Charm and bottom production

Torbjörn Sjöstrand, Lund University

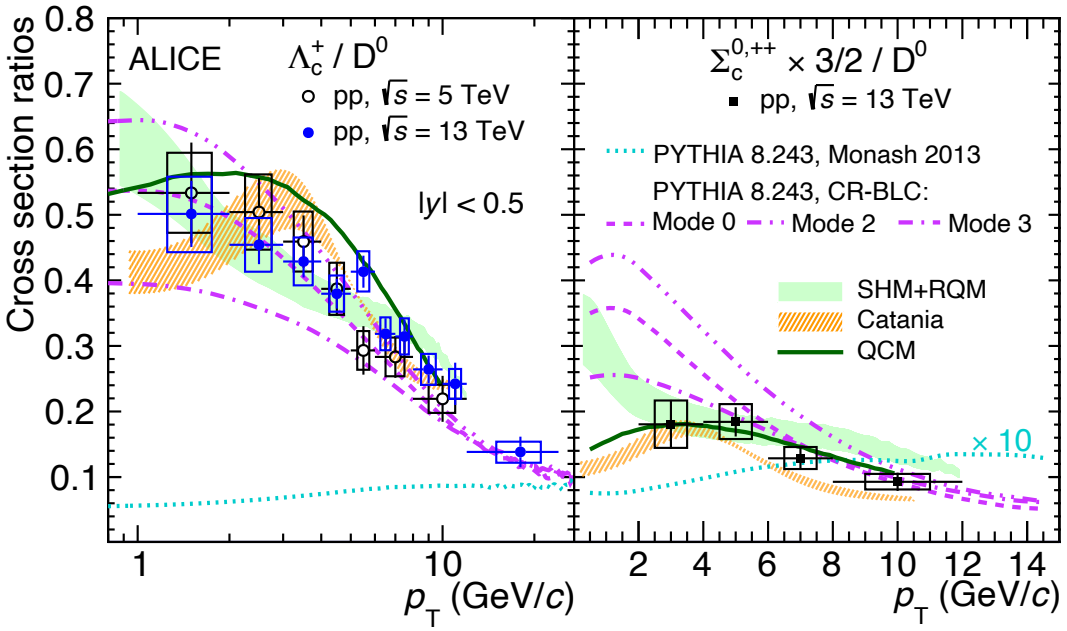
Some LHC observations in pp events:

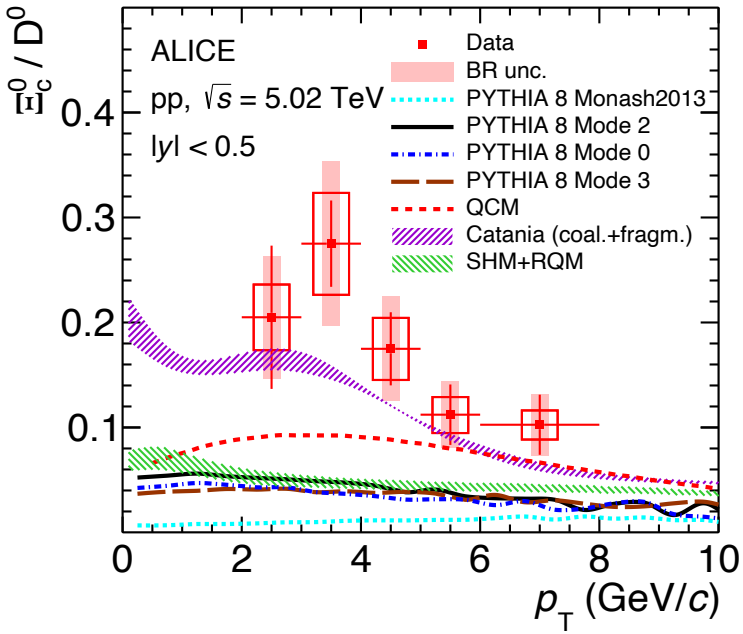
- Charm/bottom baryon-to-meson ratio is significantly enhanced relative to "vacuum" $\mathrm{e^+e^-}$.
- This is a low-$p_\perp$ phenomenon, with "vacuum" recovered for $p_\perp > 20$ GeV.
- Only mild increase with multiplicity.
- More Λ_b^0 than $\overline{\Lambda}_\mathrm{b}^0$ in forward direction.

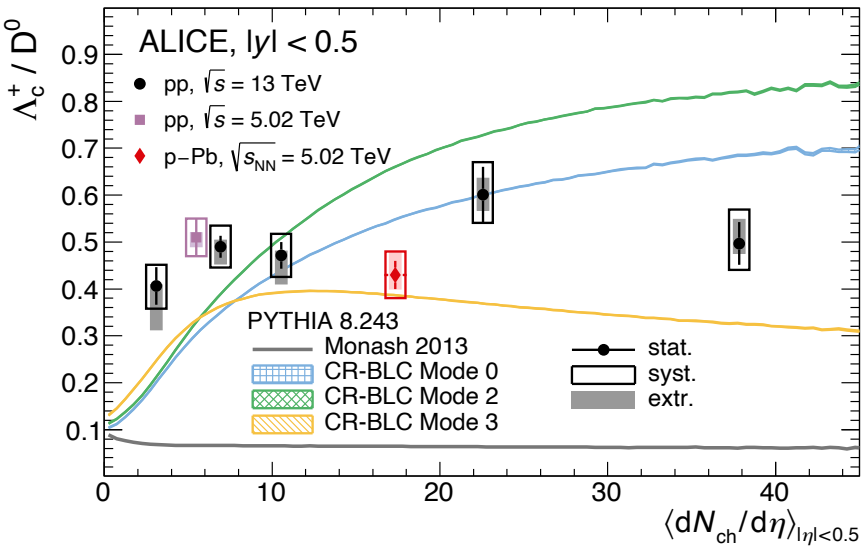
To consider

- How can this be modelled? Both string and QGP scenarios have been proposed, but do they hold water?
- Can we define observables to distinguish scenarios?

Charm baryon differential distributions







(2106.08278, 2105.05616, 2111.11948)

QCDCR option much better than PYTHIA default, but not perfect.

Catania best other model, but note dip at small $p_\perp$.

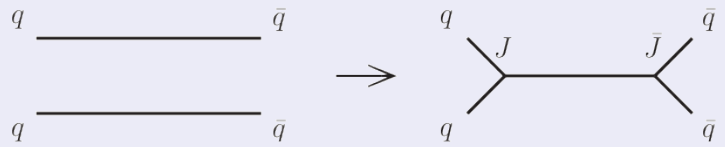
Colour reconnection models

"Recent" PYTHIA option: QCD-inspired CR (QCDCR) (1505.01681):

Ordinary string reconnection

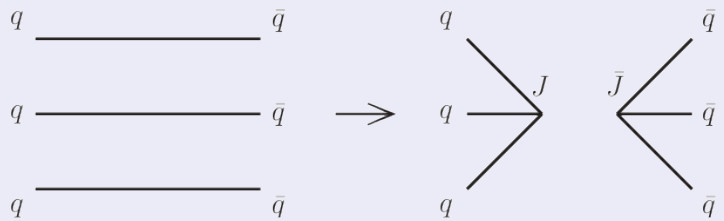
(qq̄: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection



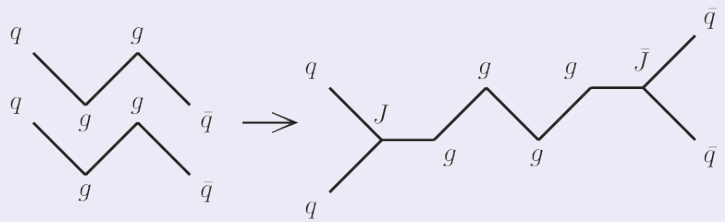
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection

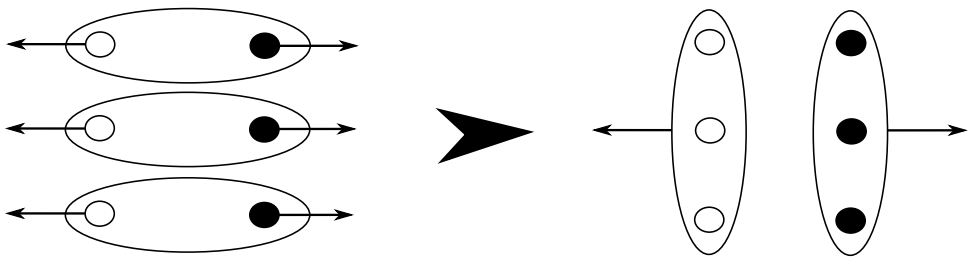


(qq̄: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection



(Depends on number of gluons)



Triple-junction also in HERWIG cluster model. (1710.10906)

Models of and conclusions on particle composition

Other models, in a heavy-ion physics spirit:

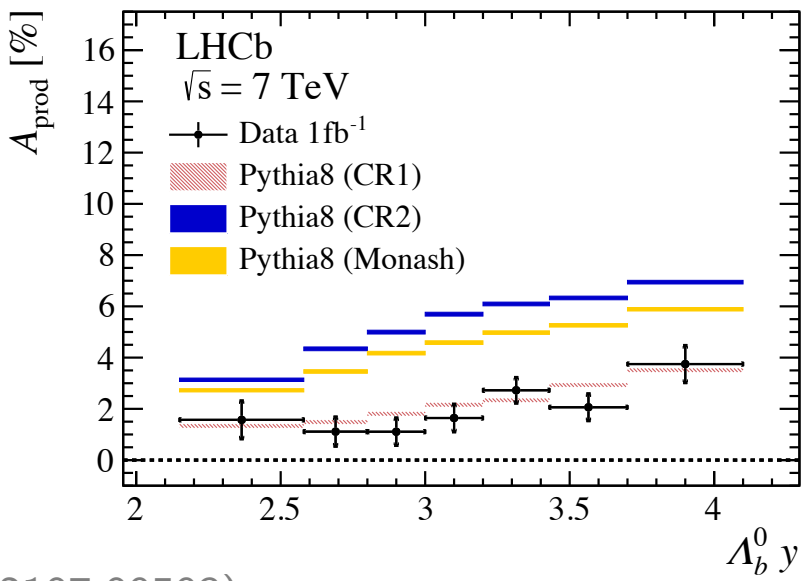
- QCM: Quark (re)Combination Mechanism, with co-moving light quarks being picked up. (1801.09402)
- SHM+RQM: Statistical Hadronization Model + Relativistic Quark Model. Thermo-statistical production with extensive feeddown from heavier charm baryon states. (1902.08889)
- Catania: use AA models of quark–gluon plasma formation. Coalescence of nearby quarks at small $p_\perp$, while "normal" fragmentation at higher $p_\perp$. (2012.12001)

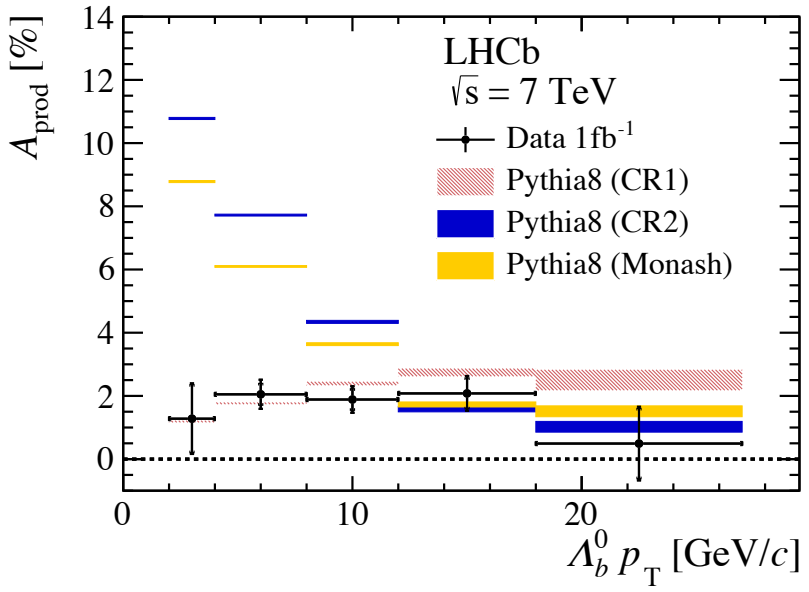
Tentative conclusion:

- "Vacuum" evolution at large $p_\perp$, like in $\mathrm{e^+e^-}$ and ep.
- Collective effects take over at small $p_\perp$, where MPIs give close-packing of quarks/gluons/strings/clusters/hadrons.

Breakdown of jet universality, like for strangeness!

Bottom asymmetries





(2107.09593)

$$A(y), A(p_\perp) = \frac{\sigma(\Lambda_{\rm b}^0) - \sigma(\overline{\Lambda}_{\rm b}^0)}{\sigma(\Lambda_{\rm b}^0) + \sigma(\overline{\Lambda}_{\rm b}^0)}$$

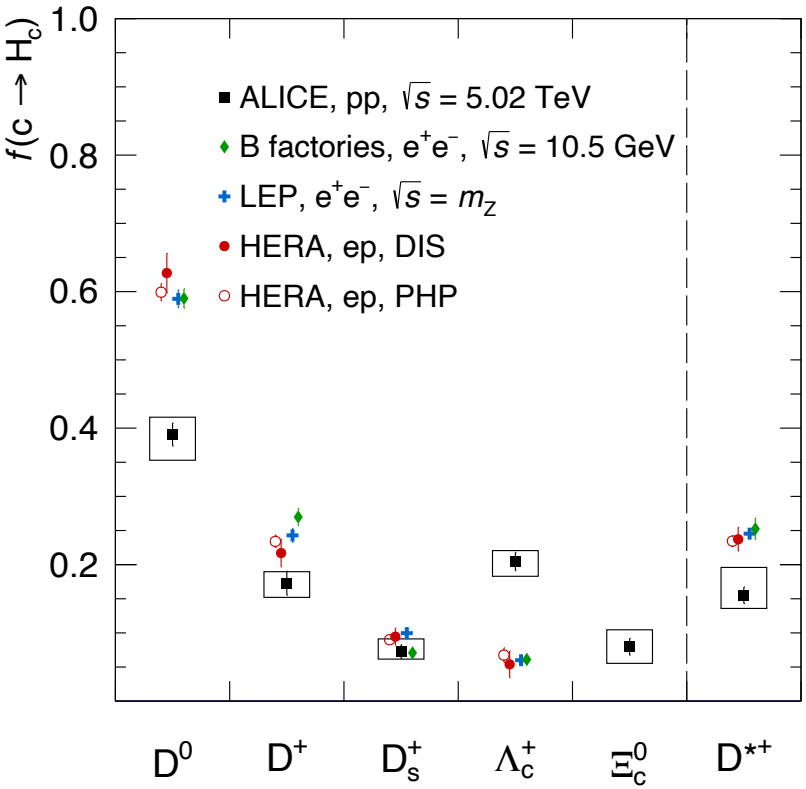
CR1 = QCDCR shows no enhancement at low $p_\perp$.
Enhanced $\Lambda_{\rm b}$ production at low $p_\perp$ from junction reconnection, like for $\Lambda_{\rm c}$, dilutes asymmetry?

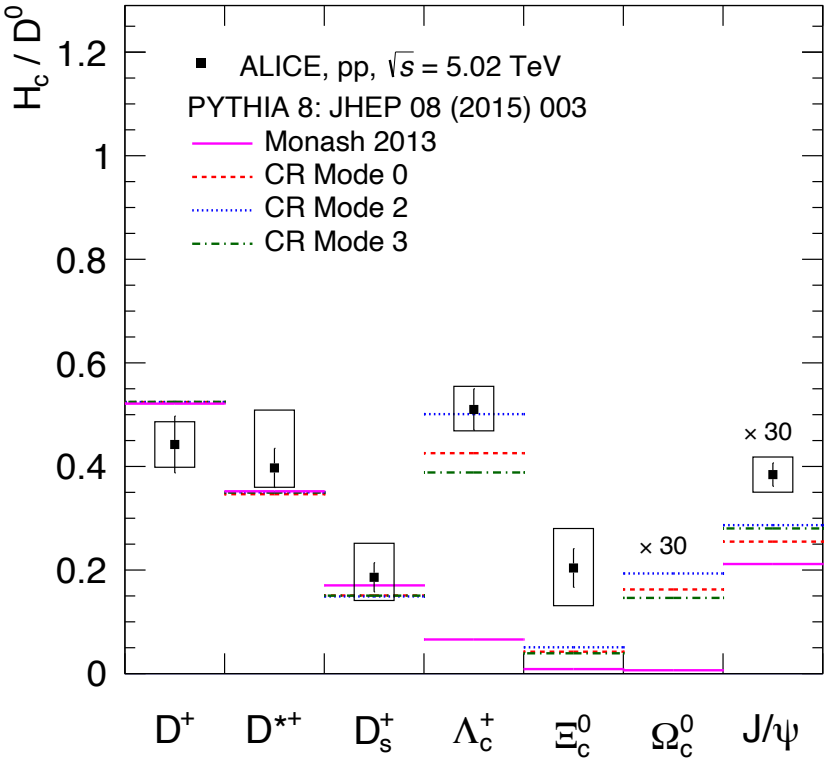
Asymmetries observed also for other charm and bottom hadrons.
Other models not yet compared with data (?).

Backup: The charm baryon enhancement

In 2017/21 ALICE found/confirmed strong enhancement of charm baryon production, relative to LEP, HERA and default PYTHIA.

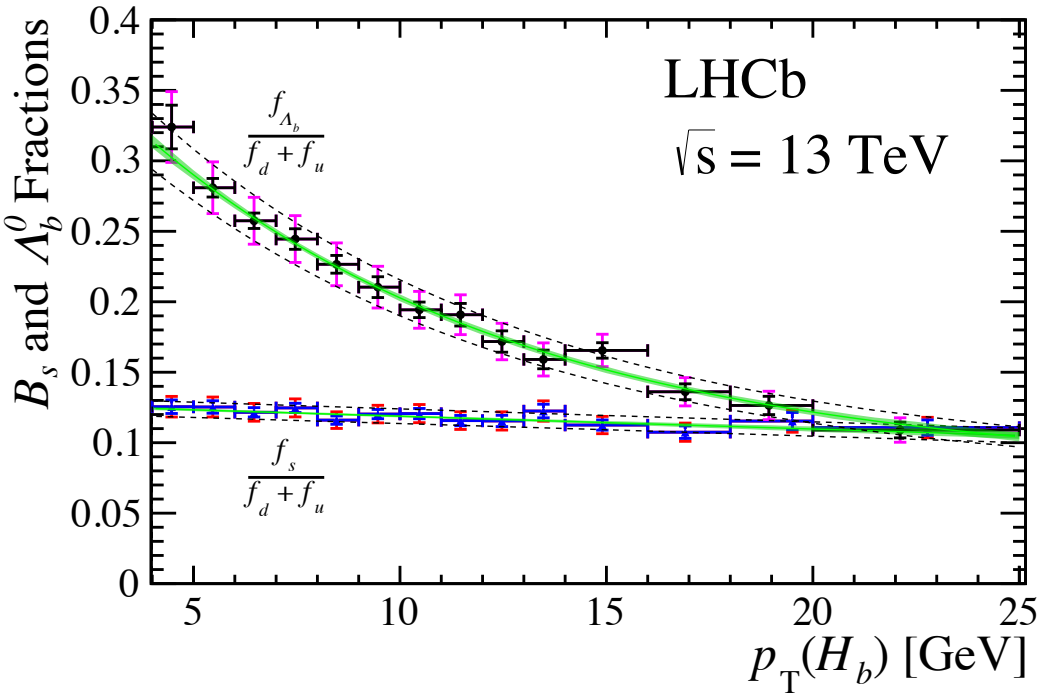
(1712.09581, 2105.06335)





The QCDCR model does much better, with junctions ⇒ baryons.

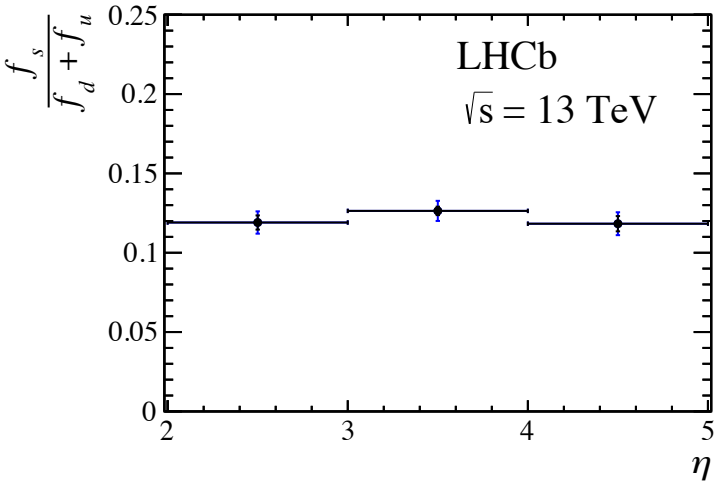
Backup: The beauty baryon enhancement

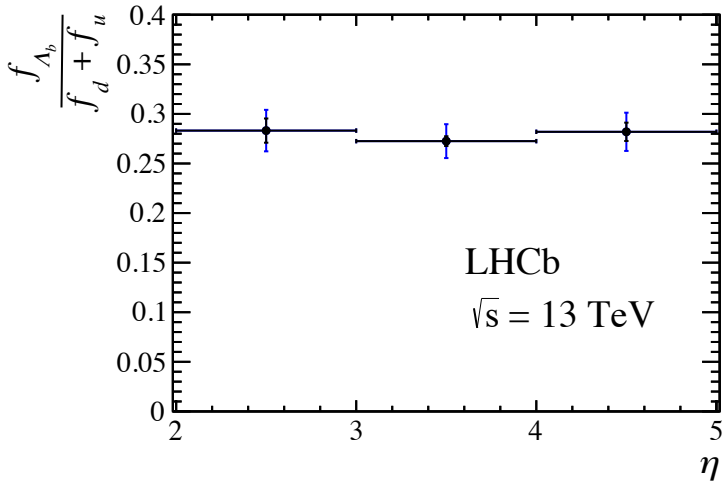


In 2019 LHCb found enhancement of Λ_b^0 production at small $p_\perp$, but flat in η.

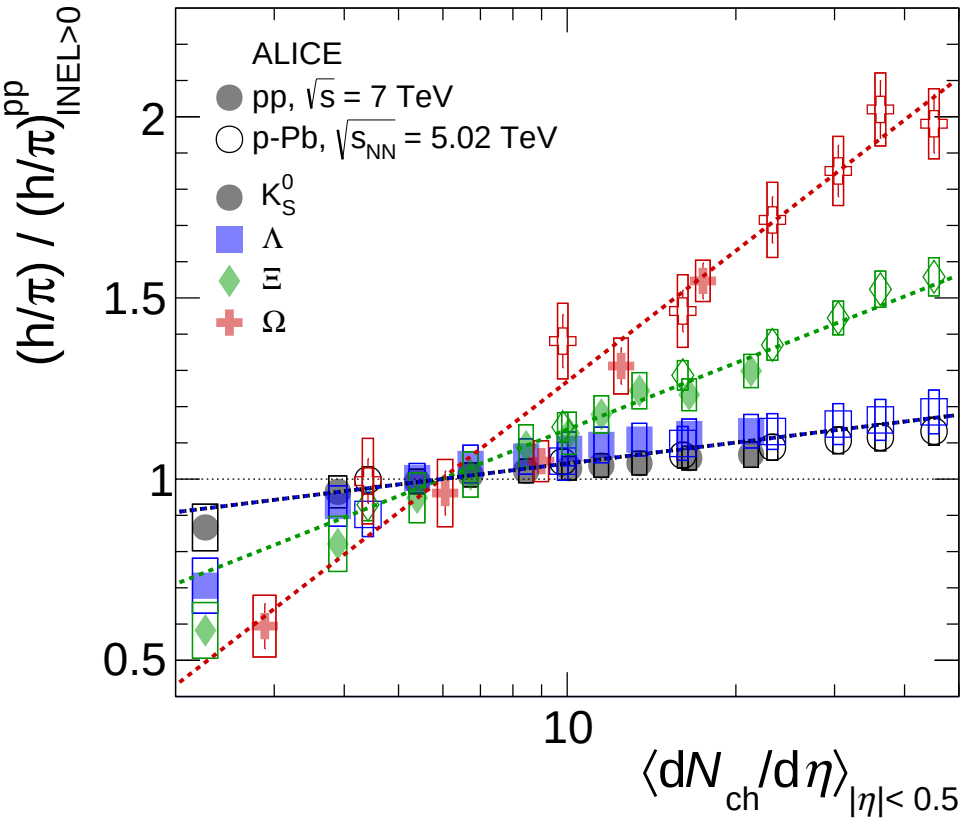
(1902.06794)

No model comparisons.

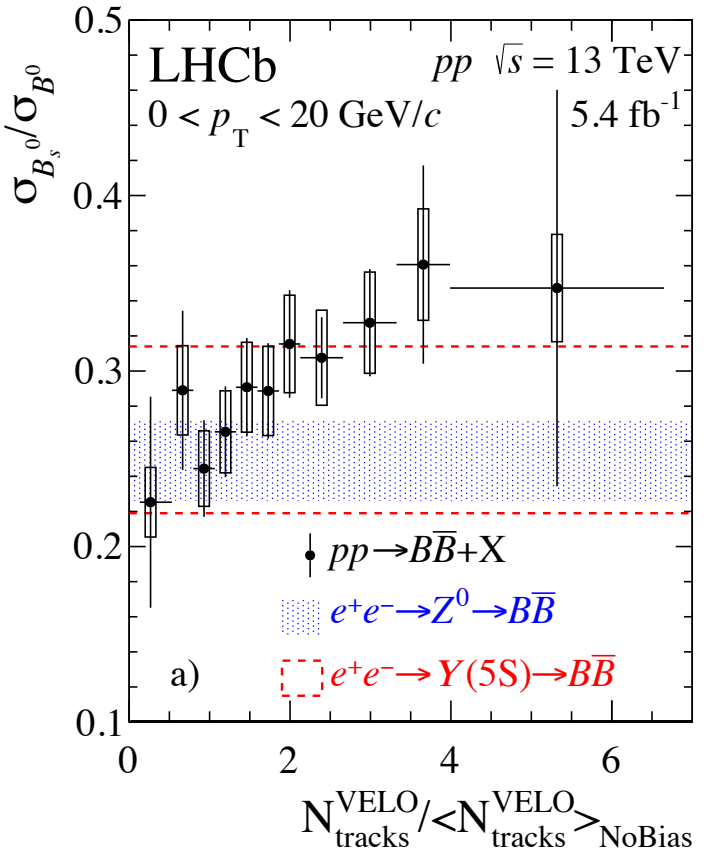




Backup: Beauty strangeness enhancement



(1606.07424)



(2204.13042)

Strangeness enhancement at high multiplicity — previous major discovery — now also observed in B^0_s/B^0 by LHCb.

Approximately described by colour ropes or core–corona models.

Backup: Catania coalescence

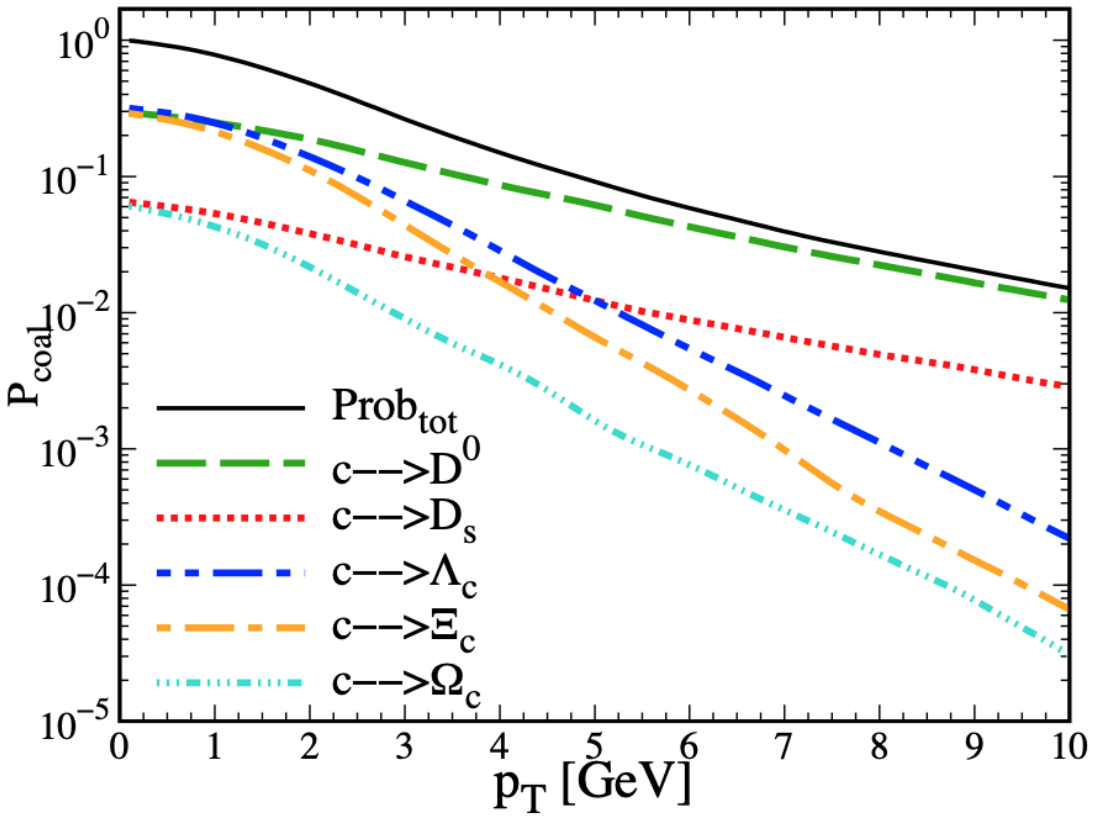
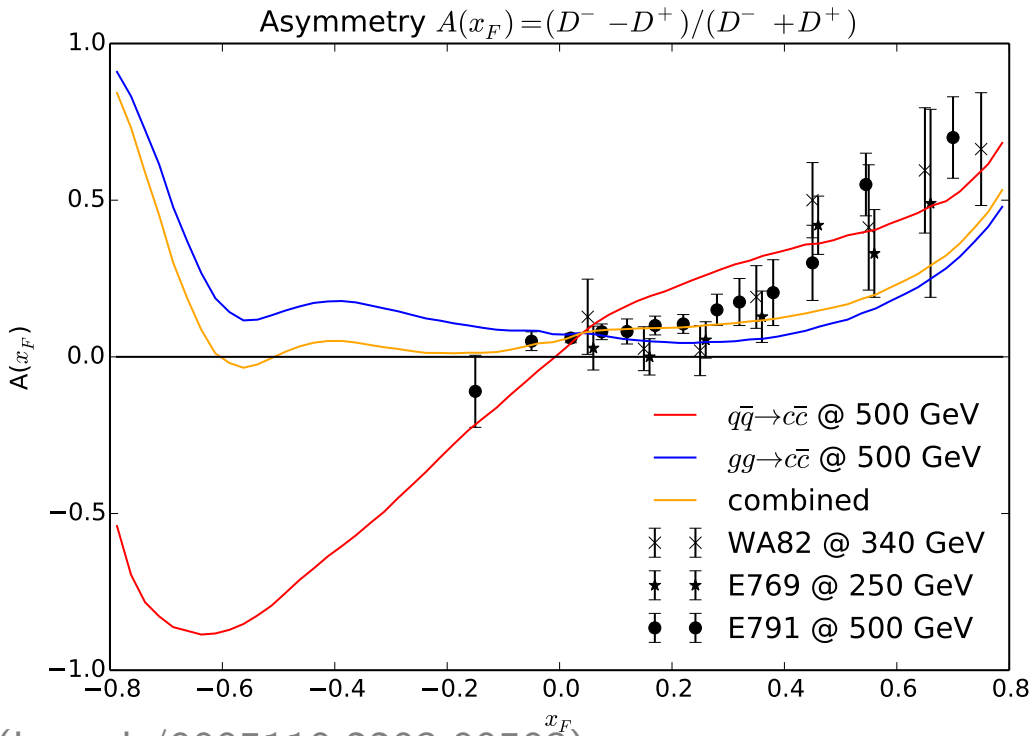


FIG. 1: (Color online) The charm quark coalescence probability as a function of the charm quark p_T for pp collisions at LHC. The different lines are the coalescence probabilities to produce the different hadron species. Black solid line is the total coalescence probability.

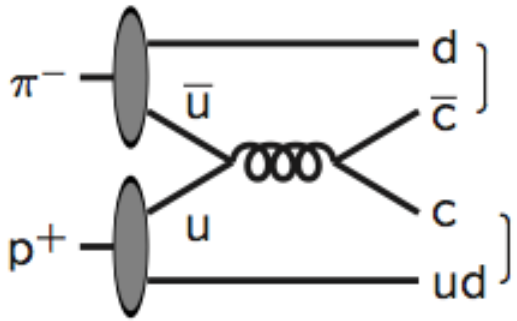
Backup: Beam drag effects

Colour flow connects hard scattering to beam remnants. Can have consequences, e.g. in $\pi^- \mathrm{p}$:

$$A(x_\mathrm{F}) = \frac{\sigma(\mathrm{D}^-) - \sigma(\mathrm{D}^+)}{\sigma(\mathrm{D}^-) + \sigma(\mathrm{D}^+)}$$



(hep-ph/0005110,2203.09503)

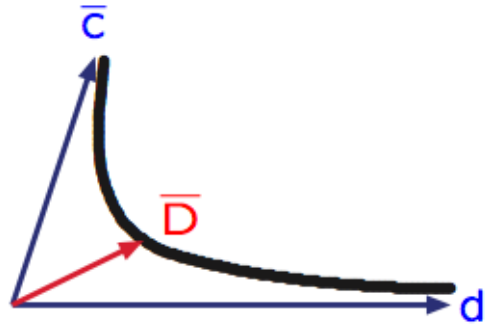


If low-mass string e.g.:

$\bar{\mathrm{c}}\mathrm{d} : \mathrm{D}^-, \mathrm{D}^{*-}$

$\mathrm{cud} : \Lambda_\mathrm{c}^+, \Sigma_\mathrm{c}^+, \Sigma_\mathrm{c}^{*+}$

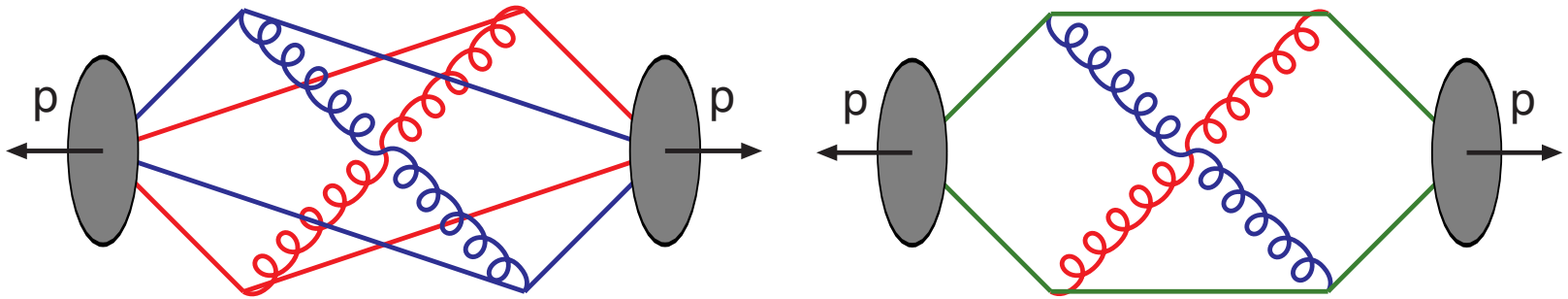
$\Rightarrow$ flavour asymmetries



Can give D "drag" to larger x_F than c quark.

Backup: Colour reconnection (CR)

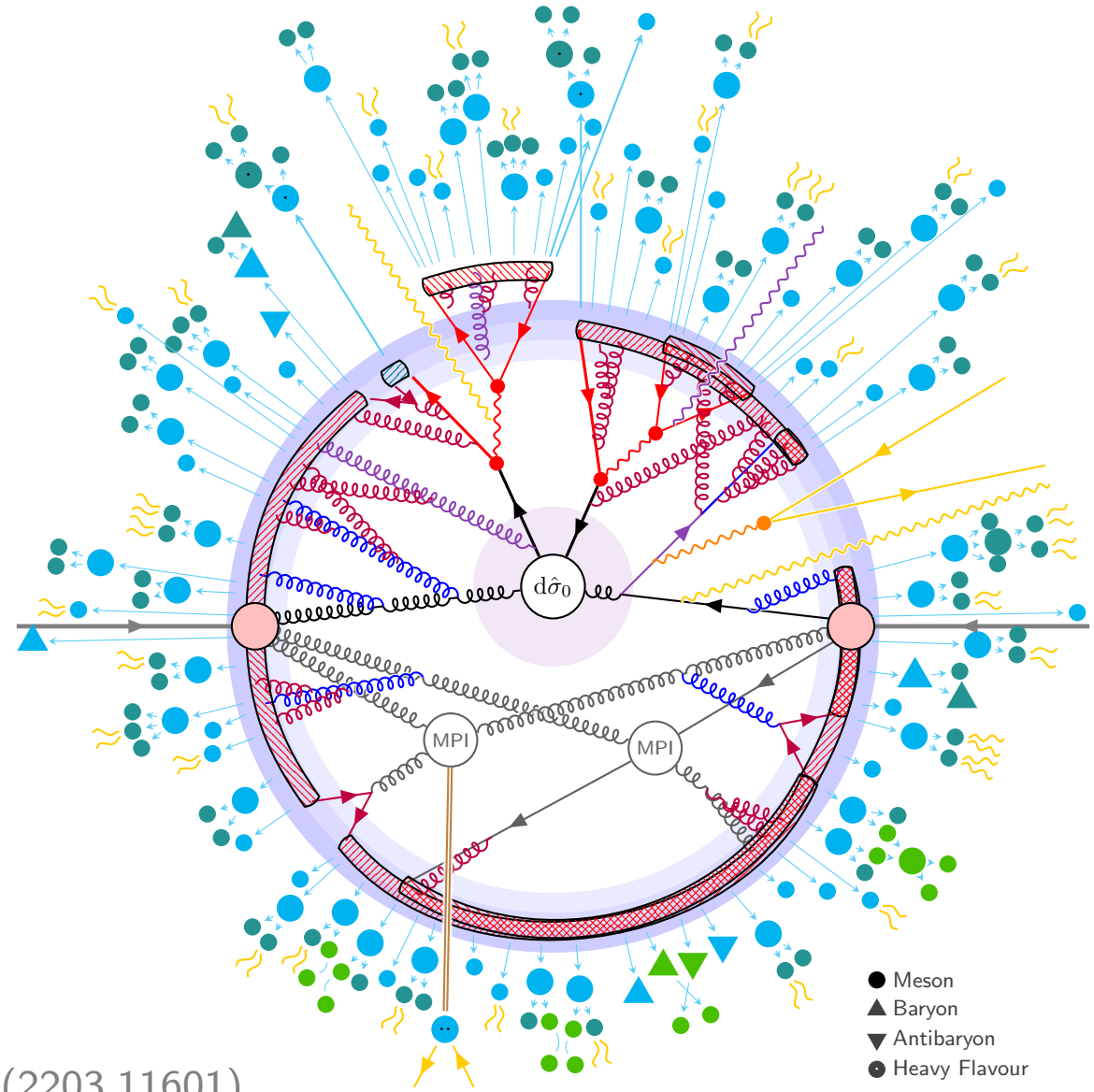
MPIs + parton showers $\Rightarrow$ many partons in an event
$\Rightarrow$ colour fields ("strings") run criss-cross.
CR: fields rearrange, to (mainly) reduce string length:



Two main confirmations:

- $\langle p_\perp \rangle (n_{\mathrm{ch}})$ is steadily rising in $\mathrm{pp}/\overline{\mathrm{p}}\mathrm{p}$ data (UA1, Tevatron, LHC), but would be (almost) flat if no CR.
- Combined LEP data on $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q_1\overline{q}_2q_3\overline{q}_4}$ is best described with 49% CR, 2.2σ away from no-CR.
  (hep-ex/0612034)

Backup: The structure of an LHC pp collision



(2203.11601)

- Hard Interaction
- Resonance Decays
- MECs, Matching & Merging
- FSR
- ISR*
- QED
- Weak Showers
- Hard Onium

- Multiparton Interactions

- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

(: incoming lines are crossed)*