



QGP tomography with ebe-DREENA framework

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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 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 = 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).

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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

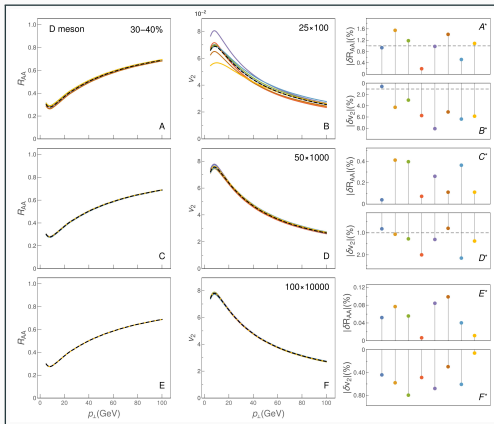
D. Z, B. Ilic, M. Djordjevic and M. Djordjevic, Phys. Rev. C **101**, no.6, 064909 (2020)

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

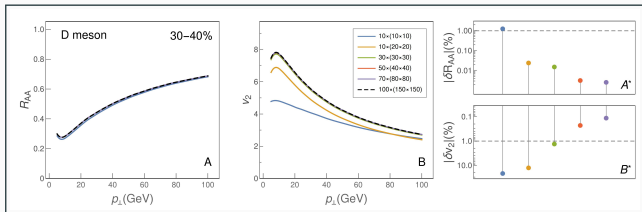
Monte Carlo sampling



not very efficient

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

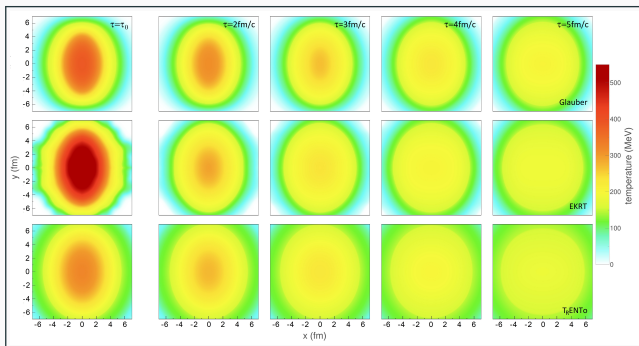
equidistant sampling



two orders of magnitude increase in the efficiency for v_2 , only 10k trajectories needed to achieve $\sim 1\%$ precision

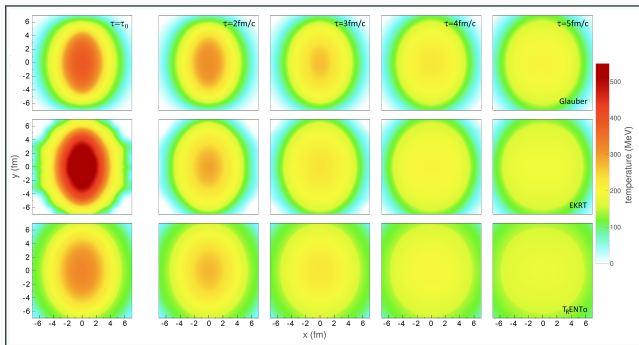
can efficiently generate predictions for all types of probes for arbitrary temperature profiles

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

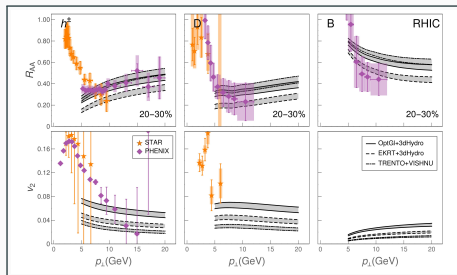
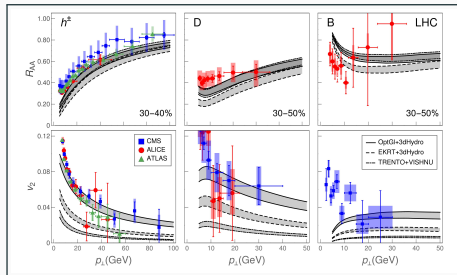


All three evolutions agree with low- p_{\perp} data. Can high p_{\perp} -data provide further constraint?

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 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

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

- 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)

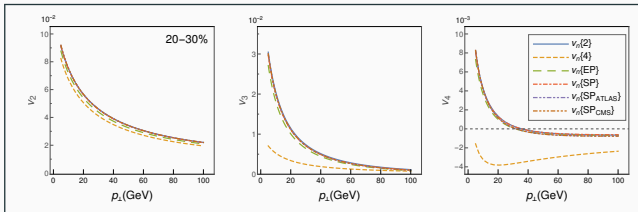
Y. He, W. Chen, T. Luo, S. Cao, L. G. Pang and X. N. Wang, [arXiv:2201.08408 [hep-ph]]

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

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

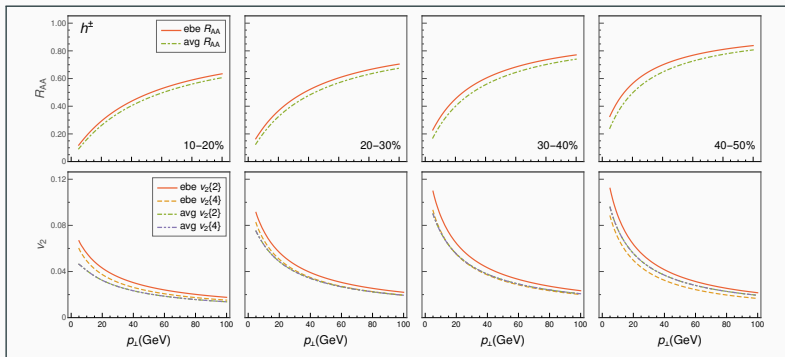
- scalar product - CMS: $v_n\{SP_{CMS}\}$

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!

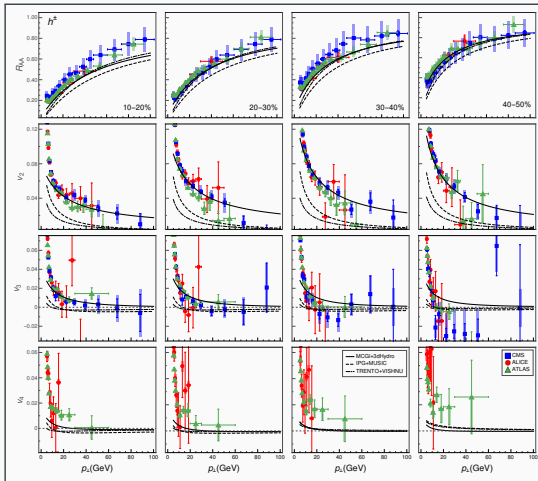
- high- p_T energy loss: ebe fluctuation vs smooth hydro background



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

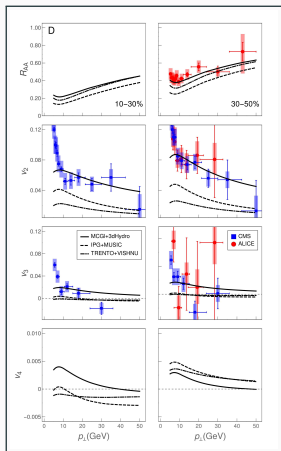
$v_2\{2\}$ differences from 14% in 40-50% up to 32% in 10-20%
 also p_{\perp} dependence of the differences

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

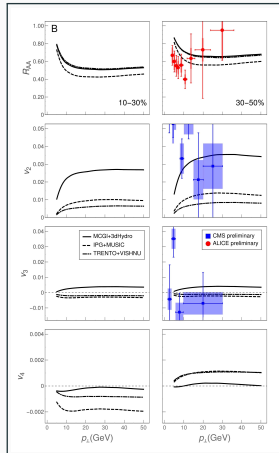


we can distinguish between different models with high- p_T energy loss

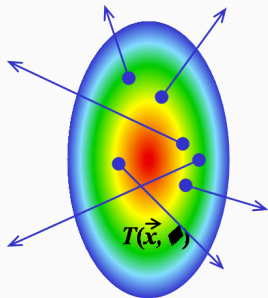
- heavy flavour, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 TeV$



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



- 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



- 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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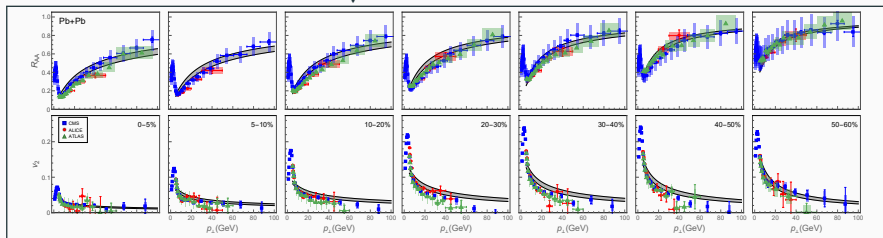


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Thank you for your attention!

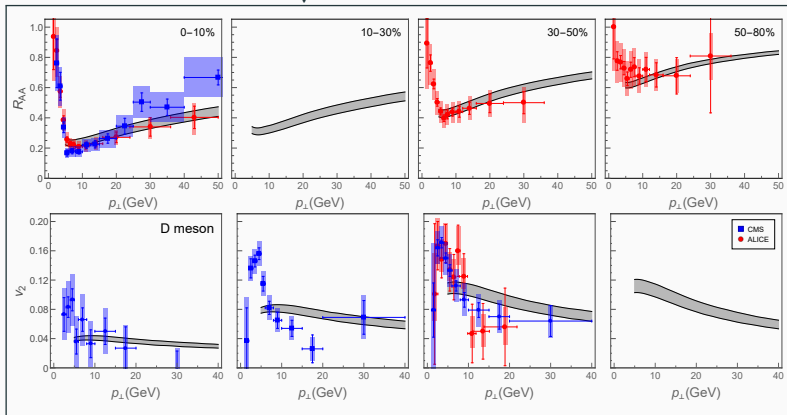
Backup slides

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



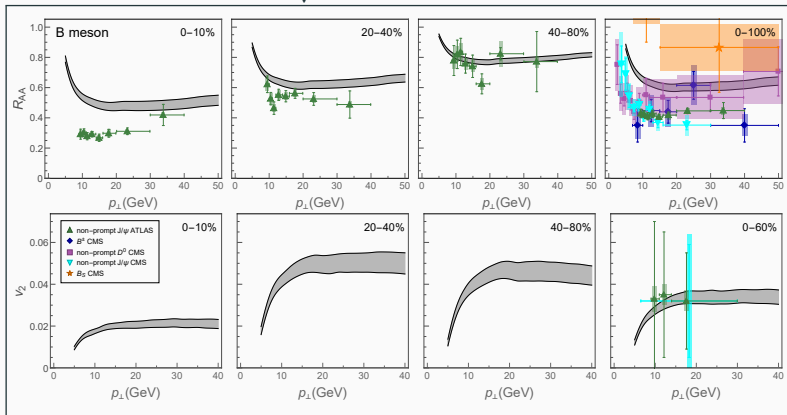
Backup slides

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



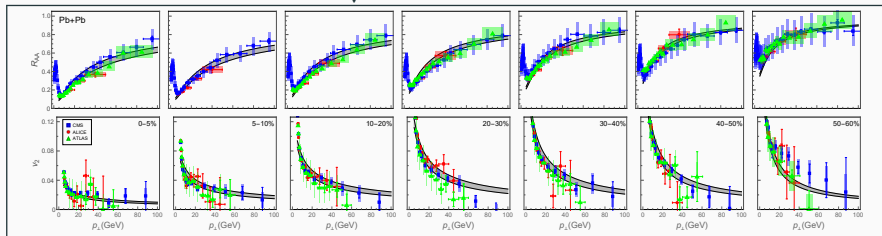
Backup slides

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



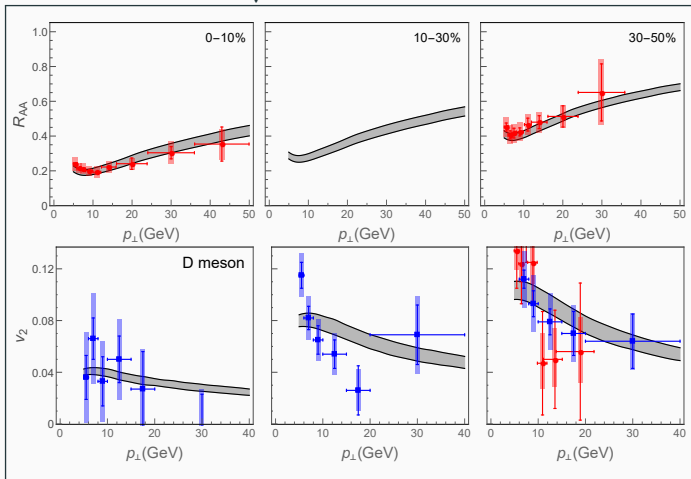
Backup slides

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



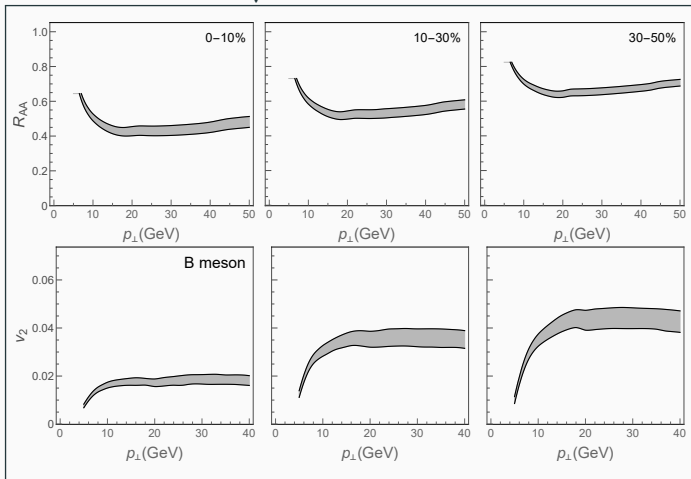
Backup slides

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



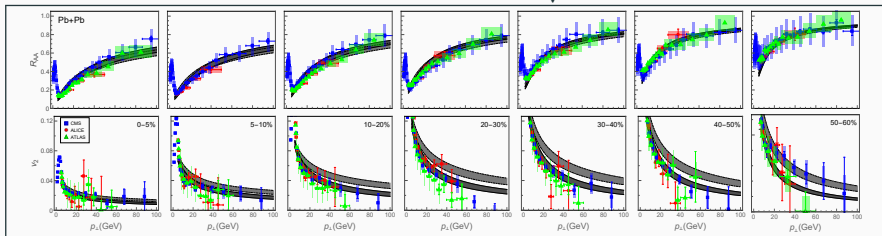
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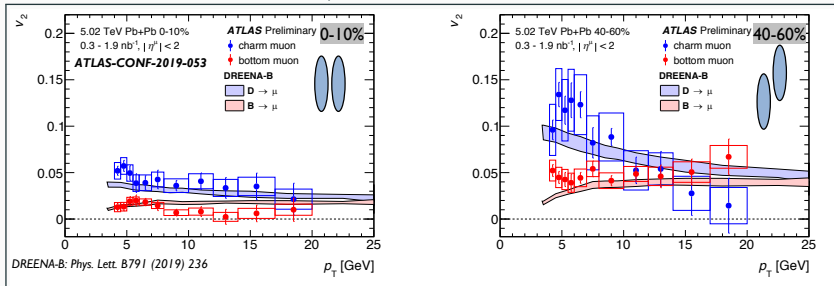
DREENA-B, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, B



Backup slides

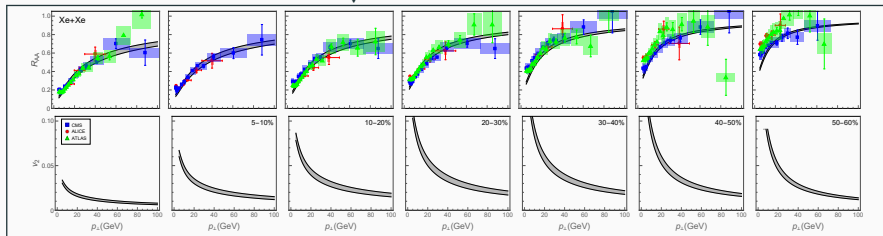
DREENA-B vs DREENA-C, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, h^\pm



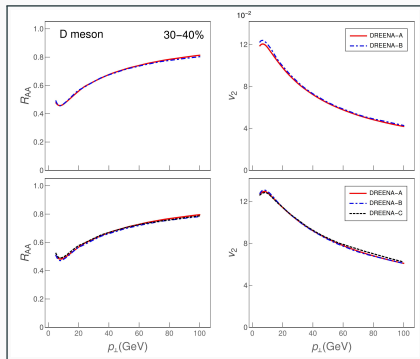
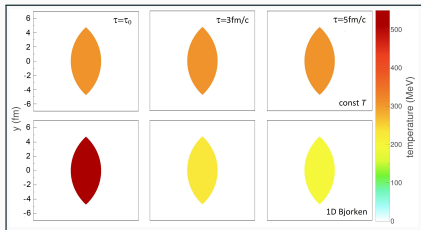
DREENA-B, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, μ 

Backup slides

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



DREENA-A limits



ebe averaging methods:

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

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

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

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

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

Backup slides

ebe averaging methods:

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

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

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

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

ebe averaging methods:

- low- p_{\perp}

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

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

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

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

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

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:

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

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

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

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

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