PYTHIA 8 for CORSIKA 8

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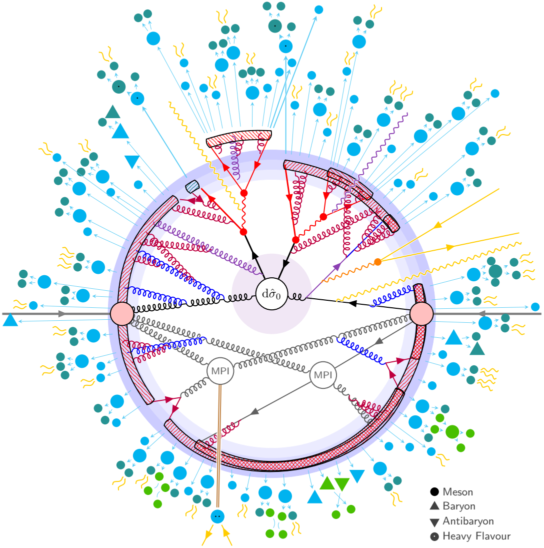
A new framework for hadronic collisions

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,
  $\star$ but thereafter works for any hadron–p/n at any energy, and
  $\star$ 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.

PYTHIA and the structure of an LHC pp collision



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

- Multiparton Interactions

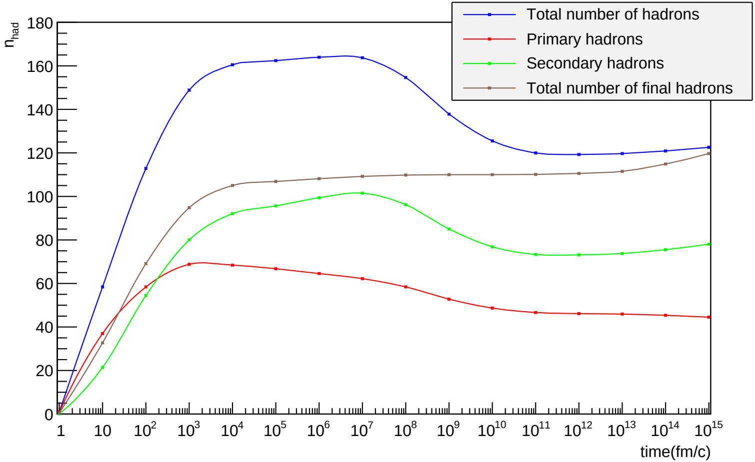
- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

(: incoming lines are crossed)*

From PYTHIA 8.3 guide, arXiv:2203.11601, 315 pp

Space–time evolution

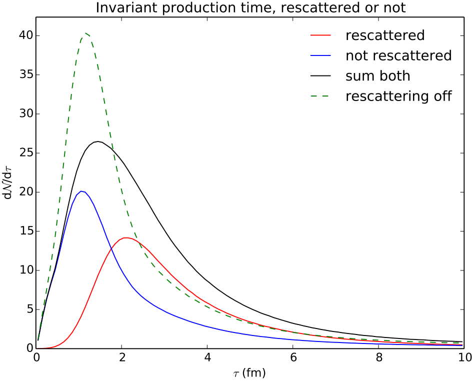
PYTHIA can now calculate production vertex of each particle, e.g. number of hadrons as a function of time for pp at 13 TeV:



S. Ferreres-Solé, TS, EPJC 78, 983

Hadronic rescattering

13 TeV nondiffractive pp events:



PYTHIA now contains framework for hadronic rescattering:

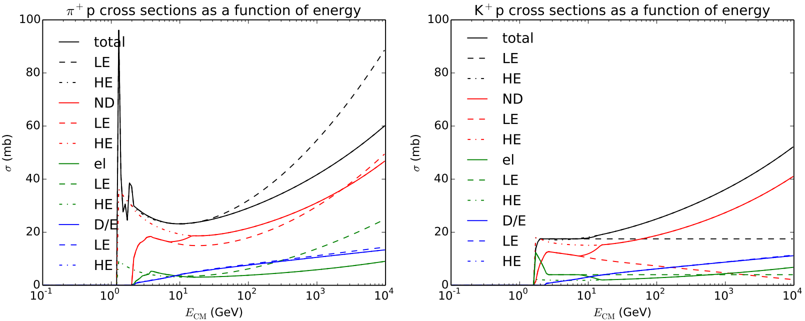
1) Space–time motion and scattering opportunities
2) Cross section for low-energy hadron–hadron collisions
3) Final-state topology in such collisions

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

Rescattering not important enough to switch on for CORSIKA, but code extends PYTHIA modelling down to $E_{\mathrm{kin}} \approx 0.2$ GeV.

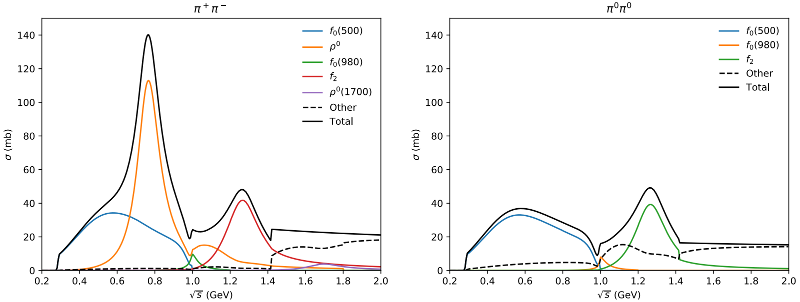
Total cross sections (1)

Two examples of total and partial cross sections:



Combines low-energy (LE) and high-energy (HE) formalisms.
LE: process-specific with detailed structure, cf. UrQMD.
HE: smooth behaviour with pomeron + reggeon ansatz.

Total cross sections (2)



Based on work by Pelaez, Rodas, Ruiz de Elvira et al.
(arXiv:1102.2183, arXiv:1907.13162, arXiv:1602.08404)

When nothing else available, use Additive Quark Model, where

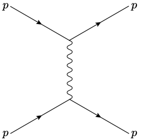
$$n_{\mathrm{q,AQM}} = n_{\mathrm{d}} + n_{\mathrm{u}} + 0.6 n_{\mathrm{s}} + 0.2 n_{\mathrm{c}} + 0.07 n_{\mathrm{b}}$$

$$\sigma^{AB} = \frac{n^A_{\mathrm{q,AQM}}}{3} \, \frac{n^B_{\mathrm{q,AQM}}}{3} \, \sigma^{\mathrm{pp}}$$

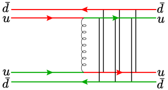
Low-energy interaction types

Low-energy cross sections, roughly up to $E_{\mathrm{cm}} = 10$ GeV, split as

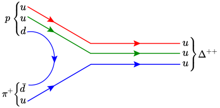
$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{ND}} + \sigma_{\mathrm{SD}(XB)} + \sigma_{\mathrm{SD}(AX)} + \sigma_{\mathrm{DD}} + \sigma_{\mathrm{CD}} + \sigma_{\mathrm{exc}} + \sigma_{\mathrm{ann}} + \sigma_{\mathrm{res}} + \ldots$$



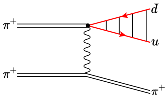
Elastic



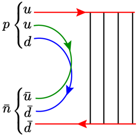
Non-diffractive



Resonant



Diffractive



Annihilation

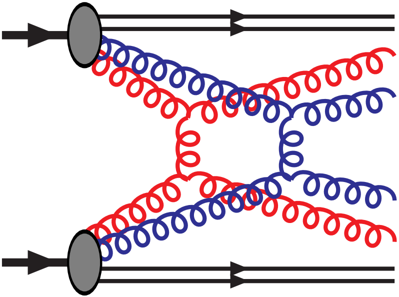
Excitation ≈ low-mass diffraction.

Also includes modelling of particle production in these types, where string fragmentation barely is applicable.

Multiparton interactions

Hadrons are composite
$\Rightarrow$ can contain many
parton–parton interactions.

In part perturbatively calculable,
but divergence for $p_\perp \to 0$,
impact-parameter description,
colour reconnection, and more.



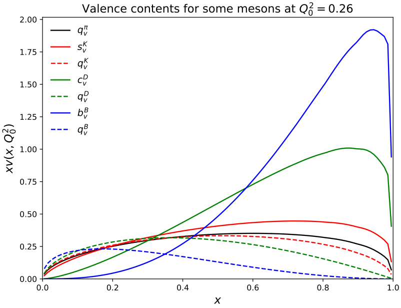
$$\frac{\mathrm{d}\sigma_{\mathrm{int}}}{\mathrm{d}p_\perp^2} = \iint \mathrm{d}x_1\,\mathrm{d}x_2\, f_1(x_1, p_\perp^2)\, f_2(x_2, p_\perp^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2}$$

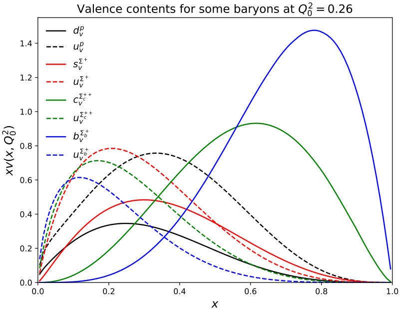
$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_{\mathrm{s}}^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_{\mathrm{s}}^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

MPI machinery gradually switched on for $E_{\mathrm{cm}} > 10$ GeV.
Related to multipomeron models, but matched to high-$p_\perp$ jets.

Parton distribution functions

When $E_{\mathrm{cm}} > 10$ GeV and we allow QCD $2 \to 2$ processes, we need to implement PDF sets for "all" hadrons, not only p:

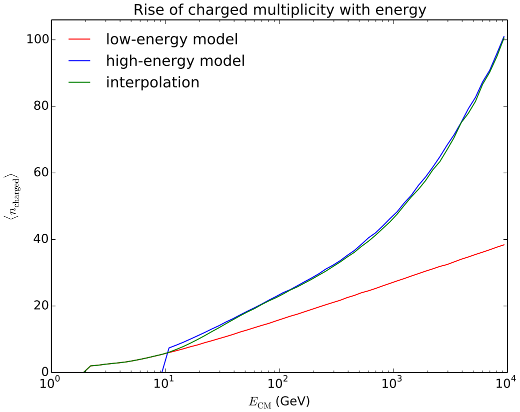




Some generators omit hard processes, to simplify and speed up. Meaningful at low energies, but more dubious at high energies, and e.g. for charm production.

Flexible beams and energies

Low energy: easy to switch between colliding hadrons and energies.
High energy: hard, since perturbative description (with PDFs) need initialization at desired energy to be used.



Smooth transition from low to high energies starting at 10 GeV.
High energies by interpolation in fixed grid of initialized energies for MPI.
Also fast switch between beam combinations by array of such grids, which takes time, but can be reused.

Why not ANGANTYR?

ANGANTYR is a rather new module of PYTHIA, intended for pp, pA and AA collisions at LHC and RHIC. Provides a good description of overall event properties, even if some aspects are not (yet) fully described.

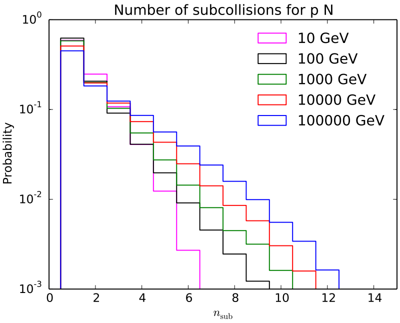
Seemingly ideal for applications such as collisions on atmospheric nuclei, but several limitations:

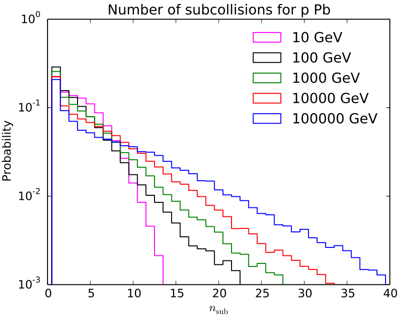
- Only addresses interactions of p and n.
- Only intended for large energies, say $\sqrt{s} > 100$ GeV.
- Initialization of nuclear geometry (and MPIs) very slow, ~ 1 minute, and then only works for one fixed energy.

On the positive side, subsequent event generation reasonably fast, in particular relative to full hydrodynamics.
Also, involves no intra-nuclear cascades in hadron-nucleus collsion, only collisions related to incoming hadron.

ANGANTYR geometry (1)

A hadron passing through a nucleus can undergo
a variable number n_{sub} of hadron-nucleon subcollisions.
Use ANGANTYR nuclear geometry package, combined with
total cross sections above, to find n_{sub} distributions:

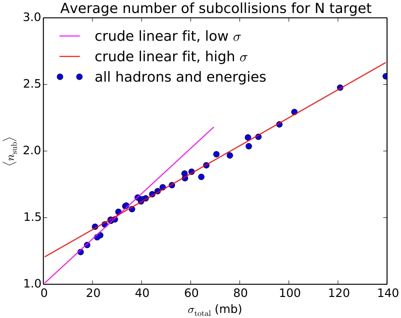


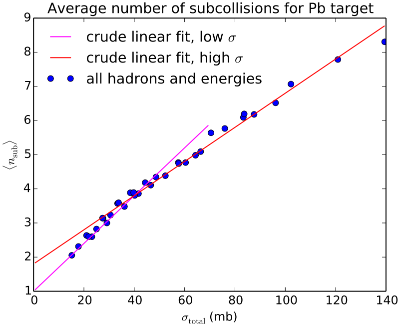


Note an approximate geometrical series = straight line in log-plot
$\Rightarrow$ characterized by one number, $\langle n_{\mathrm{sub}} \rangle$.

ANGANTYR geometry (2)

$\langle n_{\rm sub}\rangle$ depends on target A, hadron projectile h, and collision energy, but the latter two mainly in the combination $\sigma_{\rm total}^{\rm hp}(s)$:





So need one parametrization of $\langle n_{\rm sub}\rangle(\sigma_{\rm total}^{\rm hp})$ for each A.

Constraint: expect $\langle n_{\rm sub}\rangle \to 1$ when $\sigma_{\rm total} \to 0$.

Currently ^{14}N, ^{16}O, ^{40}Ar, ^{208}Pb.

(Takes $\sim$ 1 hour manual work to set up and fit for each A.)

Nuclear cross sections

In limit $\sigma_{\mathrm{total}}^{\mathrm{hp}} \to 0$ expect $\sigma_{\mathrm{total}}^{\mathrm{hA}} = A\,\sigma_{\mathrm{total}}^{\mathrm{hp}}$ (cf. ν beam).

For a "normal" $\sigma_{\mathrm{total}}^{\mathrm{hp}}$, nuclear geometry suggests
$\sigma_{\mathrm{total}}^{\mathrm{hA}} \approx A^{2/3}\,\sigma_{\mathrm{total}}^{\mathrm{hp}}$ and $\langle n_{\mathrm{sub}} \rangle \approx A^{1/3}$.

These two limits are consistent with figures on previous slide.

Assuming preserved total number of hp/hn subcollisions, whether free or bound nucleons, gives

$$\sigma_{\mathrm{total}}^{\mathrm{hA}}\,\langle n_{\mathrm{sub}} \rangle = A\,\sigma_{\mathrm{total}}^{\mathrm{hp}} \quad \Rightarrow \quad \sigma_{\mathrm{total}}^{\mathrm{hA}} = \frac{A\,\sigma_{\mathrm{total}}^{\mathrm{hp}}}{\langle n_{\mathrm{sub}} \rangle}$$

For applications in code:

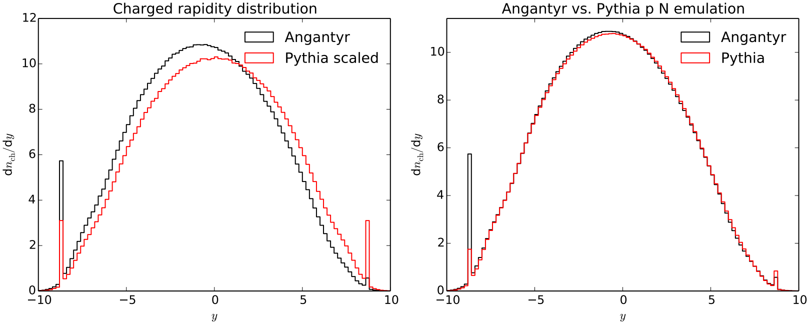
- $\sigma^{\mathrm{hp}}(s)$ (total and partial) is reasonably time-consuming, so only do it once for a hadron of given energy,
- $\langle n_{\mathrm{sub}} \rangle$ is quick and simple to evaluate, so can afterwards easily get $\sigma_{\mathrm{total}}^{\mathrm{hA}}(s)$ for different A.

ANGANTYR multiplicities

If several "independent" hp/hn subcollisions in an hA one, then naively

$$\frac{\mathrm{d}n_{\mathrm{charged}}^{\mathrm{hA}}}{\mathrm{d}y} = \langle n_{\mathrm{sub}} \rangle \frac{\mathrm{d}n_{\mathrm{charged}}^{\mathrm{hp}}}{\mathrm{d}y}$$

but net shift in A direction owing to momentum conservation.



Patched up by letting to hardest hadron in each subcollision go on to be the projectile in the next subcollision (+ some more).

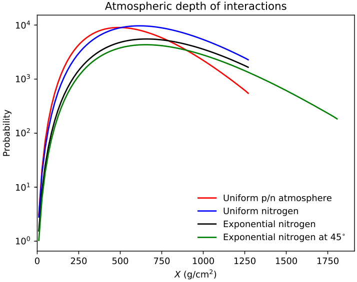
Collision generation flow

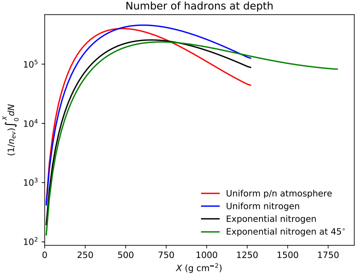
Assume an incoming hadron h collides with a nucleus A.

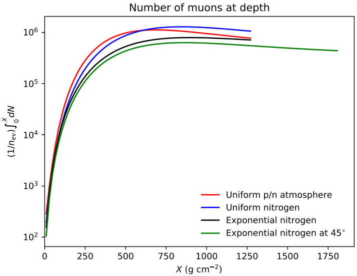
1. $n_{\mathrm{p}} = Z$, $n_{\mathrm{n}} = A - Z$.
2. Do big loop A times, unless a break before that.
3. After first time in the loop:
   - Keep going with probability $1 - 1/\langle n_{\mathrm{sub}} \rangle$, else break.
   - Pick up the new product with largest longitudinal momentum, and assign it to represent the h.
   - Break if not enough hp/hn invariant mass for collision.
   - Set changed composition nondiffractive/other processes.
4. Pick target nucleon p or n in proportions $n_{\mathrm{p}} : n_{\mathrm{n}}$. Subtract 1 from the chosen one.
5. Do the hp/hn collision, as an isolated event.
6. Copy new particles into common event and update history.
7. End of big loop.
8. Optionally do decays and/or compress the event record.

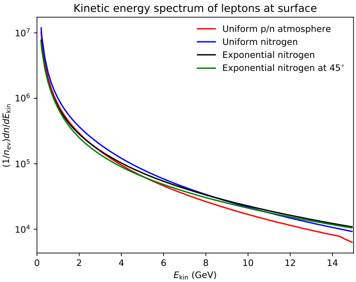
Atmospheric cascade evolution

incoming 10^8 GeV proton









The PythiaCR wrapper

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

The tentative `examples/main184.cc` attempts to offer a wrapper where CORSIKA can do the tracking, but calls `PythiaCR` to

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

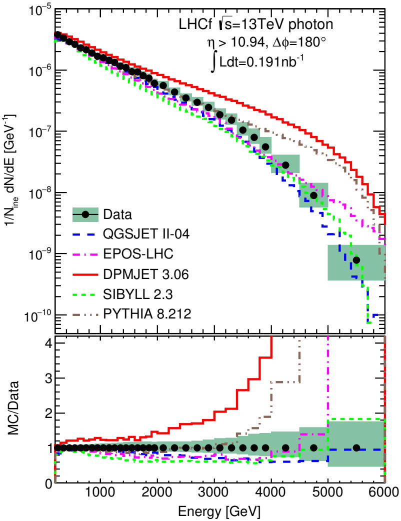
Internally two `Pythia` instances

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

PythiaCR methods

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

- `PythiaCR` constructor,
- `init` initializes all program elements,
- `sigmaSetup` calculates a hp cross section,
- `sigmaColl` calculates a hA 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.



Forward region important for cosmic-ray physics.

Current description poor, but two recent improvements:

- Forbid popcorn mechanism for remnant diquarks only; i.e. baryon then always produced at end of string, never meson
- Allow harder fragmentation function for leading baryon, by separate *a* and *b* values.

Tuning for FPF by Max Fieg shows clear improvement.

Summary and outlook

- **Pythia now may offer a realistic alternative to current hadronic-interaction models.**
- Time-efficient access to perturbative activity for collisions of “any” incoming hadron at “any” energy, by rapid beam switching and energy interpolation of MPI parameters. Not in any other generator (?), but **does it matter?**
- Includes new low- and high-energy cross section descriptions, and new sets of PDFs for a wide range of hadrons.
- Interface should allow easy calling from CORSIKA for both interactions and decays.
- Limitations: no incoming nuclei, no nuclear target breakup, no hadronic γ interactions, . . . ,
  . . . so work to be done to meet more requirements.
- **Feedback welcome.** How interesting?