

Exploring initial stages through ebeDREENA

Dusan Zigic

in collaboration with: Magdalena Djordjevic, Bithika Karmakar, Jussi Auvinen, Igor Salom, Pasi Huovinen and Marko Djordjevic



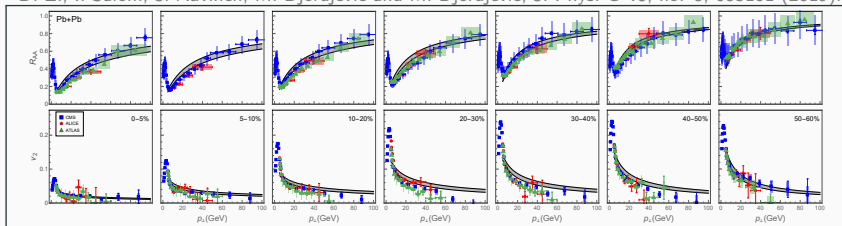
DREENA framework

- **Dynamical Radiative and Elastic ENergy loss Approach**
- fully optimized numerical procedure capable of generating high p_{\perp} predictions
- includes:
 - parton production
 - multi gluon-fluctuations
 - path-length fluctutations
 - fragmentation functions
- keeping all elements of the state-of-the art energy loss formalism, while introducing more complex medium evolutions:
 - **DREENA-C: constant temperature medium**
D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).
 - **DREENA-B: Bjorken expansion**
D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).
 - **DREENA-A: smooth (2+1)D temperature evolution**
D. Z., I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, Front. in Phys. **10**, 957019 (2022).
 - **ebe-DREENA: event-by-event fluctuating hydro background**
D. Z., J. Auvinen, I. Salom, P. Huovinen and M. Djordjevic, Phys. Rev. C **106**, no.4, 044909 (2022)

C = constant temperature

- Charged hadrons, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 TeV$

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).



for charged hadrons, qualitatively good agreement,
but overestimation of v_2 data

only average temperature as QGP property

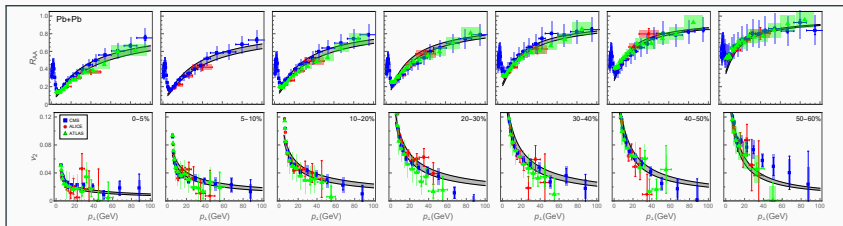
can be used to investigate path-length dependence of ϵ_{loss}

M. Djordjevic, D. Z., M. Djordjevic and J. Auvinen, Phys. Rev. C **99**, no.6, 061902 (2019)

B = 1D Bjorken evolution

- Charged hadrons, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 TeV$

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).



very good joint agreement with both R_{AA} and v_2 data
only average temperature and τ_0 as QGP properties



can be used to investigate initial evolution of QGP

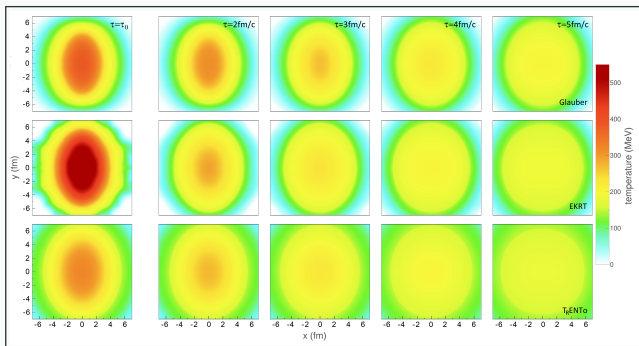
D. Z., B. Ilic, M. Djordjevic and M. Djordjevic, Phys. Rev. C **101**, no.6, 064909 (2020)

A = adaptive

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, *Front. in Phys.* **10**, 957019 (2022).

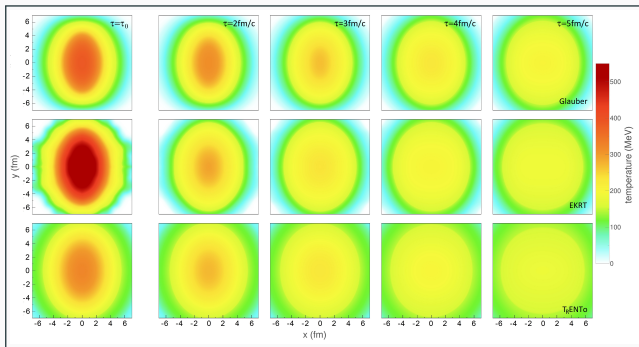
- includes any, arbitrary, medium evolution as an input
- preserve all dynamical energy loss model properties
- generate a comprehensive set of light and heavy flavor suppression predictions
- needs to be an efficient (timewise) numerical procedure

Are high- p_{\perp} observables indeed sensitive to different T evolutions?

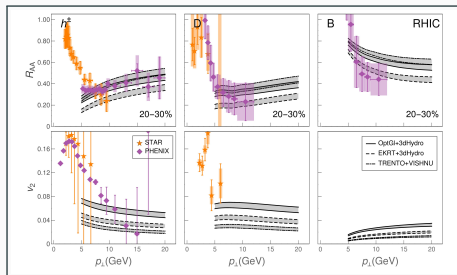
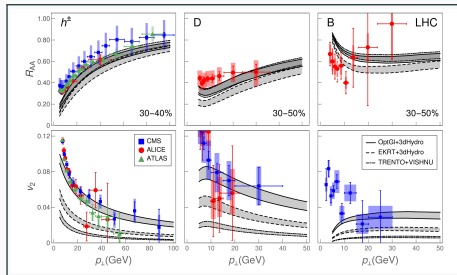


All three evolutions agree with low- p_{\perp} data. Can high p_{\perp} -data provide further constraint?

Qualitative differences



- Largest anisotropy for Glauber ($\tau_0 = 1\text{fm}$) – expected differences in high- p_{\perp} v_2
- EKRT shows larger temperature - smaller R_{AA} expected



- 'EKRT' initial conditions indeed lead to the smallest R_{AA}
- anisotropy translates to v_2 differences ('Glauber' largest, T_RENTo lowest)
- DREENA-A can differentiate between different T profiles
- heavy flavour even more sensitive to different T profiles
- additional (independent) constraint to low- p_{\perp} data

DREENA-A RECAP

- DREENA-A is a fully optimized numerical implementation of the dynamical energy loss
- can include arbitrary *smooth* temperature evolutions
- no additional free parameters within the energy loss
- limitations: higher harmonics

event-by-event DREENA

D. Z, J. Auvinen, I. Salom, P. Huovinen and M. Djordjevic, Phys. Rev. C **106**, no.4, 044909 (2022)

- generalization of DREENA-A
- high- p_{\perp} energy loss on fluctuating hydro background
- different initial conditions and hydro models
- can produce high- p_{\perp} higher harmonics
- 1st question: averaging over events

- cummulants: $v_n\{2\}, v_n\{4\}$

A. Bilandzic, R. Snellings and S. Voloshin, Phys. Rev. C **83**, 044913 (2011)

- event plane: $v_n\{EP\}$

Y. He, W. Chen, T. Luo, S. Cao, L. G. Pang and X. N. Wang, Phys. Rev. C **106**, no.4, 044904 (2022)

- scalar product: $v_n\{SP\}$

C. Andres, N. Armesto, H. Niemi, R. Paatelainen and C. A. Salgado, Phys. Lett. B **803**, 135318 (2020)

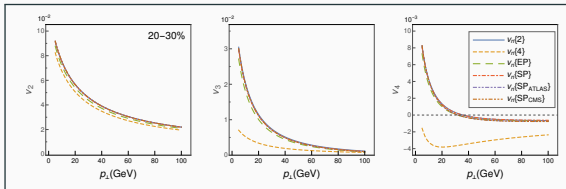
Y. He, W. Chen, T. Luo, S. Cao, L. G. Pang and X. N. Wang, Phys. Rev. C **106**, no.4, 044904 (2022)

- scalar product - ATLAS: $v_n\{SP_{ATLAS}\}$

M. Aaboud *et al.* [ATLAS], Eur. Phys. J. C **78**, no.12, 997 (2018)

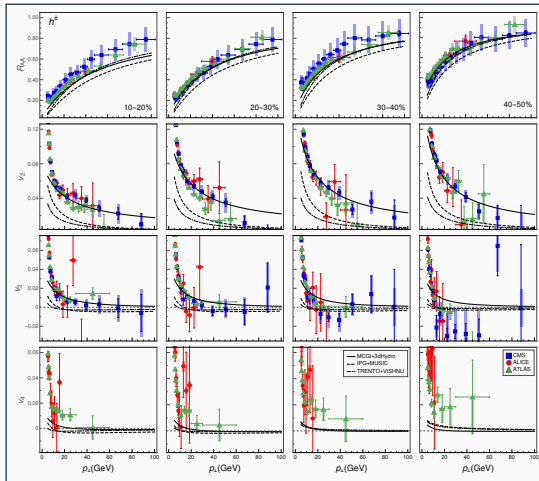
- scalar product - CMS: $v_n\{SP_{CMS}\}$

A. M. Sirunyan *et al.* [CMS], Phys. Lett. B **776**, 195-216 (2018)



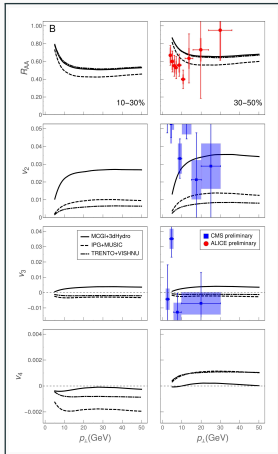
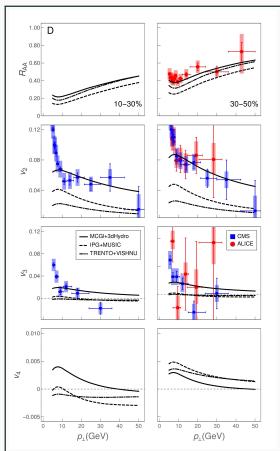
all methods, other than $v_n\{4\}$ agree with each other
no need for rapidity correlations!

- charged hadrons, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 TeV$



we can distinguish between different models with high- p_T energy loss

- heavy flavour, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 TeV$



we can distinguish between different models with high- p_T energy loss on heavy flavor as well - even more sensitive

- DREENA-A is a fully optimized numerical implementation of the dynamical energy loss formalism
- can include arbitrary temperature evolutions, both smooth and event-by-event fluctuating
- no additional fitting parameters within energy loss
- high- p_{\perp} R_{AA} , v_2 and higher harmonics show qualitative and quantitative sensitivity to details of temperature evolutions differences
- applicable to different types of flavor, collision systems and energies
- OUTLOOK: an efficient QGP tomography tool for constraining the medium properties by both high- and low- p_{\perp} data

QGP tomography

Bulk QGP properties are traditionally explored by low- p_{\perp} observables that describe the collective motion of 99.9% of QCD matter



However, some important bulk QGP properties are known to be difficult to constrain by low- p_{\perp} observables and the corresponding theory / simulations



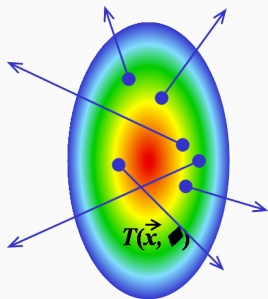
We advocate high- p_{\perp} QGP tomography, where low- and high- p_{\perp} physics jointly constrain bulk QGP parameters

Rare high energy probes are, on the other hand, almost exclusively used to understand high- p_{\perp} parton - medium interactions



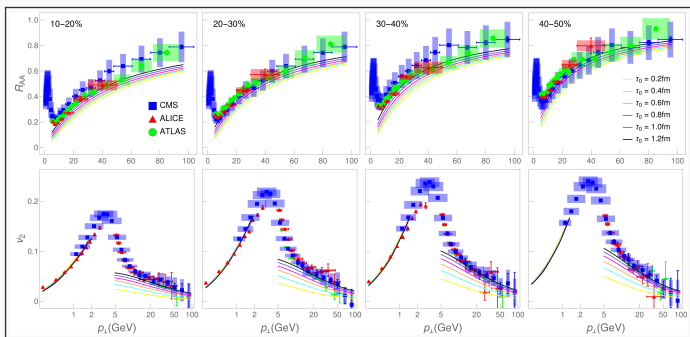
While high- p_{\perp} physics played a decisive role in QGP discovery, it has rarely been used to understand bulk QGP properties





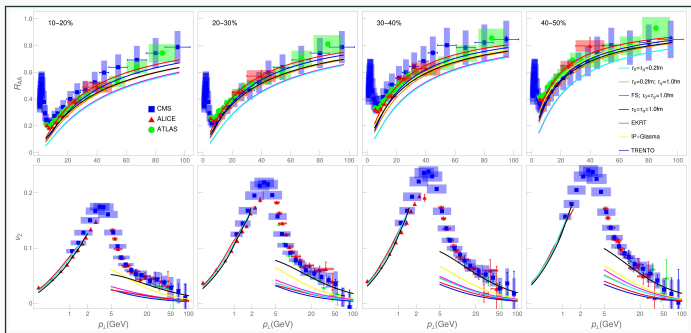
- high energy particles lose energy
- energy loss sensitive to QGP properties
- predict the energy loss of high p_{\perp} probes
- use high p_{\perp} probes to infer QGP properties:
 - QGP anisotropy
S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen and M. Djordjevic, Phys. Lett. B **835**, 137501 (2022)
 - η/s parameterization
B. Karmakar, D. Z, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic, arXiv:2305.11318 [hep-ph] (PRC in press)
talk by Magdalena Djordjevic, Monday 10:20
 - early evolution and initial stages
S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Phys. Rev. C **105**, no.2, L021901 (2022)
+ in preparation
- DREENA-A on github:
<https://github.com/DusanZigic/DREENA-A>

DREENA-A on a smooth hydro background
optical Glauber + 3dHydro
Pb+Pb, $\sqrt{s_{NN}}=5.02\text{TeV}$, h^\pm



lower $\tau_0 \rightarrow$ lower R_{AA} , higher $\tau_0 \rightarrow$ higher v_2

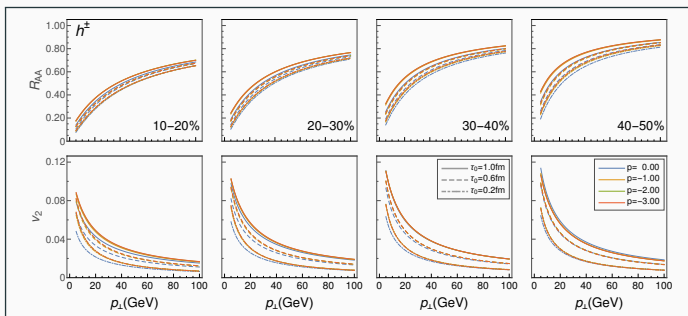
DREENA-A on a smooth hydro background
diff ic, w/ or w/o fs, diff hydro, postponed start of eloss
Pb+Pb, $\sqrt{s_{NN}}=5.02\text{TeV}$, h^\pm



high- p_\perp v_2 prefers later τ_0 regardless

Initial stages

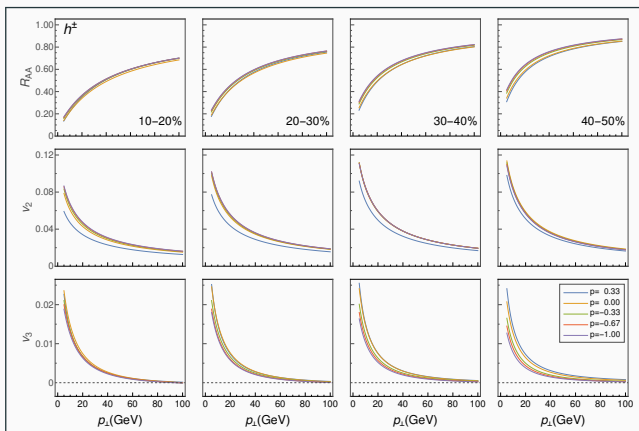
DREENA-A on a ebe fluctuating hydro background
TRENTO+VISHNU
Pb+Pb, $\sqrt{s_{NN}}=5.02\text{TeV}$, h^\pm



could not compensate earlier hydro onset with p

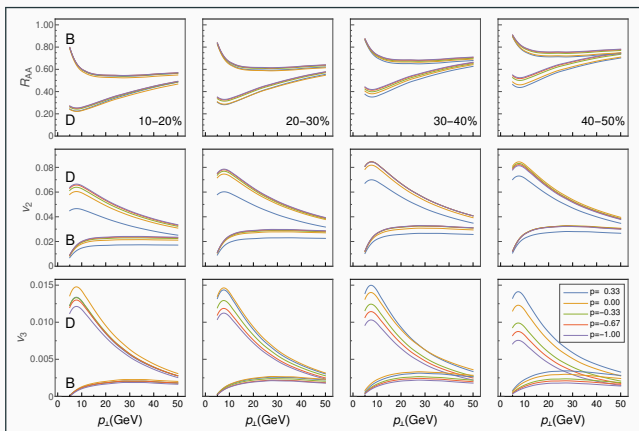
DREENA-A on a ebe TRENTO+VISHNU

Pb+Pb, $\sqrt{s_{NN}}=5.02\text{TeV}$, h^\pm



R_{AA} and v_3 higher, v_2 lower centralities

DREENA-A on a ebe TRENTO+VISHNU Pb+Pb, $\sqrt{s_{NN}}=5.02\text{TeV}$, D and B

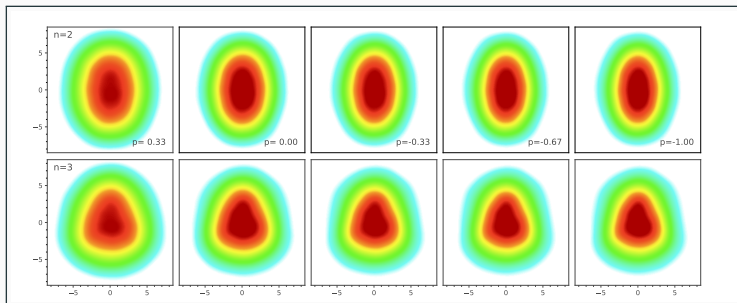


lower p higher v_2 but lower v_3

Initial stages

participant angle:

$$\Psi_n = \frac{1}{n} \arctan\left(\frac{\int dx dy r^m \sin(n\varphi) \epsilon(x,y,\tau_0)}{\int dx dy r^m \cos(n\varphi) \epsilon(x,y,\tau_0)}\right) + \frac{\pi}{n}$$



profiles are more elliptical when p decreases

triangular pattern more prominent when p increases

Summary

- different implementations of dynamical energy loss formalism:
 - DREENA-C, DREENA-B, DREENA-A, ebeDREENA
 - simplest can be used to investigate path-length dependence of energy loss and early evolution of QGP
- validation of DREENA-A and confirmation that it can differentiate between different backgrounds
- investigate different τ_0 on smooth hydro background
→ high- p_{\perp} prefers later onset of hydro
- ebe fluctuating hydro background TRENTO+VISHNU
tried to compensate smaller τ_0 with p
- fine-tune value of p and investigate impact on v_3
p impacts v_2 and v_3 in opposite ways → p=0
- different η/s parametrizations
- DREENA is a useful QGP tomography tool

Acknowledgements



European Research Council

Established by the European Commission

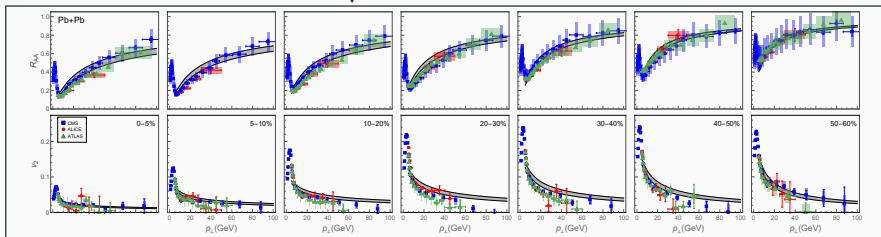


**МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА**

Thank you for your attention!

Backup slides

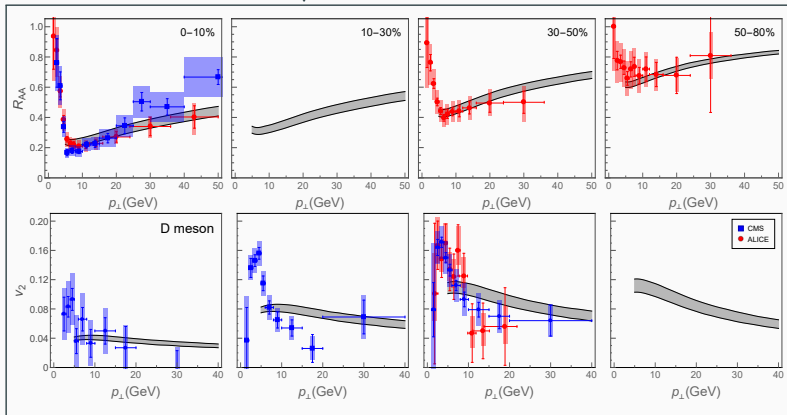
DREENA-C, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, h^\pm

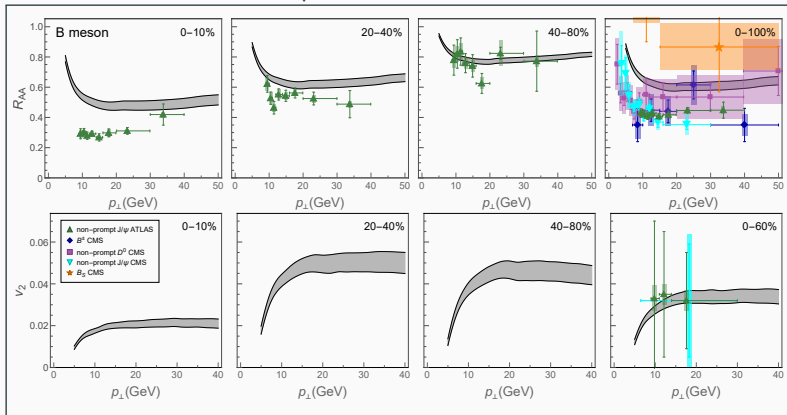


D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).

Backup slides

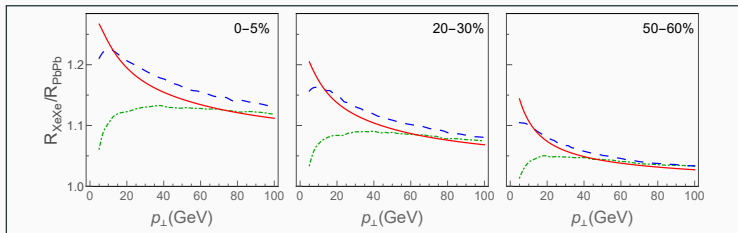
DREENA-C, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, D



DREENA-C, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, B 

Backup slides

- const T approximation is rough, however it can be used to determine path-length dependence of energy loss model
- 5.02TeV Pb+Pb and 5.44TeV Xe+Xe - main property differentiating two systems is their size
- R_{AA} ratio seem a natural choice:



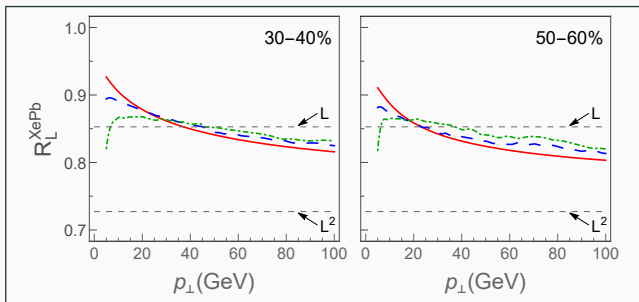
strong centrality dependency

$$\frac{\Delta E}{E} \sim T^a L^b \Rightarrow \frac{R_{XeXe}}{R_{PbPb}} \approx 1 - \xi T^a L_{Pb}^b \left(1 - \left(\frac{A_{Xe}}{A_{Pb}} \right)^{b/3} \right)$$

Backup slides

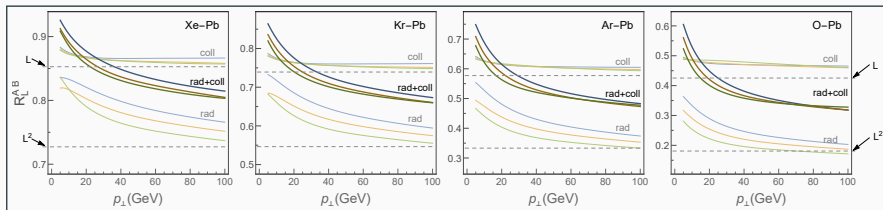
- $1 - R_{AA}$ ratio instead - path-length sensitive suppression ratio:

$$R_L^{XePb} \equiv \frac{1 - R_{XeXe}}{1 - R_{PbPb}} \approx \frac{\xi T^a L_{Xe}^b}{\xi T^a L_{Pb}^b} \approx \left(\frac{A_{Xe}}{A_{Pb}} \right)^{b/3}$$



the path length dependence can be extracted in a simple way, and there is only a weak centrality dependence

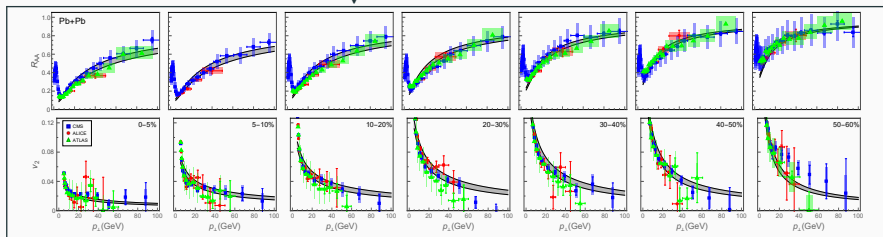
what about smaller systems?



- R_L^{AB} is almost independent on centrality for 30-60% region
- for all systems, R_L^{AB} shows same behaviour
- reliably recovers collisional and radiative energy loss path-length dependence

Backup slides

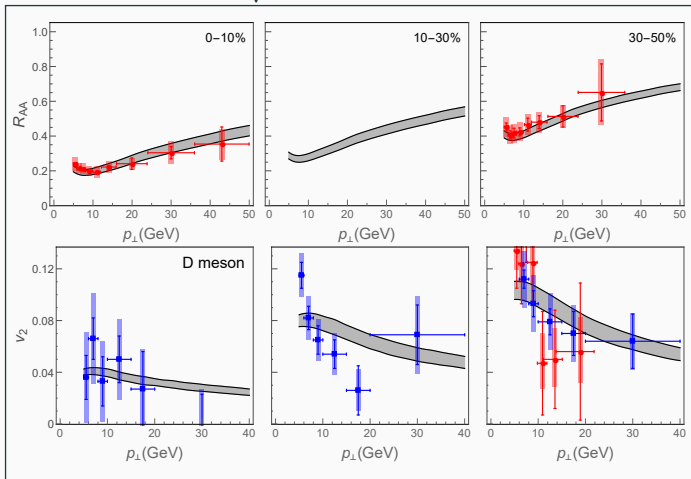
DREENA-B, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, h^\pm



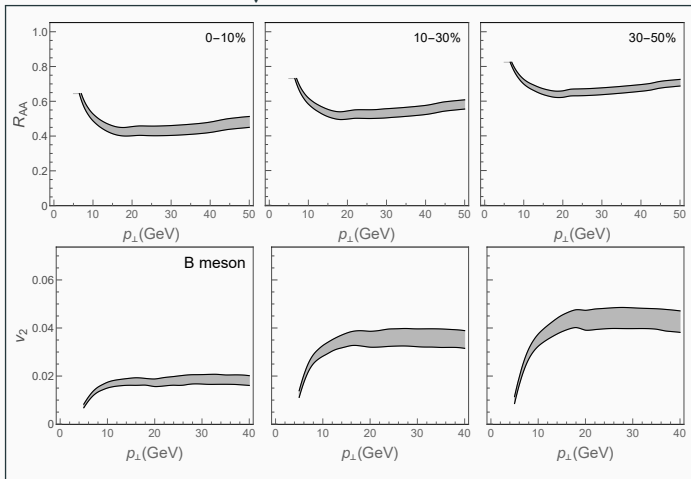
D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).

Backup slides

DREENA-B, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, D

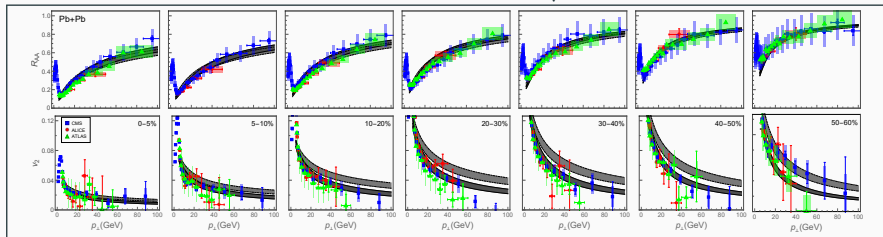


DREENA-B, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, B



Backup slides

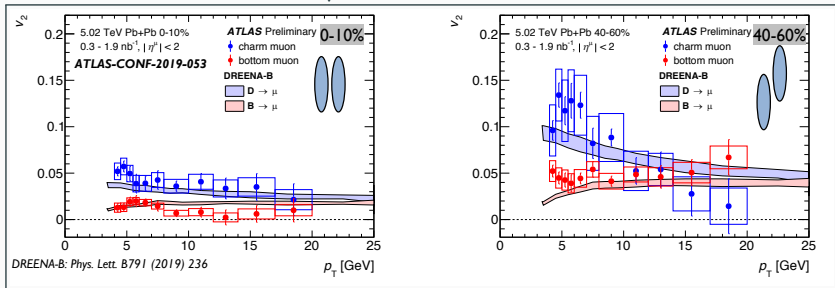
DREENA-B vs DREENA-C, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, h^\pm



D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).

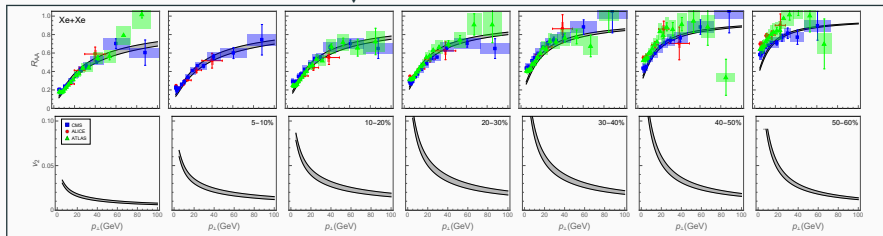
DREENA-B, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, μ



D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).

Backup slides

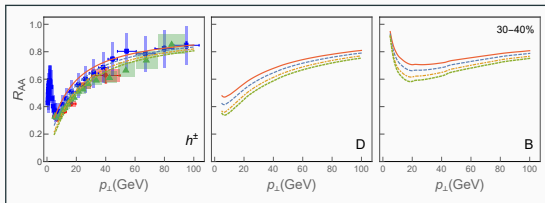
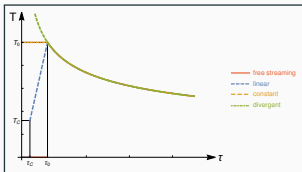
DREENA-B, $Xe + Xe$, $\sqrt{s_{NN}} = 5.44 \text{ TeV}$, h^\pm



D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).

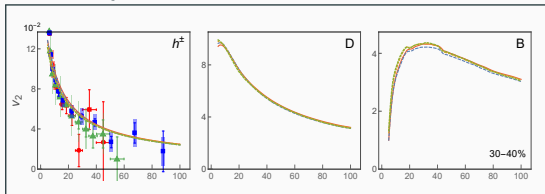
Backup slides

- previous results: interaction turned off for $\tau < \tau_0 = 0.6 \text{ fm}$
- investigate different T dependencies for $\tau (< \tau_0)$:



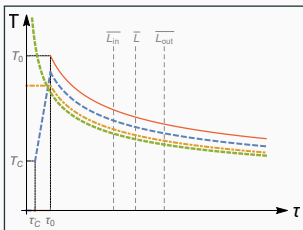
R_{AA} is notably affected
by IS

v_2 is practically not
affected by IS

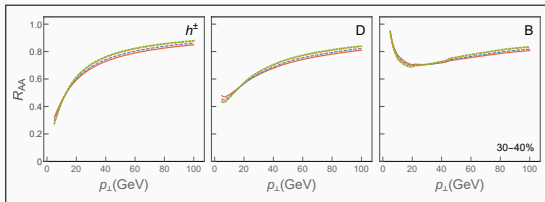


Backup slides

- fitting temperature evolution to R_{AA} :

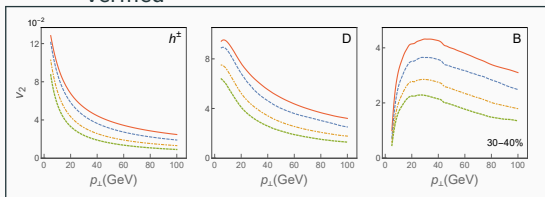


modified T -profile cases differ not only at IS, but represent different evolutions altogether

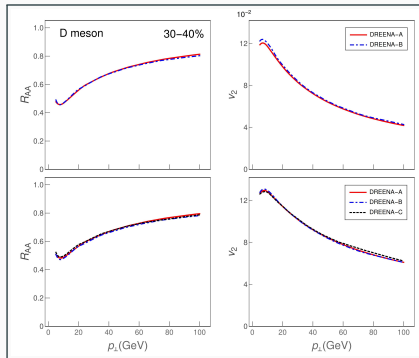
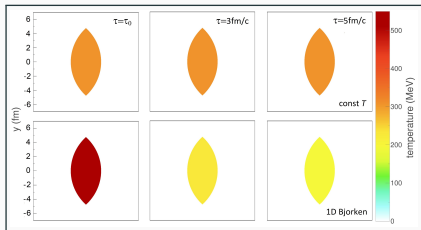


R_{AA} curves overlap is verified

v_2 is very sensitive to different evolutions



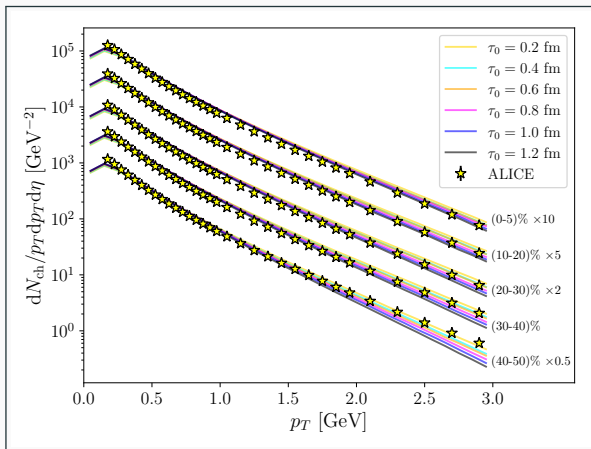
DREENA-A limits



Backup slides

p_{\perp} spectra for different thermalization time, τ_0

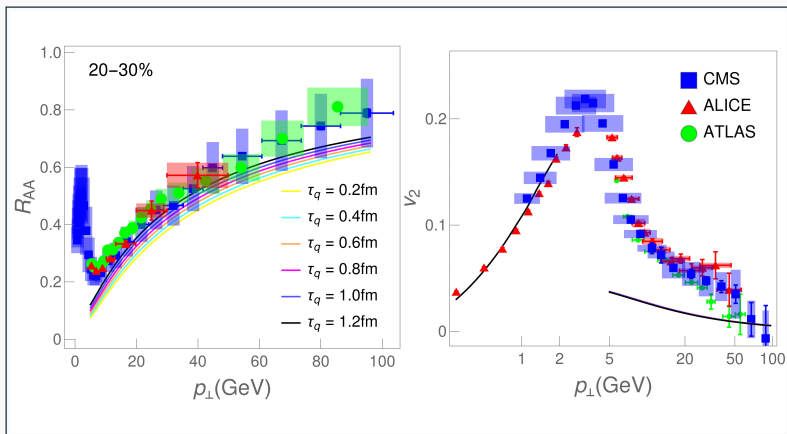
Pb+Pb, $\sqrt{s_{NN}}=5.02$ TeV



Backup slides

$\tau_0=0.2\text{fm}$, postponed energy loss, τ_q

Pb+Pb, $\sqrt{s_{NN}}=5.02\text{TeV}$



the averaging methods:

$$Q_n = \frac{1}{M} \sum_{j=1}^M e^{in\phi_j} \equiv |v_n| e^{in\Psi_n}$$

$$R_{AA}(p_{\perp}) = \frac{1}{2\pi} \int_0^{2\pi} R_{AA}(p_{\perp}, \phi) d\phi$$

$$q_n^{\text{hard}} = \frac{\frac{1}{2\pi} \int_0^{2\pi} e^{in\phi} R_{AA}(p_{\perp}, \phi) d\phi}{R_{AA}(p_{\perp})}$$

$$v_n^{\text{hard}} = \frac{\frac{1}{2\pi} \int_0^{2\pi} \cos[n(\phi - \Psi_n^{\text{hard}}(p_{\perp}))] R_{AA}(p_{\perp}, \phi) d\phi}{R_{AA}(p_{\perp})}$$

$$\Psi_n^{\text{hard}}(p_{\perp}) = \frac{1}{n} \arctan \left(\frac{\int_0^{2\pi} \sin(n\phi) R_{AA}(p_{\perp}, \phi) d\phi}{\int_0^{2\pi} \cos(n\phi) R_{AA}(p_{\perp}, \phi) d\phi} \right)$$

ebe averaging methods:

$$v_n^{\text{hard}}\{\text{SP}\} = \frac{\langle \text{Re}(q_n^{\text{hard}}(Q_n)^*) \rangle_{\text{ev}}}{\sqrt{\langle Q_n(Q_n)^* \rangle_{\text{ev}}}} = \frac{\langle |v_n^{\text{hard}}| |v_n| \cos[n(\Psi_n^{\text{hard}}(p_\perp) - \Psi_n)] \rangle_{\text{ev}}}{\sqrt{\langle |v_n|^2 \rangle_{\text{ev}}}}$$

$$v_n\{\text{EP}\} = \langle \langle \cos[n(\phi^{\text{hard}} - \Psi_n)] \rangle \rangle_{\text{ev}} = \langle v_n^{\text{hard}} \cos[n(\Psi_n^{\text{hard}} - \Psi_n)] \rangle_{\text{ev}}$$

$$v_n\{\text{SP}_{\text{ATLAS}}\} = \frac{\text{Re} \langle \langle e^{in\phi} (Q_n^{-|+})^* \rangle \rangle_{\text{ev}}}{\sqrt{\langle Q_n^- (Q_n^+)^* \rangle_{\text{ev}}}}$$

$$v_n\{\text{SP}_{\text{CMS}}\} = \frac{\text{Re} \langle Q_n Q_{nA}^* \rangle_{\text{ev}}}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle_{\text{ev}} \langle Q_{nA} Q_{nC}^* \rangle_{\text{ev}}}{\langle Q_{nB} Q_{nC}^* \rangle_{\text{ev}}}}}$$

the averaging methods:

- low- p_{\perp}

$$\tilde{Q}_n = \sum_{j=1}^M e^{in\phi_j}$$

$$v_n\{2\} = \sqrt{c_n\{2\}}, c_n\{2\} = \langle\langle 2 \rangle\rangle_{\text{ev}}, \langle 2 \rangle = \frac{|\tilde{Q}_n|^2 - M}{W_2}, W_2 = M(M-1)$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}, c_n\{4\} = \langle\langle 4 \rangle\rangle_{\text{ev}} - 2\langle\langle 2 \rangle\rangle_{\text{ev}}^2$$

$$\langle 4 \rangle = \frac{|\tilde{Q}_n|^4 + |\tilde{Q}_{2n}|^2 - 2\text{Re}|\tilde{Q}_{2n}\tilde{Q}_n^*\tilde{Q}_n^*|}{W_4} - 2\frac{2(M-2)|\tilde{Q}_n|^2 - M(M-3)}{W_4}$$

$$W_4 = M(M-1)(M-2)(M-3)$$

the averaging methods:

- high- p_{\perp}

$$q_n = \int_0^{2\pi} e^{in\phi} \frac{dN}{dp_{\perp} d\phi} d\phi, m_q = \int_0^{2\pi} \frac{dN}{dp_{\perp} d\phi} d\phi$$

$$W'_2 = m_q M, W'_4 = m_q M(M-1)(M-2)$$

$$\langle 2' \rangle = \frac{q_n \tilde{Q}_n^*}{W'_2}, \langle 4' \rangle = \frac{q_n \tilde{Q}_n \tilde{Q}_n^* \tilde{Q}_n^* - q_n \tilde{Q}_n \tilde{Q}_{2n}^* - 2Mq_n \tilde{Q}_n^* + 2q_n \tilde{Q}_n^*}{W'_4}$$

$$d_n\{2\} = \langle\langle 2' \rangle\rangle_{\text{ev}}, d_n\{4\} = \langle\langle 4' \rangle\rangle_{\text{ev}} - 2\langle\langle 2' \rangle\rangle_{\text{ev}} \langle\langle 2 \rangle\rangle_{\text{ev}}$$

$$v'_n\{2\} = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}, v'_n\{4\} = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}.$$

Backup slides

energy loss:

$$\frac{dE_{col}}{d\tau} = \frac{2C_R}{\pi v^2} \alpha_S(E T) \alpha_S(\mu_E^2(T)) \times$$

$$\int_0^\infty n_{eq}(|\vec{k}|, T) d|\vec{k}| \left(\int_0^{|\vec{k}|/(1+v)} d|\vec{q}| \int_{-v|\vec{q}|}^{v|\vec{q}|} \omega d\omega + \int_{|\vec{k}|/(1+v)}^{|\vec{q}|_{max}} d|\vec{q}| \int_{|\vec{q}|-2|\vec{k}|}^{v|\vec{q}|} \omega d\omega \right) \times$$

$$\left(|\Delta_L(q, T)|^2 \frac{(2|\vec{k}| + \omega)^2 - |\vec{q}|^2}{2} + |\Delta_T(q, T)|^2 \frac{(|\vec{q}|^2 - \omega^2)((2|\vec{k}| + \omega)^2 + |\vec{q}|^2)}{4|\vec{q}|^4} (v^2|\vec{q}|^2 - \omega^2) \right)$$

$$\frac{d^2 N_{rad}}{dx d\tau} = \int \frac{d^2 k}{\pi} \frac{d^2 q}{\pi} \frac{2 C_R C_2(G) T}{x} \frac{\mu_E(T)^2 - \mu_M(T)^2}{(q^2 + \mu_M(T)^2)(q^2 + \mu_E(T)^2)} \frac{\alpha_S(E T) \alpha_S(\frac{\mathbf{k}^2 + \chi(T)}{x})}{\pi}$$

$$\times \frac{(\mathbf{k} + \mathbf{q})}{(\mathbf{k} + \mathbf{q})^2 + \chi(T)} \left(1 - \cos \left(\frac{(\mathbf{k} + \mathbf{q})^2 + \chi(T)}{xE^+} \tau \right) \right) \left(\frac{(\mathbf{k} + \mathbf{q})}{(\mathbf{k} + \mathbf{q})^2 + \chi(T)} - \frac{\mathbf{k}}{\mathbf{k}^2 + \chi(T)} \right)$$