High-pT v4 puzzle and importance of higher harmonics in QGP tomography

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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 & 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

- 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
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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)

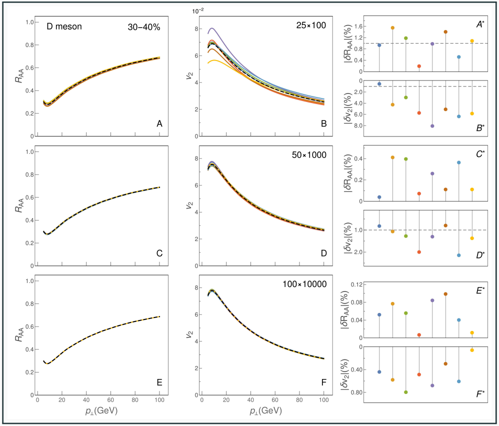
DREENA-A

A = adaptive

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

- 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



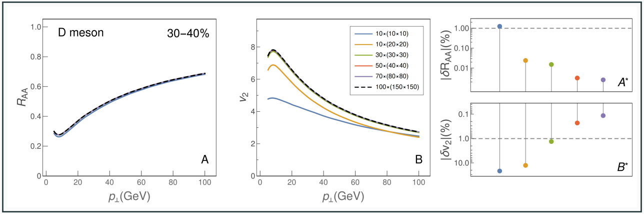
not very efficient

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

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

DREENA-A

equidistant sampling



two orders of magnitude increase in the efficiency

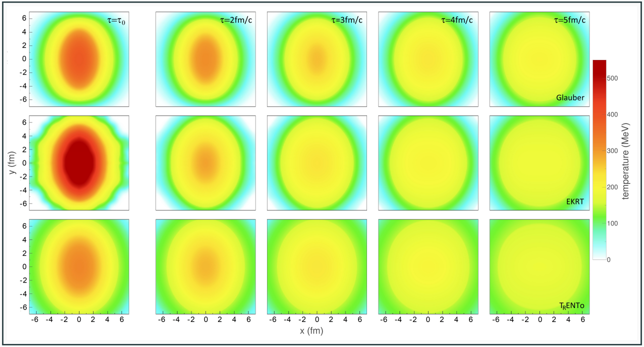
for v_2 , only 10k trajectories needed to achieve $\sim$1% precision

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

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

DREENA-A

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

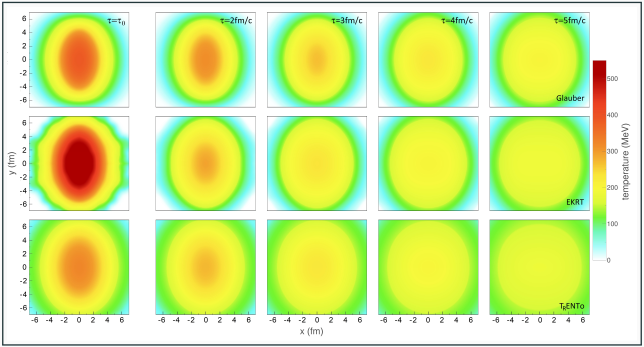


All three evolutions agree with low-$p_\perp$ data. Can high pt-data provide further constraint?

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

DREENA-A

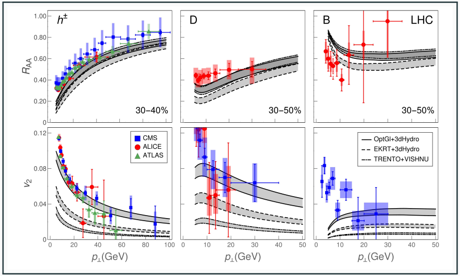
Qualitative differences

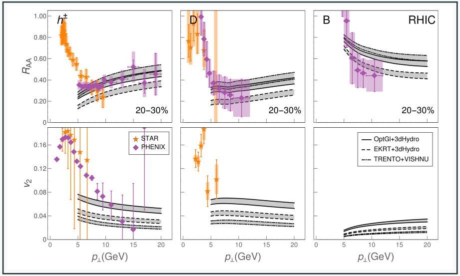


- Largest anisotropy for Glauber ($\tau_0 = 1fm$) – expected differences in high-$p_\perp$ v_2
- EKRT shows larger temperature - smaller R_{AA} expected

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 fitting parameters within energy loss
- 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, [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)

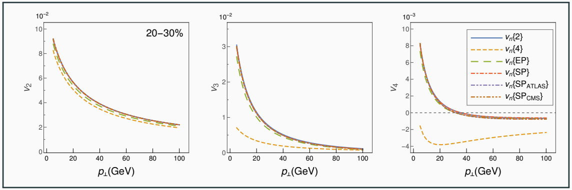
  Y. He, W. Chen, T. Luo, S. Cao, L. G. Pang and X. N. Wang, [arXiv:2201.08408 [hep-ph]]

- 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)



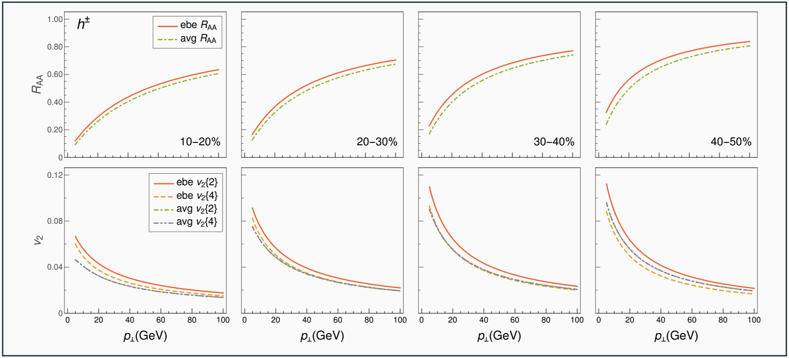
all methods, other than $v_n\{4\}$ agree with each other

no need for rapidity correlations!

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

ebeDREENA

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

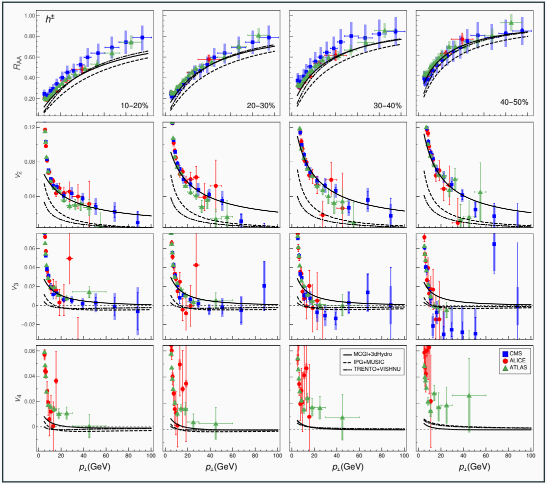


R_{AA} differences small $\sim 7\%$ and no centrality dependence

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

ebeDREENA

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

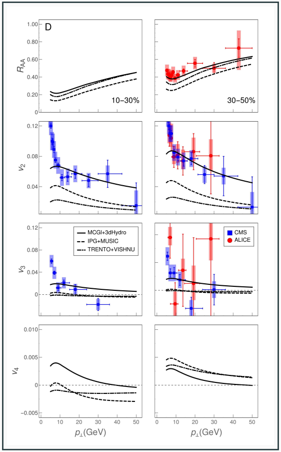


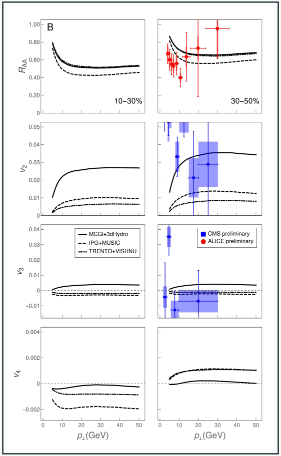
we can distinguish between different models with high-p_T energy loss

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

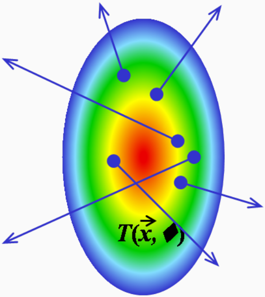
D. Z, J. Auvinen, I. Salom, P. Huovinen and M. Djordjevic, Phys. Rev. C **106**, no.4, 044909 (2022)

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

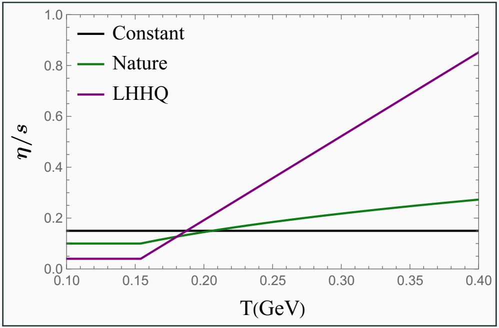
D. Z, J. Auvinen, I. Salom, P. Huovinen and M. Djordjevic, Phys. Rev. C **106**, no.4, 044909 (2022)

QGP tomography



- bulk 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, Phys. Lett. B **835**, 137501 (2022)
- DREENA-A on github:
  https://github.com/DusanZigic/DREENA-A

η/s parametrization

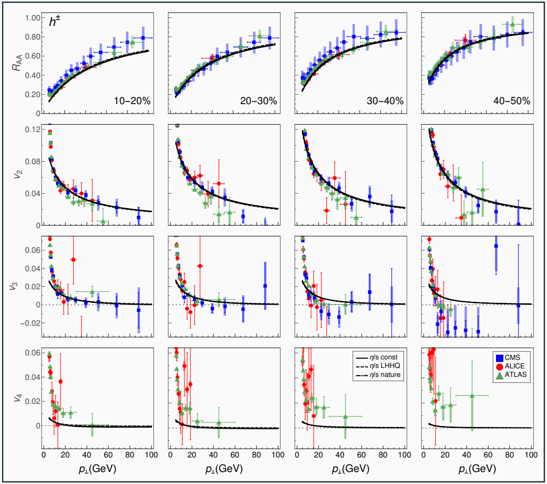


- constant η/s
- nature η/s
  J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. **15**, no.11, 1113-1117 (2019)
- LHHQ η/s
  H. Niemi, G. S. Denicol, P. Huovinen, E. Molnar and D. H. Rischke,
  Phys. Rev. Lett. **106**, 212302 (2011)

TRENTO + VISHNU + DREENA

η/s parametrization

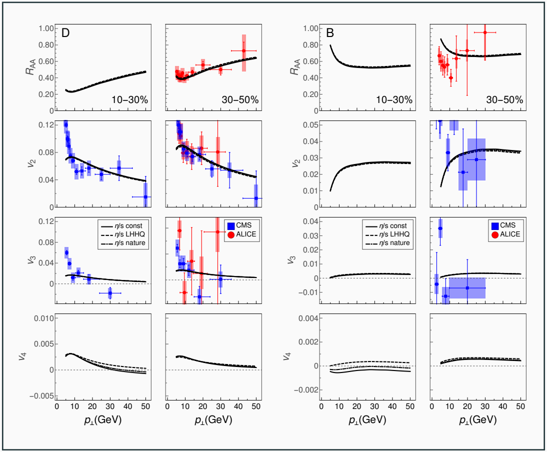
- charged hadrons, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02\,TeV$



high-p_T not sensitive to different η/s as well

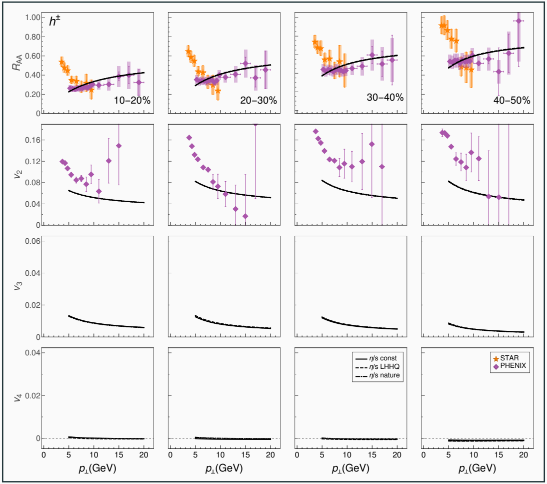
η/s parametrization

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



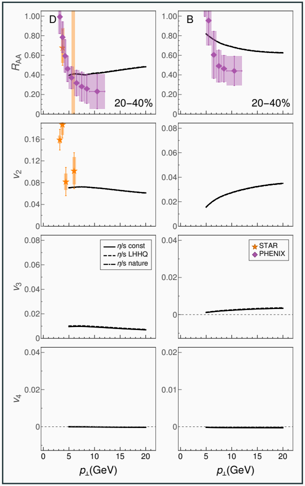
η/s parametrization

- charged hadrons, $Au + Au$, $\sqrt{s_{NN}} = 200\,GeV$



η/s parametrization

- heavy flavour, $Au + Au$, $\sqrt{s_{NN}} = 200\,GeV$



Acknowledgements

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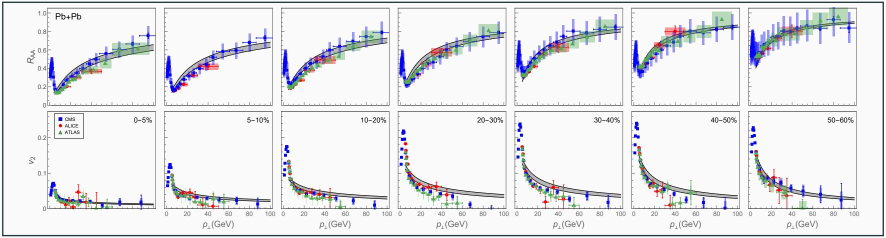
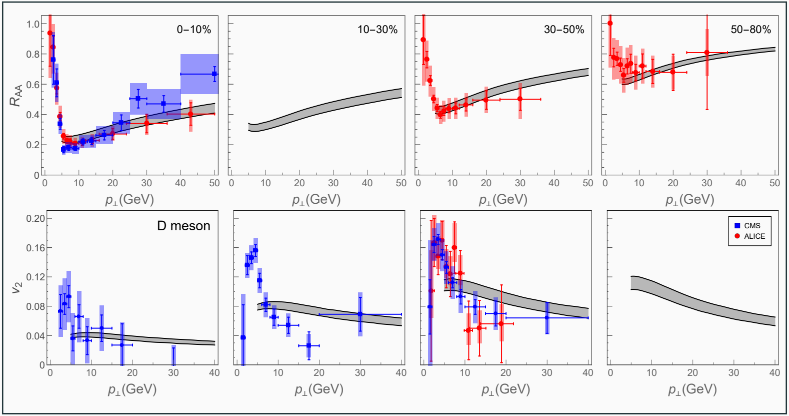
Thank you for your attention!

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



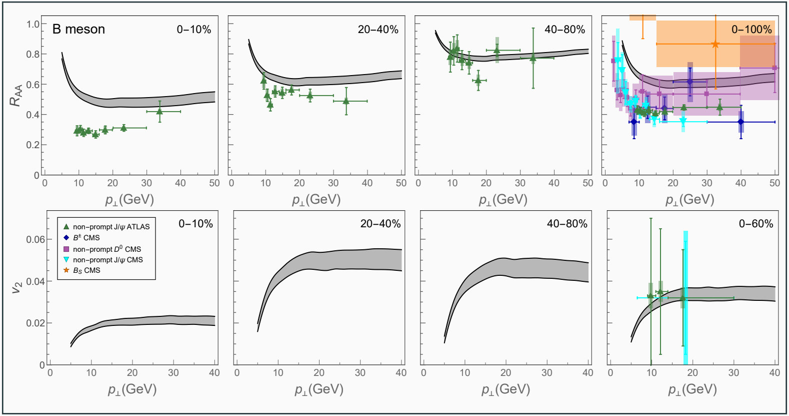
Backup slides

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



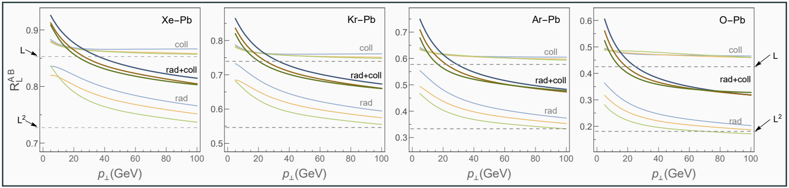
Backup slides

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



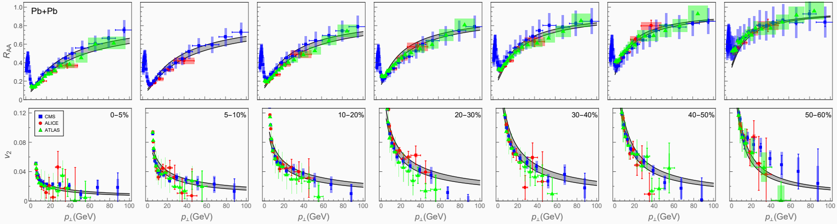
Backup slides

path-length sensitive suppression ratio



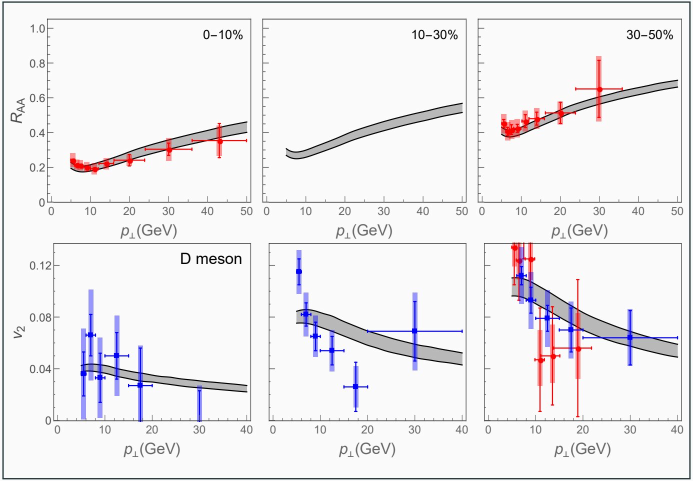
Backup slides

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



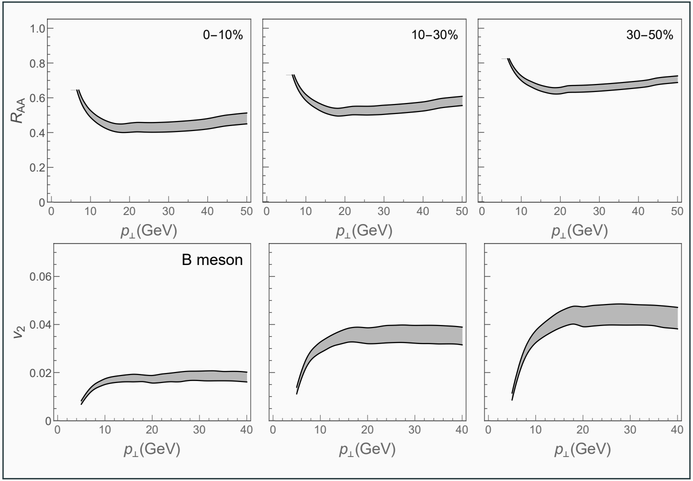
Backup slides

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



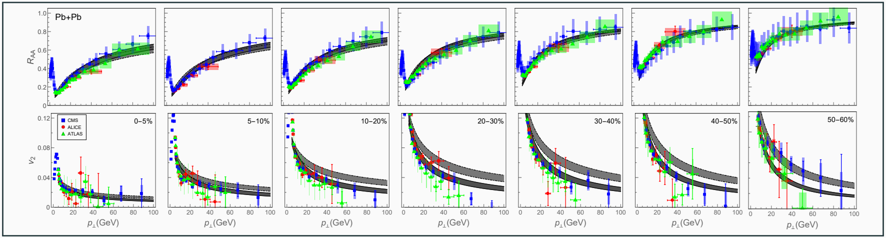
Backup slides

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



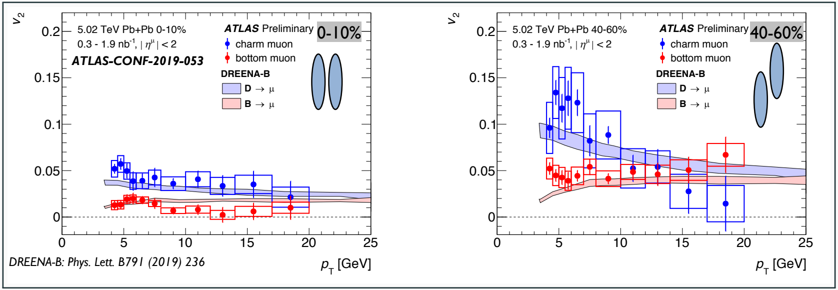
Backup slides

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



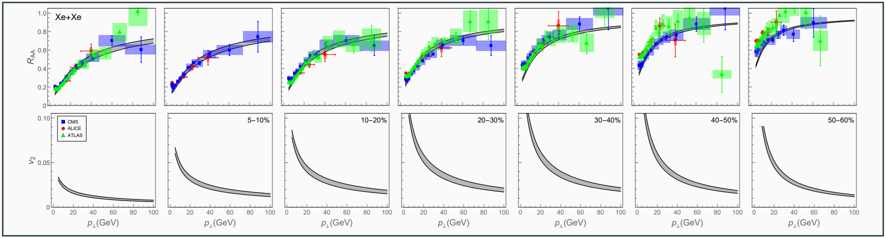
Backup slides

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

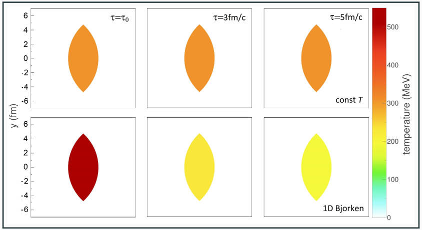


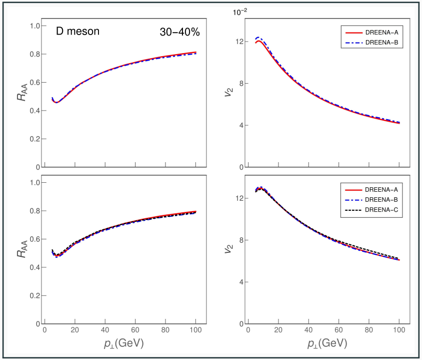
Backup slides

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



DREENA-A limits





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:

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

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

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

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

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-$p_\perp$

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

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

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

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

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

Backup slides

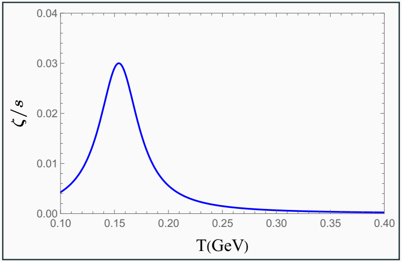
TRENTO parameters

Pb + Pb						
	p	x	n	k	w	d
const	0	7.0	90	1.19	0.5	0.5
LHHQ	0	7.0	80	1.19	0.5	0.5
nature	0	7.0	85	1.19	0.5	0.5

Au + Au						
	p	x	n	k	w	d
const	0	4.23	32	1.19	0.5	0.5
LHHQ	0	4.23	31	1.19	0.5	0.5
nature	0	4.23	32	1.19	0.5	0.5

VISHNU parameters

	τ_0	Edec	VisT0	VisHRG	VisMin	VisSlope	VisCrv	VisBulkT0	VisBulkMax	VisBulkWidth
const	1.0	0.265	0.154	0.15 0.12	0.15 0.12	0.00	1.00	0.183	0.03	0.022
LHHQ	1.0	0.265	0.154	0.04	0.04	3.30	0.00	0.183	0.03	0.022
nature	1.0	0.265	0.154	0.10	0.10	1.11	-0.48	0.183	0.03	0.022



Backup slides

energy loss:

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

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

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

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

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