

Cracking hadron and nuclear collisions open with ropes and string shoving in PYTHIA8

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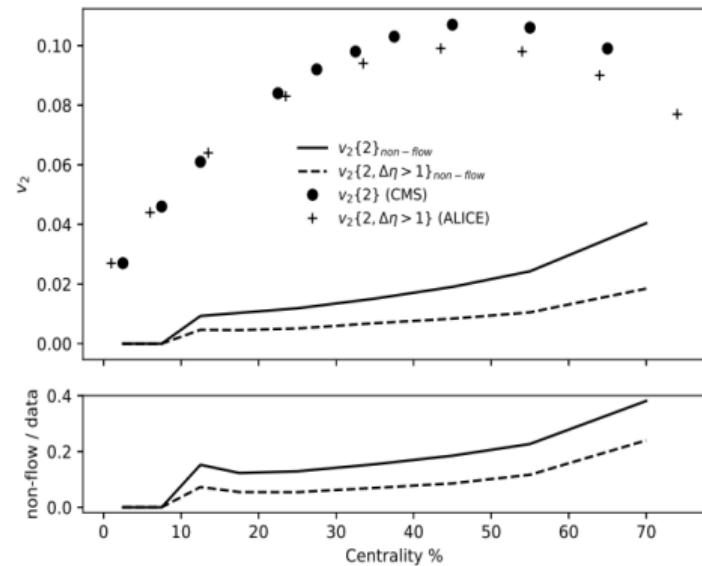


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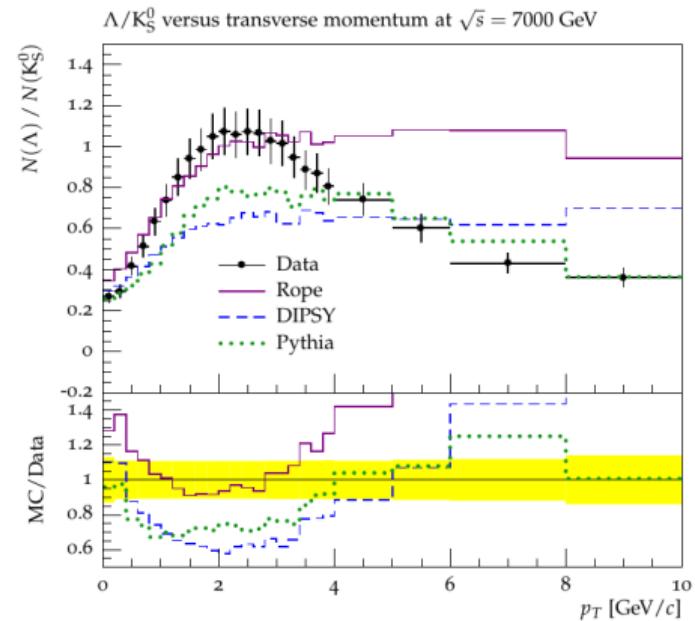
Motivation

- Aim: Observing Quark Gluon Plasma signatures within the Lund string model (PYTHIA and ANGANTYR)
- We want to observe:
 - Imprint of initial geometric anisotropy in the final state particles
 \Rightarrow correlation between particles separated in large units of rapidity
 - Modification of large Q^2 processes in small and large systems
 \Rightarrow Jet quenching &
 \Rightarrow Change in production yields of heavy flavours, e.g. strange and charm, hadrons

Observations with Lund model based MCEGs



(a) ANGANTYR $v_2\{2\}$ performance for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV[†]

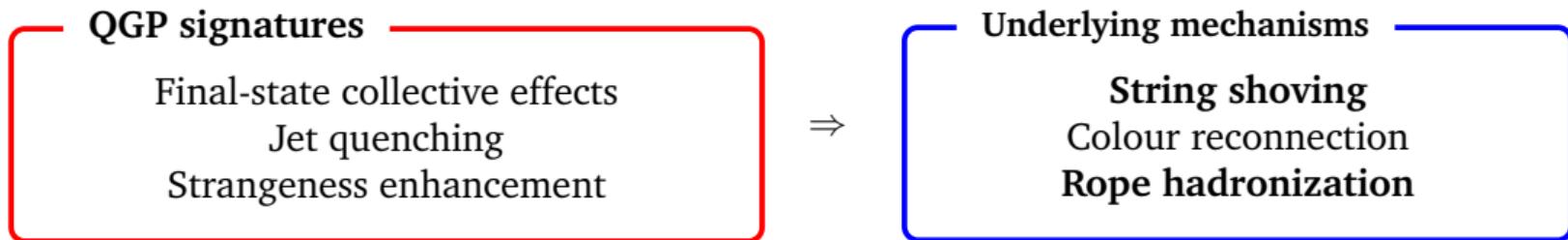


(b) Λ/K_s^0 ratio in DIPSY compared to CMS data for p-p at $\sqrt{s} = 7$ TeV[‡]

[†] Bierlich, et al., J. High Energ. Phys. 2018, 134 (2018), [‡] Bierlich, et al., J. High Energ. Phys. 2015, 148 (2015)

String interactions in Lund strings

- ✓ In transverse coordinate space \Rightarrow rope hadronization¹
- ✓ In colour space \Rightarrow colour reconnection², colour swing³
- ✓ In 3 dimensional coordinate space \Rightarrow string shoving



1. Bierlich C., Gustafson G., Lönnblad, L. et al., J. High Energ. Phys. 2015, 148 (2015).

2 .Christiansen, J.R., Skands, P.Z., J. High Energ. Phys. 2015, 3 (2015).

3. E. Avsar, Gustafson G., Lönnblad, L., JHEP 12 (2007) 012.

String shoving: Gaussian colour field and interaction force

A string of radius R will have a colour electric field of the Gaussian nature:

$$E(r_{\perp}) = C \exp\left(-\frac{r_{\perp}^2}{2R^2}\right)$$

Corresponding force $f(d_{\perp})$ per unit length between two such strings will be:

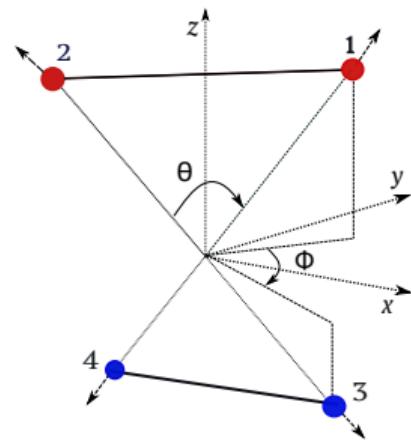
$$f(d_{\perp}) = \frac{dE_{int}}{dd_{\perp}} = \frac{g\kappa d_{\perp}}{R^2} \exp\left(-\frac{d_{\perp}^2(t)}{4R^2}\right)$$

where $E_{int} = \int[(E_1 + E_2)^2 - E_1^2 - E_2^2]$ and g is a tunable parameter($\sim \mathcal{O}(1)$).

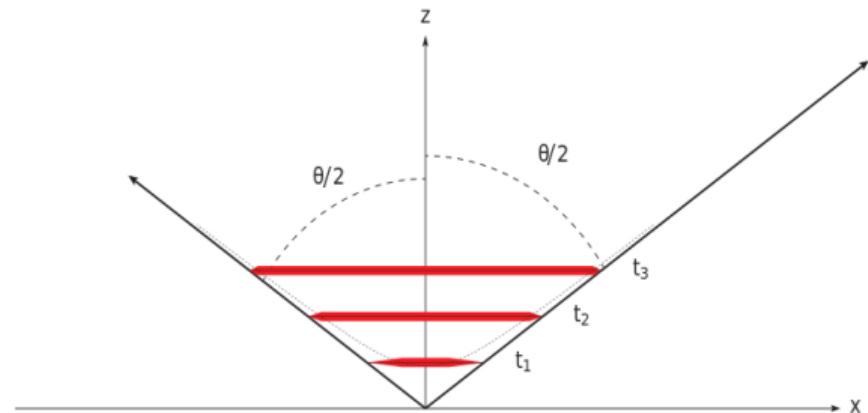
[†]Bierlich C., Gustafson G., Lönnblad L., Collectivity without plasma in hadronic collisions, Phys.Lett.B 779 (2018) 58-63

Strings in the parallel frame

With **two constraints** in string evolution: maximum width R_0 and hadronization time τ_{Had}



(a) Parallel frame with opening angle θ and skewness angle ϕ



(b) Evolution of string width in the parallel frame

[†]Bierlich, C., Chakraborty, S., Gustafson, G. et al. Setting the string shoving picture in a new frame, J. High Energ. Phys. 2021, 270 (2021)

New implementation: Rope hadronization in the parallel frame

Motivation

- Captures the essence of wider colour flux tubes when two strings are close in the transverse co-ordinate space
- Resultant higher effective string tension κ_{eff}
- Higher yield of strange quarks → strangeness enhancement

First implementation in DIPSY, with subsequent PYTHIA hadronization

- ✓ Stacking of strings to form a rope
- ✓ Formation of higher colour multiplets at the ends of colour dipoles
- ✓ Hadronization occurs for each string separately in the MC implementation

[†]Bierlich C., Gustafson G., Lönnblad, L. et al. Effects of overlapping strings in pp collisions, J. High Energ. Phys. 2015, 148 (2015)

Rope formation

- A SU(3) multiplet can be specified by two quantum numbers p and q
- A state corresponds to p coherent triplets + q coherent antitriplets

Corresponding multiplicity is given by —————

$$N = \frac{1}{2}(p+1)(q+1)(p+q+2)$$

†Bierlich C., Gustafson G., Lönnblad, L. et al., J. High Energ. Phys. 2015, 148 (2015).

Higher string tension κ_{eff}

- From lattice calculations: Tension in an isolated static rope is proportional to the quadratic Casimir operator C_2
- Relative strength of the "rope tension"

$$C_2(p, q)/C_2(1, 0) = \frac{1}{4}(p^2 + pq + q^2 + 3p + 3q)$$

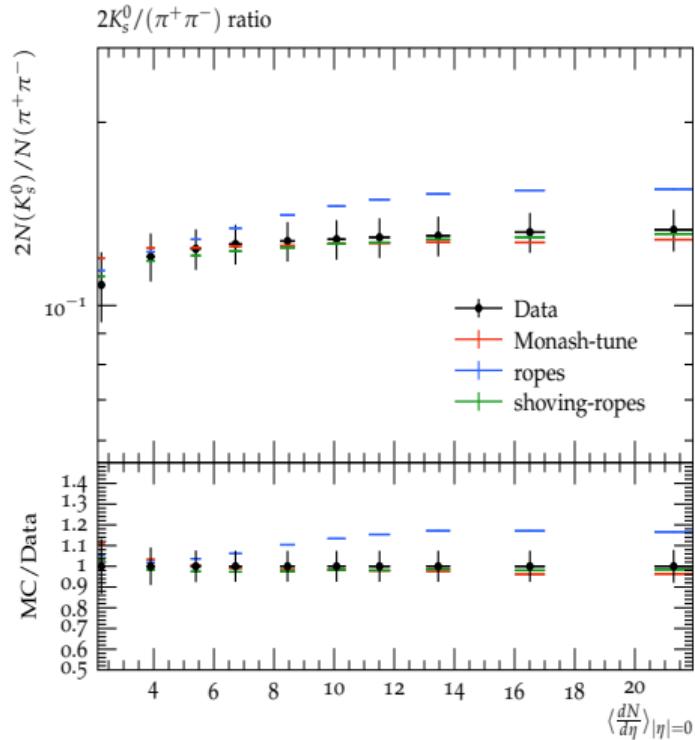
- For breakup via the transition $\{p+1, q\} \rightarrow \{p, q\}$:

$$\text{effective string tension } \kappa_{eff} = \frac{2p+q+4}{4}\kappa$$

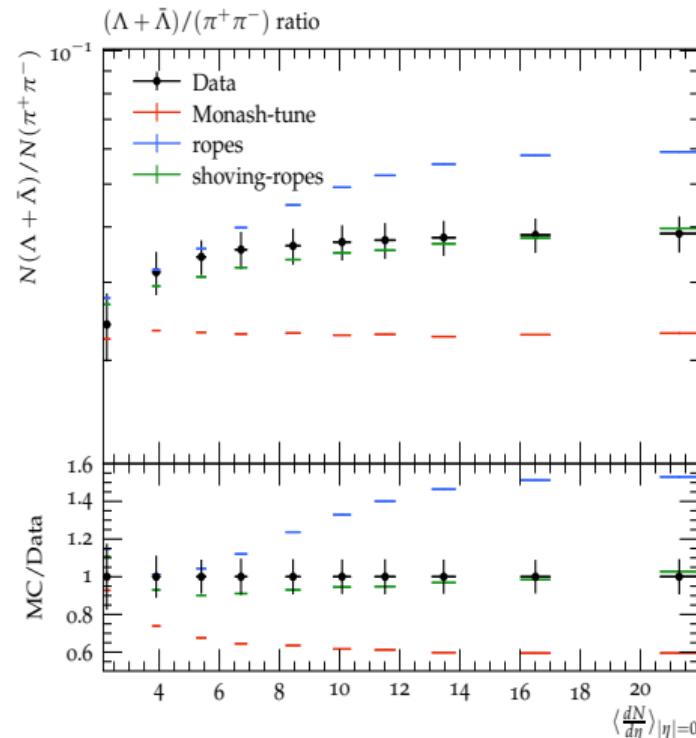
[†]Bierlich C., Gustafson G., Lönnblad, L. et al., J. High Energ. Phys. 2015, 148 (2015).

PRELIMINARY RESULTS

I: Strangeness enhancement in p-p at $\sqrt{s} = 7$ Tev in $|y| < 0.5$

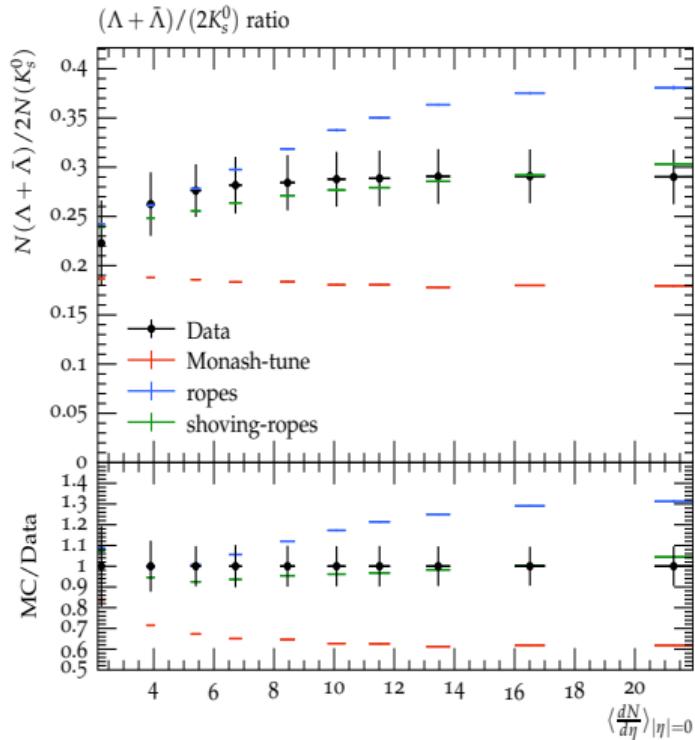


$$(a) K_s^0 = \frac{d\bar{s} - s\bar{d}}{\sqrt{2}}$$



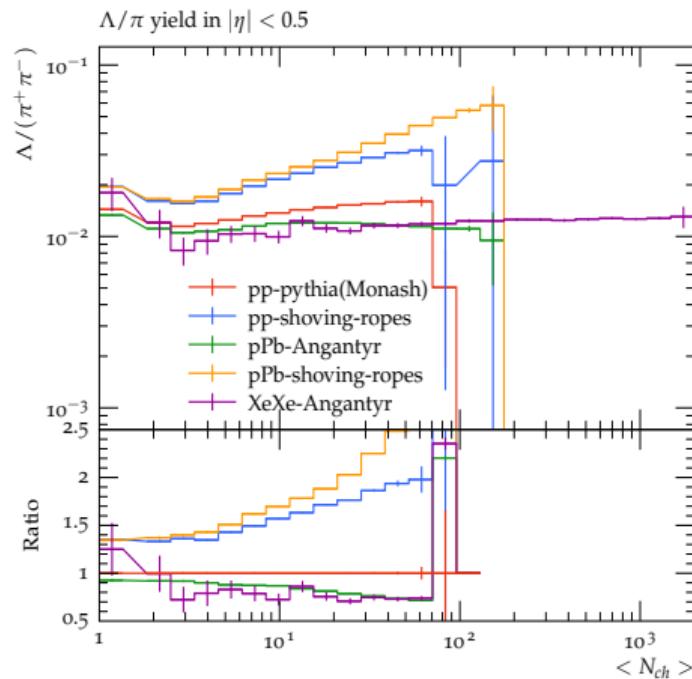
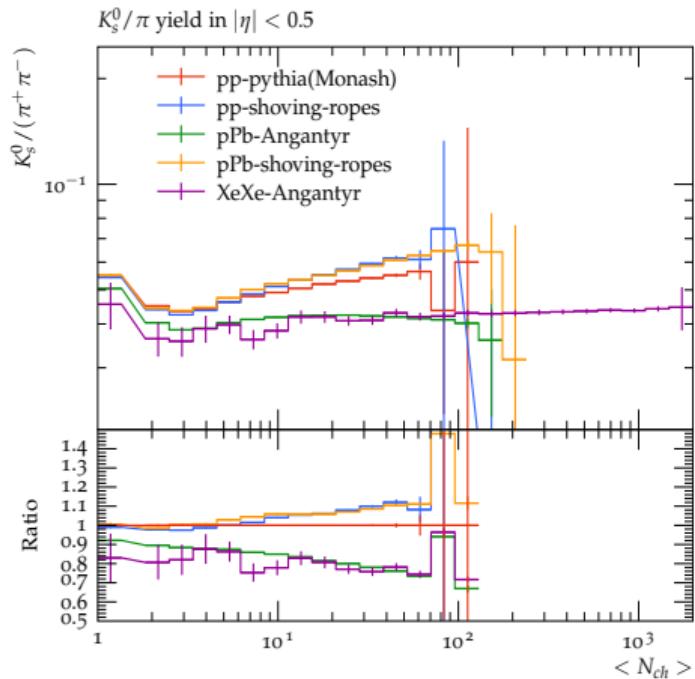
$$(b) \Lambda = uds$$

I: Strangeness enhancement in p-p at $\sqrt{s} = 7$ TeV



- MC within error bars of the data with shoving
- Better description with shoving - rules out overestimation of rope formation

II: Strangeness in p-p at 13 Tev, p-Pb at 5.02 TeV



Wanted - RIVET analysis from the experimental community for p-A and A-A strangeness yields

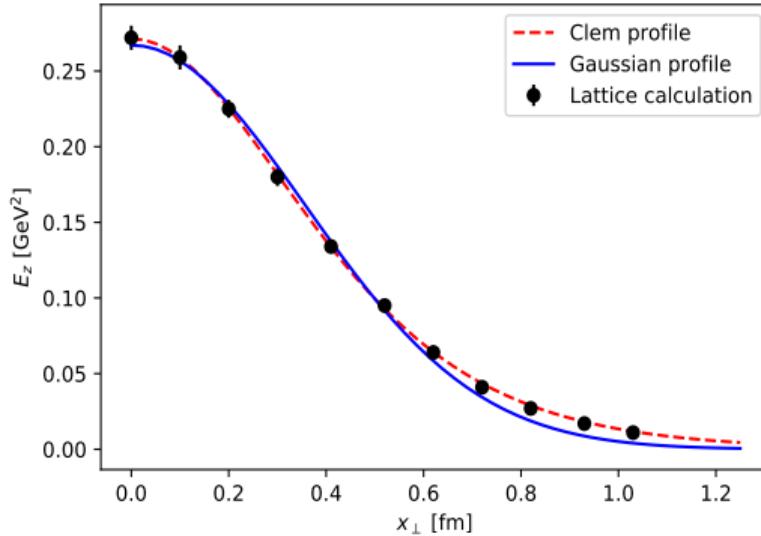
Summary:

- Conclusions from min-bias performance:
 - Inclusion of string shoving provides a realistic string density in dense systems
 - Better description of strangeness production in high-multiplicity p-p with new implementation of ropes and string shoving
 - Further tuning of fragmentation parameters required
- Outlook:
 - Upcoming in ANGANTYR and PYTHIA8: GLEIPNIR module
 - ✓ Implementation of string shoving and rope hadronization in the parallel frame
 - ✓ Generation of heavy-ion events with jet trigger including string interactions

BACKUP

More about g

Dominating colour electric field
 $\rightarrow g \sim \mathcal{O}(1)$

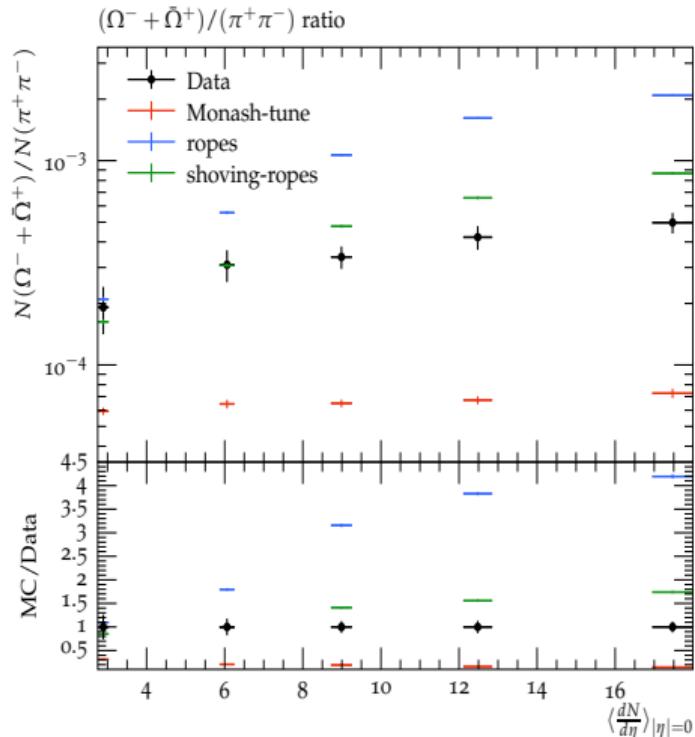


Profile of the electric field from the lattice calculation¹ compared to the fit by Clem² and a Gaussian distribution

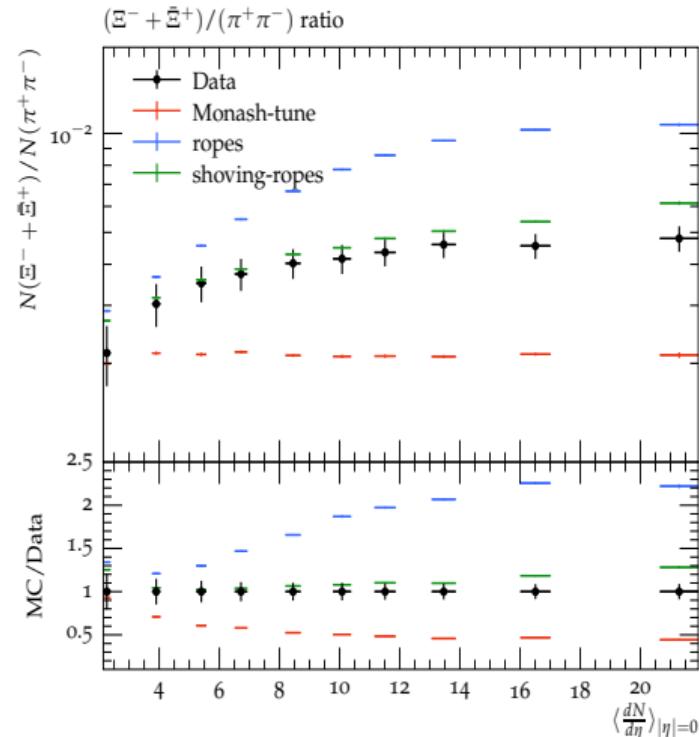
1. Baker, M., Cea, P., Chelnokov, V. et al. The confining color field in SU(3) gauge theory. Eur. Phys. J. C 80, 514 (2020).

2. J. R. Clem, J. Low Temp. Physics 18 (1975) 427

Strangeness enhancement in p-p at $\sqrt{s} = 7$ TeV

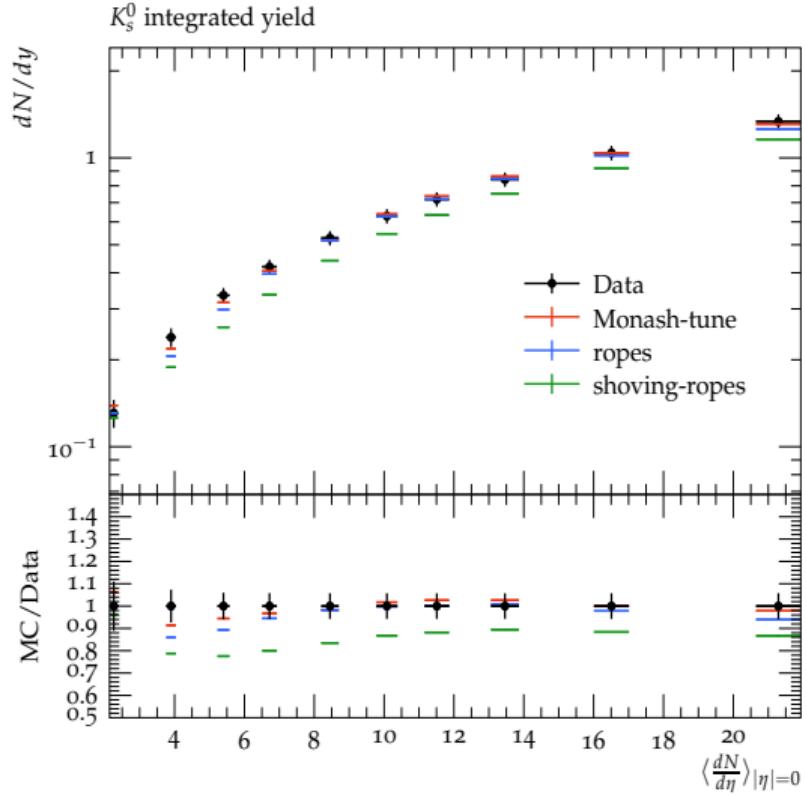
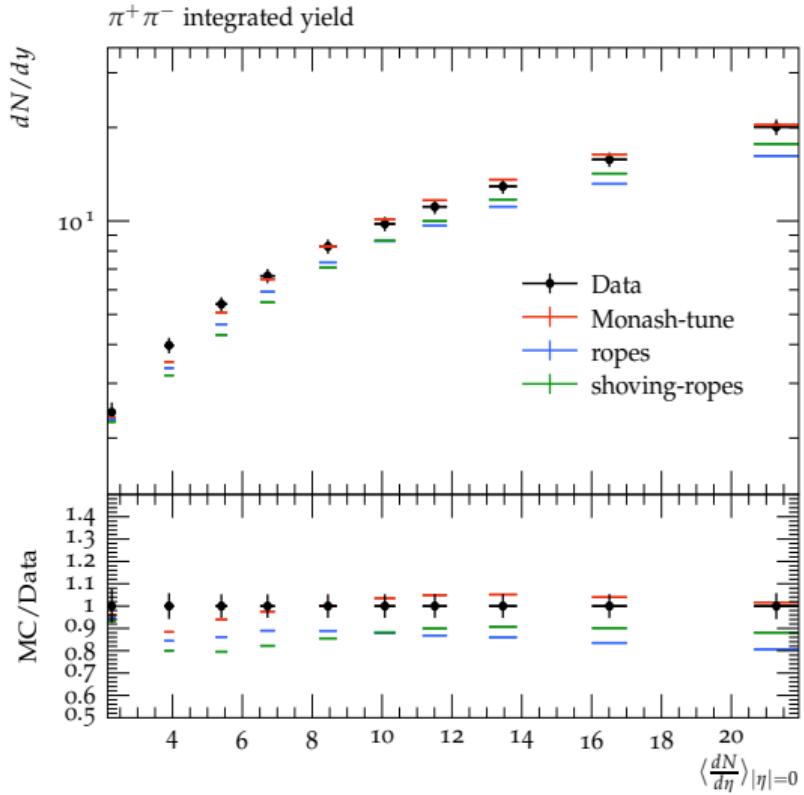


(a) $\Omega = sss$

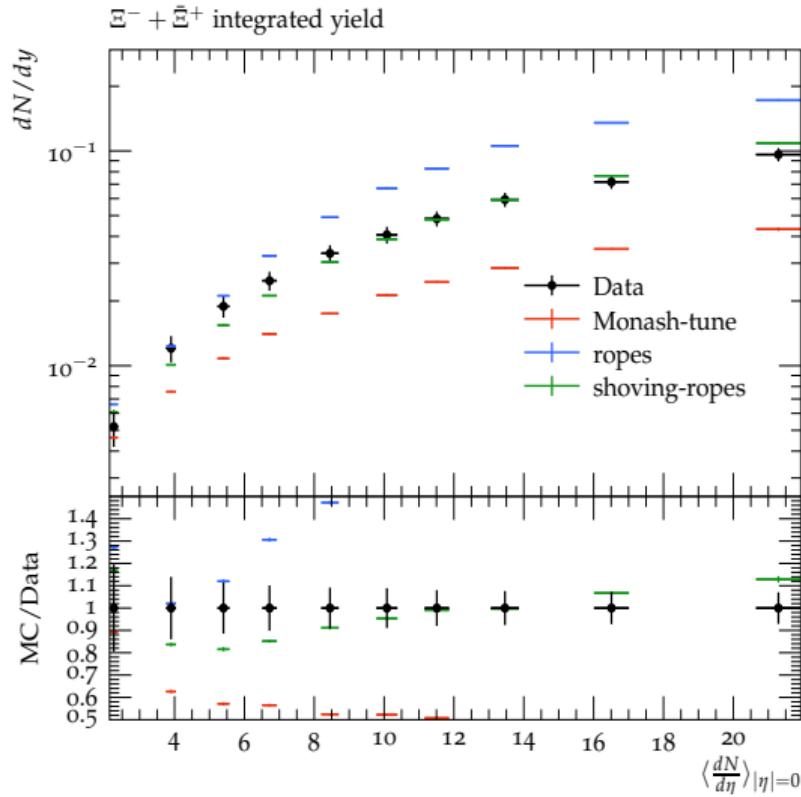
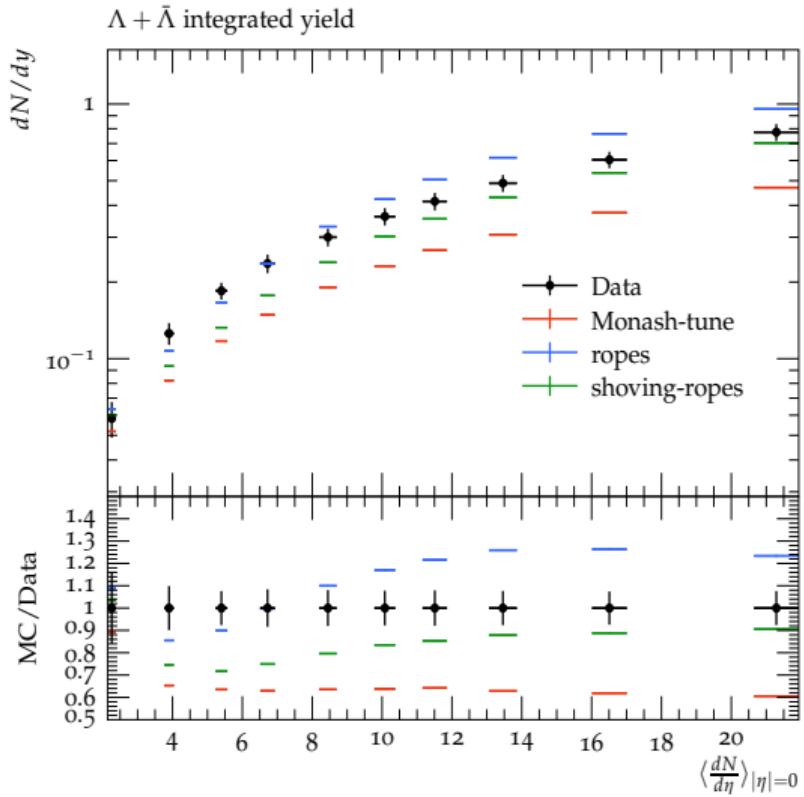


(b) $\Xi = dss$

Integrated yields with ropes and shoving



Integrated yields with ropes and shoving



Integrated yields with ropes and shoving

