Pythia 8 Forward Tuning for Neutrino Flux Predictions at SND@LHC

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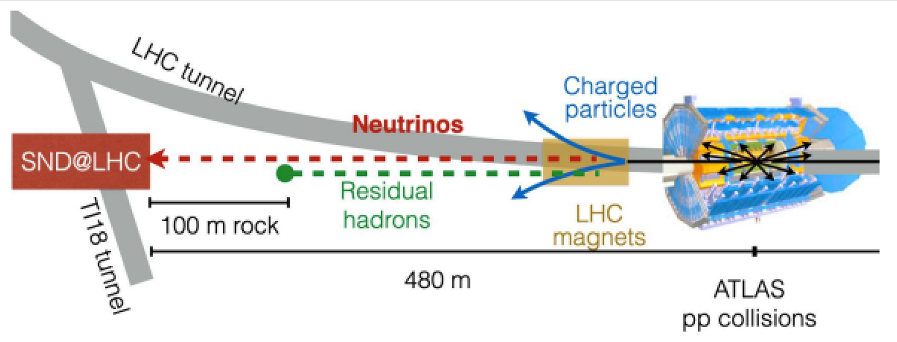
Abstract

The SND@LHC experiment investigates high-energy neutrinos produced in proton-proton collisions ($p + p \rightarrow \nu + X$) within the pseudorapidity range 7.2 < η < 8.4. While particle production in the central region (|η| < 5) is well described by perturbative theory, non-perturbative effects dominate in the forward region (η ≥ 7), increasing uncertainty in theoretical predictions. Event generators such as Pythia, mainly fitted with data from the central region, exhibit discrepancies in the forward region, observed in LHCf measurements, where an excess of mesons and a deficit of baryons are detected. To improve the description of particle production in this region, a dedicated tuning of Pythia is proposed, incorporating modifications to the Lund string model, color reconnection (QCDCR), and beam remnant fragmentation.



Introduction

In the central region of proton-proton collisions, particle production mainly occurs through multiparton interactions (MPIs). Since hadrons are particles composed of partons (quarks and gluons), MPIs represent processes in which multiple parton subcollisions happen within a single proton-proton collision event.

Beam remnants are the partons that have not been ejected during the MPIs. These are related to the initial partons of the proton, as they are the ones that did not directly participate in the main collision. Beam remnants are connected to each other through flavor (valence and sea quarks) and color (properties associated with the strong interaction). **Color correlation (CR)** indicates that the color charge neutrality is conserved in the system.

I. Lund string Model - Fragmentation

The Lund string model describes hadronization in terms of a confinement field generated between color–anticolor partons. As the partons separate, the string stores energy until it fragments into new quark-antiquark pairs, forming hadrons.

String fragmentation follows a hierarchy where the fraction of momentum *z* carried by each hadron is determined by the Lund Symmetric Fragmentation Function (LSFF):

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

where *a* and *b* are tunable parameters. More massive hadrons acquire larger *z* values, affecting the baryon distribution in the forward region.

II. Energy Distribution in String Fragmentation

When a beam remnant consists of multiple partons, the total energy and longitudinal momentum must be distributed among them.

- The momentum fraction *x* of each parton is randomly chosen from predefined distributions for valence quarks, sea quarks, and gluons and then rescaled so that their sum equals unity.
- If the remnant contains a diquark, it receives the sum of the momentum fractions of its constituent quarks, with an additional enhancement factor (default: factor 2).
- In the most common scenarios:
  - A diquark carries 100% of the remnant momentum.
  - A diquark carries, on average, 80% of the total momentum.

This energy-sharing mechanism is crucial for leading baryon production, as it determines the amount of available energy.

III. Color Reconnection (CR) and QCDCR

The default CR model in Pythia minimizes string length by reconnecting color-correlated partons but fails to properly describe baryon production.

The QCDCR model improves this by explicitly assigning color charges to partons and allowing additional reconnections if they reduce the total string length. It also accumulates a higher color charge in the remnant, requiring additional gluons to cancel the excess color charge.

This modifies the fragmentation topology in the forward region, enhancing baryon formation by increasing the diquark content in the remnant, which impacts neutron production observed at LHCf

IV. Popcorn Mechanism and Baryon Production

In standard string fragmentation, baryon-antibaryon pairs should appear as nearest neighbors along the string. However, LEP data suggest that baryons and antibaryons are more decorrelated, indicating that the default model is too simplistic.The popcorn mechanism allows diquarks to separate by inserting an intermediate meson between the baryon and antibaryon.

To improve baryon production in the forward region, this mechanism is disabled (***dpop=0***), ensuring that the diquark remains bound and enhances baryon yields

V. Diquark Fragmentation and Neutron Production

The default diquark fragmentation model in Pythia produces a neutron spectrum that is too soft in the forward region. To correct this:

- The LSFF parameters are adjusted:
  - *aremn=0.36*
  - *bremn=1.69*
- *fremn=on* is enabled, favoring leading baryon production.
- The remnant's transverse distribution is modified (*σsoft, σremn*)

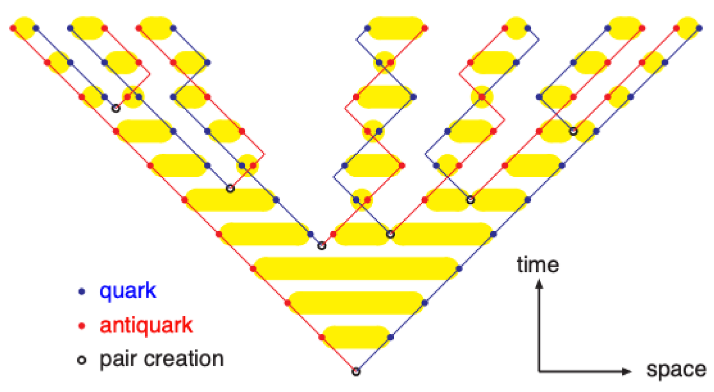
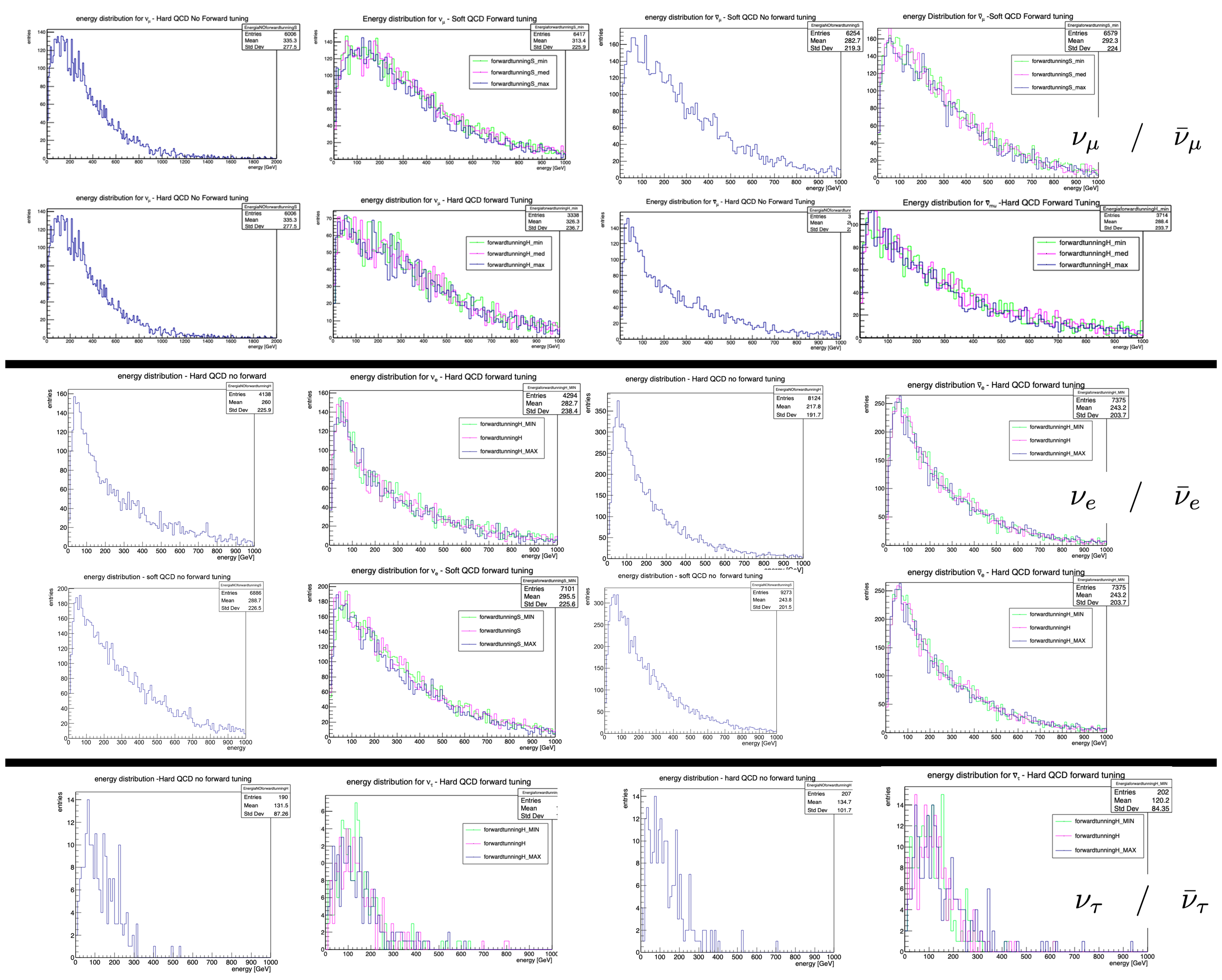


Fig. The lund Hadronization model

Neutrino fluxes

The predicted neutrino fluxes for 10[8] p+p collisions are presented. These fluxes are constrained to the pseudorapidity region covered by SND@LHC. The forward tuning parameters were evaluated to determine the uncertainty in neutrino production, resulting in the maximum and minimum neutrino flux values within a one-sigma confidence interval.



Tuning PYTHIA8 parameters for forward tuning

Full name	Shorthand	Baseline (QCDCR)	Forward Tune	Uncertainty
BeamRemnants:dampPopcorn	$d_{\rm pop}$	1	0	
BeamRemnants:hardRemnantBaryon	$f_{\rm remn}$	off	on	
BeamRemnants:aRemnantBaryon	$a_{\rm remn}$	-	0.36	
BeamRemnants:bRemnantBaryon	$b_{\rm remn}$	-	1.69	
BeamRemnants:primordialKTsoft	$\sigma_{\rm soft}$	0.9	0.58	0.26 . . . 1.27
BeamRemnants:primordialKThard	$\sigma_{\rm hard}$	1.8	1.8	
BeamRemnants:halfScaleForKT	$Q_{\rm half}$	1.5	10	
BeamRemnants:halfMassForKT	$m_{\rm half}$	1	1	
BeamRemnants:primordialKTremnant	$\sigma_{\rm remn}$	0.4	0.58	0.26 . . . 1.27

Results and Prospects

The combination of QCDCR and the popcorn mechanism significantly improves the simulation of particle production in forward collisions by complementing the hadronization processes. QCDCR reorganizes the color remnants by establishing connections that minimize the system's total energy, favoring more compact configurations that increase the likelihood of baryon formation. Meanwhile, the popcorn mechanism introduces an intermediate stage in the fragmentation of the color string, allowing baryons to form through the temporary creation of quark-antiquark pairs (mesons), even in less favorable color configurations. This combined approach not only addresses the excess of mesons and deficit of baryons observed in previous models but also enhances the description of non-perturbative QCD dynamics, aligning simulations more closely with experimental data.

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References

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