HEAVY-FLAVOUR BARYONS AT COLLIDERS
- DO WE UNDERSTAND HF HADRONISATION? -

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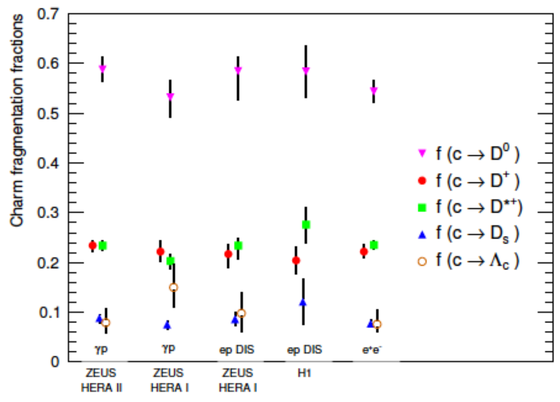
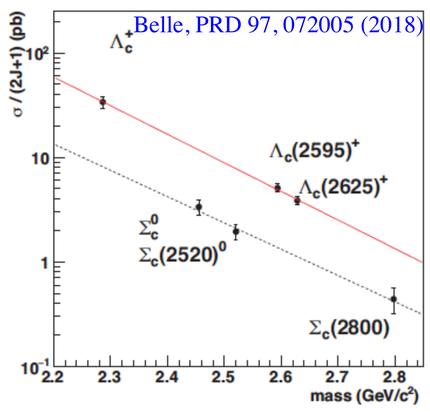
THE "VACUUM" BASELINE: e^+e^-, ep



ZEUS, JHEP 09 (2013) 058

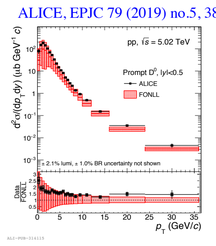


The precision of the fragmentation fractions obtained is competitive with measurements in e^+e^- collisions. All data from ep and e^+e^- collisions are in agreement with each other. This demonstrates that the fragmentation fractions of charm quarks are independent of the production process and supports the hypothesis of the universality of heavy-quark fragmentation.

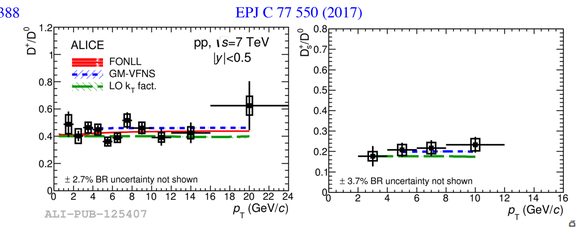
Recent Belle results (PRD 97, 072005 (2018)):
- charm fragmentation to Λ_c^+ described reasonably by PYTHIA6
- Λ_c and Σ_c states cross-sections support charm baryon production from diquark degrees of freedom and **spin-0 diquark component for Λ_c**

… AND WHAT DID NOT SURPRISE US FROM PP

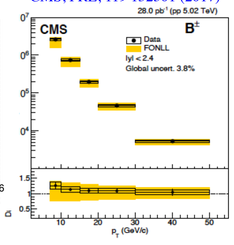
ALICE, EPJC 79 (2019) no.5, 388



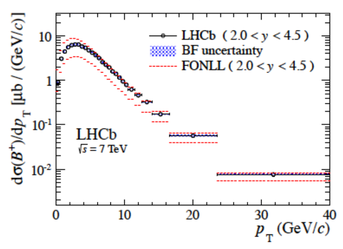
EPJ C 77 550 (2017)



CMS, PRL, 119 152301 (2017)



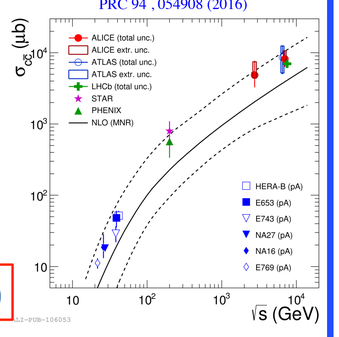
JHEP 08 (2013) 117



Plethora of data indicating that **open-charm and open-beauty meson production**
- vs. p_T and y (wide range covered)
- at very different collision energies
- charm meson species relative abundances

is **described by pQCD** calculations relying on **factorisation approach**
Extrapolated total $c\bar{c}$ (and $b\bar{b}$) cross sections described as well
… though **conclusion may need to be revisited**

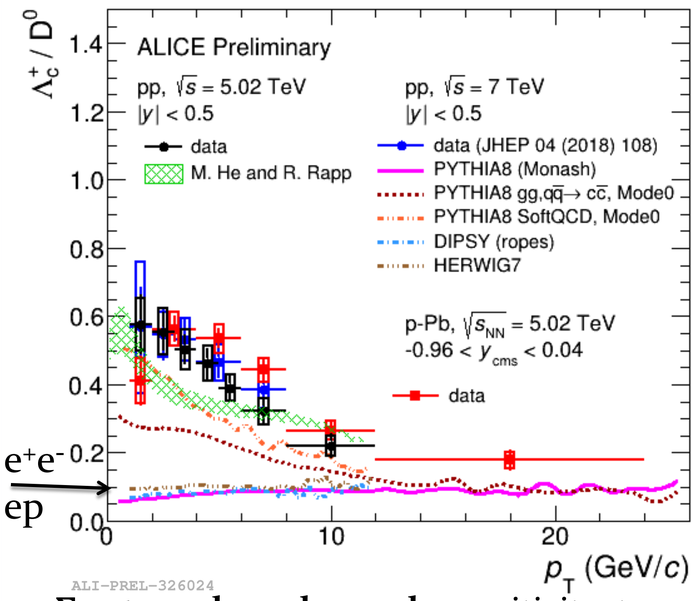
PRC 94 , 054908 (2016)



$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

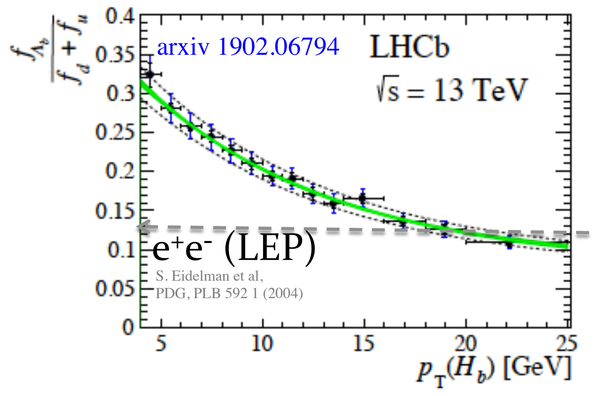
Phenomenological functions, no information/modelling of hadronisation dynamical aspects

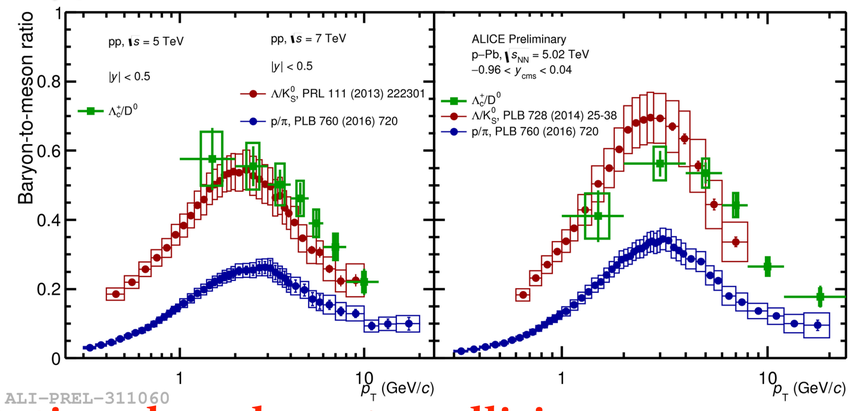
RISING UP THE HADRONIC ENVIRONMENT: PP, ($P\bar{P}$), AND P-PB "SMALL SYSTEMS"



e⁺e⁻ → ep

Σ_c strongly enhanced: sensitivity to relative importance between diquark and junction-driven baryon production

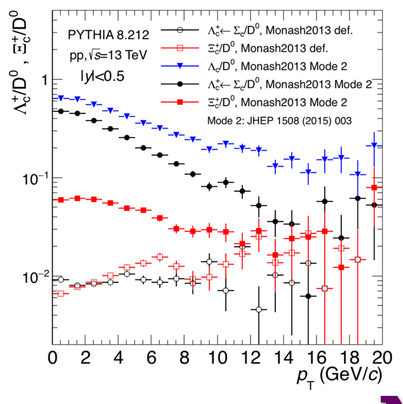




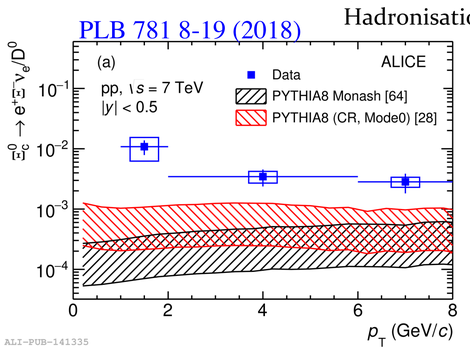
Λ_c^+/D^0 and Λ_b/B higher than expectations based on e^+e^- collisions
- showing **significant dependence on p_T** (with some tension between ALICE and LHCb results in pp at 7 TeV)

Similarity with light-flavour baryon-over-meson ratios: why? Incidental?

Λ_c^+/D^0 not reproduced by PYTHIA standard tunes, DIPSY, HERWIG. Closer to data:
- **PYTHIA8 with string formation beyond leading colour approximation** (Christiansen, Skands, JHEP 1508 (2015) 003)
  - But difficulties in reproducing light-flavour particle p_T-spectrum shapes
- **He, Rapp: feed-down from augmented set of charm-baryon states** (arxiv 1902.08889). Based on relativistic quark model (D. Ebert at al., PRD 84 014025 (2011)), Statistical Hadronisation Model and same fragm. functions used by FONLL, tuned on D^0 ALICE data.

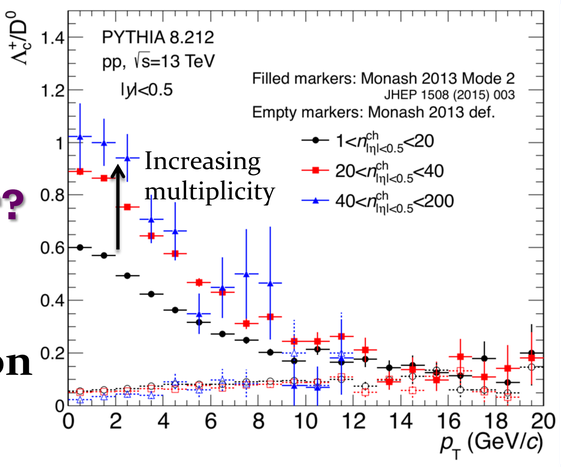


PLB 781 8-19 (2018)

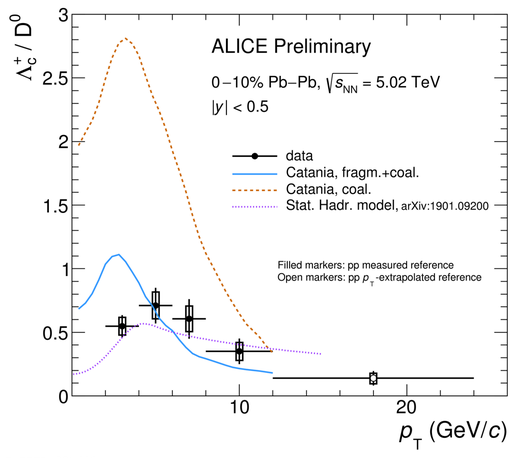


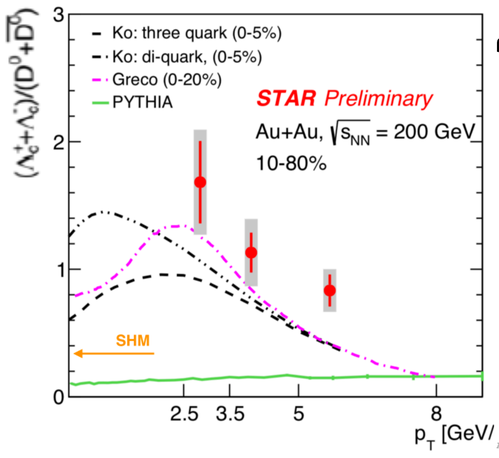
WHAT MEASUREMENTS CAN GIVE US FURTHER INSIGHT?

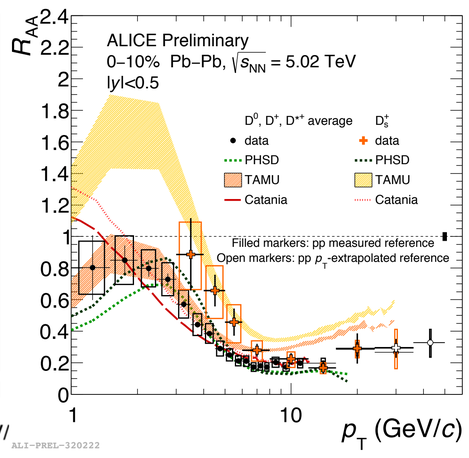
1. **Higher-mass HF-baryon states** (Σ_c, Ξ_c, Ω_c, …): direct observations present/possible at the LHC
2. Charm- and beauty-baryon **jet-momentum fraction**
3. Evolution **vs. multiplicity** and **across systems**

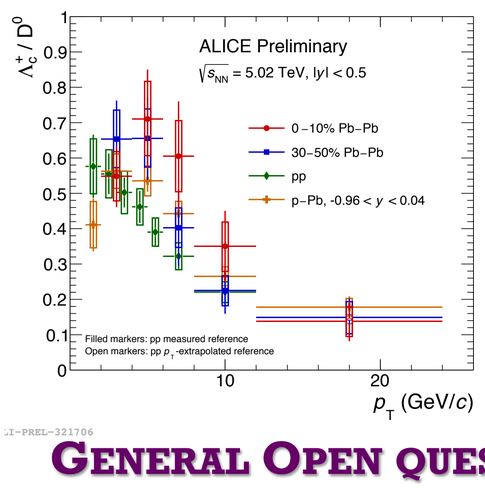


NUCLEUS-NUCLEUS: PROBING THE "FAMILIAR" COALESCENCE IDEA









No striking changes to Λ_c^+/D^0 ratio from pp to p-Pb
- also for Λ_b/B

Hint of a higher Λ_c^+/D^0 in central Pb-Pb collisions than in pp
- Increase Λ_c^+ yield or/and stronger radial flow than D?
- Maybe a trend from pp to p-Pb to Pb-Pb?

Difference between LHC and RHIC?
- **ALICE** data described within uncertainties by
  - Catania model including **both coalescence and fragmentation**
  - **Statistical Hadronisation Model**
- **STAR** data better described by **pure coalescence models**

Λ_c^+, D_s^+ and non-strange D R_{AA} and v_2 data require coherent description

Catania: EPJC (2018) 78:348; SHM: arxiv 1901.09200; TAMU: PLB 735,445-450(2014); arXiv:1905.09216; PHSD: PRC 92, 014910 (2015)

GENERAL OPEN QUESTIONS

What is the HF baryon-to-meson ratio "turn-on curve" from "vacuum" (e^+e^-) to richer and denser hadronic environments? Are central Pb-Pb and e^+e^- two "ideal" extremes?
What are the dynamical processes beyond HQ hadronisation?
- not granted that Λ_c^+ is "enhanced" by the same mechanism in Pb-Pb and pp (w.r.t. e^+e^-)
- interplay of coalescence and colour reconnection in Pb-Pb?
- are diquarks important degrees of freedom in AA?

MULTI-HEAVY-FLAVOUR BARYONS: A FUTURE REALITY BEYOND Λ_C AND Λ_B SHINING ERA IN LHC RUN 3?

Yields in central Pb-Pb

Yield/event at mid-rapidity in 0.5% Pb-Pb at 5.5 TeV:
Ξ_{cc} : 0.019 ÷ 0.38 [Bec2005], also for Ω_{cc}
0.013 ÷ 0.02 [YM2018], ~0.03 [ZHZ2017]
Ω_{ccc} : 0.001 ÷ 0.03 [Bec2005], $3\cdot10^{-4}$ [HLZ2015]
Ξ_{bc}, Ω_{bc} , B_c : $3\cdot10^{-4}$ ÷ $2.2\cdot10^{-2}$

Typical overall BR of reconstructable decay chains:
Ξ_{cc} : 0.1 ÷ 0.3%
Ω_{ccc}: 0.002% ÷ 0.01 %

References:
Beccattini, PRL 95 022301 (2005) [Bec2005]
He, Liu Zhuang PLB 746 (2015) 59-63 [HLZ2015]
Zhao, He, Zhuang, PLB 771 (2017) 349-353 [ZHZ2017]
Yao and Muller, PRD 97, 074003 (2018) [YM2018]

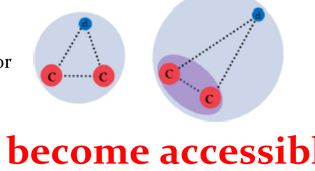
Pure coalescence particles in AA: primordial yield (from "vacuum"-like fragmentation) expected to be negligible in AA

Signature of a deconfined state… another one, but what a wonderful one!

Test of coalescence and statistical-hadronisation models

Similarities and differences with quarkonia recombination
- Statistical hadronisation [Bec2005]
- "Sudden" coalescence at hadronisation temperature, coalescence probability via Wigner function [HLZ2015], [ZHZ2017]
- Diquark formation with Potential NRQCD + Boltzmann transport of single heavy quark and bound diquark (not necessarily equilibrated) in QGP, accounting for their diffusion, regeneration and dissociation [YM2018]

Sensitivity to diquarks and chiral symmetry restoration:
Ξ_{cc}^{++} yield sensitive to coalescence happening in a tri-quark state (more likely when chiral symmetry broken for light quarks) vs. heavy di-quark + "bare" light quark [ZHZ2017]



A sequential-formation thermometer?
to probe (pre?)-hadronisation starting at different temperatures

Medium expansion → decreasing temperature
- Decreasing HQ density → reduce recombination probability
- Reduced colour screening → enhance recombination probability

Different "melting temperatures" of heavy diquarks (cc, bc, bb)
→ What is the lever arm on the yields?
- Ξ_{cc}^{++} rate from 0.02 (no melting) to 0.0125 (T_{melt}=250 MeV) [HLZ2015]

Low rates and branching ratios → experimentally very challenging … but might become accessible with future detectors
(see arXiv: 1902.01211 and Musa's talk at SQM https://indico.cern.ch/event/755366/contributions/3428151/)

Ξ_{cc} at the horizon already in run 3,4 at the LHC?