Nonperturbative models in PYTHIA

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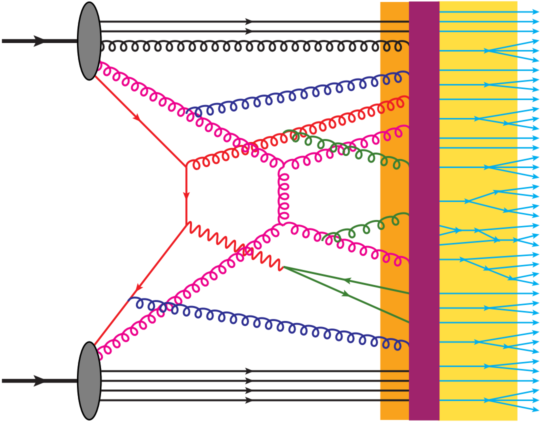
Taming the accuracy of event generators, 23-27 August 2021

Contents

The structure of an event

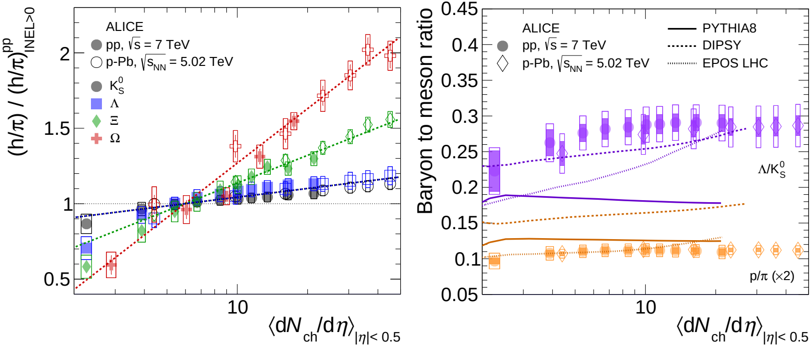
An event consists of many different physics steps to be modelled:



Parton Distributions
Matrix Elements
Initial-State Radiation
Final-State Radiation
Match and Merge
Multiparton Interactions
Beam–Beam Remnants
Colour Reconnection
Fragmentation
Collectivity (shove? ropes?)
Decays
Rescattering
Bose–Einstein
σ_{tot} = elastic + diffractive + $\cdots$
Unknown?

Many/most require nonperturbative modelling!
Evolution in dialogue with experimental observations.

A breakdown of jet universality



- **Significant strangeness enhancement; the more the merrier.**
- **Minimal baryon enhancement.**
- Not described by the Lund string fragmentation model.
- Partly addressed by colour ropes or by core–corona models.

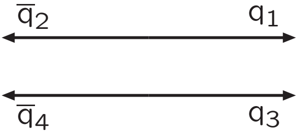
Rope hadronization (Dipsy model)

Dense environment ⇒ several intertwined strings ⇒ **rope**.

Sextet example:

$3 \otimes 3 = 6 \oplus \overline{3}$

$C_2^{(6)} = \frac{5}{2} C_2^{(3)}$



At first string break $\kappa_{\mathrm{eff}} \propto C_2^{(6)} - C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \frac{3}{2}\kappa$.

At second string break $\kappa_{\mathrm{eff}} \propto C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \kappa$.

Multiple ∼parallel strings ⇒ random walk in colour space.

Larger κ_{eff} ⇒ larger $\exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa_{\mathrm{eff}}}\right)$ ⇒ more strangeness and baryons

mainly agrees with ALICE (but p/π overestimated)

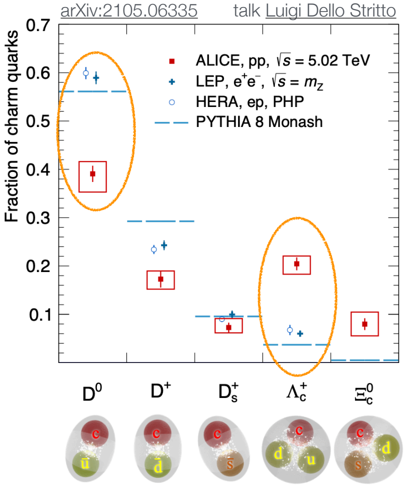
Bierlich, Gustafson, Lönnblad, Tarasov, JHEP 1503, 148

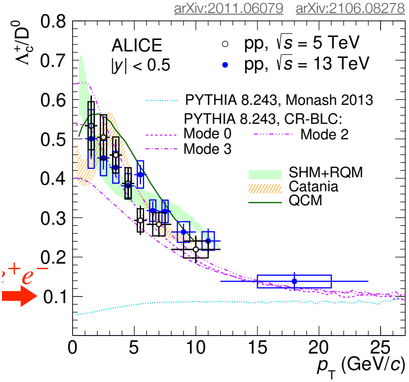
Alternative: close-packing of strings ⇒ smaller string area

⇒ (continuously) larger κ ⇒ "thermodynamical" fragmentation

N. Fischer, TS, JHEP 1701, 140

Charm hadron composition – 1





K. Reygers, EPS-HEP 2021

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

Charm hadron composition – 2

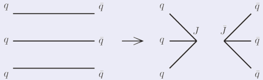
Ordinary string reconnection

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

Double junction reconnection

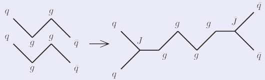
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



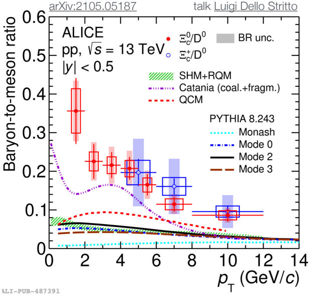
($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

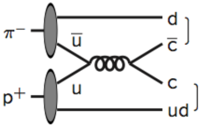


(Depends on number of gluons)

Christiansen, Skands: CR-BLC:
Colour Reconnection
Beyond Leading Colour
JHEP 08 (2015) 003
Mode 0, 2, 3: different causality restrictions, 0 = none
. . . but Ξ_c^+/D^0 still not described

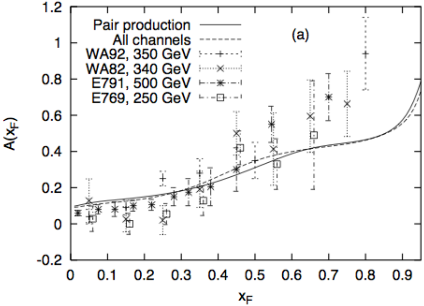


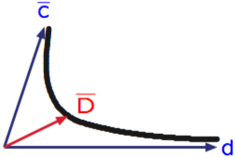
Colour flow connects hard scattering to beam remnants.
Can have consequences, e.g. in $\pi^- p$



$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

If low-mass string e.g.:
$\overline{c}d$: D^-, D^{*-}
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}
$\Rightarrow$ flavour asymmetries

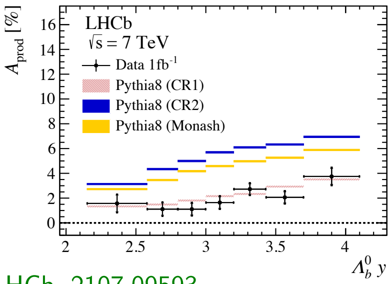


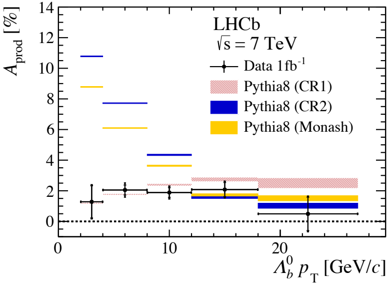


(also B asymmetries at LHC, but small)

Can give D 'drag' to larger x_F than c quark for any string mass

Bottom asymmetries





LHCb, 2107.09593

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

CR1 = CR-BLC, no enhancement at low $p_\perp$.

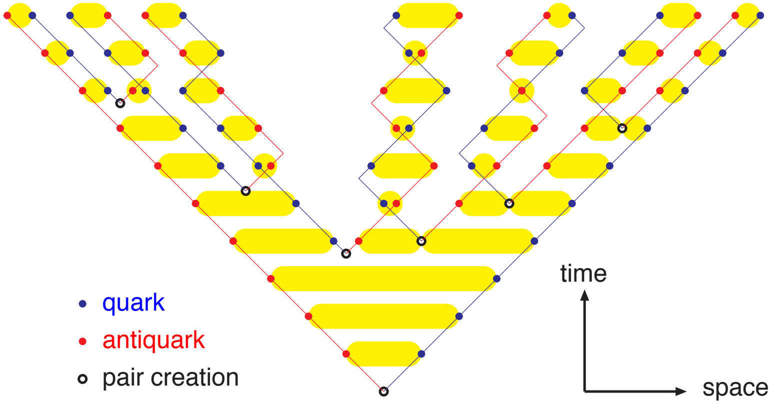
Enhanced $\Lambda_{\rm b}$ production at low $p_\perp$, like for $\Lambda_{\rm c}$, dilutes asymmetry?

Asymmetries observed also for other charm and bottom hadrons.

Revived field of study?

The Lund Model – 1

Combine yo-yo-style string motion with string breakings!

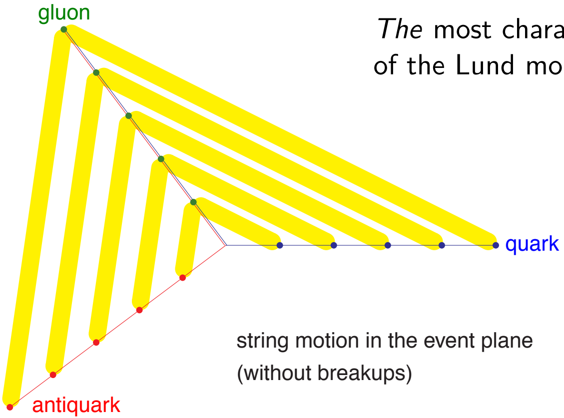


A q from one string break combines with a $\overline{\mathrm{q}}$ from an adjacent one.

String tension $\kappa \approx 1$ GeV/fm relates $(t, \mathbf{x})$ and $(E, \mathbf{p})$.

Gives simple but powerful picture of hadron production.

The Lund Model – 2

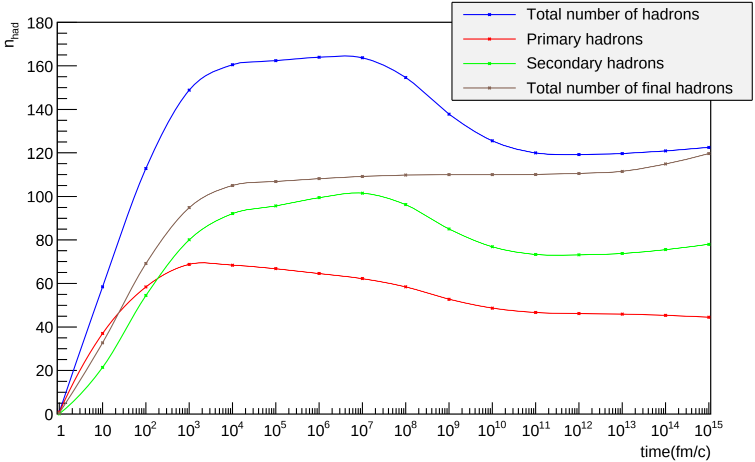


The most characteristic feature of the Lund model:

Generalizes to multiple intermediate gluons,
closed gluon loops, junction topologies.
In principle always unique relationship $(t, \mathbf{x}) \leftrightarrow (E, \mathbf{p})$,
but in practice can become quite complicated string motion.

Space–time evolution

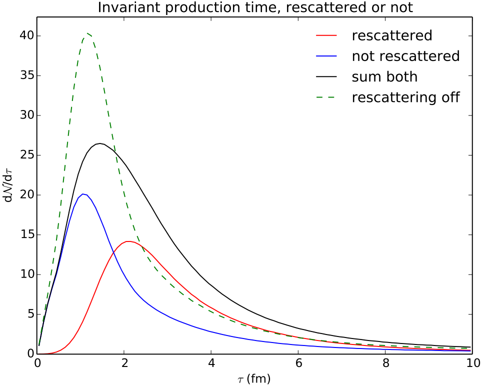
PYTHIA can now calculate production vertex of each particle, e.g. number of hadrons as a function of time for pp at 13 TeV:



S. Ferreres-Solé, TS, EPJC 78, 983

Hadronic rescattering

13 TeV nondiffractive pp events:



PYTHIA now contains framework for hadronic rescattering:

1) Space–time motion and scattering opportunities

2) Cross section for low-energy hadron–hadron collisions

3) Final-state topology in such collisions

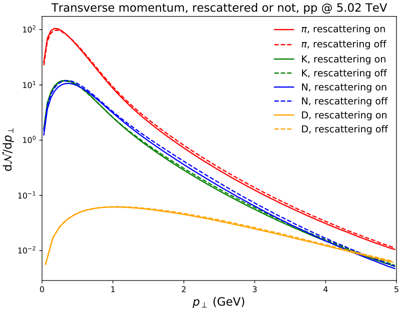
M. Utheim, TS, EPJC80, 907

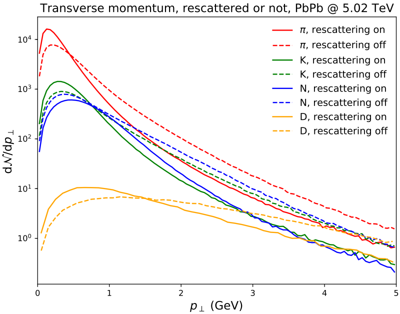
In principle already covered by other programs like UrQMD or SMASH, but then interfacing issues limits usefulness.

Rescattering effects in pp and AA – 1

Softening of pion spectrum in pp (and AA) in right direction, but more complicated for other hadrons.

Generally, observable consequences in pp minor, but important for AA modelling

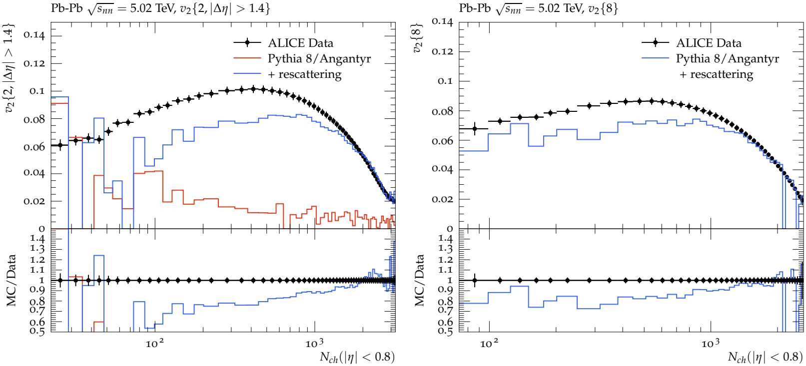




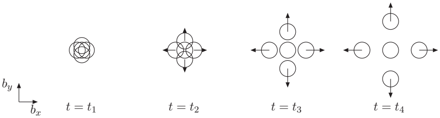
C. Bierlich, M. Utheim, TS, EPJA57, 227

Rescattering effects in pp and AA – 2

Significant contribution to collective flow in AA:

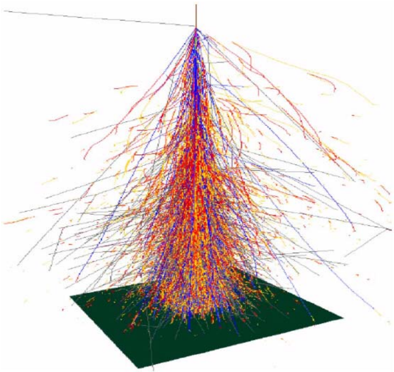


but need more, e.g. shove:



Bierlich, Gustafson, Lönnblad, PLB 779, 58 + ongoing

Cosmic ray cascades



high-energy cosmic ray
in atmosphere,
not with PYTHIA,
but could have been

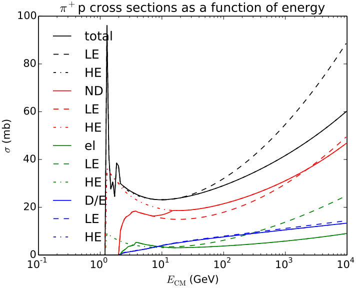
Have implemented components needed for hadronic cascade

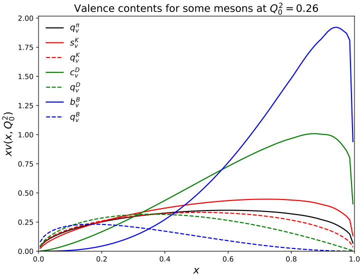
- total and partial cross sections for $h\mathrm{p}/h\mathrm{n}$, from threshold to high energies
- PDFs for different hadrons, for MPIs handling
- rapid switching between hadrons and energies
- atmosphere = nuclear targets by poor man's Angantyr

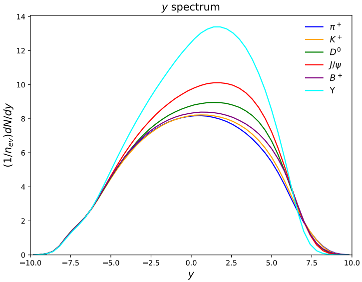
M. Utheim, TS, 2108.03481

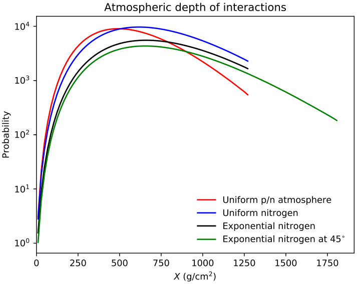
Missing: incoming nuclei or photons, electromagnetic cascades

Sample distributions

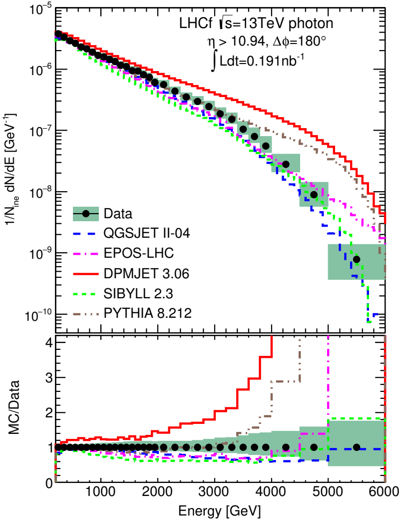


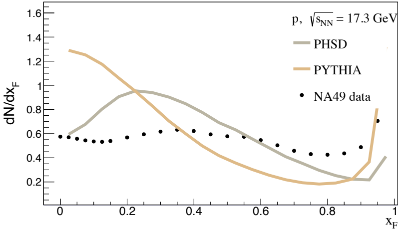






Forward data





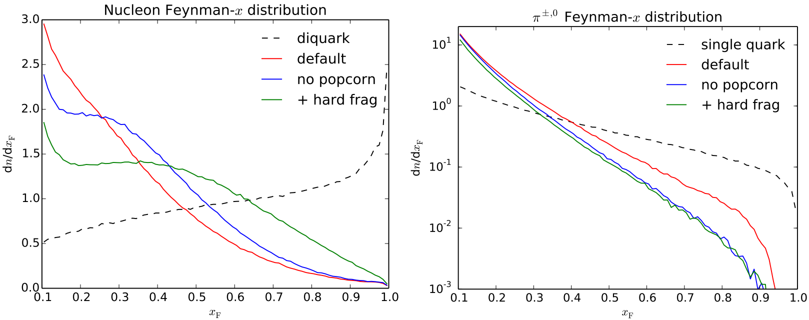
V. Kireyeu et al., arXiv:2006.14739

LHCf, PLB 78, 233

Need mechanism for protons to take more energy (from pions)? Diffractive-related or not?

Forward region also important for cosmic-ray physics.

Forward modelling



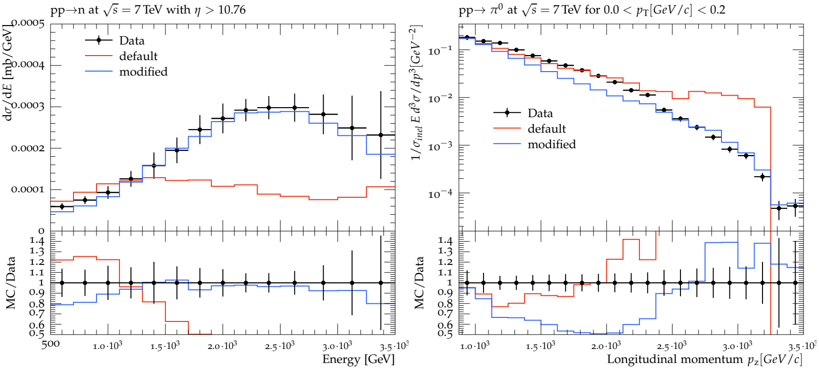
Two "improvements":

- Forbid popcorn mechanism for remnant diquarks only;
  i.e. baryon always produced at end of string, never meson
- Set a and b parameters separately in Lund fragmentation

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right)$$

with $a = 0.68 \to 0$ $(+\dots)$ and $b = 0.98 \to 2$

Comparison with LHCf



courtesy Max Fieg

Warning: limited acceptance; for baryons only at per cent level; some additional (modest) tuning of primordial $k_\perp$ also helped.

Some topics not discussed

- Tuning of fragmentation parameters, with new PSs and M&M
- Consequences of NLO (negative) PDFs in showers & MPIs
- Multi-parton PDFs (modelled in PYTHIA, but not tested)
- Partonic rescattering ($3 \to 3$ etc. in MPIs)
- Initial-state impact-parameter picture, e.g. Dipsy dipoles
- Colour reconnection and the top mass
- Differences between quark and gluon jets
- Heavy-flavour production and hadronization
- Jet quenching in high-multiplicity pp systems (?)
- Transition showers to hadronization; e.g. scale MPI, ISR, FSR
- Bose–Einstein (and Fermi–Dirac) effects
- Deuteron, tritium, helium, tetraquark, pentaquark coalescence
- Diffraction; rapidity gaps and jets
- Real and virtual photons, e.g. in ultraperipheral collisions
- . . .

Summary

Goodby jet universality, welcome new mechanisms!

- Strangeness enhancement ⇒ ropes?
- Charm baryon enhancement ⇒ junction reconnection?
- Bottom asymmetries ⇒ beam drag + above?
- Hadronic $p_{\perp}$ spectra ⇒ rescattering + more?
- Hadronic flow ⇒ shove + rescattering?
- Forward hadrons ⇒ different remnant rules?

Also other issues:

- Relation to AA: is there a Quark–Gluon Plasma already in pp?
- Applications to other fields, like cosmic rays
- ...

Before LHC we used to think the picture was messy, but now
will we ever find back to such a “simple” description?

Appendix: PYTHIA collaboration status

New organization as of May this year:

New home page: `https://pythia.org`
New mail address: `authors@pythia.org`

- Spokesperson: Peter Skands
- Code master: Philip Ilten
- Web master: Christian Bierlich

Current authors:

Christian Bierlich
Nishita Desai
Leif Gellersen
Ilkka Helenius
Philip Ilten
Leif Lönnblad
Stephen Mrenna
Stefan Prestel
Christian Preuss
Torbjörn Sjöstrand
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Marius Utheim
Rob Verheyen