PYTHIA 8 Overview

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Workshop on the tuning of hadronic interaction models
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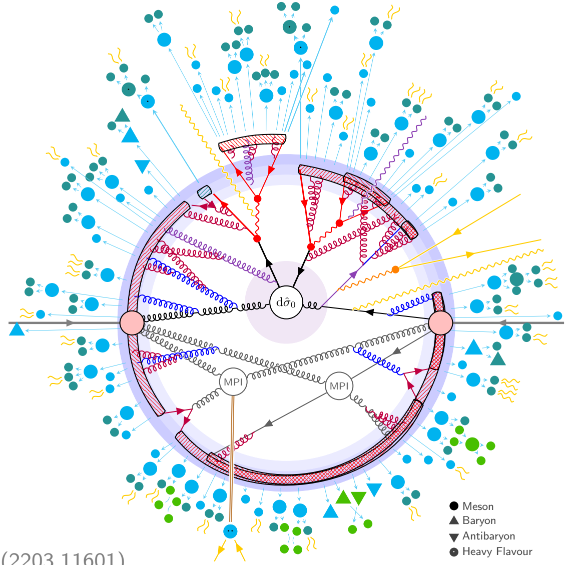
The structure of an LHC pp collision



(2203.11601)

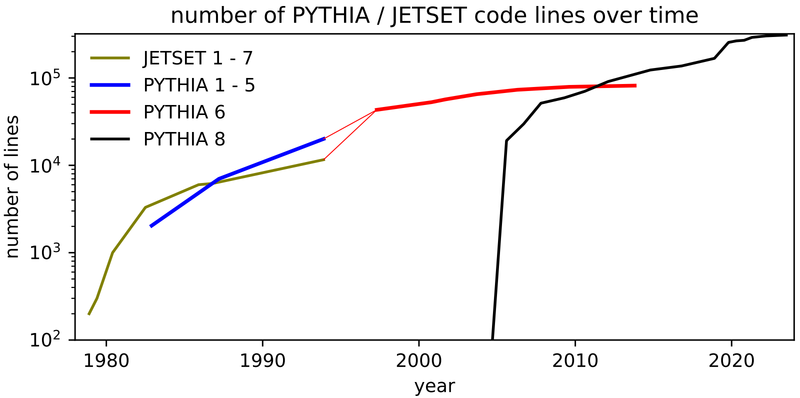
- Hard Interaction
- Resonance Decays
- MECs, Matching & Merging
- FSR
- ISR*
- QED
- Weak Showers
- Hard Onium

- Multiparton Interactions

- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

(: incoming lines are crossed)*

Code size



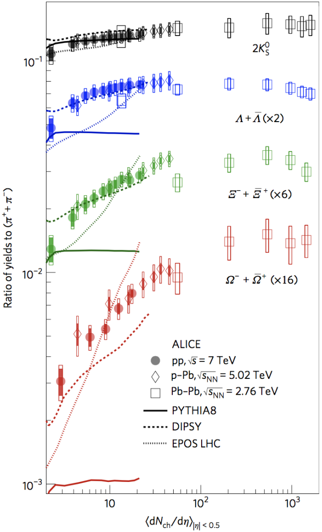
- JETSET (1978): string fragmentation, decays, e^+e^- physics.
- PYTHIA (1982): add-on for $pp/\overline{p}p$.
- PYTHIA6 (1994): integrate programs into one.
- PYTHIA8 (2004): begin transformation from Fortran to C++.

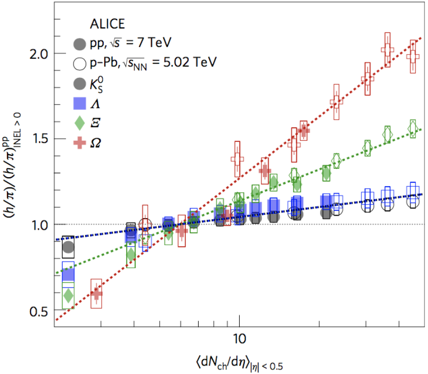
Code usage and limitations

- Most used model for hadronization part in $e^+e^-/pp/\overline{p}p$, since used "under the hood" in **many** other programs.
- Contains > 200 hard processes within and beyond the SM, but nowadays more common to use such input e.g. from MadGraph_aMC@NLO or PowHeg.
- Not perfect. Most worrisome conflicts with data:
  - strangeness enhancement at high multiplicity,
  - baryon enhancement in charm and bottom production,
  - forward particle spectra, and
  - the ridge effect at high multiplicities.

  Different studies have aimed to improve situation.
- Historical limitations for cosmic-ray applications:
  - only for high-energy interactions,
  - initialization for fixed energy and beam particles, and
  - only $e^\pm, \mu^\pm, p, \overline{p}, n, \overline{n}$ beams (not pA or AA!).

  Recent extensions open for integration with CORSIKA 8.



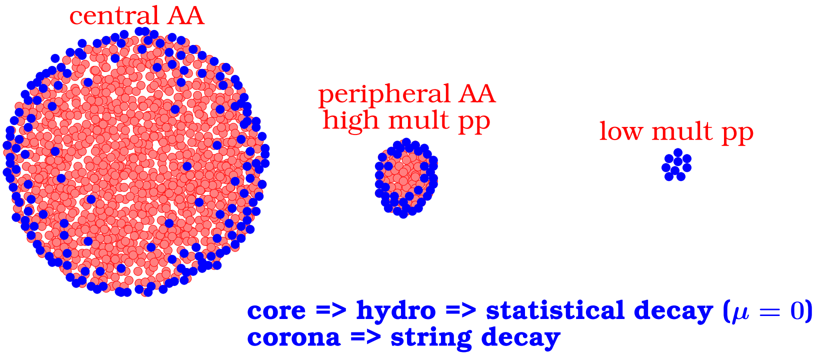


(Also observed in B_s/B^0 by LHCb.)

Signs of QGP in high-multiplicity pp collisions? If not, what else?

The Core–Corona Solution (2007)

Currently most realistic “complete” approach:
mix discrete strings with continuous quark–gluon plasma.



Allows smooth transition. Implemented in **EPOS** MC

K. Werner, PRL 98 (2007) 152301

Qualitatively agrees with ALICE, but too steep rise.

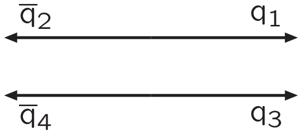
The Rope Solution (2015)

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

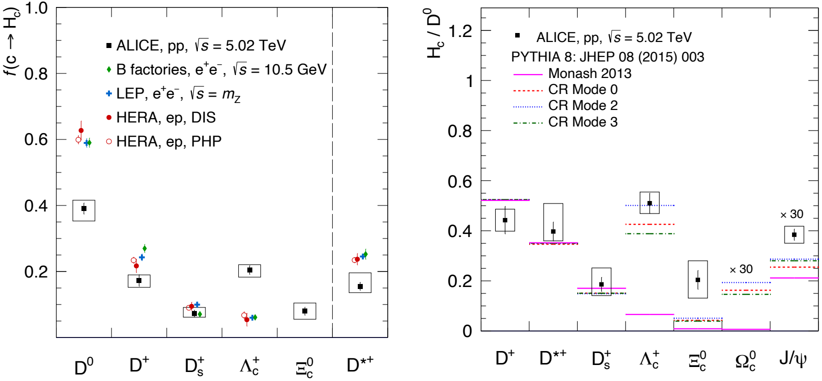
Multiple ∼parallel strings ⇒ random walk in colour space.

Larger κ_{eff} ⇒ less tunneling suppression $\exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa_{\mathrm{eff}}}\right)$

- more strangeness
- more baryons
- mainly agrees with ALICE, but p/π overestimated

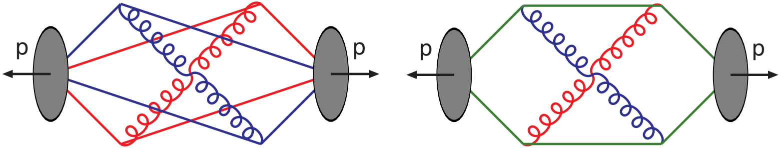
Bierlich, Gustafson, Lönnblad, Tarasov, JHEP 1503, 148;
from Biro, Nielsen, Knoll (1984), Białas, Czyz (1985), . . .

In 2017/21 ALICE found/confirmed strong enhancement of charm baryon production, relative to LEP, HERA and default PYTHIA.



Colour reconnection (CR, 1985)

MPIs + parton showers $\Rightarrow$ many partons in an event
$\Rightarrow$ colour fields ("strings") run criss-cross.
CR: fields rearrange, to (mainly) reduce string length:



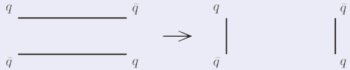
Two main confirmations:

- $\langle p_\perp \rangle(n_{\mathrm{ch}})$ is steadily rising in $\mathrm{pp}/\overline{\mathrm{p}}\mathrm{p}$ data (UA1, Tevatron, LHC), but would be (almost) flat if no CR.
- Combined LEP data on $\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^- \to \mathrm{q}_1\overline{\mathrm{q}}_2\mathrm{q}_3\overline{\mathrm{q}}_4$ is best described with 49% CR, 2.2σ away from no-CR. (hep-ex/0612034)

Extended Colour Reconnection Models (2015)

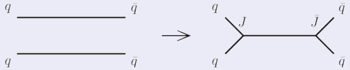
Christiansen, Skands: QCD-inspired CR (QCDCR):

Ordinary string reconnection



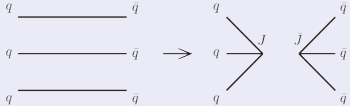
($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection



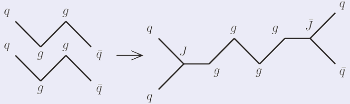
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection

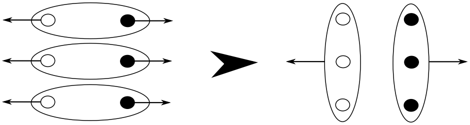


($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

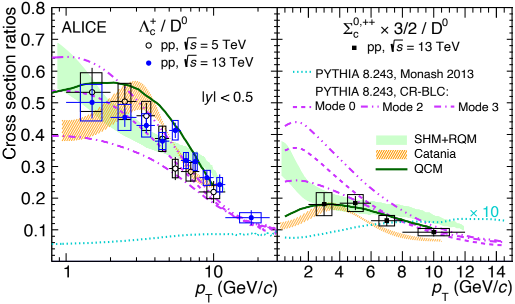


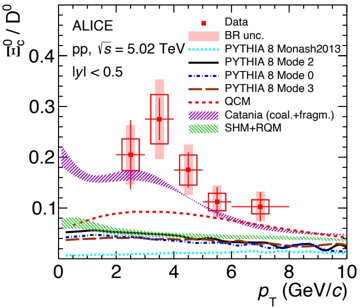
(Depends on number of gluons)

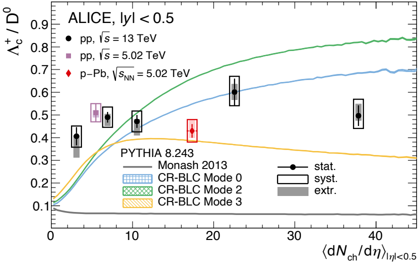


Triple-junction also in HERWIG cluster model (2017).

Charm baryon differential distributions (2021)



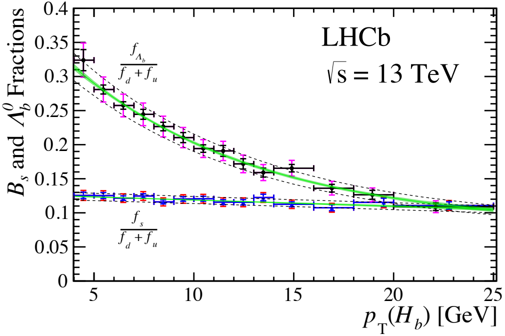




"Vacuum behaviour" recovered at larger $p_{\perp}$.

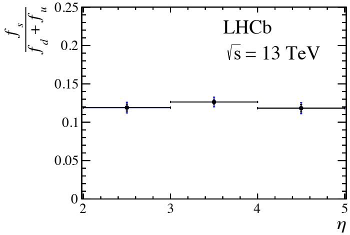
QCDCR does well for some distributions, but less so for others, so improvements needed.

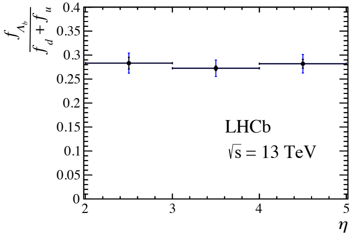
The beauty baryon enhancement (2019)



LHCb has found enhancement of Λ_b^0 production at small $p_\perp$, but flat in η.

No model comparisons available, but consistent.

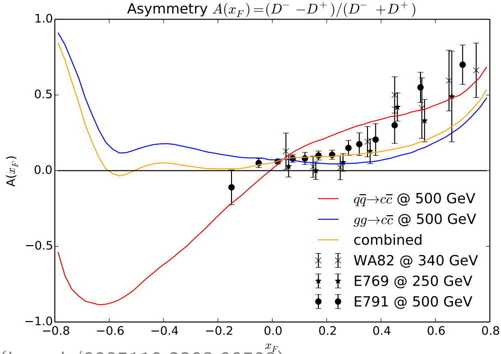




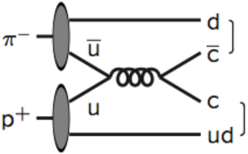
Beam drag effects

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

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



(hep-ph/0005110,2203.09503)

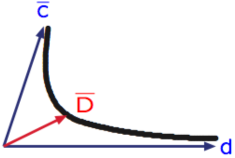


If low-mass string e.g.:

$\bar{\mathrm{c}}\mathrm{d} : \mathrm{D}^-, \mathrm{D}^{*-}$

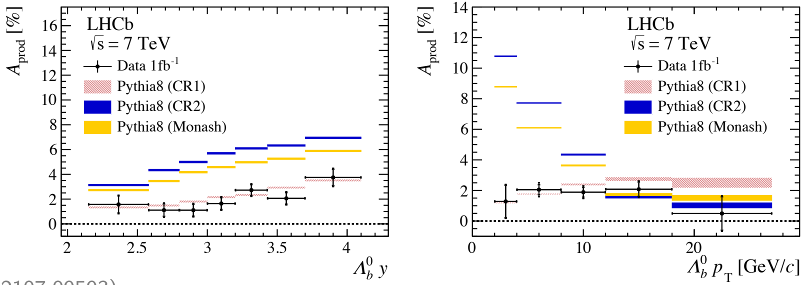
$\mathrm{cud} : \Lambda_\mathrm{c}^+, \Sigma_\mathrm{c}^+, \Sigma_\mathrm{c}^{*+}$

$\Rightarrow$ flavour asymmetries



Can give D "drag" to larger x_F than c quark.

Bottom asymmetries



(2107.09593)

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

CR1 = QCDCR, with no enhancement at low $p_{\perp}$.

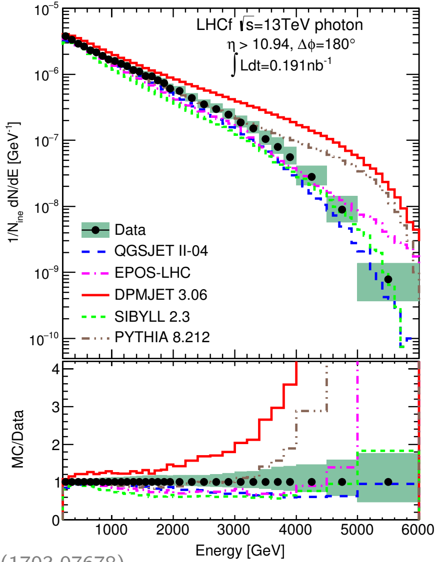
Enhanced Λ_{b} production at low $p_{\perp}$, like for Λ_{c}, dilutes asymmetry?

Asymmetries observed also for other charm and bottom hadrons.

Warning: fragmentation function formalisms unreliable at low $p_{\perp}$.

May lead to incorrect conclusions about intrinsic charm.

Forward physics



(1703.07678)

Forward region important for cosmic-ray physics ⇒ LHCf.

Also for FASER/... and the Forward Physics Facility.

Wide spread of predictions; no generator perfect.

PYTHIA: π^0 too hard, n too soft.

May require improved modelling of

- beam remnant,
- diffraction, and
- $\mathrm{c}/\mathrm{b}/\tau$ production.

Beam remnants

Assume **one** parton kicked out of proton, in pp:

1. Kick out gluon: colour octet $\mathrm{q}_1\mathrm{q}_2\mathrm{q}_3$ remnant left
   $\Rightarrow$ split momentum between two strings,
   one to $\mathrm{q}_1\mathrm{q}_2$ antitriplet and one to q_3 triplet.
2. Kick out valence quark: colour triplet diquark left,
   $\Rightarrow$ single string stretched out from beam remnant.
3. Kick out sea antiquark $\overline{\mathrm{q}}_4$: colour triplet $\mathrm{q}_1\mathrm{q}_2\mathrm{q}_3\mathrm{q}_4$ remains,
   $\Rightarrow$ split momentum between $\mathrm{B} = \mathrm{q}_1\mathrm{q}_2\mathrm{q}_4$ singlet
   and string to q_3 triplet.
4. Kick out sea quark q_4: colour antitriplet $\mathrm{q}_1\mathrm{q}_2\mathrm{q}_3\overline{\mathrm{q}}_4$ remains,
   $\Rightarrow$ split momentum between $\mathrm{M} = \mathrm{q}_1\overline{\mathrm{q}}_4$ singlet
   and string to $\mathrm{q}_2\mathrm{q}_3$ antitriplet.

13 TeV pp nondiffractive: $\sim$**85% gluons**, $\sim$5% each for others.
MPIs can give more complicated topologies, e.g. with junctions.

New forward tune

Some possible actions for harder baryons and softer mesons:

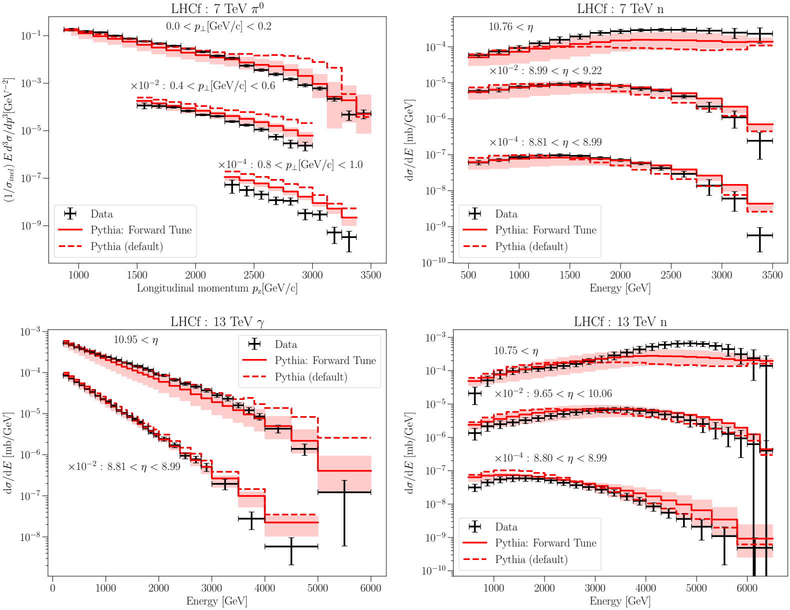
- Use QCDCR for better central baryon production.
- Make diquark remnant take more than twice quark ditto: (already default) helps some.
- In string diquark picture B and $\overline{\mathrm{B}}$ are nearest neighbours, but with popcorn allow intermediate meson: $\ldots\mathrm{BM}\overline{\mathrm{B}}\ldots$ Thus leading diquark either $\mathrm{BMM}\ldots$ or $\mathrm{MBM}\ldots$. New: forbid latter possibility (or only suppress it).
- Normal fragmentation function

$$f(z) \propto \frac{1}{z}\,(1-z)^{a}\,\exp\left(-\frac{b m_{\perp}^{2}}{z}\right)\,, \quad z = \frac{(E+p_z)_{\mathrm{hadron}}}{(E+p_z)_{\mathrm{left\ in\ string}}}$$

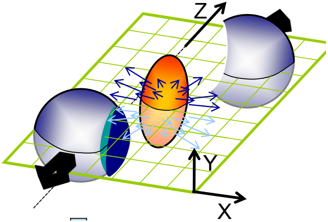
  modified with separately tuned (a and) b for leading diquark.
- Reduce primordial $k_{\perp}$ in remnant for soft collisions.

Max Fieg, F. Kling, H. Schulz, TS, arXiv:2309.08604

New forward results



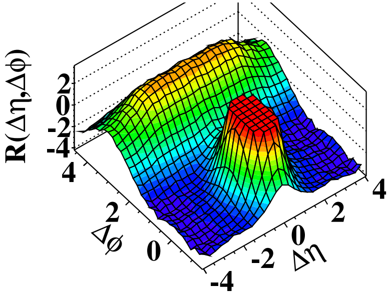
The Ridge Effect (2010)



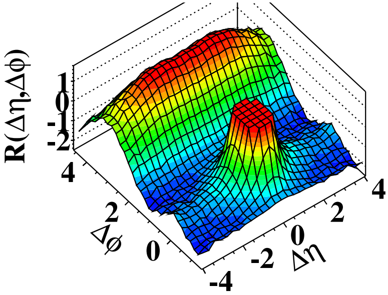
Elliptic flow in AA predicted from geometry + pressure.

Not so for pp, and yet ridge is observed at high multiplicities:

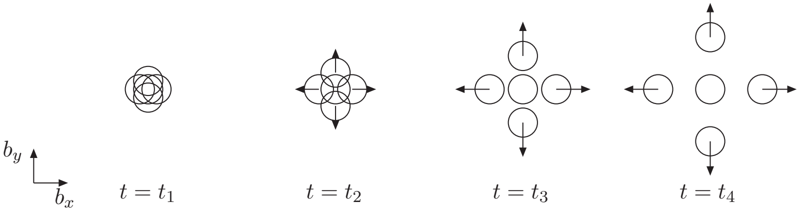
(c) CMS N$\geq$110, p_T>0.1GeV/c

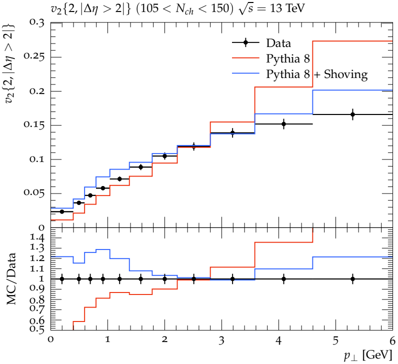


(d) CMS N$\geq$110, 1.0GeV/c<p_T<3.0GeV/c



Shove / repulsion





Overlapping string at early times can give repulsive push, so strings get transverse motion, imparted to hadrons produced from them.

Can give ridge and flow, in azimuth and $p_\perp$.

Hadronic rescattering can also contribute.

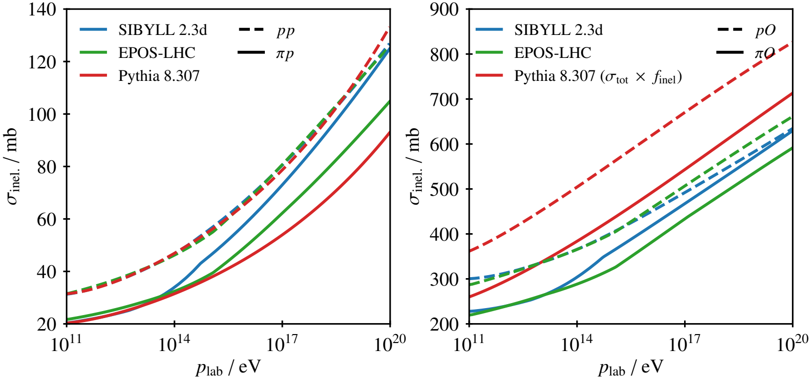
A new framework for hadronic collisions

Based on 2 articles by **Marius Utheim** & TS:
"A Framework for Hadronic Rescattering in pp Collisions",
Eur. Phys. J. C80 (2020) 907, arXiv:2005.05658
"Hadron Interactions for Arbitrary Energies and Species,
with Applications to Cosmic Rays",
Eur. Phys. J. C82 (2022) 21, arXiv:2108.03481

- Models arbitrary hadron–hadron collisions at low energies.
- Models arbitrary hadron-p/n collisions at any energy.
- Initialization slow, $\sim$ 15 minutes,
  - ⋆ but thereafter works for any hadron–p/n at any energy, and
  - ⋆ initialization data can be saved, so only need to do once.
- The ANGANTYR nuclear geometry part used to extend to hadron-nucleus at any energy.
- Native C++ simplifies interfacing PYTHIA 8 $\leftrightarrow$ CORSIKA 8.
- So far limited comparisons with data.

Comparisons with other models - 1

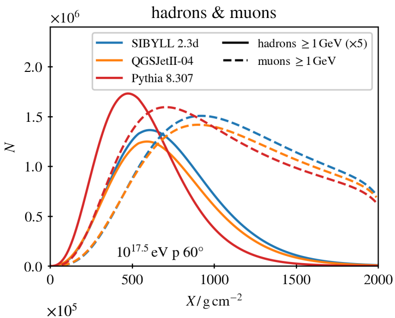
Maximilian Reininghaus, TS, M. Utheim, arXiv:2303:02792

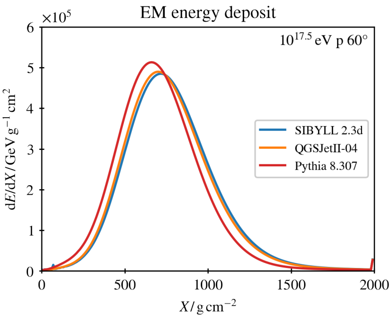


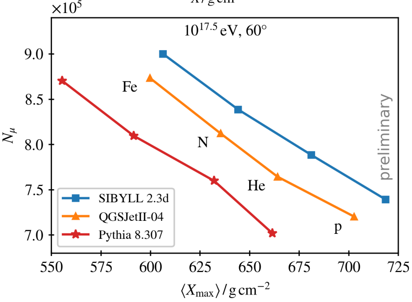
Additive quark rule $\sigma_{\pi\text{p}} \approx (2/3)\sigma_{\text{pp}}$ at high energies.

$$\sigma_{h\text{A}} = \frac{A}{\langle n_{\text{coll}} \rangle} \sigma_{h\text{p}} \quad \text{where } \langle n_{\text{coll}} \rangle \text{ comes from Angantyr}$$

Comparisons with other models - 2







The PythiaCascade wrapper

In `examples/main183.cc` a hadronic cascade is traced through the atmosphere, but poor substitute for full CORSIKA tracking.

The `examples/main184.cc` alternative separates tasks.
Interactions/decays are performed by the `PythiaCascade` class.
The main program or CORSIKA does the tracking.
Either calls `PythiaCascade` to

- provide the hA collision cross section,
- perform an hA collision, or
- perform an h decay.

Internally to `PythiaCascade` there are two `Pythia` instances:

- `PythiaMain` administrates an hA collision, and does an h decay, and
- `PythiaColl` does an hp/hn subcollision, and provides the hp/hn cross section.

PythiaCascade methods

The public `PythiaCascade` methods/references (currently) are

- `PythiaCascade` constructor,
- `init` initializes all program elements,
- `sigmaSetuphN` calculates a hp cross section,
- `sigmaColl` calculates a hA (= hn) cross section, based on the hp one above,
- `nextColl` performs an hA collision,
- `nextDecay` performs an h decay,
- `compress` reduces the event record to final particles only,
- `stat` prints error statistics at the end of the run,
- `particleData(), rndm()` references that can be used in the main program for particle data or random numbers.

Summary and outlook

- LEP era "jet universality" prediction: hadronization at LHC the same, only need to add multiparton interactions, beam remnants, colour reconnection and initial-state radiation.
- LHC data has revolutionized the picture of soft physics:
  Goodbye jet universality!
- This has led to a renewed phenomenology interest:
  Welcome new mechanisms!
- Still some way to go before a new unified picture is in place, covering the evolution from $\mathrm{e}^+\mathrm{e}^-$ to low-n_{ch} pp to AA.
- PYTHIA now has `PythiaCascade` class for handling cascades in (solid, liquid or gaseous) matter, to be used e.g. from CORSIKA 8 or GEANT 4, but
  tuning and other validation remains!
- Newer code directly based on ANGANTYR:
  see presentation by Marius Utheim on Thursday