Overview of hadron-formation studies at the LHC

- recent results and model comparisons -

B. Volkel on behalf of the ALICE, ATLAS, CMS and LHCb collaborations

QCD@LHC, Parallel A WG6&7 — 29.11.2022

Factorisation and fragmentation

$$\mathrm{d}\sigma_{\mathrm{AB}\to\mathrm{h}} = \underbrace{f_{\mathrm{a/A}}\left(x_1, Q^2\right)}_{\text{non-perturbative}} \otimes \underbrace{f_{\mathrm{b/B}}\left(x_2, Q^2\right)}_{\text{non-perturbative}} \otimes \underbrace{\mathrm{d}\sigma^{\mathrm{hard}}_{\mathrm{ab}\to\mathrm{c}}\left(x_1, x_2, Q^2\right)}_{\text{perturbative}} \otimes \underbrace{D_{\mathrm{c}\to\mathrm{h}}\left(z, Q^2\right)}_{\text{non-perturbative}}$$

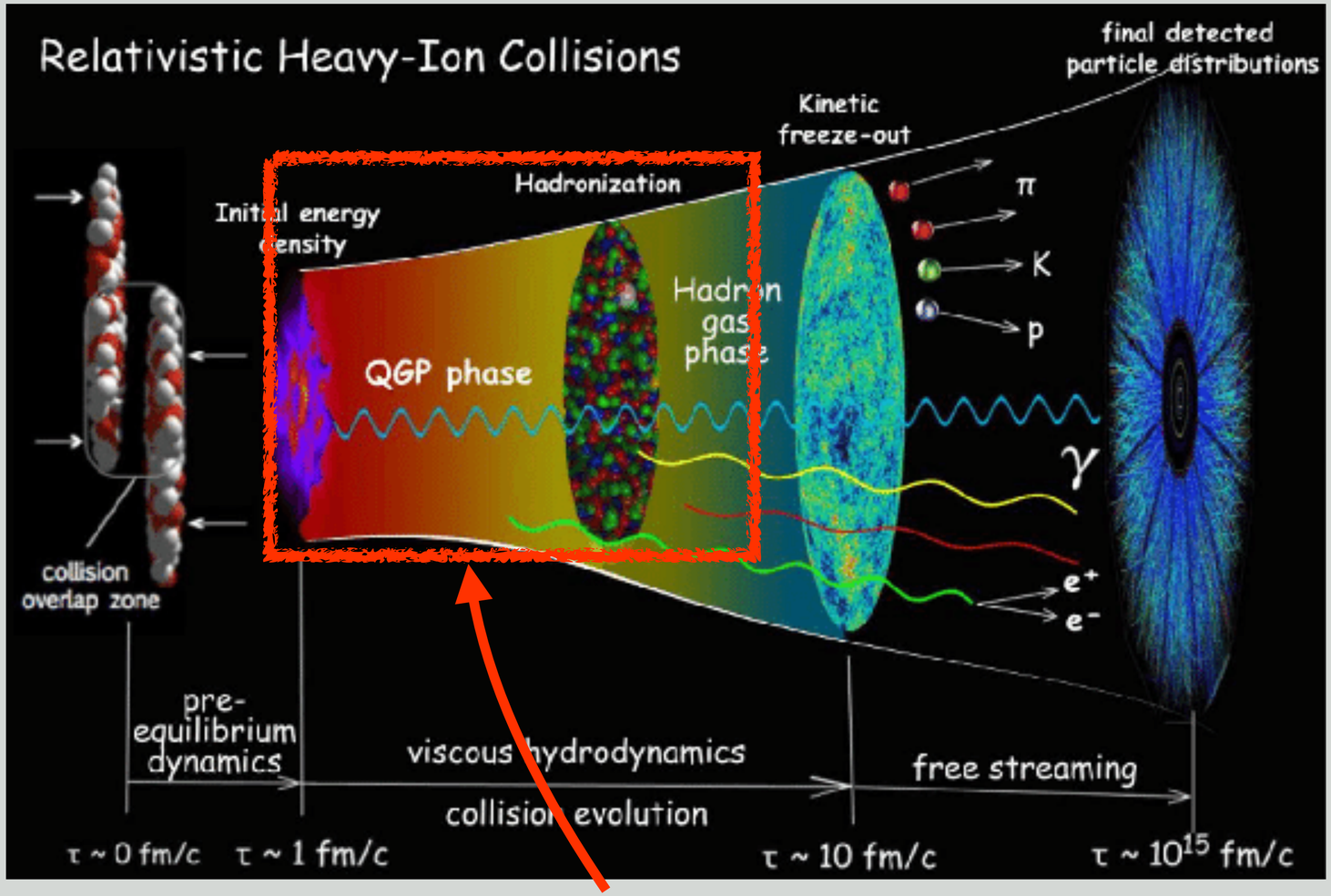
- **Factorisation** at given momentum transfer $\left(Q^2 \gg \Lambda_{\mathrm{QCD}}\right)$.
- Factorising perturbative calculations from terms obtained through measurements due to their non-perturbative nature. **Production cross section measurements provide strong test of pQCD predictions.**

Fragmentation

- Hadron h carries momentum fraction z of original Parton c.
  Independent description of all partons via fragmentation functions $D_{\mathrm{c}\to\mathrm{h}}\left(z, Q^2\right)$.
- Monte Carlo event generators
  - describe parton evolution perturbatively from high Q^2 to low cut-off scale via parton showers,
  - implement hadronisation via **phenomenological models** such as the Lund model (e.g. PYTHIA) or cluster model (e.g. SHERPA, HERWIG).

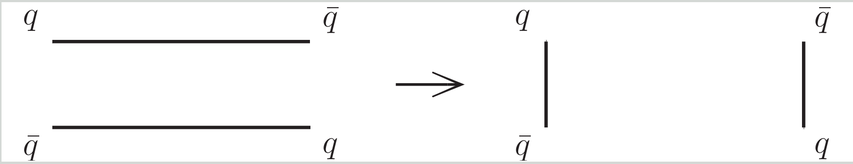
Hadronisation in the QGP

- How are hadrons formed in the presence of large partonic densities?
- **No perturbative/analytical description** possible for hadronisation. Need entirely new theoretical framework for description of QGP.
- The application of models initially developed for hadronisation in the presence of a QGP is not restricted to the application in Pb—Pb anymore.
- Model approaches:
  - colour reconnection
  - recombination
  - statistical hadronisation

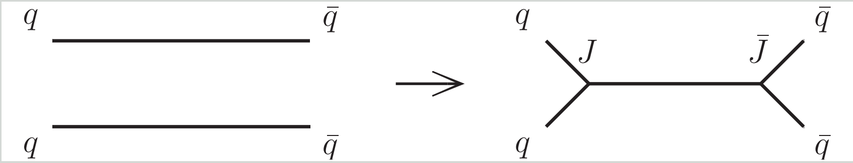


Formation and evolution of QGP and interaction between partons (from hard scattering) with it might completely change the properties of hadron formation.

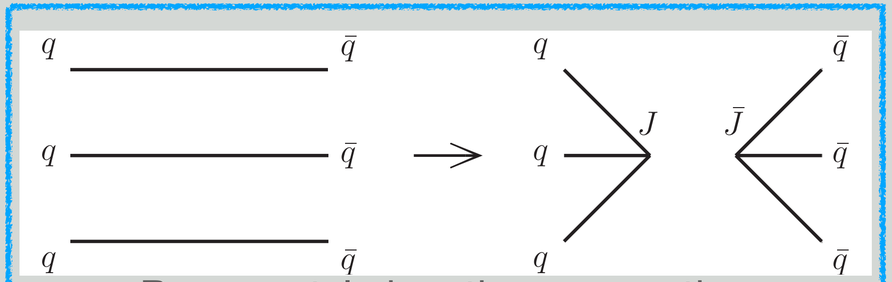
Colour reconnection (e.g. in PYTHIA8)



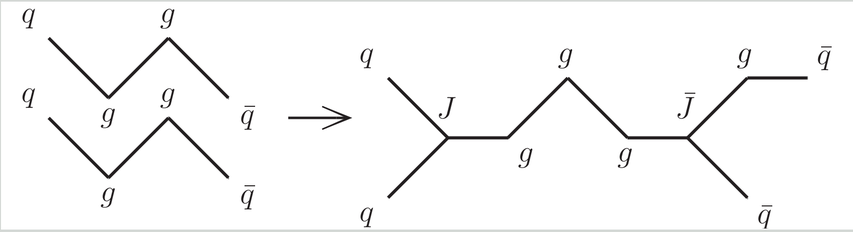
Dipole reconnection



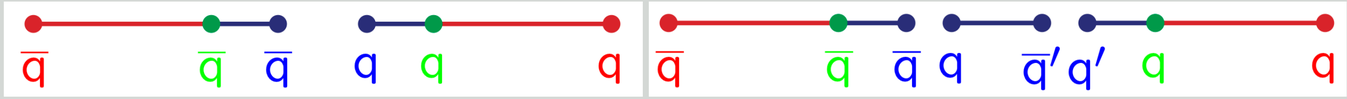
Junction-style reconnection



Baryon-style junction connection



Zipper-style junction connection

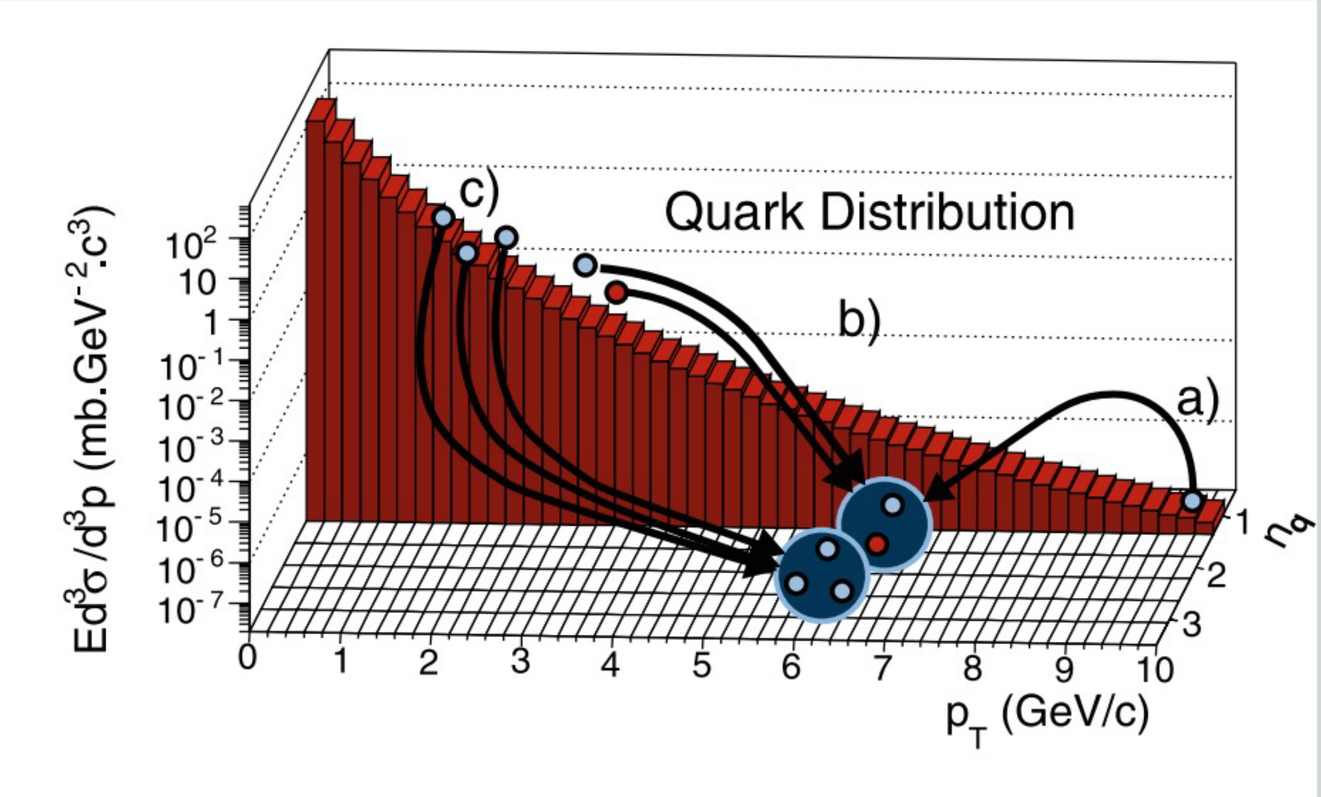


Hadron (baryon) production from string breaking in the Lund String model.

- Colour-reconnection models allow for new colour-association among partons. The argument of partons close in phase space, e.g. in events with significant MPI, **goes beyond independent fragmentation in colour-rich environments.**
- Reconnection as a re-organisation of colour strings gives rise to an **enhanced baryon production**.

J. R. Christiansen, P. Z. Skands, JHEP 08 (2015) 003
B. Andersson et al., Phys. Rept. 97 (1983) 31-145

Recombination



Intuitive picture of how baryon production in medium p_T interval is enhanced by recombination effects.

a) Hadronisation from high p_T parton into meson via fragmentation.

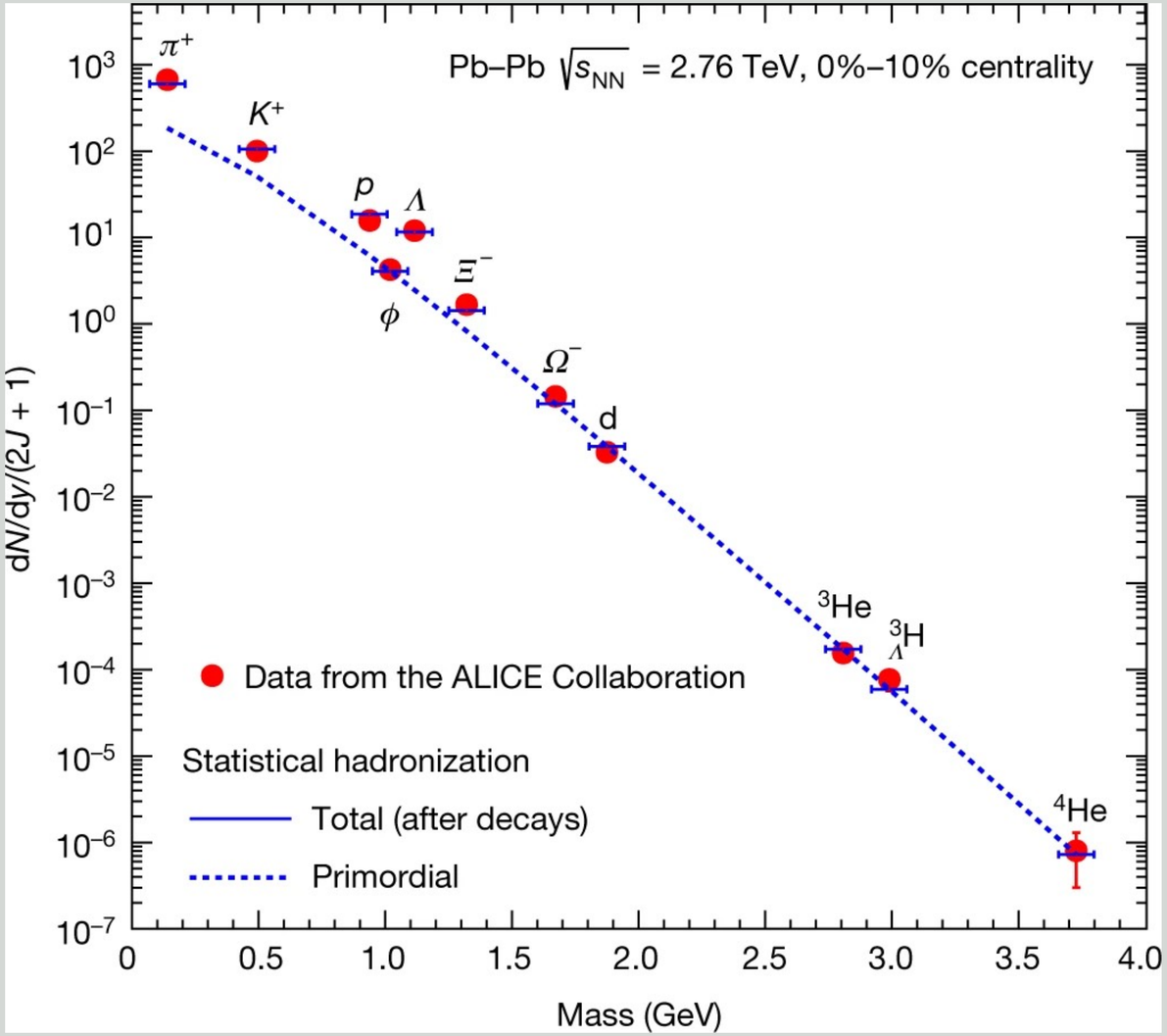
b) Meson created from 2 intermediate-p_T partons.

c) Baryon created from 3 lower-p_T partons.

- QGP is a system of thermalised (deconfined) light partons.
- **Recombination mechanism** relies on the presence of this dense deconfined partonic system.
- Partons in the medium close in phase space can recombine to form hadrons.
- At higher p_T, fragmentation dominates.
- Recombination contributes to additional **formation of baryons relative to mesons** at intermediate p_T.

Greco et al., PRL 90, 202302 (2003)
Fries, R.J. et al., PRL 90, 202303 (2003)
Hwa, Yang, PRC 67, 034902 (2003)

Statistical hadronisation



Andronic, A. et al., Nature 561, 321-330 (2018)

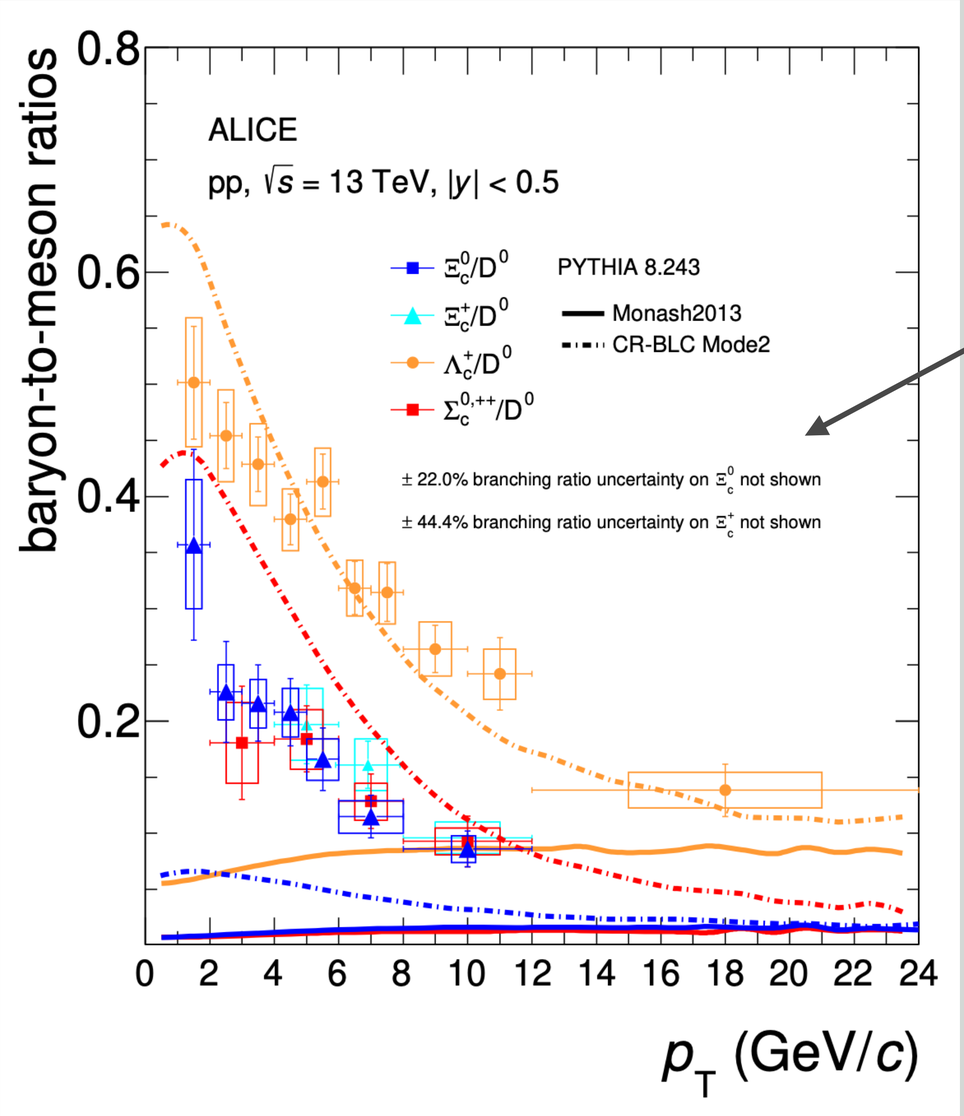
- Statistical hadronisation models (SHM) provide a **macroscopic** approach of hadronisation based on **thermodynamic description**.
  The model depends on
  - temperature and volume of the fireball,
  - chemical potentials,
  - hadron masses, spins.
- Hadron abundances according to hadron-resonance gas in chemical and thermal equilibrium.
  - Freeze-out temperature $T_{\mathrm{ch}} \approx 155\,\mathrm{MeV}$.
- Overall very good agreement between model and measured yield of **light mesons, baryons, strange hadrons and light nuclei**.
- Statistical hadronisation models also tested against measurements in smaller collision systems such as pp.

Meson/meson & baryon/meson ratios

SEE ALSO

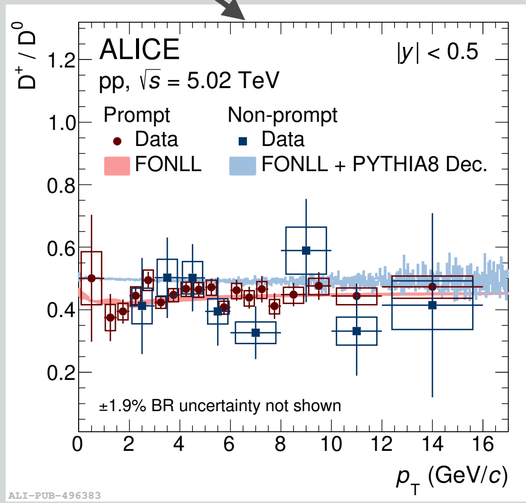
Z. Conesa del Valle: Heavy quarks and quarkonia in small system (WG4&6, Monday)
A. Geiser: Open heavy-flavour/quarkonium associated production at the LHC (WG4-WG6, Monday)
J. Zhu: Open heavy flavour production at the LHC (WG4, Tuesday)
J. Park: Experimental studies of quarkonium production at the LHC in pp and pPb collisions (WG4, Tuesday)
A. Matyja: Exclusive quarkoniom production at the LHC (WG2,4,6&7, Wednesday)

Charm baryon/meson ratios



ALICE, arXiv:2211.04384

- Spectrum of charm **meson-to-meson ratios is well described** by fragmentation and pQCD calculations.
- Charm **baryon-to-meson ratios** measured in pp collisions are **not well described** by PYTHIA8 with Monash tune.
- Only the Λ_c^+/D^0 is described well with PYTHIA8 with **Colour Reconnection** Mode2.
- Other ratios are significantly under- or overestimated by PYTHIA8, e.g. $\Xi_c^{0,+}/D^0$ or $\Sigma_c^{0,++}/D^0$, respectively. Does **strangeness** play an additional role in hadronisation?



ALICE, JHEP 05 (2021) 220

Hadronisation is not universal across collision systems as shown by mismatch between PYTHIA8 Monash tune (tuned to results obtained in e^+e^- and e^-p collisions).

Study multiplicity dependence of baryon-to-meson ratios.

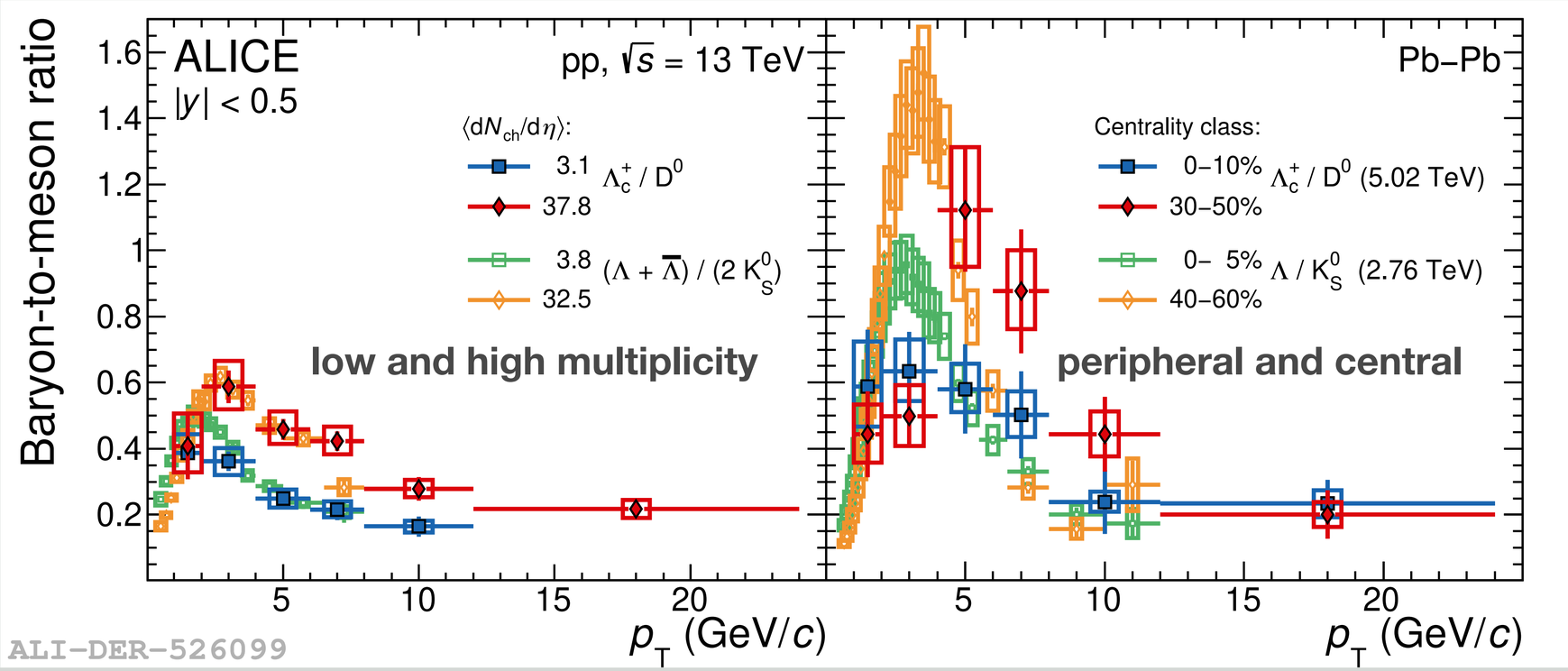
ALICE, Phys. Rev. C 104 (2021) 054905
ALICE, PRL 127 (2021) 202301
ALICE, PLB 781 (2018) 8-19
ALICE, PRL 128 (2022) 012001

ALICE, JHEP 10 (2021) 159
ALICE, PRL 127 (2021) 272001
ALICE, JHEP 04 (2018) 108

Fragmentation

Recombination

Baryon/meson ratios vs. multiplicity

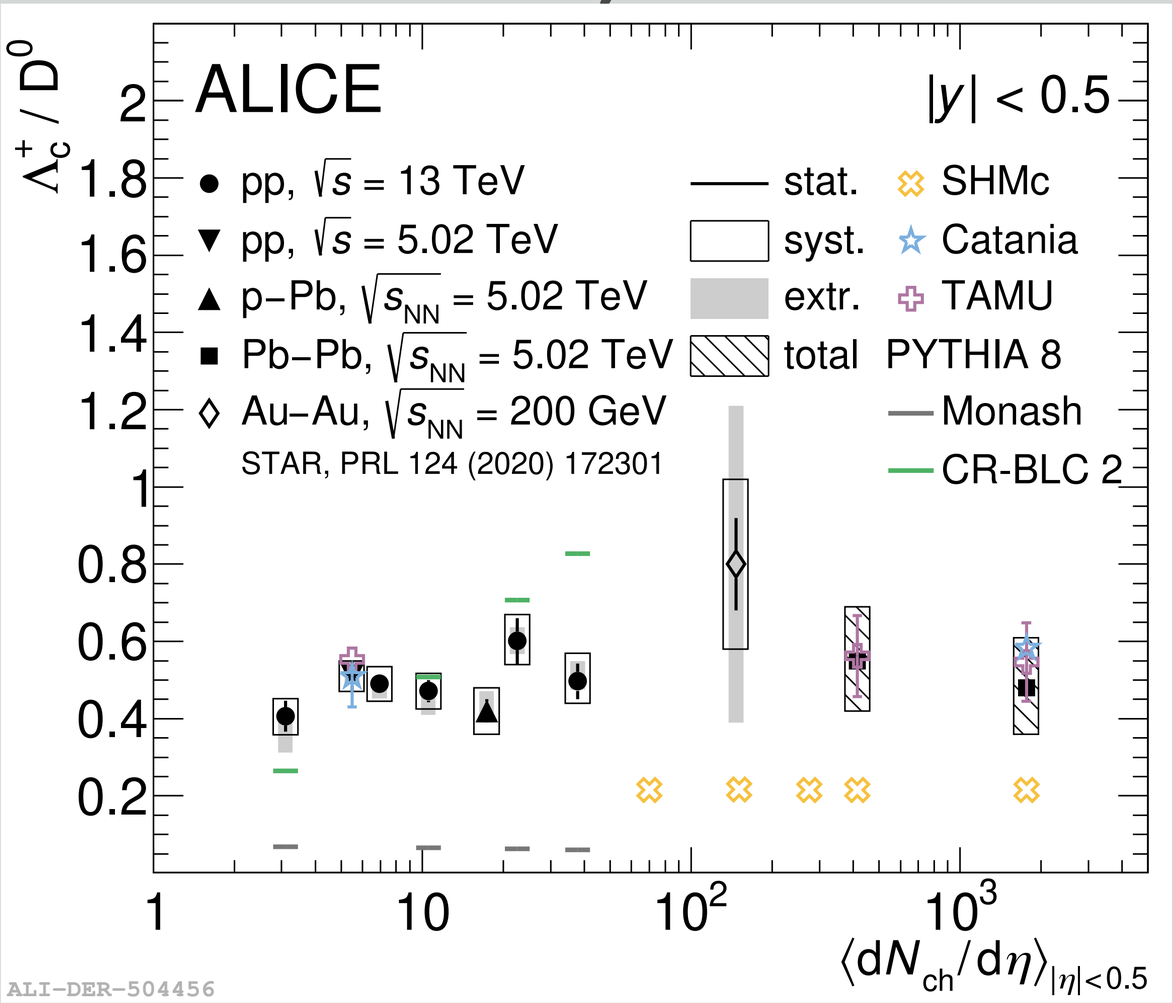


ALICE, PLB 829 (2022) 137065
ALICE, EPJC 80, 167 (2020)
ALICE, arXiv:2112.08156
ALICE, PRL 111 (2013) 222301

Are there common mechanisms at play in pp and Pb–Pb collision systems which explain the modified $c \rightarrow$ baryon formation in both systems?

- Comparing baryon-to-meson ratios in the light- and heavy-flavour sector in different **multiplicities** in pp (left plot) and different **centrality** regions in Pb—Pb collisions (right plot).
- Ratios suggest a **common modification of baryon-to-meson production** in pp as well as in Pb—Pb (right plot).
- Modification more pronounced (larger ratio) in Pb—Pb compared to pp. Can be interpreted by **hadronisation via recombination** of quarks in the QGP medium.

Charm baryon/meson ratios vs. multiplicity

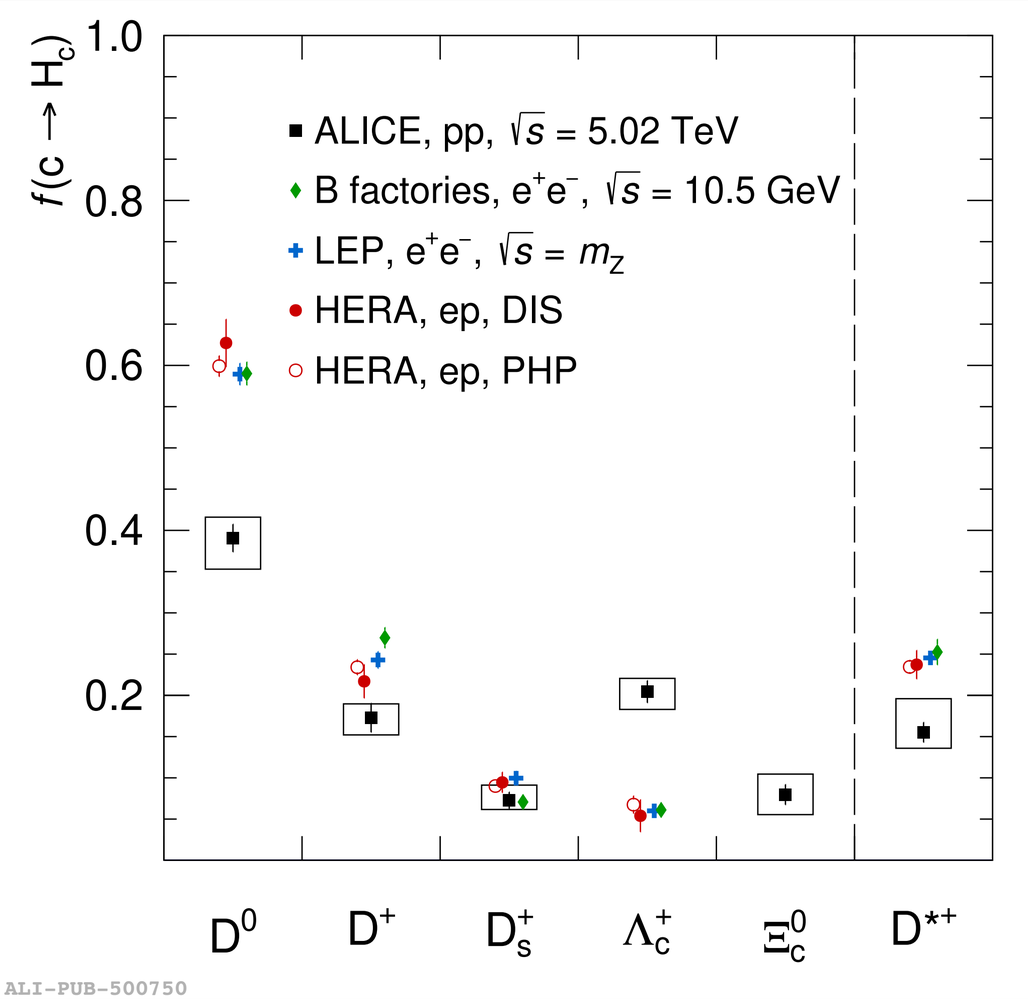


- No significant multiplicity dependency of p_T integrated ratios in data within uncertainties.
- No significant difference moving from pp to Pb—Pb.
- **No enhancement** of integrated Λ_c^+/D^0 ratio within uncertainties.
- **Redistribution of p_T among charm mesons and baryons** seems to be the main reason for the difference in the p_T spectrum (previous slide).

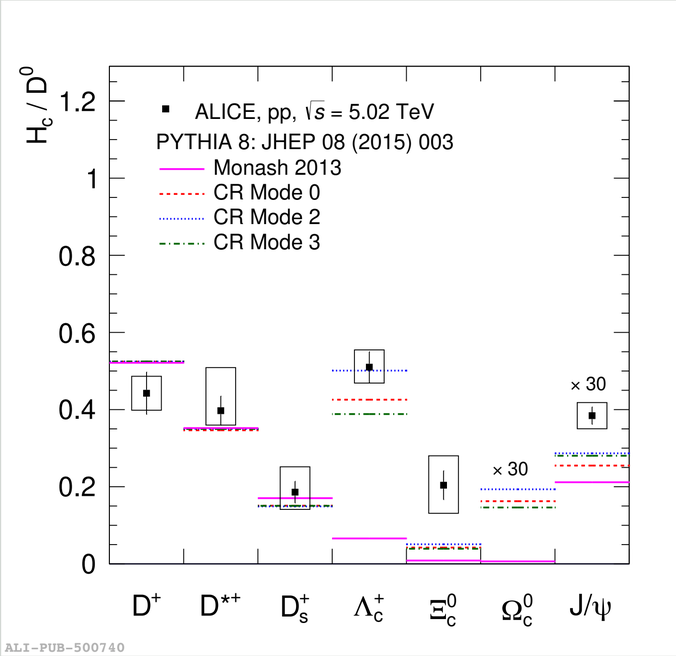
ALICE, PLB 829 (2022) 137065
ALICE, Phys. Rev. C 104 (2021) 054905
ALICE, PRL 127 (2021) 202301
ALICE, arXiv:2112.08156
STAR, Phys. Rev. Lett. 124, 172301 (2020)

SHMc: A. Andronic et al., JHEP 07 (2021) 035
TAMU: M. He, R. Rapp, PRL 124, 042301 (2020)
Catania: S. Plumari et al., EPJC 78 (2018) 348

Charm fragmentation fractions



- Charm fragmentation fraction measured for the first time using all charm-hadron ground states.
  [Ξ_c^0 fragmentation fraction measured for the first time.]
- Charm fragmentation fractions depend on the collision system.



As a consequence, PYTHIA8 with Monash tune is not able to describe the data well.

CR models in some cases describe the data better, e.g. for Λ_c^+.

Clearly, more accurate model descriptions are required which are capable of describing the observations.

Fragmentation fractions different in e^+e^- and pp collision systems. This contradicts the theory of universal hadron formation - or we are still missing a piece of the hadronisation/fragmentation mechanisms in general!

ALICE, Phys. Rev. D 105 L011103 (2022)

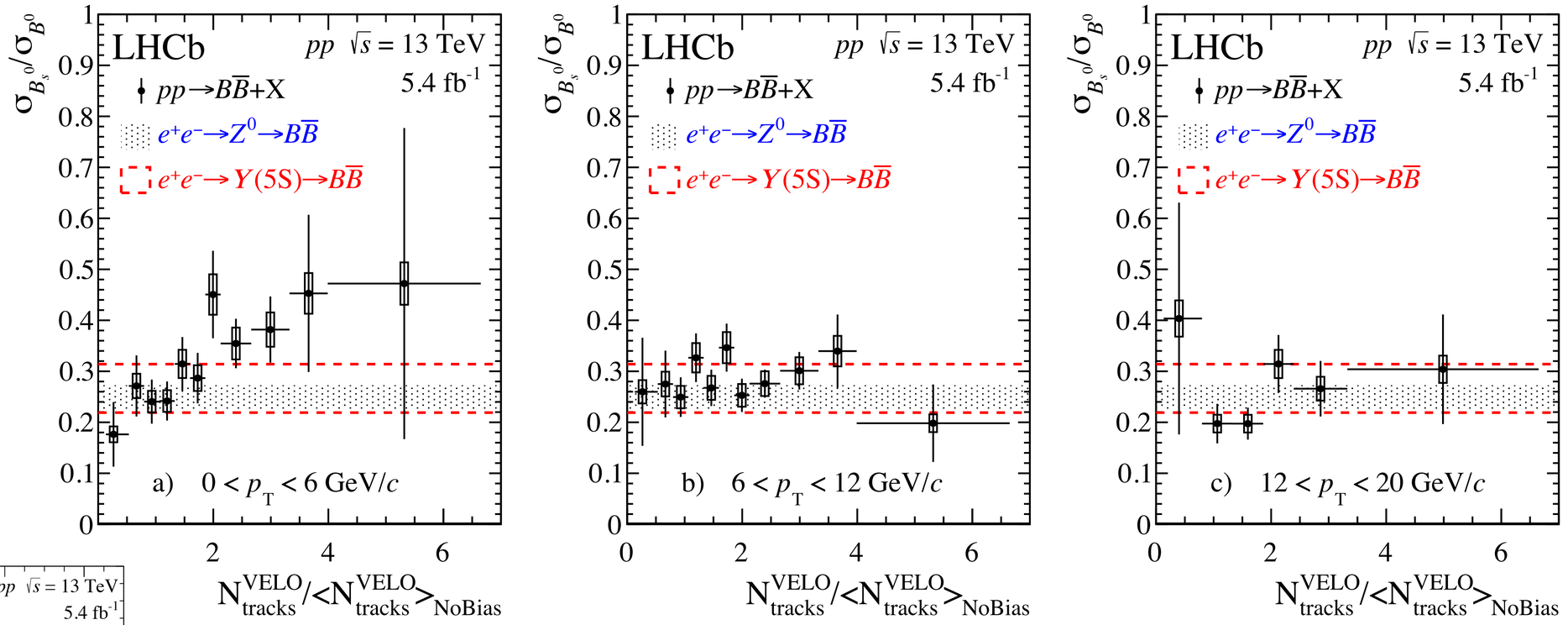
Fragmentation

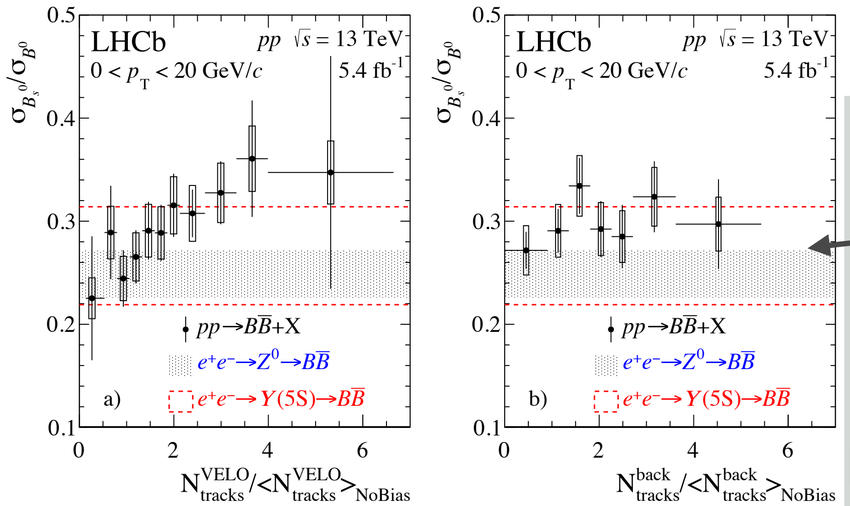
Recombination

B_s^0/B^0 production ratios

LHCb, arXiv:2204.13042

- In low p_T interval there is evidence (3.4σ), for an increasing ratio.
- Ratios in intermediate and high p_T interval are in agreement with measurements in e^+e^- collisions.





According to the authors these results could point to hadronisation via parton recombination in dense partonic environments. But more precise measurements are needed.

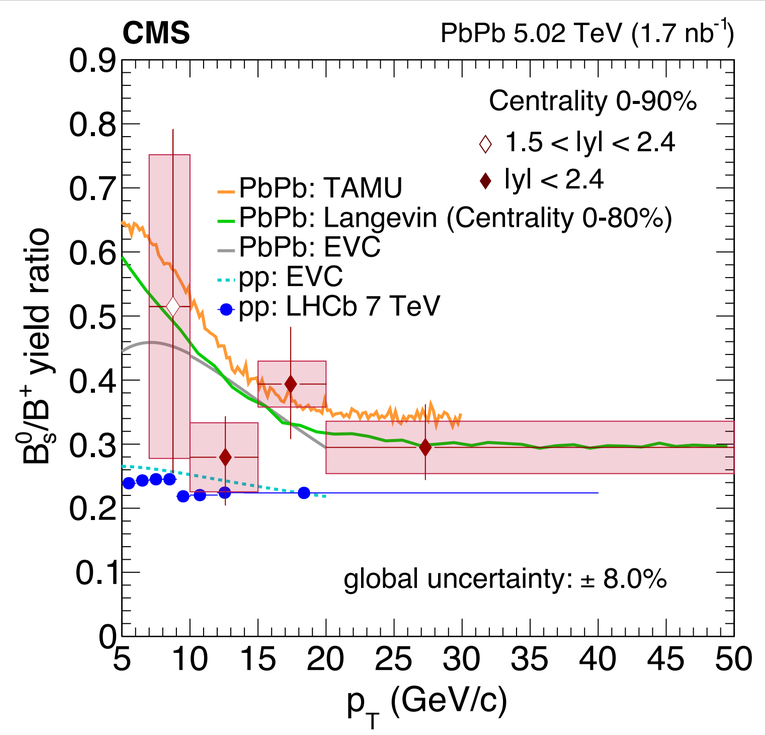
No significant dependence with backward multiplicity.

Fragmentation

Recombination

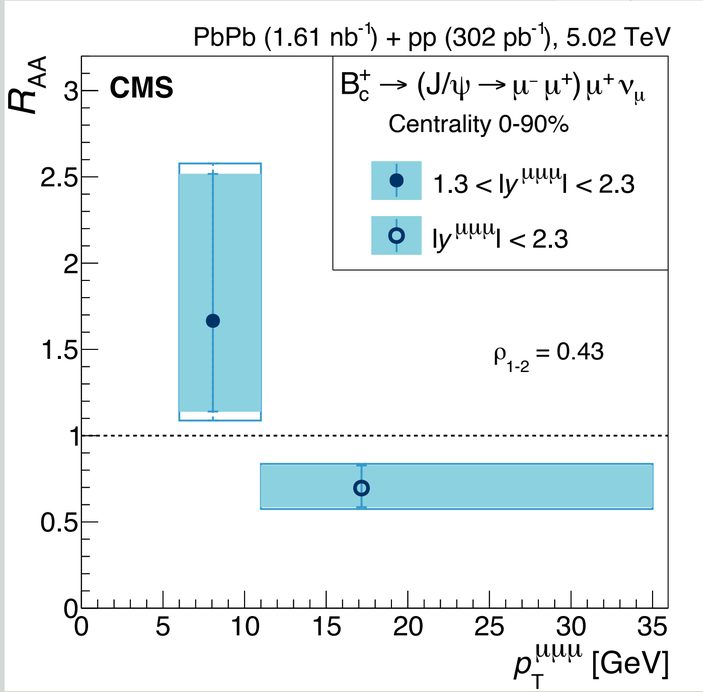
B_s^0/B^+ in Pb–Pb and observation of B_c^+ in Pb–Pb

CMS, PLB 829 (2022) 137062

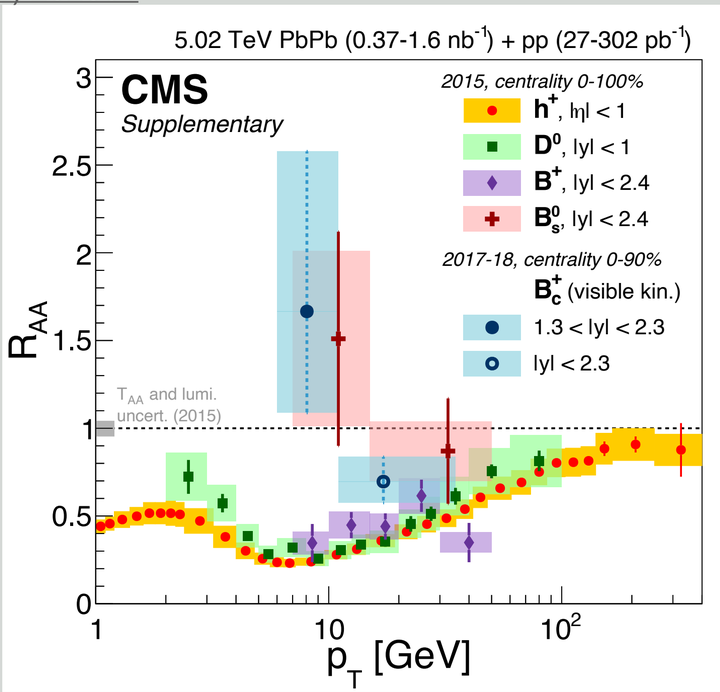


- First observation at above 5σ of B_s^0 in nucleus-nucleus collisions.
- Within uncertainties, the B_s^0/B^0 ratio in Pb—Pb is compatible with the results from pp.
- Within uncertainties, recombination models describe the data.

CMS, PRL 119, 152301 (2017) CMS, PLB 782 (2018) 474
CMS, EPJC 78 (2018) 509 CMS, JHEP 10 (2018) 174
CMS, PRL 128 (2022) 252301



- First observation of B_c^+ in Pb—Pb collisions.
- $R_{AA} > 1$ at lower p_T, increased production of B_c^+ in that kinematic region compared to pp.
- On the other hand, $R_{AA} < 1$ at higher p_T.



- Similar values for R_{AA} of B_s^0. But different for heavy-flavour mesons without additional heavy-flavour/strange quark.

More precise measurements are needed to further investigate a possible enhancement of B_s^0 and B_c^+ production.

Jet fragmentation

Going to higher p_{T}

SEE ALSO
C. B. Barrera: Measurements of jet substructure observables in ATLAS and CMS experiments (WG1&5, Monday)
R. Ehlers: Jet substructure measurements in heavy-ion collisions (WG5, Wednesday)

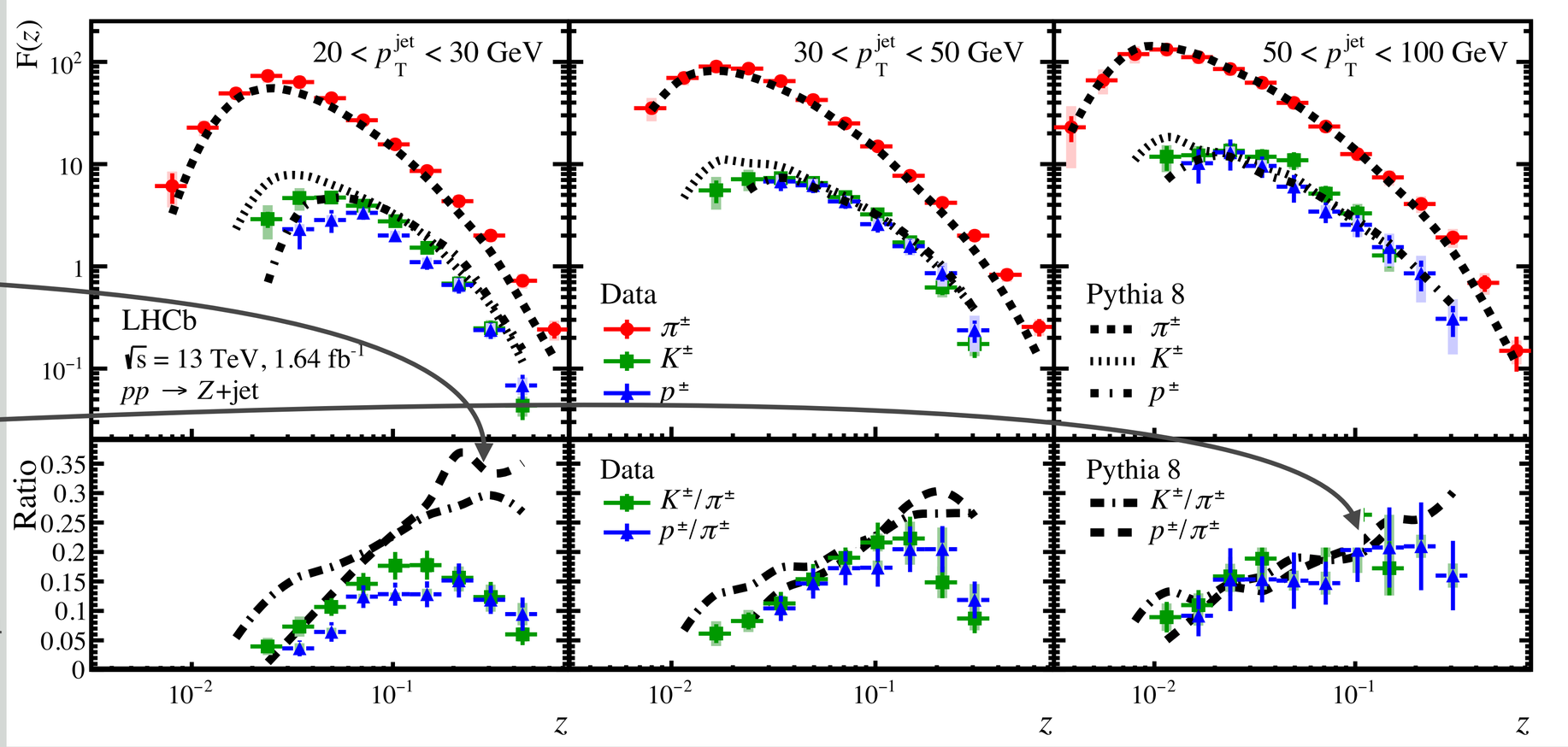
Jet fragmentation functions in pp

- Measure of light-flavour hadron momentum fraction collinear with the jet momentum in jets recoiling against a Z-boson.
- Longitudinal and transverse profiles of identified hadrons inside predominantly light-quark-initiated jets measured for the first time.

$$z = \vec{p}_{\text{had}} \cdot \vec{p}_{\text{jet}} / \left| \vec{p}_{\text{jet}} \right|^2$$

Proton (kaon and pion) fraction underestimated (overestimated) by PYTHIA8 in lowest p_T interval.

Model description better in higher p_T interval.



Results crucial for better understanding of parton shower and hadronisation in pp. Need for further MC tuning in order to describe jet substructure well.

LHCb, arXiv:2208.11691

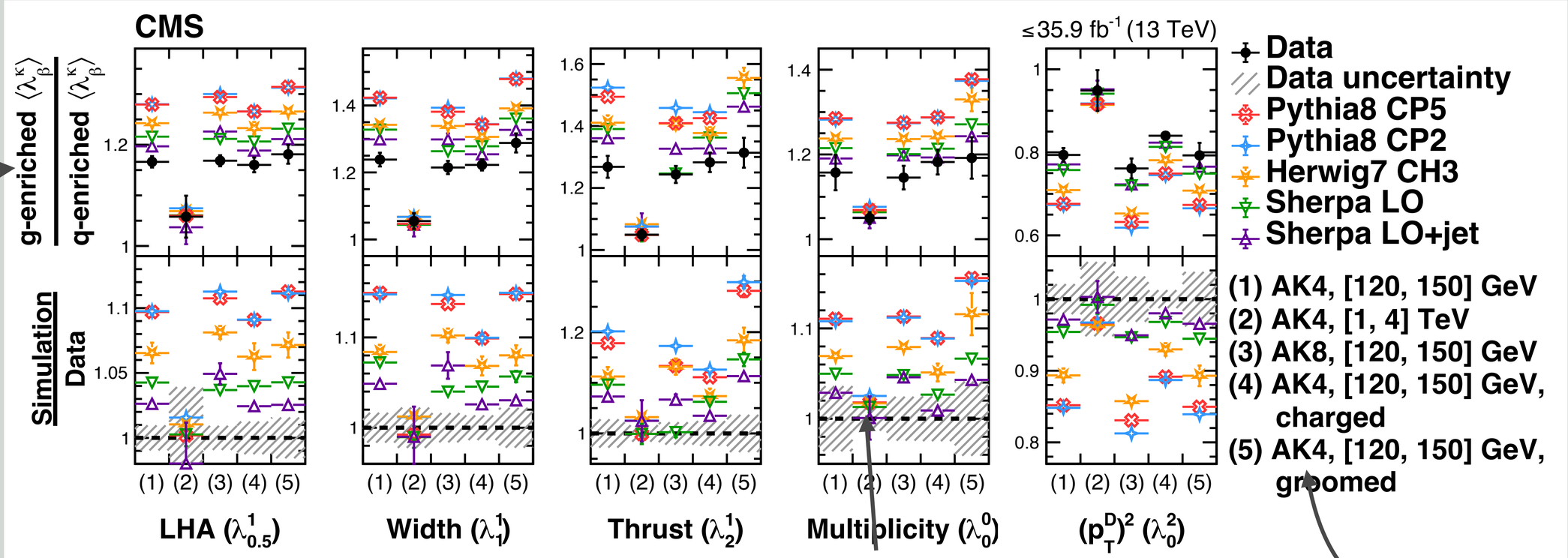
Jet substructure, gluon- and quark-initiated jets

- Compare generalised jet angularities λ_κ^β measurements of gluon- and quark-initiated jets to **various model predictions**.
- This analysis has been done for quark-enriched jets in Z+jet events for the first time.

$$\lambda_\kappa^\beta = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta$$

Ratio of mean angularity parameter for gluon- and quark-enriched jets

Results crucial and show the need for further MC tuning in order to describe jet substructure well.



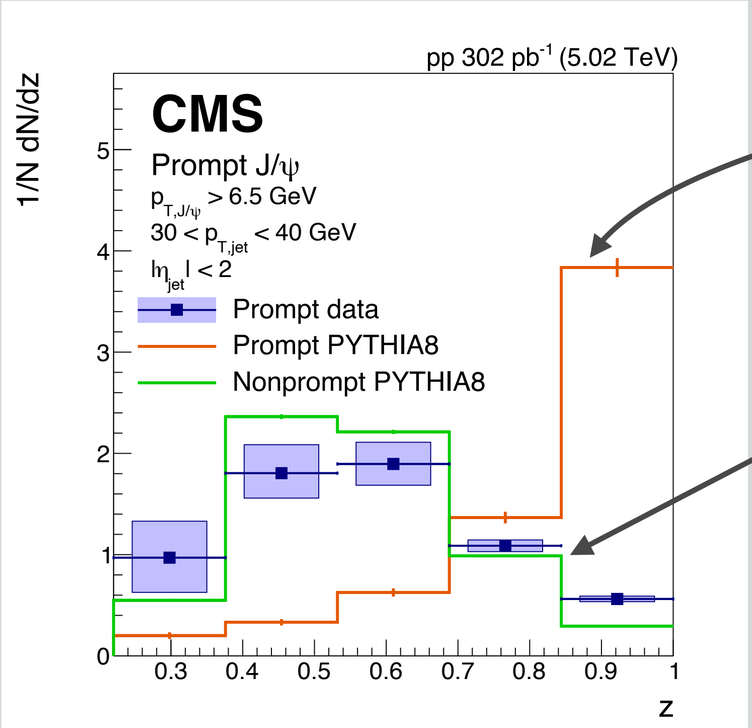
CMS, JHEP 01 (2022) 188

Best description of the data in highest jet p_T interval (2) where selected samples are expected to have similar similar composition of quark- and gluon-initiated jets.

anti-k_T with radius parameter 0.4 or 0.8

Prompt J/ψ fragmentation in jets

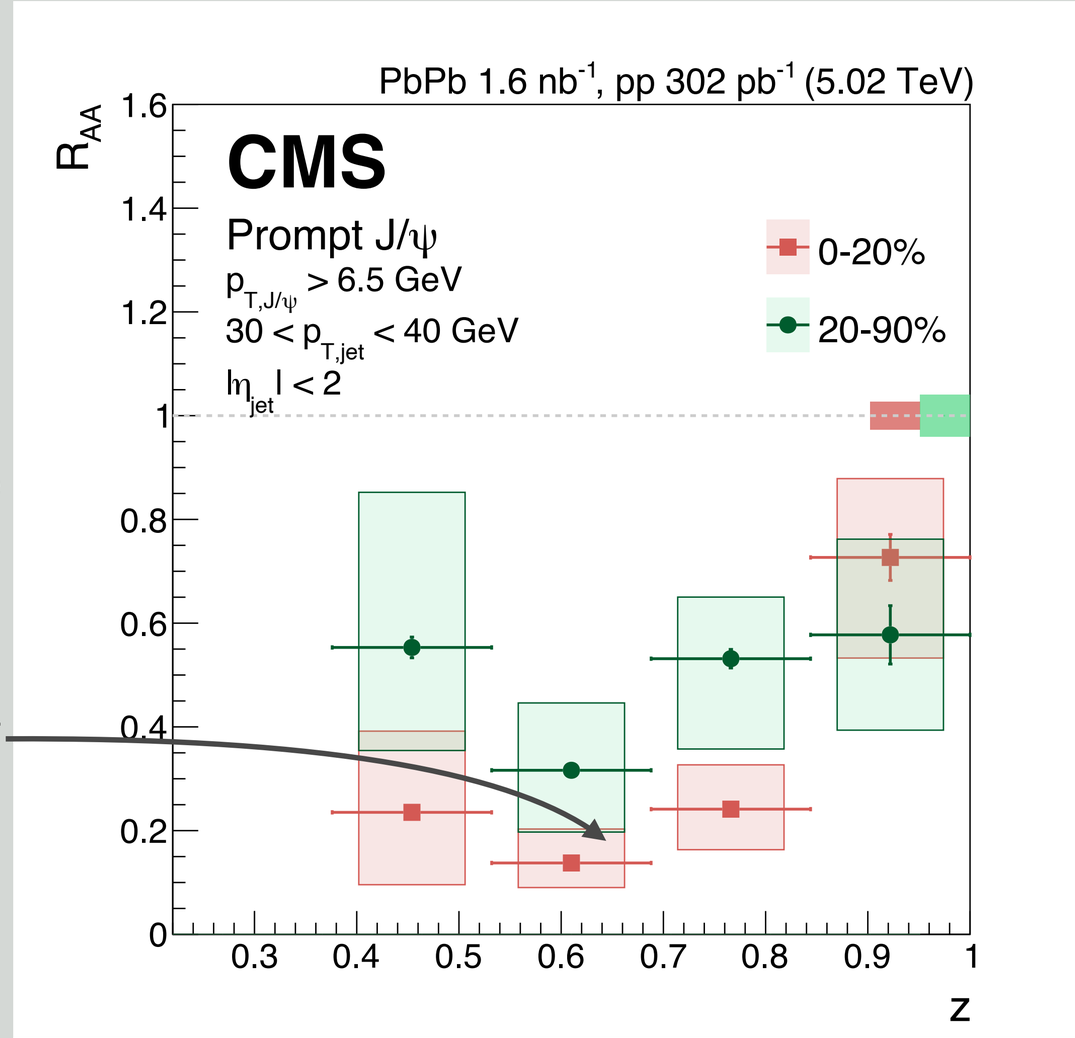
- J/ψ measured as a function of jet fragmentation variable z in pp and Pb—Pb.



PYTHIA8 predicts prompt J/ψ production with less surrounding jet activity.

Indeed, predictions of non-prompt J/ψ predictions resemble the data better.

Trend of suppressed J/ψ production with higher surrounding jet activity in central Pb—Pb collisions.



Suppression in line with interpretation of J/ψ being formed late in the shower development. Significant time for shower to interact with QGP.

CMS, PLB 825 (2021) 136842

Tuning and testing generators, model studies

In-depth model testing

SEE ALSO

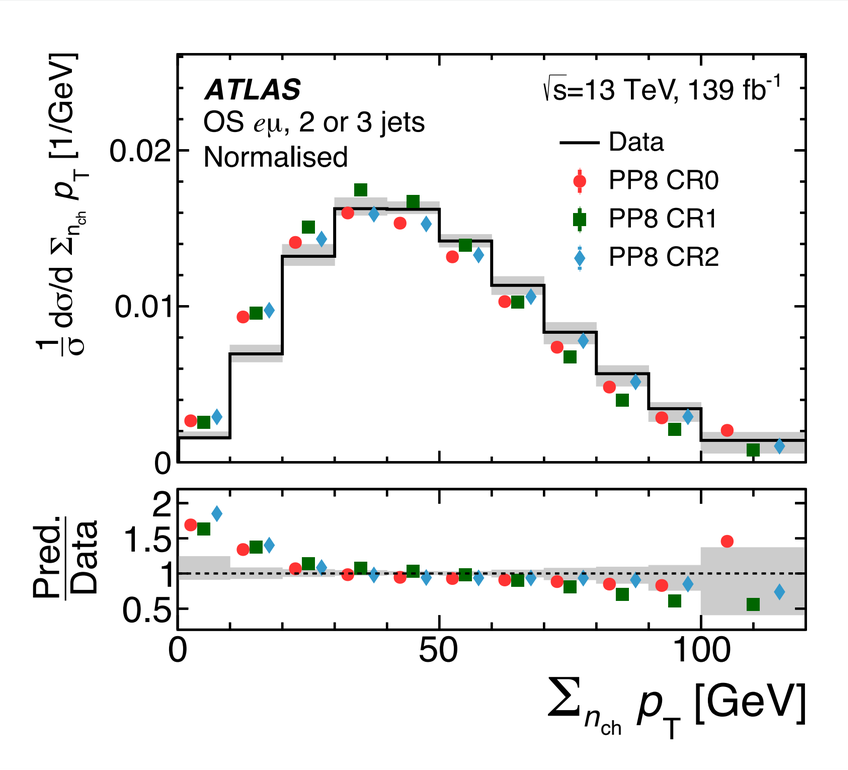
M. Seidel: Tuning of generators (WG2, Monday)

T. Menzo: Machine Learning for hadronisation (WG2, Monday)

Constraining colour reconnection in $t\bar{t}$ events

- For instance, $t\bar{t}$ decay products not sensitive to CR in current CR implementations.
  [hadronisation scale $\approx 1\,\mathrm{fm} > 0.2\,\mathrm{fm}$ (top-quark average decay length)]
- Thoroughly tested PYTHIA8 and HERWIG7 and various CR settings and observables sensitive to CR.
- In addition testing $t\bar{t}$-specific CR models of PYTHIA8.

$\sum_{n_{\mathrm{ch}}} p_{\mathrm{T}}$ Sum of transverse momentum of charged particles in certain multiplicity interval.



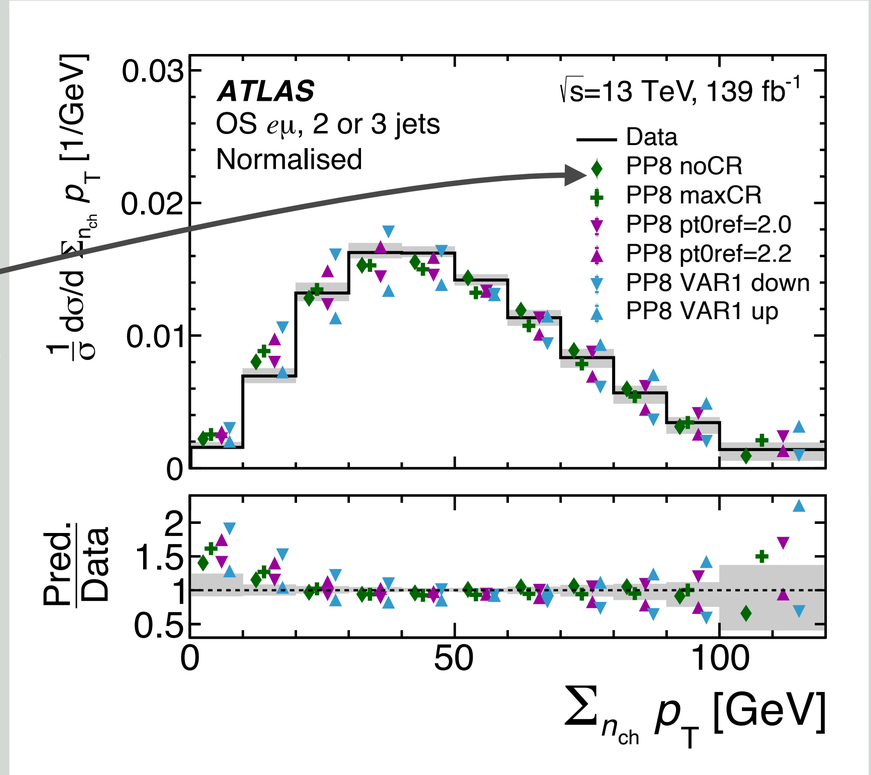
Different PYTHIA8 CR models do not describe the data well, independent of CR model tune.

Test impact of single CR parameters.

E.g. here no impact of CR-strength, however, strong impact on other observables.

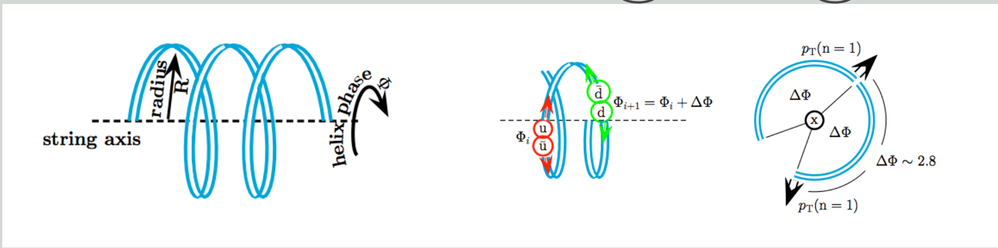
Useful and important studies to tune CR models for hadronisation.

ATLAS, arXiv:2209.07874



Helical string fragmentation

ATLAS, CONF-2022-055



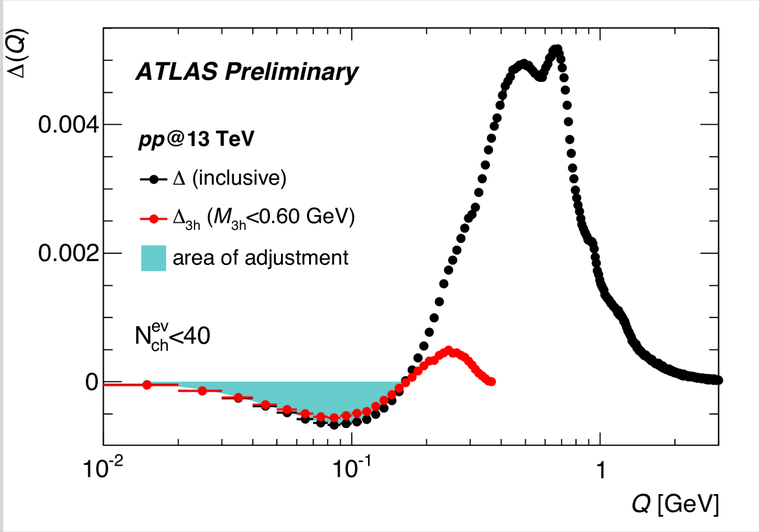
Fragmentation on a helical string. Phase difference between adjacent hadrons is $\Delta\Phi$, string tension κ and Radius R.

Model values:
$\Delta\Phi \simeq 2.8\,\mathrm{rad}$
$\kappa R \simeq 0.07\,\mathrm{GeV}$

$$\Delta(Q) = \frac{1}{N_{\mathrm{ch}}}\left[N^{\mathrm{OS}}(Q) - N^{\mathrm{LS}}(Q)\right]$$

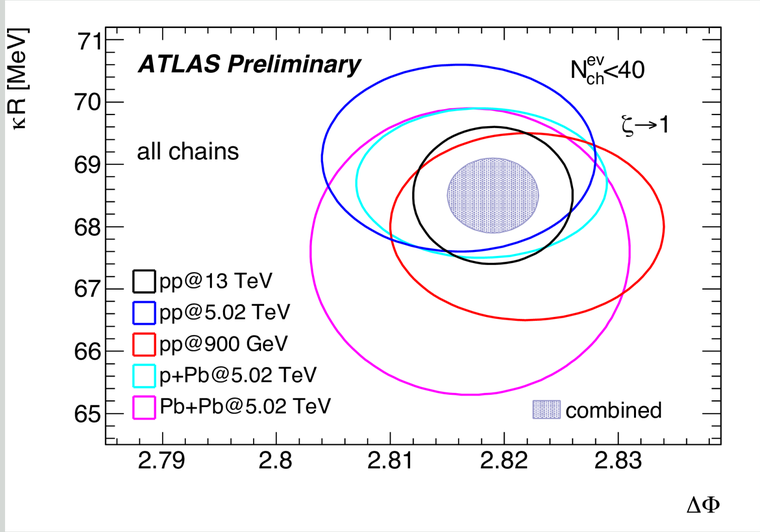
$$Q(p_i, p_j) = \sqrt{-(p_i - p_j)^2}$$

Test model predictions of a helical string fragmentation against data, covering different collision systems and centre-of-mass energies.

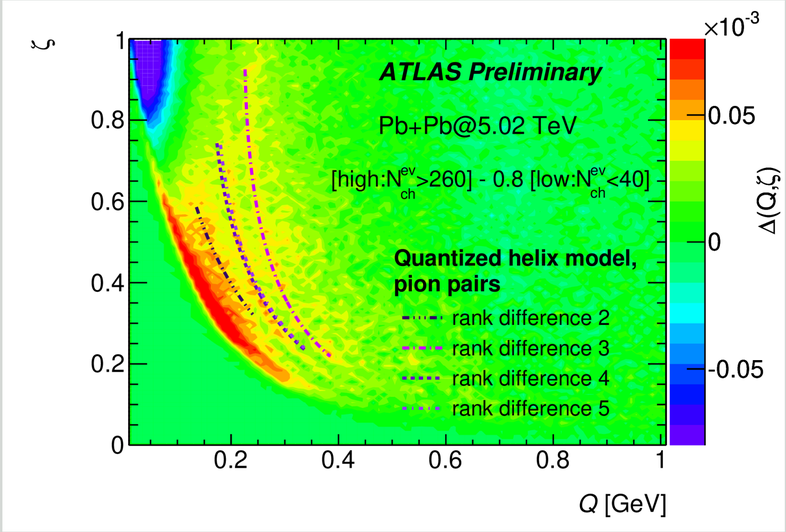


Excess of like-sign hadron pairs at low Q. Can be explained by low-mass 3-hadron chains.

Cannot be described by current MC generators.



Fits using minimum and maximum of Q-points yield $\Delta\Phi$ and κR which are in agreement over various centre-of-mass energies and collision systems.
Excess of like-sign hadron pairs seems to be affect of hadronisation.



$$\zeta\left(\vec{p}_i, \vec{p}_j\right) = \min\left(|\vec{p}_j|/|\vec{p}_i|, |\vec{p}_i|/|\vec{p}_j|\right)$$

After subtracting hard component from Pb—Pb, the data reveals striped in the (ζ, Q) plane as predicted by the helical model.

The journey continues…

- **The study of hadronisation is a very active and diverse field of research.**
  Though more and more insights are collected, there is still a lot of interesting uncharted territory.
- Many hints for non-universal fragmentation (hadronisation) in pp collisions provided by multiple studies of **baryon-to-meson** ratios in the light- and heavy-flavour sector; or there are missing pieces in our understanding and description of fragmentation.
- In addition to c-hadrons, ongoing efforts to further investigate open heavy-flavour b**-mesons** and their hadronisation properties in Pb—Pb and pp collisions.
  $\mathrm{B_c^+}$ mesons observed for the first time in Pb—Pb collisions.
- Hints for (multiplicity-dependent) **suppression of excited quarkonia** in pp and Pb—Pb.
- **Jet-substructure** measurements provide valuable insight into hadronisation mechanisms as well as stringent tests of models, in pp as well as in Pb—Pb.
- Variety of measurements **suggest altered hadronisation mechanism towards more dense final state**, in pp as well as in Pb—Pb collisions.

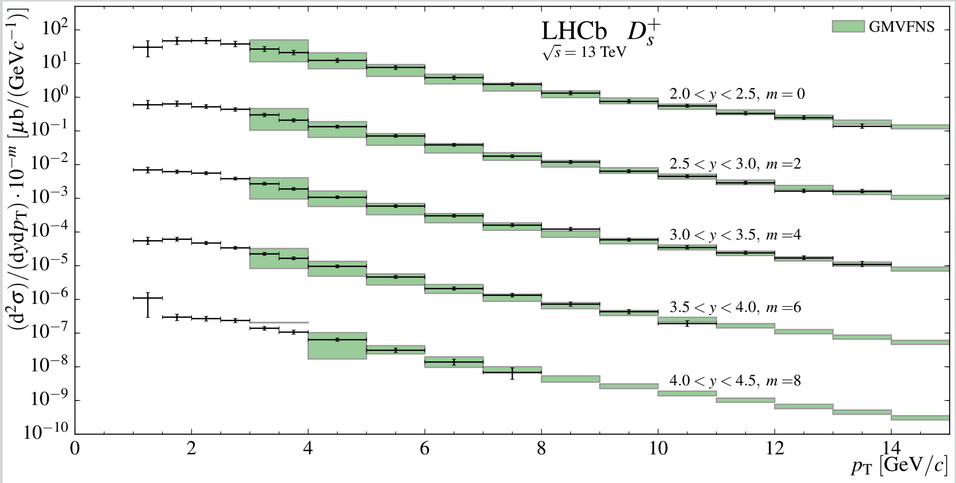
In comparison with MC event generators and hadronisation models, these measurements provide better and better understanding of hadronisation mechanisms and QCD in general.

Looking forward to continue this exciting journey with fresh LHC Run3 data!

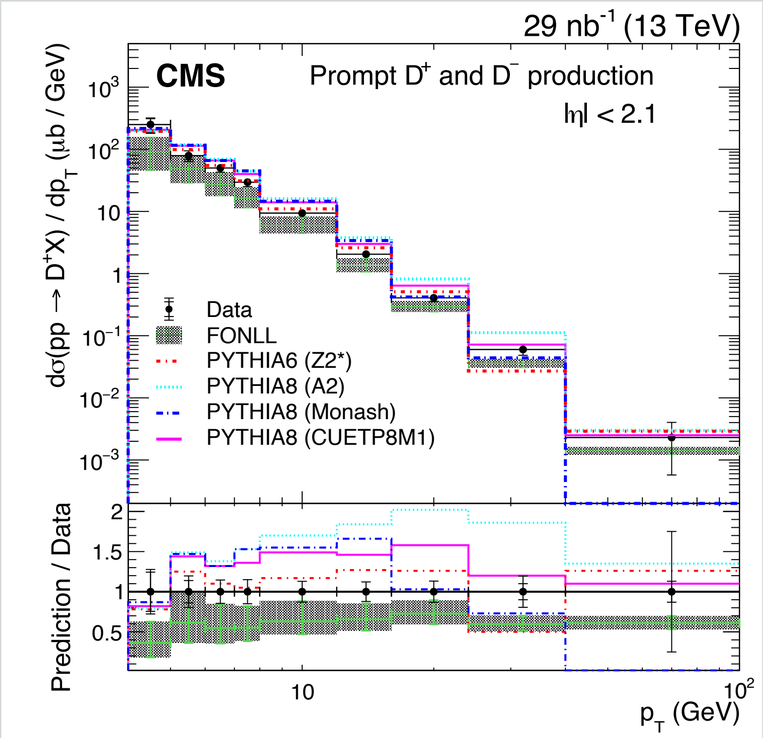
BACKUP

Charm and beauty meson production

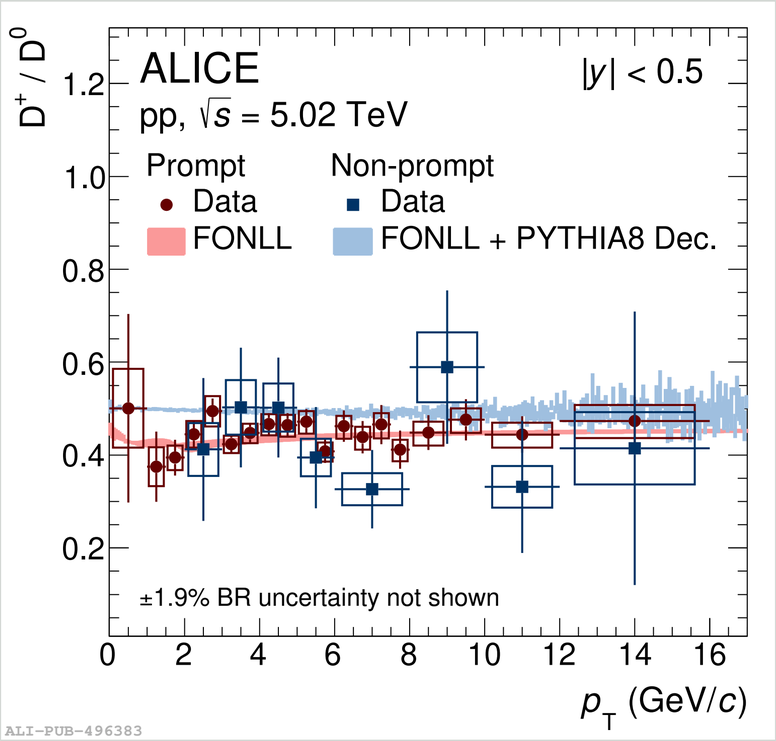
LHCb, JHEP 05 (2017) 074



CMS, JHEP 11 (2021) 225



ALICE, JHEP 05 (2021) 220

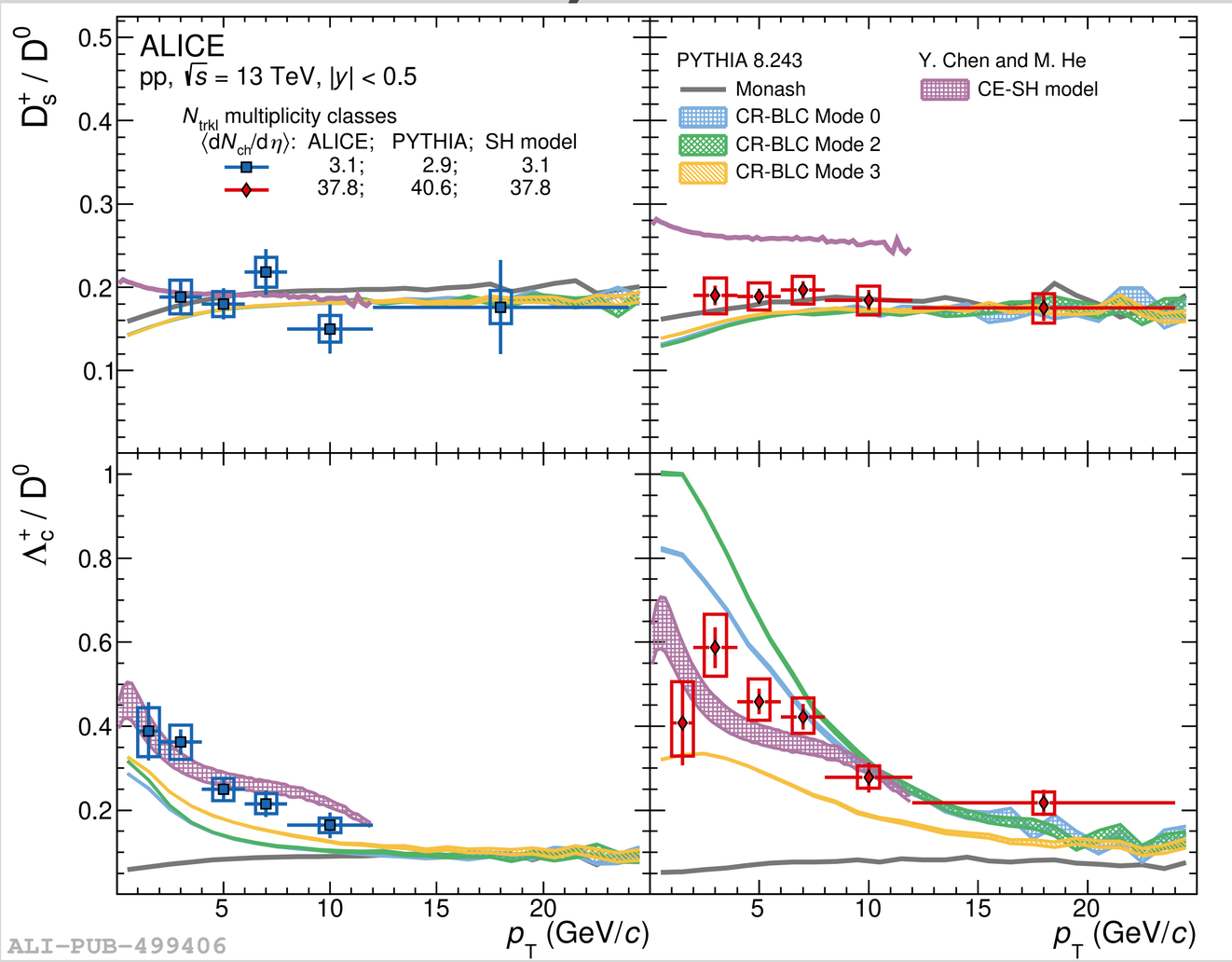


- Prompt($c \to$ D)/non-prompt ($b \to$ D) charmed-meson production in pp collisions is well described by fragmentation and pQCD calculations (FONLL and GM-VFNS).
- Different rapidity and momentum ranges as well as centre-of-mass energies are covered.
- **Production ratios** are sensitive to the fragmentation part of the factorisation theorem

Predictions based on the factorisation approach with fragmentation functions tuned on e^+e^- and e^-p describe the data well.

FONLL: M. Cacciari, et al, JHEP 10 (2012) 137
GM-VFNS: B. A. Kniehl et al, EPJC 72 (2012) 2082

Charm baryon/meson ratios vs. multiplicity

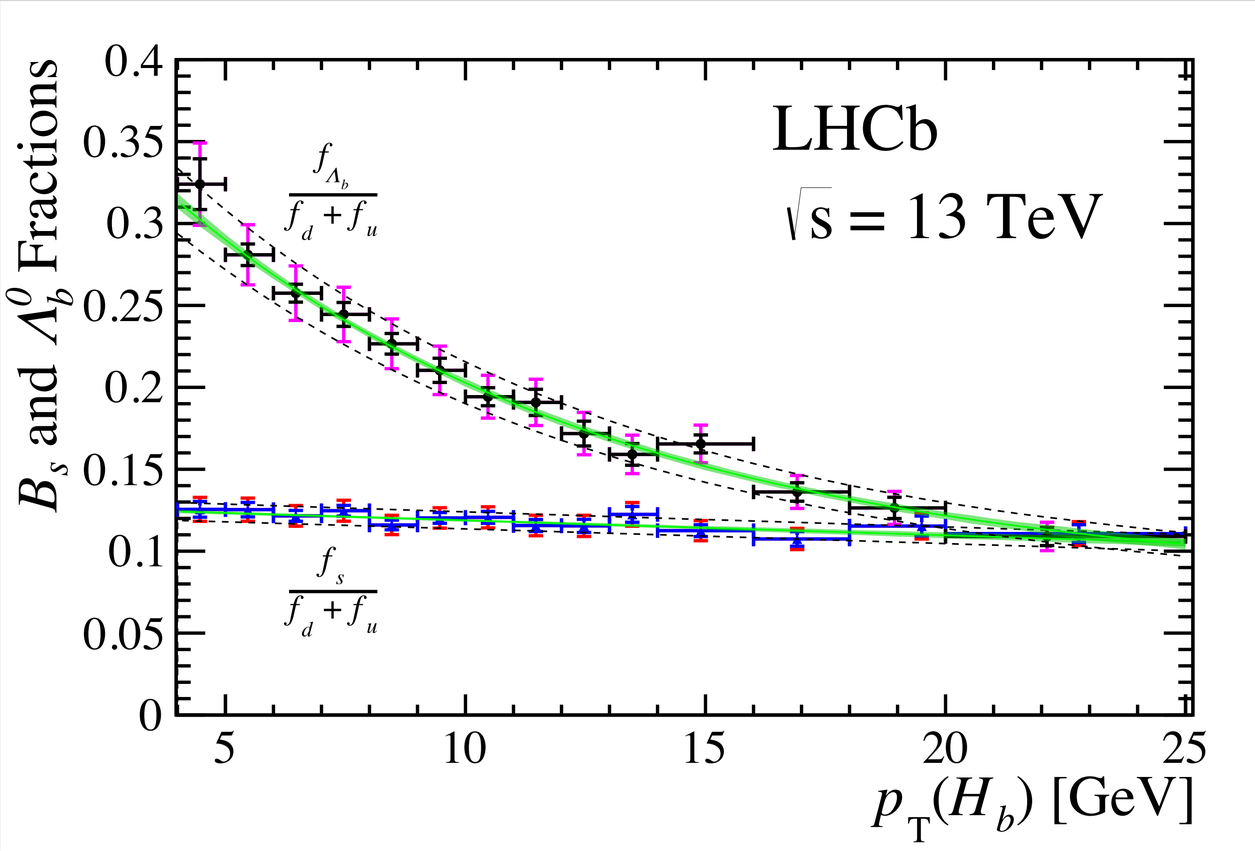


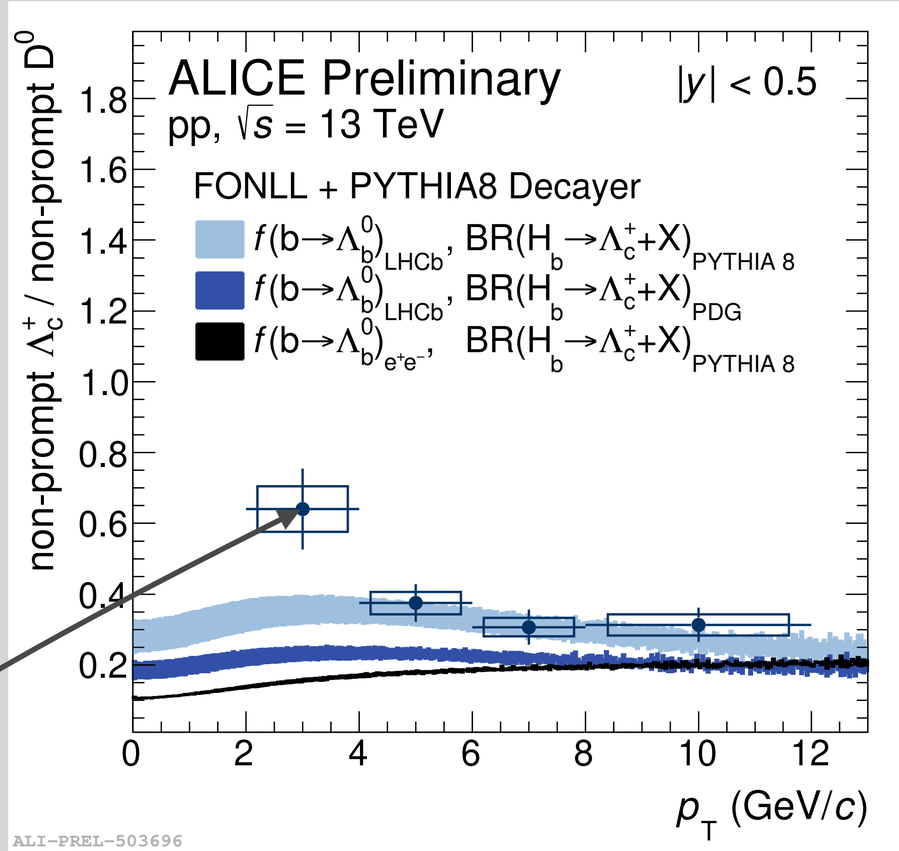
ALICE, PLB 829 (2022) 137065

- No multiplicity dependence observed for D_s^+/D^0 meson ratio as function of p_T.
- Baryon-to-meson ratio Λ_c^+/D^0 as function of p_T changes in shape with increasing multiplicity. Shape and magnitude described by **CR models as well as SHM (CE-SH)**.
- Not described by model tuned to measurements taken in e^+e^- collisions (PYTHIA8 with Monash tune).

Modified $c \to$ baryon formation compared to charm mesons. Trend increases with multiplicity and most prominent at medium and lower p_T.

Beauty baryon & meson production, ratios





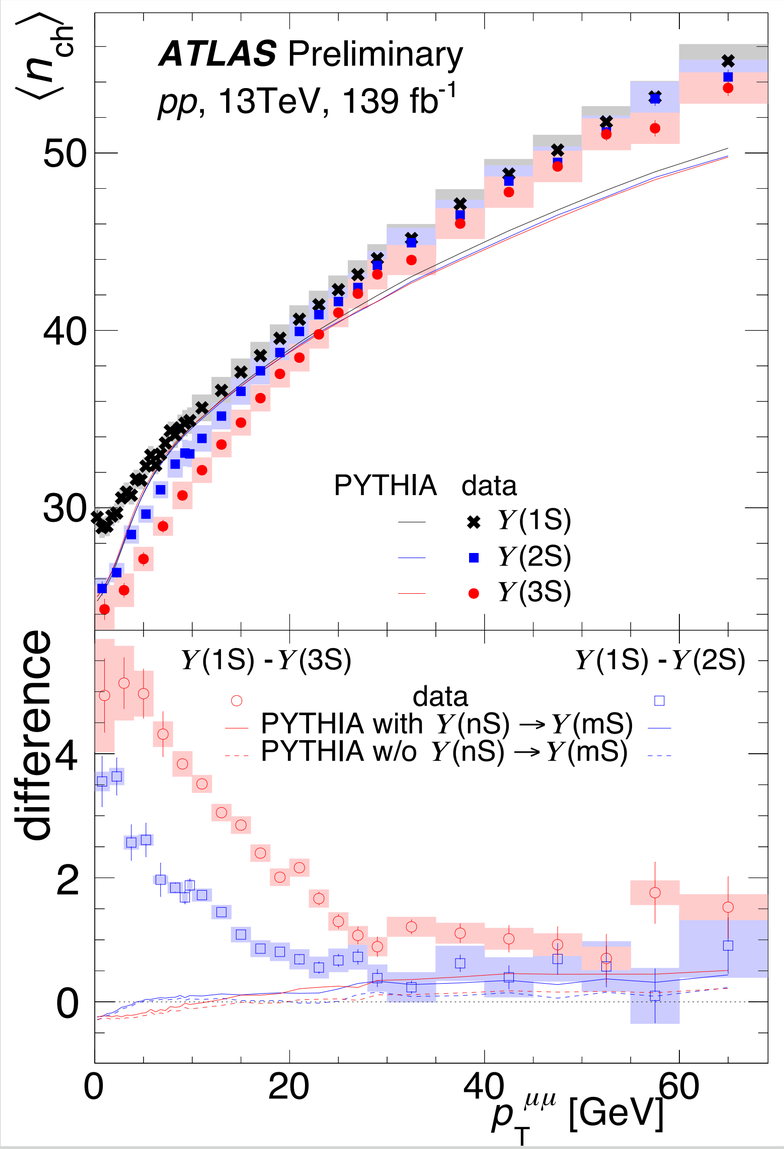
- Beauty baryon fraction needed as input to derive non-prompt charm baryon-to-meson ratios.
- Λ_b/B fraction strongly p_T dependent, only mild dependence for B_s^0/B.

- Beauty baryon fraction needed as input to derive non-prompt charm baryon-to-meson ratios.

Data only sufficiently described using fractions measured by LHCb. At low p_T the data are underestimated. Potential hint at hadronisation beyond pure in-vacuum fragmentation in the beauty sector.

LHCb, Phys.Rev. D 100 (2019) no.3, 031102

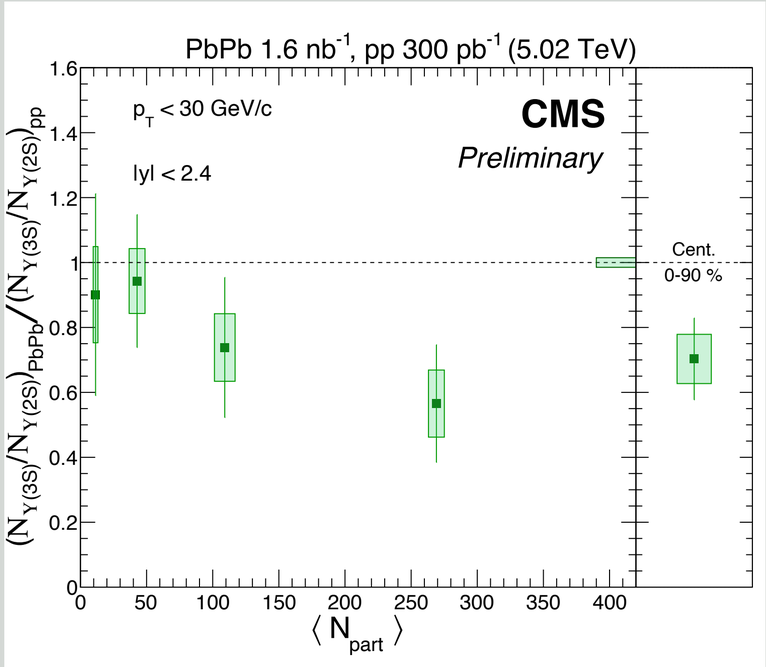
Bottomonia, $\Upsilon(nS)$



ATLAS, CONF-2022-023

- With decreasing $p_T^{\Upsilon\to\mu^+\mu^-}$ significantly less $\Upsilon(2S)$ and $\Upsilon(3S)$ are produced compared to $\Upsilon(1S)$ in pp collisions.
- Effect stronger for $\Upsilon(3S)$ compared to $\Upsilon(2S)$.
- PYTHIA8 does not describe the data well but predicts similar p_T distributions for all $\Upsilon(nS)$ states.

Possible suppression of excited $\Upsilon(nS)$ production or enhancement of $\Upsilon(1S)$ production with decreasing multiplicity.



CMS-PAS-HIN-21-007

- Double ratio comparing pp and Pb—Pb suggests increasing suppression of $\Upsilon(3S)$ compared to $\Upsilon(2S)$ with increasing number of participants in collision.

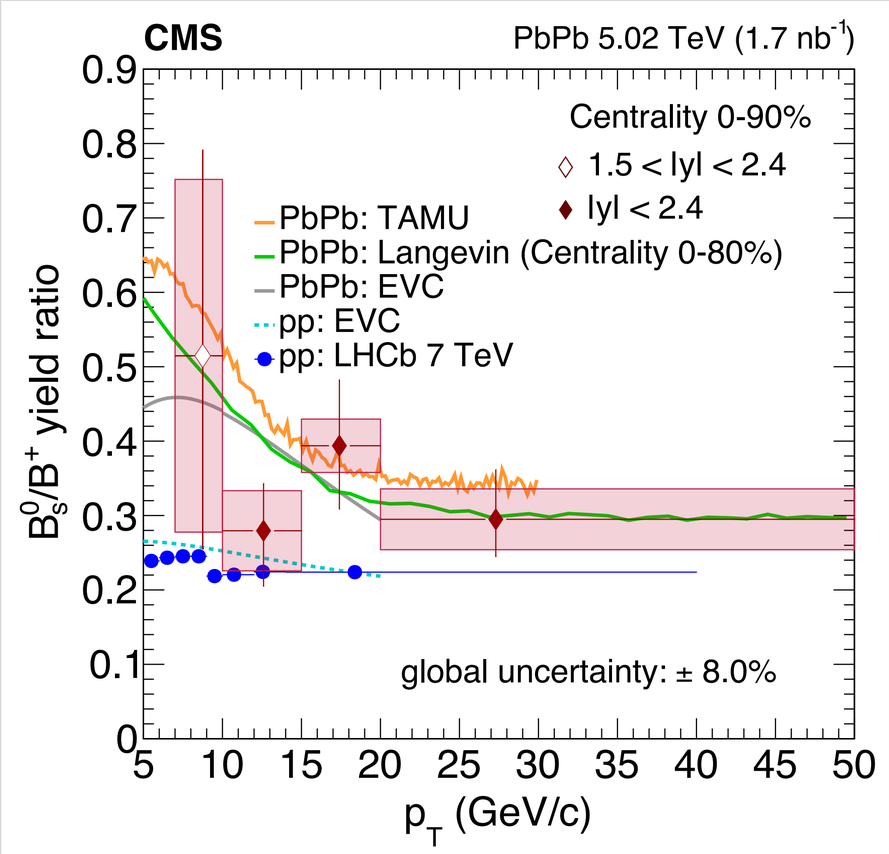
Sequential suppression of excited $\Upsilon(nS)$ states with increasing centrality in Pb–Pb in comparison with pp.

Fragmentation

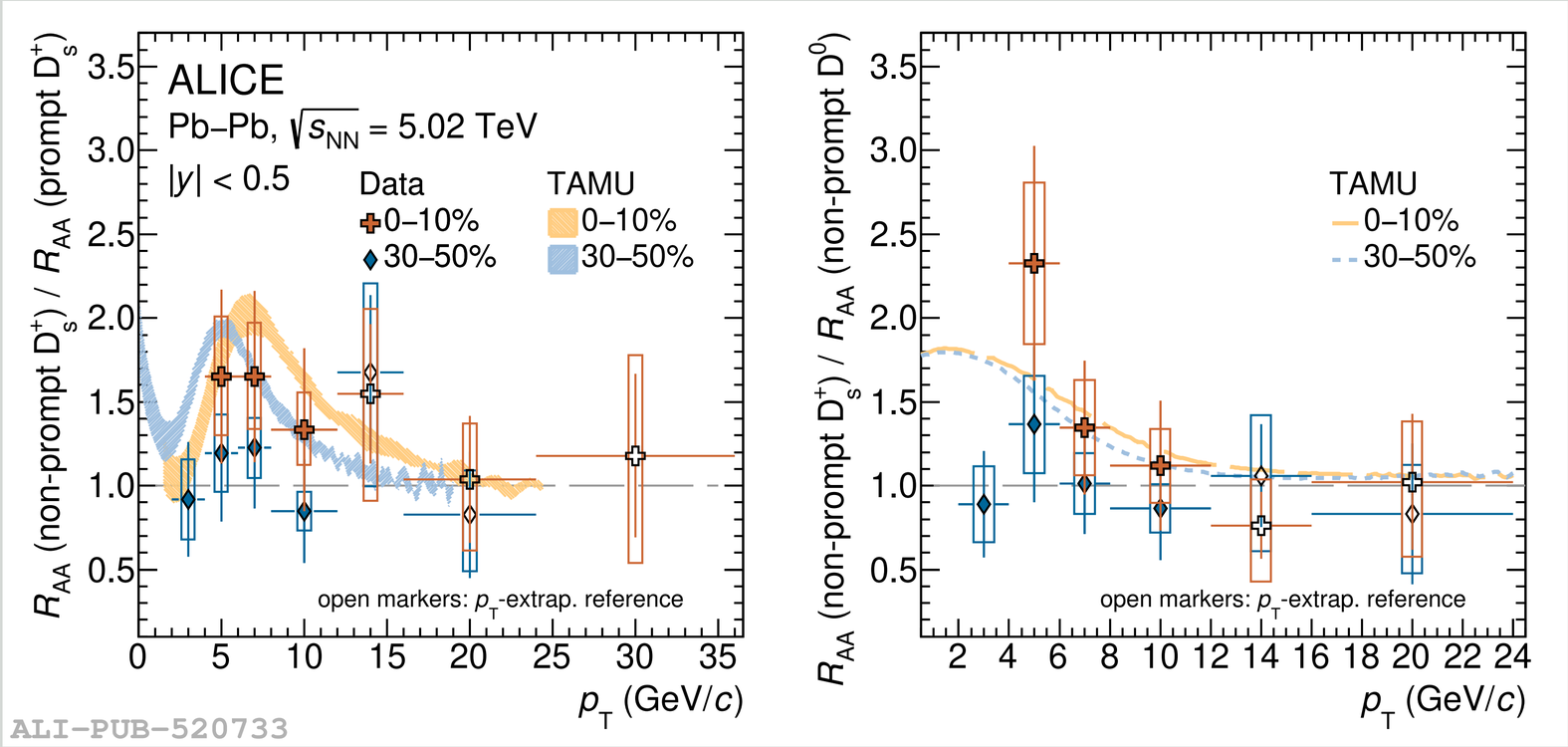
Recombination

B_s^0/B^+ in PbPb and R_{AA}

CMS, PLB 829 (2022) 137062



ALICE, arXiv:2204.10386



- Measure B_s^0/B^0 ratio in Pb—Pb suggests enhancement over measurement in pp.
- Enhancement in line with enhanced B_s^0 production via recombination.

- Hint for enhancement R_{AA} of non-prompt ratio D_s^+/D^0 ratio.
  [non-prompt D_s^+ originate from B_s^0 (50%) and B^0, B^+ (50%)]
  In accordance with enhanced hadronisation via recombination at lower/medium p_T.
- In non-prompt/prompt D_s^+ R_{AA} ratio hint for enhancement at lower p_T, consistent with larger energy loss of charm compared to beauty in the medium.