Dependence of heavy-flavour production on event activity in small systems with ALICE

Shreyasi Acharya for the ALICE Collaboration
Laboratoire de Physique de Clermont, France

International Conference on the INITIAL STAGES of High-Energy Nuclear Collisions (IS2023), COPENHAGEN
19-23 June, 2023

Heavy-quark production

Heavy quarks (charm, beauty): [Bare masses: $m_c \sim 1.3$ GeV/c^2, $m_b \sim 4.2$ GeV/c^2]

- produced at the early stages of the collision via hard scattering
- production cross-section calculated using factorization theorem:

$$\mathrm{d}\sigma^{\mathrm{hard}}_{AB\to C} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \mathrm{d}\sigma^{\mathrm{hard}}_{ab\to c}(x_a, x_b, Q^2) \otimes D_{c\to C}(z, Q^2)$$

Parton Distribution Function (PDF) | Parton hard scattering cross section | Fragmention Function (FF)

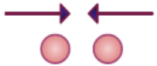
Heavy-quark production

Heavy quarks (charm, beauty): [Bare masses: $m_c \sim 1.3$ GeV/c^2, $m_b \sim 4.2$ GeV/c^2]

- produced at the early stages of the collision via hard scattering
- production cross-section calculated using factorization theorem:

$$\mathrm{d}\sigma^{\mathrm{hard}}_{AB\to C} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \mathrm{d}\sigma^{\mathrm{hard}}_{ab\to c}(x_a, x_b, Q^2) \otimes D_{c\to C}(z, Q^2)$$

Parton Distribution Function (PDF) | Parton hard scattering cross section | Fragmention Function (FF)



pp collisions:

- Test **perturbative QCD** calculations
- Study **hadronization mechanisms** in vacuum
- Baseline **reference for heavy-ion** studies

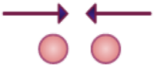
Heavy-quark production

Heavy quarks (charm, beauty): [Bare masses: $m_c \sim 1.3$ GeV/c^2, $m_b \sim 4.2$ GeV/c^2]

- produced at the early stages of the collision via hard scattering
- production cross-section calculated using factorization theorem:

$$\mathrm{d}\sigma^{\mathrm{hard}}_{AB\to C} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \mathrm{d}\sigma^{\mathrm{hard}}_{ab\to c}(x_a, x_b, Q^2) \otimes D_{c\to C}(z, Q^2)$$

Parton Distribution Function (PDF) | Parton hard scattering cross section | Fragmention Function (FF)

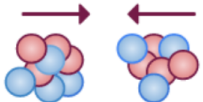


pp collisions:

- Test **perturbative QCD** calculations
- Study **hadronization mechanisms** in vacuum
- Baseline **reference for heavy-ion** studies

In heavy-ion collisions:

- Heavy quarks → probe the properties of medium formed.



Heavy-quark production

Heavy quarks (charm, beauty): [Bare masses: $m_c \sim 1.3$ GeV/c^2, $m_b \sim 4.2$ GeV/c^2]

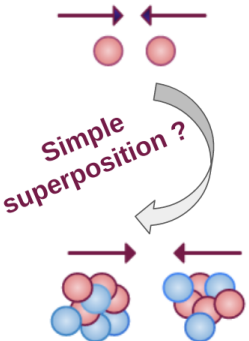
- produced at the early stages of the collision via hard scattering
- production cross-section calculated using factorization theorem:

$$\mathrm{d}\sigma^{\mathrm{hard}}_{AB\to C} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \mathrm{d}\sigma^{\mathrm{hard}}_{ab\to c}(x_a, x_b, Q^2) \otimes D_{c\to C}(z, Q^2)$$

Parton Distribution Function (PDF) | Parton hard scattering cross section | Fragmention Function (FF)

pp collisions:

- Test **perturbative QCD** calculations
- Study **hadronization mechanisms** in vacuum
- Baseline **reference for heavy-ion** studies



In heavy-ion collisions:

- Heavy quarks → probe the properties of medium formed.

Small systems and event activity

Unexpected features in high-multiplicity events of small collision systems:

- Ridge formation
  [CMS, JHEP 09 (2010) 091]
- Anisotropic flow
  [CMS, PLB 765 (2017) 193]

$\Longrightarrow$ collectivity

- Strange baryon enhancement
  [ALICE, Nature Physics 13 (2017) 535-539]

Small systems and event activity

Unexpected features in high-multiplicity events of small collision systems:

- ▷ Ridge formation
  [CMS, JHEP 09 (2010) 091]
- ▷ Anisotropic flow
  [CMS, PLB 765 (2017) 193]

$\Longrightarrow$ collectivity

- ▷ Strange baryon enhancement
  [ALICE, Nature Physics 13 (2017) 535-539]

Open questions in small systems:

▷ Are mechanisms similar to those observed in heavy-ion collisions at play?

▷ If/how particle production mechanisms are affected by different event activities?

▷ What about hard probes (heavy flavour particles)!??

Small systems and event activity

Unexpected features in high-multiplicity events of small collision systems:

- ▷ Ridge formation [CMS, JHEP 09 (2010) 091]
- ▷ Anisotropic flow [CMS, PLB 765 (2017) 193]

$\Longrightarrow$ collectivity

- ▷ Strange baryon enhancement [ALICE, Nature Physics 13 (2017) 535-539]

Open questions in small systems:

▷ Are mechanisms similar to those observed in heavy-ion collisions at play?

▷ If/how particle production mechanisms are affected by different event activities?

▷ What about hard probes (heavy flavour particles)!??

Event activity: Related to mechanisms of particle production occurring in a collision/event.

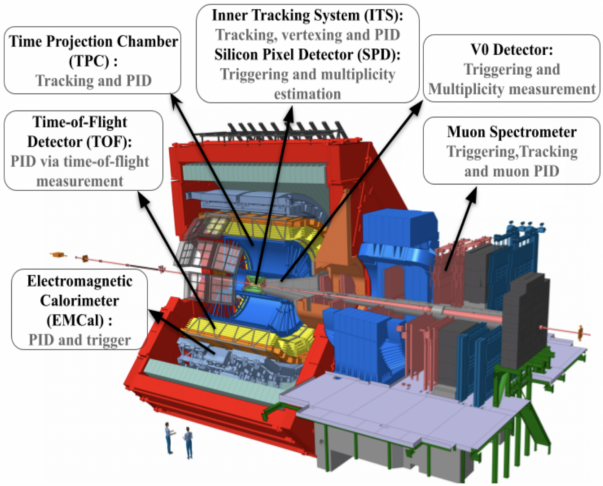
Observable to investigate hadron production as a function of event activity:

Multiplicity: Number of particles produced in a single collision

$\rightarrow$ helps to understand the interplay of hard and soft processes

$\rightarrow$ to search possible connections between small and extended interacting systems

Open heavy-flavour with the ALICE detector



Open heavy-flavour particles studied in this presentation:

$\mathbf{D^0(c\bar{d}) \rightarrow K^-\pi^+}$

$\mathbf{D^+(c\bar{u}) \rightarrow K^-\pi^+\pi^+}$

$\mathbf{D^{*+}(c\bar{u}) \rightarrow D^0\pi^+}$

$\mathbf{D_s^+(c\bar{s}) \rightarrow K^-K^+\pi^+}$

$\mathbf{\Lambda_c^+(udc) \rightarrow pK^-\pi^+}$
$\mathbf{\rightarrow pK_s^0}$

$\mathbf{D,\ B \rightarrow e + \nu_e + X(s)}$

Non-prompt mesons → Mesons from beauty hadron decays

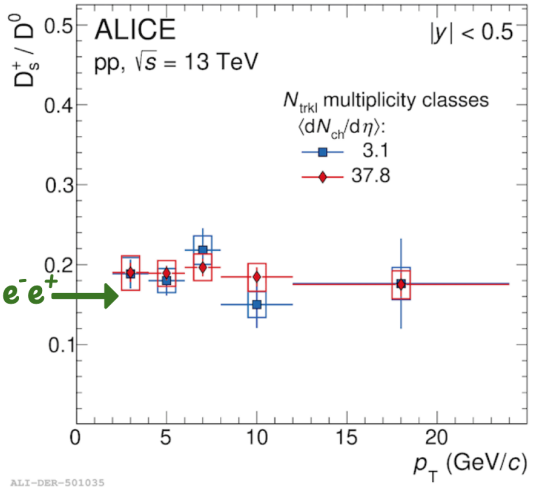
Charm hadronization in pp

ALICE, PLB 829 (2022) 137065

Meson-over-meson ratio D_s^+/D^0 vs. p_T:

- **No dependence with multiplicity** within uncertainties
- **Measurements compatible** with ratio of fragmentation fractions (FF) as measured from e^+e^- collisions at LEP

[L. Gladilin, Eur. Phys. J. C 75, 19 (2015)]



Charm hadronization in pp

ALICE, PLB 829 (2022) 137065

Baryon-over-meson ratio

Λ_c^+/D^0 vs. p_T:

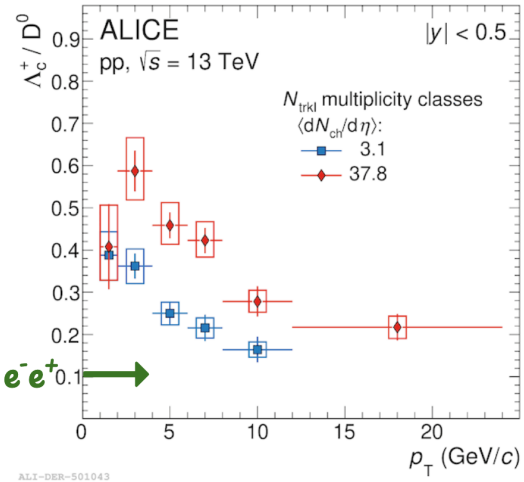
- **Increase from lowest to highest multiplicity** with significance of 5.3 σ

→ indication of **modification of hadronization** mechanisms from small to high multiplicity

- **Higher than** value measured in e^+e^- collisions

[L. Gladilin, Eur. Phys. J. C 75, 19 (2015)]

→ fragmentation not universal



Charm hadronization in pp

ALICE, PLB 829 (2022) 137065

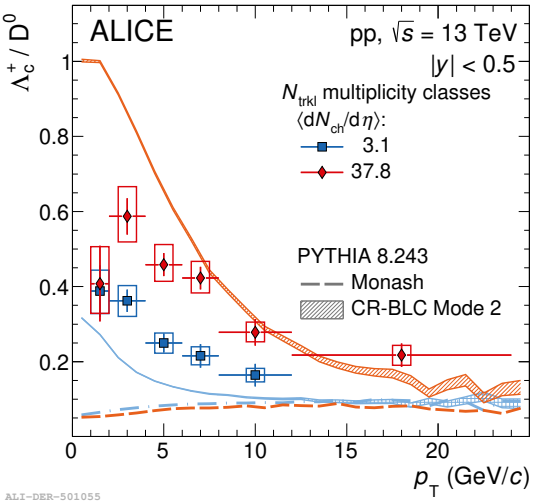
Comparison with PYTHIA 8 prediction

Λ_c^+/D^0 vs. p_T:

- Largely **underestimated** with **PYTHIA 8 Monash** tune

- **Multiplicity trend described** with **PYTHIA 8** including color reconnection mechanisms beyond the leading-color approximation **(CR-BLC Mode 2)**

  → Increase of baryon over meson ratio thanks to **new junctions induced by CR of fragments**



[Details on PYTHIA 8 in slide 15]

PYTHIA8 Monash [Eur. Phys. J. C 74 (2014) 3024],
PYTHIA8 (CR-BLC Mode2) [JHEP 08 (2015) 003]

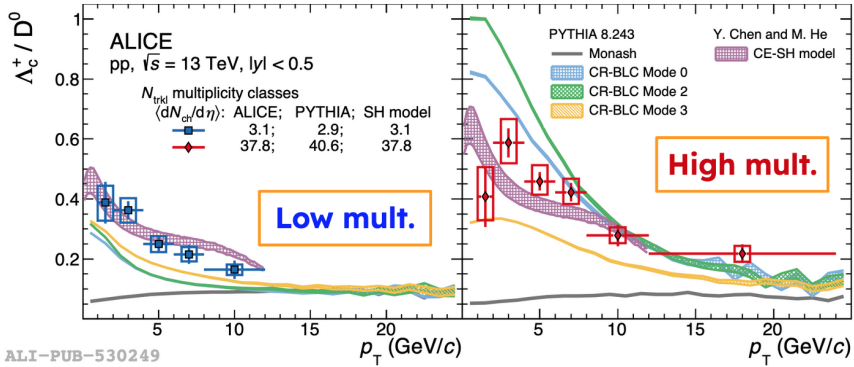
Charm hadronization in pp

Comparison with a statistical hadronisation model (SHM) prediction

Λ_c^+/D^0 vs. p_T:

ALICE, PLB 829 (2022) 137065

CE-SH model [PLB 815 (2021) 136144]



CE-SH model: Explains the multiplicity dependence

→ Canonical-ensemble statistical hadronisation model

→ Includes additional excited baryon states predicted by the Relativistic Quark Model (RQM)

Charm hadronization in pp

p_{T}-integrated $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$:

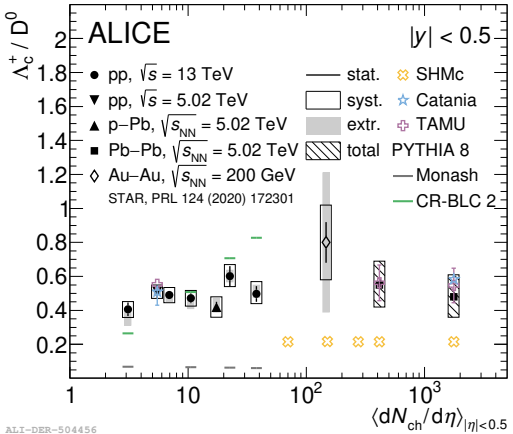
No evidence of multiplicity dependence, from low (pp) to high (central Pb–Pb) multipliplicity

→ Increasing trend in baryon/meson ratios in the p_{T} differential ratios which comes from a **re-distribution of** p_{T} that acts differently for baryons and mesons

No enhancement of p_{T}-integrated ratios in Pb-Pb with respect to to pp collisions

→ Reproduced by **fragmentation + recombination** (Catania) and qualitatively by **SHM** predictions

ALICE, PLB 829 (2022) 137065



PYTHIA8 Monash: EPJC 74 (2014) 3024
PYTHIA8 (CR-BLC Mode2): JHEP 08 (2015) 003
TAMU: PRL 124, 042301 (2020)
; [SHMc: JHEP 07 (2021) 035]; [CATANIA: PRC 96, 044905 (2017)

Beauty hadronization in pp

Normalised fraction of D^0, D^+ mesons from beauty hadron decays:

New Result

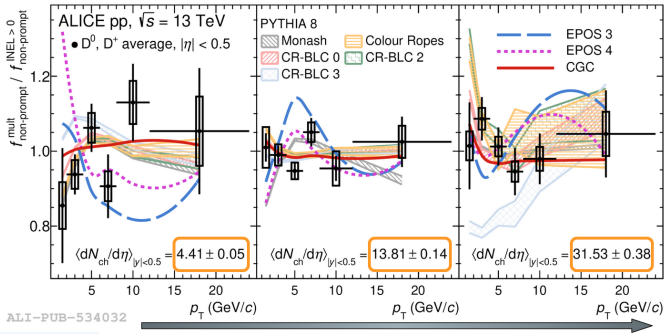
ALICE, arxiv:2302.07783

PYTHIA8 Monash: EPJC 74 (2014) 3024

PYTHIA8 (CR-BLC): JHEP 08 (2015) 003

CGC: PRD 101, 094020 (2020)

EPOS: PRC 89, 064903 (2014)



- **Compatible with unity** vs. p_T and multiplicity

→ **Similar production mechanism** of **c-quarks** and **b-quarks** in events with different multiplicities.

- **Model Comparison:** **PYTHIA 8** (Monash and CR-BLC) and **CGC** fairly reproduce data

EPOS 3, 4 predict a different p_T **dependence of the** $f^{\text{mult}}_{\text{non-prompt}} / f^{\text{INEL}>0}_{\text{non-prompt}}$ **ratios** compared to data.

Multiplicity dependent yields of c,b → e in pp and p-Pb

c,b → e: $\frac{\mathrm{d}^2N/\mathrm{d}p_\mathrm{T}\mathrm{d}\eta}{\langle \mathrm{d}^2N/\mathrm{d}p_\mathrm{T}\mathrm{d}\eta \rangle}$ vs. $\frac{\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta}{\langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta \rangle}$ **New Result**

pp collision:

Faster than linear increasing trend, and p_T **dependence**, influenced by:

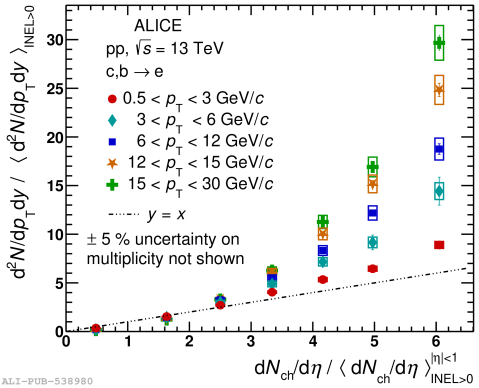
→ jet fragmentation affecting the measured multiplicity

→ fraction of electrons from charm and beauty hadron decays.

High momentum partons → accompanied by larger number of fragments → contribute to high multiplicity

↓

Auto-correlation



ALICE, arxiv:2303.13349

Multiplicity dependent yields of c,b → e in pp and p-Pb

c,b → e: $\frac{\mathrm{d}^2N/\mathrm{d}p_\mathrm{T}\mathrm{d}\eta}{\langle \mathrm{d}^2N/\mathrm{d}p_\mathrm{T}\mathrm{d}\eta \rangle}$ vs. $\frac{\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta}{\langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta \rangle}$ **New Result**

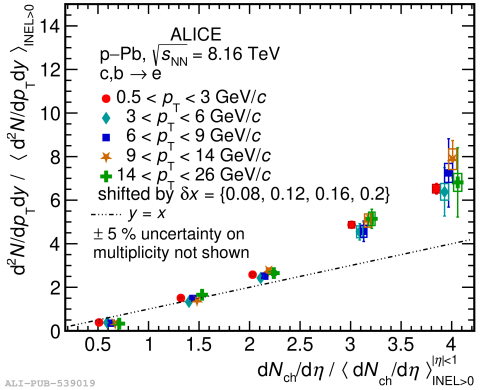
p–Pb collisions:

Faster than linear increasing trend

However, no p_T dependence is observed:

→ **Multiplicity dependence** is driven by presence of multiple binary nucleon-nucleon interaction.

→ Effect of **auto-correlation is smaller** compared to pp.



ALICE, arxiv:2303.13349

Multiplicity dependent yields of c,b → e in pp and p-Pb

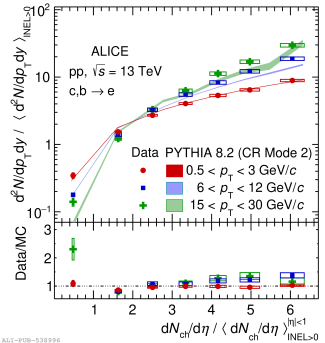
Comparison with model predictions:

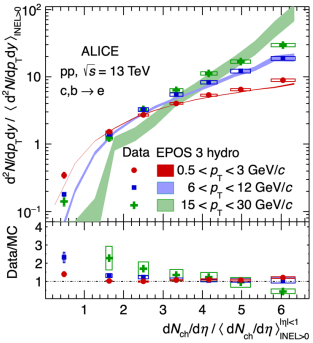
New Result

ALICE, arxiv:2303.13349

PYTHIA8 (CR-BLC): JHEP 08 (2015) 003

EPOS 3: PRC 89, 064903 (2014)



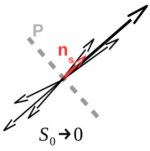


- **PYTHIA 8:** Multiparton interactions (MPI) and color reconnection (CR) mechanisms
  → **Reproduce** self normalised yield slope and p_T dependence well
- **EPOS 3:** Hard pomerons exchanges (hard probe production), hydrodynamic expansion (charged-particle multiplicity) → **Reproduce** the data well, except for the highest p_T interval

D-meson production vs. spherocity in pp

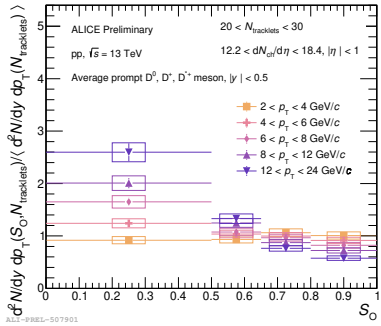
$$S_0 = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{\mathrm{T}_i} \times \hat{n}|}{\sum_i p_{\mathrm{T}_i}} \right)$$

- **Hint of a higher rate of high-p_{T} D** mesons in **low-spherocity** events, expected from **jet contribution** to event spherocity
- Similar rate of low-p_{T} D mesons at different spherocity

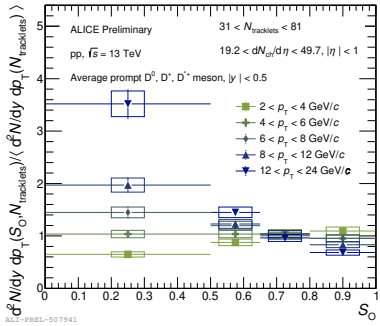


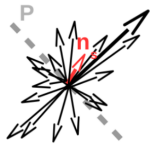
"Jetty" limit
(hard events)

Low multiplicity:



High multiplicity:





"Isotropic" limit
(soft events)

The trend of D-meson production remains the same for two different multiplicity regions

Conclusion

- Charm and beauty hadronization
  - → Charm fragmentation is not universal across different systems and events with different multiplicities.
  - → **b-quark production similar to** to c-quarks production mechanism
- Multiplicity dependence of production of heavy-flavour particles
  - → **In pp:** • Faster than linear increase of self-nomalised yield (SNY) of c,b → e with a p_{T} dependence
    • Hint of higher rate of high-p_{T} D mesons observed in low-spherocity (jetty) events
  - → **In p–Pb:** Faster than linear increase of SNY of c,b → e without any p_{T} dependence
- Model predictions
  - → **PYTHIA 8 CR-BLC** reproduces the $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$ trend; SNY of c b→ e; normalised fraction of non-prompt D-mesons well
  - → **SHM model (CE-SH)** reproduces the $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$ trend in all multiplicity ranges
  - → **EPOS 3** predictions reproduce the self-nomalised yield trend of c,b → e
  - → **CGC** predictions captures the trend of the normalised fraction of non-prompt D-mesons

More studies needed to discriminate among different theoretical descriptions and physics mechanisms. Prospects of Run 3 in the next slide.

Prospects from Run-3

- **More precise** measurements possible for **charm baryons** and **meson**.
- **Direct reconstruction of B mesons down to low** p_{T}, possible due to
  - the improved resolution on the secondary decay reconstruction due to the upgraded ITS detector
  - the much larger data samples that will be collected in all collision systems
- With **significantly higher statistics** in Run-3, more precise **differential measurements with respect to event activity** possible

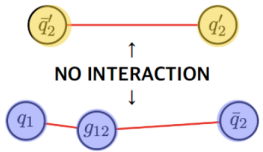
Back up

PYTHIA 8: Color Reconnection Junctions

Colour Reconnection (CR) scenario

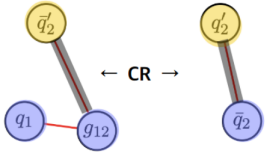
- strings rearranged between partons, so as to **reduce the total string length**
- Partons from different PI can become connected to each other

No CR



Partons created in different MPIs do not interact each other

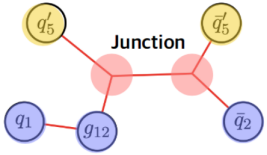
Old CR



partons from lower p_T MPI systems are added to the dipoles defined by the higher p_T MPI system → in a way that minimizes the total string length

(Monash tune)

New CR



Minimization of string length over all possible configurations

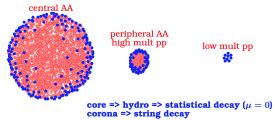
Reconnections of dipoles → junctions structure produces → enhances production of baryons

(CR Mode 'X' tune)

CR Mode 2 (Gluon-move model) : Similar to default but only gluons are considered for reconnection. For each gluon all the reconnections to all MPI systems are considered. [ATL-PHYS-PUB-2017-008]

EPOS 3: Hydrodynamics

- Primary interactions
  1. Gribov-Regge multiple scattering approach
  2. Elementary object = Pomeron = parton ladder
  3. Implementing parton saturation
- Secondary interactions
  1. Core-corona approach (to separate fluid and jet hadrons)



  2. Viscous hydrodynamics (Israel-Stewart formulation)
  3. Statistical hadronization, final state hadronic cascade (Hadronic AfterBurner: UrQMD)

EPOS details, EPOS 4

1. EPOS LHC: Effective flow (parameterised). Tuned to fit pp and pA data up to early LHC data
2. EPOS 2: 3D+1 Ideal hydrodynamics
3. EPOS 3: 3D+1 Viscous (true) hydrodynamics + saturation
4. EPOS 4: ... + Improvements leading to factorization of hard and soft scales