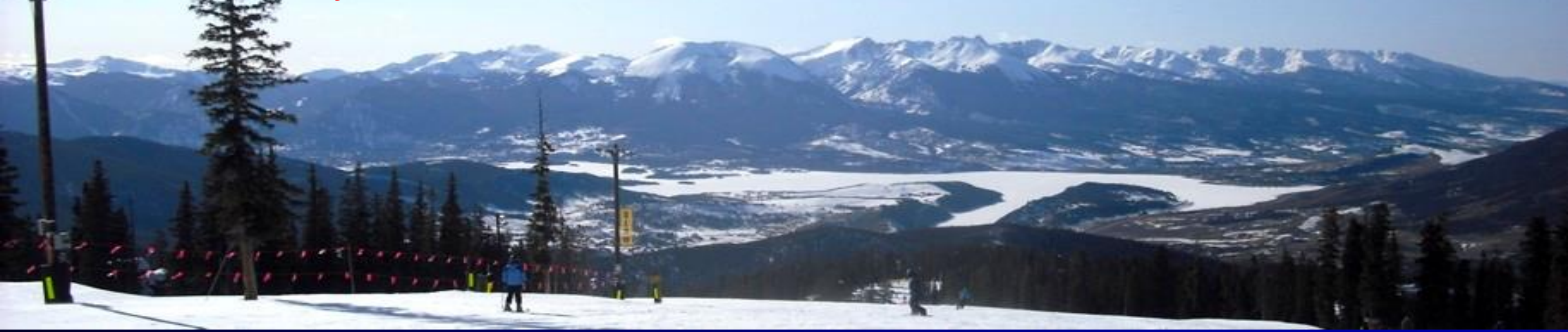
31st Winter Workshop on Nuclear Dynamics
Keystone Resort, Colorado, Jan. 25-31 2015



Jet transport parameters from jet quenching at RHIC and LHC

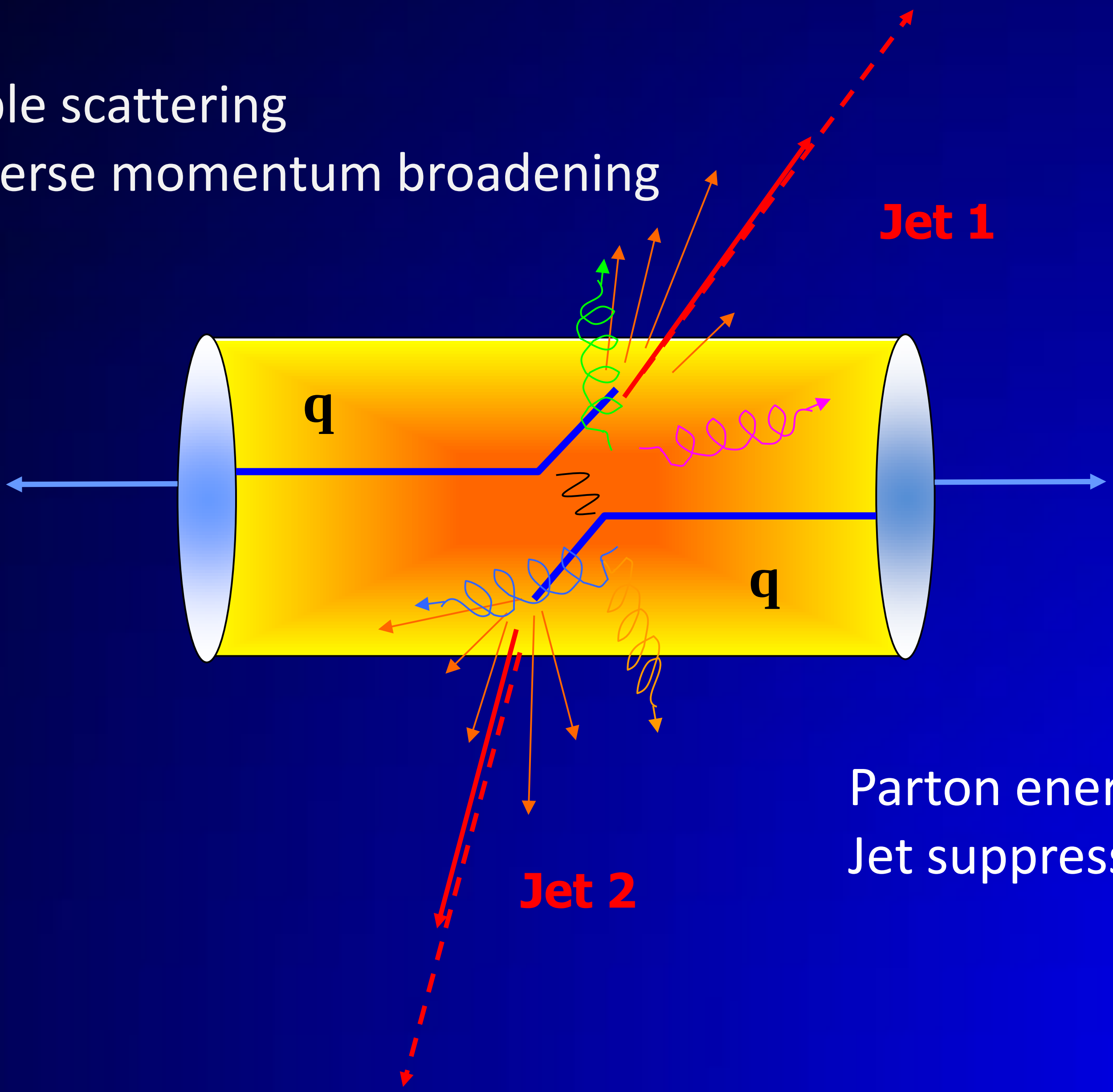
Xin-Nian Wang
Central China Normal University / Lawrence Berkeley National Lab

JET Collaboration

BERKELEY LAB

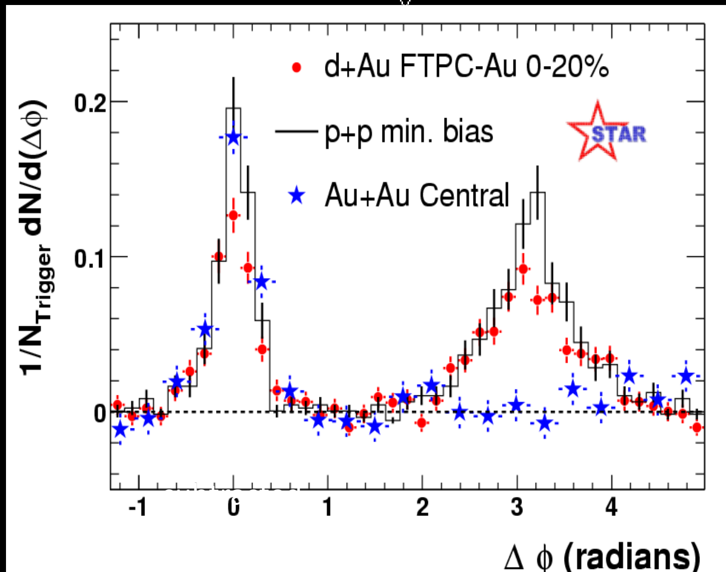
Jets in heavy-ion collisions

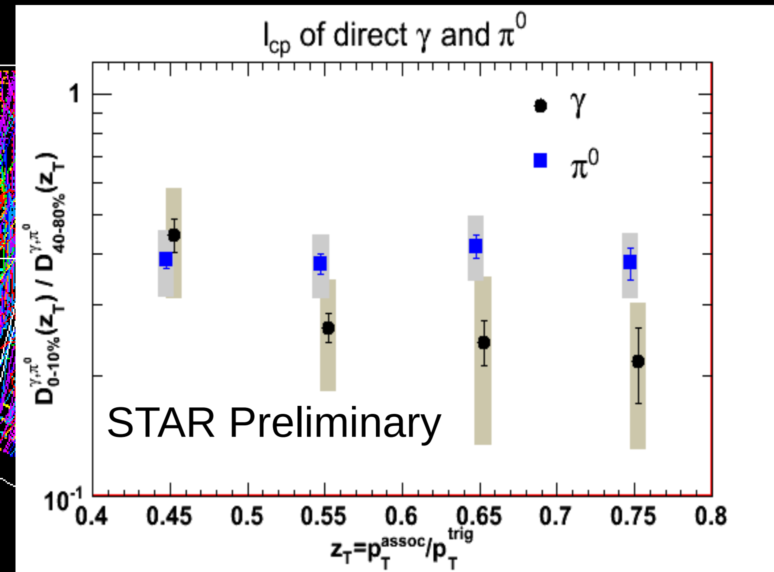
Multiple scattering
Transverse momentum broadening

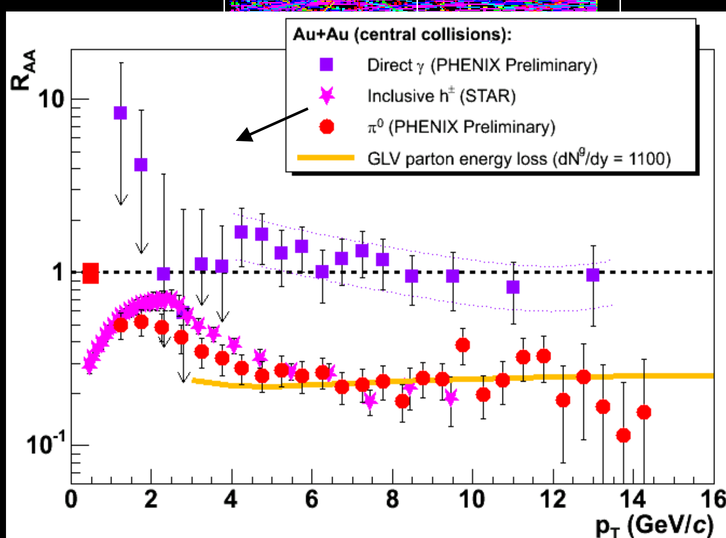


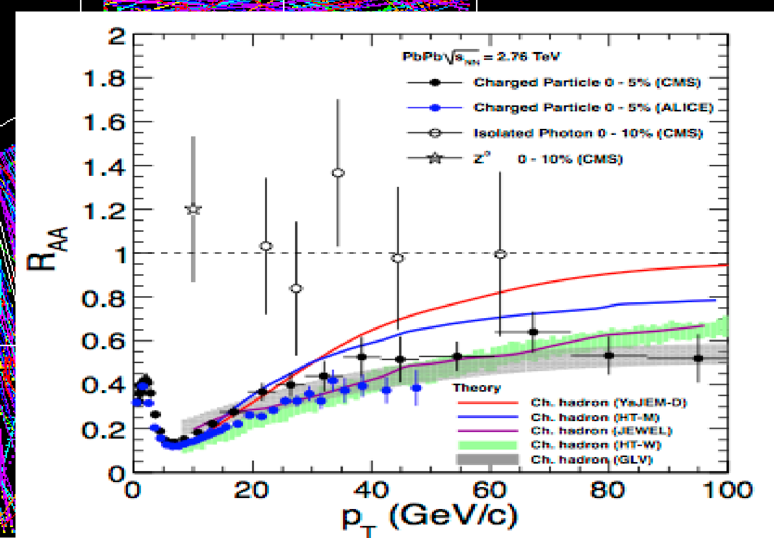
Parton energy loss
Jet suppression

Jet Quenching at RHIC & LHC

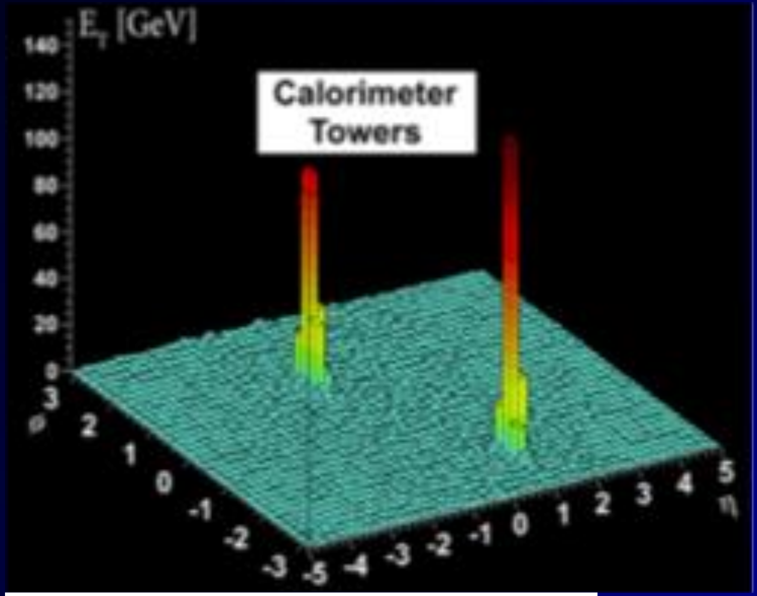


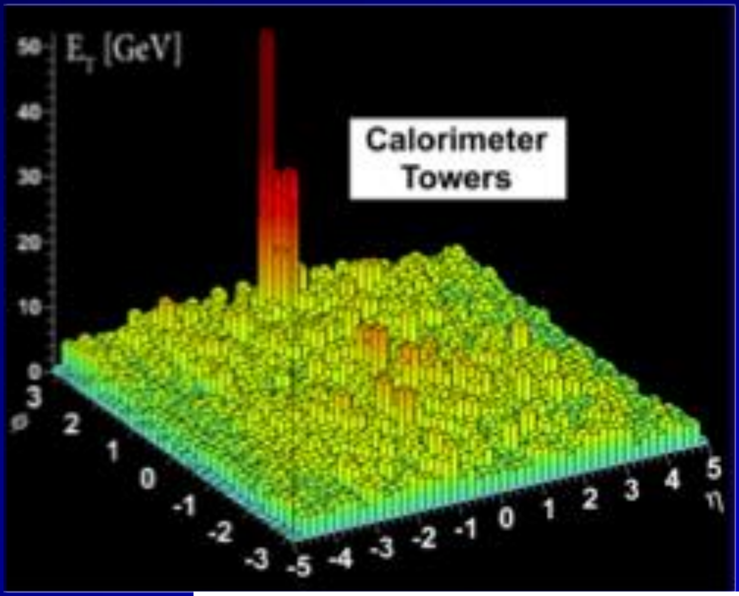


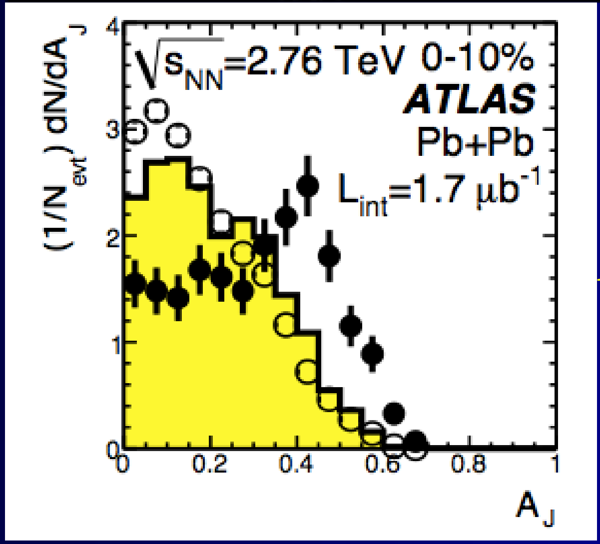




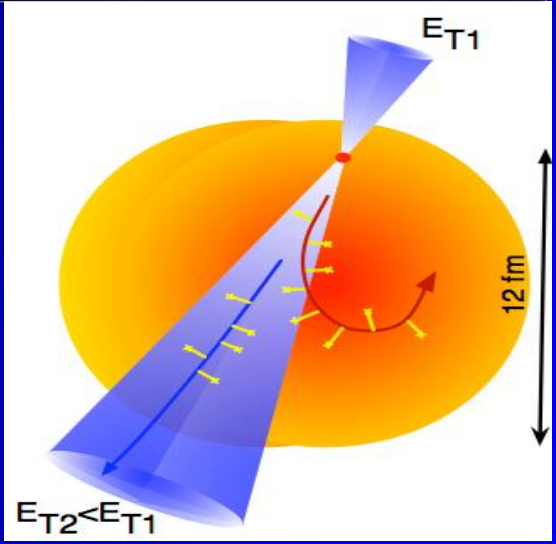
Jet Quenching at RHIC & LHC







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



Properties of QGP

- 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:

$$\eta = \lim_{\omega\to 0}\frac{1}{2\omega}\int dtdx e^{i\omega t}\langle[T_{xy}(0), T_{xy}(x)]\rangle$$

- 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:

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

- …

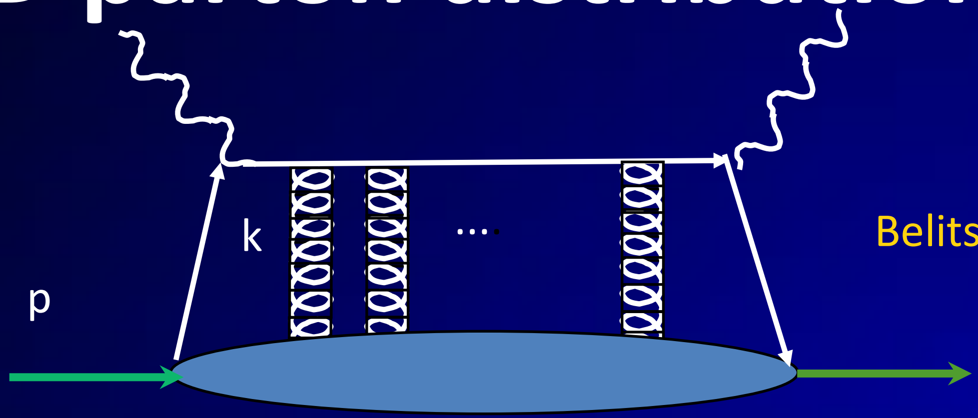
Deeply Inelastic Scattering

Quark distribution in collinear factorized pQCD parton model:

$$f_A^q(x) = \int \frac{dy^-}{4\pi} e^{ixp^+y^-} \langle A|\bar{\psi}(0)\gamma^+\psi(y^-)|A\rangle$$

quarks carrying momentum fraction x of the nucleon (nucleus)

TMD parton distribution in DIS



Belitsky, Ji and Yuan (2002)

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

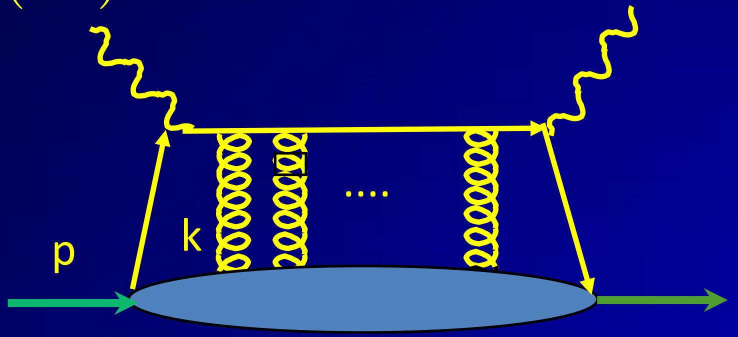
$$\mathcal{L}(0,y) = \mathcal{L}_\parallel^\dagger(\infty,0;\vec{0}_\perp)\mathcal{L}_\perp^\dagger(\infty;\vec{y}_\perp,\vec{0}_\perp)\mathcal{L}_\parallel(\infty,y^-;\vec{y}_\perp)$$

$$\mathcal{L}_\parallel(-\infty,y^-,\vec{y}_\perp) = \mathcal{P}\exp\left[-ig\int_{y^-}^{-\infty} d\xi^- A_+(\xi^-,\vec{y}_\perp)\right]$$

$$\mathcal{L}_\perp(-\infty;\vec{y}_\perp,\vec{0}) = \mathcal{P}\exp\left[-ig\int_{\vec{0}_\perp}^{\vec{y}_\perp} d\vec{\xi}_\perp\cdot\vec{A}_\perp(-\infty,\vec{\xi}_\perp)\right]$$

Parton scattering in medium

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



$$\vec{W}_\perp(y^-,\vec{y}_\perp) \equiv i\vec{D}_\perp(y) + g\int_{-\infty}^{y^-} d\xi^- \vec{F}_{+\perp}(\xi^-,y_\perp)$$

Jet transport operator
due to color Lorentz force

Liang, XNW & Zhou（2008）

$$f_A^q(x,\vec{k}_\perp) = \int \frac{dy^-}{4\pi} e^{ixp^+y^-}\langle A|\bar{\psi}(0)\gamma^+ \exp[\vec{W}_\perp(y^-)\cdot\nabla_{k_\perp}]\psi(y^-)|A\rangle\delta^{(2)}(\vec{k}_\perp)$$

p_T broadening and jet transport

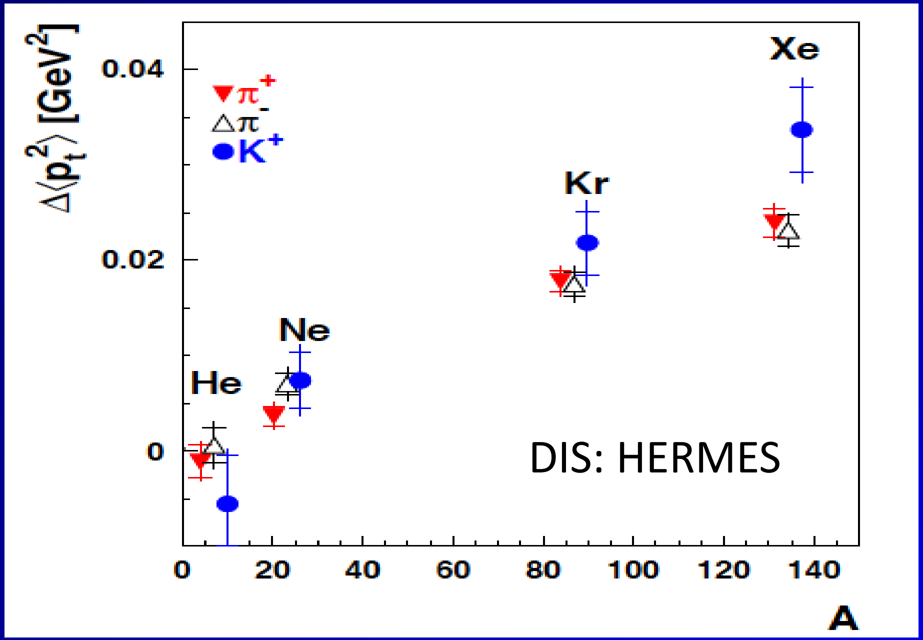
$$f_A^q(x,\vec{k}_\perp) \approx \frac{A}{\pi\Delta}\int d^2q_\perp \exp\left[-\frac{(\vec{k}_\perp-\vec{q}_\perp)^2}{L\hat{q}}\right] f_N^q(x,\vec{q}_\perp)$$

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

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

Cold nuclear matter:

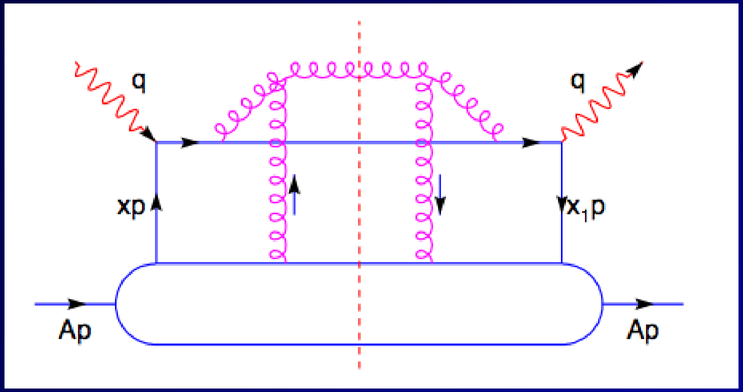
$$\hat{q}_N \approx 0.02\ \ \mathrm{GeV}^2/fm$$



Consistent with value from jet quenching in DIS:
Deng & XNW, PRC83(2010)024902;
Chang, Deng & XNW, PRC89(2014) 034911

See talk by H. Xing

Radiative energy loss and modified FF



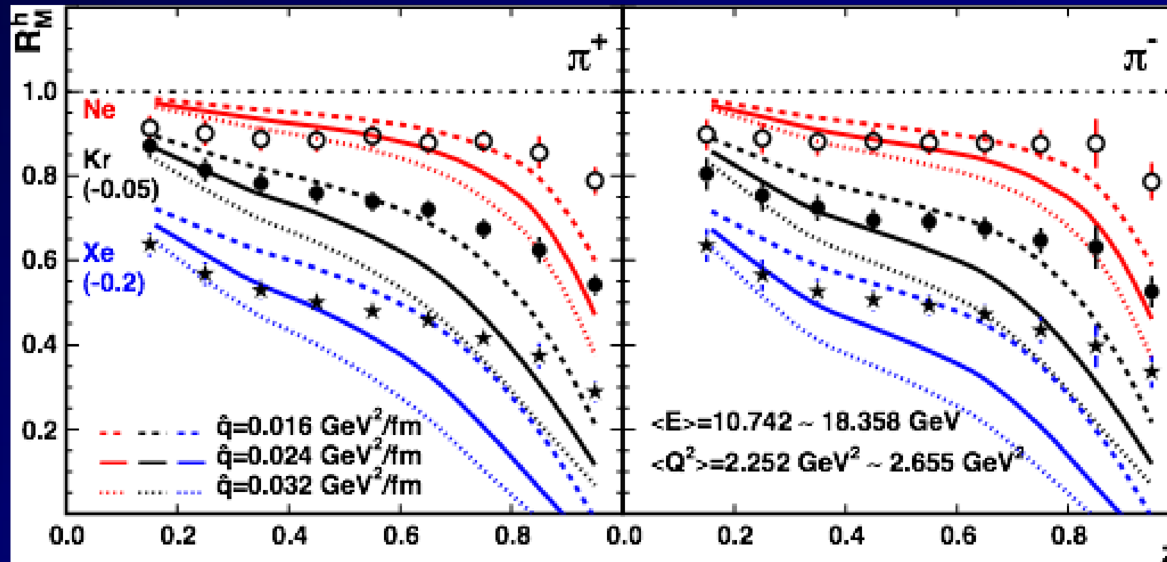
$$\Delta\gamma(z,\ell_\perp^2) = C_A \frac{1+z^2}{(1-z)_+}\frac{2}{\ell_\perp^4}\int d\xi^- \hat{q}(\xi)[1-\cos(x_L p^+ \xi^-)]$$

$$\frac{\Delta E}{E} = C_A \frac{\alpha_s}{2\pi}\int \frac{d\ell_\perp^2}{\ell_\perp^4}\int dz\,\left[1+(1-z)^2\right]\int d\xi^- \hat{q}(\xi) 2[1-\cos(x_L p^+ \xi^-)]$$

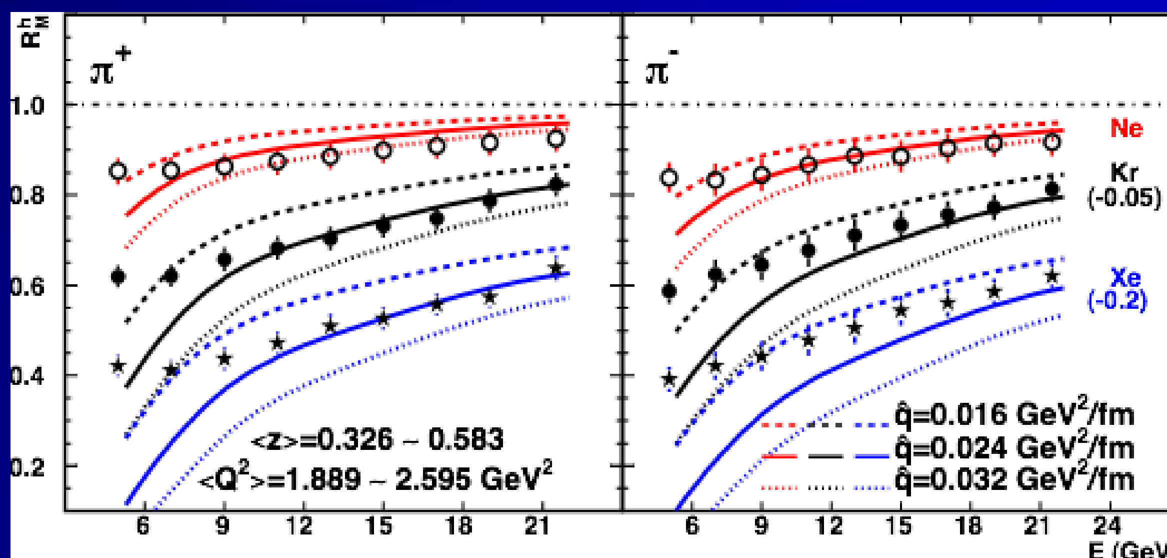
$$\Delta D_{q\to h}(z_h,Q^2) = \frac{\alpha_s}{2\pi}\int_0^{Q^2}\frac{d\ell_\perp^2}{\ell_\perp^2}\int_{z_h}^1 \frac{dz}{z}\left[\Delta\gamma(z,\ell_\perp^2) D_{q\to h}(\frac{z_h}{z}) + \cdots\right]$$

Jet quenching in DIS of large nuclei

$$R = \frac{N_h^{eA}}{N_h^{eD}}$$

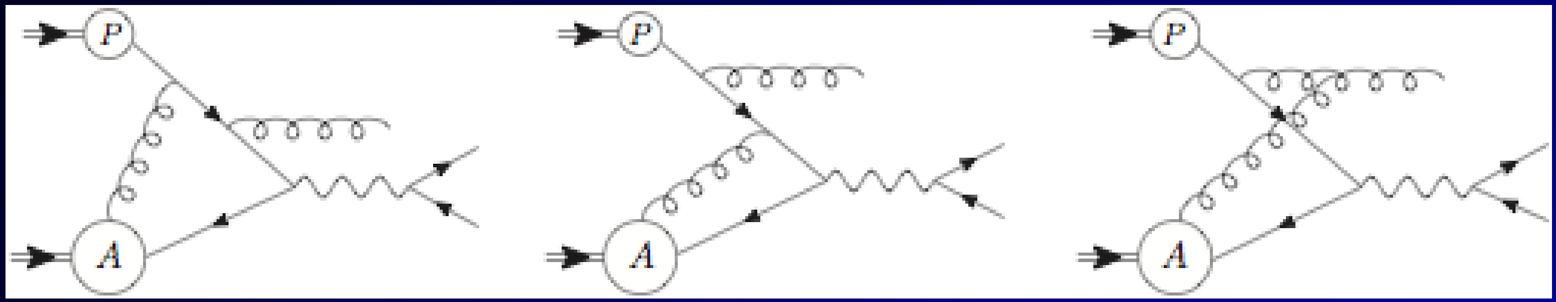


$$\hat{q}_N \approx 0.02 \;\; \mathrm{GeV}^2/fm$$

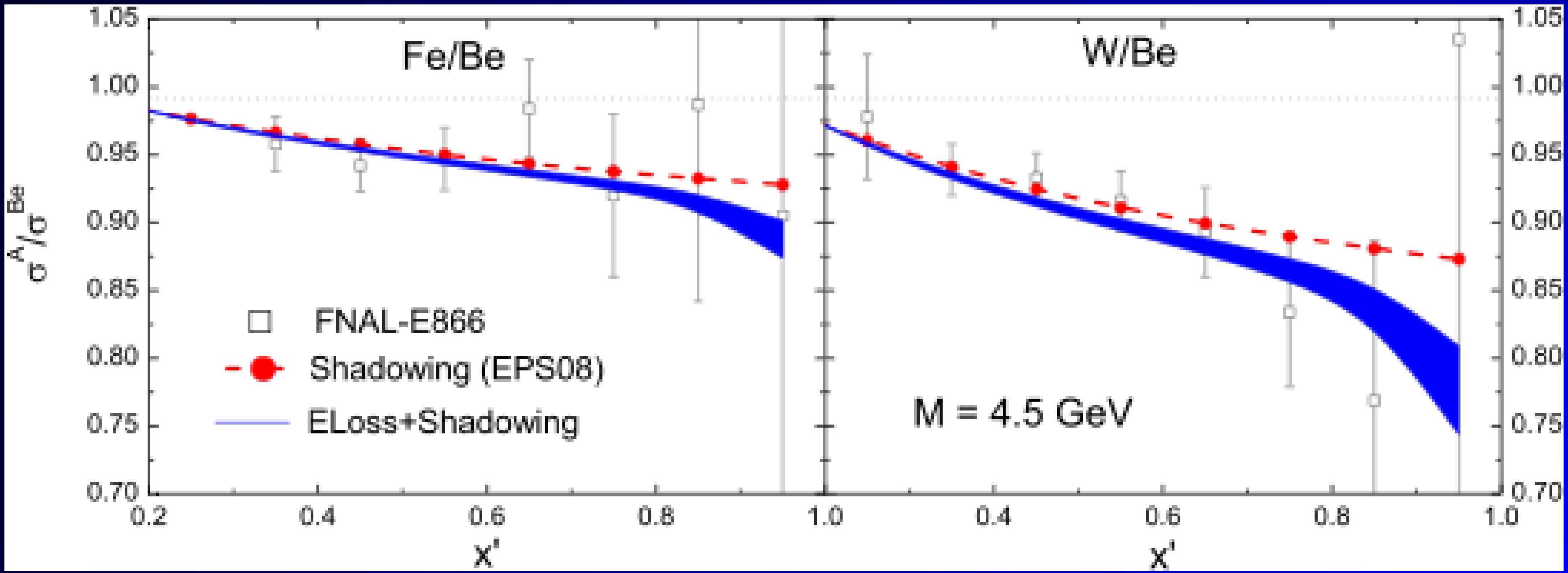


Deng & XNW (2010)

Parton E-loss in Drell-Yan in pA Collisions



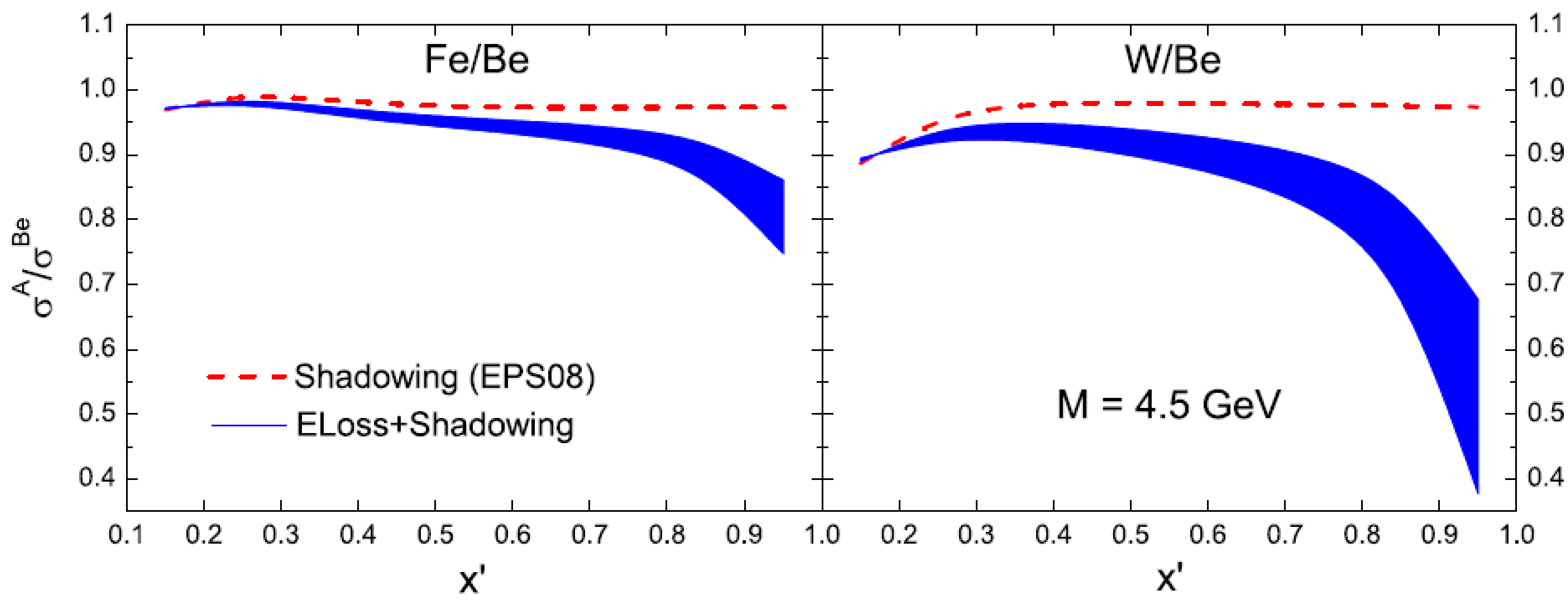
Modified initial beam parton distribution functions



Xing, Guo, E. Wang & XNW (2012) $\hat{q}_N \approx 0.02\ \ \mathrm{GeV}^2/fm$

Parton E-loss in Drell-Yan in pA Collisions

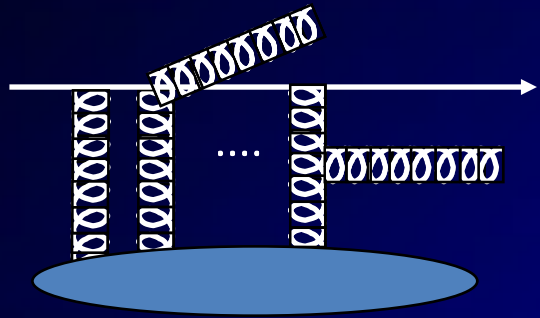
Energy loss vs Shadowing (FNAL-E906 ELab = 120 GeV)

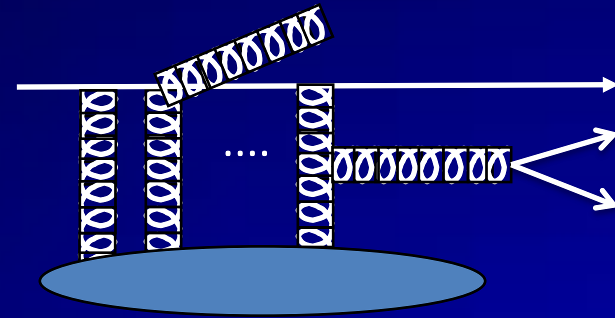


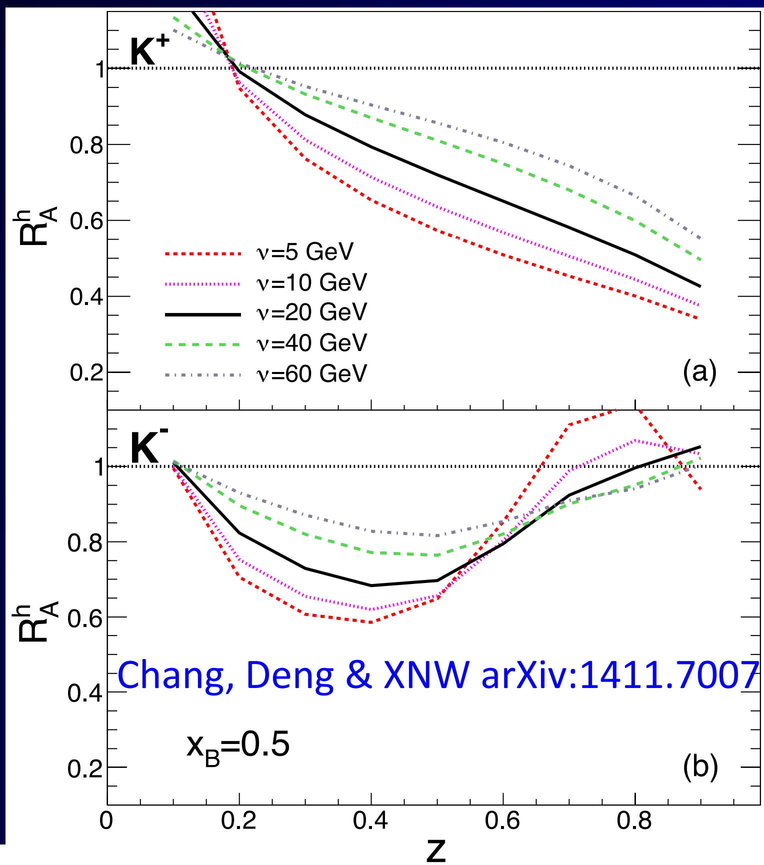
Xing, Guo, E. Wang & XNW (2012)

FNAL-E906 will provide unambiguous measurement of initial state energy loss

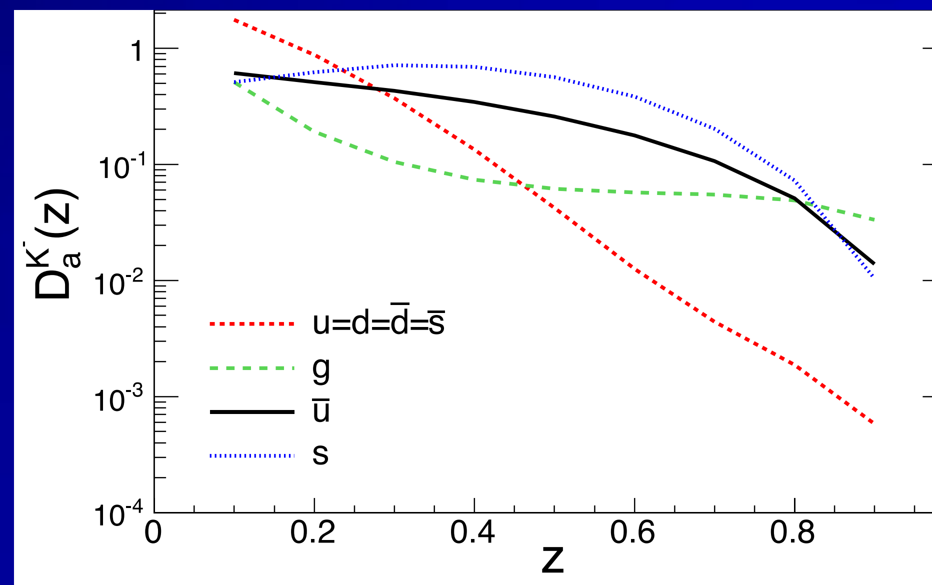
Medium-induced flavor conversion





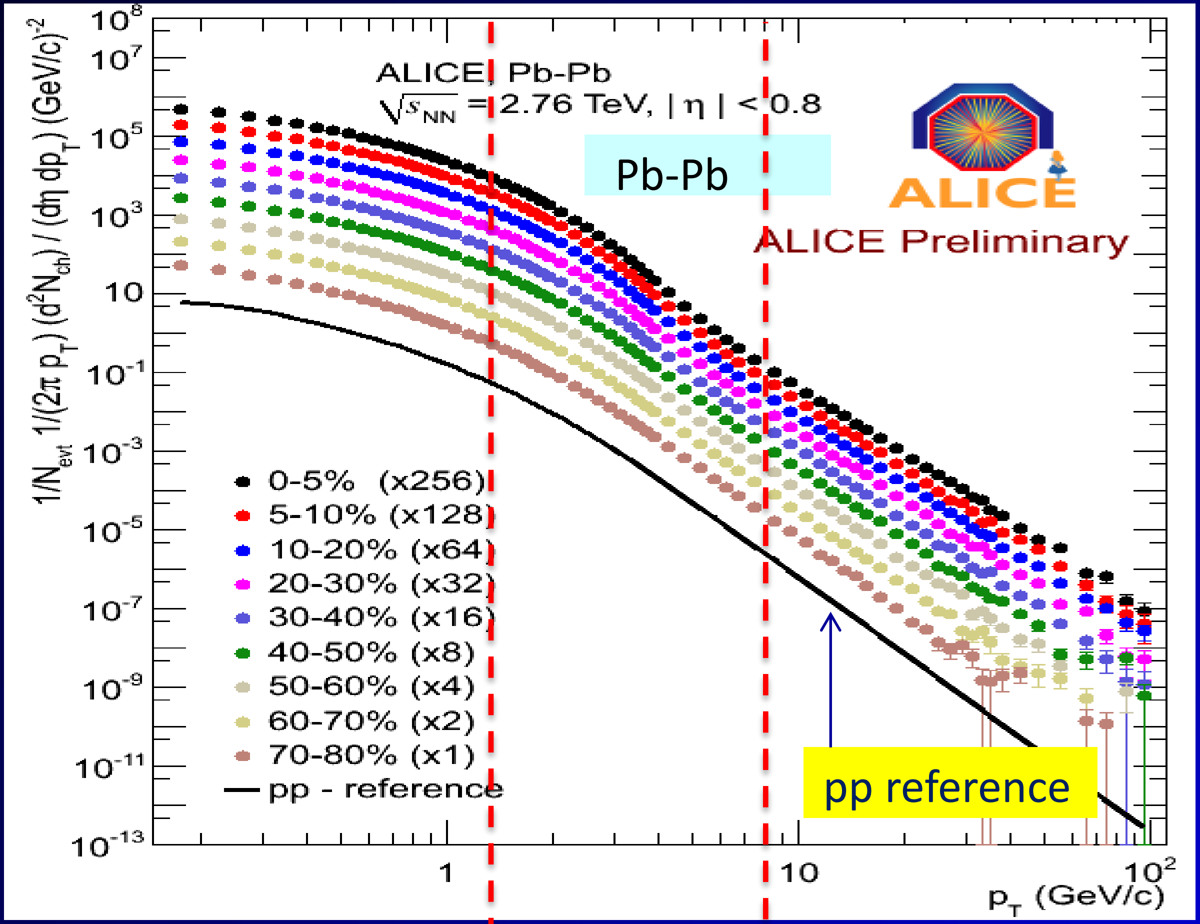


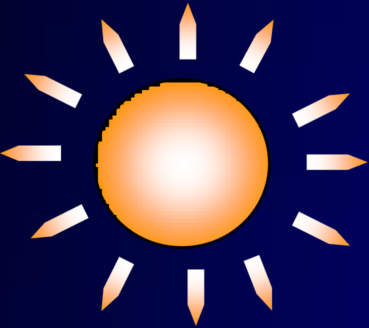
At large x_B, struck quarks are u and d

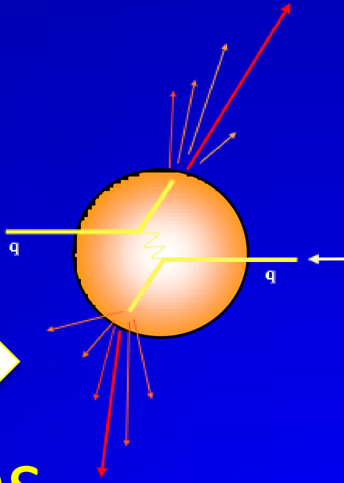


$$a \to K^{-}(s\bar{u})$$

Hard and soft probes







soft probes

hard probes

JET Collaboration

http://jet.lbl.gov

- M. Gyulassy (Columbia Univ)
- P. Romatschke (Univ of Colorado)
- S. Bass, B. Mueller (Duke Univ)
- M. Strickland (Kent State Univ)
- X.-N. Wang (LBNL)
- R. Vogt (LLNL)
- I. Vitev (LANL)
- C. Gale, S. Jeon (McGill Univ)
- U. Heinz (Ohio State Univ)
- D. Molnar (Purdue Univ)
- R. Fries, C. Ko (Texas A & M Univ)
- A. Majumder (Wayne State Univ)

Jet quenching phenomenology

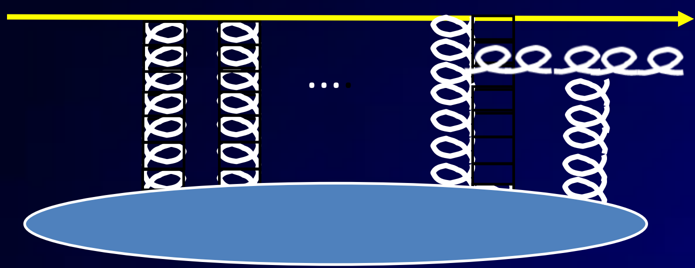
3+1D hydro + Jet transport + Hadronization

http://jet.lbl.gov

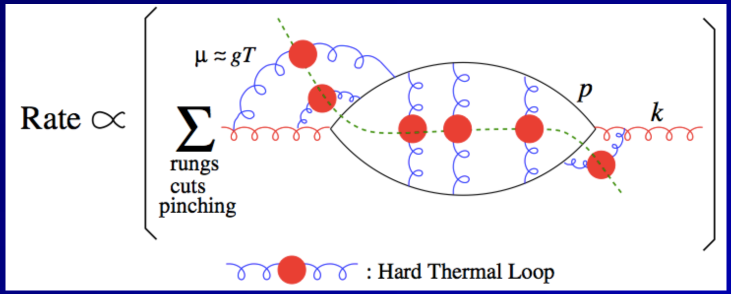
- A general framework for numerical implementation of different approaches & improvement of jet transport
- Hadronization: fragmentation & recombination
- Realistic bulk evolutions: e-by-e 3(2)+1 hydro : constrained by bulk hadron spectra, $v_{n,}$

- iEBE: E-by-E viscous hydro- generating bulk medium on-demand
- First JET package: viscous hydro+ semi-analytic jet quenching: CUJET, McGill-AMY, MARTINI-AMY, HT-BW, HT-M (will expand to other models)

Parton energy loss in Medium



(BDMPS'96) $\Delta E \approx \frac{\alpha_s N_c}{4}\hat{q}L^2$



Arnold, Moor, Yaffe (AMY'01): DS eqs.

McGill-AMY: coupled rate equations

Gyulassy-Levai-Vitev (GLV'00): Opacity expansion

$$\hat{q} = \int d^2 q_\perp \langle \rho \frac{d\sigma}{d^2 q_\perp} \rangle q_\perp^2 \qquad \frac{dN_g}{dx d^2 k_\perp}(T, \mu_D^2, L)$$

High-twist approach: Modified frag. Func. Guo & XNW'00, Zhang,Wang, XNW'03

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

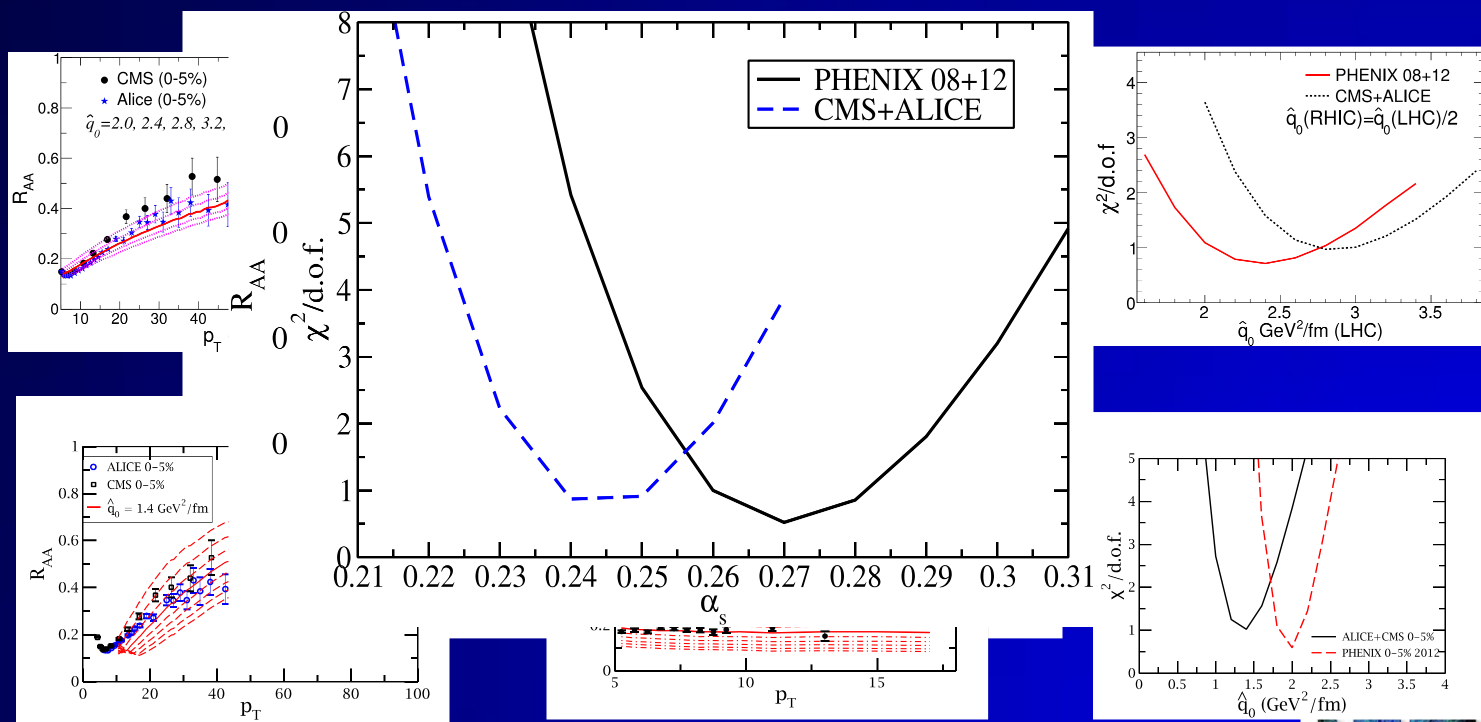
McGill-AMY, MARTINI-AMY, CUJET, HT-BW, HT-M, JEWEL, JaYEM, PCM, BAMPS ....

Jet quenching phenomenology

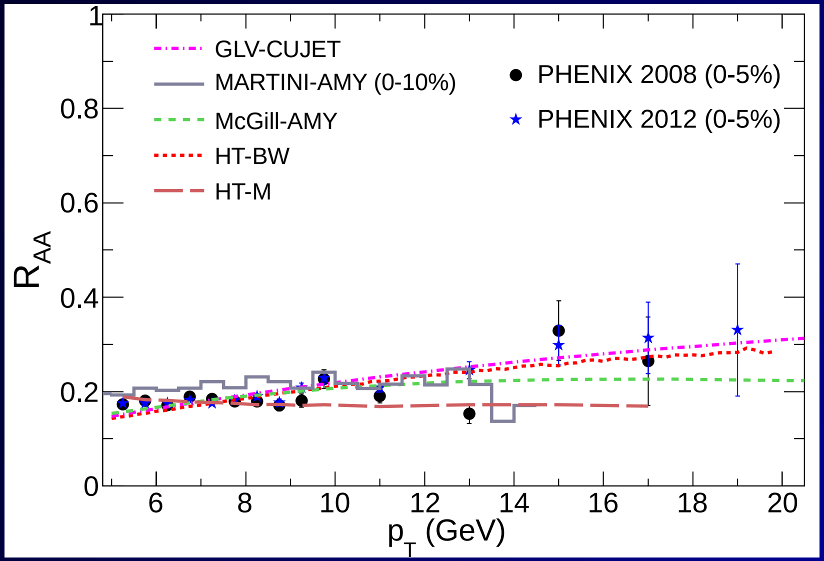
McGill-AMY

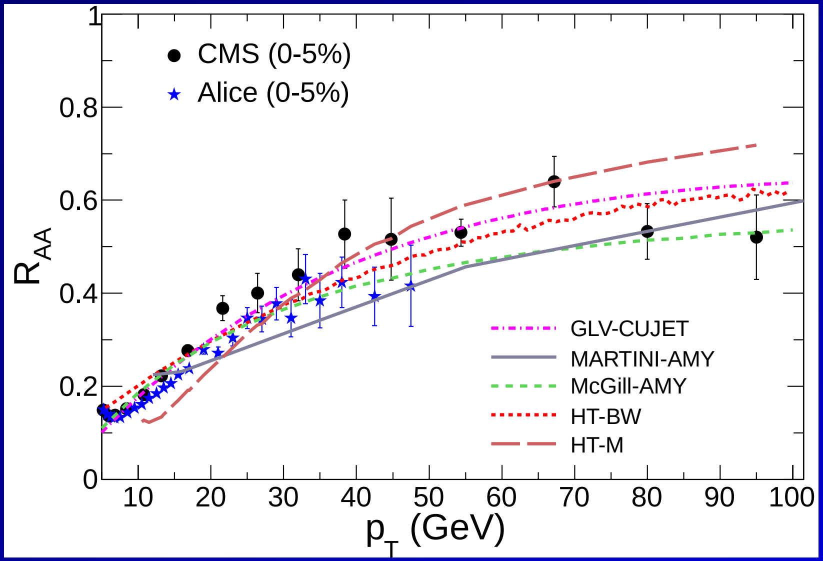
HT-BW

HT-M



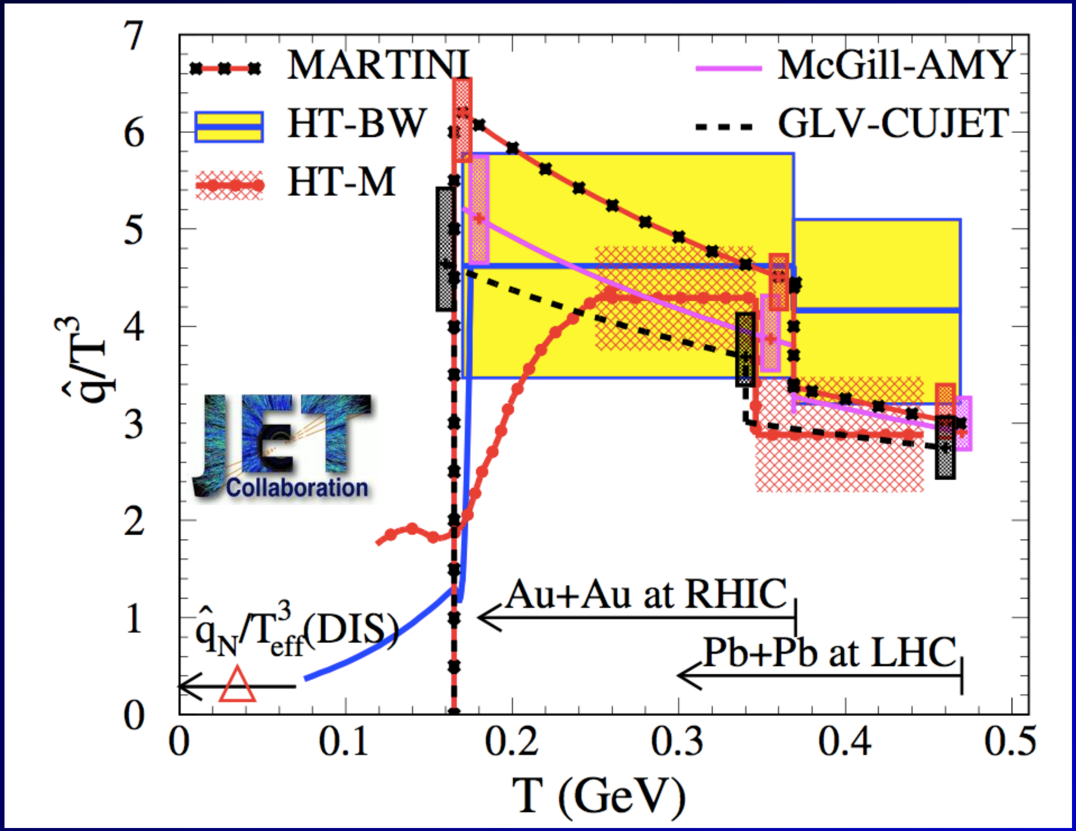
Jet quenching phenomenology





Jet transport coefficient

JET Collaboration: PRC 90 (2014) 014909 arXiv:1312.5003

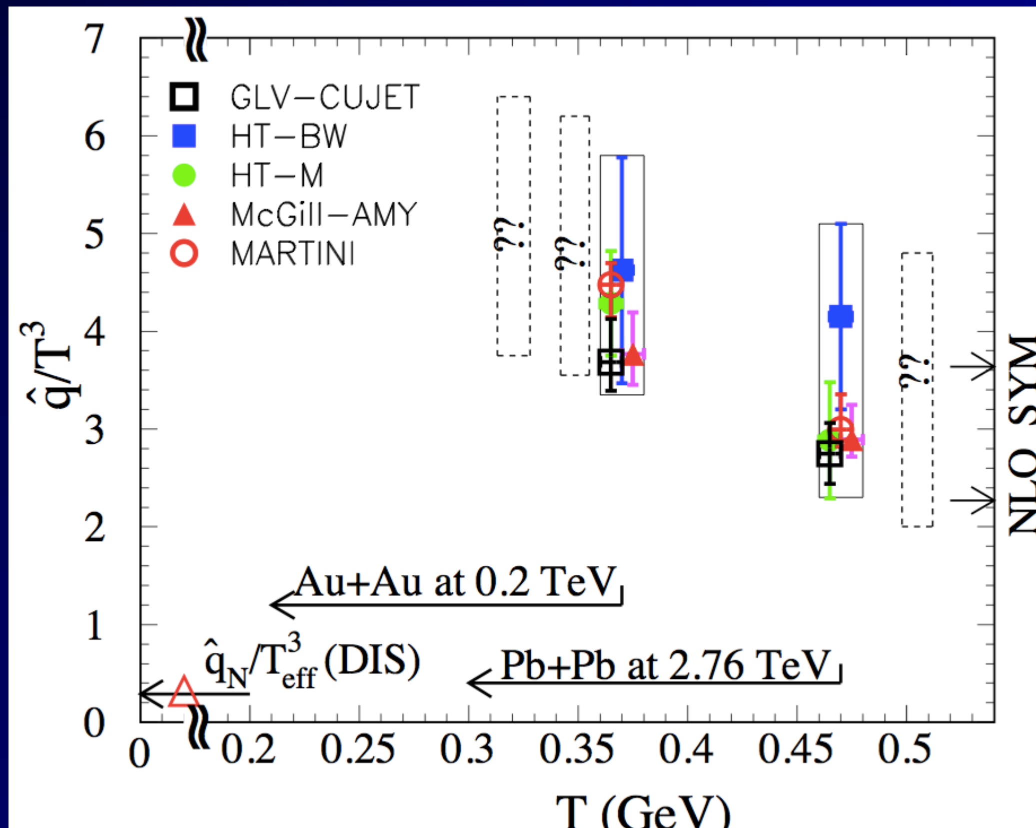


$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \ \mathrm{at} \quad \begin{matrix} \mathrm{T=370\ MeV,} \\ \mathrm{T=470\ MeV,} \end{matrix}$$

RHIC
LHC

Jet transport coefficient

JET Collaboration: PRC 90 (2014) 014909 **arXiv:1312.5003**



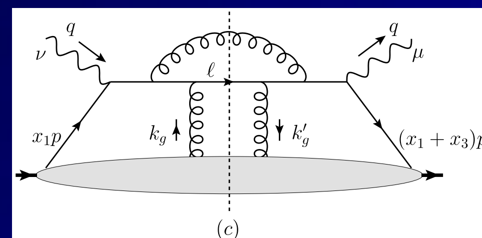
$$\hat{q}^{\rm LO}_{\rm SYM} = \frac{\pi^{3/2}\Gamma(3/4)}{\Gamma(5/4)}\sqrt{\lambda}T^3_{\rm SYM} \qquad \hat{q}^{\rm NLO}_{\rm SYM} = \hat{q}^{\rm LO}_{\rm SYM}\left(1 - \frac{1.97}{\sqrt{\lambda}}\right)$$

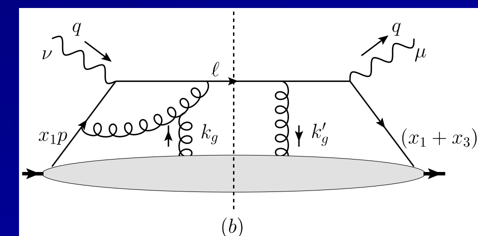
Future: dihadron, gamma-hadron, flavor dependence, jet observables
RHIC BES and LHC higher energy

NLO and factorization

arXiv:1106.1106

- Uncertainty in scale dependence of collinear LO results
- Medium properties & hard scattering factorizable?





- Complete cancellation of soft-collinear divergence
- Complete factorization of the collinear divergence

Talk by H. Xing

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

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

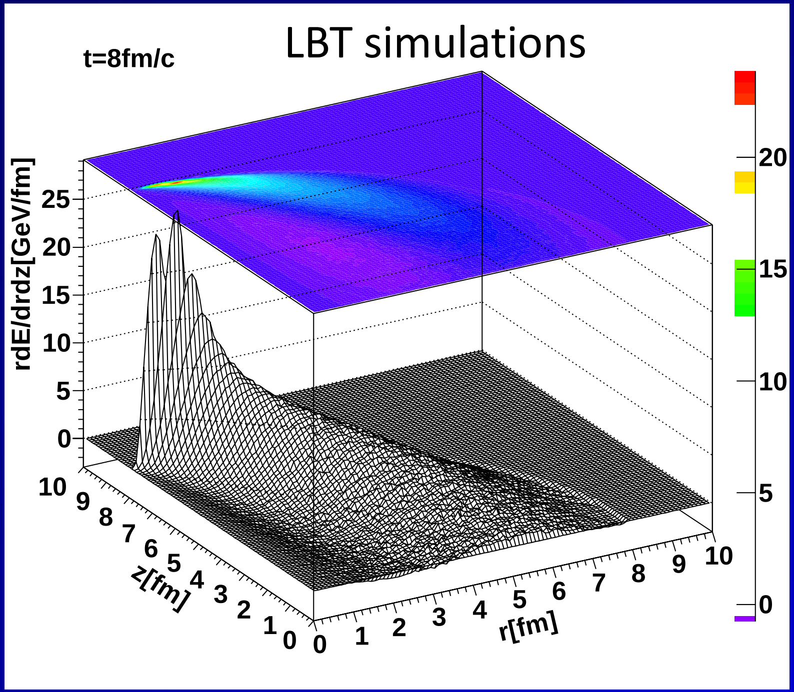
$$\hat{q} \Longrightarrow \hat{q}(E,Q^2)$$

Casalderrey-Solana & XNW (2007)

Blaizot and Mehta-Tani

Jet-induced shock waves

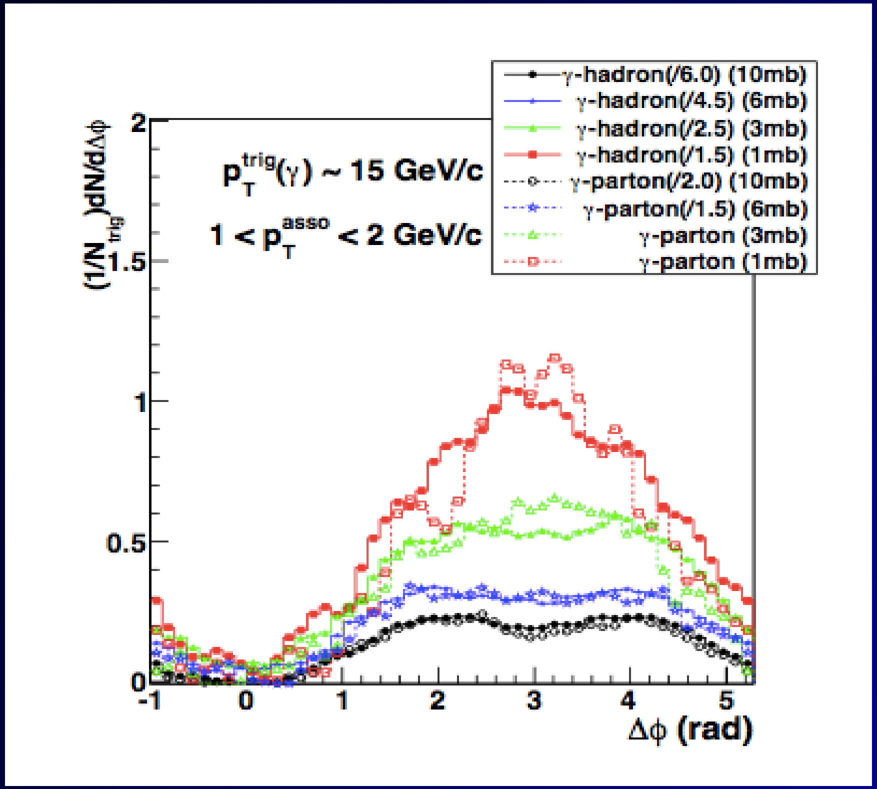
- Re-distribution of lost jet energy
- Soft-parton –medium interaction non-perturbative in nature
- Closely related to bulk transport properties in medium and EoS



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

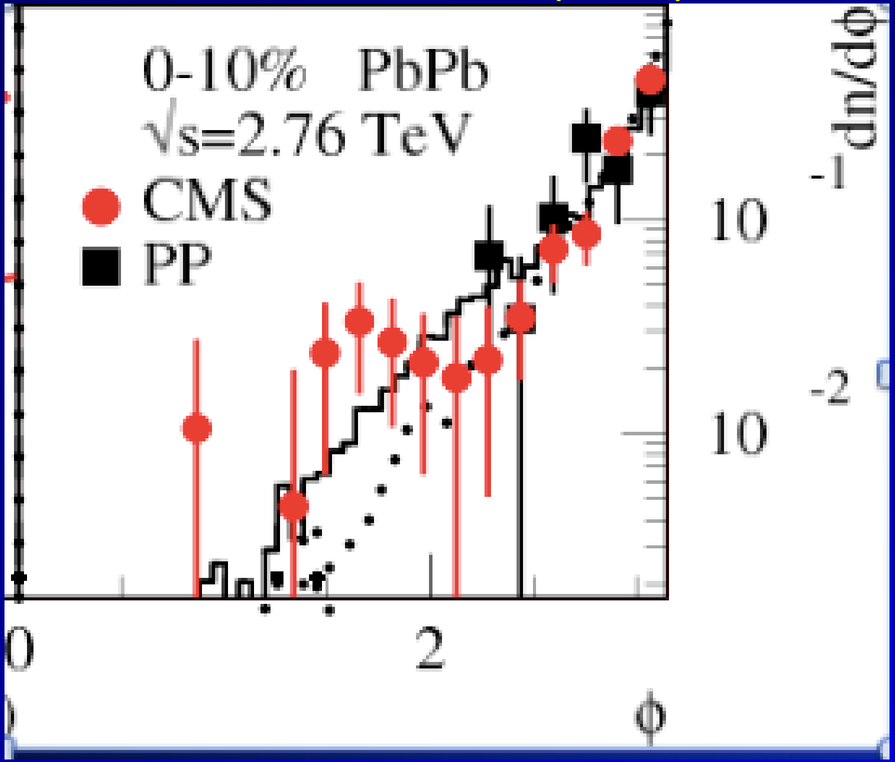
Broadening of γ-hadron correlation

γ-hadron from AMPT calculation



γ-jet from LBT

XNW and Zhu, PRL 111 (2014) 062301



Jet azimuthal angle broadening is smaller but still finite

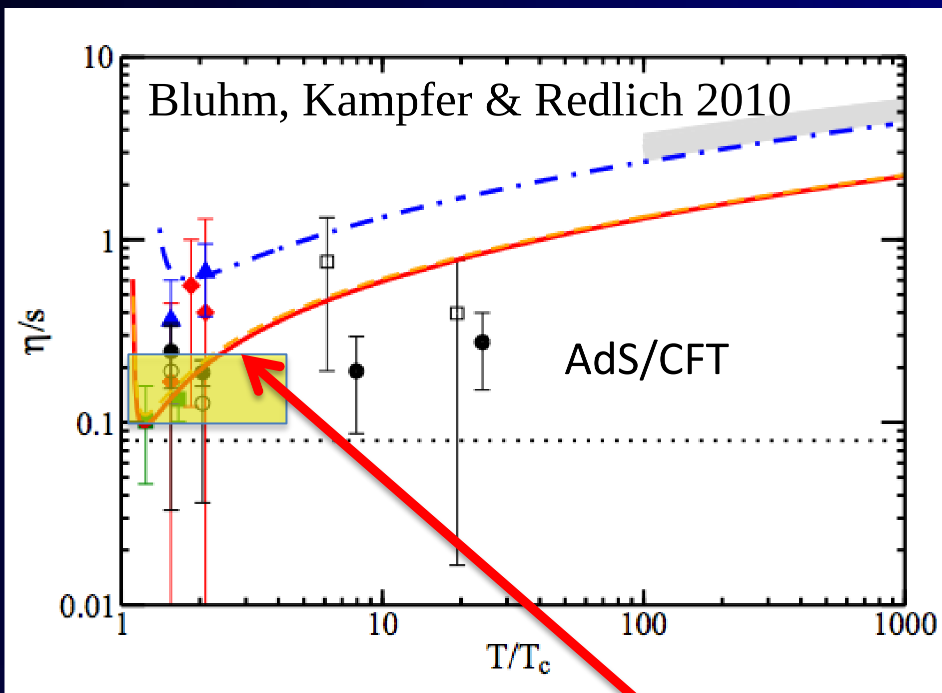
Li, Liu, Ma, XNW and Zhu, PRL 106（2010）012301

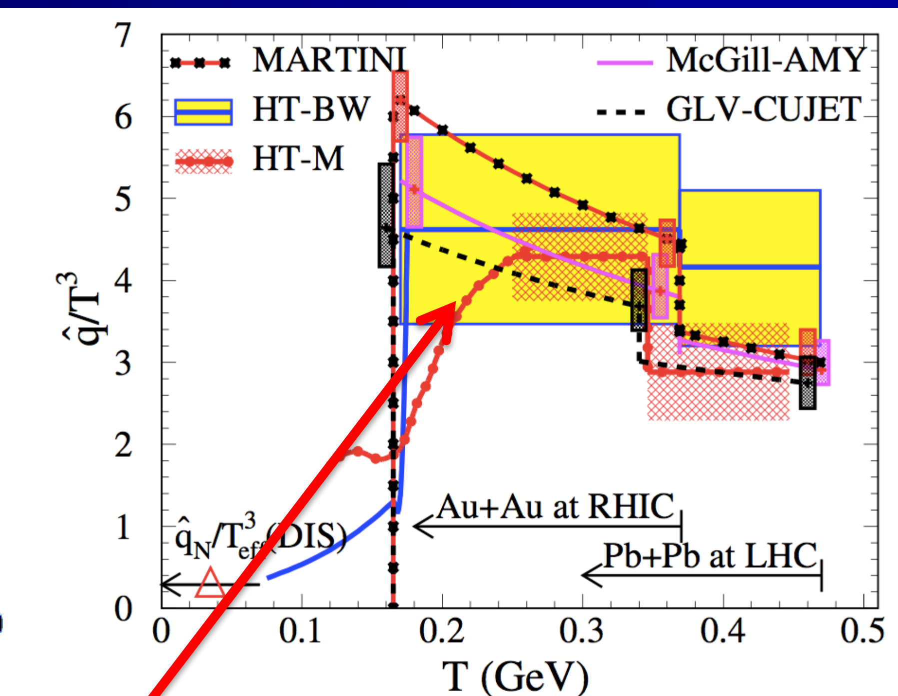
Ma and XNW, PRL 106 (2011) 162301

Summary

First step towards quantitative extraction of qhat from combined jet quenching at RHIC and LHC

Future: mapping out energy and T-dependence at RHIC & LHC





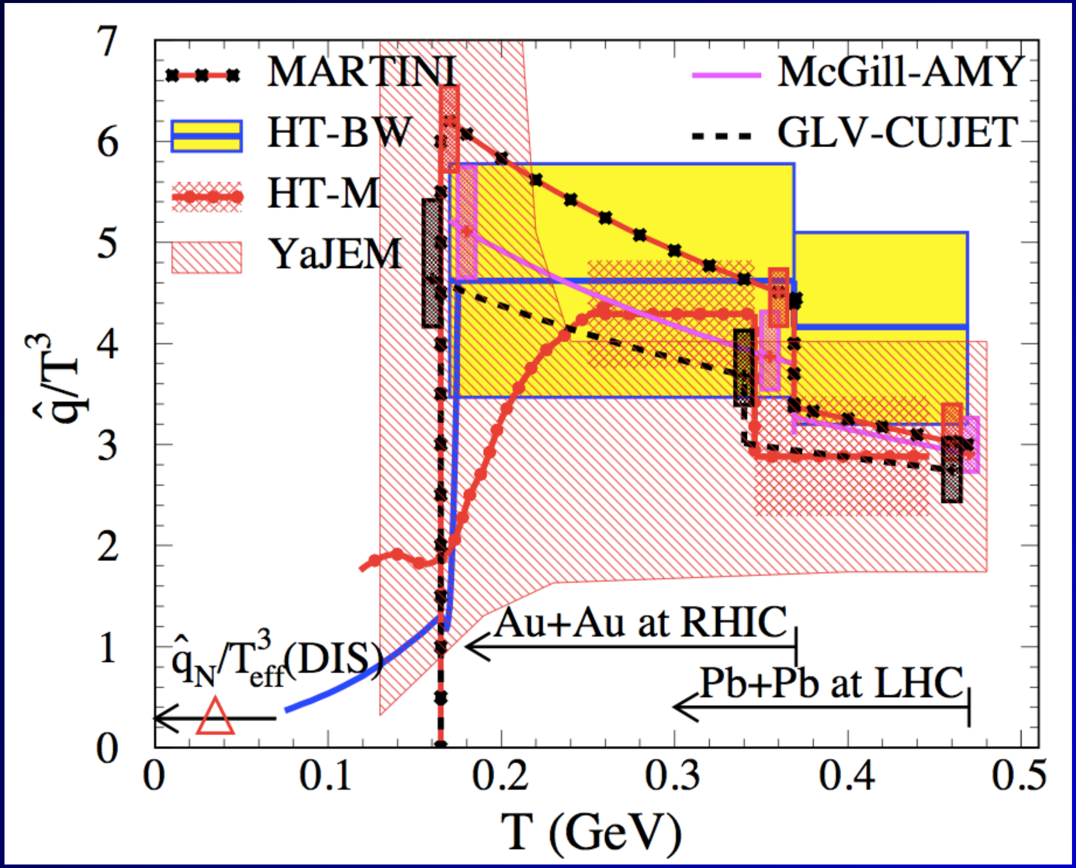
$$\frac{\eta}{s} \geq \frac{3T^3}{2\hat{q}}$$

Majumder, Muller & XNW (2007)

Backup

Jet transport coefficient

JET Collaboration: **arXiv:1312.5003**



Linear Boltzmann jet transport

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

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

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

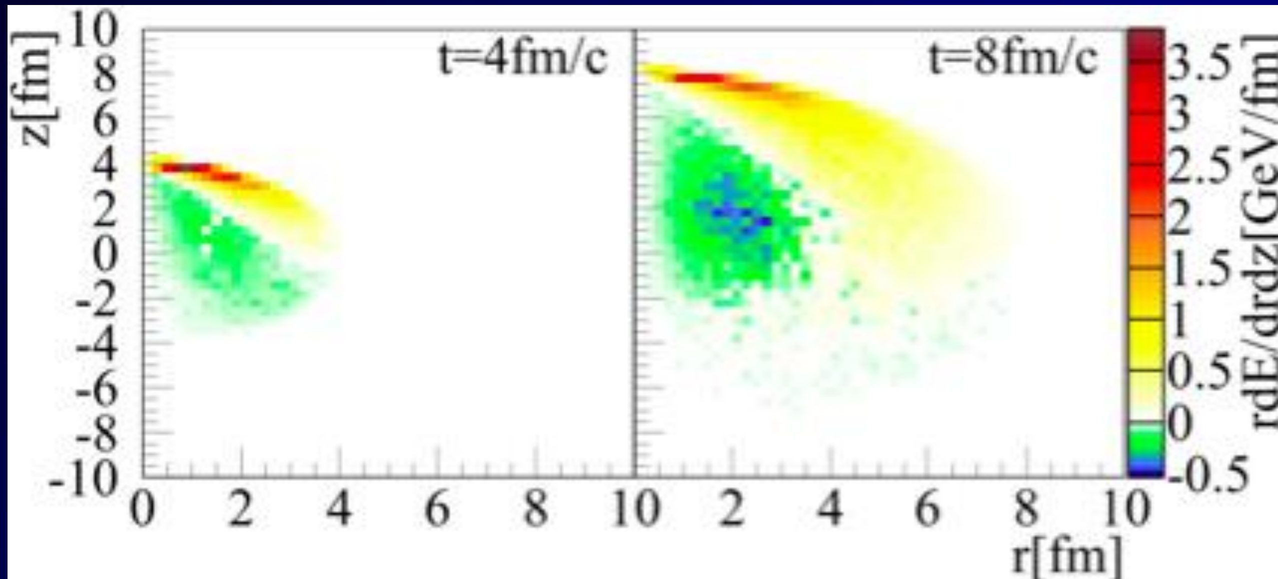
$$\frac{d\sigma}{dt} = |M_{12\to 34}|/16\pi^2 s^2$$

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

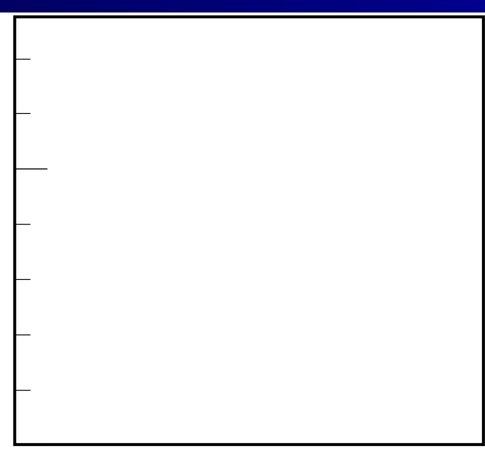
Induced radiation
$$\frac{dN_g}{dz d^2k_\perp dt} = \frac{2\alpha_s N_c}{\pi k_\perp^4} P(z)(\hat{p} \cdot u)\hat{q} \sin^2(\frac{t - t_0}{2\tau_f})$$

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

Jet-induced medium excitation

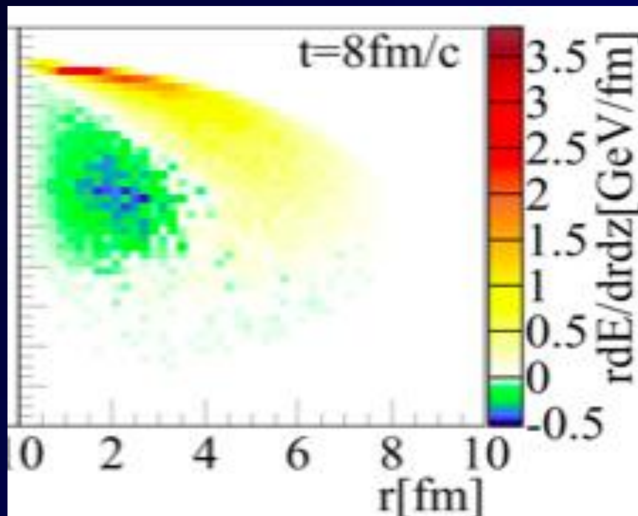


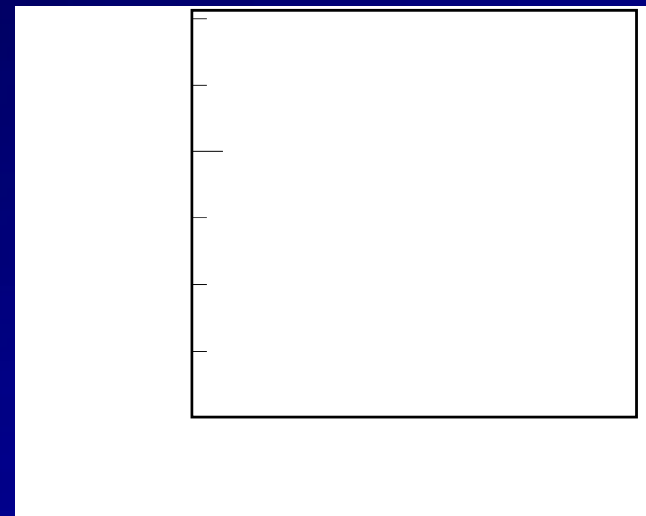
Jet propagation in a uniform medium

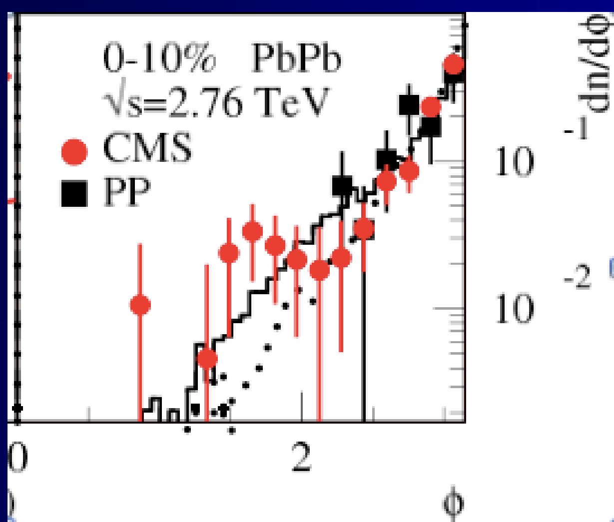


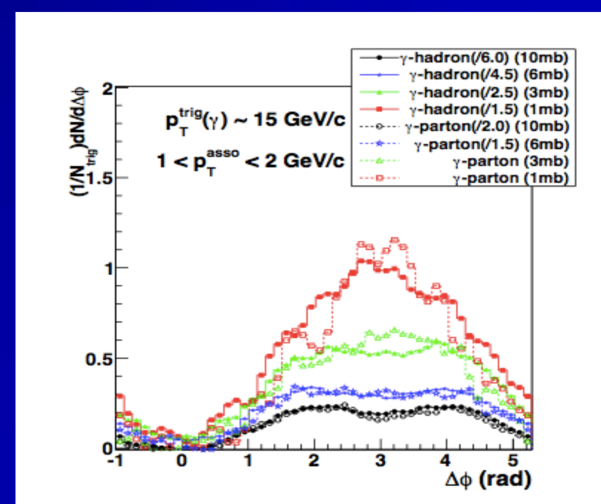
Effect of recoils and jet broadening

XNW and Zhu, PRL 111 (2014) 062301







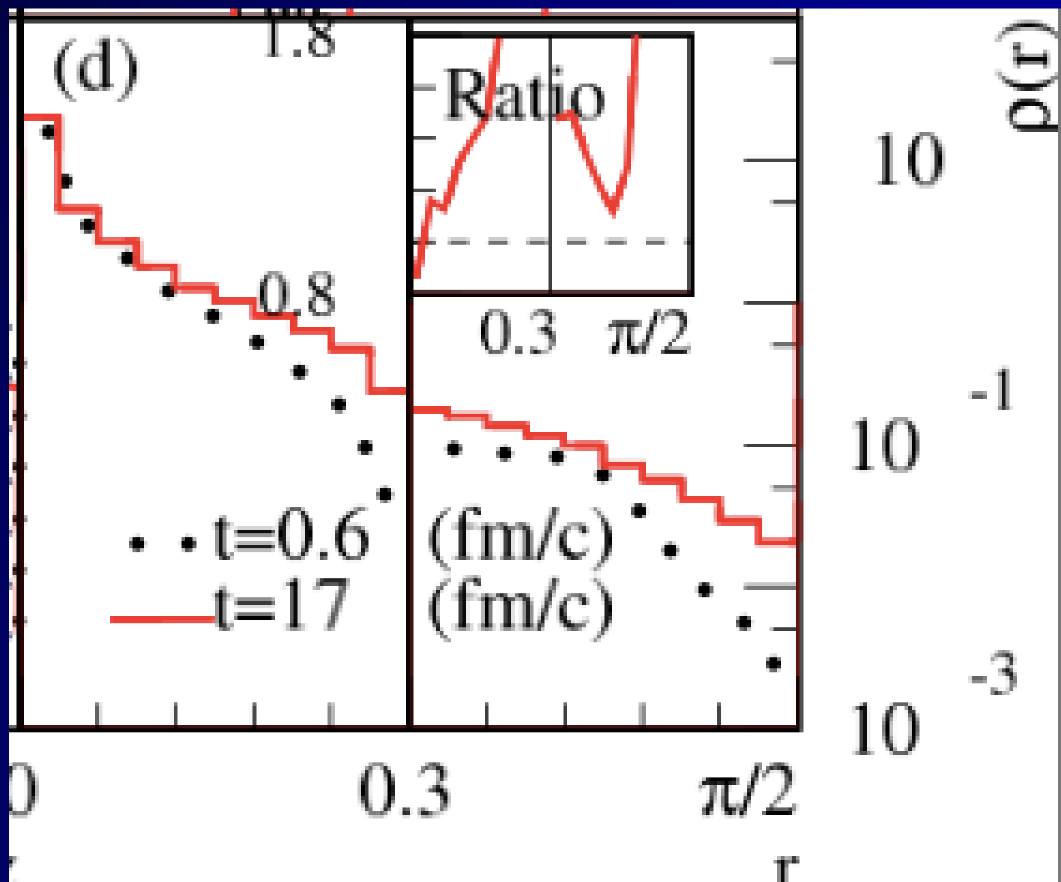


Talk by: Tan Luo (Wed.),

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

Broadening of jet transv. profile

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

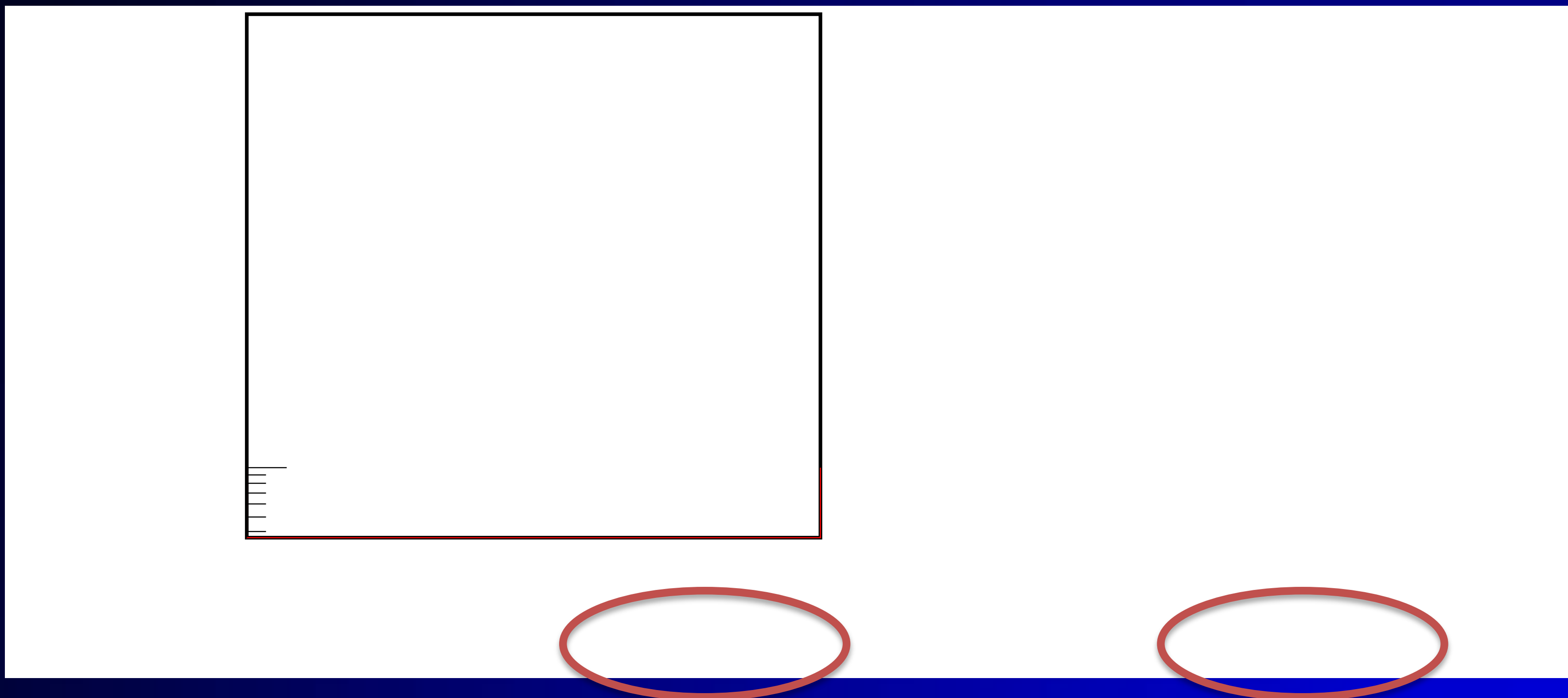


R=0.3

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

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

T-4 LO

$$+\sigma_0 \frac{\alpha_s}{2\pi} \int_{z_h}^1 \frac{dz}{z} D_{q/h}(z,\mu^2) \int_{x_B}^1 \frac{dx}{x} \left\{ \ln\left(\frac{Q^2}{\mu^2}\right) \left[\left(\delta(1-\hat{x})P_{qq}(\hat{z}) + \delta(1-\hat{z})P_{qq}(\hat{x})\right) T_F(x,0,0,\mu^2) \right.\right.$$

$$\left.\left. +\ \delta(1-\hat{z})P_{qg\to qg}(\hat{x}) \otimes T_F(x,x,x_B,\mu^2) \right] + \left(F^C(\hat{x},\hat{z}) + F^A(\hat{x},\hat{z})\right) \otimes T_F(x,x,x_B,\mu^2) \right\}$$

T-4 NLO

Finite contribution from asymmetric-cut diagrams

$$F^A(\hat{x},\hat{z}) \otimes T_F(x,x,x_B,\mu^2)$$

$$= -\frac{C_A}{2}\delta(1-\hat{z}) \frac{1+\hat{x}}{(1-\hat{x})_+} \left[T^L(x,0,x_B-x,\mu^2) - T^R(x_B,0,x-x_B,\mu^2) - T^L(x,x_B-x,x_B-x,\mu^2) + T^R(x_B, \ldots \right.$$

$$- \delta(1-\hat{x}) \frac{1+\hat{z}^2}{\hat{z}^2}(1+\hat{z})C_A \left[T^L(x,0,0,\mu^2) + T^R(x,0,0,\mu^2) \right]$$

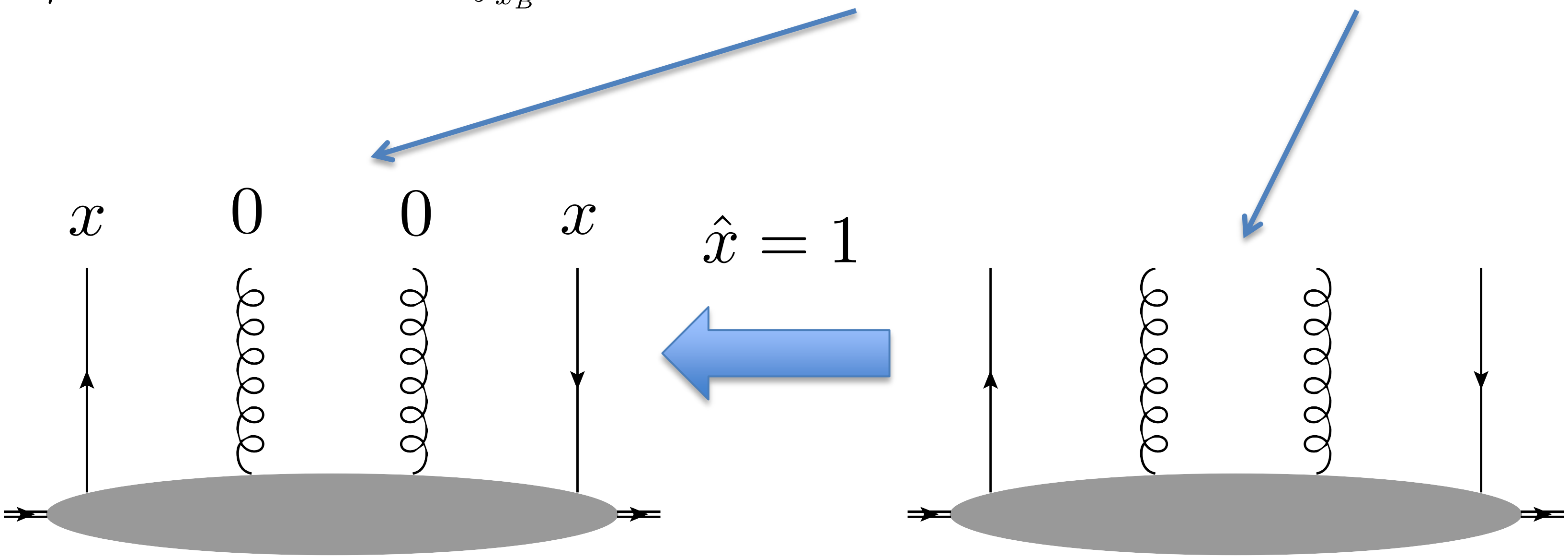
$$- \left[C_F(1-\hat{z}) + \frac{C_A}{2}\hat{z} \right] \frac{1+\hat{x}\hat{z}^2}{\hat{z}^2} x \left[\left. \frac{dT^L(x,x_2,x_B-x,\mu^2)}{dx_2} \right|_{x_2=0} + \left. \frac{dT^R(x_B,x_2,x-x_B,\mu^2)}{dx_2} \right|_{x_2=x-x_B} \right]$$

BERKELEY LAB

JET Collaboration

▪ Evolution equation for T4 - NEW

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



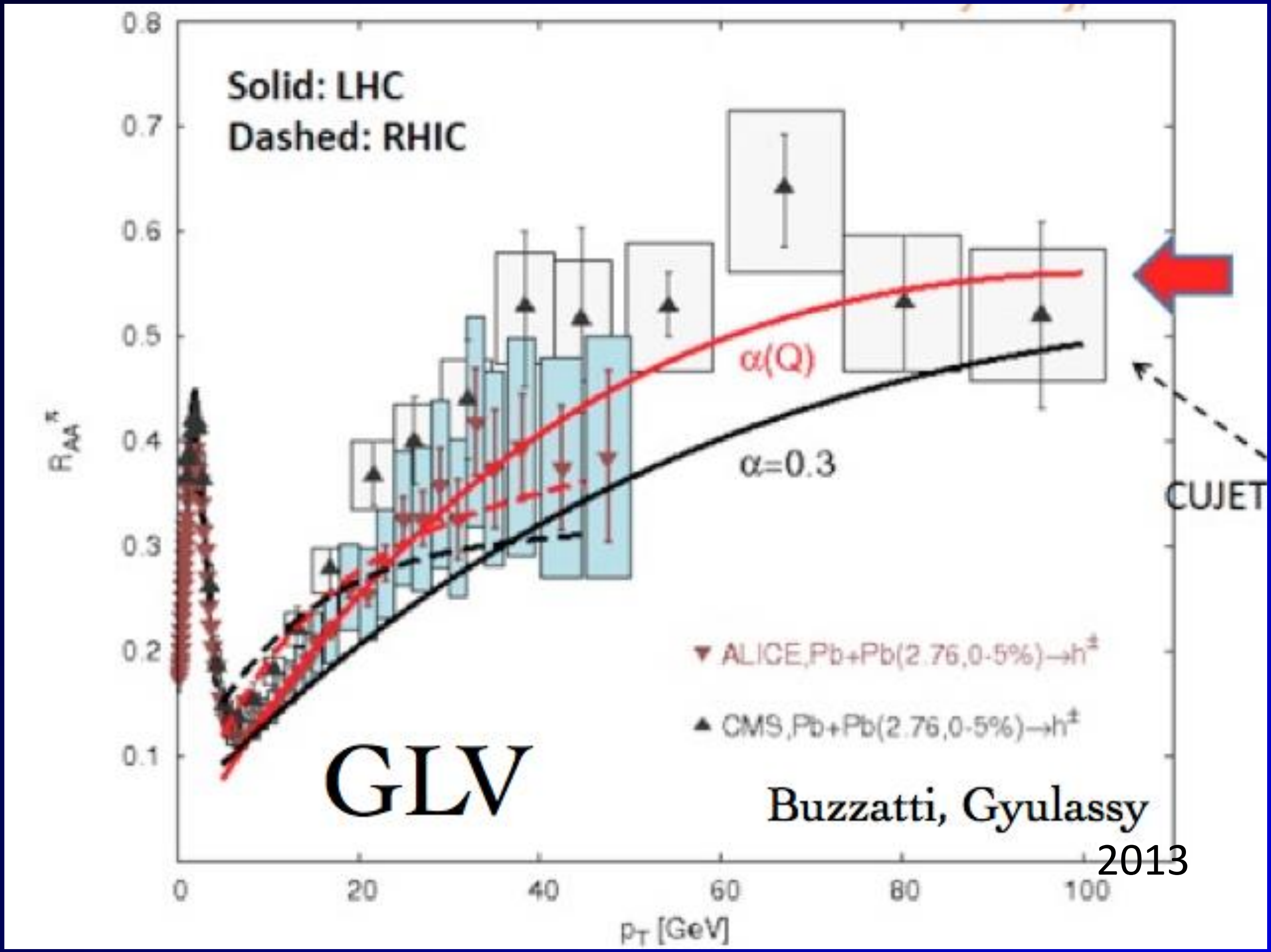
soft-soft

hard-hard & soft-hard & hard-soft

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

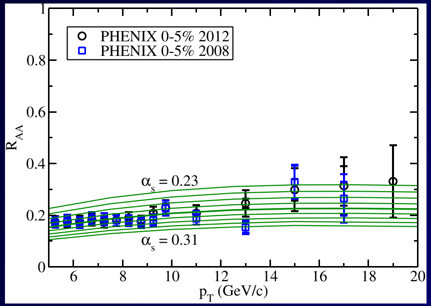
When $\hat{x} \to 1$, there is no phase space for the gluon radiation from the initial gluon.

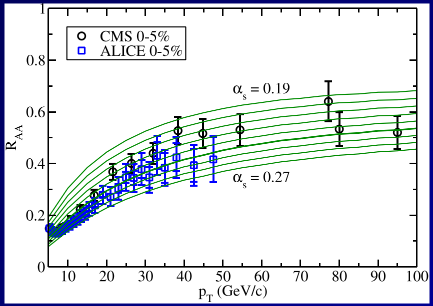
Running coupling in jet quenching

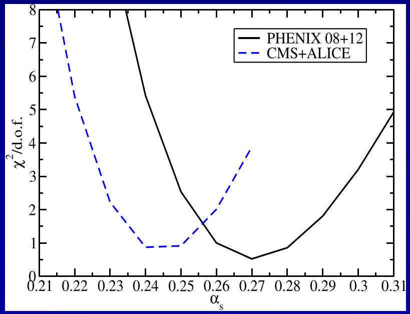


Jet quenching phenomenology

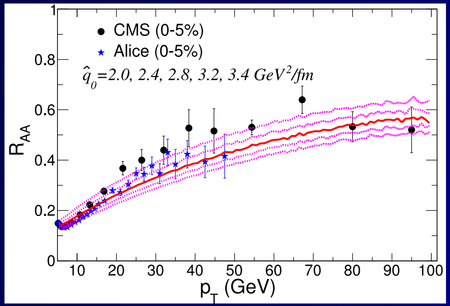
McGill-AMY

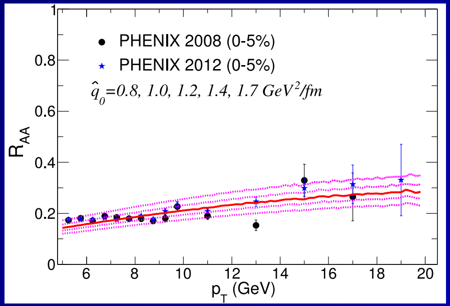


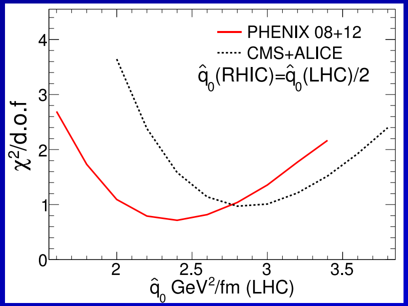




HT-BW







HT-M