collectiveQCD

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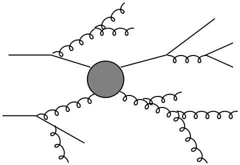
Lund

CLASH meeting
Lund 13. 02. 2019

A Monte Carlo model for jet quenching: JEWEL

Zapp, Krauss, Wiedemann, JHEP 1303 (2013) 080



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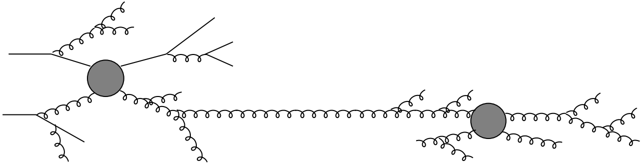

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- re-scattering: ME+PS
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics

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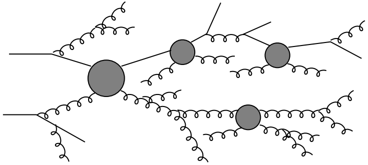

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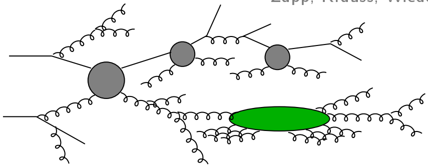

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- emission with shortest formation time is realised
  - all emissions (vacuum & medium induced) treated equally
  - hard structures remain unperturbed
- LPM interference — Zapp, Stachel, Wiedemann, JHEP 1107 (2011) 118
  - also governed by formation times
  - without kinematic restrictions

Jet shape and jet sub-structure observables

- observables built from jet constituents

  particles, partons, calorimeter cells, . . .

- characterise distribution of momentum & find structures inside jet

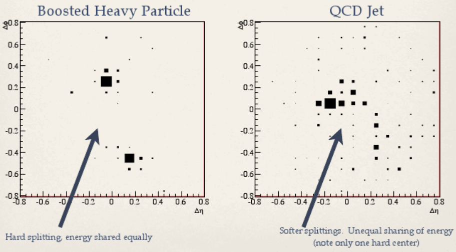


image from David Krohn

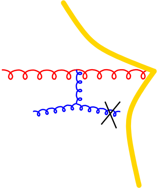
- various grooming techniques studied in p+p to separate hard structure from soft contaminations

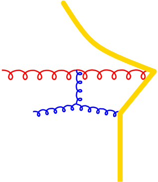
  filtering, trimming, pruning, . . .

- shapes/sub-structure of quenched jets sensitive to medium's reaction to energy & momentum deposited by jets

Medium's response to energy deposited by jets

- common assumption: immediate thermalisation
- JEWEL: three options





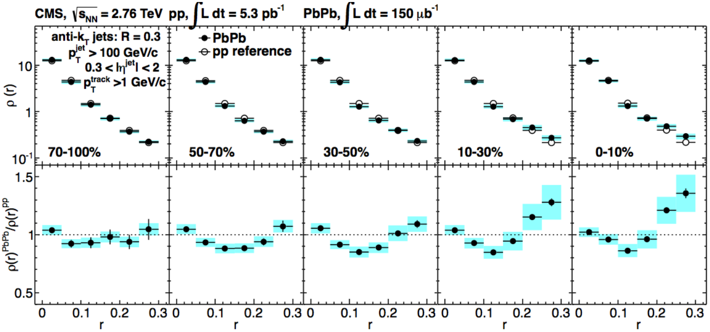
1. ignore recoiling thermal partons
2. extract source term for hydrodynamic description of medium

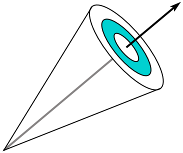
Flörchinger, Zapp, EPJC **74** (2014) no. 12, 3189

3. include recoiling partons
   - recoiling partons becomes colour neighbour of hard parton
   - recoiling partons do not re-interact — other limiting case
   - have so subtract thermal component of recoil momentum

Kunnawalkam Elayavalli, Zapp, JHEP **1707** (2017) 141

Intra-jet energy distribution: Jet profile

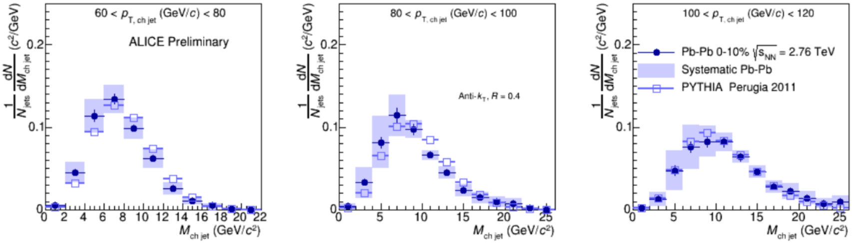




CMS, Phys. Lett. B 730 (2014) 243

- suppression of activity at intermediate r
- increase near the edge of the jet
- sensitive to soft particles at large r

Jet mass

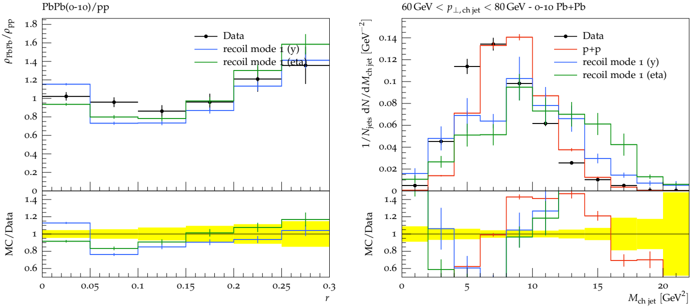


ALICE, Phys. Lett. B **776** (2018) 249

- looks like small shift towards smaller masses in Pb+Pb
- very sensitive to soft particles as large r
- How can this be reconciled with modification of jet profile?

Current activities

1. How does this constrain jet quenching models?
   - both radiative and collisional mechanisms should in priciple work
2. improve subtraction of thermal momenta in JEWEL



3. improve recoil treatment in JEWEL
   - allow for re-scattering of energetic recoils
   - more options for recoil treatment

e.g. write out $q = p_{\mathrm{rec}} - p_{\mathrm{th}}$

collectiveQCD: objectives

Central questions

- How does a field theory like QCD equilibrate?
- Is there partial equilibration in high-multiplicity p+p collisions?
- What implications does this have for
  - the interpretation of experimental data, and
  - our understanding of soft particle production?

Objectives of this proposal

- address these questions
- develop suitable tools

and make them available to the community

collectiveQCD: central ideas

- need consistent modeling of:
  - all collision systems: p+p and A+A
  - soft & hard processes
  - all stages/aspects of the collision

$\rightarrow$ proposed models

  - effective kinetic theory event generator – heavy ion inspired approach
  - SHRiMPS for heavy ions – proton-proton inspired approach
  - jet quenching: JEWEL

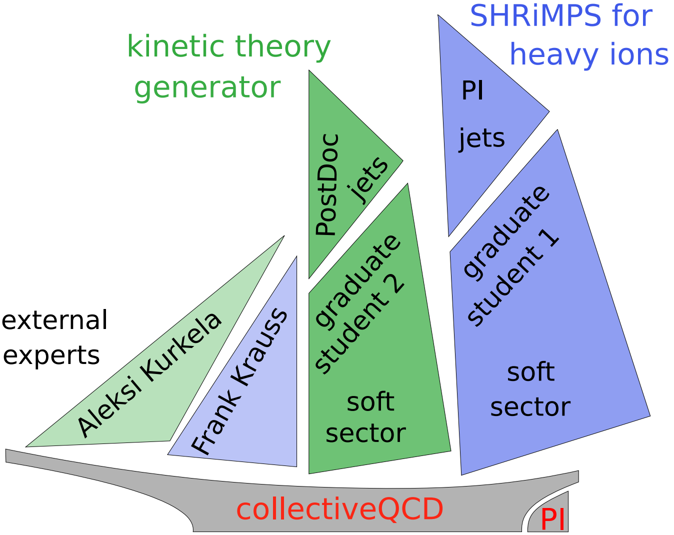
$\rightarrow$ unification & simplification of modeling

SHRiMPS: Soft and Hard Reactions involving Multi-Pomeron Scattering

JEWEL: Jet Evolution With Energy Loss

- Monte Carlo event generators $\rightarrow$ detailed comparison to data
- two different models $\rightarrow$ deal with systematic uncertainties

The team


kinetic theory
generator
SHRiMPS for
heavy ions
PI
jets
PostDoc
jets
graduate
student 1
graduate
student 2
soft
sector
soft
sector
external
experts
Aleksi Kurkela
Frank Krauss
collectiveQCD
PI

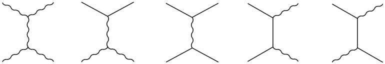
Effective kinetic theory event generator

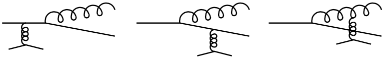
- effective kinetic theory for QCD at high temperatures

Arnold, Moore, Yaffe, JHEP **0301** (2003) 030

$$(\partial_t + \mathbf{v}\cdot\nabla_x) f(\mathbf{x},\mathbf{p},t) = -C[f]$$

- collision kernel C calculated in thermal field theory





- advantages:
  - kinetic theory equally valid in and out of equilibrium
  - consistent description of hard and soft modes
- aim of this project: turn it into phenomenology tool
- challenge: averages over neighborhood of scattering/splitting

Effective kinetic theory – I

Arnold, Moore, Yaffe, JHEP **0301** (2003) 030

Starting point

- EKT for weakly coupled QCD plasma
- $g(T) \ll 1$
- T: hard scale; gT: soft scale

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an obvious objection

- QGP at accessible energies not weakly coupled
- maybe

not clear any more whether it supports quasi-particle description

- this EKT very successful describes approach to hydrodynamic behaviour

A. Kurkela, Nucl. Phys. A **956** (2016) 136 A. Kurkela, Y. Zhu, Phys. Rev. Lett. **115** (2015) no.18, 182301

Effective kinetic theory – II

- weakly coupled QCD plasma consists of quasi-particles

  quarks & gluons

- typical momenta $\mathcal{O}(T)$
- thermal mass $\mathcal{O}(gT)$ due to colour screening
- propagate as nearly free particles
  - soft (small angle) scattering rate $\mathcal{O}(g^2 T)$
  - hard (large angle) scattering rate $\mathcal{O}(g^4 T)$

    t-,u- and s-channel diagrams contribute at leading order

  - hard near-collinear splitting/merging rate $\mathcal{O}(g^4 T)$
- formation time of near-collinear splitting/merging process: $\mathcal{O}(g^2 T)$
- additional soft scatterings during this time
- interference → LPM effect

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Elastic scattering $(2 \leftrightarrow 2)$

$$C_a^{2\leftrightarrow 2}[f] = \frac{1}{4|\mathbf{p}|\nu_a} \sum_{b,c,d} \int \mathrm{d}PS |\mathcal{M}_{ab\to cd}(\mathbf{k},\mathbf{p}',\mathbf{k}')|^2 (2\pi)^4 \delta^{(4)}(P+K-P'-K')$$
$$\times \left\{ f_a(\mathbf{p}) f_b(\mathbf{k})[1\pm f_c(\mathbf{p}')][1\pm f_d(\mathbf{k}')] - f_c(\mathbf{p}') f_d(\mathbf{k}')[1\pm f_a(\mathbf{p})][1\pm f_b(\mathbf{k})] \right\}$$

- gain and loss term
- Bose enhancement & Pauli blocking
- matrix elements
  - can use vacuum results for sufficiently hard momentum transfers q
  - for small q replace $q^2 \to (q^2 + 2\xi^2 m_{\mathrm{eff}}^2)$ in divergent denominators

only in isotropic case, in anisotropic case soft instabilities appear

York, Kurkela, Lu, Moore, Phys. Rev. 89 (2014) no.7, 074036

$$m_{\mathrm{eff}}^2 \propto \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{f(\mathbf{p})}{|\mathbf{p}|}$$

Near-collinear splitting/merging

$$C_a^{1\leftrightarrow 2}[f] = \frac{(2\pi)^3}{2|\mathbf{p}|\nu_a} \sum_{b,c} \int \mathrm{d}p'\,\mathrm{d}k'\,\delta(|\mathbf{p}| - p' - k')\gamma^a_{bc}(\mathbf{p}, p'\hat{\mathbf{p}}, k'\hat{\mathbf{p}})$$
$$\left\{ f_a(\mathbf{p})[1 \pm f_b(p'\hat{\mathbf{p}})][1 \pm f_c(k'\hat{\mathbf{p}})] - f_b(p'\mathbf{p}) f_c(k'\hat{\mathbf{p}})[1 \pm f_a(\hat{\mathbf{p}})] \right\}$$
$$+ \frac{(2\pi)^3}{|\mathbf{p}|\nu_a} \sum_{b,c} \int \mathrm{d}k\,\mathrm{d}p'\,\delta(|\mathbf{p}| + k - p')\gamma^c_{ab}(p'\mathbf{p}, \hat{\mathbf{p}}, k\hat{\mathbf{p}})$$
$$\left\{ f_a(\mathbf{p}) f_b(k'\hat{\mathbf{p}})][1 \pm f_c(p'\hat{\mathbf{p}})] - f_c(p'\mathbf{p})[1 \pm f_a(\hat{\mathbf{p}})][1 \pm f_b(k\hat{\mathbf{p}})] \right\}$$

small transverse momenta in splitting/merging process integrated over

- splitting/merging rates
  - include multiple scattering & LPM effect
  - implicitly depend on distribution functions f
  - given by solution to linear integral equation

Solving Boltzmann equation

- traditional Monte Carlo approach: discrete time steps
- violates Lorentz invariance
- no-interaction theorem:

> The only Lorentz-invariant Hamiltonian theory of N particles moving in a $6N$-dimensional phase space is the free theory.

Currie, Jordan, Sudarshan, Rev. Mod. Phys. 35 (1963) 350

- solution: go to $8N$ dimensional phase space by allowing particles to go classically off-shell Peter, Behrens, Noack, Phys. Rev. C 49 (1994) 3253
- implemented in PCPC

  Borchers, Meyer, Gieseke, Martens, Noack, Phys. Rev. C 62 (2000) 064903

  and ALPACA

  myself, unpublished

Lorentz-invariant cascade in practice

- positions and momenta of the particles functions of a Lorentz-invariant parameter s

$$\frac{\mathrm{d}x_i(s)}{\mathrm{d}s} = \{\mathcal{H}, x_i\} = -\frac{\partial \mathcal{H}}{\partial p_i} \quad ; \quad \frac{\mathrm{d}p_i(s)}{\mathrm{d}s} = \{\mathcal{H}, p_i\} = +\frac{\partial \mathcal{H}}{\partial x_i} \,.$$

- interactions ordered frame independently in s
- invariant distance of two particles i and j

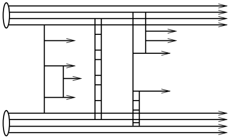
$$d_{ij}^2 = -\left(x_\mu - \frac{xp}{p^2} p_\mu\right)\left(x^\mu - \frac{xp}{p^2} p^\mu\right)$$

with $x = x_i - x_j$ and $p = p_i + p_j$

- compare d_{ij}^2 to scattering cross section to decide whether pair interacts

SHRiMPS for heavy ions

- SHRiMPS: Monte Carlo model for soft particle production in p+p
- based on Khoze-Martin-Ryskin model for soft QCD scattering
- multiple exchanges of gluon ladders

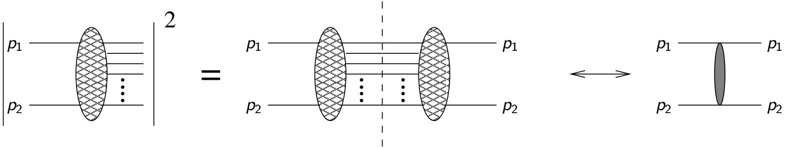


- advantage:
  - most complete view on soft QCD
- aim of this project: extend SHRiMPS to heavy ions
- challenges:
  - extend KMR-model and SHRiMPS to non-local re-scattering
  - consistently include hard processes

KMR model: Introduction

- optical theorem

$$\sigma_{\text{tot}}(s) = \frac{1}{s}\,\text{Im}[\mathcal{A}_{\text{el}}(s, t = 0)]$$



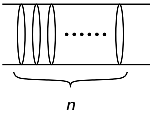
- grey blob: exchange of vacuum quantum numbers
- compute $\mathcal{A}_{\text{el}}$
  - Khoze-Martin-Ryskin (KMR) model
- cut to obtain differential total cross section
  - allows for MC event generation
  - SHRiMPS model

Soft and Hard Reactions involving Multi-Pomeron Scattering

Eikonal models

- eikonal ansatz:

$$A(s,b) = i\left(1 - e^{-\Omega(s,b)/2}\right) = i\sum_{n=1}^{\infty}$$



- Good-Walker states (diffractive eigenstates):

$$|p\rangle = \sum_{i=1}^{N_{GW}} a_i |\phi_i\rangle$$

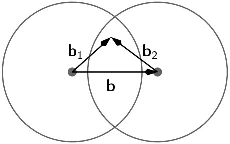
- allows for low mass diffractive excitations
- one single-channel eikonal Ω_{ik} per combination of Good-Walker states

$$\left(1 - e^{-\Omega(s,b)/2}\right) \to \sum_{i,k=1}^{N_{GW}} |a_i|^2 |a_k|^2 \left(1 - e^{-\Omega_{ik}(s,b)/2}\right)$$

KMR approach

eikonal Ω_{ik}: product of two parton densities $\omega_{i(k)}$

$$\Omega_{ik}(s,\mathbf{b}) = \frac{1}{2\beta_0^2}\int \mathrm{d}\mathbf{b}_1 \mathrm{d}\mathbf{b}_2\, \delta^2(\mathbf{b}-\mathbf{b}_1+\mathbf{b}_2)\omega_{i(k)}(y,\mathbf{b}_1,\mathbf{b}_2)\omega_{(i)k}(y,\mathbf{b}_1,\mathbf{b}_2)$$



- $\omega_{i(k)}$: density of GW state i in presence of state k
- $\omega_{i(k)}$ obey evolution equation in rapidity
- boundary conditions: form factors

here: dipole form

KMR model: evolution equations

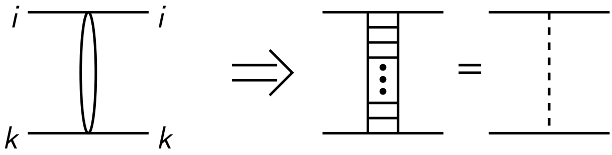
Bare Pomeron Contribution

- evolution equation for parton density

$$\frac{d\omega_{i(k)}(y)}{dy} = \Delta\omega_{i(k)}(y)$$
$$\frac{d\omega_{(i)k}(y)}{dy} = \Delta\omega_{(i)k}(y)$$

where $\Delta = \alpha_{\mathbb{P}}(0) - 1$

probability for emitting an additional gluon per unit rapidity



KMR model: evolution equations

Rescattering

- high density & strong coupling regime → rescattering

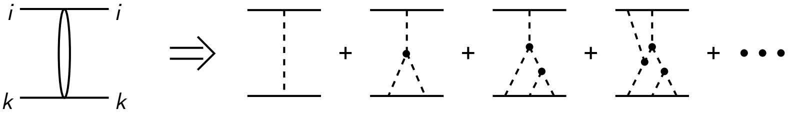
  large triple pomeron vertex

- sum over rescattering/absorption diagrams on k and i

$$\frac{\mathrm{d}\omega_{i(k)}(y)}{\mathrm{d}y} = \Delta\omega_{i(k)}(y)\left[\frac{1-e^{-\lambda\omega_{i(k)}(y)/2}}{\lambda\omega_{i(k)}(y)/2}\right]\left[\frac{1-e^{-\lambda\omega_{(i)k}(y)/2}}{\lambda\omega_{(i)k}(y)/2}\right]$$

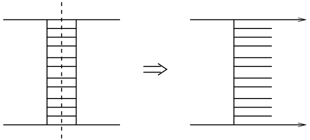
$$\frac{\mathrm{d}\omega_{(i)k}(y)}{\mathrm{d}y} = \Delta\omega_{(i)k}(y)\left[\frac{1-e^{-\lambda\omega_{i(k)}(y)/2}}{\lambda\omega_{i(k)}(y)/2}\right]\left[\frac{1-e^{-\lambda\omega_{(i)k}(y)/2}}{\lambda\omega_{(i)k}(y)/2}\right]$$

with $\lambda = g_{3\mathbb{P}}/g_{\mathbb{P}N}$



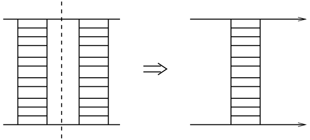
SHRiMPS model

- cutting a simple diagram:



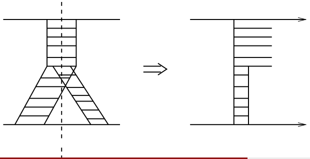
- inelastic scattering

- a even simpler diagram:



- elastic scattering

- cutting a triple-pomeron vertex:



- colour singlet exchange
- high mass diffraction

Global event properties

select elastic, low-mass diffractive or inelastic mode

according to cross sections

Elastic and low-mass diffractive

- fairly straight forward

Inelastic

- fix combination of colliding GW states

  according to contribution to inelastic cross section

- fix impact parameter
- assume ladders to be independent
- number of ladders: Poissonian with parameter Ω_{ik}
- for each ladder fix transverse position $\mathbf{b}_{1,2}$

Generating Ladders

- decompose protons using infra-red continued pdf's
- generate emissions using pseudo Sudakov form factor

$$\mathcal{S}(y_0, y_1) = \exp\left\{ -\int_{y_0}^{y_1} \mathrm{d}y \int \mathrm{d}k_\perp^2 \, \frac{C_A \alpha_s(k_\perp^2)}{\pi k_\perp^2} \times \left(\frac{q_\perp^2}{Q_0^2}\right)^{\frac{C_A}{\pi}\alpha_s(q_\perp^2)\Delta y} \times \left(\frac{1 - e^{\lambda\omega_{i(k)}(y)/2}}{\lambda\omega_{i(k)}(y)/2}\right) \left(\frac{1 - e^{\lambda\omega_{(i)k}(y)/2}}{\lambda\omega_{(i)k}(y)/2}\right) \right\}$$

QCD; Regge weight; rescattering weight

- infra-red continuation
- t-channel propagators can be colour singlets or octets

probabilities for these depend on parton densities and λ

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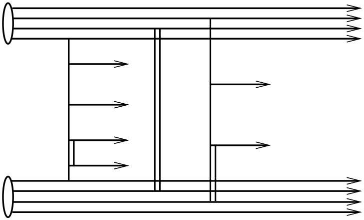
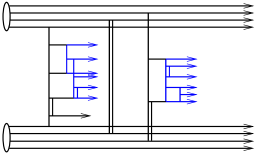


Rescattering & Hadronisation

Rescattering

- partons may exchange rescatter ladders
- rescatters of rescatters of rescatters. . .
- only local rescattering allowed



Hadronisation

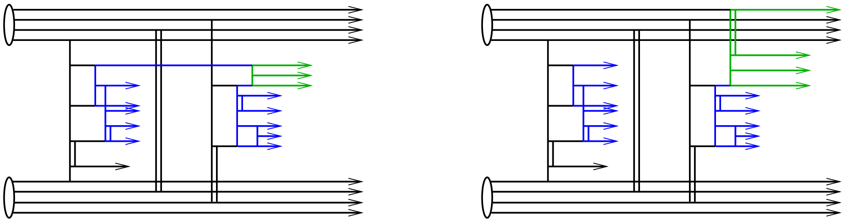
- colour reconnections
- probability for colour swap decreases with distance

similar to PYTHIA model

- hadronisation with SHERPA's cluster hadronisation

SHRiMPS for heavy ions: main tasks

- allow for non-loca re-scattering



- include quarks (secondary reggeons)
- consistently include jets & jet quenching

Conclusions

- I think this is going to be fun.
- Probably it work out as expected, but something else will come out.
- I'm looking forward to interacting with you!

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