NEW MEASUREMENTS IN THE QUARKONIA SECTOR

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on behalf of the ALICE, ATLAS, CMS and **LHCb** Collaborations

LHCP

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MODELS OF QUARKONIUM PRODUCTION

- **Sources of quarkonium:**
  - prompt hadroproduction
  - decays of higher resonances
  - production in b-hadron decays (for charmonium)

  } prompt production

  } distinguished via pseudo-proper decay time $t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$

- **No consensus on the quarkonium production mechanism**
- Nearly all approaches assume **factorisation** between the **$Q\bar{Q}$ formation** and its **hadronization** into a meson
- Essential difference in various approaches is in the **description of the hadronization:**
  - **Colour evaporation model (CEM):** application of quark-hadron duality; only the invariant mass matters;
  - **Colour-singlet model (CS)**: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} as the final-state quarkonium;
  - **Colour-octet model (CO)** (encapsulated in NRQCD): all viable colours and J^{PC} allowed for the intermediate $Q\bar{Q}$ state;

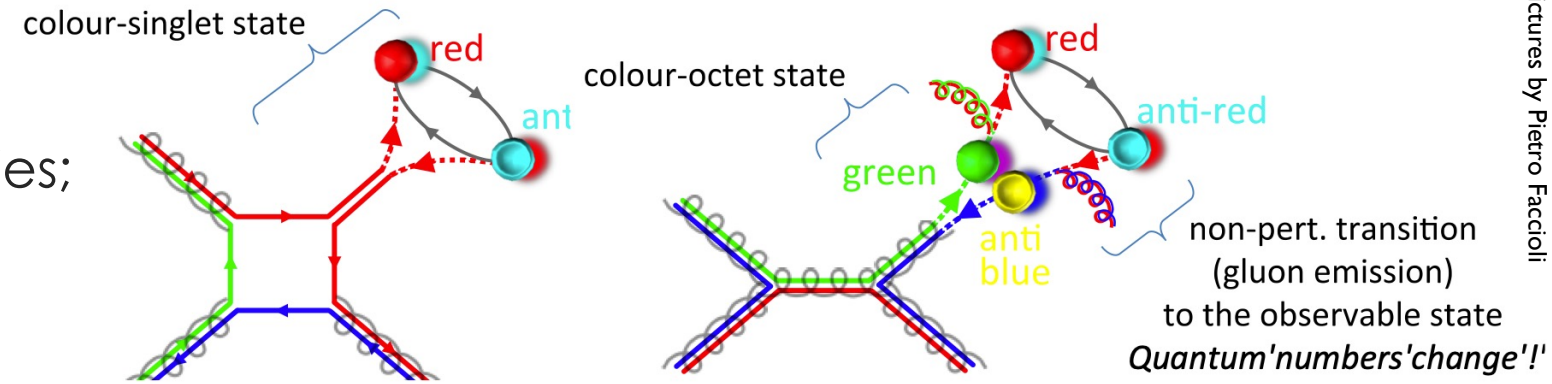
QUARKONIUM PRODUCTION IN NRQCD

- Two scales of production: hard process of **$Q\bar{Q}$ formation** and **hadronization of $Q\bar{Q}$** at softer scales
- **Factorization**: $d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle O^H(n) \rangle$

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

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

- Both **CS** and **CO states** are allowed with varying probabilities; LDMEs from experimental data



Pictures by Pietro Faccioli

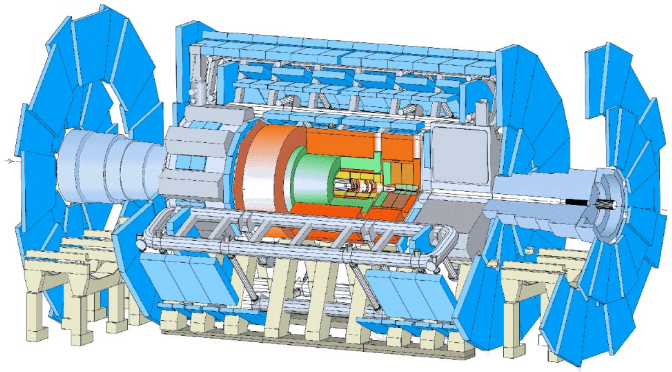
- **Universality**: same LDMEs for different √s, prompt production and production in b-decays
- Heavy-Quark **Spin-Symmetry**: links between CS and CO LDMEs of different quarkonium states

LHC DETECTORS HUNTING FOR QUARKONIUM

- **ATLAS** and **CMS**: mid-rapidity region, with muons in final state

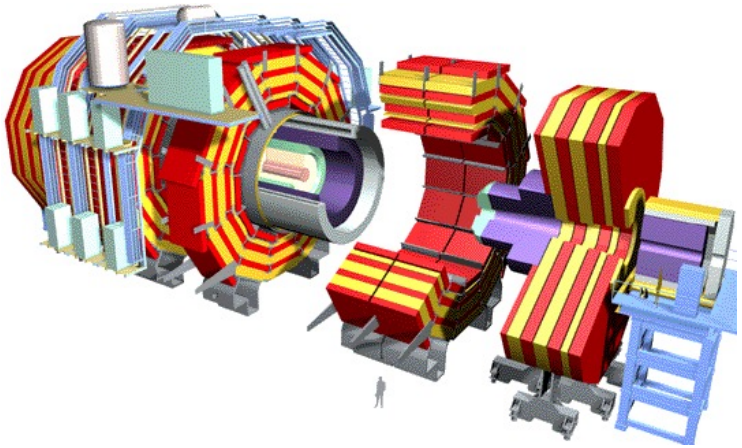
ATLAS EXPERIMENT

JINST 3 (2008) S08003



CMS

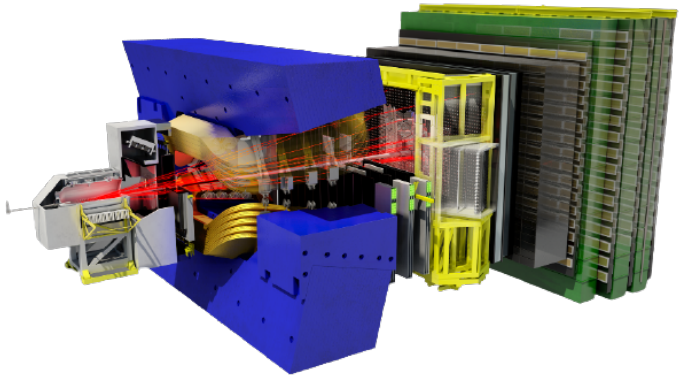
JINST 3 (2008) S08004



- **LHCb**: forward-rapidity region, with muons and hadrons in final state

LHCb

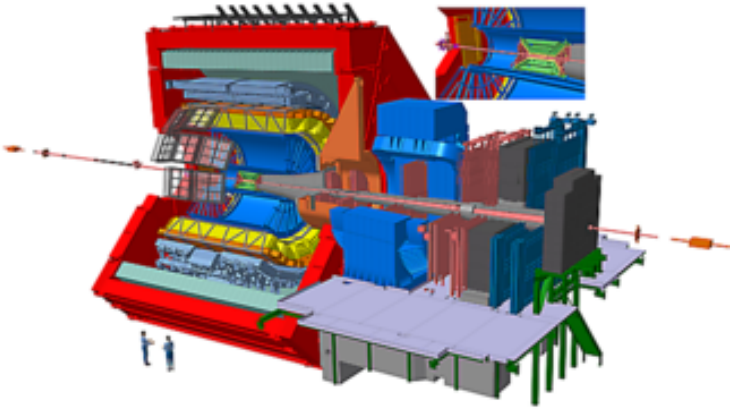
IJMPA 30 (2015) 1530022



- **ALICE**: both mid- and forward-rapidity regions, with muons and electrons in final state

ALICE

JINST 3 (2008) S08002



- **Experiments provide complementary measurements**

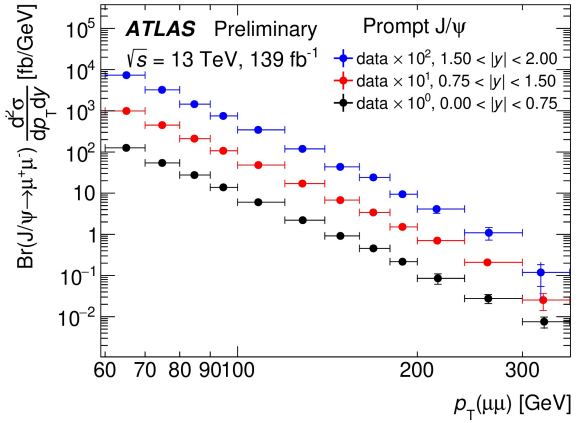
RECENT RESULTS (in pp collisions)

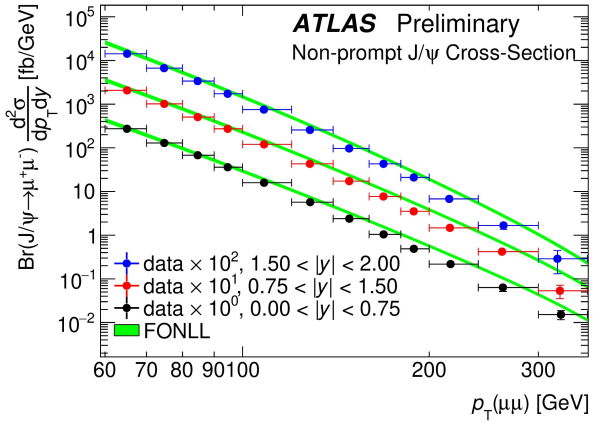
- ATLAS
  - J/ψ production in association with a $W^{\pm}$ boson at $\sqrt{s}$ = 8 TeV *JHEP 01 (2020) 095*
  - High-p_T J/ψ and ψ(2S) production at $\sqrt{s}$ =13 TeV *ATLAS-CONF-2019-047*
- CMS
  - Event-activity dependence of Υ(nS) relative production at $\sqrt{s}$ = 7 TeV *JHEP 2011 (2020) 001*
  - Υ(1S) pair production and search for resonances decaying to Υ(1S)$\mu^+\mu^-$ at $\sqrt{s}$ = 13 TeV *PLB 808 (2020) 135578*
  - Constraints on the χ_{c1} versus χ_{c2} polarizations at $\sqrt{s}$ = 8 TeV *PRL 124 (2020) 162002*
  - Study of J/ψ meson production from jet fragmentation at $\sqrt{s}$ = 8 TeV *PLB 804 (2020) 135409*
- LHCb
  - η_c(1S) production at $\sqrt{s}$ = 13 TeV *EPJC 80 (2020) 191*
  - ψ(2S) production at $\sqrt{s}$ = 7 and 13 TeV *EPJC 80 (2020) 185*
  - Observation of structure in the J/ψ-pair mass spectrum *SB 65 (2020) 23, 1983-1993*
- ALICE
  - J/ψ production at mid-rapidity at $\sqrt{s}$ = 5.02 TeV *JHEP 10 (2019) 084*
  - Multiplicity dependence of J/ψ production at midrapidity at $\sqrt{s}$ = 13 TeV *PLB 810 (2020) 135758*

J/ψ DIFFERENTIAL PRODUCTION CROSS-SECTIONS

[ATLAS-CONF-2019-047](#)
[JHEP 10 (2019) 084](#)

- ATLAS EXPERIMENT prompt and from-b $J/\psi \rightarrow \mu^+\mu^-$ at 13 TeV
- Measured **differential production cross-sections** in fiducial region $60 < p_T < 360$ GeV/c, $|y| < 2.0$
- **Good agreement between data and FONLL at low-p_T,** with theory exceeding prediction at high-p_T





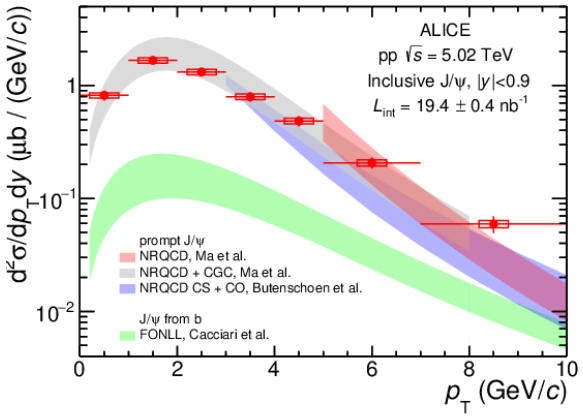
FONLL: [JHEP 10 (2012) 137](#)

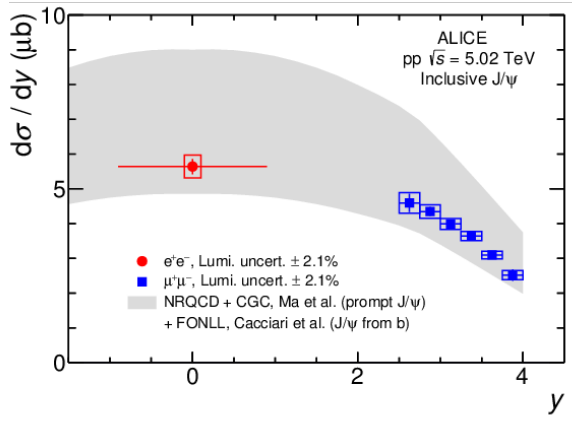
- ALICE inclusive $J/\psi \rightarrow e^+e^-$ at 5.02 TeV
- **J/ψ production for unpolarized case:**

$p_T > 0\ GeV/c, |y| < 0.9$

$$\frac{d\sigma_{J/\psi}}{dy} = 5.64\ \pm 0.22_{stat} \pm 0.33_{syst}\ \pm 0.12_{\mathcal{L}}\ \mu b$$

- Changing λ_θ in range[-1, +1] production varies from −24% to +15%
- **Good agreement between data and nonrelativistic QCD + colour glass condensate** (NRQCD+CGC)



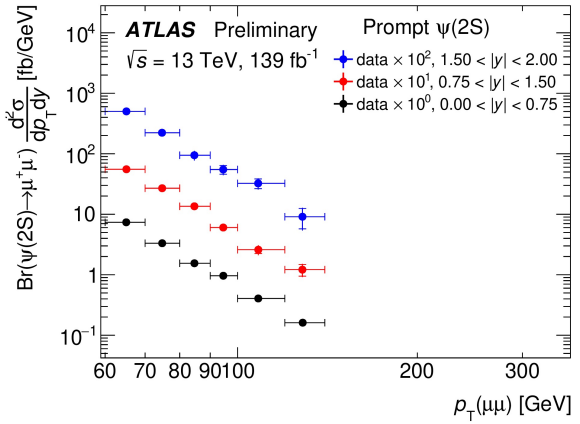


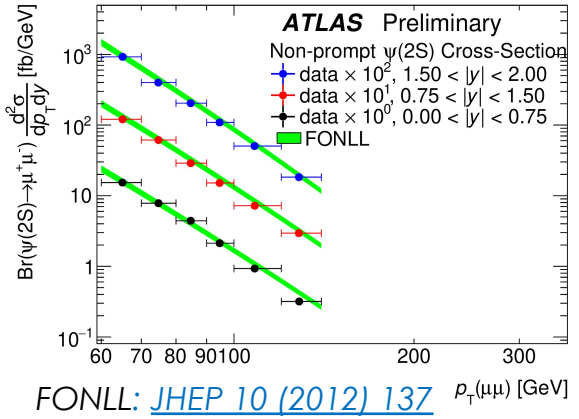
NRQCD+CGC: [PRL 113 (2014) 192301](#)
NRQCD CS+CO: [PRL 106 (2011) 022003](#)
NRQCD: [PRL 106 (2011) 042002](#)
FONLL: [JHEP 10 (2012) 137](#)

ψ(2S) DIFFERENTIAL PRODUCTION CROSS-SECTIONS

[ATLAS-CONF-2019-047](#)
[EPJC 80 (2020) 185](#)

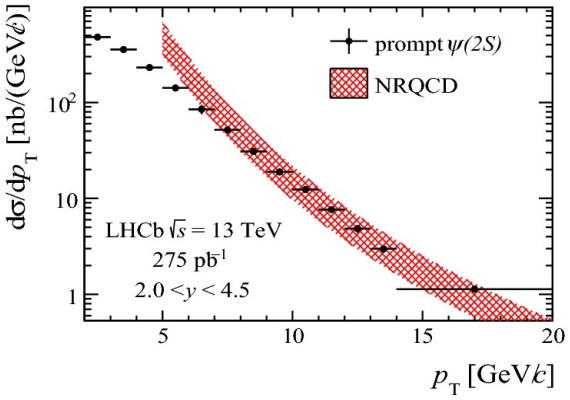
- ATLAS EXPERIMENT prompt and from-b ψ(2S)→μ⁺μ⁻ at 13 TeV
- Measured **differential production cross-sections** in fiducial region $60 < p_T < 140$ GeV/c, $|y| < 2.0$

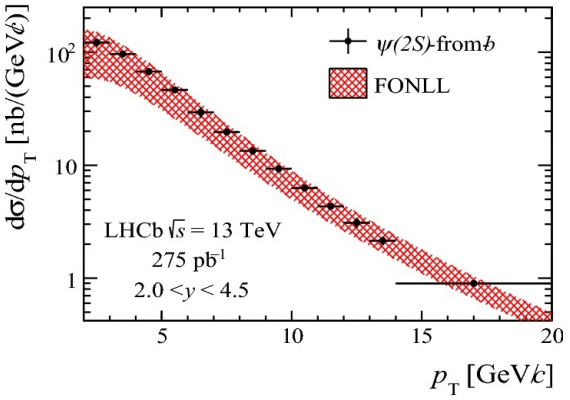




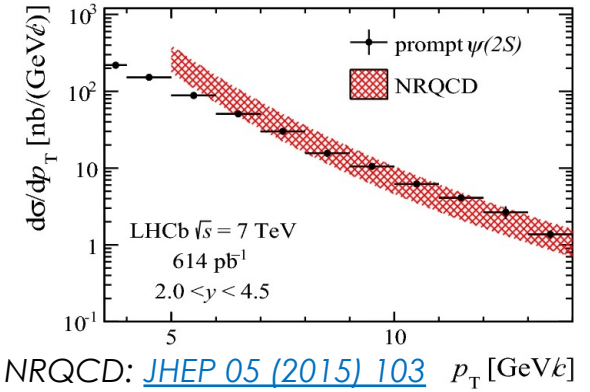
FONLL: [JHEP 10 (2012) 137](#)

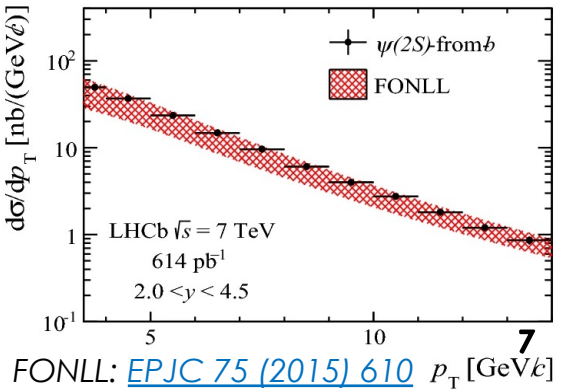
- LHCb prompt and from-b ψ(2S)→μ⁺μ⁻ at 7 and 13 TeV
- Complementary measurement in different rapidity regions: $p_T < 20$ GeV/c, $2.0 < y < 4.5$





- **Reasonable agreement between NRQCD and data** for $p_T > 7$ GeV/c
- **Good agreement with FONLL** for production in b-decays **for both experiments**





NRQCD: [JHEP 05 (2015) 103](#)
FONLL: [EPJC 75 (2015) 610](#)

$\eta_c(1S)$ PRODUCTION IN LHCb AT $\sqrt{s}$=13 TeV

[EPJC 80 (2020) 191]

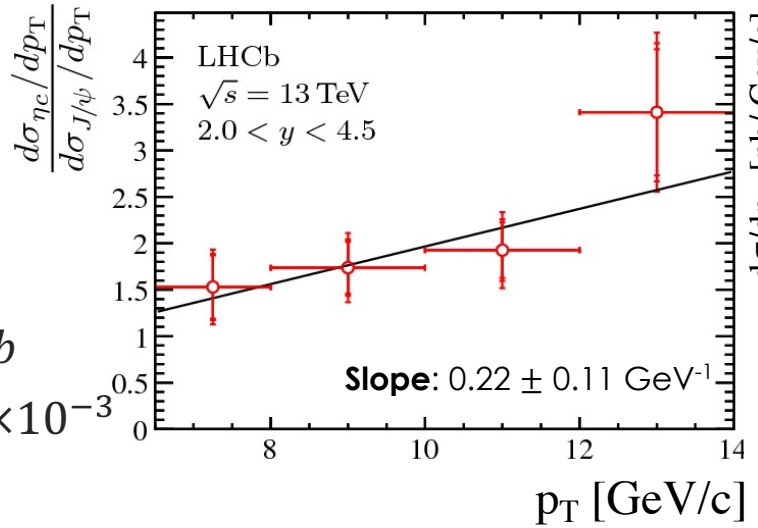
- **relative $\eta_c/J/\psi$** and **absolute η_c** p_T-differential production **cross-sections**

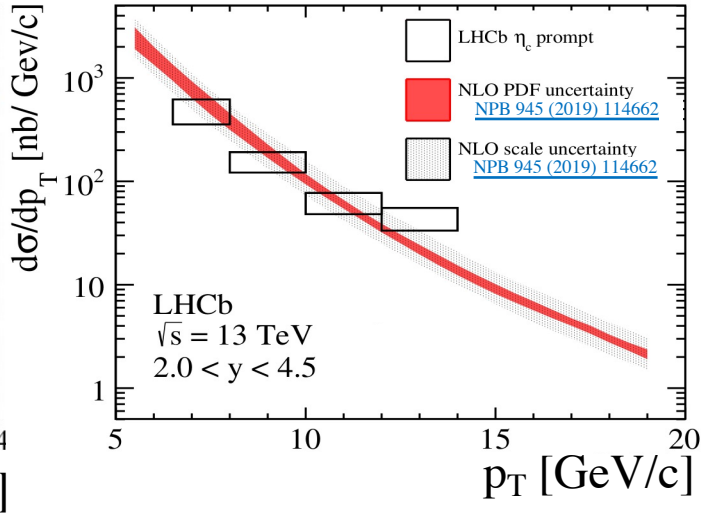
- **$\eta_c(1S)$ production:**

$6.5 < p_T < 14.0$ GeV/c, $2.0 < y < 4.5$

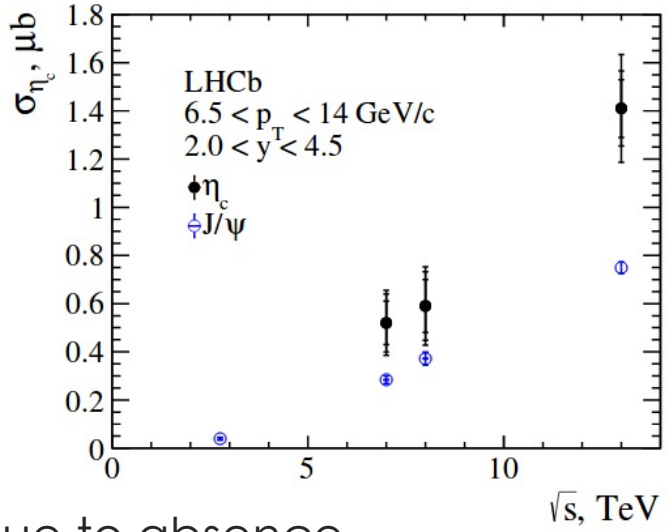
$$\sigma_{\eta_c}^{prompt} = 1.26 \pm 0.11_{stat} \pm 0.08_{syst} \pm 0.14_{J/\psi}\ \mu b$$

$$\mathfrak{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{J/\psi})\times 10^{-3}$$





- Results may **provide** important **link between J/ψ production and polarization**

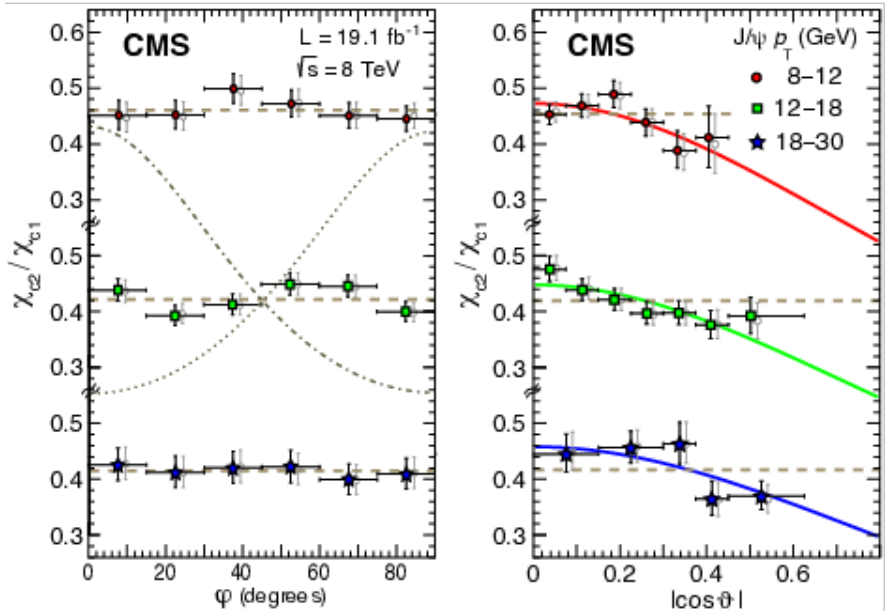


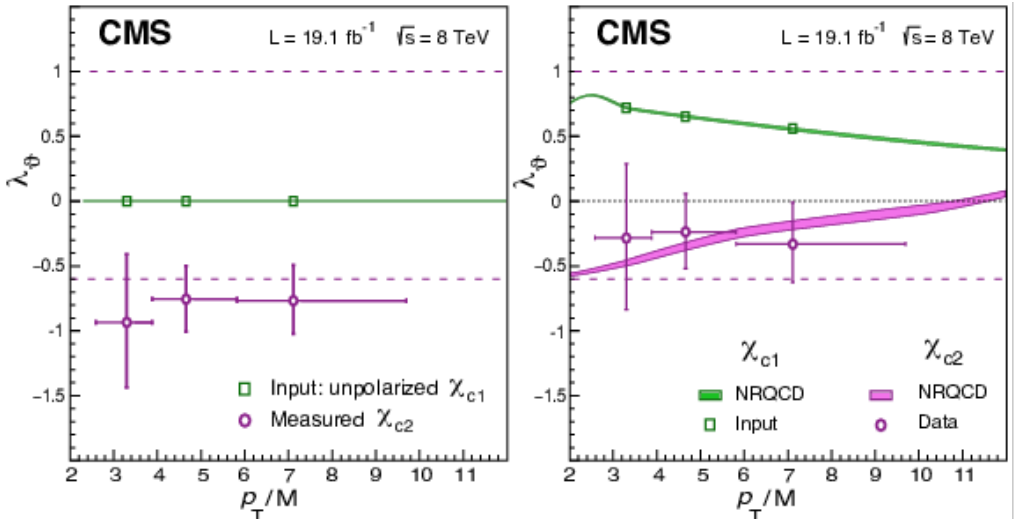
- **$\eta_c(1S)$ production can be described by CS contribution only;** measurement in extended p_T is required: **larger slope** would indicate **possible CO contribution**

- **Interpretation of $\eta_c(2S)/\psi(2S)$ much cleaner** than for $\eta_c(1S)/J/\psi$ due to absence of feed-down contributions: **dedicated LHCb trigger in 2018**

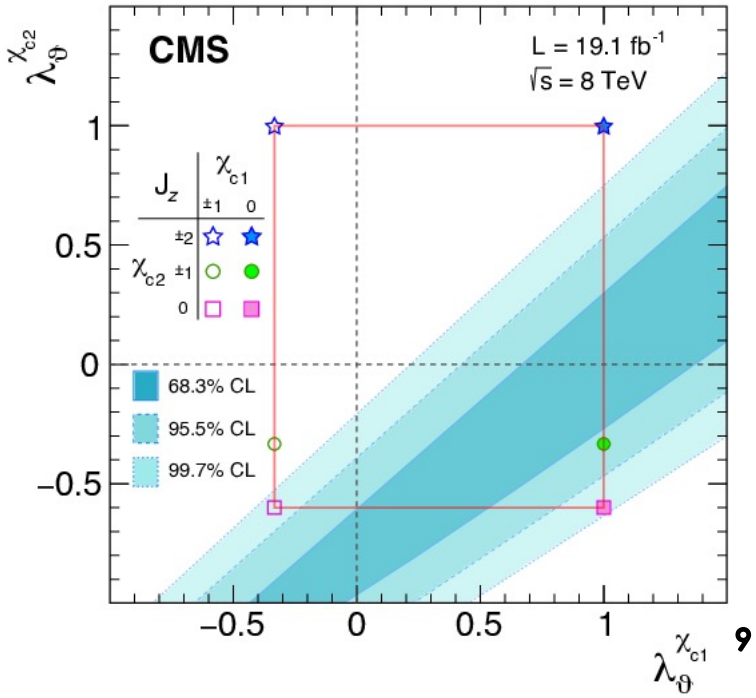
χ_{c1} VS χ_{c2} POLARIZATION IN CMS AT $\sqrt{s}$=8 TeV

PRL 124 (2020) 162002





- **First measurement of *P*-wave quarkonium polarization** with χ_{c2}/χ_{c1} ratios as a function of $|\cos\Theta^{HX}|$ and φ^{HX}



- Unpolarized scenario and large part of the physically allowed region (red rectangle) excluded at 99.7 % CL

  → at least one state is strongly polarized

- **Good agreement with NRQCD prediction**

J/ψ PRODUCTION VS MULTIPLICITY AT √s= 13 TeV

[PLB 810 (2020) 135758]

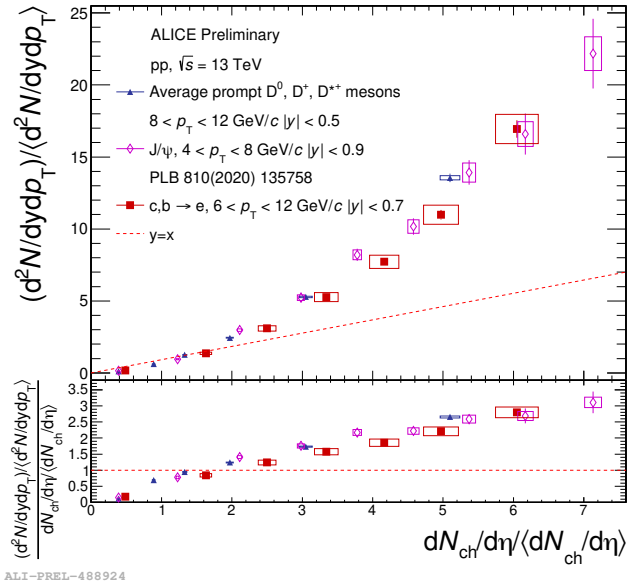
- **Multiplicity dependence** of production **can provide insights on parton level processes and on interplay between hard and soft mechanisms** in particle production

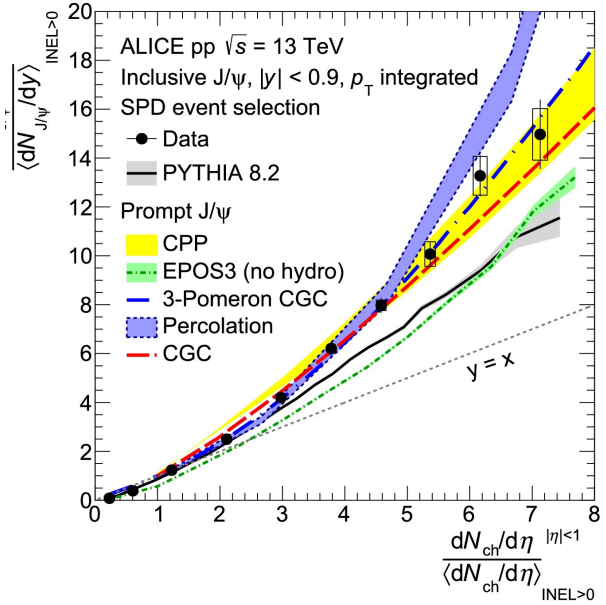
- **Stronger than linear increase** of relative J/ψ production **as function of multiplicity** is observed for p_T-integrated yields
  - increase is stronger for high-p_T J/ψ

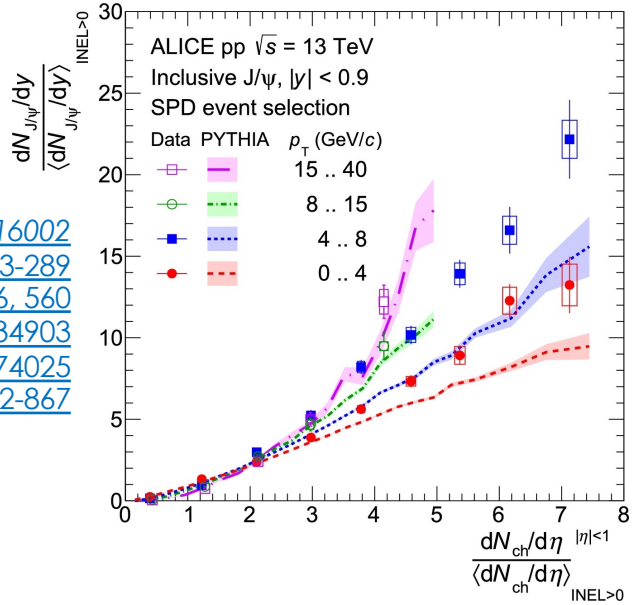
- Trends qualitatively (for some models, quantitatively) reproduced by theoretical models

- **More stringent tests of models and validation of physics mechanisms are needed**
  - disentangling feed-down from b-hadrons

- Ongoing analysis at forward-rapidity to further constrain model comparison







CPP: [PRD88 (2013) 116002]
EPOS3: [PR 350 (2001) 93-289]
3-Pomeron CGC: [EPJC 80 (2020) 6, 560]
Percolation: [PRC 86 (2012) 034903]
CGC: [PRD 98 (2018) 7, 074025]
PYTHIA8: [CPC 178 (2008) 852-867]

Y(nS) PRODUCTION VS MULTIPLICITY AT √s= 7 TeV

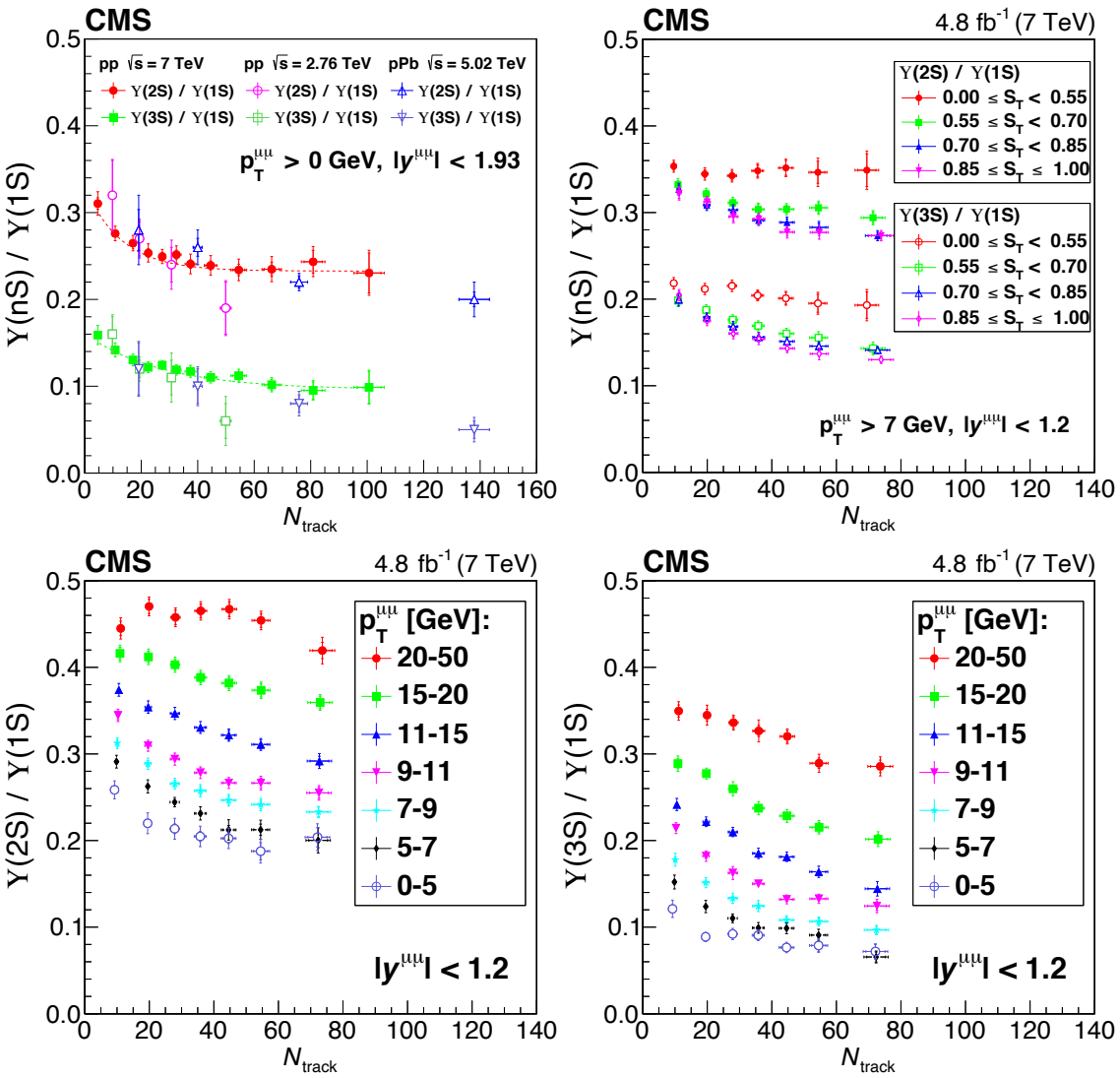
JHEP 2011 (2020) 001

- Event-activity dependencies provide connection with underlying event (UE) and help interpreting production in heavy ion collisions

- **For Y(nS) production vs Multiplicity**
  - decrease is stronger at lower Y(nS) p_T
  - ratio increases with p_T as observed in CMS before

- **Decrease is linked to UE**:
  - disappears in low-sphericity region – jet-like events
  - appears in a similar way for $S_T > 0.55$

- No effect found from Y(nS) isolation



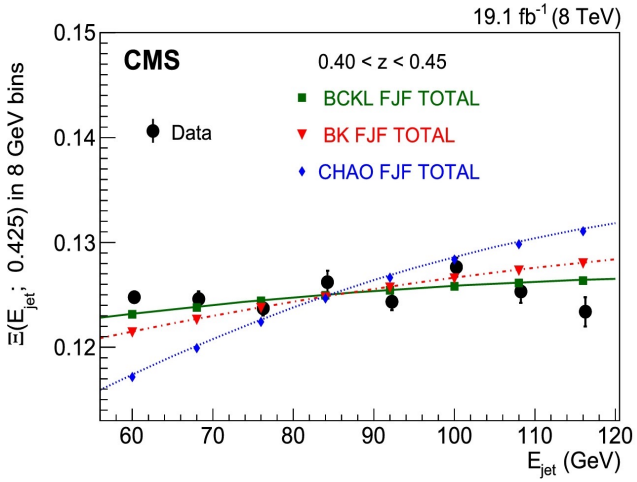
J/ψ PRODUCTION FROM JET FRAGMENTATION

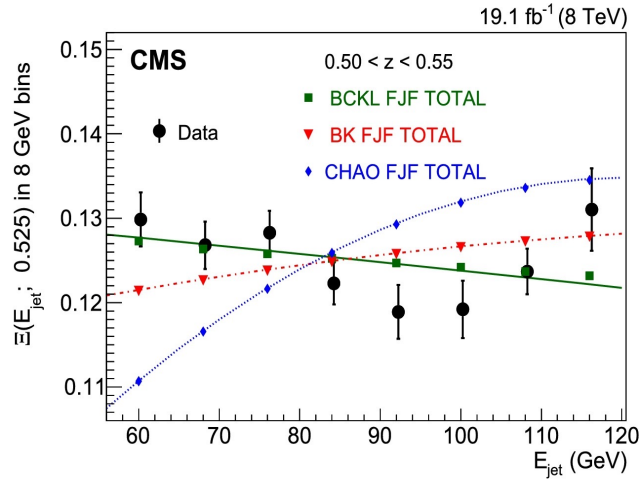
[PLB 804 (2020) 135409]

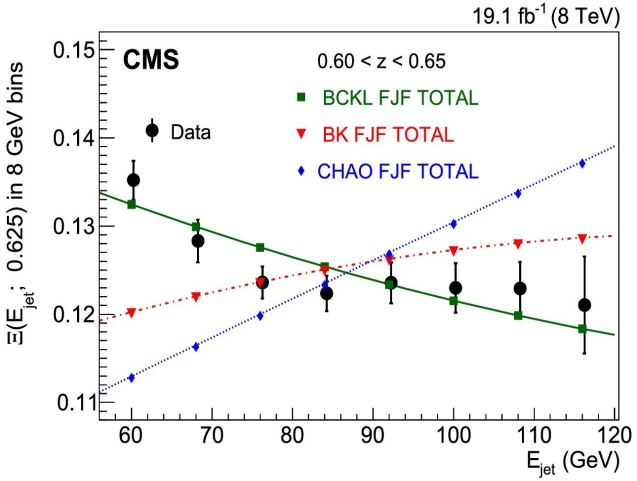
- Analysis combines measurement with **Fragmenting jet function (FJF)** approach and three **different sets of LDMEs**
- **3 z subregions considered** for z ∈ [0.3, 0.8] where $z=E_{J/\psi}/E_{jet}$:
  - [0.40, 0.45], [0.50, 0.55], and [0.60, 0.65]
  - in each subregion FJF terms have different jet energy distributions for given LDMEs
- **J/ψ fraction from jets**

  $E_{J/\psi} > 15$ GeV, $|y_{J/\psi}| < 1$

  $f_{tot} = (85 \pm 3_{stat} \pm 7_{syst})\%$







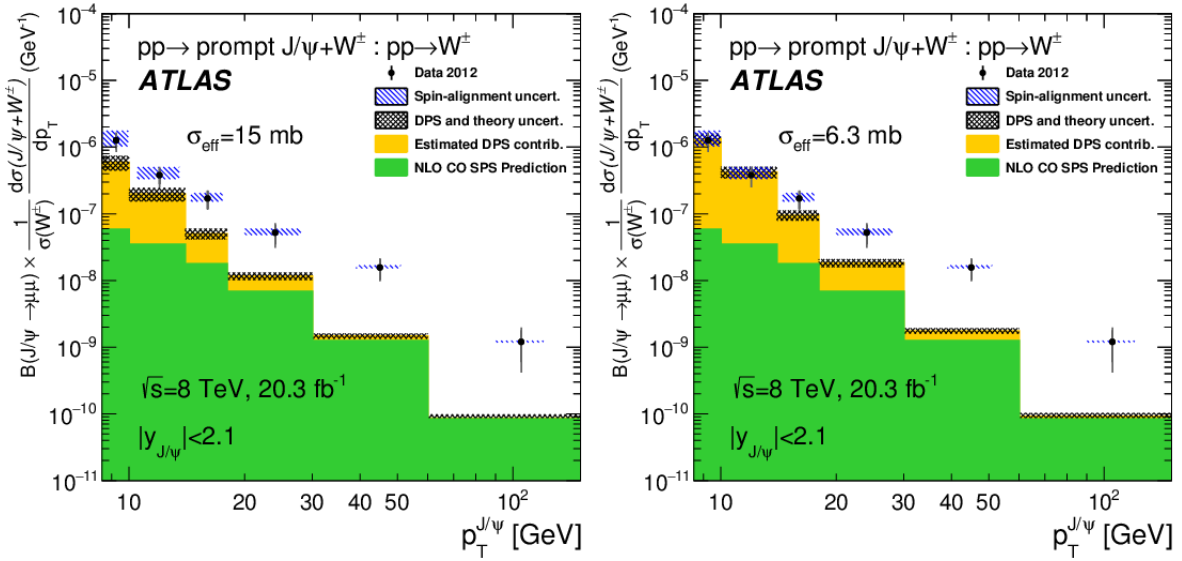
- FJF analysis describes J/ψ production from central gluonic jets and can distinguish different sets of LDMEs
- **Data is consistent with NRQCD treatment of FJF process** using LDMEs from BCKL [PRL 113 (2014) 2, 022001]

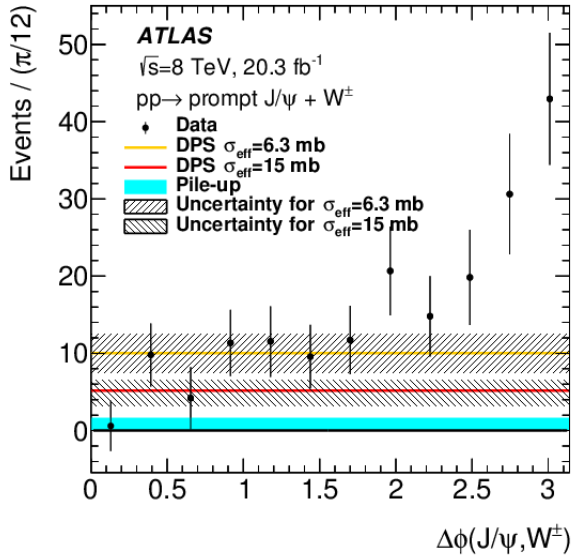
BCKL: PRL 113 (2014) 022001
BK: MPLA 28 (2013) 1350027
CHAO: PRL 108 (2012) 242004
FJF Model: JHEP 11 (2014) 003

J/ψ+W± PRODUCTION IN ATLAS AT √s = 8 TeV

[JHEP 01 (2020) 095]

- Single (SPS)/double (DPS) parton scattering
  → J/ψ+W± from same/different parton pairs
- **Associated prompt *J/ψ+W±* production** can be signature of SPS CO processes
- **p_T-differential cross-sections** of J/ψ+W± for different DPS contributions and **Δφ** between J/ψ and W±
- Measured prompt J/ψ+W± production compared with theoretical prediction at NLO for CO prompt production processes
- **Larger SPS yield** may indicate **significant contributions from SPS CS mechanism**





DI-Υ(1S) AND SEARCH FOR RESONANCES IN Υ(1S)μ⁺μ⁻

[PLB 808 (2020) 135578]

- **DPS process** can **provide information on partons** p_T, their correlations inside proton and can **help understanding various backgrounds**

- **Υ(1S) pair production for unpolarized case**

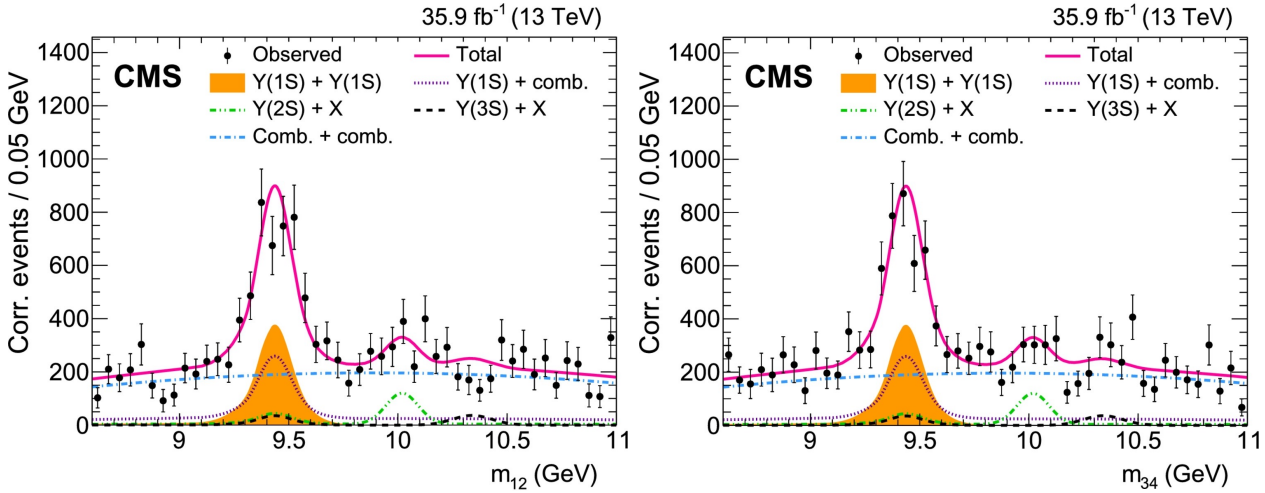
  $\sigma_{\Upsilon(1S)\Upsilon(1S)} = 79 \pm 11_{stat} \pm 6_{syst} \pm 3_{\mathcal{B}}\, pb$, |y|<2.0

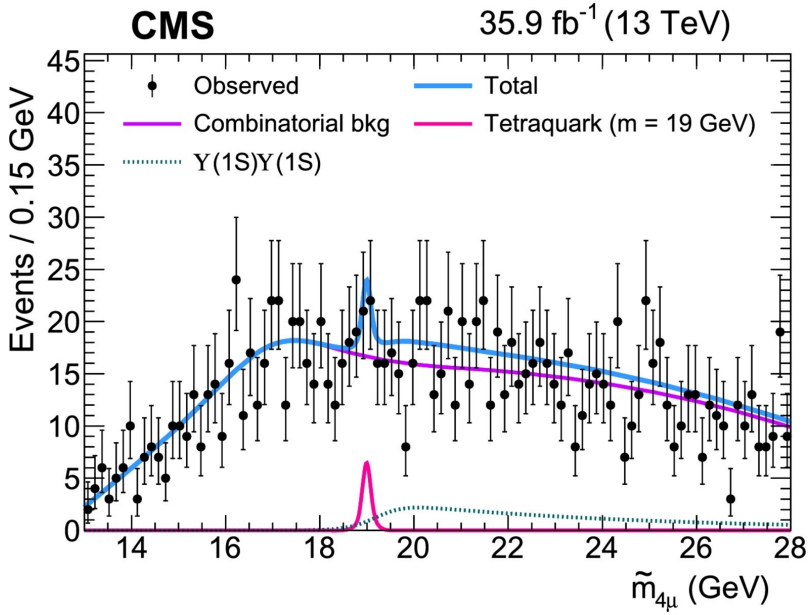
- Charging λ_θ in range[-1, +1] production varies from −60% to +25%

- First measurement of DPS contribution to $\sigma_{\Upsilon(1S)\Upsilon(1S)}$

  $f_{DPS} = (39 \pm 14)\%$

- **No excess** of events compatible with signal is observed **in 4-μ invariant mass spectrum**





DI-J/ψ PRODUCTION AND SEARCH FOR RESONANSES [SB 65 (2020)23, 1983-1993]

- **First observation of fully heavy tetraquark candidate**
- Threshold structure with a few possible interpretations:
  - One BW, combination of two BWs, feed-down…
- Additional study together with spin-parity measurement required to explain nature of threshold structure
- **Peak at 6.9 GeV: X(6900)**, consistent with BW structure
  - Without interference:

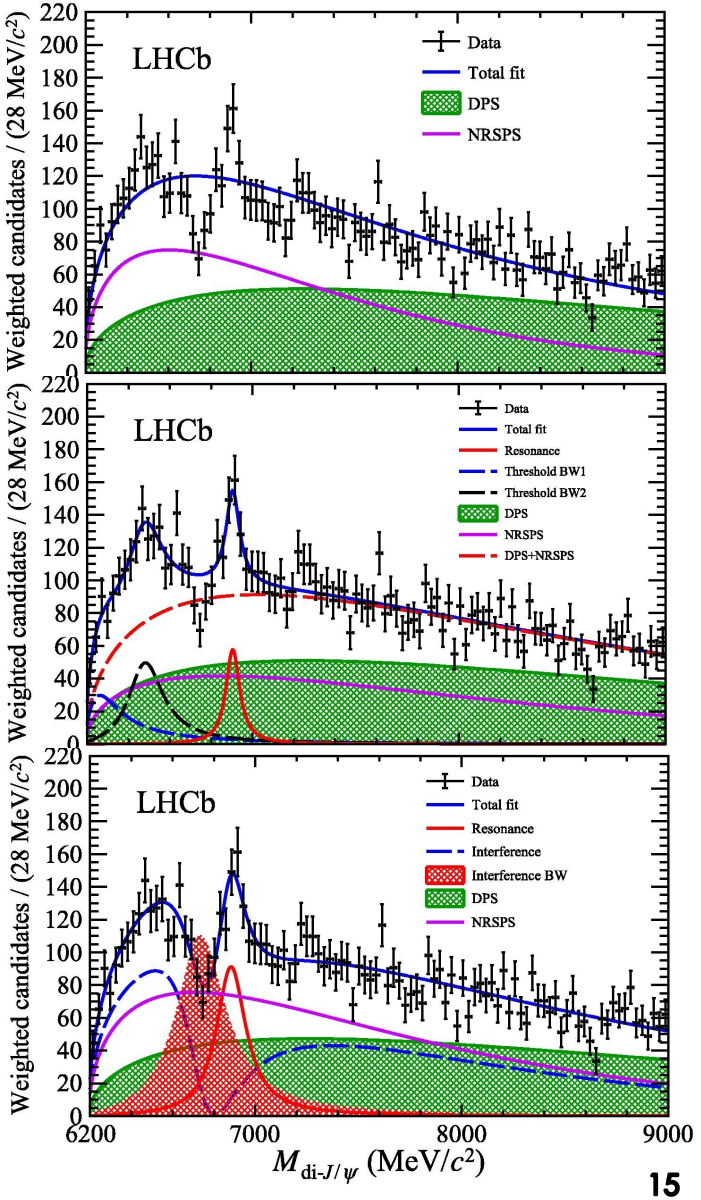
$$m_{X(6900)} = 6905 \pm 11_{stat} \pm 7_{syst}\ MeV/c^2$$

$$\Gamma_{X(6900)} = 80 \pm 19_{stat} \pm 33_{syst}\ MeV/c^2$$

  - With interference:

$$m_{X(6900)} = 6886 \pm 11_{stat} \pm 11_{syst}\ MeV/c^2$$

$$\Gamma_{X(6900)} = 168 \pm 33_{stat} \pm 69_{syst}\ MeV/c^2$$



SUMMARY

- **J/ψ** and **ψ(2S)** prompt and from b-decays **production** at different energies:
  - Reasonable agreement between theory and data
  - **Upcoming results from ALICE** at mid-rapidity at $\sqrt{s}$=5.02 and 13 TeV and forward-rapidity at $\sqrt{s}$=5.02, 8 and 13 TeV
- **η_c(1S)** prompt and from b-decays p_T-differential **production** cross-sections
  - **HQSS** allows to **provide constraint to J/ψ** production and polarization
  - **dedicated LHCb trigger** in 2018 for **η_c(2S) production**
- **χ_c polarization**:
  - First measurement of ***P*-wave quarkonium** polarization – **unpolarized scenario excluded**
- Event-activity dependence:
  - Important for understanding processes in heavy ion collisions
  - **More stringent tests** of models and validation of physics mechanisms are **needed**
- Associated and di-quarkonium production:
  - Probing production mechanism via J/ψ+$W^{\pm}$ production
  - **Two new structures** found in **di-J/ψ**
  - Looking forward to Run3 data

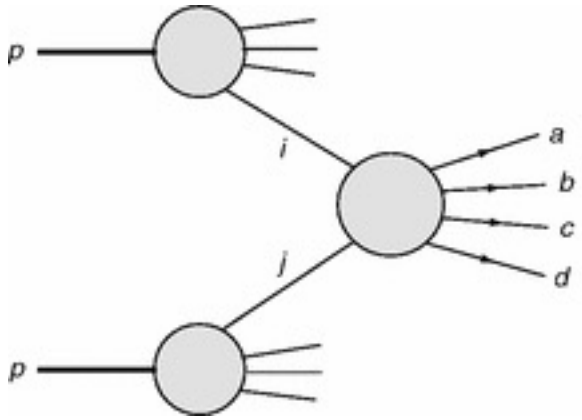
Thank you
for your attention!

BACKUP SLIDES

ASSOCIATED PRODUCTION: DPS AND SPS

PRD 84 (2011) 074021
ATL-PHYS-SLIDE-2021-129

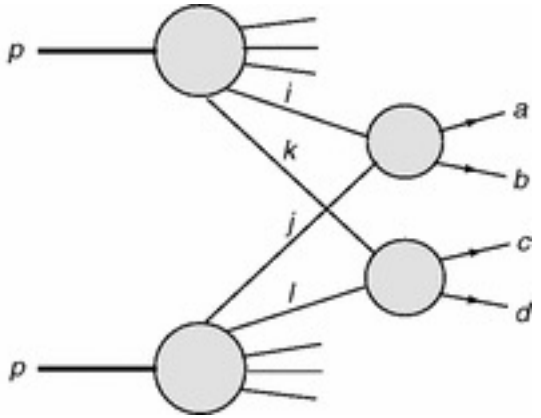
The production of two objects in the same pp collision can be due to



- **Single-Parton Scattering (SPS):**
  - the two objects are produced via a subprocess in a single interaction of two partons
  - can be treated in the usual way, once the subprocess cross section is calculated
  - expected to be "back-to-back" in transverse plane
- **Double-Parton Scattering (DPS):**
  - simultaneous interaction of two pairs of partons, each producing one of the two objects, assumed to be uncorrelated
  - one can apply the usual parton model / QCD formalism TWICE, once for subprocess A and once for subprocess B
  - Dimensional factor σ_{eff} determines the scale of the cross section

$$\sigma_{\mathrm{A+B}}^{DPS} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

  - assumed (hoped?) to be independent of process and energy



J/ψ, ψ(2S) AND Υ(nS) PRODUCTION

- Production measurement via l^+l final state
- Cross-section determination in bin[p_T,y]

$$\frac{d^2\sigma}{dydp_T} = \frac{N(q\bar{q} \to l^+l^-)}{\mathcal{L} \times \varepsilon \times \mathcal{B}(q\bar{q} \to l^+l^-) \times \Delta y \times \Delta p_T}$$

- $\mathcal{L}$: integrated luminosity
- ε: total efficiency
- $N(q\bar{q} \to l^+l^-)$: number of signal candidates in the given (p_T, y) bin
- $\Delta y \times \Delta p_T$: bin width

- **Prompt** and ***b*-decay production of charmonium** distinguished via pseudo-proper decay time:

$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$

- **Full kinematic range cross-section**

$\eta_c(1S)$ PRODUCTION AT $\sqrt{s}$=13 TeV

Eur.Phys.J.C 80(2020) 191

- Cross-section determination:

$$\frac{\sigma(\eta_c)}{\sigma(J/\psi)} = \frac{N^p_{\eta_c}}{N^p_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}$$

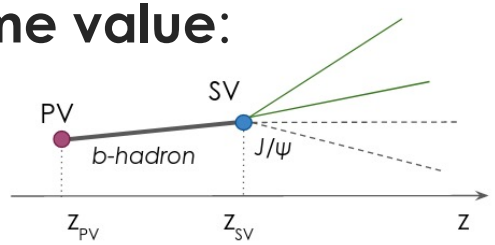
$$\frac{\mathcal{B}_{b\to\eta_c X}}{\mathcal{B}_{b\to J/\psi X}} = \frac{N^b_{\eta_c}}{N^b_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}$$

- Extracted from DATA
- Calculated from PDG:

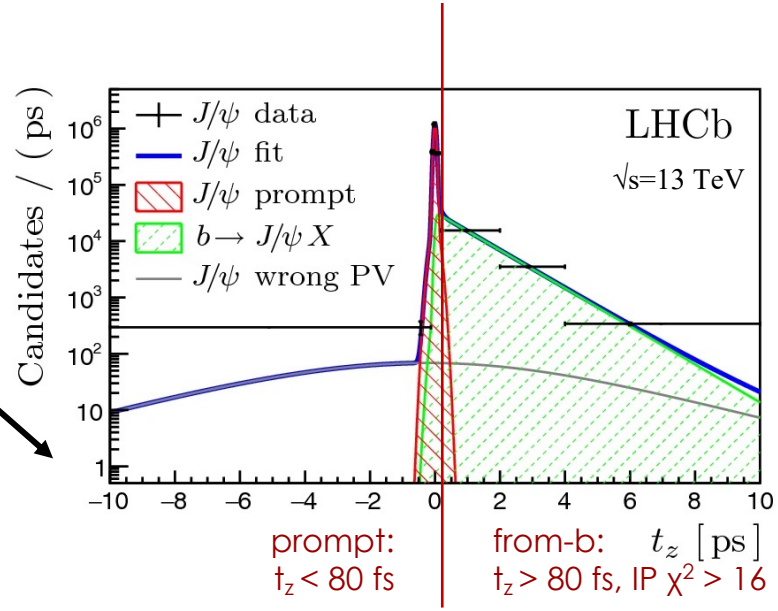
$$\mathcal{B}_{J/\psi\to p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$$
$$\mathcal{B}_{\eta_c(1S)\to p\bar{p}} = (1.45 \pm 0.14) \times 10^{-3}$$

- From Simulation

- **Prompt** and ***b*-decay production** distinguished via **decay time value**:



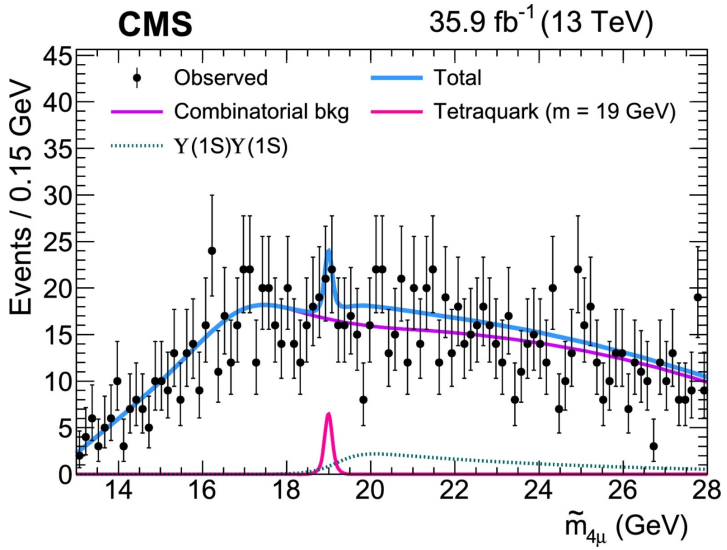
$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$

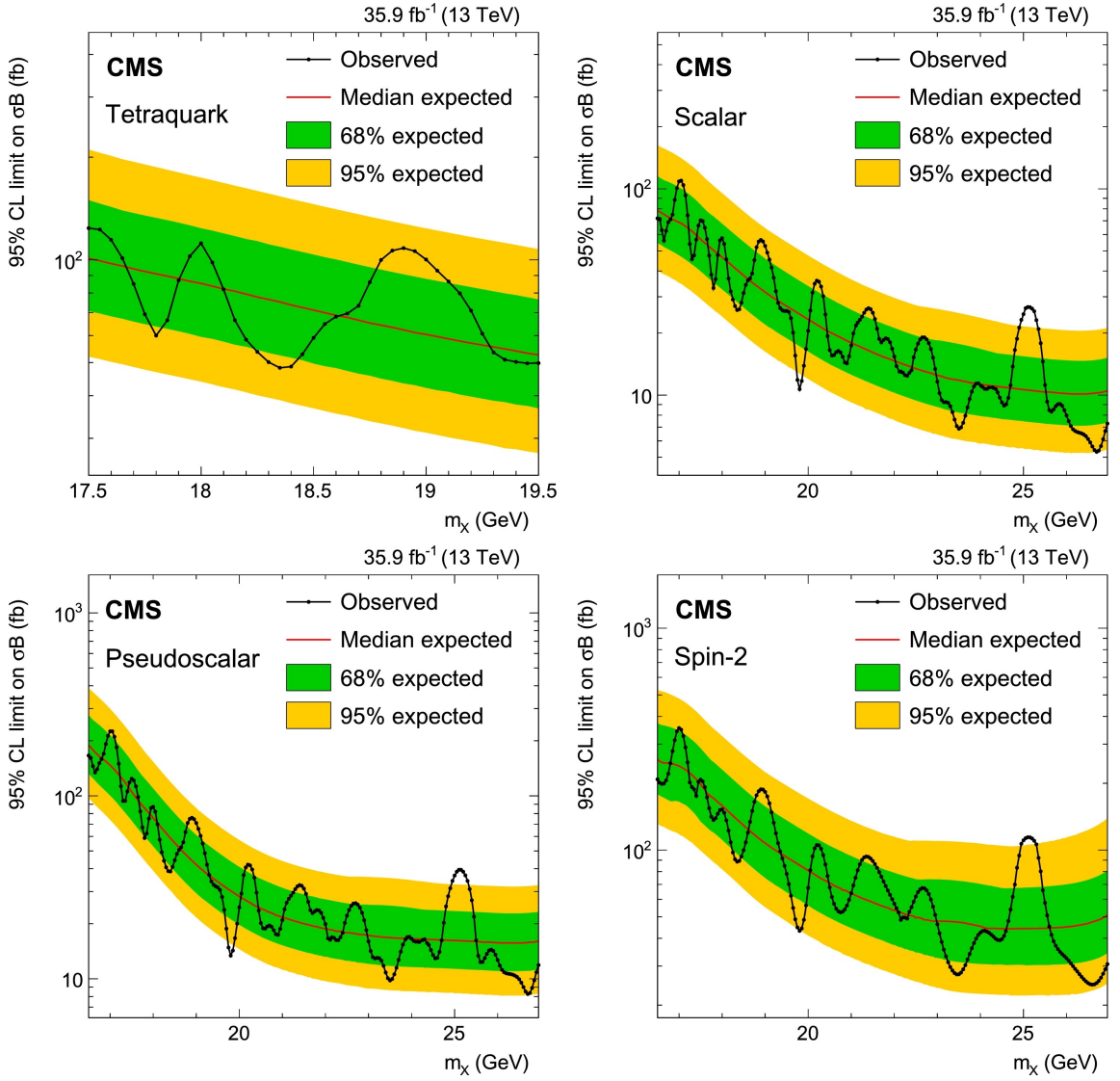


- **Cross-feed** between samples are accounted in simultaneous fit
- **Two techniques** are used for cross-section measurement

Y(1S)Y(1S) AND SEARCH FOR RESONANCES IN Y(1S)$\mu^+\mu^-$ [PLB 808 (2020) 135578]

- **Limits cover 4 hypothesis:**
  - tetraquark
  - scalar
  - pseudoscalar
  - spin-2
- **2.4σ** only for M=25.1 GeV
- **No excess** of events compatible with signal is observed **in 4-μ invariant mass spectrum**

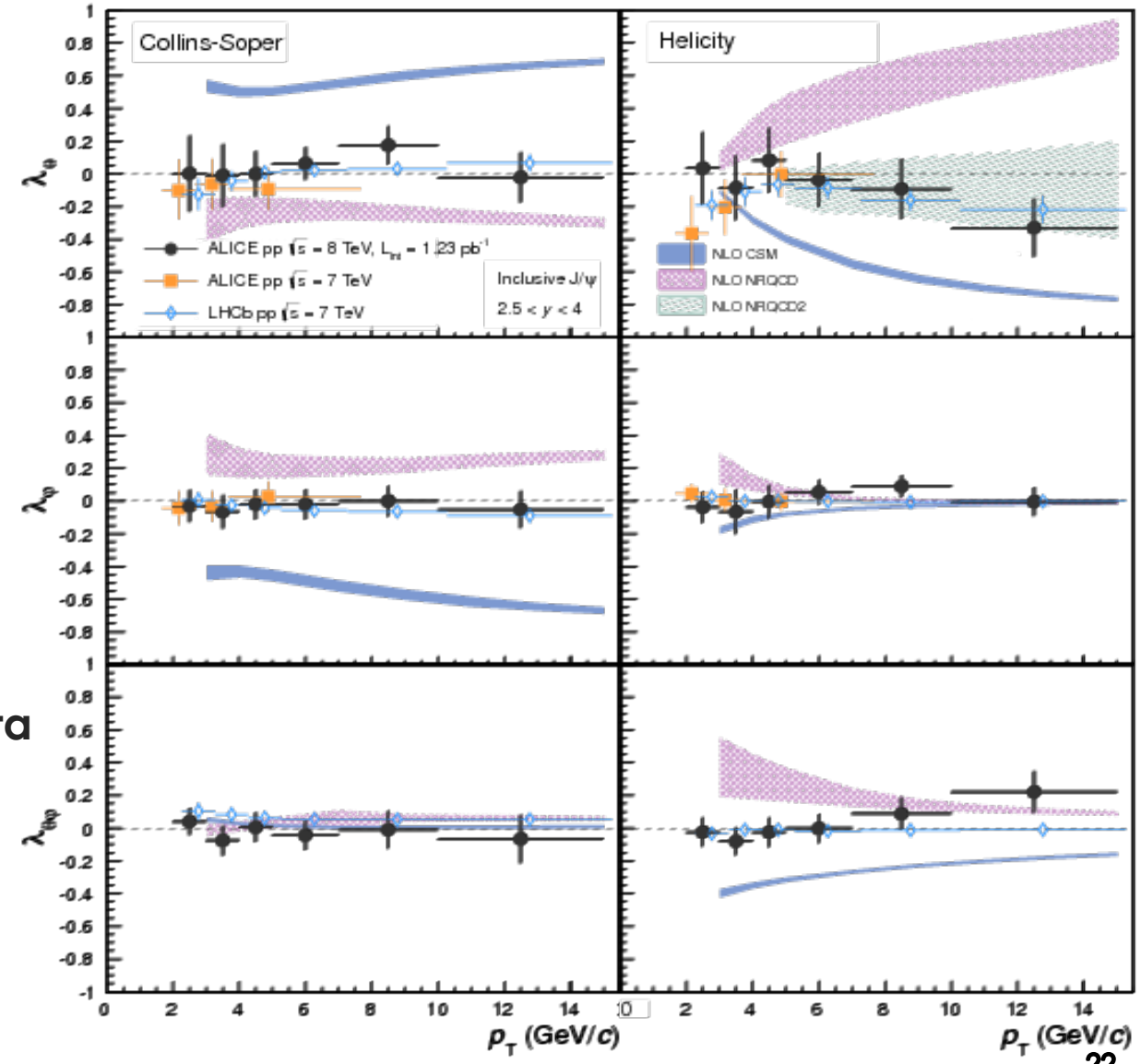




J/ψ POLARIZATION IN ALICE AT √s=8 TeV

EPJC 78 (2018) 7

- Polarization measured via angular distributions of muons in quarkonium rest frame
- Two different **polarization frames** are used:
  Helicity and **Collins- Soper**
- Good agreement between ALICE and LHCb measurements at $\sqrt{s}$ = 7 TeV
- **No significant J/ ψ polarization observed**
- **Tension between existing NRQCD prediction and data**
- **Better agreement for NRQCD+CGC** [JHEP 1812(2018)057]; however tensions still present



ADDITIONAL PAPERS

- ATLAS:
  - Relative B_c/B^+ production measurement at $\sqrt{s}$ = 8 TeV – *Submitted to PRD*
- CMS:
  - Measurement of quarkonium production cross sections at $\sqrt{s}$= 13 TeV *PLB 780 (2018) 251*
- ALICE
  - Inclusive J/ψ polarization at forward rapidity at $\sqrt{s}$ = 8 TeV *EPJC 78 (2018) 7*