

Energy loss of heavy flavor quarks in color string medium of p+p

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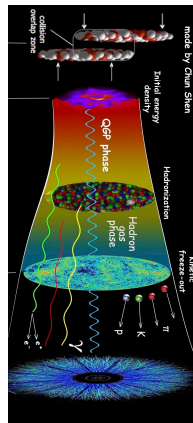


- 1 Heavy Flavor (HF) quarks as medium probes
- 2 Basics of quark-gluon (color) string models
- 3 Our hybrid approach: HF quarks in color string medium
- 4 Preliminary results on HFs energy loss
- 5 Conclusion and outlook

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HF quarks and strongly interacting medium

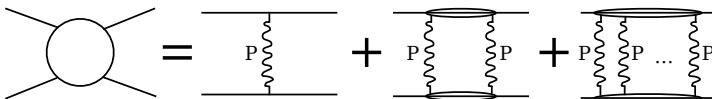
- produced in initial **hard scatterings** via $gg \rightarrow Q\bar{Q}$, $q\bar{q} \rightarrow Q\bar{Q}$
- interactions within **non-equilibrated medium**:
 - strong classical gluon fields (early stages)
 - not yet equilibrated partons (before QGP)
- interactions within **thermalized QGP**
 - elastic (dominant at lower HF's p_T)
 - radiative (dominant at higher HF's p_T)
- hadronisation**
 - coalescence (dominant at lower HF's p_T)
 - fragmentation (dominant at higher HF's p_T)
- final-state** hadron re-scatterings



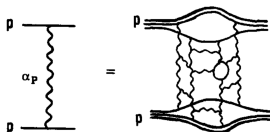
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Advent of the colour string model of particle production

- pre-QCD Regge-Gribov: high-energy elastic scattering amplitude as multiple **Pomeron exchanges** [Gribov, JETP **53** (1967) 654]



- dominant contribution of QCD topological expansion in **large N_c and N_f limits** – cylindrical diagram $\leftrightarrow$ Pomeron exchange [Veneziano, Phys. Lett. B **52** (1974) 220; Nucl. Phys. B **117** (1976) 519]



[Capella, Phys. Rep. **236** (1994) 225]

Advent of the colour string model of particle production

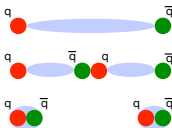
- **space-time localisation** of the cylindrical pomeron exchange diagram with unitarity cut: two-rapidity-chains fragmenting into soft particles [Capella et al. Phys. Lett. B **81** (1979) 68; Kaidalov,

Phys. Lett. B **116** (1982) 459; Artru, Phys. Rep. **97** (1983) 147;

Werner, Phys. Rep. **232** (1993) 87]

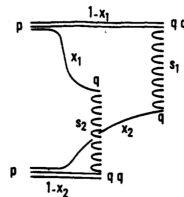
- **Cornell potential** between confined colour charges [Eichten et al. Phys. Rev. Lett. **34** (1975) 369], $q\bar{q}$ pair production

$$V(r) = -\frac{4}{3} \cdot \frac{\alpha_s}{r} + \sigma \cdot r,$$

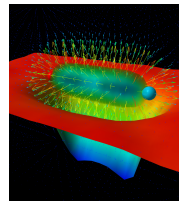


○ α_s - QCD running coupling

○ σ - string tension



[Capella, Phys. Rep. **236** (1994) 225]



[Varilly, Thesis (2006) MIT]

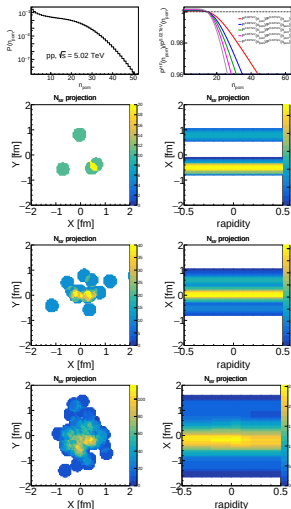
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Monte-Carlo event generator

- 1 HF quarks extracted from PYTHIA
- 2 pure longitudinal color strings formed between colliding partons, $n_{\text{str}} = 2n_{\text{pom}}$
- 3 strings overlap $\Rightarrow$ rearrangement of color fields
- 4 binned medium structure in X-Y-rapidity space
- 5 cell energy density from k_{cell} strings

$$\varepsilon_{\text{cell}} = \frac{\sigma \sqrt{k_{\text{cell}}}}{\pi r_{\text{str}}^2}, \quad \sigma = 1 \frac{\text{GeV}}{\text{fm}}, \quad r_{\text{str}} = 0.25 \text{ fm}$$

- ⑥ massive string endpoint oscillations $\frac{dp_z}{dt} = -\sigma \Rightarrow$ fluctuating string medium
- ⑦ HF travels through it in straight trajectory defined by initial p_T (no diffusion)
- ⑧ deterministic energy-loss model



HF quark's in-medium interactions

Elastic scatterings off gluons [Thoma, Gyulassy, Nucl. Phys. B 351 (1991) 491] within color strings with momentum transfer $\hat{t}$

$$\frac{d\sigma}{d\hat{t}} = \frac{2\pi\alpha_s^2}{(\hat{t} + \mu^2)\hat{t}}$$

CUJET3 thermal running coupling [Xu, Liao, Gyulassy, Chin. Phys. Lett. 32 (2015) 092501] with $\alpha_c = 0.9$ and $T_c = 160$ MeV

$$\alpha_s^{\text{th}}(Q^2) = \frac{\alpha_c}{1 + \frac{11}{4\pi}\alpha_c \ln(Q^2/T_c^2)}$$

Gluon screening with Debye mass in thermal medium [Gossiaux, Aichelin, Phys. Rev. C 78 (2008) 014904; J. Phys. G 36 (2009) 064028]

$$\mu = T\sqrt{4\pi\alpha_s^{\text{th}}(\mu^2)}$$

HF quark's in-medium interactions

Momentum loss rate of HF quark

$$\frac{dp}{dt} = 16 \int \frac{d^3k}{(2\pi)^3} \rho(k) \Phi \int_{\hat{t}_{\min}}^{\hat{t}_{\max}} d\hat{t} \frac{d\sigma}{d\hat{t}} \Delta p(\hat{t}, k, p),$$

$\Delta p(\hat{t}, k, p)$ - one-collision momentum loss, Φ - flux of HF quarks

Momentum distribution of medium gluons

$$\rho_{\text{aniso}}(k) = \frac{1}{e^{\frac{\sqrt{k_T^2 + (1+\xi)k_Z^2}}{\Lambda}} - 1} \xrightarrow[\xi \rightarrow 0]{\text{thermalization}} \rho_{\text{iso}}(k) = \frac{1}{e^{k/T^{\text{eff}}} - 1},$$

$\xi > -1$ - anisotropy parameter [Romatschke, Strickland, Phys. Rev. D 68 (2003) 036004; 70 (2004) 116006], Λ - momentum scale, $k = \sqrt{k_T^2 + k_Z^2}$

HF quark's in-medium interactions

Matching **geometrical** (string configurations) and **computed** (gluon momentum distribution assumption) medium energy density

- anisotropic case $\Leftrightarrow$ anisotropic non-thermalized hydro

$$\Lambda_{\text{cell}} = \sqrt[4]{\frac{\varepsilon_{\text{cell}}}{16\pi^2/60}} \cdot \left(\frac{1}{1+\xi} + \frac{\arctan\sqrt{\xi}}{\sqrt{\xi}} \right)^{-\frac{1}{4}}$$

- isotropic case $\Leftrightarrow$ pure gluonic equilibrated QGP

$$\Lambda_{\text{cell}} \xrightarrow{\xi \rightarrow 0} T_{\text{cell}}^{\text{eff}} = \sqrt[4]{\frac{\varepsilon_{\text{cell}}}{16\pi^2/30}}$$

- cell-by-cell correspondence for $\varepsilon_{\text{cell}} \in [0.04, 0.4]$ GeV⁴ gives

$$\xi + 1 = 1, \Lambda_{\text{cell}} = T_{\text{cell}}^{\text{eff}} \in [0.29, 0.53] \text{ GeV}$$

$$\xi + 1 = 10, \Lambda_{\text{cell}} \in [0.42, 0.74] \text{ GeV}$$

$$\xi + 1 = 100, \Lambda_{\text{cell}} \in [0.56, 1.0] \text{ GeV}$$

$$\xi + 1 = 1000, \Lambda_{\text{cell}} \in [0.75, 1.33] \text{ GeV}$$

HF quark's in-medium interactions

Momentum loss rate in non-thermalized $\xi > 0$ anisotropic medium

$$\begin{aligned}
 \frac{dp}{dt} = & \frac{4}{3} \pi (\Lambda_{\text{cell}}^{\text{eff}})^2 \alpha_s^{\text{th}}(\mu_{\text{cell}}^2) \alpha_s^{\text{th}}(6E\Lambda_{\text{cell}}) \\
 & \times \ln \left[\frac{\sqrt{6E\Lambda_{\text{cell}} - m^2 + \frac{m^4}{12\Lambda_{\text{cell}}p} \ln \frac{m^2 + 6\Lambda_{\text{cell}}(E+p)}{m^2 + 6\Lambda_{\text{cell}}(E-p)}}}{\mu_{\text{cell}}} \right] \\
 & \times (1 - \varepsilon) \left[\frac{1}{\xi + \varepsilon^2} \cdot \left\{ \frac{\arctan \sqrt{\xi}}{\sqrt{\xi}} \left(\xi + \frac{1 + \xi}{1 - \varepsilon} - \frac{2\xi}{\gamma} \right) \right. \right. \\
 & \left. \left. + 1 + \ln \frac{1 - \varepsilon}{1 + \varepsilon} \cdot \left(\frac{\varepsilon}{\gamma} + \frac{1}{2} \right) \right\} + \frac{12\zeta(3)}{\pi^2} \cdot \frac{\Lambda_{\text{cell}}}{E} \cdot \frac{1}{(\xi + 1)^{\frac{3}{2}}} \right. \\
 & \left. \times \left\{ \frac{\operatorname{arctanh} \sqrt{\gamma}}{\gamma^{\frac{3}{2}}} - \frac{1}{\gamma} \right\} \right], \quad \varepsilon = \frac{p}{E}, \quad \gamma = \frac{\xi + \varepsilon^2}{\xi + 1}
 \end{aligned}$$

HF quark's in-medium interactions

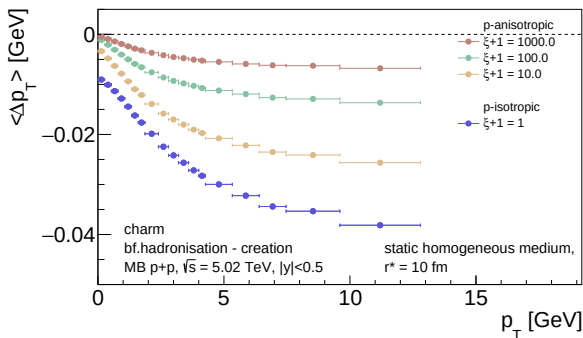
Momentum loss rate in effective thermalized isotropic medium

$$\begin{aligned}
 \frac{dp}{dt} = & \frac{4}{3} \pi (T_{\text{cell}}^{\text{eff}})^2 \alpha_s^{\text{th}}(\mu_{\text{cell}}^2) \alpha_s^{\text{th}}(6ET_{\text{cell}}^{\text{eff}}) \\
 & \times \ln \left[\frac{\sqrt{6ET_{\text{cell}}^{\text{eff}} - m^2 + \frac{m^4}{12T_{\text{cell}}^{\text{eff}}p} \ln \left[\frac{m^2 + 6T_{\text{cell}}^{\text{eff}}(E+p)}{m^2 + 6T_{\text{cell}}^{\text{eff}}(E-p)} \right]}}{\mu_{\text{cell}}} \right] \\
 & \times \left\{ \frac{E}{p^3} \left((2E - p)p - (E^2 + m^2 - Ep) \sinh^{-1} \left(\frac{p}{m} \right) \right) \right. \\
 & \left. + \frac{12\zeta(3) T_{\text{cell}}^{\text{eff}}}{\pi^2} \frac{(E - p)}{p^3} \left(E \sinh^{-1} \left(\frac{p}{m} \right) - p \right) \right\}
 \end{aligned}$$

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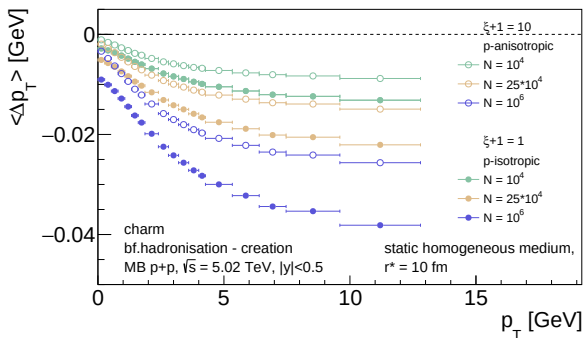
Brick test I

- static infinite homogeneous medium
- high string density equivalent to $k_{\text{cell}} = 100$ (extremely HM events)
- constant quark propagation time $t_{\text{max}} = 1.5 \text{ fm}/c$
- medium gluon $k_z - k_T$ anisotropy $\xi + 1 = 1000, 100, 10, 1$



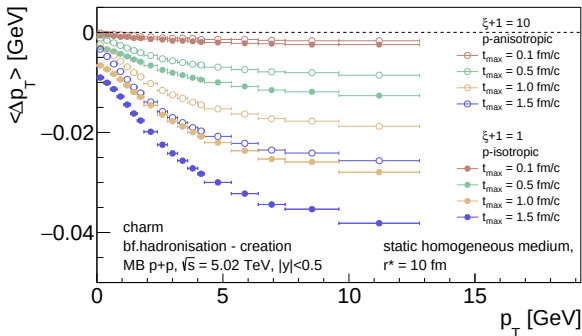
Brick test II

- static infinite homogeneous medium
- *varying string density*
- constant quark propagation time $t_{\max} = 1.5 \text{ fm}/c$
- medium gluon $k_z - k_T$ anisotropy $\xi + 1 = 10$ and 1



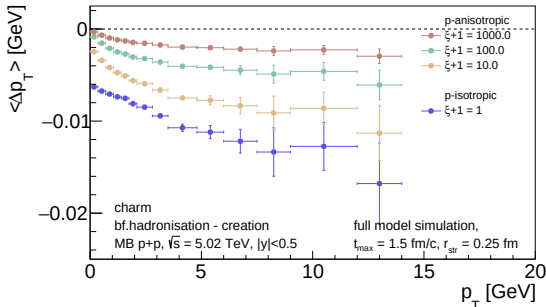
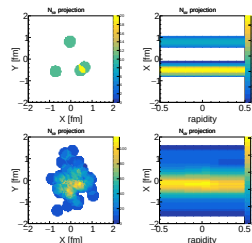
Brick test III

- static infinite homogeneous medium
- high string density equivalent to $k_{\text{cell}} = 100$ (extremely HM events)
- *varying quark propagation time*
- medium gluon $k_z - k_T$ anisotropy $\xi + 1 = 10$ and 1



Full model simulations

- event-by-event fluctuating medium shape
- cell-by-cell fluctuations of string density
- time evolution of string density
- position-dependent quark escape time
- medium gluon $k_z - k_T$ anisotropy



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Summary

- ◇ extended [Prokhorova, Andronov, Physics 6 (2024) 264] model
- ◇ small HF quarks' p_T loss in elastic scatterings off gluons in strings
- ◇ p_T loss decreases with momentum anisotropy ξ of medium gluons
- ◇ Comparison to other models:
 - **EPOS4HQ** [Zhao et al. Phys. Rev. C 111 (2025) 014907]:
 - $\tau \geq 0.4$ fm $\sim$ propagation in thermalized QGP (hydro)
 - medium: T-dependent transport coefficients, flow velocity
 - HF stochastic trajectory (diffusion)
 - collisional (thermal partons) + radiative (gluons) energy loss
 - **Glasma** [Carrington et al. Phys. Rev. C 105 (2022) 0649107]:
 - $\tau < 0.15$ fm $\sim$ propagation in classical YM fields
 - static medium: 0th-order in τ -expansion $\sim$ color flux tubes
 - HF stochastic trajectory (field kicks)
 - chromoelectric and chromomagnetic field-induced energy loss

Outlook

- add radiative losses
- test dynamical switch from anisotropic to thermalized medium
- include hadronisation:
 - for independent strings: Lund-like fragmentation?
 - for high ε areas: AMPT-like string melting?
- include hadron rescatterings
- study $\hat{q}$, R_{AA} and v_n of HF quark
- compare with HF hadron data

Thank you for your attention!

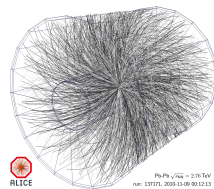
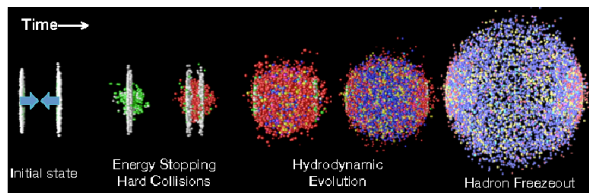


BACKUP

in Heavy Ion collisions

Modern view: Lorentz-contracted nuclei collide $\rightarrow$ QGP formation, expansion, cooling, freeze-out $\rightarrow$ final state particles reach detectors

$t = 0$ fm $0 < t < 1.5$ fm $1.5 < t < 10$ fm $t > 10$ fm

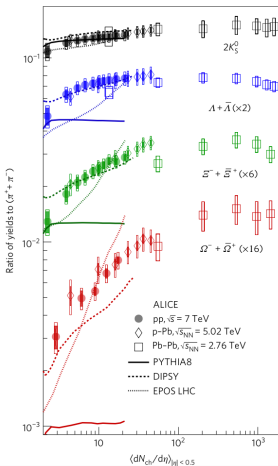


- QGP indirect **signals**: strangeness enhancement, azimuthal flows, jet quenching etc.
- deduced **QGP properties**: strongly coupled quarks and gluons, almost perfect relativistic fluid, $T_{\text{crit}} \sim 150$ MeV, $\varepsilon_{\text{crit}} \sim 1$ GeV/fm³

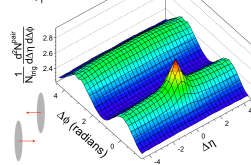
in pp collisions

unexpected collectivity in a reference p+p system

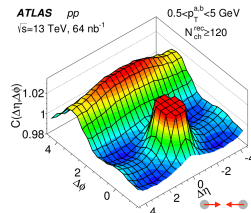
strangeness enhancement



(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{ch}^{0-90^\circ} < 260$
 $1 < p_T^{V0} < 3$ GeV/c
 $1 < p_T^{assoc} < 3$ GeV/c

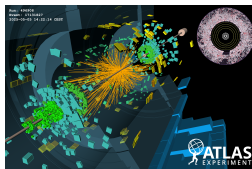
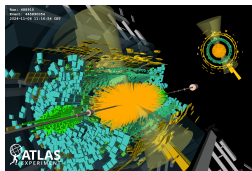
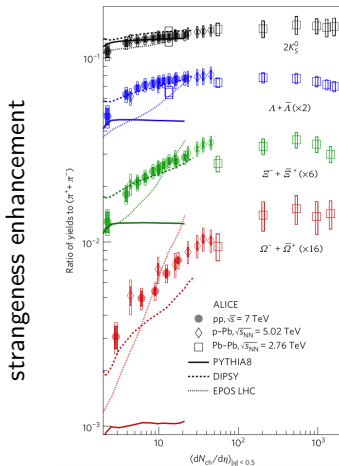
Pb+Pb
← ridge!

ATLAS pp
 $\sqrt{s} = 13$ TeV, 64 nb^{-1}
 $0.5 < p_T^{a,b} < 5$ GeV
 $N_{ch}^{rec} \geq 120$

HM
p+p
← ridge?

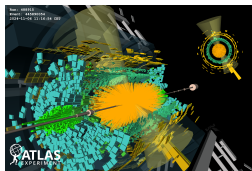
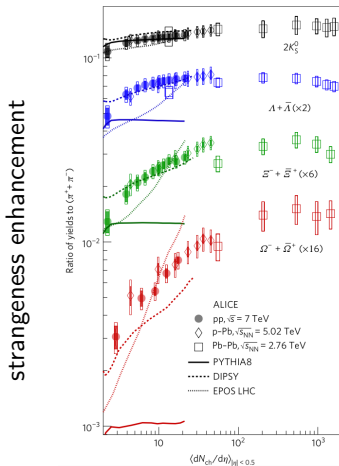
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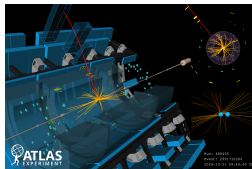


in pp collisions

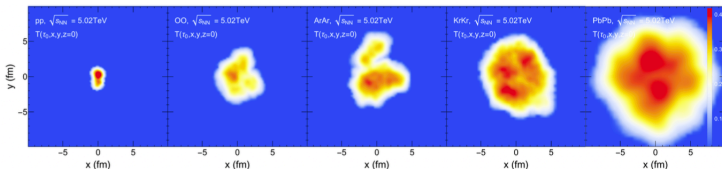
unexpected collectivity in a reference p+p system



Pb+Pb

LM
p+p

Is QGP also formed in p+p?



[J. Zhao et al., Phys. Rev. C 111 (2025) 014907]

- **Tiny Droplet of Liquid?**

- ◇ small size: $\sim 1\text{--}2$ fm vs ~ 10 fm in Pb+Pb
- ◇ short lifetime: $\tau \sim 1\text{--}2$ fm $\rightarrow$ challenging to equilibrate
- ◇ if hydro interpretation: poorly known initial conditions

- **Fast Equilibration?**

- ◇ hydrodynamic attractors (universal flow patterns)?
- ◇ strong fields (no QGP) fake collective behavior?
- ◇ only momentum-space isotropization matters?

This talk: minbias p+p at 5.02 TeV

production of $Q\bar{Q}$ pair in initial hard scattering

$gg \rightarrow Q\bar{Q}, q\bar{q} \rightarrow Q\bar{Q}$ from PYTHIA

interactions with pre-equilibrated medium

- strong classical gluon fields (early stages) $\sim$ **color strings**
- not yet equilibrated partons (~~just before QGP~~) **for future**

~~interactions with QGP medium~~ **NO ad hoc medium**

- elastic collisions (dominant at lower HF's p_T) $\sim$ **HF with gluons**
- radiative loss (dominant at higher HF's p_T) **for future**

hadronisation

- coalescence (dominant at lower HF's p_T) **for future**
- fragmentation (dominant at higher HF's p_T)

hadron re-scatterings

- UrQMD-like **for future**

What we propose

Idea:

- examine modifications of p_T spectra of HF quarks propagating in color string medium in p+p system
- medium evolution based on string dynamics (no hydro assumed)
- extend model of interacting color strings [D. Prokhorova, E. Andronov, Physics 6 (2024) 264]

Why interesting:

- usually: suppression of high- p_T hadrons $\sim$ QGP signal
- however: QGP may not be formed in p+p
- often: p_T modification in pre-QGP is neglected
- however: large anisotropies and high energy densities of field configurations in glasma-like models can significantly alter HF's p_T

Model description

① Hard vs soft regimes **new!**

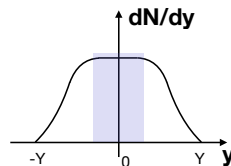
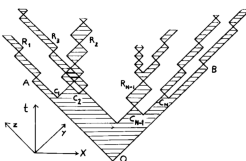
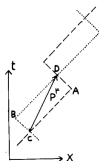
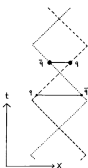
- **new!** extract HF quarks from proton-proton PYTHIA event:
HardQCD: all, gg2ccbar, gg2bbbar, qqbar2ccbar, qqbar2bbbar = on
- **new!** remaining energy used for soft pomeron creation
- cut pomerons [A. Kaidalov et al. Phys. Lett. B **117** (1982) 247] → strings in an event: $n_{\text{str}} = 2n_{\text{pom}}$ [A. Capella et al. Phys. Rep. **236** (1994) 225] :

$$P(n_{\text{pom}}) = C(z) \frac{1}{zn_{\text{pom}}} \left(1 - \exp(-z) \sum_{l=0}^{n_{\text{pom}}-1} \frac{z^l}{l!} \right), \quad z = \frac{2w\gamma s^\Delta}{R^2 + \alpha' \ln s}$$

$w = 1.5$, $\Delta = \alpha(0) - 1 = 0.2$, $\gamma = 1.035 \text{ GeV}^{-2}$, $R^2 = 3.3 \text{ GeV}^{-2}$, $\alpha' = 0.05 \text{ GeV}^{-2}$
from [V. Vechernin, S. Belokurova, J. Phys. Conf. Ser. **1690** (2020) 012088]

Color string evolution and fragmentation

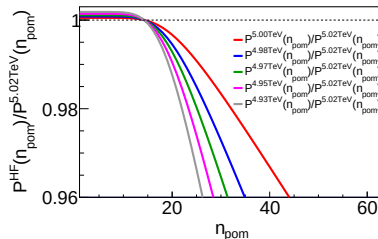
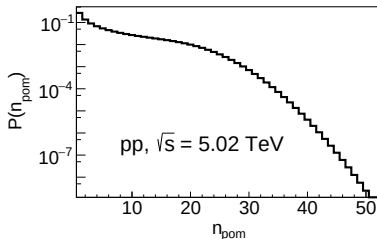
- ◇ in 1 + 1 space-time: massless relativistic string is a **yo-yo mode** solution of $dp/dt = \pm \sigma_T$ equation of motion [X. Artru, Phys. Rep. **97** (1983) 147]
- ◇ probabilistic string fragmentation depends on hatched area spanned during quarks motion [B. Andersson, G. Gustafson, G. Ingelman, T. Sjostrand, Phys. Rep. **97** (1983) 31]
- ◇ colourless hadrons **uniformly** distributed over rapidity, $y = \frac{1}{2} \ln \left(\frac{p_0 + p_z}{p_0 - p_z} \right)$



- ◇ common approximation: **infinite** in rapidity strings
- ◇ convenient for finite experimental acceptances at **mid-rapidity** [S. Belokurova, V. Vechernin, Symmetry **12** (2020) 110]

Model description

Examples of modified event-by-event n_{pom} distributions:



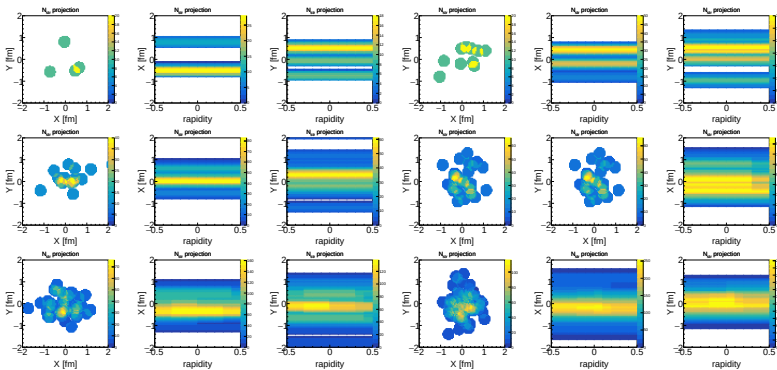
2 Proton composition:

- inside each proton $N_{\text{part}} = N_{\text{str}} = 2 \cdot n_{\text{pom}}$, which includes valence quark, valence diquark, sea pairs
- partons' $p_Z = x \cdot p_{\text{beam}}$ sampled from PDFs [A. Buckley et al. Eur. Phys. J. C **75** (2015) 132]

Model description

③ Strings formation

- pure longitudinal strings between partons of two protons
- in X-Y distributed according to Gaussian (0.0, 0.5) fm



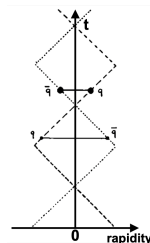
Model description

4 Strings evolution [C. Shen, B. Schenke, Phys. Rev. C **97** (2018) 024907]

For a **parton at string end** with m and $p_z = xp_{\text{beam}}$:

- ◇ initial rapidity: $y_{\text{init}} = \sinh^{-1} \left(\frac{p_z}{m} \right)$
- ◇ equations of motion: $\frac{dp_z}{dt} = -\sigma, \quad \frac{dE}{dz} = -\sigma$
- ◇ proper time before flip ($\tilde{y}$ in string rest frame):

$$\Delta\tau_{\text{max}} = \frac{m}{\sigma} \sqrt{2(\cosh(\tilde{y}_{\text{init}} - 1))} - \textbf{periodicity!}$$



- relation between proper time $\Delta\tau$ and lab time Δt intervals:

$$\Delta t = \Delta\tau \left(\pm \frac{\sigma\Delta\tau}{2m} \sinh(y_{\text{init}}) + \cosh(y_{\text{init}}) \sqrt{\frac{\sigma^2\Delta\tau^2}{4m^2} + 1} \right)$$

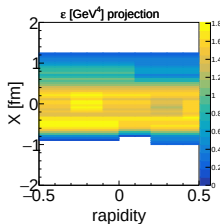
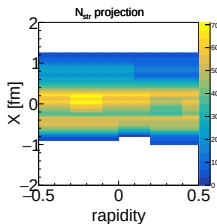
- change of rapidity: $y_{\text{loss}} = \cosh^{-1} \left(\frac{\sigma^2\Delta\tau^2}{2m^2} + 1 \right)$
- final rapidity after proper time $\Delta\tau$: $y_{\text{fin}} = y_{\text{init}} \pm y_{\text{loss}}$

Model description

5 String medium characteristics

- finite transverse size $\rightarrow$ strings overlap $\rightarrow$ interplay of randomly oriented color fields [M. Braun et al. Int. J. Mod. Phys. A **14** (1999) 2689]
- fine granulation of **X-Y-rapidity space**, $\Delta t = 0.1$ fm/c **time steps**
- new!** number of strings in a cell, k_{cell} , gives energy density, $\varepsilon_{\text{cell}}$:

$$\varepsilon_{\text{cell}} = \frac{\sigma \sqrt{k_{\text{cell}}}}{\Delta S_{\text{str}}}, \quad \sigma = 1 \frac{\text{GeV}}{\text{fm}}, \quad \Delta S_{\text{str}} = \pi r_{\text{str}}^2, \quad r_{\text{str}} = 0.25 \text{ fm}$$



$$k_{\text{cell}} \in [1, 100]$$

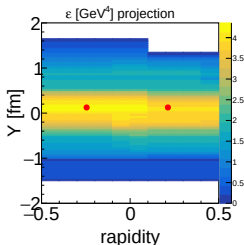
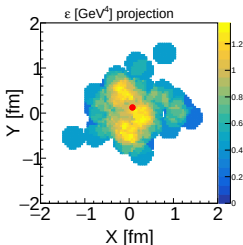
$$\varepsilon_{\text{cell}} \in [5, 50] \frac{\text{GeV}}{\text{fm}^3}$$

$$\varepsilon_{\text{cell}} \in [0.04, 0.4] \text{ GeV}^4$$

Model description

⑥ HF production **new!**

- PYTHIA provides mass and $\vec{p}$ of HF quarks but $X = Y = 0$
- at $t = 0$ fm/c HF quark pair inserted in string medium



Model description

⑦ HF propagation **new!**

- every $\Delta t = 0.1$ fm HF quarks propagate in **changing string medium** during $t = 1.5$ fm
- deterministic energy-loss model (keeps initial p_T direction):
 - ◇ straight trajectories (no stochastic noise, no diffusion)
 - ◇ no large-angle scatterings
 - ◇ no change of rapidity slice (focus on transverse loss)

