Hard Probes Overview

Guang-You Qin

Central China Normal University

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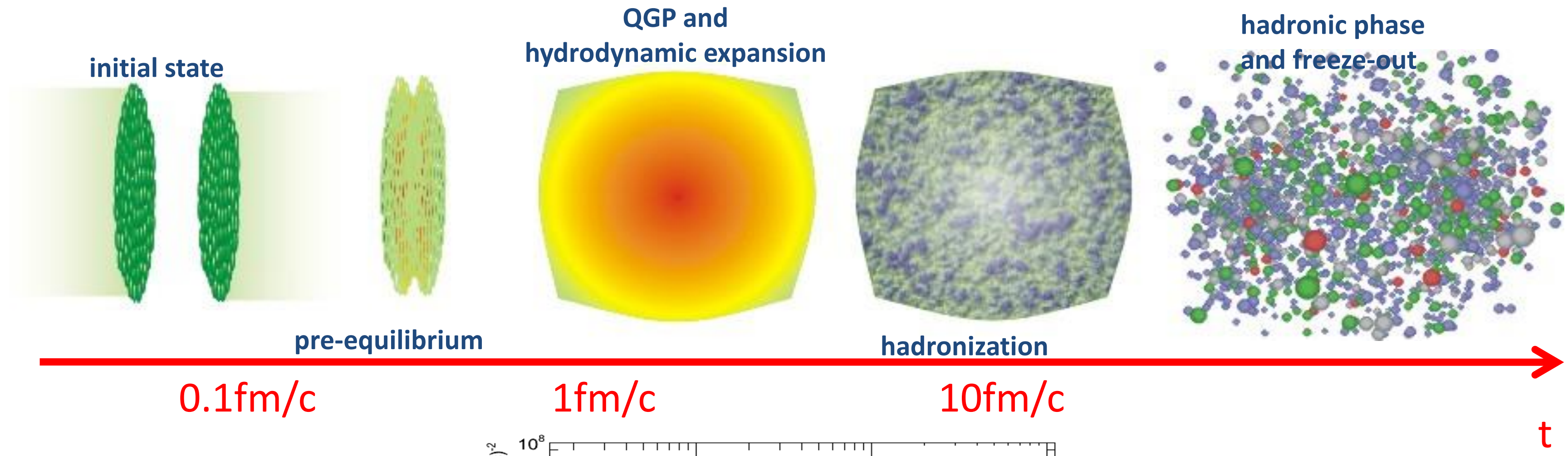
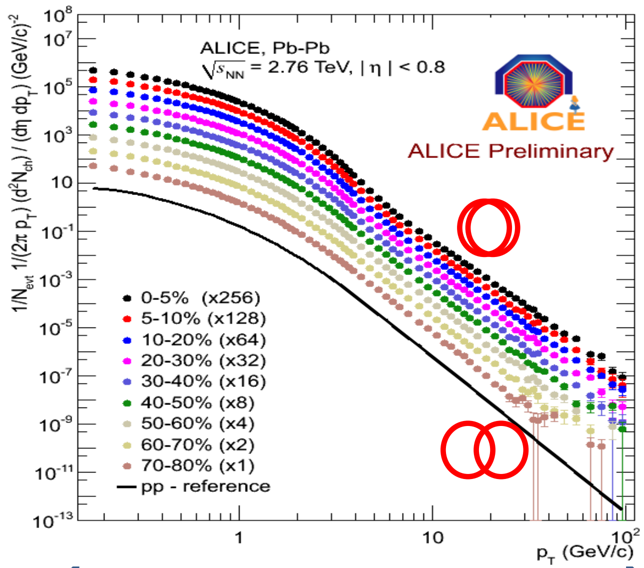
Probes of QGP in Heavy-Ion Collisions





"jet" sec., August 6

Anisotropic Flow
…
Collectivity, Fluidity

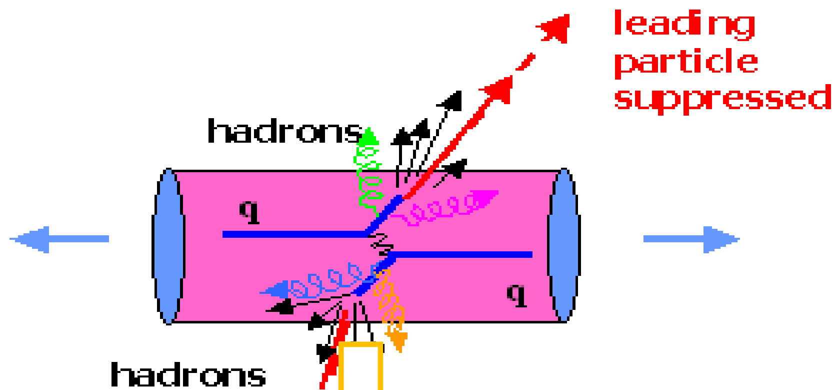
Jet Quenching
…
Color Opacity

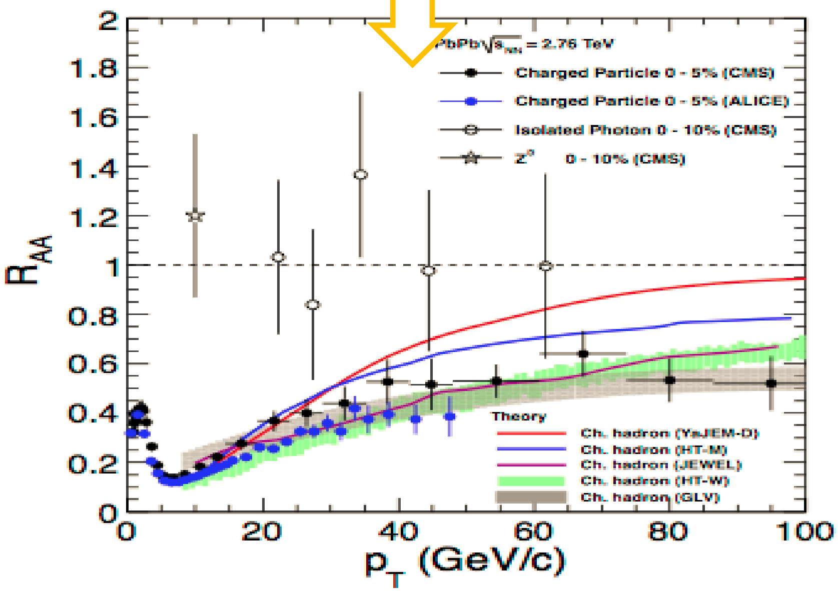
This Talk

Soft Probes

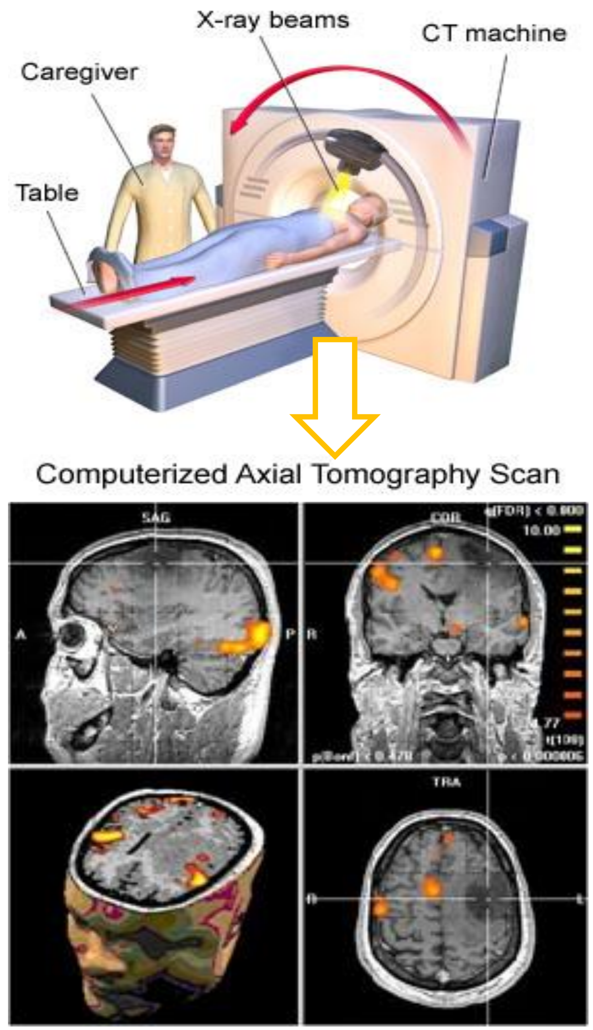
Hard Probes

Jet quenching & jet tomography

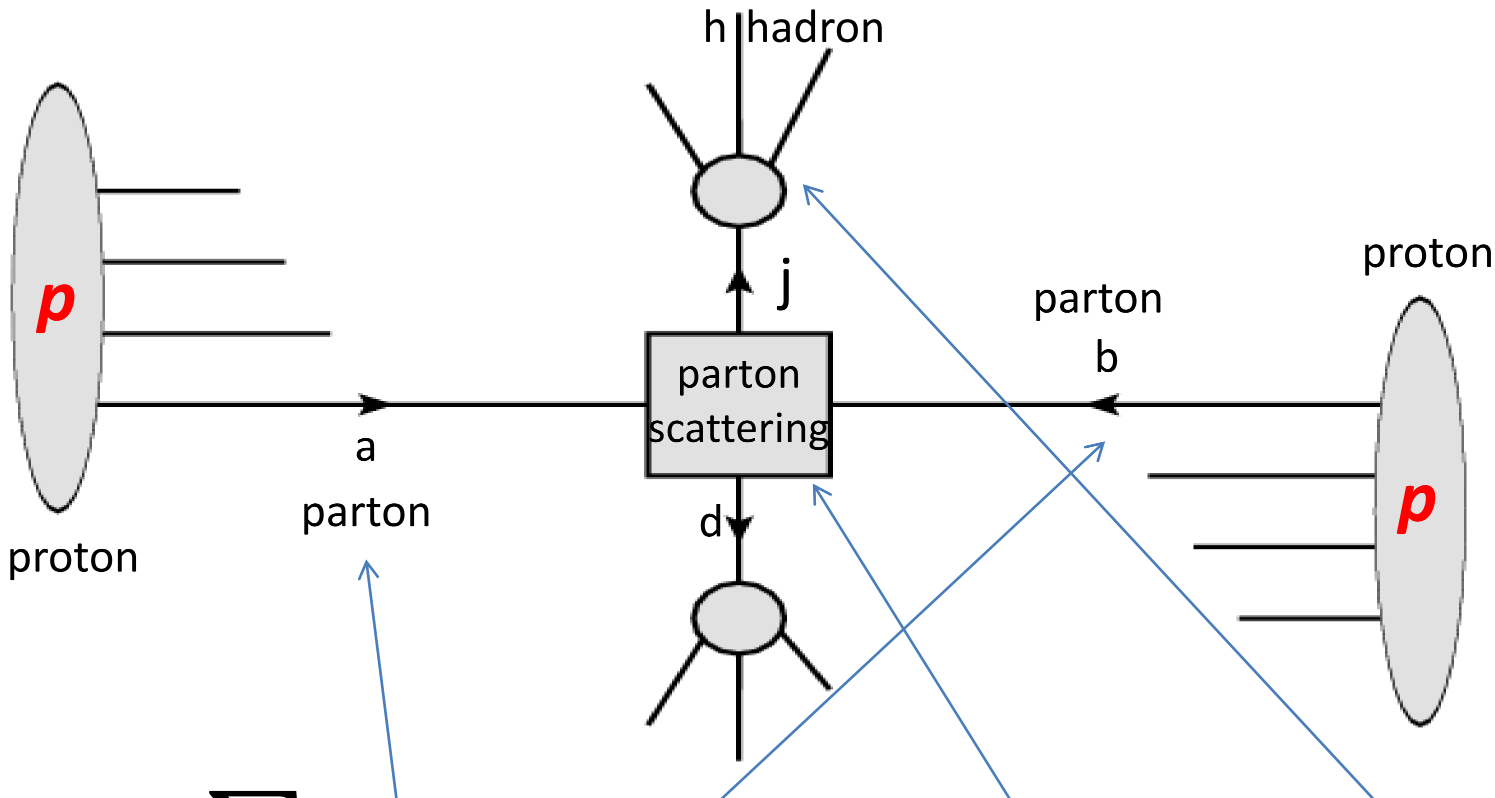




$$R_{AA} = \frac{dN^{AA} / d^2 p_T dy}{N_{coll} dN^{pp} / d^2 p_T dy}$$



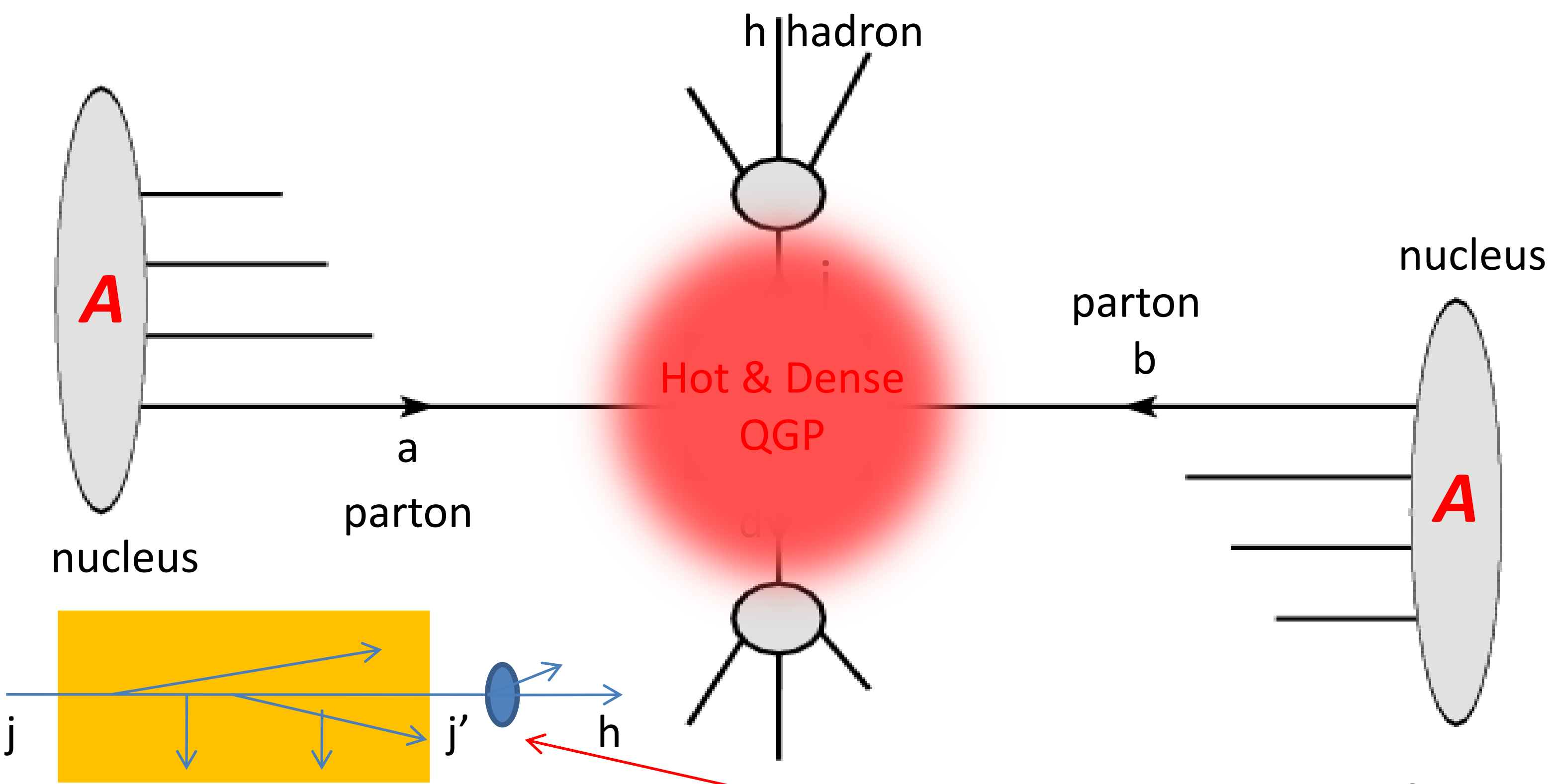
General framework of jet quenching study



$$d\sigma_h = \sum_{abjd} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\rightarrow jd} \otimes D_{h/j}$$

pQCD factorization: Large-p_T processes may be factorized into **long-distance** pieces in terms of **PDF & FF**, and **short-distance** parts describing **hard interactions** of partons.

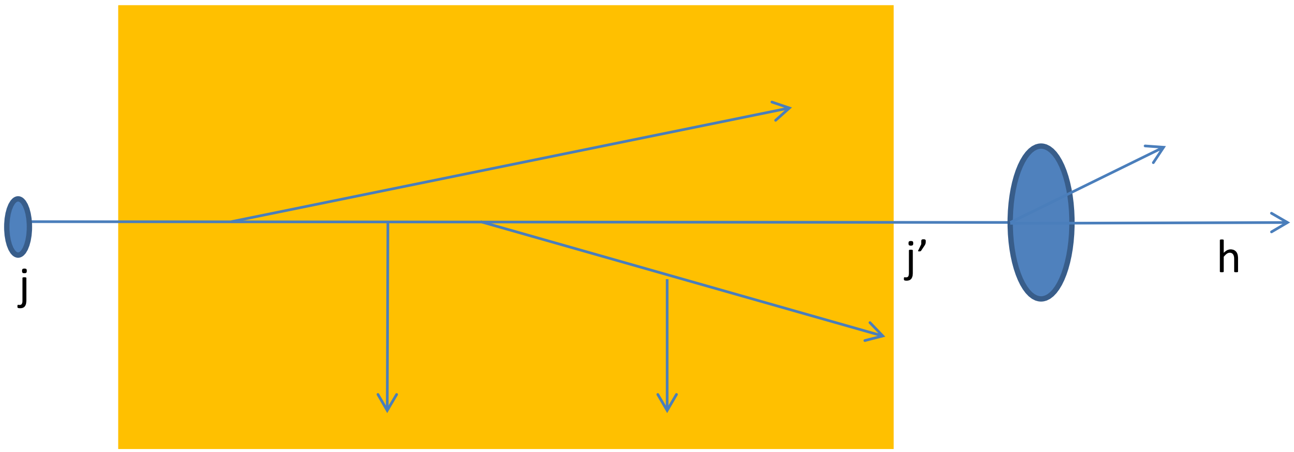
General framework of jet quenching study



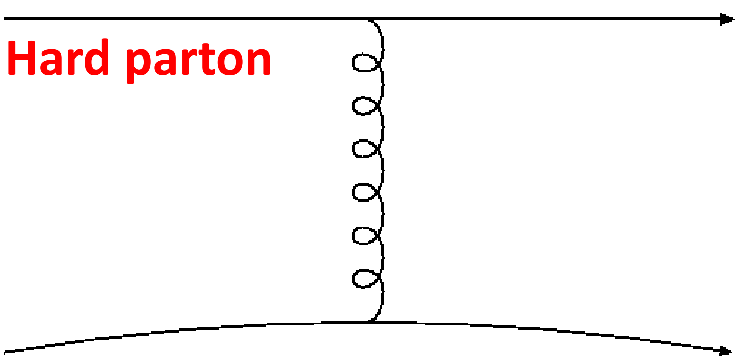
$$d\tilde{\sigma}_h = \sum_{abjd} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jd} \otimes \tilde{D}_{h/j}$$

$$d\tilde{\sigma}_h = \sum_{abjj'd} f_a \otimes f_b \otimes d\sigma_{ab\to jd} \otimes P_{j\to j'} \otimes D_{h/j'}$$

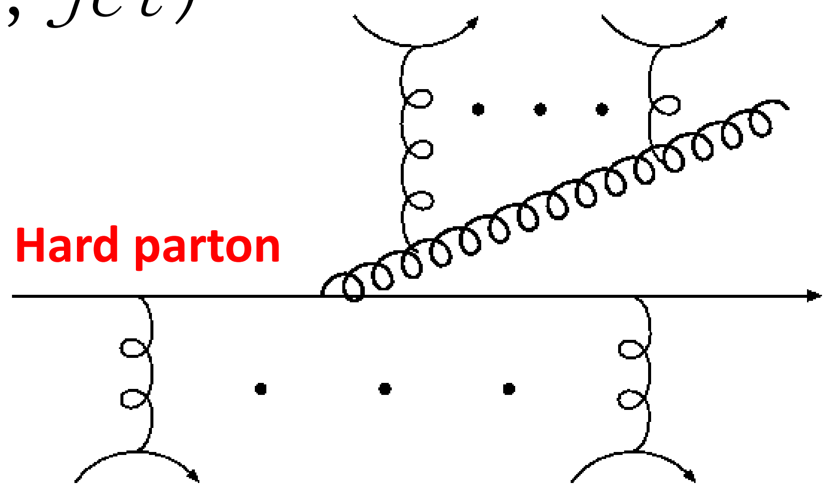
Jet evolution and energy loss in QGP



$$P_{j \to j'}(medium, jet)$$



Elastic (collisional)



Inelastic (radiative)

Rad. E-loss

- **Single gluon emission**
  - **Multiple soft scatterings (BDMPS-Z, ASW, AMY)**
  - **Few hard scatterings (DGLV, HT)**
  - **Recent developments:**
    - **AMY: finite L** (Caron-Huot, Gale 2010)
    - **GLV: finite dynamical medium** (Djordjevic, Heinz, 2008)
    - **DGLV: non-zero magnetic mass** (Djordjevic, Djordjevic, 2012)
    - **Higher Twist (HT): multiple scatterings** (Majumder 2012)

$$\frac{dN_g}{dx\,dk_\perp^2\,dt}(T, E, \ldots) = ?$$

BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe
DGLV: Djordjevic-Gyulassy-Levai-Vitev
HT: Wang-Guo-Majumder

- **Mutiple gluon emission**
  - **Poisson convolution (BDMPS/ASW/DGLV)**

$$\mathrm{P}(\Delta E) = \sum_{n=0}^{\infty} \frac{e^{-\langle N_g \rangle}}{n!} \left[\prod_{i=1}^{n} \int d\omega \frac{dI(\omega)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i \right)$$

  - **Rate equation (AMY)**

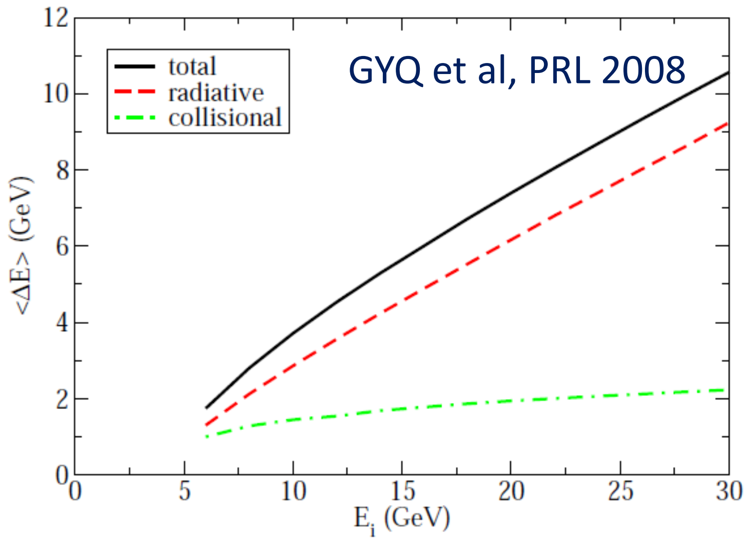
$$\frac{df(p,t)}{dt} = \int dk f(p+k,t) \frac{d\Gamma(p+k,k)}{dk\,dt} - \int dk f(p,t) \frac{d\Gamma(p,k)}{dk\,dt}$$

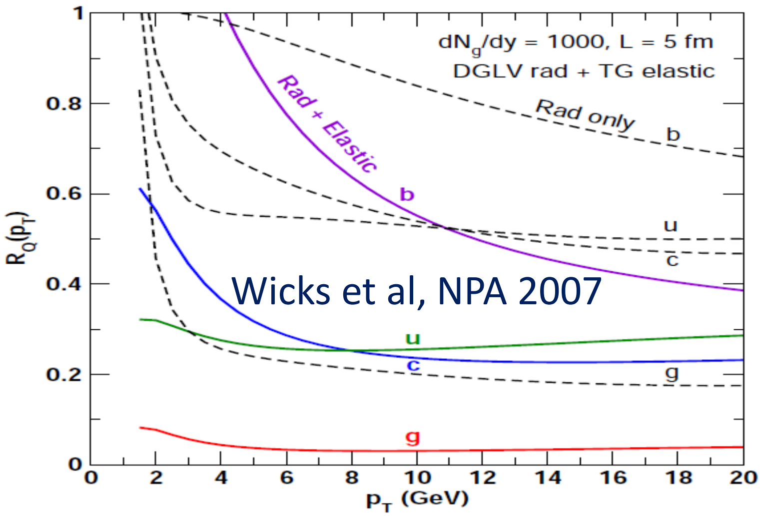
  - **DGLAP-like evolution equation (HT)**

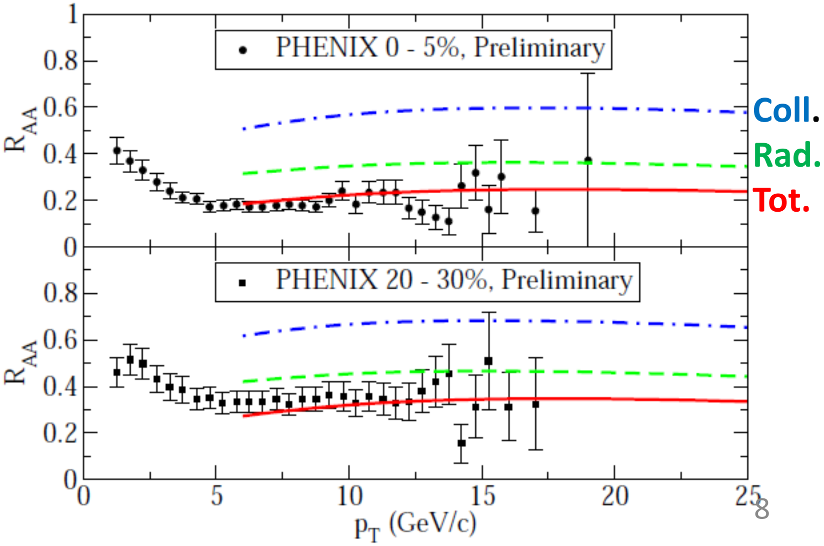
$$\frac{\partial \tilde{D}(z,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} \int \frac{dy}{y} P(y) \int d\zeta^- K(\zeta^-, q^-, y, Q^2) \tilde{D}\left(\frac{z}{y}, Q^2\right)$$

Coll. E-loss

- **First studied by Bjorken:**
  - Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic (GLV), 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008...
- **Main findings:**
  - **dE/E small compared to rad. for large E**
  - **Sizable contribuition in R_{AA} calculation (especially for heavy flavors)**
  - **Important for studying full jet energy loss and medium response (see later)**







Jet quenching parameter

Jet transport coefficient:

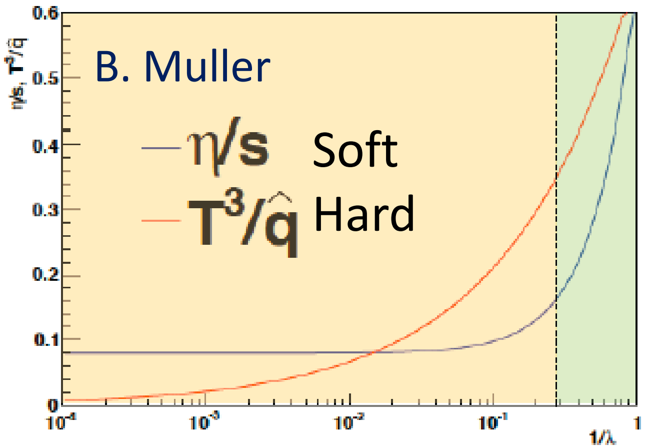
$$\hat{q} = \frac{d\langle \Delta p_\perp^2 \rangle}{dt} = \int \frac{dk_\perp^2}{(2\pi)^2} k_\perp^2 \frac{d\sigma}{dk_\perp^2} \approx \frac{4\pi\alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{\mu+}(0) F_\mu^+(y^-) \right\rangle$$

BDMPS-Z (Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov) $\Delta E_{\mathrm{rad}} \approx \alpha_s N_c \hat{q} L^2$

Higher-Twist (Wang-Guo-Majumder)

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s}{\pi} P(x) \frac{\hat{q}}{k_\perp^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe
DGLV: Djordjevic-Gyulassy-Levai-Vitev



At weak coupling:

$$\frac{T^3}{\hat{q}} \approx \# \frac{\eta}{s}$$

At strong coupling:

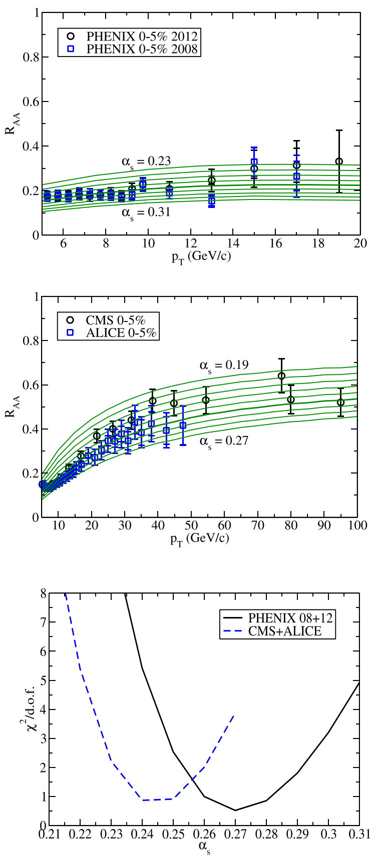
$$\frac{T^3}{\hat{q}} << \# \frac{\eta}{s}$$

If they can determined precisely, we may figure out how (at what scale) QGP becomes strongly coupled (from a weakly-coupled high T regime)

Majumder, Muller, Wang, PRL 2007

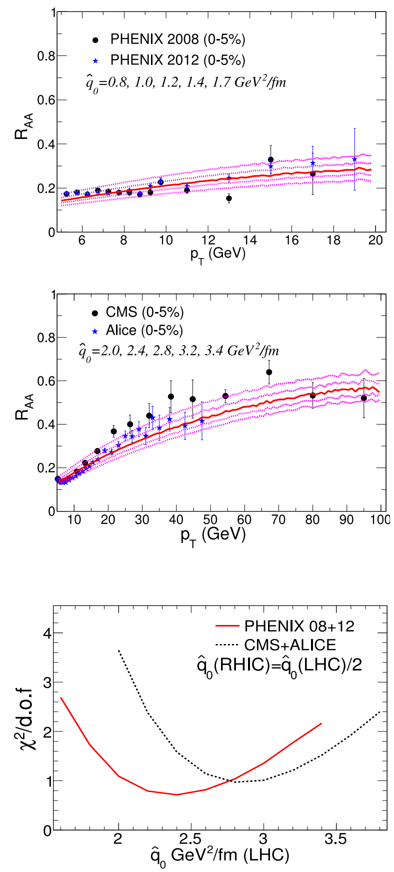
Jet quenching @ RHIC & LHC

McGill-AMY



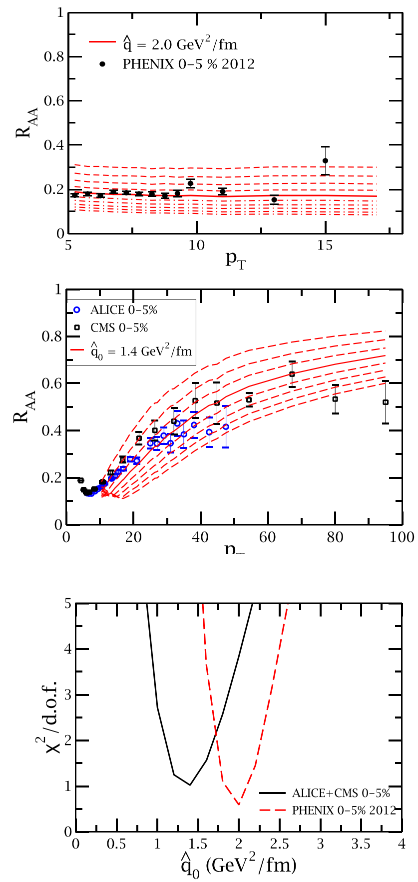
GYQ, et al, PRL 2008

HT-BW



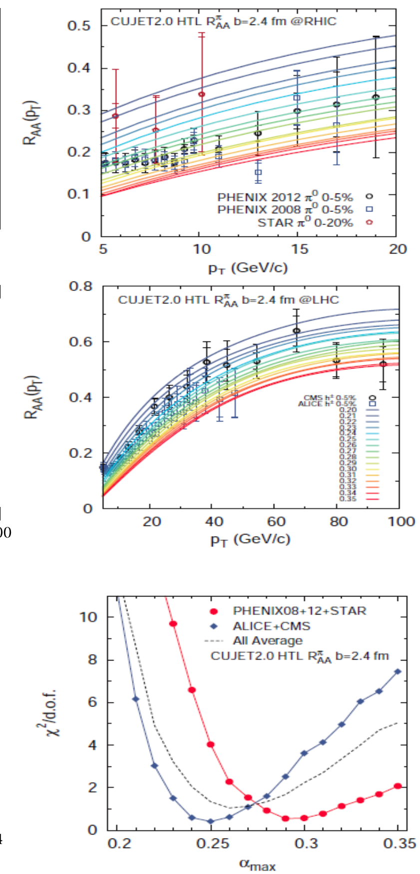
Chen, Hirano, Wang, Wang, Zhang, PRC 2011

HT-M



Majumder, Chun, PRL 2012

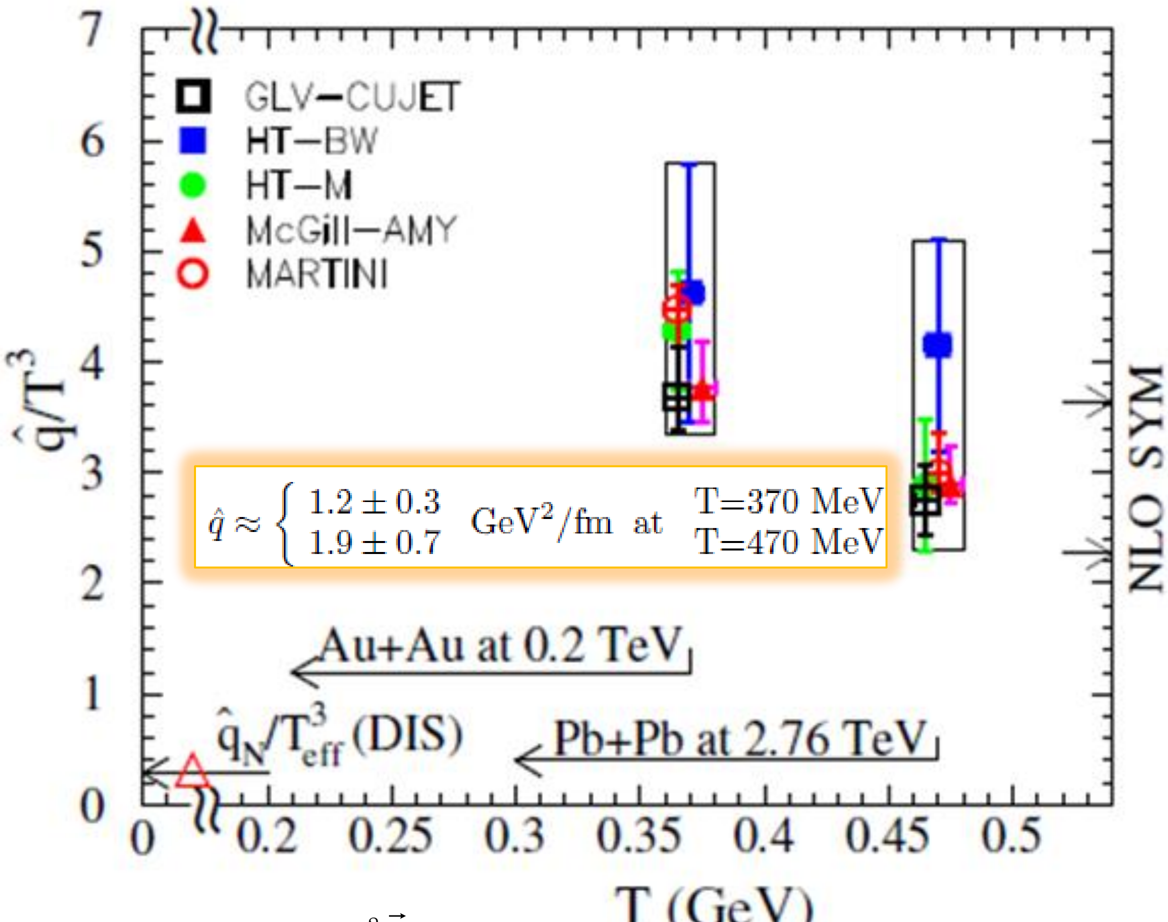
CUJET



Xu, Buzzatti, Gyulassy, arXiv: 1402.2956

JET Collaboration, arXiv:1312.5003 [nucl-th]

Extracting jet quenching parameter



$$\hat{q} = \frac{1}{L}\int \frac{d^2\vec{k}_\perp}{(2\pi)^2} k_\perp^2 P(\vec{k}_\perp, L) \approx \frac{4\pi\alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle F^{\mu+}(0) F_\mu^+(y^-)\right\rangle$$

JET Collaboration, arXiv:1312.5003 [nucl-th]

McGill-AMY:
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008
HT-BW:
Chen, Hirano, Wang, Wang, Zhang, PRC 2011
HT-M:
Majumder, Chun, PRL 2012
GLV-CUJET:
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MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009
NLO SYM:
Zhang, Hou, Ren, JHEP 2013

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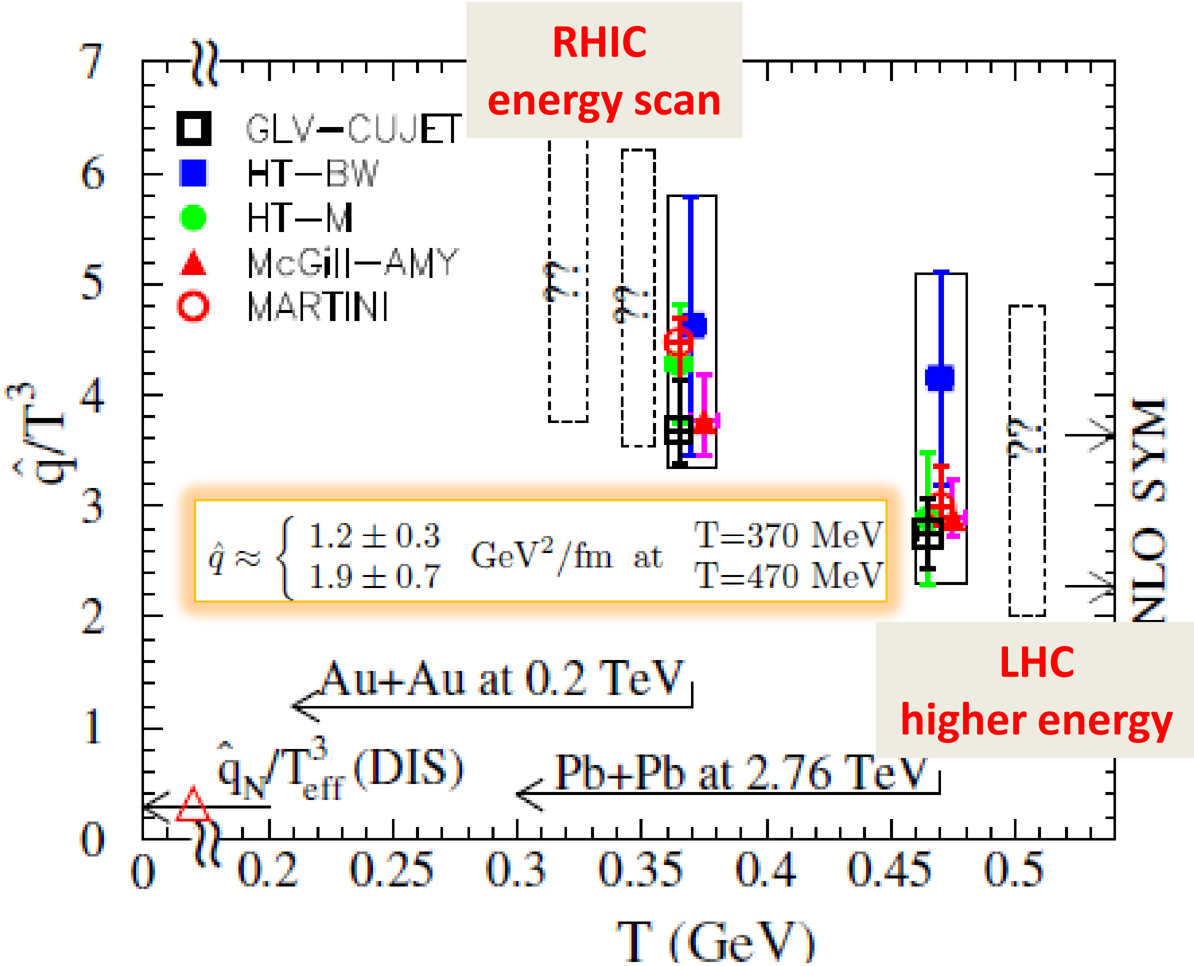

$$\hat{q} = \int \frac{dk_\perp^2}{(2\pi)^2} k_\perp^2 \frac{d\sigma}{dk_\perp^2} \approx \frac{4\pi\alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{\mu +}(0) F_\mu^+(y^-) \right\rangle$$

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Schenke, Gale, Jeon, PRC 2009
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Map the temperature dependence of jet transport parameters

q^{hat} from lattice

$$\hat{q} = \frac{1}{L}\int \frac{d^2\vec{k}_\perp}{(2\pi)^2} k_\perp^2 P(\vec{k}_\perp, L)$$

$$P(\vec{k}_\perp, L^-) = \int \frac{d^2\vec{k}_\perp}{(2\pi)^2} e^{-i\vec{k}_\perp\cdot\vec{y}_\perp} P(\vec{y}_\perp, L^-)$$

$$P(\vec{y}_\perp, L^-) = \frac{1}{N_c} Tr\left\langle W(\vec{y}_\perp, L^-)\right\rangle$$

$$\frac{dP(\vec{y}_\perp, L^-)}{dL} = -V(\vec{y}_\perp)P(\vec{y}_\perp, L^-)$$

$$V(\vec{y}_\perp) = \int \frac{d^2\vec{k}_\perp}{(2\pi)^2}(1 - e^{i\vec{k}_\perp\cdot\vec{y}_\perp}) C(\vec{k}_\perp)$$

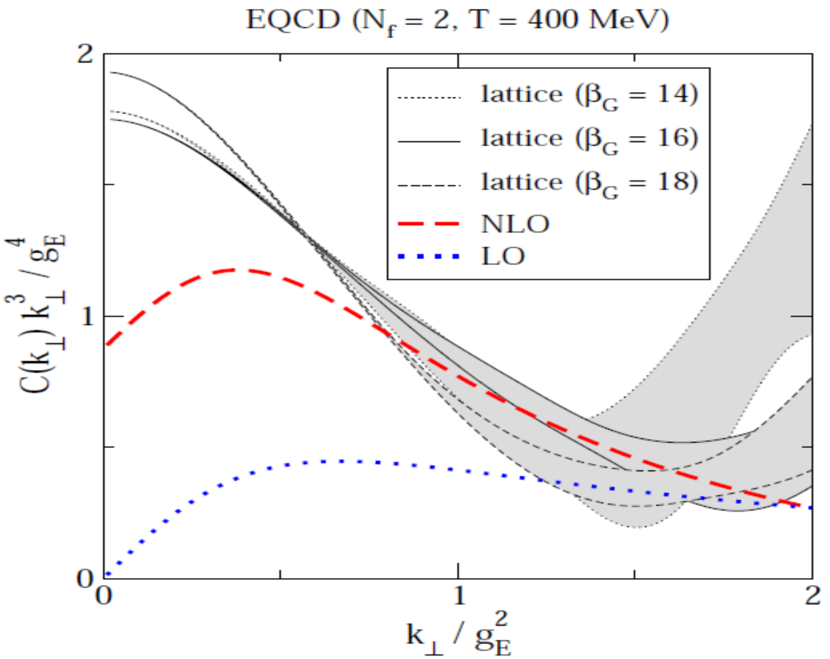
Majumder, PRC 2013; Panero, Rummukainen, Schafer, PRL 2014; Laine, Rothkopf, JHEP 2013; arXiv:1310.2413; Caron-Huot, PRD 2009; Benzke, Brambilla, Escobedo, Vairo, JHEP 2013; D'Eramo, Lekaveckas, Liu, Rajagopal, JHEP 2013

JET Collaboration

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \begin{array}{l} T=370\ \text{MeV} \\ T=470\ \text{MeV} \end{array}$$

Quenched SU(2): $\hat{q} \approx 1.3 - 3.3\text{GeV}^2/\text{fm}@T = 400MeV$

Lattice EQCD: $\hat{q} \approx 6\text{GeV}^2/\text{fm} \pm 20\%@RHIC$



Discrepancy is unclear so far and needs further investigation

Renormalization of q^{hat}

- **Radiative correction to transverse momentum broadening $\langle p_T^2 \rangle$** (Wu, JHEP 2011; Liou, Mueller, Wu, NPA 2013)

$$\left\langle p_\perp^2 \right\rangle_{rad} = \hat{q}_0 L \left[C_2 \frac{\alpha_s N_c}{\pi} \ln^2\left(\frac{L}{\tau_0}\right) + C_1 \frac{\alpha_s N_c}{\pi} \ln\left(\frac{L}{\tau_0}\right) + C_0 \right]$$

$$\tau_0 \approx 1/T << L$$

- **The double-logarithmic corrections may be absorbed into a redefinition of jet quenching parameter q^{hat}** (Iancu, arXiv:1403.1996; Blaizot, Mehtar-Tani, arXiv:1403.2323)

$$\hat{q}(\tau) = \hat{q}_0 \left[1 + \frac{\bar{\alpha}}{2} \ln\left(\frac{\tau}{\tau_0}\right) \right]$$

$$\frac{\partial \hat{q}(\tau, Q^2)}{\partial \ln \tau} = \int_{\hat{q}\tau}^{Q^2} \frac{dq^2}{q^2} \bar{\alpha} \hat{q}(\tau, q^2)$$

- **For large media, anomalous length dependence of q^{hat} and mean energy loss**

$$\hat{q}(L) \propto L^\gamma, \left\langle p_\perp^2 \right\rangle \propto \hat{q}_0 L^{1+\gamma}, \left\langle \Delta E \right\rangle \propto \hat{q}_0 L^{2+\gamma}$$

$$\gamma = 2\sqrt{\bar{\alpha}} = 2\sqrt{\alpha_s N_c / \pi}$$

Renormalization of q^{hat}

- **Calculate NLO QCD corrections to transverse momentum broadening in hadron production in SIDIS**

$$\frac{d\langle k_\perp^2\sigma\rangle_{NLO}}{dz} = \sigma_0 T_{qg}(x,0,0,\mu_f^2)\otimes H_{NLO}(x,x_B,Q^2,\mu_f^2)\otimes D(z,\mu_f^2)$$

- **Collinear divergence is factorized into the redefinition of PDF & twist-4 quark-gluon correlation function**

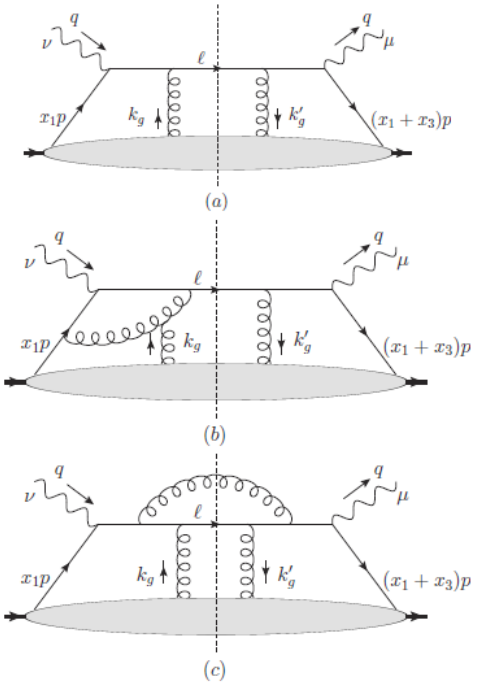
$$\frac{\partial}{\partial \ln\mu_f^2}T_{qg}(x_B,0,0,\mu_f^2) = \frac{\alpha_s}{2\pi}\int_{x_B}^1\frac{dx}{x}\left[\mathcal{P}_{qg\to qg}\otimes T_{qg} + P_{qg}(\hat{x})T_{gg}(x,0,0,\mu_f^2)\right]$$

- **Neglecting the momentum and spatial correlations of two nucleons**

$$T_{qg}(x_B,0,0,\mu_f^2)\approx\frac{N_c}{4\pi^2\alpha_s}f_{q/A}(x_B,\mu_f^2)\int dy^-\hat{q}(\mu_f^2,y^-)$$

- **The scale dependence of q^{hat}**

$$\frac{\partial\hat{q}(\mu^2)}{\partial\ln\mu^2} = \frac{\alpha_s}{2\pi}C_A\ln\left(\frac{1}{x_B}\right)\hat{q}(\mu^2) \qquad \hat{q}(\mu^2) = \hat{q}(\mu_0^2)\exp\left[\frac{\alpha_s}{2\pi}C_A\ln\left(\frac{1}{x_B}\right)\ln\left(\frac{\mu^2}{\mu_0^2}\right)\right]$$

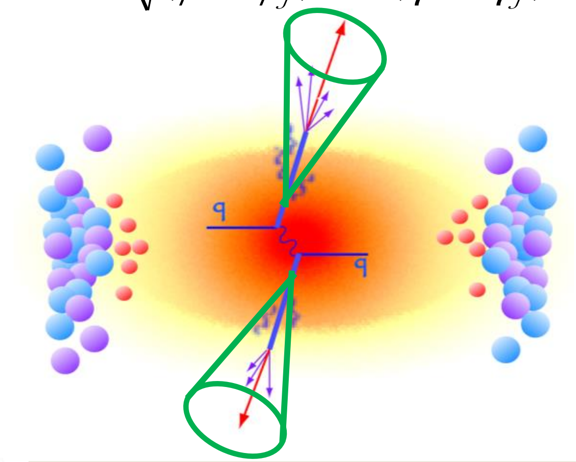


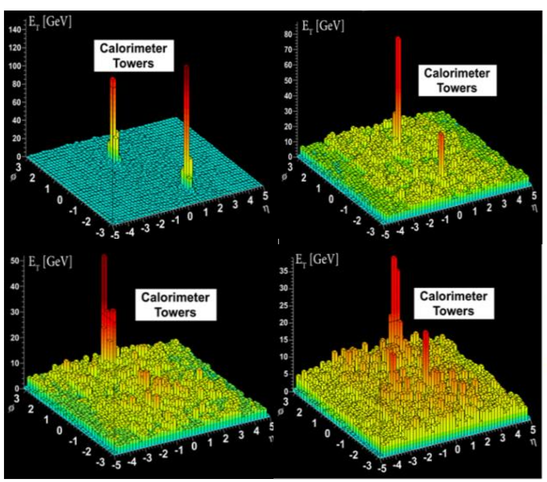
Kang, Wang, Wang, Xing, PRL 2014

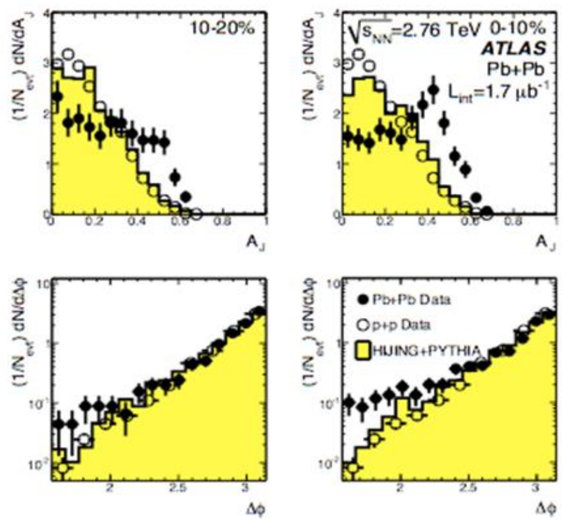
Full jet

- **Recombining hadron/parton fragments, hoping to get the original parton energy/momentum**
- **Full jets might be more discriminative with sub-leading fragments**
- **Significant contribution from background in AA collisions; need reliable tools to disentangle jets from background**

$$R = \sqrt{(\phi - \phi_J)^2 + (\eta - \eta_J)^2}$$



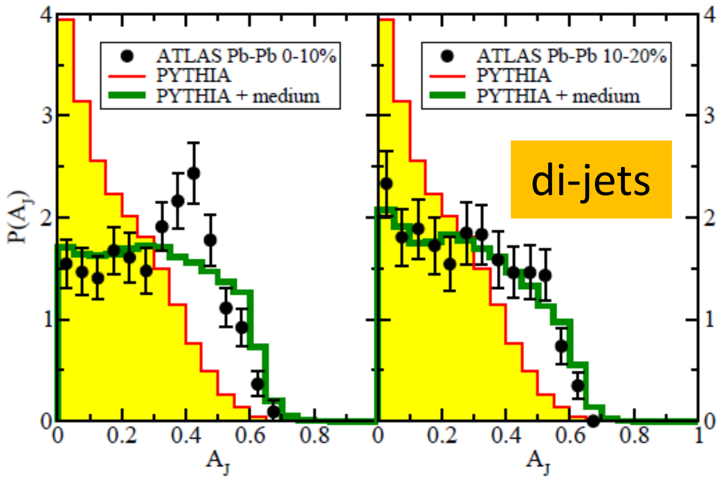




- **Strong modification of dijet E imbalance distribution**
- **Angular distribution is largely unchanged**
- **Implying significant E loss for subleading jets**

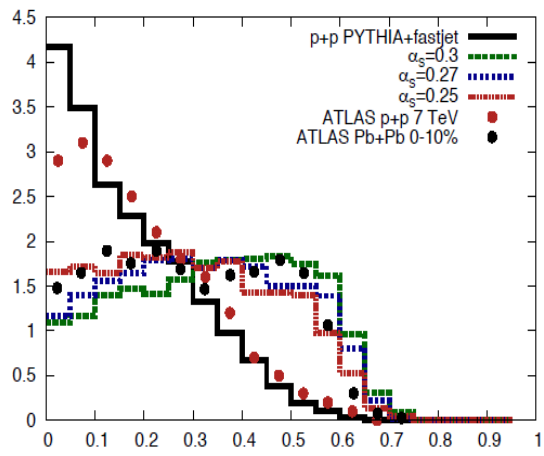
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Energy imbalance of di-jets and γ-jets

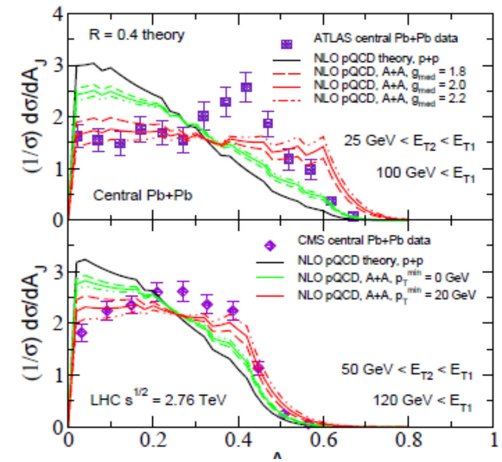


di-jets

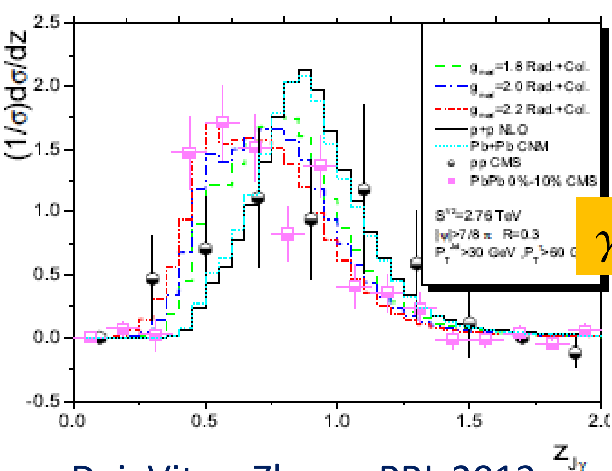
GYQ, Muller, PRL, 2011



Young, Schenke, Jeon, Gale, PRC, 2011

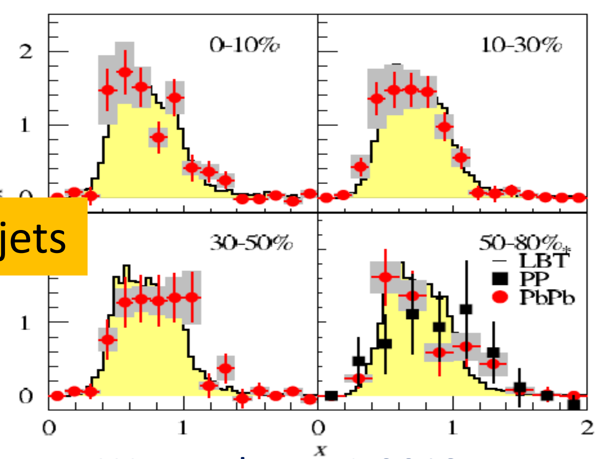


He, Vitev, Zhang, 2011



γ-jets

Dai, Vitev, Zhang, PRL 2013

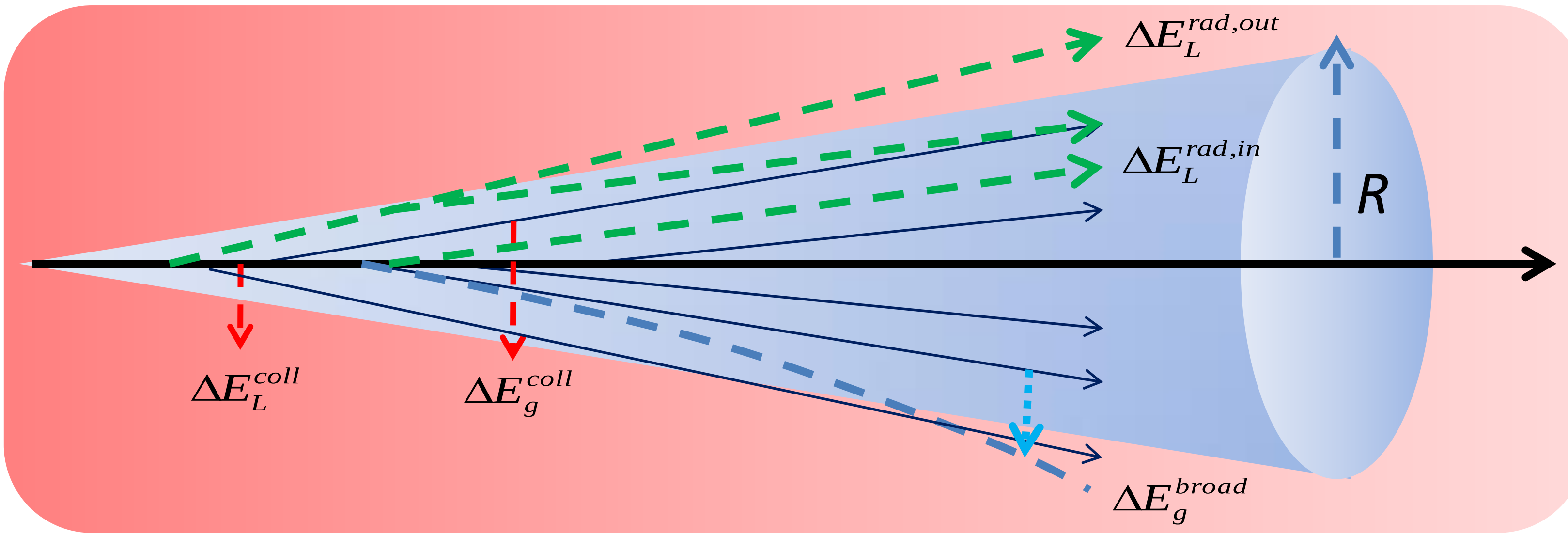


Wang, Zhu, PRL 2013

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad z_{J\gamma} = \frac{p_{T,\gamma}}{p_{T,J}}$$

The shift of the distribution can be well explained by energy loss based models

Jet shower evolution in medium

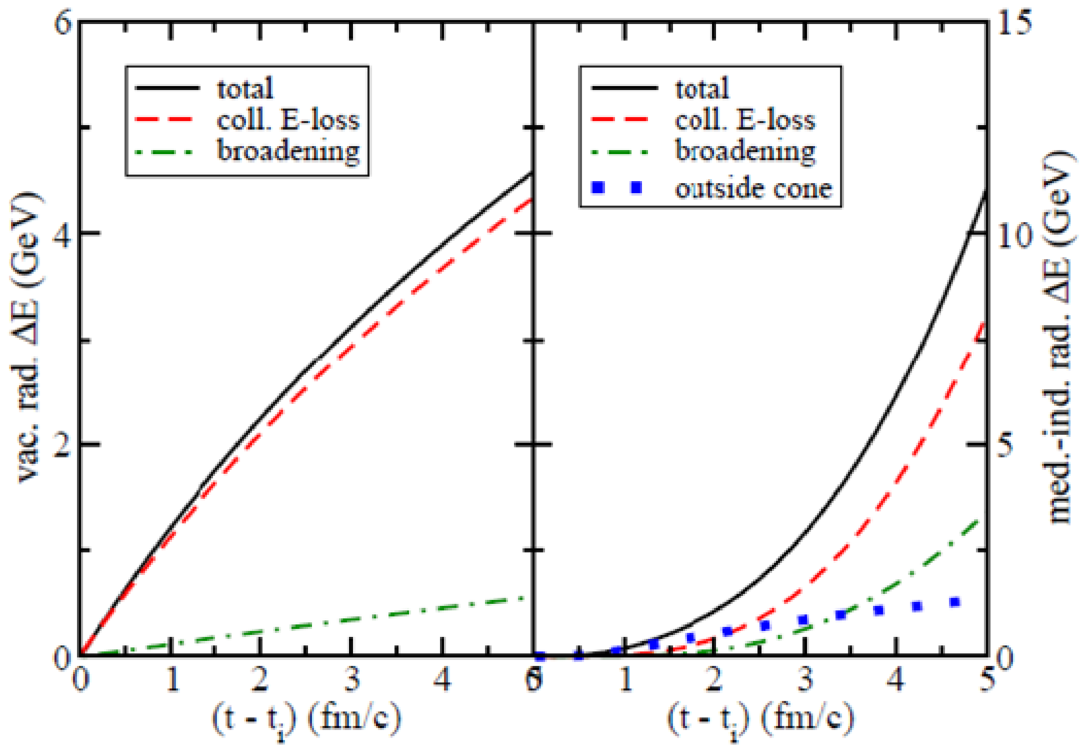


$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e}\,\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\,\hat{q}\nabla^2_{k_\perp} f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

E_{tot} = E_{in} + E_{lost}
= E_{in} + E_{out}(radiation) + E_{out}(broadening) + E_{th}(collision)

GYQ, Muller, PRL, 2011, arXiv: 1012.5280

Full jet energy loss



Collisional energy loss of radiated partons or medium absorption of soft radiations gives large contribution

Jet collimation mechanism: soft partons are stripped off by the medium (Casalderrey-Solana, Milhano, Wiedemann, JPG 2011)

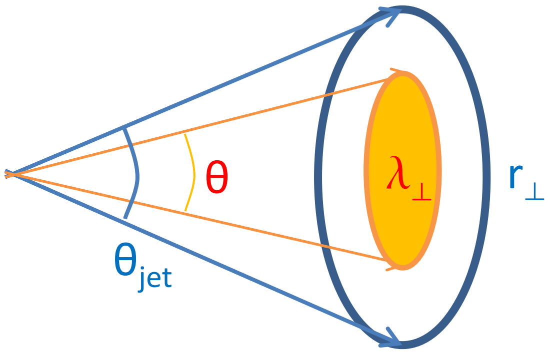
Similar findings (Blaizot, Iancu, Mehtar-Tani, PRL 2013; Tywoniuk, Mehtar-Tani, arXiv: 1401.8293)

$$E_{tot} = E_{in} + E_{lost}$$
$$= E_{in} + E_{out}(\text{radiation}) + E_{out}(\text{broadening}) + E_{th}(\text{collision})$$

GYQ, Muller, PRL, 2011, arXiv: 1012.5280

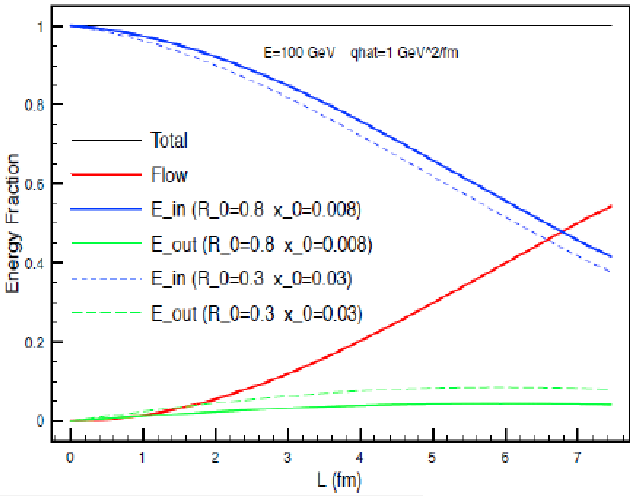
Energy flows to soft gluons

- **If medium color field varies over jet transverse size $r_\perp$, then jet color coherence will be rapidly lost via re-scattering, opening up the phase space for soft (large angle) emissions** (Armesto, Ma, Mehtar-Tani, Salgado,Tywoniuk, Iancu, Casalderray-Solana, Blaizot, Dominguez,2011, 2012)
- **Use probability description & solve rate equation to study multiple gluon emissions** (Blaizot, Iancu, Mehtar-Tani, PRL 2013; Tywoniuk, Mehtar-Tani, arXiv: 1401.8293)
- **Jet energy is rapidly degraded into many soft gluons carrying O(T) energy**
- **Three different phase spaces for radiated gluons, separated by two scales x_0 & x_{th}**
- **Color decoherence manifests in the final sate as the excess of soft particles**



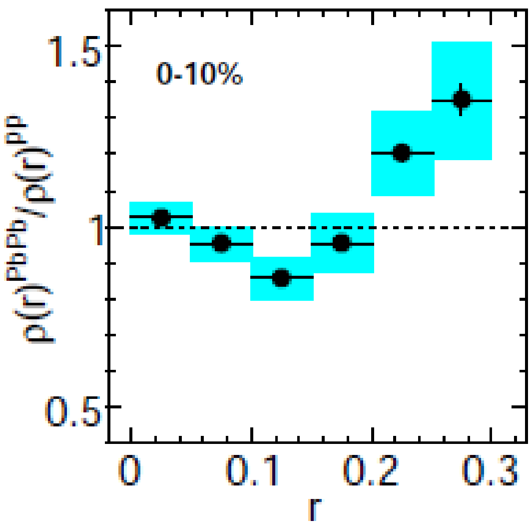
$$r_\perp = \theta_{jet} L$$

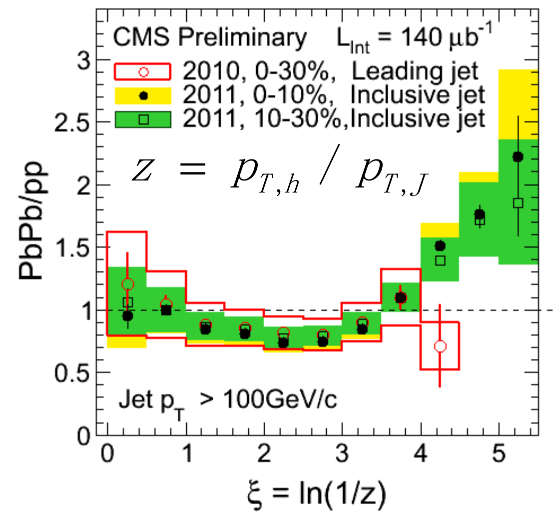
$$\lambda_\perp = 1 / k_\perp = 1 / (\theta\omega) = \sqrt{\hat{q} L}$$

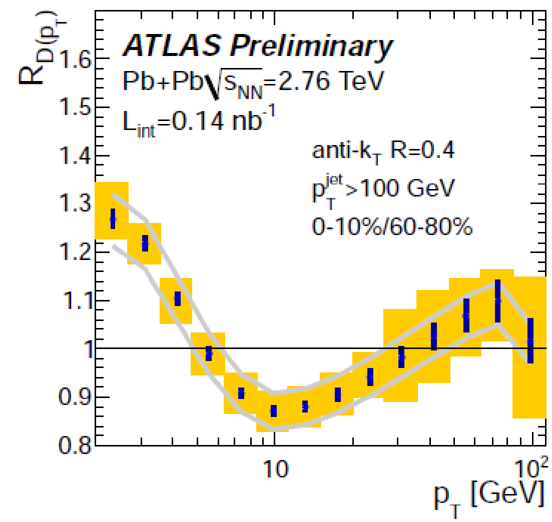


$$\mathbf{E_{tot} = E_{in}(x>x_0) + E_{out}(x_{th}<x<x_0) + E_{flow}(x<x_{th})}$$

Full jet substructure







Medium modification of jet fragment profiles

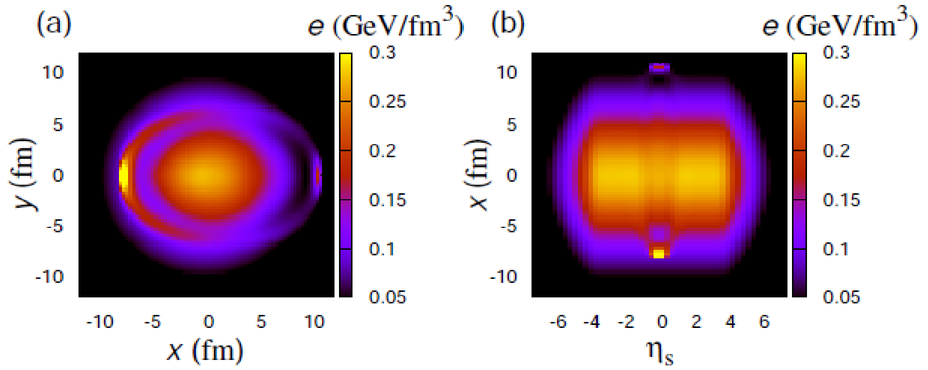
- **Little change @ small r**
- **Depletion @ intermediate r, z, p_T**
- **Excess @ large r; low & high z, p_T**

Many details affect jet substructure

- **Recoiled partons & medium response** (Wang, Zhu, PRL 2013)
- **Different hadronization mechanisms: fragmentation and coalescence** (Ma, PRC 2013)
- **Sophisticated experimental jet finding conditions (biased jets?) are needed to compare theory and data** (Ramos, Renk, arXiv:1401.5283)

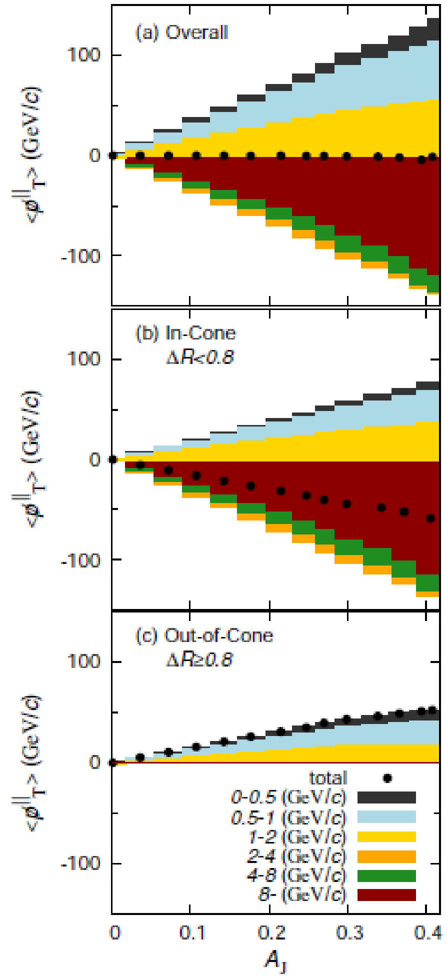
Medium response to lost energy
Where does the lost energy go?

- **Hard partons lose energy in medium; some of lost energy is deposited into medium and makes medium excitations**



Tachibana, Hirano, arXiv:1402.6469

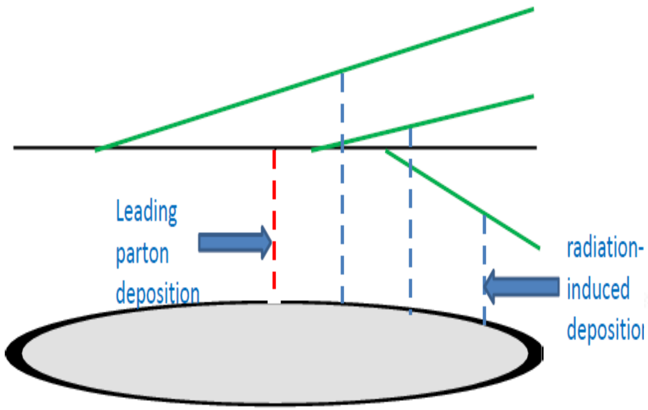
See Yasuki Tachibana's talk

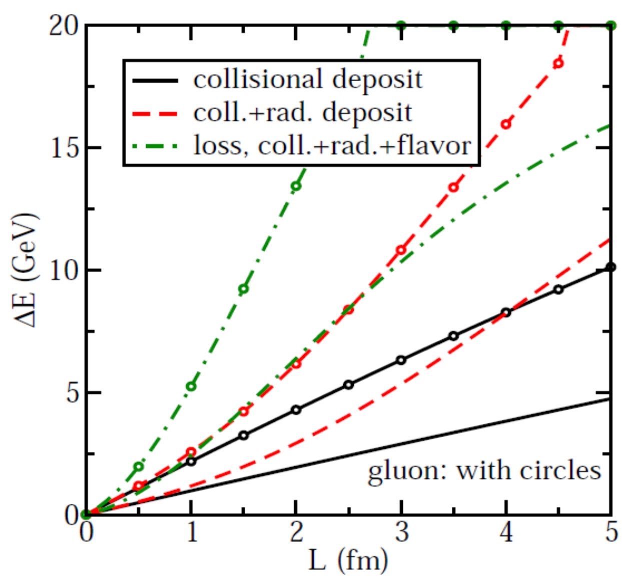


- **Simulate medium response to back-to-back 2 parton propagation using (3+1)-D ideal hydrodynamics**
- **The redistribution of deposited energy through hydrodynamic evolution consistent with CMS result, i.e., the lost energy is carried by soft particles at large angles**

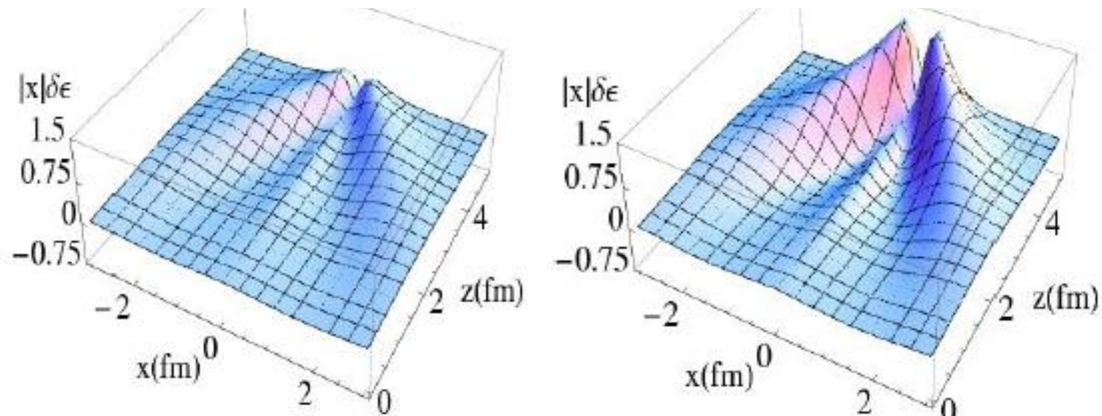
Full jet energy deposition & medium response

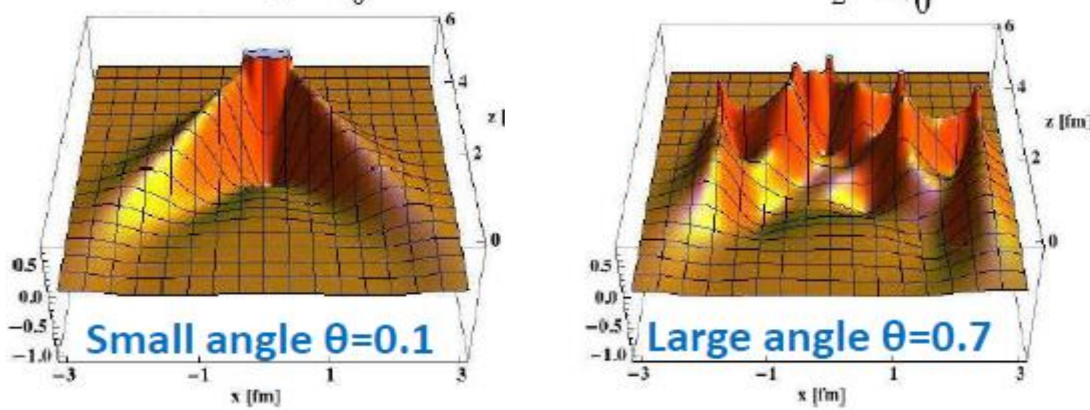
Energy deposition & medium response for jet showers are different from single partons





Single parton **Parton shower**

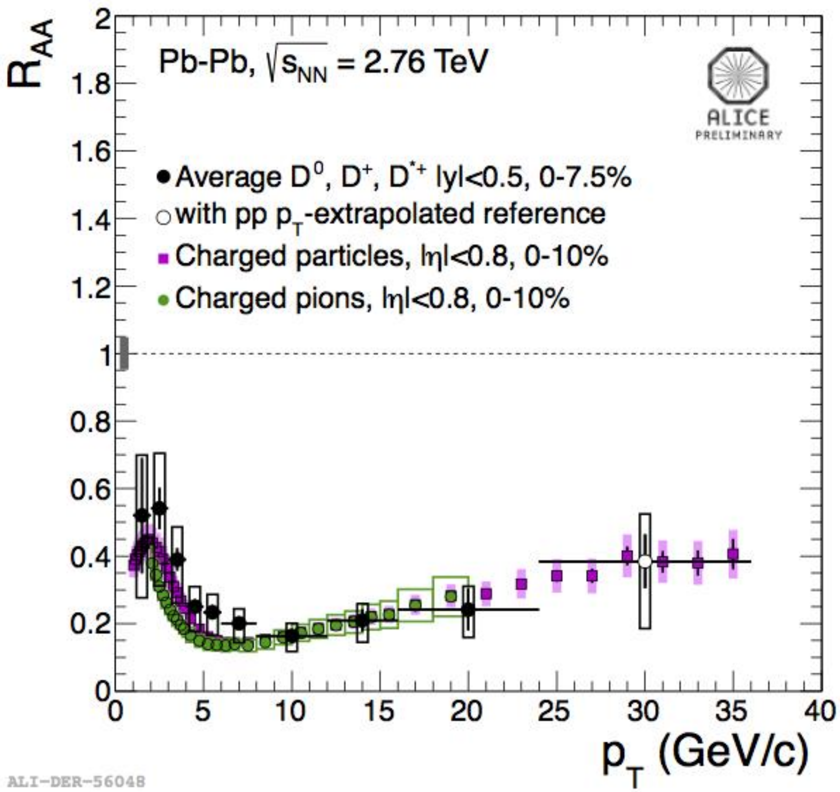


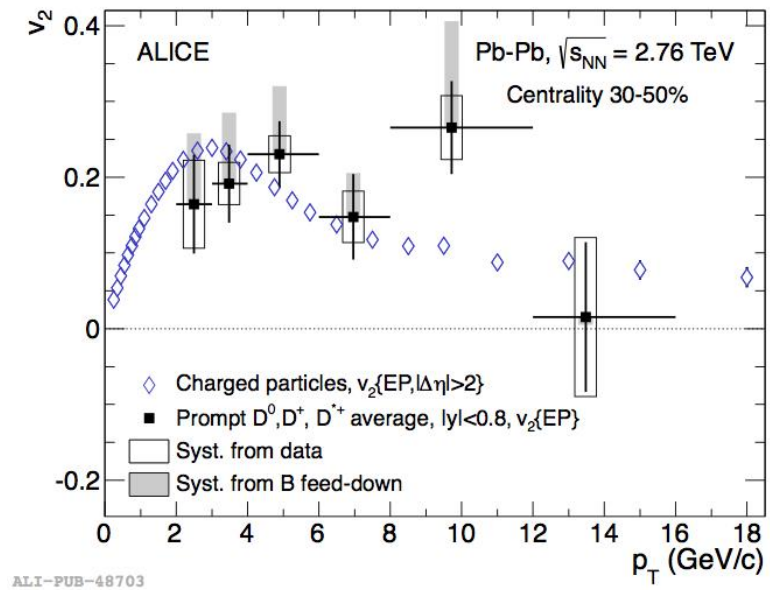


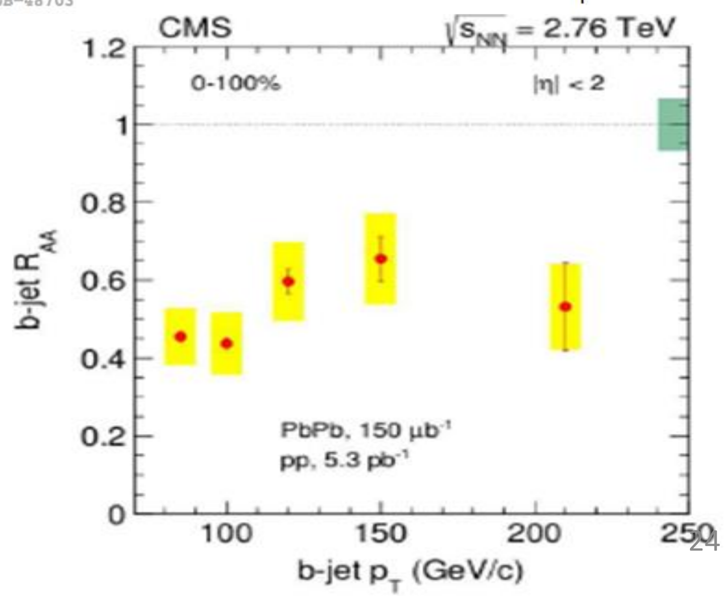
GYQ, Majumder, Song, Heinz, PRL 2009; Neufeld, Muller, PRL 2009 ; Neufeld, Vitev, PRC 2012

Jet + hydro, see Sangwook Ryu's talk, August 6

Heavy flavors





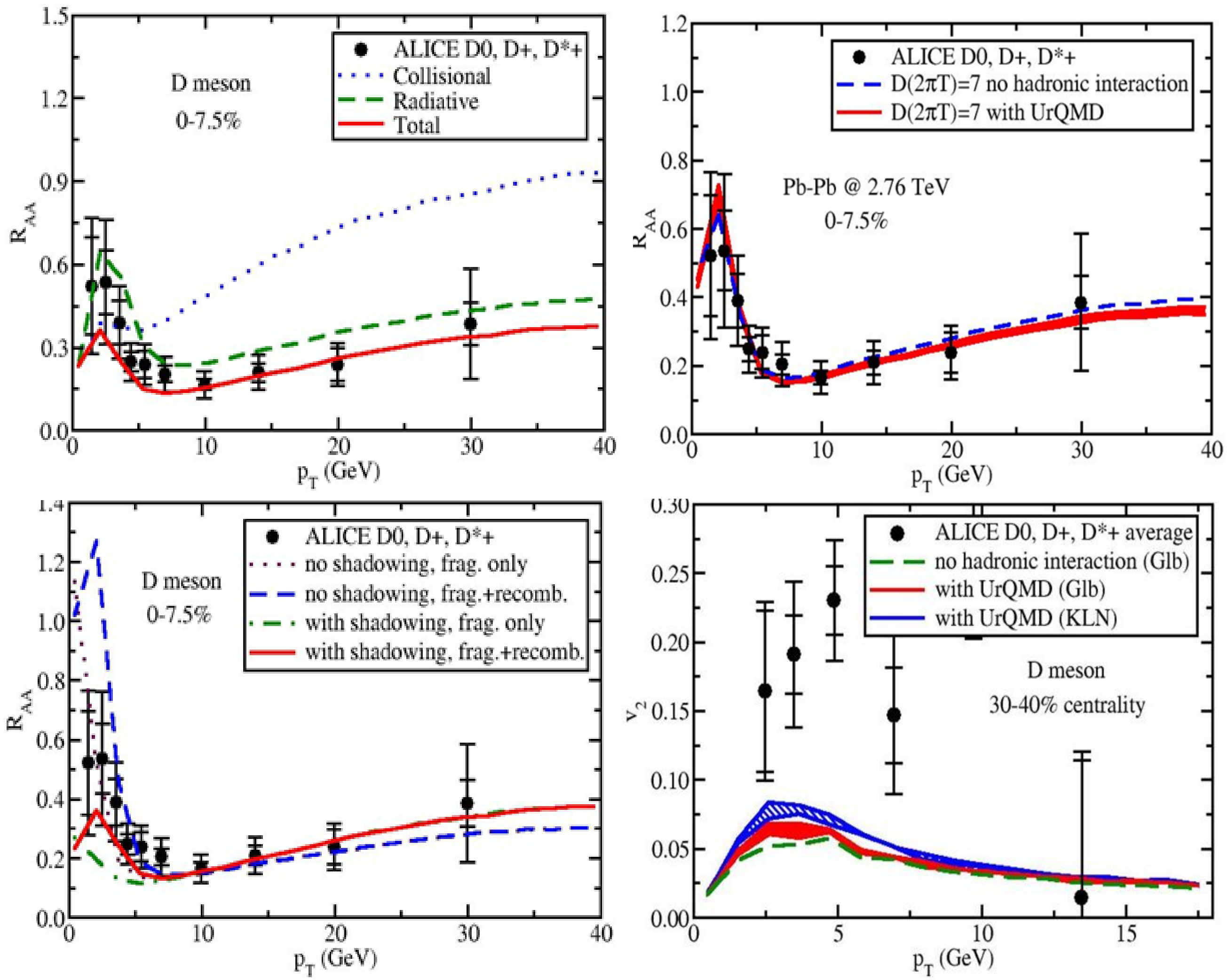


Heavy quarks are expected to lose less energy in QGP due to finite masses

Strong suppression and flow anisotropy have been observed for heavy flavor mesons and tagged jets!

“heavy flavor” sec. August, 6

Heavy flavors



Cao, GYQ, Bass, PRC 2013

Collisional energy loss dominate low p_T, radiative energy loss dominates high p_T

Recombination gives sizable contribution at intermediate p_T

Rescatterings of D mesons in hadron gas increases a little bit quenching at high p_T and enhancement at low p_T

Large v2 difficult for the model

Summary

- **Systematic studies of jet quenching at RHIC and the LHC**
  - Discrepancy of q^{hat} from JET Collaboration and Lattice needs further investigation
  - Map out the temperature dependence of q^{hat}
- **Progress in NLO jet broadening (q^{hat} renormalization)**
  - Full NLO energy loss calculation to be developed
- **Full jet energy loss**
  - Soft components of jets easily lost due to jet-medium interaction
  - Need more detailed study of full jet substructure
- **Progress in studying medium response to lost energy**
  - Thermalization of lost energy not fully understood
  - Need simulate jet transport/evolution and medium response simultaneously
- **Heavy flavors**
  - radiative & collisional, fragmentation & recombination, partonic + hadronic interactions
  - Large v_2