Jet Flavor Tomography of Quark Gluon Plasma at RHIC and LHC

Phys. Rev. Lett. 108, 0223101 (2012)
Nucl. Phys. A855, 307 (2011)

Alessandro Buzzatti

Miklos Gyulassy

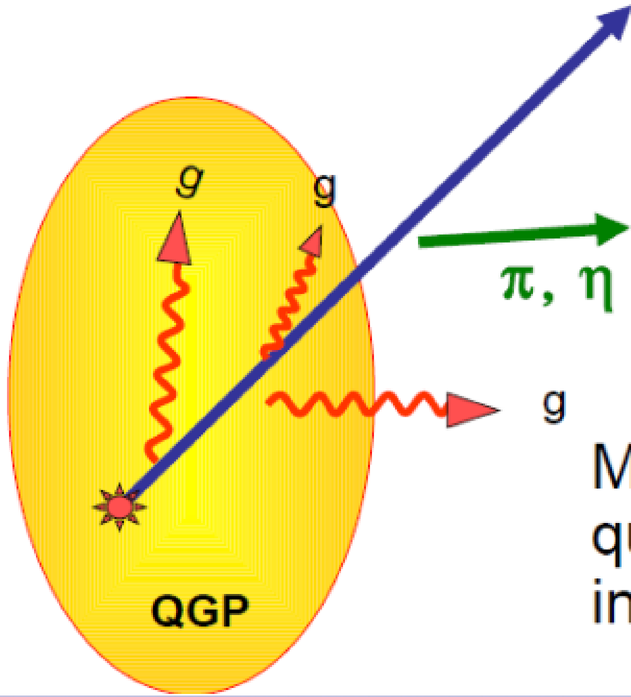
Outline

- **CUJET 1.0**
  - **Presentation of the model**
- **Flavor dependent R_{AA} at RHIC and LHC**
  - **Level crossing**
  - **Systematic errors**
- **Alpha running**
  - **Comparison with latest CMS and ALICE data**
- **Conclusions**

Jet Tomography

Jet Tomography: GLV, DGLV, WHDG, CUJET1.0

Gyulassy, Levai, Vitev, Djordjevic, Wicks, Horowitz, Buzzatti



Quark or Glue Jet probes:

$$(\eta,\ p_T\ ,\ \phi - \phi_{reac}\ ,\ M_Q\ )_{init}$$

Hadron jet fragments:

$$(\eta,\ p_T\ ,\ \phi - \phi_{reac}\ )_{final}$$

Measurements of hadronic/leptonic quenching patterns provides information about QGP density

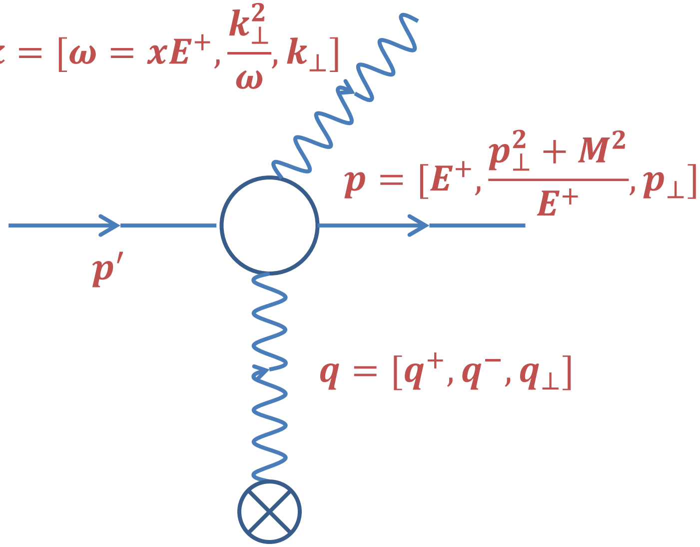
$$\Delta E^{rad} \propto \alpha_s^3 \int d\tau\ \tau\ \rho_{QGP}(\tau, \vec{r}(\tau))\, \mathrm{Log}\left(\frac{E_{Jet}}{T}\right)$$

$$\Delta E^{elas} \propto \alpha_s^2 \int d\tau\ \rho_{QGP}^{2/3}(\tau, \vec{r}(\tau))\, \mathrm{Log}\left(\frac{E_{Jet}}{T}\right)$$

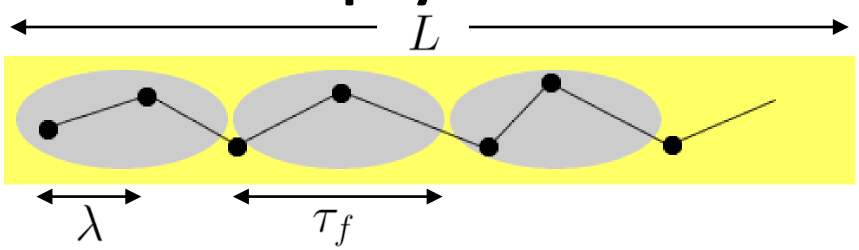
Energy loss – Radiative

Incoherent limit: Gunion-Bertsch

- $$\frac{dN}{dx dk_\perp} = \frac{1}{x}\frac{\alpha_s C_A}{\pi^2}\frac{q_\perp^2}{k_\perp^2 (q_\perp - k_\perp)^2}$$
  - Incoming quark is on-shell and massless
  - The non-abelian nature of QCD alters the spectrum from the QED result
  - Multiple scattering amplitudes are summed incoherently



Formation time physics

- 

$$\tau_f \sim \frac{2\omega}{k_\perp^2}$$

  - $\tau_f < \lambda < L$ Incoherent multiple collisions
  - $\lambda < \tau_f < L$ LPM effect (radiation suppressed by multiple scatterings within one coherence length)
  - $\lambda < L < \tau_f$ Factorization limit (acts as one single scatterer)

DGLV model

$$x\frac{dN^{(n)}}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{1}{n!}\int\prod_{i=1}^{n}\left(d^2\mathbf{q}_i\,\frac{L}{\lambda_g(i)}\left[\bar{v}_i^2(\mathbf{q}_i)-\delta^2(\mathbf{q}_i)\right]\right)\times$$

$$\times\left(-2\,\tilde{\mathbf{C}}_{(1,\cdots,n)}\cdot\sum_{m=1}^{n}\tilde{\mathbf{B}}_{(m+1,\cdots,n)(m,\cdots,n)}\left[\cos\left(\sum_{k=2}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)\right]\right)$$

Soft Radiation ($E \gg \omega$, $x \ll 1$)
Soft Scattering ($E \gg q$, $\omega \gg k_T$)

Opacity series expantion $\longrightarrow$ $\left(\frac{L}{\lambda}\right)^n$

Radiation antenna $\longrightarrow$ *Cascade terms*

$$\tilde{\mathbf{C}}_{(i_1 i_2\cdots i_m)} = \frac{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})}{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})^2+m_g^2+M^2x^2},$$

$$\tilde{\mathbf{B}}_{(i_1 i_2\cdots i_m)(j_1 j_2\cdots i_n)} = \tilde{\mathbf{C}}_{(i_1 i_2\cdots j_m)} - \tilde{\mathbf{C}}_{(j_1 j_2\cdots j_n)}\ .$$

Gunion – Bertsch $\quad \tilde{\mathbf{B}}_i = \tilde{\mathbf{H}} - \tilde{\mathbf{C}}_i\,,$

Hard $\quad \tilde{\mathbf{H}} = \frac{\mathbf{k}}{\mathbf{k}^2+m_g^2+M^2x^2}\,,$

LPM effect $\longrightarrow$

$$\Omega_{(m,\cdots,n)} = \underbrace{\frac{(\mathbf{k}-\mathbf{q}_m-\cdots-\mathbf{q}_n)^2}{2xE}}_{Inverse\ formation\ time} + \underbrace{\frac{m_g^2+M^2x^2}{2xE}}_{Mass\ effects}$$

Scattering center distribution $\longrightarrow$ $\Delta z_k = z_k - z_{k-1} \sim L/(n+1)$

CUJET 1.0

- **Geometry**
  - Glauber model
  - Bjorken longitudinal expansion
- **Energy loss**
  - DGLV – MD Radiative energy loss model
  - Energy loss fluctuations (Poisson expansion)
  - Full dynamical computation:
  - $\frac{dN_g}{dx}(x_\perp, \phi) =$

$$\frac{C_R \alpha_s}{\pi} \int d\tau \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{1}{x} \frac{\frac{9}{2}\pi\alpha^2}{q^2(q^2+\mu^2(\tau))} \times \frac{2(k+q)}{(k+q)^2+\chi(\tau)} \left(\frac{(k+q)}{(k+q)^2+\chi(\tau)} - \frac{k}{k^2+\chi(\tau)} \right) \times \left(1 - cos\left[\frac{(k+q)^2+\chi(\tau)}{2xE} \tau \right] \right) \rho_{QGP}(x_\perp + \hat{\phi}\tau, \tau)$$

$$\boxed{\mu(\tau) = gT(x_\perp + \hat{\phi}\tau, \tau)} \qquad \boxed{\chi(\tau) = M^2x^2 + m_g{}^2(\tau)(1-x)}$$

- **Detailed convolution over initial production spectra**
- **In vacuum Fragmentation Functions**

CUJET 1.0

- **Geometry**
  - **Glauber model**
  - **Bjorken longitudinal expansion**
- **Energy loss**
  - **DGLV – MD Radiative energy loss model**
  - **Energy loss fluctuations (Poisson expansion)**
  - **Full dynamical computation:**

Possibility to evaluate systematic theoretical uncertainties such as sensitivity to formation and decoupling phases of the QGP evolution, local running coupling and screening scale variations, and other effects out of reach with analytic approximations;

- **Detailed convolution over initial production spectra**
- **In vacuum Fragmentation Functions**

Effective Potential

Static potential (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 potential (MD)

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

- Scattering centers recoil
- Includes not screened color-magnetic effects (HTL gluon propagators)
- Only first order in opacity

Interpolating potential (CUJET)

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

- Introduces effective Debye magnetic mass
- Interpolates between the static and HTL dynamical limits
- Magnetic screening allows full opacity series

Hydrodynamic expansion

- The local thermal equilibrium is established at τ_0

$$\boldsymbol{s(\tau) = s_0 \frac{\tau_0}{\tau}}$$ **(entropy equation)**

$$\boldsymbol{s_0 \approx 3.6\, \rho_0 = 3.6\, \frac{1}{\pi R^2 \tau_0} \frac{dN}{dy}}$$

($\frac{dN}{dy}$ is the observed rapidity density)

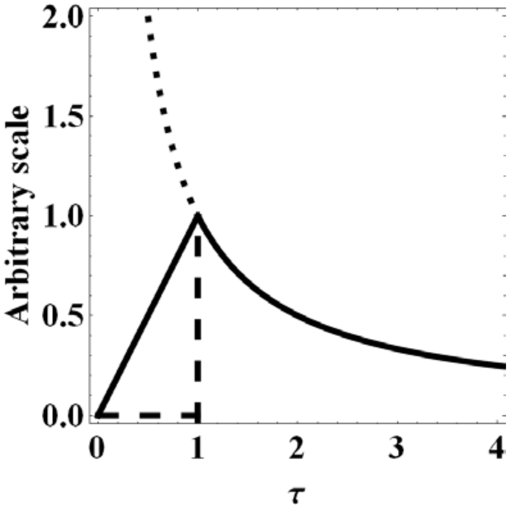
MONOTONIC density dependence

$$\boldsymbol{\rho_{QGP}(x_\perp, \tau) = \frac{1}{\tau_0} \frac{\rho_{part}(x_\perp)}{N_{part}} \frac{dN}{dy} f\left(\frac{\tau}{\tau_0}\right)}$$

- Before equilibrium

Temporal envelopes: linear, divergent, freestreaming

$$\boldsymbol{f\left(\frac{\tau}{\tau_0}\right) = \begin{cases} \frac{\tau}{\tau_0}, \frac{\tau_0}{\tau}, 0 & (\tau < \tau_0) \\ \frac{\tau_0}{\tau} & (\tau > \tau_0) \end{cases}}$$



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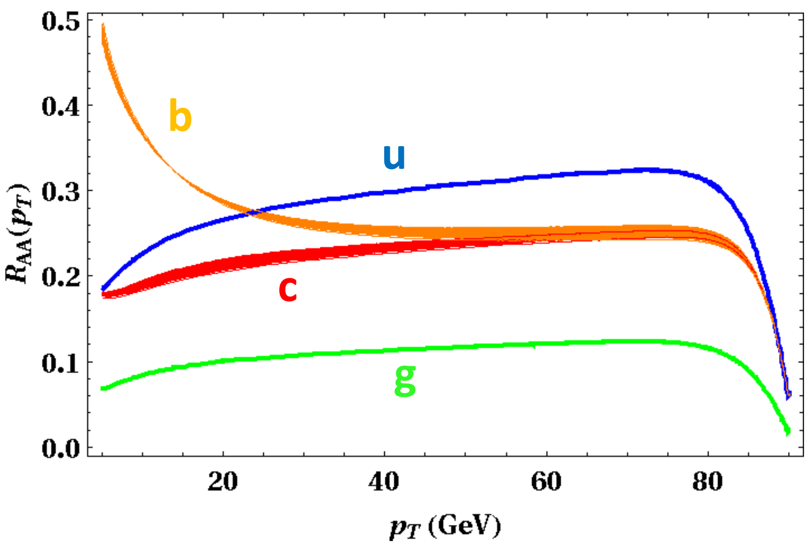
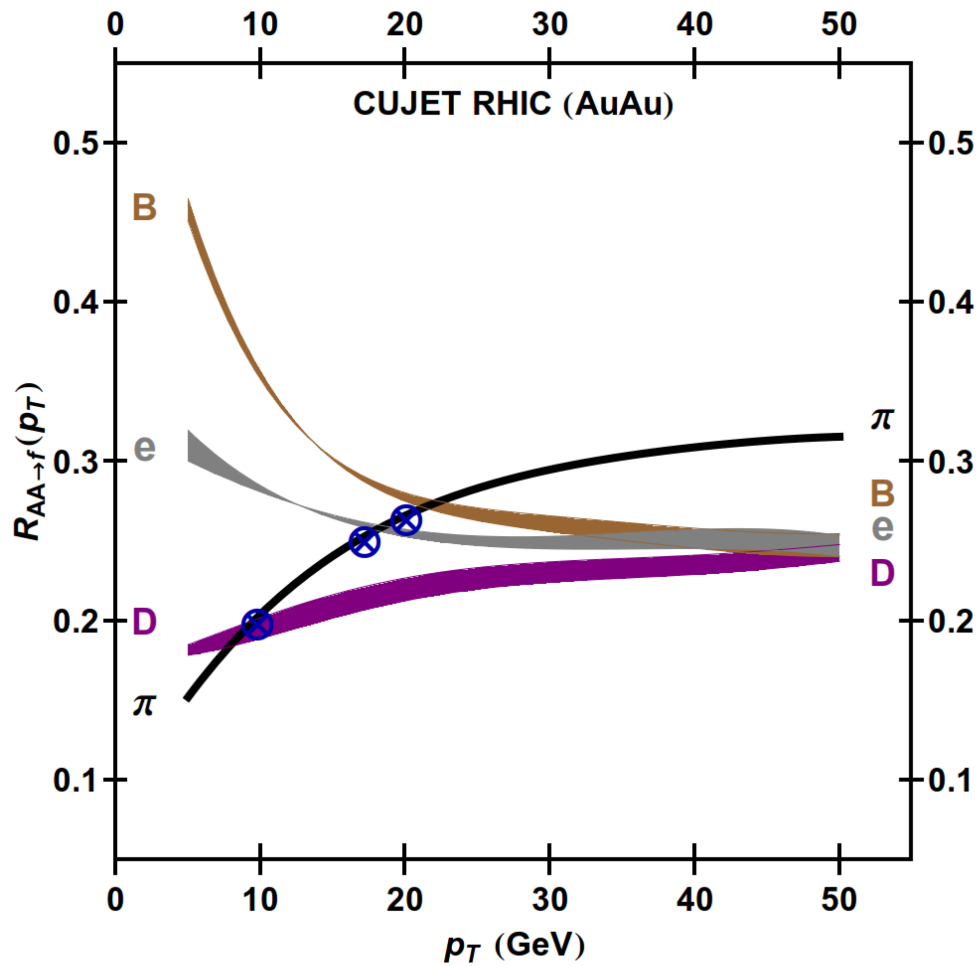
RHIC Results

$0 - 5\%\ centrality, dNdy = 1000, \alpha_s = 0.3, \tau_0 = 1fm/c$



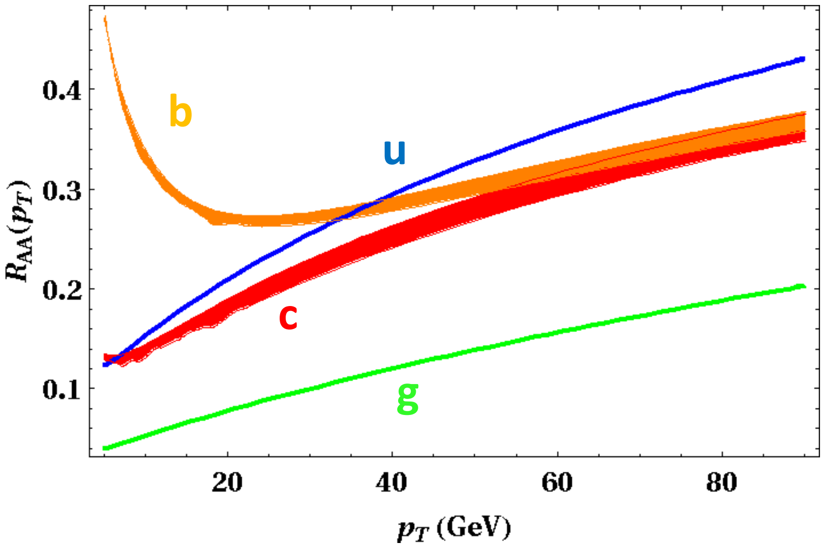


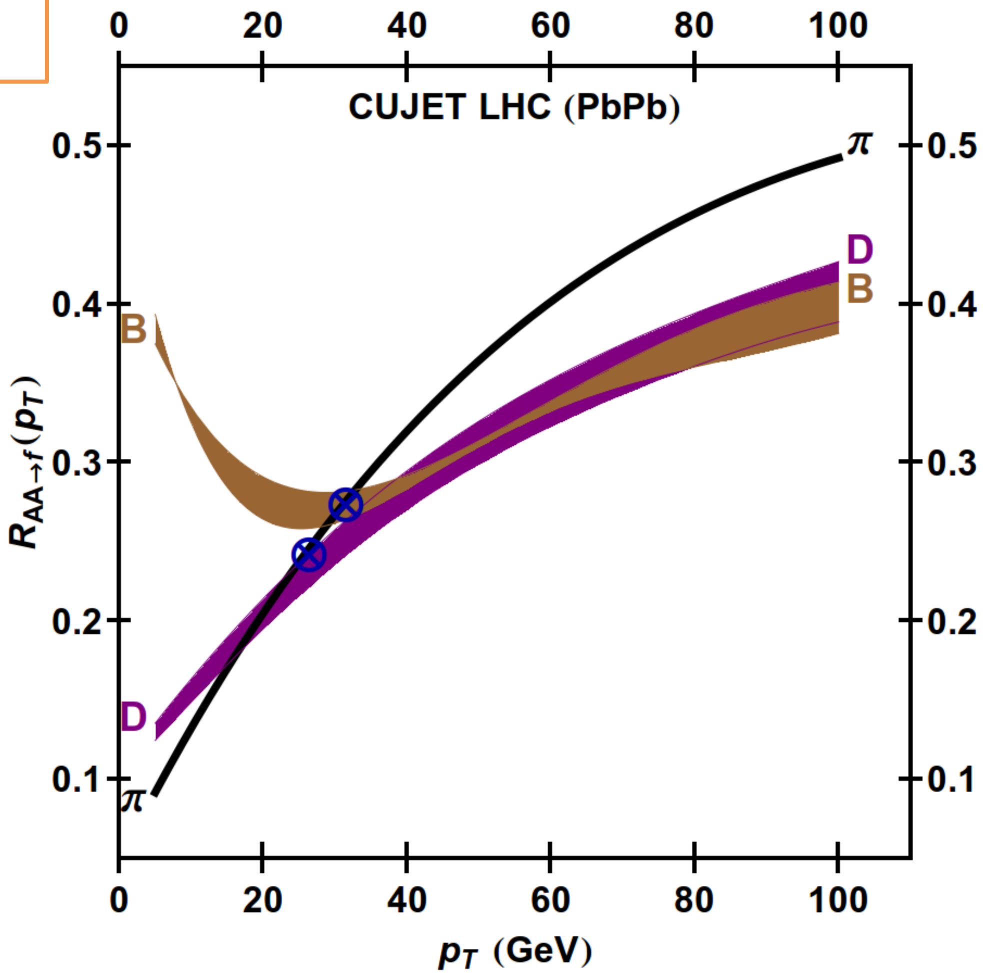
Inversion of R_{AA} flavor hierarchy at sufficiently high p_t

AB and M. Gyulassy, Phys. Rev. Lett. 108, 0223101 (2012)

LHC Results

Parameters constrained by RHIC
$dNdy = 2200$

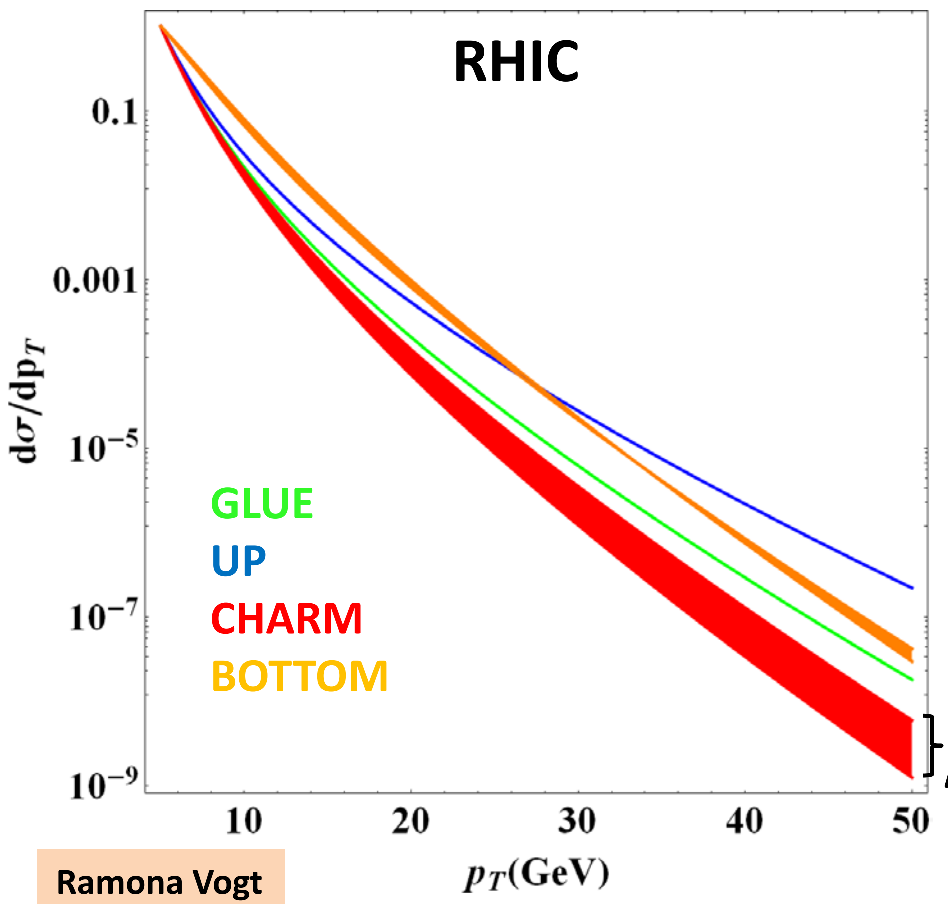




AB and M. Gyulassy, Phys. Rev. Lett. 108, 0223101 (2012)

Initial pQCD spectra

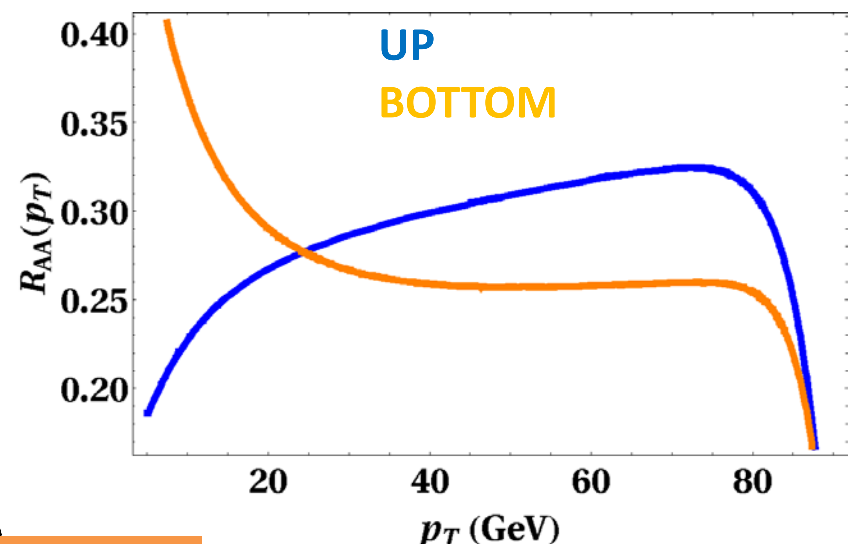
Initial quark production spectra



Ramona Vogt

NLO-FONLL uncertainty

- **Competing effects between increased density and harder production spectra**
  - **RHIC density and spectra**
  - LHC density, RHIC spectra
  - LHC density and spectra



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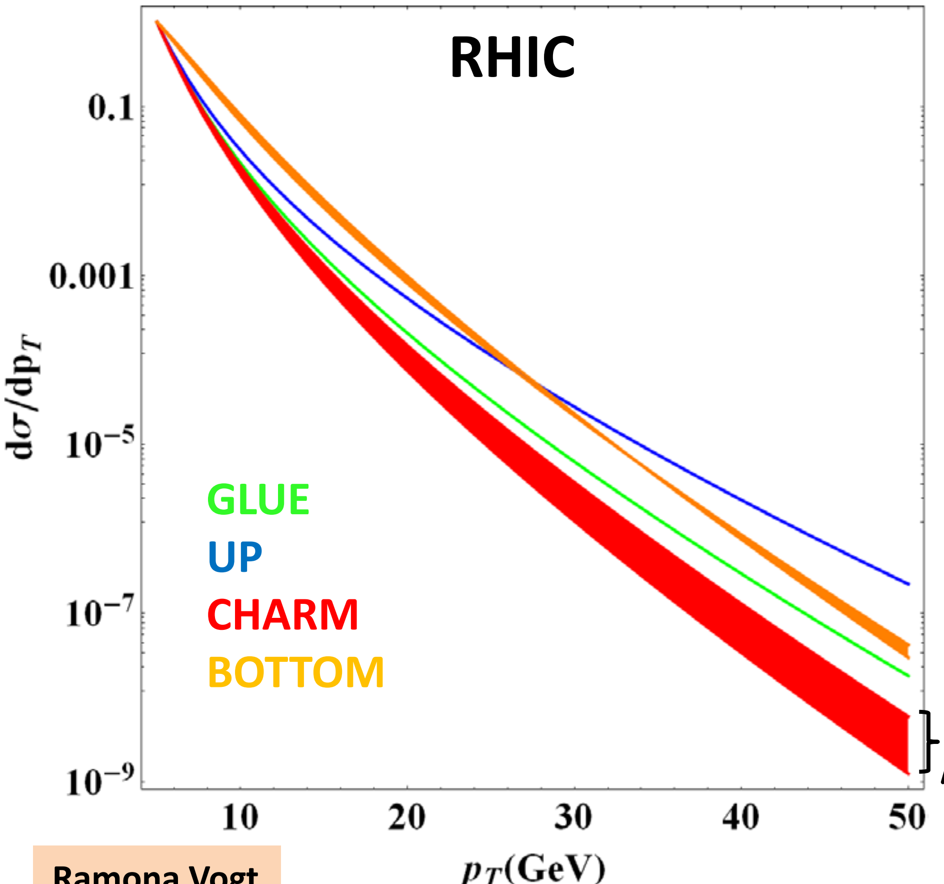

Ramona Vogt

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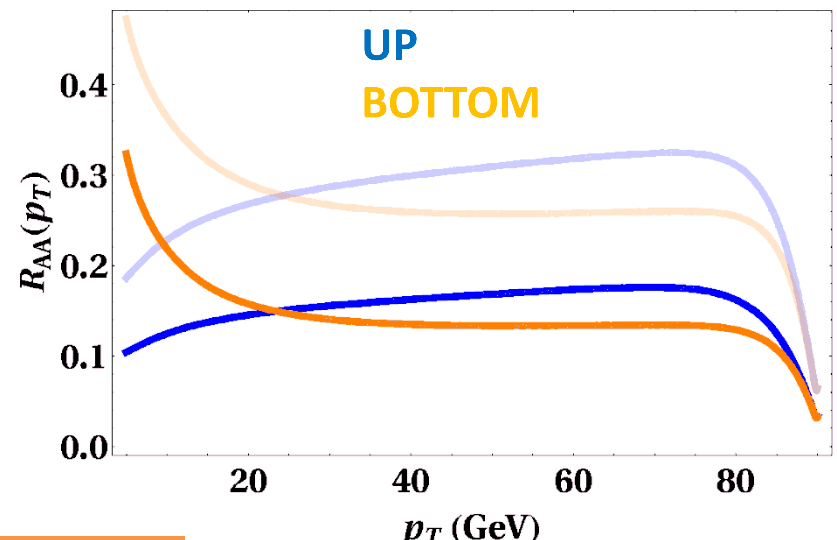

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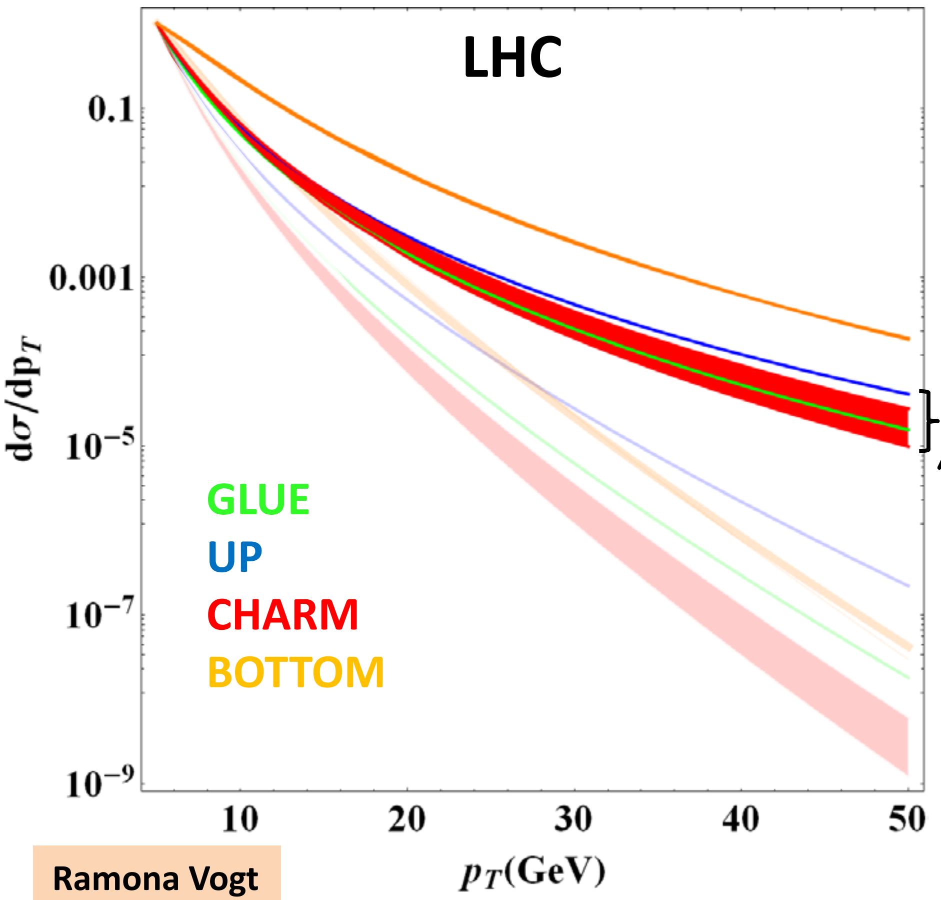

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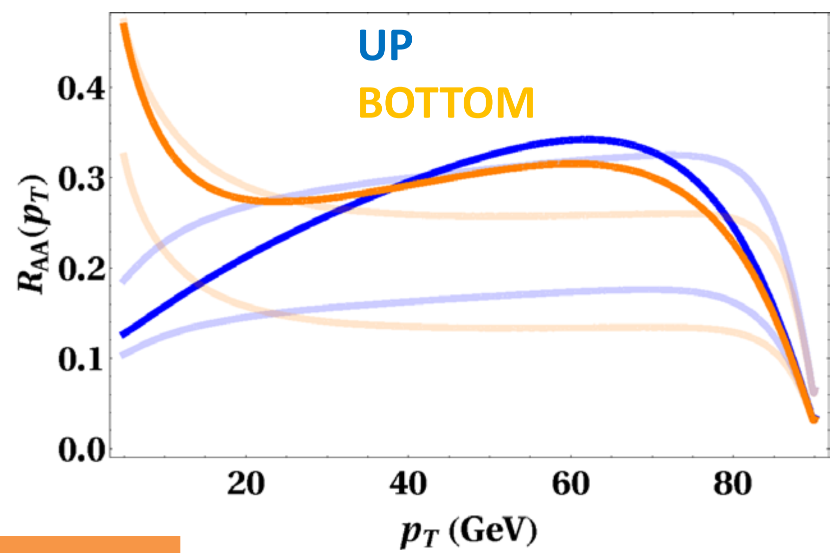
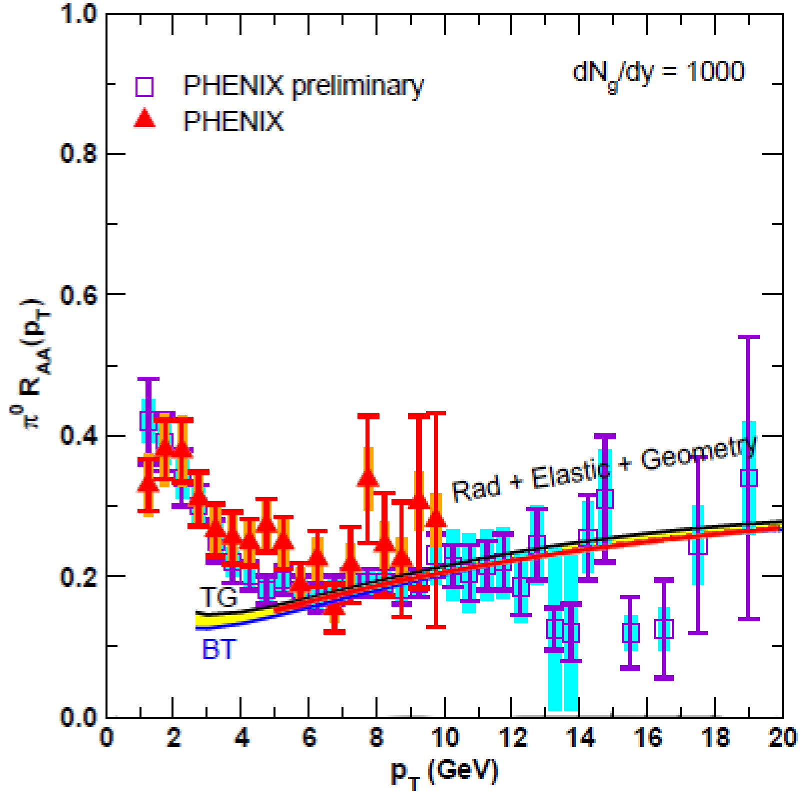
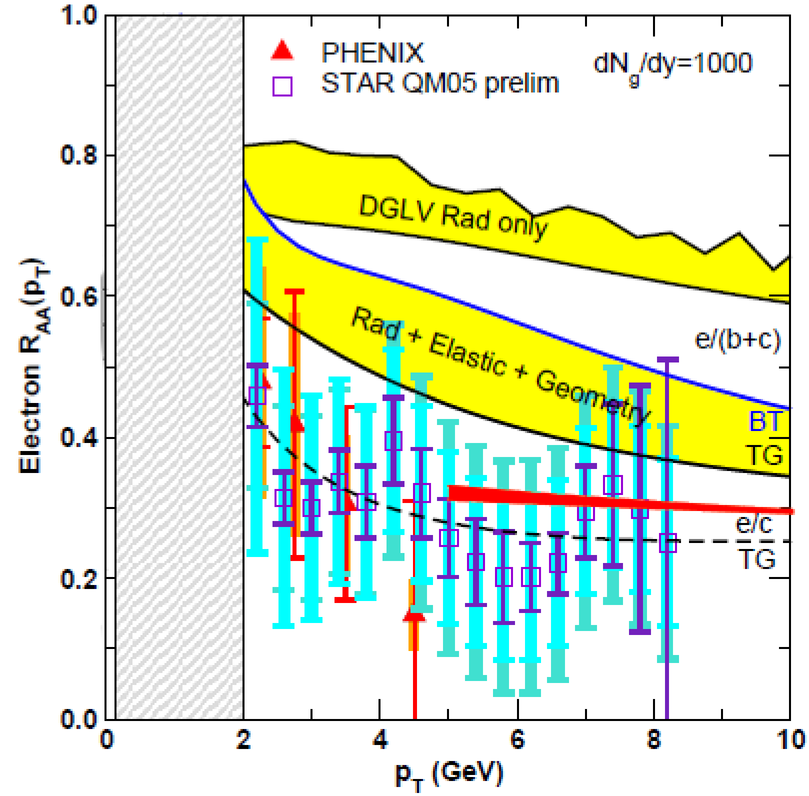


Pions and Electrons at RHIC

LIGHT QUARKS



HEAVY QUARKS

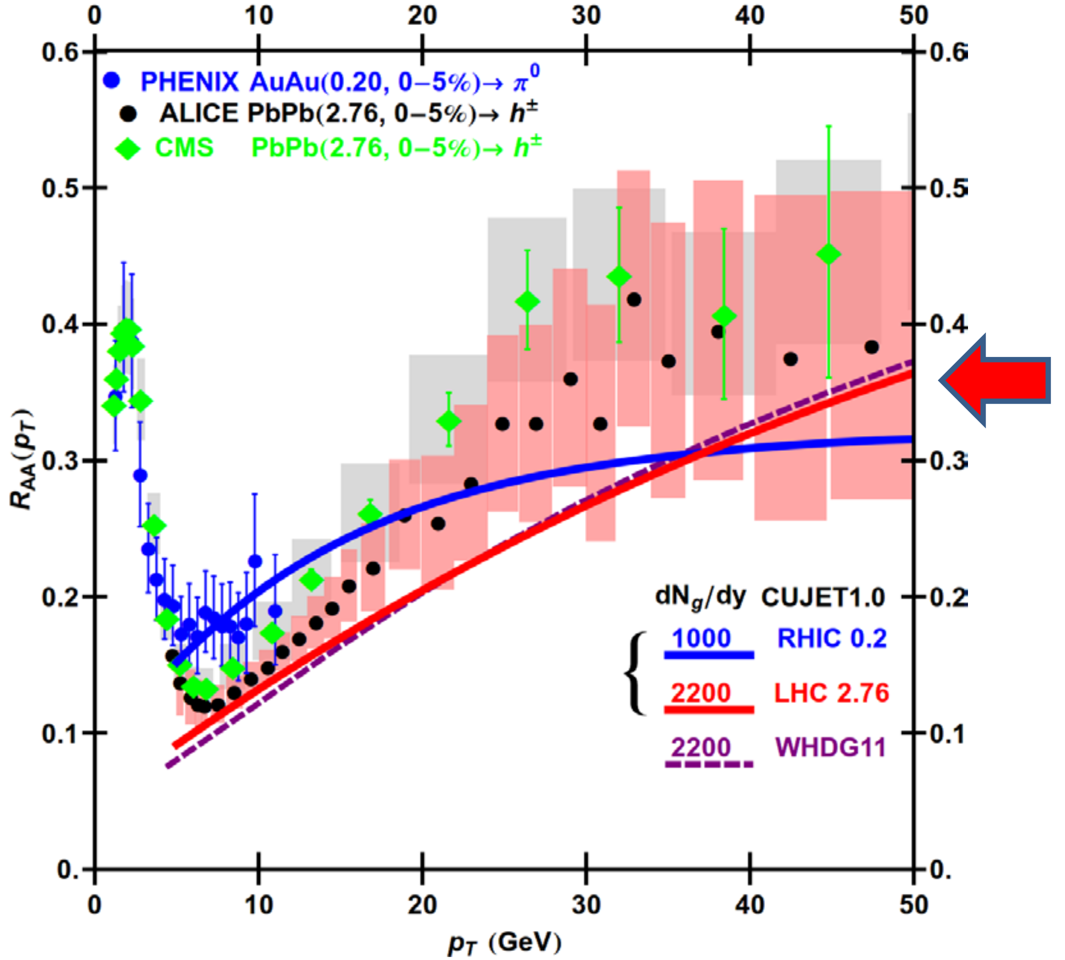


Wicks, Horowitz, Djordjevic, Gyulassy / NPA (2007)

CUJET solves the Heavy Quark puzzle…

Pions at LHC

AB and M. Gyulassy, Phys. Rev. Lett. 108, 0223101 (2012)



…but doesn't excel at explaining the surprising transparency at LHC

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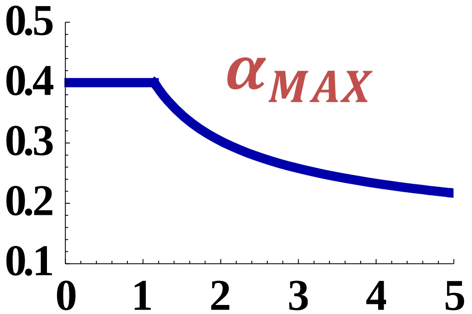
Alpha scales

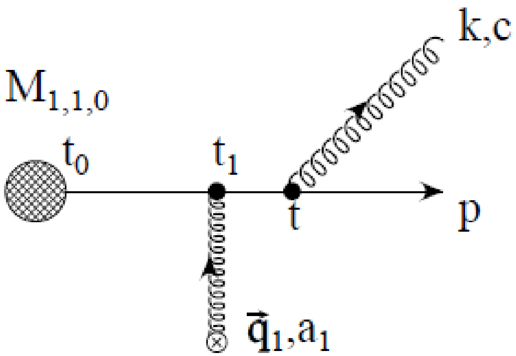
- **Introduce one-loop alpha running**

$$\alpha_s(q^2) = \frac{2\pi}{9}\frac{1}{Log[{}^{q}/_{\Lambda}]}$$

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



– $$Radiative = \begin{cases} \alpha(q^2)^2 \\ \alpha(\frac{k_\perp^2}{x(1-x)})^2 \\ \mu = g(\alpha(2T^2))T \end{cases}$$



– $$Elastic = \begin{cases} \alpha(ET) \\ \alpha(\mu^2) \end{cases}$$

S. Peigne and A. Peshier, Phys.Rev. D77 (2008) 114017

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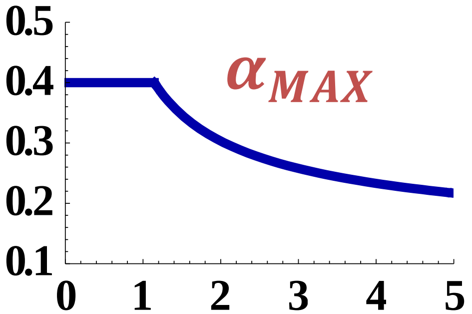
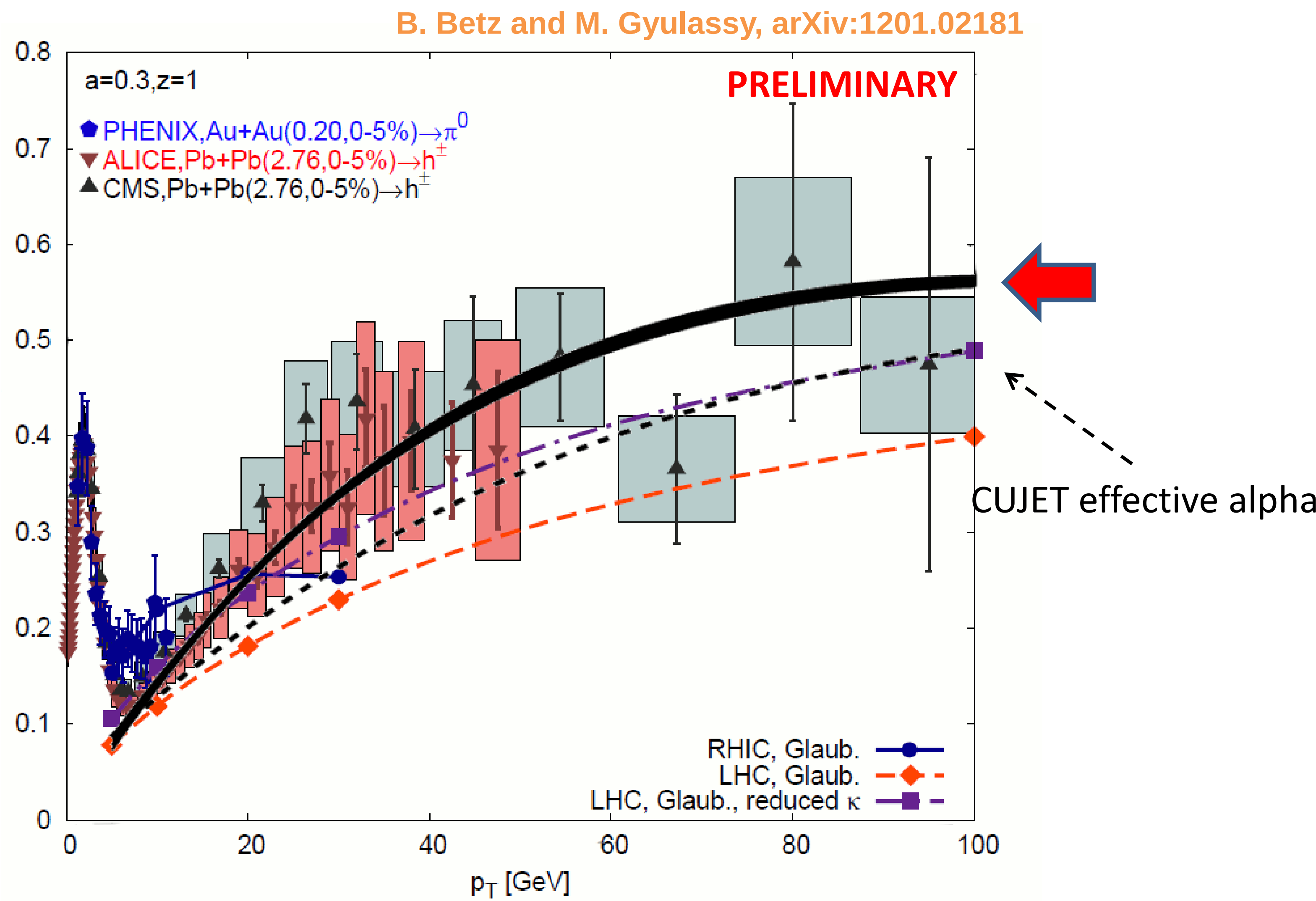


– **Systematic uncertainties:**

Vary $\alpha(\kappa^2) = \begin{cases} \kappa \to \kappa/2 \\ \kappa \to 1.25\,\kappa \end{cases}$

Fit LHC Pion data at $40\ GeV$ **fixing** $\alpha_{MAX} = \{0.3, 0.4, 0.6\}$

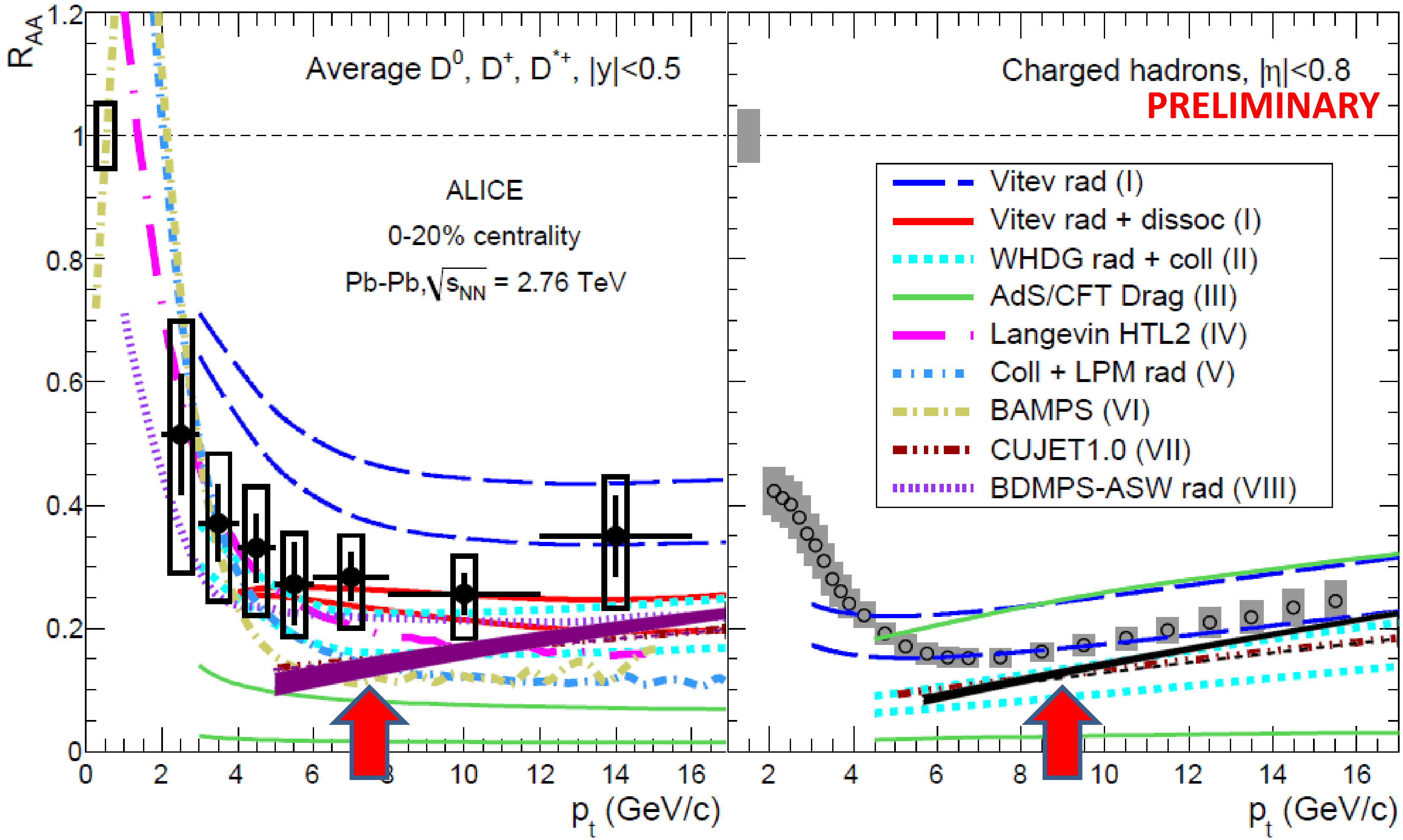
LHC Pions



Alpha running offers excellent agreement with data!

ALICE Data comparison

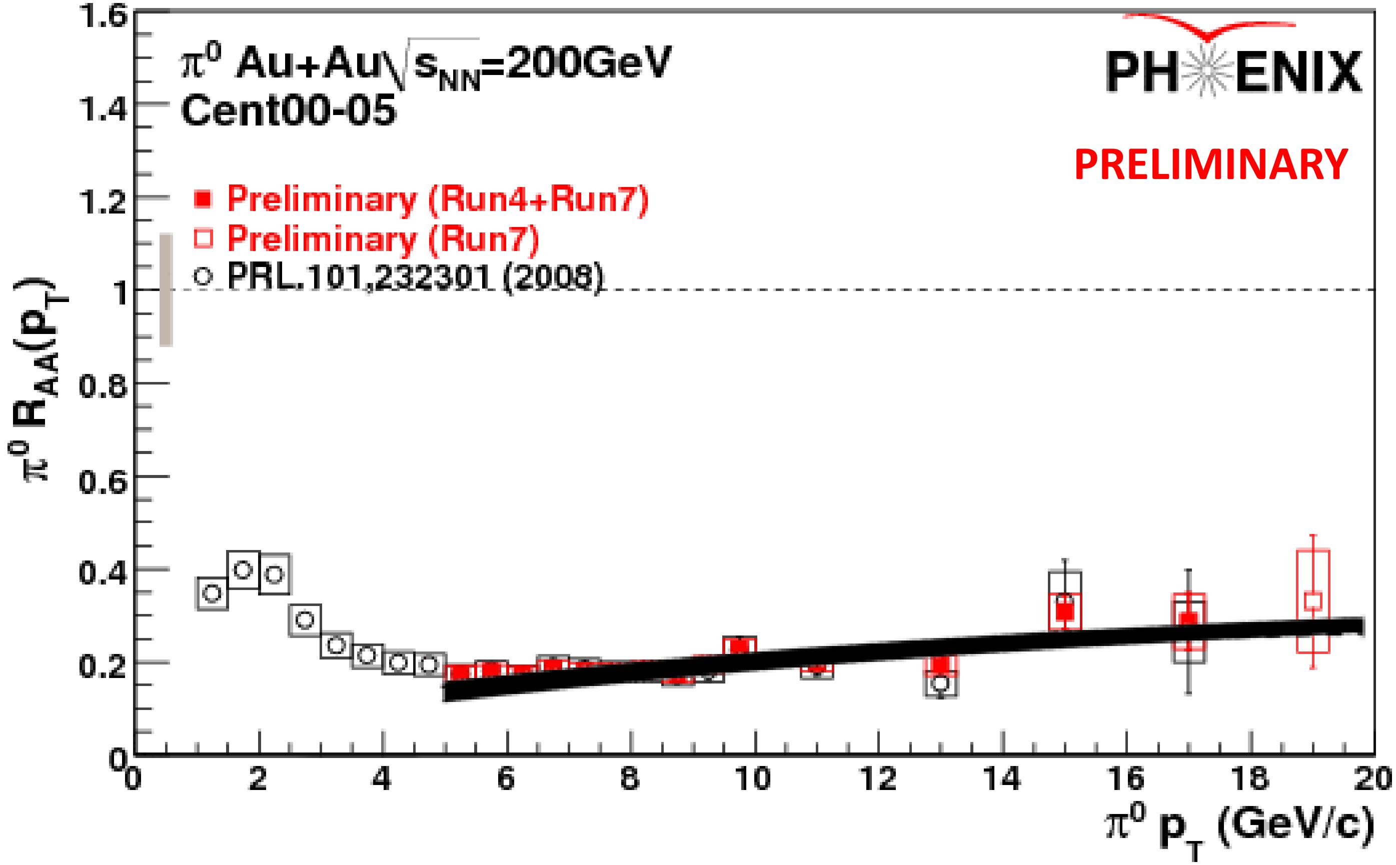
ALICE Collaboration, arXiv:1203.2160



Even at low p_t the model behaves well…

RHIC Pions

PHENIX Collaboration



…while keeping good agreement with RHIC

Energy loss

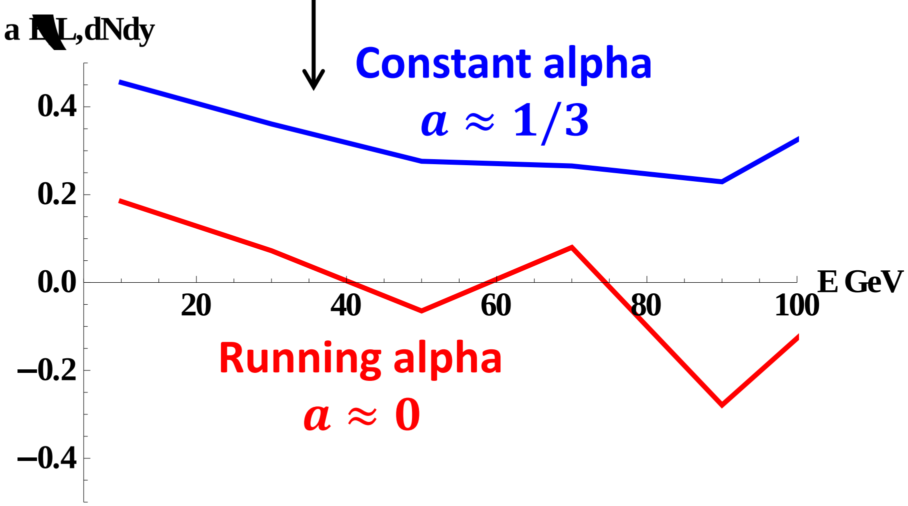
- Consider a simplified power law model for Energy loss:

$$\frac{\Delta E}{E} = \kappa E^{a-1} L^{b} \rho^{c}$$

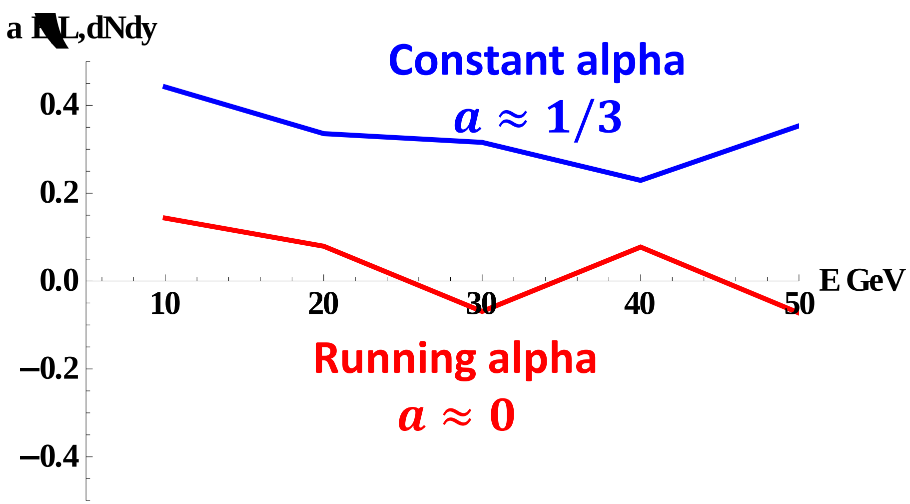
W. A. Horowitz and M. Gyulassy, arXiv:1104.4958

B. Betz and M. Gyulassy, arXiv:1201.0218

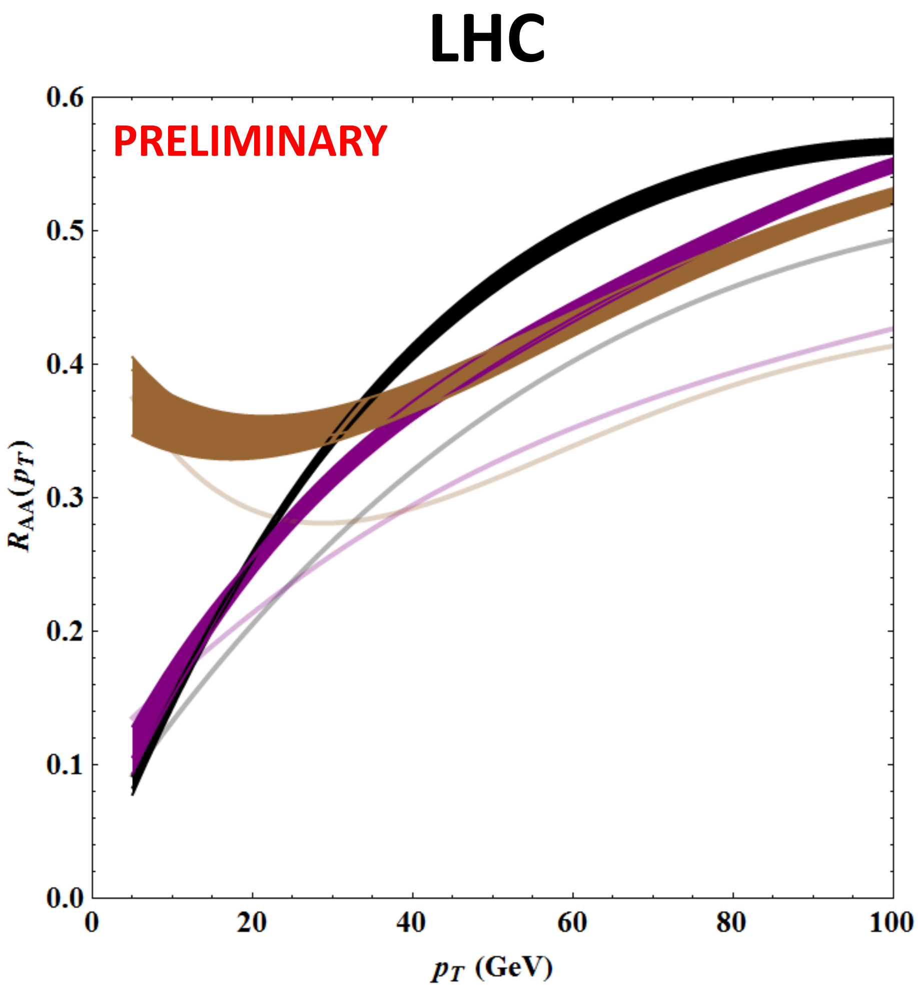
LHC

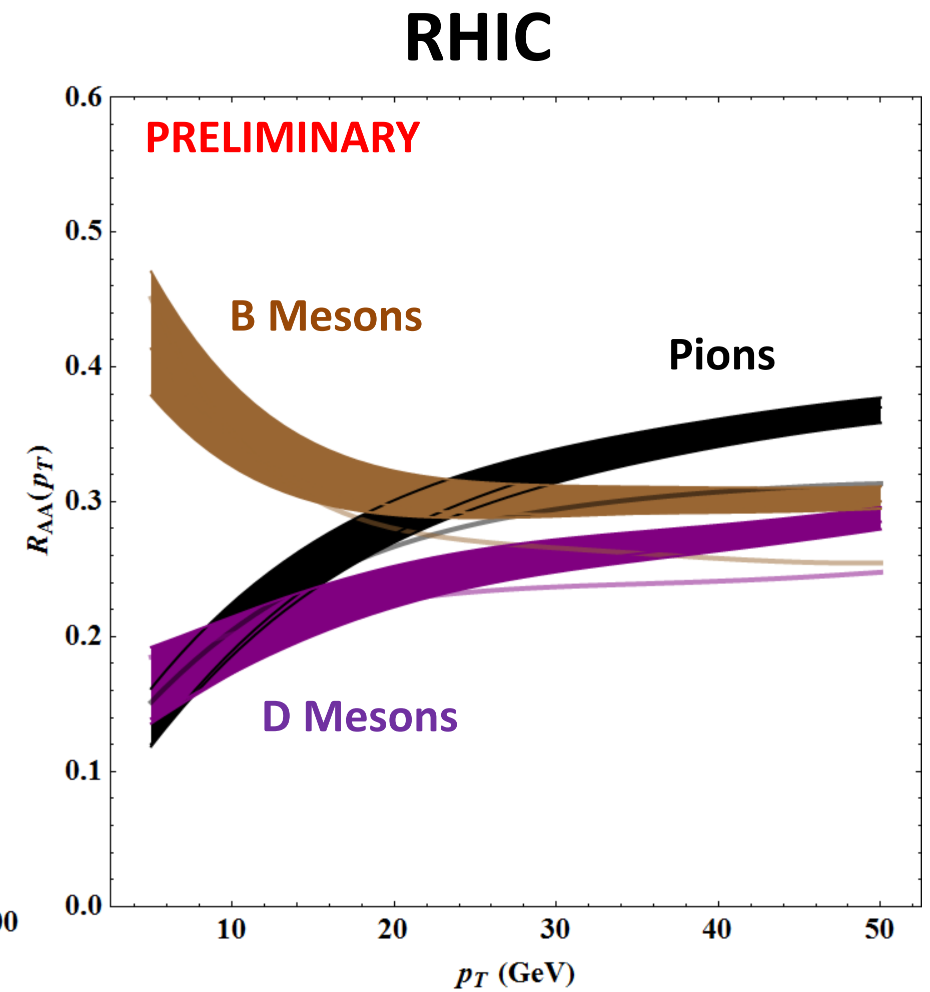


RHIC



Level crossing





Conclusions

MODEL

- **CUJET offers a reliable and flexible model able to compute leading hadron Jet Energy loss and compare directly with data**
  - Satisfactory results when looking at flavor and density dependence of R_{AA}
  - Possibility to study systematic theoretical uncertainties
  - Easy to improve

ACHIEVEMENTS

- **New RHIC electron predictions now consistent with uncertainties of data (Heavy Quark puzzle)**
- **Strong prediction of novel level crossing pattern of flavor dependent R_{AA}**
- **Evidence of running alpha strong coupling constant**
  - Good agreement with recent LHC data

FUTURE

- **Necessity to fit as many orthogonal observable as possible**
  - Non central collision R_{AA}
  - Elliptic flow v_2

BACKUP

Beyond first order in opacity

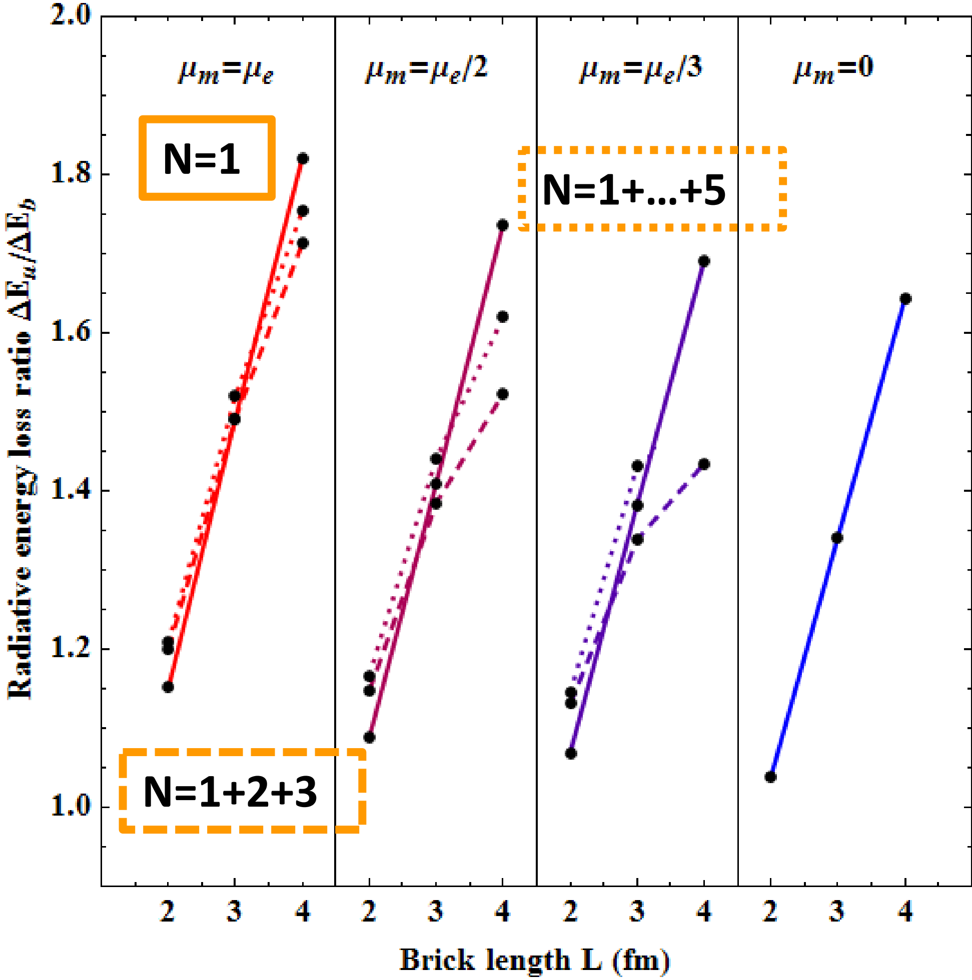
Interpolate between DGLV and MD with a new effective potential

$$\frac{1}{(q^2+\mu^2)^2} \xleftarrow{DGLV} \frac{1}{(q^2+\mu_m^2)(q^2+\mu_e^2)} \xrightarrow{MD} \frac{1}{q^2(q^2+\mu^2)}$$

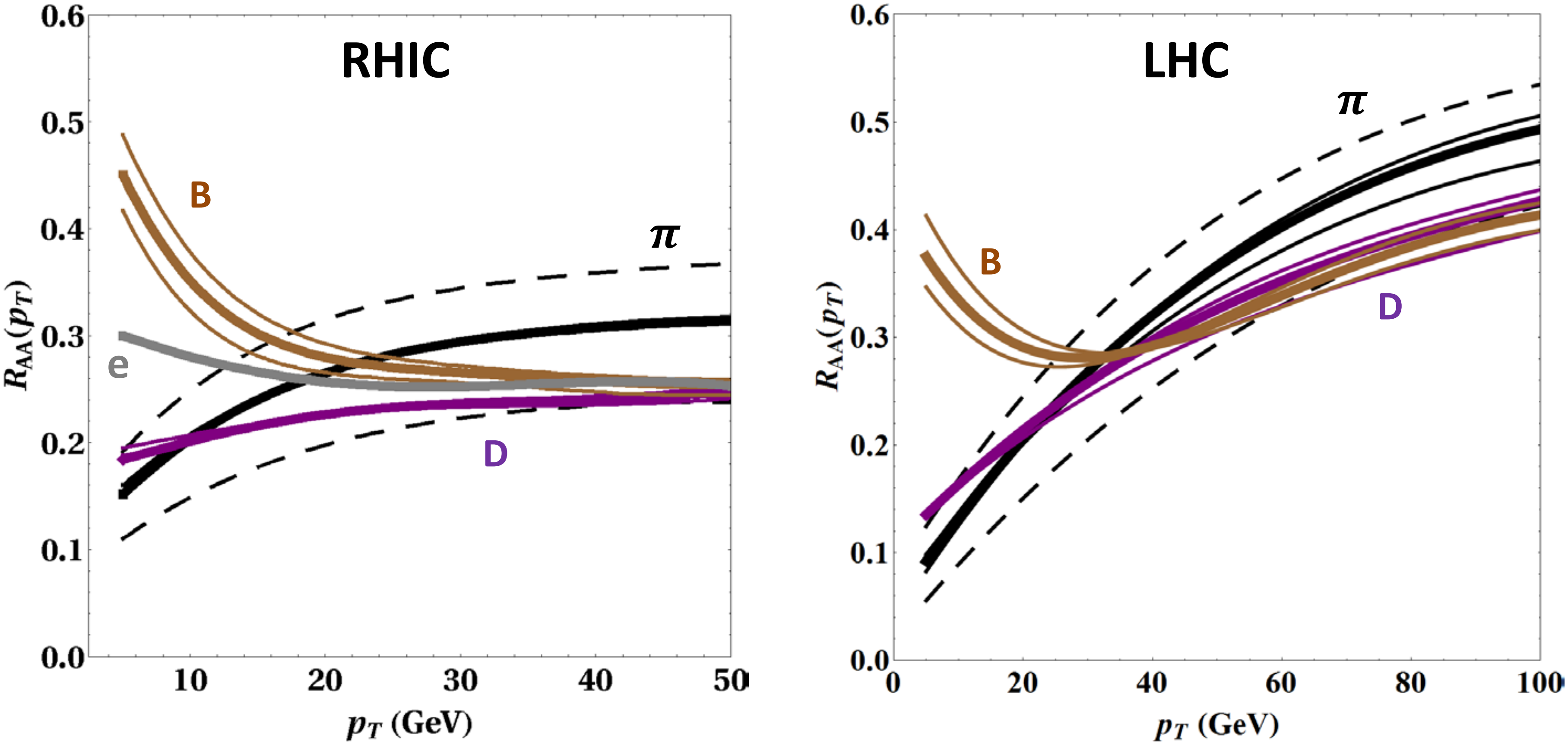
It is possible to study the limit $\mu_m \to 0$ for values of $\mu_m \gtrsim \mu_e/3$

- The mean free path $\frac{1}{\lambda} = \int d\mathbf{q}\,\frac{d\sigma}{d\mathbf{q}}\rho$ is divergent for μ_m=0

$\left(\frac{\Delta E_u}{\Delta E_b}\right)$ ratio improves for N>1 and $\mu_m \to 0$, but likely not enough.



τ_0 sensitivity



THICK: *Linear* with $\alpha_s = 0.3$

THIN: *Divergent* with $\alpha_s = 0.27$ *or* *Freestreaming* with $\alpha_s = 0.325$

DAHSED: *Divergent* *or* *Freestreaming* with $\alpha_s = 0.3$

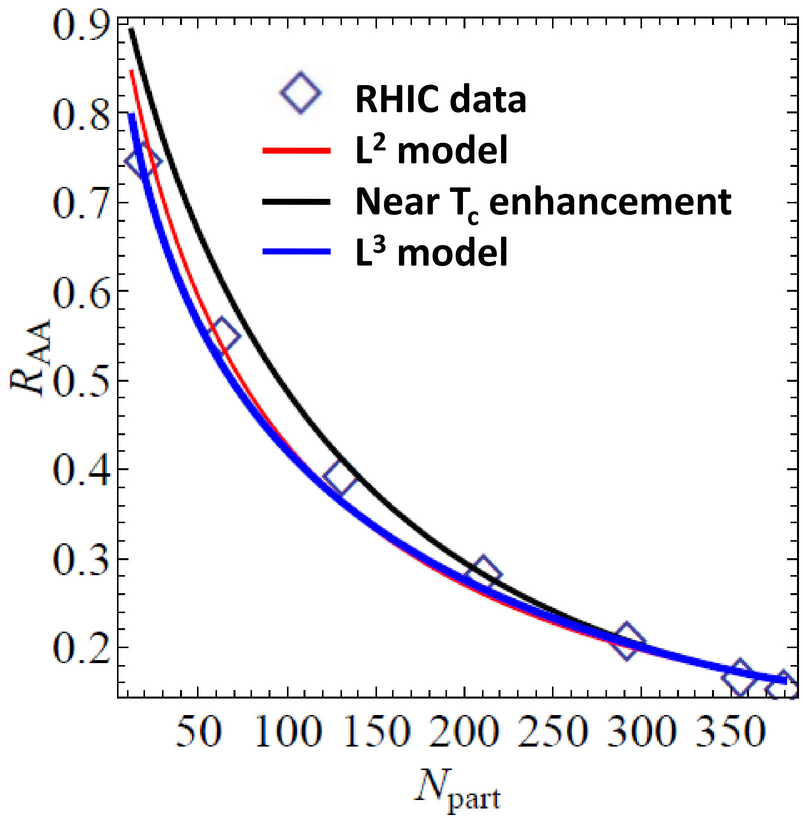
Magnetic monopoles

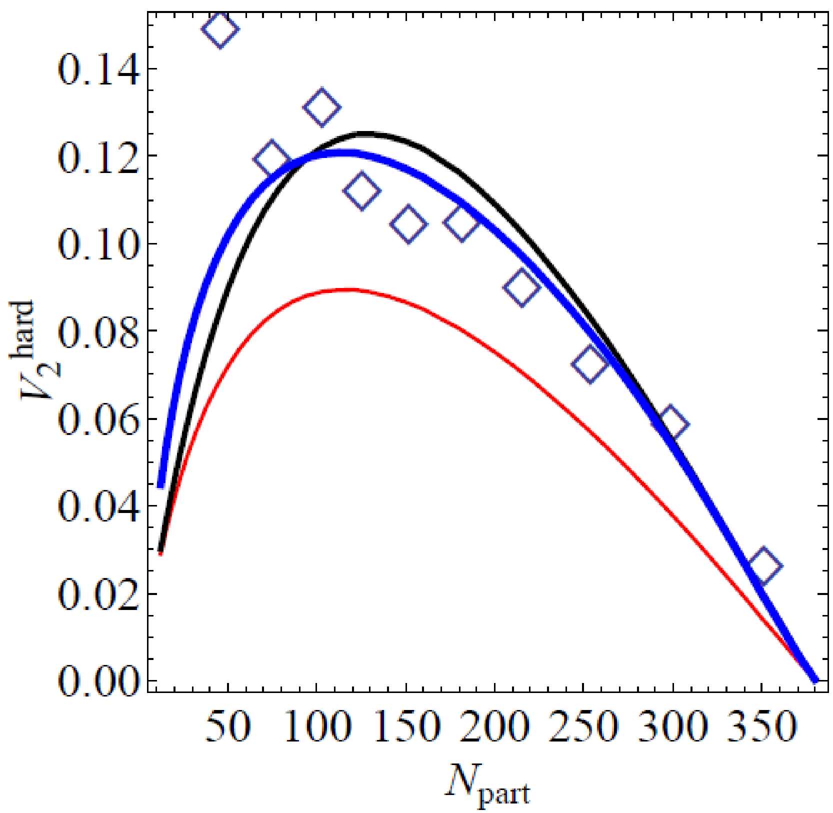
Magnetic monopole enhancement

– **Nonlinear density dependence near T_c**

AdS/CFT

Jinfeng Liao, arXiv:1109.0271





Elastic energy loss and Fluctuations

Bjorken elastic collisions

$$\boxed{\frac{dE}{dx} = -C_R \pi \alpha^2 T^2 \, log[B]}$$

- Soft scattering
- Thoma-Gyulassy model $\longrightarrow$ $B_{TG} = \frac{4pT}{E-p+4T}/\mu$

Energy loss fluctuations

- **The probability of losing a fractional energy $\varepsilon = \frac{\Delta E}{E}$ is the convolution of Radiative and Elastic contributions**

$$P(\varepsilon) = \int dx \, P_{rad}(\varepsilon) \, P_{el}(x-\varepsilon)$$

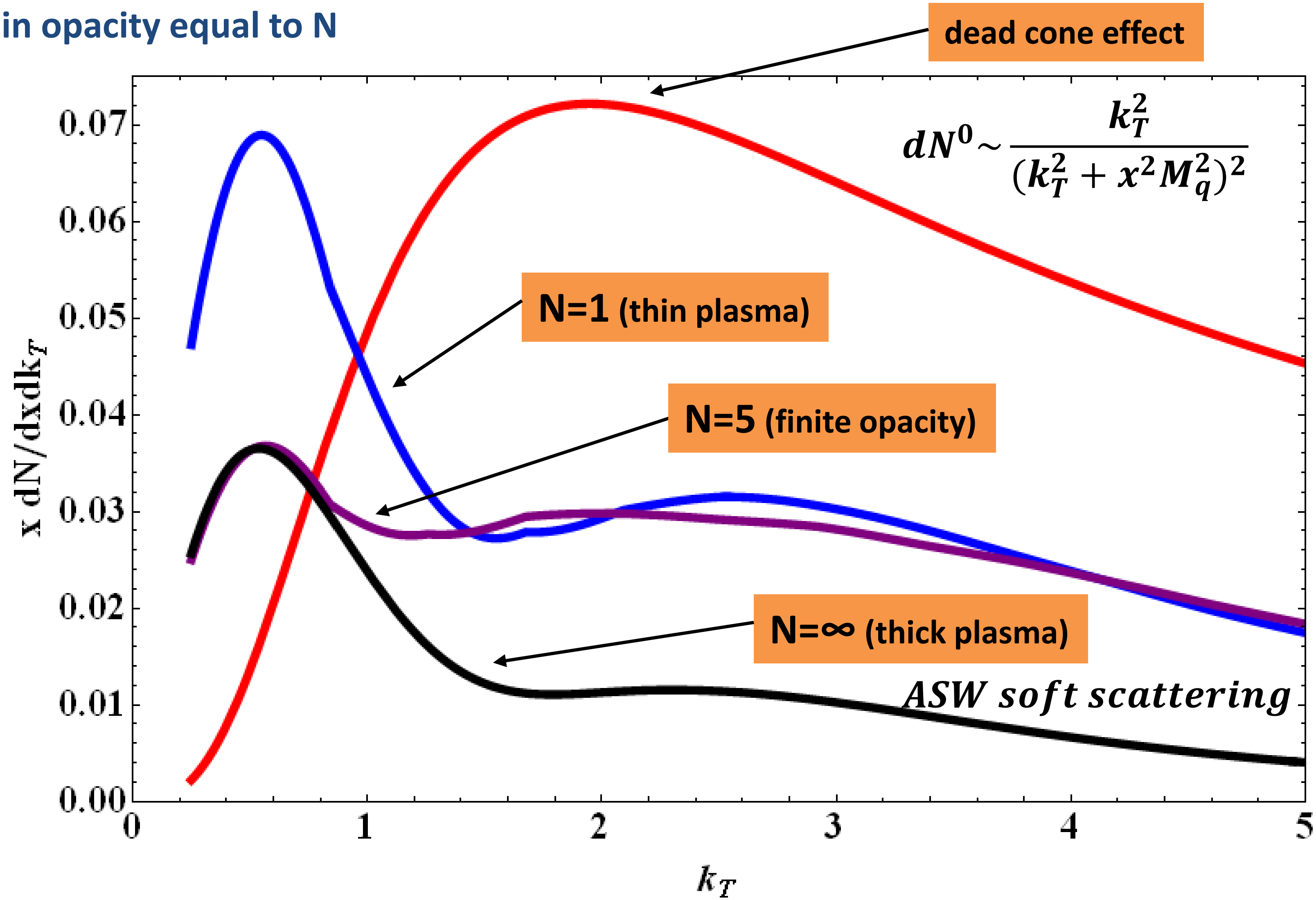
Poisson expansion of the number of INCOHERENTLY emitted gluons

- Radiative: $P_{rad}(\varepsilon) = P_0 \delta(\varepsilon) + \widetilde{P}(\varepsilon)|_0^1 + P_{stop}\delta(1-\varepsilon)$
- Elastic: $P_{el}(\varepsilon) = e^{-<N_c>}\delta(\varepsilon) + Ne^{-\frac{(\varepsilon-\bar{\varepsilon})}{4T\bar{\varepsilon}}}$

Gaussian fluctuations

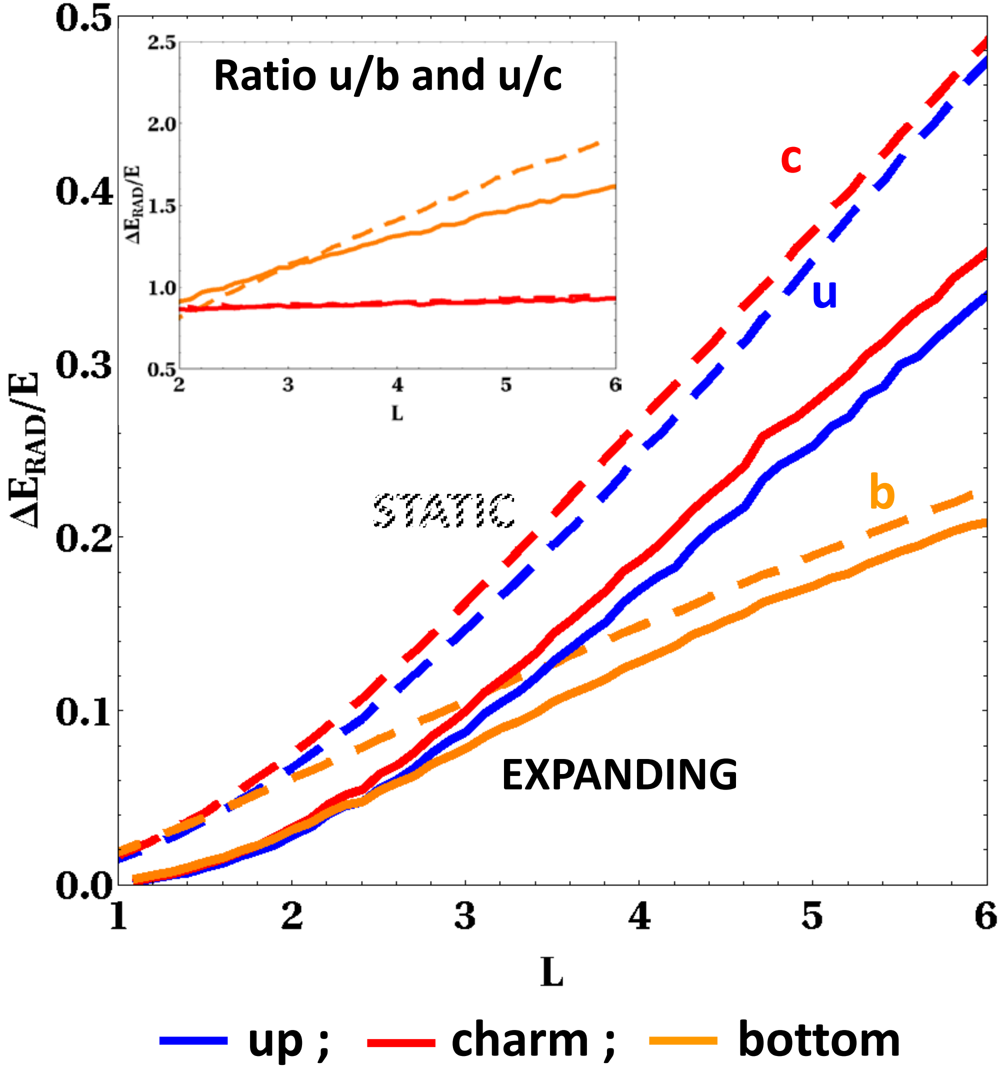
k_T distribution

En=20GeV, x=0.25, bottom quark, plasma thickness 5fm
Order in opacity equal to N

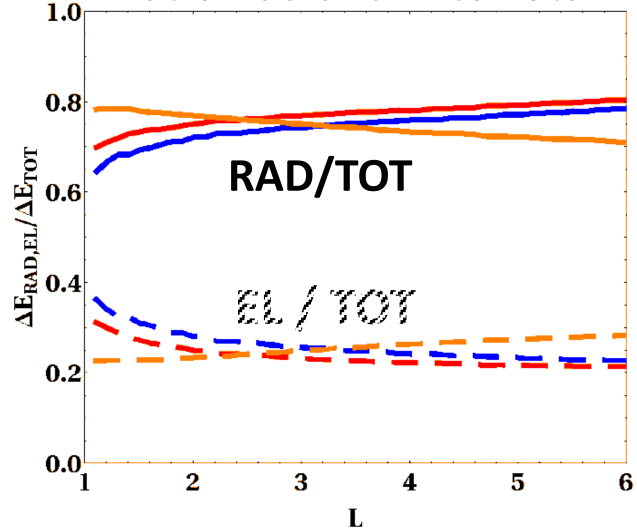


Energy loss

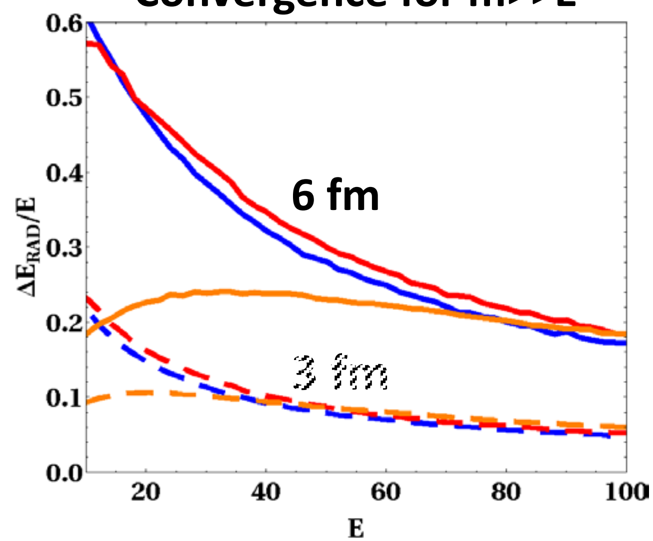
Energy loss vs L



Ratio Rad and El to Total



Convergence for m>>E



Temporal envelope

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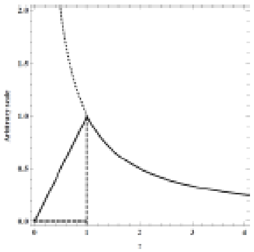
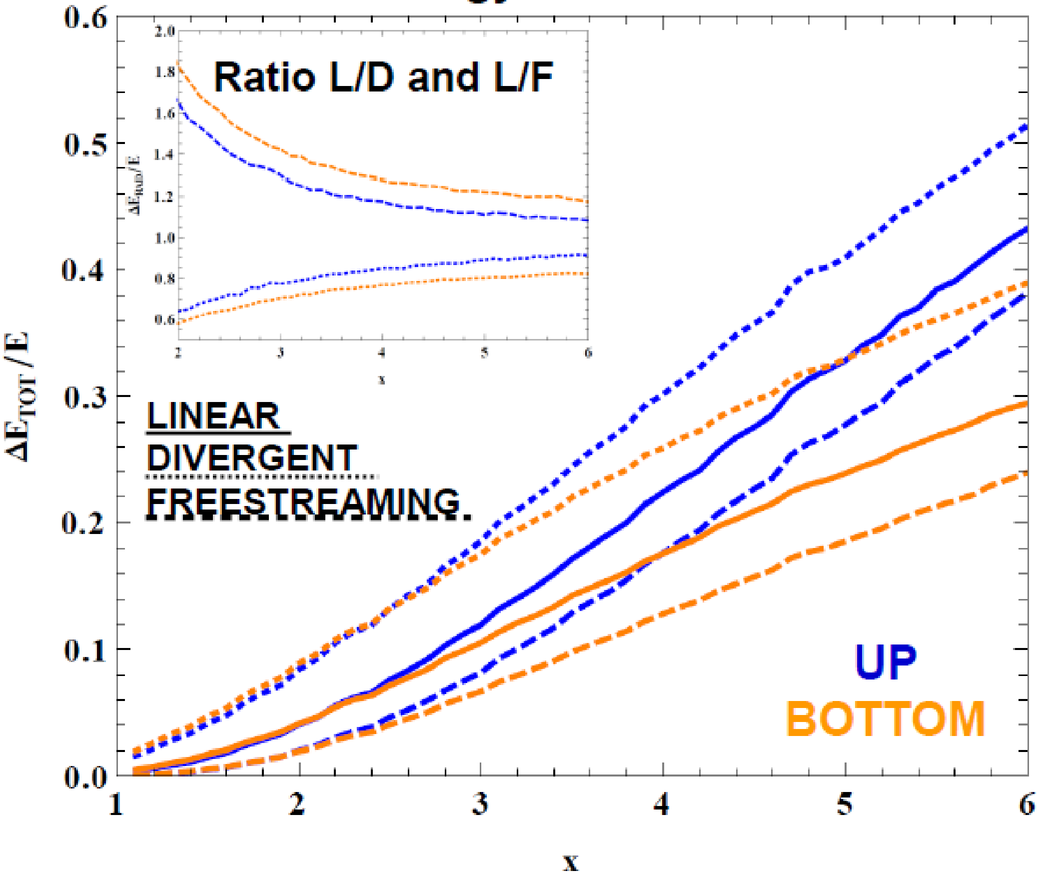
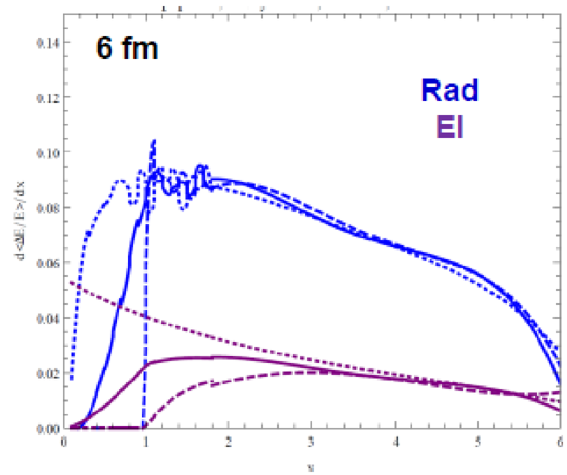
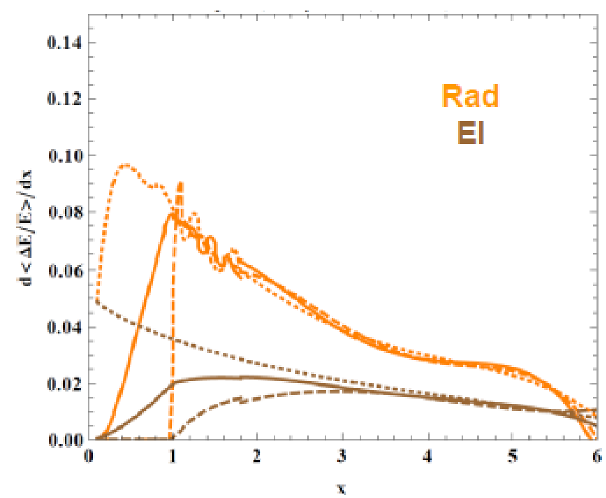


Energy loss vs L



Differential Energy Loss $\frac{d\langle\Delta E/E\rangle}{dx}$

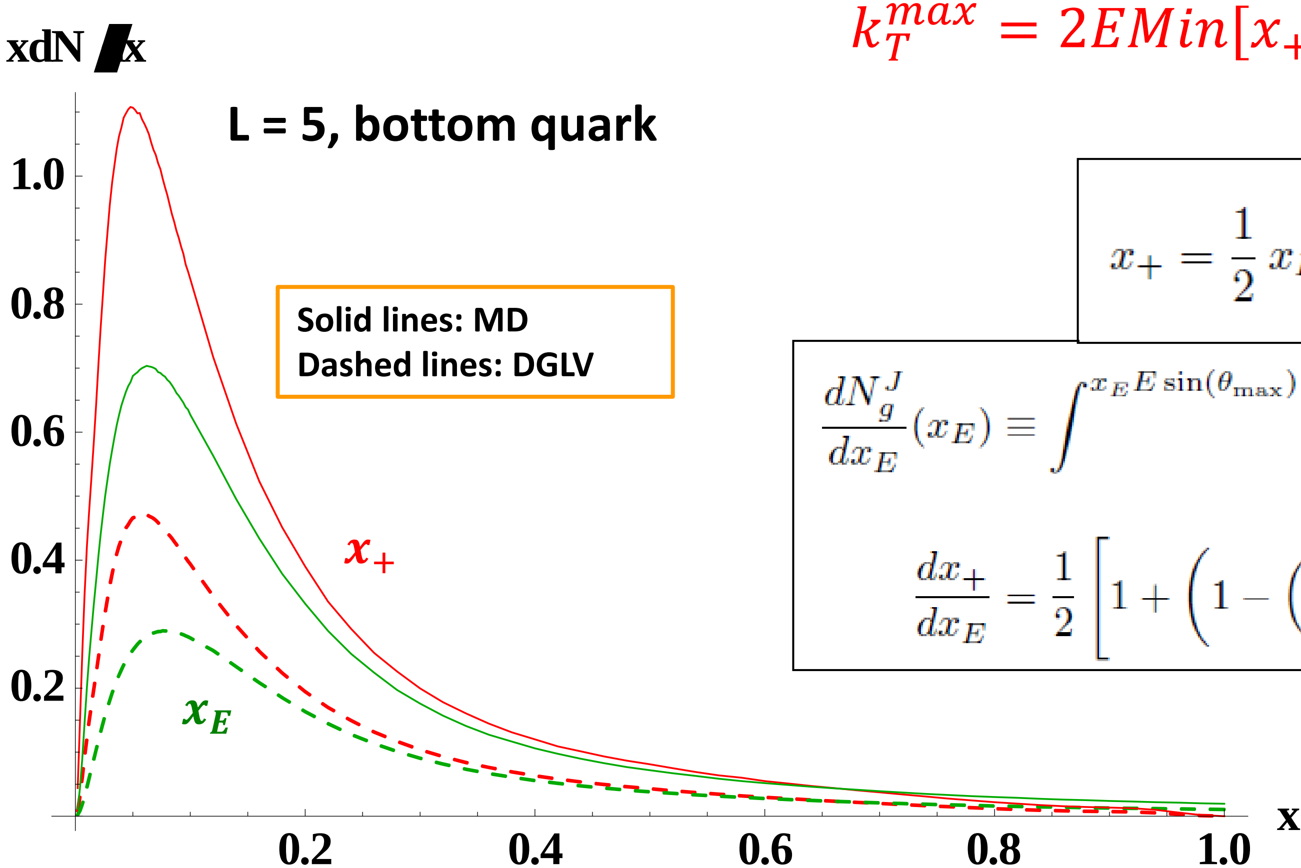




k_T sensitivity

- Collinear approximation: $x_E = x_+ \left(1 + O\left(\frac{k_T}{x_+ E^+}\right)^2\right)$
  - DGLV formula has the same functional form for x_E or x_+
  - Different kinematic limits: $k_T^{max} = x_E E$

    $k_T^{max} = 2EMin[x_+, 1 - x_+]$



$$x_+ = \frac{1}{2} x_E \left(1 + \sqrt{1 - \left(\frac{k_T}{x_E E}\right)^2}\right)$$

$$\frac{dN_g^J}{dx_E}(x_E) \equiv \int^{x_E E \sin(\theta_{\max})} dk_T \frac{dx_+}{dx_E} \frac{dN_g}{dx_+ dk_T}(x_+(x_E)),$$

$$\frac{dx_+}{dx_E} = \frac{1}{2}\left[1 + \left(1 - \left(\frac{k_T}{x_E E}\right)^2\right)^{-1}\right].$$

Scaling violation

- **BDMPS predicts the scaling of the induced intensity x-spectrum with** $\hat{q} \sim \mu^2/\lambda$ **through the z variable** $z \equiv \left|\omega_0^2\right| L^2, \quad \omega_0^2 \equiv -i\frac{\left[(1-x)C_A + x^2 C_s\right]\hat{q}}{2x(1-x)E}$