2nd Workshop on "Jet modification in RHIC and LHC era"

Wayne State University, Aug. 20-22, 2013

High-twist approach to jet quenching

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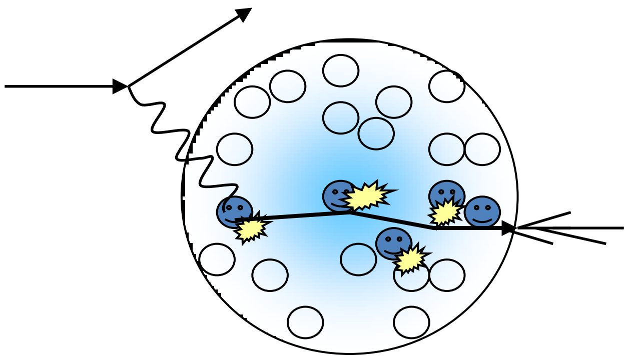
High-twist approach to multiple scattering



$$p = [p^+, 0, \vec{0}_\perp] \text{ momentum per nucleon}$$

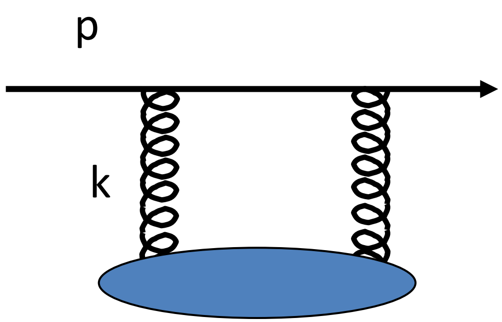
$$q = [-x_B p^+, q^-, \vec{0}_\perp], \quad x_B = -q^2 / 2q \cdot p$$

Loosely bound nucleus (p^+, q^- >> binding energy)

$$\langle\langle \cdots \rangle\rangle_A = \frac{1}{2p^+} \rho_A(\xi_N) \langle N(p) | \cdots | N(p) \rangle$$

Twist-expansion and gauge Invariance

$$\int dk^+ \frac{e^{ik^+(y_1^- - y_2^-)}}{2k^+ p^- - k_\perp^2 + i\varepsilon} = -i\frac{2\pi}{2p^-}\theta(y_2^- - y_1^-)e^{i\frac{k_\perp^2}{2p^-}(y_1^- - y_2^-)}$$



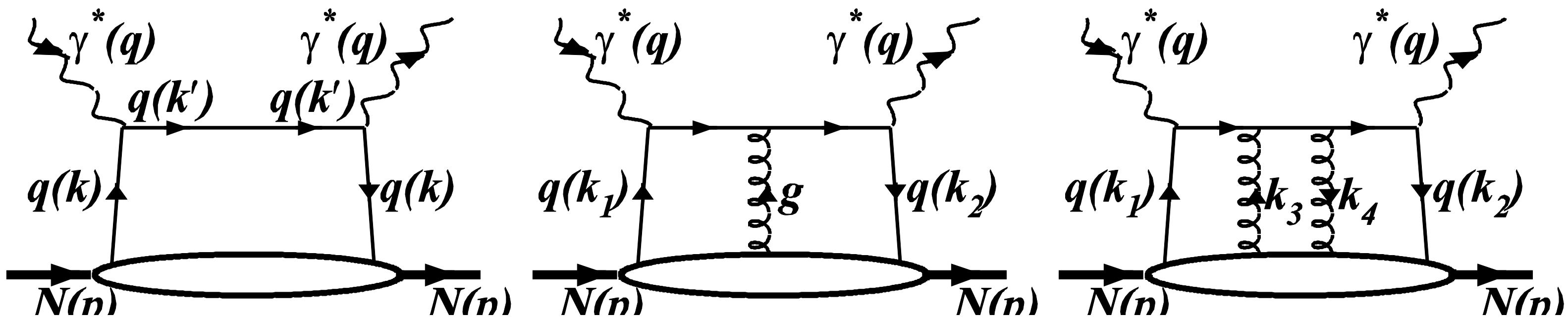
Expansion in k_T $\qquad \vec{k}_\perp \Rightarrow i\vec{\partial}_\perp$

One should also consider $\qquad \vec{A}_\perp \qquad i\vec{\partial}_\perp - g\vec{A}_\perp \equiv i\vec{D}_\perp$

Final matrix elements should contain: $\qquad \cdots D(y_1)L(y_1, y_2)D(y_2)L(y_2, y_3)\cdots$

TMD factorization

Collinear Expansion



$$W_{\mu\nu}^{(n)} = \int \prod_i d^4k_i \, \mathrm{Tr}\left[\hat{H}_{\mu\nu}^{\sigma\rho\cdots}(k) \langle A | \bar{\psi} A_\rho A_\sigma \cdots \psi | A \rangle \right]$$

Collinear expansion:

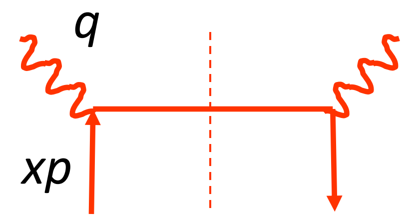
$$\hat{H}_{\mu\nu}^{\sigma\rho\cdots}(k) = \hat{H}_{\mu\nu}^{\sigma\rho\cdots}(0) + (k - xp)\cdot\partial_k \hat{H}_{\mu\nu}^{\sigma\rho\cdots}(k)|_{k=xp} + \cdots$$

$$A_\sigma = \frac{p_\sigma}{p^+} A^+ + \omega_\sigma^\rho A_\rho \qquad \omega_\sigma^\rho k_\rho = (k - xp)_\sigma$$

$$(k - xp)\cdot\partial_k \hat{H}_{\mu\nu}^{(0)}(k) + \omega_\sigma^\rho A_\rho \hat{H}_{\mu\nu}^{(1)\sigma}(k) \Rightarrow \hat{H}_{\mu\nu}^{(1)\sigma}(x,x)\,\omega_\sigma^\rho (\partial_\rho + igA_\rho)$$

Collinear Expansion (cont'd)

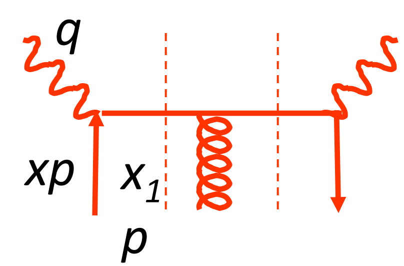
$$\frac{dW_{\mu\nu}^{(0)}}{d^2\ell_\perp} = \frac{1}{2\pi}\int \frac{d^4k}{(2\pi)^4}\delta^{(2)}(\vec{\ell}_\perp - \vec{k}_\perp)\mathrm{Tr}[\hat{H}_{\mu\nu}^{(0)}(x)\hat{\Phi}^{(0)}(k)]$$



'Twist-2' unintegrated quark distribution

$$\hat{\Phi}^{(0)}(k) = \int d^4y e^{ik\cdot y}\langle A|\bar{\psi}(0)\mathcal{L}(0,y)\psi(y)|A\rangle$$

$$\frac{dW_{\mu\nu}^{(1)}}{d^2\ell_\perp} = \frac{1}{2\pi}\int \frac{d^4k}{(2\pi)^4}\frac{d^4k_1}{(2\pi)^4}\sum_{c=L,R}\delta^{(2)}(\vec{\ell}_\perp - \vec{k}_{c\perp})\mathrm{Tr}[\hat{H}_{\mu\nu}^{(1,c)\rho}(x,x_1)\omega_\rho^{\rho'}\hat{\Phi}_{\rho'}^{(1)}(k,k_1)]$$



'Twist-3' unintegrated quark distribution

$$\hat{\Phi}_\rho^{(1)}(k,k_1) = \int d^4y d^4y_1 e^{ik\cdot y+ik_1\cdot y_1}\langle A|\bar{\psi}(0)\mathcal{L}(0,y_1)D_\rho(y_1)\mathcal{L}(y_1,y)\psi(y)|A\rangle$$

Liang & XNW' 06

TMD (unintegrated) quark distribution

$$\hat{\Phi}^{(0)}(k) = \int d^4 y e^{ik\cdot y} \langle A | \bar{\psi}(0) \mathcal{L}(0,y) \psi(y) | A \rangle$$

$$\frac{1}{2}\mathrm{Tr}\left[\gamma^\sigma \hat{\Phi}^{(0)}(k,s)\right] = p^\sigma f_A^q(k) \quad + (k - xp)^s f_{A^\wedge}(k) + e^{sabd} p_a k_b s_d f_{1T}^\wedge$$

+

$$\hat{\Phi}_\rho^{(1)}(k) = \int d^4 y e^{ik\cdot y} \langle A | \bar{\psi}(0) L(0,y) D_\rho(y) \psi(y) | A \rangle$$

Contribute to azimuthal and single spin asymmetry

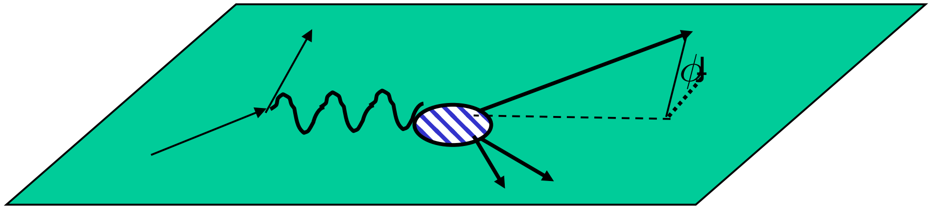
$$f_A^q(x) = \int dk^- d^2 k_\perp f_A^q(k)$$

Twist-two integrated quark distribution

LO DIS cross section up to twist-4

$$\frac{d\sigma}{dx_B dy d^2k_\perp} = \frac{2\pi\alpha_{em}^2 e_q^2}{Q^2 y}\Big\{[1+(1-y)^2] f_q^N(x_B,k_\perp) - 4(2-y)\sqrt{1-y}\frac{|\vec{k}_\perp|}{Q} x_B f_{q\perp}^{(1)N}(x_B,k_\perp)\cos\phi$$
$$-4(1-y)\frac{|\vec{k}_\perp|^2}{Q^2} x_B[\varphi_{\perp 2}^{(1)N}(x_B,k_\perp) - \tilde{\varphi}_{\perp 2}^{(1)N}(x_B,k_\perp)]\cos 2\phi$$
$$+8(1-y)\left(\frac{|\vec{k}_\perp|^2}{Q^2} x_B[\varphi_{\perp 2}^{(1)N}(x_B,k_\perp) - \tilde{\varphi}_{\perp 2}^{(1)N}(x_B,k_\perp)] + \frac{2x_B^2M^2}{Q^2} f_{q(-)}^N(x_B,k_\perp)\right)$$
$$-2\left[1+(1-y)^2\right]\frac{|\vec{k}_\perp|^2}{Q^2} x_B \varphi_{\perp 2}^{(2,L)N}(x_B,k_\perp)\Big\}.$$

Liang & XNW (2007)
Gao, Liang & XNW (2010)
Song, Gao Liang & XNW (2011), (2013)



Azimuthal asymmetry:

$$\langle \cos\phi \rangle_{eA} = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}\frac{k_T}{Q}\frac{x_B f_{A\perp}^q(x_B,k_T)}{f_A^q(x_B,k_T)}$$

TMD (unintegrated) quark distribution

$$f_A^q(x,\vec{k}_\perp) = \frac{1}{2}\int dk^- Tr[\hat{\Phi}^{(0)}(k)\gamma^+]$$

$$= \int \frac{dy^-}{4\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - ik_\perp\cdot y_\perp}\left\langle A\middle|\bar{\psi}(0)\gamma^+ L(0;y)\psi(y)\middle|A\right\rangle$$

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

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

Longitudinal gauge link

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

Transverse gauge link

Belitsky, Ji & Yuan' 2003

Transport Operator

Taylor expansion

$$\int \frac{d^2 y_\perp}{(2\pi)^2} e^{-i\vec{k}_\perp \cdot \vec{y}_\perp} F(\vec{y}_\perp) = \exp\left[i\vec{\nabla}_{k_\perp} \cdot \vec{\partial}_{y_\perp} \right] F(0)\delta^{(2)}(\vec{k}_\perp)$$

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

$$i\vec{\partial}_{y_\perp} \mathcal{L}(0,y) = \mathcal{L}(0,y)\left[\underbrace{i\vec{D}_\perp(y) + g\int_{-\infty}^{y^-} d\xi^- \mathcal{L}_\parallel^\dagger(\xi;y)\vec{F}_{+\perp}(\xi)\mathcal{L}_\parallel(\xi;y)|_{\xi_\perp=\vec{y}_\perp}}_{\vec{W}_\perp(y^-,\vec{y}_\perp)} \right]$$

$\vec{W}_\perp(y^-,\vec{y}_\perp)$ Transport operator

Color Lorentz force:

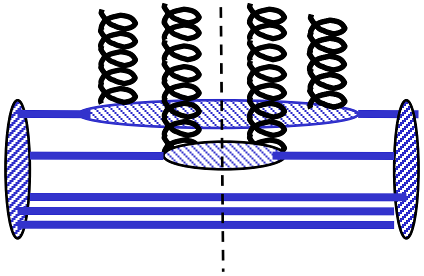
$$\frac{d\vec{p}_\perp}{dt} = g\vec{F}_{\perp m} v^m$$

All info in terms of collinear quark-gluon matrix elements

Liang, XNW & Zhou’ 08

Momentum Broadening

$$\left\langle\left\langle W_\perp^{2n}\right\rangle\right\rangle_A \sim \left[\int dy \frac{\rho_A(y)}{2p^+}\langle N|F_{+\perp}F_{+\perp}|N\rangle\right]^n \sim \left[\int dy \rho_A(y) x G_N(x)\right]^n$$



2-gluon correlation approximation

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

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

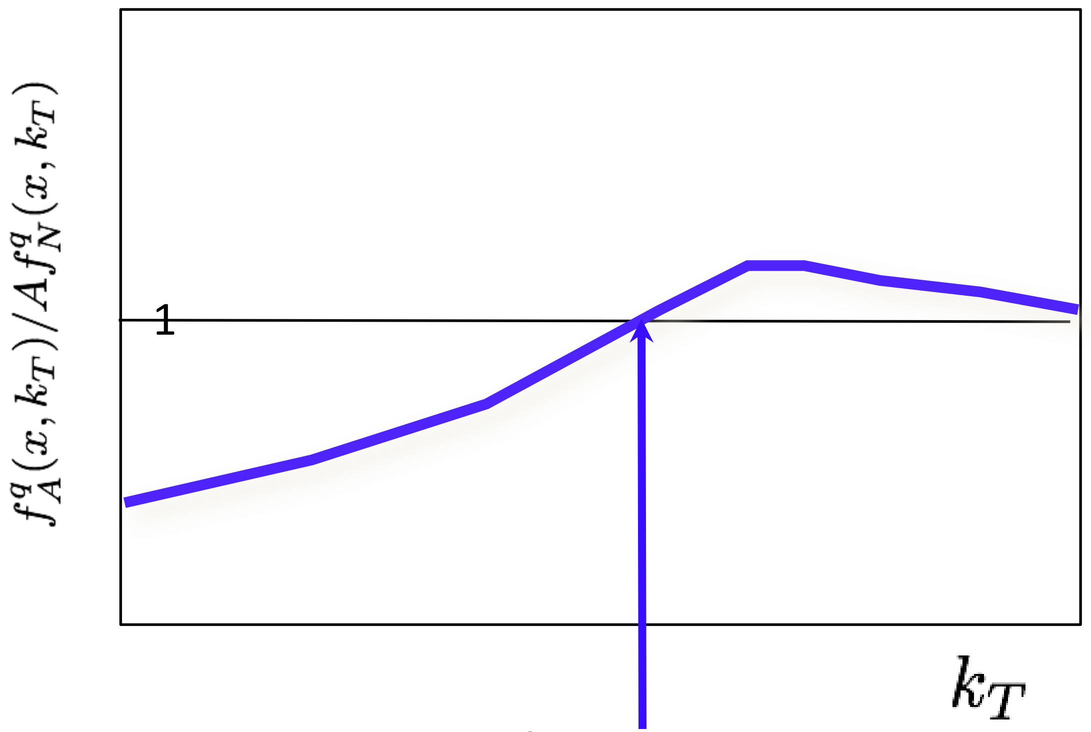
Liang, XNW & Zhou' 08
Majumder & Muller' 07
Kovner & Wiedemann' 01
BDMPS' 96

$$\hat{q}(\xi_N) \equiv \frac{4\pi^2\alpha_s C_F}{N_c^2-1}\rho_A(\xi_N) x G_N(x)|_{x\approx 0}$$

Jet transport parameter

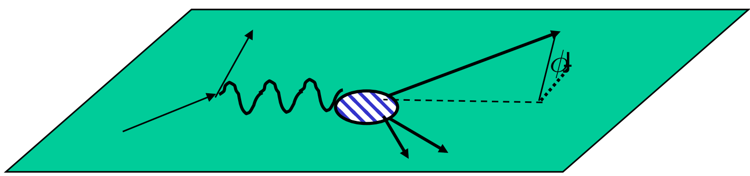
P_T Broadening

$$f_N^q(x, k_T) \sim 1/(k_T^2 + p_0^2)^\alpha$$



$$\hat{q}(\xi_N) \equiv \frac{4\pi^2 \alpha_s C_F}{N_c^2 - 1} \rho_A(\xi_N) x G_N(x)|_{x \approx 0}$$

Nuclear dependence of <cosϕ>



$$\frac{\langle \cos\phi \rangle_A}{\langle \cos\phi \rangle_N} \approx \frac{\alpha}{\alpha + \Delta}$$

Induced gluon emission in twist expansion

$$W_{\mu\nu}^{D} \propto \int d^2k_T e^{ik\cdot(y_1-y_2)} H_{\mu\nu}^{D}(p,q,k_T)\langle A|\bar{\psi}\gamma^{+}A^{+}(y_1)A^{+}(y_2)\psi|A\rangle$$

Collinear expansion:

$$H_{\mu\nu}^{D}(p,q,k_T) = H_{\mu\nu}^{D}(p,q,0) + \partial_{k_T} H_{\mu\nu}^{D}(p,q,0)k_T + \partial_{k_T}^{2} H_{\mu\nu}^{D}(p,q,0)k_T^2 + \cdots$$

$H_{\mu\nu}^{D}(p,q,0) \Rightarrow$ Eikonal contribution to vacuum brems.

Double scattering

$$W_{\mu\nu}^{D} \propto \partial_{k_T}^{2} H_{\mu\nu}^{D}(p,q,k_T=0)\langle A|\bar{\psi}\gamma^{+}F^{+\sigma}F^{+}{}_{\sigma}\psi|A\rangle$$

Modified Fragmentation

$$\Delta D_{q\to h}(z_h, Q^2) = \frac{\alpha_s}{2\pi}\int_0^{Q^2}\frac{d\ell_\perp^2}{\ell_\perp^4}\int_{z_h}^1\frac{dz}{z}\left[\Delta\gamma(z, x_L)D_{q\to h}(\frac{z_h}{z}) + \cdots\right]$$

Guo & XNW'00

Modified splitting functions

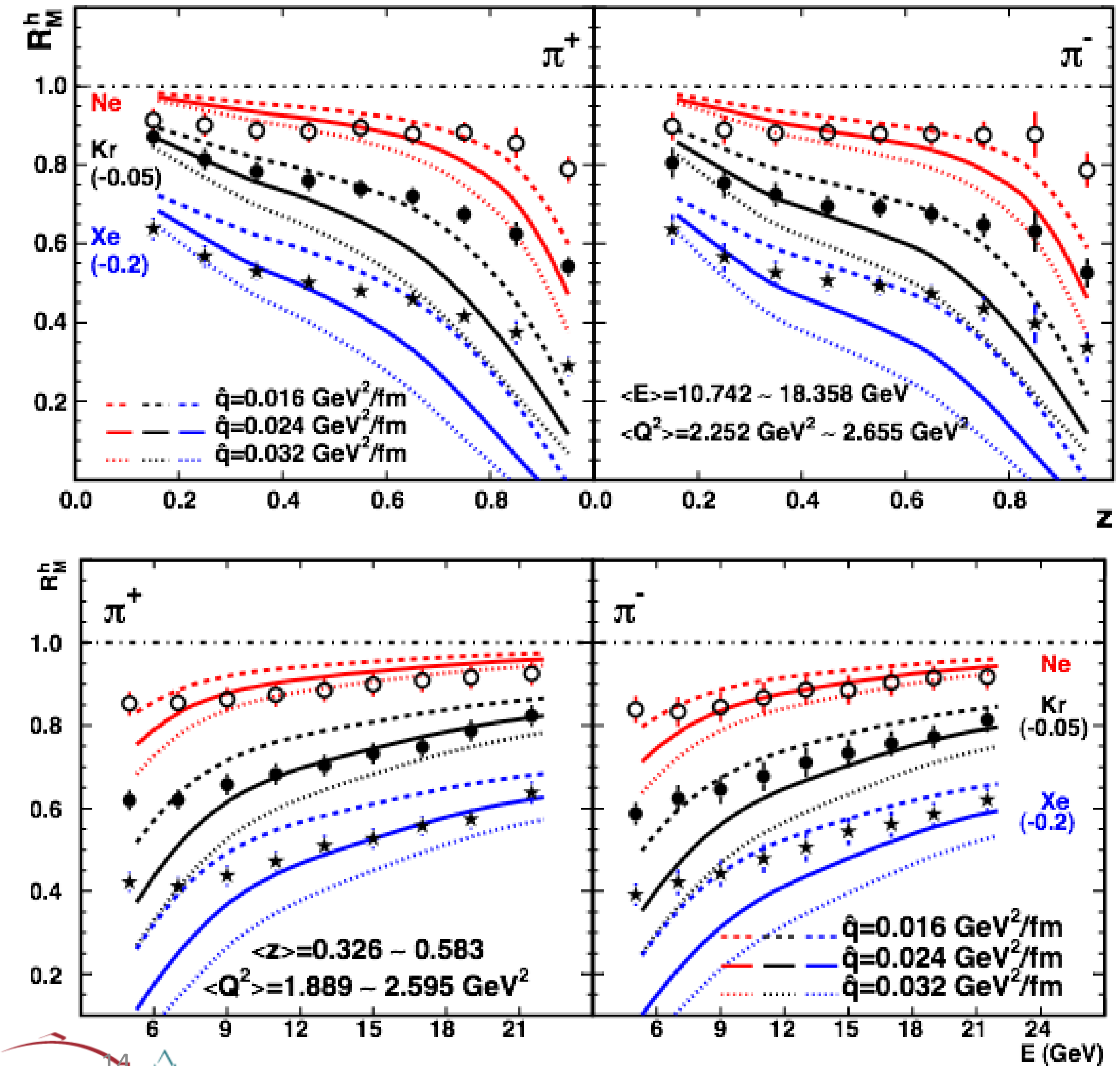
$$\Delta\gamma(z, x_L) = \frac{1+z^2}{(1-z)_+}\frac{T_{qg}^A(x, x_L)}{f_a^A(x)}\frac{C_A 2\pi\alpha_s}{N_c} - \delta(1-z)v(\ell_\perp^2)$$

Two-parton correlation:

$$T_{qg}^A(x, x_L) = \int\frac{dy^-}{2\pi}dy_1^- dy_2^- e^{-ix_B p^+ y^-}\langle A|\bar{\psi}(0)\frac{\gamma^+}{2}F_\sigma^+(y_1^-)F^{+\sigma}(y_2^-)\psi(y^-)|A\rangle$$

$$\times\left(1-e^{-ix_L p^+ y_2^-}\right)\left(1-e^{ix_L p^+(y_1^- - y^-)}\right)$$

DIS of large nuclei

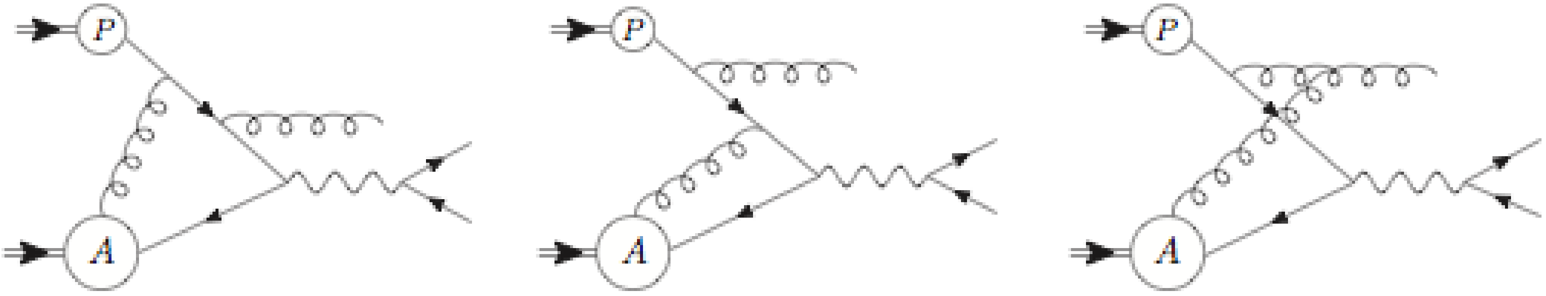


$$R = \frac{N_h^{eA}}{N_h^{eD}}$$

Deng & XNW (2010)

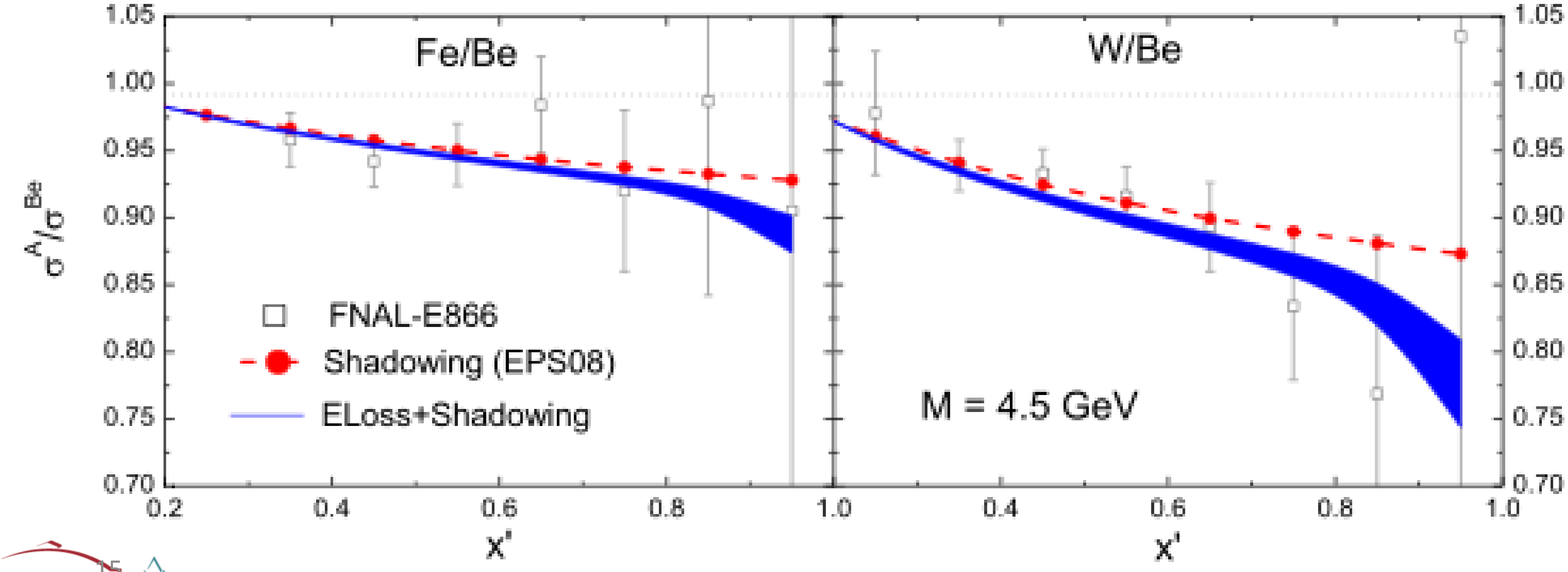
$$\hat{q}_N \approx 0.02 \; \mathrm{GeV}^2/\mathrm{fm}$$

Drell-Yan in pA Collisions



Xing & XNW, NPA 879 (2012)77

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



Validity of collinear expansion

Collinear expansion:

$$H^D_{\mu\nu}(p,q,k_T) = H^D_{\mu\nu}(p,q,0) + \partial_{k_T} H^D_{\mu\nu}(p,q,0) k_T + \partial^2_{k_T} H^D_{\mu\nu}(p,q,0) k_T^2 + \cdots$$

Region of validity: $\ell_\perp^2 \gg k_\perp^2 \geq Q_0^2$ pQCD

If one is bold and goes beyond no one has gone before:

$\ell_\perp^2 \ll k_\perp^2 \geq Q_0^2$ One has to re-sum higher-twist terms (Or model the behavior of small l_T behavior)

Need to include all: $T^A_{qg}(x_B, x_L)$, $x_L \dfrac{\partial T^A_{qg}(x_B, x_L)}{\partial x_L}$, $x_L^2 \dfrac{\partial^2 T^A_{qg}(x_B, x_L)}{\partial^2 x_L}$

LPM limits $L_A \geq \dfrac{2z(1-z)E}{\ell_\perp^2}$

Comparison with GLV

$$\frac{dN_{\rm HT}}{dz} = \frac{N_c\alpha_s}{\pi}\frac{1+(1-z)^2}{z}\int\frac{d\ell_T^2}{\ell_T^4}\int d\xi[c(x_L)\hat{q}(\xi,0)+\hat{q}(\xi,x_L)]$$
$$\left[1-\cos\frac{\ell_T^2\xi}{2q^- z(1-z)}\right].$$

$$\frac{dN_{\rm GLV}}{dz} = \frac{C_A\alpha_s}{\pi}\frac{1+(1-z)^2}{z}\int d\xi\rho_A(\xi)\sigma_{qN}\mu^2\int\frac{d\ell_T'^2}{\ell_T'^2(\ell_T'^2+\mu^2)}$$
$$\left[1-\cos\frac{\ell_T'^2\xi}{2q^- z(1-z)}\right].$$

$\hat{q} \leftrightarrow \rho_A\sigma_g\mu^2$ ρ_A quasi-particle density

Modified DGLAP Evolution

Berkeley Lab

$$\frac{\partial \tilde{D}_q^h(z_h,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_{z_h}^1 \frac{dz}{z}\Big[\tilde{\gamma}_{q\to qg}(z,\mu^2)\tilde{D}_q^h(\frac{z_h}{z},\mu^2) + \tilde{\gamma}_{q\to gq}(z,\mu^2)\tilde{D}_g^h(\frac{z_h}{z},\mu^2)\Big]$$

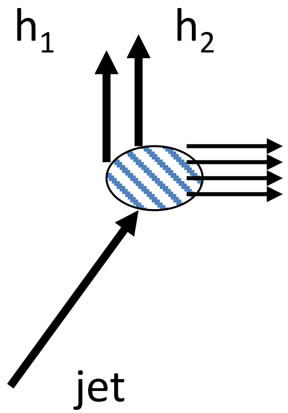
$$\frac{\partial \tilde{D}_g^h(z_h,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_{z_h}^1 \frac{dz}{z}\Big[\sum_{q=1}^{2n_f}\tilde{\gamma}_{g\to q\bar{q}}(z,\mu^2)\tilde{D}_q^h(\frac{z_h}{z},\mu^2) + \tilde{\gamma}_{g\to gg}(z,\mu^2)\tilde{D}_g^h(\frac{z_h}{z},\mu^2)\Big]$$

Modified splitting functions

$$\tilde{\gamma}_{a\to bc}(z,l_T^2) = \gamma_{a\to bc}(z) + \Delta\gamma_{a\to bc}(z,l_T^2)$$

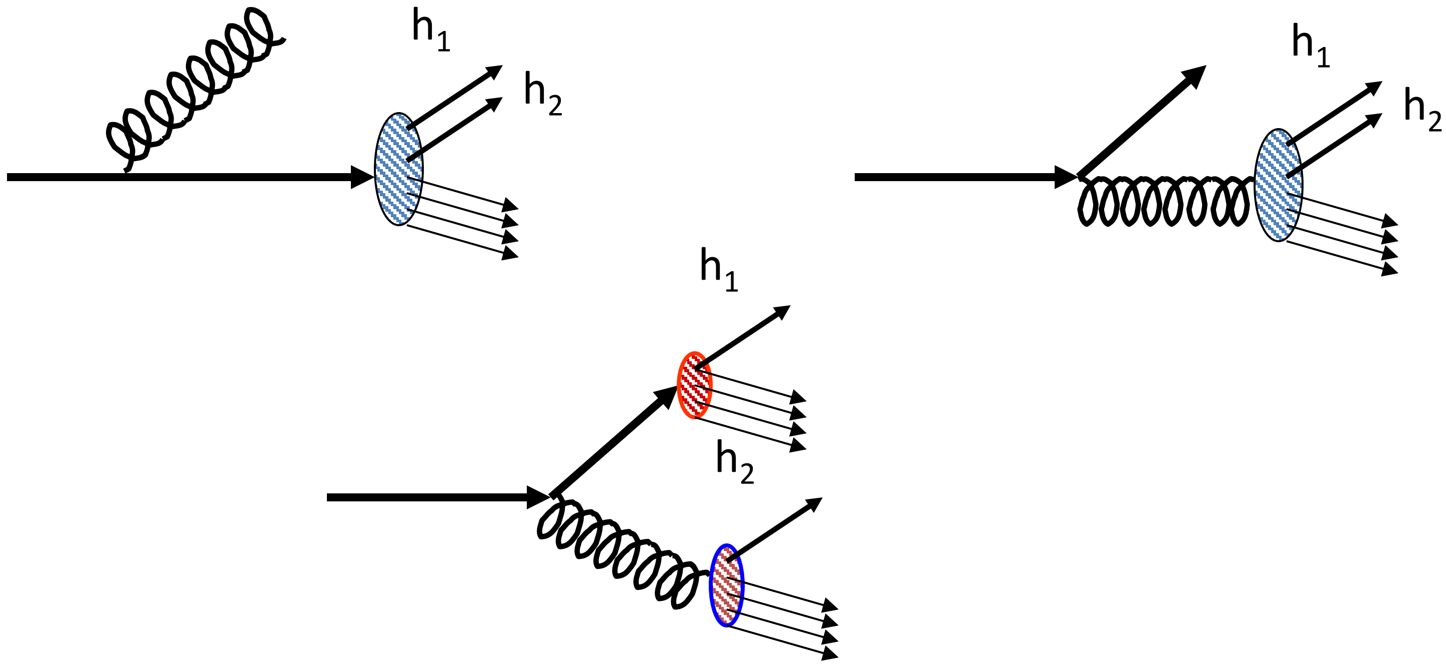
Di-hadron fragmentation function

Majumder & XNW'04



$$D_{q\to h1h2}(z_1,z_2) \propto \sum_S Tr\left[\frac{\gamma^+}{2}\langle 0|\psi_q(0)|\, p_{h1}p_{h2},S\rangle\langle p_{h1}p_{h2},S\,|\bar{\psi}_q(y^-)|0\rangle\right]$$

DGLAP for Dihadron Fragmentation

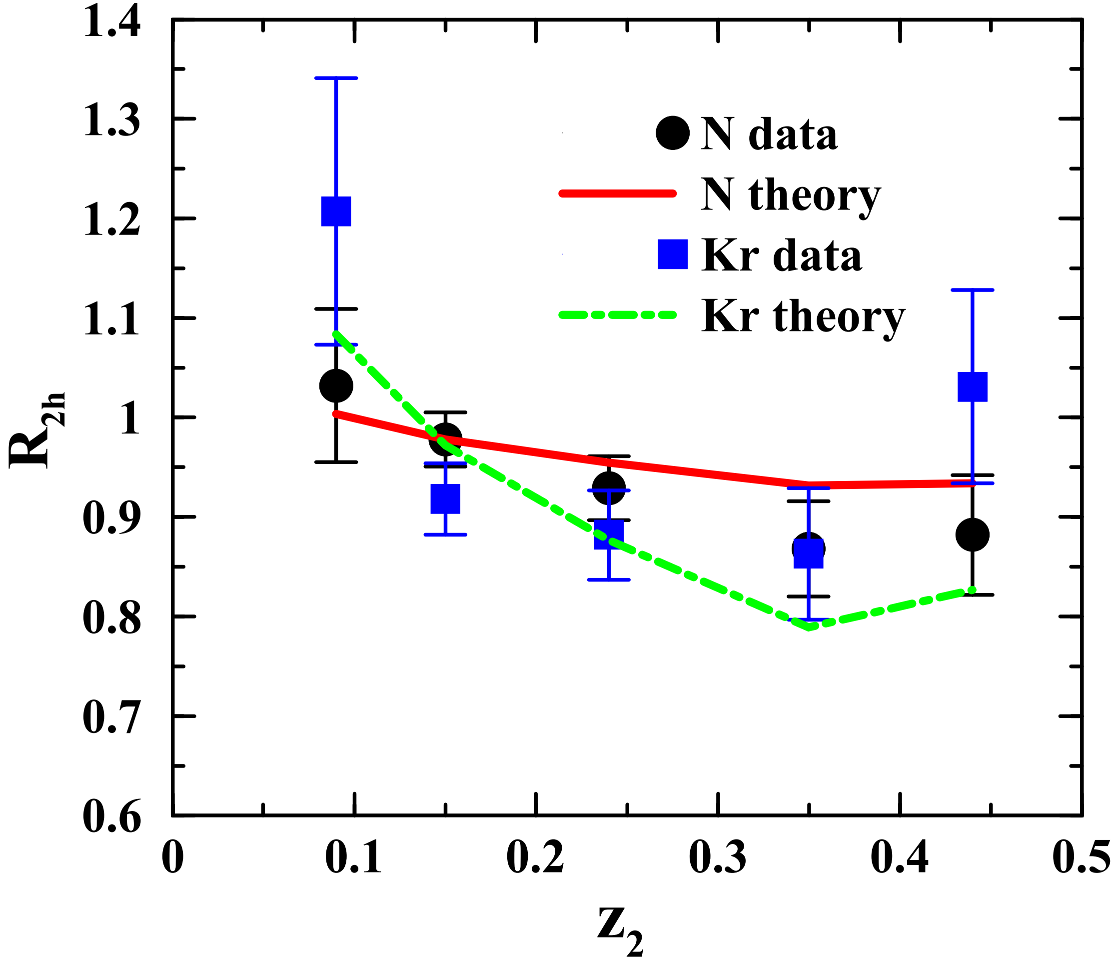


$$\frac{\partial D^q_{h_1h_2}(z_1,z_2,Q^2)}{\partial \ln Q^2} = \int_{z_1+z_2}^{1} \frac{dy}{y^2} P_{q\to qg}(y) D^q_{h_1h_2}\left(\frac{z_1}{y},\frac{z_2}{y},Q^2\right) + (g\to h_1h_2)$$

$$+\int_{z_1}^{1-z_2}\frac{dy}{y(1-y)}\hat{P}_{q\to qg}(y) D^q_{h_1}\left(\frac{z_1}{y},Q^2\right) D^g_{h_2}\left(\frac{z_2}{1-y},Q^2\right) + (q\leftrightarrow g)$$

Medium Modified Dihadron

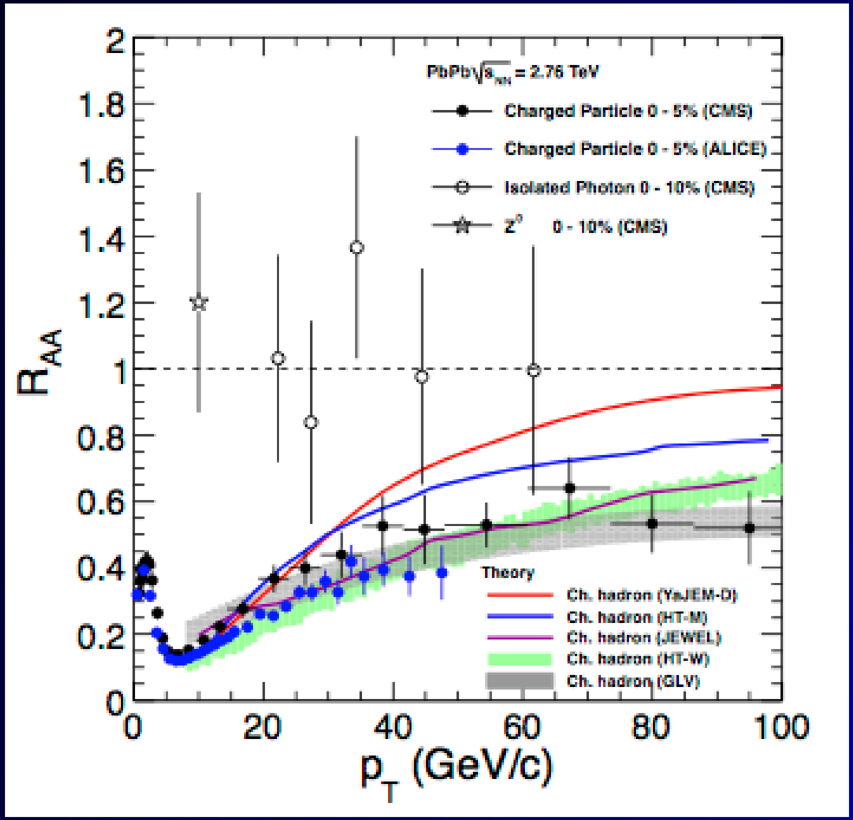
Triggering h_1 ⟹ $D(z_1,z_2)/D(z_1)$

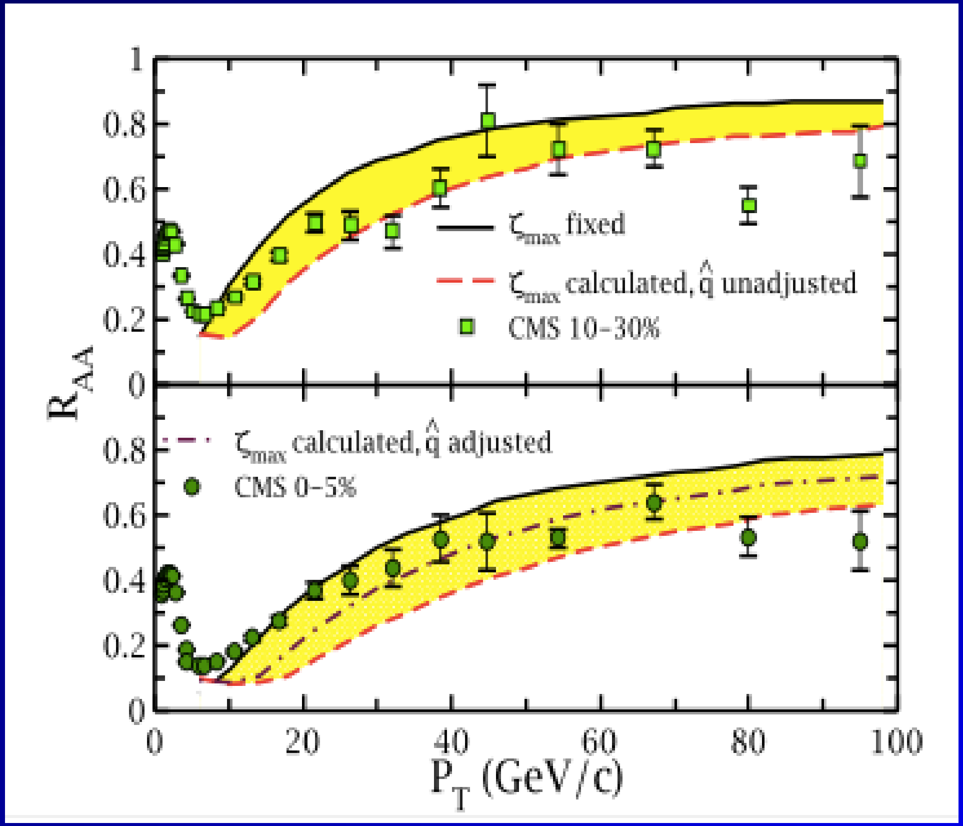


Jet quenching at LHC

$\hat{q} = 2 \times 1.67 \ \text{GeV}^2/fm$

$\hat{q} = 2 \times 2.2 \ \text{GeV}^2/fm$





Muller, Schukfrat & Wyslouch 2012

Majumder 2012

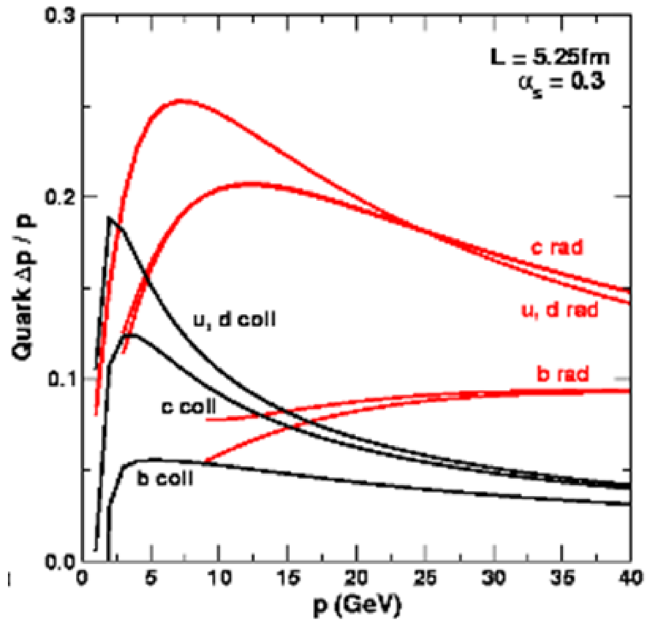
Elastic versus radiative e-loss

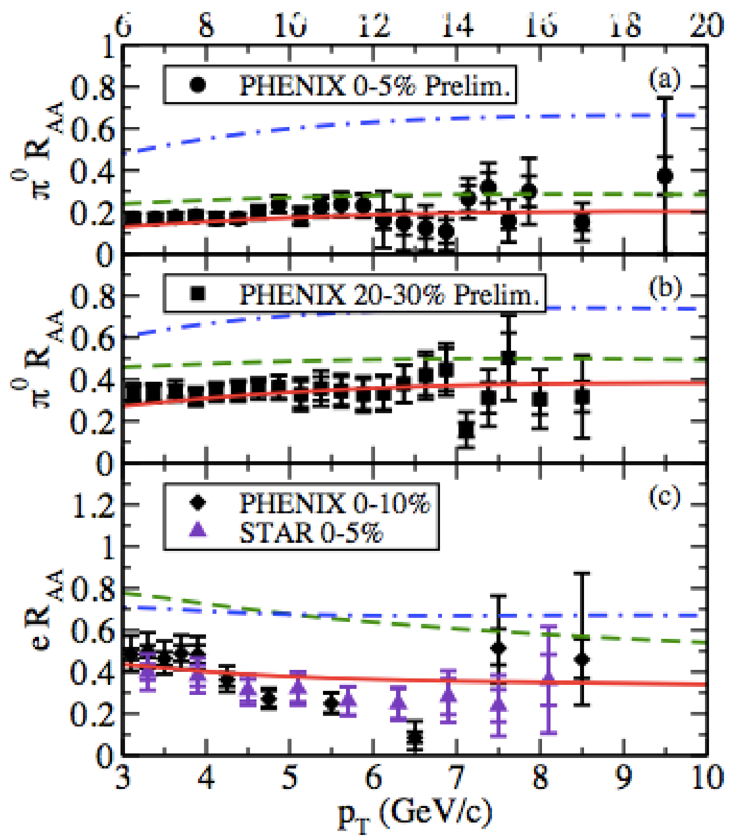
Majumder 2008
Qin and Majumder 2010

$$\hat{e}_{2lc} = [4\pi^2 \alpha_s C_R/(N_c^2 - 1)] \int dy^- \langle F^{+-}(y^-) F^{+-}(0) \rangle.$$

$$\frac{\partial \phi}{\partial L^-} = \hat{q}_{lc} \nabla^2_{q_\perp} \phi + \hat{e}_{lc} \frac{\partial \phi}{\partial q^-} + \hat{e}_{2lc} \frac{\partial^2 \phi}{\partial q^{-2}},$$

Gyulassy
Wicks, etc



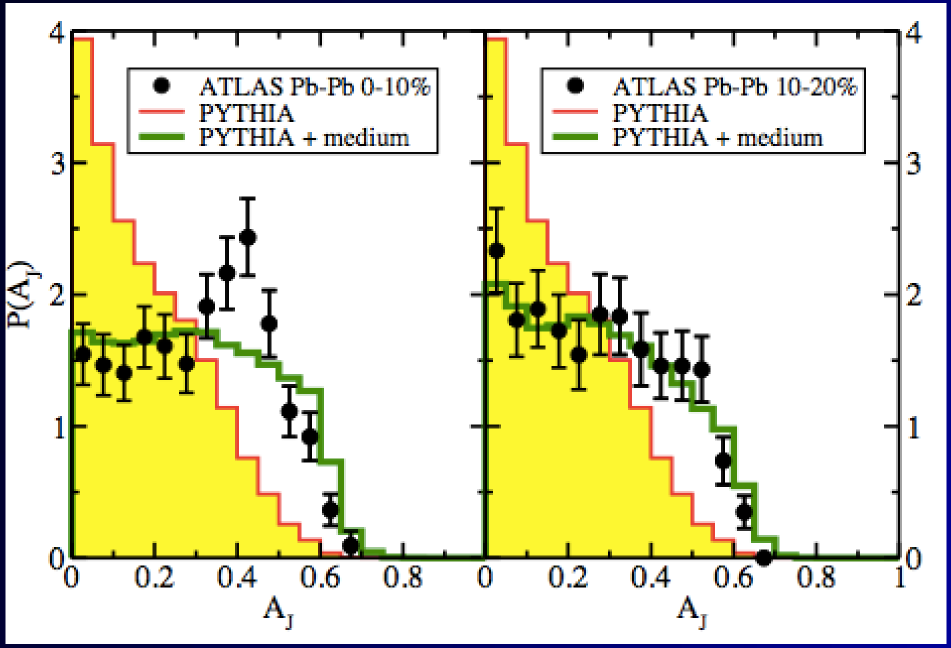


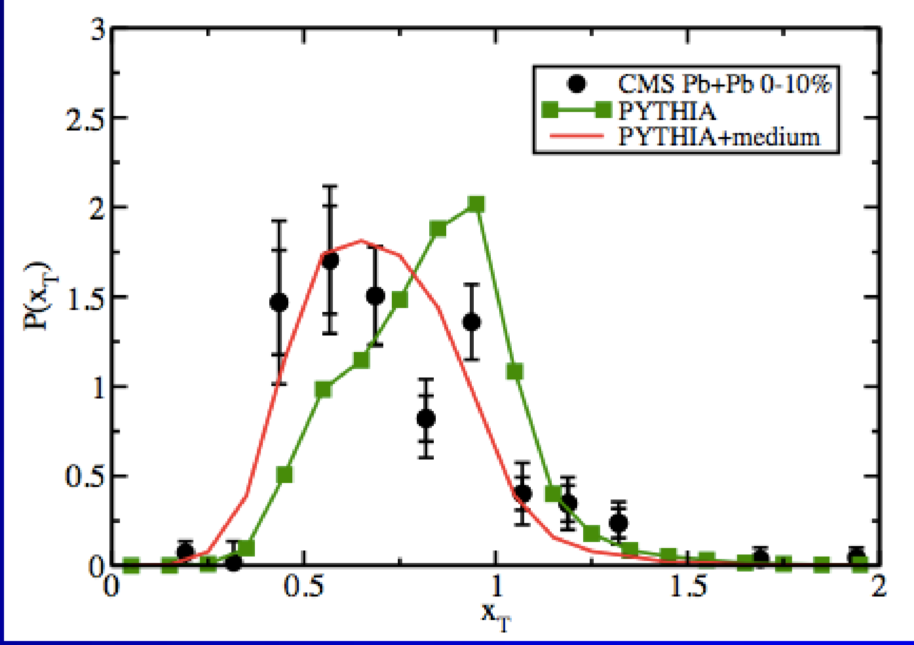
Dijet and gamma-jet asymmetry

$$P_{\rm rad}(t,\Delta t) = \langle N_g(t,\Delta t)\rangle = \Delta t \int dx dl_\perp^2 \frac{dN_g}{dx dl_\perp^2 dt}$$

$$\frac{dN_g}{dx dl_\perp^2 dt} = \frac{2\alpha_s}{\pi} P(x) \frac{\hat{q}}{l_\perp^4} \sin^2\left(\frac{t-t_i}{2t_{\rm form}}\right)$$

Qin and Muller (2011); Qin **arXiv:1210.6610**



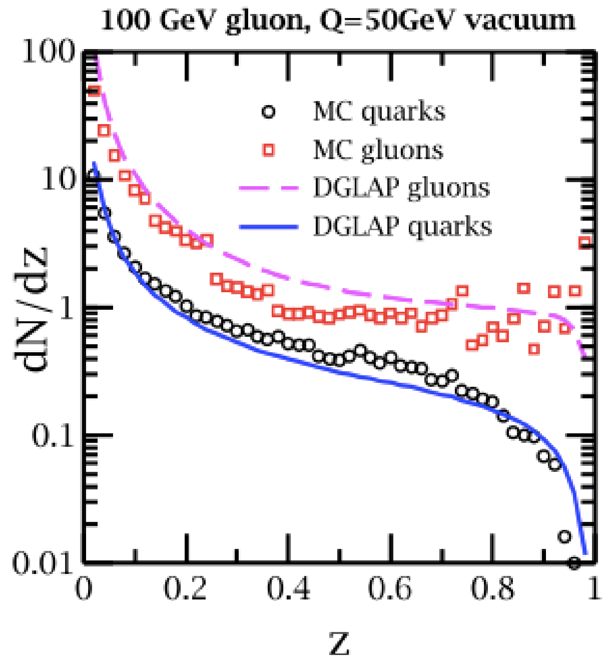


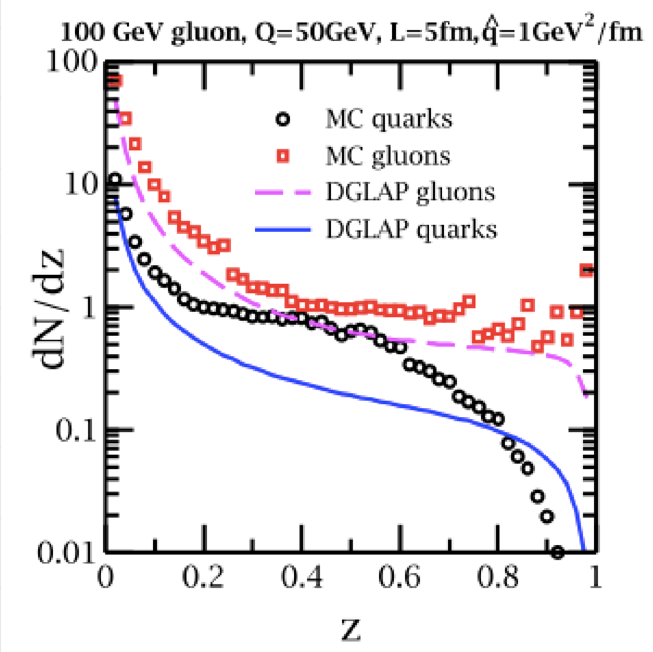
MC simulation of jet transport

Numerical simulation of mDGLAP equations:

$$K_{p^-,Q^2}(y,\zeta) = \frac{2\hat{q}}{Q^2}\left[2 - 2\cos\left\{\frac{Q^2(\zeta-\zeta_i)}{2p^-y(1-y)}\right\}\right]$$

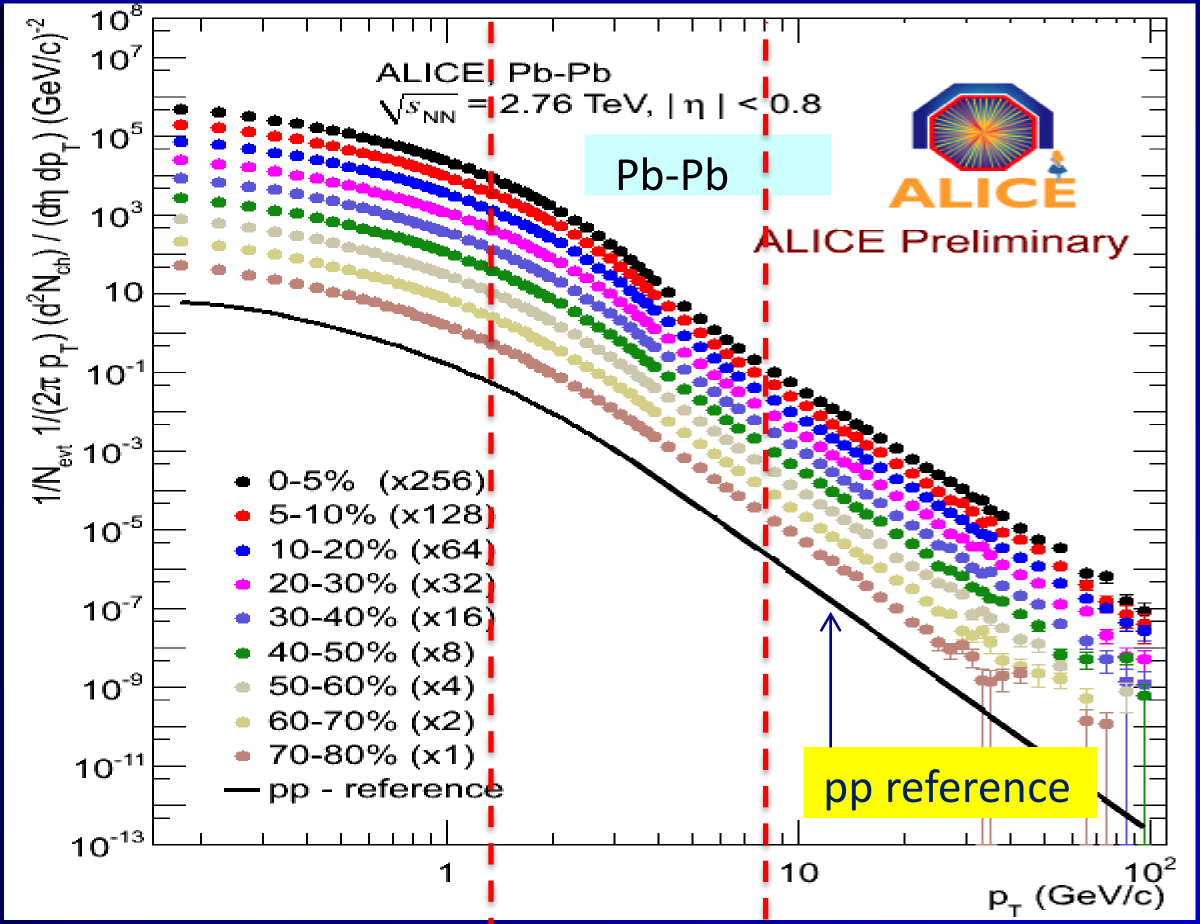
Use the radiative Kernel in the Sudakov form factor and parton splitting

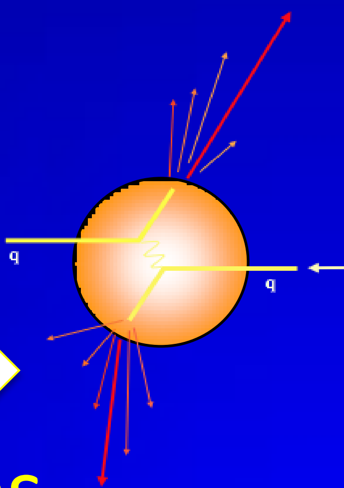




Majumder 2013

Interplay between hard and soft probes





soft probes

hard probes

Linear Boltzmann jet transport

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

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

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

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

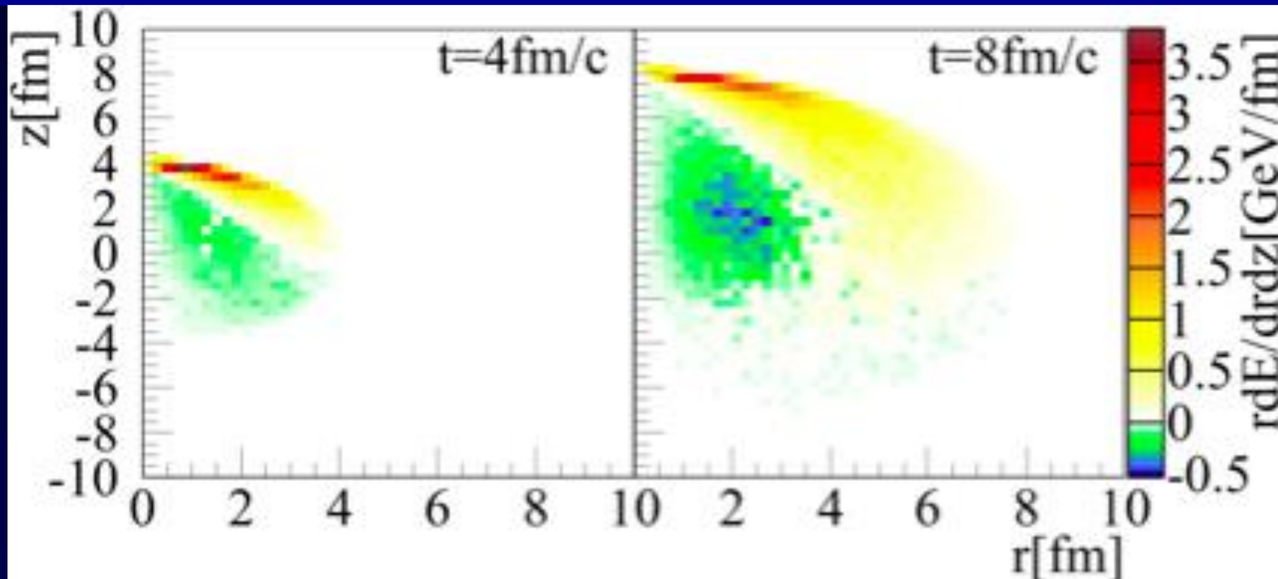
$$\mu_D^2 = (\frac{3}{2}) 4\pi\alpha_s T^2$$

Induced radiation

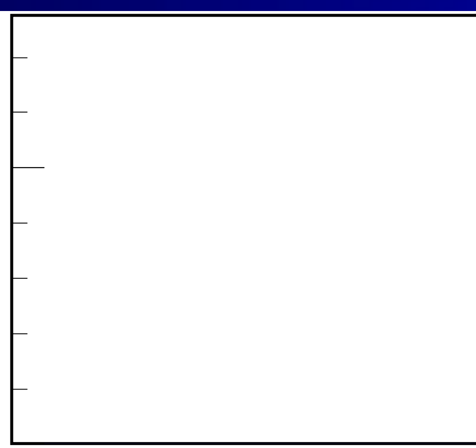
$$\frac{dN_g}{dz d^2k_\perp dt} = \frac{2\alpha_s N_c}{\pi k_\perp^4} P(z)(\hat{p} \cdot u)\hat{q}\sin^2(\frac{t - t_0}{2\tau_f})$$

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

Jet-induced medium excitation

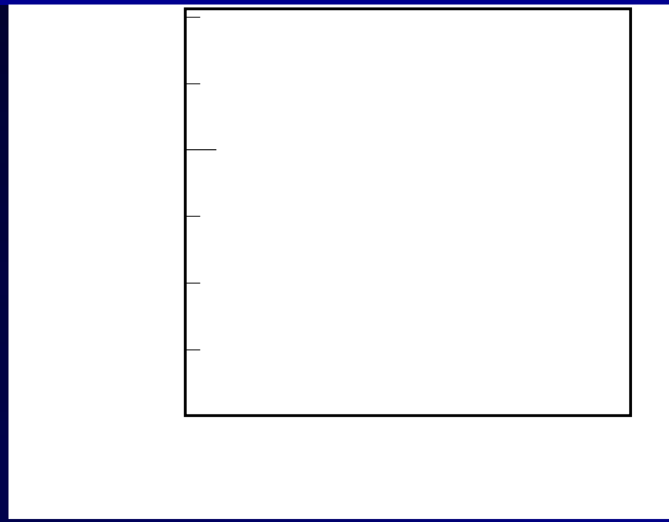


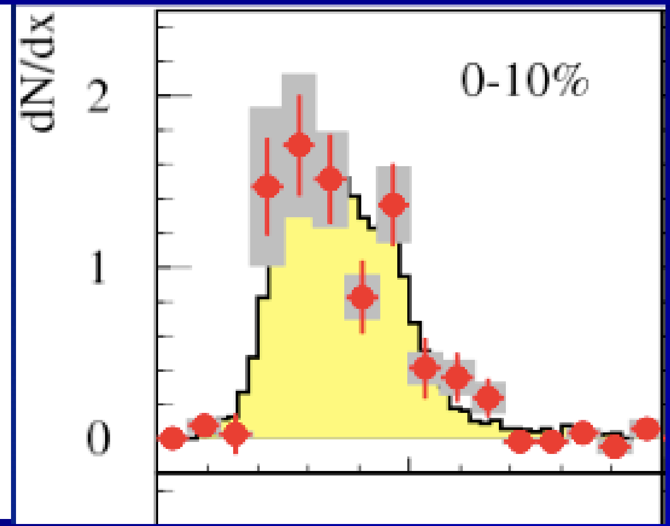
Jet propagation in a uniform medium



γ-jets in an expanding medium

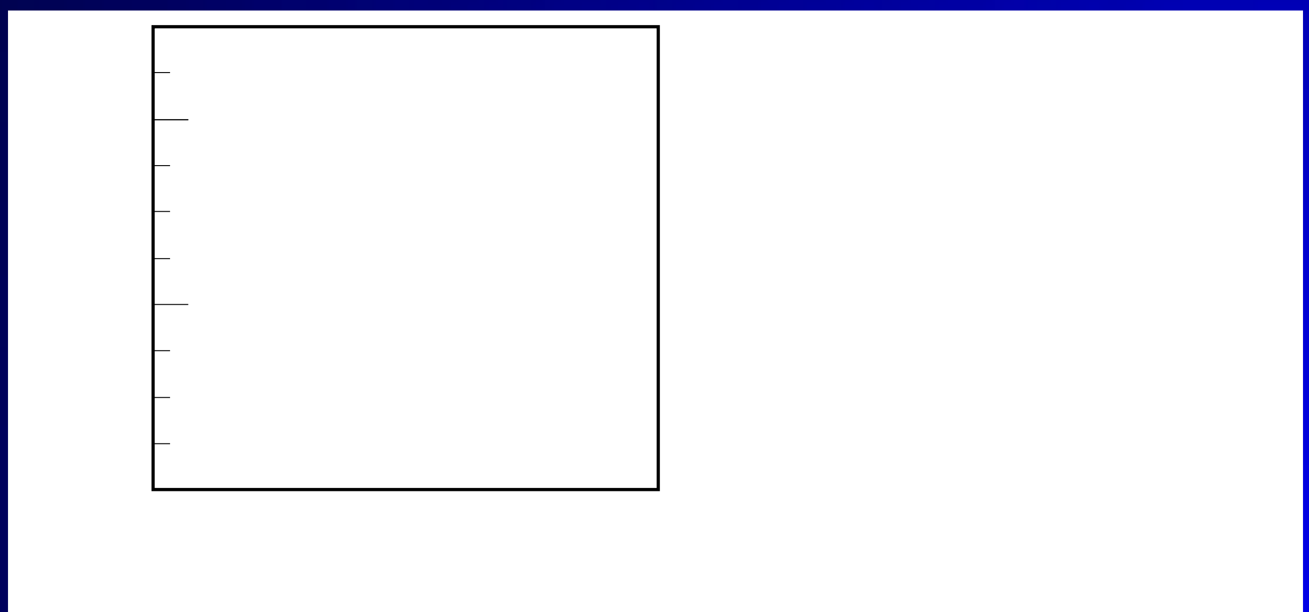
Similar results by Dai, Vitev and Zhang, PRL 110 (2013) 032302





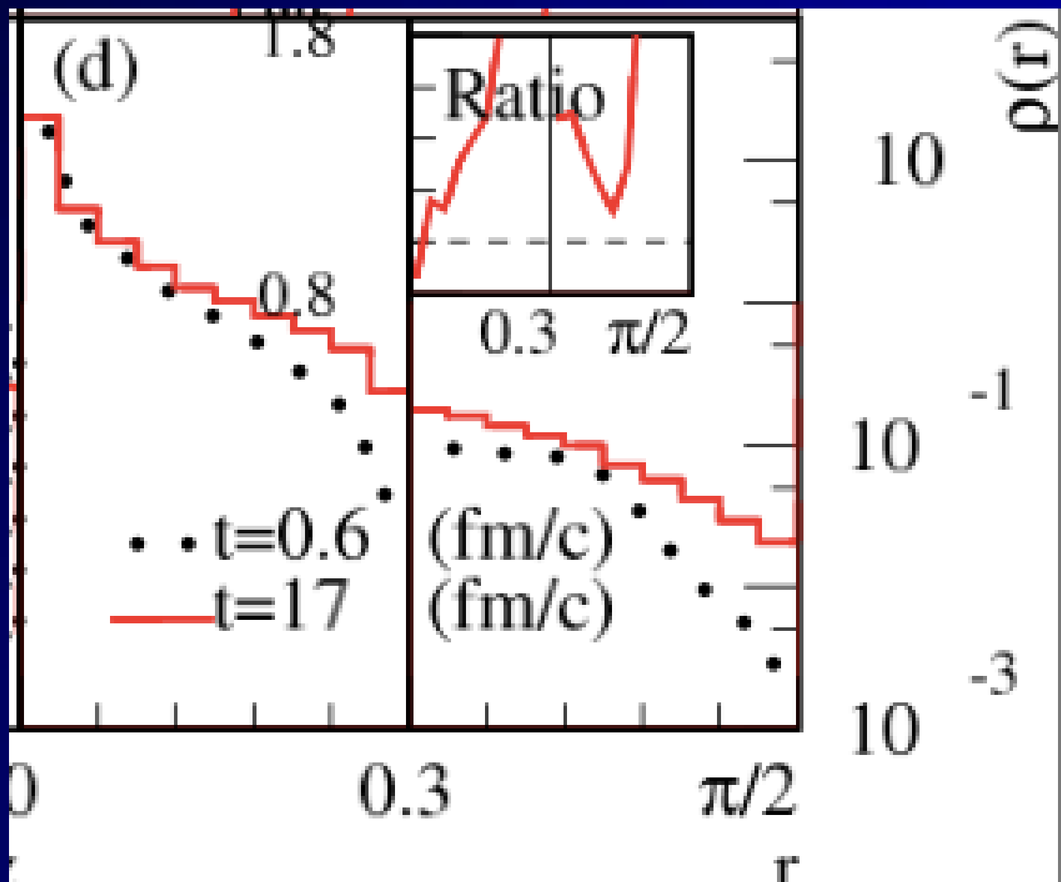
XNW and Zhu, PRL 111 (2013) 062301

$$x = \frac{P_T}{P_T^{\gamma}}$$



Broadening of jet transv. profile

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

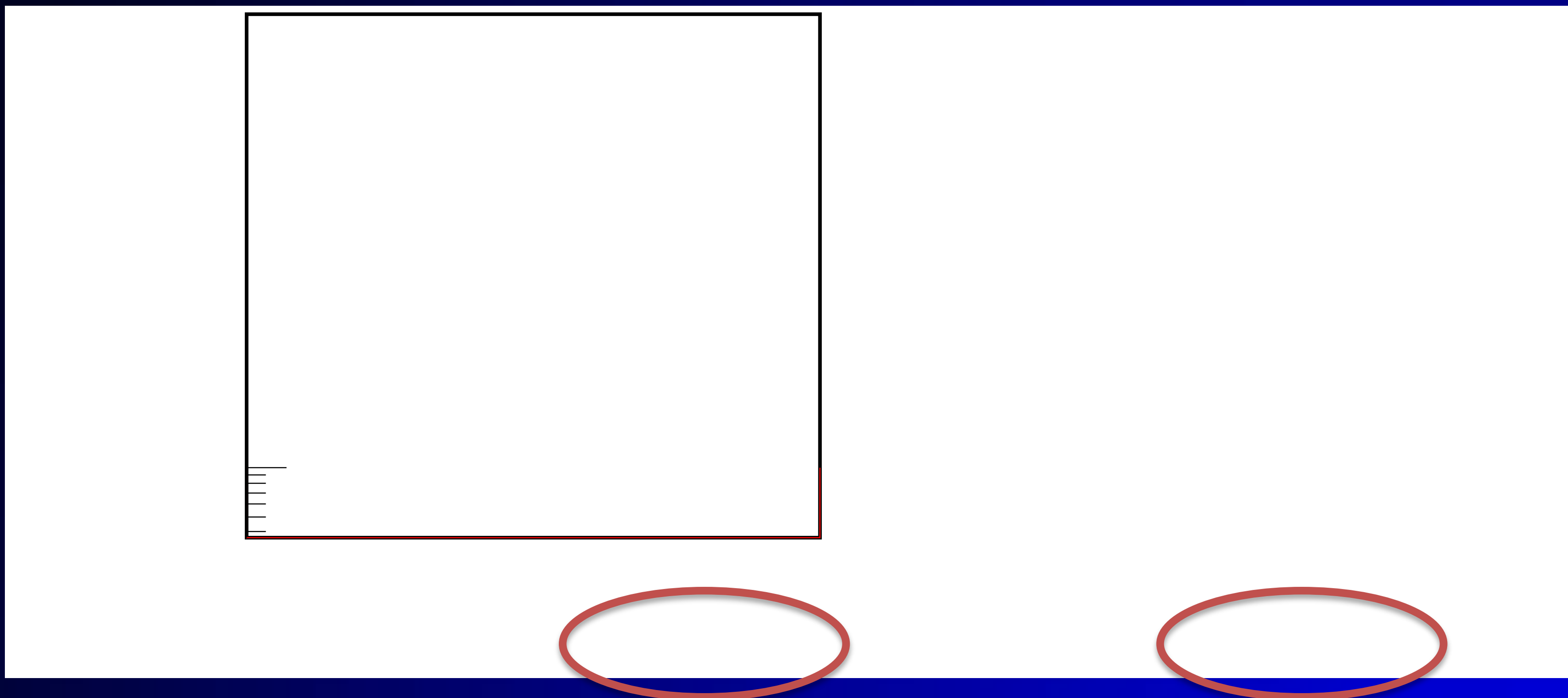


R=0.3

Medium mod. of frag function

Seen in CMS & ATLAS single jets

XNW and Zhu, PRL 111(2013)062301

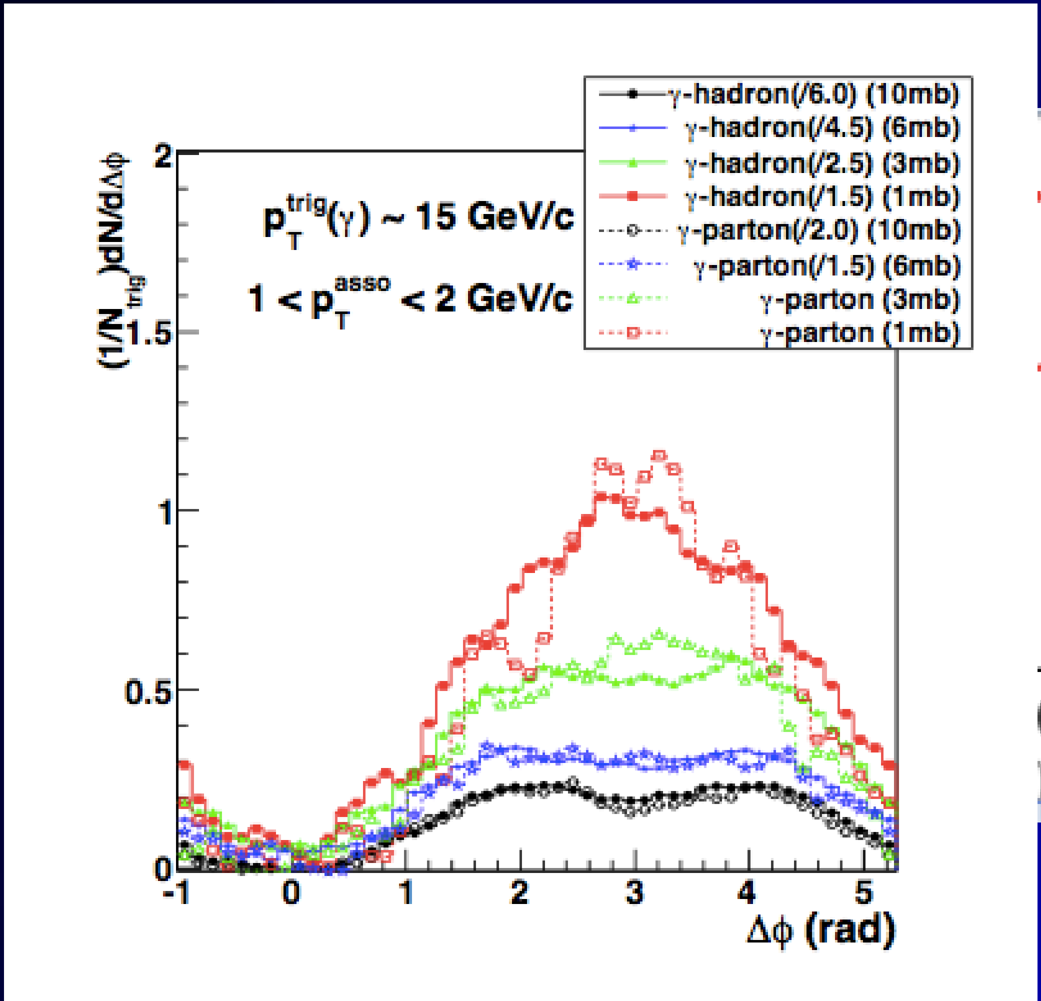


XNW, Huang & Sarcevic (1996)

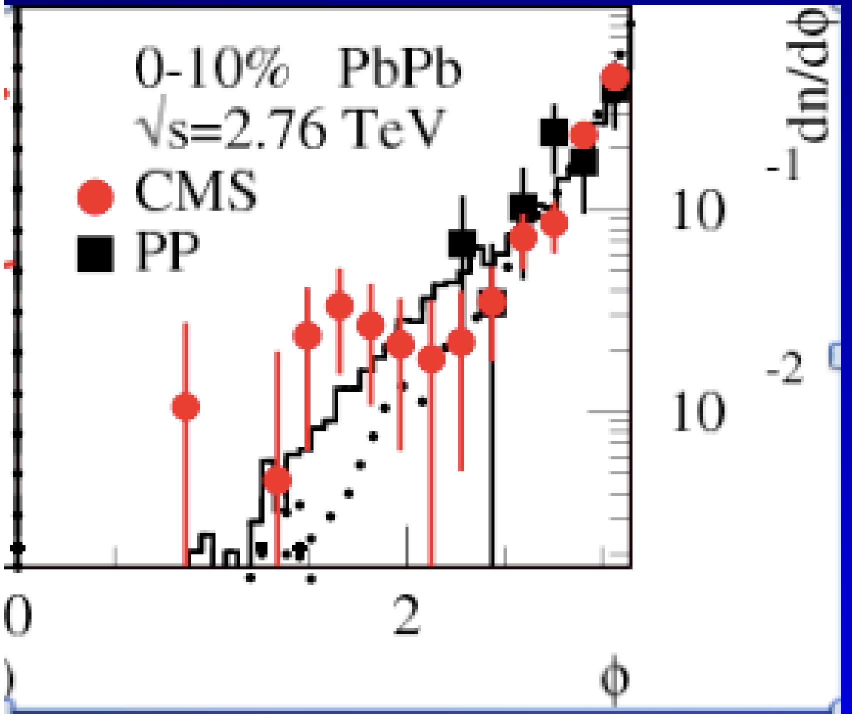
Energy of reconstructed jet dominated by leading particle
Suppression of fragmentation functions relative to initial energy

Broadening of γ-hadron correlation

γ-hadron from AMPT calculation



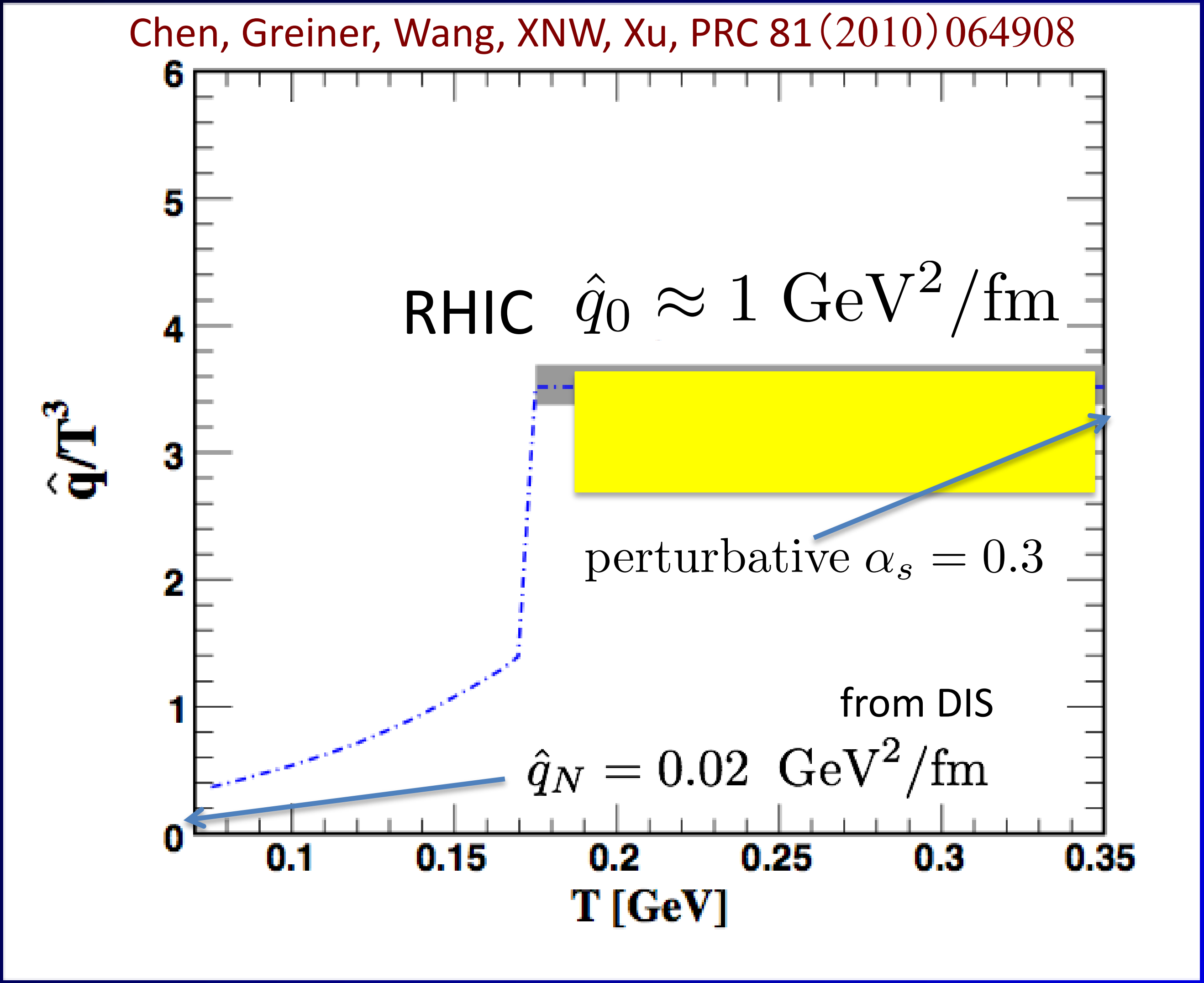
γ-jet from LBT



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

Future perspective: extracting qhat



Deng & XNW PRC 81 (2010) 024902

Future perspective: NLO

See talk by Hongxi Xing on Thuyrsday @ NLO meeting

SIDIS

$$\frac{d\langle \ell_{hT}^2 \sigma\rangle}{dz_h} = \sigma_0 \int_{z_h}^1 \frac{dz}{z} D_{q/h}(z,\mu^2) \int_{x_B}^1 \frac{dx}{x} T_F(x,0,0,\mu^2)\delta(1-\hat{x})\delta(1-\hat{z})$$
$$+ \sigma_0 \frac{\alpha_s}{2\pi} \int_{z_h}^1 \frac{dz}{z} D_{q/h}(z,\mu^2) \int_{x_B}^1 \frac{dx}{x} \left\{ \ln\left(\frac{Q^2}{\mu^2}\right) \left[\left(\delta(1-\hat{x}) P_{qq}(\hat{z}) + \delta(1-\hat{z}) P_{qq}(\hat{x})\right) T_F(x,0,0,\mu^2) \right.\right.$$
$$\left.\left. + \ \delta(1-\hat{z}) P_{qg\to qg}(\hat{x}) \otimes T_F(x,x,x_B,\mu^2) \right] + \left(F^C(\hat{x},\hat{z}) + F^A(\hat{x},\hat{z})\right) \otimes T_F(x,x,x_B,\mu^2) \right\}$$

DY

$$\frac{d\langle q_T^2 \sigma\rangle^{DY}}{dQ^2} = \sigma_0^{DY} \int \frac{dx'}{x'} f_{\bar{q}}(x',\mu^2) \int \frac{dx}{x} T_F(x,0,0,\mu^2)\delta(1-z)$$
$$+ \sigma_0^{DY} \frac{\alpha_s}{2\pi} \int \frac{dx'}{x'} f_{\bar{q}}(x',\mu^2) \int \frac{dx}{x} H^{NLO}(z,x) \otimes T_F(x,x,x_B,\mu^2)$$

DGLAP Eq. for Twist-4 correlation function:

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

BERKELEY LAB

MC approach to jet medium interaction

3+1D hydro + Jet transport + Hadronization

Berkeley-Wuhan Hybrid MC

3+1D hydro + Linear Boltzmann Jet Transport

Jet-induced medium excitation & anisotropic flow
Jet quenching in an anisotropic/expanding medum

Hydro description of A+A Collisions

- Hydrodynamic: $$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Delta T^{\mu\nu}$$

$$\Delta T^{\mu\nu} = \eta(\Delta^\mu u^\nu + \Delta^\nu u^\mu) + (\frac{2}{3}\eta - \zeta)H^{\mu\nu}\partial_\rho u^\rho$$

  - a low-momentum effective theory
  - Inputs from first principle QCD (lattice QCD) EoS $p(\varepsilon)$, transport coefficients $\xi(T)$, $\zeta(T)$ (??)
  - Initial condition: parton prod. & thermalization

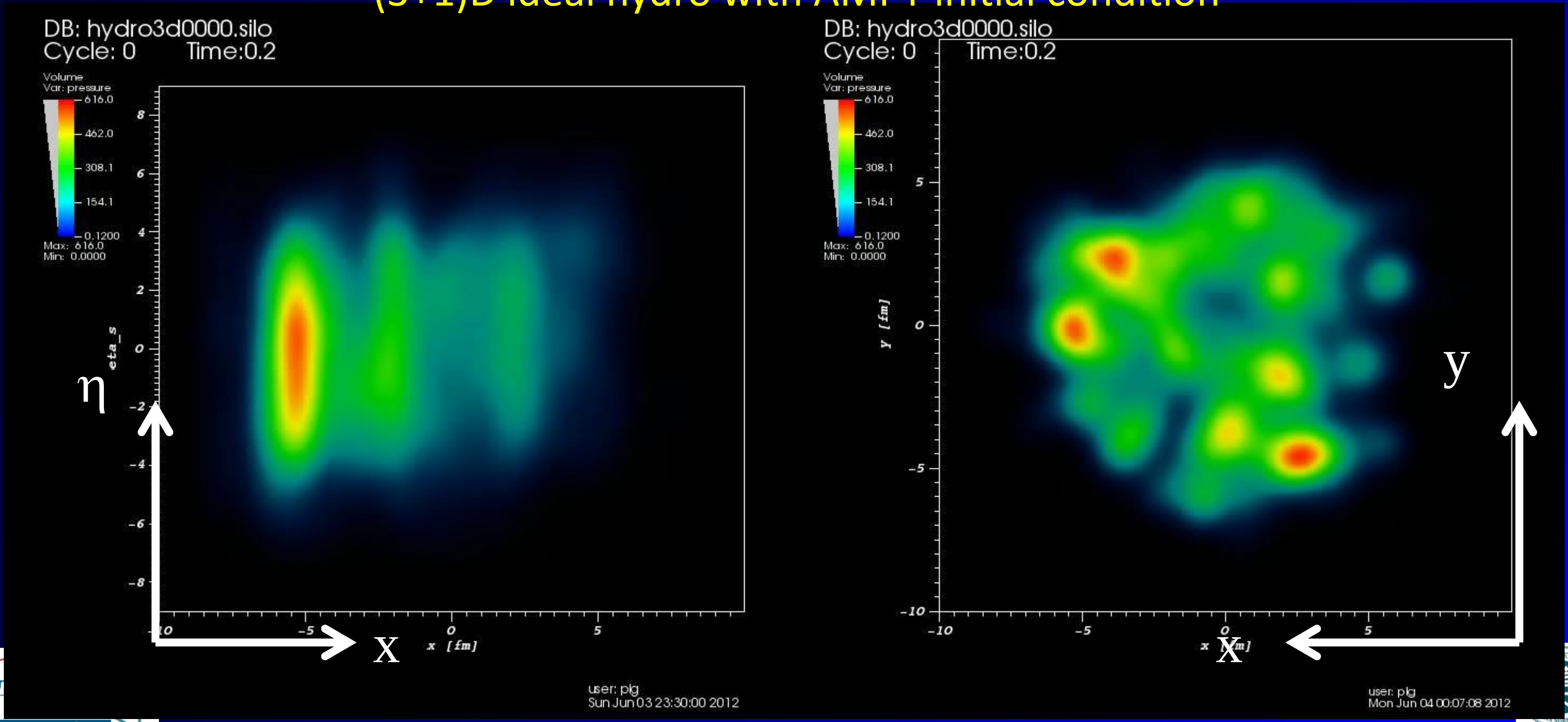
Initial conditions for hydro

2D fluctuating geometry: MC- Glauber, MC-KLN

2D fluctuating geometry + QM: IP-Glasma

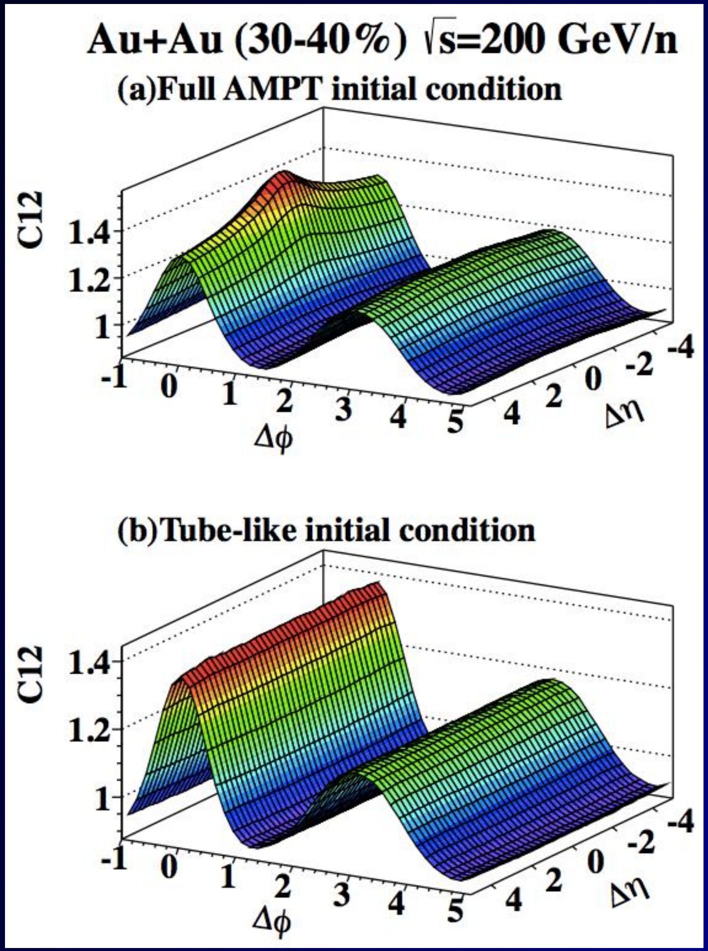
3D fluctuating geometry +QM: HIJING, AMPT, NeXus, UrQMD

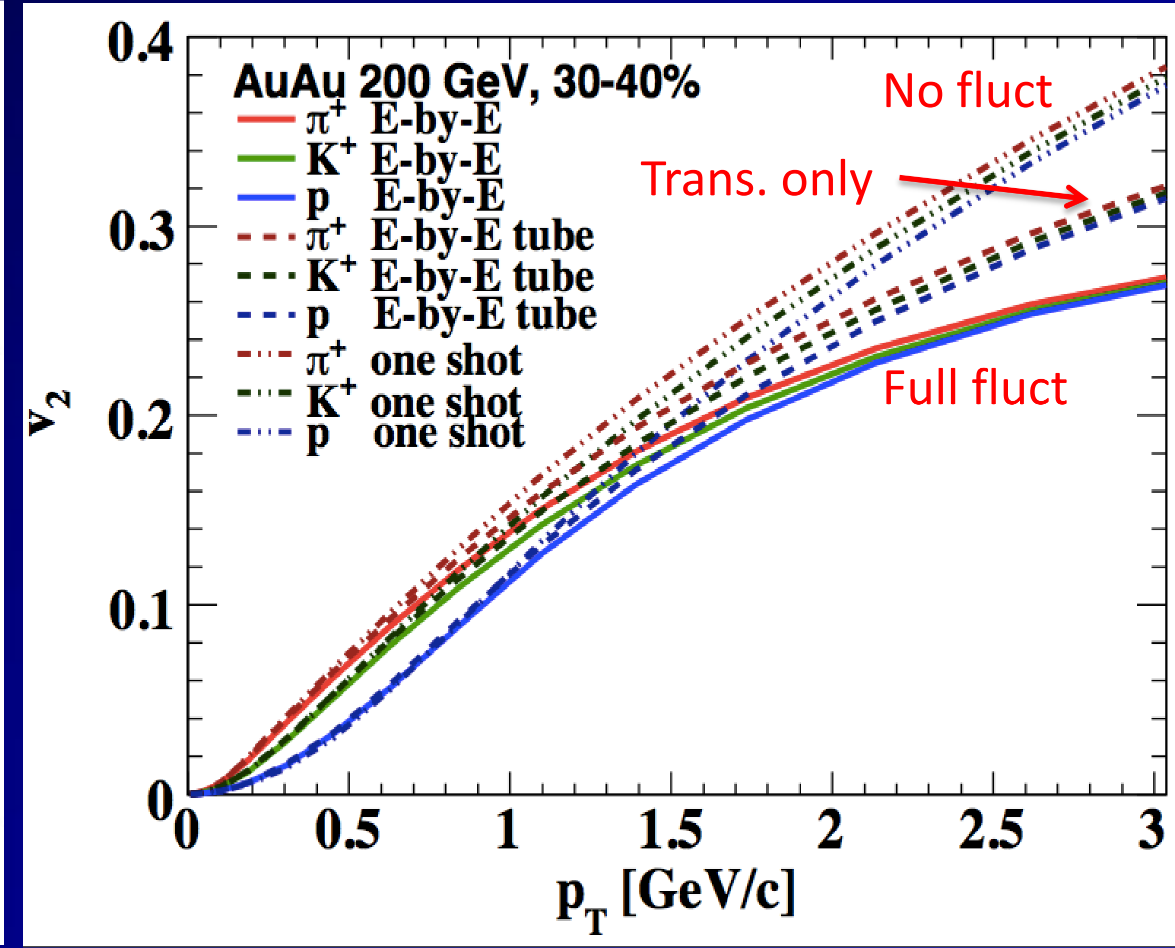
(3+1)D ideal hydro with AMPT initial condition



Effects of tran. & long. fluctuations

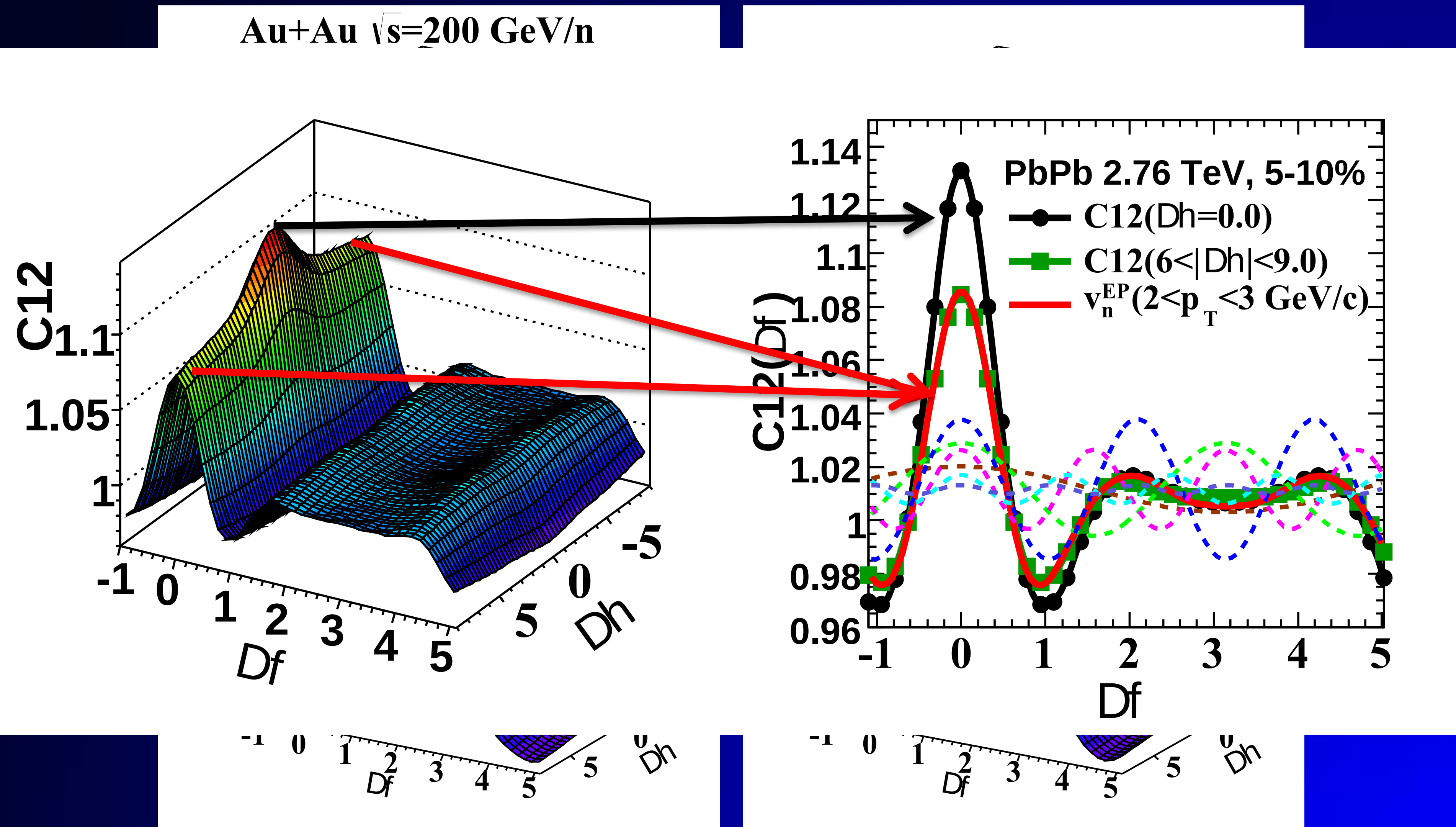
Pang , Wang and XNW PRC 81 (2012) 031903





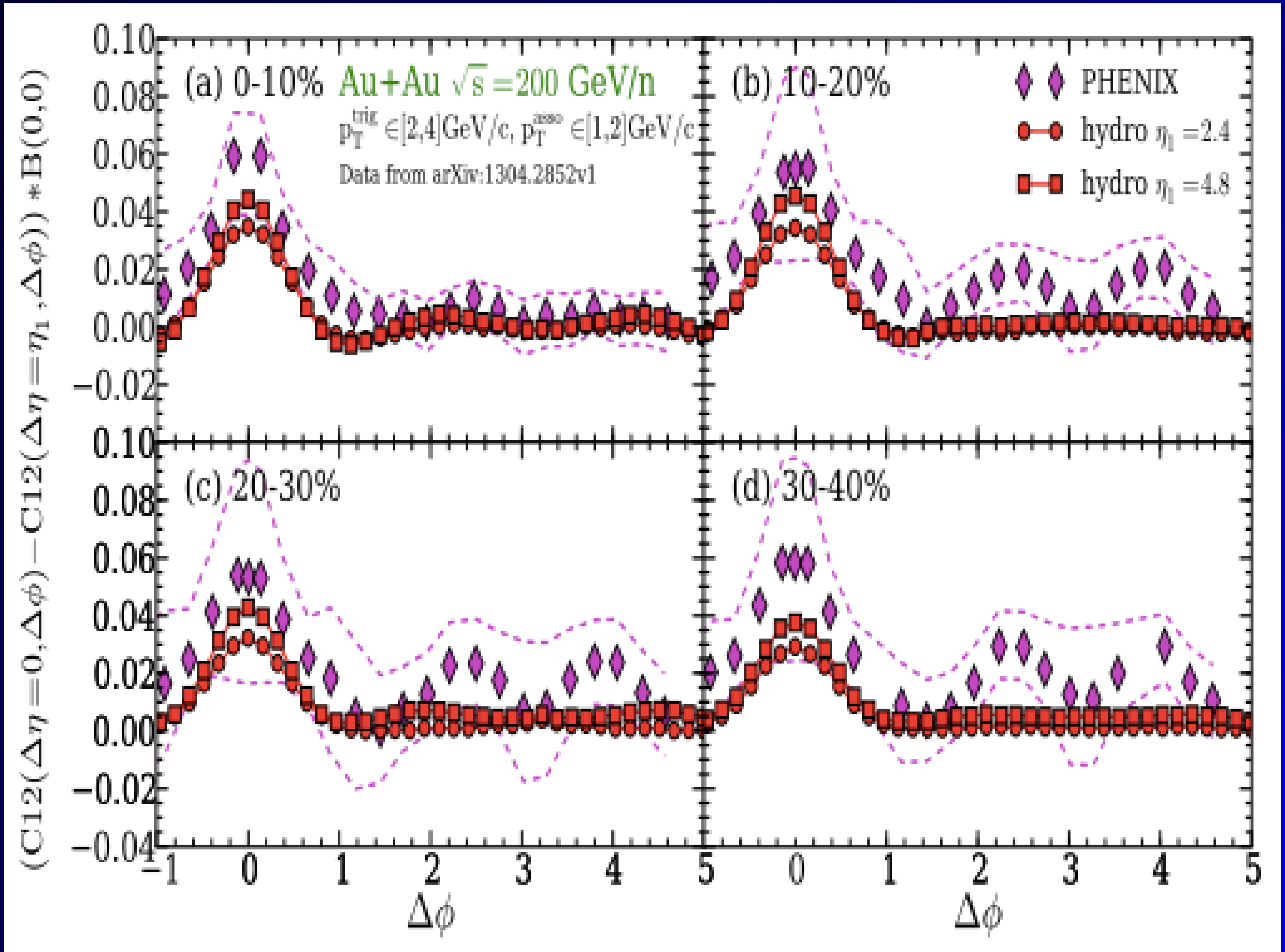
Anisotropic flow & relics of minijets

Pang, Wang & XNW 2013 (preliminary)



Anisotropic flow & relics of minijets

$$[C_{12}(\Delta\eta = 0) - C_{12}(\Delta\eta = 2.5)]\, B(0,0)$$

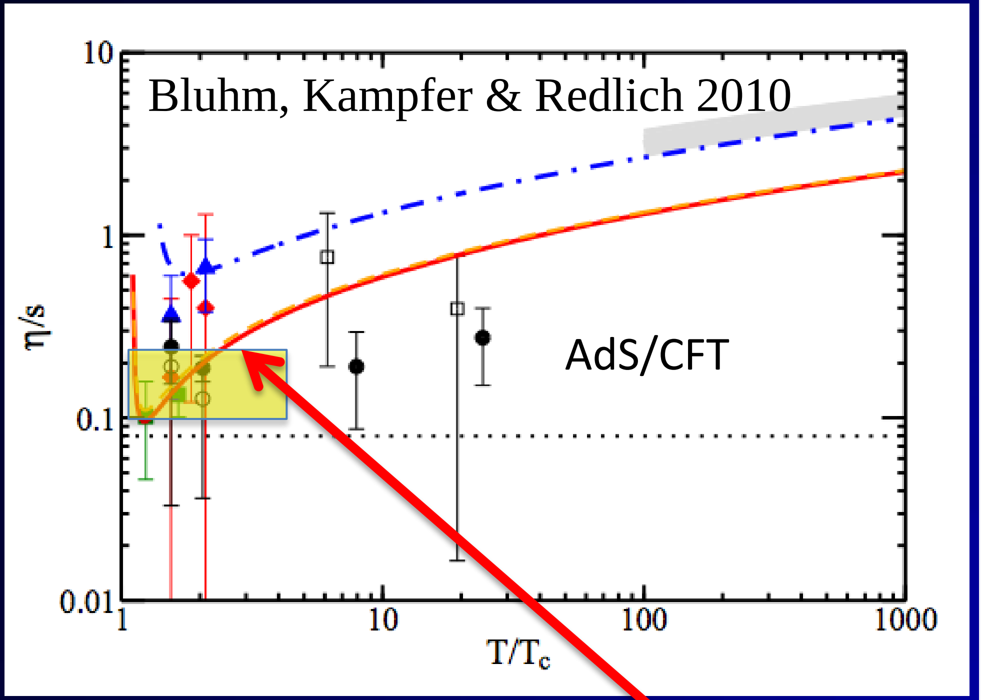


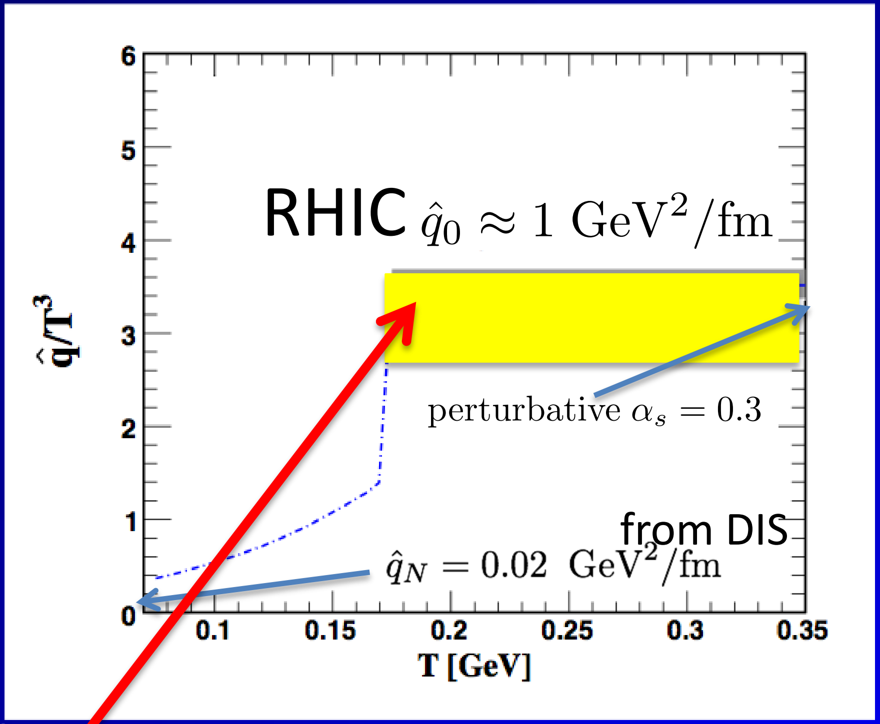
Pang, Wang & XNW 2013 (preliminary)

Summary

Hard probes and anisotropic flows provide unprecedented constraints on the transport properties of the sQGP in A+A

Future: mapping out T-dependence at RHIC & LHC





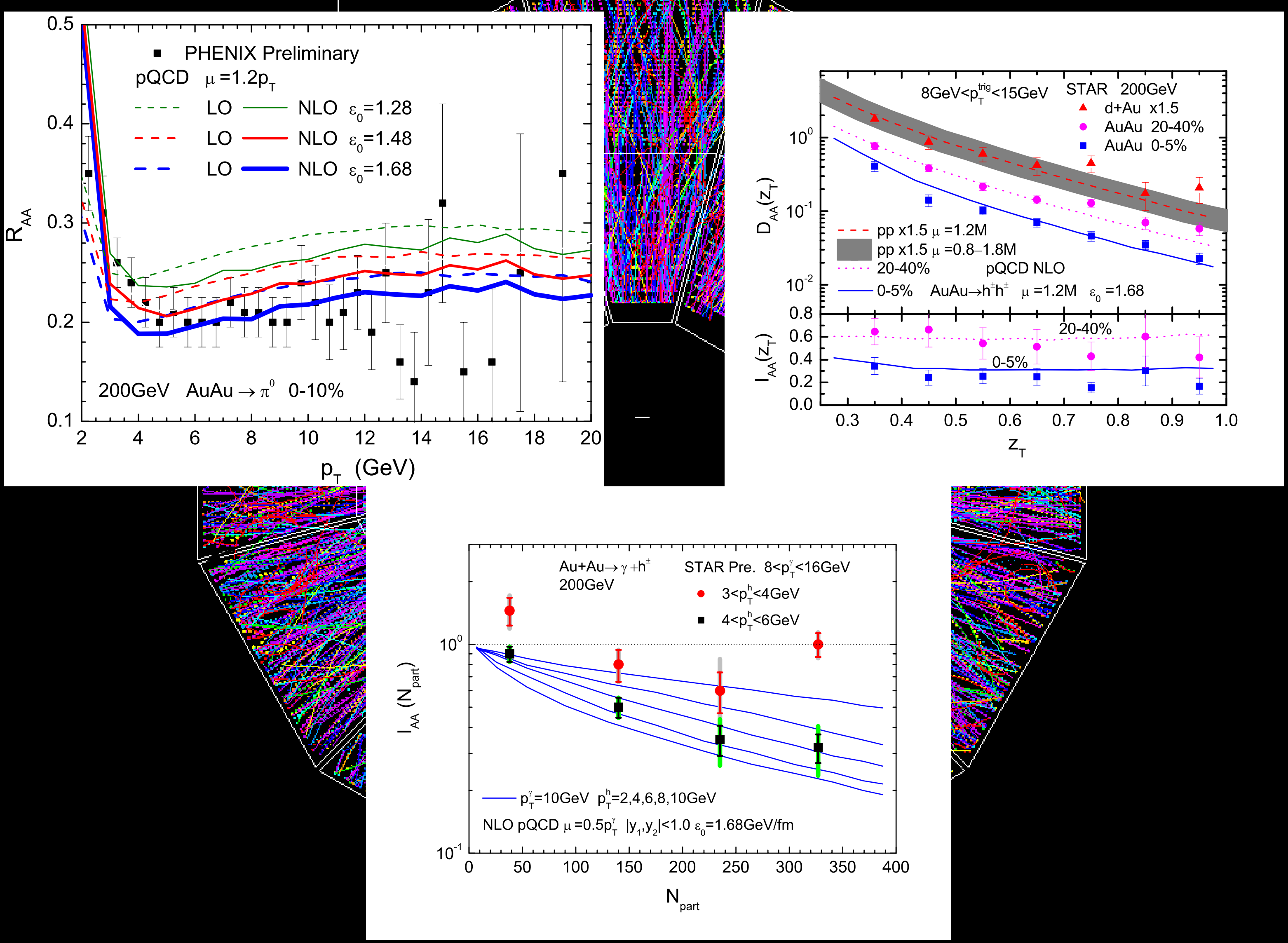
$$\frac{\eta}{s} \geq \frac{3T^3}{2\hat{q}}$$

Majumder, Muller & XNW 2007

Jet Quenching phenomena at RHIC

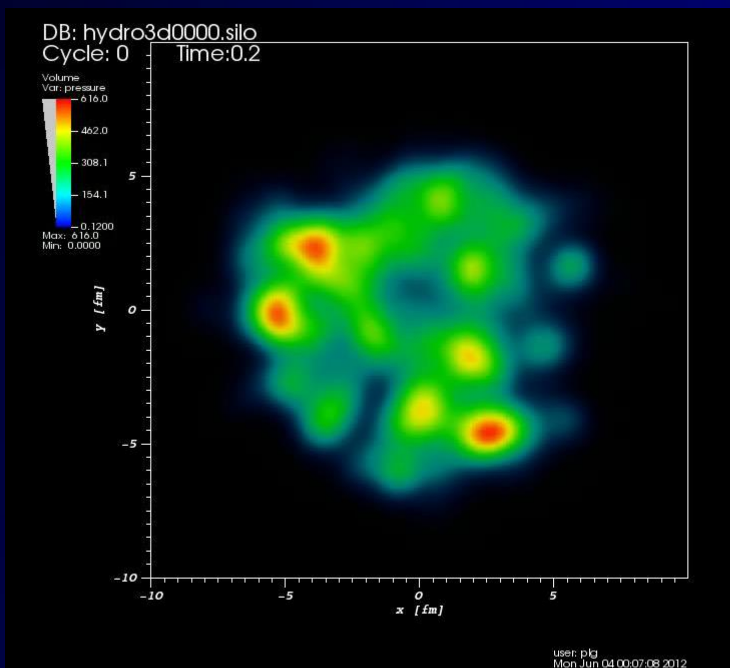
Zhang, Owns, Wang, XNW, PRL 98 (2007) 212301

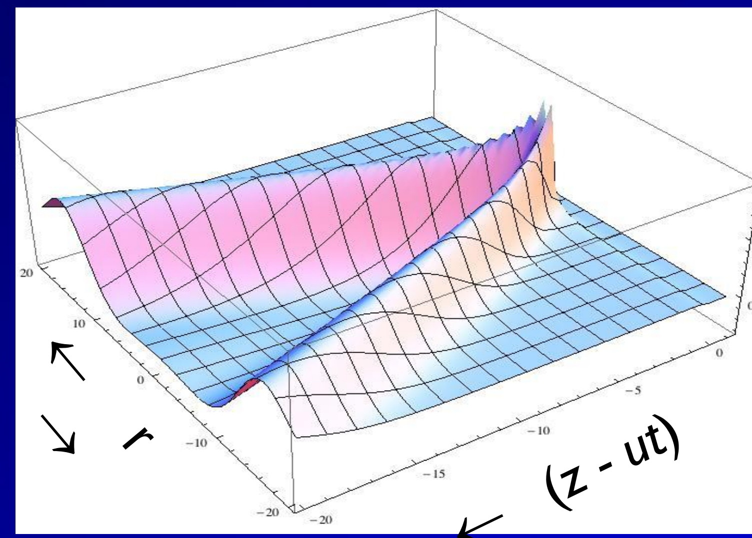
Zhang, Owns, Wang, XNW, PRL 103 (2009) 032302



Hydro dynamics of dense matter

$$\partial_\mu T^{\mu\nu} = j^\nu$$

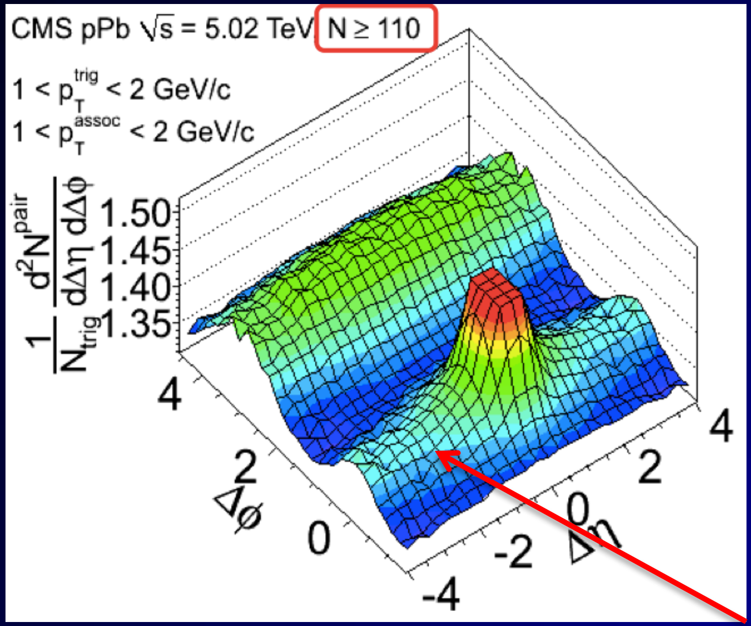


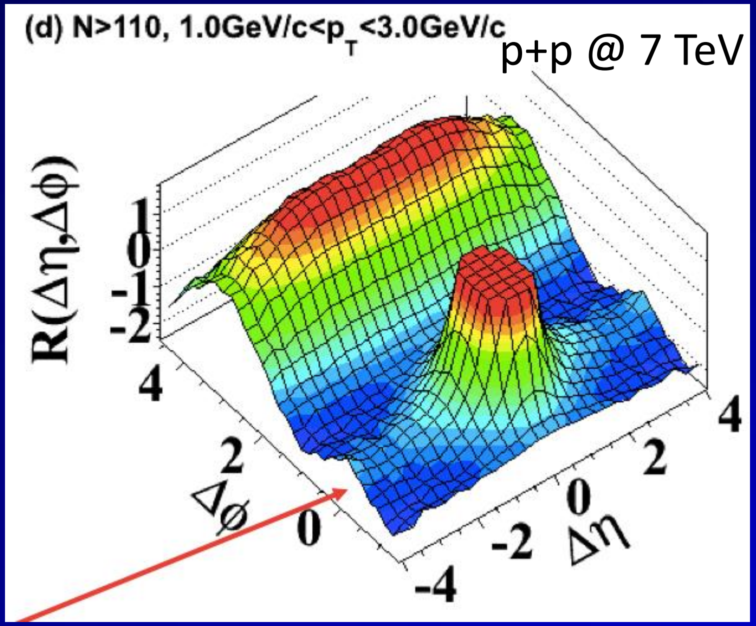


c_s

EOS of QGP

QGP in p+p & p+A collisions?





Collective flow in high multiplicity events of p+p & pA?

But no jet quenching! Werner et al '12, Bozek & Broniowski'13

Maybe from initial state: glasma? Venugapalan & Dusling et al, '12

But large values of v3!

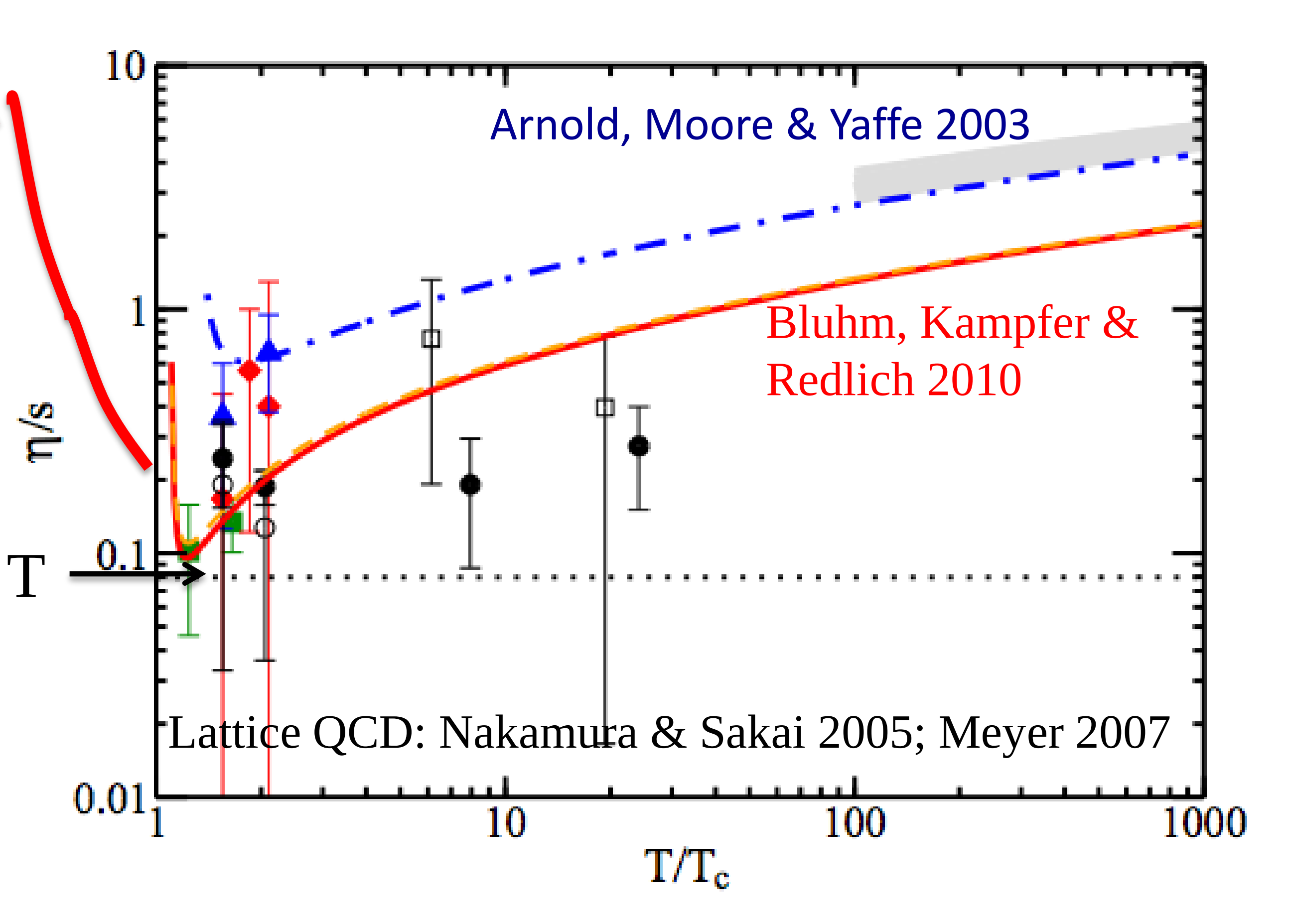
See talks by Roland (G1)

Transport properties of QCD matter

$$\eta = \lim_{\omega\to 0} \frac{1}{2\omega} \int dt dx e^{i\omega t} \langle [T^{ij}(x,t), T^{ij}(0,0)] \rangle$$

$$\frac{\eta}{s} = \frac{15}{16\pi} \frac{f_\pi^4}{T^4}$$

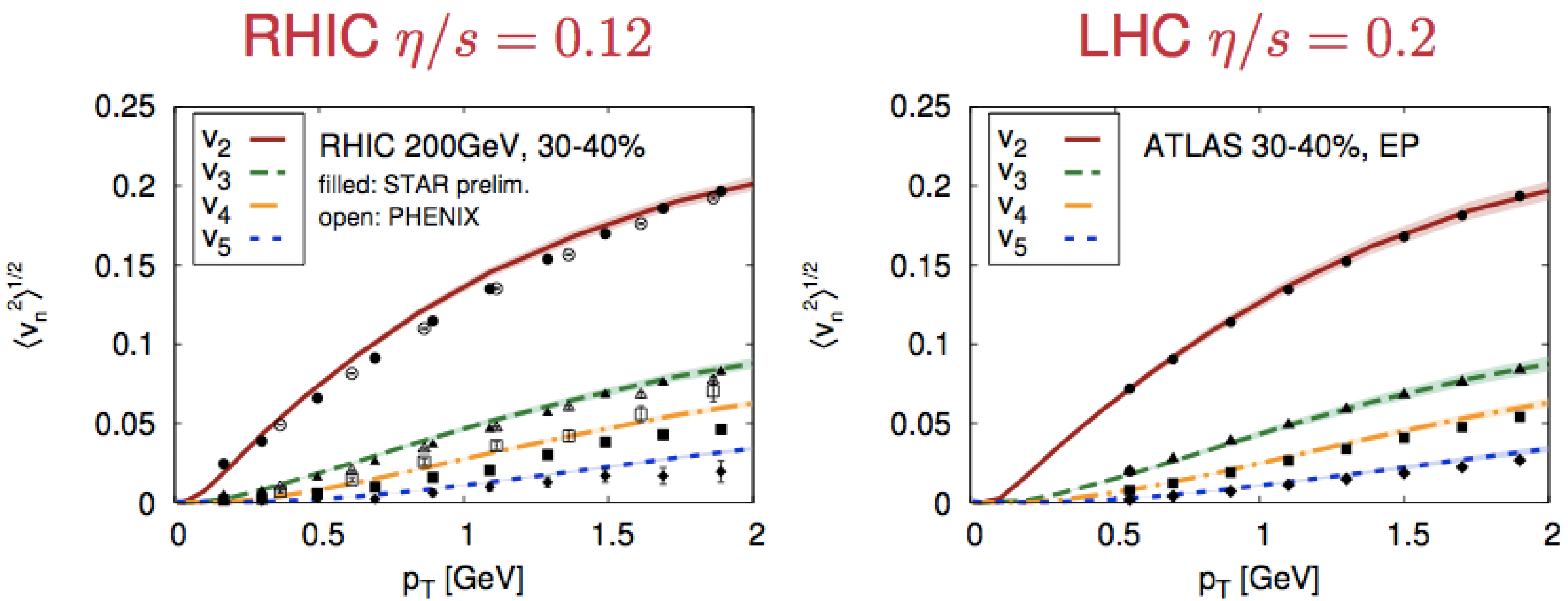
pion gas
Prakash'93



AdS/CFT

Viscosity of QGP in A+A collisions

Heinz & Song 2010 Gale, Jeon, Schenke, Tribedy & Venugopalan 2013

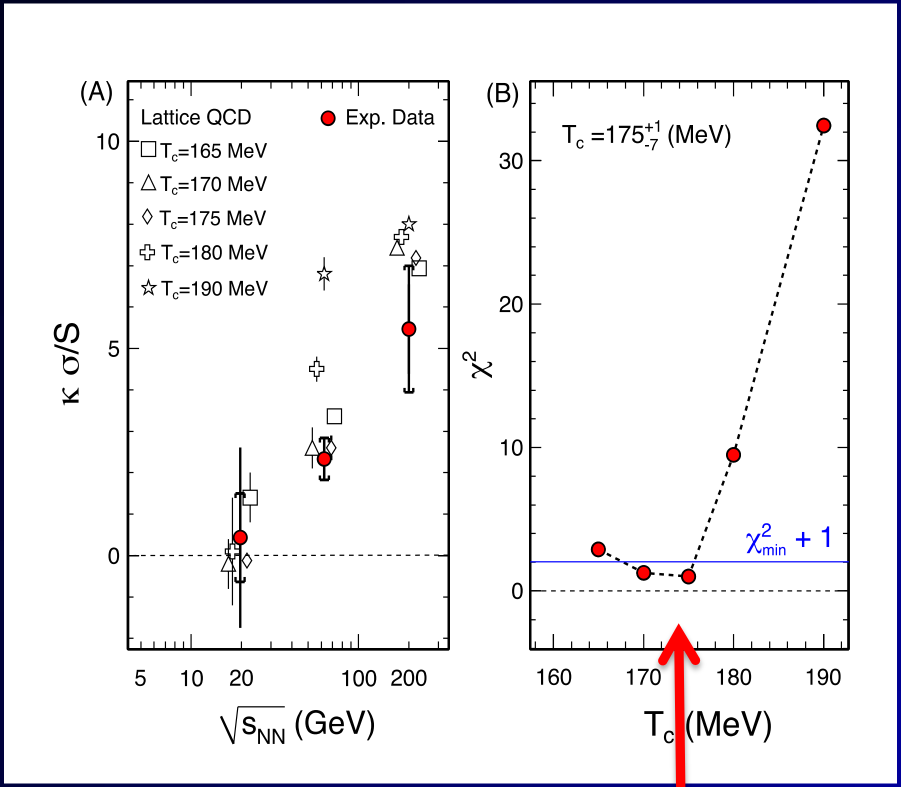


Fluctuation + viscous hydro required to fit all v_n

Viscosity at LHC is larger than at RHIC

See talk by Schenke (Wednesday, IUPAP prize)

Phase structure of QCD matter



$$[B^n] = VT^{n-1}\chi_B^{(n)}\left(\frac{T}{T_c}, \frac{\mu_B}{T}\right)$$

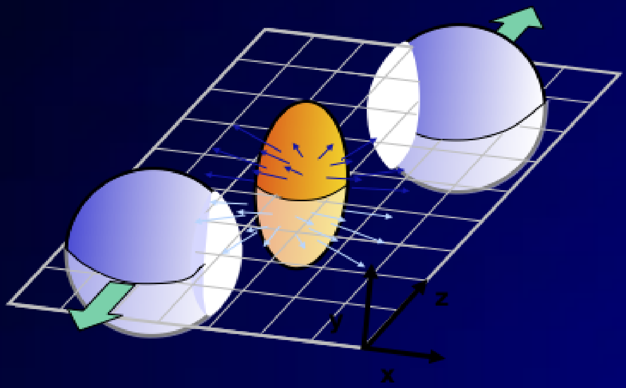
Fluctuation and T_c

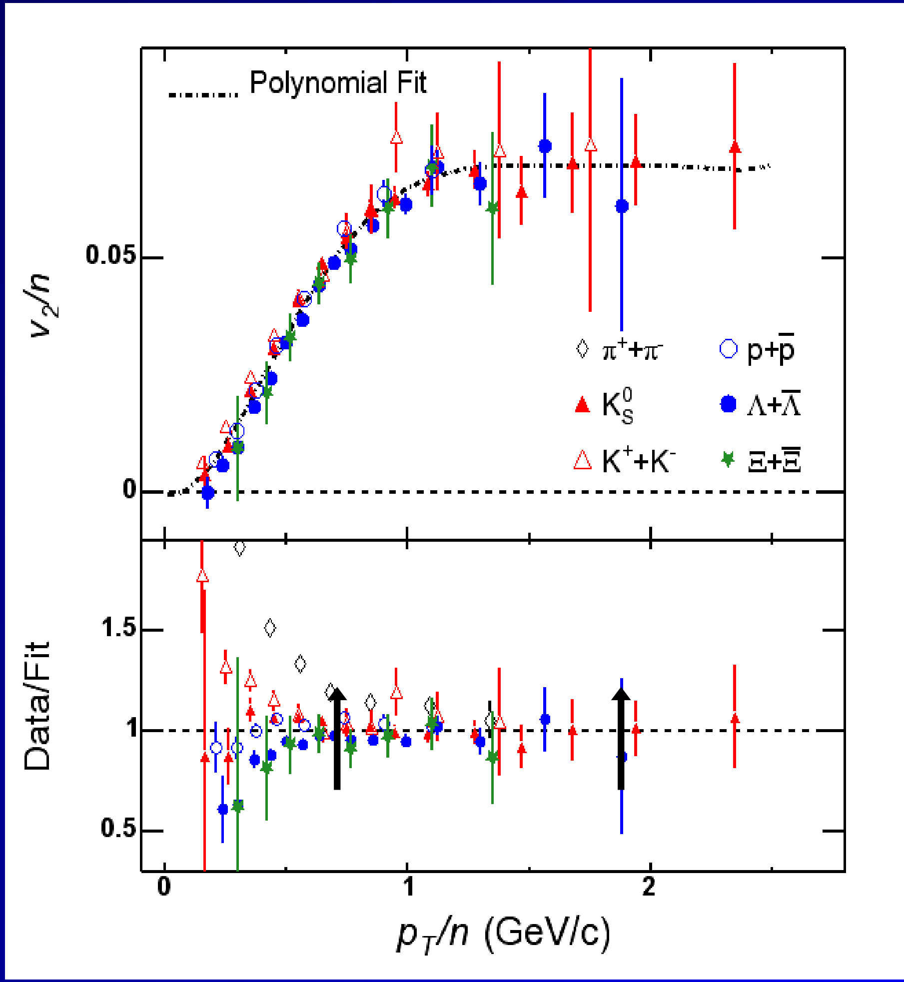
$$T_c = 175 \text{ MeV} \approx 2 \times 10^{14} \text{ K}$$

Quark number scaling of v2

STAR: Phys. Rev. Lett. **92**, 052302(04)

Anisotropic flow



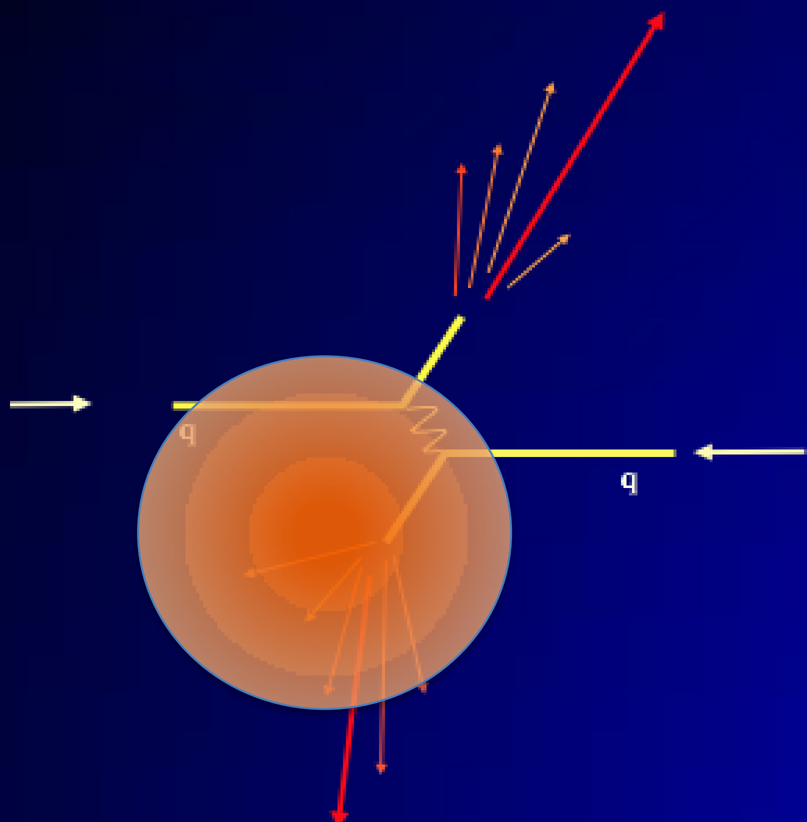


n: valence quark

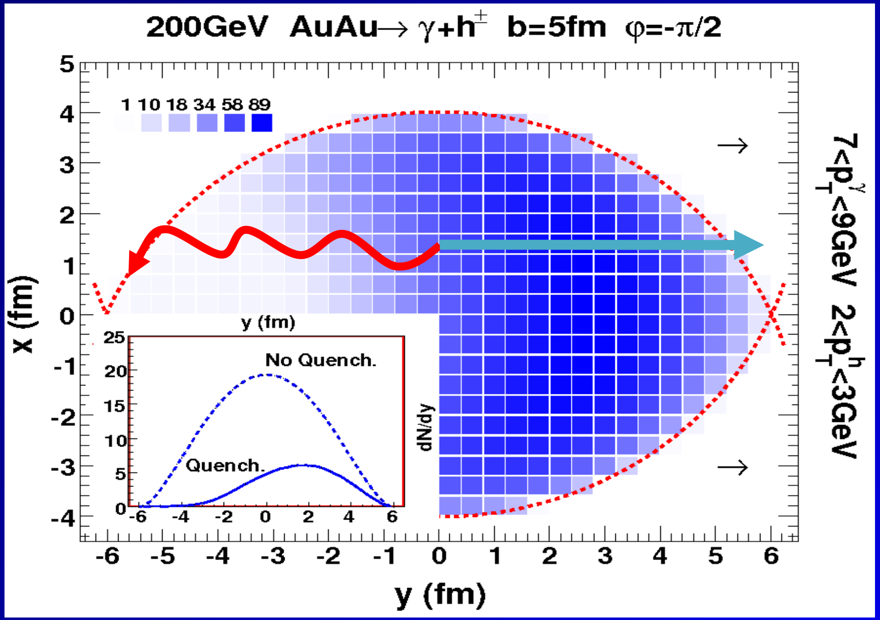
$$\frac{v_2(p_T/n)}{n}$$

Hard probes of dense matter

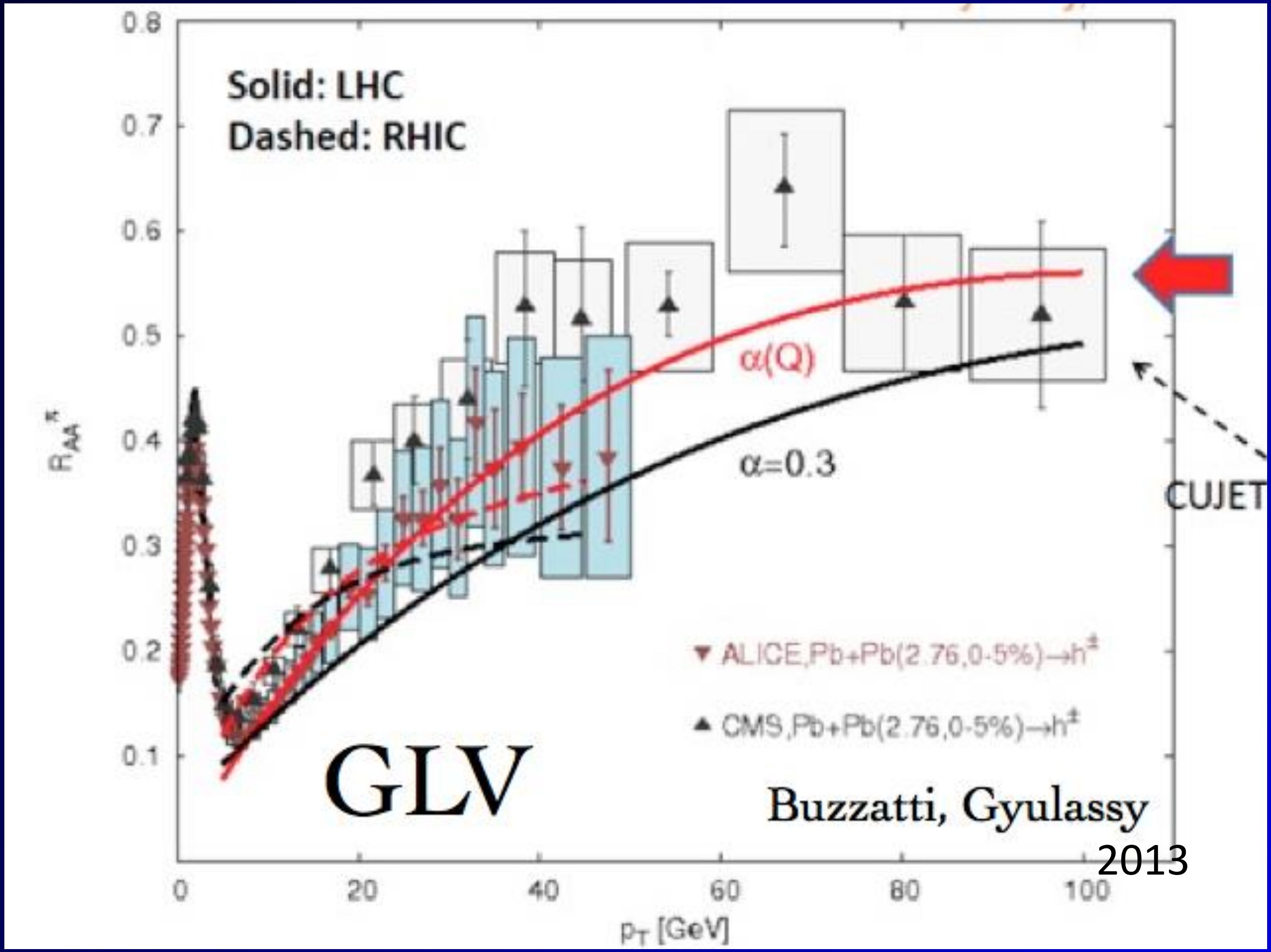
Jet quenching via parton energy loss



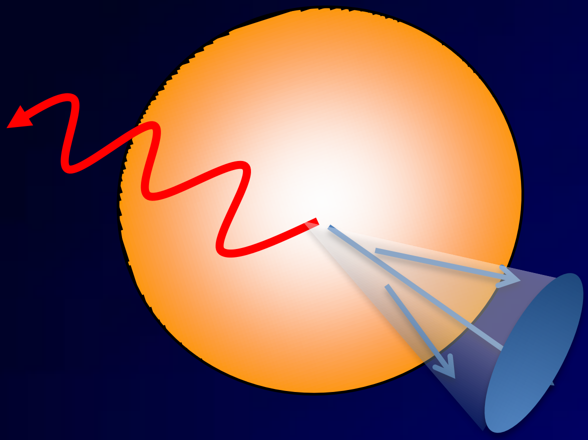
$$\frac{dE}{dx} \sim \rho(x)$$



Running coupling in jet quenching

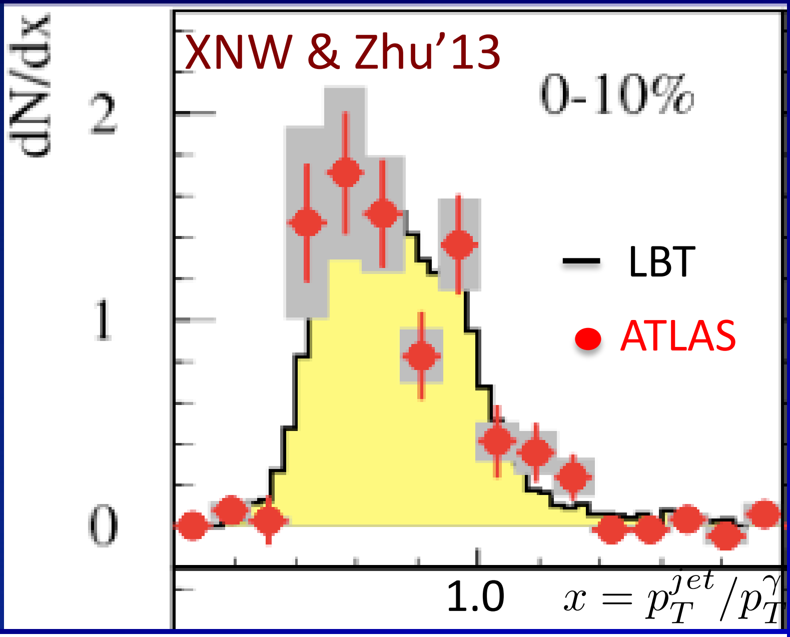


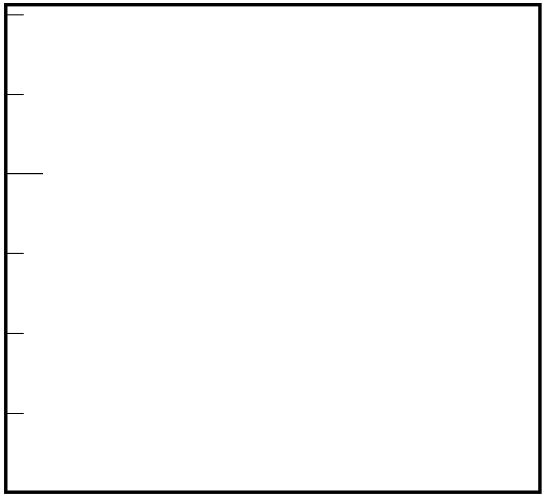
Gamma-jet asymmetry



$$\Delta E/E \approx 15\%$$

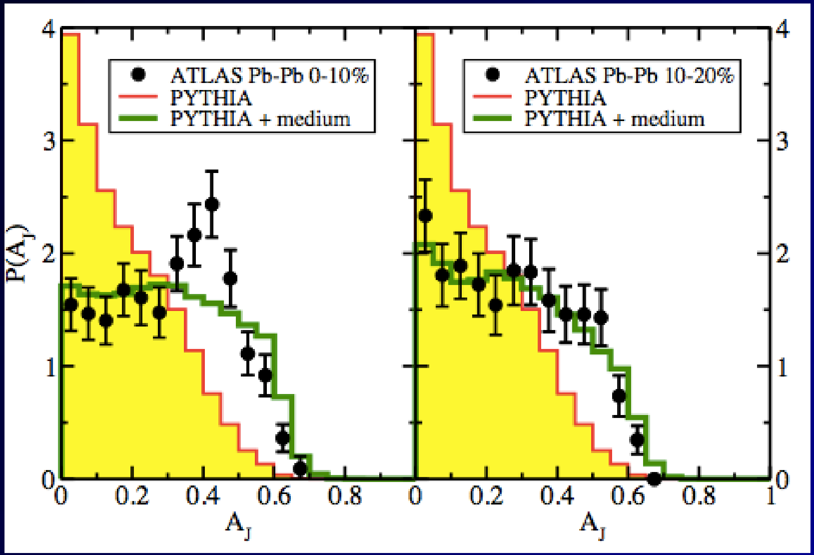
Rapid expansion & recoiled parton



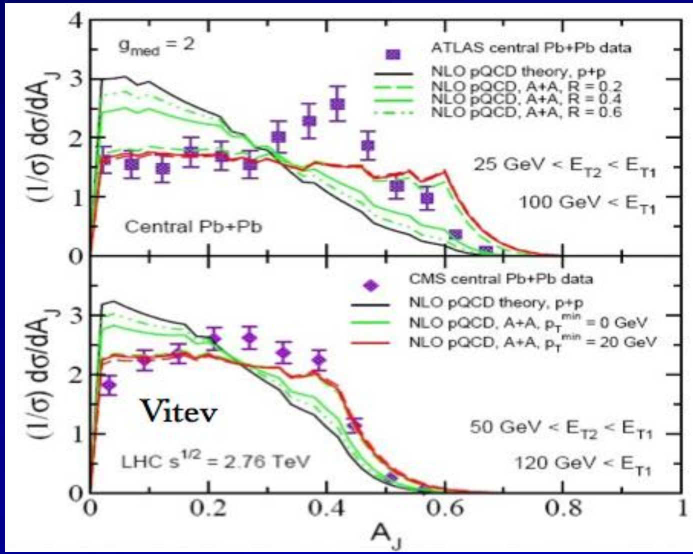


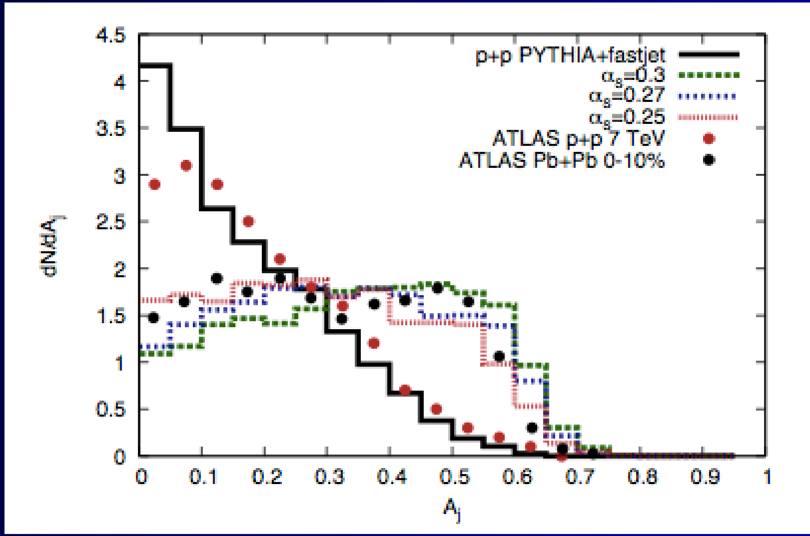
Dijet asymmetry at LHC

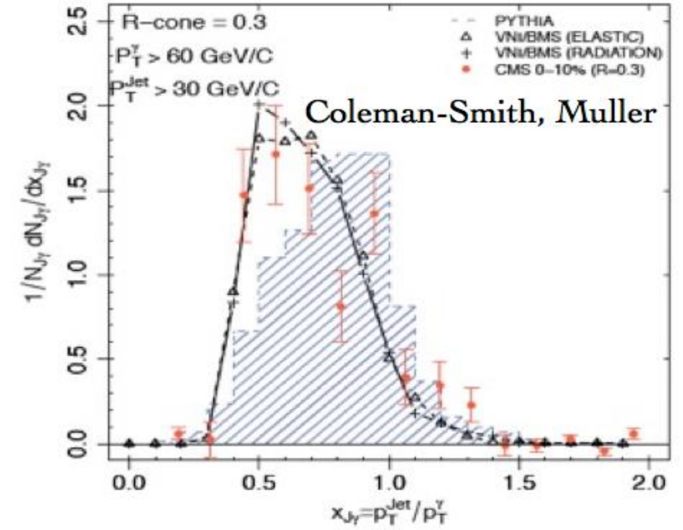
Qin & Muller' 2012



He, Vitev & Zhang' 2012



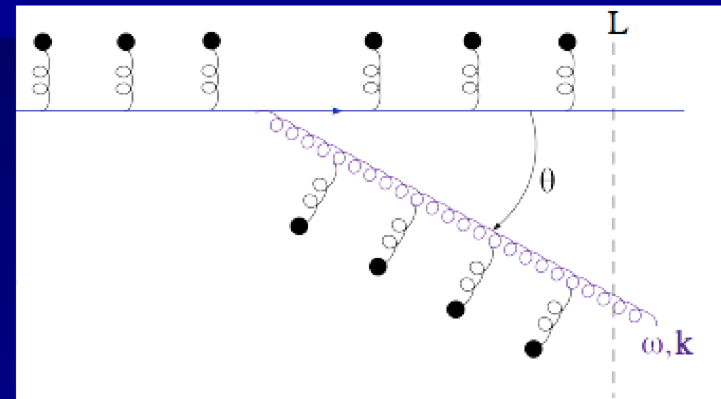




Young, Schenke, Jeon & Gale, 2012

Multiple scattering & angular ordering

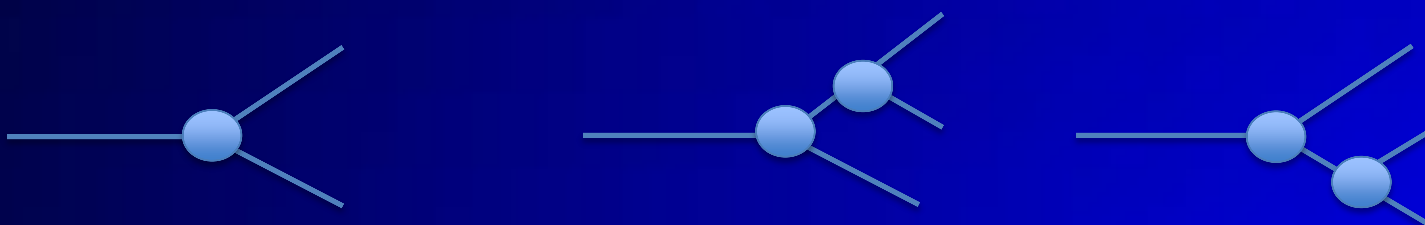
Formation time $$\frac{1}{\tau_f} \sim \frac{k_T^2}{2\omega}$$



$$\tau_f(\omega) \sim \sqrt{\frac{2\omega}{\hat{q}}} \qquad \theta \sim k_T/\omega \sim (\hat{q}/\omega^3)^{1/4}$$

Color coherence is rapidly lost in medium, independent emission is enhanced by L/τ_f

Blaizot, Dominguez, Iancu, Mehtar-Tani’ 12
Mehta-Tani,Salgado,Tywoniuk’10



Multi-scattering ⟶ Many-body int. ⟶ Hydrodynamics

JET Collaboration

Hard QCD Physics @ CCNU

- Jet physics:
  - W^2Z^2: Enke Wang, XNW, Benwei Zhang, Hanzhong Zhang – High-twist approach to parton energy loss
  - Bowen Xiao – hard processes at small x
  - Guangyou Qin – AMY jet quenching, and flow
  - Defu Hou – jet quenching in AdS/CFT
  - Chunbin Yang – Oregon-Wuhan (Hwa-Yang) recombination
  - Fuming Liu -- Direct photons
- Experiments:
  - ALICE@LHC, STAR@RHIC
- Lattice QCD
  - Hengtong Ding