Hyperfine splitting in strings and rope hadronization for jets

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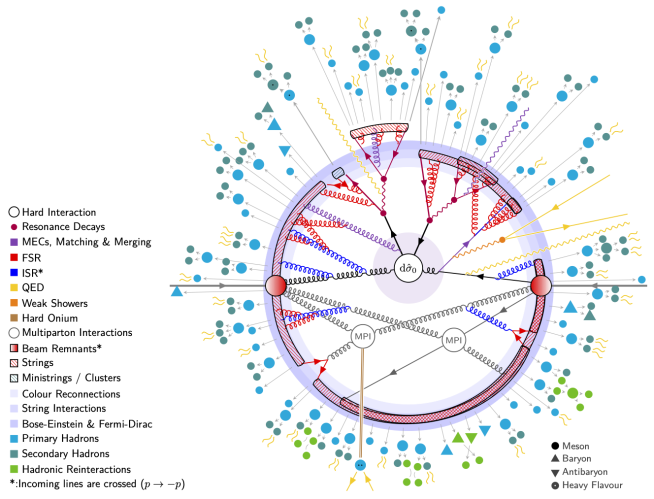
Based on: `arXiv:2201.06316, 2202.12783`

March 2nd 2022, ALICE Week

PYTHIA: Monte Carlo for e^+e^-, ep, pp, pA, AA and more

General purpose event generator for pp and much, much more!



Recent years: Renewed focus on hadronization models → *small system collectivity*.

This talk

- *The baseline* (single string hadronization) is crucial for further model development.
    - *New development* based quark spin–spin interactions.
    - Historically tuned to LEP, opportunity for ALICE low-mult tuning?

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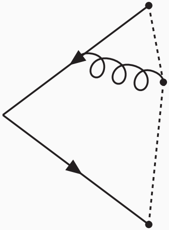
- *The baseline* (single string hadronization) is crucial for further model development.
    - *New development* based quark spin–spin interactions.
    - Historically tuned to LEP, opportunity for ALICE low-mult tuning?
- *News on ropes* (coherent multi-string hadronization) improved and generalized geometry calculation.
    - Necessary ingredient for pA and AA ropes.
    - Now: rope effects in jet fragmentation: opportunities for ALICE measurements?

Fragmentation of a single string (Lund strings: Phys.Rept. 97 (1983) 31-145)

- Non-perturbative fragmentation, Lund strings, $\kappa \approx 1$ GeV/fm.
- Tuned to LEP data, cleanest environment, poor statistics.



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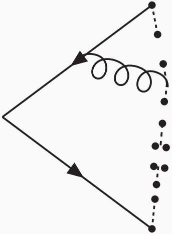
Flavour by tunnelling

♠ $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$, where m is the quark mass → parameter.



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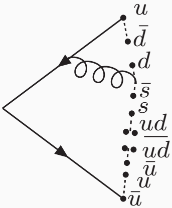

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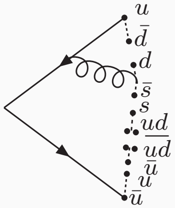


From quarks to hadrons

♣ eg. $\rho^0 = \frac{1}{\sqrt{2}}\left(|\mathrm{u}\bar{\mathrm{u}}\rangle + |\mathrm{d}\bar{\mathrm{d}}\rangle\right)$ not so clear.

1. Spin factors.
2. Mass suppression parameters
3. **SU(6)** Clebsch–Gordans (fl × sp).

- ⋆ Not very predictive!
- ⋆ *Crucial* for event generation.

No easy choice of parameters! (CB, Chakraborty, Gustafson, Lönnblad: 2201.06316)

- Example: Vector/Pseudoscalar meson parameter: $y_{\mathrm{ud}} \times 3$.
  1. Two string breaks produce a $\mathrm{u}\bar{\mathrm{d}}$ state.
  2. $Q = 1$ and $S = 0 \rightarrow \rho^+$ (vector) or π^+ (pseudo–scalar).
  3. $\mathcal{P}_{\pi^+} = \frac{1}{1+3y_{\mathrm{ud}}}, \mathcal{P}_{\rho^+} = \frac{3y_{\mathrm{ud}}}{1+3y_{\mathrm{ud}}}$, where $\mathcal{P}_\pi + \mathcal{P}_\rho = 1$.
- Numerically $y_{\mathrm{ud}} = 0.5$ and $y_{\mathrm{s}} = 0.55$: "mass splitting" parameters.

Should split even further!

♠ Colour magnetic moments $\propto$

$$1/\mu_{\mathrm{ud}}^2, \;\; 1/(\mu_{\mathrm{ud}}\mu_{\mathrm{s}}), \;\; 1/\mu_{\mathrm{s}}^2$$

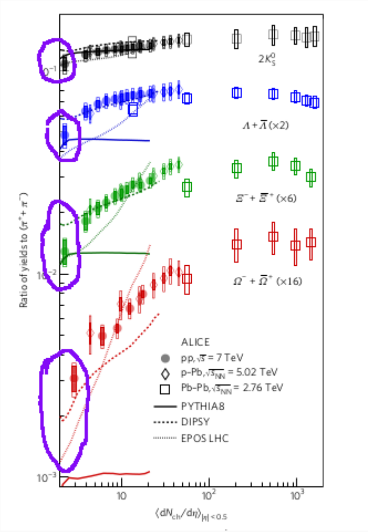
♣ Simple ansatz:

$$y(n_{\mathrm{s}}) = y_1 + n_{\mathrm{s}} y_2$$

- Similar argument for diquarks (implementation slightly more complicated).

Why should I care?

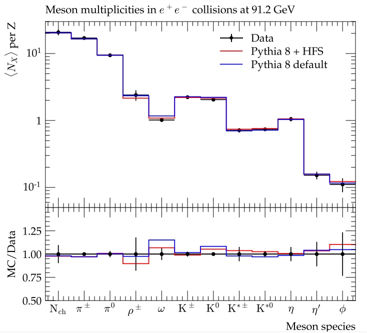
- Low multiplicity is parametrization of LEP!

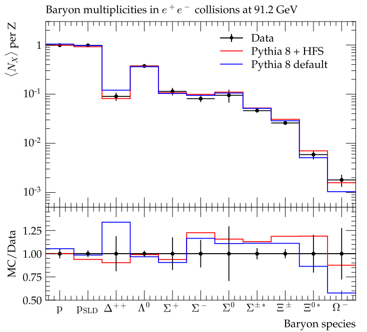


- Any model must get baseline right.
- Important not to ignore historical data.
- Venues for further exploration?

Results in e^+e^-

- Not too much data on interesting final states.
- Tension and “data rot” (extrapolation to full phase space).



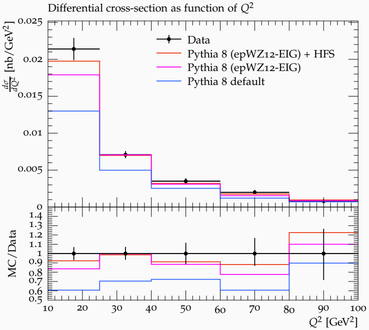


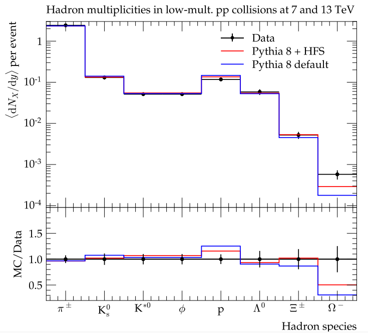
Interesting for ALICE

- ⋆ Data will rot. Differential preservation key (Rivet).
- ⋆ Possibilities for re-tuning before model-exclusion.

Results in *ep* and pp

- DIS = smallest had. system. ZEUS → ϕ enhancement? No!
- Low multiplicity pp: Notable changes. To the better?





Interesting for ALICE

- ⋆ ALICE low multiplicity tunes an option?
- ⋆ Note Ω and p. Both warrants further study!

Rope Hadronization (CB, Gustafson, Lönnblad, Tarasov: 1412.6259 – explored heavily in 80's and 90's!)

- Overlapping strings combine into *multiplet* with effective string tension $\tilde{\kappa}$.

Effective string tension from the lattice

$$\kappa \propto C_2 \Rightarrow \frac{\tilde{\kappa}}{\kappa_0} = \frac{C_2(\text{multiplet})}{C_2(\text{singlet})}.$$

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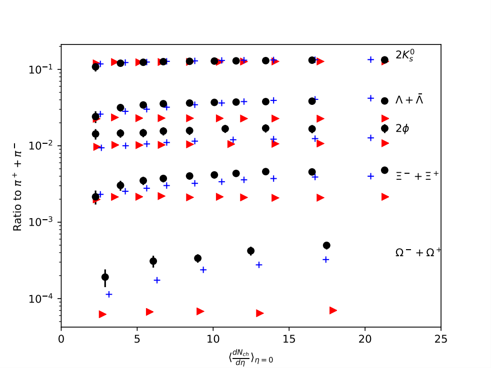
Strangeness enhanced by:

$$\rho_{LEP} = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right) \rightarrow \tilde{\rho} = \rho_{LEP}^{\kappa_0/\kappa}$$

- QCD + geometry extrapolation from LEP.
- Can *never* do better than LEP initial conditions!

Strangeness enhancement from ropes

- Good description of strangeness enhancement.
- In PYTHIA for years, used in several ALICE publications.

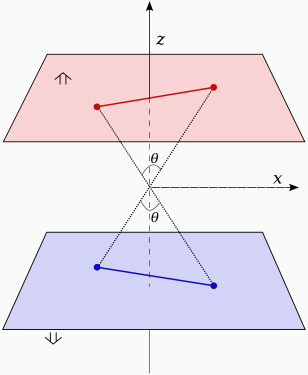


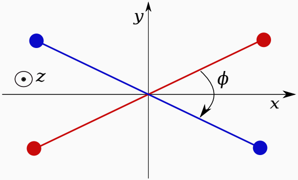
(Black ALICE data, red PYTHIA default, blue PYTHIA with ropes)

- Assumption: *all strings parallel to beam axis*.
- Hyperfine effects not included, baseline is off!

New developments (CB, Chakraborty, Gustafson, Lönnblad: 2202.12783)

- New calculation of string overlaps → arbitrary geometry.
- Stepping stone for pA and AA, crucial for jets!

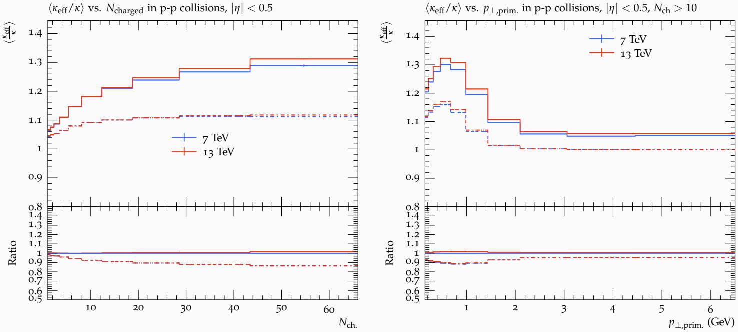




- Still caveats before universally applicable.
- Special cases can already be tested!

Model behaviour minimum bias pp

- Key model result is effective $\kappa \rightarrow$ enhancement.
- Can now be studied differentially!



Interesting for ALICE

- ⋆ $\langle dN/d\eta\rangle|_{|\eta|<0.5}$ natural scaling variable.
- ⋆ Maximal effect at $p_\perp \approx 1$ GeV. ALICE territory.

Jet observables

- Non-observation of jet-quenching in pp is high priority!
- Difficult as no reference, and multiplicity gives jet bias.
- *Generator based predictions a way out?*

Z+jet observables

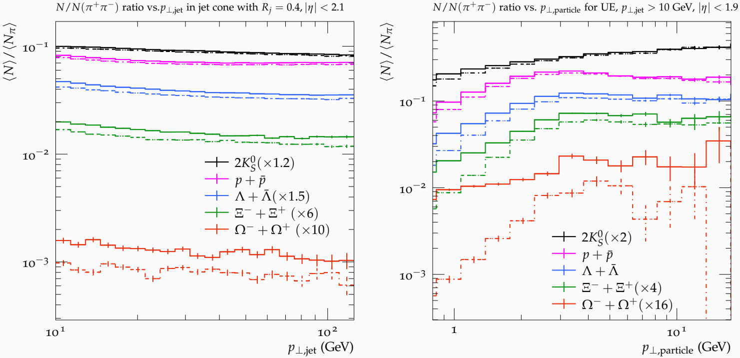
♠ Subtract UE under Z, can work across systems.

♣ Flavour ratios inside and outside jet
($\sqrt{s} = 13$ TeV, anti-kT, $R_j = 0.4$, $\Delta\phi_{jet,Z} > 2\pi/3$)

- Also potential without Z-bosons, subtraction more tricky.

Jet observables, results I

- Larger effects in UE than jet, hints at pp jet modification.

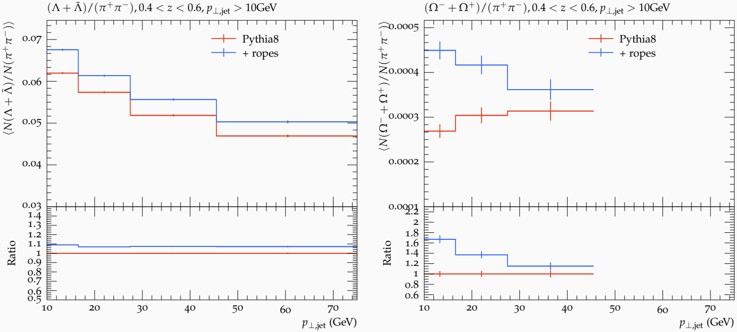


Interesting for ALICE

- ⋆ PID–in–jets measurements that no-one else can do (?).
- ⋆ Small effects → lots of data (HL-LHC?).

Results II: Inside the jets

- More differential → larger effects.
- Expect largest effect at low $z = p_{\perp,\text{particle}}/p_{\perp,\text{jet}}$.
- Cannot technically go near $z = 1$ yet.



- Largest theory caveat is string radius.

Summary

- New developments on string and rope hadronization.
  1. Updated baseline model including hyperfine splitting effects.
  2. Improved geometry handling of rope hadronization, allowing jet effects.
- Opportunities: transition to more quantitative regime!
  1. Be aware of baselines and tuning when doing model comparisons.
  2. Strangeness in jets a venue for small system jet modifications.
  3. Models in continuous development.

Thank you for the invitation!