



A running coupling explanation of the surprising transparency of the QGP at LHC

Phys. Rev. Lett. 108, 0223101 (2012)
arXiv:1207.6020 (2012)

Alessandro Buzzatti

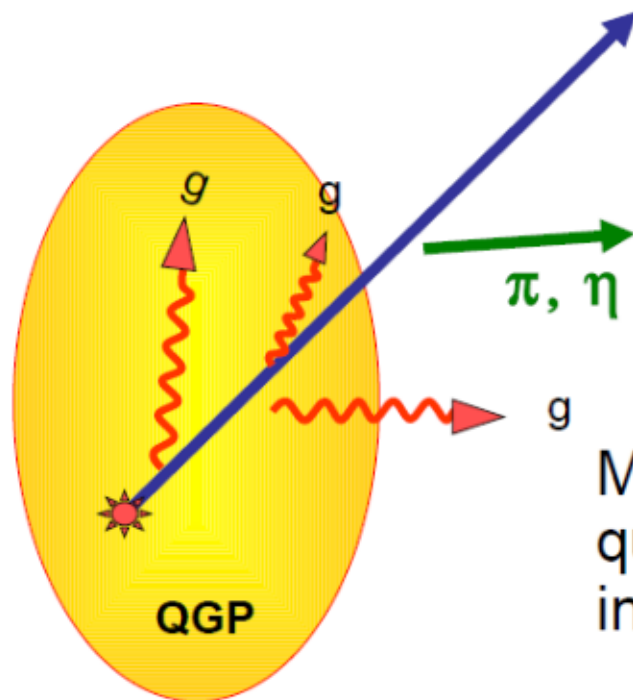
Miklos Gyulassy



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

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

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



Quark or Glue Jet probes:

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

Hadron jet fragments:

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

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

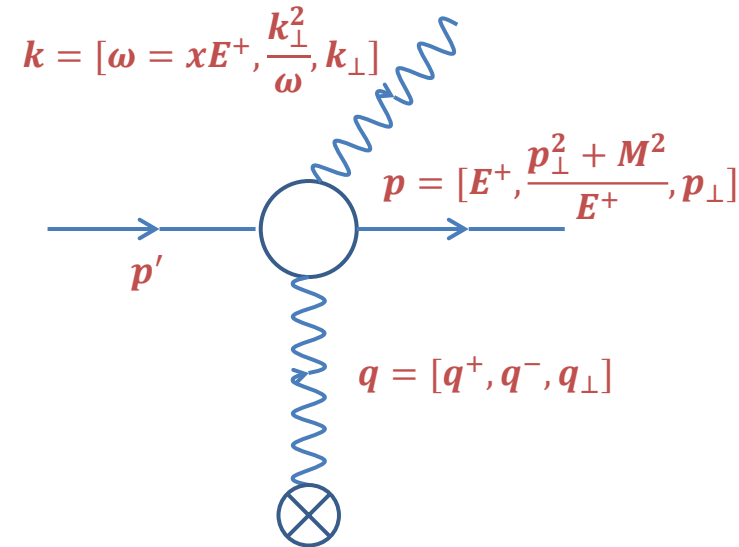
$$\Delta E^{\text{rad}} \propto \alpha_s^3 \int d\tau \tau \rho_{\text{QGP}}(\tau, \vec{r}(\tau)) \text{Log}\left(\frac{E_{\text{Jet}}}{T}\right)$$

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

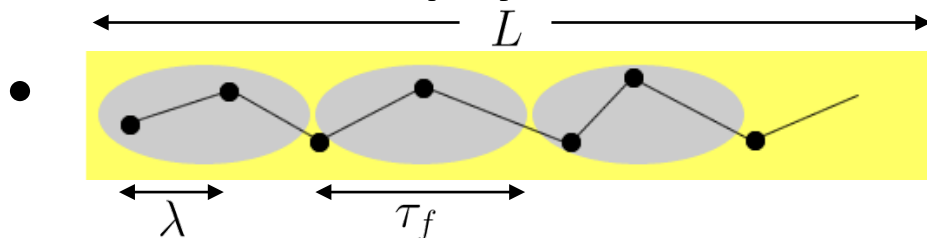
Incoherent limit: Gunion-Bertsch

$$\bullet \quad \frac{dN}{dxdk_{\perp}} = \frac{1}{x} \frac{\alpha_s C_A}{\pi^2} \frac{q_{\perp}^2}{k_{\perp}^2 (q_{\perp} - k_{\perp})^2}$$

- 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)

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

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

Opacity series expansion $\rightarrow \left(\frac{L}{\lambda}\right)^n$

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

Radiation antenna \rightarrow Cascade terms

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

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

Gunion – Bertsch

$$\tilde{\mathbf{B}}_i = \tilde{\mathbf{H}} - \tilde{\mathbf{C}}_i,$$

Hard

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

LPM effect \rightarrow

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

Inverse formation time *Mass effects*

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

- **Geometry**

- Glauber model
- Bjorken longitudinal expansion

- **Energy loss**

- DGLV – MD Radiative energy loss model
- Energy loss fluctuations (Poisson expansion)
- Full path length integration:

$$\begin{aligned}
 & - \frac{dN_g}{dx}(x_\perp, \phi) = \\
 & \frac{C_{R\alpha_s}}{\pi} \int d\tau \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{1}{x} \frac{\frac{9}{2}\pi\alpha^2}{q^2(q^2 + \mu^2(\tau))} \times \frac{2(k+q)}{(k+q)^2 + \chi(\tau)} \left(\frac{(k+q)}{(k+q)^2 + \chi(\tau)} - \frac{k}{k^2 + \chi(\tau)} \right) \times \\
 & \left(1 - \cos \left[\frac{(k+q)^2 + \chi(\tau)}{2xE} \tau \right] \right) \rho_{QGP}(x_\perp + \hat{\phi}\tau, \tau)
 \end{aligned}$$

$$\mu(\tau) = gT(x_\perp + \hat{\phi}\tau, \tau)$$

$$\chi(\tau) = M^2 x^2 + m_g^2(\tau)(1-x)$$

- Elastic energy loss contributions

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

- **Geometry**
 - Glauber model
 - Bjorken longitudinal expansion
 - **Energy loss**
 - DGLV – MD Radiative energy loss model
 - Energy loss fluctuations (Poisson expansion)
 - Full path length integration:
 - ...
- 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;
- Elastic energy loss contributions
 - **Detailed convolution over initial production spectra**
 - **In vacuum Fragmentation Functions**

- The local thermal equilibrium is established at τ_0

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

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

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

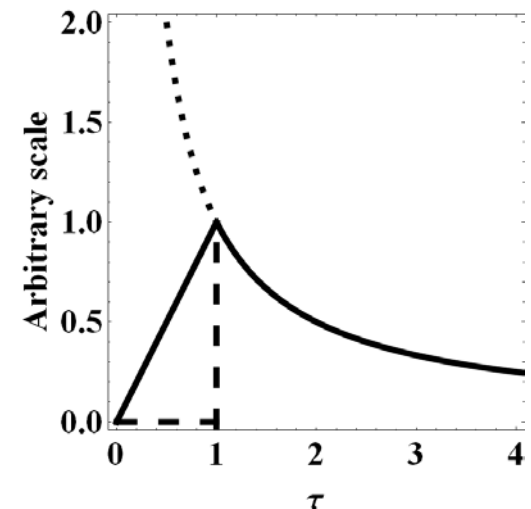
MONOTONIC density dependence

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

- Before equilibrium

Temporal envelopes: linear, divergent, freestreaming

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

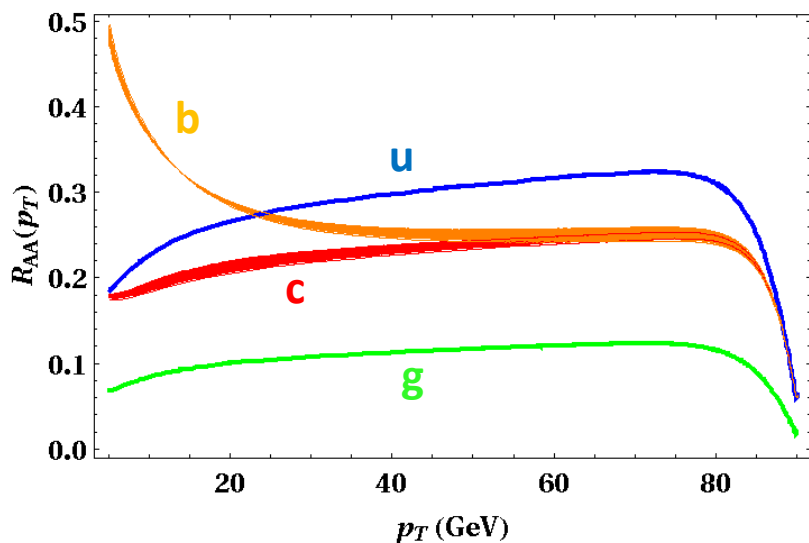


- Opacity order expansion
- Choice of interaction potential
- Pre-equilibrium phase
 - **ALSO:**
- pp Spectra
- Running coupling scales

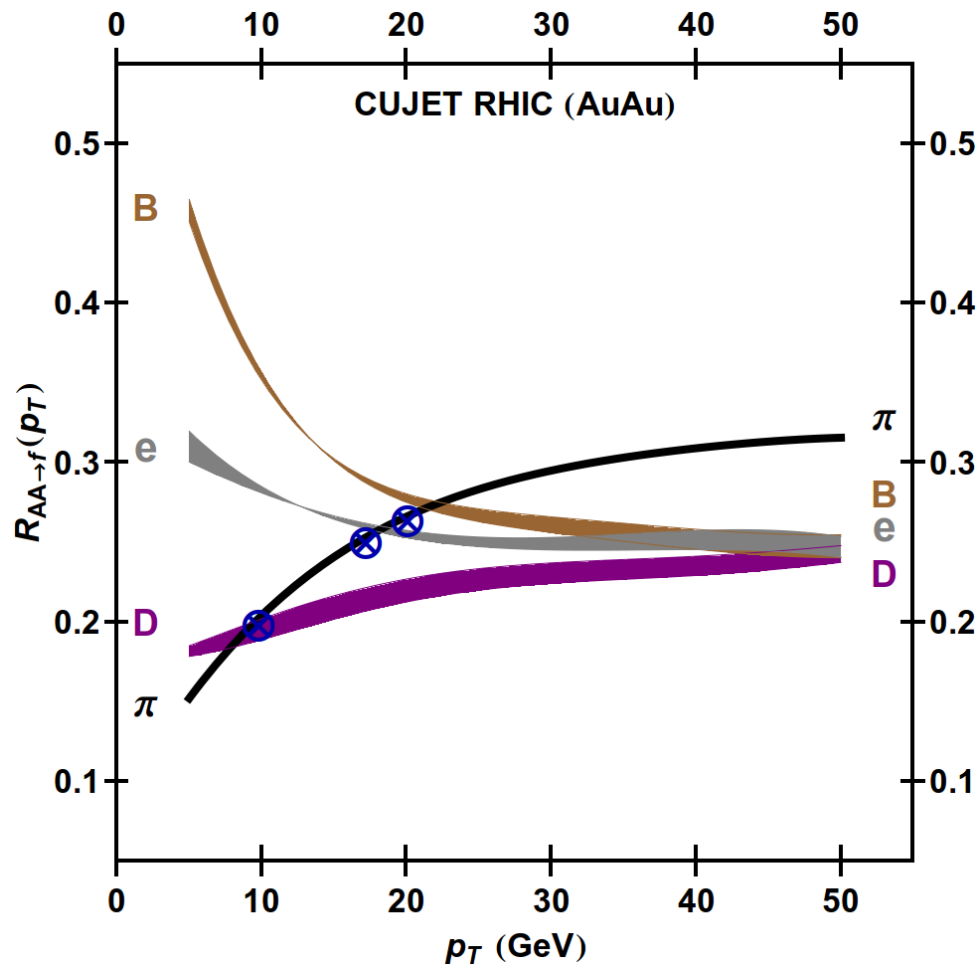
1. One free parameter in the model: α_s^{eff}
2. Fit α_s^{eff} to 10GeV RHIC Pion data $\alpha_s^{eff} \approx 0.3 \pm 10\%$
3. All other predictions are fully constrained

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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)

Parameters constrained by RHIC
 $dNdy = 2200$

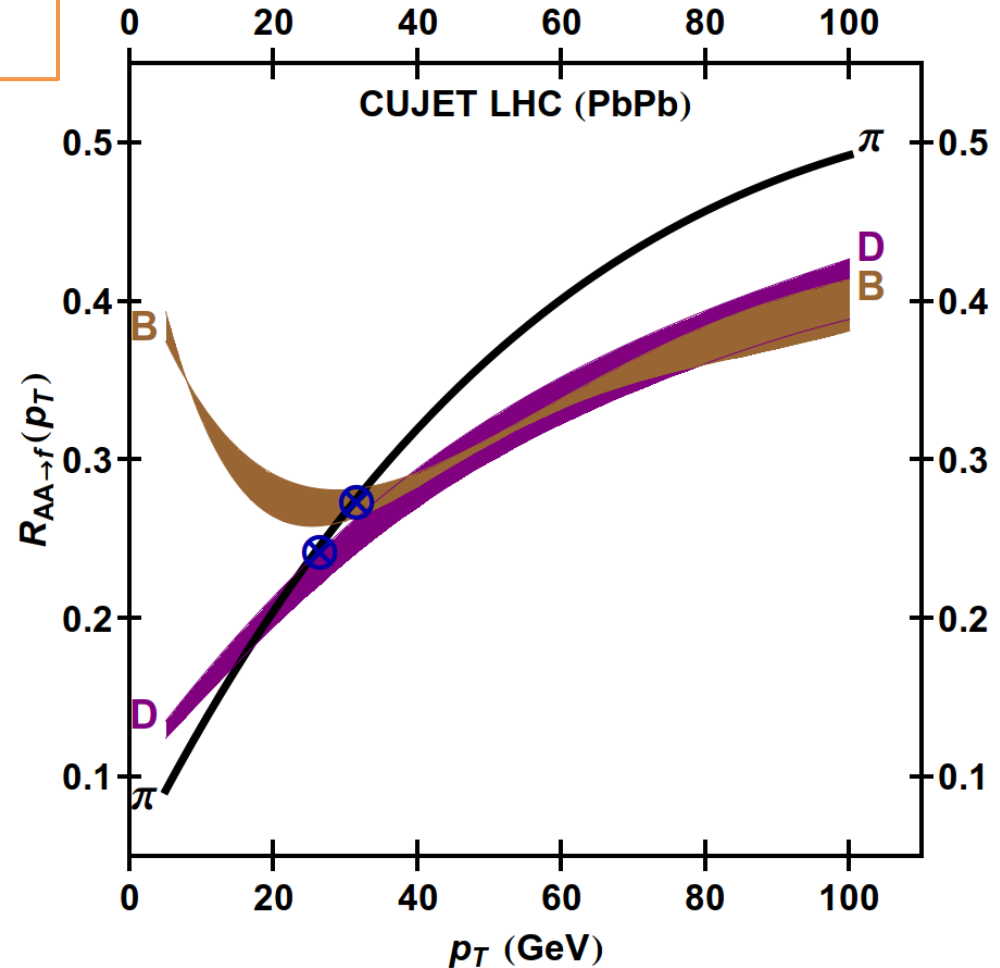
Competing effect between Energy loss ordering...

$$\Delta E(\text{light}) \approx \Delta E(c) > \Delta E(b)$$

...and pp Production spectra

$d\sigma(c, b)$ harder than $d\sigma(\text{light})$

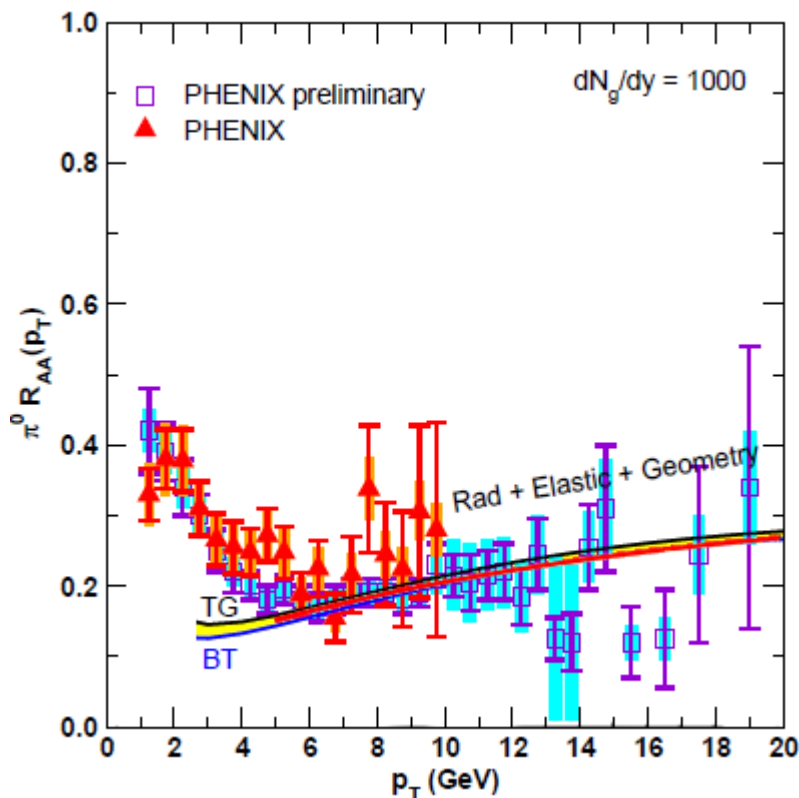
$$RAA \sim (1 - \Delta E/E)^{n-2}$$



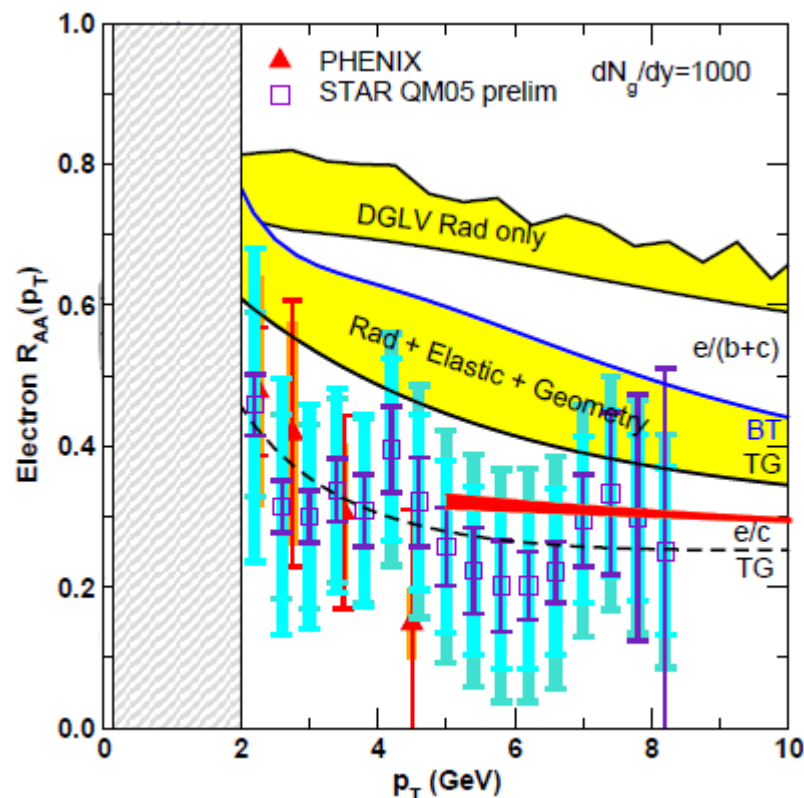
AB and M. Gyulassy, *Phys. Rev. Lett.* **108**, 0223101 (2012)

Alessandro Buzzatti – Columbia University

LIGHT QUARKS



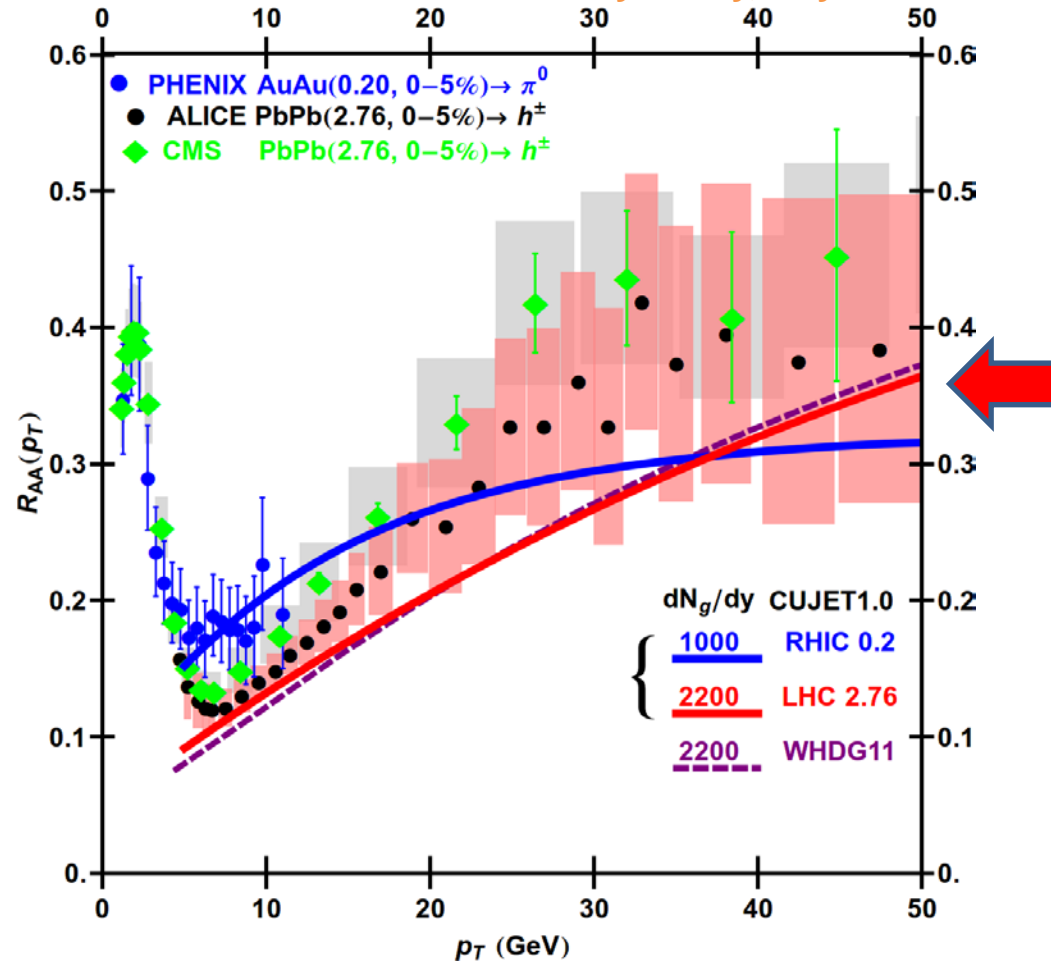
HEAVY QUARKS



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

CUJET solves the Heavy Quark puzzle...

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



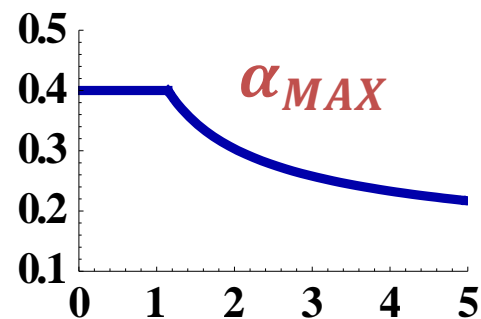
...but doesn't excel at explaining the surprising transparency at LHC

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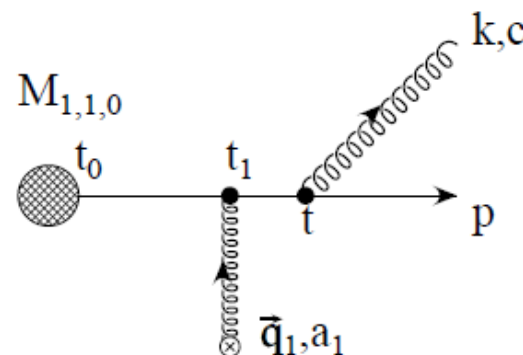
- Introduce one-loop alpha running

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

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



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



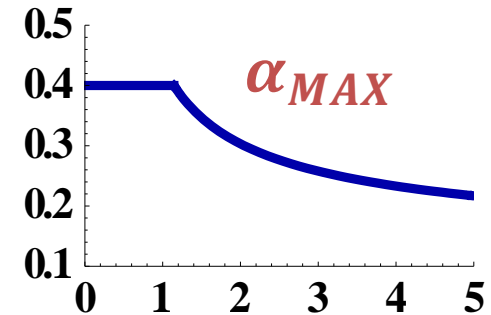
$$\text{Elastic} = \begin{cases} \alpha(ET) \\ \alpha(\mu^2) \end{cases}$$

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

- Introduce one-loop alpha running

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

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



– Systematic uncertainties:

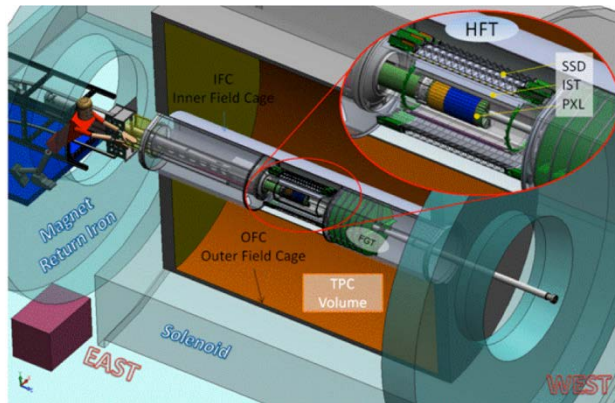
$$\text{Vary } \alpha(Q^2) = \begin{cases} Q \rightarrow -50\% \\ Q \rightarrow +25\% \end{cases}$$

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

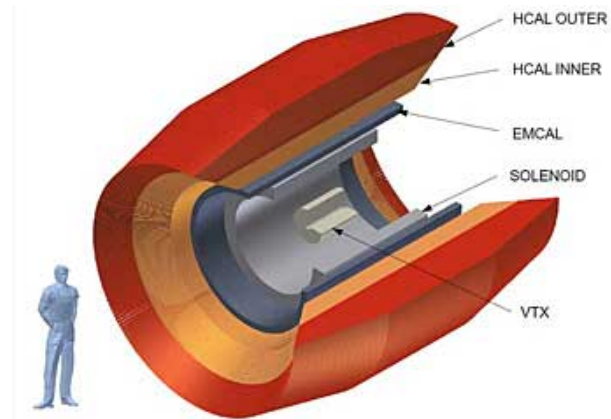
It is natural to use LHC results as our benchmark due to the extended p_T range available

however

RHIC remains an essential tool to constraint our models

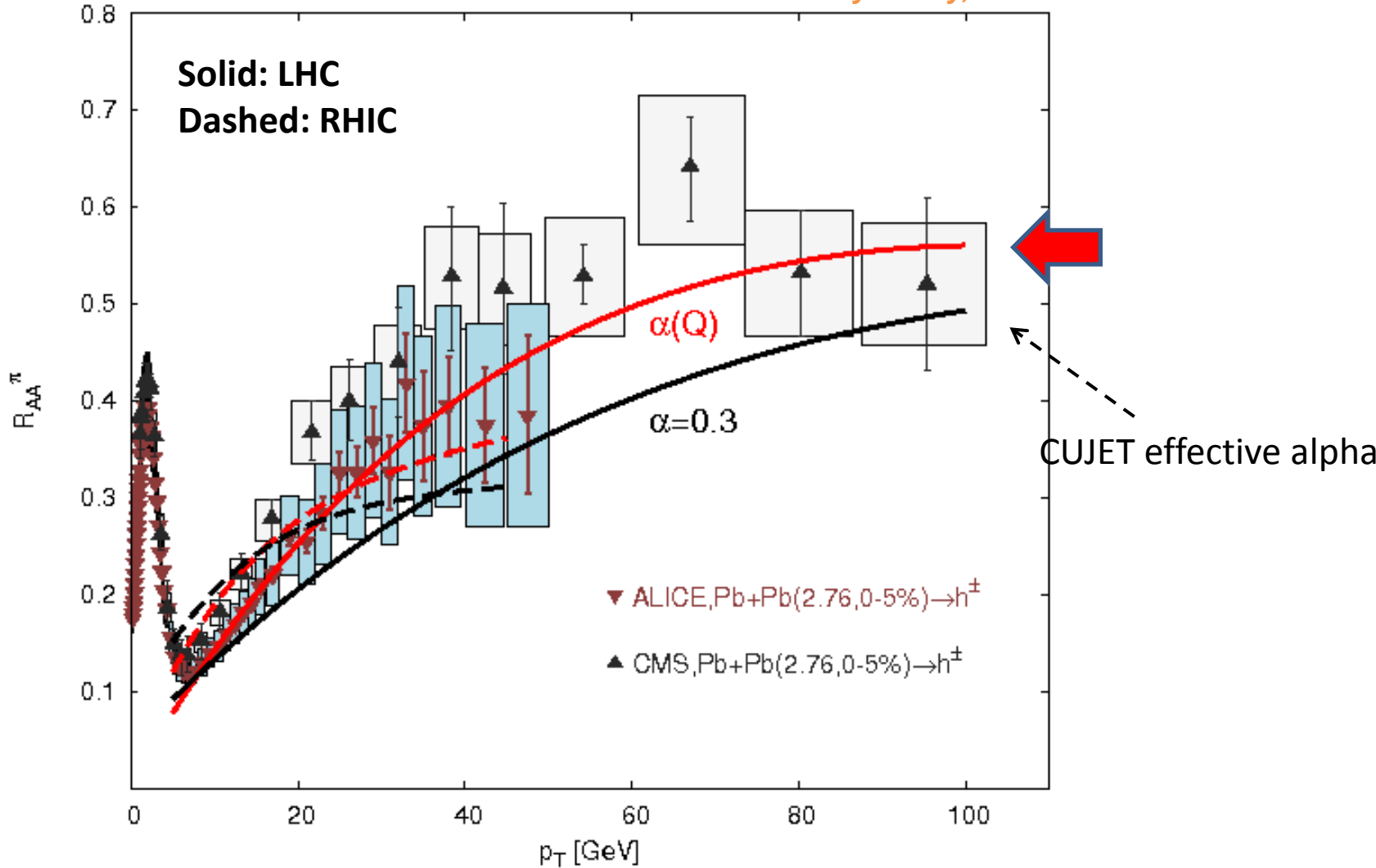


STAR HFT



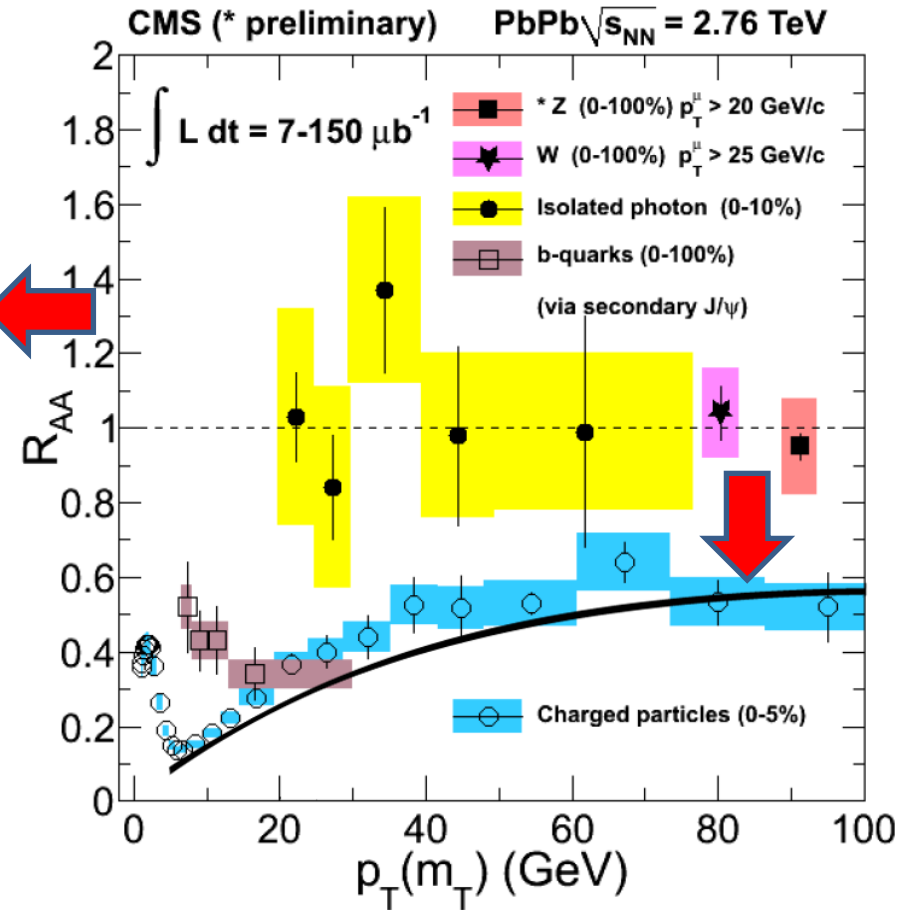
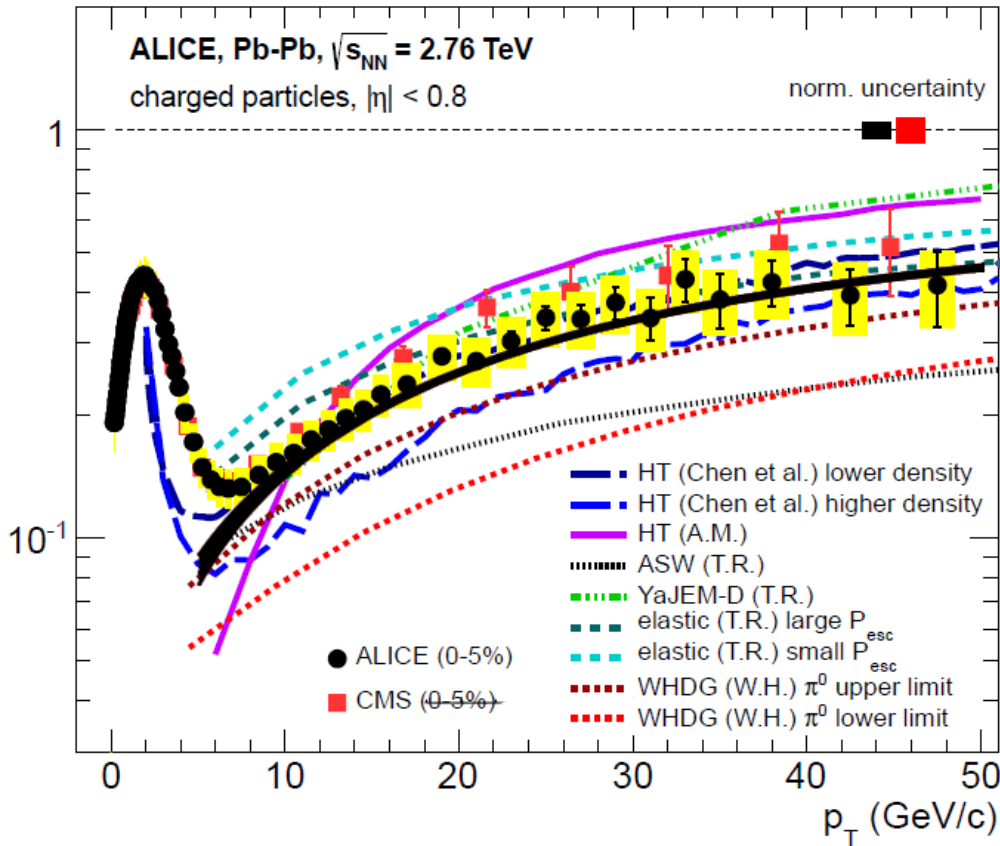
sPHENIX

See also B. Betz and M. Gyulassy, arXiv:1201.02181

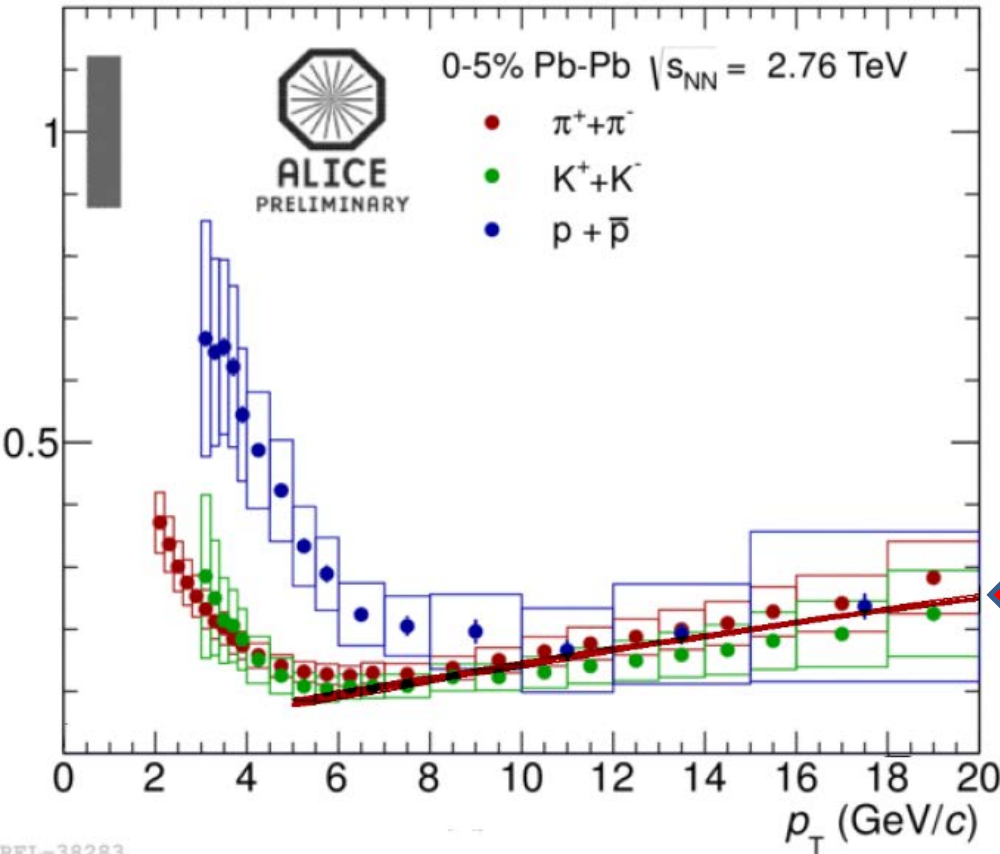


ALICE Collaboration

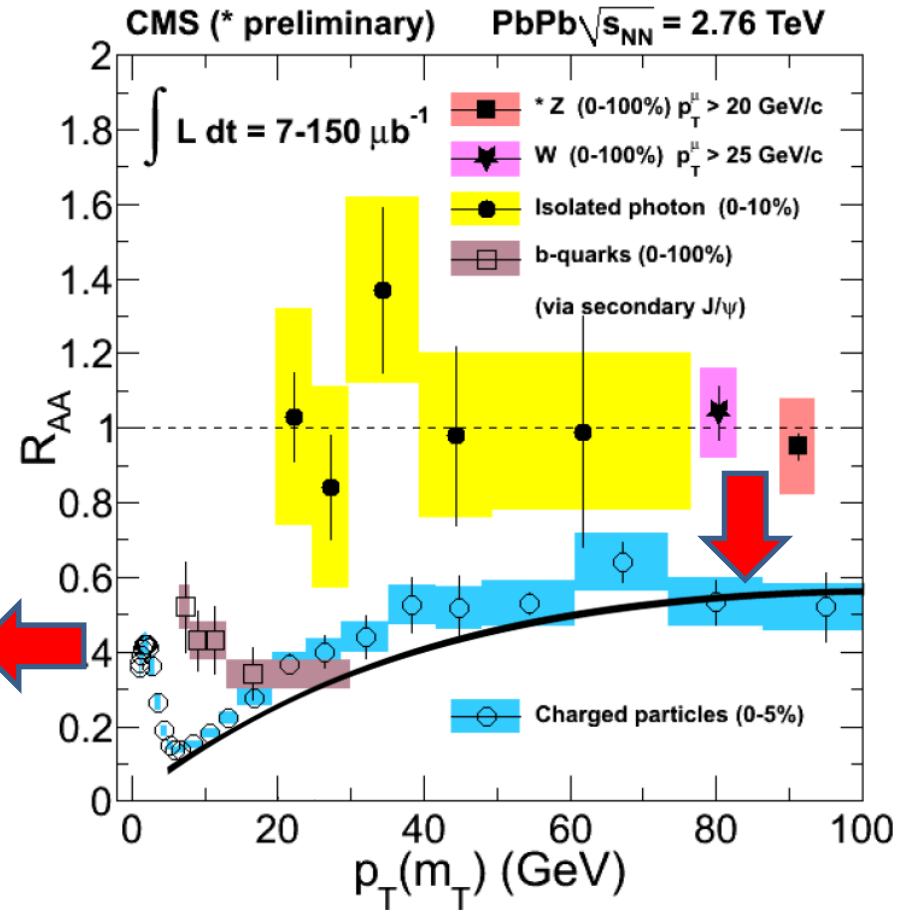
CMS Collaboration



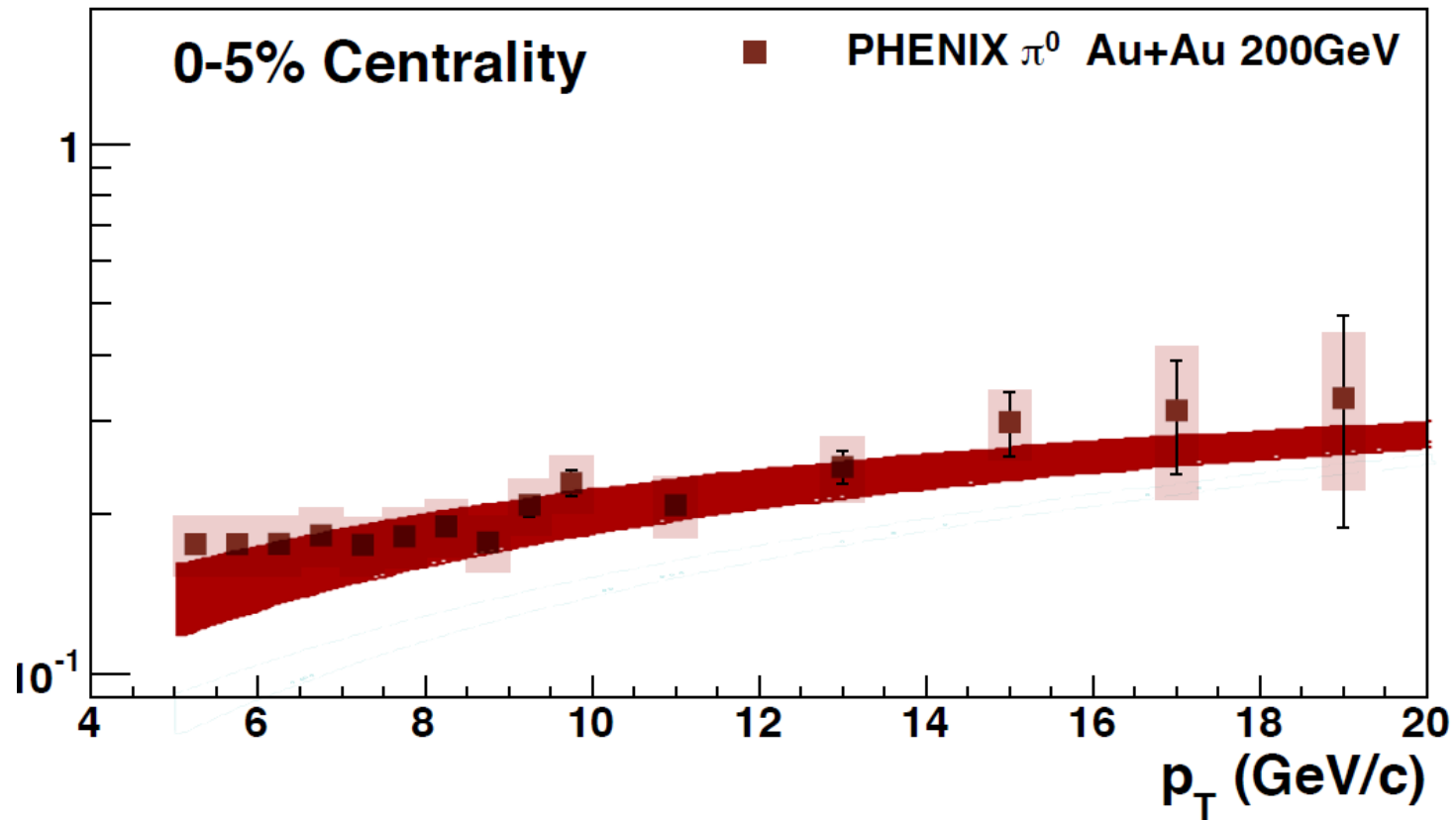
ALICE Collaboration



CMS Collaboration

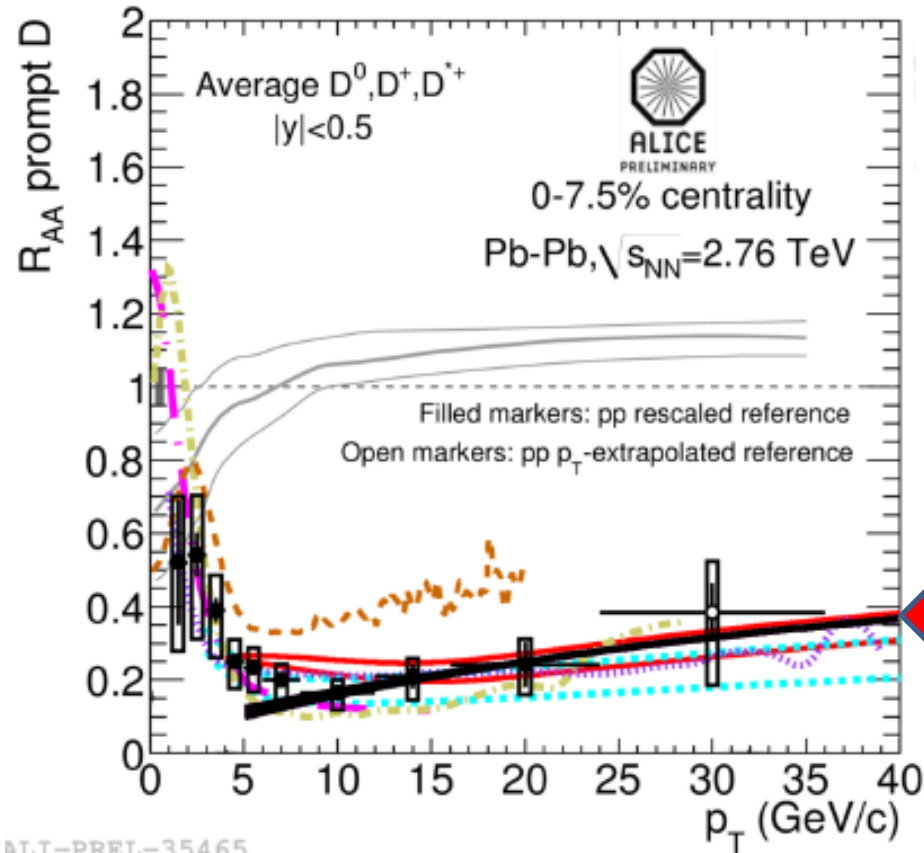


PHENIX Collaboration

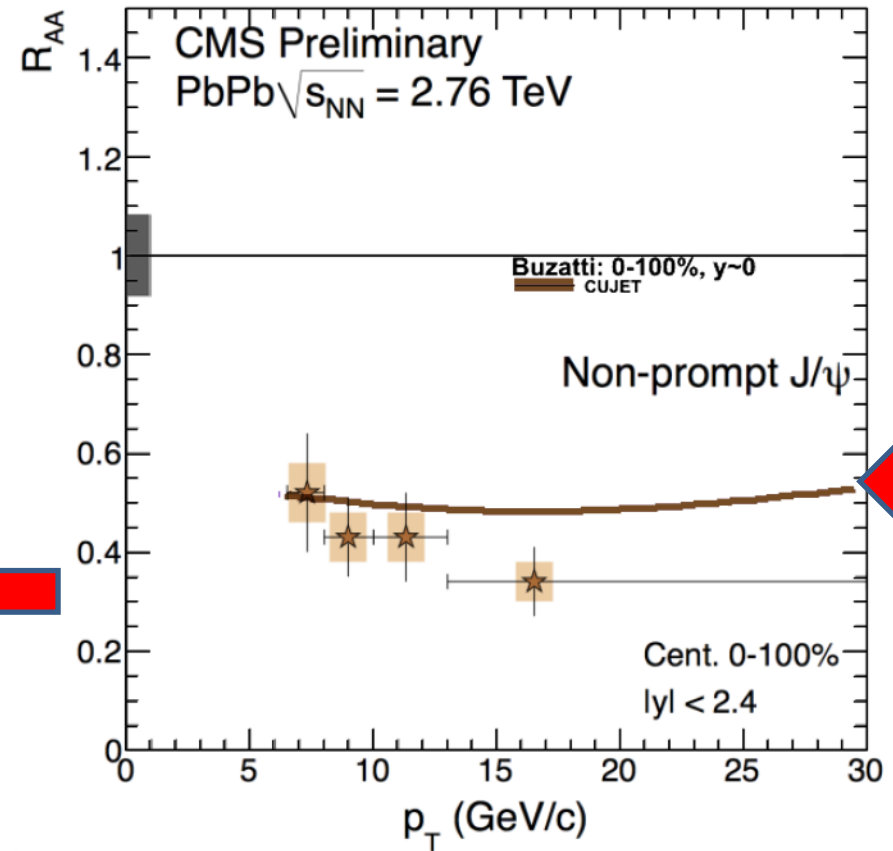


ALICE Collaboration

CMS Collaboration



CMS-PAS HIN-12-014



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
 - Simultaneous agreement with RHIC and LHC data

FUTURE

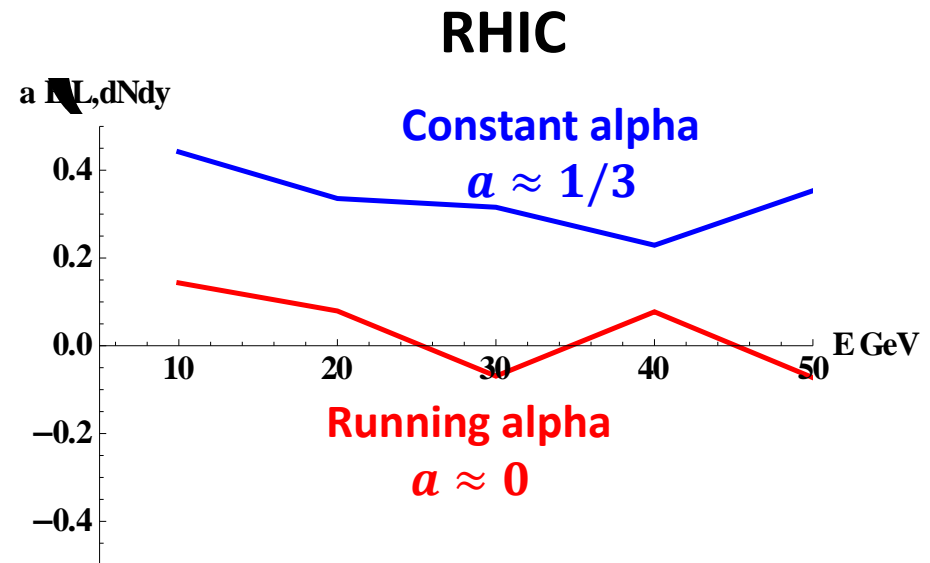
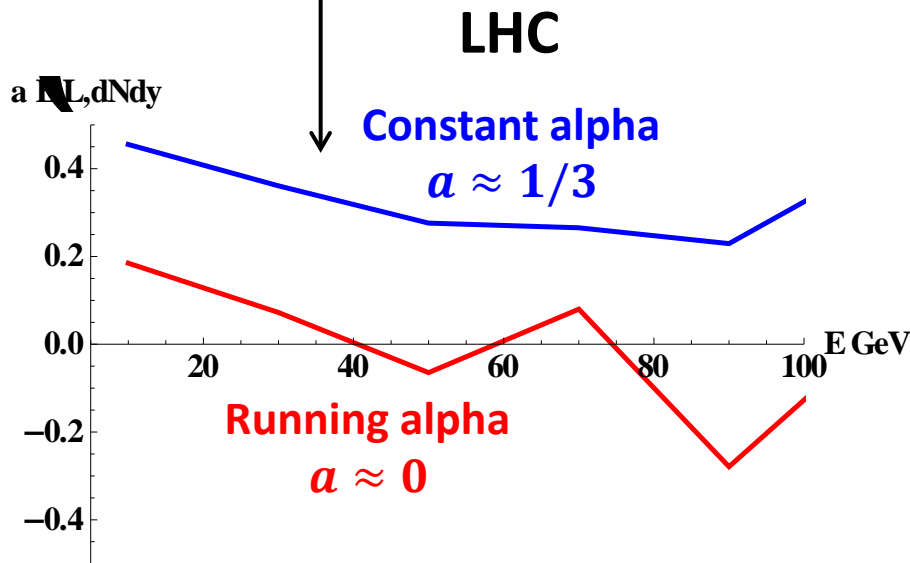
- Necessity to fit as many orthogonal observable as possible
 - Non central collision R_{AA}
 - Elliptic flow v_2

- Consider a simplified power law model for Energy loss:

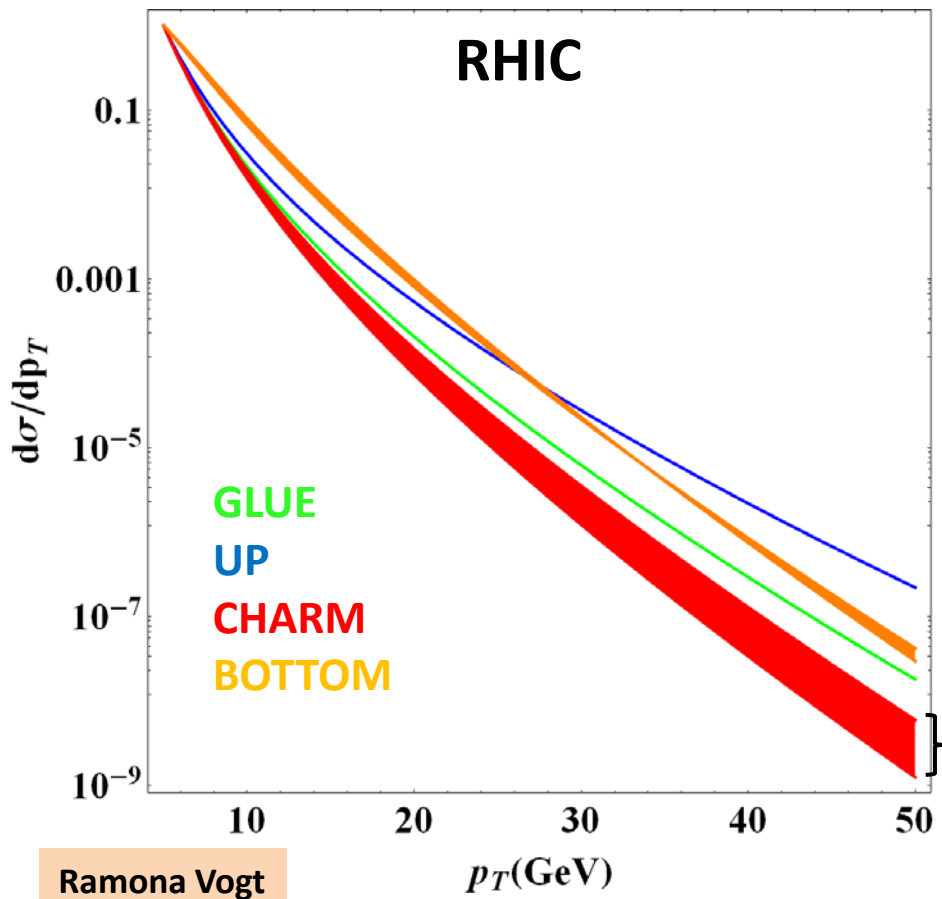
$$\frac{\Delta E}{E} = \kappa E^{a-1} L^b \rho^c$$

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

B. Betz and M. Gyulassy, arXiv:1201.0218



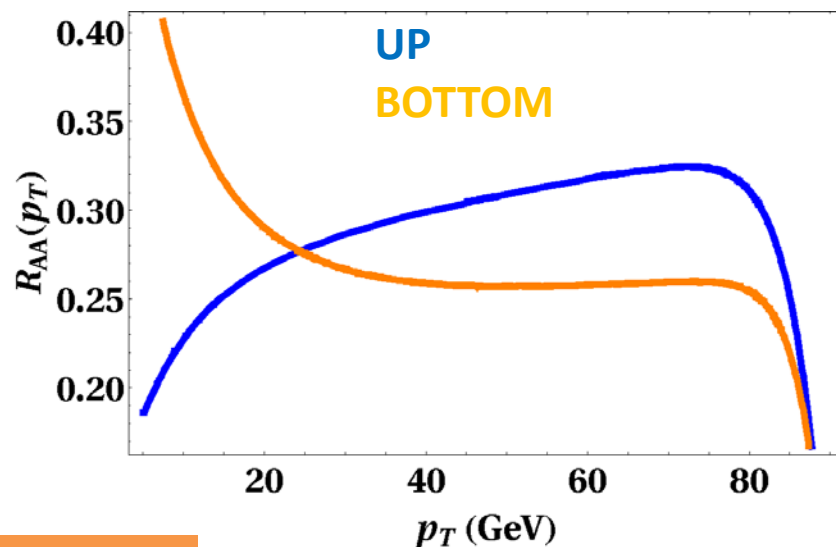
Initial quark production spectra



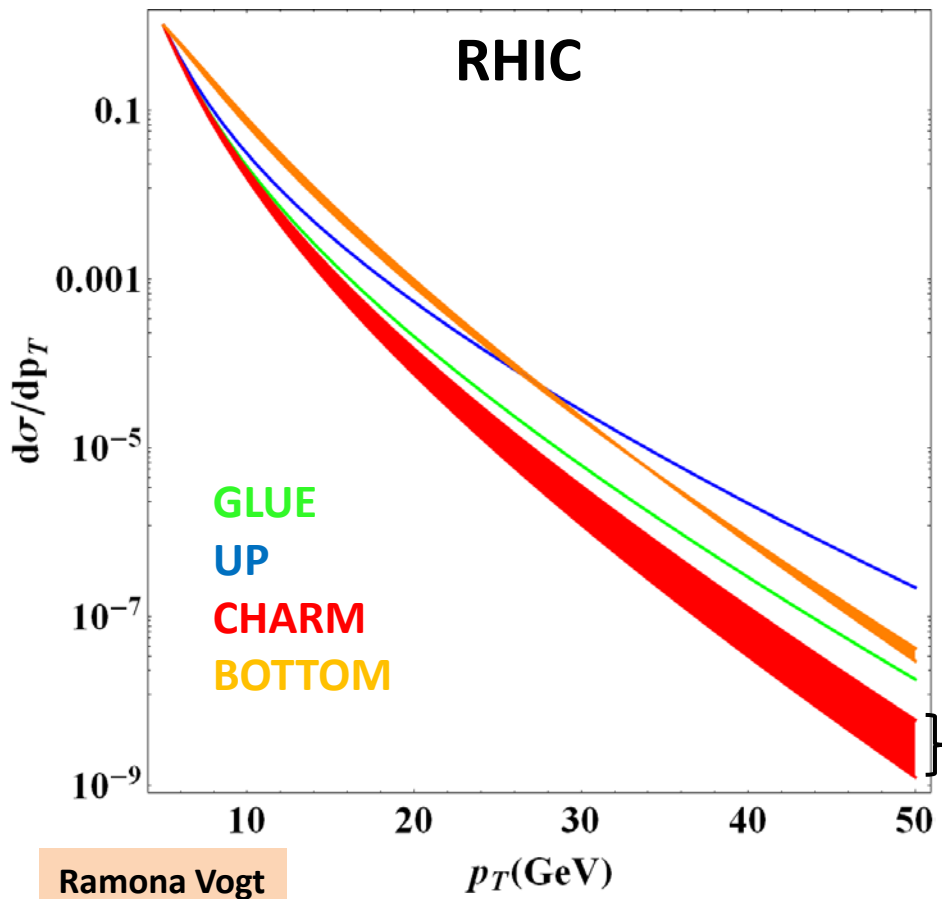
NLO-FONLL uncertainty

Competing effects between increased density and harder production spectra

- RHIC density and spectra
- LHC density, RHIC spectra
- LHC density and spectra



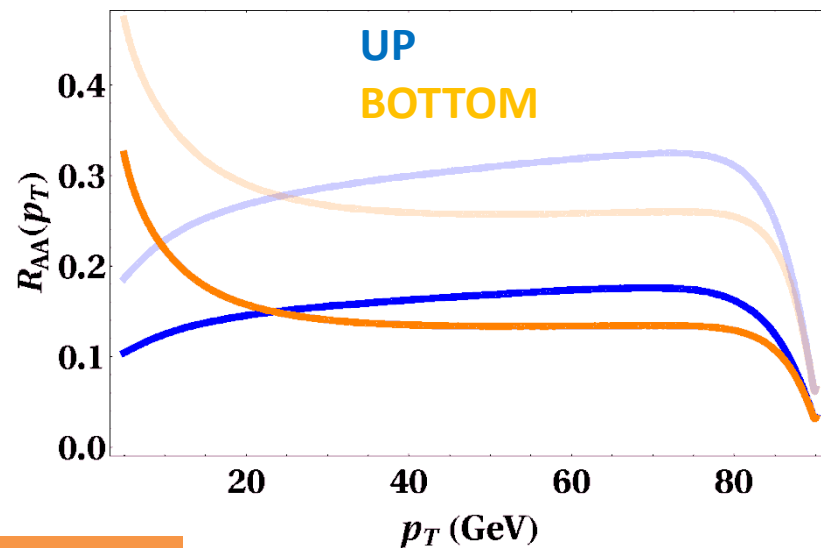
Initial quark production spectra



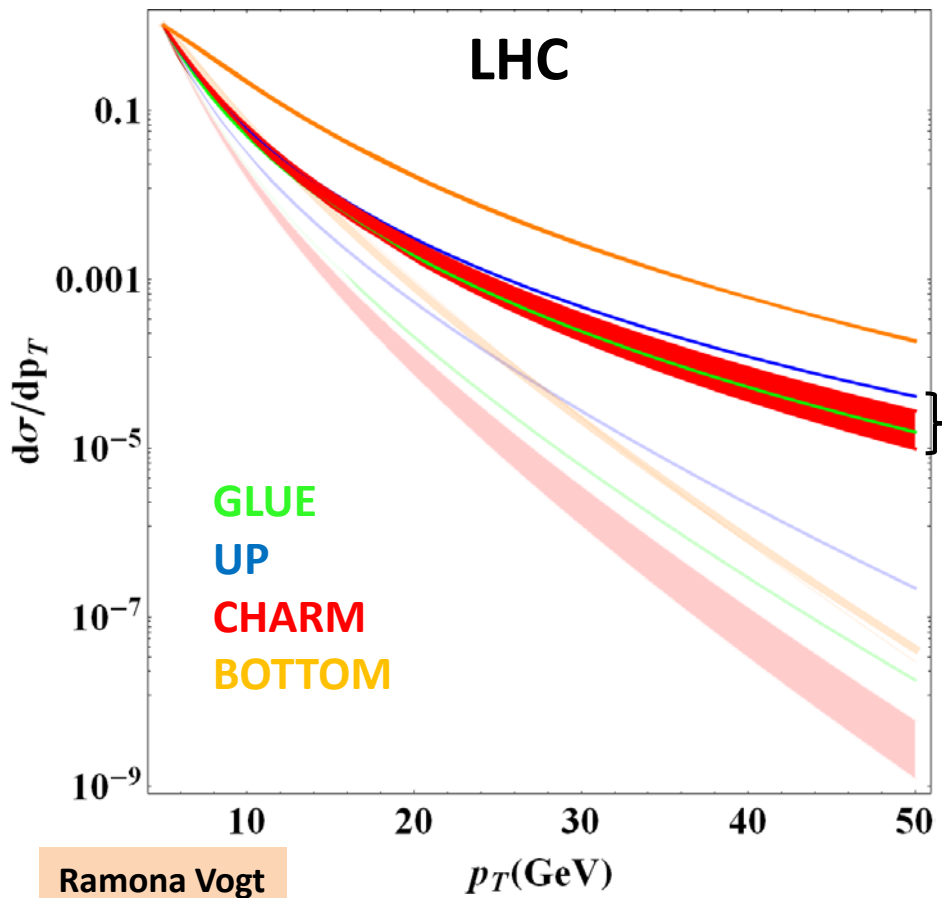
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Initial quark production spectra

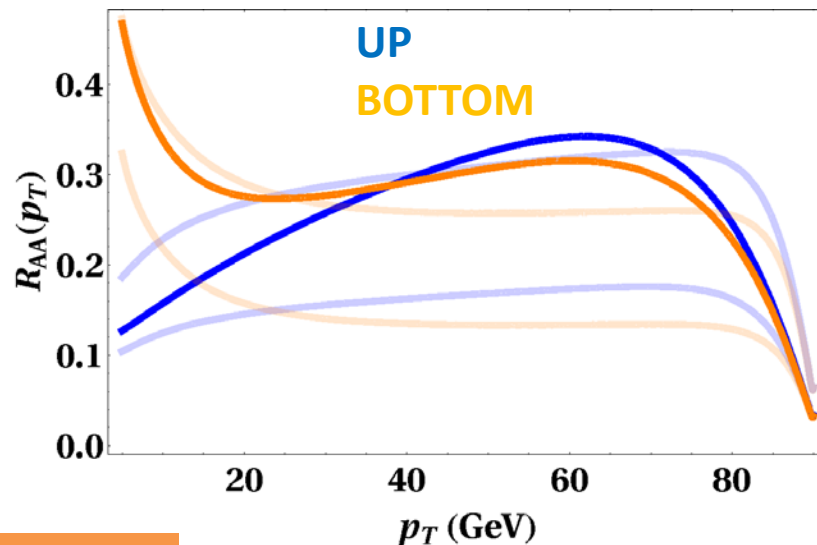


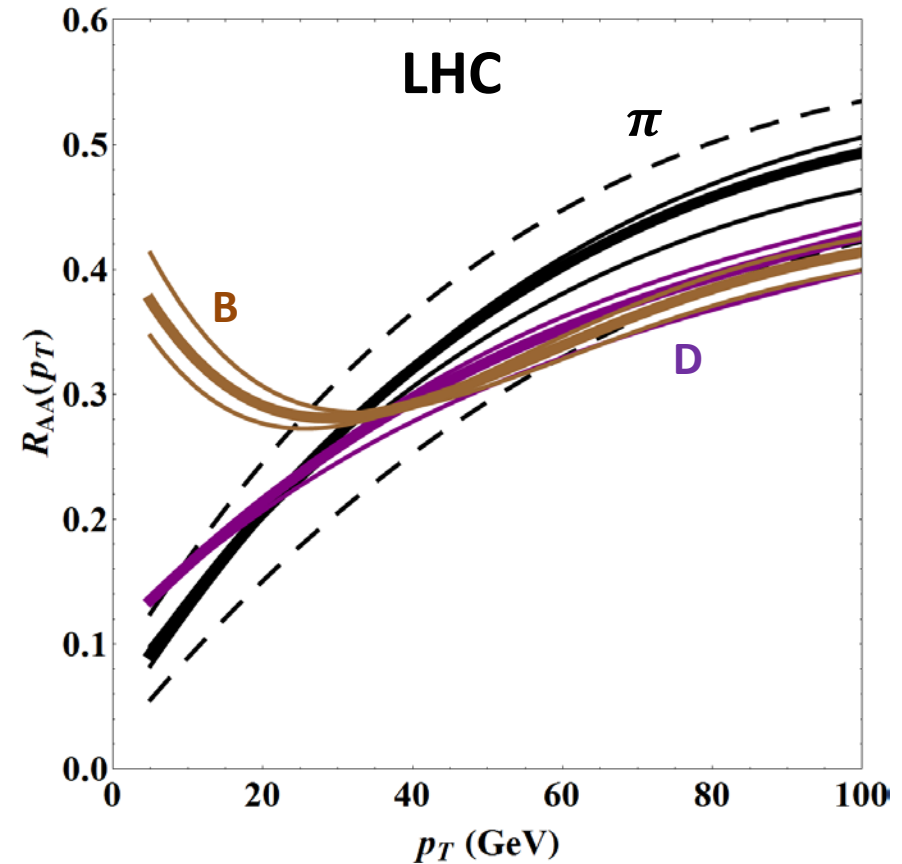
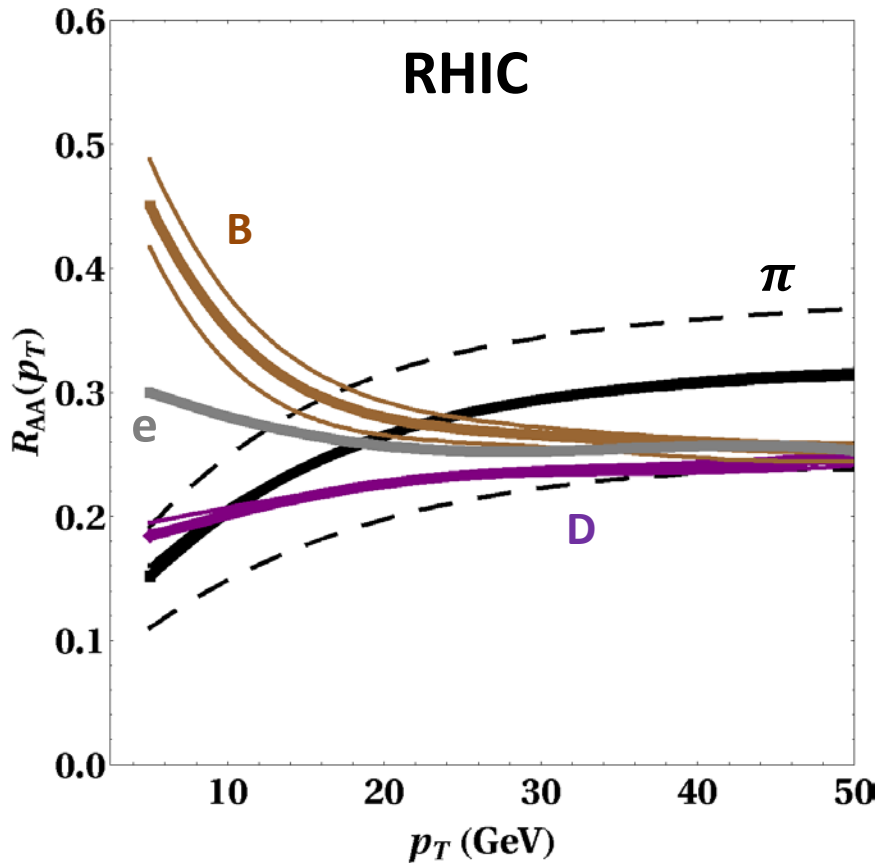
Ramona Vogt

NLO-FONLL uncertainty

Competing effects between increased density and harder production spectra

- RHC density and spectra
- LHC density, RHC spectra
- **LHC density and spectra**





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 $\alpha_s = 0.3$

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

Interpolate between DGLV and MD with a new effective potential

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

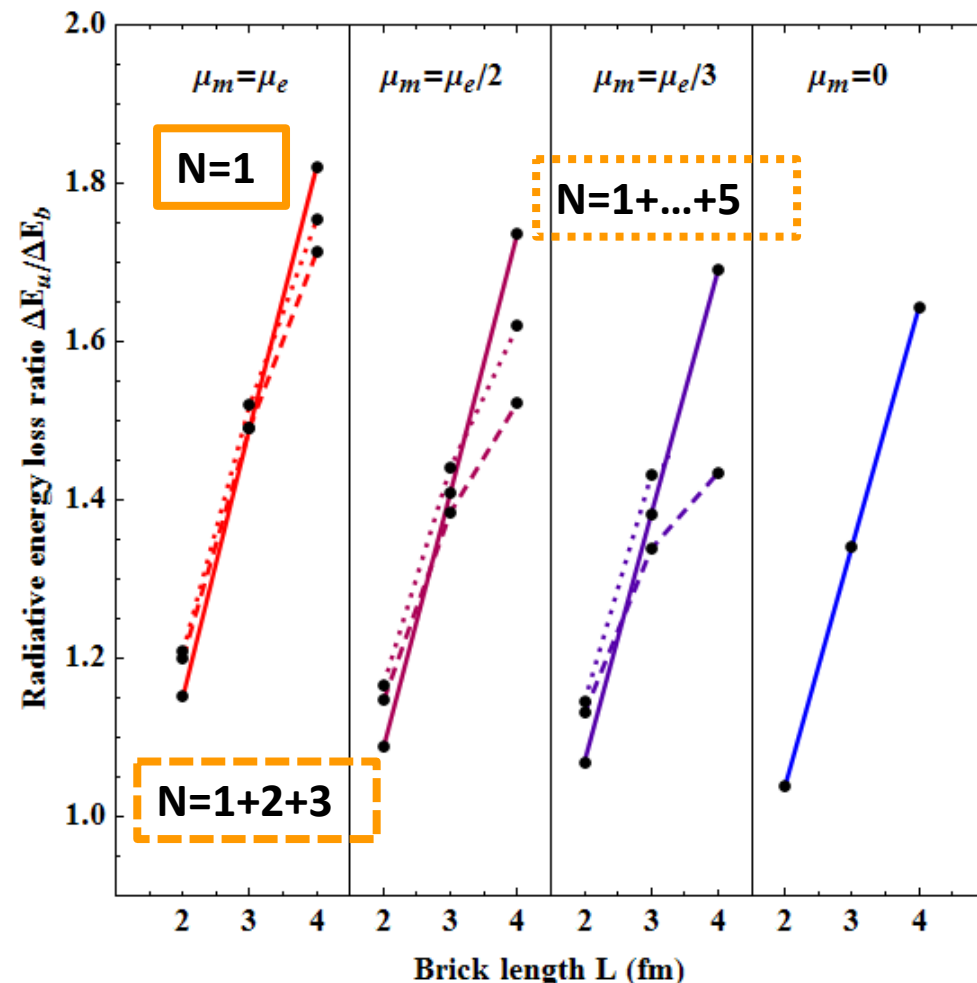
It is possible to study the limit

$\mu_m \rightarrow 0$ for values of $\mu_m \gtrsim \mu_e/3$

- The mean free path $\frac{1}{\lambda} = \int dq \frac{d\sigma}{dq} \rho$

is divergent for $\mu_m=0$

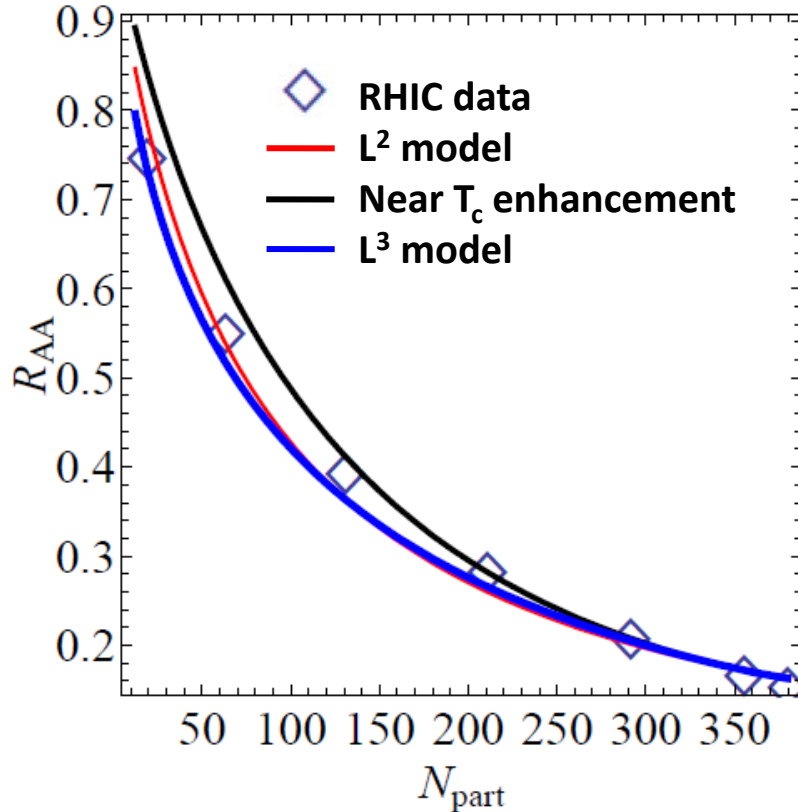
$\left(\frac{\Delta E_u}{\Delta E_b}\right)$ ratio improves for $N>1$ and $\mu_m \rightarrow 0$, but likely not enough.



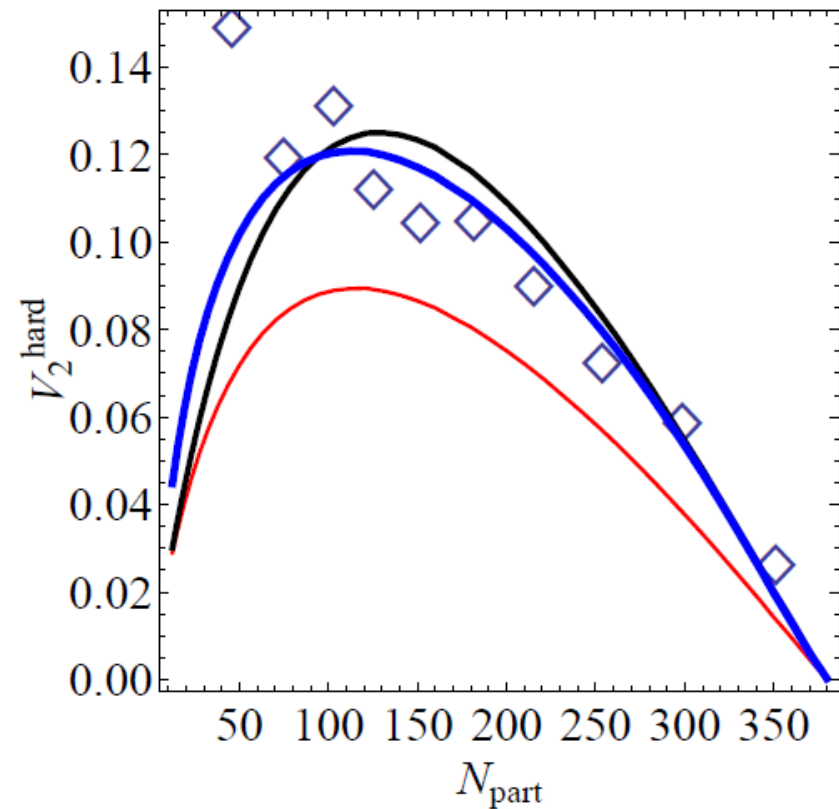
Magnetic monopole enhancement

- Nonlinear density dependence near T_c

AdS/CFT



Jinfeng Liao, arXiv:1109.0271



Bjorken elastic collisions

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

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

Energy loss fluctuations

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

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

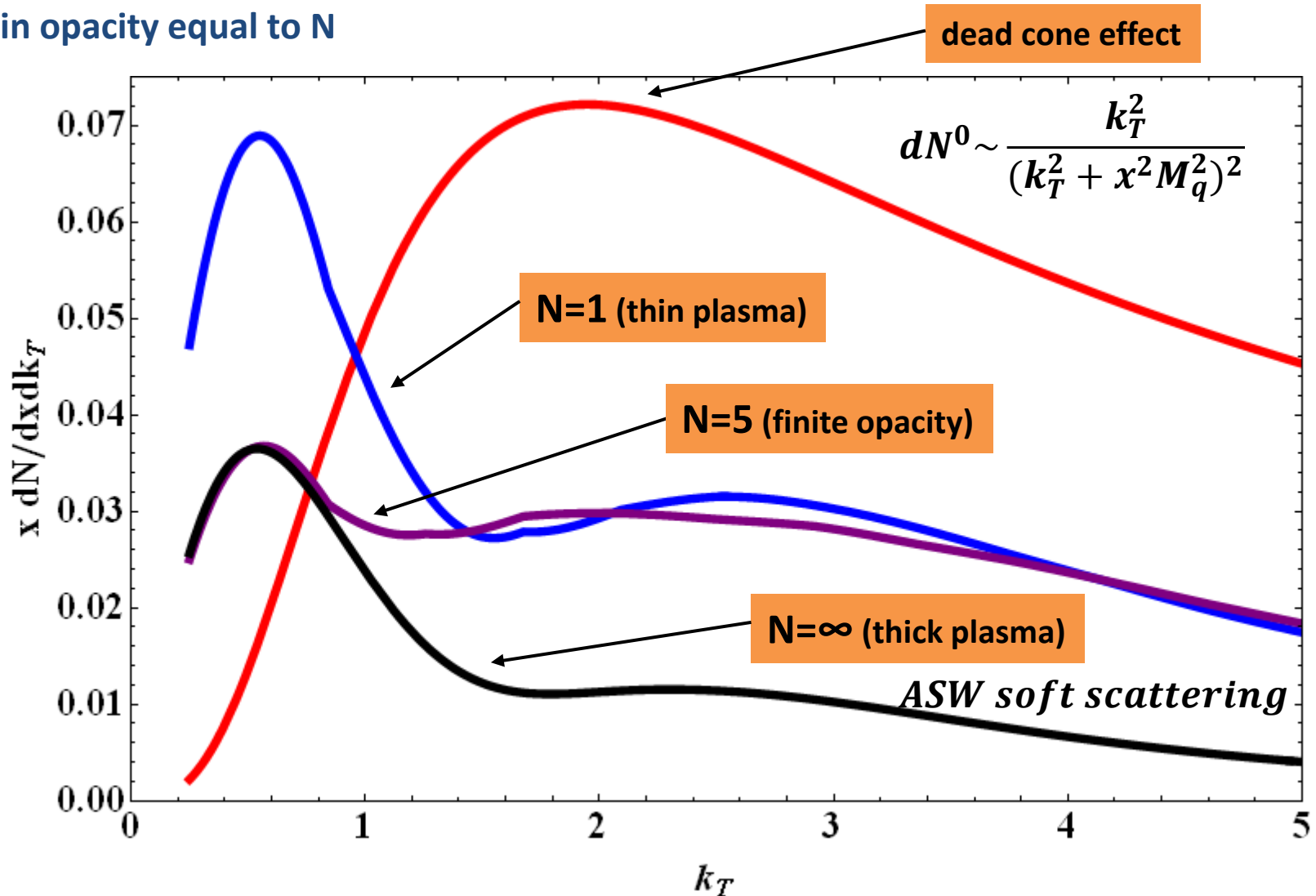
- Radiative: $P_{rad}(\varepsilon) = P_0 \delta(\varepsilon) + \tilde{P}(\varepsilon)|_0 + P_{stop} \delta(1 - \varepsilon)$

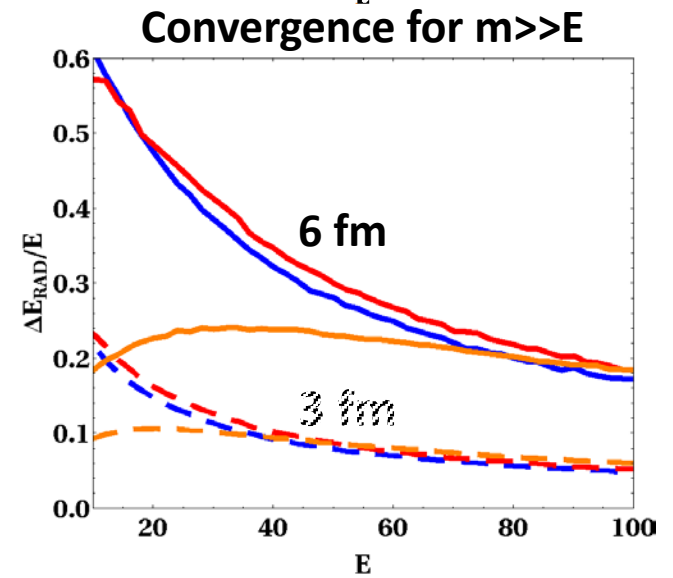
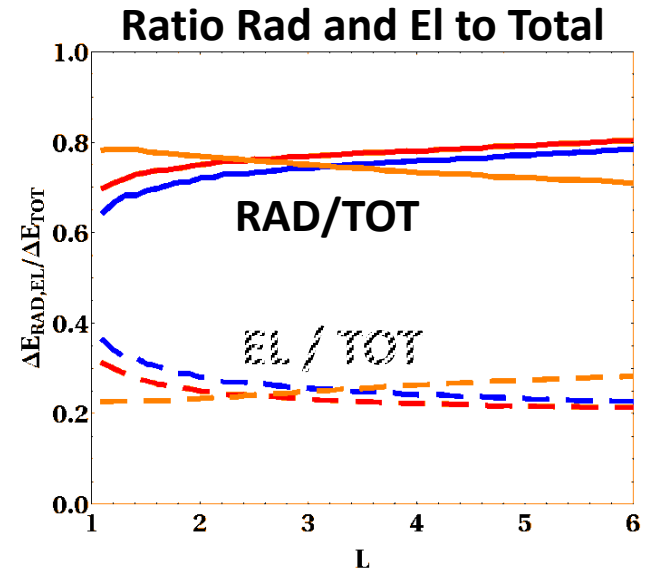
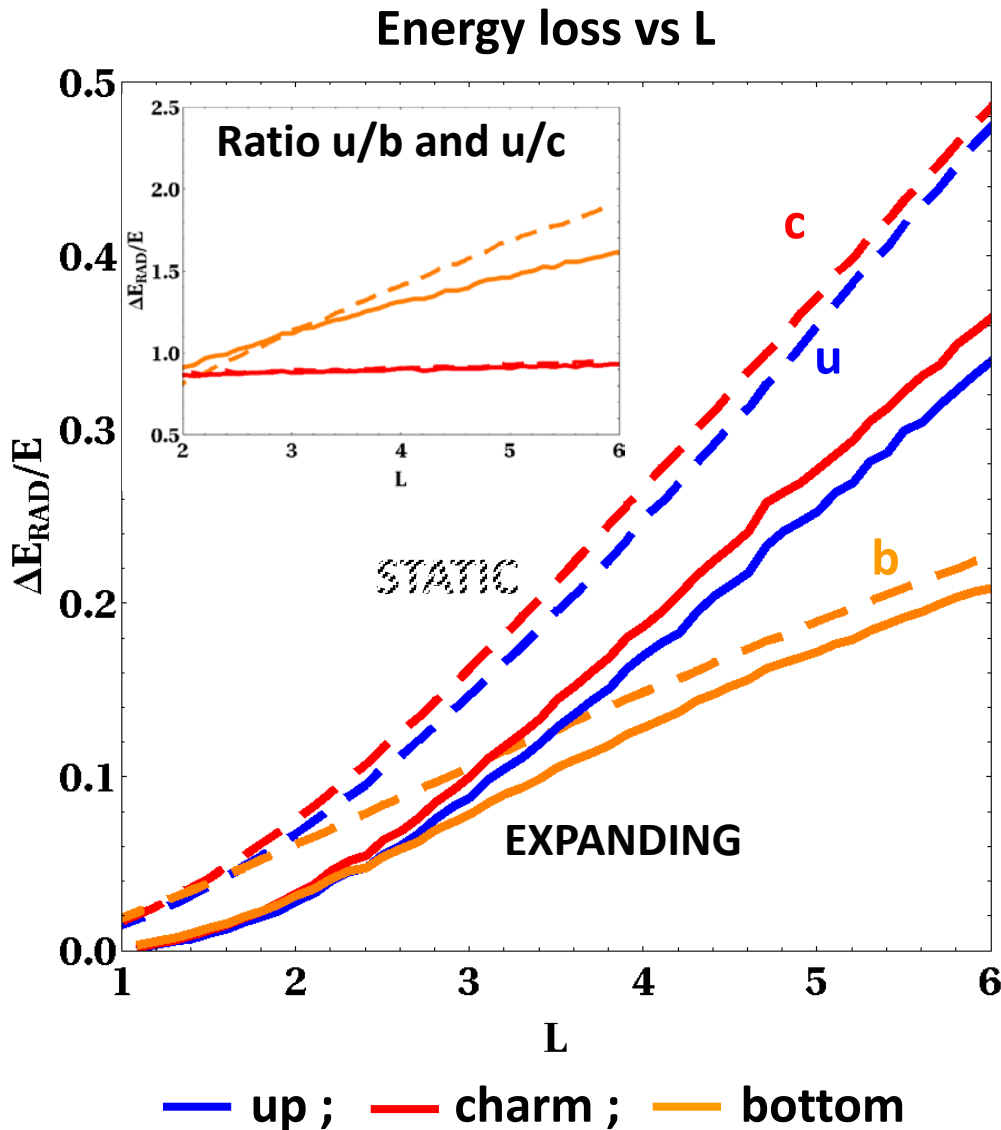
- Elastic: $P_{el}(\varepsilon) = e^{-\langle N_c \rangle} \delta(\varepsilon) + N e^{-\frac{(\varepsilon - \bar{\varepsilon})}{4T\bar{\varepsilon}}}$

Poisson expansion of the number of INCOHERENTLY emitted gluons

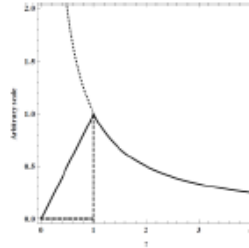
Gaussian fluctuations

$E_n=20\text{GeV}$, $x=0.25$, bottom quark, plasma thickness 5fm
Order in opacity equal to N

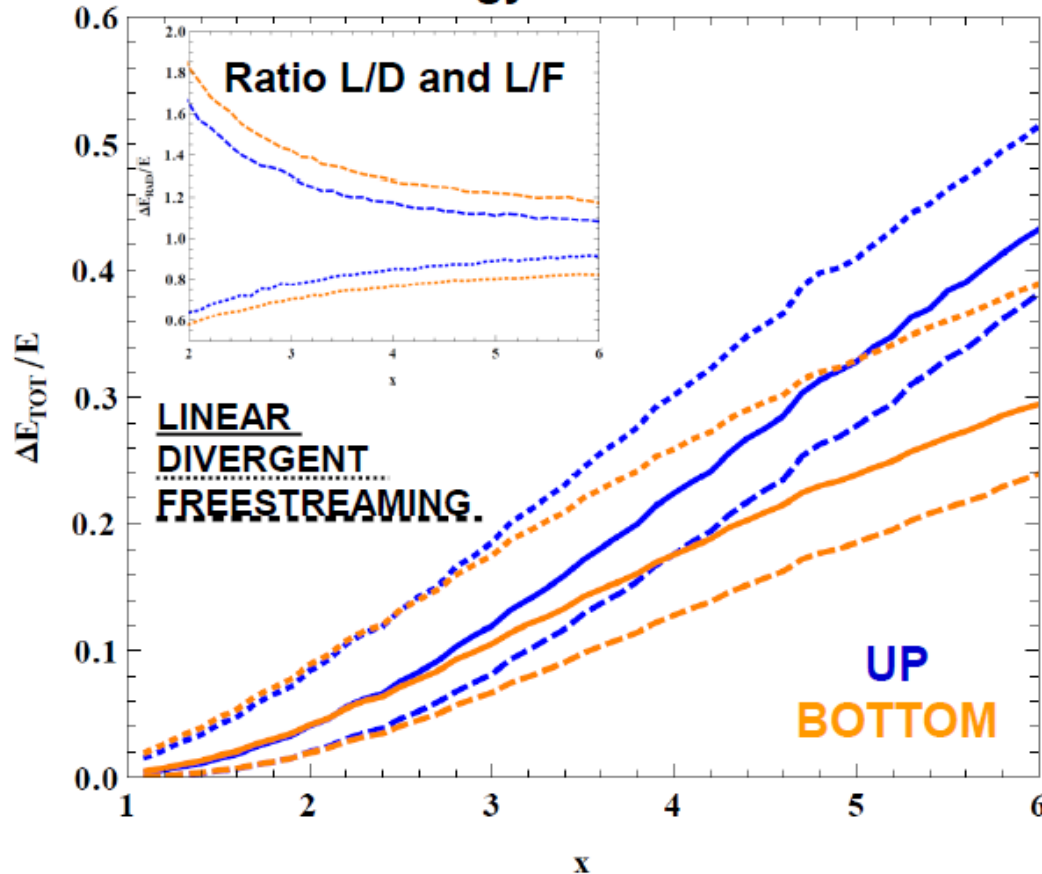




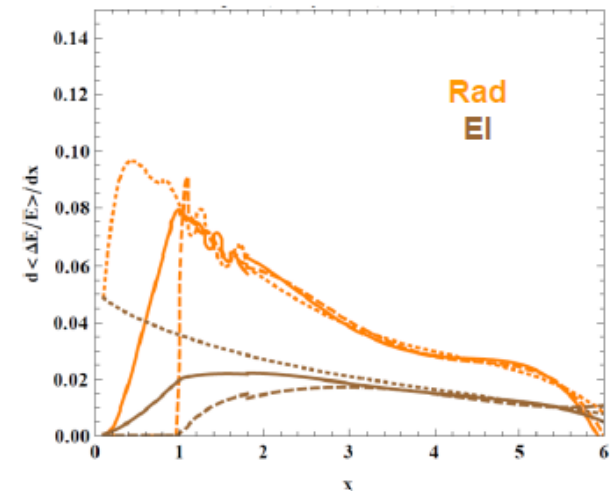
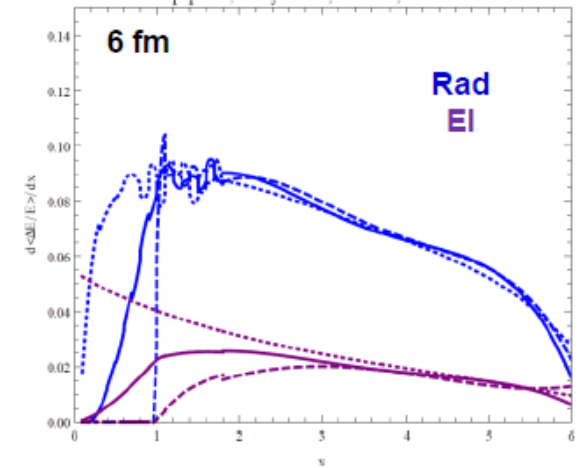
$$f\left(\frac{\tau}{\tau_0}\right) = \begin{cases} \frac{\tau}{\tau_0}, \frac{\tau_0}{\tau}, 0 & (\tau < \tau_0) \\ \frac{\tau_0}{\tau} & (\tau > \tau_0) \end{cases}$$



Energy loss vs L



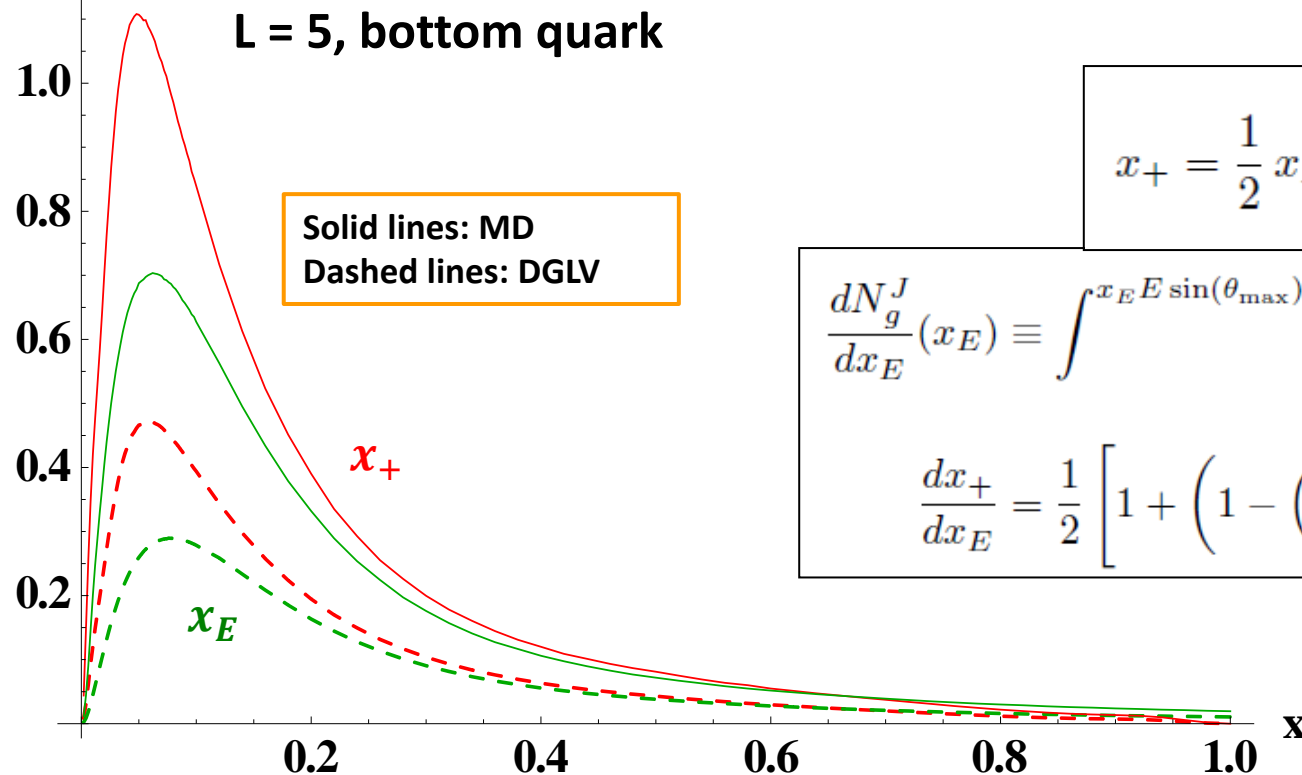
Differential Energy Loss $\frac{d\langle\Delta E/E\rangle}{dx}$



- 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: $k_T^{max} = x_E E$

$$k_T^{max} = 2E \text{Min}[x_+, 1 - x_+]$$

$x dN/x$



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

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

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

- BDMPS predicts the scaling of the induced intensity x-spectrum with $\hat{q} \sim \mu^2/\lambda$

through the z variable $z \equiv |\omega_0^2| L^2, \quad \omega_0^2 \equiv -i \frac{[(1-x)C_A + x^2 C_s] \hat{q}}{2x(1-x)E}$

$E=100, x=0.05, M_q=0.25, \hat{q}=0.25, \mu=\sqrt{\hat{q} \lambda}, m_g=\mu/\sqrt{2}, L=1-5$ (adj.)

$\lambda=0.5$ | $\lambda=1$ | $\lambda=2$ | BDMPS

