The AMPT Model Updated with New nPDFs and Heavy Flavor Production

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Outline

• Motivation
• New PDFs and nuclear shadowing for AMPT
• Light flavor observables
• Improvements of heavy quark productions in AMPT
• Open charm observables
• Summary & Outlook
A Multi-Phase Transport (AMPT) serves as a comprehensive event generator for heavy ion collisions. So it aims to evolve the system from initial condition to final observables; include particle productions of different flavours at different \( P_T \) & \( y \); keep non-equilibrium features and dynamics (e.g. intrinsic fluctuations and correlations).

For comprehensive event generator of relativistic heavy ion collisions

**We need:**
- Initial particle/energy production
- Pre-equilibrium interactions: equilibration, thermalization, initial flow
- Space-time evolution of QGP
- Hadronization/QCD phase transition
- Hadronic interactions

**Choices:**
- HIJING 2-component model (+string melting), CGC, pQCD, PYTHIA-AA, ...
- Parton cascade (ZPC, BAMPS, MPC), AdS/CFT, CGC, FRG, NJL, ...
- Parton cascade (ZPC, BAMPS, MPC), (ideal, viscous, anisotropic) hydrodynamics, ...
- Quark coalescence/parton recombination, string fragmentation, cluster fragmentation, Cooper-Frye, independent fragmentation, rate equations, statistical hadronization,...
- Hadron cascade (ART, RQMD, SMASH, UrQMD), thermal model, ...

The AMPT model currently includes the **green** components.
String melting version applies when we expect initial matter to be QGP.
Anisotropic particle escape is dominant contribution of $v_2$ for small systems & even for semi-central AuAu at RHIC.

At very large $\sigma$ or opacity, hydrodynamic collective flow will be the dominant contribution of $v_2$. 

L He et al. PLB 753 (2016)  
ZWL et al. NPA 956 (2016)
A b=10fm Au+Au event at 200AGeV from String Melting AMPT

Initial overlap region has an irregular geometry (will lead to $v_3$)

$\sigma_p = 3$mb

Beam axis

60fm-long box
Improve AMPT with Modern PDFs of Nuclei

Modern nPDFs should improve AMPT on heavy flavor & high $p_T$ observables:

$$\frac{d\sigma_{Q\bar{Q}}}{dp_T^2dy_1dy_2} = K \sum_{a,b} x_1 f_a(x_1, \mu_F^2)x_2 f_b(x_2, \mu_F^2) d\sigma^{ab\to Q\bar{Q}}/dt$$

$$f_i^p/A(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2)$$

We now use (arXiv:1903.03292) CTEQ6.1M PDFs for free nucleon; EPS09s: spatial-dependent nuclear shadowing, has $Q^2$ evolution.
PDF of Free Nucleon

*Duke-Owens*: used in the current published AMPT model & HIJING 1.0; *outdated*: too few small-\(x\) partons.

*GRV94L*: used in HIJING 2.0.

*CJ15*: experiments data at LHC utilized, *modern PDF*.

*CTEQ6.1M*: used in our AMPT update; \(\approx CJ15\).

Note: *EPS09sNLO* was calculated with *CTEQ6M* \(\sim CTEQ6.1M\).*

Deng et al. PRC 83 (2011)
Accardi et al., PRD 93 (2016)
The HIJING Two-Component Model

Key input parameters in the model:

\[ \sigma_{el} = \frac{\pi}{\sqrt{s}} \int_0^\infty db^2 \left[ 1 - e^{\chi(b,s)} \right]^2 \]

\[ \sigma_{tot} = 2\pi \int_0^\infty db^2 \left[ 1 - e^{\chi(b,s)} \right] \]

\[ \sigma_{in} = \frac{\pi}{\sqrt{s}} \int_0^\infty db^2 \left[ 1 - e^{2\chi(b,s)} \right] \]
Fitting $p_0$ & $\sigma_{soft}$ in Two-Component Model

We determine $p_0$ & $\sigma_{soft}$ at different energies (4, $\sim 10^5$) GeV by fitting data on total and elastic $pp$ cross sections.

$\rightarrow p_0$ for $pp$ collisions ($p_{0}^{pp}$) increases strongly with energy (like in HIJING 2.0).

*Note: $p_0 = 2\text{GeV}/c$ in HIJING 1.0*
With constant Lund parameters \( a=0.8 \) & \( b=0.4/\text{GeV}^2 \), string melting version of AMPT can reasonably describe \( pp \) data.

The Lund symmetric fragmentation function:

\[
f(z) \propto z^{-1}(1 - z)^a \exp(-b m_T^2 / z)
\]
π and K productions from AMPT are consistent with data.

Model describes the general energy dependence of proton and pbar yields.

At low energies AMPT underestimates pbar yields but overestimates proton yields.
Using same parameters as $pp$, string melting AMPT **fails** to describe $AA$.

- It overestimates most particle yields and gives too-soft $p_T$ spectra.
Introduction of Nuclear Scaling of Minijet Cutoff $p_0$

For AA, we use a higher $p_0$ to decrease $\sigma_{jet}$ and suppress hard component’s contribution to particle productions.

For central AA, we introduce

$$p_0^{AA} = p_0^{pp} A q(s)$$

motivated by $Q_s$ in saturation model.

$q(s)$: starts from 0 at 200A GeV, $\sim 0.16$ at $\sim 10^7$A GeV.
Particle Productions in $AA$ Collisions

After $A$-scaling of $p_0$, string melting version of AMPT can reasonably describe central $AA$ data at RHIC and LHC energies (with constant Lund parameters $a=0.8$ & $b=0.15/GeV^2$)
After updating the AMPT Model with New nPDFs, we only see limited improvements on the description of light flavor (LF) productions (e.g. Lund a is now a constant for pp & AA at all energies).

We expect bigger effects/improvements on high $p_T$ & heavy flavors (HF).
Heavy Flavors in the AMPT Model

HF are complimentary probes of QGP;
traditionally “rare probes”, but charm is abundant at high energy AA.

\[ m_c, m_b \gg \Lambda_{QCD} \]: initial production is in good control since it can be calculated by pQCD.

\[ m_c, m_b \gg T \]:
- secondary production is less important, so \# is ~conserved throughout evolution
- produced earlier and thus interact earlier \( (v_1) \)
- may not fully thermalize with light flavors, but degree of thermalization reflects strength of heavy-light interaction and properties of QGP.

*AMPT describes initial productions of HF and LF on same footing, therefore preserving conservation laws & e-by-e correlations; HF & LF modeled by same parton cascade & w/o small-angle approx.*
Improve Heavy Flavor Productions in AMPT

\[ gg \rightarrow gg \] cross section in leading-order pQCD:

\[
\frac{d\sigma_{gg}}{dt} = \frac{9\pi\alpha_s^2}{2s^2} \left( 3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2} \right)
\]

\[
\approx \frac{9\pi\alpha_s^2}{2} \left( \frac{1}{t^2} + \frac{1}{u^2} \right) \approx \frac{9\pi\alpha_s^2}{2t^2}
\]

is divergent for massless g, so HIJING uses a \textbf{minijet cutoff} \( p_0 \) for minijets of all flavors.

But heavy flavor production may NOT be subject to this cutoff due to heavy quark mass >> \( \Lambda_{\text{QCD}} \) (e.g. in FONLL)

\[ g + g \rightarrow Q + \bar{Q}, \quad q + \bar{q} \rightarrow Q + \bar{Q}, \]

1) So we now remove the \( p_0 \) cut on HF productions in the two-component model HIJING & AMPT.
\( \sigma_{\text{jet}} \) in the HIJING two component model currently only includes light flavor (LF: u/d/s) minijets.

Then HF & LF minijets are generated according to their relative cross sections.

2) We now include HF in \( \sigma_{\text{jet}} \):
\[
\sigma_{\text{jet}} = \sigma_{\text{jet}}^{LF} + \sigma_{\text{jet}}^{HF}
\]

this is not only for self-consistency but also important since \( \sigma_{\text{jet}}^{HF} \) can be a sizable fraction of \( \sigma_{\text{jet}} \) at high energies (given the high \( p_0 \) cut for LF minijets).
Charm Quark Productions in \textit{pp} Collisions

- Old/public AMPT charm yield \textless{}\textless{} data
- Removing $p_0$ greatly enhances charm yield
- Updated AMPT model well describes world data
Charm Quark Productions in $pp$ Collisions

- Removal of $p_0$ generates a wider rapidity distribution compared to old AMPT

- Removal of $p_0$ enhances charm yield mostly at lower $p_T$
Open Charm Hadrons in $pp$ Collisions

$pp$ at 200 GeV

- $D^0$ yield & $p_T$ spectrum in updated AMPT are roughly consistent with STAR data
- Ratios of certain charm hadrons are very different from old AMPT (e.g. larger increase of $\Lambda_c$)
Open Charm Hadrons in \( pp \) Collisions

\( pp \) at 7 TeV

- Enhancements relative to old AMPT are mostly at lower \( p_T \)

- Reasonable agreement with data for various open charm hadrons
Charm Quark Productions in AA Collisions

- Removing $p_0$ greatly enhances charm yield
- Updated AMPT yield $>>$ Old/public AMPT
- Shadowing effect becomes sizable for charm at LHC energies
Open Charm Hadrons in AA Collisions

AuAu at 200A GeV

- $D^0$ yield roughly consistent with STAR data
- $D^*$ yield is much higher than old AMPT
- $D^0$ spectrum is softer than data, but depends on parton cross section and flavor excitation process (not yet explored)
Open Charm Hadrons in AA Collisions

PbPb at 5.02 TeV

- Updated AMPT underestimate LHC data, especially at higher $p_T$
- Could be related to flavor excitation processes (*not yet included*)
Ratios of Open Charm Hadrons

We tuned primordial D*/D & charm B/M ratios in new quark coalescence He & ZWL (2017) to the average pp data; AA results are then predictions.
Summary & Outlook

We have updated the AMPT model with new PDFs in nuclei.

We have improved heavy flavor productions by removing minijet transverse momentum cutoff $p_0$ for HF & by including HF cross section into $σ_{\text{jet}}$.

Updated string melting AMPT describes open charm data much better, especially for $pp$ collisions and $AA$ up to RHIC energies.

*This lays the foundation for future HF studies (with simultaneous light flavor studies) within the AMPT transport approach.*