Cosmic Rays with PYTHIA 8

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slides collected from some recent presentations
(Heidelberg 2022, Wuppertal 2024)

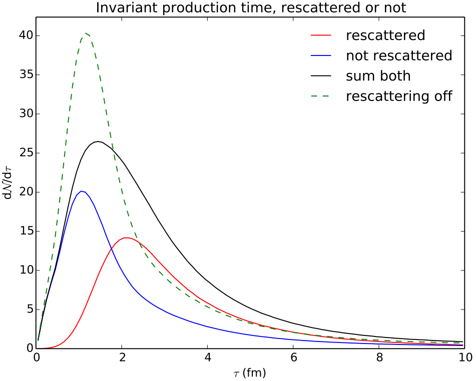
A new framework for hadronic collisions

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.

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

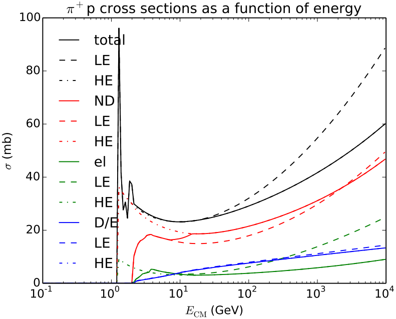
3) Final-state topology in such collisions

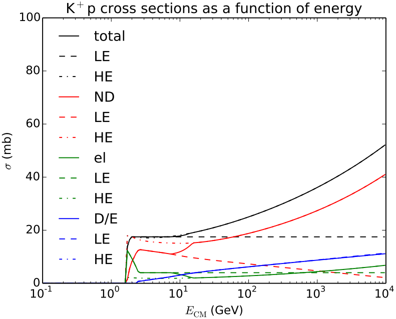
Already covered by other programs like UrQMD or SMASH, but then interfacing issues limits usefulness.

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

Two examples of total and partial cross sections:



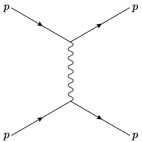


Combines low-energy (LE) and high-energy (HE) formalisms.
LE: process-specific with detailed structure, cf. UrQMD.
HE: smooth behaviour with pomeron + reggeon ansatz.
When nothing else available, use Additive Quark Model, where

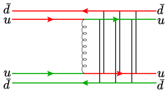
$$n_{\mathrm{q,AQM}} = n_{\mathrm{d}} + n_{\mathrm{u}} + 0.6 n_{\mathrm{s}} + 0.2 n_{\mathrm{c}} + 0.07 n_{\mathrm{b}}$$

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

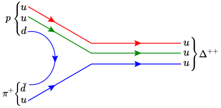
$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{ND}} + \sigma_{\mathrm{SD}(XB)} + \sigma_{\mathrm{SD}(AX)} + \sigma_{\mathrm{DD}} + \sigma_{\mathrm{CD}} + \sigma_{\mathrm{exc}} + \sigma_{\mathrm{ann}} + \sigma_{\mathrm{res}} + \ldots$$



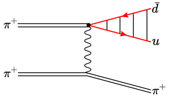
Elastic



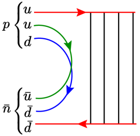
Non-diffractive



Resonant



Diffractive



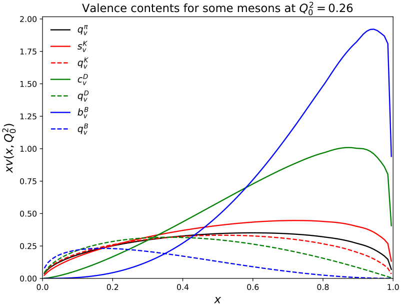
Annihilation

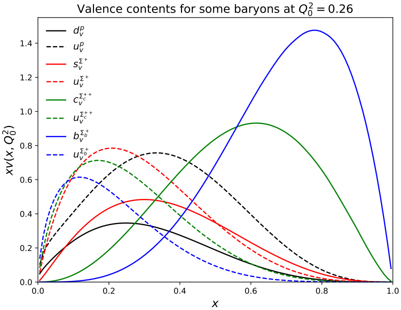
Excitation ≈ low-mass diffraction.

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

Parton distribution functions

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

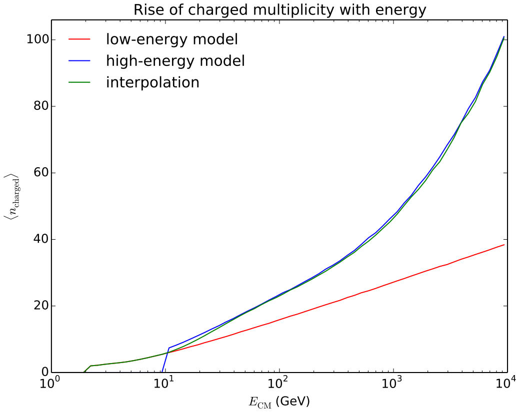




Some generators omit hard processes, to simplify and speed up. Meaningful at low energies, but more dubious at high energies, and e.g. for charm production.

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.

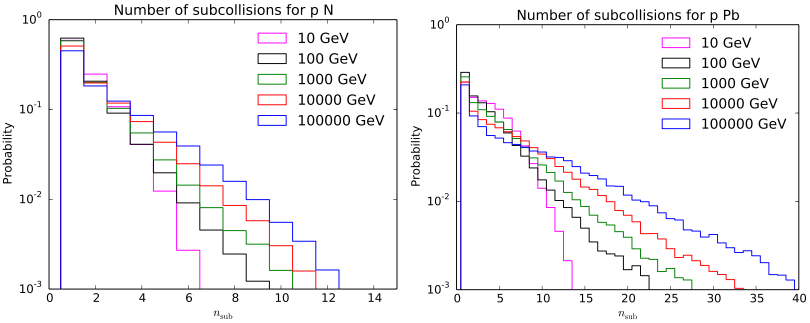
Seemingly ideal for applications such as collisions on atmospheric nuclei, but several limitations:

- 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)

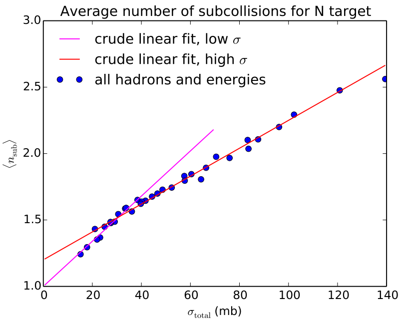
A hadron passing through a nucleus can undergo a variable number n_{sub} of hadron-nucleon subcollisions.
Use ANGANTYR nuclear geometry package, combined with total cross sections above, to find n_{sub} distributions:

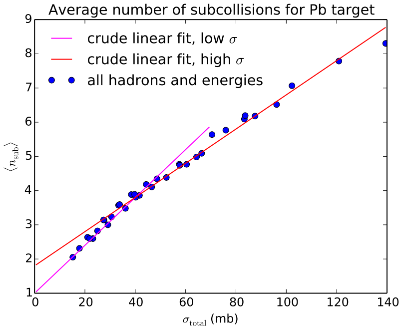


Note an approximate geometrical series = straight line in log-plot
$\Rightarrow$ characterized by one number, $\langle n_{\mathrm{sub}} \rangle$.
Room for improvement; notably store $n_{\mathrm{sub}} = 1$ separately.

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 ^{2}H, ^{4}He, ^{9}Be, ^{12}C, ^{14}N, ^{16}O, ^{27}Al, ^{40}Ar, ^{56}Fe, ^{63}Cu, ^{84}Kr, ^{107}Ag, ^{129}Xe, ^{197}Au, ^{208}Pb, with interpolation if necessary.

Nuclear cross sections

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

For a "normal" $\sigma^{\mathrm{hp}}_{\mathrm{total}}$, nuclear geometry suggests $\sigma^{\mathrm{hA}}_{\mathrm{total}} \approx A^{2/3}\,\sigma^{\mathrm{hp}}_{\mathrm{total}}$ 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

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

For applications in code:

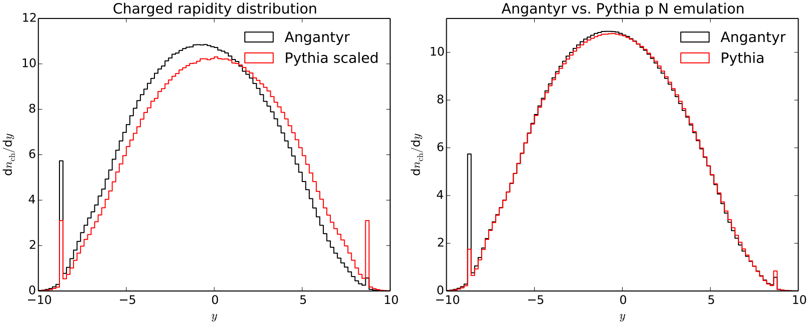
- $\sigma^{\mathrm{hp}}(s)$ (total and partial) is reasonably time-consuming, so only do it once for a hadron of given energy,
- $\langle n_{\mathrm{sub}} \rangle$ is quick and simple to evaluate, so can afterwards easily get $\sigma^{\mathrm{hA}}_{\mathrm{total}}(s)$ for different A.

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).

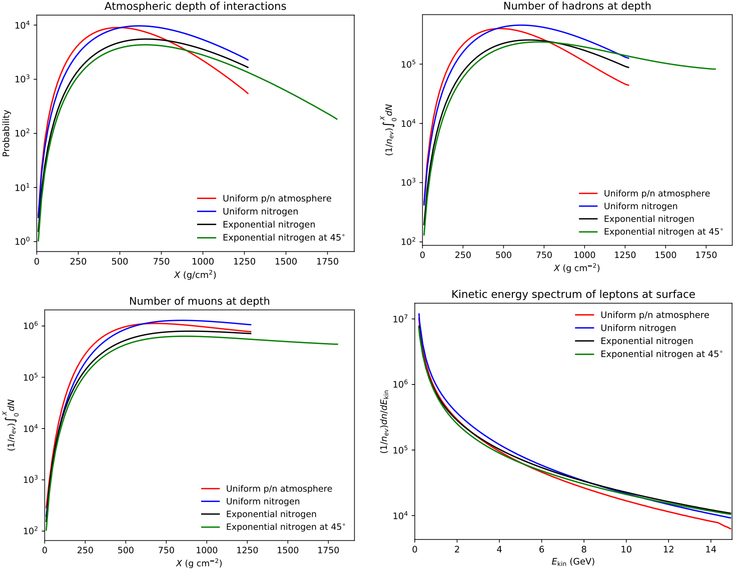
Collision generation flow

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.

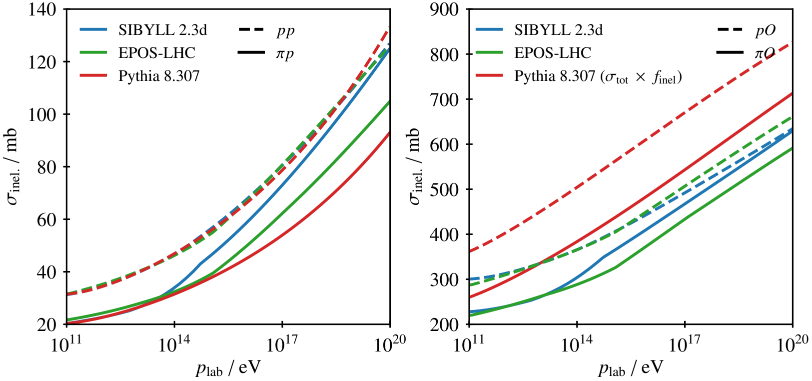
Atmospheric cascade evolution

incoming 10^8 GeV proton



Comparisons with other models - 1

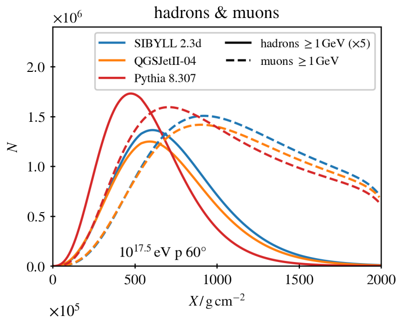
Maximilian Reininghaus, TS, M. Utheim, arXiv:2303:02792

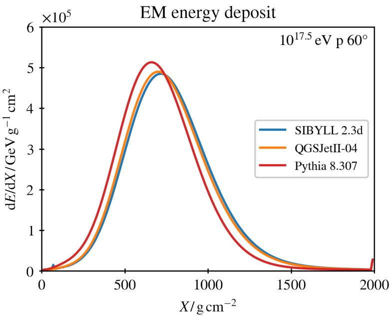


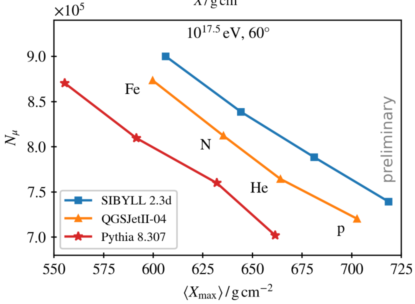
Additive quark rule $\sigma_{\pi\mathrm{p}} \approx (2/3)\sigma_{\mathrm{pp}}$ at high energies.

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

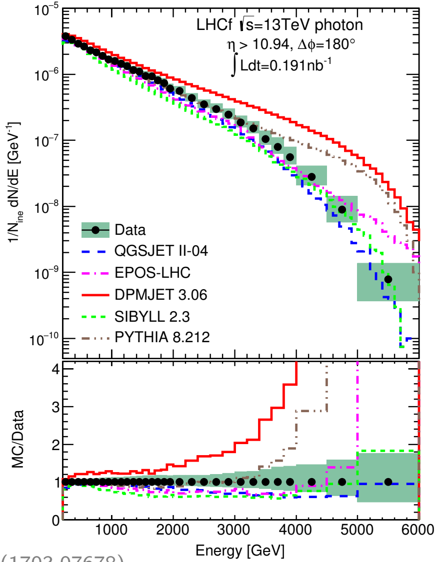
Comparisons with other models - 2







Forward physics



(1703.07678)

Forward region important for cosmic-ray physics $\Rightarrow$ 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
- $\mathrm{c/b/}\tau$ production.

Beam remnants

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

1. Kick out gluon: colour octet $\mathrm{q_1 q_2 q_3}$ remnant left
   $\Rightarrow$ split momentum between two strings,
   one to $\mathrm{q_1 q_2}$ antitriplet and one to $\mathrm{q_3}$ triplet.
2. Kick out valence quark: colour triplet diquark left,
   $\Rightarrow$ single string stretched out from beam remnant.
3. Kick out sea antiquark $\mathrm{\overline{q}_4}$: colour triplet $\mathrm{q_1 q_2 q_3 q_4}$ remains,
   $\Rightarrow$ split momentum between $\mathrm{B = q_1 q_2 q_4}$ singlet
   and string to $\mathrm{q_3}$ triplet.
4. Kick out sea quark $\mathrm{q_4}$: colour antitriplet $\mathrm{q_1 q_2 q_3 \overline{q}_4}$ remains,
   $\Rightarrow$ split momentum between $\mathrm{M = q_1 \overline{q}_4}$ singlet
   and string to $\mathrm{q_2 q_3}$ 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:

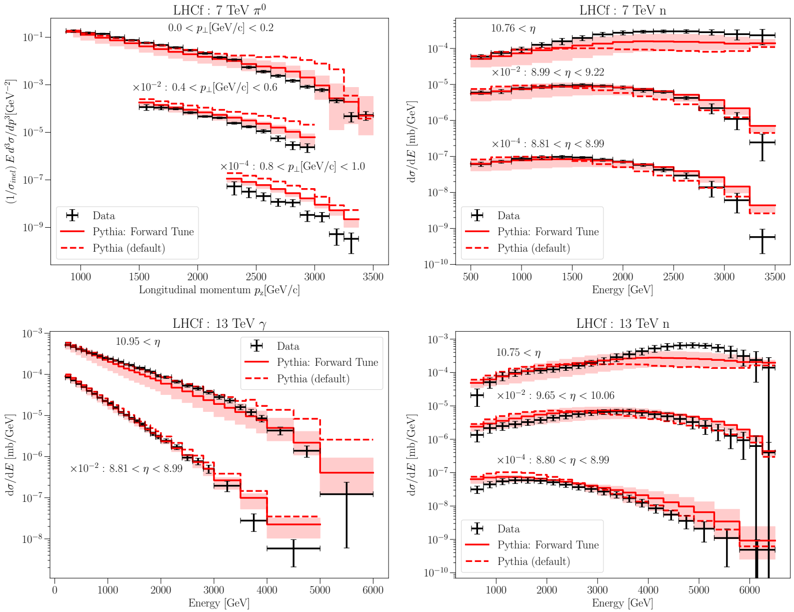
- Use QCDCR for better central baryon production.
- Make diquark remnant take more than twice quark ditto: (already default) helps some.
- In string diquark picture B and $\overline{\mathrm{B}}$ are nearest neighbours, but with popcorn allow intermediate meson: $\ldots\mathrm{BM}\overline{\mathrm{B}}\ldots$
  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 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

- **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.
- Interfaced to GEANT (Einar Elén).
- Limitations: no incoming nuclei, no nuclear target breakup, no hadronic γ interactions, very few data comparisons, . . . , . . . so work to be done to meet more requirements.
- ANGANTYR could solve some of these problems.

Marius on ANGANTYR - 1

This project

Current objective: *To implement hadron-ion interactions for generic hadrons.*

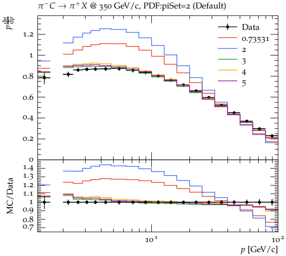
- One main use case is hadronic cascades, e.g. using PYTHIA as the interaction model in CORSIKA 8.
- Another use case is for the VMD part of the photon wave function.
- Also relevant for direct comparisons, e.g. to NA61/SHINE π^- C data.
- Technical requirement: change beam types and energies on an event-by-event basis.

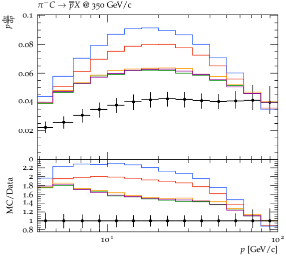
Hadron-proton interactions already exist in PYTHIA [arXiv:2108.03481]. In this talk, I will present this framework, then introduce the changes we have made to extend this to ANGANTYR. Finally we look at some results, comparing to HERA and LHC data.

Marius on ANGANTYR - 2

$\pi^- C$ at NA61/SHINE [arXiv:2209.10561v1]

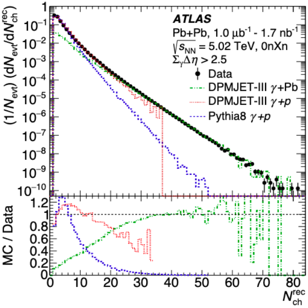
In collaboration with Chloé Gaudu

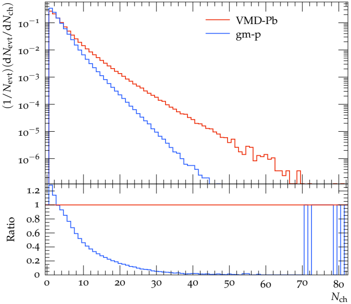




- The different colours refer to different values of the $p_{0,\perp}^{\mathrm{ref}}$ parameter, which represents a saturation scale in MPI evolution.
- ANGANTYR shows good agreement in meson spectra.
- Baryons are less well described.
- Low energy framework is not applied here.

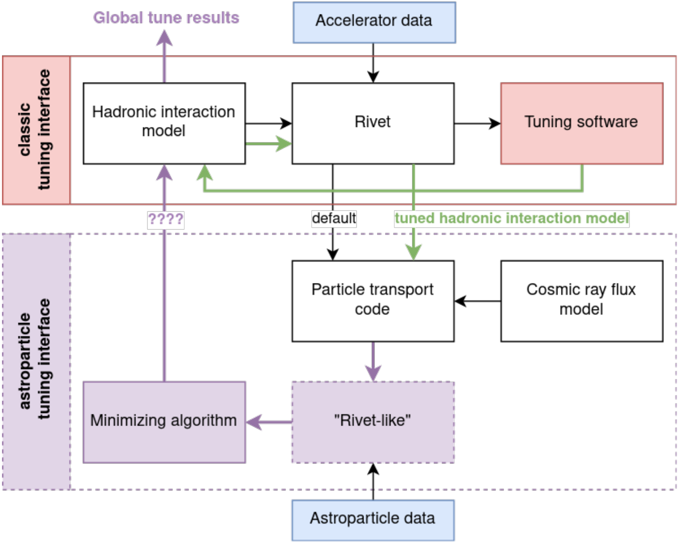
ATLAS γ + Pb multiplicities [arXiv:2101.10771]





- The ATLAS data is not corrected for the limited efficiency, estimated to ~ 80 %.
- Qualitatively speaking, the shift from γp to γPb is consistent with data.
- In γp, the VMD component has less average multiplicity than in full photoproduction. This could be the other way around for γPb.

Workshop on the tuning of hadronic interaction models



(figure by C. Gaudu, at Wuppertal meeting, 22 – 25 January 2024)