Value of event-by-event fluctuations and v4 puzzle for QGP tomography

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

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

DREENA framework

- **D**ynamical **R**adiative and **E**lastic **EN**ergy loss **A**pproach

- 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 temperature 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, arXiv:2110.01544 [nucl-th].
  - ebe-DREENA: event-by-event fluctuating hydro background
    D. Z, J. Auvinen, I. Salom, P. Huovinen and M. Djordjevic, in preparation

DREENA-C & DREENA-B

- DREENA-C = constant temperature medium

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

  - qualitatively good agreement with the data
  - rough approximation - good for testing path-length dependence of energy loss

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

DREENA-C & DREENA-B

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

  - qualitatively good agreement with the data
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    M. Djordjevic, D. Z, M. Djordjevic and J. Auvinen, Phys. Rev. C **99**, no.6, 061902 (2019)

- DREENA-B = 1D Bjorken evolution

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

  - qualitatively and quantitatively good agreement with the data - only thermalization time as QGP property
  - good for testing initial stages without impacting anything else

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

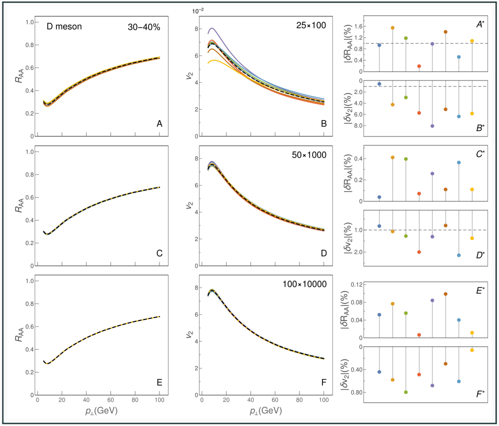
DREENA-A

A = adaptive

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, arXiv:2110.01544 [nucl-th].

- C & B good test for energy loss but no bulk medium properties to extract
- 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

Monte Carlo sampling



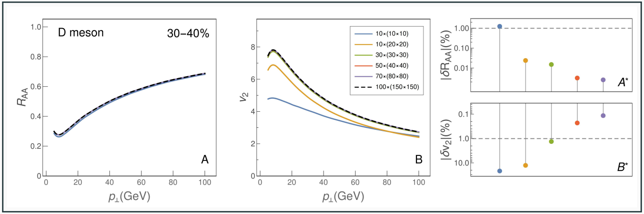
not very efficient

for v_2 , one million trajectories needed to achieve a precision below 1%

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, arXiv:2110.01544 [nucl-th].

DREENA-A

equidistant sampling



two orders of magnitude increase in the efficiency

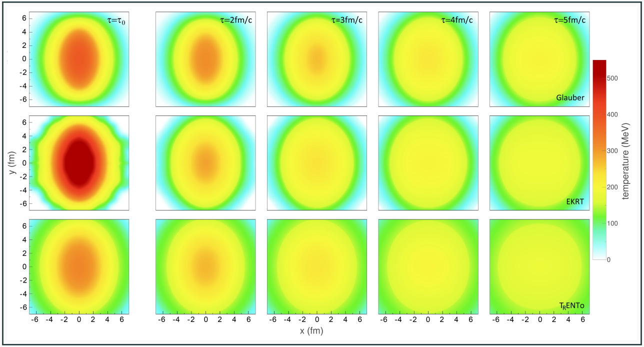
for v_2 , only 10k trajectories needed to achieve $\sim$1% precision

can efficiently generate predictions for all types of probes for arbitrary temperature profiles

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, arXiv:2110.01544 [nucl-th].

DREENA-A

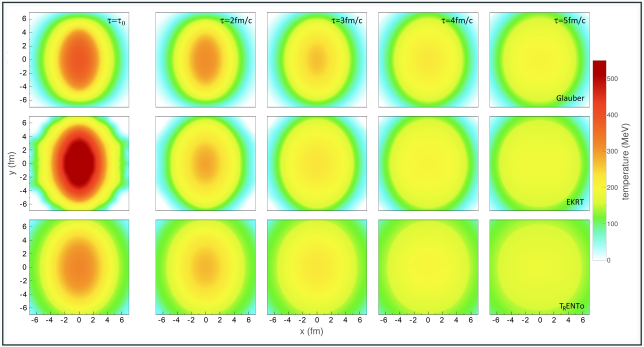
Are high-$p_\perp$ observables indeed sensitive to different T evolutions?



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

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, arXiv:2110.01544 [nucl-th].

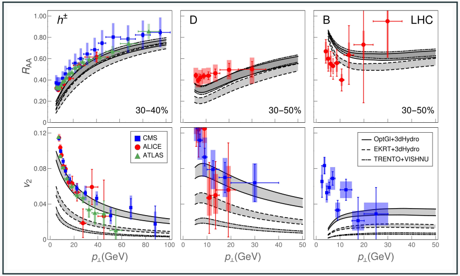
Qualitative differences

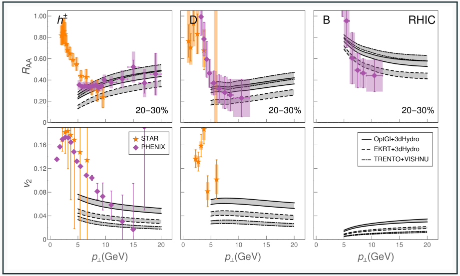


- Largest anisotropy for Glauber ($\tau_0 = 1fm$) – expected differences in high-$p_\perp$ v_2
- EKRT shows larger temperature - smaller R_{AA} expected

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, arXiv:2110.01544 [nucl-th].

DREENA-A





- 'EKRT' initial conditions indeed lead to the smallest R_{AA}
- anisotropy translates to v_2 differences ('Glauber' largest, T$_{\mathrm{R}}$ENTo 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

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, arXiv:2110.01544 [nucl-th].

DREENA-A OUTLOOK

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

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, arXiv:2110.01544 [nucl-th].

event-by-event DREENA

- 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

ebeDREENA

- 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, [arXiv:2201.08408 [hep-ph]].

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

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

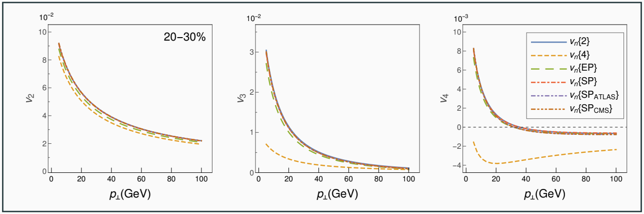
  Y. He, W. Chen, T. Luo, S. Cao, L. G. Pang and X. N. Wang, [arXiv:2201.08408 [hep-ph]]

- 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)

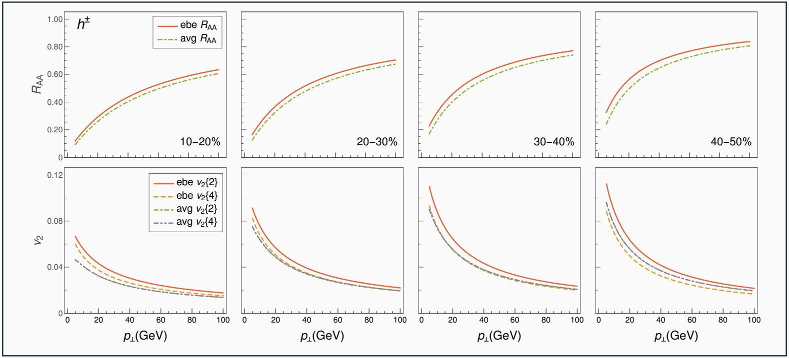


all methods, other than $v_n\{4\}$ agree with each other

no need for rapidity correlations!

ebeDREENA

- high-p_T energy loss: ebe fluctuation vs smooth hydro background

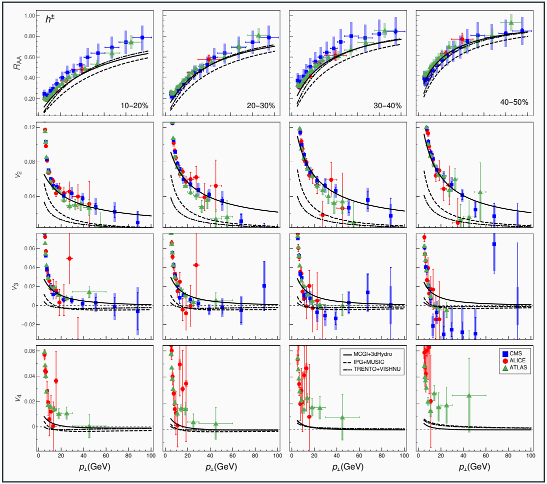


R_{AA} differences small $\sim 7\%$ and no centrality dependence

$v_2\{2\}$ differences from 14% in 40-50% up to 32% in 10-20%
also $p_\perp$ dependence of the differences

ebeDREENA

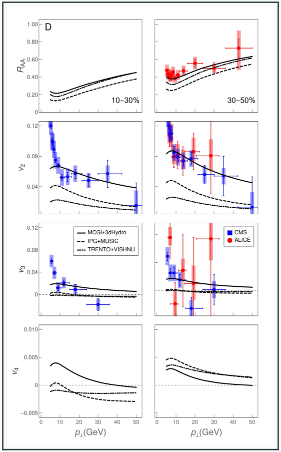
- charged hadrons, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02\,TeV$

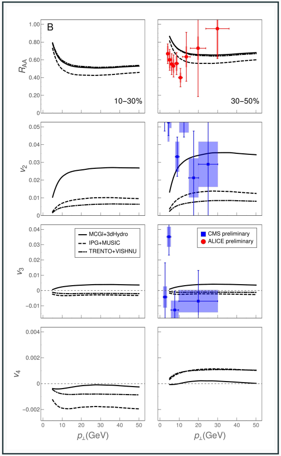


we can distinguish between different models with high-p_T energy loss

ebeDREENA

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



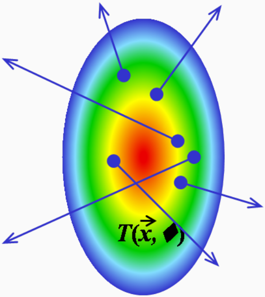


we can distinguish between different models with high-p_T energy loss on heavy flavour as well - even more sensitive

ebeDREENA

- DREENA-A is a fully optimized numerical implementation of the dynamical energy loss formalism
- can include arbitrary temperature profiles, 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 T profile 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 GPQ properties traditionally explored by low-$p_\perp$ observables
- 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:
  - early evolution
    S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Phys. Rev. C **105**, no.2, L021901 (2022)
  - jet anisotropy
    S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen and M. Djordjevic, [arXiv:2110.02029 [nucl-th]]
- DREENA-A on github:
  https://github.com/DusanZigic/DREENA-A

Acknowledgements

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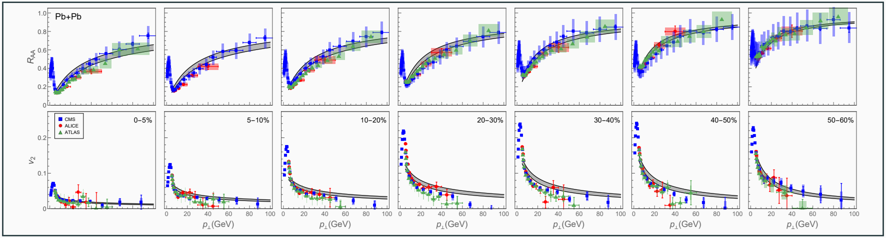
МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

Thank you for your attention!

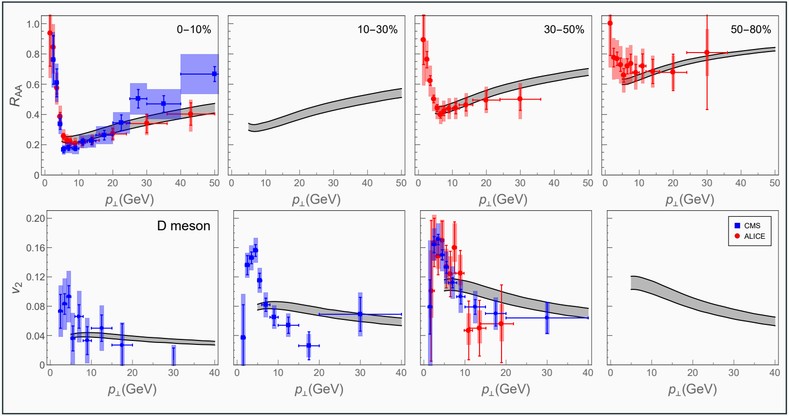
Backup slides

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



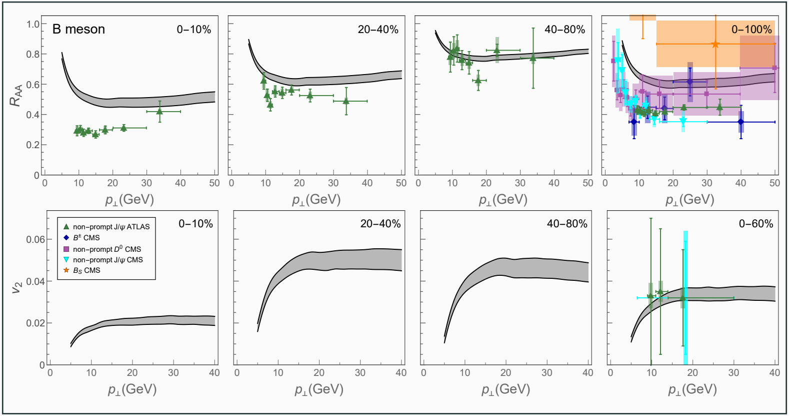
Backup slides

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



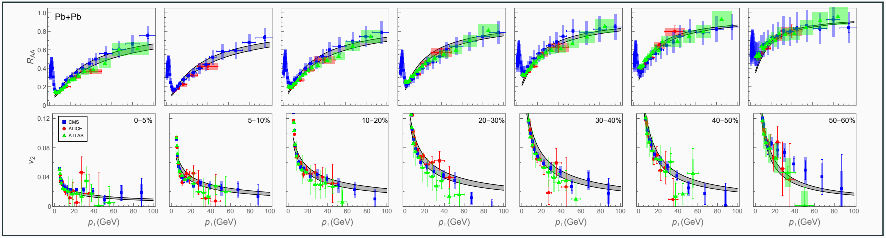
Backup slides

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



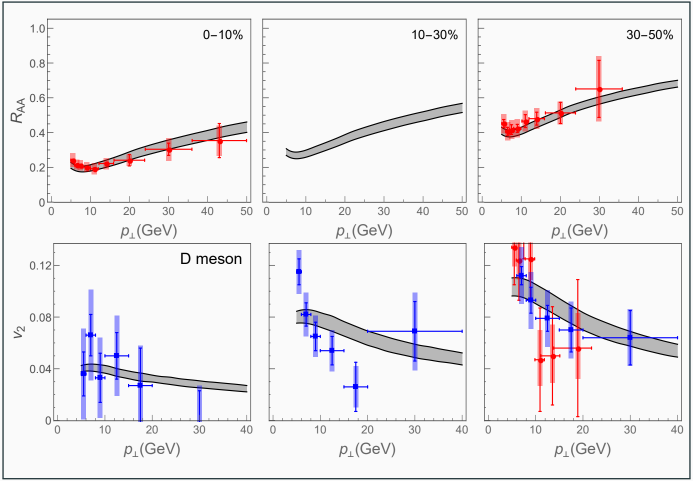
Backup slides

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



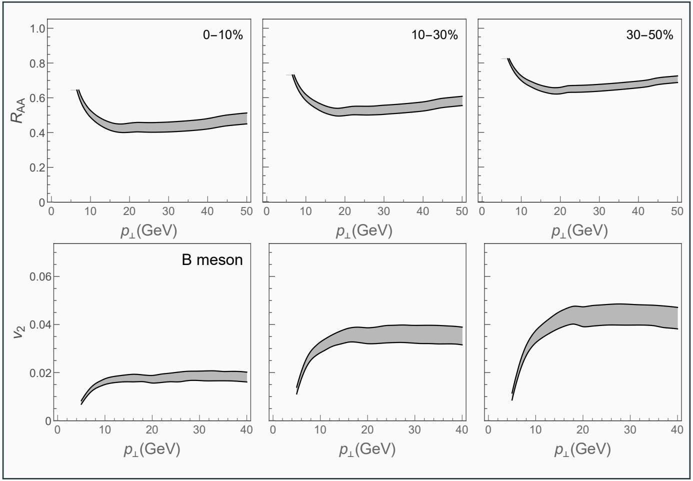
Backup slides

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



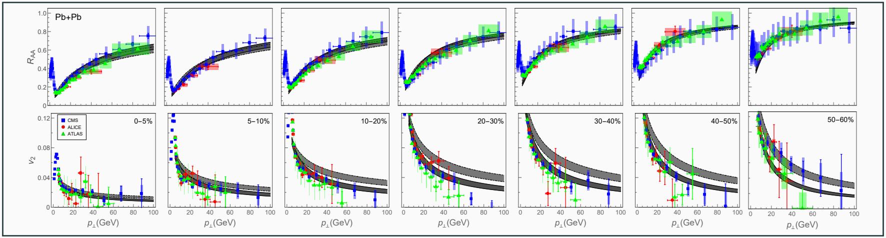
Backup slides

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



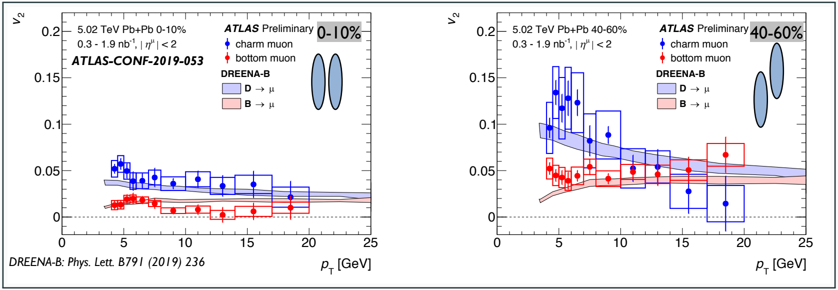
Backup slides

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



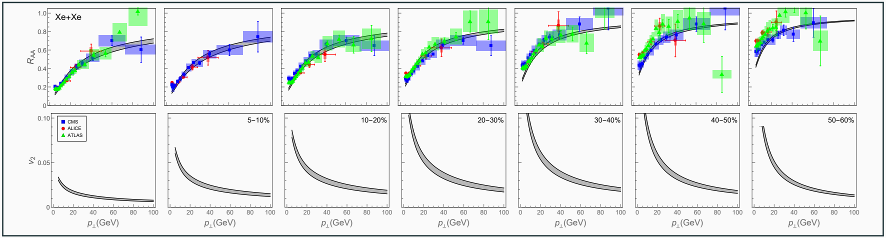
Backup slides

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

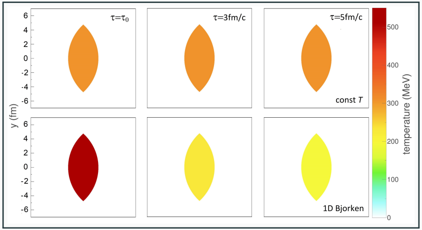


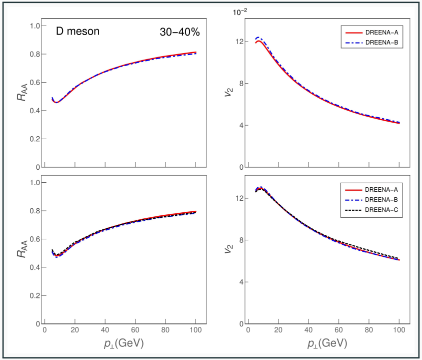
Backup slides

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



DREENA-A limits





ebe averaging methods:

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

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

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

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

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

Backup slides

ebe averaging methods:

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

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

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

$$v_n\{\mathrm{SP_{CMS}}\} = \frac{\mathrm{Re}\,\langle Q_n Q_{nA}^*\rangle_{\mathrm{ev}}}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^*\rangle_{\mathrm{ev}}\langle Q_{nA} Q_{nC}^*\rangle_{\mathrm{ev}}}{\langle Q_{nB} Q_{nC}^*\rangle_{\mathrm{ev}}}}}$$

Backup slides

ebe averaging methods:

- low-$p_\perp$

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

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

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

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

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

Backup slides

ebe averaging methods:

- high-$p_\perp$

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

$$W_2' = m_q M, W_4' = m_q M(M-1)(M-2)$$

$$\langle 2' \rangle = \frac{q_n \tilde{Q}_n^*}{W_2'}, \langle 4' \rangle = \frac{q_n \tilde{Q}_n \tilde{Q}_n^* \tilde{Q}_n^* - q_n \tilde{Q}_n \tilde{Q}_{2n}^* - 2M q_n \tilde{Q}_n^* + 2 q_n \tilde{Q}_n^*}{W_4'}$$

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

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

Backup slides

energy loss:

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

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

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

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

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