Town meeting on Phases of QCD Matter
Temple University, September 13-15, 2014

Probing properties of QGP with jets at RHIC and LHC: a theoretical perspective

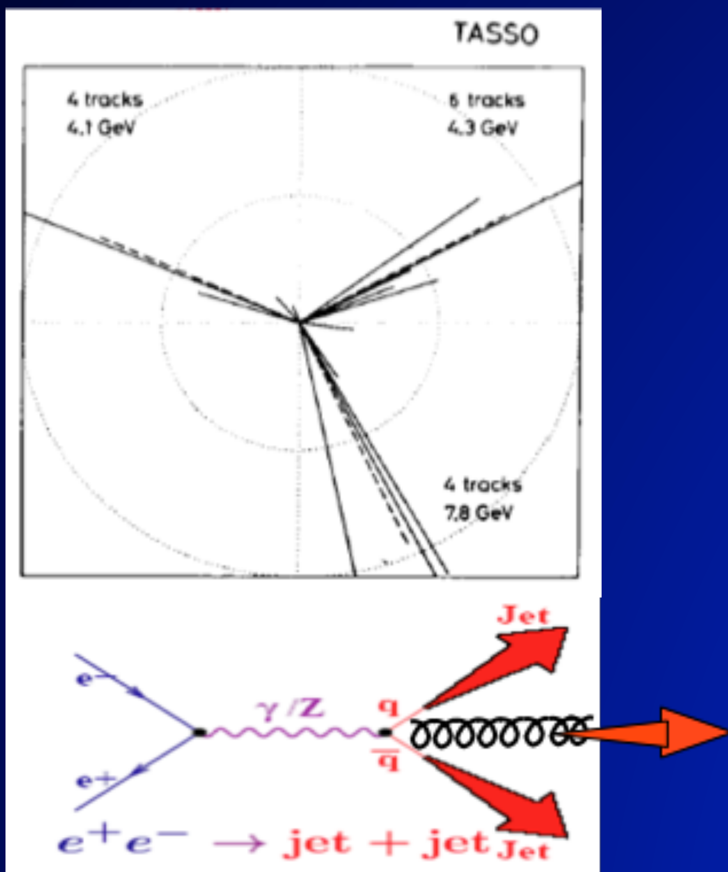
Xin-Nian Wang
CCNU/LBNL

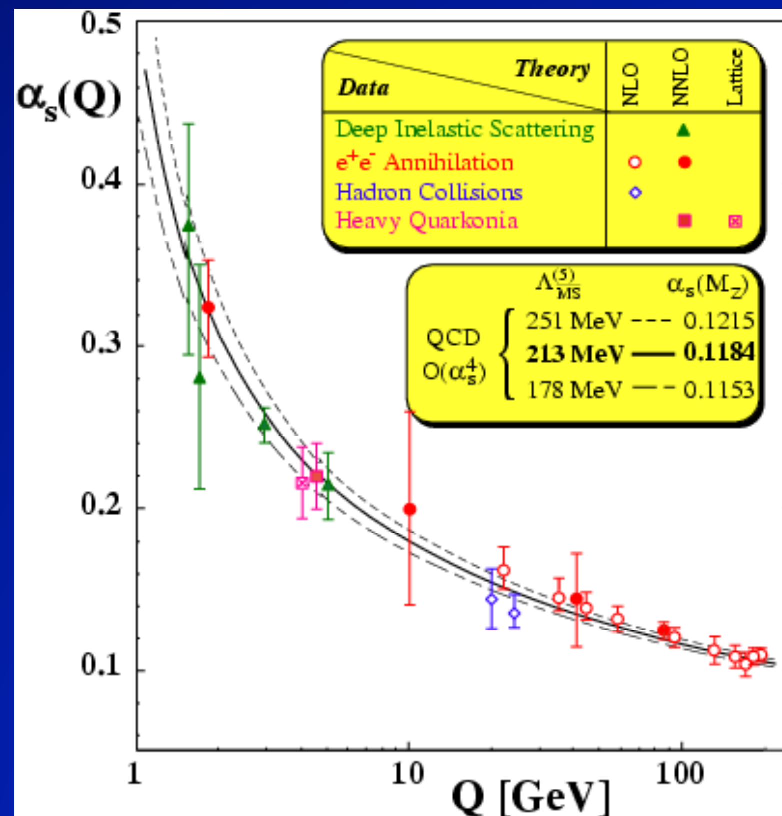
Compelling question: What are the properties of sQGP as probed by jets

- Do we have theoretical and experimental tools?
- Is there a defined theoretical framework?
- What future developments required?
- Why one needs RHIC when we have LHC?

Jets in high-energy collisions

--tools for studying QCD and new discoveries

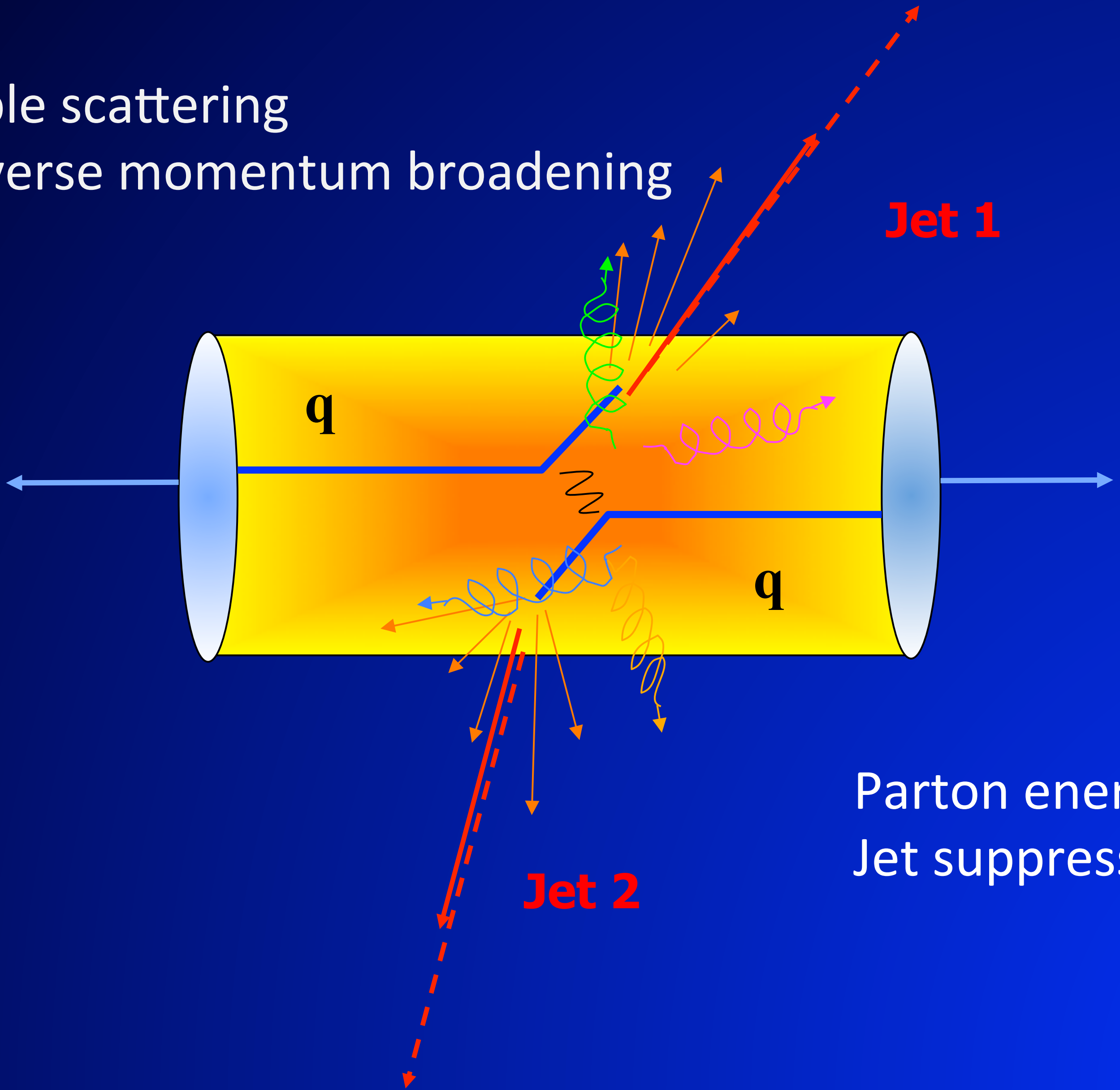




S Bethke J. Phys. G26 (2000) R27

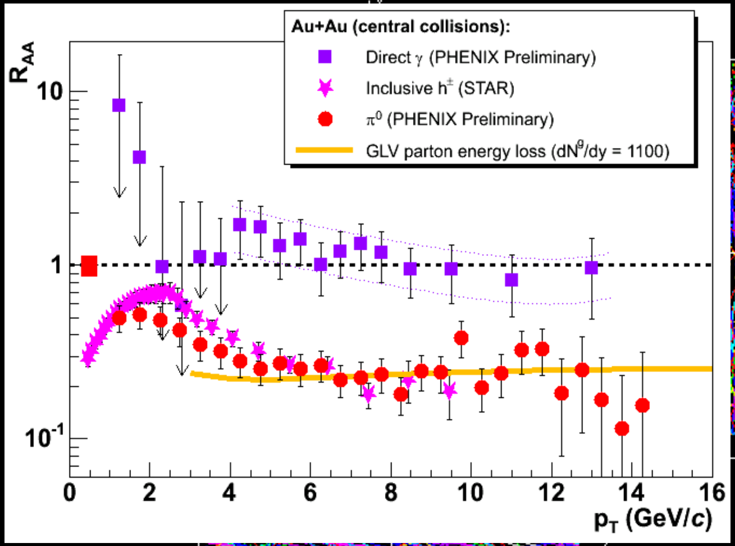
Jets in heavy-ion collisions

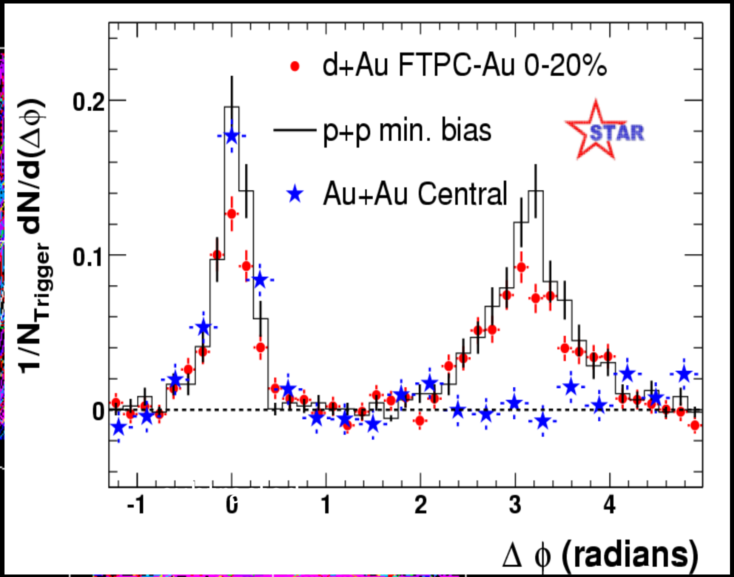
Multiple scattering
Transverse momentum broadening

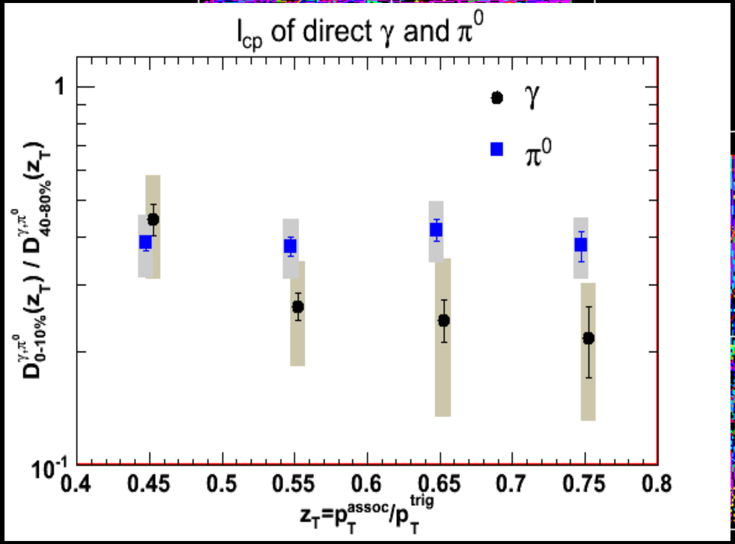


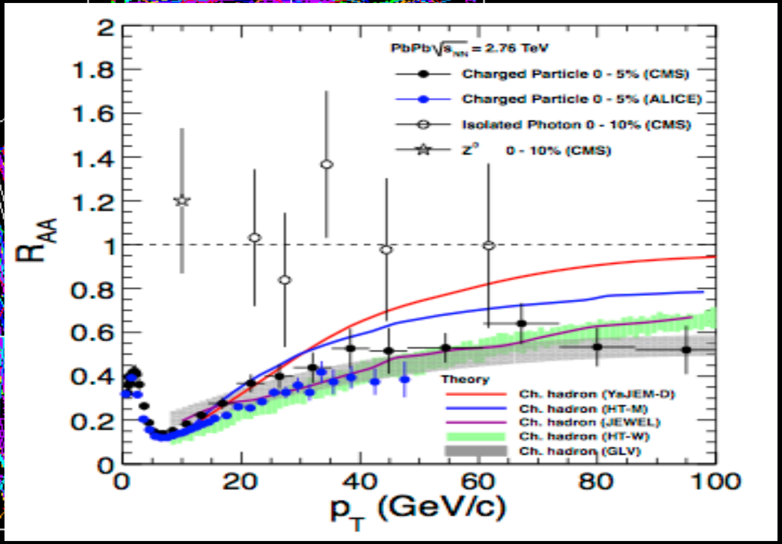
Parton energy loss
Jet suppression

Jet Quenching at RHIC & LHC

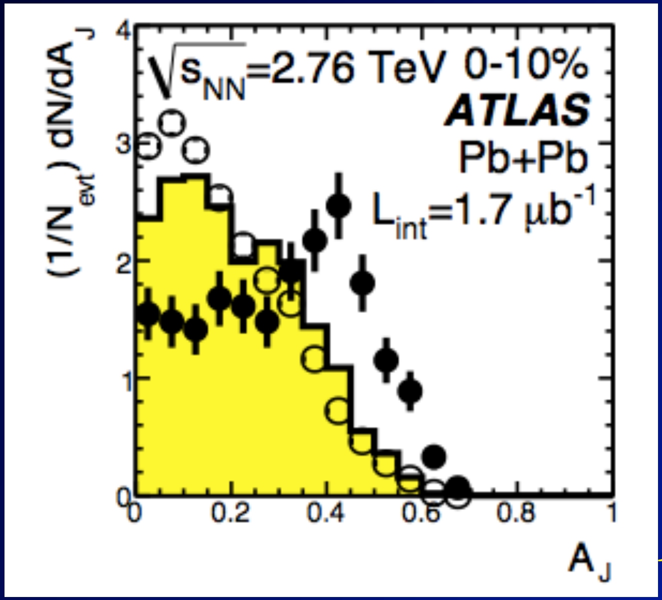


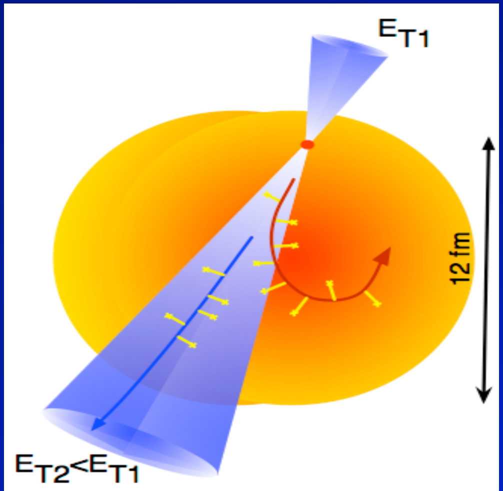




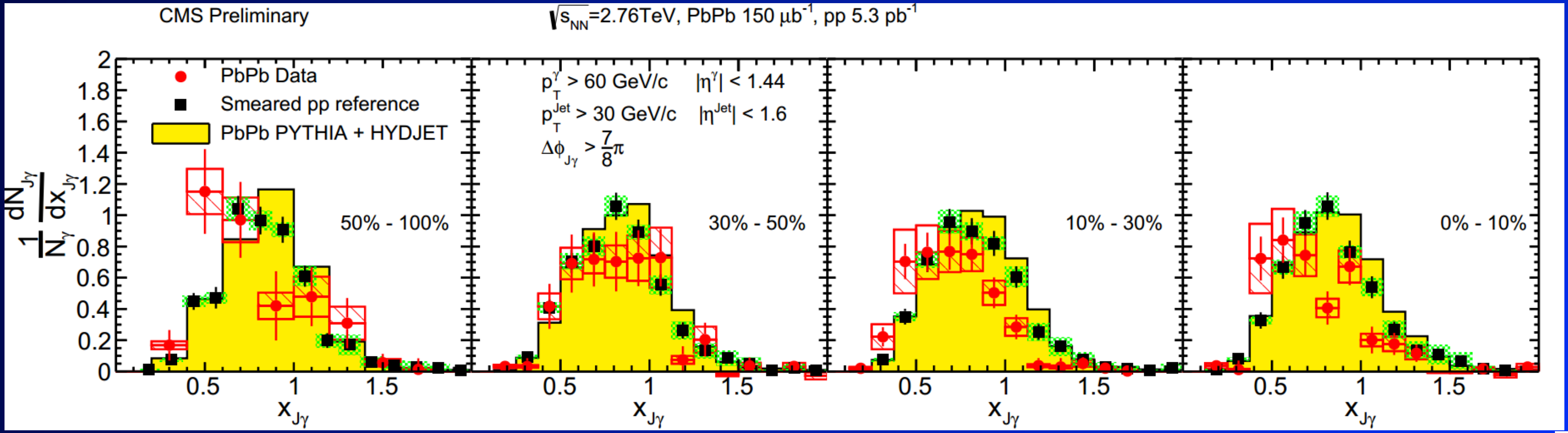


Jet Quenching at RHIC & LHC





$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

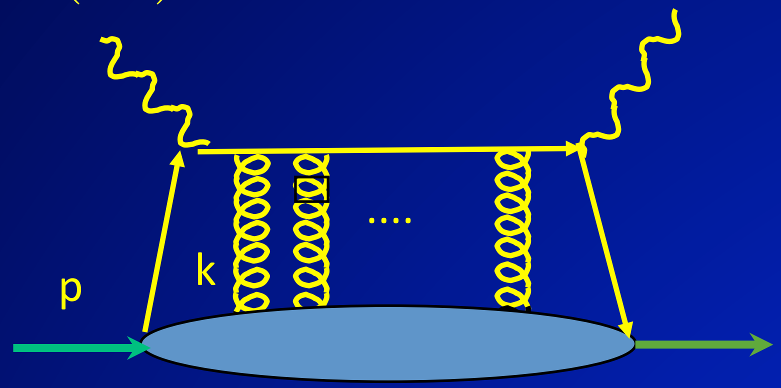


What properties of QGP jets probe

- Space-time profile: $T_{\mu\nu}(x) : T(x), u(x)$
- EOS: $T_{\mu\nu} \Longleftrightarrow \epsilon, P, s, c_s^2 = \partial p / \partial \epsilon$
- Bulk transport: $\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt dx e^{i\omega t} \langle [T_{xy}(0), T_{xy}(x)] \rangle$
- EM response: $W_{\mu\nu}(q) = \int \frac{d^4x}{4\pi} e^{iq\cdot x} \langle j_\mu(0) j_\nu(x) \rangle$
- Jet transport: $\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int \frac{dy^-}{\pi} \langle F^{\sigma +}(0) F_\sigma^{\ +}(y) \rangle$
- … $\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int \frac{dy^-}{\pi} \langle F^{+-}(0) F_{+-}(y) \rangle$

Parton propagation in medium

$$f_A^q(x,\vec{k}_\perp) = \int \frac{dy^-}{4\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp} \langle A|\bar{\psi}(0)\gamma^+\mathcal{L}(0,y)\psi(y)|A\rangle$$



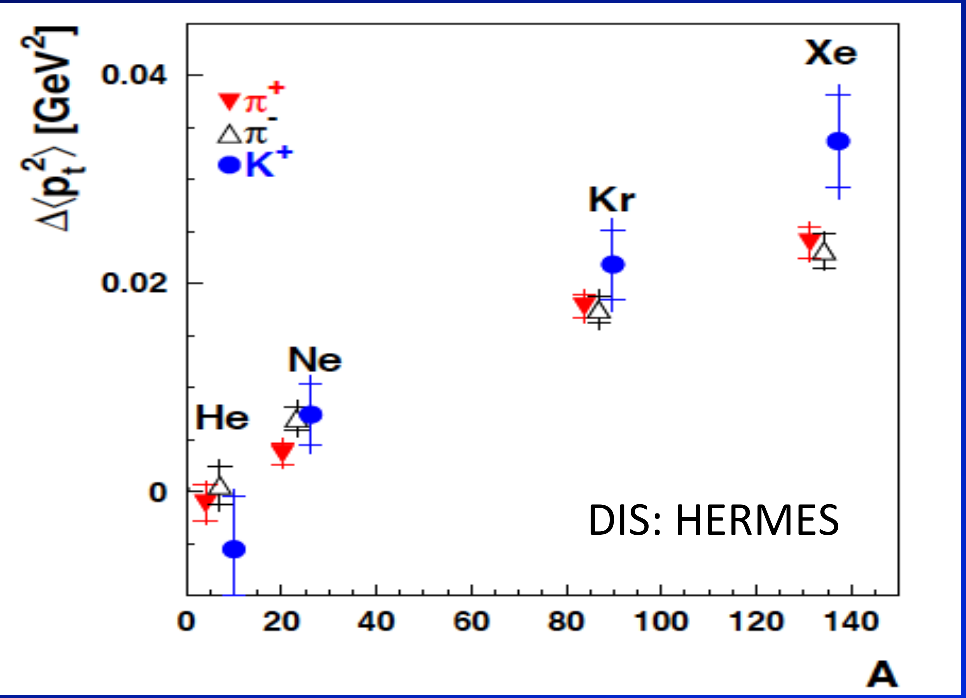
$$f_A^q(x,\vec{k}_\perp) \approx \frac{A}{\pi\Delta}\int d^2q_\perp \exp\left[-\frac{(\vec{k}_\perp-\vec{q}_\perp)^2}{L\hat{q}}\right] f_N^q(x,\vec{q}_\perp)$$

Transverse momentum broadening: $\langle \Delta k_\perp^2\rangle = \int d\xi^- \hat{q}(\xi)$

$$\hat{q} = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int\frac{dy^-}{\pi}\langle F^{\sigma+}(0)F_\sigma^{\ +}(y)\rangle = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\rho_A x G_N(x)|_{x\to 0}$$

p_T broadening and jet transport

$$\langle \Delta k_\perp^2 \rangle = \int d\xi^- \hat{q}(\xi)$$



Cold nuclear matter in DIS:

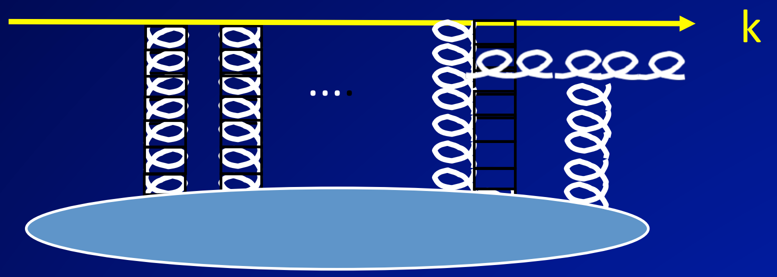
$$\hat{q}_N \approx 0.02\ \ \mathrm{GeV}^2/fm$$

Consistent with value from jet quenching in DIS:

Deng & XNW, PRC83(2010)024902;

Chang, Deng & XNW, PRC89(2014) 034911

Parton energy loss in Medium



Medium modification of jet splitting function:

$$\Delta\gamma(z,\ell_\perp^2) = C_A \frac{1+z^2}{(1-z)_+} \frac{2}{\ell_\perp^4} \int d\xi^- \hat{q}(\xi)[1-\cos(x_L p^+ \xi^-)]$$

Parton energy loss:

$$\frac{\Delta E}{E} = \frac{2\alpha_s N_c}{\pi} \int \frac{d\ell_T^2}{\ell_\perp^4} dz[1+(1-z)^2] \int d\xi^- \hat{q}(\xi) \sin^2(x_L p^+ \xi^-)$$

Difference approximations:

HTLpQCD (AMY), Opacity expansion(GLV), High-twist (HT), SCET

Numerical implementation of multiple emission, propagation and evolution:

McGill-AMY, MARTINI-AMY, CUJET, HT-BW, HT-M, JEWEL, JaYEM, PCM, BAMPS ....

Jet quenching phenomenology

3+1D hydro + Jet transport + Hadronization

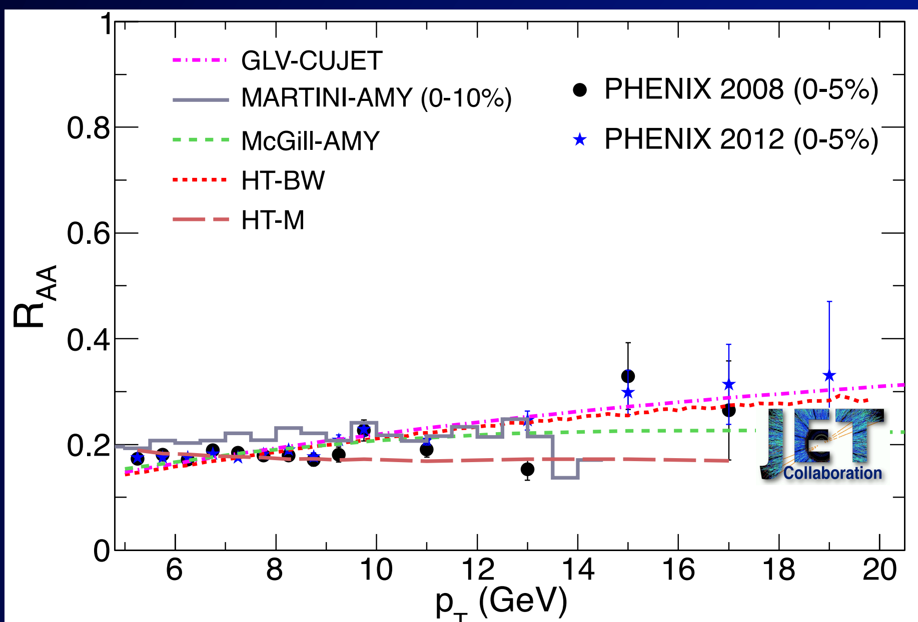
- Numerical implementation of jet propagation in medium: elastic scattering, induced gluon emission , multiple scattering and gluon emission, LPM interference
- Realistic bulk evolutions: e-by-e 3(2)+1 hydro : constrained by bulk hadron spectra, $v_{n,}$
- Hadronization: fragmentation & recombination

http://jet.lbl.gov

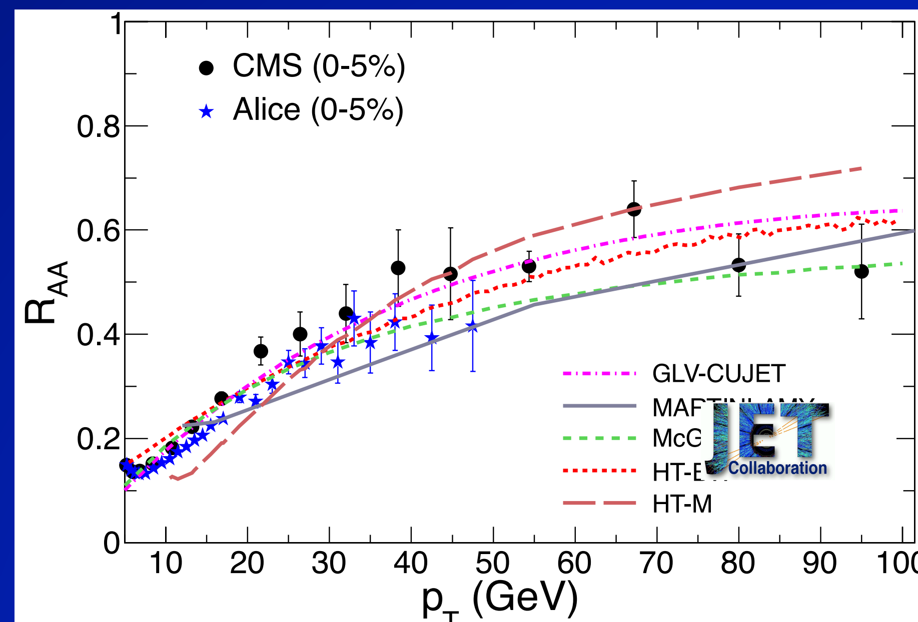
Jet quenching phenomenology

Suppression of single hadron spectra at RHIC and LHC

Best χ^2 fits with different model calculations :



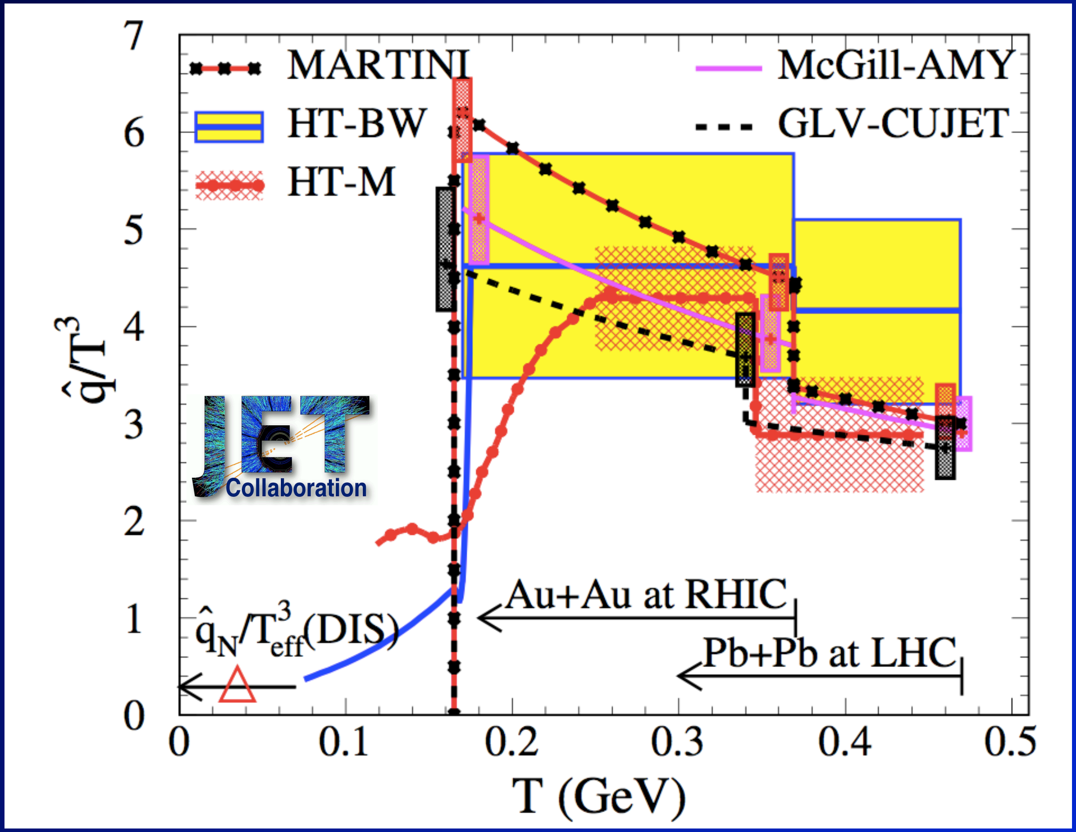
RHIC



LHC

Jet transport coefficient

JET Collaboration: arXiv:1312.5003

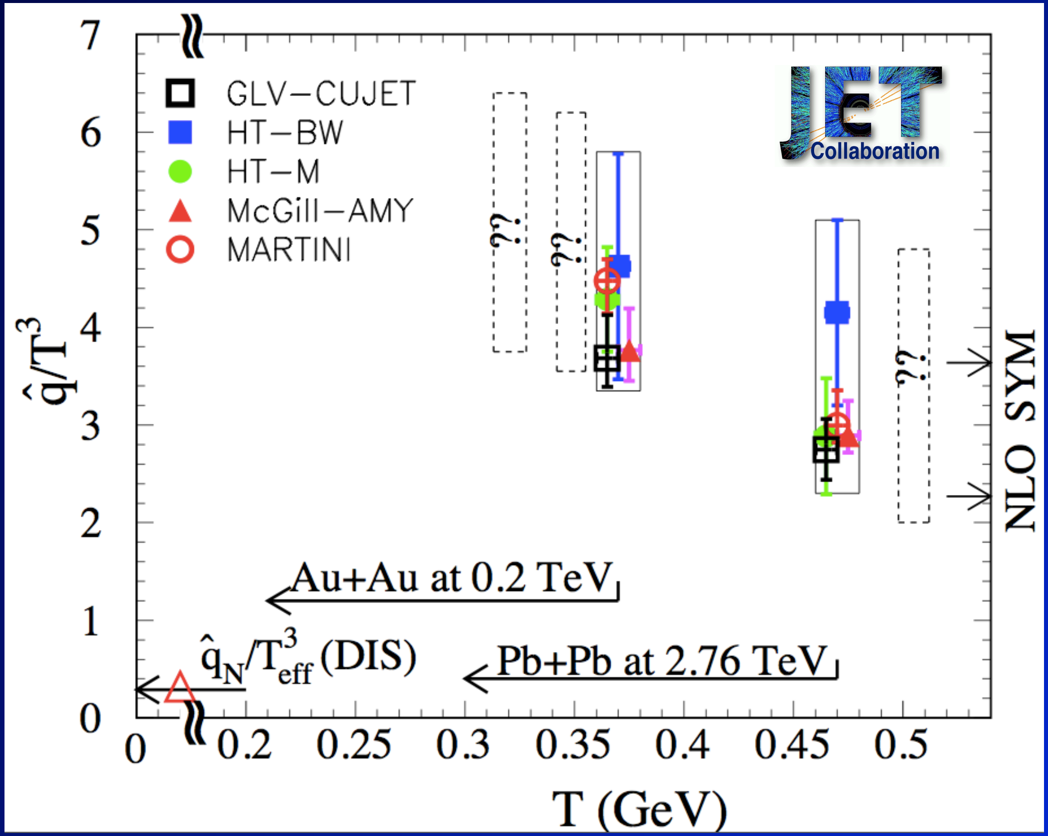


$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \ \mathrm{at} \ \ \begin{matrix} \mathrm{T{=}370\ MeV,} \\ \mathrm{T{=}470\ MeV,} \end{matrix}$$

RHIC
LHC

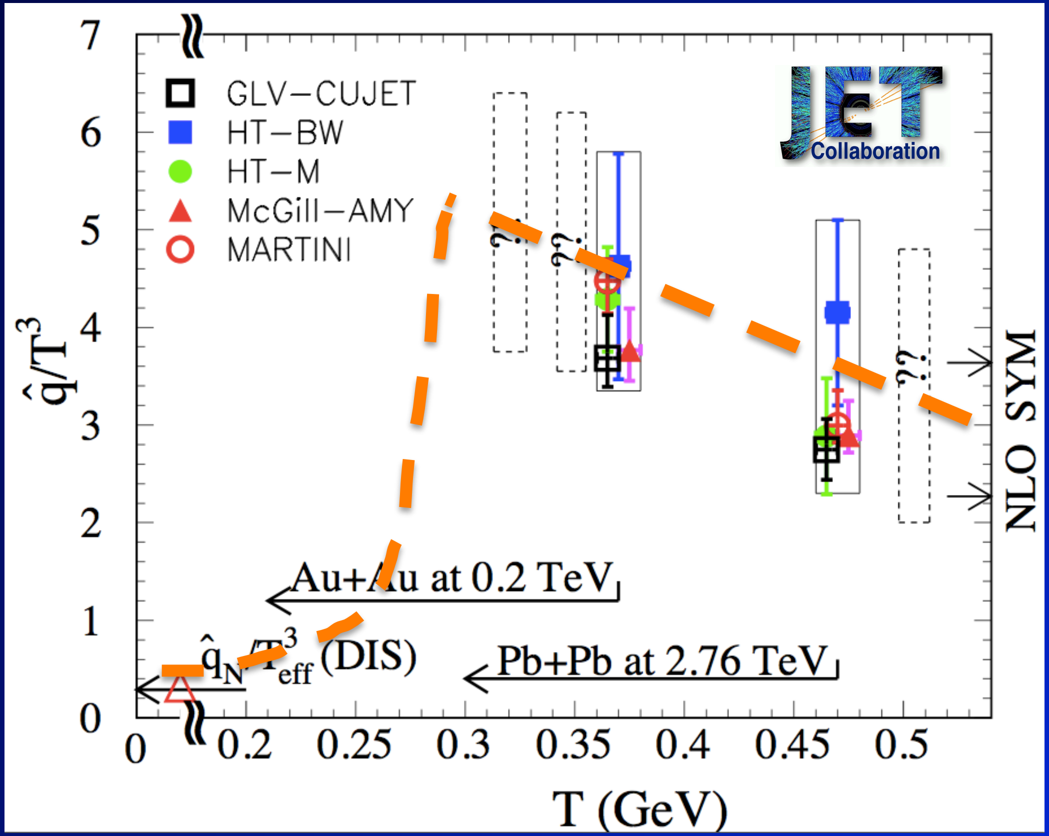
T-dependence of jet transport coefficient ?

JET Collaboration: **arXiv:1312.5003**



T-dependence of jet transport coefficient ?

JET Collaboration: **arXiv:1312.5003**

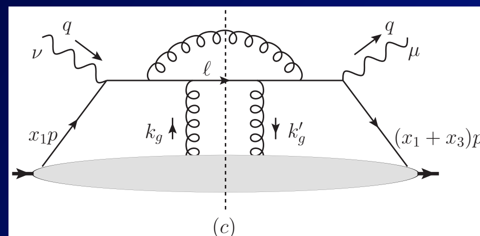


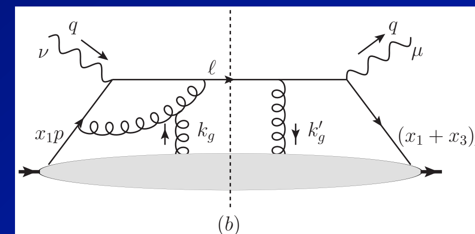
Scan over the initial T at RHIC and LHC higher energies

Reduction of uncertainties: dihadron, gamma-hadron, flavor dependence, anisotropy, jet observables

NLO and Q-evolution of qhat

- Uncertainty in scale dependence of collinear LO results





- Cancellation of soft-collinear divergence
- Factorization of the collinear divergence

PRL 112, 102001(2014)

$$\frac{d\langle k_\perp^2 \sigma\rangle_{\rm NLO}}{dz_h} = \sigma_0 D_h(z,\mu_f^2) \otimes H_{\rm NLO}(x, x_B, Q^2, \mu_f^2) \otimes T_{qg}(x, x_1, x_2, \mu_f^2)$$

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

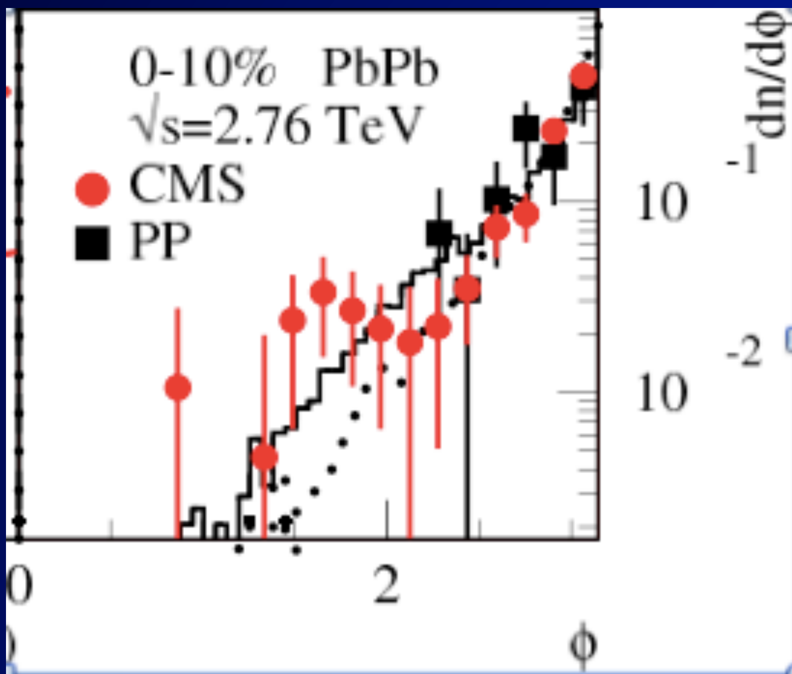
$$\hat{q} \Longrightarrow \hat{q}(E, Q^2)$$

Structure of the medium at different scales

Pin point the quasi-particles in QGP

Beyond extracting jet transport parameters

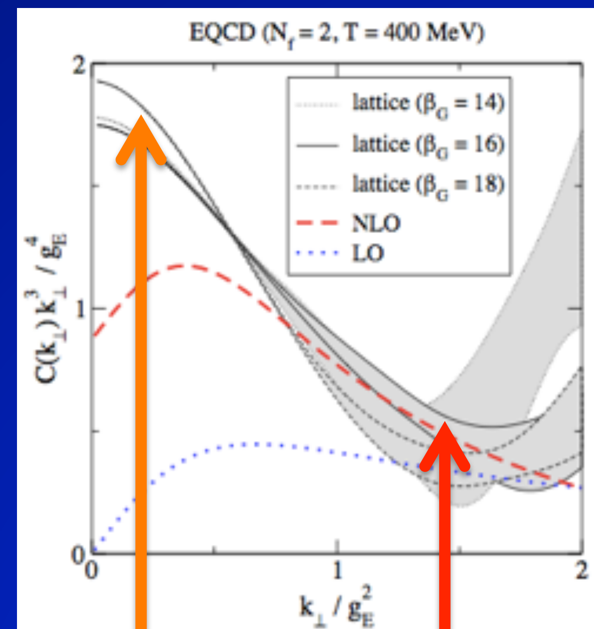
Linear Boltzmann Transport (LBT) simulations



Enhancement of large angle di-jet, γ-jet,

γ-hadron correlation

Laine & Rothkopf (2013)



Hard/large angle scattering

Soft scattering

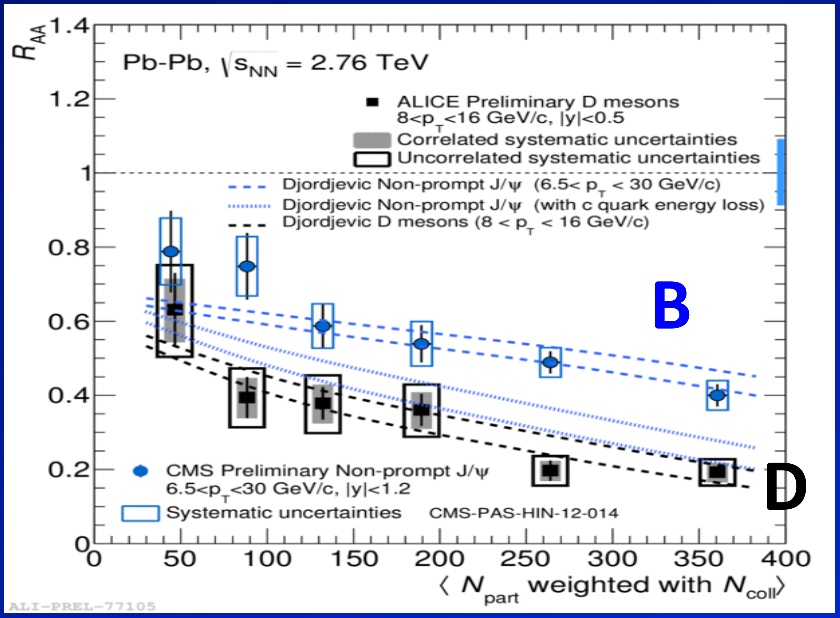
Non-perturbative

Quasi-particles seen by heavy quarks

Mass effect: dead-cone in gluon radiation
(Dokshitzer & Kharzeev (2001)

$$\frac{dN_g}{d\ell_T^2} \sim \frac{\alpha_s}{\ell_T^2} \rightarrow \frac{\alpha_s \ell_T^2}{(\ell_T^2 + z^2 M^2)^2}$$

Smaller radiative energy loss
(Should be similar to light quarks $p_T >> M$)



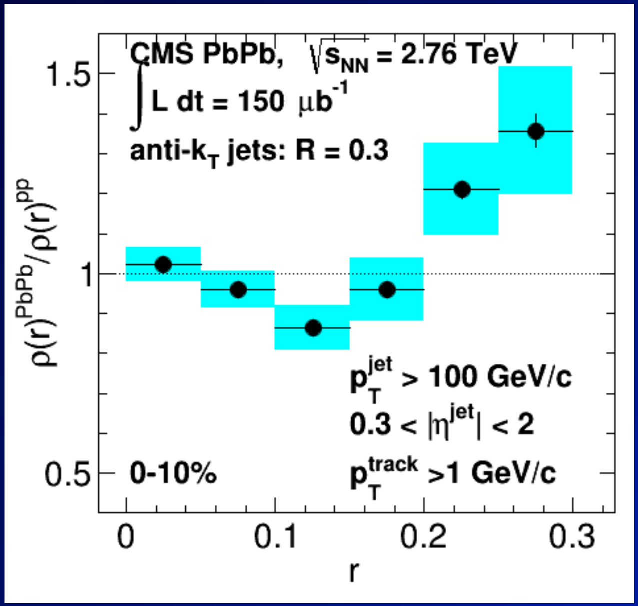
$$R^h_{AA} \approx R^D_{AA} < R^B_{AA}$$

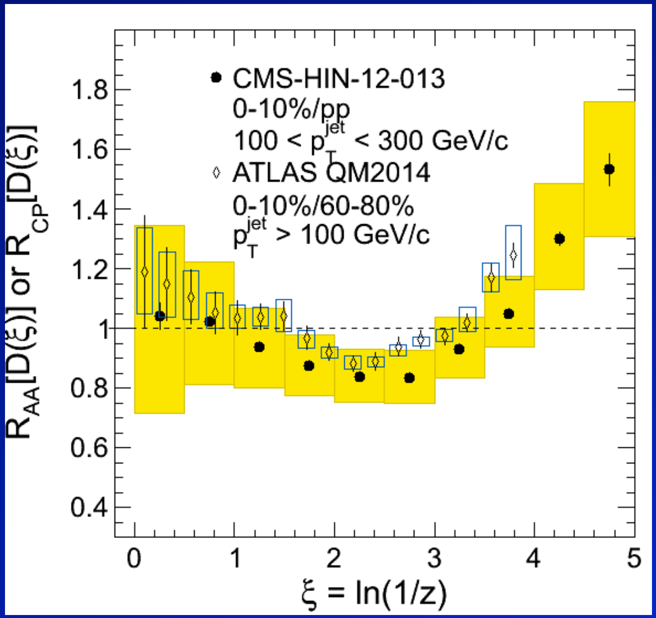
Detailed study of Interplay between elastic and radiative energy loss

$\hat{e}/\hat{q}$ → Properties of quasi-particles in QGP
(close to Tc and at highest T)

Modification of jet structure

jet transverse profile



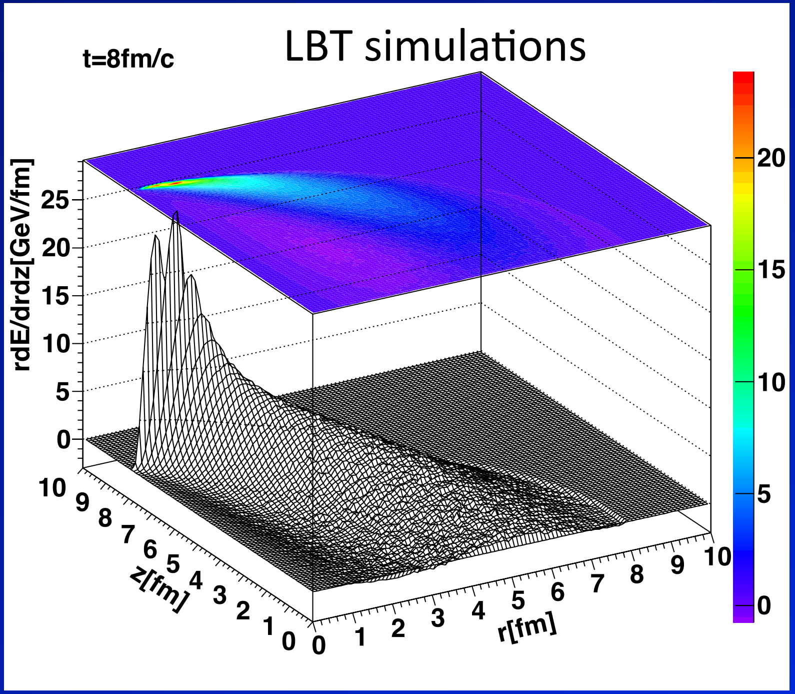


Fragmentation function

- Modified QCD evolution of jet parton shower
  - Include both vacuum and medium induced splitting
  - Incorporate space-time and Q^2-evolution
  - Incorporate possible color de-coherence
  - Parton hadronization (recombination) in medium
  - Jet-induced medium excitation (shock waves)

Jet-induced shock waves

- Re-distribution of lost jet energy
- Soft-parton –medium interaction non-perturbative in nature
- Closely related to bulk transport properties in medium and EoS

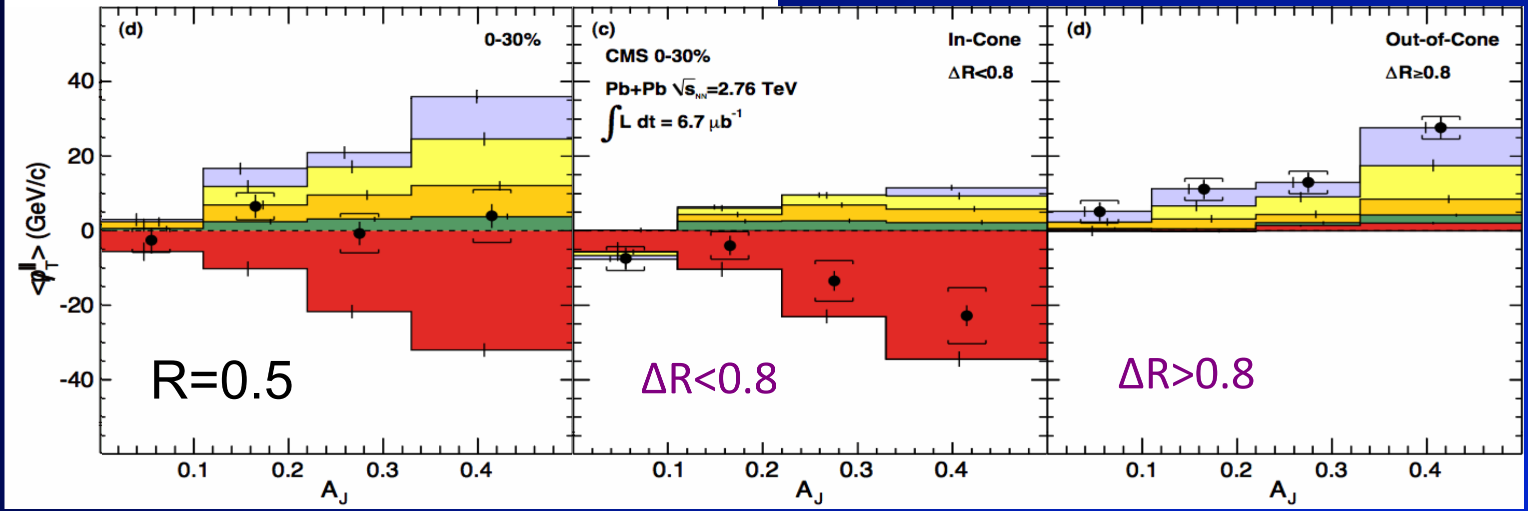


- Jet-induced medium excitation in turn will influence the jet structure (both frag. func. and profile)

Dissipation of the missing jet energy

$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Miss jet energy balanced by low pt hadron outside the jet cone

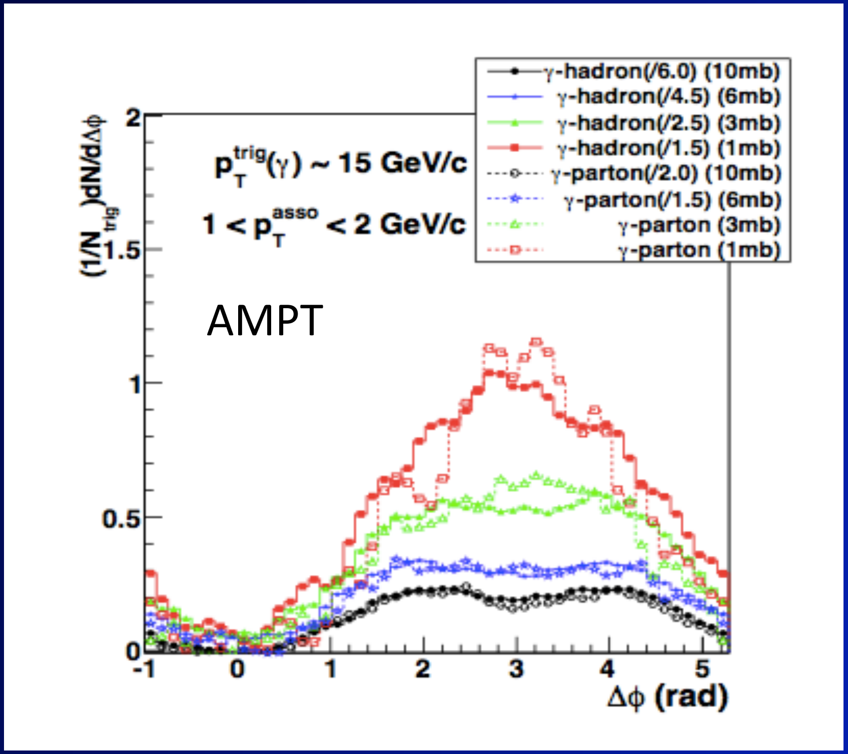


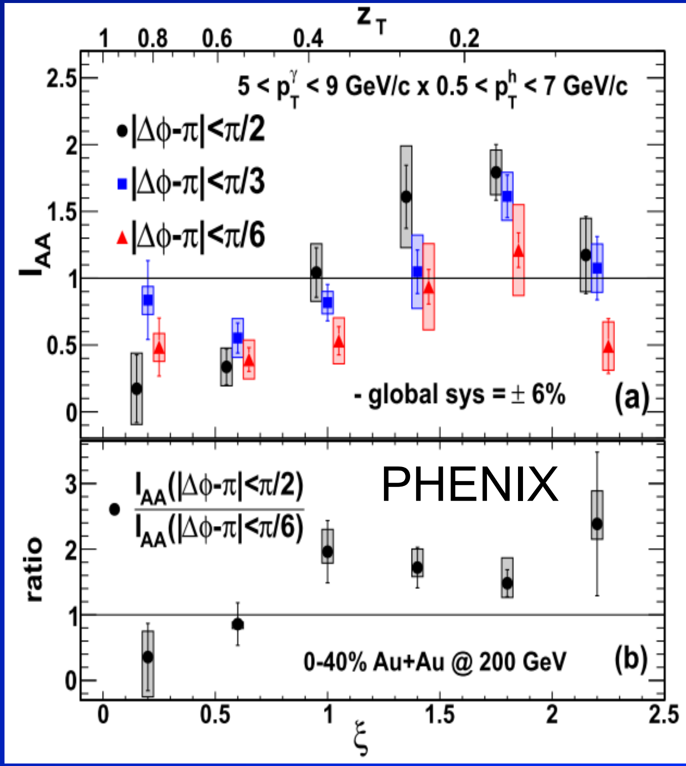
- Jet propagation coupled with 3+1D e-by-e hydro
- Realistic modeling of geometric bias in dijet
- Mod of underlying flow by jet-medium interaction

γ-hadron correlations

As a probe of both large angle scattering and jet-induced medium excitation

- Less geometric bias
- No contamination from elliptic flow





PRL 106 (2011) 162301

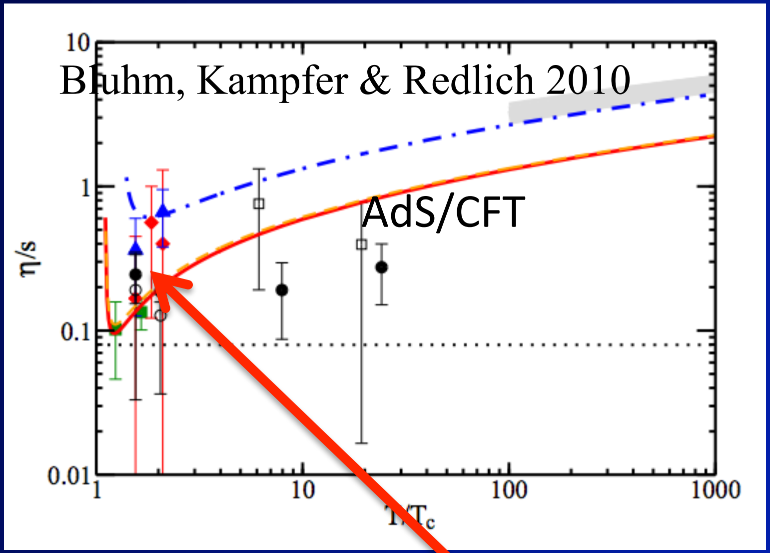
Summary (long)

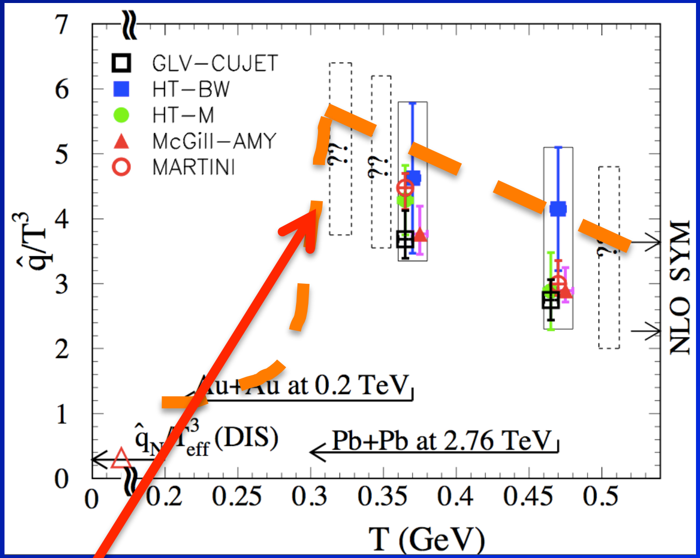
- Jet quenching - a leading signal of hot & dense medium- is observed over a wide range of experimental measurements
- Experimental studies at RHIC and LHC combined with theoretical & phenomenological development lead to extracted values of jet transport parameter qhat
- Future combined RHIC & LHC studies and improved theoretical calculation can shed light on the T and scale-dependence of qhat, fine structure of the medium, and medium response to jet-induced excitation (bulk transport)

Summary (short)

- Jet quenching provided important evidence of sQGP in A+A at RHIC and LHC
- Continued study of jets at RHIC , together with data from LHC, is critical for determination of many important properties of sQGP, complementing that offered by soft probes.

Bulk and jet transport properties





$$\frac{\eta}{s} \geq \frac{3T^3}{2\hat{q}}$$

Majumder, Muller & XNW (2007)

Backup

Linear Boltzmann jet transport

$$p_1 \cdot \partial f_1(p_1) \;=\; -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) \left|M_{12\to 34}\right|^2 (2\pi)^4 \delta^4(\sum_i p_i),$$

$$f_i(p) = (2\pi)^3 \delta^3(\vec{p}_i - \vec{p}_0)\delta^3(\vec{x} - \vec{x}_0 - t\vec{v}_i)[i = 1,3]$$

$$f_i(p_i) = \frac{1}{e^{p_i \cdot u/T} \pm 1}(i = 2,4)$$

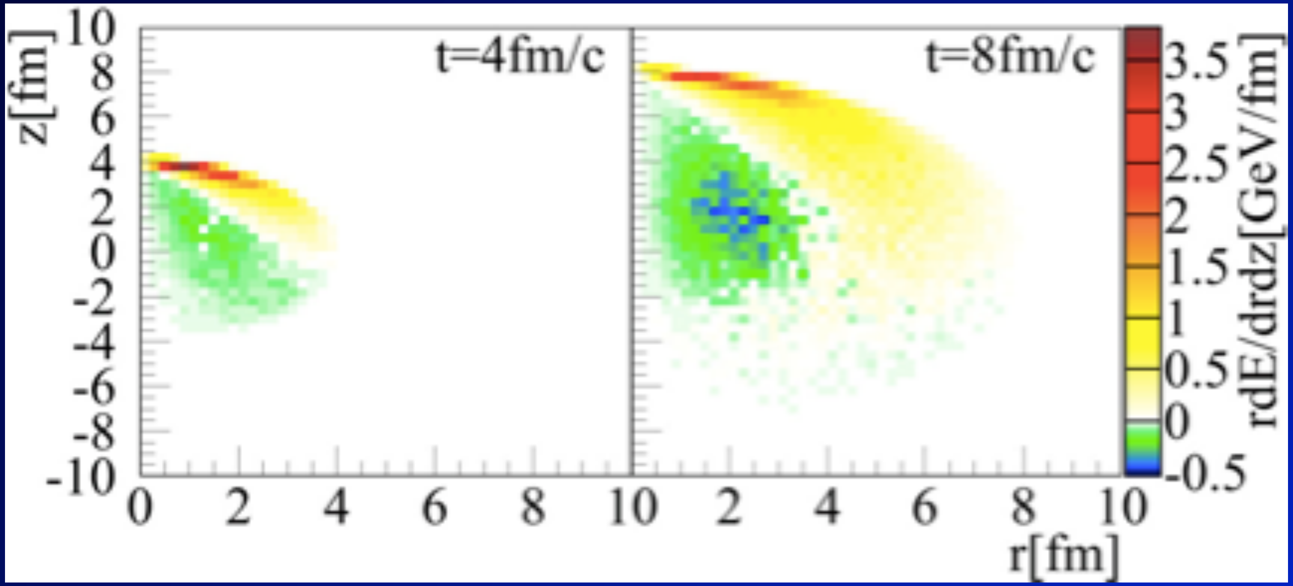
$$\frac{d\sigma}{dt} = |M_{12\to 34}|/16\pi^2 s^2$$

$$\mu_D^2 = (\frac{3}{2})4\pi\alpha_s T^2$$

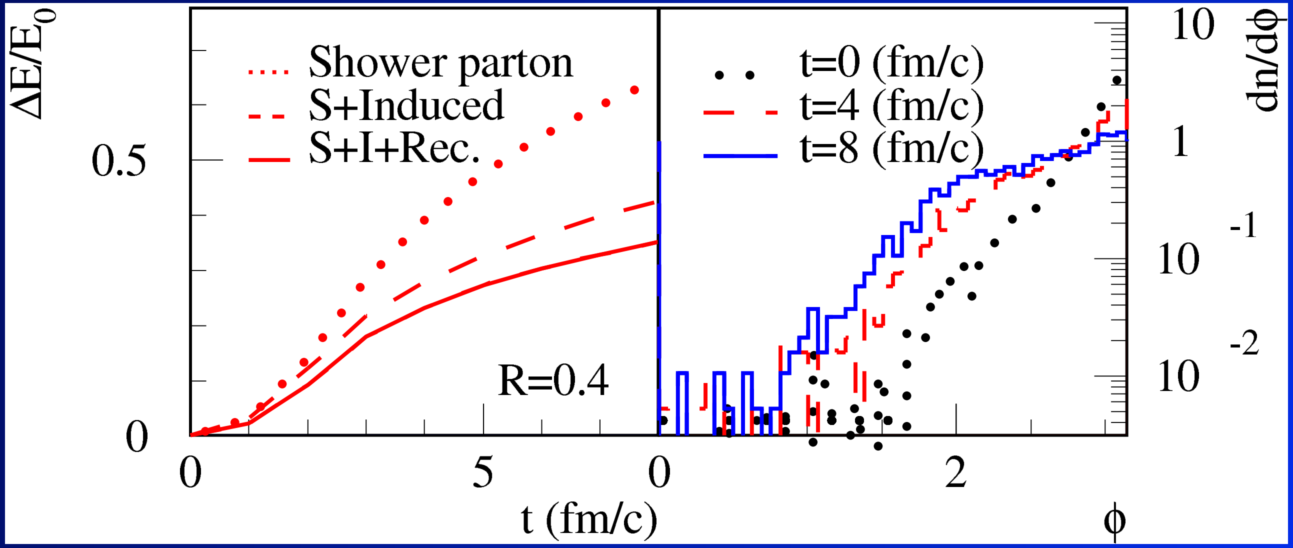
Induced radiation $$\frac{dN_g}{dz d^2k_\perp dt} = \frac{2\alpha_s N_c}{\pi k_\perp^4} P(z)(\hat{p}\cdot u)\hat{q}\sin^2(\frac{t - t_0}{2\tau_f})$$

Li, Liu, Ma, XNW and Zhu, PRL 106（2010）012301
XNW and Zhu, PRL 111 (2013) 062301

Jet-induced medium excitation

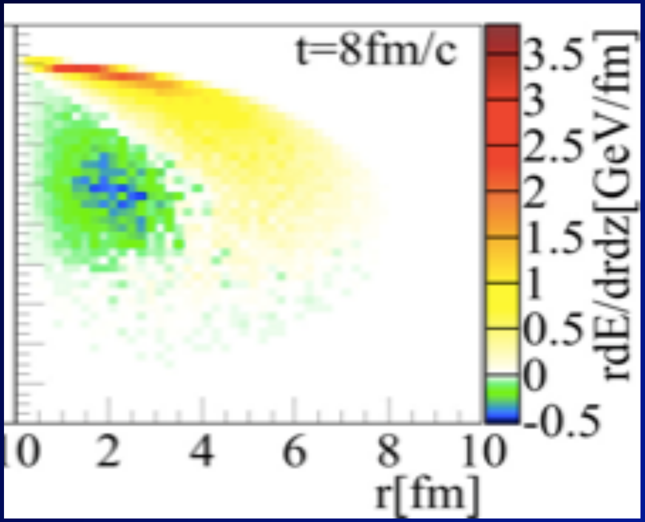


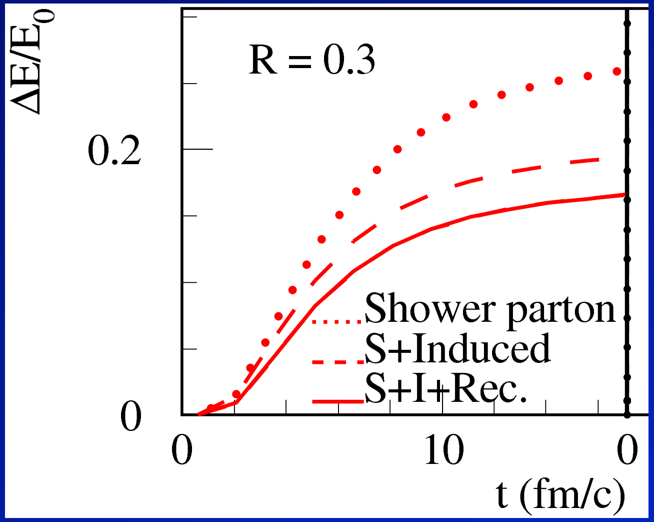
Jet propagation in a uniform medium

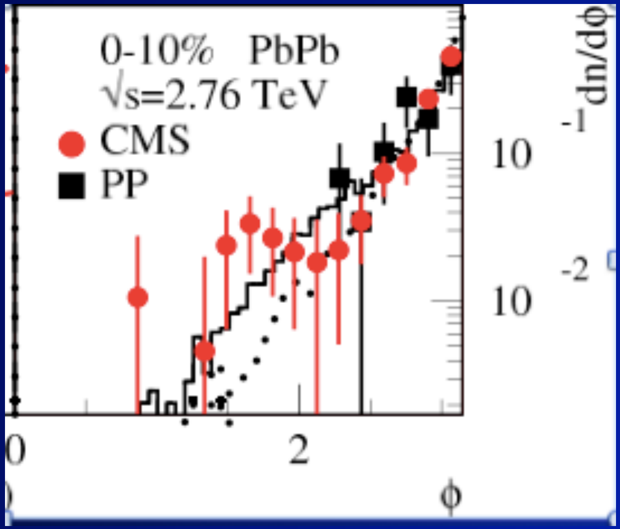


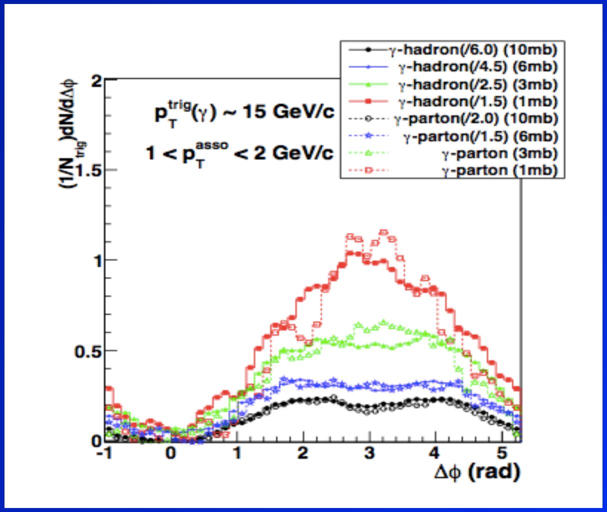
Effect of recoils and jet broadening

XNW and Zhu, PRL 111 (2014) 062301







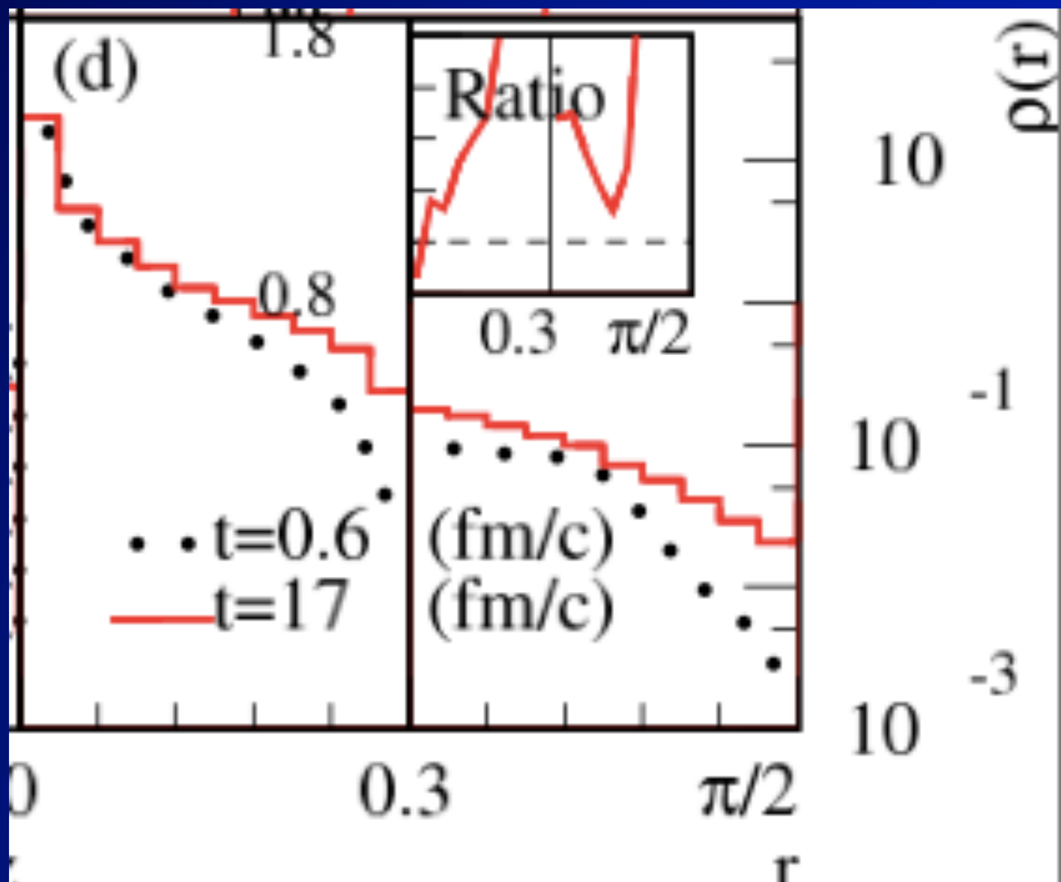


Talk by: Tan Luo (Wed.),

Li, Liu, Ma, XNW and Zhu (2010)
Ma and XNW (2011)

Broadening of jet transv. profile

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{\rm jet}}\sum_{\rm jets}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)},$$

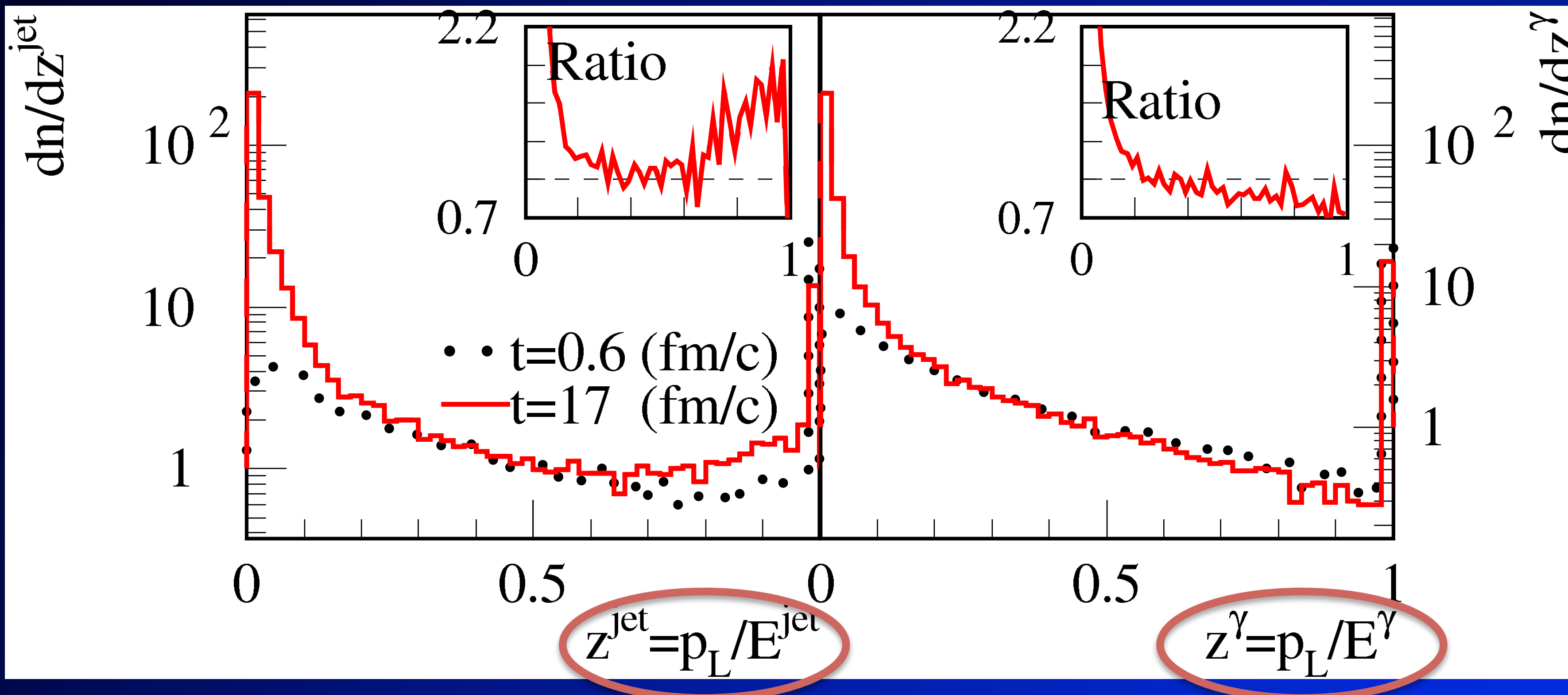


R=0.3

Medium mod. of frag function

Seen in CMS & ATLAS single jets

XNW and Zhu, PRL 111(2013)062301



XNW, Huang & Sarcevic (1996)

Energy of reconstructed jet dominated by leading particle
Suppression of fragmentation functions relative to initial energy

Factorization at twist-4

- Transverse momentum square weighted cross section

$$\frac{d\langle \ell_{hT}^2 \sigma\rangle}{dz_h} = \boxed{\sigma_0 \int_{z_h}^1 \frac{dz}{z} D_{q/h}(z,\mu^2) \int_{x_B}^1 \frac{dx}{x} T_F(x,0,0,\mu^2)\delta(1-\hat{x})\delta(1-\hat{z})}$$

$\longrightarrow$ T-4 LO

$$\boxed{\begin{aligned}&+\sigma_0 \frac{\alpha_s}{2\pi} \int_{z_h}^1 \frac{dz}{z} D_{q/h}(z,\mu^2) \int_{x_B}^1 \frac{dx}{x} \left\{ \ln\left(\frac{Q^2}{\mu^2}\right) \left[\left(\delta(1-\hat{x})P_{qq}(\hat{z}) + \delta(1-\hat{z})P_{qq}(\hat{x})\right) T_F(x,0,0,\mu^2) \right.\right. \\ &\left.\left. + \ \delta(1-\hat{z})P_{qg\to qg}(\hat{x}) \otimes T_F(x,x,x_B,\mu^2)\right] + \left(F^C(\hat{x},\hat{z}) + F^A(\hat{x},\hat{z})\right) \otimes T_F(x,x,x_B,\mu^2) \right\}\end{aligned}}$$

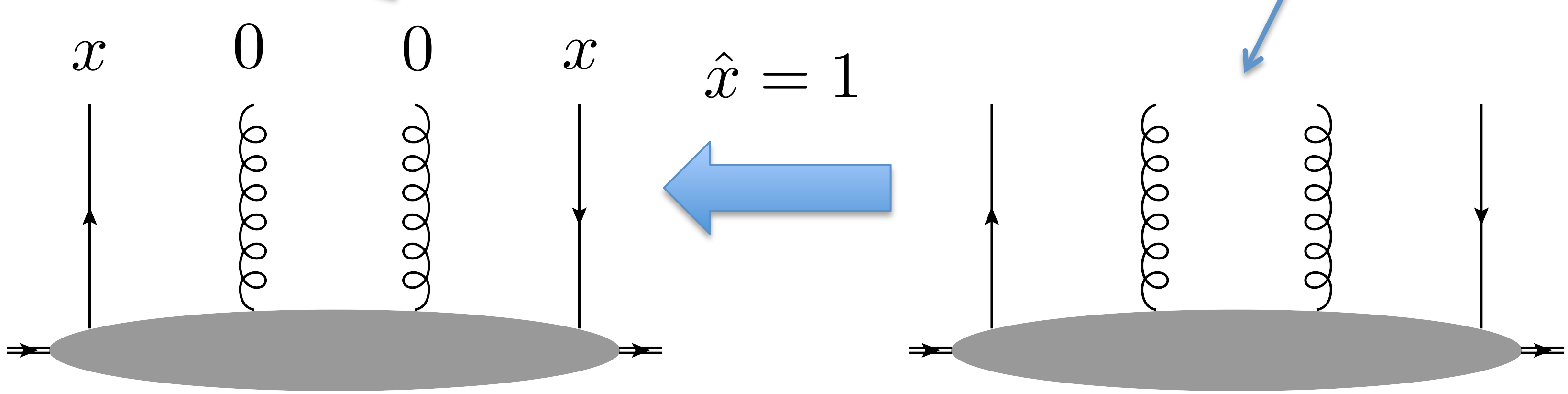
T-4 NLO

Finite contribution from asymmetric-cut diagrams

$$\begin{aligned}&F^A(\hat{x},\hat{z}) \otimes T_F(x,x,x_B,\mu^2) \\ &= -\frac{C_A}{2}\delta(1-\hat{z})\frac{1+\hat{x}}{(1-\hat{x})_+}\left[T^L(x,0,x_B-x,\mu^2) - T^R(x_B,0,x-x_B,\mu^2) - T^L(x,x_B-x,x_B-x,\mu^2) + T^R(x_B, \ldots\right. \\ &\quad - \delta(1-\hat{x})\frac{1+\hat{z}^2}{\hat{z}^2}(1+\hat{z})C_A\left[T^L(x,0,0,\mu^2) + T^R(x,0,0,\mu^2)\right] \\ &\quad - \left[C_F(1-\hat{z}) + \frac{C_A}{2}\hat{z}\right]\frac{1+\hat{x}\hat{z}^2}{\hat{z}^2}x\left[\left.\frac{dT^L(x,x_2,x_B-x,\mu^2)}{dx_2}\right|_{x_2=0} + \left.\frac{dT^R(x_B,x_2,x-x_B,\mu^2)}{dx_2}\right|_{x_2=x-x_B}\right]\end{aligned}$$

- Evolution equation for T4 - NEW

$$\mu^2 \frac{\partial}{\partial \mu^2} T_F(x_B, 0, 0, \mu^2) = \frac{\alpha_s}{2\pi} \int_{x_B}^{1} \frac{dx}{x} \left[P_{qq}(\hat{x}) T_F(x, 0, 0, \mu^2) + P_{qg\to qg}(\hat{x}) \otimes T_F(x, x, x_B, \mu^2) \right]$$



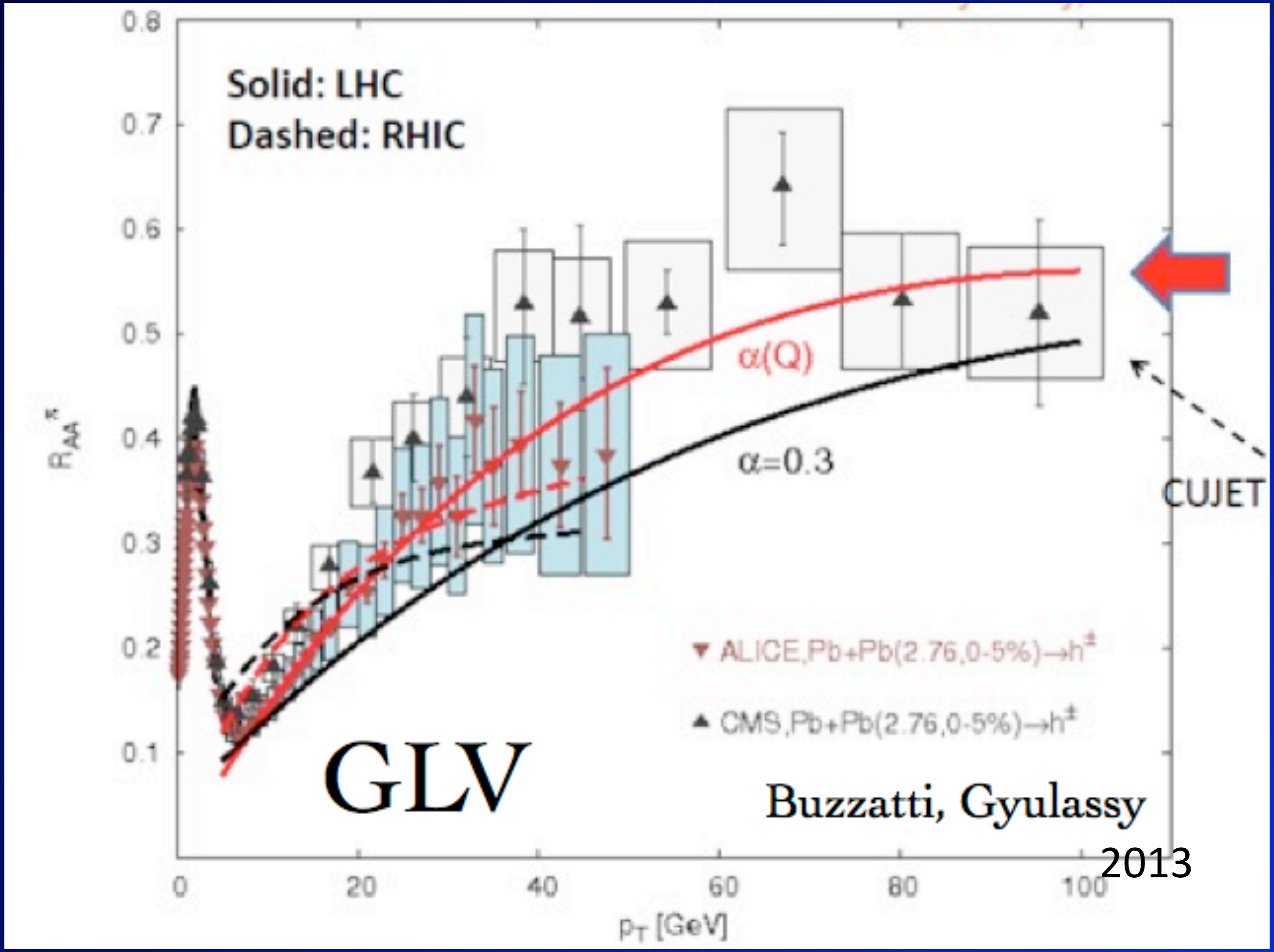
soft-soft

hard-hard & soft-hard & hard-soft

$$P_{qg\to qg}(\hat{x}) \otimes T_F(x, x, x_B)$$
$$= C_A \left[\frac{2}{(1-\hat{x})_+} T(x_B, x - x_B, x) - \frac{1}{2} \frac{1+\hat{x}}{(1-\hat{x})_+} \left(T(x, 0, x_B - x) + T(x_B, x - x_B, x - x_B) \right) \right]$$

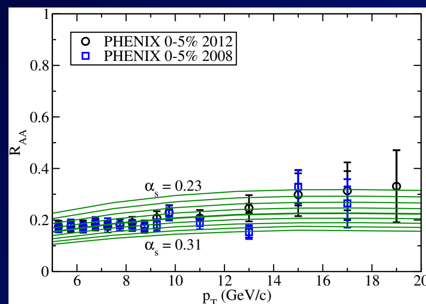
When $\hat{x} \longrightarrow 1$, there is no phase space for the gluon radiation from the initial gluon.

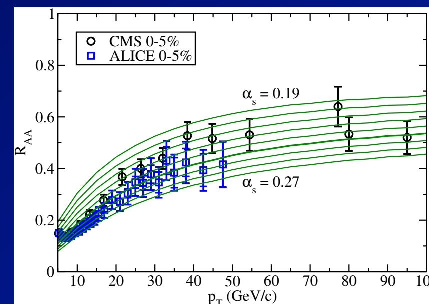
Running coupling in jet quenching

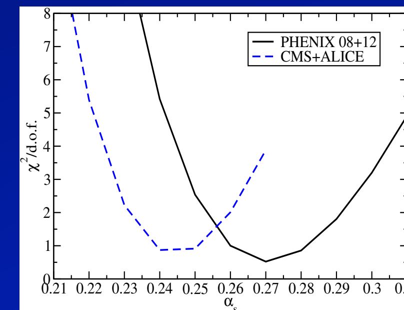


Jet quenching phenomenology

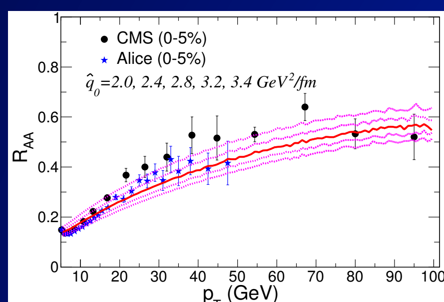
McGill-AMY

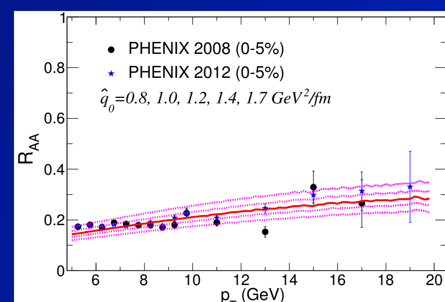


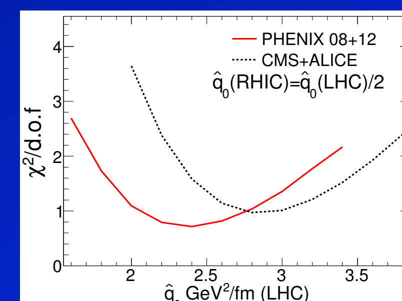




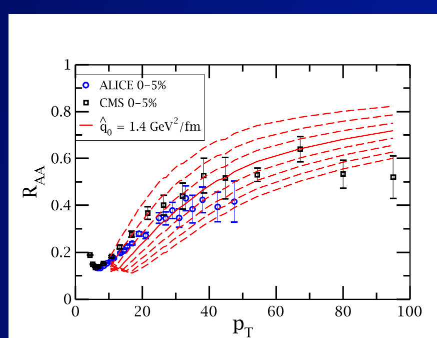
HT-BW

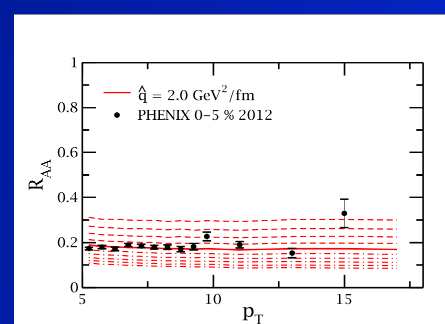


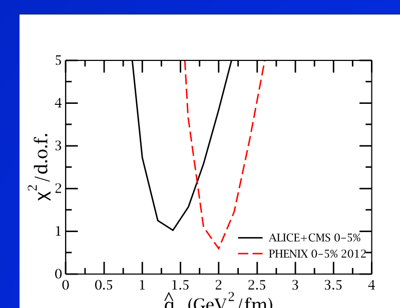




HT-M

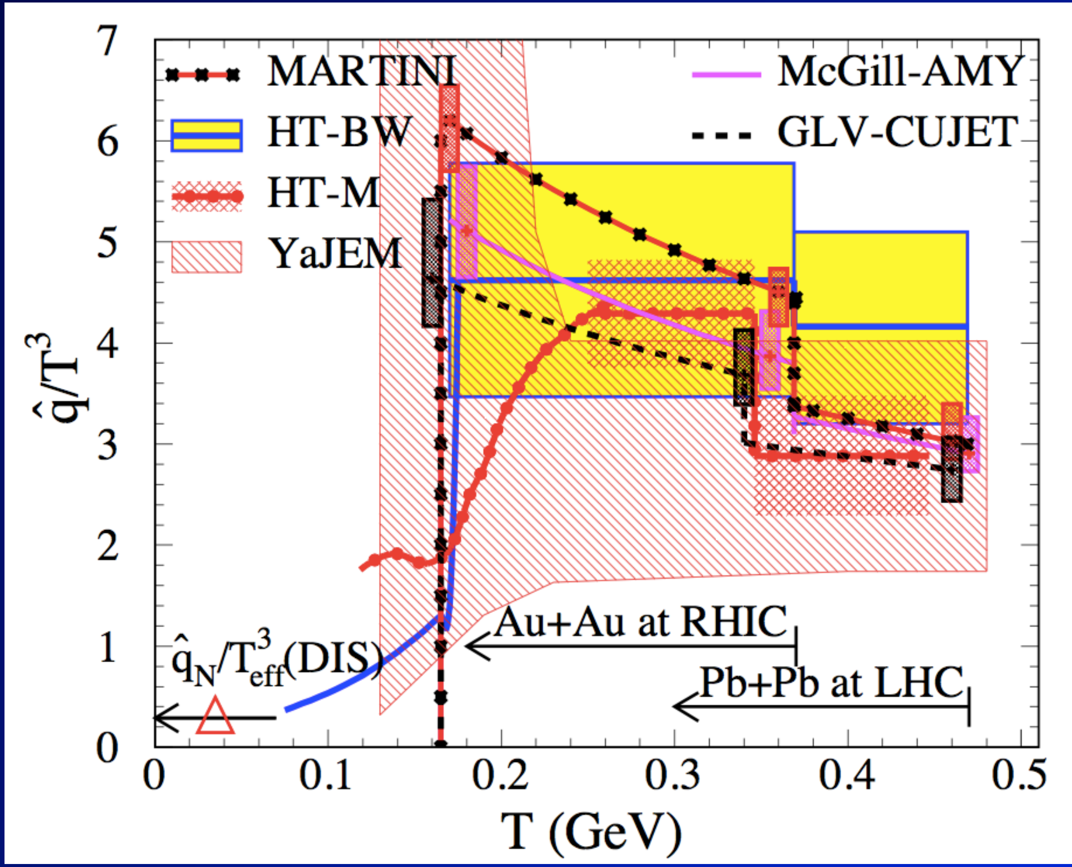






Jet transport coefficient

JET Collaboration: **arXiv:1312.5003**



Jet quenching phenomenology

McGill-AMY

HT-BW

HT-M