

# Jet Quenching in Relativistic Heavy-Ion Collisions

HEPIC - Instituto de Física da USP

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May 2nd 2020



10th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

#### Motivation

Jet Quenching. Model used:

 JEWEL[arXiv: 1212.1599, arXiv: 1311.0048];

#### Goal

- Realistic medium evolution
- Differential predictions
- Multiparticle final state



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# Jet Quenching



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# v-USPhydro



**v-USPhydro**[arXiv: 1305.1981, arXiv: 1406.3333]

- smoothed particle hydrodynamics(Lagrangian method);
- 2+1 dimensions;
- shear viscosity  $(\frac{\eta}{s} = 0.047);$



## The simulation



	Scenarios	
	Initial conditions	Evolution
Glauber+Bjorken	Glauber	
$T_RENTO+Bjorken$	T <sub>R</sub> ENTo <sup>1</sup>	Bjorken Expansion
MC-KLN+Bjorken	MC-KLN <sup>2</sup>	
MC-KLN +v-USPhydro	MC-KLN	2 1 v USPhydro codo
$T_{R}ENTo$ +v-USPhydro	T <sub>R</sub> ENTo	

 $^{1}arXiv: 1412.4708$  $^{2}arXiv: nucl-th/0611017$ 

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# Jet Observables



The observables chosen were the following:

- Mass;
- Girth;
- Dispersion;
- v<sub>n</sub>;
- x<sub>J</sub>;



Following arXiv: 1509.07334, we generalize:

$$v_n^{\mathrm{ch\, jet}}(p_T^{\mathrm{ch\, jet}}) = \frac{\pi}{4} \frac{N_{\mathrm{in}}(p_T^{\mathrm{ch\, jet}}) - N_{\mathrm{out}}(p_T^{\mathrm{ch\, jet}})}{N_{\mathrm{in}}(p_T^{\mathrm{ch\, jet}}) + N_{\mathrm{out}}(p_T^{\mathrm{ch\, jet}})}$$

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$$v_2^{\rm ch\,jet}(p_T^{\rm ch\,jet}) = \frac{\pi}{4} \frac{N_{\rm in}(p_T^{\rm ch\,jet}) - N_{\rm out}(p_T^{\rm ch\,jet})}{N_{\rm in}(p_T^{\rm ch\,jet}) + N_{\rm out}(p_T^{\rm ch\,jet})}$$





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PbPb  $\sqrt{s_{\rm NN}}=2.76~{\rm TeV}$  anti-kt R=0.2  $|\eta|<0.8$  40 GeV/c  $<{\rm p_T}<60~{\rm GeV/c}$  arXiv: 1807.06854

$$g = \frac{\sum_{i} p_{i}^{T} \Delta R_{i}}{p_{i}^{T}}$$



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Jet Quenching in Relativistic Heavy-Ion Collis

anti-kt R = 0.4 $|\eta| < 0.8$  $40\,\mathrm{GeV/c} < \mathrm{p_T} < 60\,\mathrm{GeV/c}$ 

arXiv: 1702.00804





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PbPb  $\sqrt{s_{\rm NN}} = 2.76~{\rm TeV}$  anti-kt R = 0.4 $|\eta| < 0.8$ arXiv: 1509.07334 arXiv: 1306.6469



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# Predictions for Run II with $\mathrm{T}_{R}\mathrm{ENTo}{+}\mathsf{vUSP}{-}\mathsf{hydro}$

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 $\sqrt{\mathrm{s_{NN}}} = 5.02 \,\mathrm{TeV}$  anti-kt R = 0.4  $|\eta| < 2.1$ 



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# Predictions for $v_n$



 $\begin{array}{l} V_2 \\ \sqrt{\mathrm{s}_{\mathrm{NN}}} = 5.02 \ \mathrm{TeV} \ \mathrm{anti-kt} \\ R = 0.2 \\ |\eta| < 1.2 \end{array}$ 



**PbPb** 5.02 TeV

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# Predictions for $v_n$



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**PbPb** 5.02 TeV

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 $\mathsf{PbPb}\ 5.02\,\mathrm{TeV}$ 

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edo	Jet Quenching in Relativistic Heavy-Ion Collis	May 2nd 2020	13 / 15



V3  $\sqrt{s_{NN}} = 5.02 \,\mathrm{TeV}$  anti-kt  $\dot{R} = 0.2$  $|\eta| < 1.2$ 

> 0.008 0.006 0.004 $v_3$ 0.002 0.000 -0.0020 - 10%10 - 20%20 - 40%40 - 60%

PbPb  $5.02 \,\mathrm{TeV}$ 

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 $\mathsf{PbPb}\ 5.02\,\mathrm{TeV}$ 



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#### **Conclusions and Outlook**



#### Conclusions

Sensitivity		
Observable Sensitive to medium expansion		
Girth	No	
$p_T^D$	No	
Mass	No	
Jet v <sub>n</sub>	Yes	

Are Jet Quenching models sensitive to hydro?

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#### **Conclusions and Outlook**



#### **Conclusions**

Sensitivity		
Observable   Sensitive to medium expansion?		
Girth	No	
$p_T^D$	No	
Mass	No	
Jet v <sub>n</sub>	Yes	

Are Jet Quenching models sensitive to hydro?

- From the shape perspective? Not the ones we have studied;
- From the anisotropic flow perspective? Yes!
- There is indication that Jet Quenching is sensitive to hydrodynamics;
- Observables that look at event-by-event fluctuations, i.e. v<sub>2</sub>, might give further constraint both on hydro models and on the Jet Quenching models themselves;

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• A new tool was developed to study interplay of jets and medium;

#### **Conclusions and Outlook**



## Outlook

- Study other observables (*z<sub>g</sub>*,n-subjetiness,...);
- Look for new ones;
- Study each observable dependence to each IC and hydro parameter (ζ,η);
- Use other IC and hydro models;
- Implement realistic EOS, local  $u_{\mu}$  and heavy-flavor on JEWEL;

# Backup

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JEWEL calculates  $T(x, y, \tau)$  as it generates events.

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JEWEL calculates  $T(x, y, \tau)$  as it generates events. This can't be done with arbitrary ICs and hydro.

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JEWEL calculates  $T(x, y, \tau)$  as it generates events. This can't be done with arbitrary ICs and hydro. So, a method was developed to read external profiles.

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Then it is saved into a grid.

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Then it is saved into a grid.

- *h* = 0.3 fm;
- $d\tau = 0.1 \, {\rm fm/c};$
- Bicubic interpolation;

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Events are generated reading this grid.

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PbPb 0-10%  
$$\sqrt{\mathrm{s}_{\mathrm{NN}}}=2.76\mathrm{TeV}$$
 anti-kt  
 $R=0.4$   
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PbPb 0-10%  $\sqrt{s_{NN}} = 2.76 \text{TeV}$  anti-kt R = 0.2  $|\eta| < 0.8$   $40 \text{ GeV/c} < p_{T} < 60 \text{ GeV/c}$  $g = \frac{\sum_{i} p_{i}^{T} \Delta R_{i}}{p_{i}^{T}}$ 

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Jets are defined through an algorithm that must satisfy certain conditions.

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collinear safe;



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- collinear safe;
- infrared safe; •



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#### Anti-kt

Jets are defined through an algorithm that must satisfy certain conditions.

- collinear safe;
- infrared safe;



#### 

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#### Anti-kt



Based on a two particle distance;

$$d_{ij} = \min(p_{t\,i}^{-2}, p_{t\,j}^{-2}) \frac{\Delta R_{ij}}{R}$$
$$d_{i} = p_{t\,i}^{-2}$$

Where:

$$\Delta \mathbf{R} = \sqrt{\Delta \phi^2 + \Delta \eta^2}$$

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#### Anti-kt





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JEWEL keeps recoil

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#### **JEWEL** keeps recoil

Thermal contamination must be subtracted

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#### JEWEL keeps recoil

Thermal contamination must be subtracted 4 Moment Subtraction:

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#### JEWEL keeps recoil

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Thermal momenta  $\longrightarrow$  ghost particles



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4 Moment Subtraction:

Thermal momenta  $\longrightarrow$  ghost particles

Particles close enough to these ghost particles are classified as thermal momenta.

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#### JEWEL keeps recoil

Thermal contamination must be subtracted

4 Moment Subtraction:

Thermal momenta  $\longrightarrow$  ghost particles

Particles close enough to these ghost particles are classified as thermal momenta.

4 thermal momenta summed up and subtracted from the observable.

#### Quark-Gluon Plasma



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The experimental way of studying the Quark-Gluon Plasma are Relativistic Heavy-Ion Collisions



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The experimental way of studying the Quark-Gluon Plasma are Relativistic Heavy-Ion Collisions



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## Relativistic Heavy-Ion Collisions



The experimental way of studying the Quark-Gluon Plasma are Relativistic Heavy-Ion Collisions



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# Relativistic Heavy-Ion Collisions





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### JEWEL<sup>*a,b,c*</sup> (Jet Evolution with Energy Loss)



<sup>a</sup> Eur.Phys.J. C74 (2014) no.2,2762 [arXiv:1212.1599] <sup>b</sup> JHEP 1303 (2013) 080 [arXiv:0804.3568]

<sup>c</sup> arXiv:1707.01539

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Runs with PYTHIA;



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#### JEWEL<sup>*a,b,c*</sup> (Jet Evolution with Energy Loss)

- Runs with PYTHIA;
- Based on BDMPS-Z formalism;



<sup>a</sup> Eur.Phys.J. C74 (2014) no.2,2762 [arXiv:1212.1599] <sup>b</sup> JHEP 1303 (2013) 080 [arXiv:0804.3568]

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Jet Quenching in Relativistic Heavy-Ion Collis

May 2nd 2020 13

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### JEWEL<sup>*a,b,c*</sup> (Jet Evolution with Energy Loss)

- Runs with PYTHIA;
- Based on BDMPS-Z formalism;
- Perturbative and minimal in assumptions;

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<sup>a</sup> Eur.Phys.J. C74 (2014) no.2,2762 [arXiv:1212.1599] <sup>b</sup> JHEP 1303 (2013) 080 [arXiv:0804.3568]

<sup>c</sup> arXiv:1707.01539

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### JEWEL<sup>*a,b,c*</sup> (Jet Evolution with Energy Loss)

- Runs with PYTHIA;
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- Perturbative and minimal in assumptions;
- Implements the LPM effect;



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#### JEWEL<sup>*a,b,c*</sup> (Jet Evolution with Energy Loss)

- Runs with PYTHIA;
- Based on BDMPS-Z formalism;
- Perturbative and minimal in assumptions;
- Implements the LPM effect;
- Allows differential and geometric treatment(jet shape);

<sup>a</sup> Eur.Phys.J. C74 (2014) no.2,2762 [arXiv:1212.1599] <sup>b</sup> JHEP 1303 (2013) 080 [arXiv:0804.3568]

<sup>c</sup> arXiv:1707.01539



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- First, a pair of partons is generated in PYTHIA;
- JEWEL then propagates these partons in a dense and hot medium;
- Once the partons leave the medium, the event is handed back to PYTHIA for hadronization;

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In its default:

$$\epsilon(x, y, b, \tau) = \epsilon(x, y, b, \tau_i) \left(\frac{\tau}{\tau_i}\right)^{-4/3}$$

and

$$T(x, y, b, au) \propto \epsilon^{1/4}(x, y, b, au_i) \left(rac{ au}{ au_i}
ight)^{-1/3}$$



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### Bjorken



A variant of the Bjorken model is used. The (proper)time dependence is given by

$$\epsilon(\mathbf{x}, \mathbf{y}, \mathbf{b}, \tau) = \epsilon(\mathbf{x}, \mathbf{y}, \mathbf{b}, \tau_i) \left(\frac{\tau}{\tau_i}\right)^{-4/3}$$

and

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$$T(x, y, b, au) \propto \epsilon^{1/4}(x, y, b, au_i) \left(rac{ au}{ au_i}
ight)^{-1/3}$$

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Objective, solve the conservation equation equation:

$$\partial_{\mu}T^{\mu\nu} + \Gamma^{\nu}_{\lambda\mu}T^{\lambda\mu} = 0 \tag{1}$$

Where:

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$$T^{\mu\nu} = (\epsilon + \rho + \Pi)u^{\mu}u^{\nu} - (\rho + \Pi)g^{\mu\nu}$$
(2)

Where  $\epsilon$  is the local energy density, p is the local pressure in terms of  $\epsilon$  according to an equation of state, and  $\Pi$  is the out-of-equilibrium term.

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The method employed, Smoothed Particle Hydrodynamics requires the definition of a reference density:

$$\partial_{\mu}(\tau\gamma\sigma u^{\mu}) = 0 \tag{3}$$

With this definition, the equations of motion, then become:

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The method employed, Smoothed Particle Hydrodynamics requires the definition of a reference density:

$$\partial_{\mu}(\tau\gamma\sigma u^{\mu}) = 0 \tag{3}$$

With this definition, the equations of motion, then become:

$$\gamma \frac{d}{d\tau} \left( \frac{\epsilon + p + \Pi}{\sigma} u_i \right) = \frac{\partial_i (p + \Pi)}{\sigma}$$
(4a)  
$$\gamma \frac{d}{d\tau} \left( \frac{s}{\sigma} \right) + \left( \frac{\Pi}{\sigma} \right) \frac{\theta}{T} = 0$$
(4b)  
$$\tau_{\Pi} \gamma \frac{d}{d\tau} \left( \frac{\Pi}{\sigma} \right) + \left( \frac{\Pi}{\sigma} \right) + \left( \frac{\zeta}{\sigma} \right) \theta = 0$$
(4c)

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Smoothed Particle Hydrodynamics

$$\tau\gamma\sigma \to \sigma^* = \sum_{\alpha=1}^{N_{SPH}} \nu_{\alpha} W[\mathbf{r} - \mathbf{r}_{\alpha}(\tau); h]$$
(5)

where  $\sigma$  is a local density,  $\tau$  is the proper time and  $\gamma$  is the relativistic boost factor. The generalized current is:

$$\mathbf{j}^{*}(\mathbf{r},\tau) = \sum_{\alpha=1}^{N_{SPH}} \nu_{\alpha} \frac{d\mathbf{r}_{\alpha}(\tau)}{d\tau} W[\mathbf{r} - \mathbf{r}_{\alpha}(\tau); h]$$
(6)

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#### For densities associated with extensive quantities we have:

$$a(\mathbf{r},\tau) = \sum_{\alpha=1}^{N_{SPH}} \nu_{\alpha} \frac{a(\mathbf{r}_{\alpha}(\tau))}{\sigma^{*}(\mathbf{r}_{\alpha}(\tau))} W[\mathbf{r} - \mathbf{r}_{\alpha}(\tau); h]$$
(7)

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The evolution equations for the SPH "particles" then become:

$$\sigma^* \frac{d}{d\tau} \left( \frac{(\epsilon + p + \Pi)_{\alpha}}{\sigma_{\alpha}} u_{i,\alpha} \right) =$$

$$\tau \sum_{\beta=1}^{N_{SPH}} \nu_{\beta} \sigma_{\alpha}^{*} \left( \frac{(p+\Pi)_{\beta}}{\sigma_{\beta}^{2}} + \frac{(\epsilon+p+\Pi)_{\alpha}}{\sigma_{\alpha}^{2}} \right) \partial_{i} W[\mathbf{r} - \mathbf{r}_{\beta}(\tau); h] \quad (8a)$$

$$\gamma_{\alpha} \frac{d}{d\tau} \left(\frac{s}{\sigma}\right)_{\alpha} + \left(\frac{\Pi}{\sigma}\right)_{\alpha} \left(\frac{\theta}{T}\right)_{\alpha} = 0$$
(8b)

$$\tau_{\Pi_{\alpha}}\gamma_{\alpha}\frac{d}{d\tau}\left(\frac{\Pi}{\sigma}\right)_{\alpha}\left(\frac{\Pi}{\sigma}\right)_{\alpha} + \left(\frac{\zeta}{\sigma}\right)_{\alpha}\theta_{\alpha} = 0$$
(8c)

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## Smooth Glauber<sup>3</sup>



$$n(b, x, y) = T_A(x - \frac{b}{2}, y) \left( 1 - \exp\left(-\sigma_{NN}T_B(x + \frac{b}{2}, y)\right) \right)$$
$$+ T_B(x + \frac{b}{2}, y) \left( 1 - \exp\left(-\sigma_{NN}T_A(x - \frac{b}{2}, y)\right) \right)$$

<sup>3</sup>JEWEL Default

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## Smooth Glauber<sup>3</sup>



$$n(b, x, y) = T_A(x - \frac{b}{2}, y) \left( 1 - \exp\left(-\sigma_{NN}T_B(x + \frac{b}{2}, y)\right) \right)$$
$$+ T_B(x + \frac{b}{2}, y) \left( 1 - \exp\left(-\sigma_{NN}T_A(x - \frac{b}{2}, y)\right) \right)$$

Where:

$$T(x,y) = \int dz \rho(x,y,z)$$

And  $\rho$  is the Woods-Saxon potential.

<sup>3</sup>JEWEL Default

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### **Smooth Glauber**





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#### $\mathrm{T}_{\mathrm{R}}\mathrm{ENTo}^{\,\textit{a}}$

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#### $\mathrm{T_RENTo}\,^{a}$

• parametric model based on Glauber;

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## T<sub>R</sub>ENTo



### $T_{\rm R} {\rm ENTo}^{\,a}$

- parametric model based on Glauber;
- includes fluctuations event-by-event;

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 $T_{\rm R} ENTo^{\,a}$ 

 nucleon positions are generated according to a Woods-Saxon potential;

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 $\mathrm{T_RENTo}\,{}^{a}$ 

- nucleon positions are generated according to a Woods-Saxon potential;
- they collide with probability  $P = 1 - \exp(\sigma_{gg} \int dx dy \int dz \rho_A \int dz \rho_B);$

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 $\mathrm{T_RENTo}\,{}^{a}$ 

- nucleon positions are generated according to a Woods-Saxon potential;
- they collide with probability  $P = 1 - \exp(\sigma_{gg} \int dx dy \int dz \rho_A \int dz \rho_B);$
- the protons that do collide are kept and compose the thickness function T<sub>A</sub>;

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 $\mathrm{T_RENTo}\,{}^{a}$ 

- nucleon positions are generated according to a Woods-Saxon potential;
- they collide with probability  $P = 1 - \exp(\sigma_{gg} \int dx dy \int dz \rho_A \int dz \rho_B);$
- the protons that do collide are kept and compose the thickness function  $T_A$ ;
- the thickness functions are combined through  $f = \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$ ;

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### Frame Title



$$f = \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$



<sup>a</sup> arXiv:1412.4708 [nucl-th]

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### MC-KLN<sup>a</sup>



- Based on CGC with kt factorization;
- Has a physical mechanism;



<sup>a</sup> arXiv:0707.0249 [nucl-th]

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### **MC-KLN**



#### Cross-section for gluon interaction:

$$\sigma \sim \alpha_s(Q^2)\pi r_{gl}^2 \sim \alpha_s(Q^2)rac{\pi}{Q^2}$$

$$\frac{A}{\pi R_0^2}\sigma = \alpha_s(Q^2)\frac{\pi}{Q^2} \sim 1$$



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### **MC-KLN**



Gluon distribution function:

$$\phi_{\pm}(k_T^2; x_T) = \frac{Q_s^2(1-x)^4}{\alpha_s \max(Q_s^2, k_T^2)} \left( \frac{n_{part}^A(x_{\perp}, \pm b)}{T_A(x \pm b/2, y)} \right)$$
$$\frac{dN_g}{dx_T dY} \sim \int \frac{d^2 p_T}{p_T^2} \int d^2 k_T \alpha_s(k_T)$$
$$\times \phi_{\pm} \left( \frac{(p_T + k_T)^2}{4}; x_T \right) \phi_{-} \left( \frac{(p_T - k_T)^2}{4}; x_T \right)$$

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# MC-KLN



Energy density:

$$\epsilon(x_T, b) = \text{const} \times \left[\frac{dN_g}{d^2 x_T dY}\right]^{(4/3)}$$



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The observables chosen were the following:

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 $M_{jet} = \sqrt{p_{jet}^{\mu} p_{jet \,\mu}} = \sqrt{\left(E_{jet}^2 - \left(\sum_i \vec{p}_i\right)^2\right)}$ 

The observables chosen were the following:

> Mass; •





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 $M_{jet} = \sqrt{p_{jet}^{\mu} p_{jet \,\mu}} = \sqrt{\left(E_{jet}^2 - \left(\sum_i \vec{p}_i\right)^2\right)}$ 

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The observables chosen were the following:

> • Mass:



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The observables chosen were the following:

- Mass;
- Girth; •



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The observables chosen were the following:

- Mass;
- Girth;
- Dispersion;



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The observables chosen were the following:

- Mass;
- Girth;
- Dispersion;
- v<sub>n</sub>;



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# Jet Observables

The observables chosen were the following:

- Mass;
- Girth;
- Dispersion;
- v<sub>n</sub>;
- x<sub>J</sub>;

Following arXiv: 1509.07334, we generalize:

$$v_2^{\mathrm{ch\, jet}}(p_T^{\mathrm{ch\, jet}}) = rac{\pi}{4} rac{N_{\mathrm{in}}(p_T^{\mathrm{ch\, jet}}) - N_{\mathrm{out}}(p_T^{\mathrm{ch\, jet}})}{N_{\mathrm{in}}(p_T^{\mathrm{ch\, jet}}) + N_{\mathrm{out}}(p_T^{\mathrm{ch\, jet}})}$$





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The observables chosen were the following:

- Mass;
- Girth;
- Dispersion;

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- v<sub>n</sub>;
- xj;



Following arXiv: 1509.07334, we generalize:

$$v_{3}^{\mathrm{ch\, jet}}(\rho_{T}^{\mathrm{ch\, jet}}) = \frac{\pi}{4} \frac{N_{\mathrm{in}}(\rho_{T}^{\mathrm{ch\, jet}}) - N_{\mathrm{out}}(\rho_{T}^{\mathrm{ch\, jet}})}{N_{\mathrm{in}}(\rho_{T}^{\mathrm{ch\, jet}}) + N_{\mathrm{out}}(\rho_{T}^{\mathrm{ch\, jet}})}$$

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