Forward Charm

Torbjörn Sjöstrand

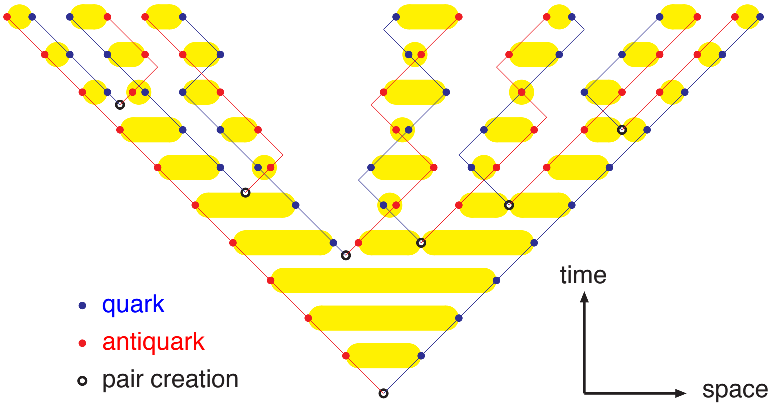
Department of Astronomy and Theoretical Physics,
Lund University

FPF study group, 5 December 2022

The Lund Model

Assume linear confinement with a string tension $\kappa \approx 1$ GeV/fm.

Motion of quarks and antiquarks with intermediate string pieces:



A q from one string break combines with a $\overline{q}$ from an adjacent one.

Gives simple but powerful picture of hadron production.

Boost properties

Consider a boost β along the z axis, with $p^{\pm} = E \pm p_z$:

$$\left\{ \begin{array}{l} E' = \gamma(E + \beta p_z) \\ p'_z = \gamma(p_z + \beta E) \end{array} \right. \quad \Longrightarrow \quad \left\{ \begin{array}{l} p^{+\prime} = k p^{+} \\ p^{-\prime} = \frac{1}{k} p^{-} \end{array} \right. \quad \text{with } k = \sqrt{\frac{1+\beta}{1-\beta}}$$

with similar contraction/compression of $t^{\pm} = t \pm z$.

This preserves transverse masses, $m_{\perp}^2 = m^2 + p_{\perp}^2 = p^{+} p^{-}$, and invariant times, $\tau^2 = t^2 - z^2 = t^{+} t^{-}$ (for $x = y = 0$), while rapidity $y' = y + \ln k$.

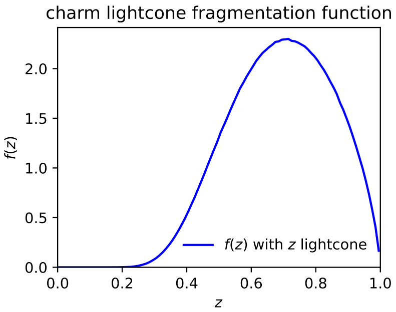
The fragmentation process is boost invariant:
same result if you boost the partons before fragmentation or if you first fragment them and then boost the hadrons.
Applies for all boosts, but here specifically longitudinal ones.

Fragmentation function

Fragmentation functions $f(z)$ for the (charm) quark $\to$ hadron transition must be formulated in terms of lightcone variables

$$z = p_h^+ / p_q^+$$

to preserve the longitudinal boost invariance of the string.



Many shapes proposed, e.g. Lund-Bowler:

$$f(z) \propto \frac{1}{z^{1+r_q b m_q^2}} (1-z)^a \exp\left(-\frac{b m_{\perp h}^2}{z}\right)$$

where a, b and r_q are free parameters ($a \geq 0, b > 0, 0 \leq r_q \leq 1$).

String pull

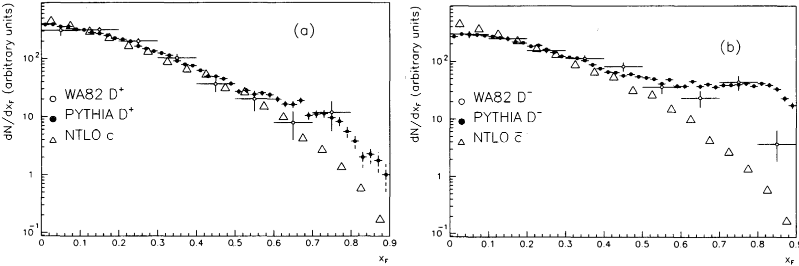
Consider a back-to-back $\mathrm{c}\overline{\mathrm{c}}$ system, along the $\pm z$ axis.
The string tension pulls the c backwards and the $\overline{\mathrm{c}}$ forwards:

$p^{+}_{\mathrm{D}} = z p^{+}_{\mathrm{tot}}$ for a D hadron $(\mathrm{D}^0, \mathrm{D}^+, \Lambda_{\mathrm{c}}^+, \ldots)$ from the c,
while for a $\overline{\mathrm{D}}$ hadron $(\overline{\mathrm{D}}^0, \overline{\mathrm{D}}^-, \overline{\Lambda}_{\mathrm{c}}^-, \ldots)$ from the $\overline{\mathrm{c}}$:

$$\left\{ \begin{array}{l} p^{-}_{\overline{\mathrm{D}}} = z p^{-}_{\mathrm{tot}} (\approx z p^{-}_{\overline{\mathrm{c}}}) \\ p^{+}_{\overline{\mathrm{D}}} = \dfrac{m^2_{\perp\overline{\mathrm{D}}}}{p^{-}_{\overline{\mathrm{D}}}} = \dfrac{m^2_{\perp\overline{\mathrm{D}}}}{z p^{-}_{\mathrm{tot}}} \end{array} \right. \Longrightarrow \left\{ \begin{array}{l} E_{\overline{\mathrm{D}}} = \frac{1}{2} \left(\dfrac{m^2_{\perp\overline{\mathrm{D}}}}{z p^{-}_{\mathrm{tot}}} + z p^{-}_{\mathrm{tot}} \right) \\ p_{z\overline{\mathrm{D}}} = \frac{1}{2} \left(\dfrac{m^2_{\perp\overline{\mathrm{D}}}}{z p^{-}_{\mathrm{tot}}} - z p^{-}_{\mathrm{tot}} \right) \end{array} \right.$$

The smaller the z, the less negative the p_z of the $\overline{\mathrm{D}}$ meson.
If $z < m_{\perp\overline{\mathrm{D}}} / p^{-}_{\mathrm{tot}}$ it even flips sign, $p_z > 0$.

Factorization breakdown in fixed-target $\pi^- p$



($x_{\mathrm{F}} = p_L^* / p_{L,max}^*$, L = longitudinal, * = in CM)

WA82, Phys.Lett. B305 (1993) 402

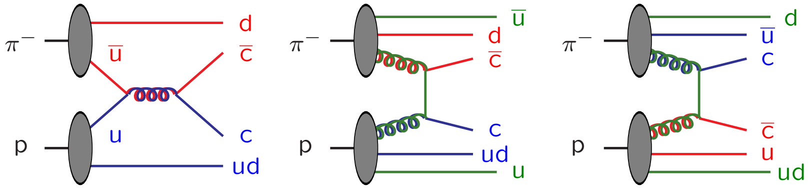
Fragmentation function factorization

$$\frac{\mathrm{d}\sigma_{\mathrm{D}}}{\mathrm{d}x_{\mathrm{F}}} = \frac{\mathrm{d}\sigma_{\mathrm{c}}}{\mathrm{d}x_{\mathrm{F}}} \otimes f(z) \quad , \quad 0 < z < 1 \quad , \quad z \approx \frac{x_{\mathrm{F,D}}}{x_{\mathrm{F,c}}} \approx \frac{E_{\mathrm{D}}}{E_{\mathrm{c}}} \approx \frac{p_{\mathrm{D}}^+}{p_{\mathrm{c}}^+}$$

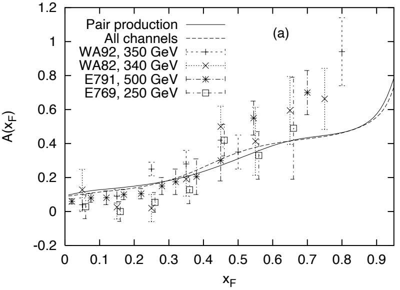
does not work!

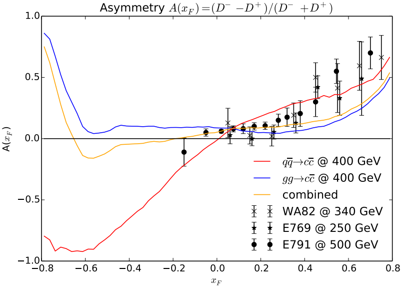
Production asymmetries in fixed-target $\pi^- \mathrm{p}$

$\mathrm{u}\overline{\mathrm{u}} \to \mathrm{c}\overline{\mathrm{c}}$ pulls $\overline{\mathrm{D}}$ forwards, while $\mathrm{gg} \to \mathrm{c}\overline{\mathrm{c}}$ can pull either D or $\overline{\mathrm{D}}$:



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

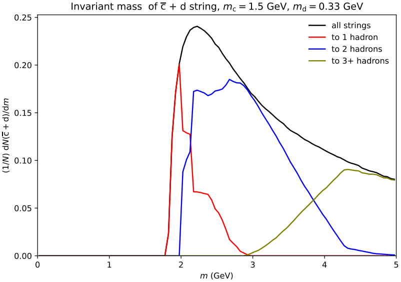




Low-mass strings in fixed-target $\pi^- p$

A string with small invariant mass can collapse to a single hadron, with four-momentum conserved by exchange with other string:

$$\left.\begin{array}{l} \overline{c}d \to D^-, D^{*-}, \ldots \\ c\overline{u} \to D^0, D^{*0}, \ldots \end{array}\right\} \implies D^{\pm} \text{ asymmetry in } gg \to c\overline{c}$$



Minimum string mass given by constituent quark masses:

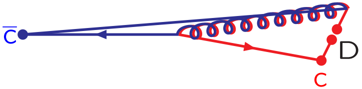
$$m_c = 1.5 \text{ GeV}$$
$$m_d = 0.33 \text{ GeV}$$
$$m_{\overline{c}d,\min} = m_c + m_d = 1.83 \text{ GeV}$$

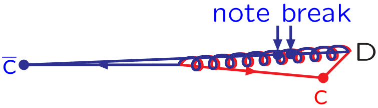
A choice of lower masses would give more collapse.

In target remnant also $cud \to \Lambda_c^+, \Sigma_c^+, \Sigma_c^{*+}, \ldots$; relevant for LHC?

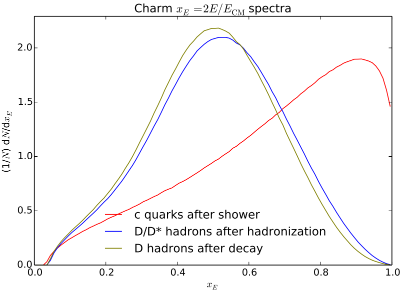
Fragmentation in $Z^0 \to c\bar{c}$

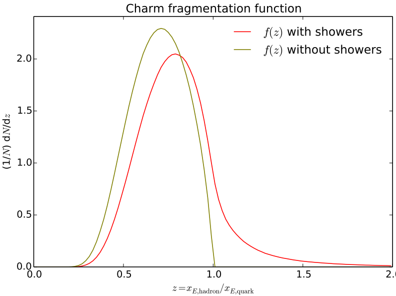
Consider $Z^0 \to c\bar{c} \to c\bar{c}g\ (\to \ldots)$.
Parton showers give gluons around the $c\bar{c}$ directions,
with energy that partly can be recovered in the hadronization step.





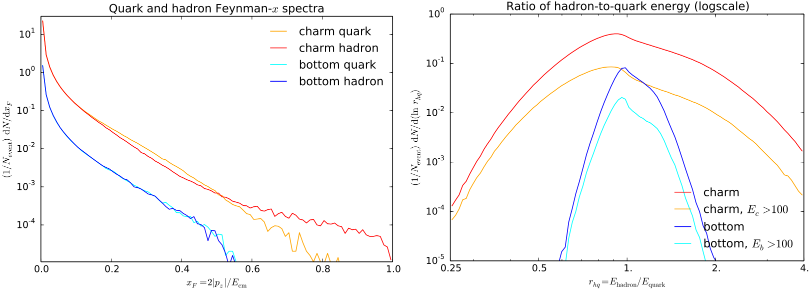
Can be viewed as the gluons helping pull forwards.





Beam drag at the LHC

At LHC, c and b quarks appear to be dragged approximately as much forwards as backwards, with significant fluctuations.

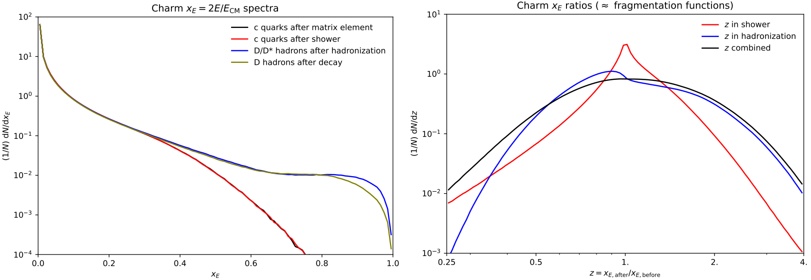


Results above for inclusive sample of minimum bias events, i.e. only a fraction of the generated events contribute.

Again fragmentation function factorization does not work!

A closer look at beam drag (1)

Now consider only events with hard processes $\mathrm{q\overline{q}} \to \mathrm{c\overline{c}}$ or $\mathrm{gg} \to \mathrm{c\overline{c}}$, with no c or b production in the showers. Only a few % of total c.

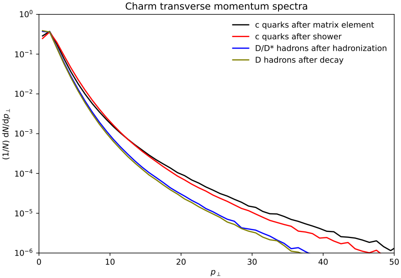


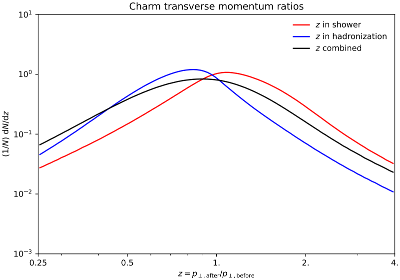
Note 1: parton showers allow $z > 1$! Similar to string pull: in a dipole shower the other end of the dipole can be ahead. Then a branching like $\mathrm{c} \to \mathrm{c'g}$ involves a DGLAP z. With $p_{\mathrm{c'}}^- = z p_{\mathrm{c}}^-$ you again get $p_{\mathrm{c'}}^+ \propto 1/z$.

Note 2: significant hardening at large x_E in $\mathrm{c} \to \mathrm{D}$.

A closer look at beam drag (2)

The $p_\perp$ spectrum behaves a bit more like naive expectations:



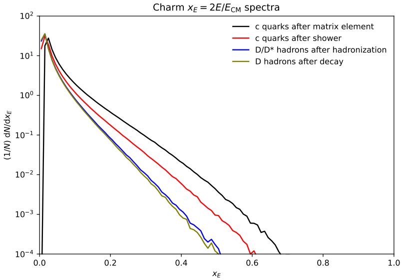


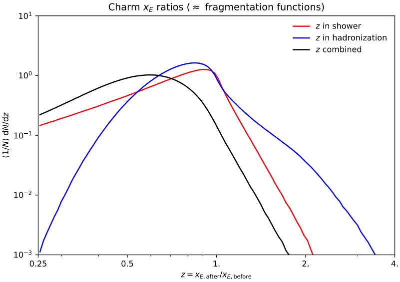
But note that the shower effect can go in either direction:

- Final-state radiation almost always decreases $p_\perp$.
- Initial-state radiation can kick a c or $\overline{\mathrm{c}}$ to significantly higher $p_\perp$.
- Also primordial $k_\perp$ can increase $p_\perp$ some.

A closer look at beam drag (3)

If we require $p_{\perp,\mathrm{ME}} > 100$ GeV:





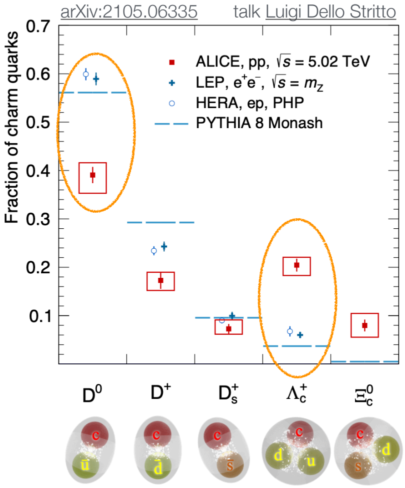
Now expected hierarchy of curves is there, and $z > 1$ less common.
The same pattern in $p_{\perp}$ spectra.
Gradual transition of behaviour from low-$p_{\perp}$ to high-$p_{\perp}$.

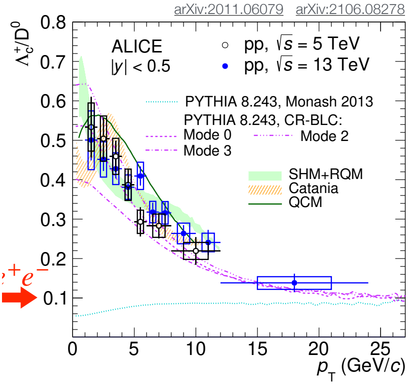
Fragmentation function factorization begins to make sense only for $p_{\perp} > 10$ GeV.

Does not help for FPF applications!

Charm hadron composition

LHC offered a surprise!





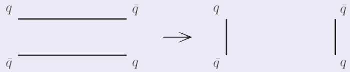
K. Reygers, EPS-HEP 2021

Λ_c^+/D^0 four times higher than in e^+e^-!
But e^+e^- result recovered at large $p_\perp$.

QCD-based colour reconnection

Colour Reconnection (CR) is an essential component of the Multiparton Interactions (MPI) framework.
QCDCR extension by Christiansen & Skands, JHEP 08 (2015) 003

Ordinary string reconnection

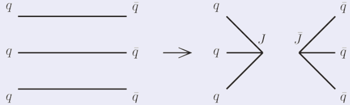


($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection

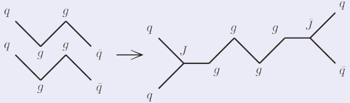
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

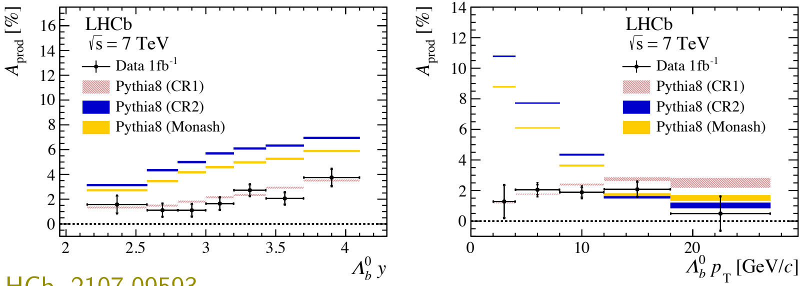


(Depends on number of gluons)

Mainly QCDCR at small $p_{\perp}$, where there are more parallel strings.

Bottom production asymmetries

Asymmetries predicted and observed also for charm and bottom hadrons at the LHC, but full picture not yet clear.



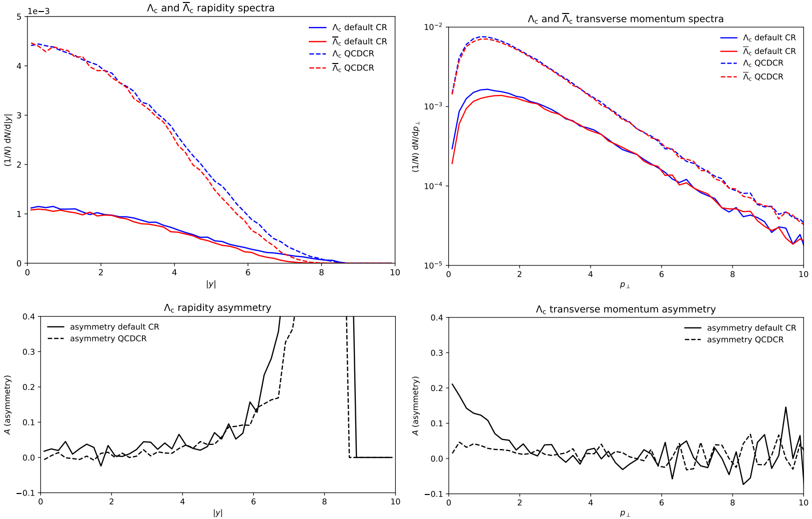
LHCb, 2107.09593

$$A = \frac{\sigma(\Lambda_{\mathrm{b}}^0) - \sigma(\overline{\Lambda}_{\mathrm{b}}^0)}{\sigma(\Lambda_{\mathrm{b}}^0) + \sigma(\overline{\Lambda}_{\mathrm{b}}^0)}$$

Enhanced Λ_{b} production at low $p_{\perp}$, like for Λ_{c}, dilutes asymmetry?

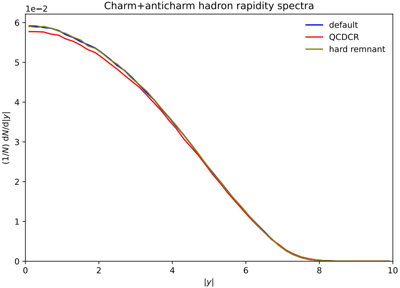
Λ_{c} production and asymmetries

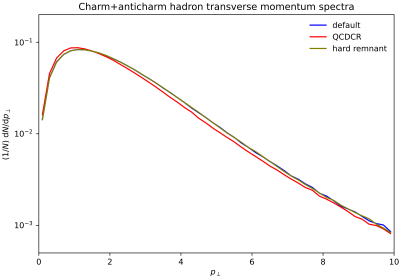
Asymmetries $A = (\Lambda_{\mathrm{c}}^{+} - \overline{\Lambda}_{\mathrm{c}}^{-})/(\Lambda_{\mathrm{c}}^{+} - \overline{\Lambda}_{\mathrm{c}}^{-})$ for inclusive event sample:

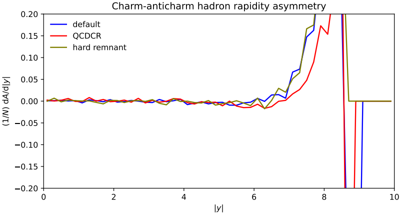


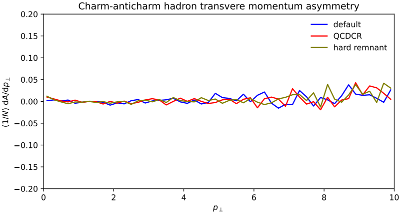
Very close to Λ_{b} behaviour above! (But not same cuts.)

Compare inclusive (anti)charm hadron production:









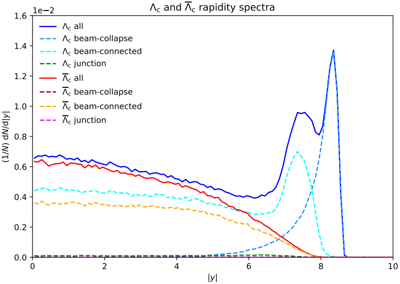
“hard remnant” = harder baryon from beam-remnant diquark.

Issues and conclusion

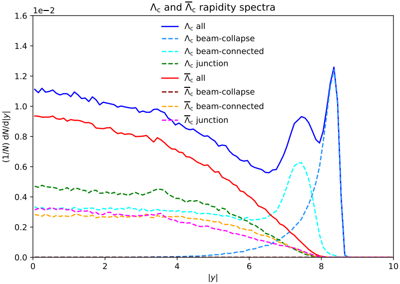
- Naively $\mathrm{d}\sigma(\mathrm{D}) = \mathrm{d}\sigma(\mathrm{c}) \otimes P_{\mathrm{flavour}}(\mathrm{c} \to \mathrm{D}) \otimes f(z = E_{\mathrm{D}}/E_{\mathrm{c}})$.
  Such factorization is strongly broken in forward direction.
- A D/B hadron can be harder than the mother c/b quark.
  Beware in studies of potential intrinsic charm.
  E.g.: does not affect $\sigma(\mathrm{c}\overline{\mathrm{s}} \to \mathrm{W}^+)$, but well recoiling $\overline{\mathrm{c}}$.
- Strong Λ_c enhancement (yet another) break of jet universality.
  Need better understanding of Colour Reconnection and more.
- Uncertainty also from familiar issues:
  PDF, m_{c}, α_{s}, NLO, shower, match&merge, ...
- Spread of predictions for forward charm/bottom spectra?
  Beware of models that cannot explain the $(\pi^- \mathrm{p})$ data.
- Further experimental input is most welcome.

Again consider only $q\overline{q} \to c\overline{c}$ and $gg \to c\overline{c}$ charm production.

Default CR:



QCDCR:



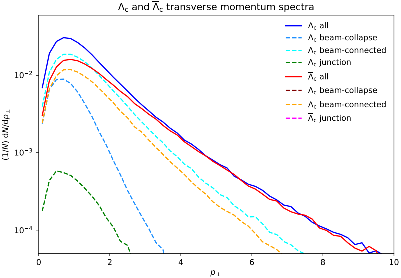
- Clear signal of collapse $c + ud_{beam} \to \Lambda_c$.
- Clear signal of strong beam drag for Λ_c also without collapse.
- No similar signals for $\overline{\Lambda}_c$.
- QCDCR adds more Λ_c and $\overline{\Lambda}_c$, but centrally only.
- QCDCR increases central $\Lambda_c - \overline{\Lambda}_c$ asymmetry, unlike Λ_b data.

But recall that only subset of charm data, likely with some bias.

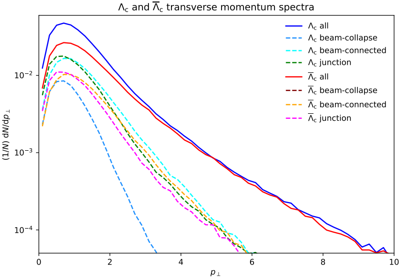
Λ_{c} production and asymmetries (3)

Still only $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{c}\overline{\mathrm{c}}$ and $\mathrm{gg} \to \mathrm{c}\overline{\mathrm{c}}$, but now for $p_{\perp}$ spectra.

Default CR:



QCDCR:



- Collapse $\mathrm{c} + \mathrm{ud}_{\mathrm{beam}} \to \Lambda_{\mathrm{c}}$ gives smallest $\langle p_{\perp} \rangle$.
- Junctions and beam-connected give intermediate $\langle p_{\perp} \rangle$.
- Other $\Lambda_{\mathrm{c}}/\overline{\Lambda}_{\mathrm{c}}$ give largest $\langle p_{\perp} \rangle$.

Again small charm subset, but physically meaningful trends.

Λ_c production and asymmetries (4)

From Snowmass article: