XXIV QUARK MATTER DARMSTADT 2014

JET Collaboration

Qualitative extraction of qhat from combined jet quenching at RHIC and LHC

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BERKELEY LAB

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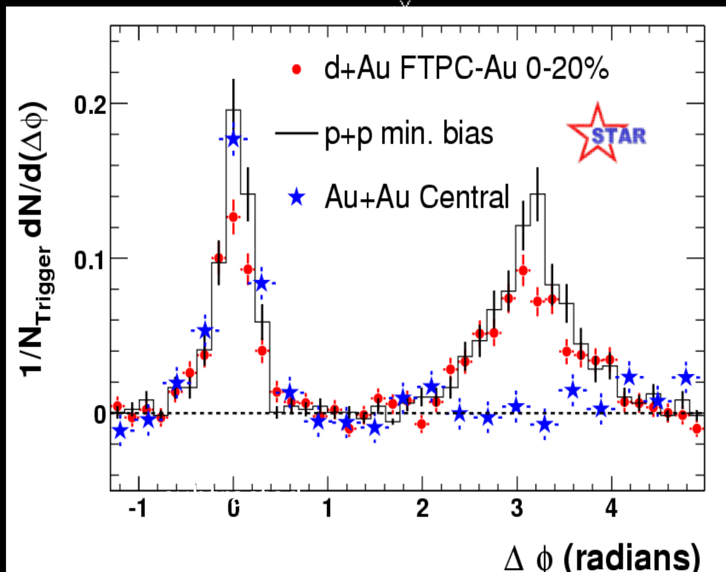
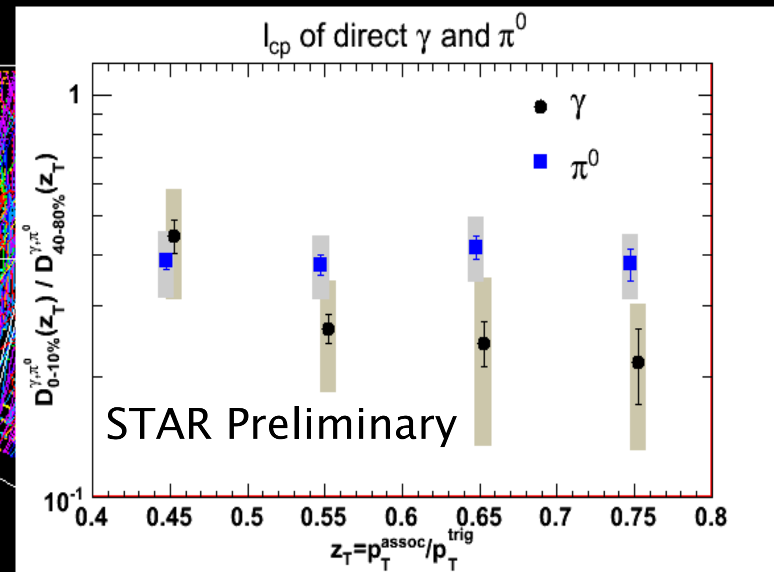
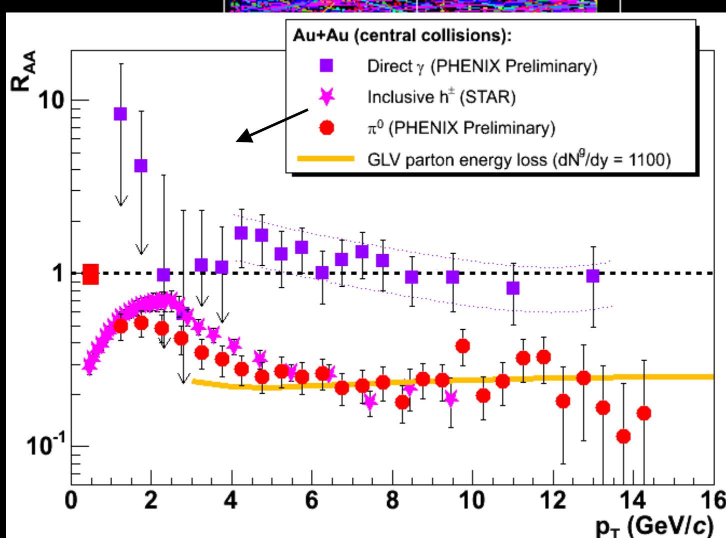
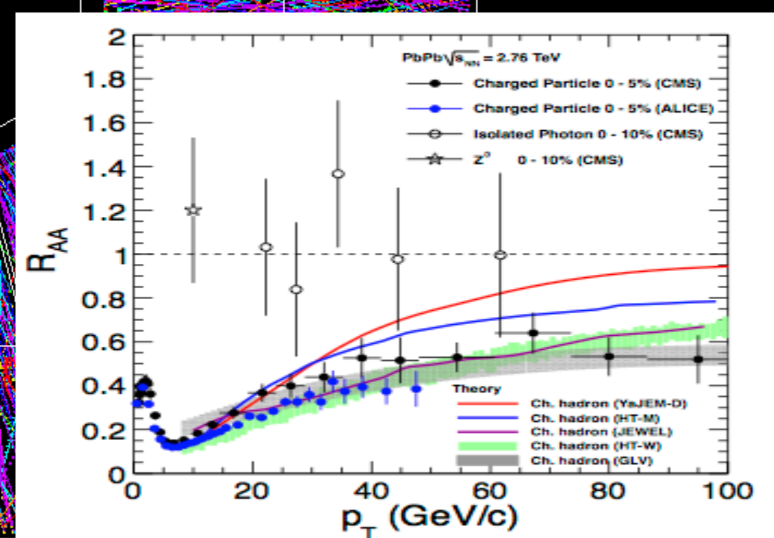
Jet Quenching at RHIC & LHC

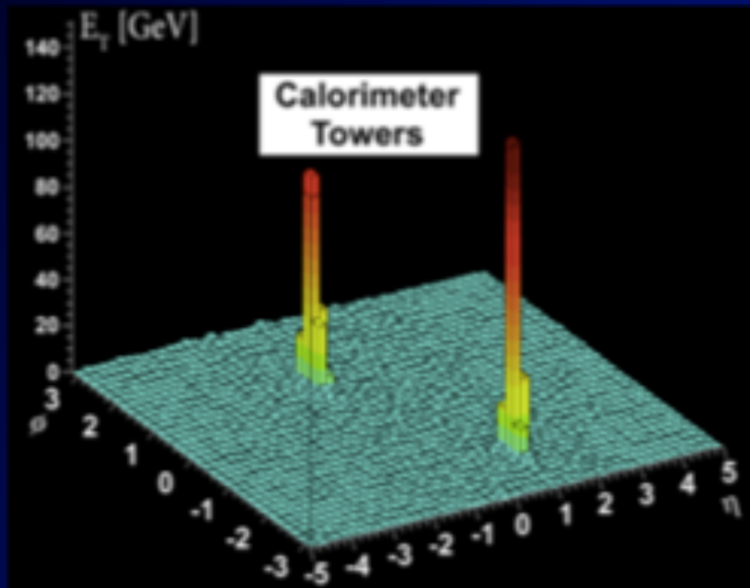


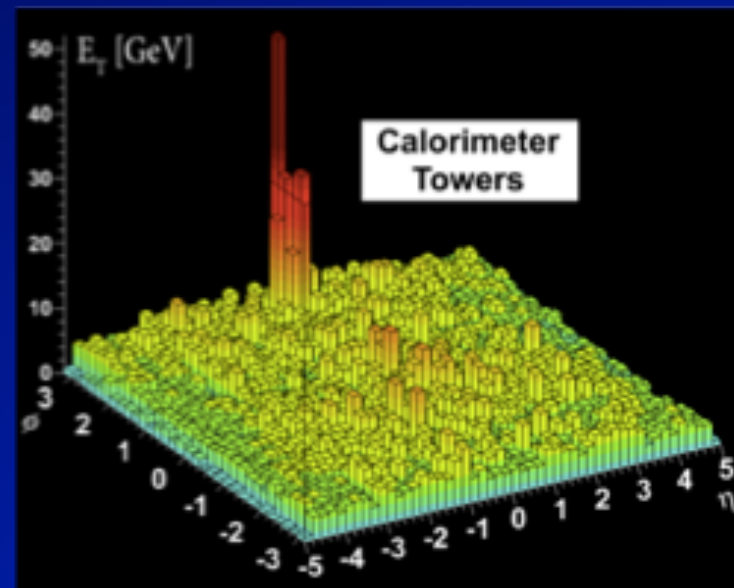


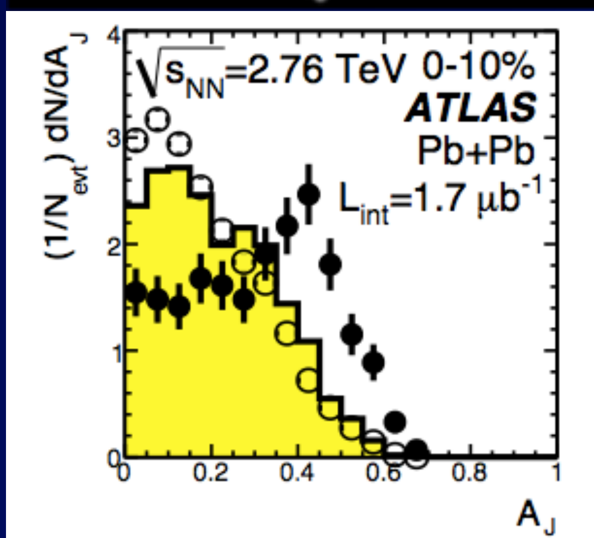




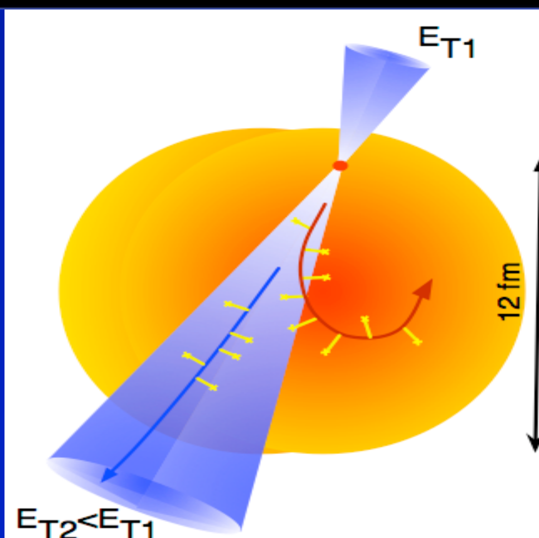
Jet Quenching at RHIC & LHC







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



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:

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

- 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:

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

- …

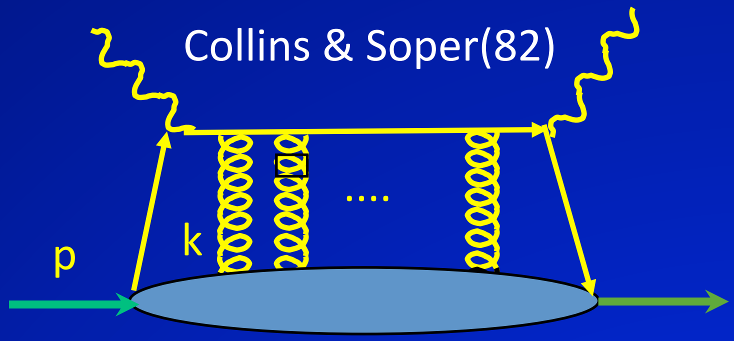
Parton scattering in medium

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

For an on-shell quark

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

$$f(y_\perp, L) = \frac{1}{N_c}\mathrm{Tr}\langle \mathcal{L}(0, L^-, \vec{y}_\perp)\rangle$$



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

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

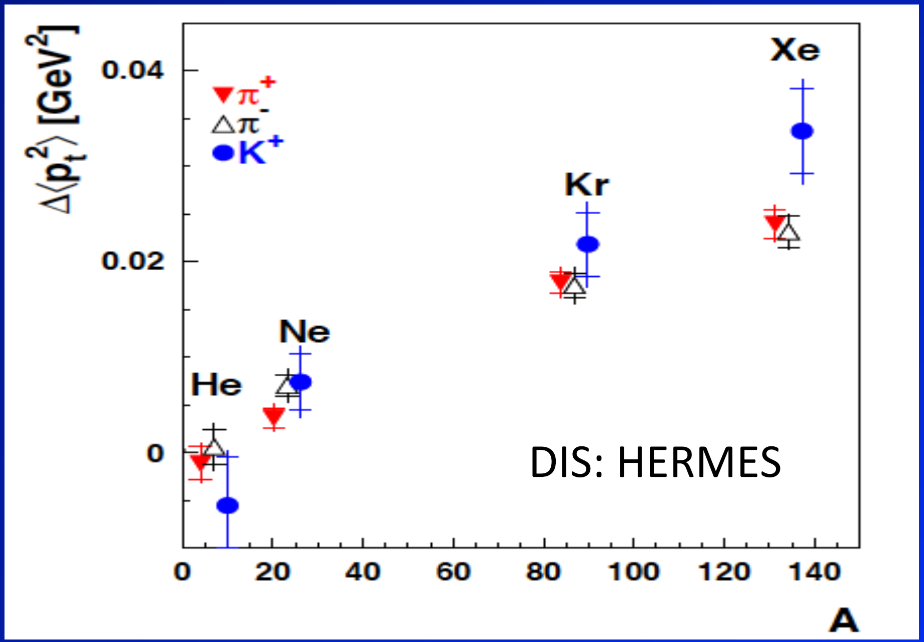
$$f_A^q(x,\vec{k}_\perp) \approx \frac{A}{\pi\Delta}\int d^2q_\perp \exp\left[-\frac{(\vec{k}_\perp-\vec{q}_\perp)^2}{L\hat{q}}\right] f_N^q(x,\vec{q}_\perp)$$

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

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

Cold nuclear matter:

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

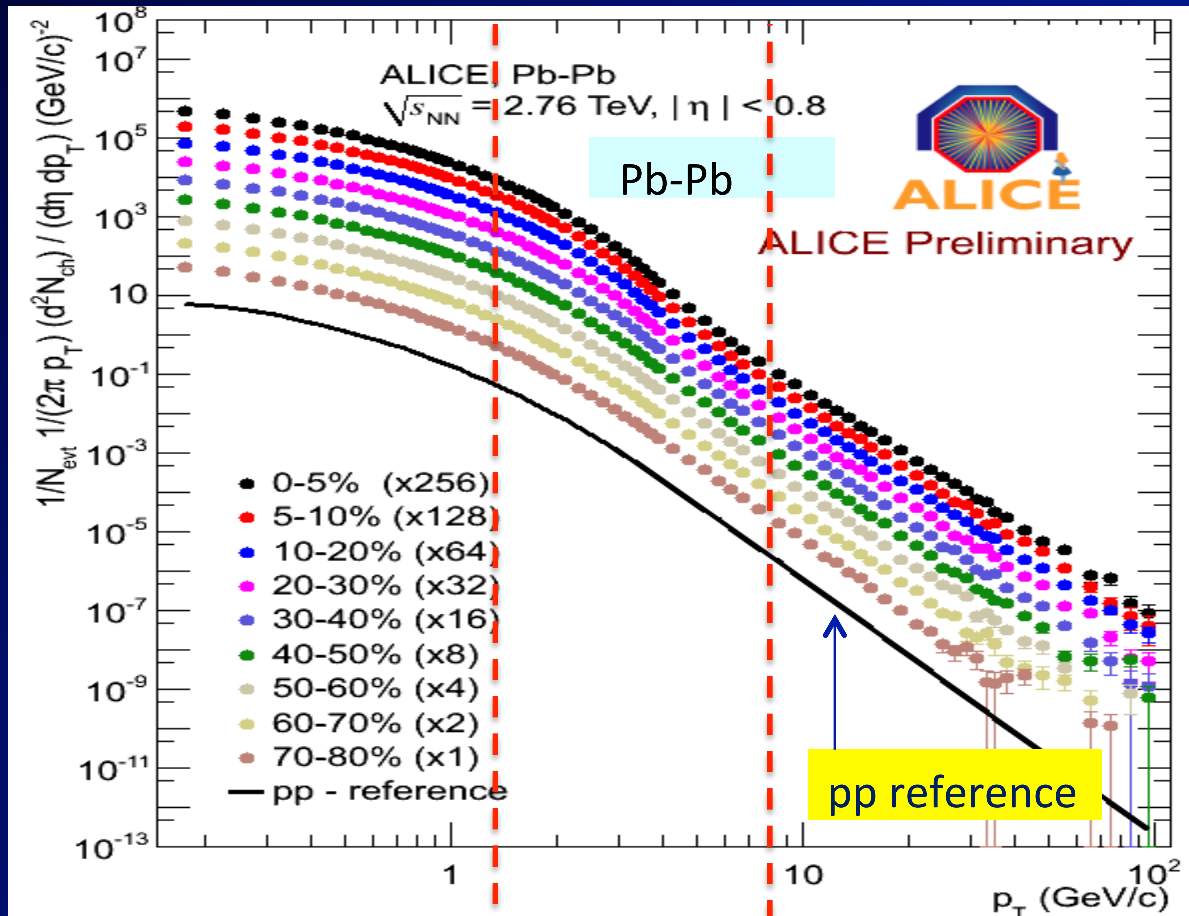


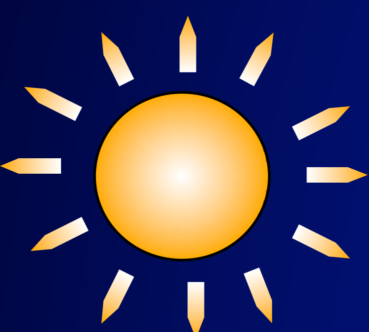
Consistent with value from jet quenching in DIS:

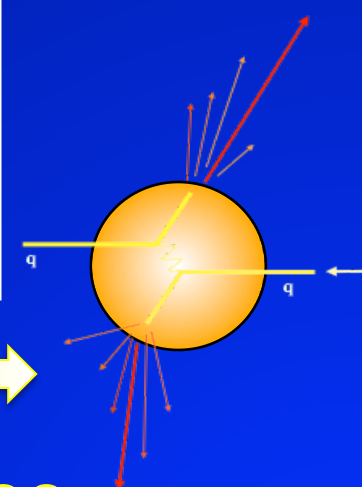
Deng & XNW, PRC83(2010)024902;

Chang, Deng & XNW, PRC89(2014) 034911

Hard and soft probes







soft probes

hard probes

JET Collaboration

http://jet.lbl.gov

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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

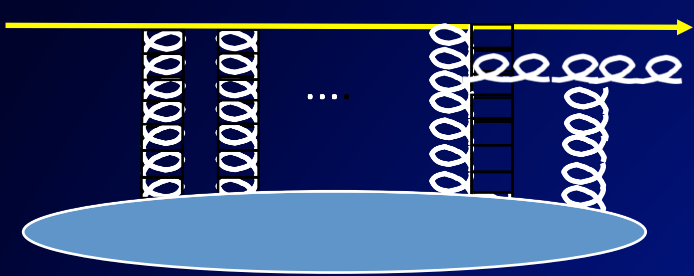
3+1D hydro + Jet transport + Hadronization

- 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, $v_{n,}$

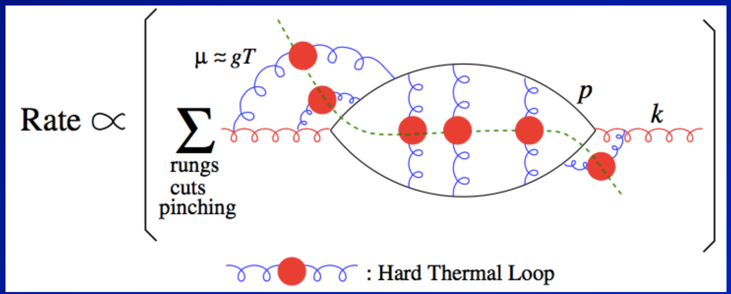
http://jet.lbl.gov

- 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

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

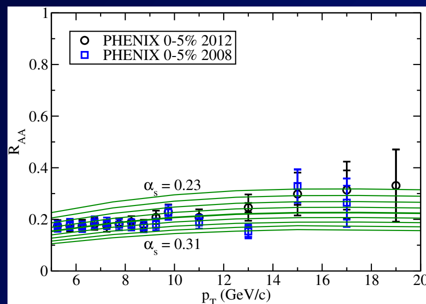
High-twist approach: Modified frag. Func. Guo & XNW'00, Zhang,Wang, XNW'03

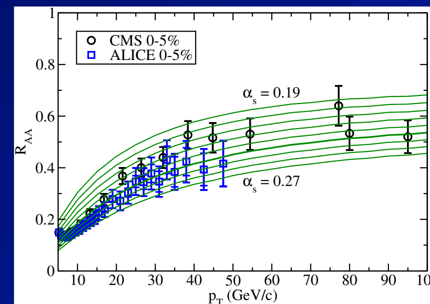
$$\frac{\Delta E}{E} = \frac{2\alpha_s N_c}{\pi} \int \frac{d\ell_T^2}{\ell_\perp^4} dz[1+(1-z)^2] \int d\xi^- \hat{q}(\xi) \sin^2(x_L p^+ \xi^-)$$

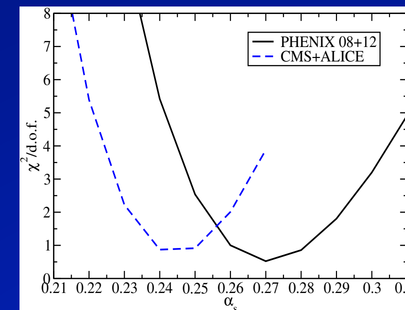
McGill-AMY, MARTINI-AMY, CUJET, HT-BW, HT-M, JEWEL, JaYEM, PCM, BAMPS ….

Jet quenching phenomenology

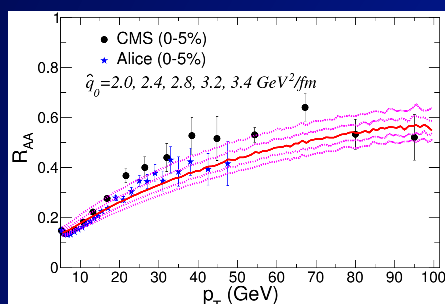
McGill-AMY

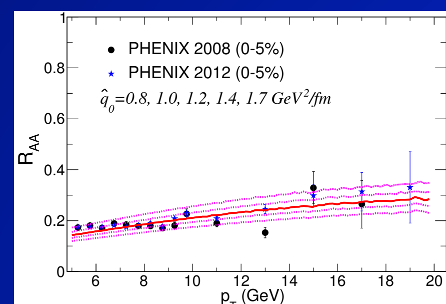


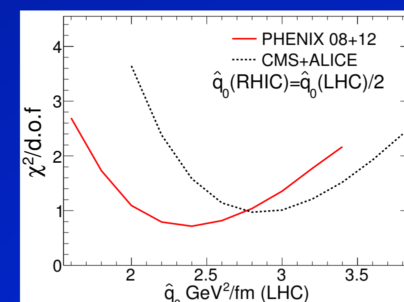




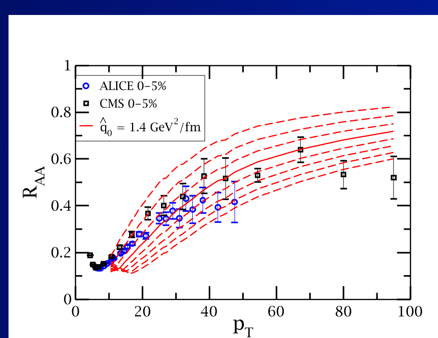
HT-BW

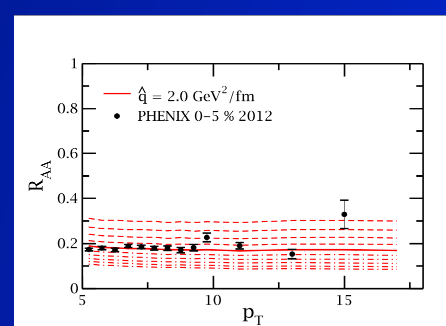


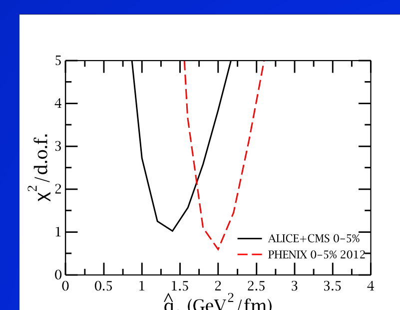




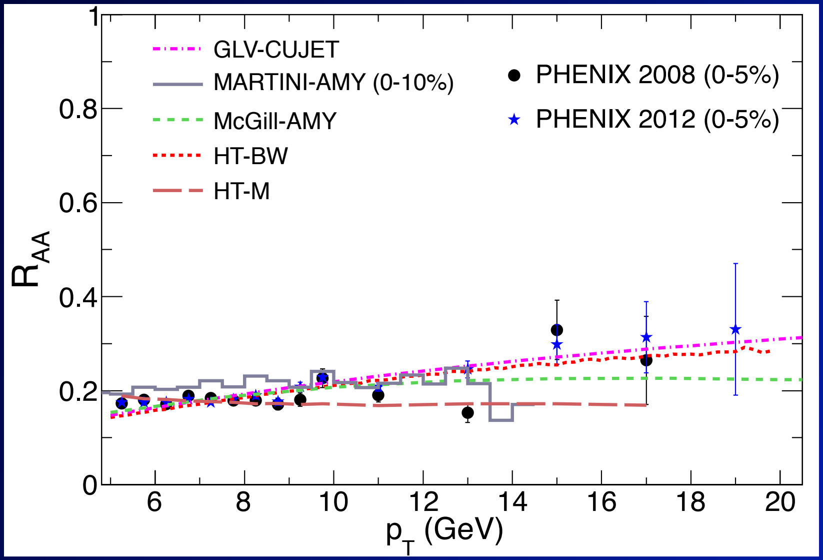
HT-M

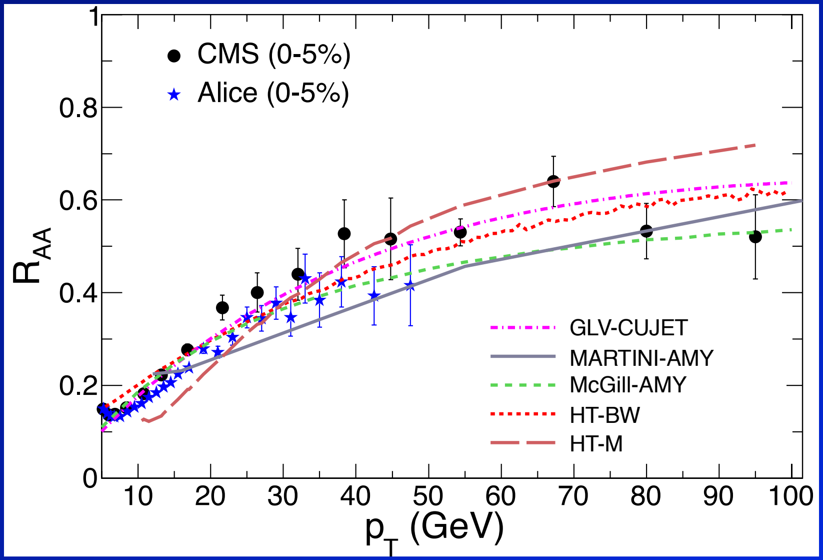






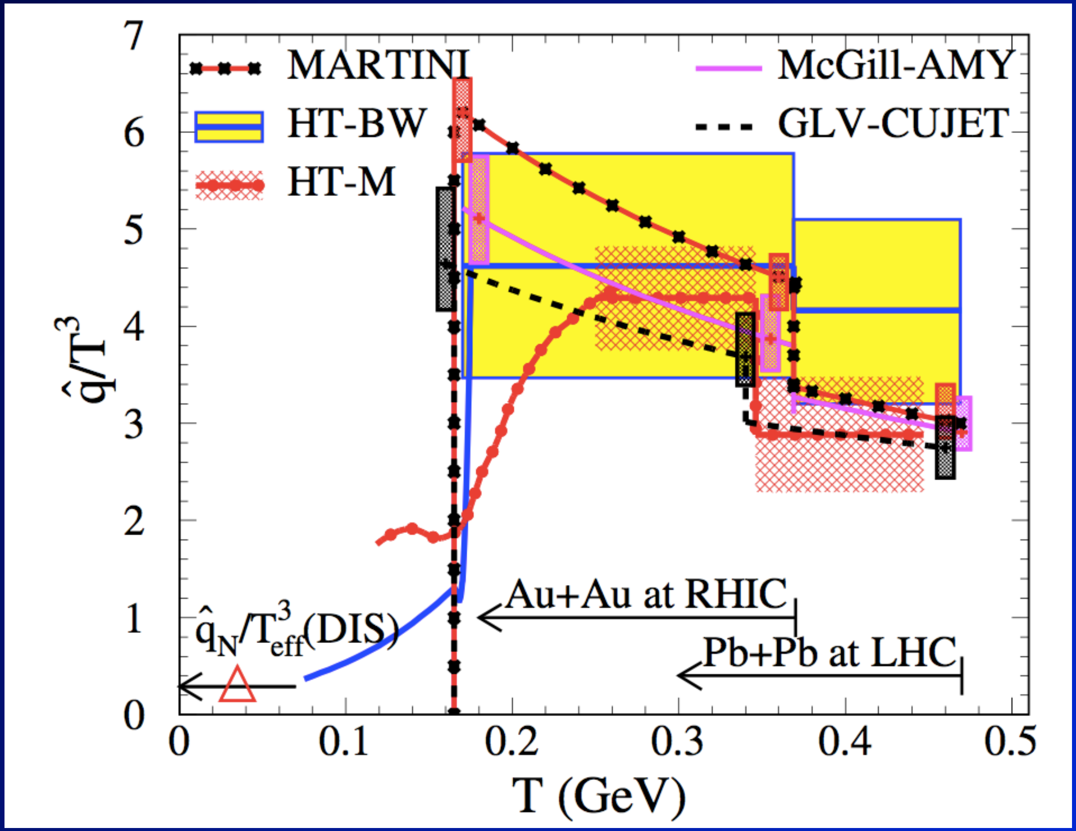
Jet quenching phenomenology





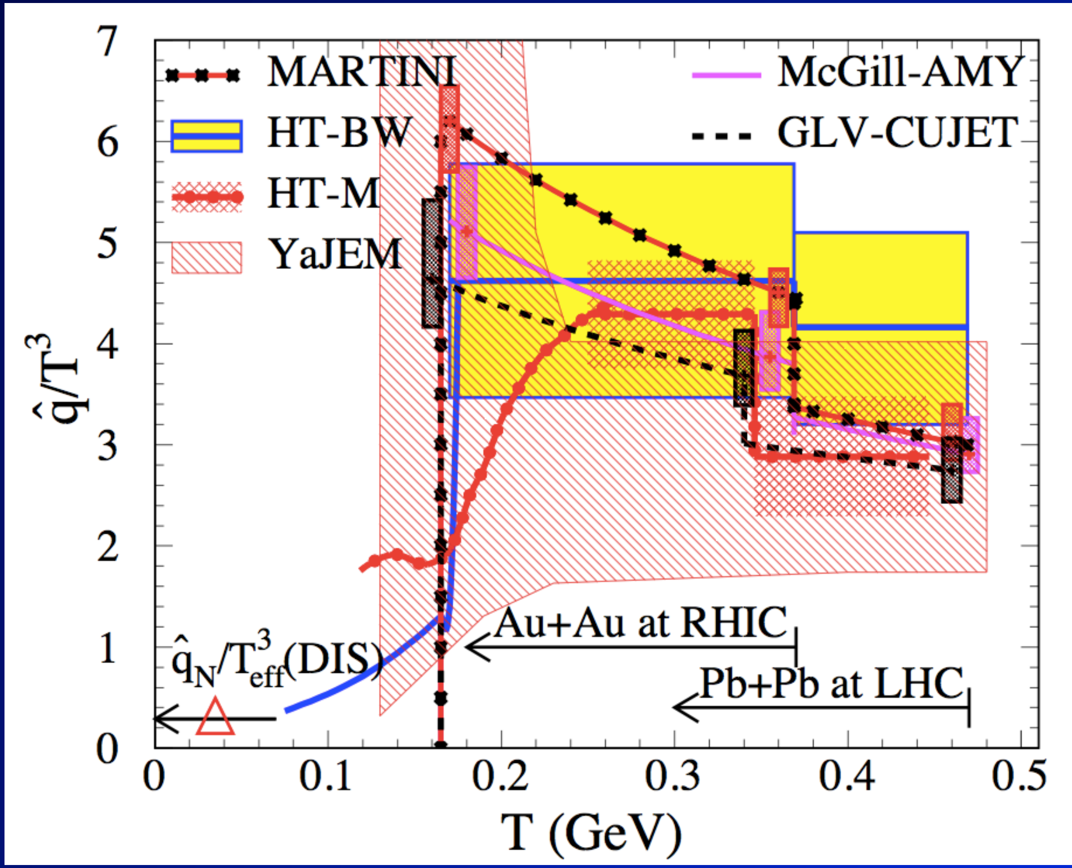
Jet transport coefficient

JET Collaboration: **arXiv:1312.5003**



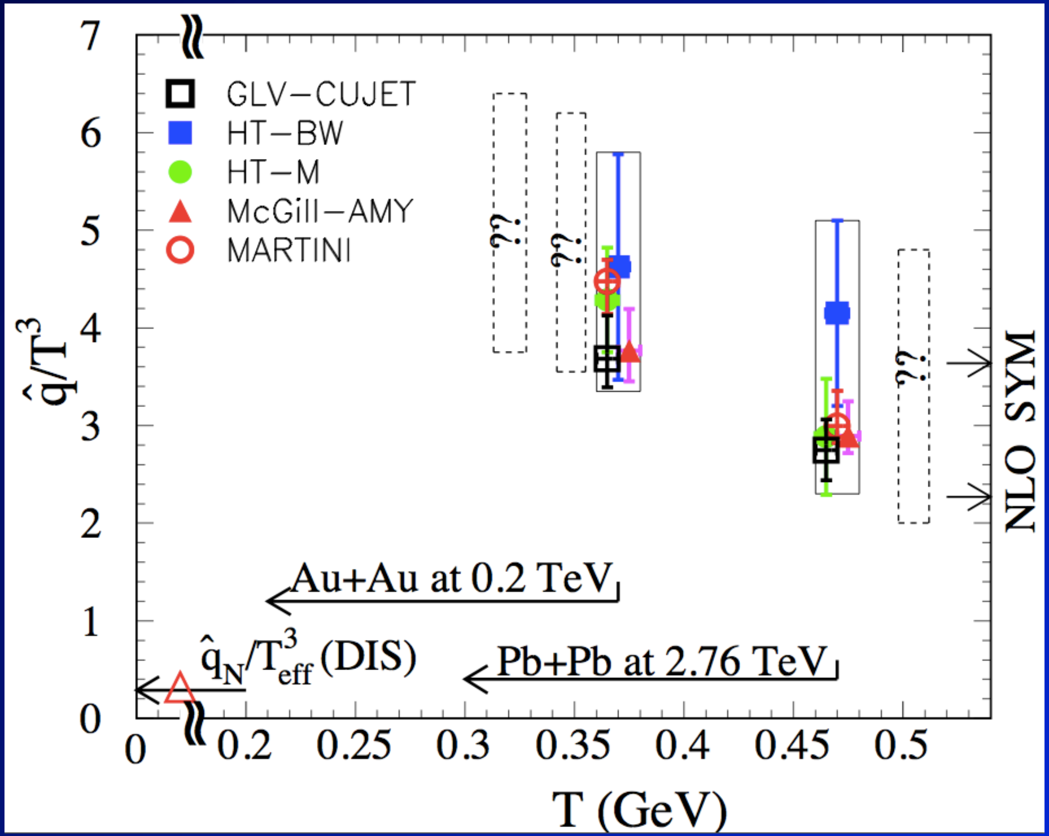
Jet transport coefficient

JET Collaboration: **arXiv:1312.5003**



Jet transport coefficient

JET Collaboration: **arXiv:1312.5003**



$$\hat{q}^{\rm LO}_{\rm SYM} = \frac{\pi^{3/2}\Gamma(3/4)}{\Gamma(5/4)}\sqrt{\lambda}T^3_{\rm SYM}$$

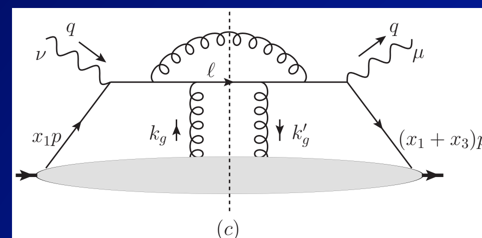
$$\hat{q}^{\rm NLO}_{\rm SYM} = \hat{q}^{\rm LO}_{\rm SYM}\left(1 - \frac{1.97}{\sqrt{\lambda}}\right)$$

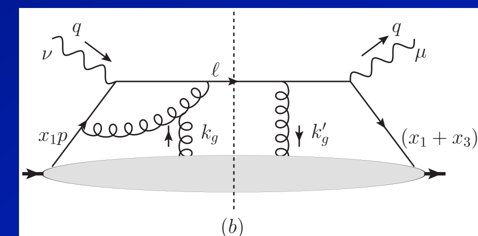
Future: dihadron, gamma-hadron, flavor dependence, jet observables
RHIC BES and LHC higher energy

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

Hongxi Xing (Wed.)

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

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

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

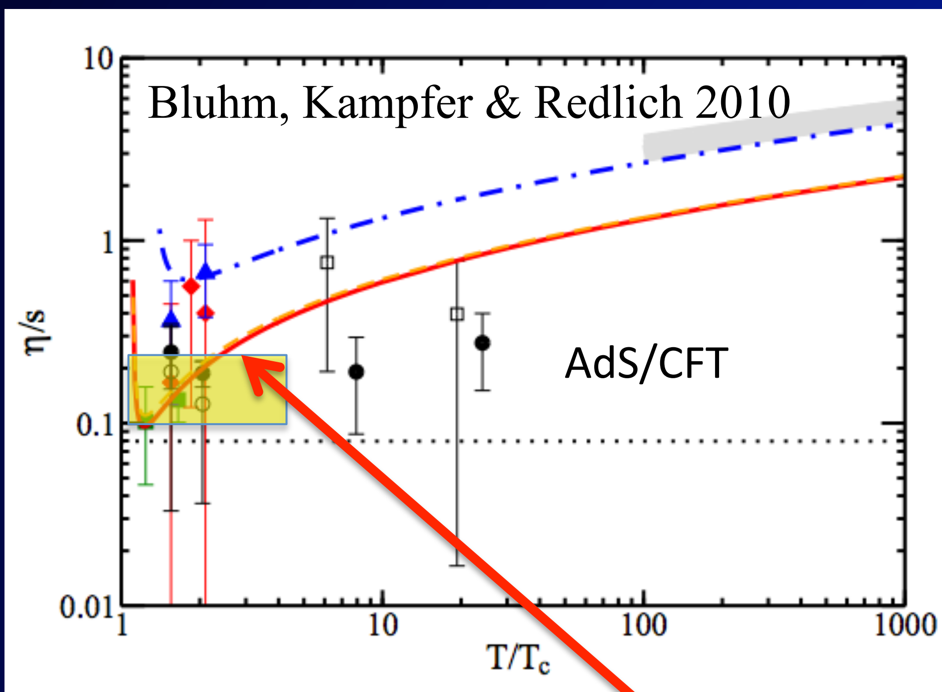
Casalderrey-Solana & XNW (2007)

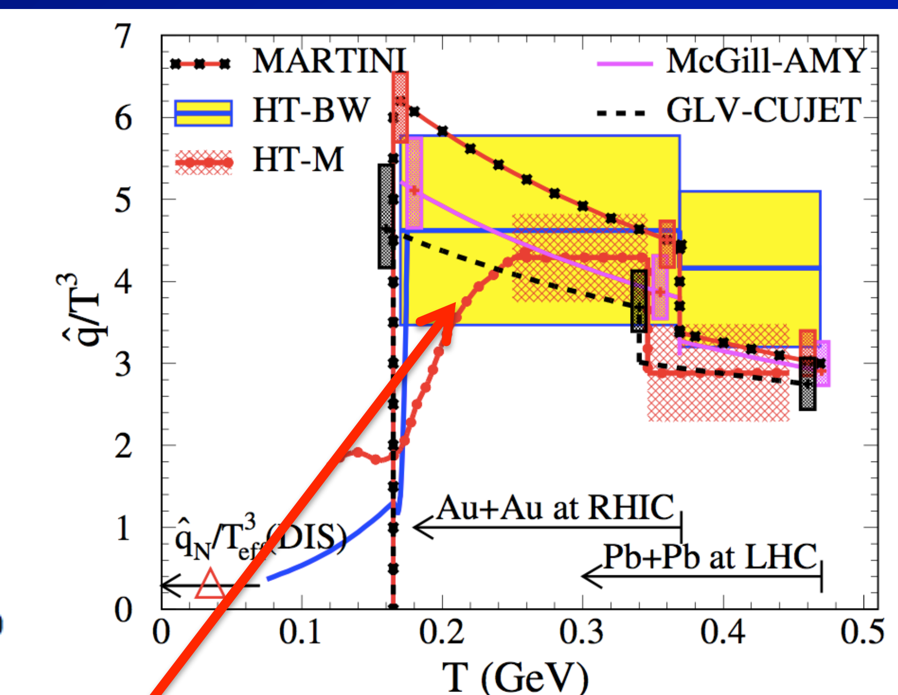
Mehta-Tani (Wed.)

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





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

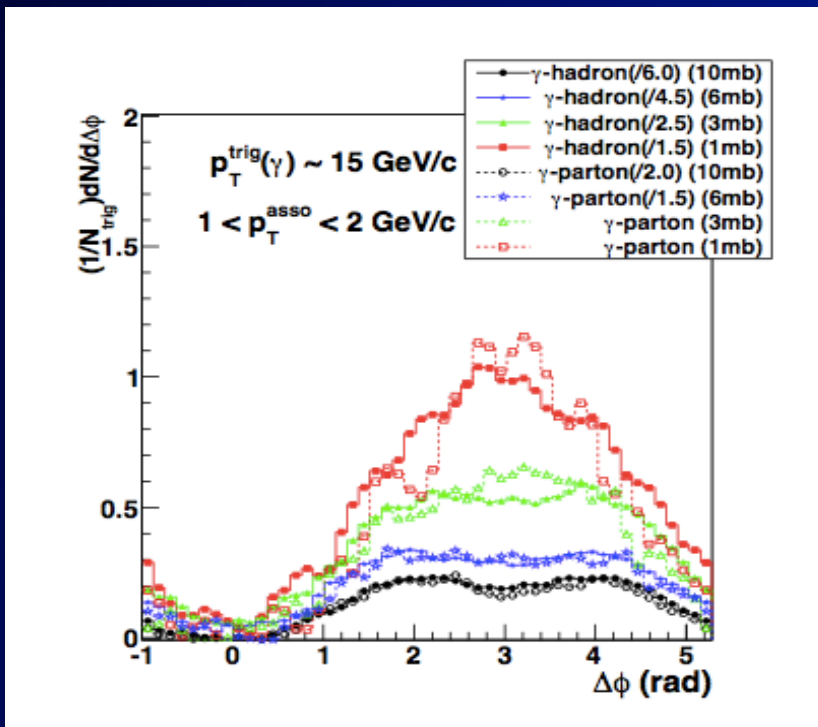
Majumder, Muller & XNW (2007)

JET Collaboration

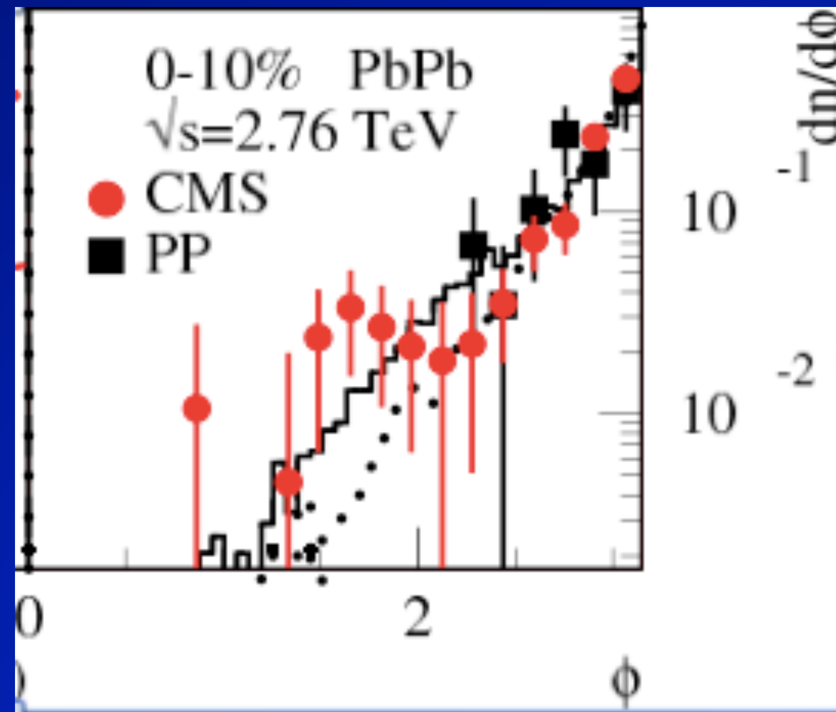
Backup

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

Linear Boltzmann jet transport

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

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

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

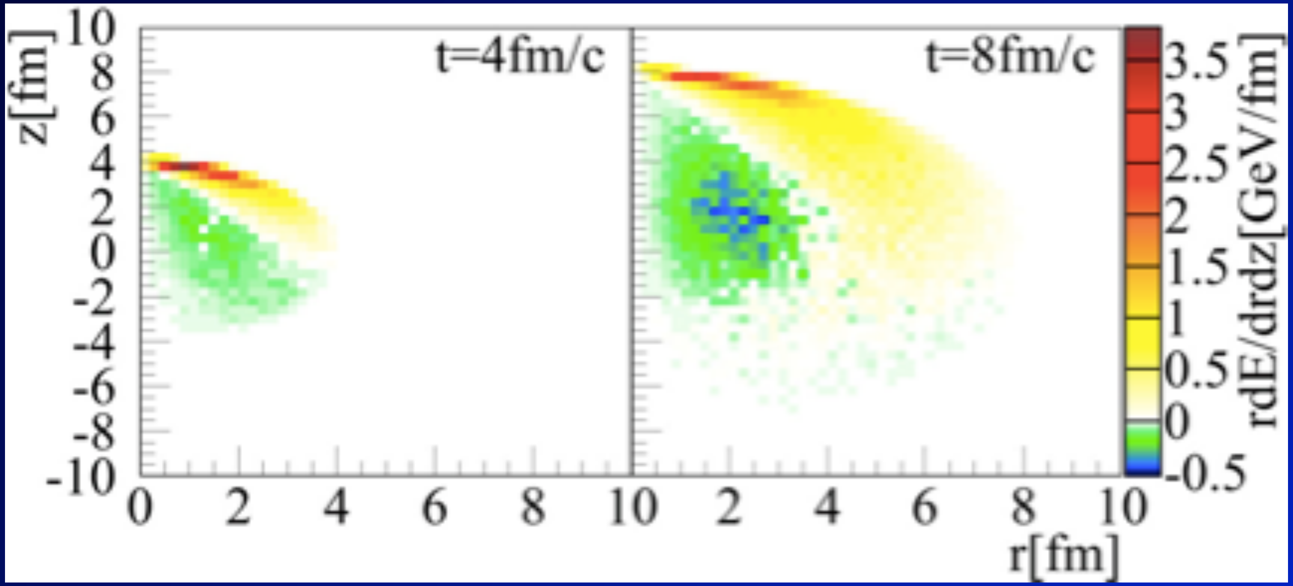
$$\frac{d\sigma}{dt} = |M_{12\to 34}|/16\pi^2 s^2$$

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

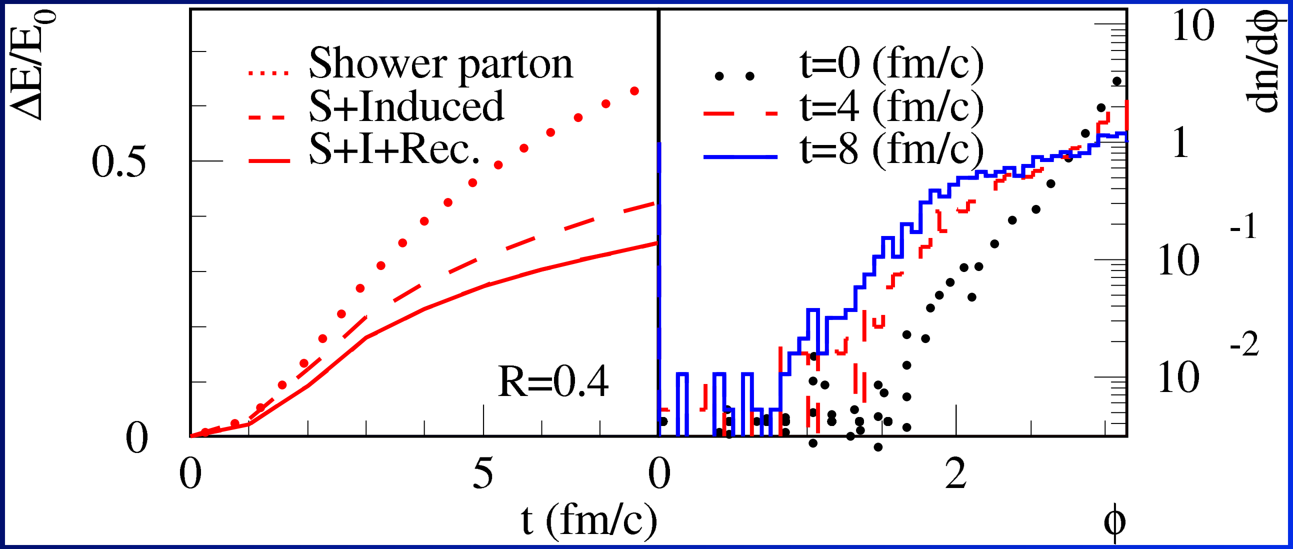
Induced radiation $$\frac{dN_g}{dz d^2 k_\perp dt} = \frac{2\alpha_s N_c}{\pi k_\perp^4} P(z)(\hat{p} \cdot u)\hat{q} \sin^2(\frac{t - t_0}{2\tau_f})$$

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

Jet-induced medium excitation

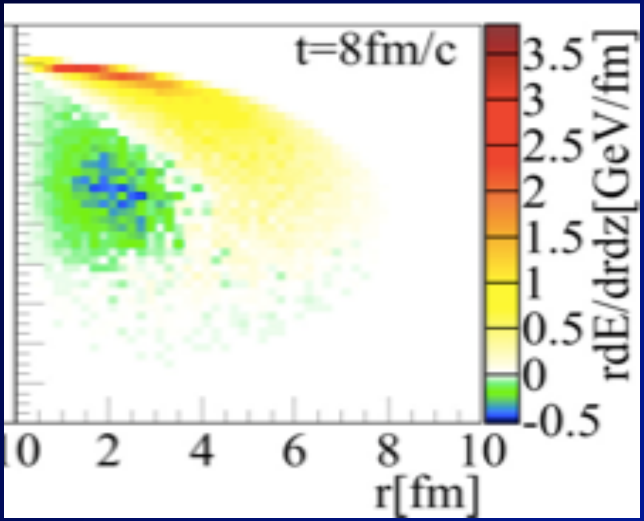


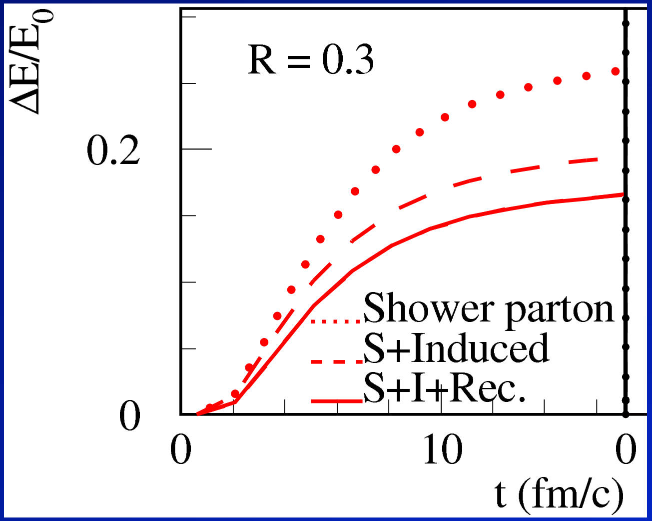
Jet propagation in a uniform medium

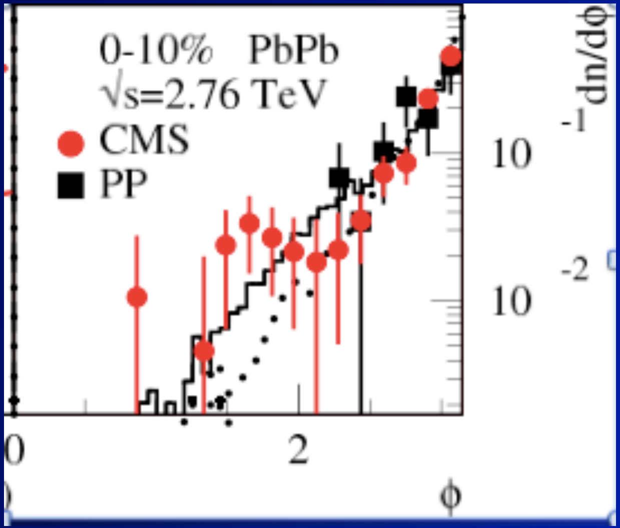


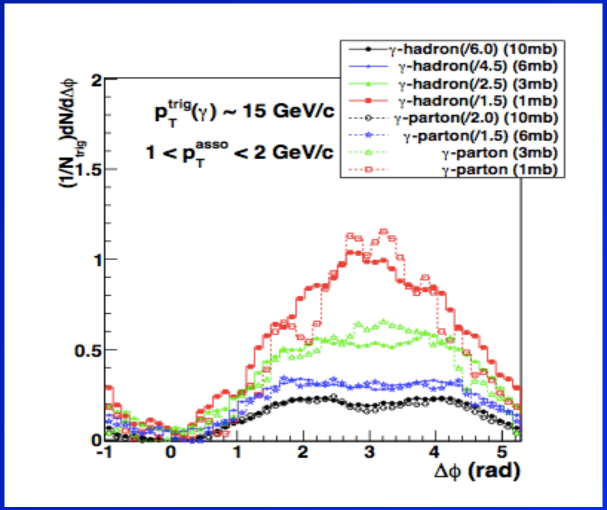
Effect of recoils and jet broadening

XNW and Zhu, PRL 111 (2014) 062301







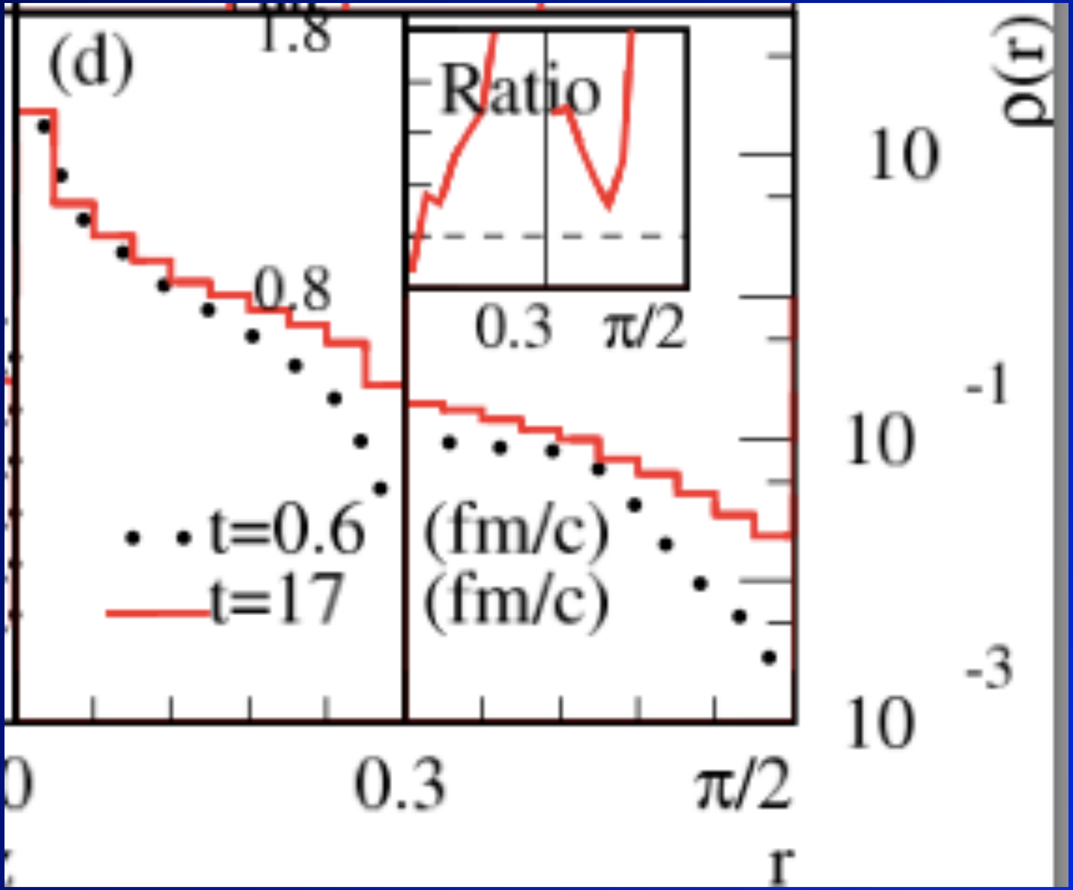


Talk by: Tan Luo (Wed.),

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

Broadening of jet transv. profile

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

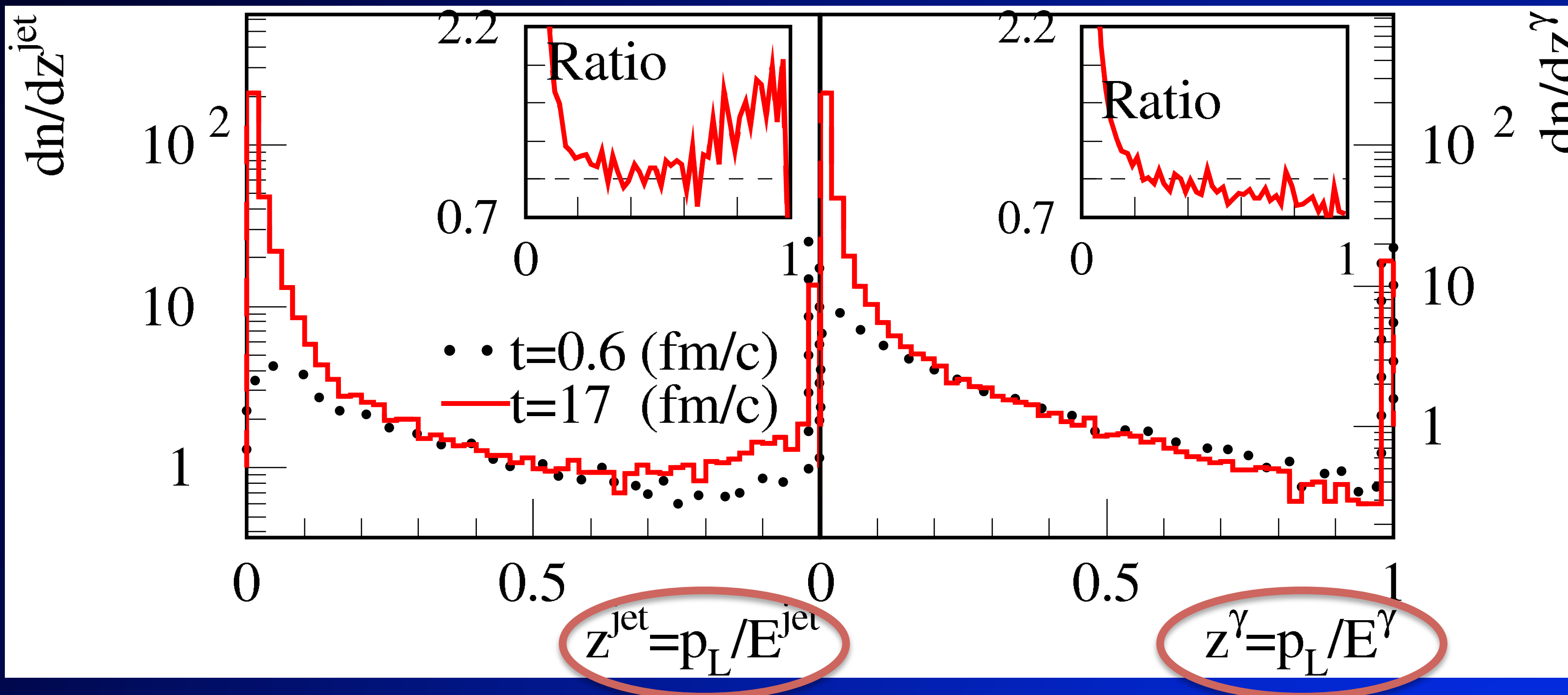


R=0.3

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

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

T-4 LO

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

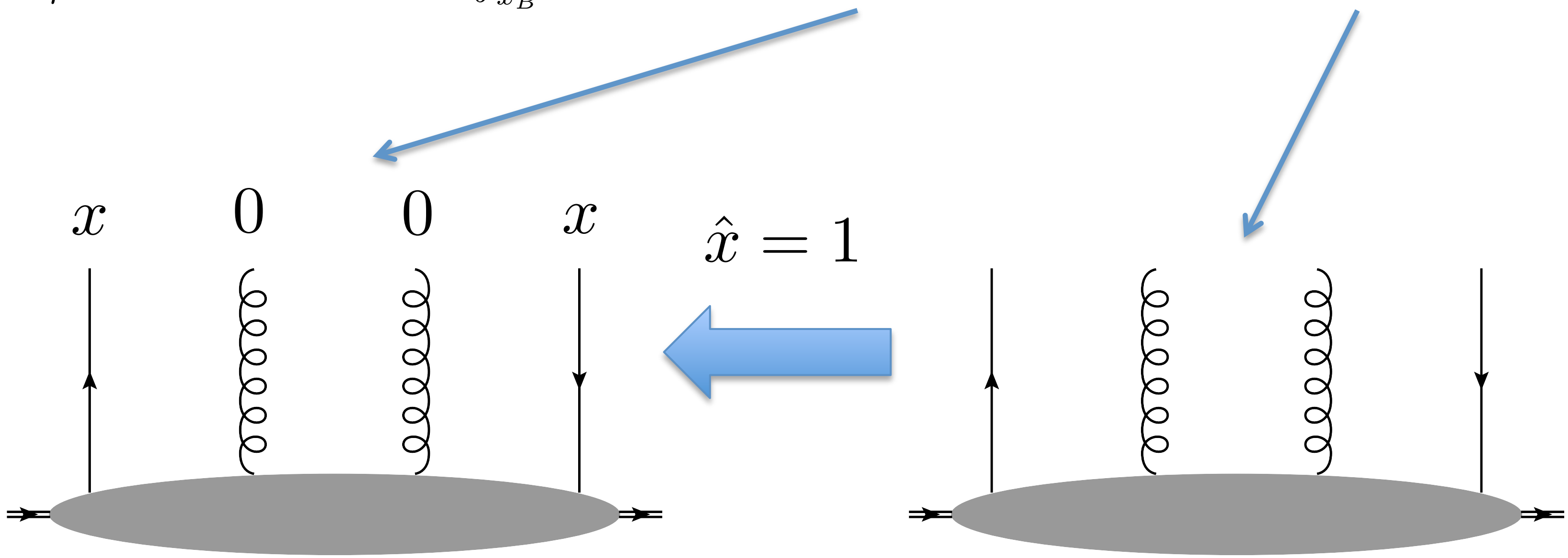
T-4 NLO

Finite contribution from asymmetric-cut diagrams

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

Evolution equation for T4 - NEW

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



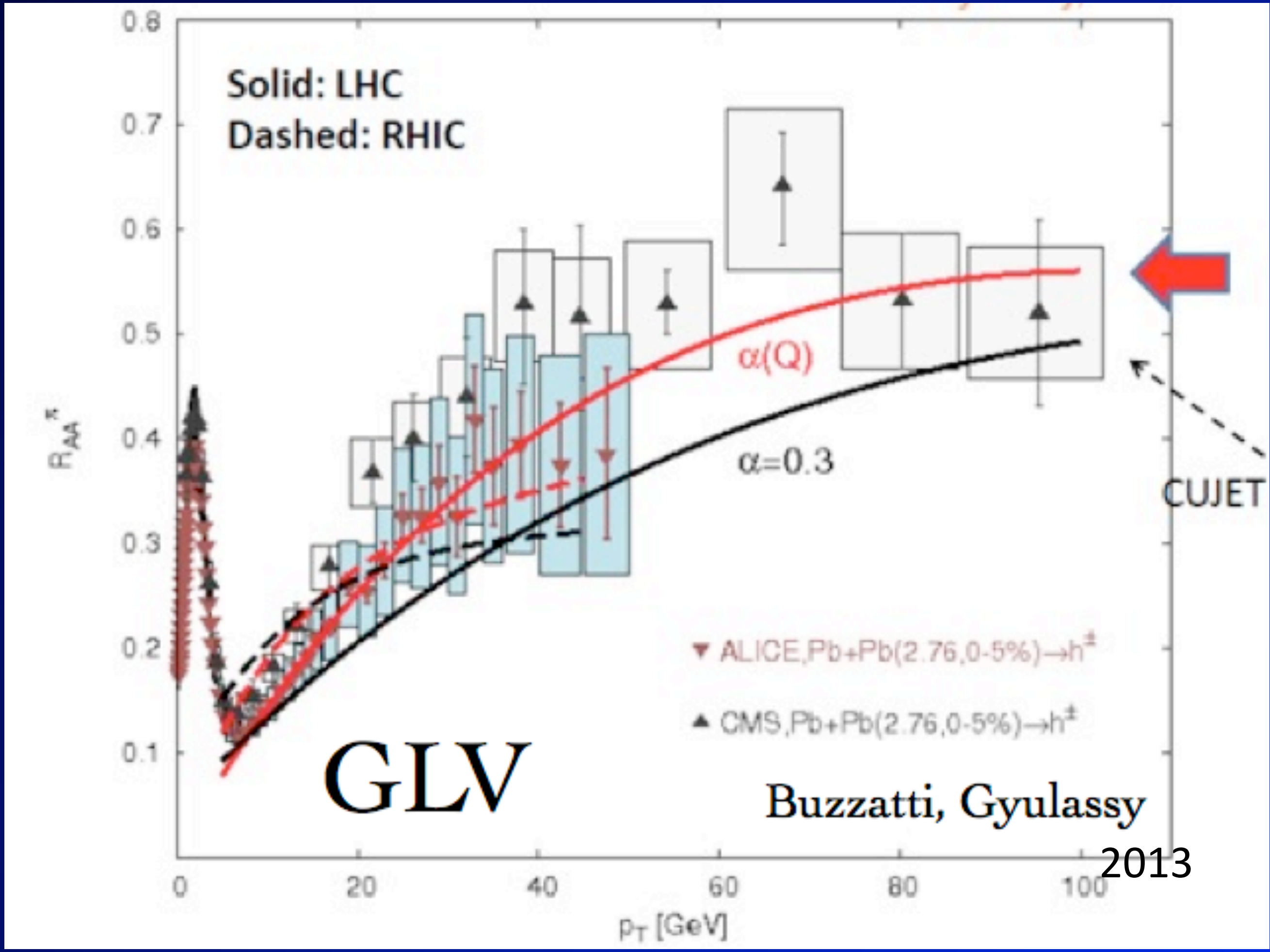
soft-soft

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