COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

JET Collaboration

Azimuthal Jet Flavor Tomography with CUJET2.0 of Nuclear Collisions at RHIC and LHC

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Based on

Jiechen Xu, Alessandro Buzzatti, and Miklos Gyulassy, arXiv:1402.2956, arXiv:1404.0384

Alessandro Buzzatti, and Miklos Gyulassy , arXiv:1106.3061, arXiv:1210.6417

For JET Summer School 2014 Student Talk, UC Davis, CA

Outline

- Part I: CUJET2.0: A pQCD Model for Azimuthal Jet Flavor Tomography at RHIC and LHC
  - Radiative jet energy loss in QGP: (D)GLV Opacity Expansion
  - Pre-CUJET: WHDG/DGLV, heavy quark puzzle
  - CUJET1.0 = dynamical fixed coupling DGLV + elastic + trans. Glauber & long. Bjorken
  - The surprising transparency of QGP at LHC, multi-scale running strong coupling
  - CUJET2.0 = dynamical running coupling DGLV + elastic + 2+1D viscous hydro
  - CUJET2.0 results on pion/charged hadron RAA and jet transport coefficient
- Part II: CUJET2.0 Jet Quenching Phenomenology
  - Why light quark and charged hadron RAA at RHIC and LHC are almost the same?
  - Heavy flavor RAA
  - Why pion and beauty RAA have an crossover?
- Part III: The jet v2 open problem
  - Puzzle: consistency with (RAA & v2) AND (RHIC & LHC) AND (central & peripheral)
  - CUJET2.0: reaction plane dependent jet quenching pattern
  - CUJET2.0: light flavor v2
  - CUJET2.0: heavy flavor v2
- Summary and Outlook

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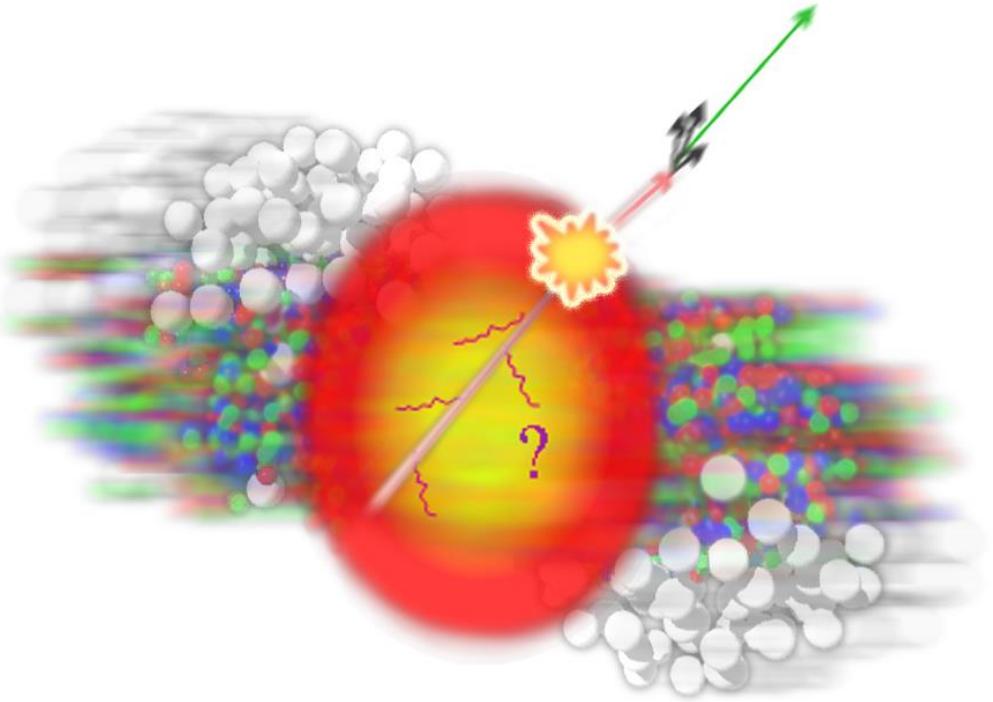
Jet Tomography

- Hard processes happen before the formation of the medium
  - Hard parton production in AA collisions can be calculated in the pQCD paradigm
- Quarks and gluons have final state interaction
  - Parton shower will be modified by interacting with the medium

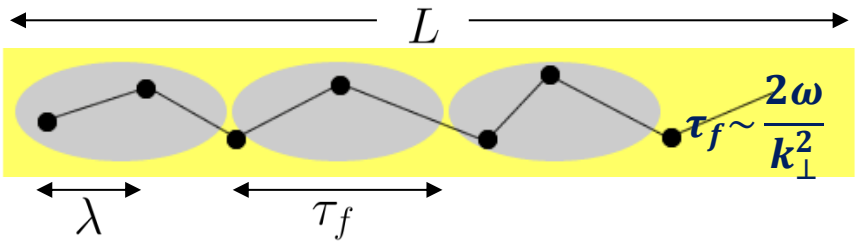


- One can use quark or glue jet as a probe, measure the quenching pattern of hadron/lepton jet fragments, and gain information about the QGP evolution profile
  - Or the other way: with a known medium density evolution to study the parton medium interaction mechanism

Radiative Energy Loss

- Jet quenching models in the pQCD framework based on different underlying assumptions
  - Finite temperature field theory (AMY)
  - Higher twist (HT)
  - Multiple soft scattering (BDMPS-Z and ASW)
  - Opacity expansion (GLV)

- GLV
  - The plasma is modeled by a series of static or dynamical scattering centers.
  - Energy loss is formulated as an expansion in the number of parton-medium scatterings (opacity expansion)
    - Dominated by the first hard contribution. ("Thin plasma")
  - Include interference of "vacuum" radiation, interference with vertex radiation and interference among subsequent scatterings



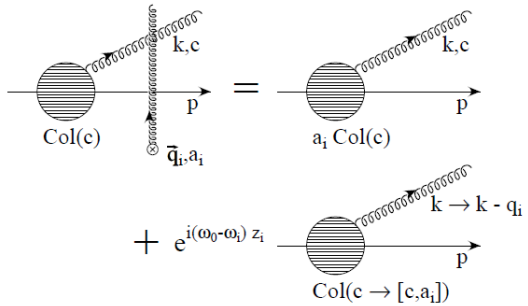
- $\tau_f < \lambda < L$ **Incoherent multiple collisions**
- $\lambda < \tau_f < L$ **LPM effect**
- $\lambda < L < \tau_f$ **"Factorization" limit**

(D)GLV Opacity Expansion

$$x\frac{dN_g^n}{dxd^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{1}{n!}\left(\frac{L}{\lambda_g}\right)^n \int\prod_{i=1}^{n}\left(d^2\mathbf{q}_i\left(|\bar{v}_i(\mathbf{q}_i)|^2-\delta^2(\mathbf{q}_i)\right)\right)$$

$$\times\ -2\,\mathbf{C}_{(1\cdots n)}\cdot\sum_{m=1}^{n}\mathbf{B}_{(m+1\cdots n)(m\cdots n)}$$

$$\times\left(\cos\left(\sum_{k=2}^{m}\Omega_{(k\cdots n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\Omega_{(k\cdots n)}\Delta z_k\right)\right)$$



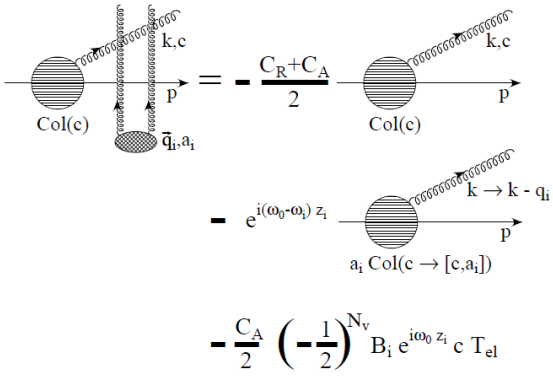
$$\mathbf{C}_{(1\cdots n)} = \frac{\mathbf{k}-\mathbf{q}_1-\cdots-\mathbf{q}_n}{(\mathbf{k}-\mathbf{q}_1-\cdots-\mathbf{q}_n)^2+\chi^2}$$

$$\mathbf{H} = \frac{\mathbf{k}}{\mathbf{k}^2+\chi^2}$$

$$\mathbf{B}_{(i)} = \mathbf{H}-\mathbf{C}_{(i)}$$

$$\mathbf{B}_{(1\cdots m)(1\cdots n)} = \mathbf{C}_{(1\cdots m)}-\mathbf{C}_{(1\cdots n)}$$

$$\Omega_{m\cdots n} = \frac{(\mathbf{k}-\mathbf{q}_m-\cdots-\mathbf{q}_n)^2+\chi^2}{2xE}$$



$$\chi^2 = M^2x^2+m_g^2(1-x) \qquad m_g = \mu/\sqrt{2}\ ,\ \mu = gT\sqrt{N_c/3+N_f/6}$$

$$|\bar{v}_i(\mathbf{q}_i)|^2 = \frac{{\mu_i}^2}{\pi(\mathbf{q}_i^2+{\mu_i}^2)^2}$$

WHDG/DGLV

Path length fluctuations

$$L(\vec{x}_\perp,\phi) = \int d\tau \rho_p(\vec{x}_\perp + \tau\hat{n}(\phi))/\langle\rho_p\rangle$$

$$P(\quad E_i \quad \to E_i - \Delta_{rad} - \Delta_{el}) = \int \frac{d\phi}{2\pi}\int \frac{d^2\vec{x}_\perp}{N_{bin}(b)} T_{AA}(\vec{x}_\perp,\vec{b}) \otimes P_{rad}\ (\Delta_{rad}; L(\vec{x}_\perp,\phi)) \otimes P_{el}(\Delta_{el}; L(\vec{x}_\perp,\phi)).$$

Collisional energy loss

$$\frac{dE^{el}}{dx} = C_R\pi\alpha_s^2 T^2(1+\frac{n_f}{6})f(v)\log(B_c)$$

$$f(v) = \frac{1}{v^2}\left(v + \tfrac{1}{2}(v^2-1)\log(\frac{1+v}{1-v})\right) \overset{v\to 1}{\longrightarrow} 1$$

$$B_{\rm Bj} = (4E_pT)\,/\,(\mu^2)$$

$$B_{\rm TG} = \left(\frac{4pT}{(E_p - p + 4T)}\right)/(\mu)$$

$$B_{\rm BT} = \begin{cases} \left(2^{\frac{n_f}{6+n_f}}\ 0.85\ E_pT\right)/\left(\frac{\mu^2}{3}\right) & E_p \gg \frac{M^2}{T} \\ \left(4^{\frac{n_f}{6+n_f}}\ 0.36\ \frac{(E_pT)^2}{M^2}\right)/\left(\frac{\mu^2}{3}\right) & E_p \ll \frac{M^2}{T} \end{cases}$$

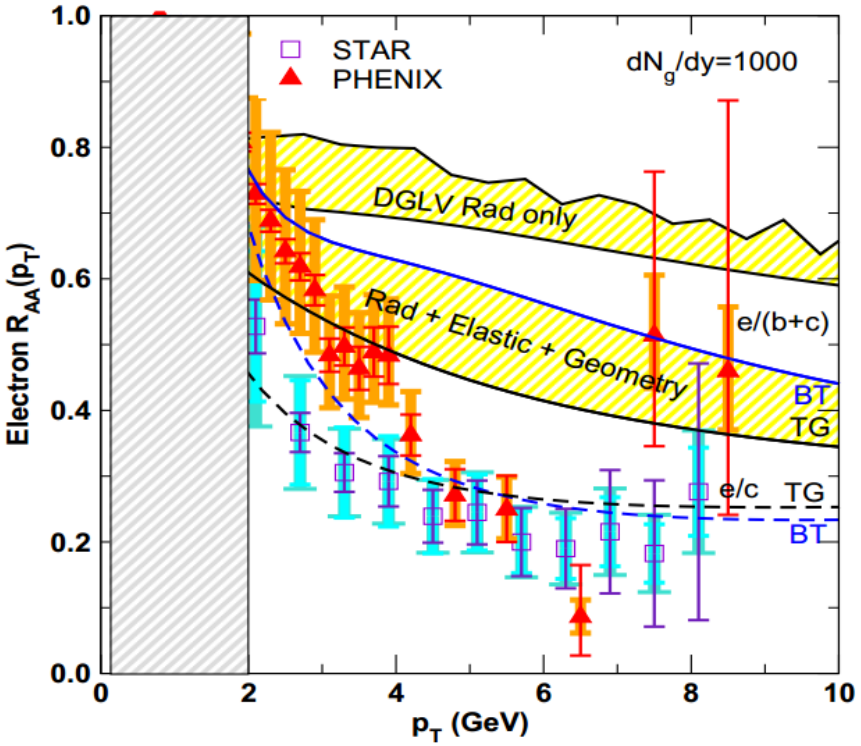
Convolutions over radiative and elastic

$$P_Q^I(\epsilon; L) = \int dx P_{Q,rad}(x; L) P_{Q,el}(\epsilon - x; L)$$

Power law assumption of heavy quark pQCD spectra

$$Ed^3\sigma_Q/d^3k \propto 1/p_T^{n+2}$$

$$R_Q^I = \int \frac{d\phi}{2\pi}\int \frac{d^2\vec{x}_\perp}{N_{bin}(b)} T_{AA}(\vec{x}_\perp,\vec{b}) \int d\epsilon(1-\epsilon)^n P_Q^I(\epsilon; L(\vec{x}_\perp,\phi)),$$



WHDG, NPA784,426(2007)

❖ "Heavy Quark Puzzle"

CUJET1.0 = dynamical DGLV + elastic + trans. Glauber + long. Bjorken

Path length fluctuations

$$L(\vec{x}_\perp,\phi)=\int d\tau \rho_p(\vec{x}_\perp+\tau\hat{n}(\phi))/\langle\rho_p\rangle$$

$$P(\quad E_i \quad \to E_i-\Delta_{rad}-\Delta_{el})=$$
$$\int\frac{d\phi}{2\pi}\int\frac{d^2\vec{x}_\perp}{N_{bin}(b)}T_{AA}(\vec{x}_\perp,\vec{b})\otimes$$
$$P_{rad}\ (\Delta_{rad};L(\vec{x}_\perp,\phi))\otimes P_{el}(\Delta_{el};L(\vec{x}_\perp,\phi)).$$

$$T(\mathbf{z})\big|_{\tau MAX}=T_f$$

Power law assumption of heavy quark pQCD spectra

$$Ed^3\sigma_Q/d^3k\propto 1/p_T^{n+2}$$

$$R_Q^I=\int\frac{d\phi}{2\pi}\int\frac{d^2\vec{x}_\perp}{N_{bin}(b)}T_{AA}(\vec{x}_\perp,\vec{b})$$
$$\int d\epsilon(1-\epsilon)^n P_Q^I(\epsilon;L(\vec{x}_\perp,\phi)),$$

$$\frac{d\sigma'^{pp\to q}}{dp_f d\phi}(p_f;\mathbf{x}_0,\phi)=\int_{p_i^{min}}^{p_i^{max}}dp_i\ P(p_f,p_i;\mathbf{x}_0,\phi)\frac{d\sigma^{pp\to q}}{dp_i}(p_i)$$

$$\frac{d\sigma^{AA\to q}}{dp_f d\phi}(p_f;\phi)=\int d\mathbf{x}_0\ \rho_{binary}(\mathbf{x}_0)\ \frac{d\sigma'^{pp\to q}}{dp_f d\phi}(p_f;\mathbf{x}_0,\phi)$$

Radiative energy loss fluctuations

$$P_{rad}(\epsilon)=P_0\delta(\epsilon)+\tilde{P}(\epsilon)\big|_0^{\epsilon_{MAX}}+P_1\delta(\epsilon_{MAX}-\epsilon)$$

ASSUME Poisson distribution for the number of INCOHERENTLY emitted gluons

Elastic energy loss fluctuations

$$P_{el}(\epsilon)=e^{-\overline{N}_c}\delta(\epsilon)+\mathcal{N}e^{-\frac{(\epsilon-\overline{\epsilon})^2}{4T\overline{\epsilon}/E}}$$

Gaussian fluctuation for multiple collisions

Fragmentation

$$\frac{d\sigma^h}{dp}(p)=\sum_i\int_{p/p_{max}}^1 dx\ \frac{d\sigma^i}{dp}\left(\frac{p}{x}\right)\ D^{i\to h}\left(x;\frac{p}{x}\right)$$

Effective Potential

Static QCD medium (DGLV)

$$|\bar{v}_i(q_i)|^2 = \frac{1}{\pi}\frac{\mu(z_i)^2}{(q^2+\mu(z_i)^2)^2}$$

- Static scattering centers
- Color-electric screened Yukawa potential (Debye mass)
- Full opacity series

Dynamical QCD medium (Djordjevic; Gelis; Zakharov)

$$|\bar{v}_i(q_i)|^2 = \frac{1}{\pi}\frac{\mu(z_i)^2}{q^2(q^2+\mu(z_i)^2)}$$

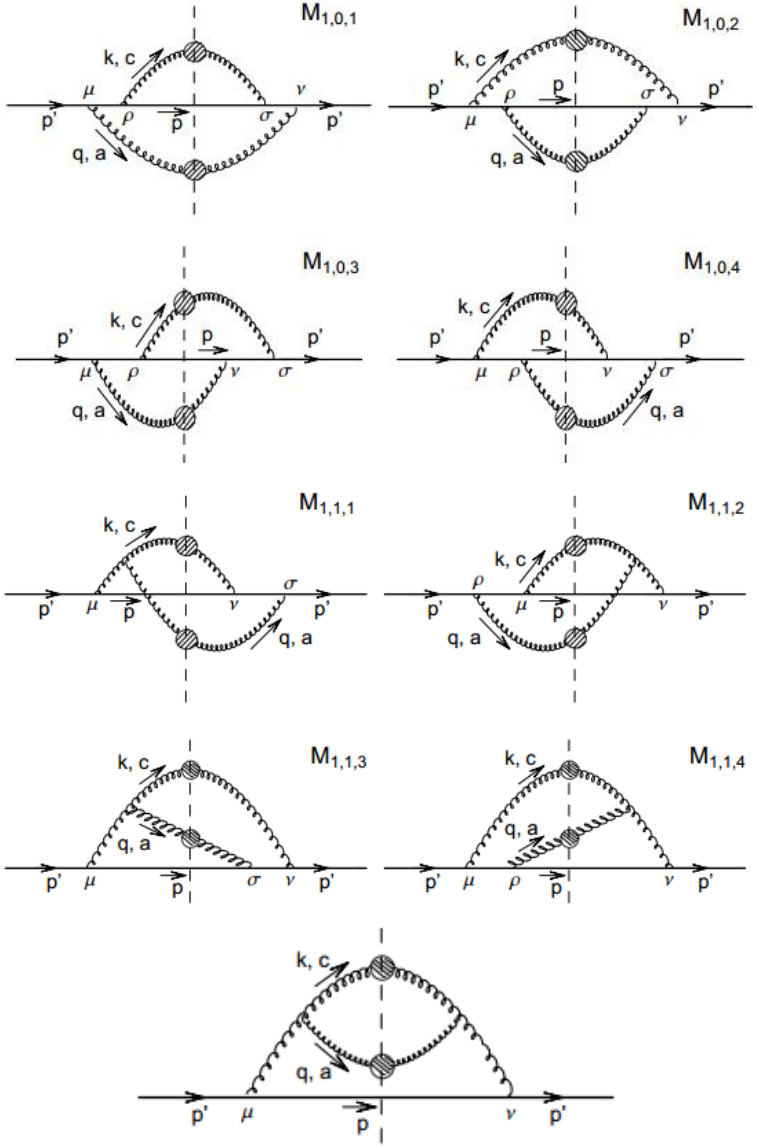
- Dynamical scattering centers
- Includes color-magnetic effects (1-HTL gluon propagators)
- Only first order in opacity

Interpolating potential (CUJET)

$\mu_e = f_E\,\mu$ $\qquad$ $\mu_m = f_M\,\mu$

$$|\bar{v}_i(q_i)|^2 = \frac{\mathcal{N}(\mu_e,\mu_m)}{\pi}\frac{\mu_e(z_i)^2-\mu_m(z_i)^2}{(q^2+\mu_e(z_i)^2)(q^2+\mu_m(z_i)^2)}$$

- Introduces effective color-magnetic screening mass
- Add f_E and f_M allows one to interpolate between the static and dynamical limits, and further explore Non-HTL regime
- Magnetic screening allows full opacity series



$$\lambda_{\rm dyn} \Longleftrightarrow \lambda_{\rm stat} = \frac{\lambda_{\rm dyn}}{c(n_f)} \quad \left[\frac{\mu^2}{\boldsymbol{q}^2(\boldsymbol{q}^2+\mu^2)}\right]_{\rm dyn} \Longleftrightarrow \left[\frac{\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}\right]_{\rm stat}$$

Djordjevic and Heinz, PRC (2008)

Kernel of CUJET1.0

Radiative: dynamical DGLV

$$x_E\frac{dN_g^{n=1}}{dx_E}(\mathbf{x}_0,\phi)=\frac{18C_R\alpha_s}{\pi^2}\frac{4+n_f}{16+9n_f}\int d\tau\;\rho(\mathbf{z})\int d^2\mathbf{k}\int d^2\mathbf{q}\;\alpha_s^2|\tilde{v}(\mathbf{q},\mathbf{z})|^2$$
$$\times\;\frac{-2(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}\left(\frac{\mathbf{k}}{\mathbf{k}^2+\chi^2(\mathbf{z})}-\frac{(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}\right)$$
$$\times\;\left(1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}{2x_+E}\tau\right)\right)$$
$$\times\;\left(\frac{x_E}{x_+}\right)J(x_+(x_E))$$

$$|\tilde{v}(\mathbf{q},\mathbf{z})|^2=\frac{f_E^2-f_M^2}{(\mathbf{q}^2+f_E^2\mu^2(\mathbf{z}))(\mathbf{q}^2+f_M^2\mu^2(\mathbf{z}))}$$

$$\chi^2(\mathbf{z})=M^2x_+^2+m_g^2(\mathbf{z})(1-x_+),\;m_g(\mathbf{z})=\mu(\mathbf{z})/\sqrt{2}$$

$$\mu^2(\mathbf{z})=g^2f_E^2T(\mathbf{z})^2\,(1+n_f/6)=4\pi\alpha_sf_E^2T(\mathbf{z})^2\,(1+n_f/6)$$

$$0\le k_\perp\le x_EE\;,\;0\le q_\perp\le \mathrm{Min}\{k_\perp,\sqrt{4ET(\mathbf{z})}\}$$

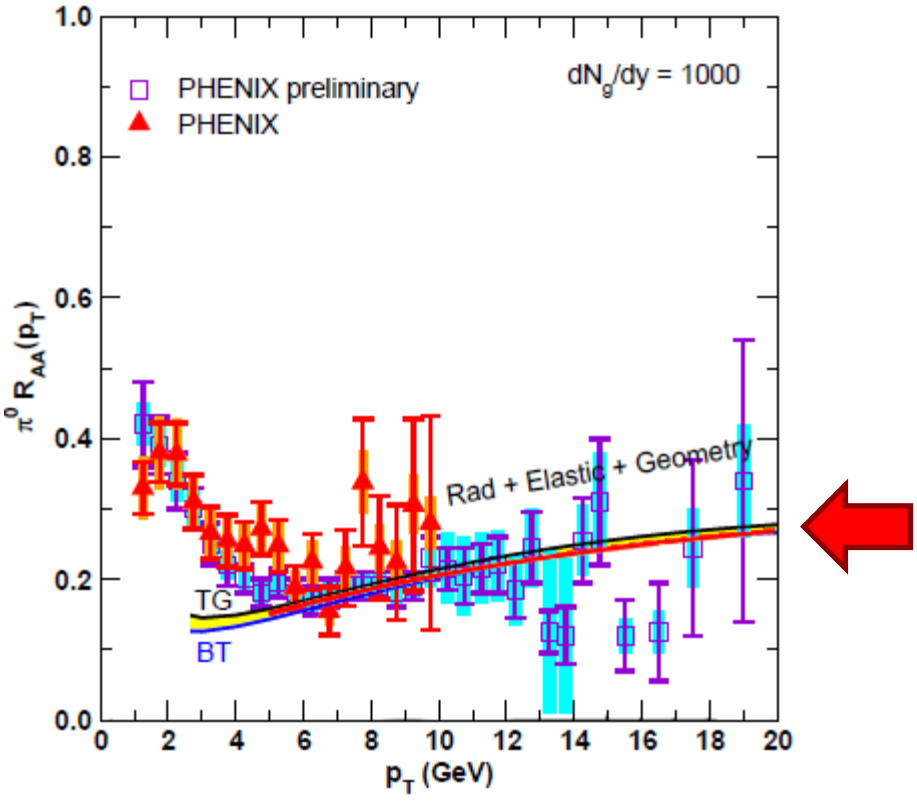
$$x_+(x_E)=\frac{1}{2}x_E\left(1+\sqrt{1-\left(\frac{k_\perp}{x_EE}\right)^2}\right)\qquad J(x_+(x_E))\equiv\frac{dx_+}{dx_E}=\frac{1}{2}\left(1+\left(1-\left(\frac{k_\perp}{x_EE}\right)^2\right)^{-1}\right)$$

Elastic: Thoma-Gyulassy (TG)

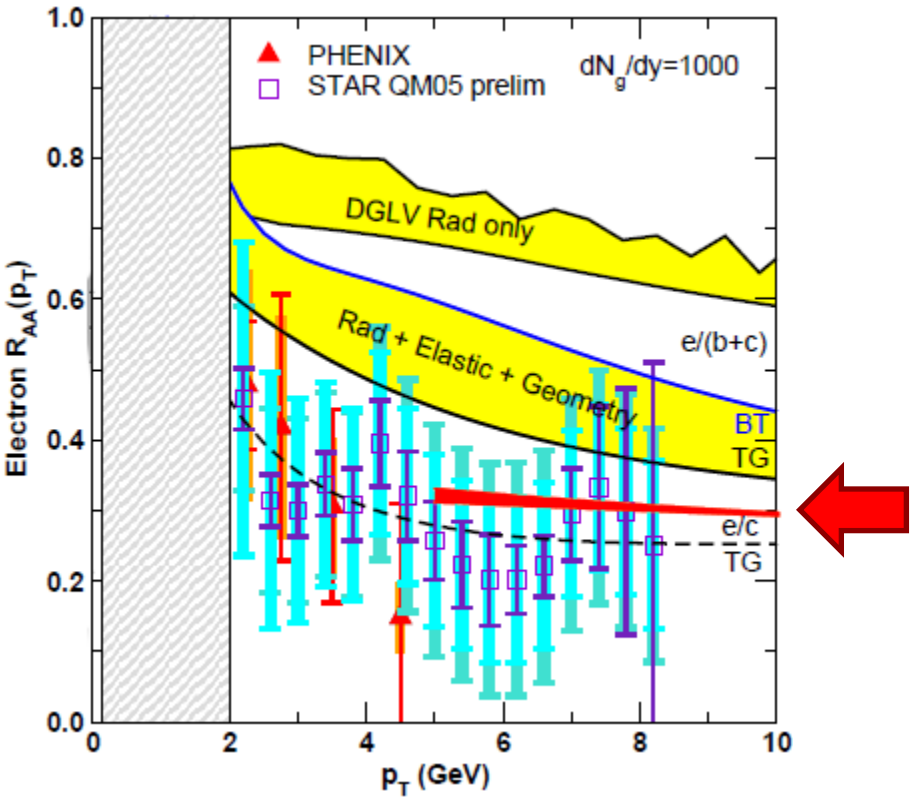
$$\frac{dE(\mathbf{z})}{d\tau}=-C_R\pi\alpha_s^2T(\mathbf{z})^2\left(1+\frac{n_f}{6}\right)\log\left(\frac{4T(\mathbf{z})\sqrt{E(\mathbf{z})^2-M^2}}{\left(E(\mathbf{z})-\sqrt{E(\mathbf{z})^2-M^2}+4T(\mathbf{z})\right)\mu(\mathbf{z})}\right)$$

CUJET1.0: To solve heavy quark puzzle

Light Quarks



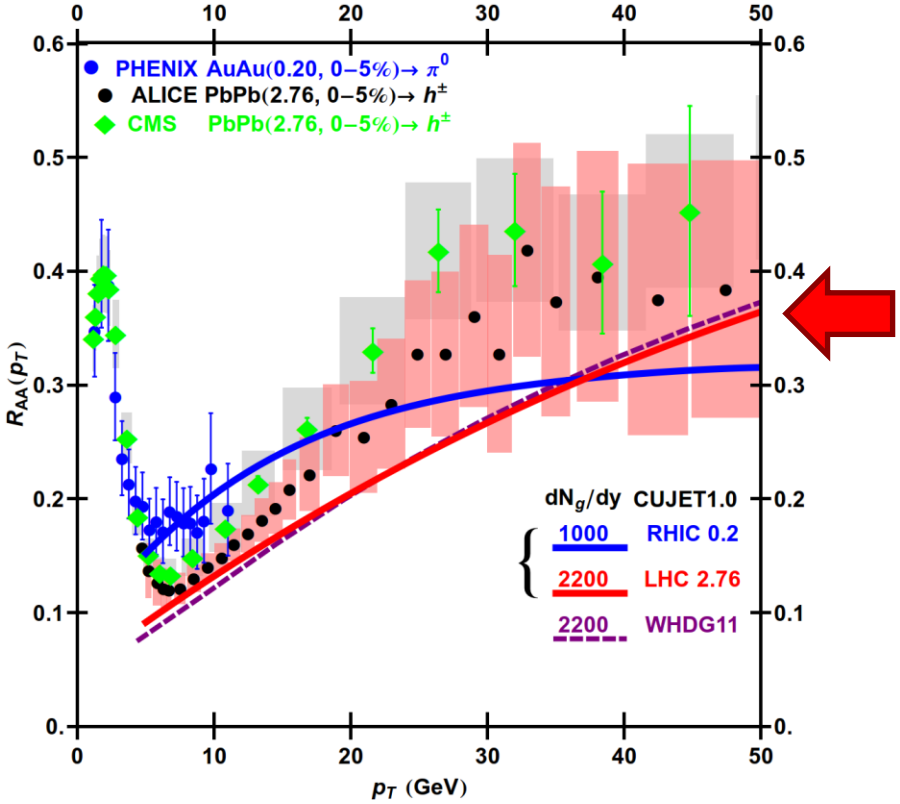
Heavy Quarks



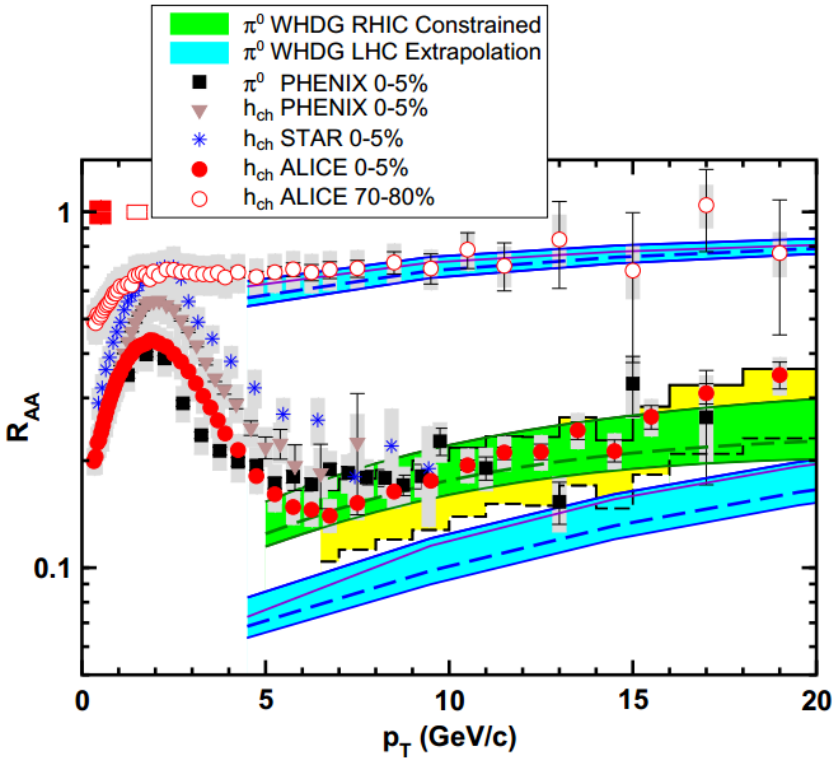
Wicks, Horowitz, Djordjevic, Gyulassy, NPA (2007)

- Combining dynamical DGLV opacity series and TG elastic energy loss, taking into account more realistic path length fluctuation and convolute over initial production spectra without simplification, CUJET1.0 explains the non-photonic electron R_{AA} at RHIC

CUJET1.0: The surprising transparency at LHC



Buzzatti and Gyulassy, PRL108,022301(2012)



Horowitz and Gyulassy, NPA872,265(2011)

- The CUJET1.0 complication did not explain the surprising transparency of sQGP at LHC
- Extented pT range probed at LHC → Introduce running coupling (phenomenologically motivated, rigorous NLO calculation is what to be done)

Recall fixed coupling CUJET1.0 at first order in opacity

Radiative: dynamical DGLV

$$x_E \frac{dN_g^{n=1}}{dx_E}(\mathbf{x}_0,\phi) = \frac{18 C_R \alpha_s}{\pi^2}\frac{4+n_f}{16+9n_f}\int d\tau\ \rho(\mathbf{z}) \int d^2\mathbf{k} \int d^2\mathbf{q}\ \alpha_s^2 |\tilde{v}(\mathbf{q},\mathbf{z})|^2$$
$$\times\ \frac{-2(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}\left(\frac{\mathbf{k}}{\mathbf{k}^2+\chi^2(\mathbf{z})} - \frac{(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}\right)$$
$$\times\ \left(1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}{2x_+E}\tau\right)\right)$$
$$\times\ \left(\frac{x_E}{x_+}\right) J(x_+(x_E))$$

$$|\tilde{v}(\mathbf{q},\mathbf{z})|^2 = \frac{f_E^2 - f_M^2}{(\mathbf{q}^2+f_E^2\mu^2(\mathbf{z}))(\mathbf{q}^2+f_M^2\mu^2(\mathbf{z}))}$$

$$\chi^2(\mathbf{z}) = M^2x_+^2 + m_g^2(\mathbf{z})(1-x_+),\ m_g(\mathbf{z}) = \mu(\mathbf{z})/\sqrt{2}$$

$$\mu^2(\mathbf{z}) = g^2 f_E^2 T(\mathbf{z})^2\,(1+n_f/6) = 4\pi\alpha_s f_E^2 T(\mathbf{z})^2\,(1+n_f/6)$$

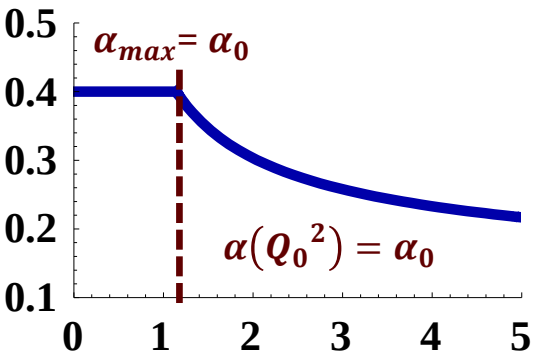
Elastic: Thoma-Gyulassy (TG)

$$\frac{dE(\mathbf{z})}{d\tau} = -C_R\pi\alpha_s^2 T(\mathbf{z})^2\left(1+\frac{n_f}{6}\right)\log\left(\frac{4T(\mathbf{z})\sqrt{E(\mathbf{z})^2-M^2}}{\left(E(\mathbf{z})-\sqrt{E(\mathbf{z})^2-M^2}+4T(\mathbf{z})\right)\mu(\mathbf{z})}\right)$$

Multi-scale Running Coupling: Radiative

- Introduce one-loop running strong coupling

$$\alpha_s \longrightarrow \alpha_s(Q^2) = \begin{cases} \alpha_0 & \text{if } Q \le Q_0 \\ \dfrac{2\,\pi}{9\,\log(Q/\Lambda_{QCD})} & \text{if } Q > Q_0 \end{cases}$$

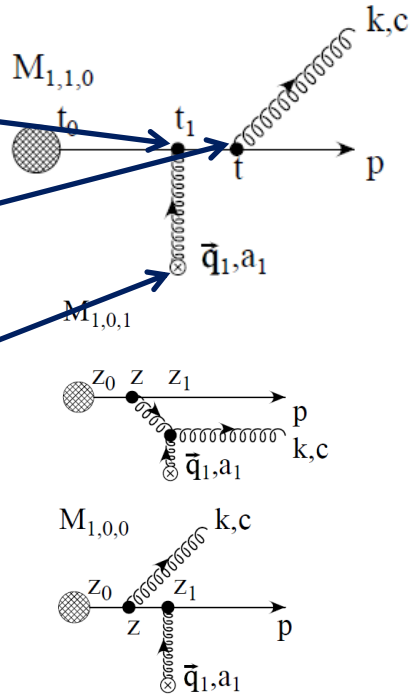


B. G. Zakharov, JETP Lett. 88 (2008) 781-786

- Two powers of $\alpha_s(Q^2)$ originate from the jet-medium interaction vertices; the exchanged transverse momentum is **q**, and $Q^2 = \mathbf{q}^2$
- One power $\alpha(Q^2)$ originates from the radiated gluon vertex; the off-shellness of the intermediate quark propagator in the amplitude where the gluon is emitted after the scattering is

$$Q_2^2 = q^2 - M^2 = \frac{\mathbf{k}^2}{x_+(1-x_+)} + \cancel{\frac{x_+ M^2}{1-x_+}} + \cancel{\frac{m_g^2}{x_+}}$$

- An ambiguity arises from other amplitudes for example if the radiated gluon scatters with q instead of the quark. In eikonal limit, assuming mass effects are negligible, keep only k perp term
- One power of the thermal coupling originates from the Debye mass $m_D(\alpha(Q^2), T)$; the scale is set to be proportional to the temperature of the plasma, $Q^2 = (2T)^2$



Multi-scale Running Coupling: Elastic

- S. Peigne and A. Peshier, PRD 77, 114017 (2008)
- In the limit of E >> k (the momentum of target particle in the medium), approximate parton-parton elastic cross section as

$$\frac{d\sigma_{i,j}}{d\hat{t}} = \frac{2\pi\alpha^2}{\hat{t}^2} c_{i,j}$$

- Energy loss per unit length

$$\frac{dE}{dx} = \int d^3k\, \rho_i(k)\Phi \int_{\hat{t}_{MIN}}^{\hat{t}_{MAX}} d\hat{t} \frac{d\sigma_{i,j}}{d\hat{t}} \cdot (E - E') \quad \begin{cases} E - E' = -\dfrac{\hat{t}}{2k(1-\cos\theta)} \\ \Phi = 1 - \cos\theta \ . \end{cases}$$

$$\frac{dE}{dx} = -\pi C_R \frac{\alpha^2}{\beta^2}\left(1 + \frac{n_f}{6}\right)\log B \longleftrightarrow \frac{dE}{dx} = \frac{4\pi}{3} C_F \alpha_s^2 T^2 \left(\frac{1}{v} + \frac{v^2-1}{2v^2}\log\frac{1+v}{1-v}\right)\log\left(\frac{k_{max}}{\mu_D}\right)$$

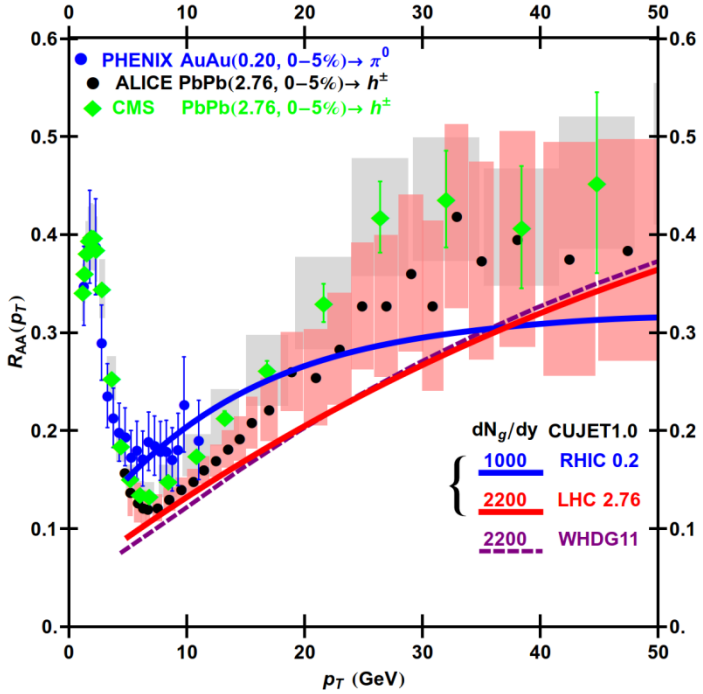
$$\alpha_s^2 \int_{\mu^2}^{4ET} \frac{d\hat{t}}{\hat{t}} \longrightarrow \int_{\mu^2}^{4ET} \frac{d\hat{t}}{\hat{t}} \alpha_s^2(\hat{t})$$

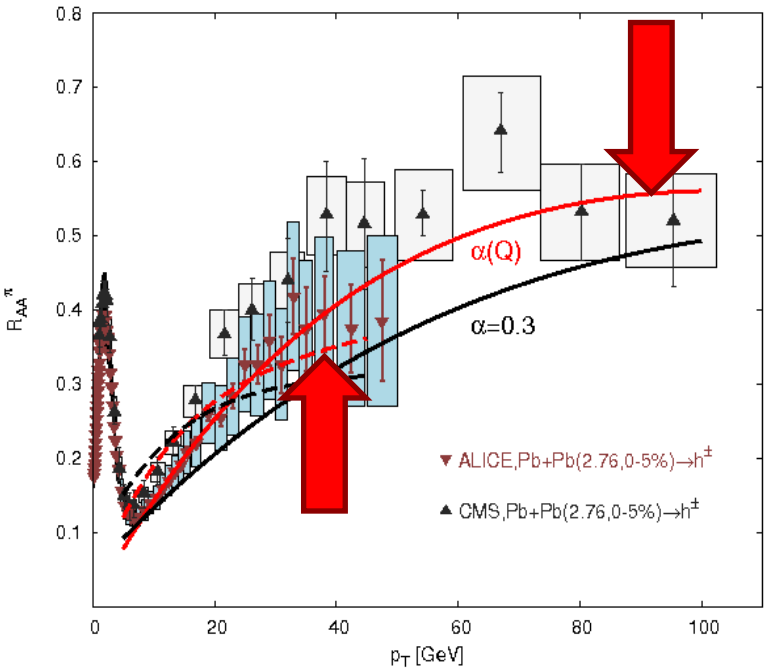
$$\alpha_s(|t|) = \left[4\pi\beta_0 \ln\left(|t|/\Lambda^2\right)\right]^{-1}$$

$$q_\perp^{MAX} = \sqrt{4ET}$$

$$\alpha_s^2 \log\frac{4ET}{\mu^2} \longrightarrow \alpha_s(\mu^2)\alpha_s(4ET)\log\frac{4ET}{\mu^2(\alpha_s(4T^2);T)}$$

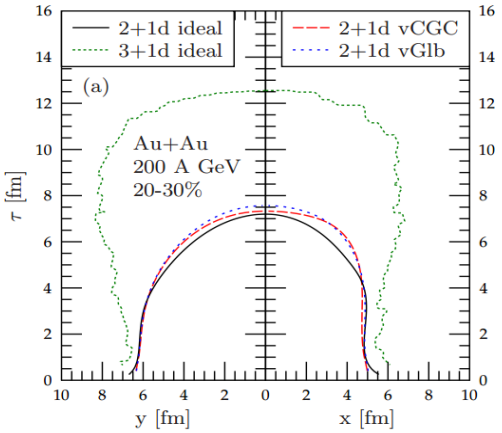
Radiative Running Coupling Effects at LHC via CUJET1.0

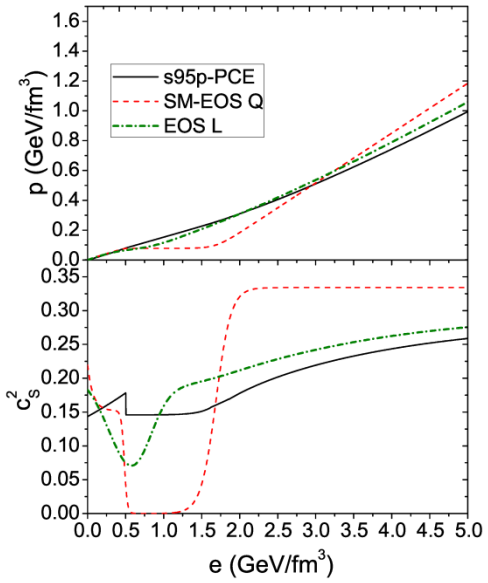




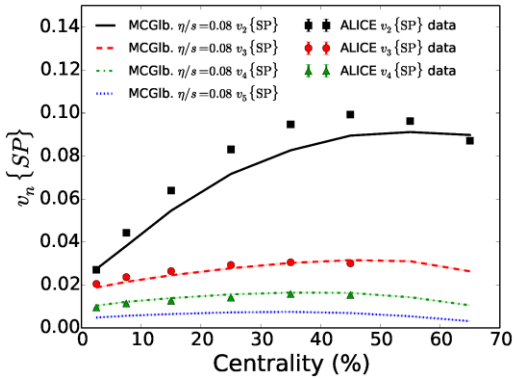
- Running coupling CUJET fits (by eye ball) the pion RAA of RHIC and LHC with the same maximum coupling 0.4 in a Glauber transverse + Bjorken longitudinal profile, but RAA's low pT rising and high pT saturating behavior is not manifest enough

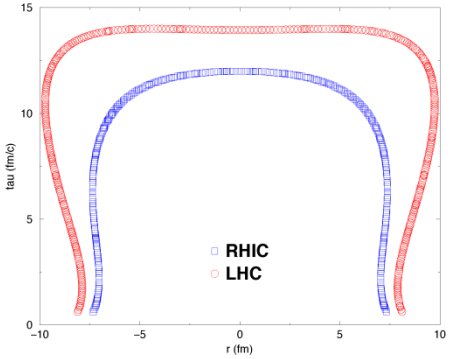
CUJET2.0 = rcDGLV + Elastic + 2+1D Viscous Hydro





- Couple rcDGLV to VISH 2+1D expanding QGP fluid fields (T(x,t),v(x,t))
- RHIC Au+Au 200AGeV & LHC Pb+Pb 2.76ATeV
  - Equaiton of State: s95p-v0-PCE
  - Initial Condition: MC-Glauber
  - η/s=0.08
  - Initial Time: 0.6fm/c
  - Cooper-Frye freeze-out temperature: 120MeV
- Compatible with measurements of low pT particle production spectra and flow harmonics

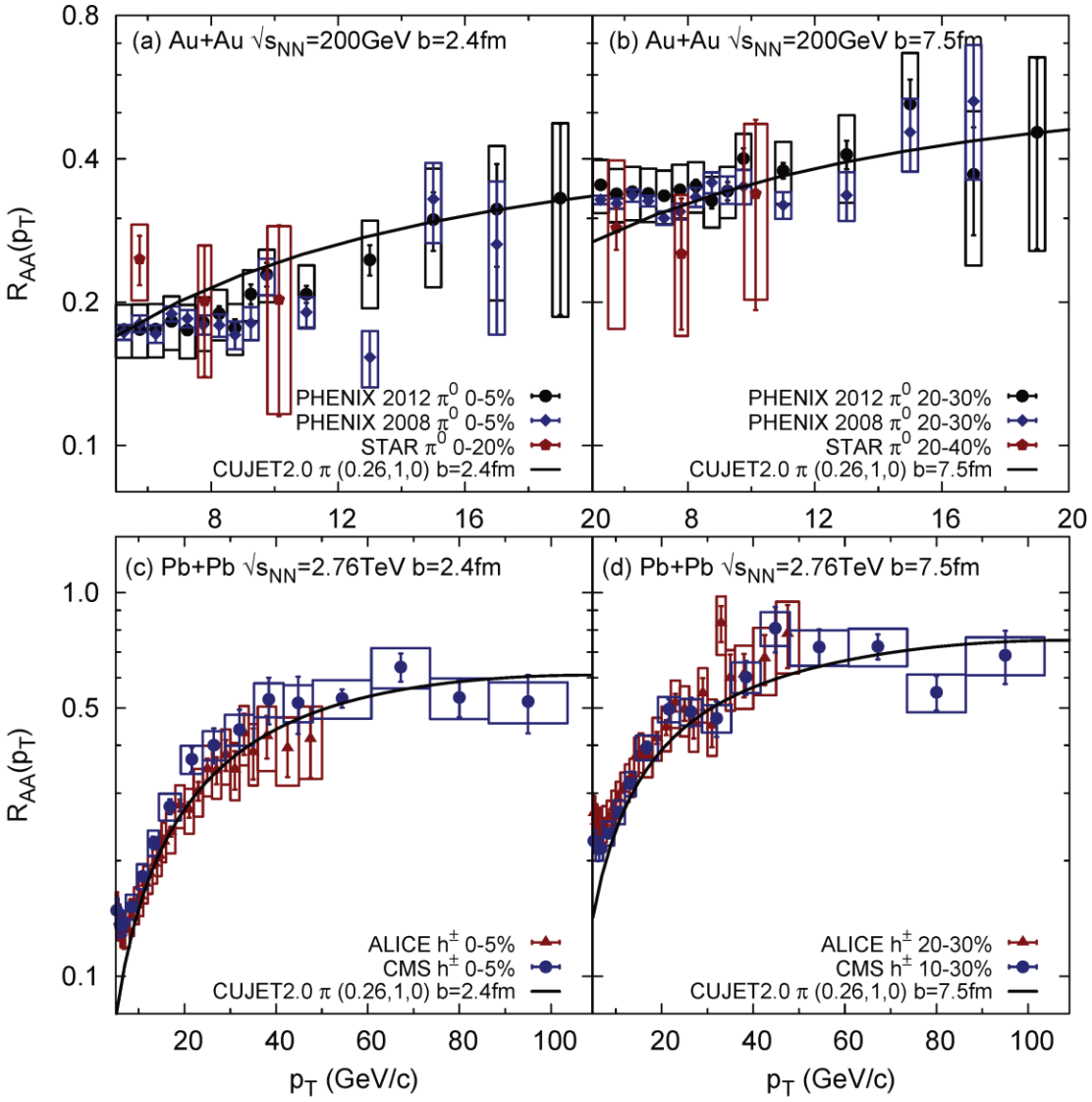




T. Renk, H. Holopainen, U. Heinz and C. Shen, PRC 83, 014910 (2011)
C. Shen, U. Heinz, P. Huovinen and H. Song, PRC 82, 054904 (2010)
H. Song and U. Heinz, PRC 78, 024902 (2008)

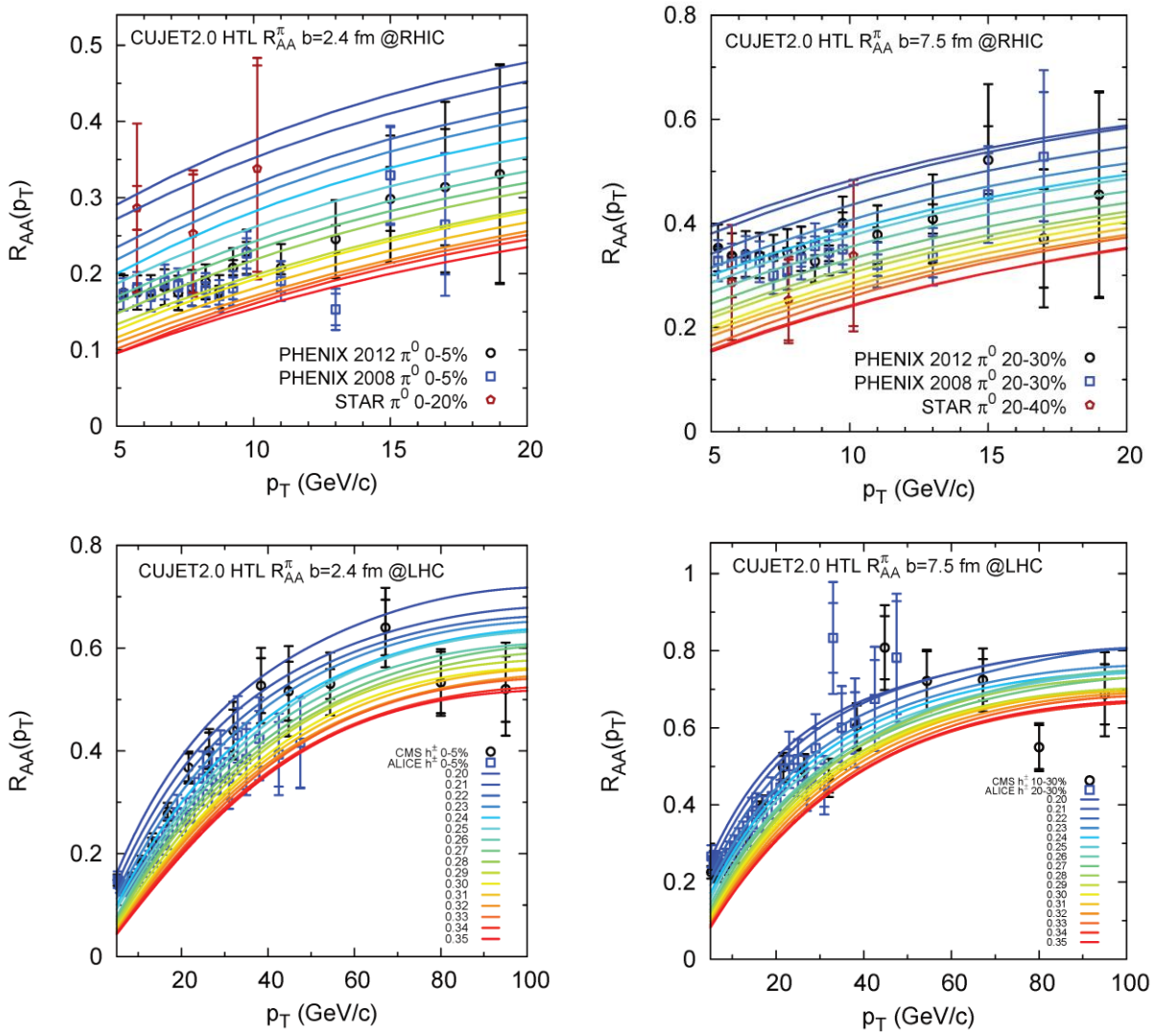
Chun Shen, Private Communication

CUJET2.0 Result: R_{AA} at RHIC and LHC



- $(\alpha_{max}, f_E, f_M) = (0.26, 1, 0)$
- The pion R_{AA} is compatible with both RHIC and LHC data in both central and semi-peripheral collisions
  - The same choice of running coupling but with a different medium evolution background can still explain the surprising transparency at LHC
- Clearer tendency of R_{AA} flattening at high p_T
- The coupling strength significantly deceases in an transverse expanding medium comparing to the static case
  - Comparing to a static medium, longer jet path length in a transverse expanding medium compensates the reduction in density and results in overall enhanced quenching

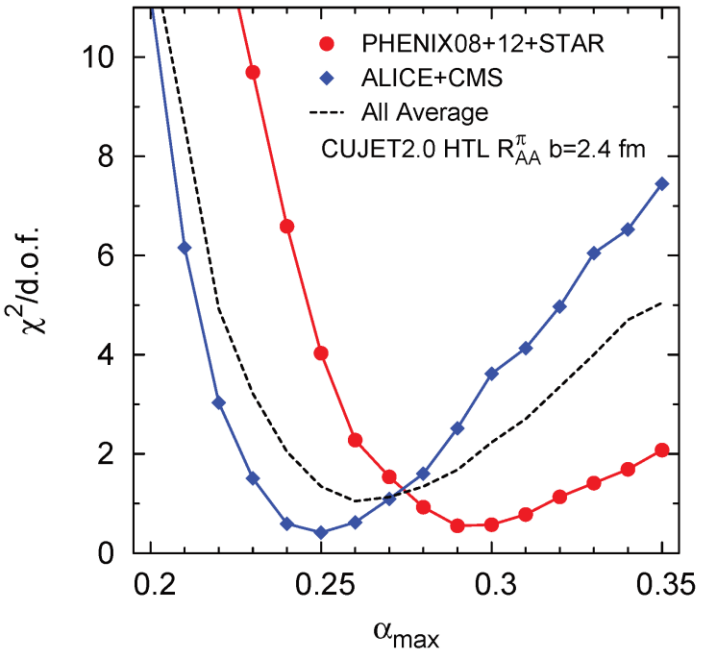
Fits by eyeball are not good enough, need chi^2 to quantify

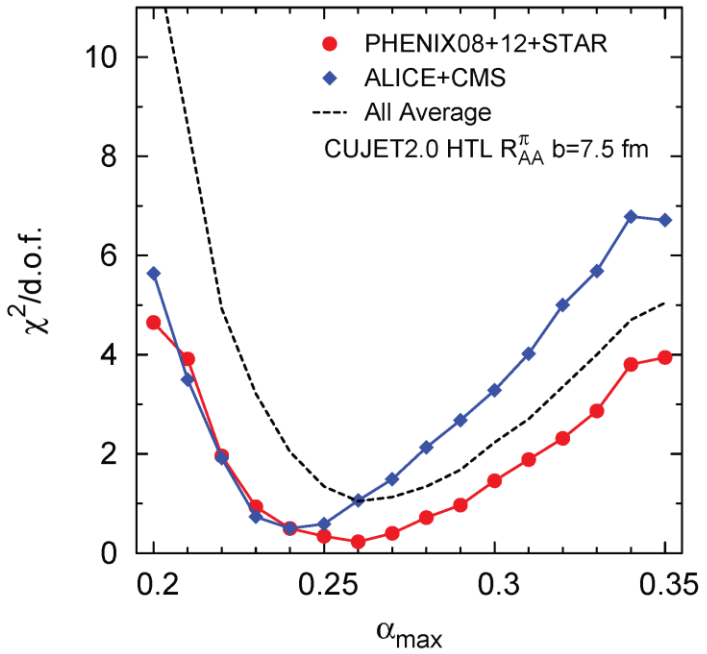


The JET Collaboration, arXiv:1312:5003

- Chi^2 analysis is necessary to determine the best fit amax value, we choose to compare data above 8GeV/c
- At low amax the increment in RAA is near uniform → asymptotically the fixed coupling limit
- Band width remains almost the same at RAA flattening region → for high pT rc is less important than expanding medium

Fits by eyeball are not good enough, need chi^2 to quantify





The JET Collaboration, arXiv:1312:5003

α_{max}	RHIC $\tilde{\chi}^2 < 1$	LHC $\tilde{\chi}^2 < 1$	RHIC $\tilde{\chi}^2 < 2$	LHC $\tilde{\chi}^2 < 2$
$b = 2.4$ fm	0.28-0.32	0.24-0.27	0.26-0.35	0.23-0.28
$b = 7.5$ fm	0.23-0.29	0.23-0.25	0.22-0.31	0.22-0.27

- $\alpha_{max} = 0.26 - 0.27$, if limit $\chi^2/d.o.f. < 2$ separately
- $\alpha_{max} = 0.25 - 0.27$, if average $\chi^2/d.o.f. < 1.5$

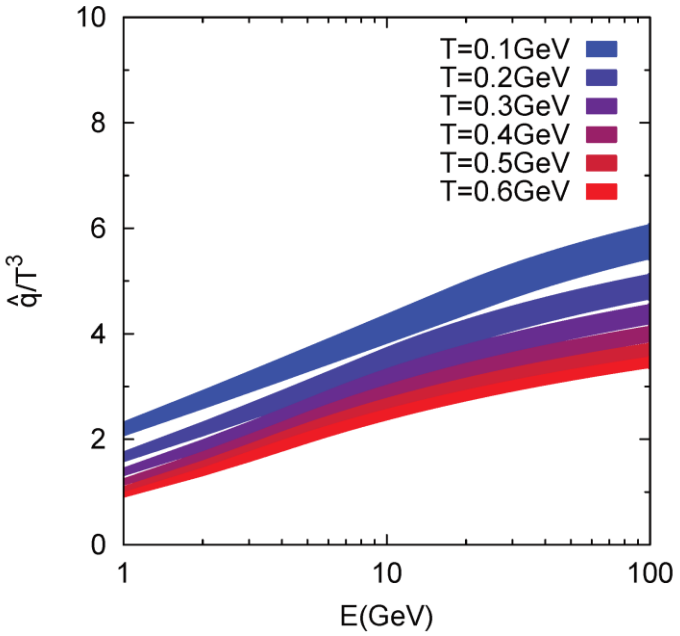
Jet Transport Coefficient in CUJET2.0

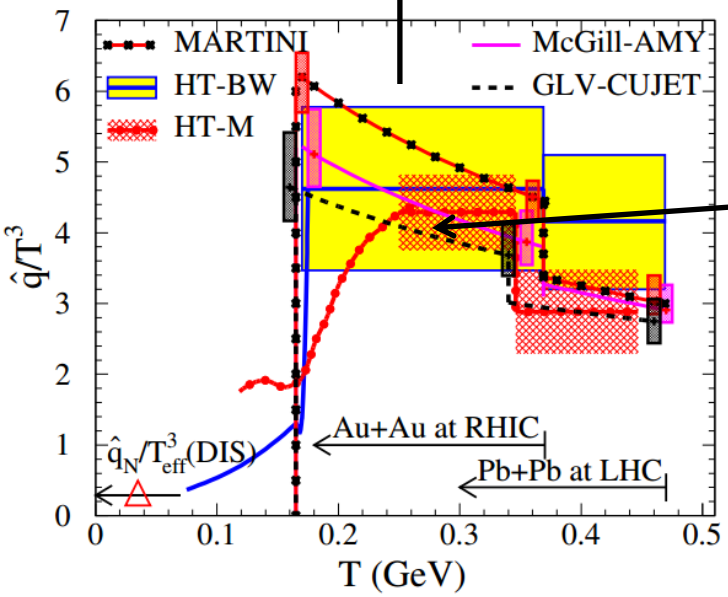
$$\hat{q}(E,T;\alpha_{max},f_E,f_M)=\rho(T)\int_0^{4ET} d\mathbf{q}^2\mathbf{q}^2\frac{d\sigma_{\rm eff}}{d\mathbf{q}^2}$$

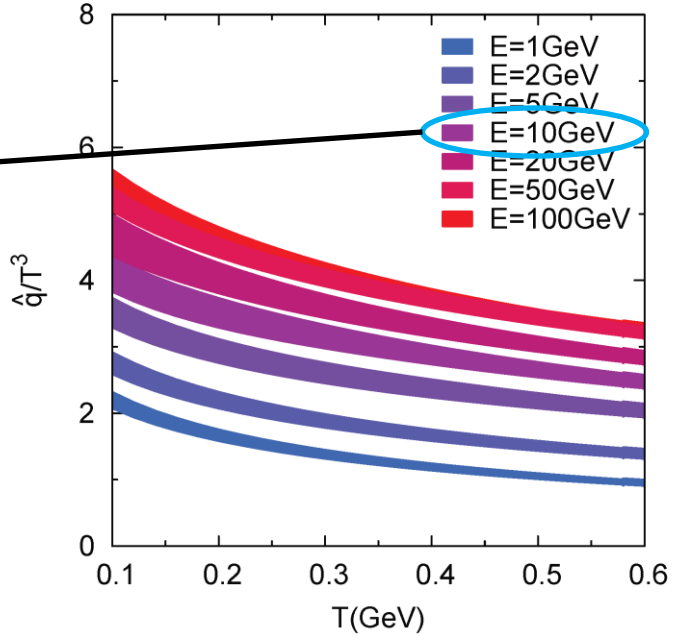
$$\frac{d\sigma_{\rm eff}}{d\mathbf{q}^2}=\frac{\alpha_{\rm s}^2(\mathbf{q}^2)(f_E^2-f_M^2)}{(\mathbf{q}^2+f_E^2\mu^2(T))(\mathbf{q}^2+f_M^2\mu^2(T))}$$

$$\mu(T)=T\sqrt{4\pi\alpha_s(4T^2)(1+n_f/6)}$$

$$\frac{\hat{q}}{T^3}\approx\begin{cases}4.6\pm1.2 & \text{at RHIC,}\\ 3.7\pm1.4 & \text{at LHC,}\end{cases}$$







The JET Collaboration, arXiv:1312:5003

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- Part I: CUJET2.0: A pQCD Model for Azimuthal Jet Flavor Tomography at RHIC and LHC
  - Radiative jet energy loss in QGP: (D)GLV Opacity Expansion
  - Pre-CUJET: WHDG/DGLV, heavy quark puzzle
  - CUJET1.0 = dynamical fixed coupling DGLV + elastic + trans. Glauber & long. Bjorken
  - The surprising transparency of QGP at LHC, multi-scale running strong coupling
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  - Why light quark and charged hadron RAA at RHIC and LHC are almost the same?
  - Heavy flavor RAA
  - Why pion and beauty RAA have an crossover?
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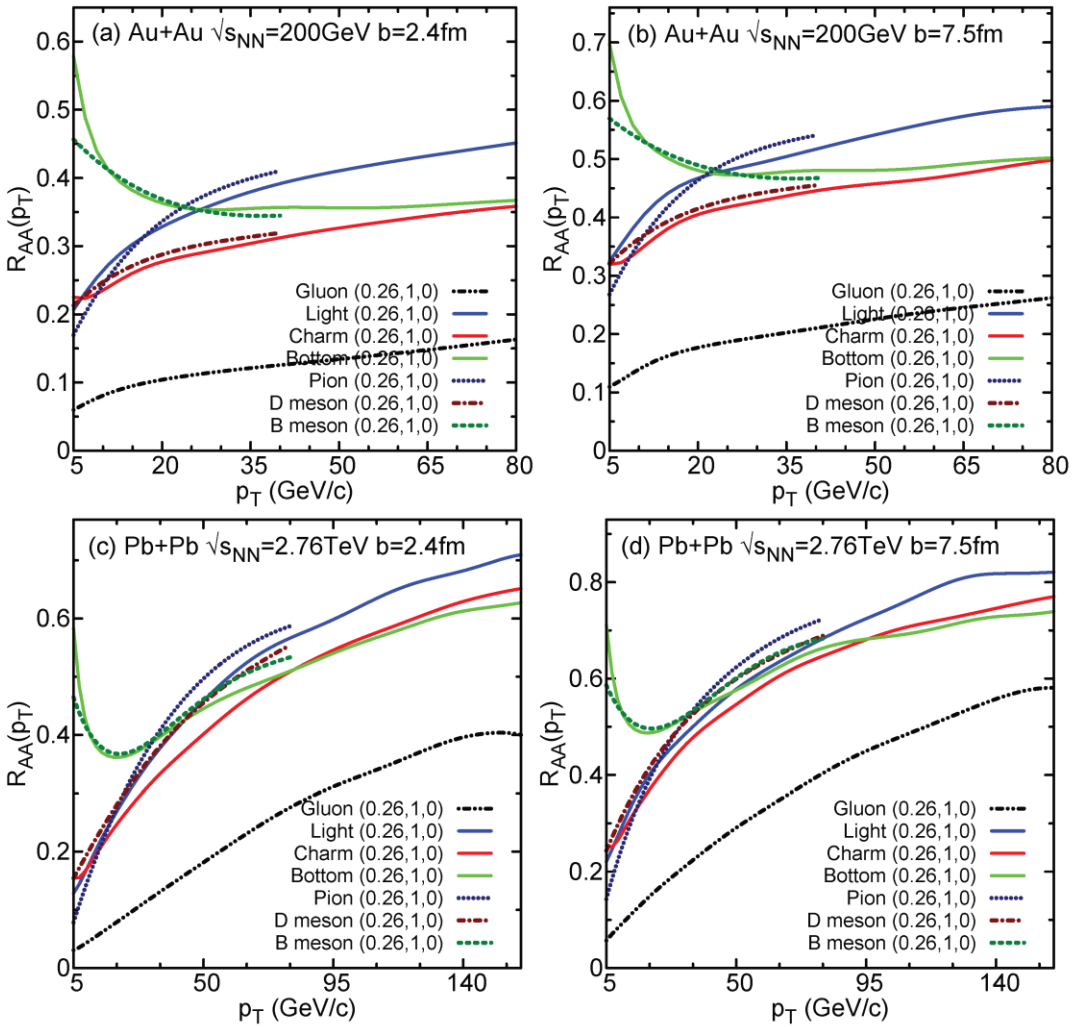
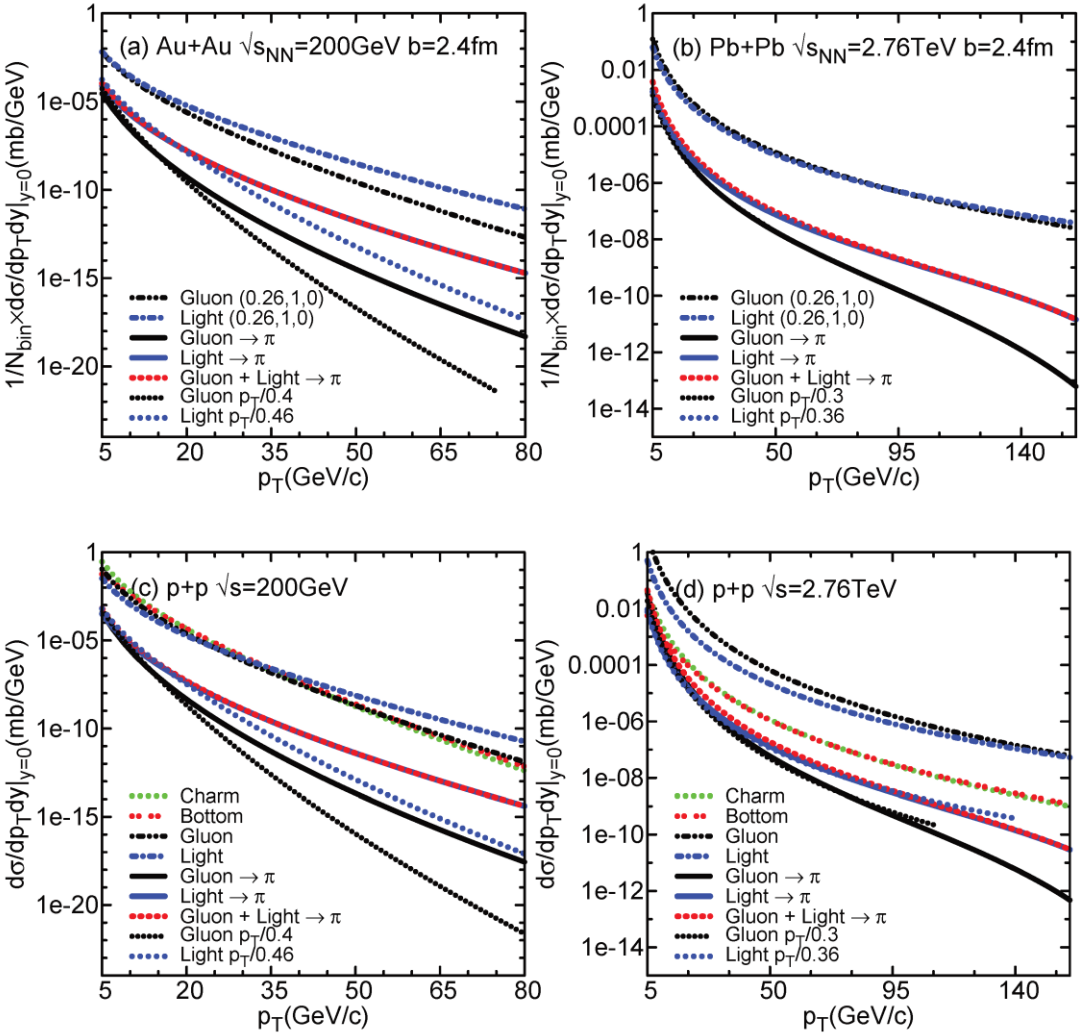
  - CUJET2.0: light flavor v2
  - CUJET2.0: heavy flavor v2
- Summary and Outlook

Partonic and Hadronic RAA vs pT at RHIC and LHC



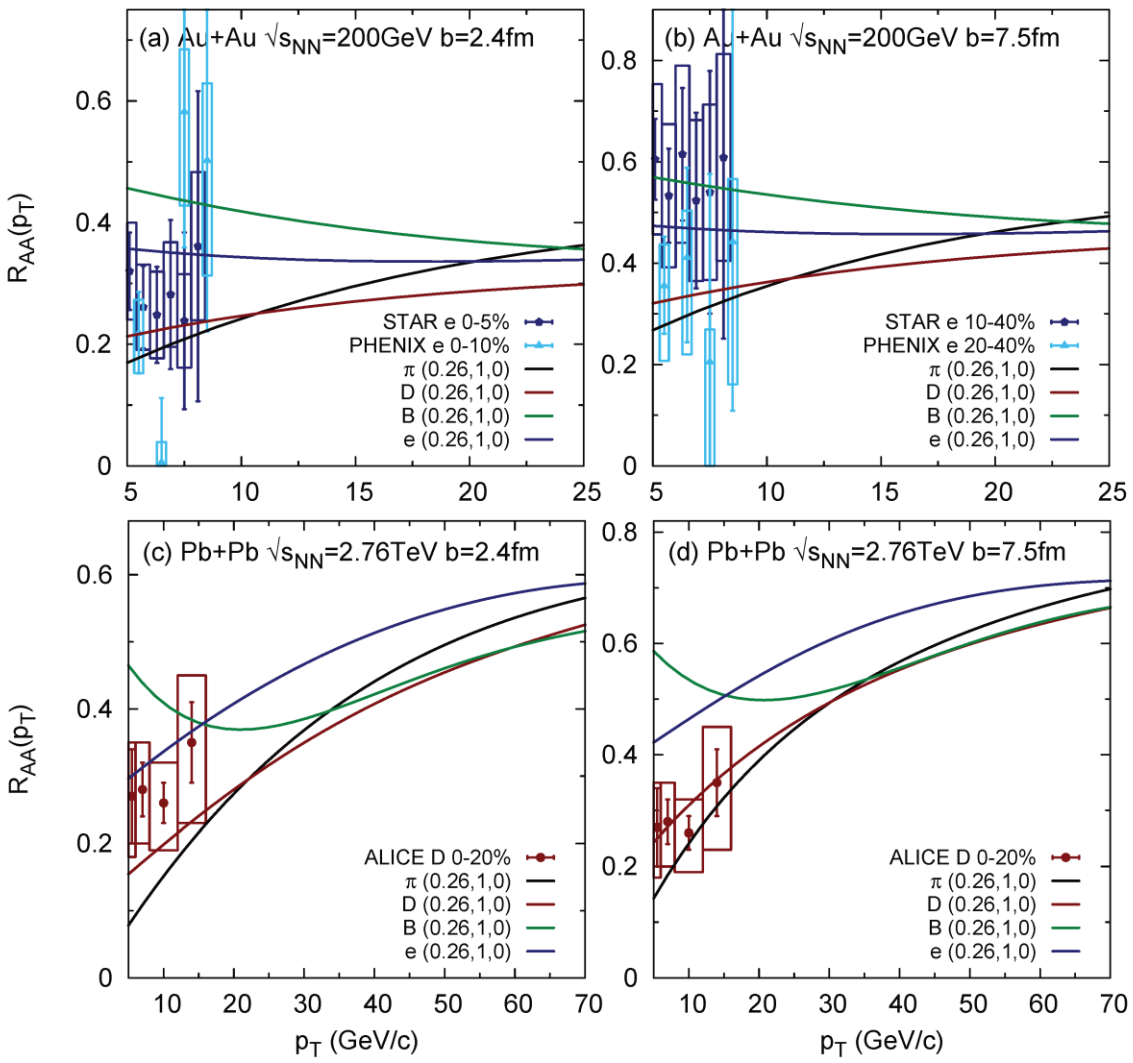
- Light quark RAA and pion/charged hardron RAA are almost the same at both RHIC and LHC, despite the fact that at LHC the gluon production is larger than quark

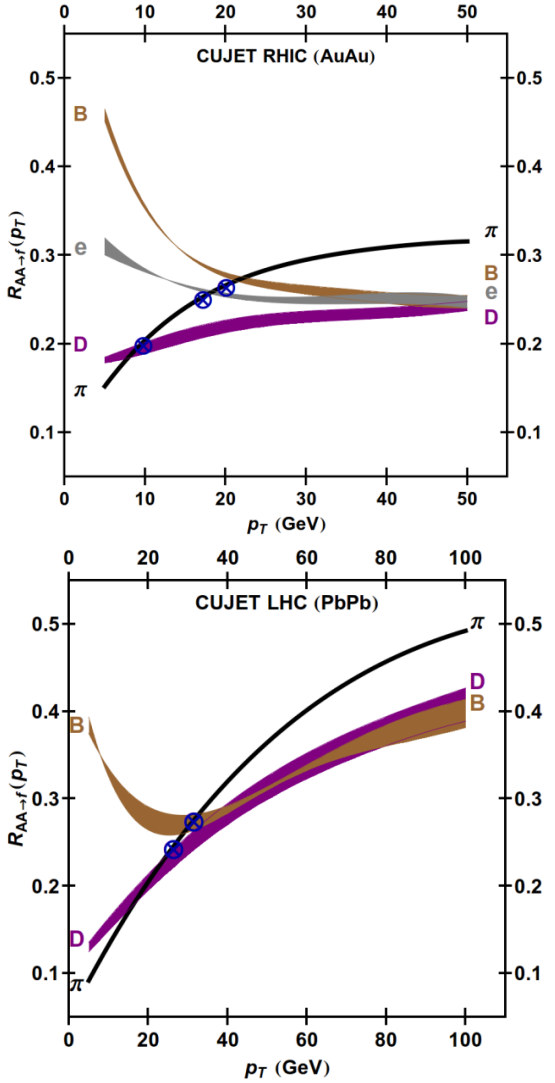
Similarity between light quark and pion RAA at RHIC and LHC



- Larger Casimir for gluon (C_R=3) than quark (C_R=4/3) leads to more energy loss for the gluon, brings their AA production spectra at LHC to the same level
- Different fragmentation ratios of gluon and quark to pion make the light quark's contribution to pion AA spectrum dominant

CUJET2.0 Result: Heavy Flavor at RHIC and LHC

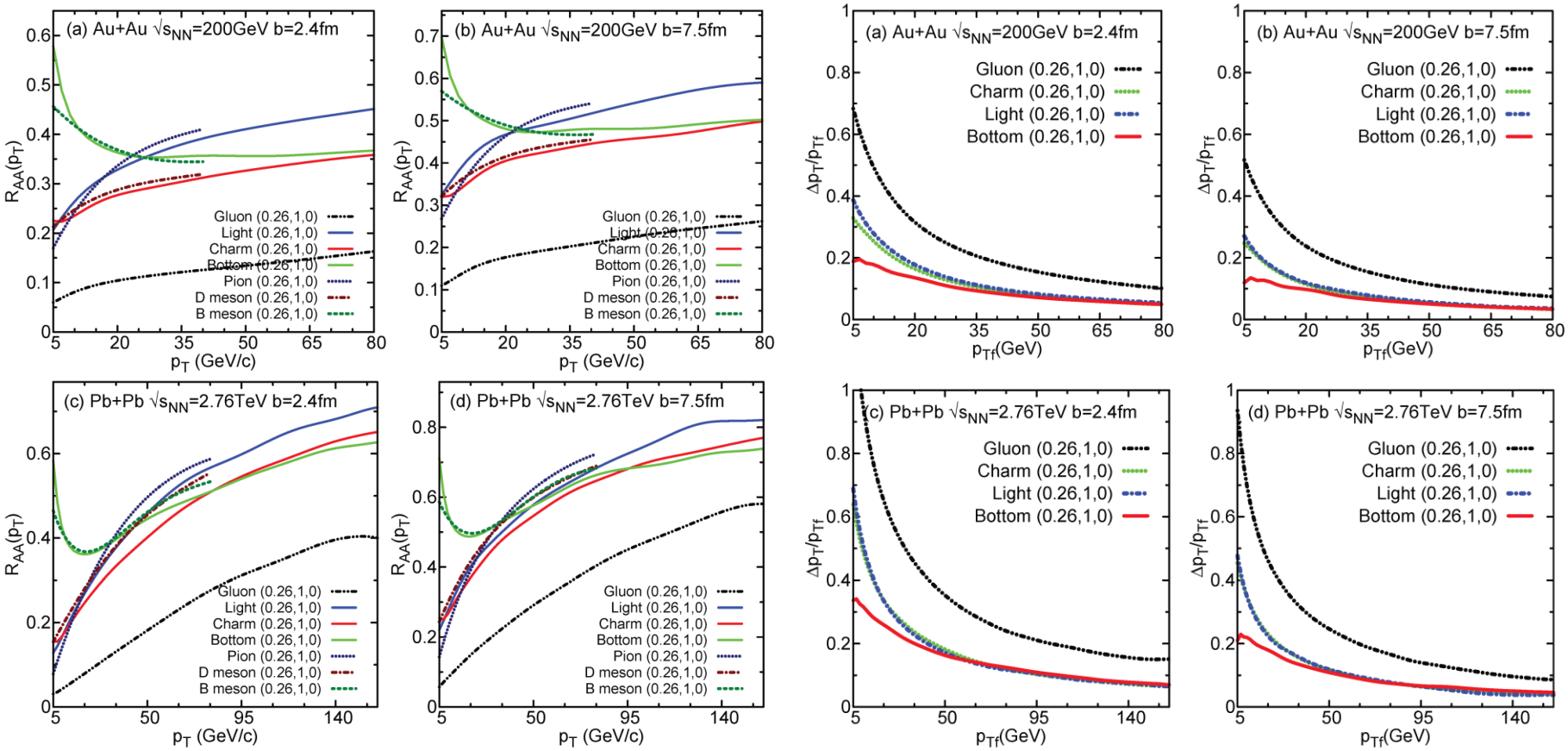




Buzzatti and Gyulassy, PRL (2012)

- Both CUJET1.0 and 2.0 solve "Heavy Quark Puzzle", suggesting the importance of realistic path length fluctuation, no approximation of initial production spectra and include dynamical QCD medium effect
- RAA crossing pattern insensitive to running coupling and medium evolution profile → Mass ordering encoded in DGLV+TG
- At low pT, charm and pion mixed together, beauty RAA is well above them

Why pion and beauty RAA have a level crossing?



$$\frac{d\bar{\sigma}^{AA\to h}}{d^3p_f} \equiv \frac{1}{N_{bin}}\frac{d\sigma^{AA\to h}}{d^3p_f} = \frac{d\sigma^{pp\to q}}{d^3p_i} \otimes P(E_i(p_i) \to E_f(p_f)) \otimes D(q \to h)$$

- The pp spectrum and partonic energy loss theory combined to lead to the level crossing, and the former plays a more critical role

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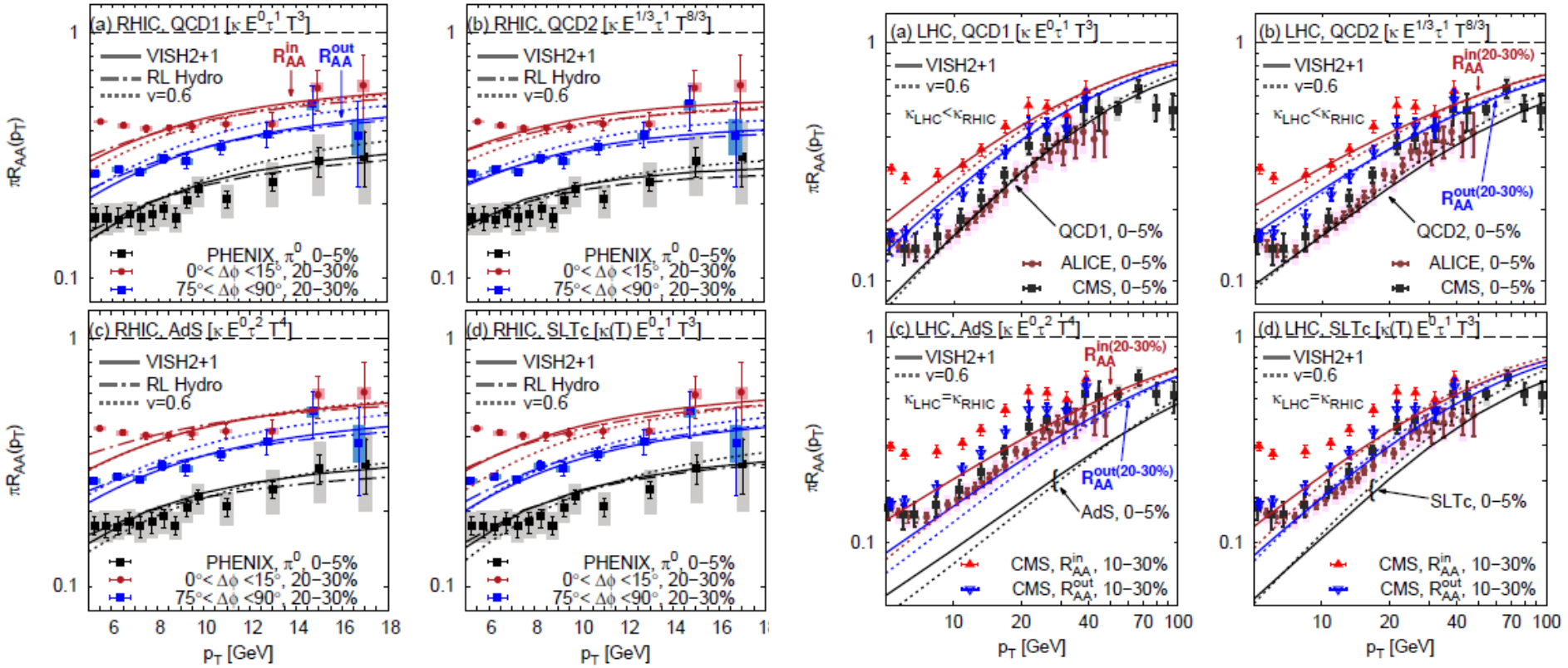
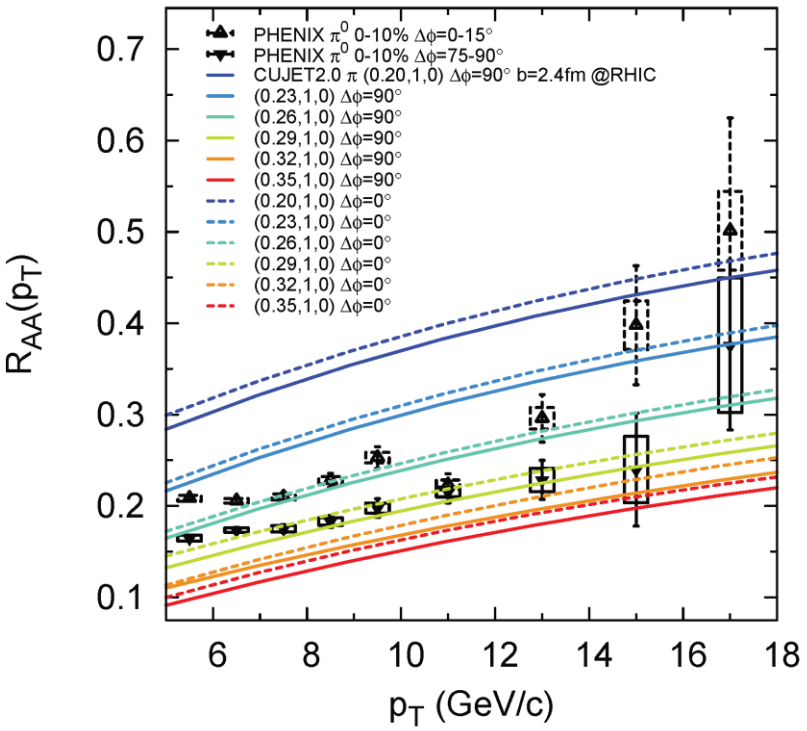
Consistency with (RAA & v2) AND (RHIC & LHC) AND (central & peripheral)

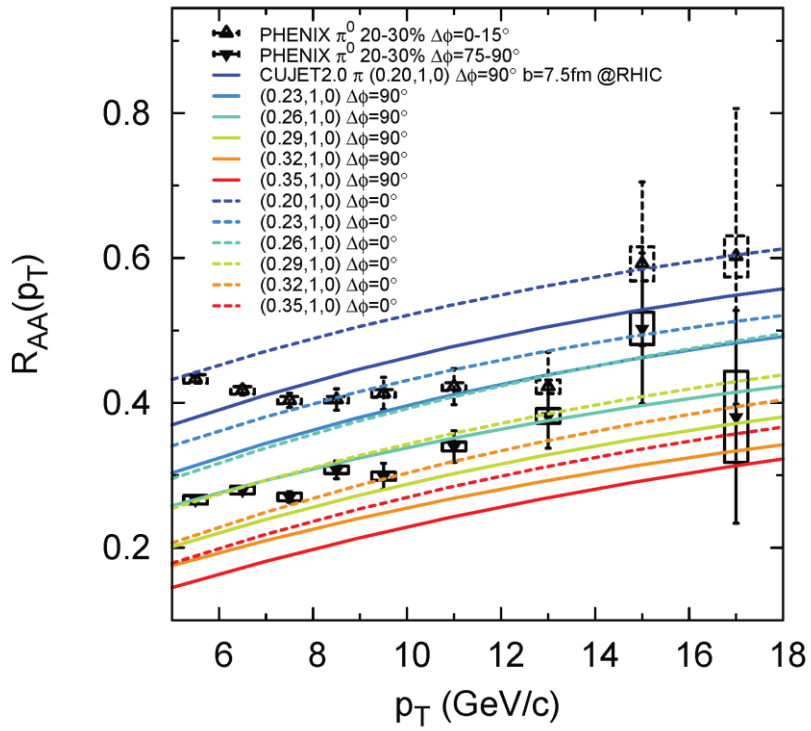


- B. Betz and M. Gyulassy, arXiv:1305.6458
  - QCD1→ rcCUJET1.0; QCD2 → fcCUJET1.0; AdS → fixed t'Hooft conformal falling string; SLTc → Shuryak-Liao assuming Tc dominated
  - VISH2+1-Shen,Heinz,Song; RL-Romatschke,Luzum
  - QCD1 (0,1,3) (WITHOUT energy loss fluctuation) is the simplest minimal dEdx phenomenology compatible with all 8 combinations of jet quenching data
- D. Molnar and S. Deke, arXiv:1305.1046
  - R_{AA} and v_2 cannot be satisfied with the same set of parameters in MPC+GLV

CUJET2.0 Result: pion suppression factor w.r.t. reaction plane

$$\frac{dN_h}{dydp_Td\phi} = \frac{dN_h}{dydp_T}\frac{1}{2\pi}\left(1 + 2v_1\cos\phi + 2v_2\cos 2\phi + \cdots\right) \rightarrow \begin{cases} R_{AA}^{in}(y,p_T) = \dfrac{\frac{dN_h^{AA}}{dydp_Td\phi}|_{\phi=0}}{N_{binary}\frac{dN_h^{pp}}{dydp_Td\phi}|_{\phi=0}} = \dfrac{\frac{dN_h^{AA}}{dydp_T}\frac{1}{2\pi}\left(1 + 2v_1 + 2v_2 + \cdots\right)}{N_{binary}\frac{dN_h^{pp}}{dydp_Td\phi}|_{\phi=0}} \\ R_{AA}^{out}(y,p_T) = \dfrac{\frac{dN_h^{AA}}{dydp_Td\phi}|_{\phi=\frac{\pi}{2}}}{N_{binary}\frac{dN_h^{pp}}{dydp_Td\phi}|_{\phi=\frac{\pi}{2}}} = \dfrac{\frac{dN_h^{AA}}{dydp_T}\frac{1}{2\pi}\left(1 - 2v_2 - \cdots\right)}{N_{binary}\frac{dN_h^{pp}}{dydp_Td\phi}|_{\phi=\frac{\pi}{2}}} \end{cases}$$





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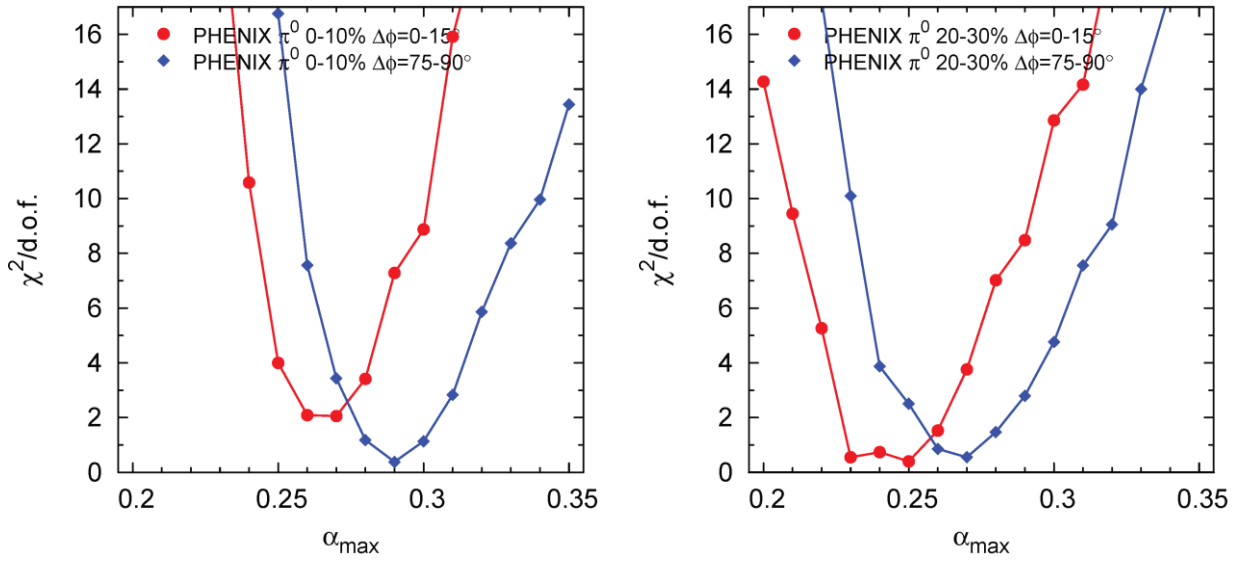
$b = 2.4$ fm	0.28-0.32	0.24-0.27	0.26-0.35	0.23-0.28
$b = 7.5$ fm	0.23-0.29	0.23-0.25	0.22-0.31	0.22-0.27

- No amax can reproduce the gap between RAAin and RAAout at RHIC
- Recall the chi^2<2 spans a pT range for each collision → What is the best v2 within uncertainty?

CUJET2.0 Result: pion suppression factor w.r.t. reaction plane



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- Choose $\alpha_{max} = 0.23$ $(7.5fm + IN)$, 0.26 $(7.5fm + OUT)$, 0.26 $(7.5fm + IN)$, 0.29 $(7.5fm + OUT)$, the average R_{AA} falls within respective $\chi^2/d.o.f. <$ 2 window, while R_{AA}^{in} and R_{AA}^{out} are in perfect agreements with RHIC data
- As less as 10% azimuthal variation of path averaged α_{max} can account for the underestimated gap between R_{AA}^{in} and R_{AA}^{out} at RHIC
- Interesting ordering: in terms of naive path length from the origin, $7.5fm + IN < 7.5fm + OUT \approx 2.4fm + IN < 2.4fm + OUT$, the corresponding α_{max}: $0.23 < 0.26 = 0.26 < 0.29$.
- Model is fully constrained at RHIC, how about extrapolation to LHC?

CUJET2.0 Result: pion v2

$$\begin{cases} R_{AA}^{in}(p_T) \approx \dfrac{\frac{dN_h^{AA}}{dydp_T}(1+2v_2+2v_4\cdots)}{N_{binary}\frac{dN_h^{pp}}{dydp_T}} = R_{AA}^{h}(1+2v_2+2v_4\cdots) \quad , \\ R_{AA}^{out}(p_T) = \dfrac{\frac{dN_h^{AA}}{dydp_T}(1-2v_2-2v_4\cdots)}{N_{binary}\frac{dN_h^{pp}}{dydp_T}} = R_{AA}^{h}(1-2v_2-2v_4\cdots) \quad . \end{cases}$$

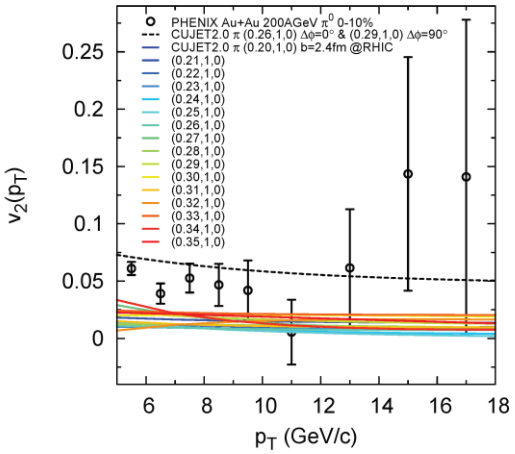
$$\downarrow$$

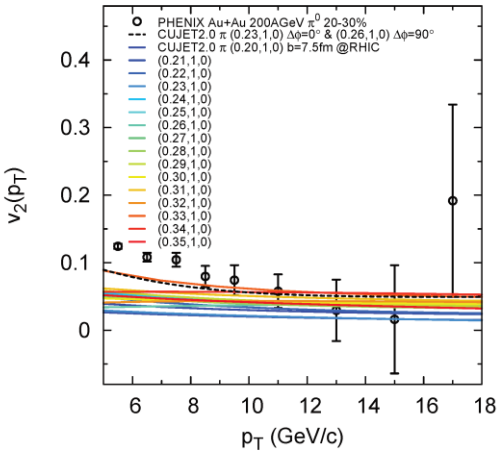
$$\begin{cases} R_{AA}^{in}(p_T) \approx R_{AA}^{h}(1+2v_2) \quad , \\ R_{AA}^{out}(p_T) \approx R_{AA}^{h}(1-2v_2) \quad , \end{cases}$$

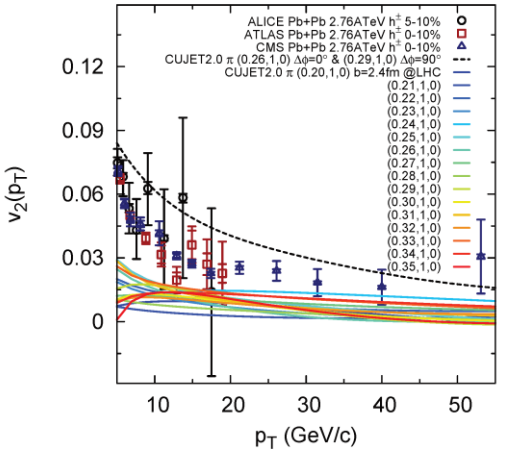
$$\downarrow$$

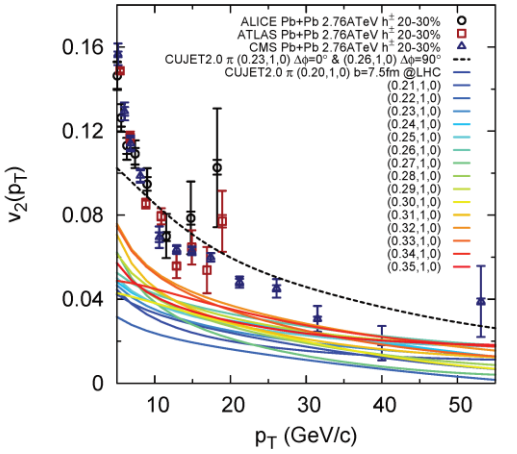
$$v_2(p_T) = \frac{1}{2}\frac{R_{AA}^{in}(p_T) - R_{AA}^{out}(p_T)}{R_{AA}^{in}(p_T) + R_{AA}^{out}(p_T)}$$

- Extrapolation to LHC fits v2!
  - RAA is compatible with data in this anisotropic amax scenario as well
  - As less as 10% azimuthal variation in jet path averaged strong coupling can render simultaneous fit of RAA and v2
  - This magnitude of variation is very modest in comparison to Shuryak-Liao huge non-perturbative near Tc enhancement of the effective jet medium coupling
- On the other hand, given this sensitivity of v2 on amax, calculating the exact running scales in GLV are important
  - NLO or BLM?









$\chi^2/d.o.f.$ $(b = 7.5$ fm$)$	v_2, RHIC	v_2, LHC	R_{AA}, RHIC	R_{AA}, LHC
$\alpha_{max}^{in} = 0.23,\ \alpha_{max}^{out} = 0.23$	3.72	43.03	0.93	0.73
$\alpha_{max}^{in} = 0.26,\ \alpha_{max}^{out} = 0.26$	2.06	24.89	0.23	1.06
$\alpha_{max}^{in} = 0.23,\ \alpha_{max}^{out} = 0.26$	0.50	4.92	0.42	0.54

On the azimuthal angle dependence of maximum coupling constant in CUJET2.0

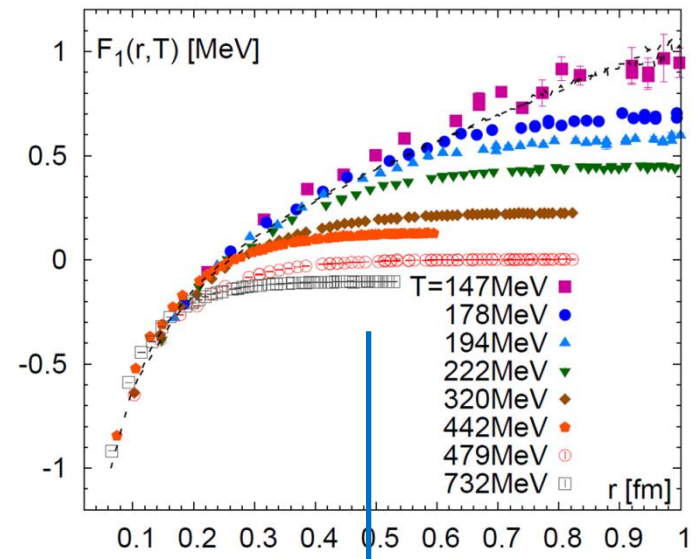
- Lattice QCD free energy of static qqbar pair
  - Bazavov and Petreczky, J.Phys.Conf.Ser.458 (2013) 012012 & J.Phys.Conf.Ser.432 (2013) 012003
- Interpolate the form of effective potential and running coupling from lattice data

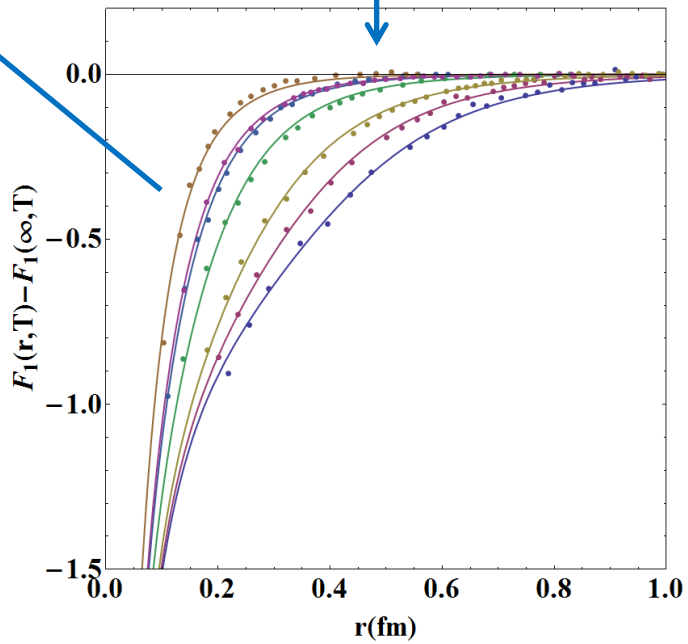
$$F_1(r,T) - F_1(\infty,T) = -\frac{0.71e^{-0.635T^{0.395}r}}{r\log[(\frac{0.35}{r})^3 + (\frac{T}{156})^3]}$$

$$\alpha_s(q, T(\mathbf{z} = \vec{x}_{0\perp} + \tau\hat{\phi})) \rightarrow \alpha_{max}(\hat{\phi})$$

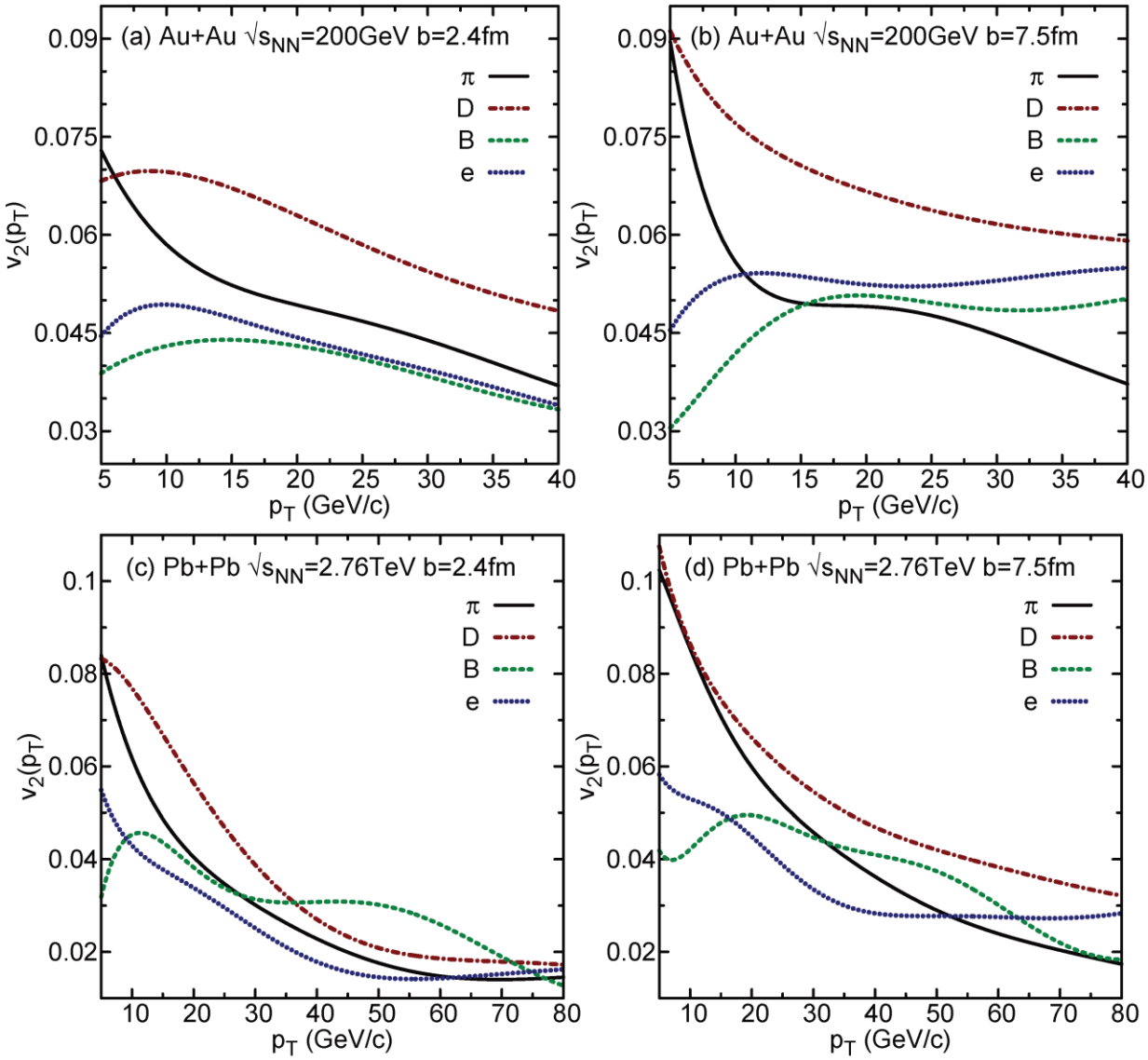
- The running strong coupling has local temperature dependence, since in present framework the coupling runs solely with energy, this local T effect may be reflected as azimuthal variation of path averaged maximum coupling

Bazavov and Petreczky, J.Phys.Conf.Ser.458 (2013) 012012 & 432 (2013) 012003





CUJET2.0 Result: heavy flavor v_2



- B meson v2 has a peak at pT~10GeV @ b=2.4fm and pT~20GeV @ b=7.5fm at both RHIC and LHC
- Semi-ordering of the position of the peak for different flavor v2

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  - CUJET2.0 = dynamical running coupling DGLV + elastic + 2+1D viscous hydro
  - CUJET2.0 results on pion/charged hadron RAA and jet transport coefficient
- Part II: CUJET2.0 Jet Quenching Phenomenology
  - Why light quark and charged hadron RAA at RHIC and LHC are almost the same?
  - Heavy flavor RAA
  - Why pion and beauty RAA have an crossover?
- Part III: The jet v2 open problem
  - Puzzle: consistency with (RAA & v2) AND (RHIC & LHC) AND (central & peripheral)
  - CUJET2.0: reaction plane dependent jet quenching pattern
  - CUJET2.0: light flavor v2
  - CUJET2.0: heavy flavor v2
- Summary and Outlook

Summary and Outlook

Summary

- CUJET2.0 = running coupling DGLV + Elastic + 2+1D Viscous Hydro.
- CUJET can solve heavy quark energy loss puzzle mainly because of the inclusion of pQCD pp spectra and realistic path length fluctuations.
- After contrained all paramters at RHIC, CUJET2.0 can explain LHC charged hadron RAA's steep rising and subsequent flattening feature.
- CUJET2.0 predicts that beauty and pion/charged hadron RAA have a robust intersection which is largely resulted from the shape of the pp spectrum.
- As less as 10% azimuthal variation in path averaged strong coupling can gain simultaneous fit of both R_{AA} and v_2 at both RHIC and LHC in both central and semi-peripheral collisions within the CUJET2.0 framework.

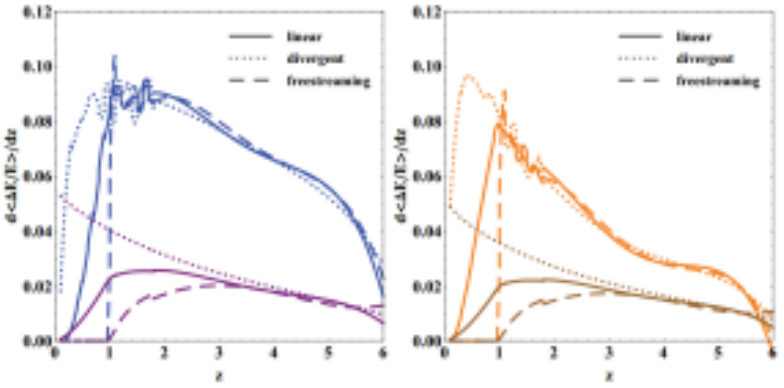
Outlook

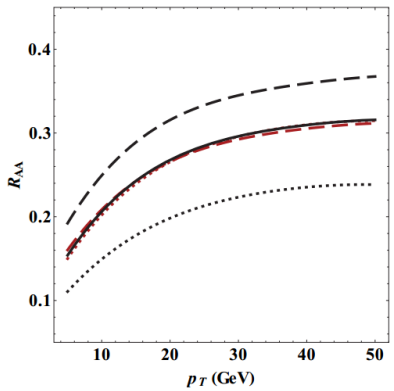
- Extrapolate an effective running coupling and scattering potential from lattice QCD data of non-perturbative qqbar potential V(r,T), examine whether lattice QCD predicts the correct jet medium physics near Tc.
- Explore Shuryak-Liao magnetic monopole Tc enhancement picture in the CUJET2.0.
- Develop the algorithm to realize calculation of jet-hadron correlation observables in the CUJET.

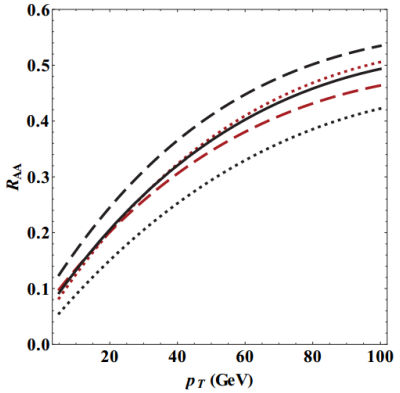
Thank you!

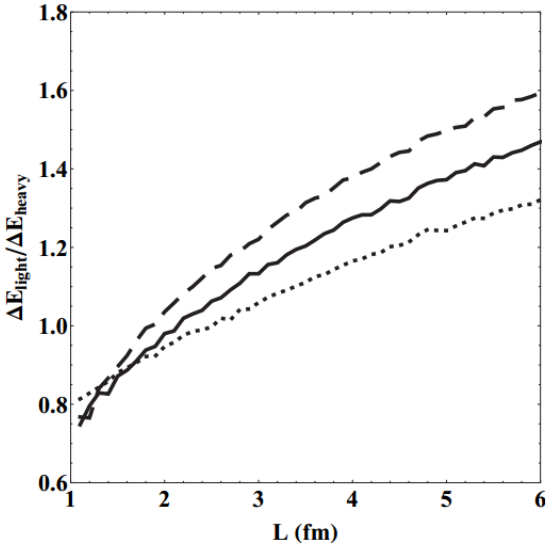
Backup

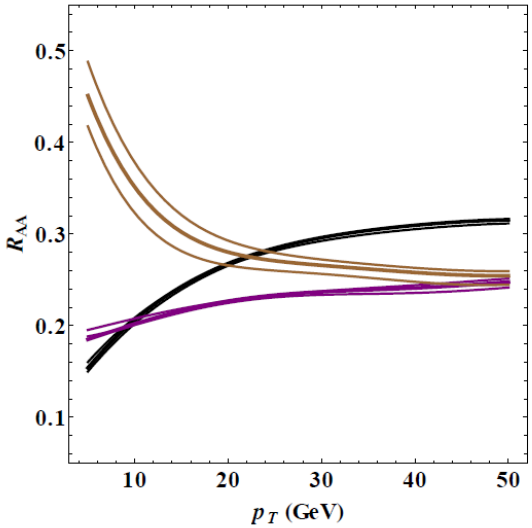
Heavy Flavor – Pre-thermal Scheme

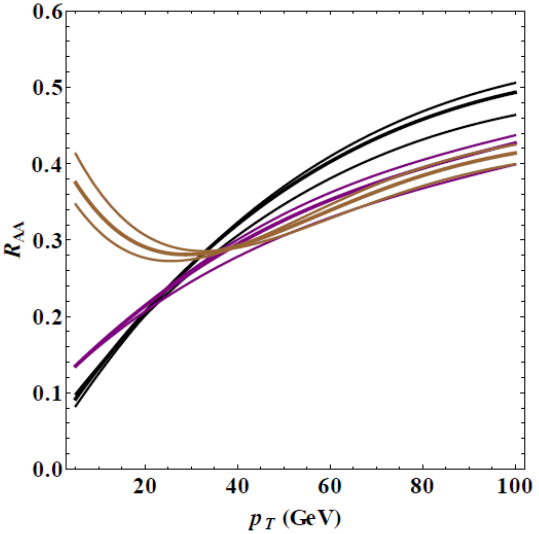




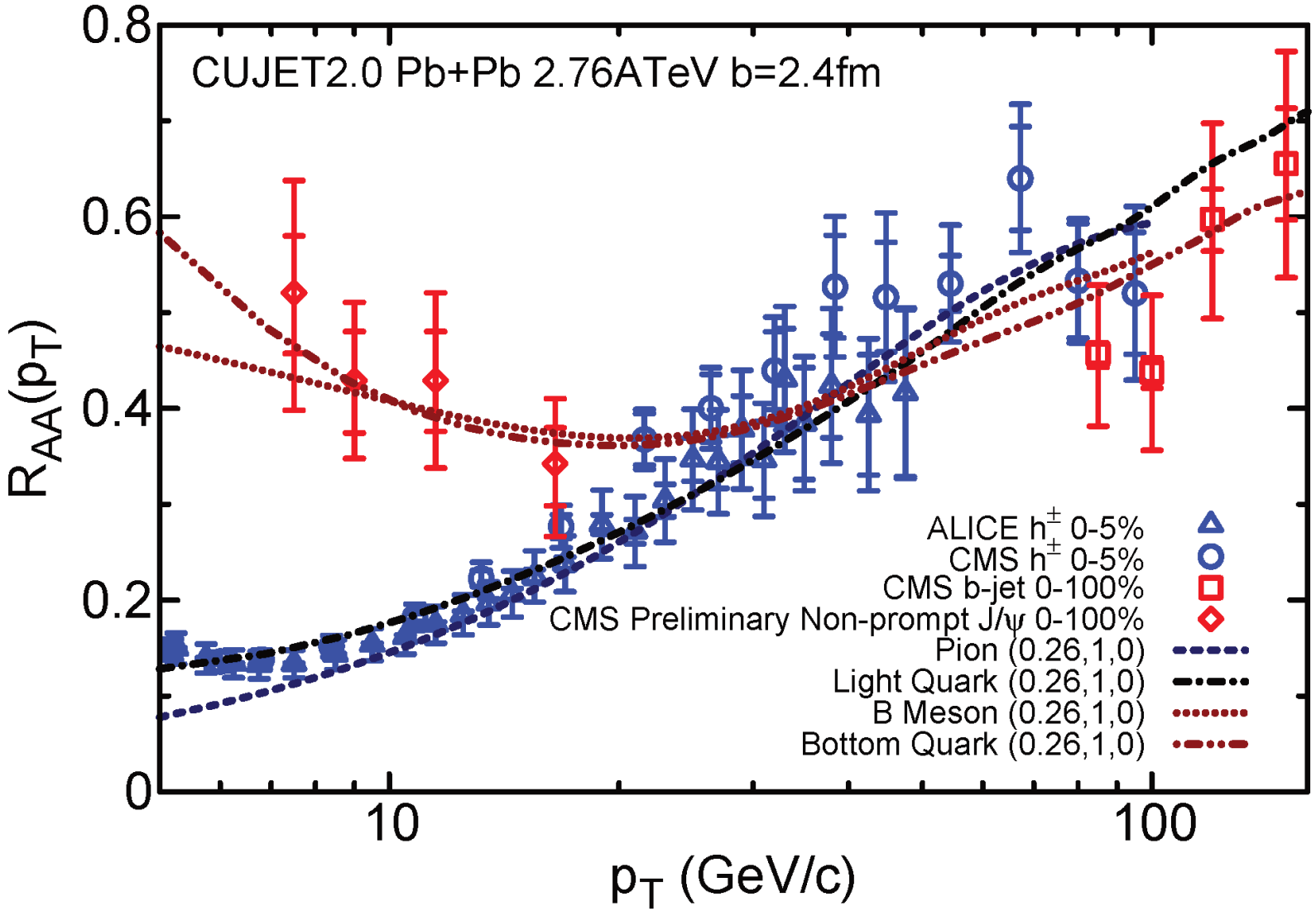




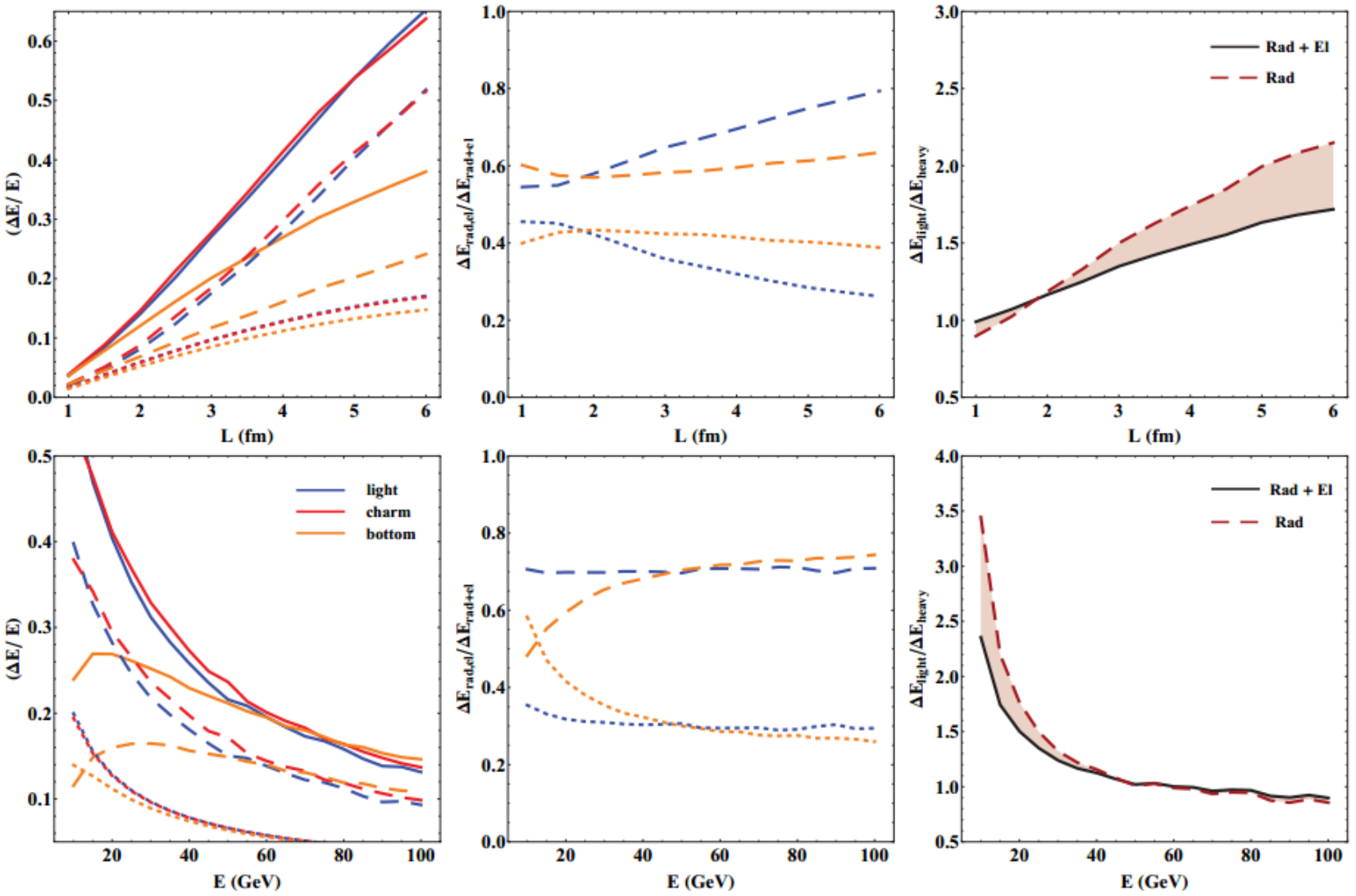




Crossing


CUJET2.0 Pb+Pb 2.76ATeV b=2.4fm
$R_{AA}(p_T)$
p_T (GeV/c)
0.8
0.6
0.4
0.2
0
10
100
ALICE $h^{\pm}$ 0-5%
CMS $h^{\pm}$ 0-5%
CMS b-jet 0-100%
CMS Preliminary Non-prompt J/ψ 0-100%
Pion (0.26,1,0)
Light Quark (0.26,1,0)
B Meson (0.26,1,0)
Bottom Quark (0.26,1,0)

Radiative vs Elastic



Higher Order in Opacity

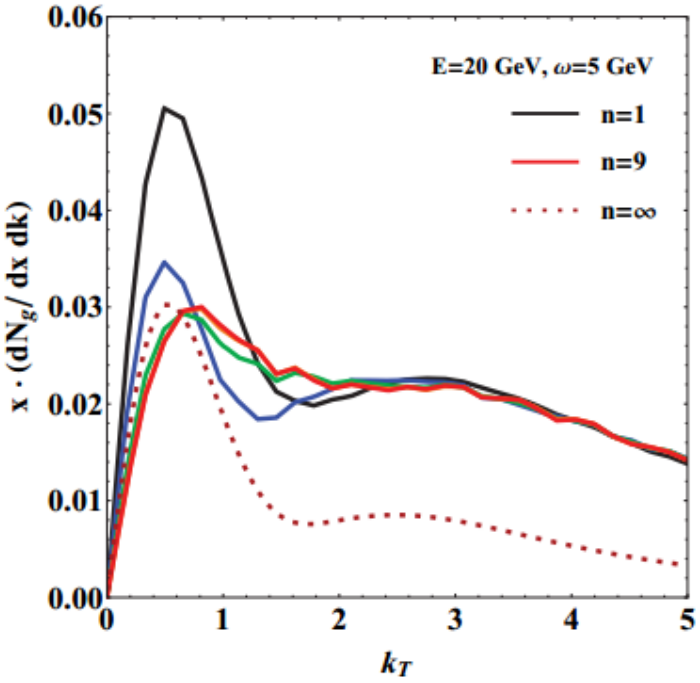


Figure 15. Radiated gluon transverse momentum distribution for a heavy quark jet with energy $E = 20$ GeV traversing a brick plasma of size $L = 5$ fm emitting a gluon with energy $\omega = 5$ GeV. The mass of the quark $M = 4.75$ GeV. The DGLV opacity series calculated up to n=1 (black), 3 (blue), 5 (green), 7 (orange), 9 (red) are shown in the figure. The opacity expansion computed up to ninth order is shown to converge to the ASW multiple soft scattering limit (maroon, dashed) for small $k_\perp \lesssim \hat{q}L \approx 1$ GeV. At large $k_\perp$, differs from the ASW limit, DGLV has a robust Laudau tail. Other parameters used in the simulation are: $\lambda = 1.16$ fm, $\mu = 0.5$ GeV, $m_g = 0.356$ GeV, $T = 0.258$ GeV, $n_f = 0$, $\alpha_s = 0.3$.

Running Coupling Effect 1

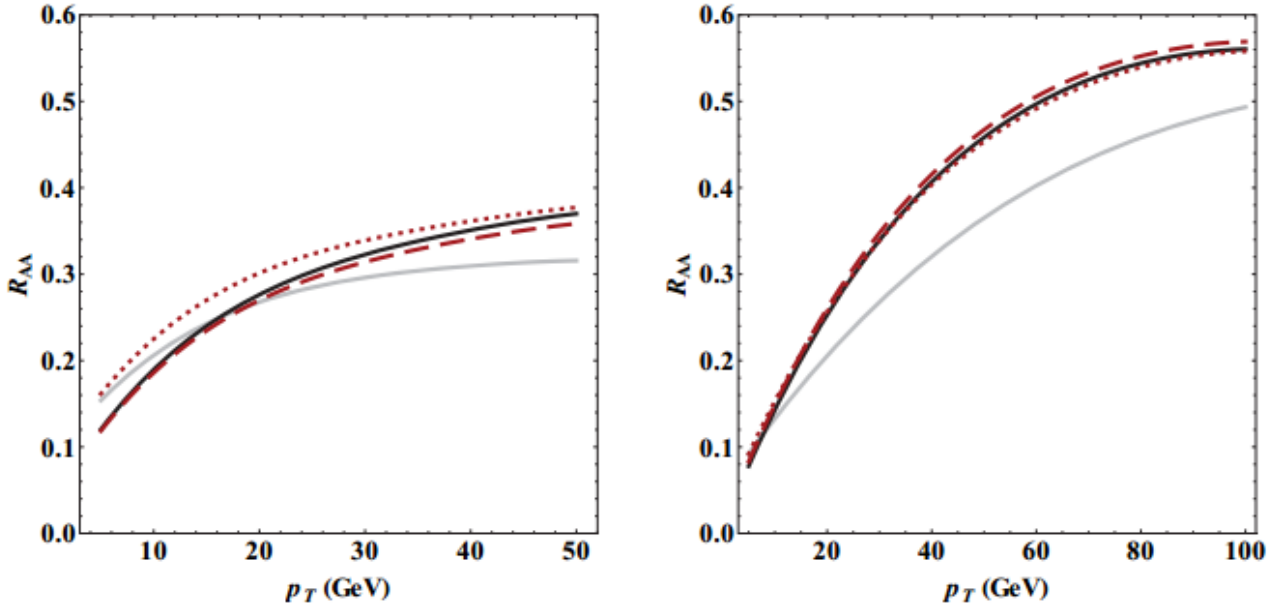


Figure 1. Fixed and running coupling pion R_{AA} results are compared side to side at RHIC (*left*) and LHC (*right*) in CUJET with Glauber static transverse plus Bjorken longitudinal expanding background. The gray opaque curves use a fixed coupling with $\alpha_s = 0.3$, while the black curves use a running coupling with $\alpha_{max} = 0.4$. The difference is notable, especially in the higher energy range available at the LHC, while RHIC results are left almost unchanged. The sensitivity to the variation of running scales Q_i (cf. Eq. (2.1) and following) is measured by the red curves: on one side we decrease the value of all scales Q_i by 50% and lower α_{max} to 0.3 (red dashed), on the other we increase all scales Q_i by 25% and increase at the same time α_{max} to 0.6 (red dotted). α_{max} is constrained to fit $R_{AA}^{\pi,LHC}(p_T \approx 30\ \text{GeV}) = 0.35$.

Running Coupling Effect 2

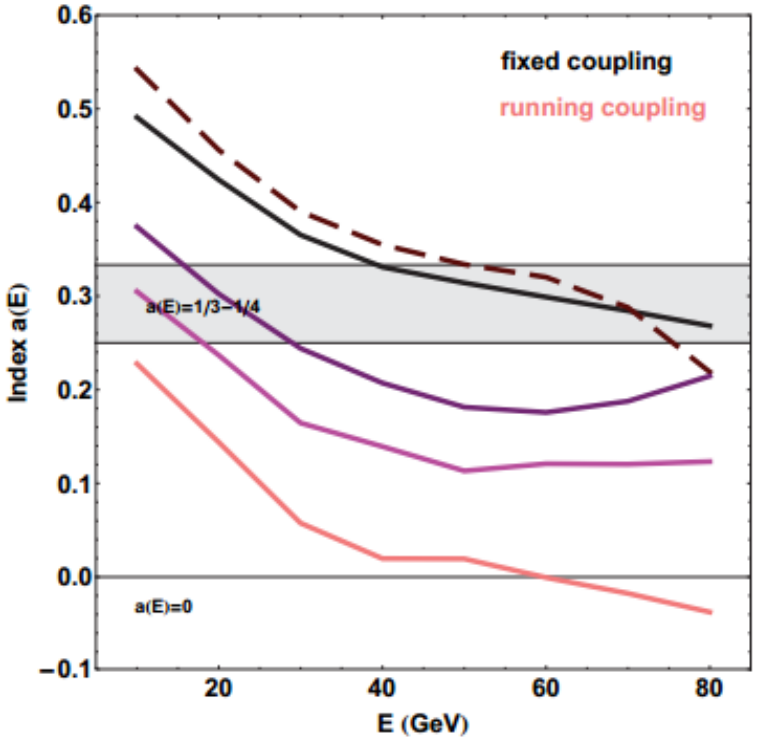
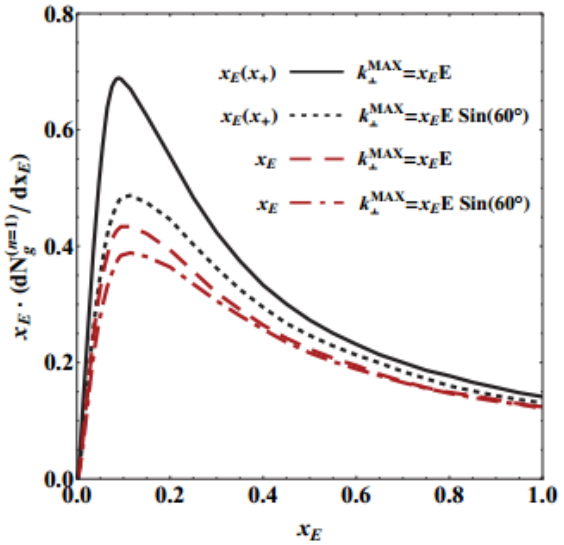


Figure 2. Energy loss index $a(E)$ (cf. Eq. (2.9)) for different assumptions of the running coupling in CUJET: fixed effective $\alpha_s = 0.3$ (black), only thermal coupling running (dashed red), only $\alpha_s^2(\mathbf{q}^2)$ running (purple), only $\alpha_s^2(\mathbf{k}^2/(x(1-x)))$ running (magenta), all couplings running (pink). The saturated α_{max} value is chosen to be equal to 0.4, which corresponds to approximately $Q_0 \sim 1$ GeV. The plot shows the energy loss of a light quark ($M = 0.2$ GeV) traveling from the origin of the transverse plane and through a gluonic plasma ($n_f = 0$) of size $L = 5$ fm, whose density profile is generated from Glauber model and resembles the medium created in a Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV $b = 0$ fm collision.

xE vs x+



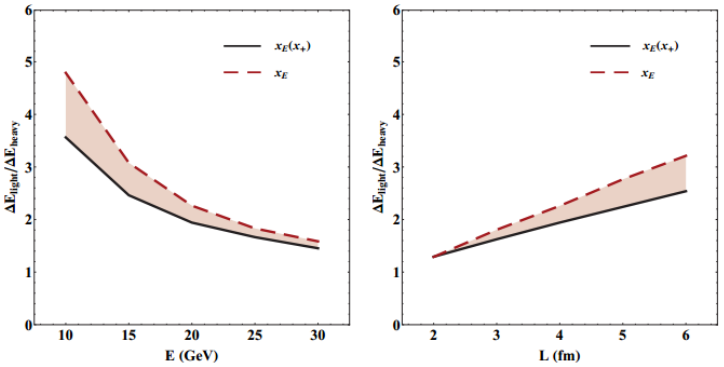
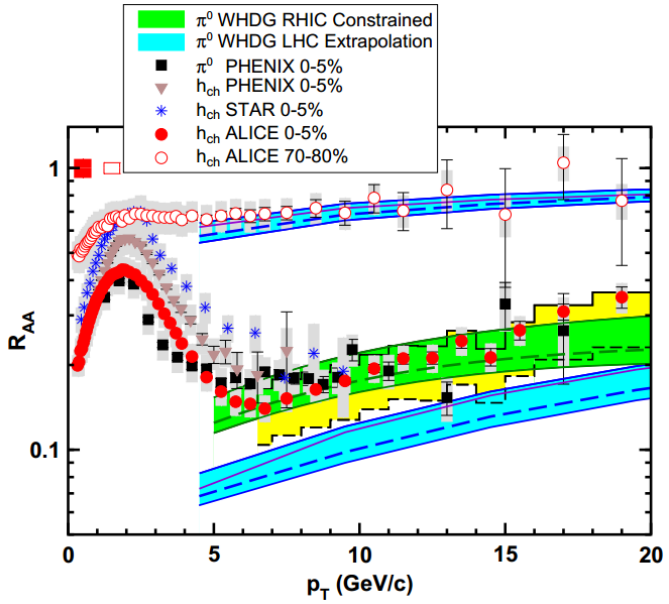


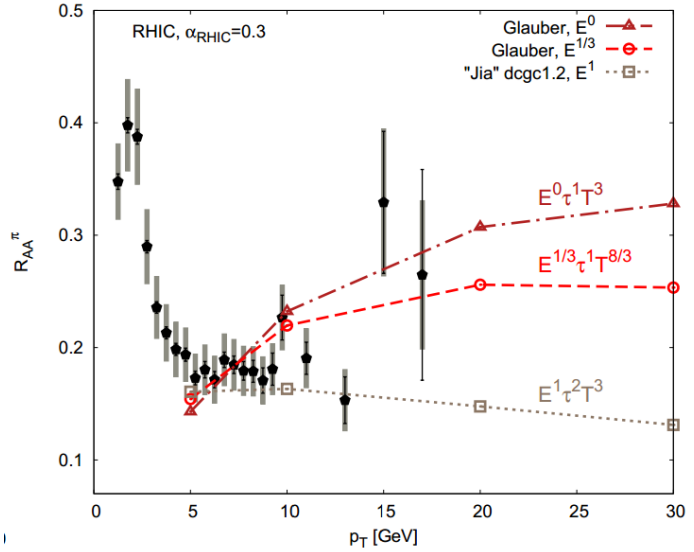
Figure 17. Energy loss ratio between light ($M_l = 0.2$ GeV) and heavy quark ($M_b = 4.75$ GeV) jets in a brick, for different interpretations of x as in Fig. 16. Here $\alpha_s = 0.3$, $L = 5$ fm (*left*), $E = 20$ GeV (*right*) and the energy loss has been computed at first order $n = 1$ in opacity. An error of approximately $\sim 25\%$ is introduced for sufficiently small energies and large plasma sizes. Other parameters used in the simulation are: $\lambda = 1.16$ fm, $\mu = 0.5$ GeV, $m_g = 0.356$ GeV, $T = 0.258$ GeV, $n_f = 0$.

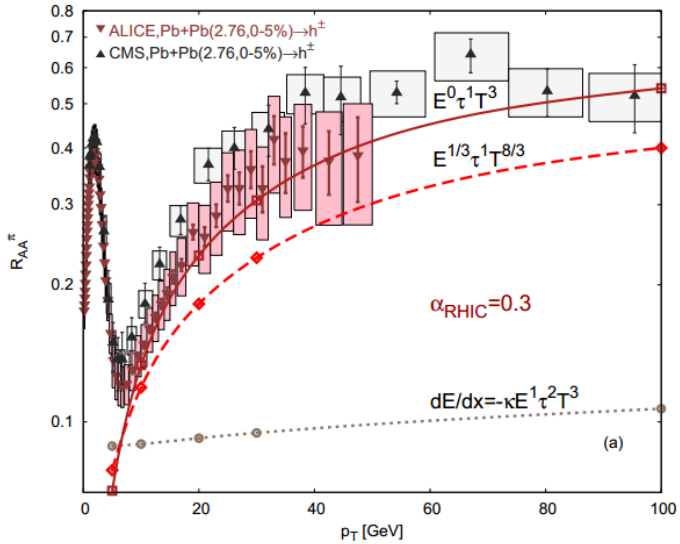
Figure 16. $k_\perp$ integrated, $n = 1$ gluon number distribution generated by a $E = 20$ GeV light quark ($M = 0.2$ GeV) jet traversing a brick plasma of thickness $L = 5$ fm. The two interpretations of x as gluon fractional energy (x_E) or gluon fractional plus-momentum (x_+) lead to remarkably different results, especially in the soft $x \ll 1$ region. The uncertainty due to the choice of θ^{MAX} is noticeable but less prominent. Other parameters used in the simulation are: $\lambda = 1.16$ fm, $\mu = 0.5$ GeV, $m_g = 0.356$ GeV, $T = 0.258$ GeV, $n_f = 0$, $\alpha_s = 0.3$.

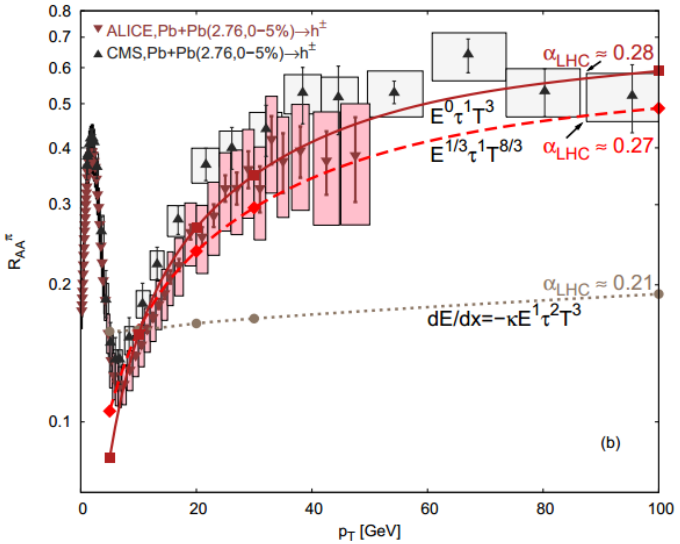
Cf. also W. Horowitz and B. Cole (2010)

The surprising transparency of sQGP at LHC







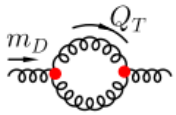


- Weaker than linear density dependence of jet opacity on the density NPA872,265(2011), PRC86,024903(2012)

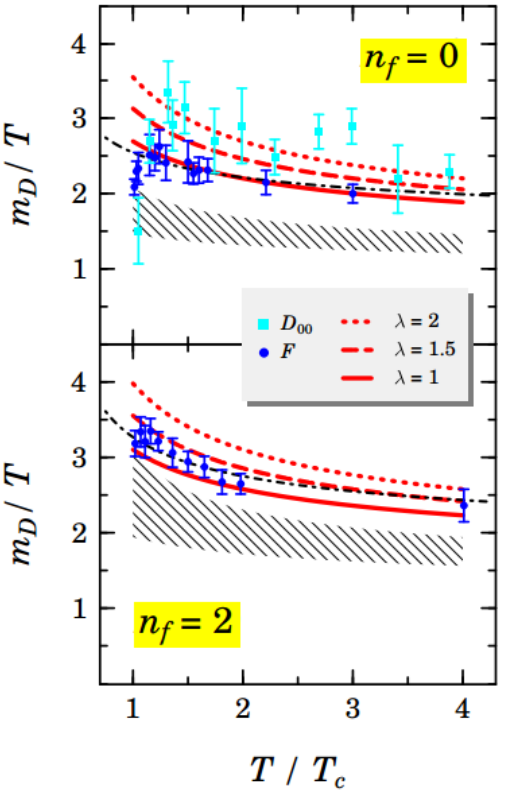
Questioning: scales in thermal coupling

- Peshier, arXiv:hep-ph/0601119 & Djordjevic and Djordjevic, arXiv:1307.4098

$$m_D^2 = \tfrac{1}{3} N_c \left(1 + \tfrac{1}{6} n_f\right) 4\pi\alpha(m_D^2)\, T^2 = \frac{\mu_E^2}{\Lambda_{QCD}^2} \ln\left(\frac{\mu_E^2}{\Lambda_{QCD}^2}\right) = \frac{1 + n_f/6}{11 - 2/3\, n_f} \left(\frac{4\pi T}{\Lambda_{QCD}}\right)^2$$

> be related to a specific quantity/scale. The correct scale, which should be an outcome of the calculation rather than 'chosen', is crucial in particular for larger coupling. The relevant scale for the Debye mass,
>
> $m_D^2 \sim$  $+ \ldots \sim \alpha(m_D^2) T^2 ,$
>
>
>
> is m_D itself, not the typical loop momentum $Q_T \sim 2\pi T$ as often presumed. It's the interplay between vacuum and thermal fluctuations (accounted for by renormalization) that leads to the implicit Eq. (7), which is manifestly finite and gauge and renormalization group invariant. The soft(er) scale in the coupling, $m_D \sim \sqrt{\alpha} T \ll T$ for $\alpha \ll 1$, yields stronger screening than previously estimated from (1). Remarkably, both the novel result

Peshier, arXiv:hep-ph/0601119



Dynamical (non-Thermal) Radiative Running Coupling(s)

- Horowitz and Kovchegov, Nucl. Phys. A849, 72 (2011)

ABSTRACT: We calculate running coupling corrections for the lowest-order gluon production cross section in high energy hadronic and nuclear scattering using the BLM scale-setting prescription. In the final answer for the cross section the three powers of fixed coupling are replaced by seven factors of running coupling, five in the numerator and two in the denominator, forming a 'septumvirate' of running couplings, analogous to the 'triumvirate' of running couplings found earlier for the small-x BFKL/BK/JIMWLK evolution equations. It is interesting to note that the two running couplings

To include running coupling corrections we will follow the BLM scale-setting procedure [54]. We will first resum the contribution of all quark bubble corrections giving powers of $\alpha_\mu N_f$, with N_f the number of quark flavors and α_μ the physical coupling at some arbitrary renormalization scale μ. We will then complete N_f to the full beta-function by replacing

$$N_f \to -6\,\pi\,\beta_2 \tag{3.1}$$

in the obtained expression. Here

$$\beta_2 = \frac{11 N_c - 2 N_f}{12\,\pi} \tag{3.2}$$

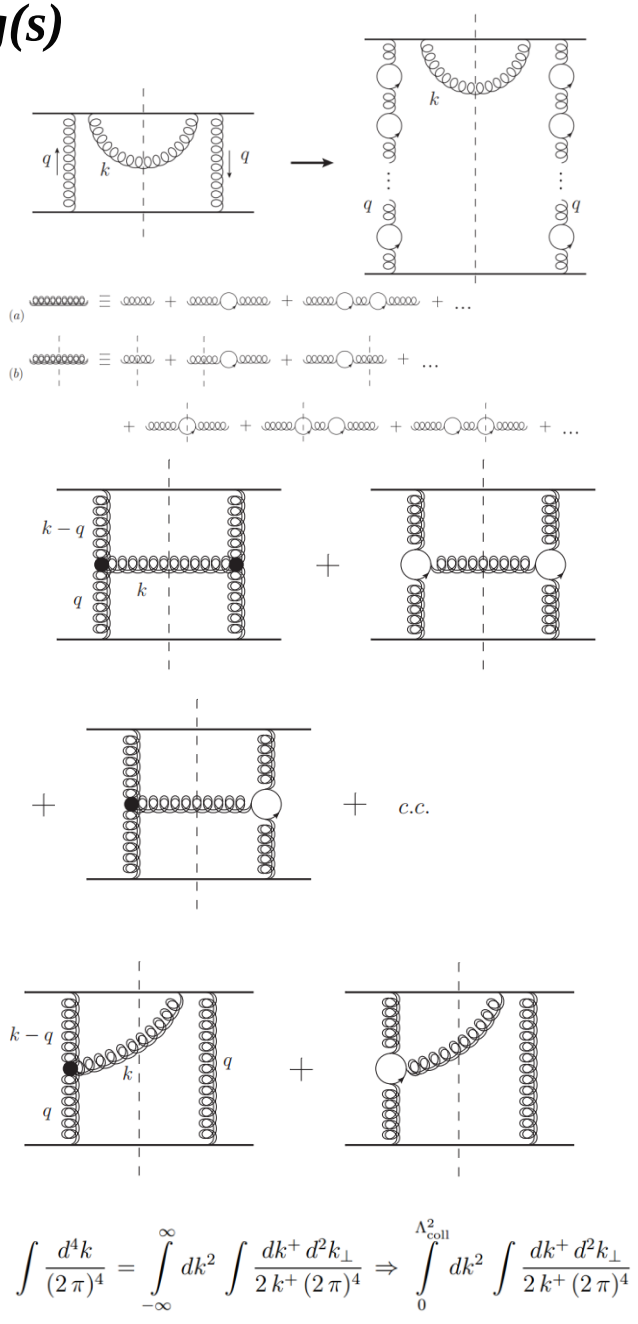
is the one-loop QCD beta-function. After this, the powers of $\alpha_\mu\,\beta_2$ should combine into physical running couplings

$$\alpha_s(Q^2) = \frac{\alpha_\mu}{1 + \alpha_\mu\,\beta_2\,\ln\frac{Q^2}{\mu^2}} \tag{3.3}$$

$$\frac{d\sigma}{d^2k_T\,dy} = \frac{2\,C_F}{\pi^2}\,\frac{\alpha_s\left(\Lambda^2_{\rm coll}\,e^{-5/3}\right)}{\boldsymbol{k}^2}\int\frac{d^2q}{\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2}\,\frac{\alpha_s^2\left(\boldsymbol{q}^2\,e^{-5/3}\right)\,\alpha_s^2\left((\boldsymbol{k}-\boldsymbol{q})^2\,e^{-5/3}\right)}{\alpha_s\left(Q^2\,e^{-5/3}\right)\,\alpha_s\left(Q^{*2}\,e^{-5/3}\right)} \tag{3.31}$$

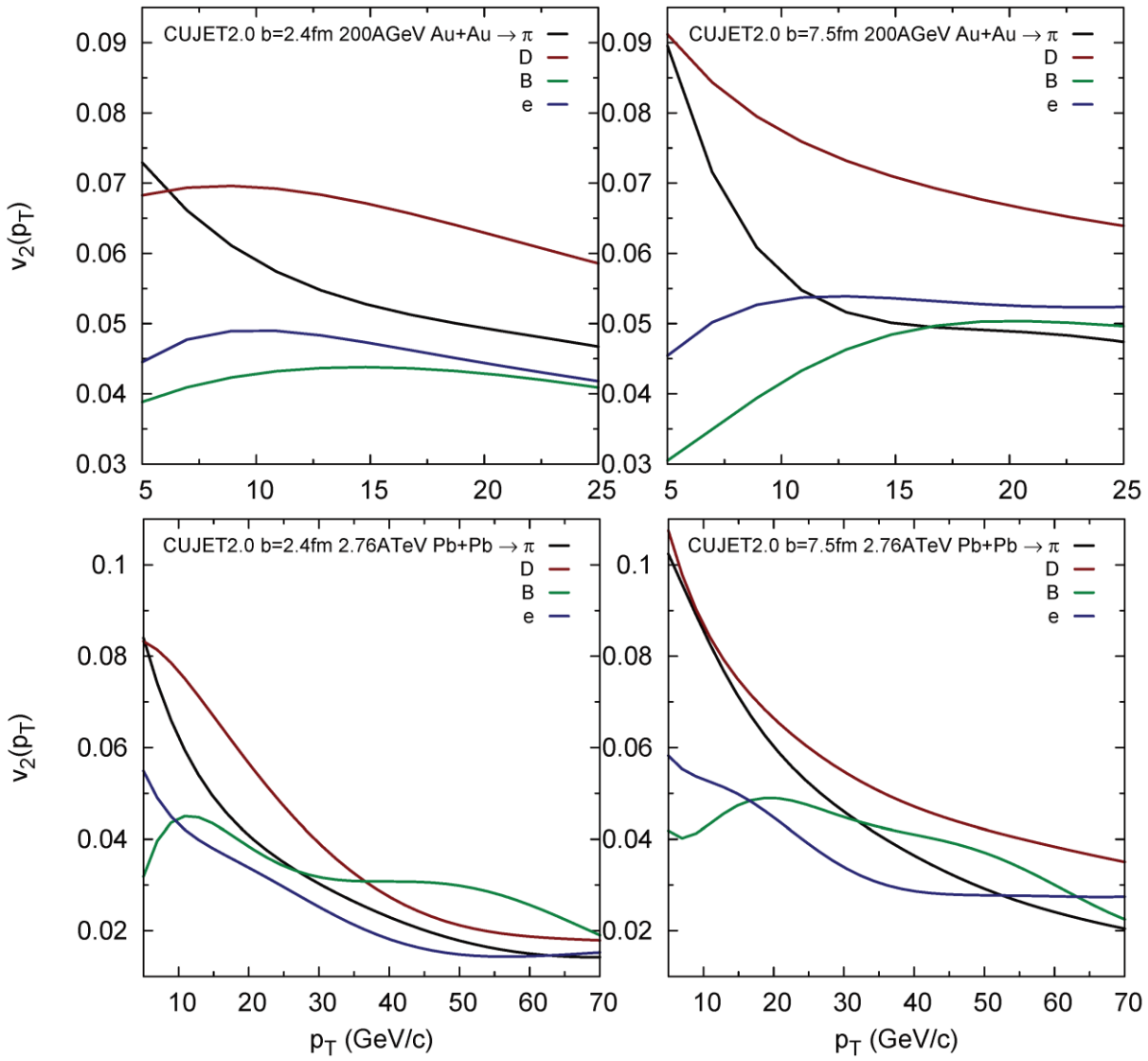
with the $\mu_{\overline{\rm MS}}$-independent momentum scale Q defined by

$$\begin{aligned}
\ln\frac{Q^2}{\mu^2_{\overline{\rm MS}}} &= \frac{1}{2}\,\ln\frac{\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2}{\mu^4_{\overline{\rm MS}}} - \frac{1}{4\,\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^6}\left\{\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^3\right. \\
&\times\left\{\left[\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2-\left(\boldsymbol{q}^2\right)^2\right]\left[\left(\boldsymbol{k}^2\right)^2+\left((\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right)^2\right]+2\,\boldsymbol{k}^2\left[\left(\boldsymbol{q}^2\right)^3-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^3\right]\right. \\
&\left.-\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\left[2\,\left(\boldsymbol{k}^2\right)^2+3\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^2-3\,\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]\right]\ln\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{\boldsymbol{q}^2}\right)\right\} \\
&+i\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^3\left\{\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]\left[\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]-\left(\boldsymbol{q}^2\right)^2-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2\right]\right. \\
&\left.+\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\left(\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]-2\,\left(\boldsymbol{k}^2\right)^2-2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^2\right)\ln\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{\boldsymbol{q}^2}\right)\right\} \\
&\times\left.\sqrt{2\,\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2+2\,\boldsymbol{k}^2\,(\boldsymbol{k}-\boldsymbol{q})^2+2\,\boldsymbol{q}^2\,\boldsymbol{k}^2-\left(\boldsymbol{k}^2\right)^2-\left(\boldsymbol{q}^2\right)^2-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2}\right\}.
\end{aligned} \tag{3.32}$$



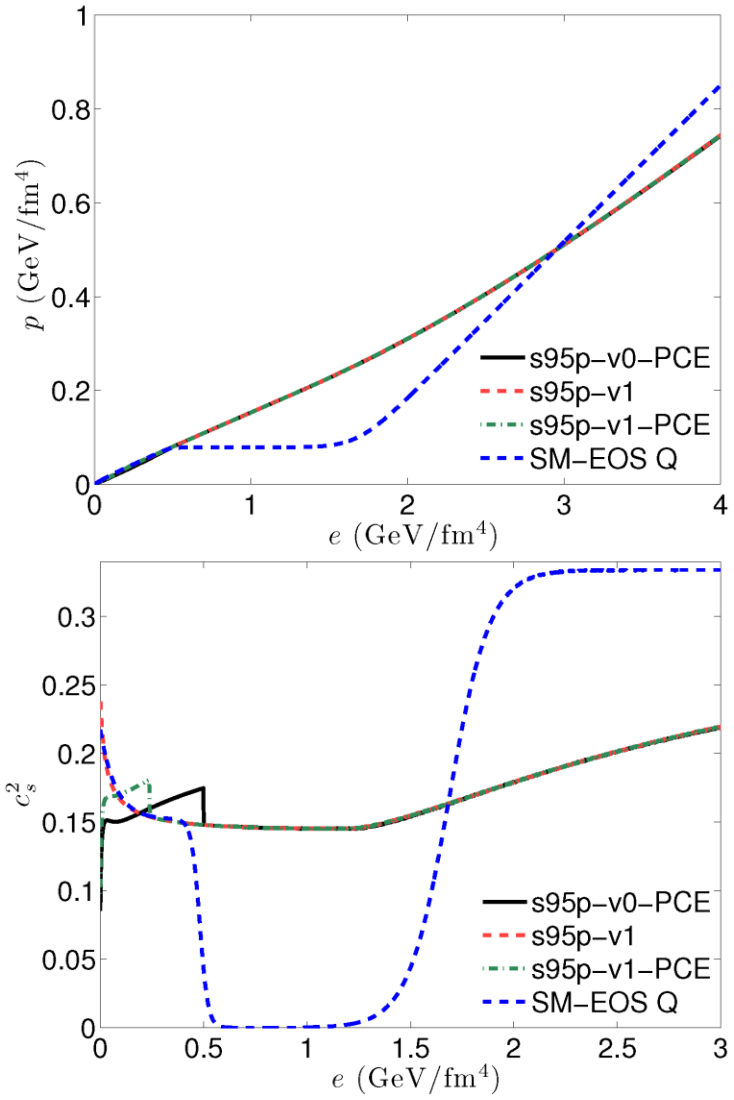
$$\int\frac{d^4k}{(2\,\pi)^4} = \int\limits_{-\infty}^{\infty} dk^2\int\frac{dk^+\,d^2k_\perp}{2\,k^+\,(2\,\pi)^4} \Rightarrow \int\limits_{0}^{\Lambda^2_{\rm coll}} dk^2\int\frac{dk^+\,d^2k_\perp}{2\,k^+\,(2\,\pi)^4}$$

CUJET2.0 Result: flavor v_2

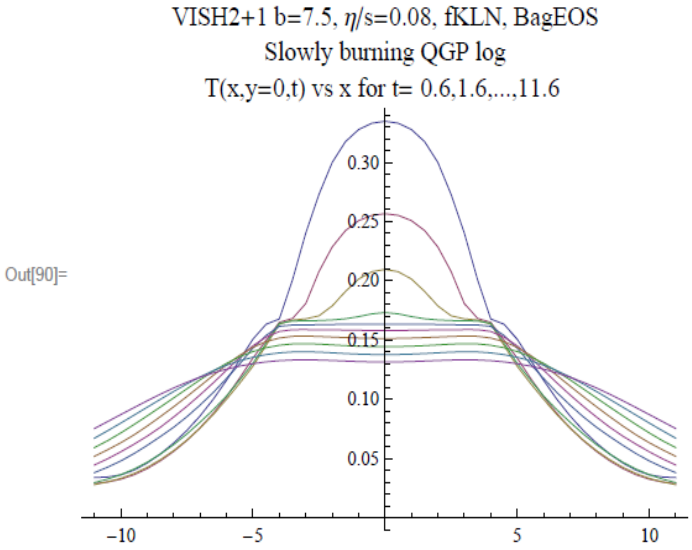


- B meson v2 has a peak at pT~10GeV @ b=2.4fm and pT~20GeV @ b=7.5fm at both RHIC and LHC
- Semi-ordering of the position of the peak for different flavor v2

VISH2+1 More on EOS

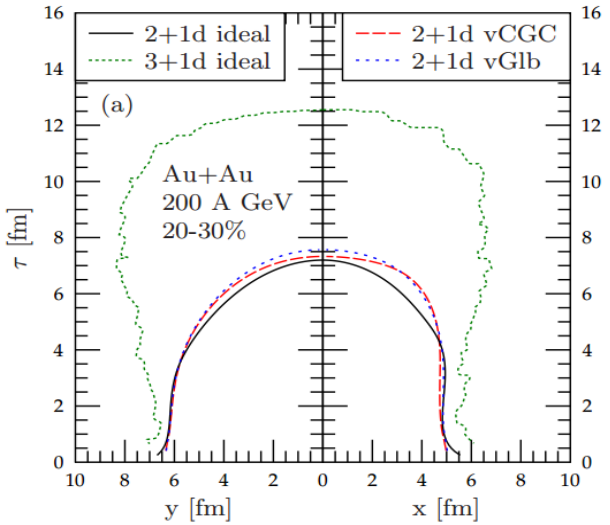


- **VISH2 + 1 with eta = 0.08 ideal fluid results for RHIC b = 7 fm**

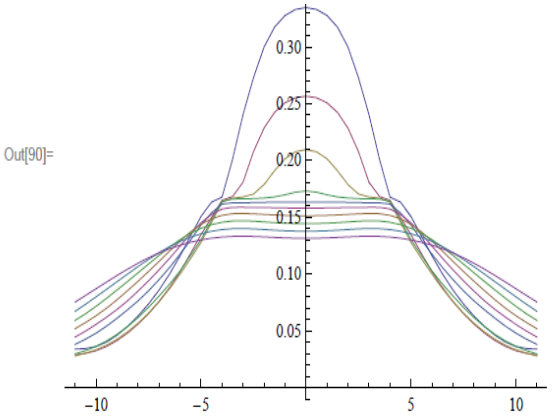


T. Renk, H. Holopainen, U. Heinz and C. Shen, PRC 83, 014910 (2011)
C. Shen, U. Heinz, P. Huovinen and H. Song, PRC 82, 054904 (2010)
H. Song and U. Heinz, PRC 78, 024902 (2008)

CUJET2.0 = rcDGLV + Elastic + 2+1D Viscous Hydro



T. Renk, H. Holopainen, U. Heinz and C. Shen, PRC 83, 014910 (2011)
C. Shen, U. Heinz, P. Huovinen and H. Song, PRC 82, 054904 (2010)
H. Song and U. Heinz, PRC 78, 024902 (2008)



- Couple rcDGLV to VISH 2+1D expanding QGP fluid fields (T(x,t),v(x,t))
- RHIC Au+Au 200AGeV
  - Equaiton of State: s95p-PCE
  - Initial Condition: MC-Glauber
  - η/s=0.08
  - Initial Time: 0.6fm/c
  - Cooper-Frye freeze-out temperature: 120MeV
- LHC Pb+Pb 2.76ATeV
  - Equaiton of State: s95p-PCE
  - Initial Condition: MC-Glauber
  - η/s=0.08
  - Initial Time: 0.6fm/c
  - Cooper-Frye freeze-out temperature: 120MeV
- Compatible with measurements of low pT particle production spectra and flow harmonics