DREENA: A State-of-the-Art Tomography Framework for Unveiling the Properties of Quark-Gluon Plasma

Dusan Zigic

in collaboration with: Magdalena Djordjevic, Bithika Karmakar, 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

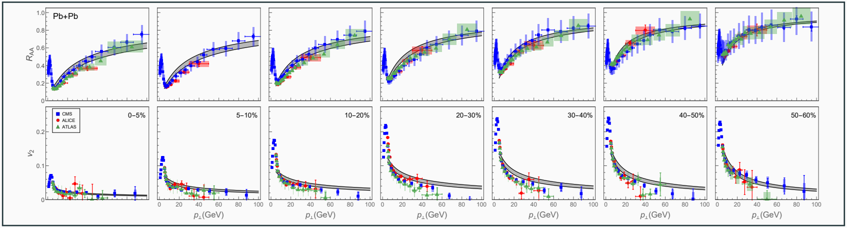
- fully optimized numerical procedure capable of generating high $p_\perp$ predictions
- includes:
  - parton production
  - multi gluon-fluctuations
  - path-length fluctutations
  - fragmentation functions
- keeping all elements of the state-of-the art energy loss formalism, while introducing more 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, 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)

DREENA-C

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).

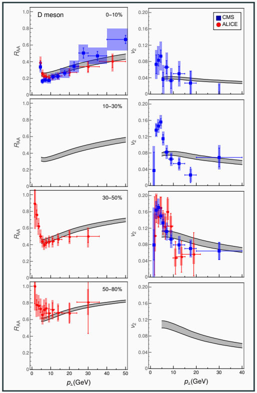


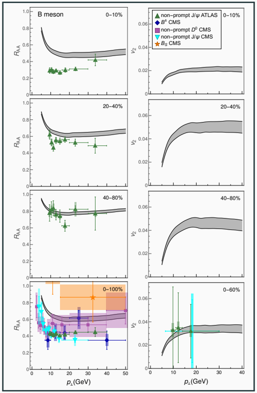
for charged hadrons, qualitatively good agreement, but overestimation of v_2 data

only average temperature as QGP property

DREENA-C

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





solid agreement w/ data, large error bars

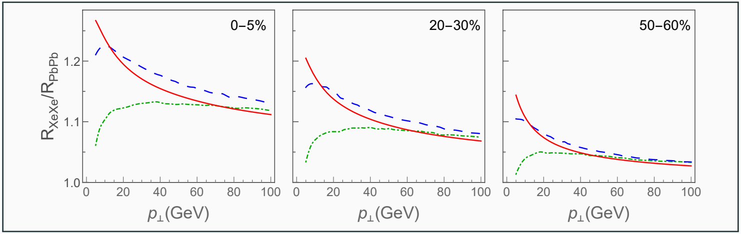
non-zero v_2 for B mesons

only average temperature as QGP property

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

DREENA-C

- 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

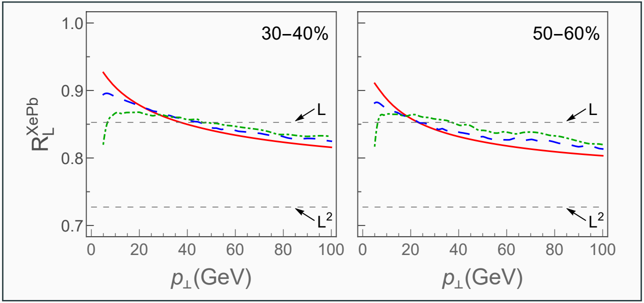
$$\frac{\Delta E}{E} \sim T^a L^b \Rightarrow \frac{R_{XeXe}}{R_{PbPb}} \approx 1 - \xi T^a L_{Pb}^b \left(1 - \left(\frac{A_{Xe}}{A_{Pb}}\right)^{b/3}\right)$$

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

DREENA-C

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

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

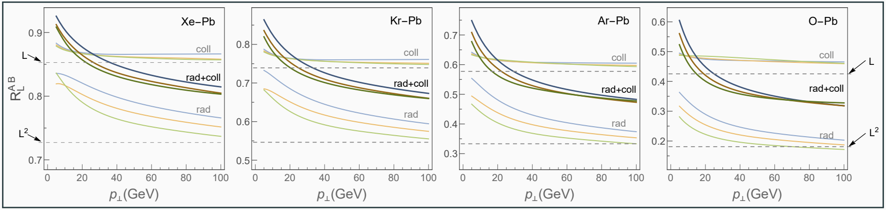


the path length dependence can be extracted in a simple way, and there is only a weak centrality dependence

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

DREENA-C

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

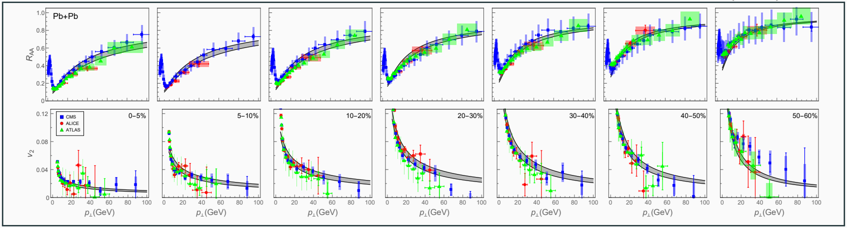
M. Djordjevic, D. Z, M. Djordjevic and J. Auvinen, Phys. Rev. C **99**, no.6, 061902 (2019)

DREENA-B

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).

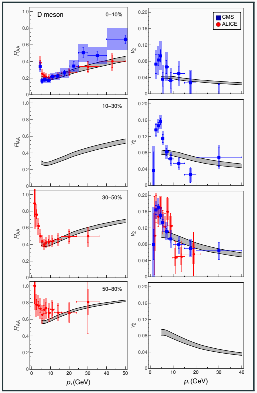


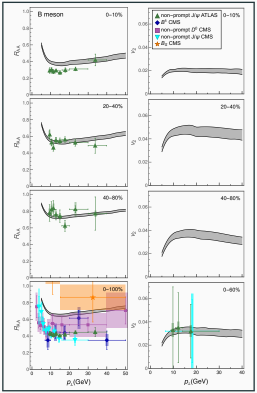
very good joint agreement with both R_{AA} and v_2 data

only average temperature and thermalization time as QGP properties

DREENA-B

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





solid agreement w/ data

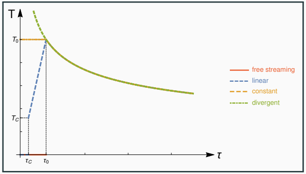
non-zero v_2 for B mesons

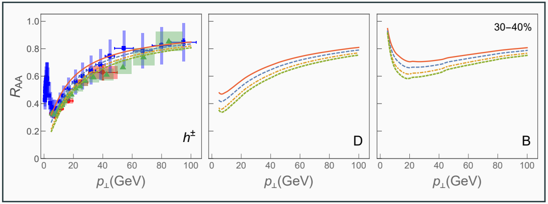
only average temperature and τ_0 as QGP properties

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

DREENA-B

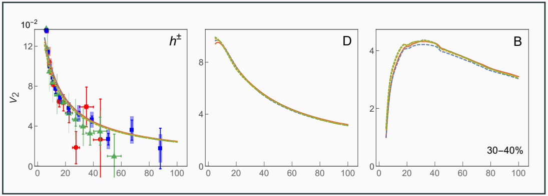
- previous results: interaction turned off for $\tau < \tau_0 = 0.6fm$
- investigate different T dependencies for τ $(< \tau_0)$:





R_{AA} is notably affected by IS

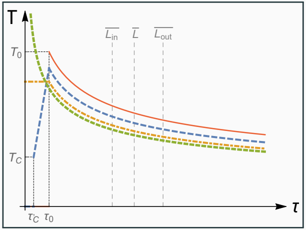
v_2 is practically not affected by IS



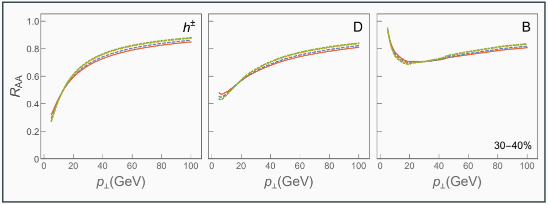
D. Z, B. Ilic, M. Djordjevic and M. Djordjevic, Phys. Rev. C **101**, no.6, 064909 (2020)

DREENA-B

- fitting temperature evolution to R_{AA}:

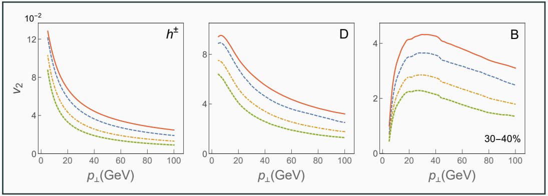


modified T -profile cases differ not only at IS, but represent different evolutions altogether



R_{AA} curves overlap is verified

v_2 is very sensitive to different evolutions



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

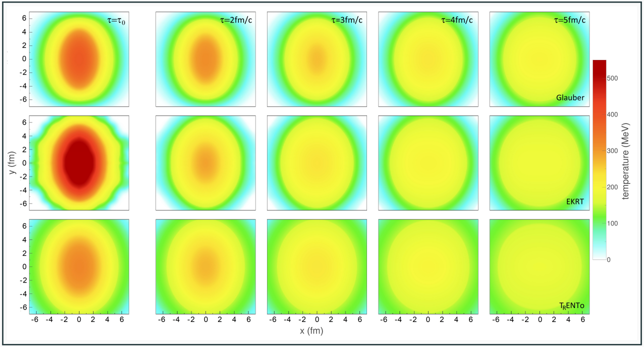
DREENA-A

A = adaptive

D. Z, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, 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

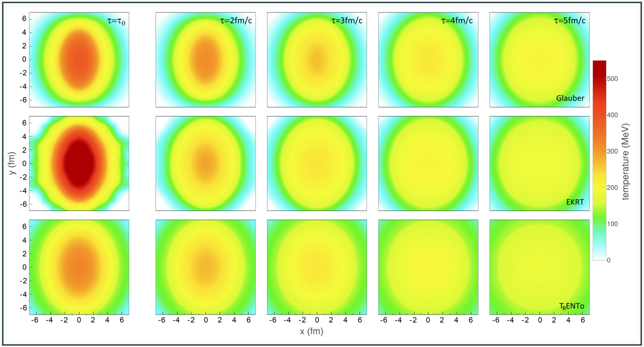
Are high-$p_\perp$ observables indeed sensitive to different T evolutions?



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

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

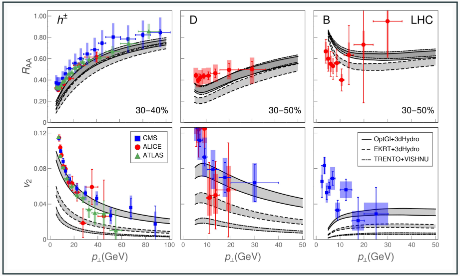
Qualitative differences

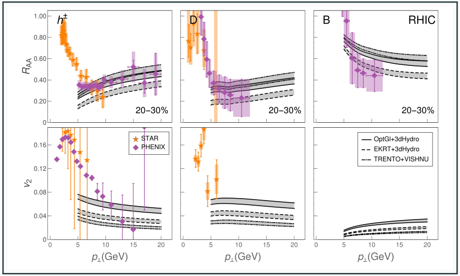


- Largest anisotropy for Glauber ($\tau_0 = 1fm$) – expected differences in high-$p_\perp$ v_2
- EKRT shows larger temperature - smaller R_{AA} expected

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

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, Front. in Phys. **10**, 957019 (2022).

DREENA-A OUTLOOK

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

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

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

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, 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)

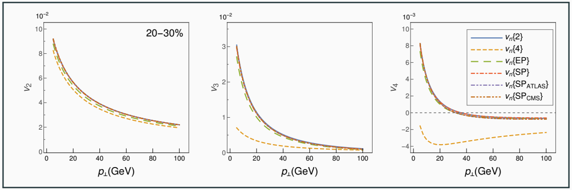
  Y. He, W. Chen, T. Luo, S. Cao, L. G. Pang and X. N. Wang, Phys. Rev. C **106**, no.4, 044904 (2022)

- 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)



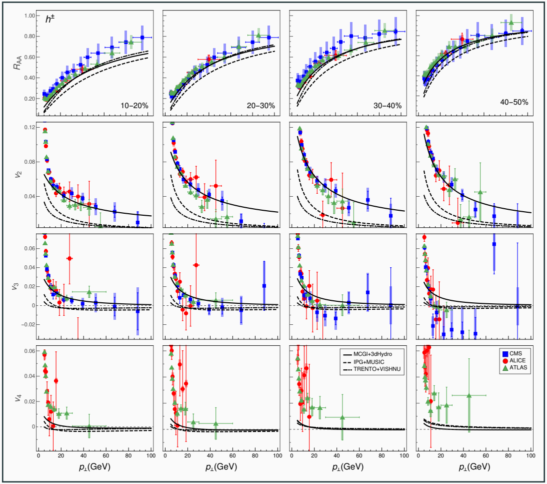
all methods, other than $v_n\{4\}$ agree with each other

no need for rapidity correlations!

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

ebeDREENA

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

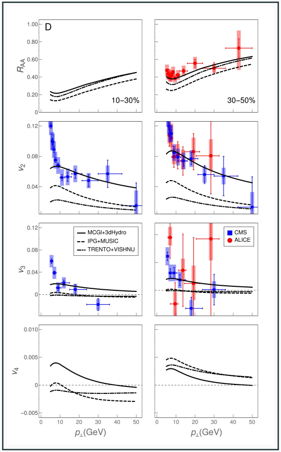


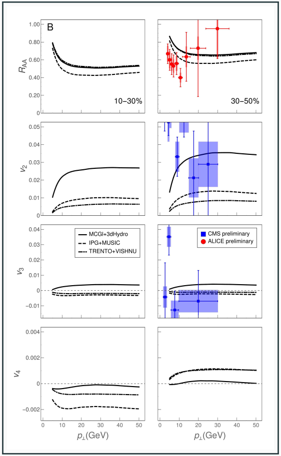
we can distinguish between different models with high-p_T energy loss

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

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

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

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

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

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 corresponding theory/simulations

⬊

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

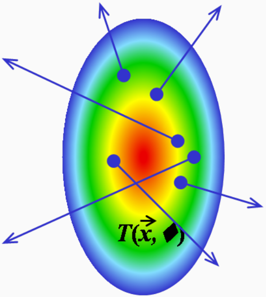
⬇

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

⬋

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

QGP tomography



- 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)
    talk by Magdalena Djordjevic, Wednesday 10:15
  - QGP anosotropy
    S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen and M. Djordjevic, Phys. Lett. B **835**, 137501 (2022)
    talk by Stefan Stojku, Tuesday 10:00
  - η/s parameterization
    B. Karmakar, D. Z, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic, [arXiv:2305.11318 [hep-ph]]
    talk by Bithika Karmakar, Wednesday 14:50
- DREENA-A on github: https://github.com/DusanZigic/DREENA-A

Acknowledgements

European Research Council

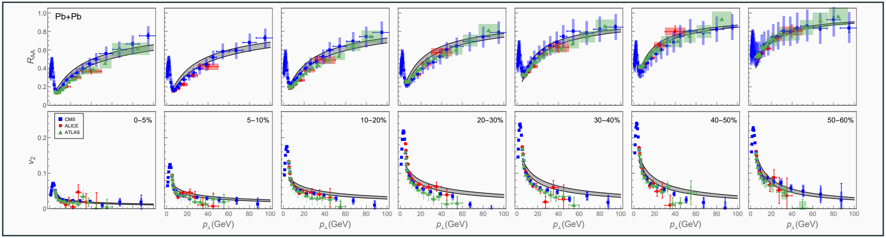
Established by the European Commission

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

Thank you for your attention!

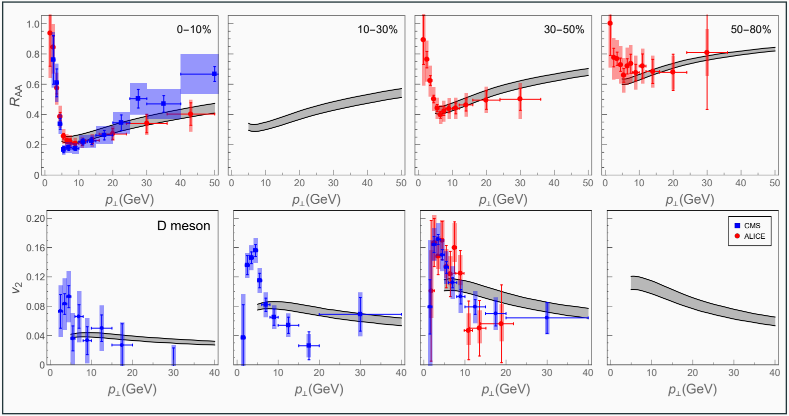
Backup slides

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



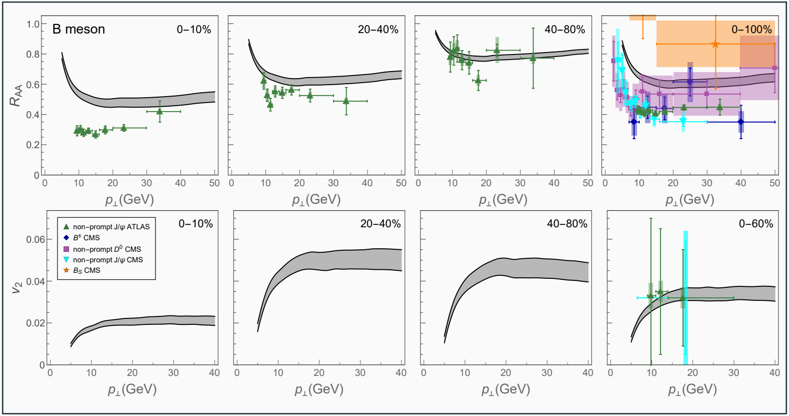
Backup slides

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



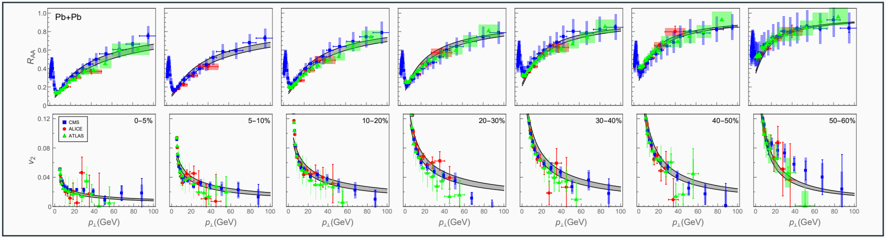
Backup slides

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

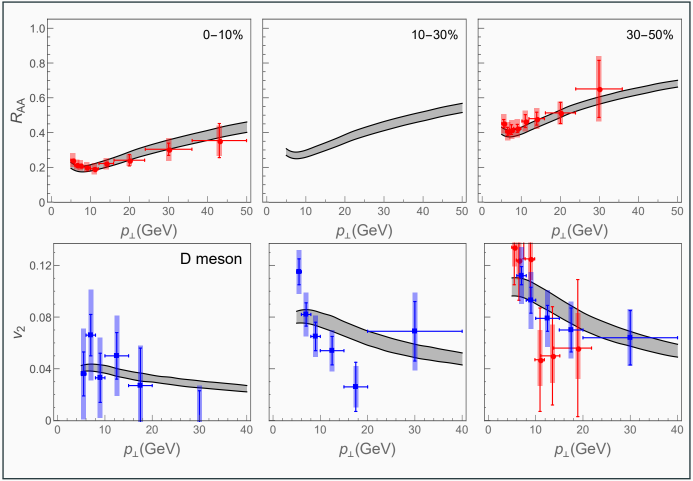


Backup slides

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

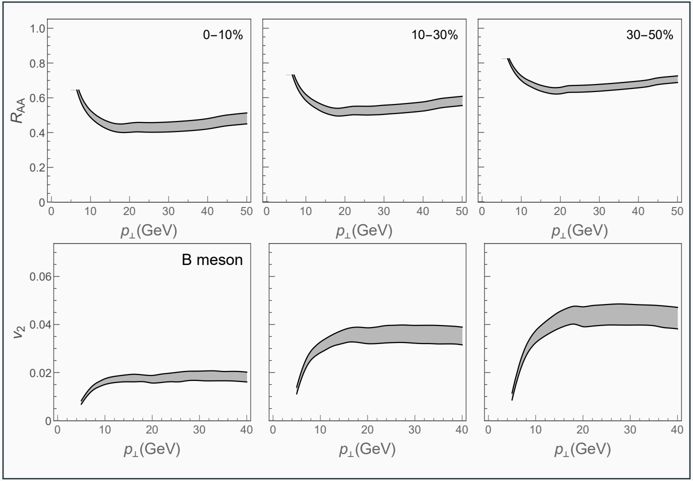


DREENA-B, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02\,TeV$, D



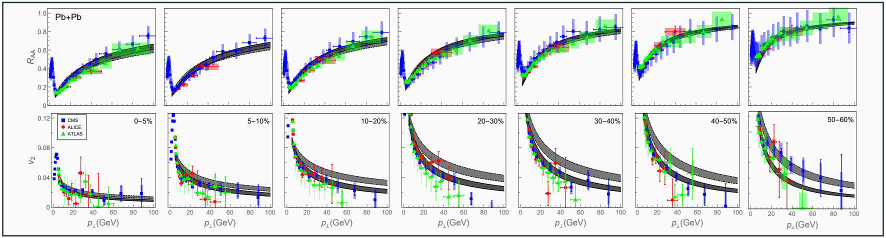
Backup slides

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



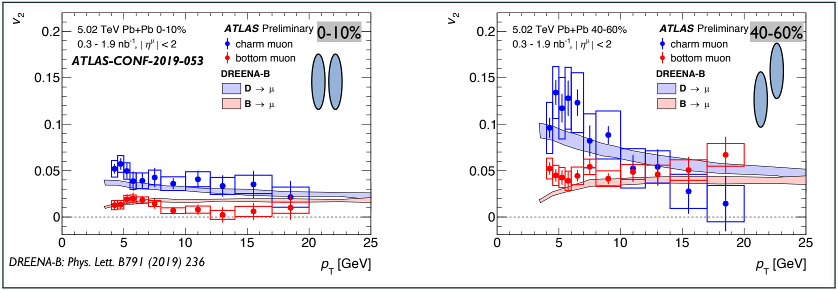
Backup slides

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



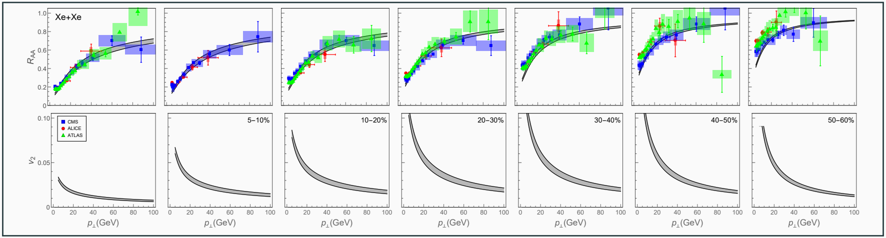
Backup slides

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

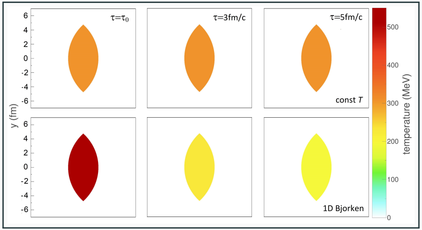


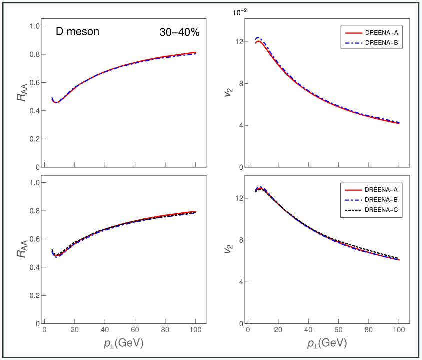
Backup slides

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



DREENA-A limits





Backup slides

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:

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

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

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

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

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-$p_\perp$

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

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

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

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

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

Backup slides

energy loss:

$$\frac{dE_{col}}{d\tau} = \frac{2C_R}{\pi\, v^2}\alpha_S(E\,T)\,\alpha_S(\mu_E^2(T)) \times$$
$$\int_0^\infty n_{eq}(|\vec{\mathbf{k}}|,T)d|\vec{\mathbf{k}}| \left(\int_0^{|\vec{\mathbf{k}}|/(1+v)} d|\vec{\mathbf{q}}| \int_{-v|\vec{\mathbf{q}}|}^{v|\vec{\mathbf{q}}|} \omega d\omega \; + \int_{|\vec{\mathbf{k}}|/(1+v)}^{|\vec{\mathbf{q}}|_{max}} d|\vec{\mathbf{q}}| \int_{|\vec{\mathbf{q}}|-2|\vec{\mathbf{k}}|}^{v|\vec{\mathbf{q}}|} \omega d\omega \right) \times$$
$$\left(|\Delta_L(q,T)|^2 \frac{(2|\vec{\mathbf{k}}|+\omega)^2-|\vec{\mathbf{q}}|^2}{2} + |\Delta_T(q,T)|^2 \frac{(|\vec{\mathbf{q}}|^2-\omega^2)((2|\vec{\mathbf{k}}|+\omega)^2+|\vec{\mathbf{q}}|^2)}{4|\vec{\mathbf{q}}|^4}(v^2|\vec{\mathbf{q}}|^2-\omega^2)\right)$$

$$\frac{d^2 N_{\rm rad}}{dx d\tau} = \int \frac{d^2k}{\pi}\,\frac{d^2q}{\pi}\,\frac{2\,C_R C_2(G)\,T}{x}\,\frac{\mu_E(T)^2-\mu_M(T)^2}{(\boldsymbol{q}^2+\mu_M(T)^2)(\boldsymbol{q}^2+\mu_E(T)^2)}\,\frac{\alpha_S(E\,T)\,\alpha_S(\frac{\boldsymbol{k}^2+\chi(T)}{x})}{\pi}$$
$$\times \frac{(\boldsymbol{k}+\boldsymbol{q})}{(\boldsymbol{k}+\boldsymbol{q})^2+\chi(T)}\left(1-\cos\left(\frac{(\boldsymbol{k}+\boldsymbol{q})^2+\chi(T)}{xE^+}\,\tau\right)\right)\left(\frac{(\boldsymbol{k}+\boldsymbol{q})}{(\boldsymbol{k}+\boldsymbol{q})^2+\chi(T)} - \frac{\boldsymbol{k}}{\boldsymbol{k}^2+\chi(T)}\right)$$