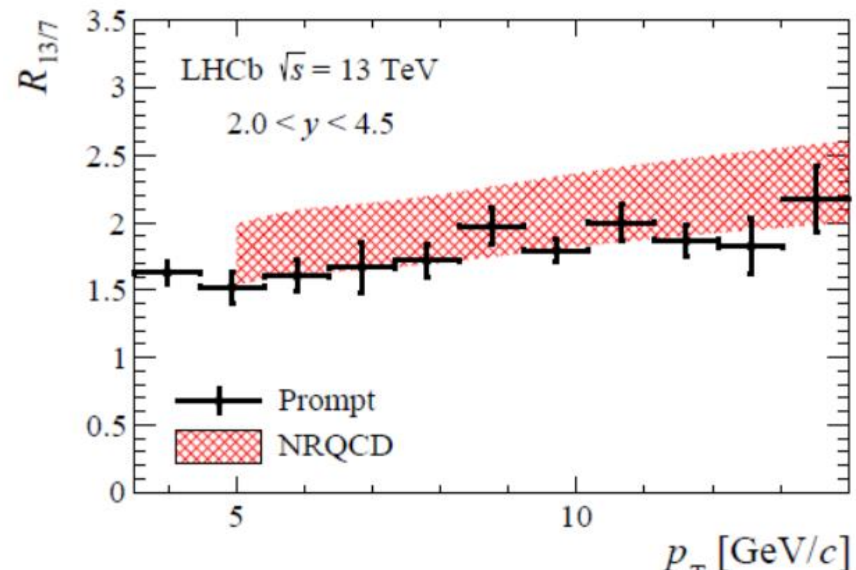
arXiv:1908.03099

$\sqrt{s}$ = 7, 13 TeV, ∫Ldt ~ 614, 275 pb^{-1}

- Uncertainties partly cancel in ratios
- Ratio between the ψ(2S) and J/ψ production cross-sections



- Ratio between the ψ(2S) production cross-sections at $\sqrt{s}$ = 13 and 7 TeV



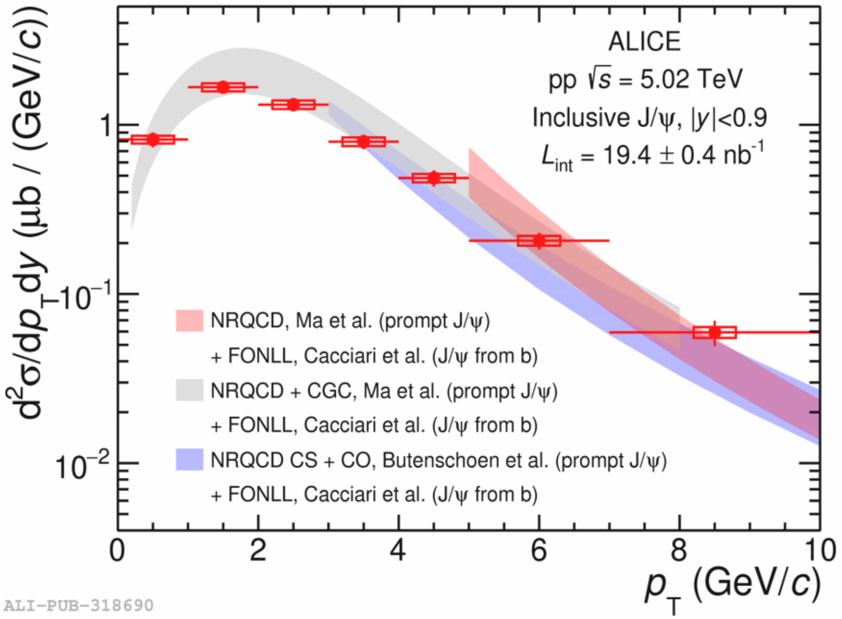
- **Overall good description** for both ratios
- Important to extend theory prediction to lower p_T

J/ψ production at mid rapidity

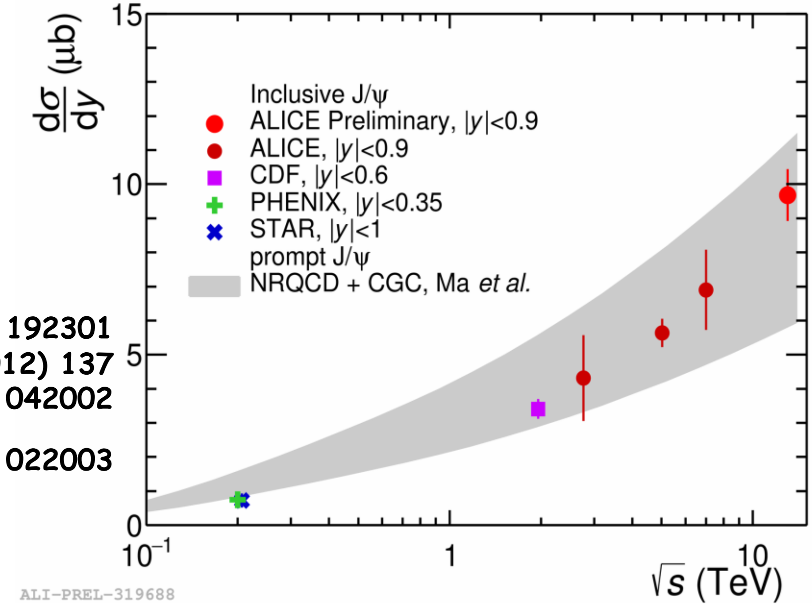
arXiv:1905.07211

- J/ψ p_T differential cross-section down to very low p_T at mid-rapidity

$\sqrt{s}$ = 5.02 TeV, $\int L dt$ ~ 19.4 nb^{-1}



PRL 113 (2014) 192301
JHEP 10 (2012) 137
PRL 106 (2011) 042002
PRL 106 (2011) 022003



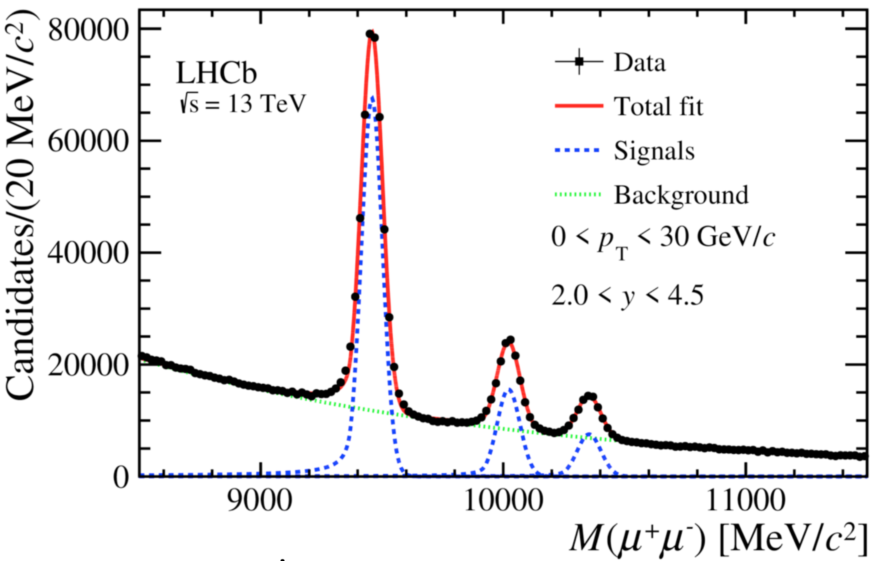
- Important **constraint to understand J/ψ production mechanism** and new pp reference
- **NRQCD + Colour-Glass-Condensate describes p_T differential cross-section and $\sqrt{s}$ dependence**

Υ(nS) production at 13 TeV

JHEP 07 (2018) 134

$\sqrt{s}$ = 13 TeV, $\int L dt \sim 277\ pb^{-1}$

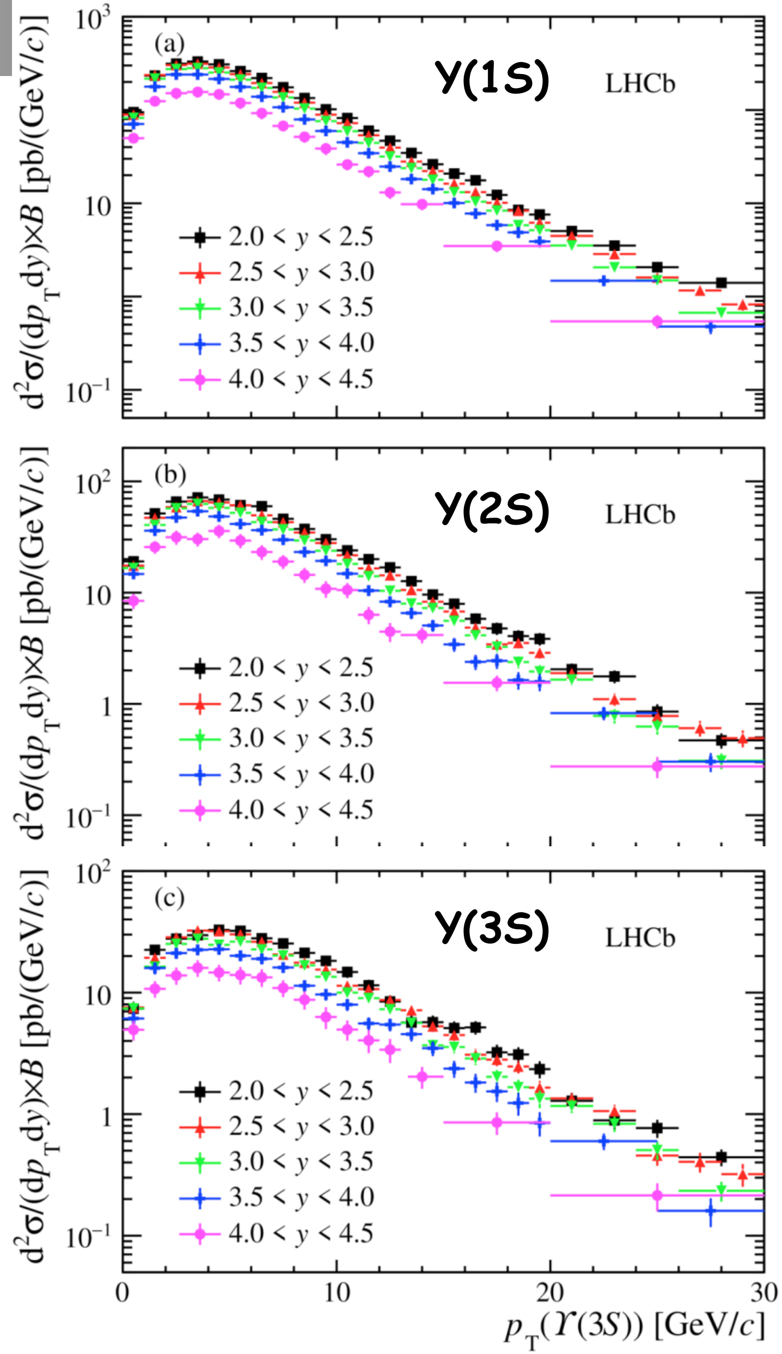
- Clean signals from $\Upsilon(nS) \to \mu\mu$ decays



- Assume no polarization
- **Integral cross-sections of Υ(1S), Υ(2S) and Υ(3S)** in the LHCb fiducial region $0 < p_T < 15$ GeV/c, $2.0 < y$ 4.5:

$$4687 \pm 10 \pm 294\ \text{pb}$$
$$1134 \pm 6 \pm 71\ \text{pb}$$
$$561 \pm 4 \pm 36\ \text{pb}$$

- **Double differential cross-sections** $d^2\sigma/dp_T dy \times BR(\Upsilon(nS) \to \mu\mu)$

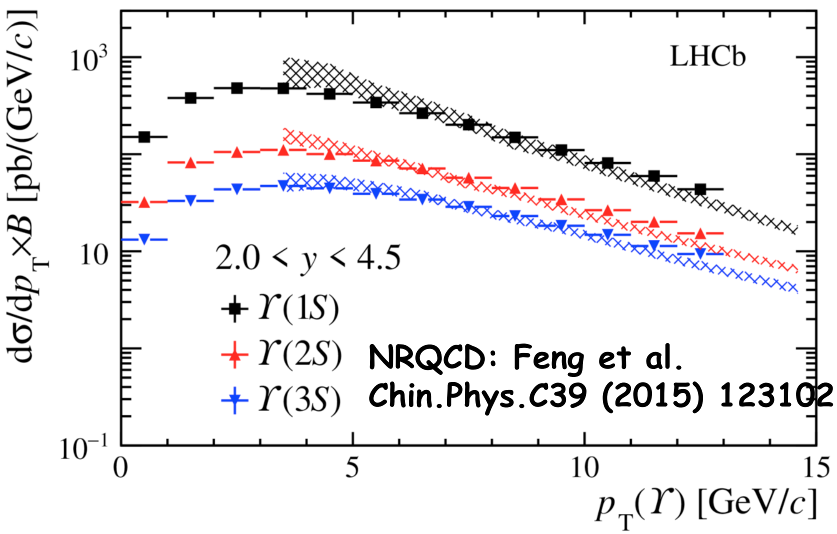


Υ(nS) production at 13 TeV

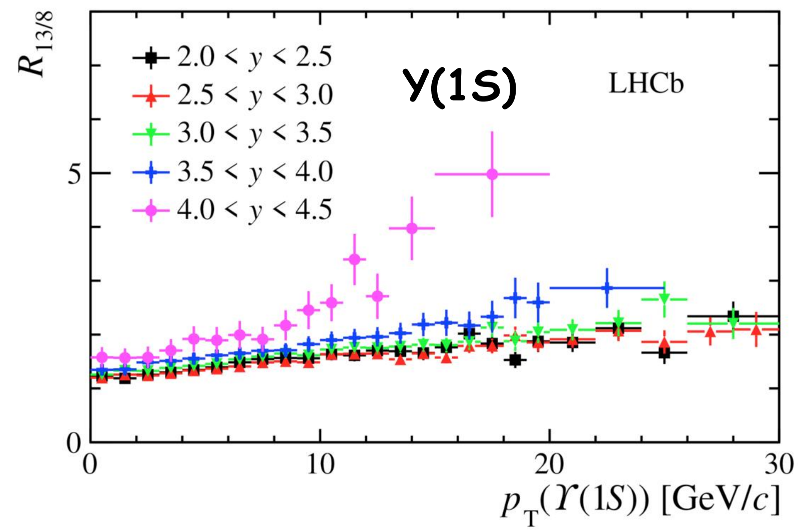
JHEP 07 (2018) 134

$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 277 pb^{-1}

- **p_T-differential cross-sections**
  $d^2\sigma/dp_T dy \times BR(\Upsilon(nS)\to\mu\mu)$

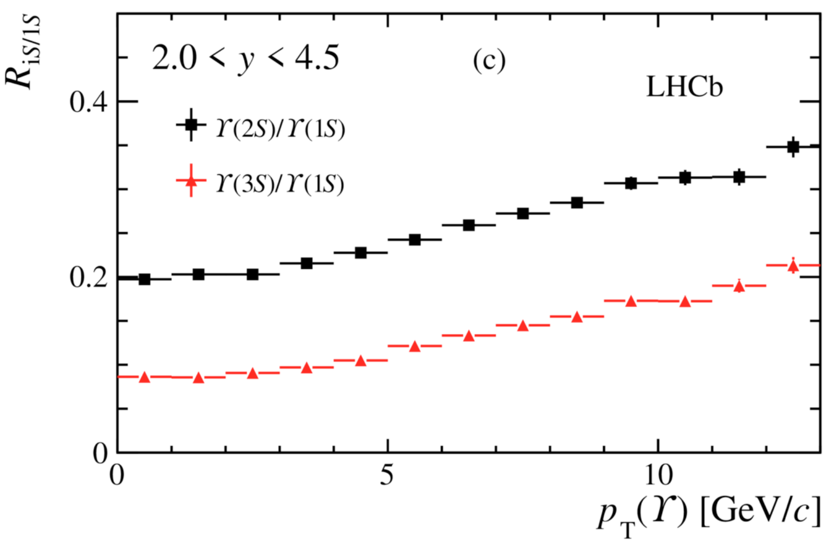


- **Ratio of cross sections: 13 and 8 TeV**



- **Good agreement with NRQCD** predictions
- Cross-section **ratios between Υ(nS) states**

- Consistently above unity
- Growths with p_T and y for all states

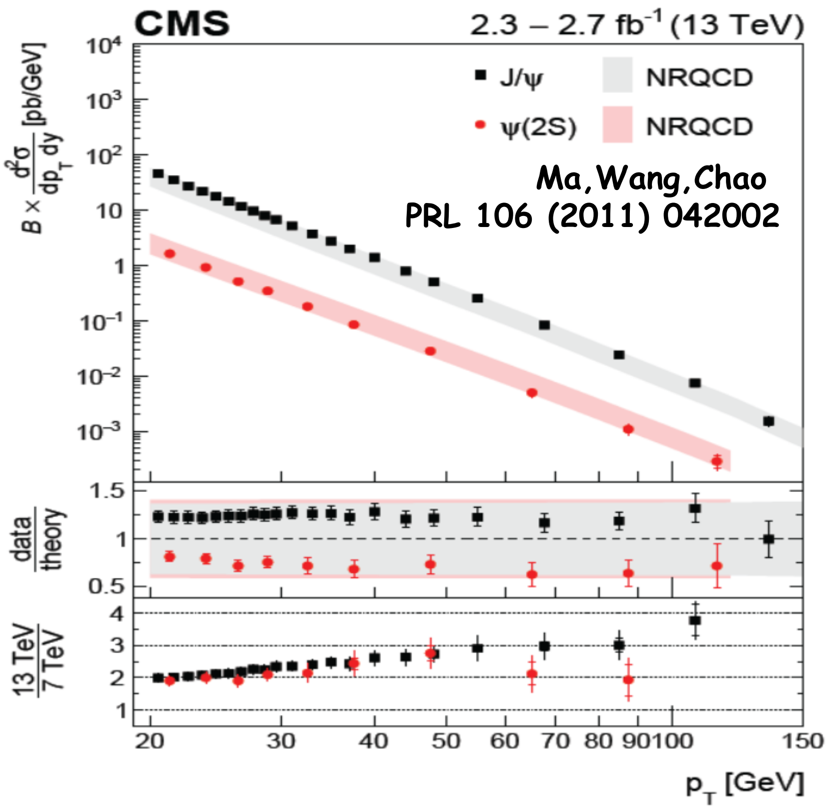


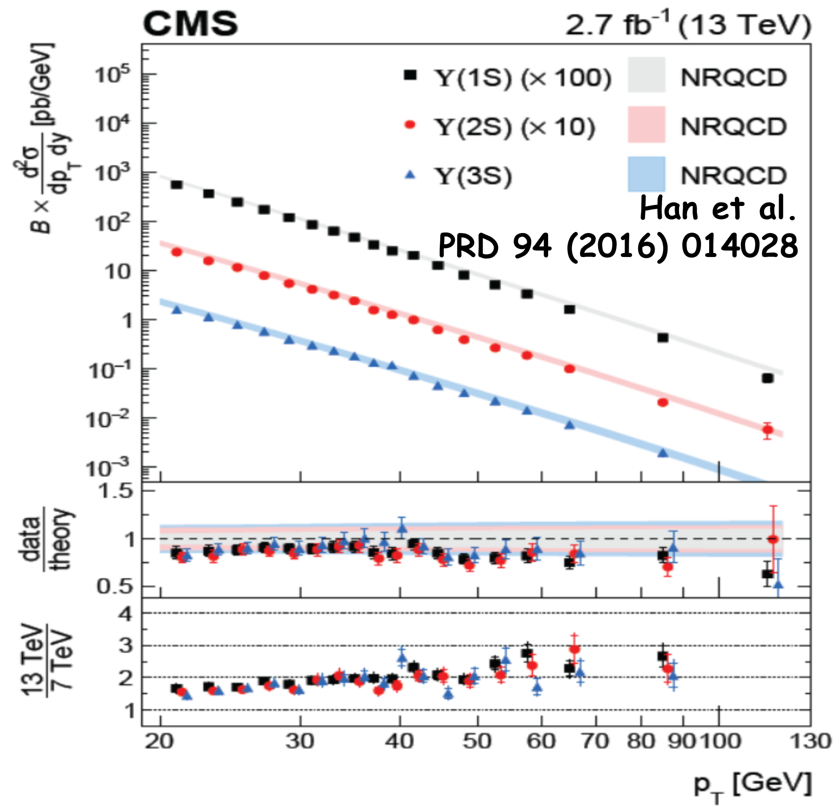
- **Suppression of n>1 states at low p_T**
- No significant dependence on y
- Increasing suppression of higher states: indication of melting in pp collisions ?

Measurement of quarkonium production cross section

❑ Study of **J/ψ, ψ(2S), Υ(1S), Υ(2S) and Υ(3S) states** PLB 780 (2018) 251

❑ **Integral and double-differential cross-sections** times di-muon branching fractions $\int L dt$ = 2.7 (2.3) fb^{-1} at $\sqrt{s}$=13 TeV





❑ In general, **good theory-experiment agreement**

❑ Theory tends to (< 1σ) underestimate (overestimate) the J/ψ (ψ(2S)) cross section

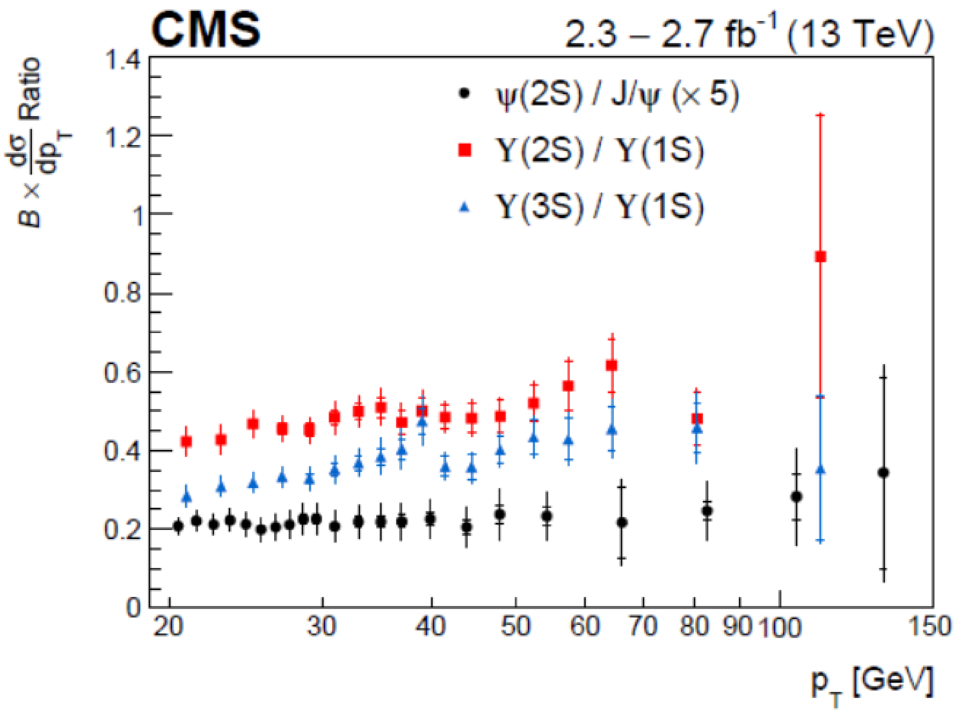
❑ **Ratios of cross sections at 13 TeV to 7 TeV** increase as expected from the pdf evolution

Bands: theory uncertainties from LDME extraction, renormalization scales, choice of m_c and m_b, and uncertainty from BR(QQ→μμ)

PLB 780 (2018) 251

$\int L dt$ = 2.7 (2.3) fb^{-1} at $\sqrt{s}$=13 TeV

- Production cross sections times di-muon branching fractions of **the radial excitations relative to the ground state**

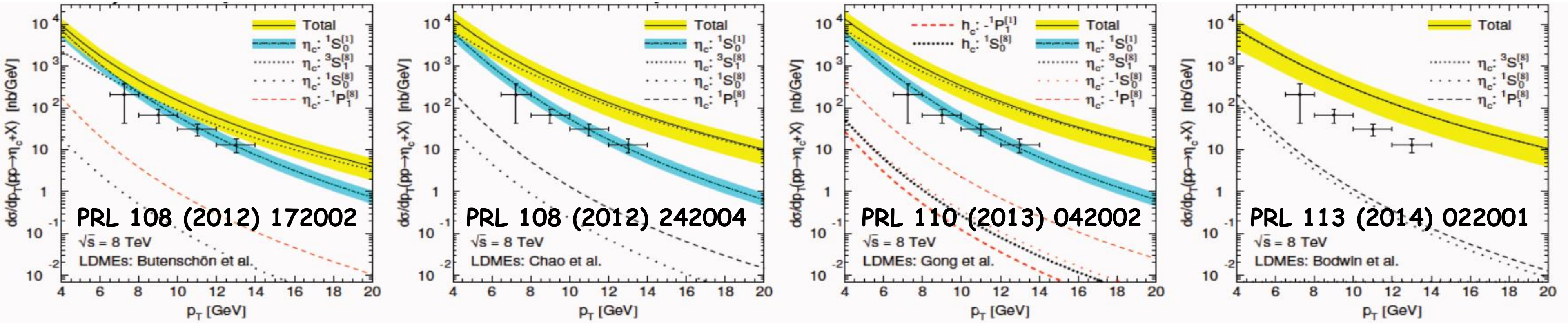


- Consistent with the LHCb results

$\eta_c(1S)$ production

- Four LDMEs describing J/ψ production and polarization
- Linked to LDMEs describing $\eta_c(1S)$ production
- First $\eta_c(1S)$ prompt production measurement at 7, 8 TeV: LHCb **EPJC 75 (2015) 311** using $\eta_c(1S) \to p\bar{p}$

Butenschoen, He, Kniehl, **arXiv:1411.5287**

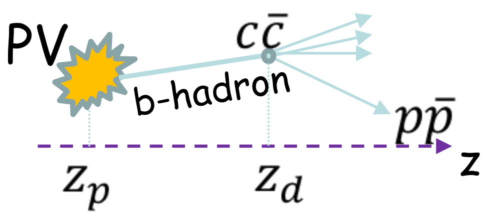


- Results described by **CS NLO**, below expected CO contribution
- New impressive progress in theory description, integrating LHCb result in LDME calculations:
  - Han, Ma, Meng, Shao, Chao **PRL 114 (2015) 092005**
  - Zhang, Sun, Sang, Li **PRL 114 (2015) 092006**
- Theory description still covers limited p_T range
- Further tests with **measurements at different $\sqrt{s}$ and of other linked observables**

$\eta_c(1S)$ production

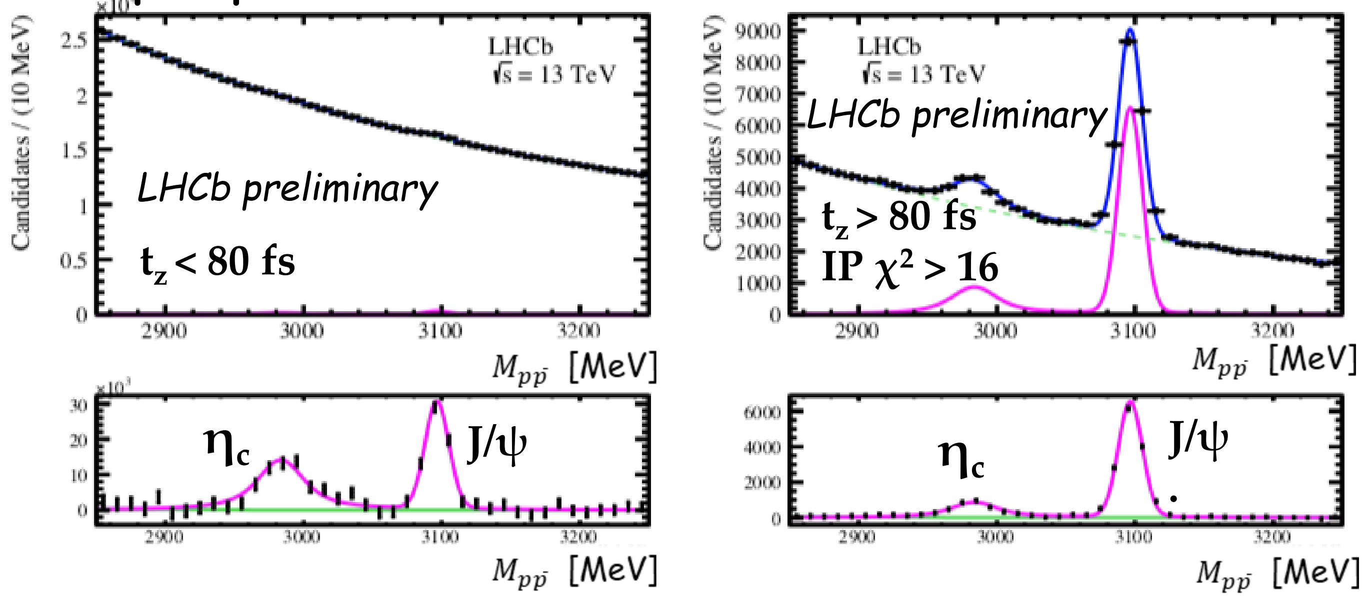
LHCb-PAPER-2019-024
$\sqrt{s}$ = 13 TeV, $\int L dt \sim 2$ fb^{-1}

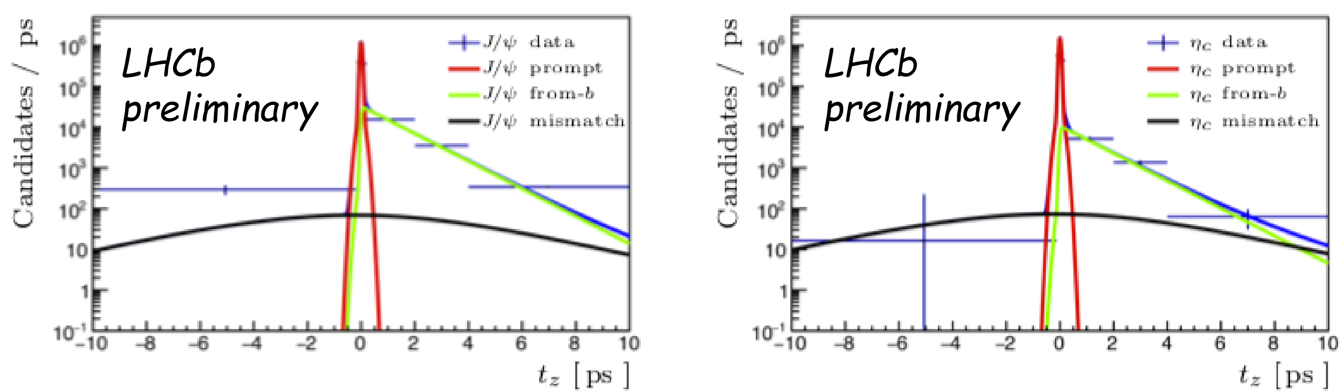
- **New analysis** with 13 TeV data, measurement relative to J/ψ
- **Selection** (as analysis with 7, 8 TeV) or **pseudo-proper lifetime fit** (as J/ψ analyses) to separate prompt charmonium and charmonium from b-decays



$$t_z = \frac{(z_d - z_p) M_{p\bar{p}}}{p_z}$$

prompt-enriched | **b-hadron-enriched**





- Both techniques yield consistent results

$\eta_c(1S)$ production

LHCb-PAPER-2019-024

$\sqrt{s}$ = 13 TeV, $\int L dt \sim 2$ fb^{-1}

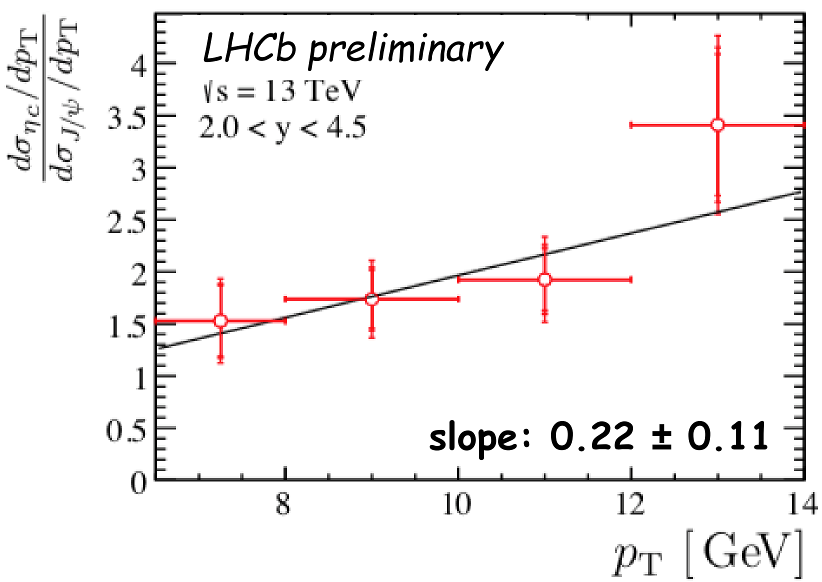
- **First measurement of $\eta_c(1S)$ production cross section at 13 TeV**

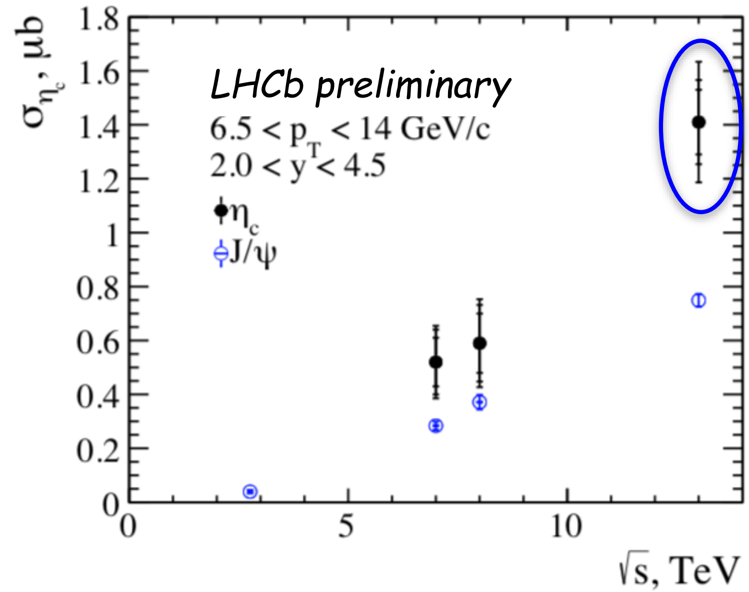
$$(\sigma_{\eta_c})_{13\,\mathrm{TeV}}^{6.5\,\mathrm{GeV}<p_T<14.0\,\mathrm{GeV},\,2.0<y<4.5} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14\,\mu\mathrm{b}$$

- Color Single model prediction: Feng, Shao, Lansberg, Zhang, Usachov, He **NPB 945 (2019) 114662**

$$1.56^{+0.83}_{-0.49}\ {scale}\ {}^{+0.38}_{-0.17}\ {CT14NLO}\ \mu\mathrm{b}$$

- **Consistent with being described by CSM**
- $\sqrt{s}$ cross-section dependence
- p_T-differential **prompt production**





- **Inclusive production in b-decays:** $\mathcal{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{norm}) \times 10^{-3}$
- Consistent and more precise than previous result

$\eta_c(2S)$ ($\rightarrow p\bar{p}$) prompt production at $\sqrt{s}$=13 TeV

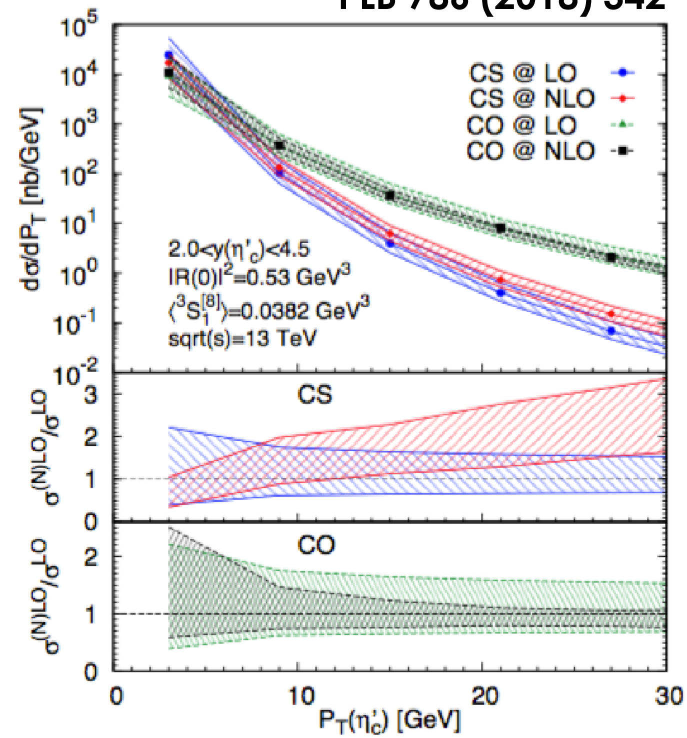
- LHCb measured **$\eta_c(2S)$ production in b-hadron decays** **EPJC 77 (2017) 609, PLB 769 (2017) 305**

$$\mathcal{B}(b \rightarrow \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \rightarrow \phi\phi) = (6.34 \pm 1.81 \pm 0.57 \pm 1.89_{\text{BR}}) \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow \eta_c(2S)K^+) \times \mathcal{B}(\eta_c(2S) \rightarrow p\bar{p}) = (3.47 \pm 0.72 \pm 0.20 \pm 0.16_{\text{BR}}) \times 10^{-8}$$

Lansberg, Shao, Zhang
PLB 786 (2018) 342

- Similar to J/ψ and $\eta_c(1S)$, but **feed-down free system: $\psi(2S)$ and $\eta_c(2S)$**
- Motivated by theory calculations
- **Dedicated LHCb trigger in 2018**



- To be described **simultaneously with $\psi(2S)$ production**

Simultaneous study of J/ψ and $\eta_c(1S)$ production in b-decays

- From EPJC 75 (2015) 311 and Chin. Phys. C40 (2016) 100001:

$$\frac{\mathcal{B}(b\to\eta_c(1S)^{direct}X)}{\mathcal{B}(b\to J/\psi^{direct}X)} = 0.691\pm0.090\pm0.024\pm0.103_{\mathrm{BR}}$$

- Relation between LDME from HQSS:

$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle.$$

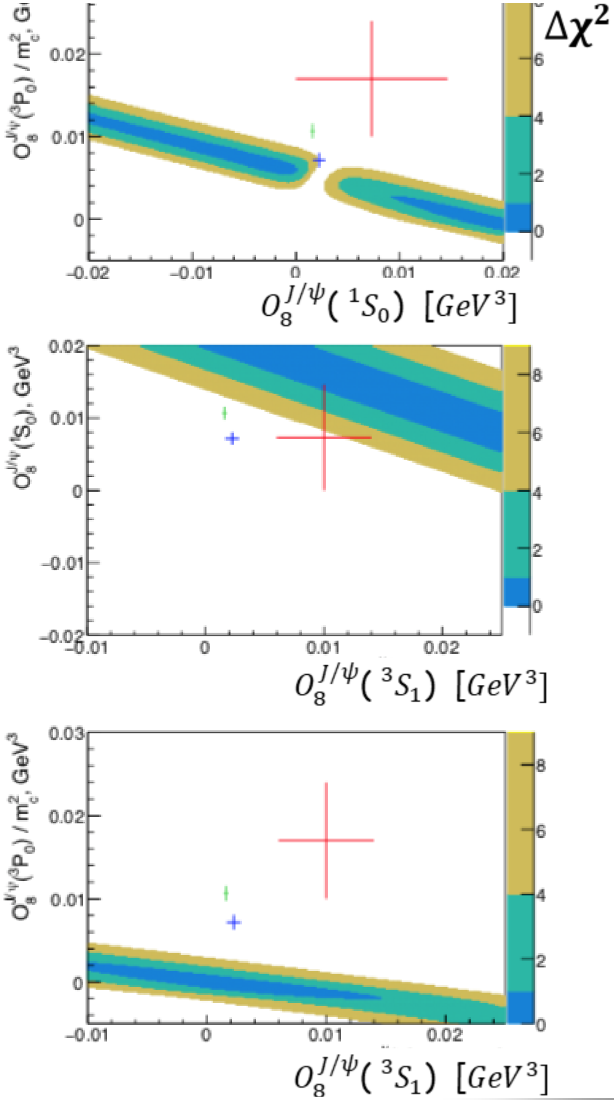
- Branching fractions calculated in **Beneke, Maltoni, Rothstein** PRD 59 (1999) 054003
- Fix CS LDME from potential model $\langle O_8^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$
- **Fit three LDME to two measurements**

$$\frac{\mathcal{B}(b\to\eta_c(1S)^{direct}X)}{\mathcal{B}(b\to J/\psi^{direct}X)} \qquad \mathcal{B}(b\to J/\psi^{direct}X)$$

- Consecutively fix remaining LDME from **Chao et al.**, PRL 108 (2012) 242004
- **Theory calculations should be revisited**, higher order corrections maybe needed

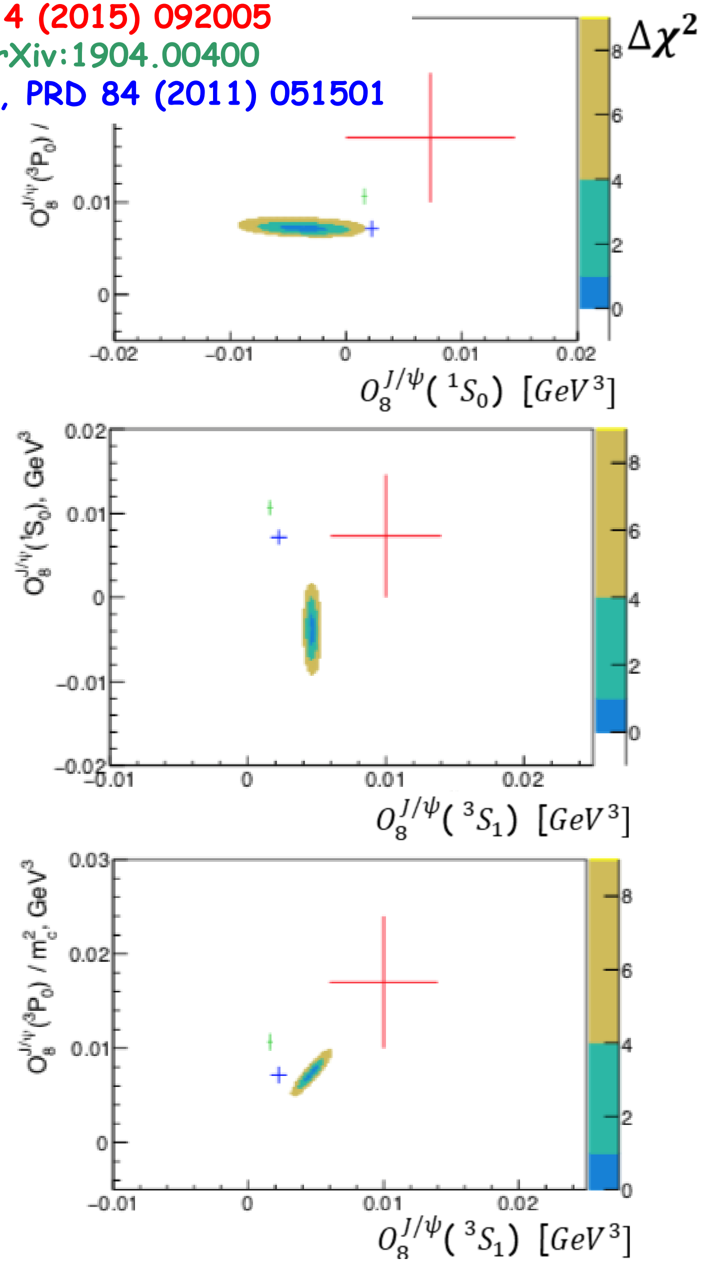
Usachov,Shao et al.

Shao et al., PRL 114 (2015) 092005
Baranov. Lipatov, arXiv:1904.00400
Butenschoen, Kniehl, PRD 84 (2011) 051501



Shao et al., PRL 114 (2015) 092005
Baranov. Lipatov arXiv:1904.00400
Butenschoen, Kniehl, PRD 84 (2011) 051501

- **Simultaneous fits to J/ψ and $\eta_c(1S)$ LDMEs, prompt and b-decay production**
- **Short distance coefficients** for prompt production from H.-S. Shao



- This technique constrains theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia from b-inclusive decays** under **assumptions of factorization, universality and HQSS**, with **different charmonium states**
- Alternatively, once hadroproduction and production in b-decays measured for charmonium states with linked LDMEs, the above **assumptions can be tested quantitatively**

Production of open charm and beauty in pp collisions

Asymmetry of D_s production at 7 and 8 TeV

JHEP 08 (2018) 008

$\sqrt{s}$ = 7, 8 TeV, $\int L dt \sim 1, 2\ fb^{-1}$

- Expected **asymmetry in charmed mesons with u and d quarks**
  - c and $\bar{c}$ hadronise differently due to the presence of u, d valence quarks
  - $\bar{c}$ preferably forms mesons, c can additionally form baryons with valence quarks
- **D_s does not contain valence quarks, only indirect effect of asymmetry expected**
  - Sensitive test for non-perturbative QCD models
  - Essential input for direct CP violation in decays of D_s mesons
- Production asymmetry

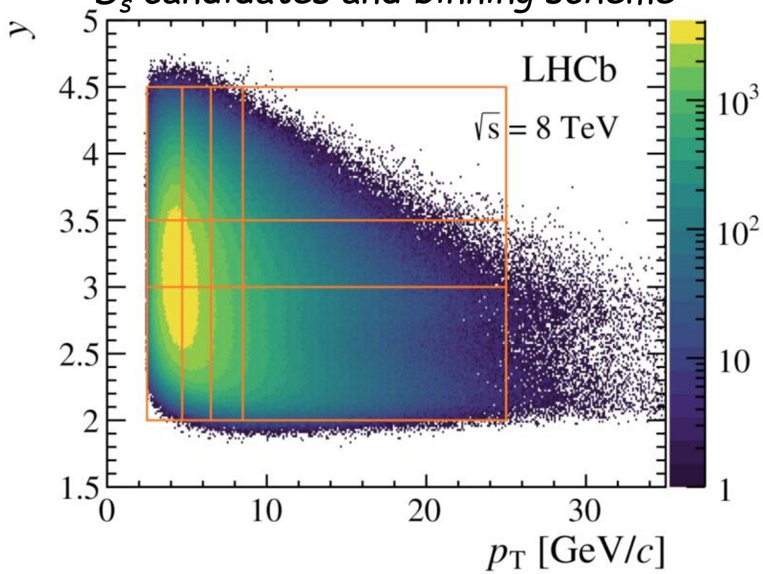
raw asymmetry, detection asymmetry

$$A_P(D_s^+) = \frac{1}{1 - f_{bkg}}\left(A_{raw} - A_D - f_{bkg} A_P(B)\right)$$

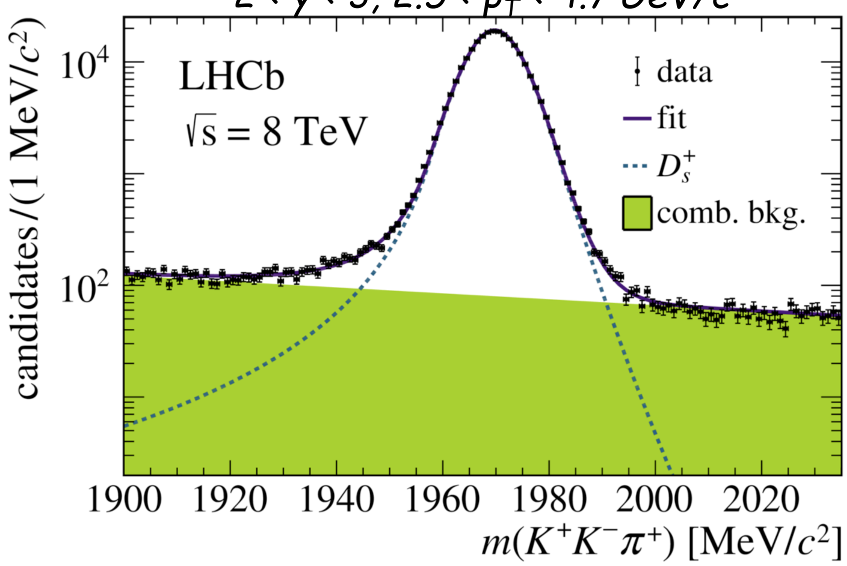
fraction of Ds from b-decyas, B-production asymmetry

- Decay chain $D_s \to \varphi\pi^+$, $\varphi \to K^+K^-$, measurements include D_s from D_s^* decays

D_s candidates and binning scheme



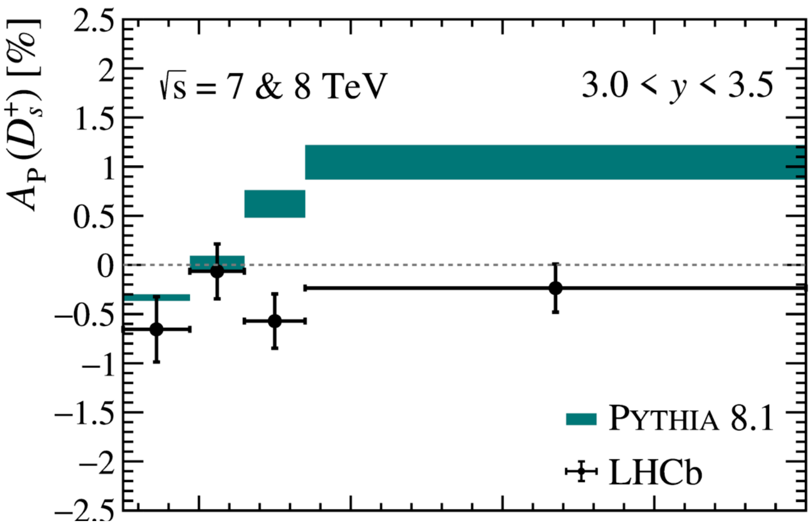
2 < y < 3, 2.5 < p_T < 4.7 GeV/c

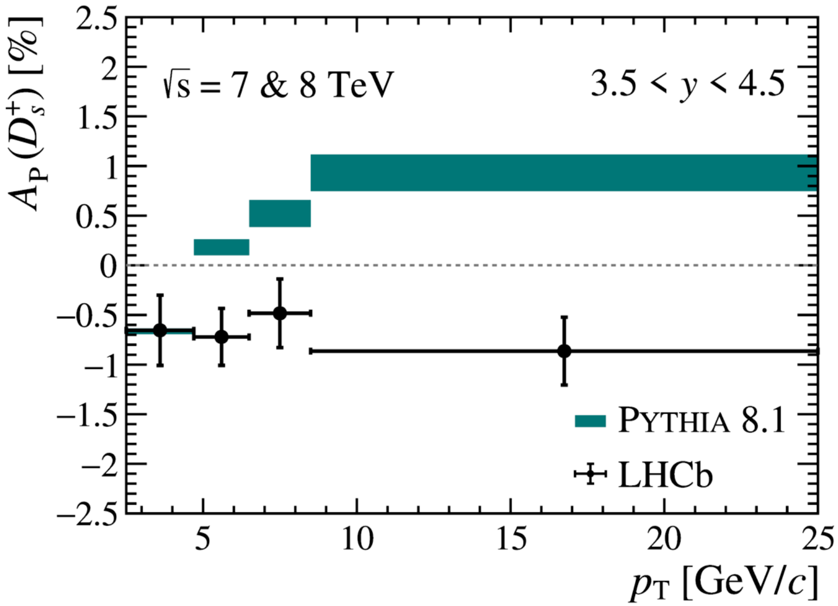


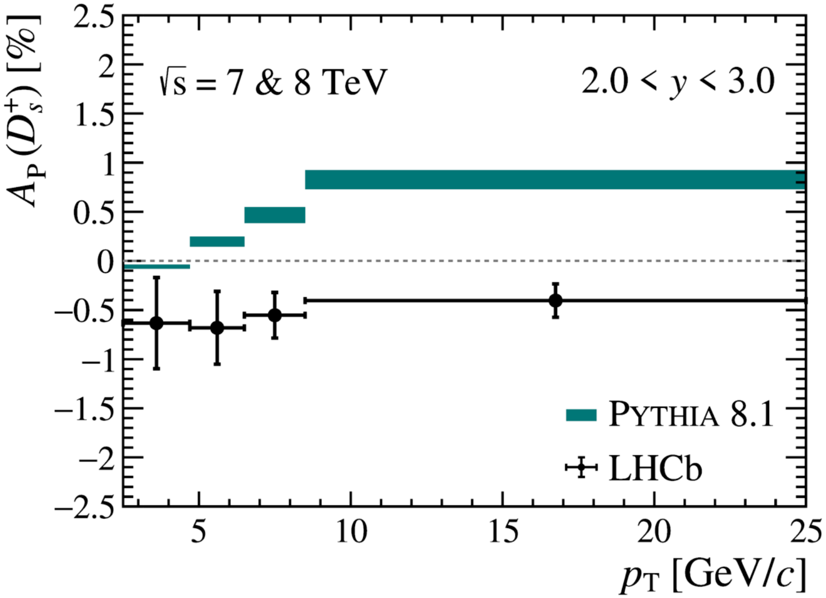
JHEP 08 (2018) 008

$\sqrt{s}$ = 7, 8 TeV, $\int Ldt \sim 1, 2\ fb^{-1}$

- Differential **production asymmetry in p_T and rapidity bins**







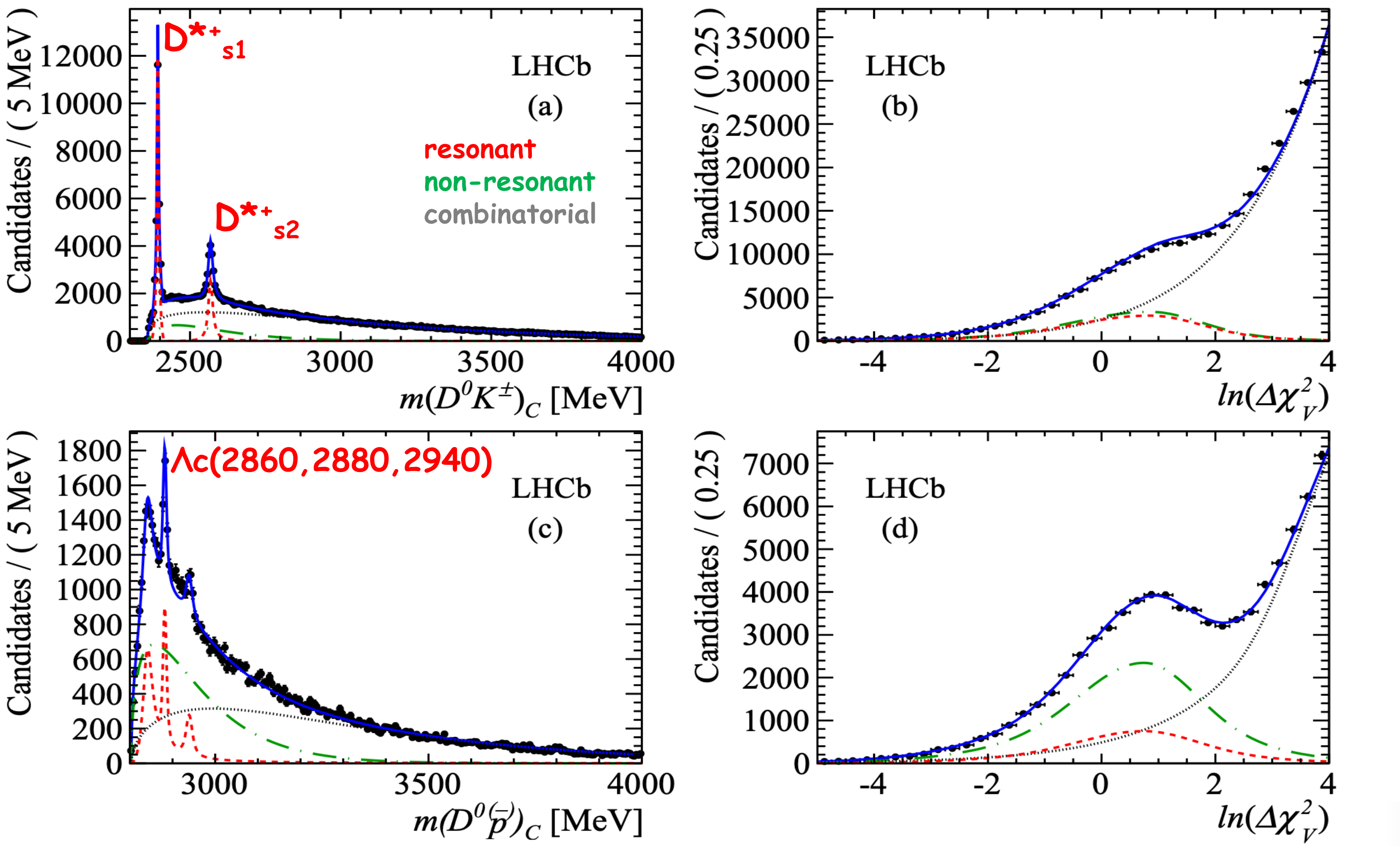
- **3.3σ non-zero asymmetry in combined data**
- No significant dependence on $\sqrt{s}$, y, p_T
- PYTHIA 8.1 prediction is off and shows stronger dependence on y and p_T than data

Relative Λ_b and B_s production in pp collisions

arXiv:1902.06794, EPJC 77 (2017) 609

$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 1.67\ fb^{-1}$

- **Measure $f_s/(f_u+f_d)$ and $f_{\Lambda b}/(f_u+f_d)$ with semi-leptonic decays to $H_c\mu\nu_\mu X$**, where $H_c = D^0, D^+, D_s, \Lambda_c$.
- Analysis in 2D bins of b-hadron p_T and η, measurement in $4 < p_T < 25$ GeV/c and $2 < \eta < 5$
- The (non)resonant $B_s \rightarrow (D^0K^+)\mu\nu$ and $\Lambda_b \rightarrow (D^0p^+)\mu\nu$ yields from simultaneous fits to mass distributions and vertex likelihood difference $\chi^2(D\mu) - \chi^2(D\mu h)$



arXiv:1902.06794, EPJC 77 (2017) 609

$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 1.67 fb^{-1}

- **B^0 yield** estimated from the **D^0 $\mu\nu_\mu$X** final state:

$$n_{\rm corr}(B\to D^0\mu^-) = \frac{1}{\mathcal{B}(D^0\to K^-\pi^+)\epsilon(B\to D^0)}\times \left[n(D^0\mu^-) - n(D^0K^+\mu^-)\frac{\epsilon(\overline{B}{}^0_s\to D^0)}{\epsilon(\overline{B}{}^0_s\to D^0K^+)} - n(D^0p\mu^-)\frac{\epsilon(\Lambda^0_b\to D^0)}{\epsilon(\Lambda^0_b\to D^0p)}\right]$$

- **B$^+$ yield** estimated from total **D$^+$ $\mu\nu_\mu$X final state**, relying on isospin symmetry:

  B$_s$ → D$^+$K^0 $\mu\nu$ from B$_s$ → D^{0}K$^+$ $\mu\nu$

  Λ_b → D$^+$n $\mu\nu$ from Λ_b → D^{0}p $\mu\nu$

$$n_{\rm corr}(B\to D^+\mu^-) = \frac{1}{\epsilon(B\to D^+)}\left[\frac{n(D^+\mu^-)}{\mathcal{B}(D^+\to K^-\pi^+\pi^+)} - \frac{n(D^0K^+\mu^-)}{\mathcal{B}(D^0\to K^-\pi^+)}\frac{\epsilon(\overline{B}{}^0_s\to D^+)}{\epsilon(\overline{B}{}^0_s\to D^0K^+)} - \frac{n(D^0p\mu^-)}{\mathcal{B}(D^0\to K^-\pi^+)}\frac{\epsilon(\Lambda^0_b\to D^+)}{\epsilon(\Lambda^0_b\to D^0p)}\right].$$

- **B$_s$ yield** estimated from total **D$_s$ $\mu\nu_\mu$X final state:**

$$n_{\rm corr}(\overline{B}{}^0_s\to D^+_s\mu^-) = \frac{n(D^+_s\mu^-)}{\mathcal{B}(D^+_s\to K^+K^-\pi^+)\epsilon(\overline{B}{}^0_s\to D^+_s\mu^-)} - N(\overline{B}{}^0+B^-)\mathcal{B}(B\to D^+_s\overline{K}{}^0)\frac{\epsilon(\overline{B}\to D^+_s\overline{K}{}^0\mu^-)}{\epsilon(\overline{B}{}^0_s\to D^+_s\mu^-)}.$$

and the estimated decays to D$^+$K^0$\mu\nu_\mu$X final state

$$n_{\rm corr}(\overline{B}{}^0_s\to DK\mu^-) = \kappa\frac{n(D^0K^+\mu^-)}{\mathcal{B}(D^0\to K^-\pi^+)\epsilon(\overline{B}{}^0_s\to D^0K^+\mu^-)},$$

- **Λ_b yield** estimated from total **H$_c$ $\mu\nu_\mu$X final state:**

$$n_{\rm corr}(\Lambda^0_b\to H_c\mu^-) = \frac{n(\Lambda^+_c\mu^-)}{\mathcal{B}(\Lambda^+_c\to pK^-\pi^+)\epsilon(\Lambda^0_b\to\Lambda^+_c)} + 2\frac{n(D^0p\mu^-)}{\mathcal{B}(D^0\to K^-\pi^+)\epsilon(\Lambda^0_b\to D^0p)}$$

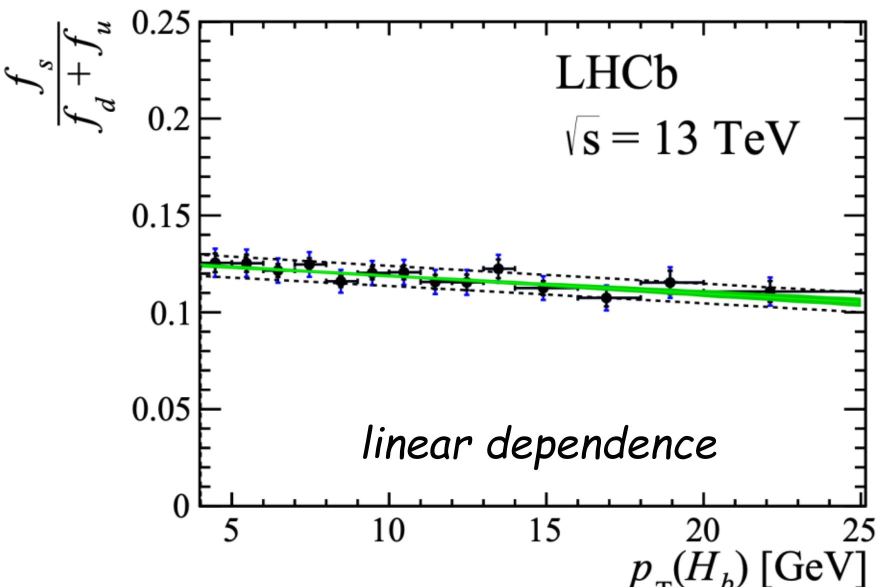
arXiv:1902.06794, EPJC 77 (2017) 609

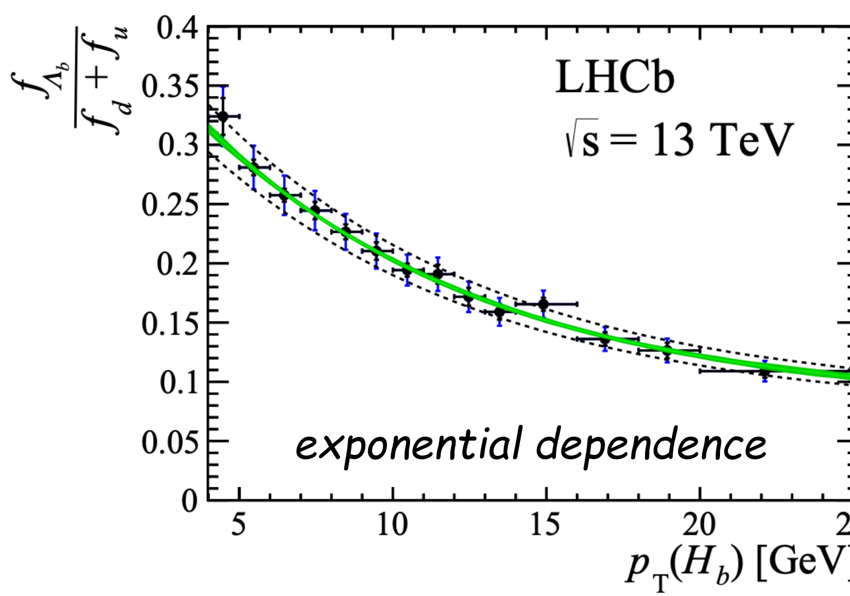
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 1.67\ fb^{-1}$

- Assuming the same semileptonic widths, **first measurement of b-hadron fractions at 13 TeV**:

$$\frac{f_s}{f_u+f_d} = \frac{n_{\rm corr}(\overline{B}{}^0_s \to D\mu^-)}{n_{\rm corr}(B \to D^0\mu^-) + n_{\rm corr}(B \to D^+\mu^-)} \frac{\tau_{B^-}+\tau_{\overline{B}{}^0}}{2\tau_{\overline{B}{}^0_s}}(1-\xi_s) - \frac{\mathcal{B}(B \to D_s\overline{K}\mu^-)}{\langle \mathcal{B}_{\rm SL}\rangle} \frac{\epsilon(\overline{B} \to D_s^+)}{\epsilon(\overline{B}{}^0_s \to D_s^+)} = 0.122(6)$$

$$\frac{f_{\Lambda_b^0}}{f_u+f_d} = \frac{n_{\rm corr}(\Lambda_b^0 \to H_c\mu^-)}{n_{\rm corr}(B \to D^0\mu^-) + n_{\rm corr}(B \to D^+\mu^-)} \frac{\tau_{B^-}+\tau_{\overline{B}{}^0}}{2\tau_{\Lambda_b^0}}(1-\xi_{\Lambda_b^0}) = 0.259(18)$$



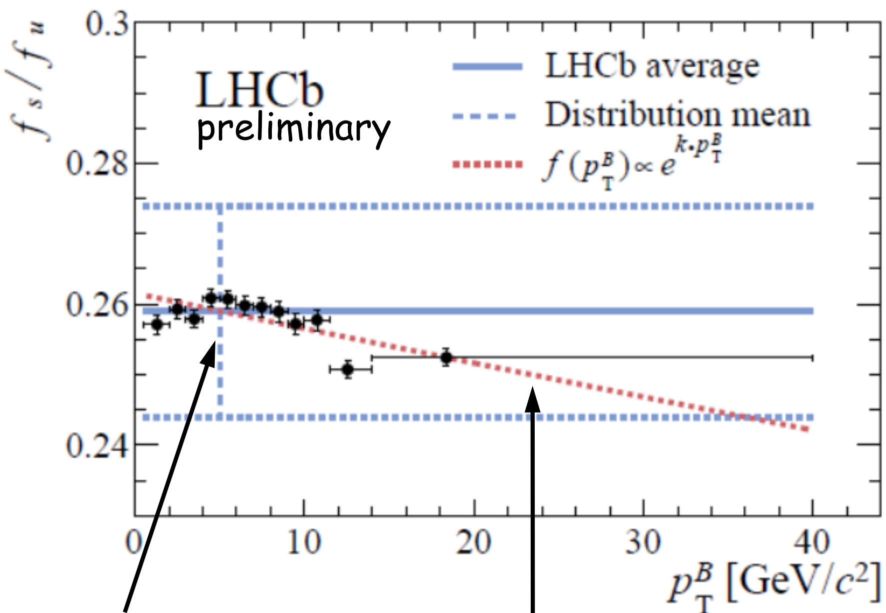


- **Production ratio for both B_s and Λ_b: p_T dependence, no η dependence**

- f_s/f_u from relative $B^- \to J/\psi K^-$ and $B_s \to J/\psi \phi$ yields — LHCb-PAPER-2019-020
- **B_s production depending on $\sqrt{s}$** — $\sqrt{s}$ = 7, 8, 13 TeV, $\int L dt \sim 1, 2, 1.4\ fb^{-1}$

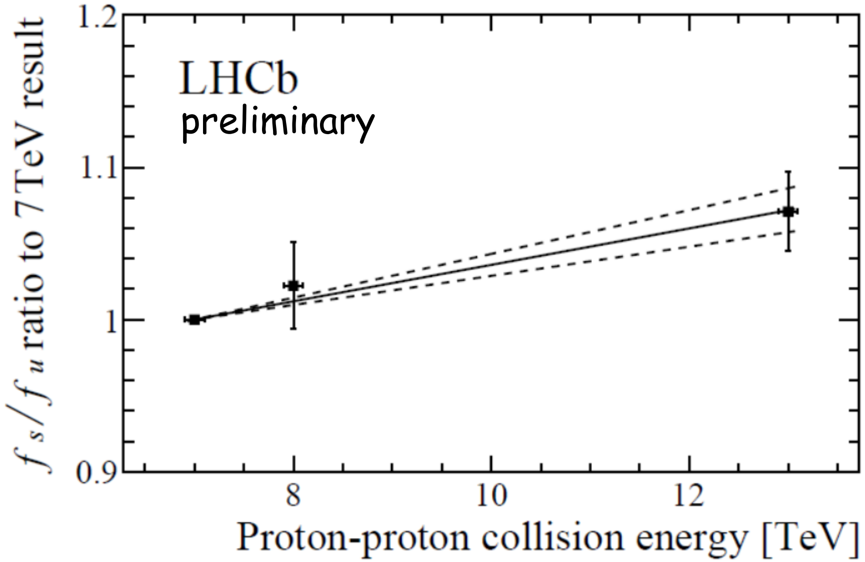
$$\mathcal{R}_{8\,\mathrm{TeV}}/\mathcal{R}_{7\,\mathrm{TeV}} = 1.026 \pm 0.010(\mathrm{stat}) \pm 0.020(\mathrm{syst})$$
$$\mathcal{R}_{13\,\mathrm{TeV}}/\mathcal{R}_{7\,\mathrm{TeV}} = 1.071 \pm 0.010(\mathrm{stat}) \pm 0.018(\mathrm{syst})$$

- Double ratios indicate a 2.9σ increase with $\sqrt{s}$, though still consistent with no dependence



Scale to match f_s/f_d at 7 TeV
LHCb-CONF-2013-011 (for illustration)

Significance of the variation ~6σ



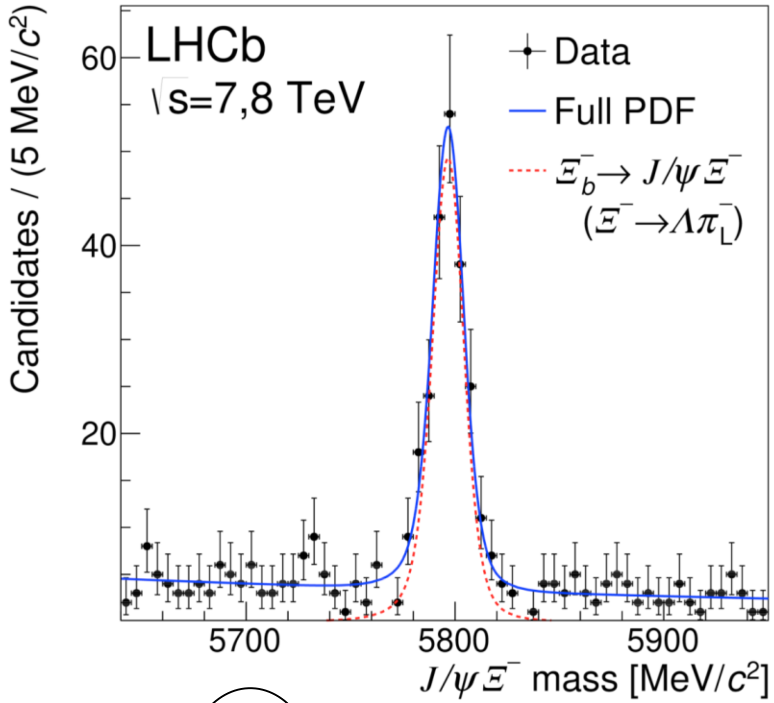
- Consistent with B_s and Λ_b study
- **Measured p_T dependence suggests the f_s/f_d dependence on $\sqrt{s}$**
- Essential when using data at other $\sqrt{s}$ value for normalization

Ξ_b production in pp collisions

PRD 99 (2019) 052006

$\sqrt{s}$ = 7, 8, 13 TeV, $\int L dt$ ~ 1, 2, 1.6 fb^{-1}

- Decay chane $\Xi_b \to J/\psi\, \Xi^-$, $\Xi^- \to \Lambda\, \pi^-$
- Measure production ratios to kinematically similar decay $\Lambda_b \to J/\psi\, \Lambda$
- Replace branching fraction by decay width × lifetime



Measured

Determine

3/2 in SU(3) flavor symmetry

$$R \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi\, \Xi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, \Lambda)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\Gamma(\Xi_b^- \to J/\psi\, \Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi\, \Lambda)} \frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}}$$

Known (PDG)

- **First measurement of Ξ_b production:**

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0_{\mathrm{SU(3)}}) \times 10^{-2} \quad [\sqrt{s} = 7, 8\,\mathrm{TeV}],$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.5_{\mathrm{SU(3)}}) \times 10^{-2} \quad [\sqrt{s} = 13\,\mathrm{TeV}].$$

Search for Higgs-like particle in association with b-quark in $p\bar{p}$ collisions

❑ A search for a **spin-zero non-SM particle** φ produced in association with a b-quark and decaying to $b\bar{b}$

PRD 99 (2019) 052001

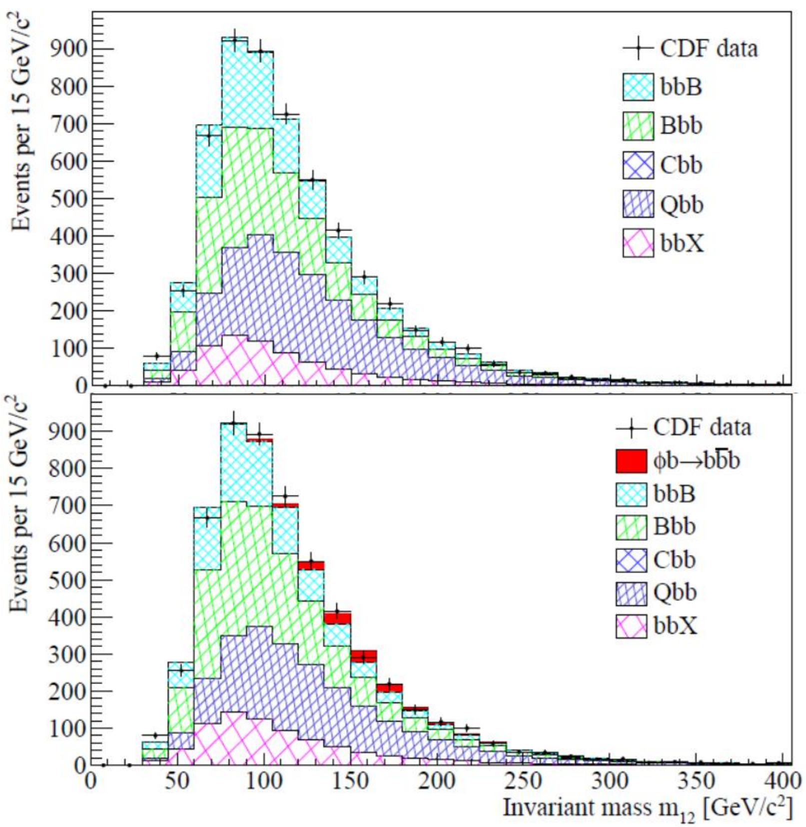
$\sqrt{s}$ = 1.96 TeV, ∫Ldt ~ 5.4 fb^{-1}

❑ Predicted in MSSM or DM models

Nilles, Phys.Rept. 110 (1984) 1
Izaguirre,Krnjaic,Shuve, PRD 90 (2014) 055002
Berlin,Hooper,McDermott, PRD 89 (2014) 115022

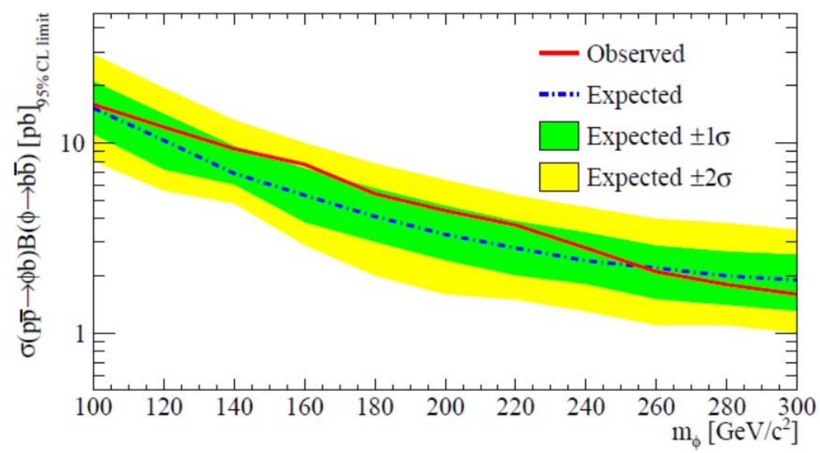
❑ A 2σ excess over SM background prediction compatible with the signal of 100-150 GeV/c^2 φ boson from previous CDF+D0 combined analysis; CMS exclusion limits

❑ New CDF analysis on independent data, requiring at least three b-jets



❑ Triple-tagged events projected to m_{12} **with background-only hypothesis** and **with φ scalar component** (mass of 160 GeV/c^2)

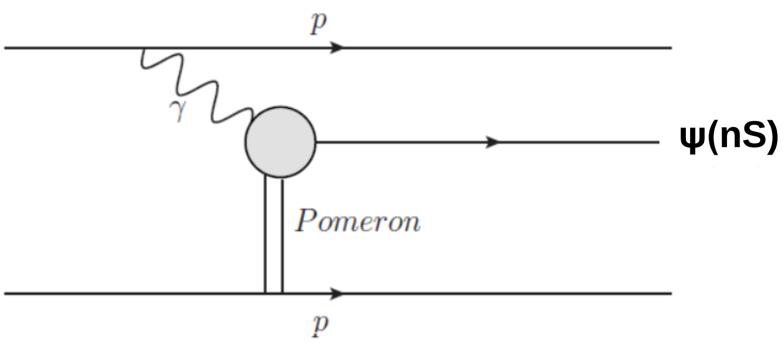
❑ Observed and expected 95% CL limits on $\sigma(p\bar{p} \to \varphi b) \times BR(\varphi \to b\bar{b})$ as functions of m_φ



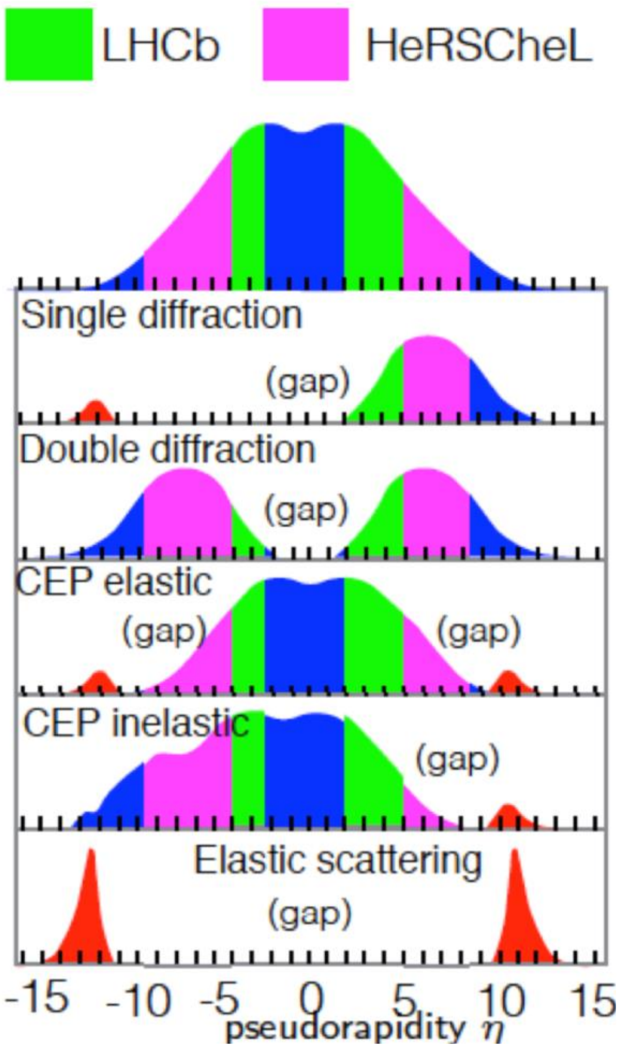
❑ Established UL excludes the previously observed excess at 95%CL

Central Exclusive Production of HF

- **QCD tests with clean theoretical interpretation**
- Only **CS production**
- Sensitivity with cross-sections in the LHCb coverage down to $x \sim 1.5 \times 10^{-5}$



- **CEP: large rapidity gap**

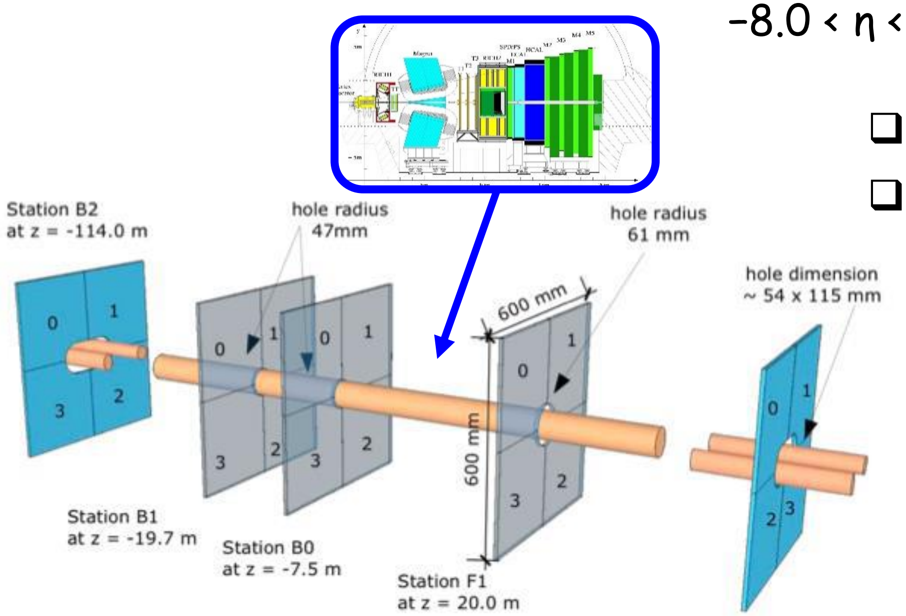


Central Exclusive Production of J/ψ and ψ(2S) at 13 TeV

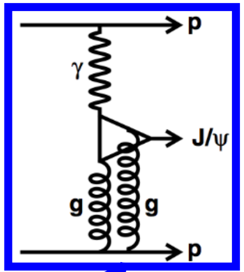
JHEP 10 (2018) 167

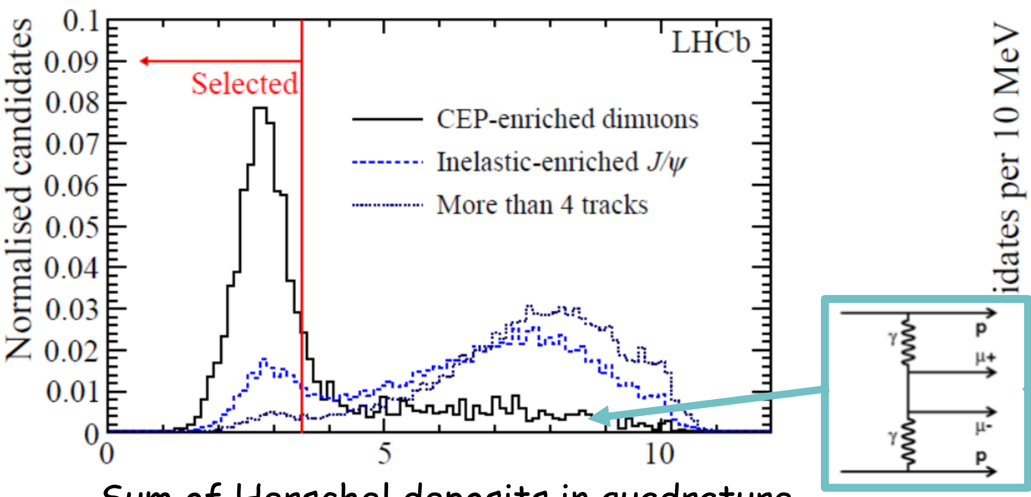
$\sqrt{s}$=13 TeV, ∫Ldt ~0.2 fb^{-1}

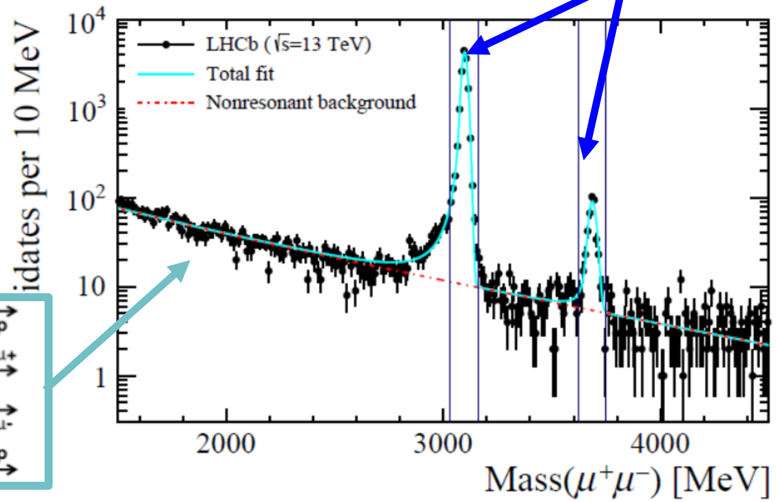
- **Herschel detector** increases rapidity gap in forward region $-8.0 < \eta < -1.5$, $5.0 < \eta < 8.0$



- Dedicated CEP trigger
- **Exclusivity**: precisely two forward muons; no backward tracks; no activity in SPD (< 10 hits). Quantify with p_T spectrum.







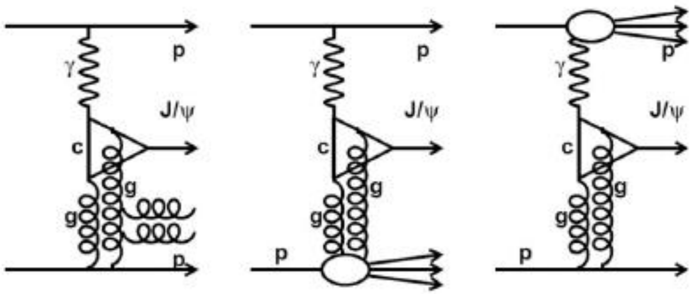
Signal shape

JHEP 10 (2018) 167

- Estimated from Superchic using $\exp(-\, b\, p_T^2)$
- Slope b estimated from HERA data, agreement to the fit of LHCb data

Inelastic backgrounds

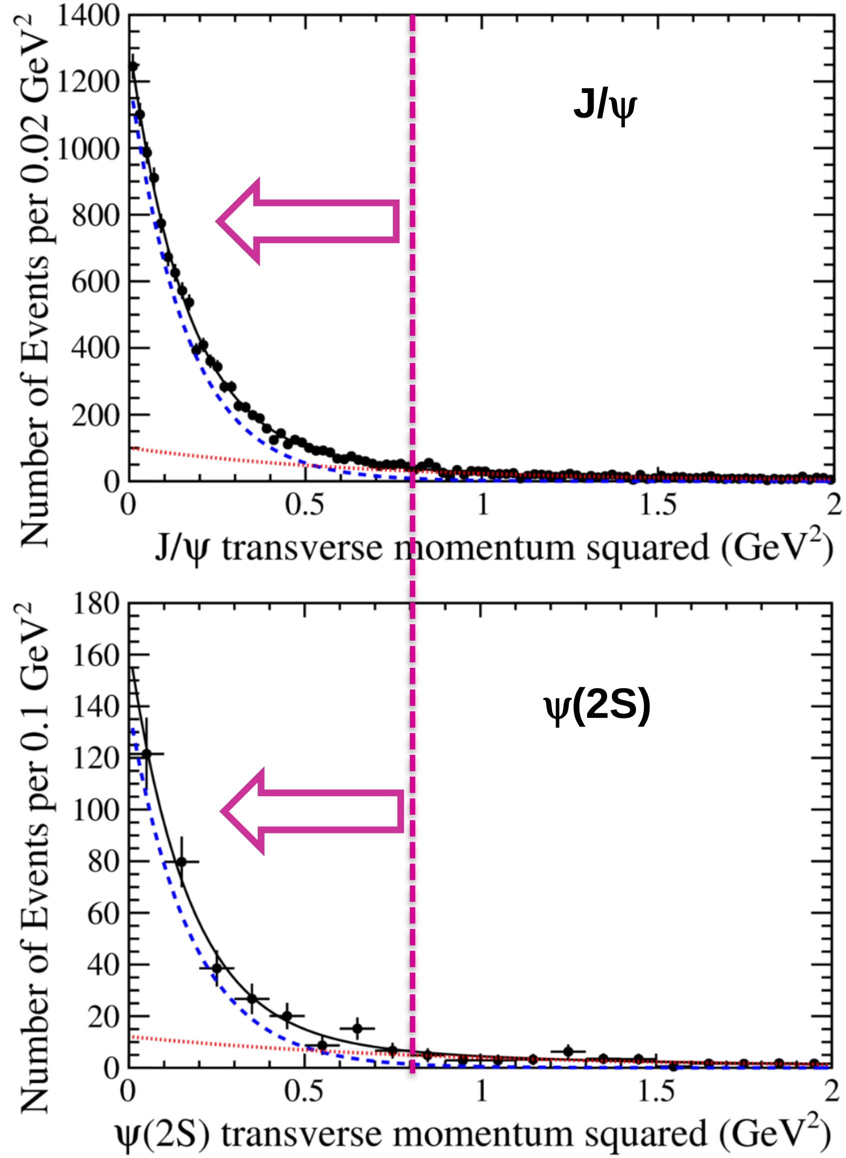
- One/two protons dissociate(s) or additional gluon radiations. Extra particles are undetected.
- P_T shape estimated from data, cross checked with PYTHIA, LPAIR



Feed-down

$\psi(2S) \to J/\psi\pi\pi$: $2.5 \pm 0.2\%$
$\chi_c \to J/\psi\gamma$ $7.6 \pm 0.9\%$
$X(3872) \to \psi(2S)\gamma$ $2.0 \pm 2.0\%$

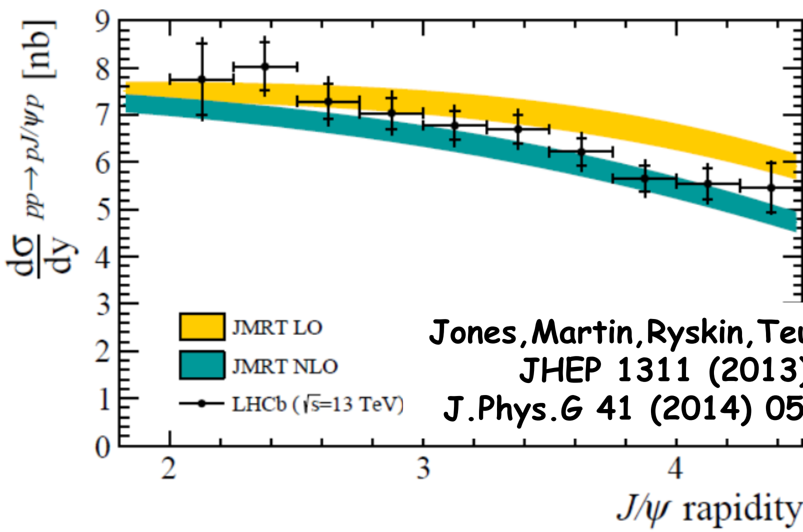
$\sqrt{s}$=13 TeV, $\int L dt$ ~0.2 fb^{-1}



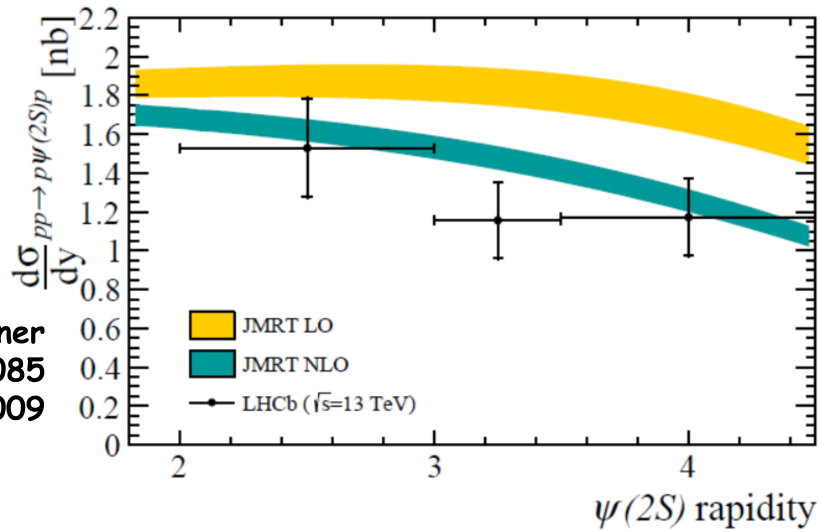
JHEP 10 (2018) 167

$\sqrt{s}$=13 TeV, $\int L dt$ ~0.2 fb^{-1}

- **Differential cross-sections** compared to theory predictions



Jones, Martin, Ryskin, Teubner
JHEP 1311 (2013) 085
J.Phys.G 41 (2014) 055009



- **Integrated cross-sections** times branching fractions

$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \pm 24 \pm 16 \text{ pb}$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 9.4 \pm 0.9 \pm 0.6 \pm 0.4 \text{ pb}$$

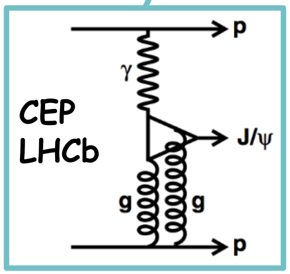
- **Good agreement with NLO predictions**
- Confirms a hint of NLO importance from the analysis at 7 TeV

JHEP 10 (2018) 167

$\sqrt{s}$=13 TeV, $\int L dt \sim 0.2\ fb^{-1}$

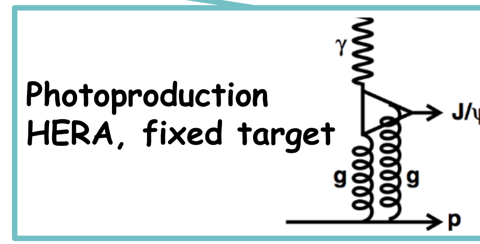
- The cross-section for the CEP of vector mesons in pp collisions is related to the **photo-production cross-section**:

$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{dn}{dk_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{dn}{dk_-}\sigma_{\gamma p\to\psi p}(W_-)$$



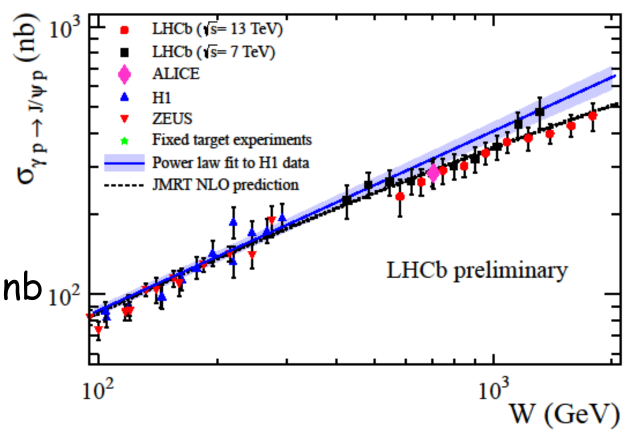
Gap survival

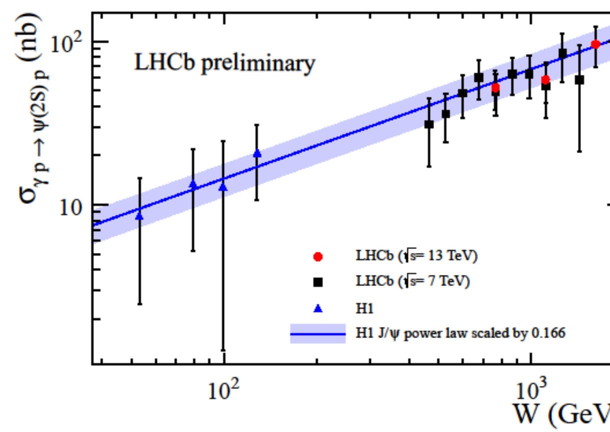
Photon flux



Jones, Martin, Ryskin, Teubner, JHEP 1311 (2013) 085, J.Phys.G 41 (2014) 055009, and update

- Compilation of photo-production cross-section measurements
- H1 measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\ GeV)^{0.67}$ nb





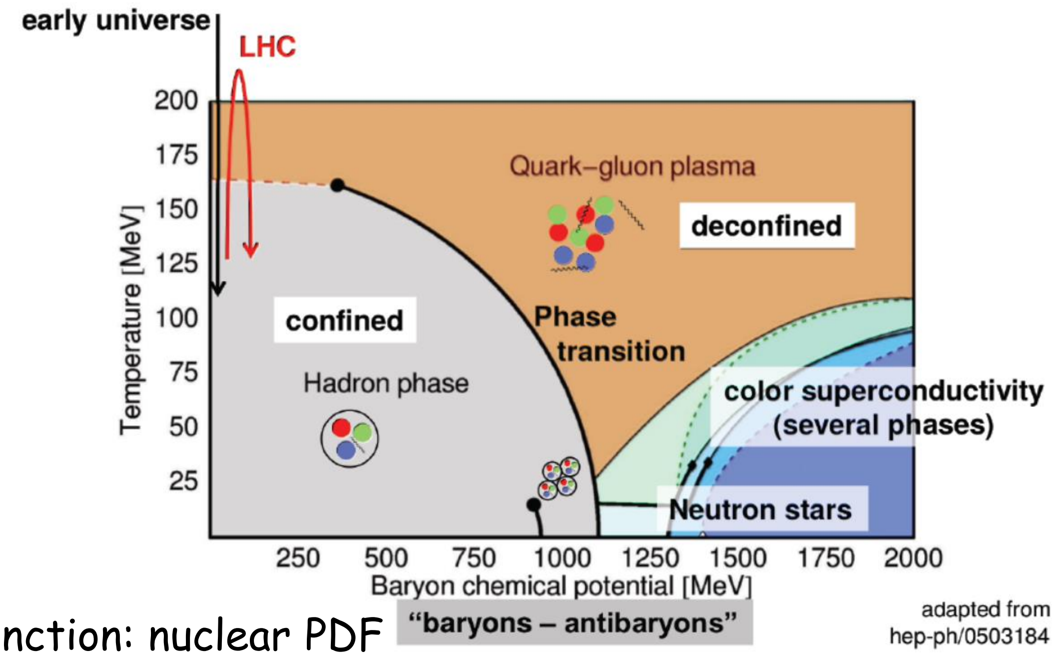
- Good agreement between LHCb results at 7 and 13 TeV
- J/ψ photo-production cross-section: **deviation from a pure power-law extrapolation of HERA data; agreement to theory prediction**

Flavours in heavy ion collisions

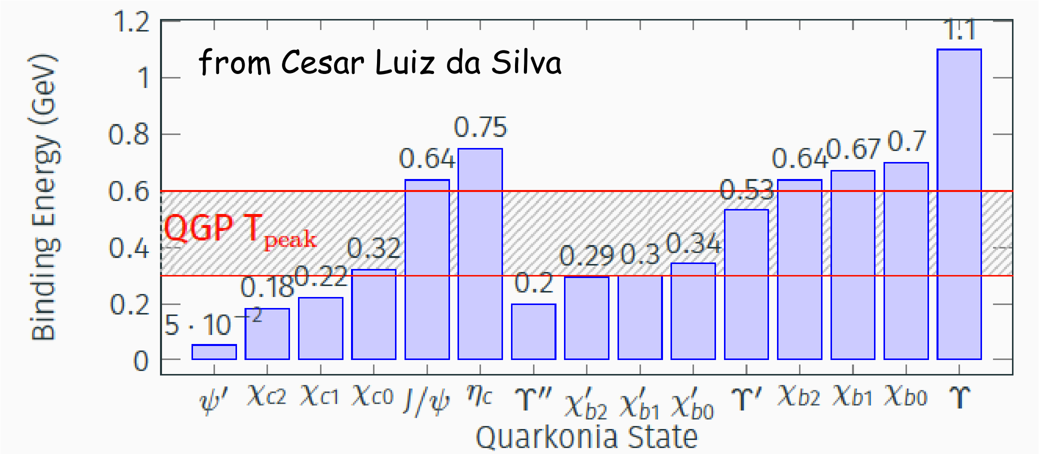
Dedicated talks at HADRON 2019

- Fate of Heavy Quark Bound States inside Quark-Gluon Plasma, Xiaojun YAO
- Quarkonia production in heavy ion collisions at LHCb, Zhenwei YANG
- Production of open heavy flavour hadrons in pPb and fixed-target collisions LHCb, Jiayin SUN

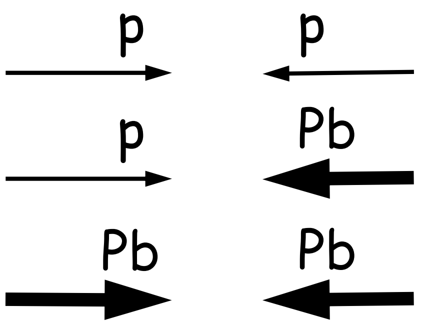
- **Suppression of heavy flavour** production in heavy ion collisions as a **signature of QGP formation**
- **Combine information from pp, pPb and PbPb collisions to distinguish QGP effects**
  - **pp**: reference, no nuclear effects
  - **pPb**: + cold nuclear matter effects
    - Modified parton distribution function: nuclear PDF
    - Absorption and coherent energy loss in nuclear matter
    - Possible formation of Color Glass Condensate
  - **PbPb**: + hot nuclear matter, possible formation of QGP
    - Quarkonium as a medium thermometer



adapted from hep-ph/0503184



- **Collision data at LHC**
  - **pp collisions** $\sqrt{s_{NN}}$ = 7, 8, 13 TeV
  - **pPb collisions** $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV
  - **PbPb collisions** $\sqrt{s_{NN}}$ = 5 TeV
  - Short XeXe run in 2017

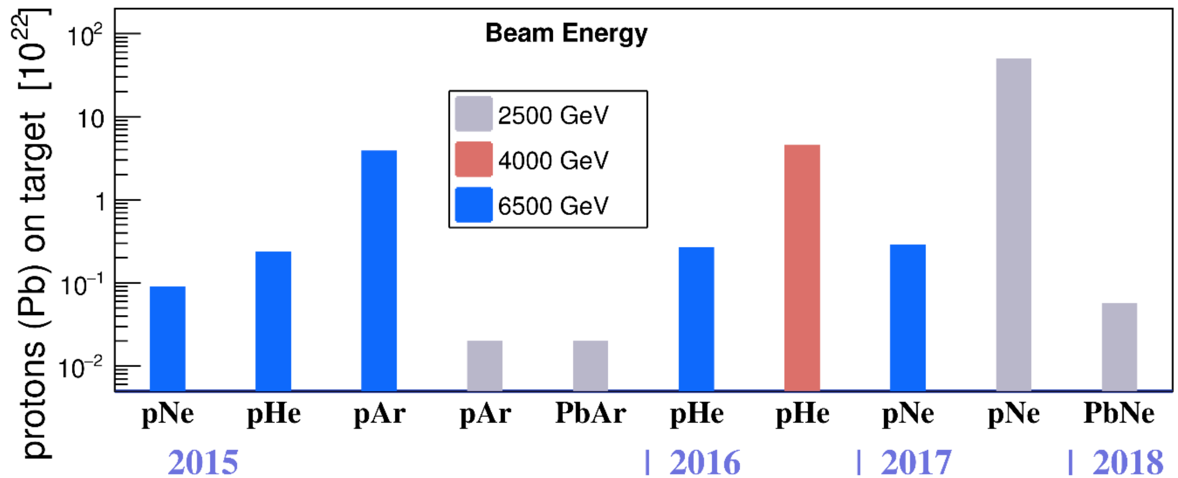


LHCb SMOG: System for Measuring Overlap with Gas

- Inject He, Ne, Ar into VELO at ~2×10^{-7} mbar
- Designed to measure beam profile
- Data taking in **fixed-target mode**

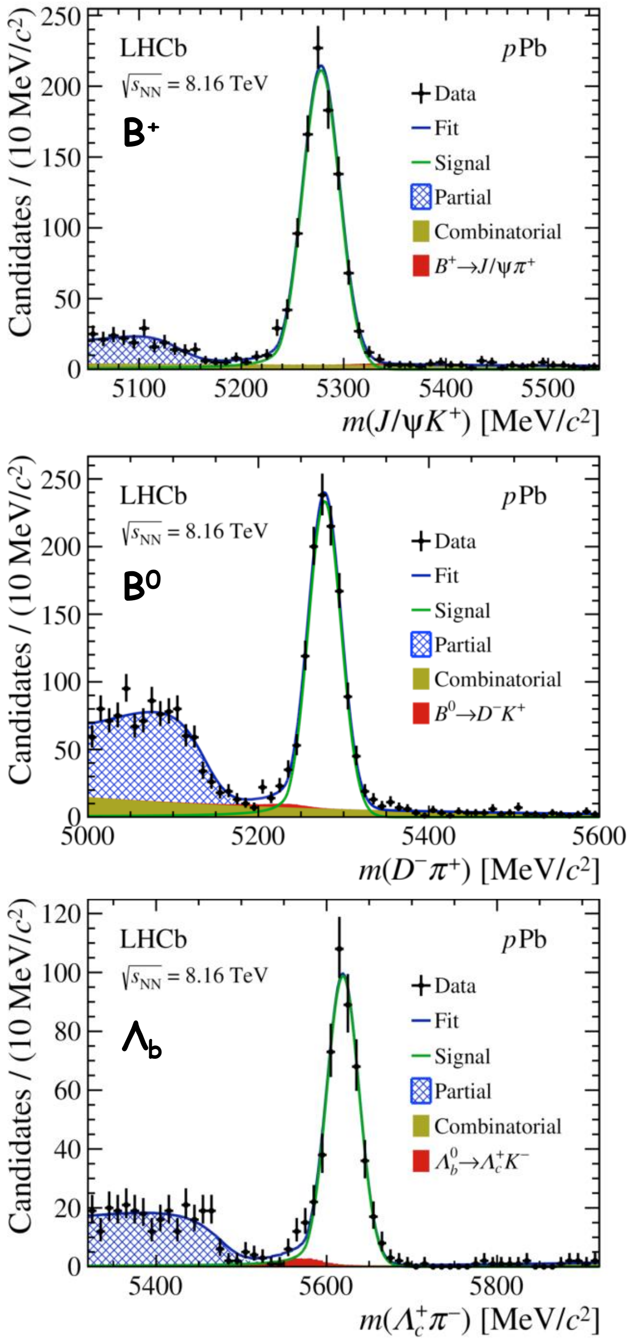
JINST 9 (2014) P12005

$\sqrt{s_{NN}}$ = 69, 110 GeV



- Measure **nuclear modification factor** R_{pA}
- Measure **forward-backward ratio** R_{FB}

$$R_{pA}(y, p_T, \sqrt{s_{NN}}) \equiv \frac{1}{A} \frac{d^2\sigma_{pA}(y, p_T, \sqrt{s_{NN}})/dy dp_T}{d^2\sigma_{pp}(y, p_T, \sqrt{s_{NN}})/dy dp_T}$$

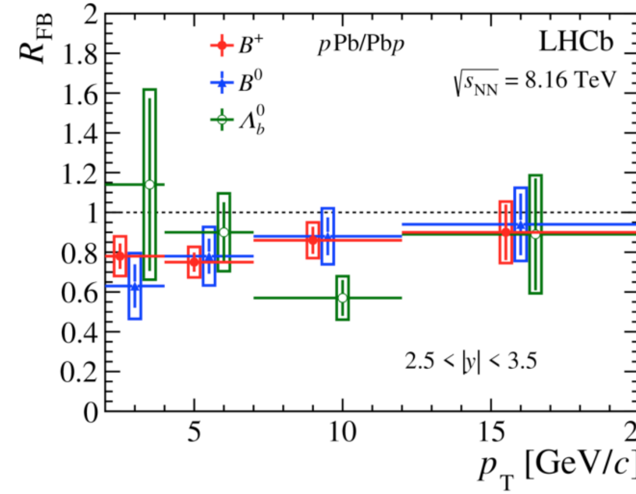


- **B^0, B^+, Λ_b hadrons**
- **Double diff. cross-sections** $d^2\sigma/dp_T dy$

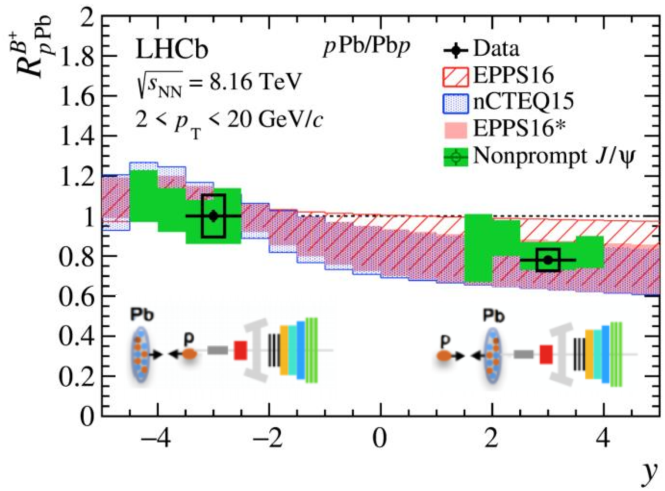
PRD 99 (2019) 052011

$\sqrt{s_{NN}}$ = 8.16 TeV, $\int Ldt$ ~ 12, 19 nb^{-1}

- Low background in invariant mass distributions



- **Nuclear effects**
- Small effects in agreement with predictions
- Similar for all analyzed b-hadrons



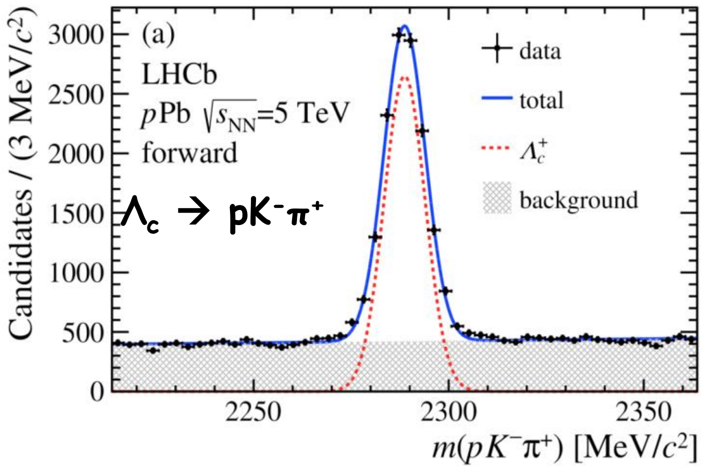
Escola et al., EPJC 77 (2017) 163
Kovarik et al., PRD 93 (2016) 085037

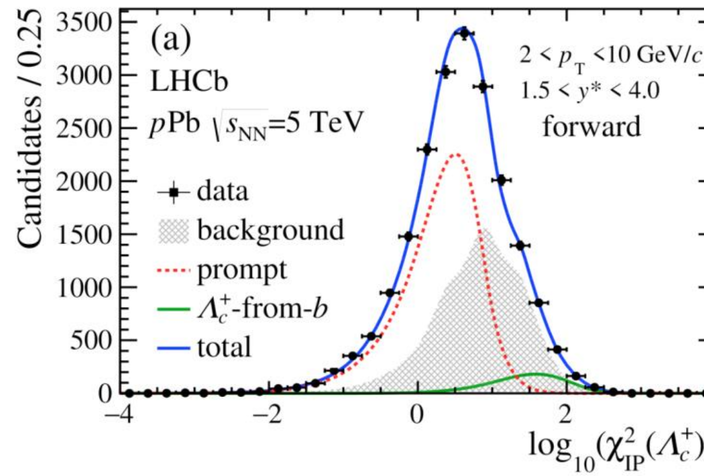
- Comparable to J/ψ from b-decays and smaller than for prompt J/ψ (as expected from $m_b > m_c$)

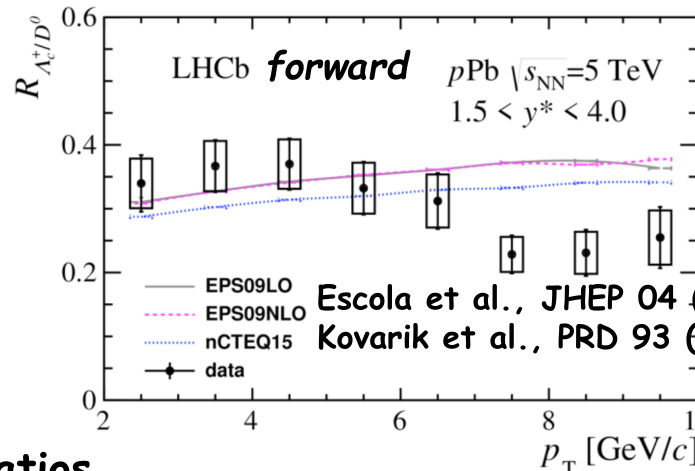
- **Double differential cross-section** in y^*, p_T, **cross-section ratios**: forward-backward, baryon-to-meson

JHEP 02 (2019) 102
$\sqrt{s_{NN}}$ = 5.02 TeV, $\int Ldt \sim 1.6\ nb^{-1}$

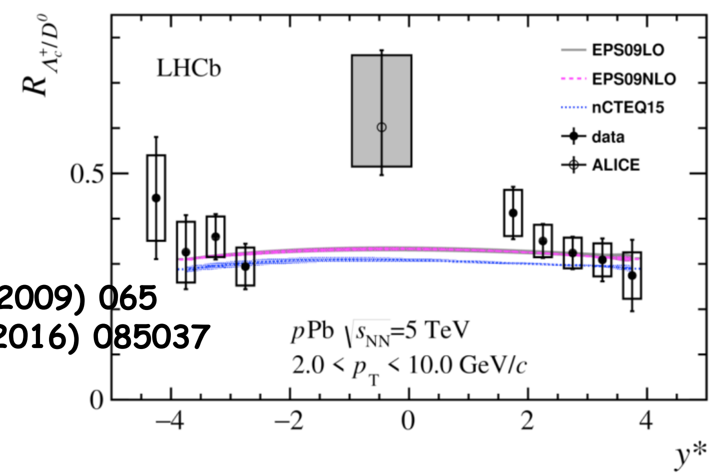
- **Prompt Λ_c** from fit of $\log(\chi^2_{IP})$ distribution: difference in χ^2 when fitting primary vertex with and without Λ_c candidate
- Combinatorial background measured in sidebands







Escola et al., JHEP 04 (2009) 065
Kovarik et al., PRD 93 (2016) 085037

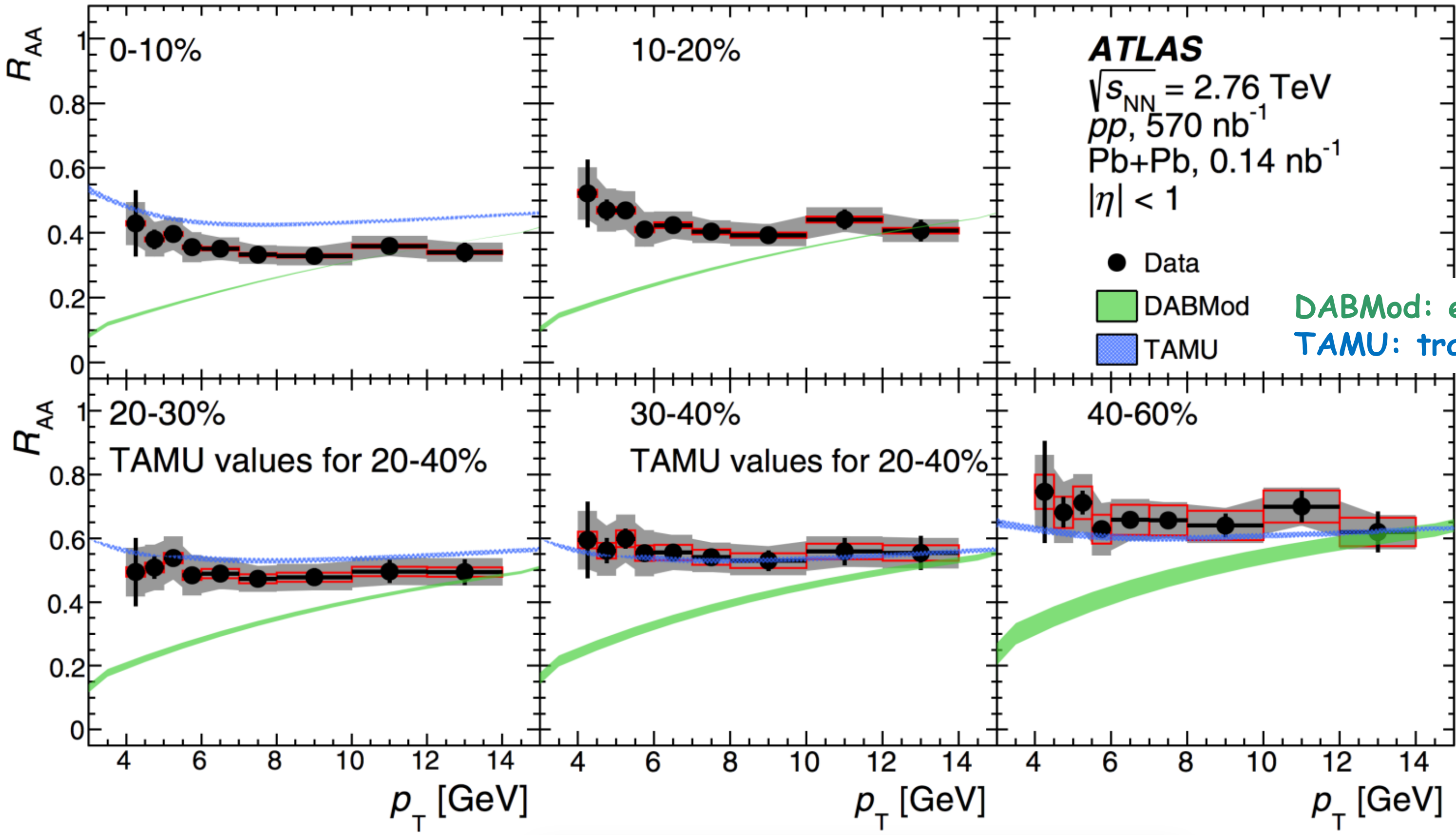


- FB ratios consistent with predictions
- **Baryon-to-meson ratios**
  - At forward rapidity lower than predictions at $p_T > 7$ GeV/c
  - ALICE + LHCb suggest more peaked shape at mid-rapidity

Heavy flavour semileptonic decays in PbPb collisions

- **Suppression of muons from heavy-flavor decays**
- Centrality intervals 0-10%, 10-20%, 20-30%, 30-40%, 40-60%

PRC 98 (2018) 044905
$\sqrt{s_{NN}}$ = 2.76 TeV, $\int Ldt \sim 0.14\ nb^{-1}$



DABMod: energy loss model
TAMU: transport model

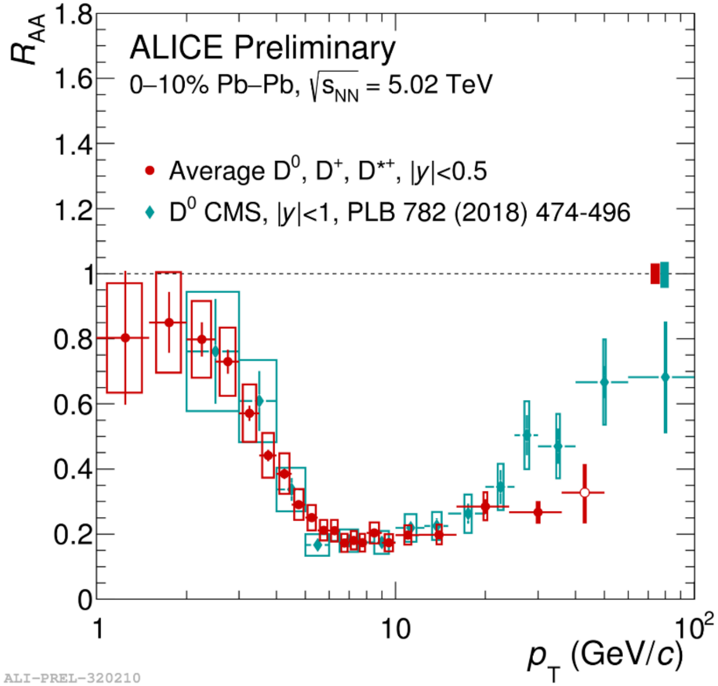
- Nuclear modification factor R_{AA} independent of p_T; less than unity i.e. **suppressed production of heavy-flavor muons in PbPb collisions**

D-meson production in PbPb collisions

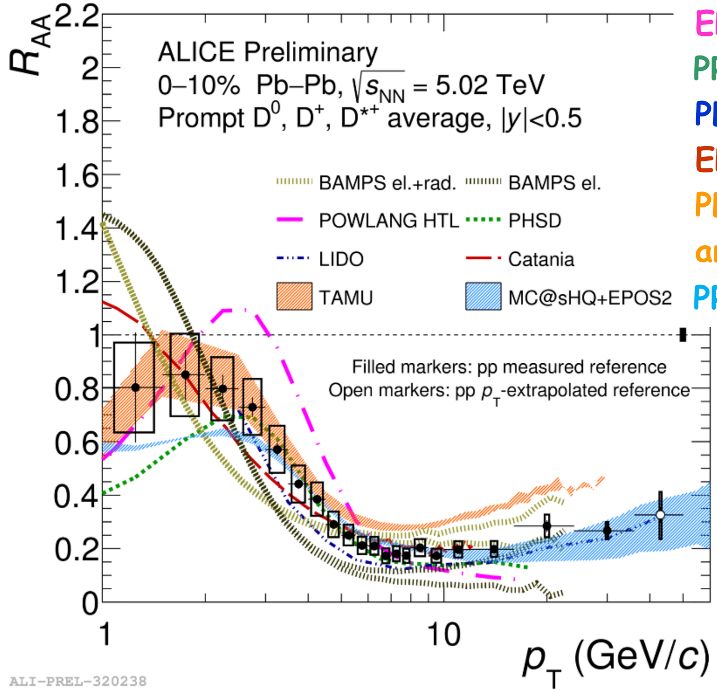
ALICE

Preliminary result
$\sqrt{s_{NN}}$ = 5.02 TeV

- ❑ New measurement of D^0, D^+, D_s and D^{*+} production
- ❑ 2018 data sample, reduced uncertainties, better constrain **low-p_T range**



- ❑ ALICE and CMS results compatible in the common p_T range
- ❑ Progress towards determination of total $c\bar{c}$ cross section



JPG 42 (2016) 115106
EPJC 75 (2015) 121
PRC 92 (2015) 014910
PLB 777 (2018) 255
EPJC 78 (2018) 348
PLB 735 (2014) 445
arXiv:1905.09216
PRC 89 (2014) 014905

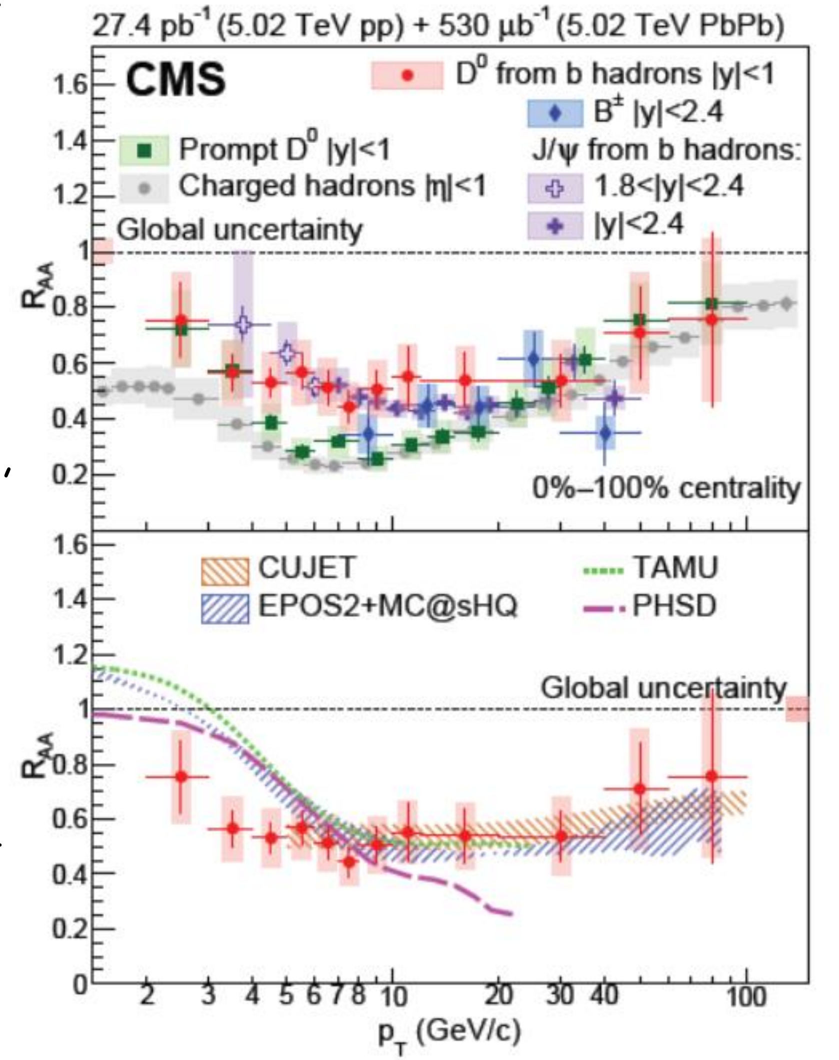
- ❑ Description of charm-interaction and diffusion in the medium at low p_T
- ❑ **Interplay of CNM (shadowing), collisional and radiative energy loss, coalescence and realistic medium evolution required to describe data**

Beauty suppression via D^0 mesons from b-decays in PbPb collisions

- Inclusive **B → D^0X** transitions followed by $D^0 \to K\pi$

PRL 123 (2019) 022001
$\sqrt{s_{NN}}$ = 5.02 TeV, $\int Ldt \sim 0.53\ nb^{-1}$

- Distinguish between D^0 from b-decays and prompt D^0 via closest approach of D^0 path to the collision vertex
- Spectrum in pp collisions is close to the UL of a FONLL pQCD
- In PbPb collisions B → D^0X rate is suppressed in 2 < p_T < 100 GeV
- **R_{AA} is higher for B → D^0X than for prompt D^0 mesons or charged hadrons around 10 GeV/c**, in line with quark mass ordering of suppression
- **At low p_T, stronger R_{AA} suppression than from models**. Could indicate stronger energy loss of b quarks in QGP than predicted, or enhanced b-baryon production due to quark coalescence in PbPb collisions



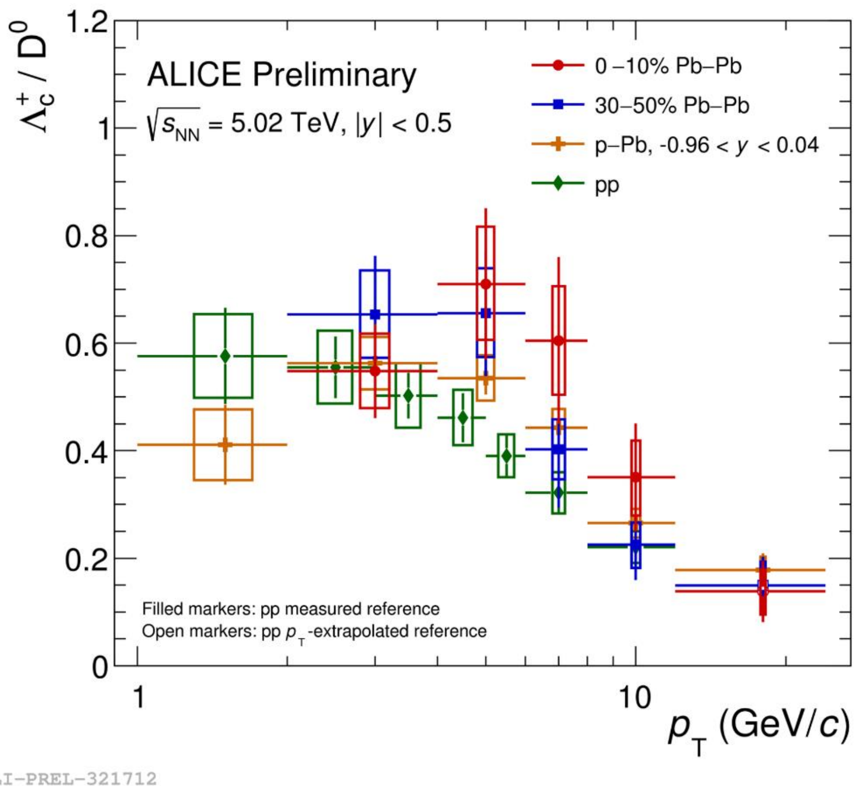
Λ_c production in PbPb collisions

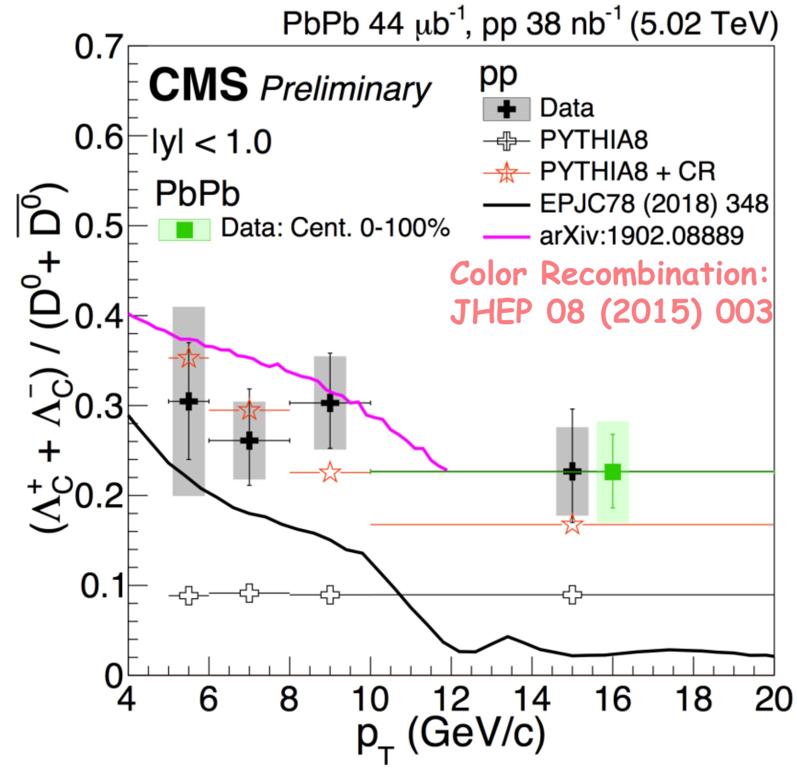
ALICE | CMS

Preliminary result | arXiv:1906.03322

$\sqrt{s_{NN}}$ = 5 TeV, $\int Ldt \sim 1.6\ nb^{-1}$ | $\sqrt{s_{NN}}$ = 5 TeV, $\int Ldt \sim 44\ \mu b^{-1}$

- **Coalescence contribution** to baryon production is expected to be more significant than for mesons
- p_T dependent enhancement predicted for the Λ_c/D^0 production ratio





- **ALICE result described by the model including both coalescence and fragmentation**
- **No significant role of coalescence seen by CMS at larger p_T**

EPJC 78 (2018) 348

Heavy flavour flow harmonics

PRC 98 (2018) 044905

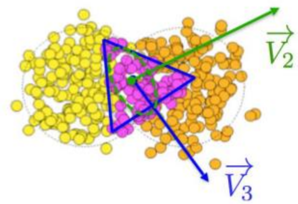
$\sqrt{s_{NN}}$ = 2.76 TeV, $\int Ldt \sim 0.14\ nb^{-1}$

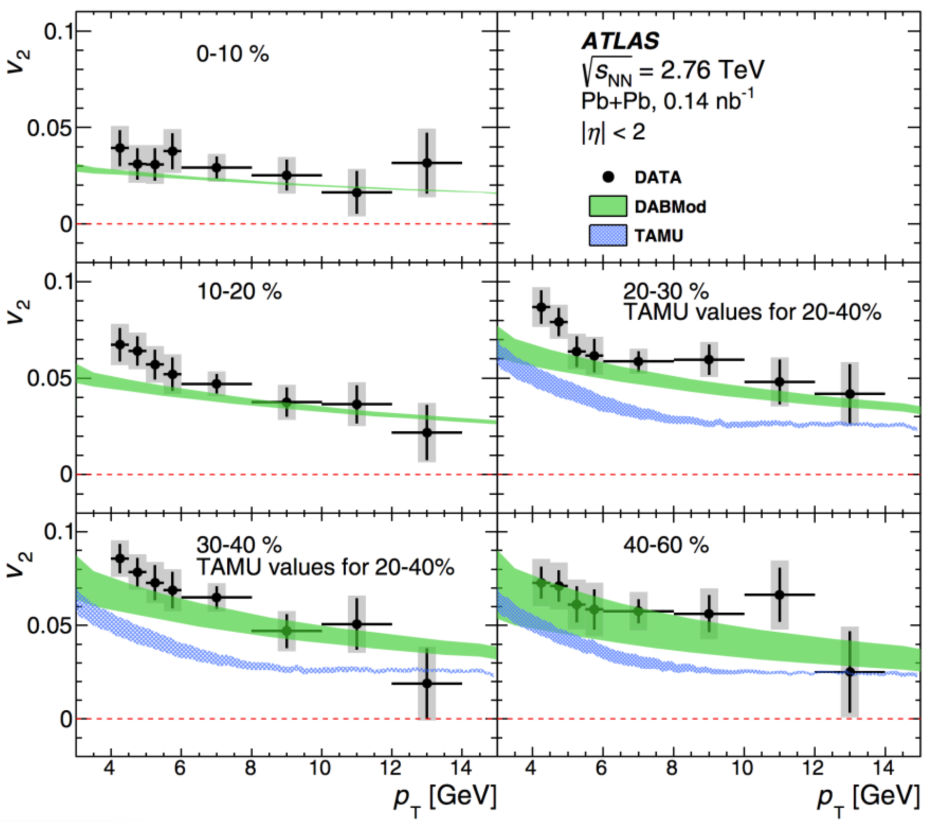
- **Azimuthal anisotropy** of particles produced in PbPb collisions characterized by harmonic coefficients in Fourrier expansion:

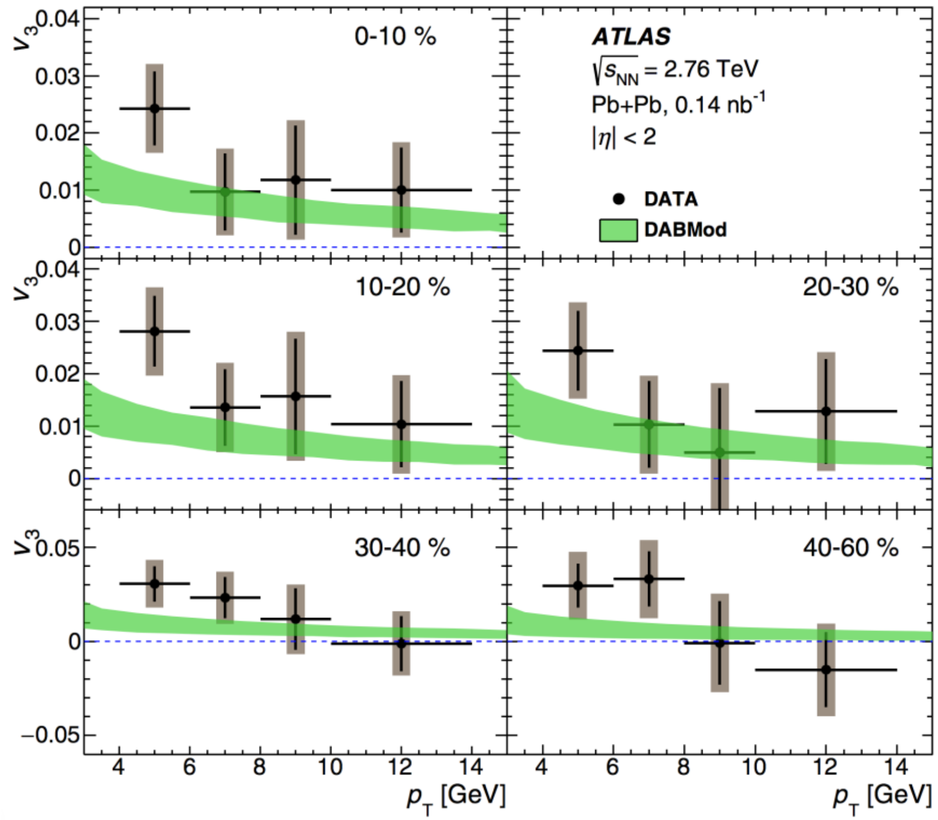
$$v_n = \langle \cos(n(\varphi-\psi_n)) \rangle$$

particle momentum azimuthal angle

azimuthal angle of particle momentum relative to the symmetry plane







- Stronger centrality dependence for v_2 than for v_3
- **Qualitative description of v_2 and v_3 p_T dependence**, DABMod more consistent
- Models still unable to describe HF suppression and flow simultaneously

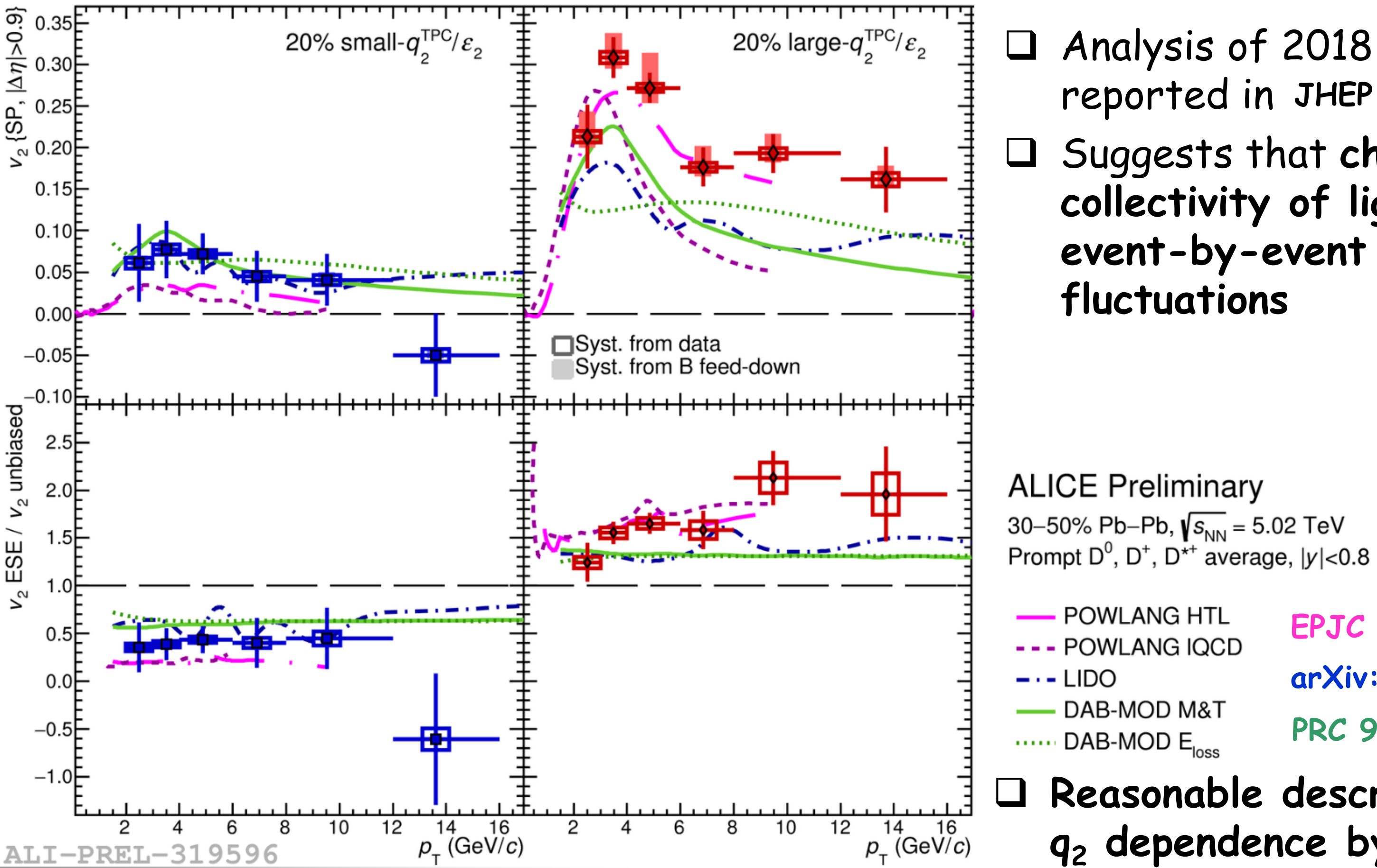
Event shape engineering with D mesons

Preliminary result

❑ Event shape engineering (ESE) investigates the **dynamics of HQ in medium**, $\sqrt{s_{NN}}$ = 5.02 TeV based on observation of large v_n event-by-event variation at fixed collision centrality

❑ Clear difference of D-meson v_2 in events with small and large second-order reduced flow-vector q_2

$$q_2 = |Q_2|/\sqrt{M}, \quad Q_2 = \begin{pmatrix} \sum_{i=1}^{M}\cos(2\varphi_i) \\ \sum_{i=1}^{M}\sin(2\varphi_i) \end{pmatrix}$$



❑ Analysis of 2018 data clarifies effect reported in JHEP 02 (2019) 150

❑ Suggests that **charm is sensitive to collectivity of light-hadron bulk and event-by-event initial-conditions fluctuations**

EPJC 75 (2015) 121

arXiv:1810.08177

PRC 96 (2017) 064903

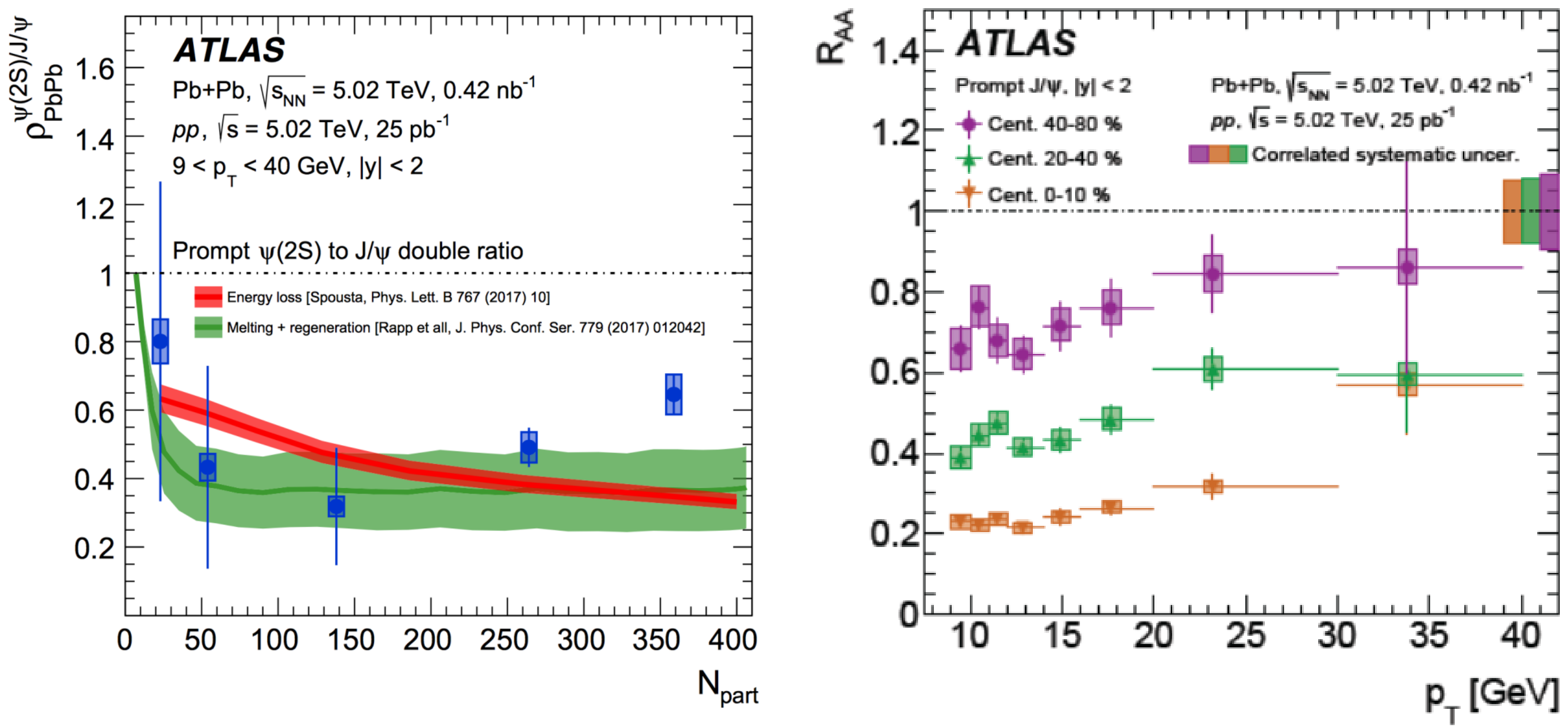
❑ **Reasonable description of elliptic flow q_2 dependence by transport models**

Charmonia breaking in PbPb collisions

- Production of **prompt** and **non-prompt charmonia** in PbPb collisions

EPJC 78 (2018) 762
$\sqrt{s_{NN}}$ = 5.02 TeV, ∫Ldt ~ 0.42 nb^{-1}

- **Production double-ratio** and **nuclear modification factor** R_{AA} for prompt J/ψ



- **Suppression of ψs in PbPb collisions increasing with event centrality**
- **ψ(2S) additional breaking** in p_T region where coalescence may not be important
- Same suppression of non-prompt J/ψ and ψ(2S), consistent with arising from b-quarks propagating through medium
- Confirm previous results of ALICE and CMS

JHEP 11 (2018) 194

$\sqrt{s_{NN}}$ = 8.16 TeV, $\int L dt$ ~ 7.6 nb^{-1}

- **Double diff. cross-sections** $d^2\sigma/dp_T dy$ **for Υ(1S) and Υ(2S), integral for Υ(3S)**

- **Nuclear modification R enhanced at low p_T**
- Agreement with HELAC-Onia predictions at high p_T

- Suppression factor

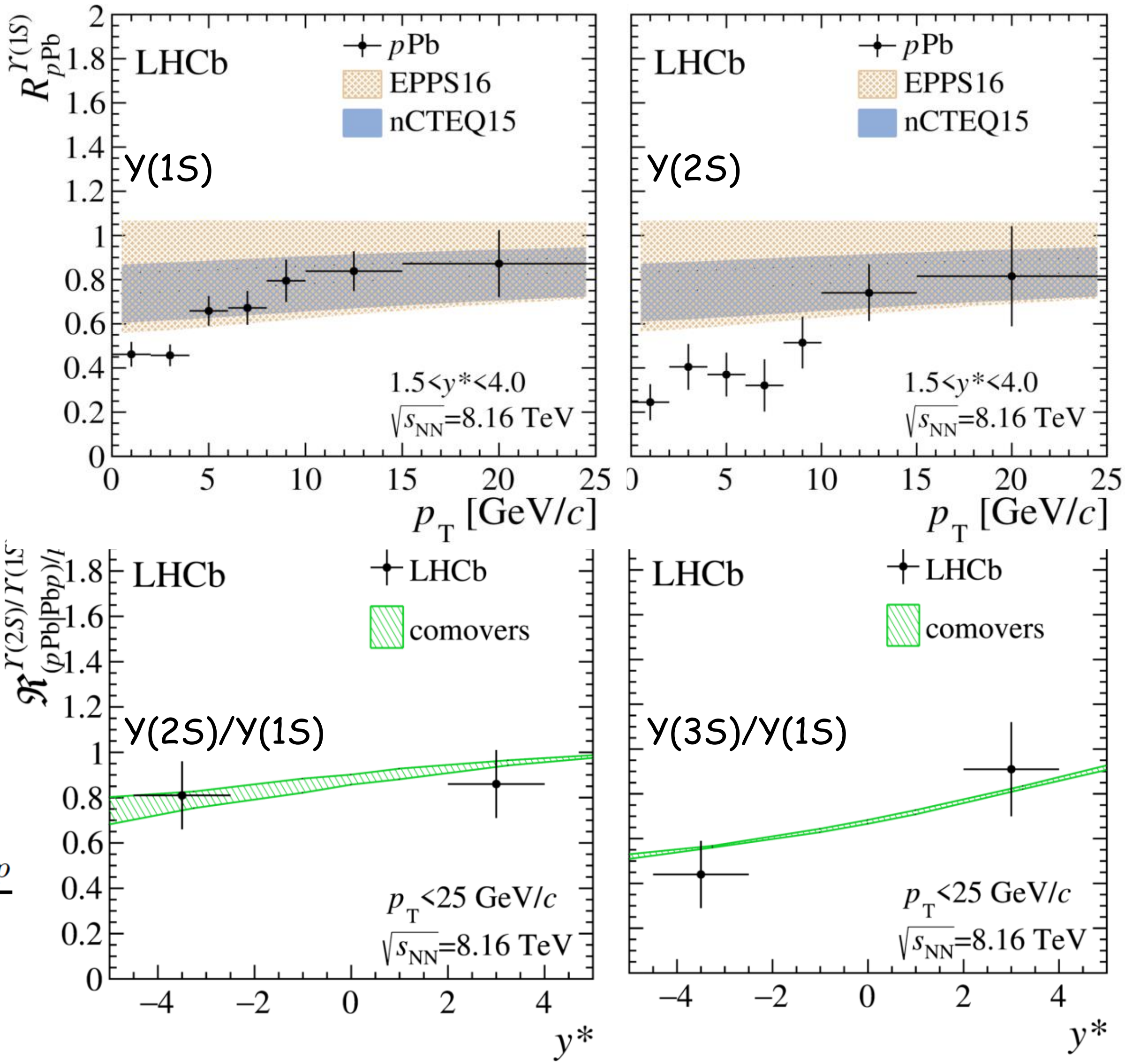
$$R(\Upsilon(nS)) = \frac{[d^2\sigma/dp_T dy^*](\Upsilon(nS))}{[d^2\sigma/dp_T dy^*](\Upsilon(1S))}$$

- **Suppression of n > 1 states** in agreement with predictions and previous measurements
- Stronger suppression at low p_T

- **Nuclear modification of suppression factor**

$$\Re^{\Upsilon(nS)/\Upsilon(1S)}_{(pPb|Pbp)/pp} = \frac{R(\Upsilon(nS))_{pPb|Pbp}}{R(\Upsilon(nS))_{pp}}$$

- Enhanced suppression of Υ(3S) in pPb compared to pp at negative rapidity

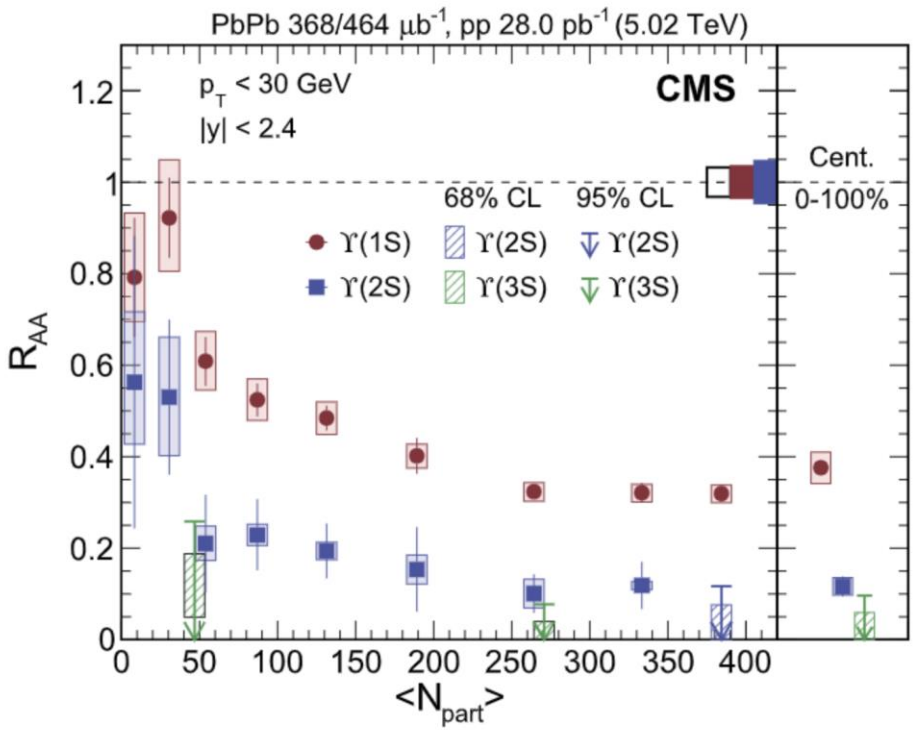


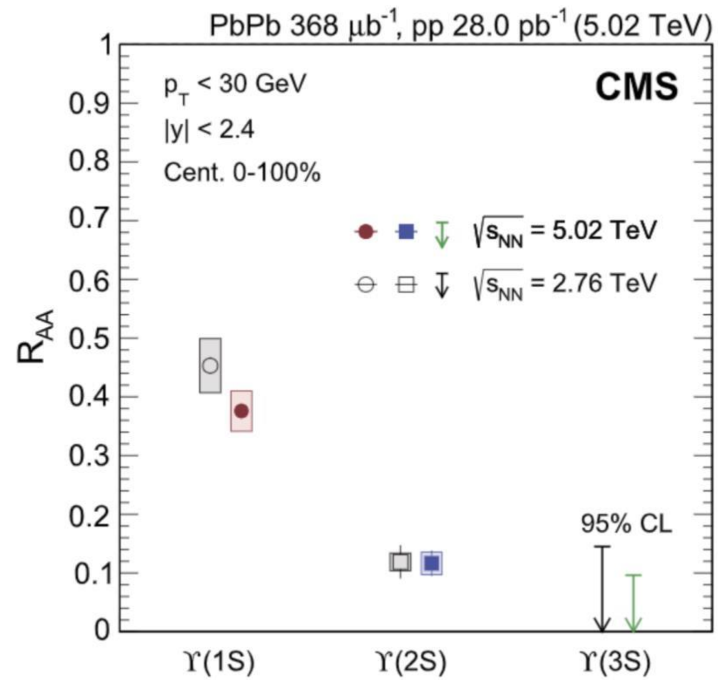
Υ(nS) nuclear modification in PbPb collisions

PLB 790 (2019) 270

$\sqrt{s_{NN}}$ = 5.02 TeV, ∫Ldt ~ 368, 464 μb^{-1}

- New result for **nuclear modification factor** R_{AA} for Υ(nS) states

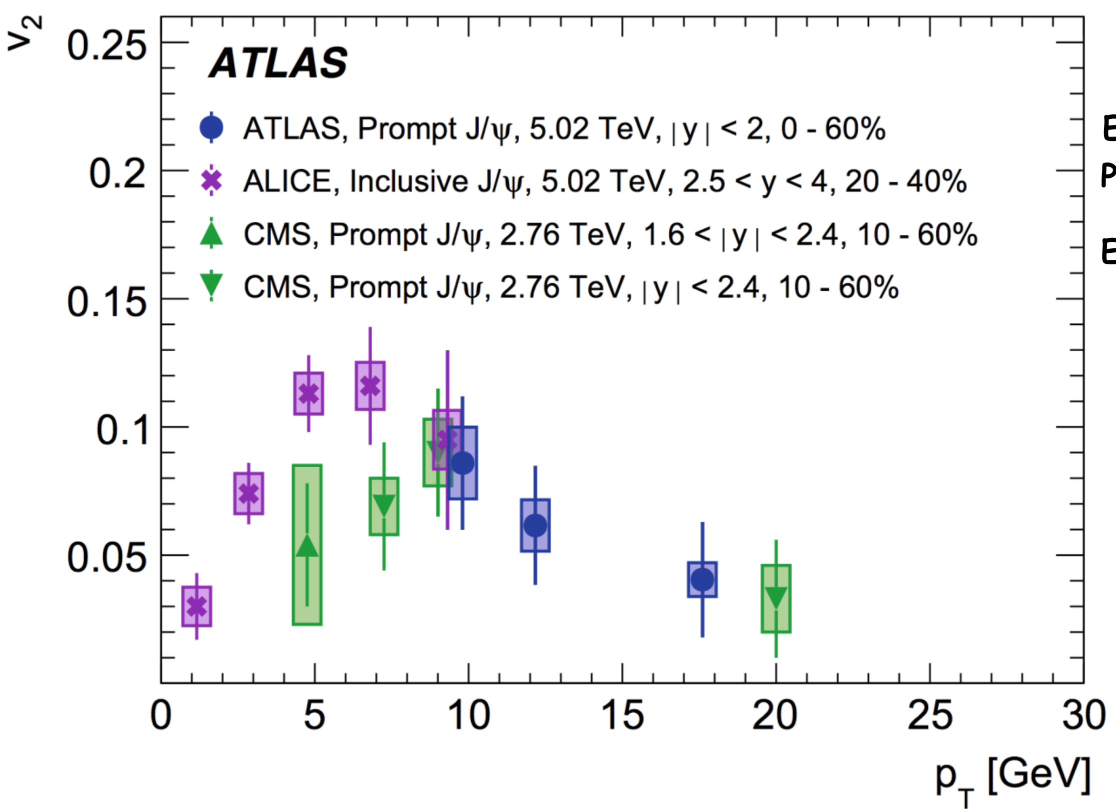




- **All three Υ(nS) states suppressed** with sequential suppression ordering R_{AA} (Υ(1S)) > R_{AA} (Υ(2S)) > R_{AA} (Υ(3S))
- Strongest upper limit on R_{AA} (Υ(3S)) integrated over p_T, rapidity and centrality
- **Consistent with the result at $\sqrt{s_{NN}}$ = 2.76 TeV**

J/ψ elliptic flow in PbPb collisions

- **Elliptic flow of prompt and non-prompt J/ψ** covering wide p_T region



EPJC 78 (2018) 784
PRL 119 (2017) 242301
EPJC 77 (2017) 252

- **Hydrodynamic peak** is observed around 7 GeV, flow attributed to charmonium coalescence/recombination

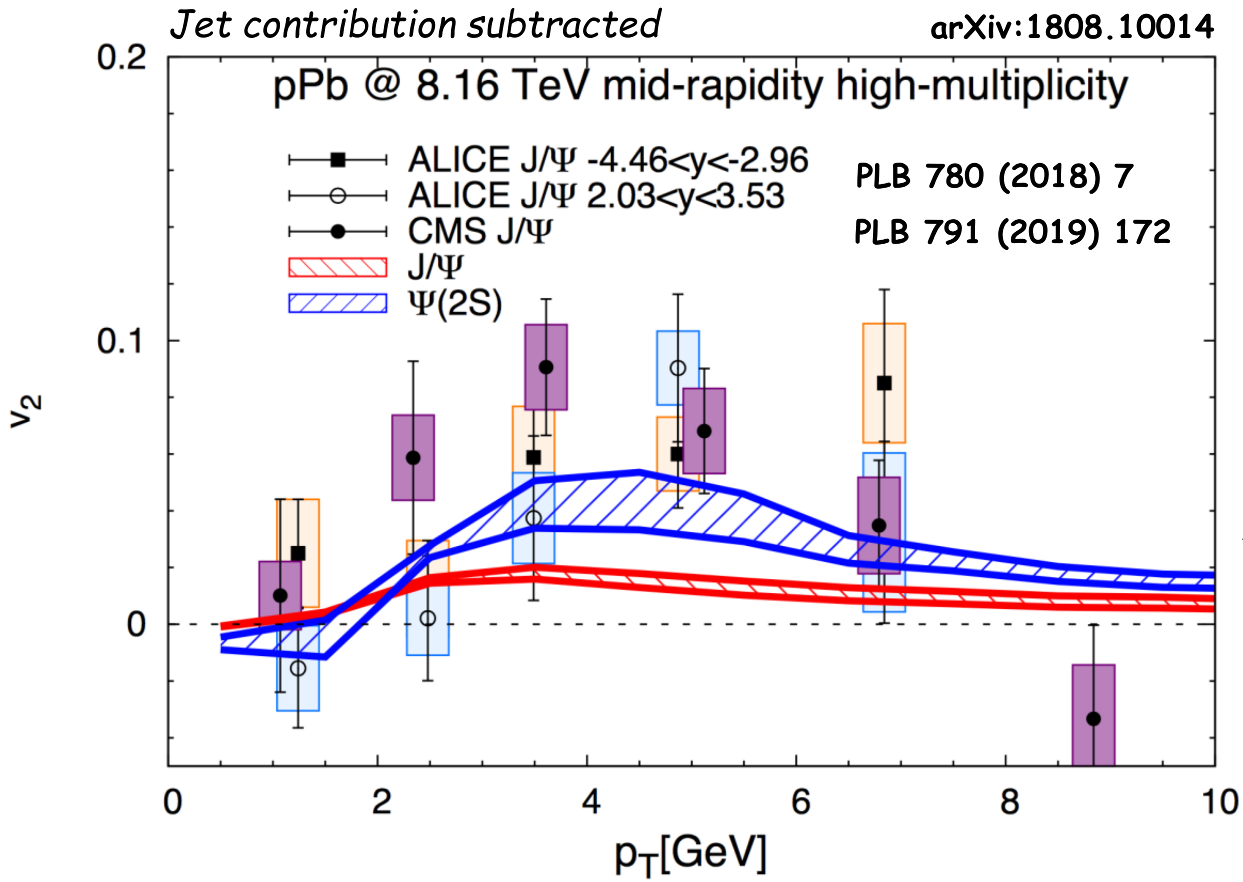
Zhou et al., PRC 89 (2014) 054911
Yan et al., PRL 97 (2006) 232301

- **Substantial v_2 at high p_T**, suppression of J/ψ due to absorption and melting or energy loss

Kopeliovich et al., PRC 91 (2015) 024911
Arleo, PRL 119 (2017) 062302
Spousta, PLB 767 (2017) 10

J/ψ elliptic flow in pPb collisions

- Charmonium **elliptic flow in pPb collisions**



ALICE
$\sqrt{s_{NN}}$ = 5.02 TeV, $\int Ldt$ ~ 8.1, 5.8 nb^{-1}
$\sqrt{s_{NN}}$ = 8.16 TeV, $\int Ldt$ ~ 8.7, 12.9 nb^{-1}

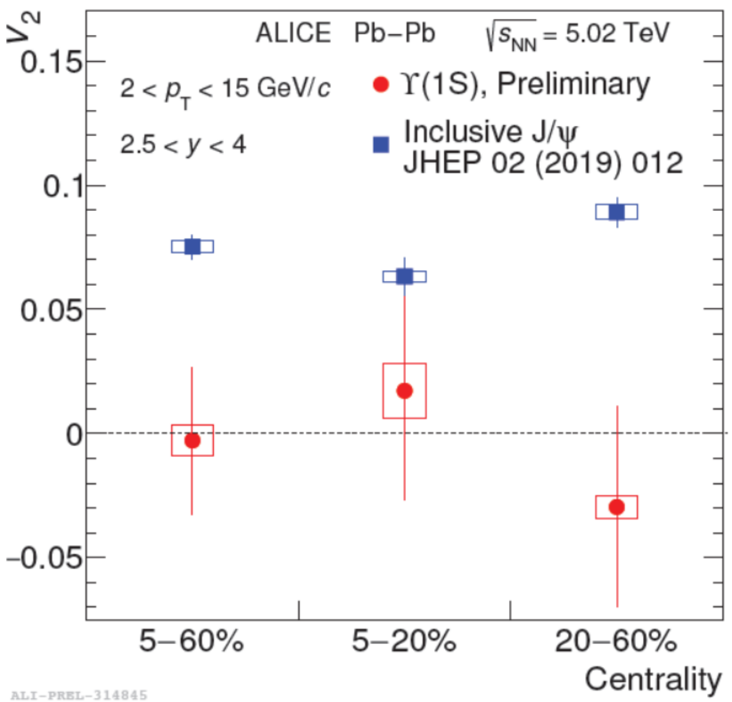
CMS
$\sqrt{s_{NN}}$ = 8.16 TeV, $\int Ldt$ ~ 186 nb^{-1}

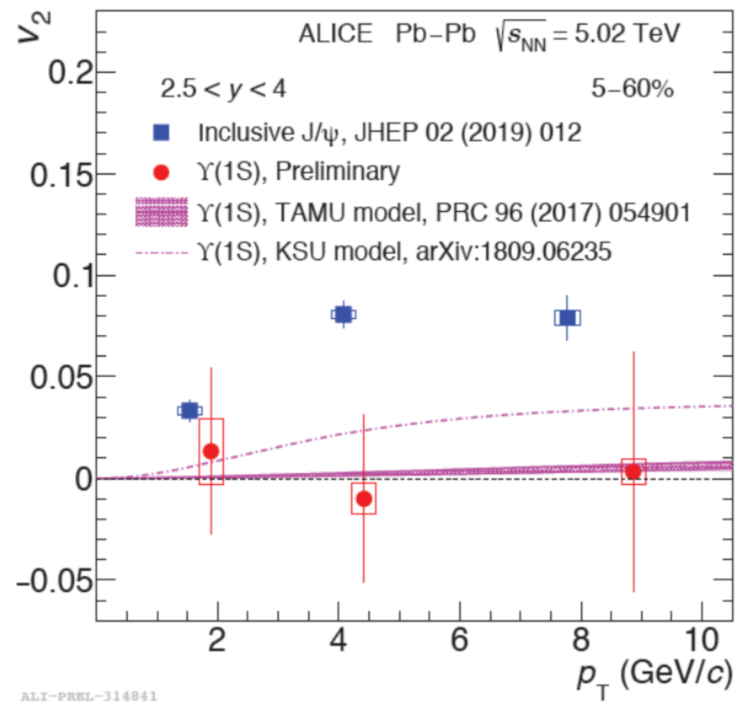
- Coalescence in small systems ?
- The model describing J/ψ R_{pA} using transport in medium cannot describe v_2
- Challenge for hydrodynamics descriptions

Υ(1S) elliptic flow in PbPb collisions

Preliminary result
$\sqrt{s_{NN}}$ = 5.02 TeV

- First measurement of **Υ(1S) elliptic flow at forward rapidity in PbPb collisions** (2015+2018 datasets)





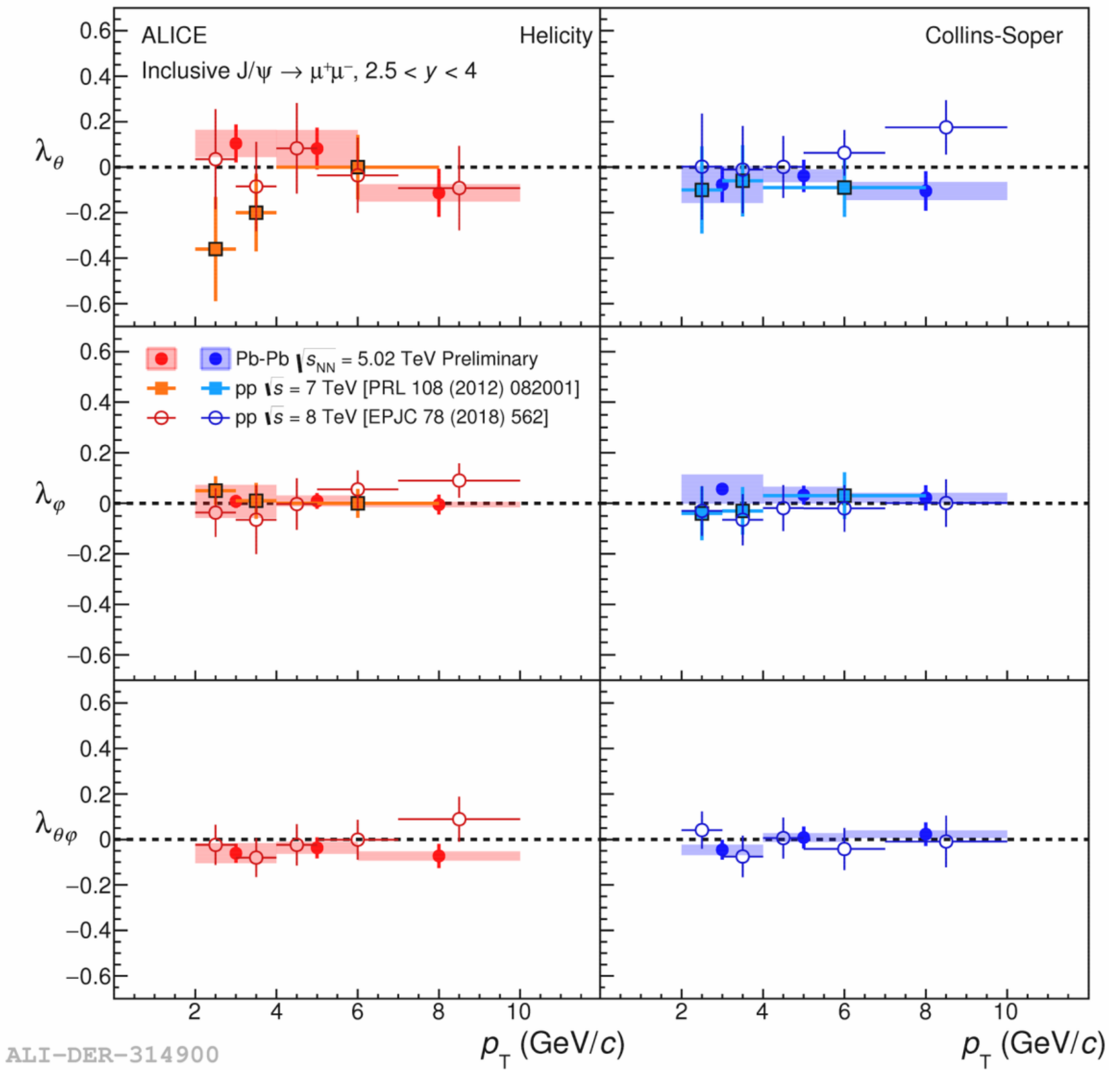
- **Υ(1S) v_2 compatible with zero or with small positive values** predicted by theory
  - KSU: path-length dependence of dissociation of initially created bottomonia
  - TAMU: includes also possible formation via recombination
- Indication of v_2 lower than that of inclusive J/ψ in $3 < p_T < 15$ GeV/c

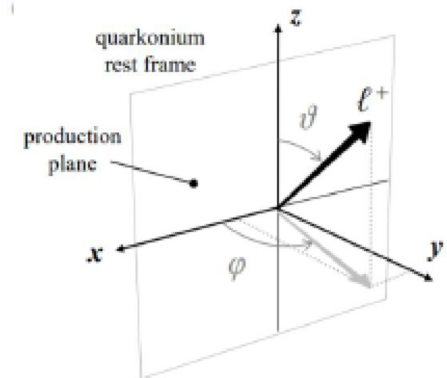
Υ(1S) elliptic flow in PbPb collisions

Preliminary result
$\sqrt{s_{NN}}$ = 5.02 TeV

- **First measurement of J/ψ polarisation in AA collisions at colliders**

$$W(\cos\vartheta,\varphi) \propto \frac{1}{3+\lambda_\vartheta} \cdot \left(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi\right)$$





- 2015 data
- **Compatible with zero and with pp-collision data** in both Helicity and Collin-Soper frames
- Possible future studies with different polarisation axes to probe potential effects from vorticity and EM field

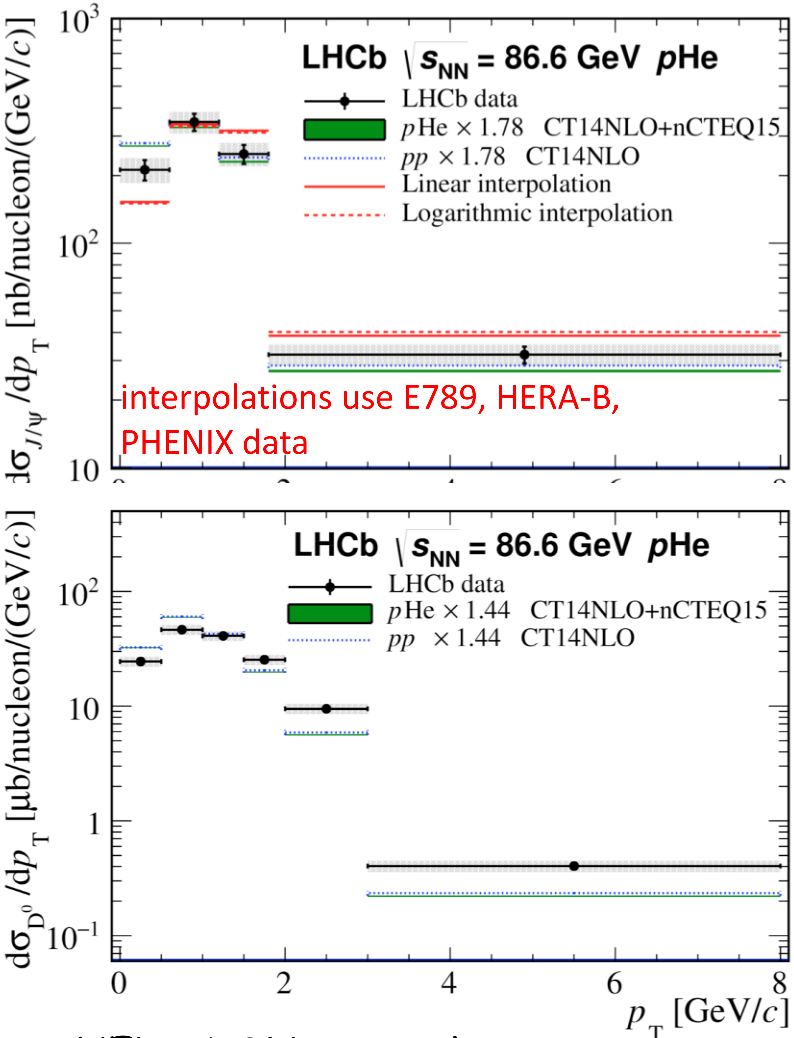
J/ψ and D^0 production in p(Ar,He) collisions

- First measurement of charm production in fixed-target mode

PRL 122 (2019) 132002

pHe: $\sqrt{s_{NN}}$ = 87 GeV, $\int Ldt$ ~ 7.6 nb^{-1}

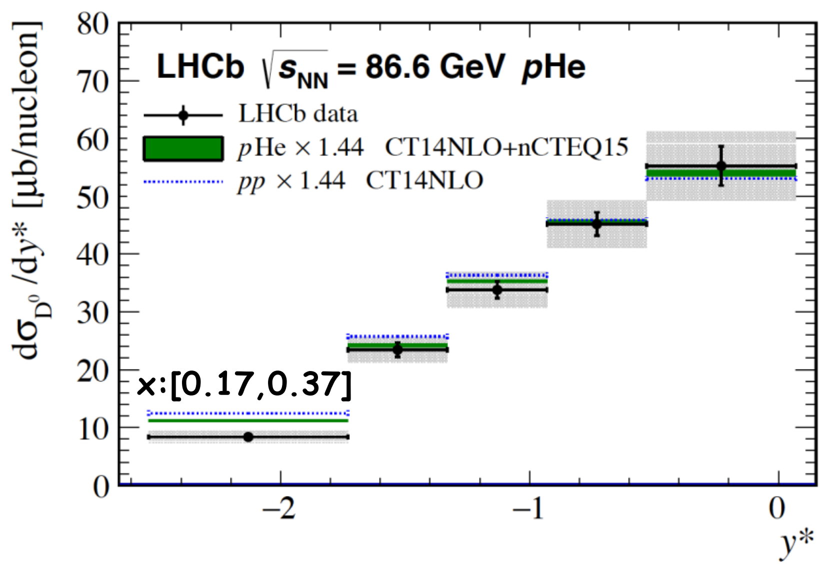
- **pAr**(gas) and **pHe**(gas) collisions



- HELAC-ONIA predictions differ in amplitude and shape

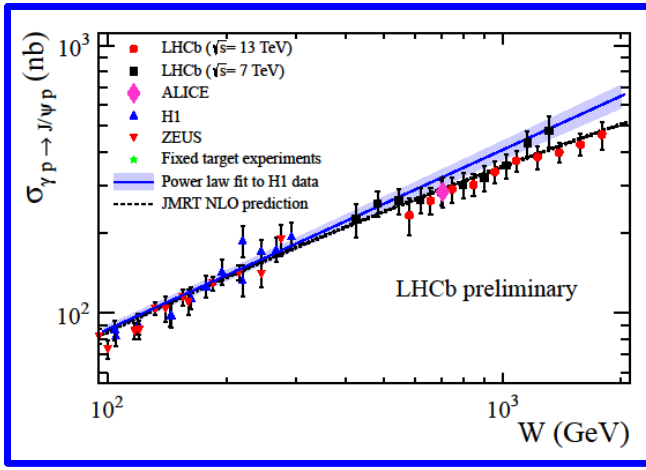
- Substantial intrinsic valence-like charm content of the nucleon expected in
  Pumplin, Lai, Tung, PRD 75 (2007) 054029;
  Dulat et al., PRD 89 (2015) 073004

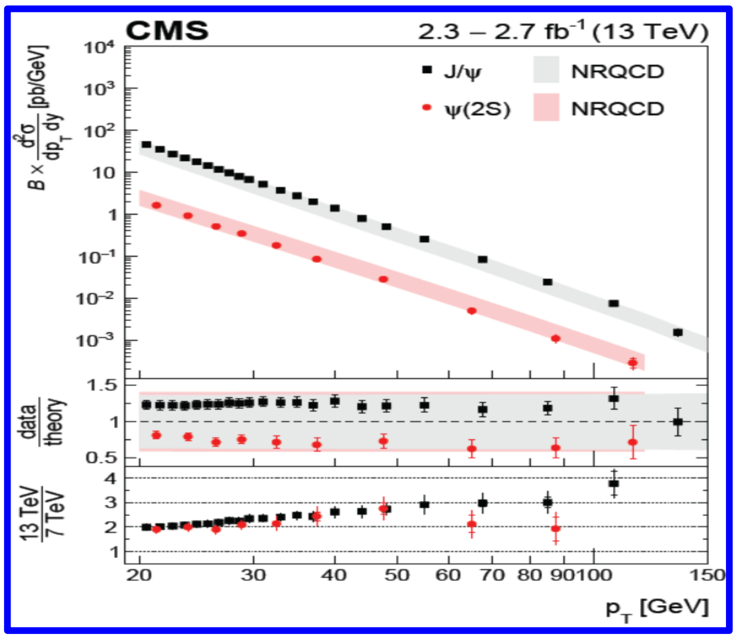
- Would contribute at large x and could be visible in most backward bin of pHe data



- Data agree with predictions without any intrinsic valence-like charm contribution
- No evidence of substantial intrinsic charm content of the nucleon

- Thanks to excellent LHC machine and LHC experiments operation, **many new results on HF production**
- New results on **quarkonia and open flavour production** aiming at a comprehensive model capable to provide a simultaneous description of observables for all measured states and production sources in the entire p_T range





- **Theory/experiment** agreement made great progress since Tevatron days
- FONLL describes b-hadron production reasonably well, with caveats; prompt charmonia still puzzle
- Specific processes allowing a clean interpretation

- Rapidly developing physics of **heavy flavor production in heavy ion collisions**
- Yet another **effort needed in both theory and experiment to establish a consistent picture of HF production**