Hard Probes 2013, Cape Town, South Arica, Nov. 4-8,2013

Theory: what have hard probes taught us about the quark-gluon plasma?

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

Properties of QGP

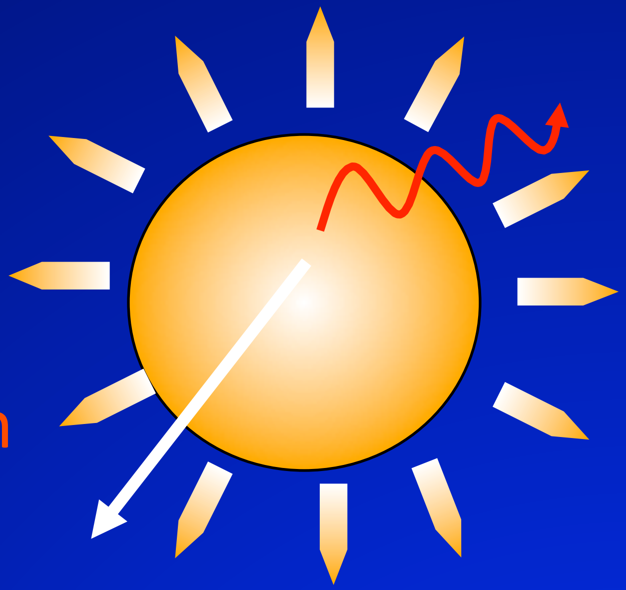
- Space-time profile: $$T_{\mu\nu}(x) : T(x), u(x)$$
- EOS: $$T_{\mu\nu} \Longleftrightarrow \epsilon, P, s, c_s^2 = \partial p/\partial\epsilon$$
- EM response: $$W_{\mu\nu}(q) = \int \frac{d^4x}{4\pi} e^{iq\cdot x}\langle j_\mu(0) j_\nu(x)\rangle$$
- Bulk transport: $$\eta = \lim_{\omega\to 0}\frac{1}{2\omega}\int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

Probes of QGP in A+A Collisions

Dynamic System:

- EM emission: Medium response
  to EM interaction

  γ production, J/Ψ suppression



- Hard probes: medium response to strong interaction

  Jet quenching

- Soft probes: Bulk properties of medium
  collective flow

EM probes of QGP

- Large v_2 of direct photons

PHENIX (2011)

van Hees, Gale & Rapp (2011)

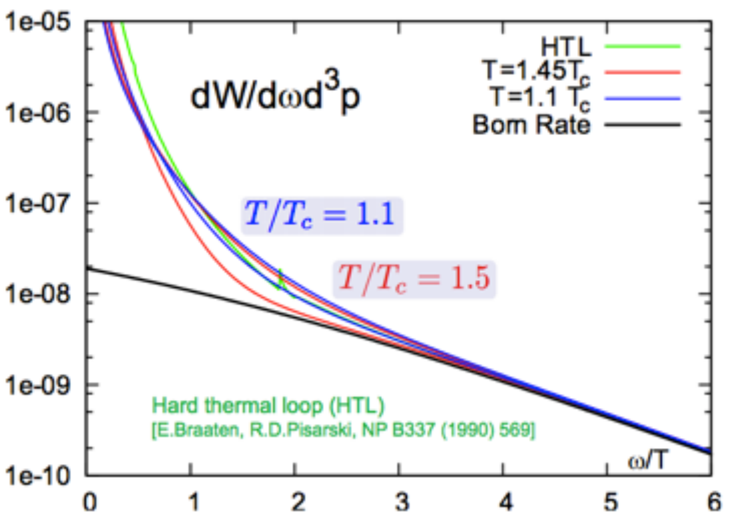
- Viscous correction to EM emission rate:

$$q\frac{dR_\gamma}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}}{2(e+p)}\Gamma_{\mu\nu}$$

Talks by: U. Heinz, S. Chun

- NLO thermal rate in QGP

- Quenched Lattice QCD (dilepton rate)
  – Full QCD results?



O. Kaczmarek, lattice 2013,

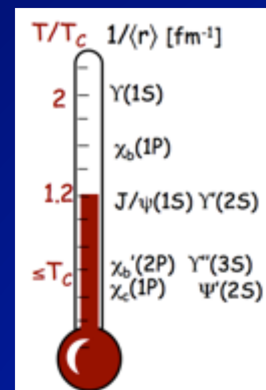
Talks by: H. Ding, Laine, Ghiglieri

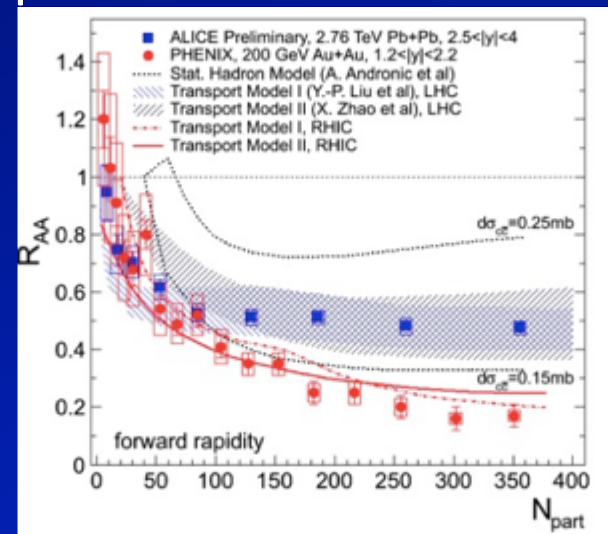
Color screening in QGP

J/ψ suppression at RHIC & LHC

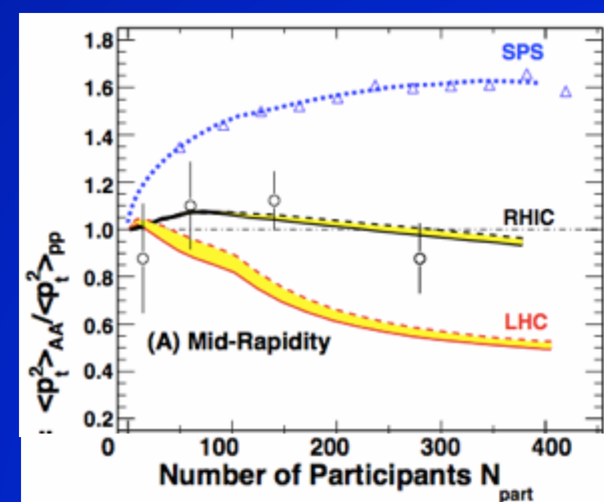
Matsui & Satz (86)

Screening of color charges in QGP: (thermometer?)
- Dissolve qarkonium states
- LQCD study of spectra func & screening mass





Recombination increasingly at work:
- Colliding energy dependence
- Detailed balance with screened potential
- Suppression of Υ states



Talks by: Ding, Mocsy, Petreczky

P. Zhuang, et al. (2013)

Parton scattering in medium

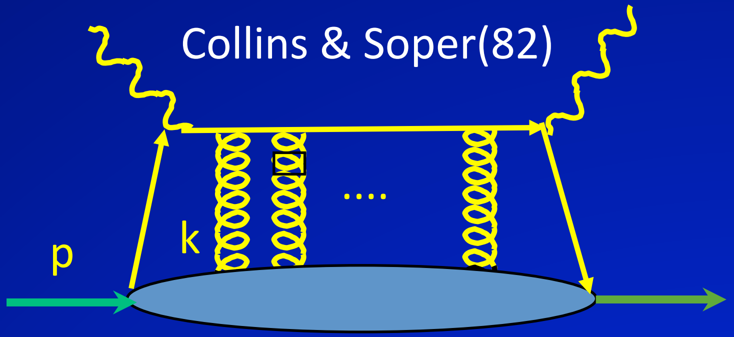
$$f_A^q(x,\vec{k}_\perp) = \int \frac{dy^-}{4\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp}\langle A|\bar{\psi}(0)\gamma^+\mathcal{L}(0,y)\psi(y)|A\rangle$$

Collins & Soper(82)

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

Jet transport operator
due to color Lorentz force

Liang, XNW & Zhou（2008）



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

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

(BDMPS'96)

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

Jet transport in thermal QCD medium

$$f(\vec{k}_\perp, L) = \int d^2 y_\perp e^{-i\vec{k}_\perp\cdot\vec{y}_\perp} f(y_\perp, L), \quad f(y_\perp, L) = \frac{1}{N_c}\mathrm{Tr}\langle \mathcal{L}(0, L^-, \vec{y}_\perp)\rangle$$

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

Analytic continuation: Majumder (2012)

Tilt the parton into space-like or boost to the rest frame of the probe

Caron-Huot (2009), Ji (2013): $\langle \mathcal{W}(0)\mathcal{W}(y^-)\rangle \to \langle \mathcal{W}(0,0)\mathcal{W}(0,z)\rangle + \mathcal{O}(T/p_z)$

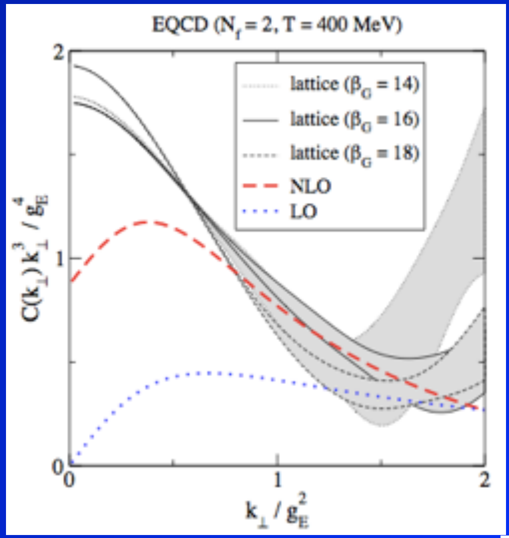
EQCD: for soft mode ; match to NLO pQCD at higher k_T

Panero, Rummukainen & Schaefer (2013)

$$\hat{q}_{\mathrm{EQCD}} \approx 0.55 g_E^6 \qquad \hat{q}_{\mathrm{NLO}} \approx 0.47 g_E^6$$

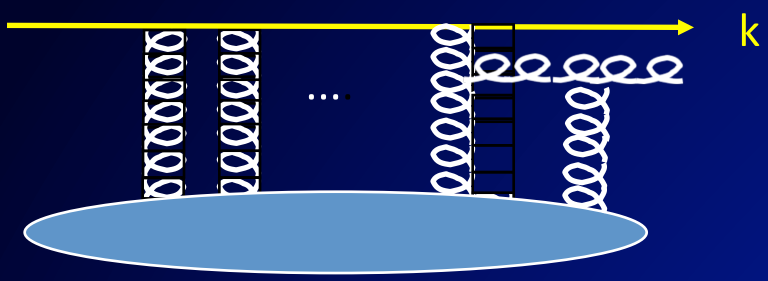
$$V(y_\perp) = -\frac{d\ln f(y_\perp, L)}{dL} = \int \frac{d^2 k_\perp}{(2\pi)^2}(1 - e^{i\vec{k}_\perp\cdot\vec{y}_\perp}) C(k_\perp)$$

D'Eramo, et al (2012)

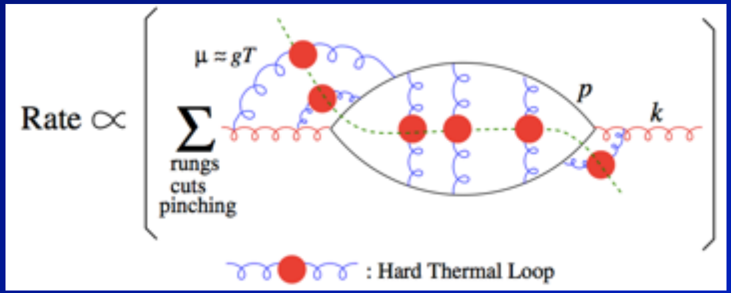


Laine & Rothkopf (2013)

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: couple rate equations

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

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

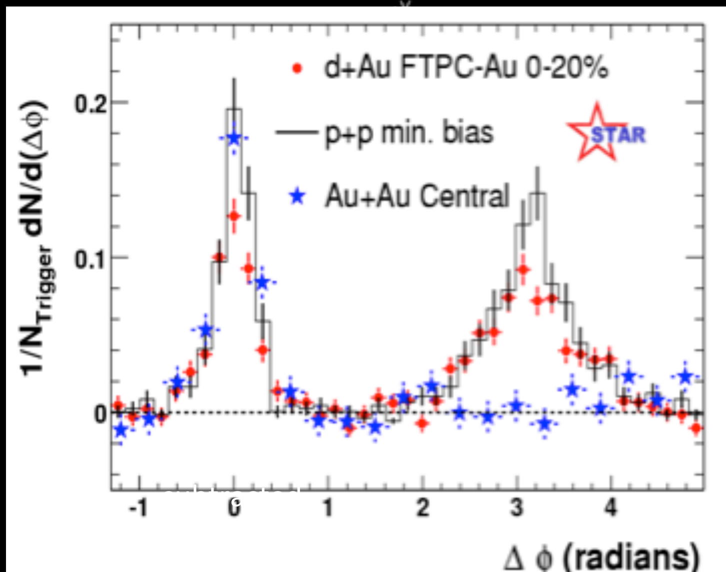
High-twist approach: Modified frag. Func. Guo & XNW'00, Zhang,Wang, XNW'03

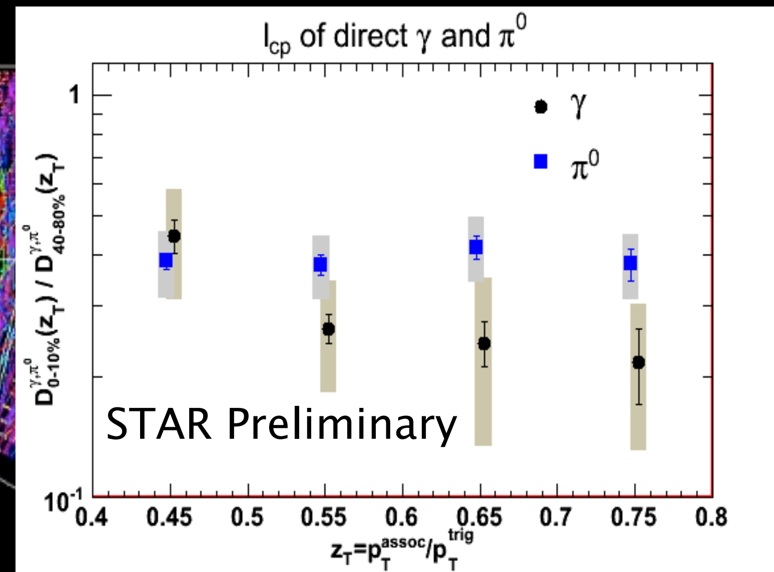
$$\frac{\Delta E}{E} = \frac{2\alpha_s N_c}{\pi} \int \frac{d\ell_T^2}{\ell_\perp^4} dz [1 + (1-z)^2] \int d\xi^- \hat{q}(\xi) \sin^2(x_L p^+ \xi^-)$$

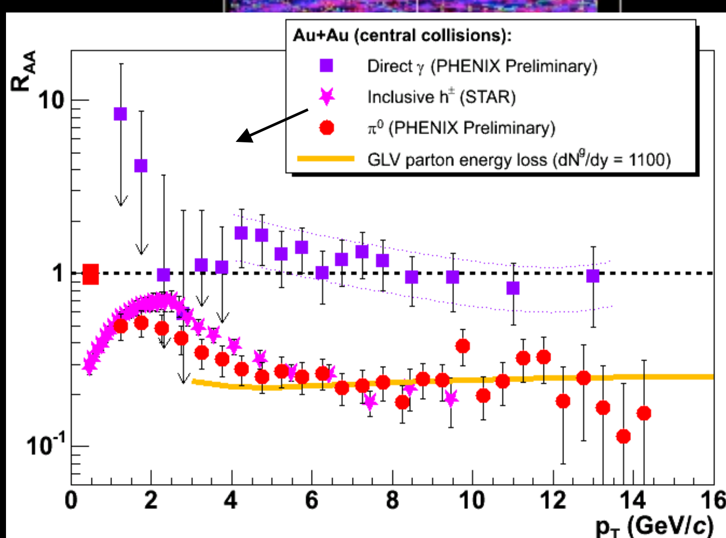
McGill-AMY, MARTINI-AMY, CUJET, HT-BW, HT-M, JEWEL, JaYEM, PCM, BAMPS ....

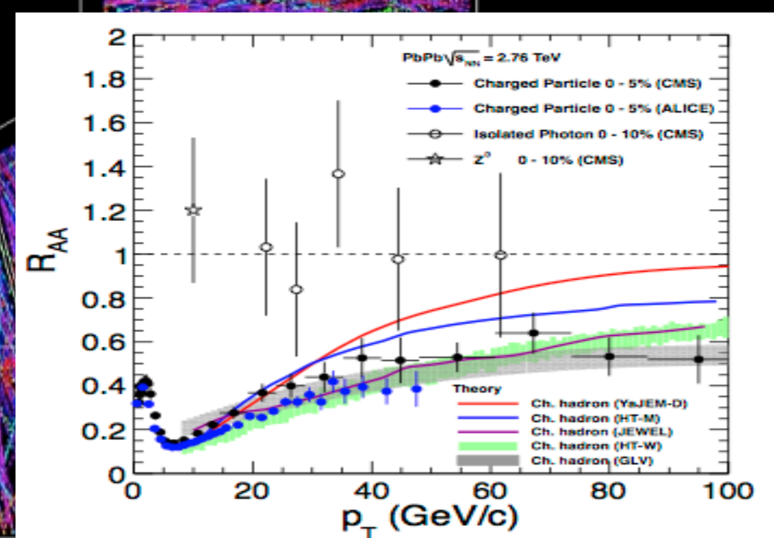
Talks by: Renk, Cao, Cole-Smith, Greiner, Molnar, Uphoff ,Xu, Zapp,

Jet Quenching at RHIC & LHC

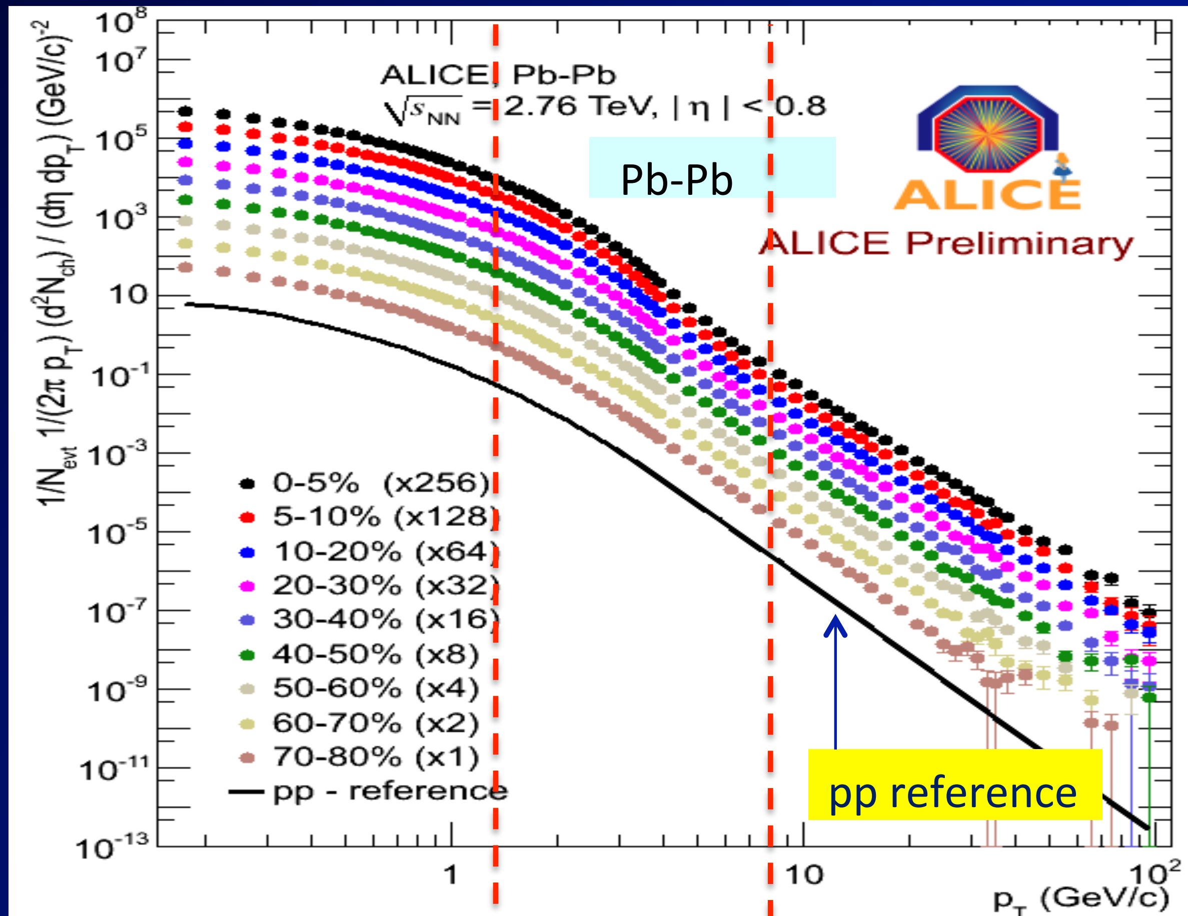


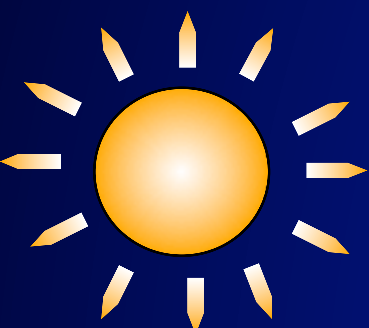


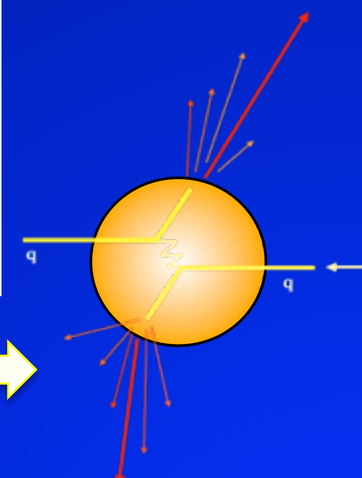




Hard and soft probes







soft probes

hard probes

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

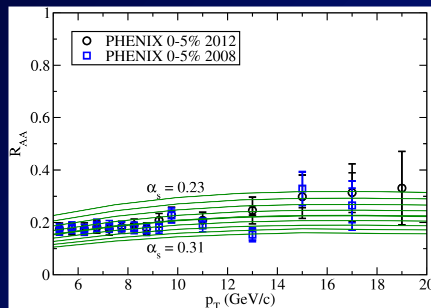
JET Collaboration

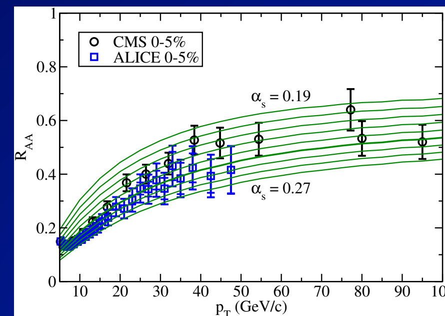
- iEBE: E-by-E viscous hydro- generating bulk medium on-demand
- First JET package: viscous hydro+ semi-analytic jet quenching: CUJET, McGill-AMY, MARTINI-AMY, HT-BW, HT-M (will expand to other models)

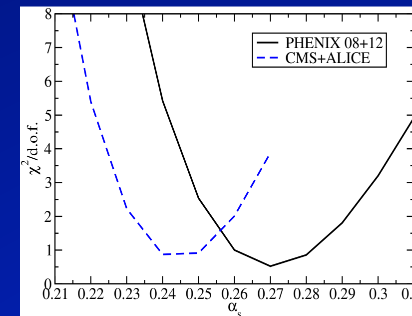
BERKELEY LAB

Jet quenching phenomenology

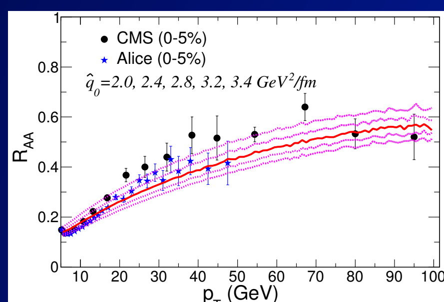
McGill-AMY

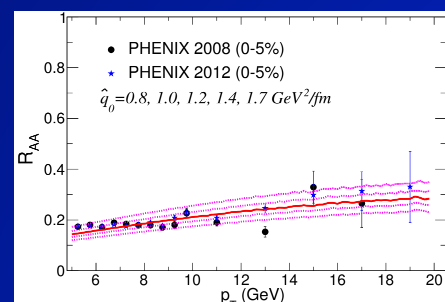


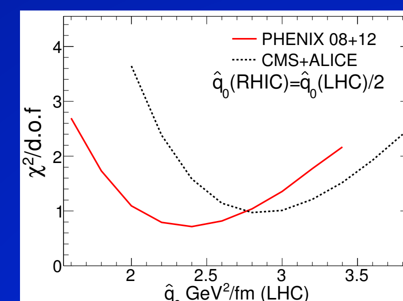




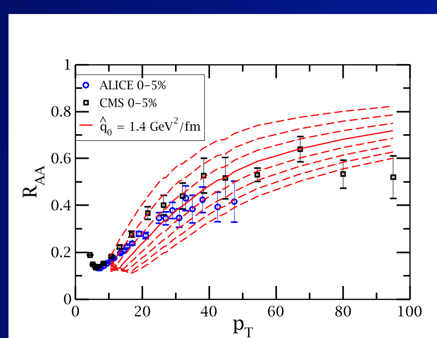
HT-BW

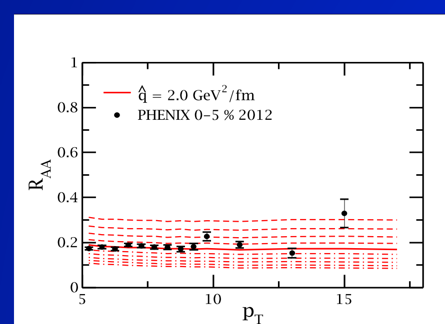


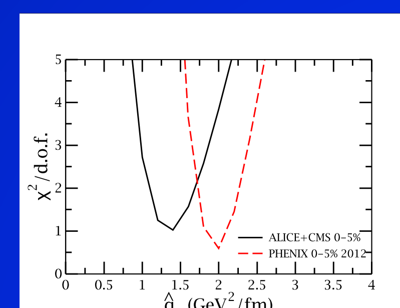




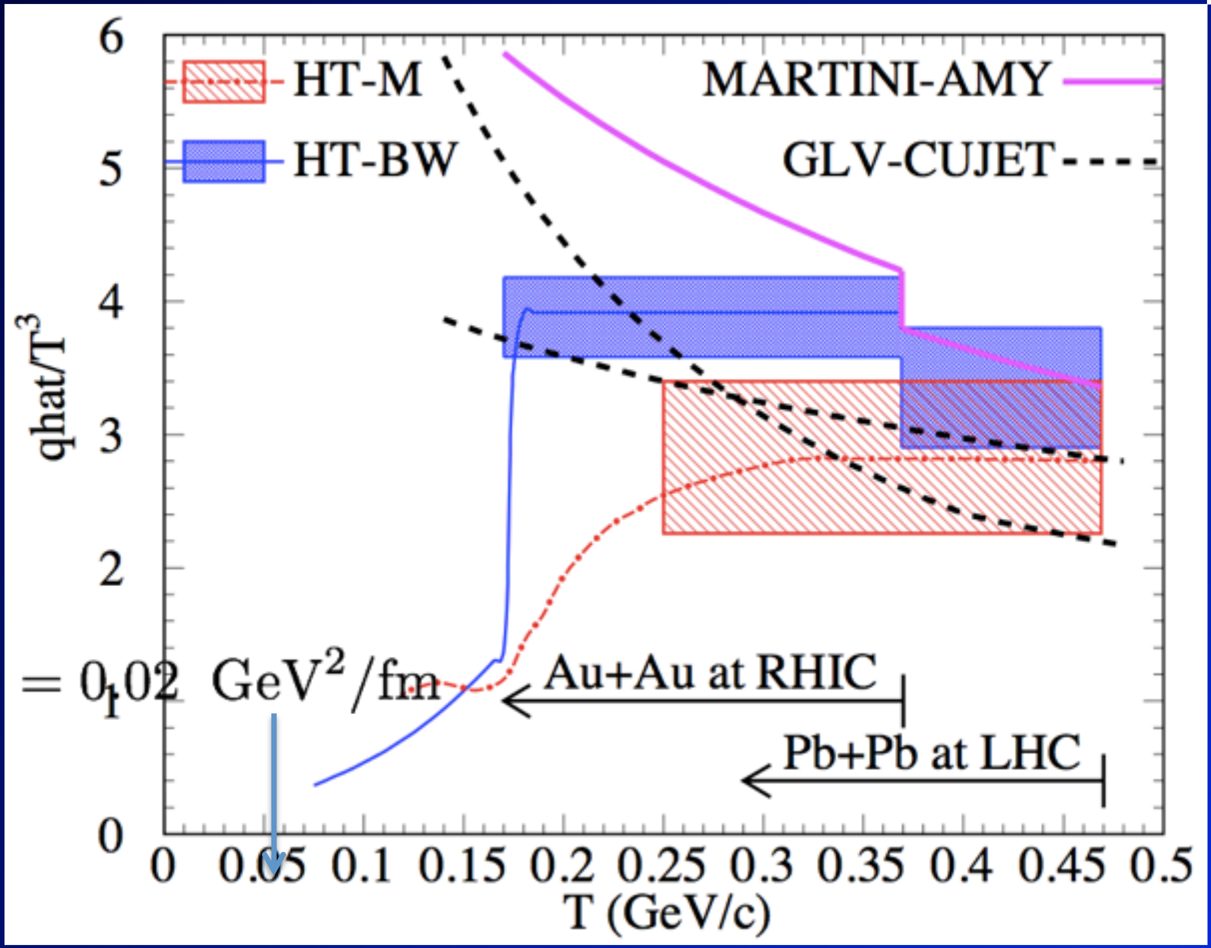
HT-M







Jet transport coefficient



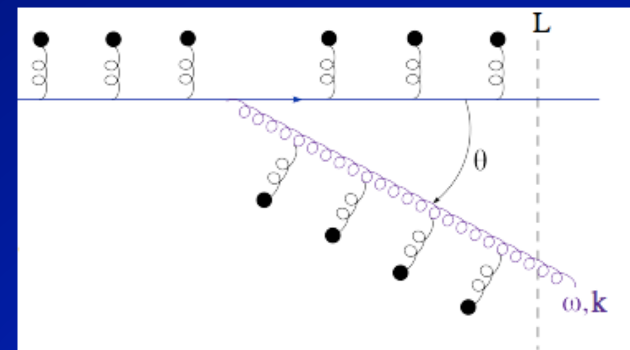
JET Collaboration (preliminary)

Future: dihadron, gamma-hadron, flavor dependence, jet observables

Multiple gluon emissions

Iteration of single gluon emission:

mDGLAP (HT), MC of rate equation (JEWEL, MARTINI, LBT, PCM)



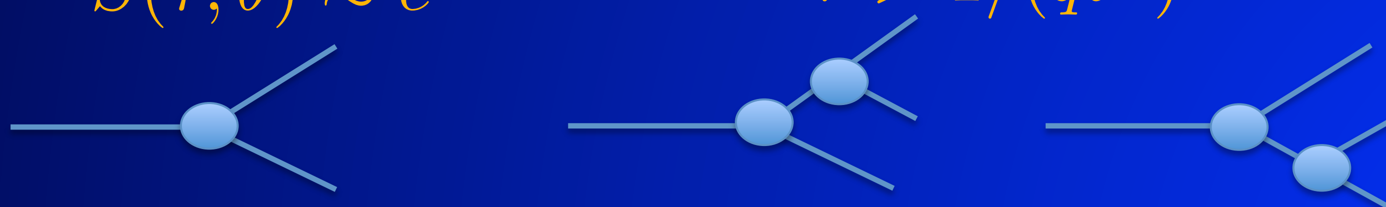
Formation time $\frac{1}{\tau_f} \sim \frac{k_T^2}{2\omega}$

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

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

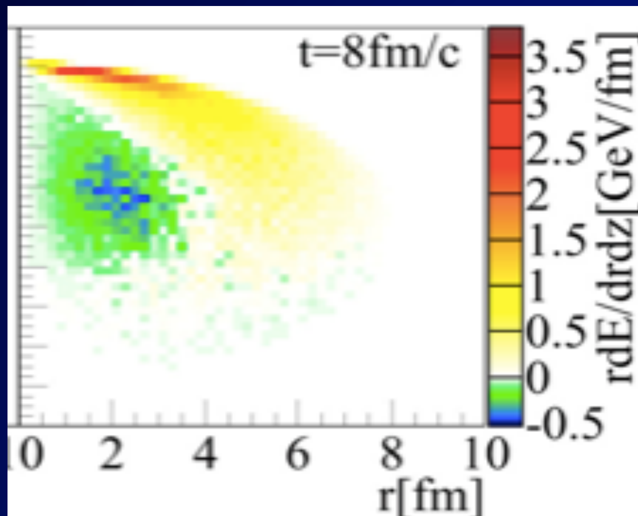
$$S(\tau, \theta) \approx e^{-\hat{q}\theta^2\tau^3} \qquad \tau > 1/(\hat{q}\theta^2)^{1/3}$$

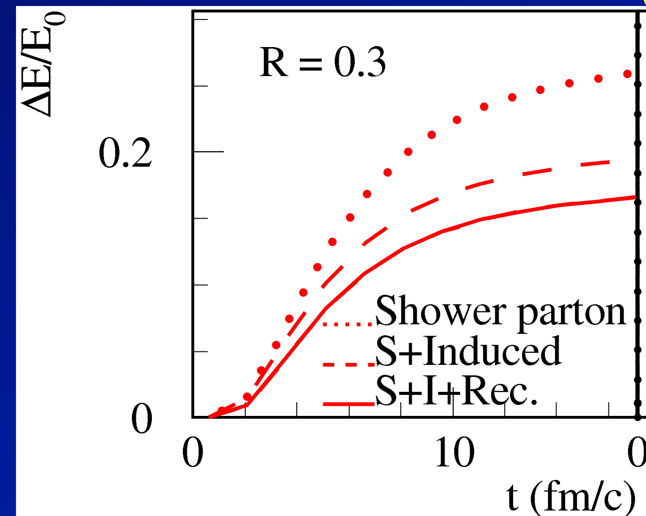


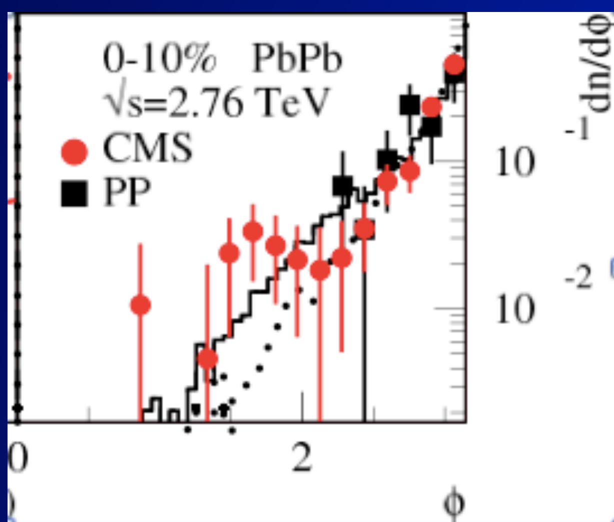
Talks by: Iancu, Salgado, ,Mehtar-Tani , Apolinário, Tywoniuk ,Wu

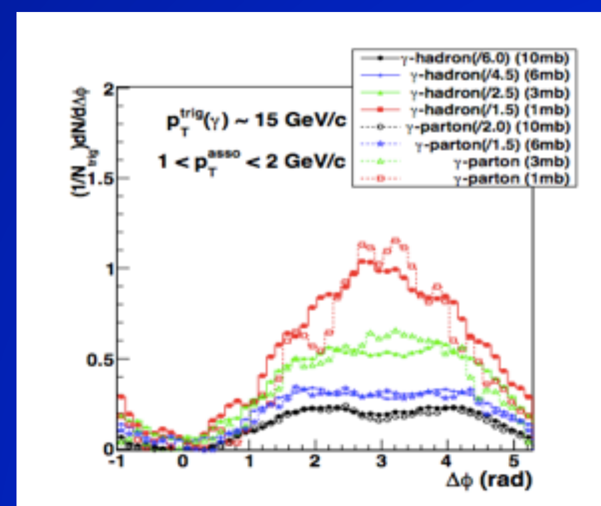
Effect of recoils and jet broadening

XNW and Zhu (2013)









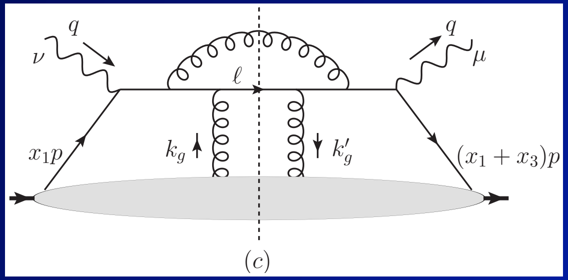
Li, Liu, Ma, XNW and Zhu（2010）
Ma and XNW (2011)

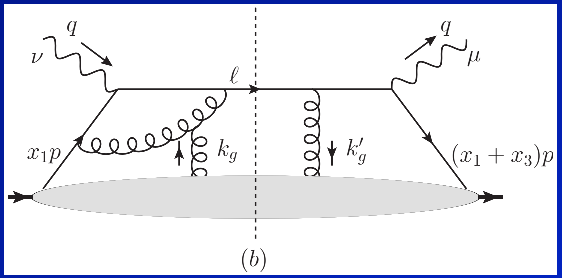
Talks by: Zhu, Luo,

NLO and factorization

arXiv:1106.1106

- Uncertainty in scale dependence of collinear LO results
- Medium properties & hard scattering factorizable?
- NLO qhat and e-loss: Mueller & Wu (2012), Teaney et al (2013)





- Complete cancellation of soft-collinear divergence
- Complete factorization of the collinear divergence Kang, Wang, XNW, Xing (2013)

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

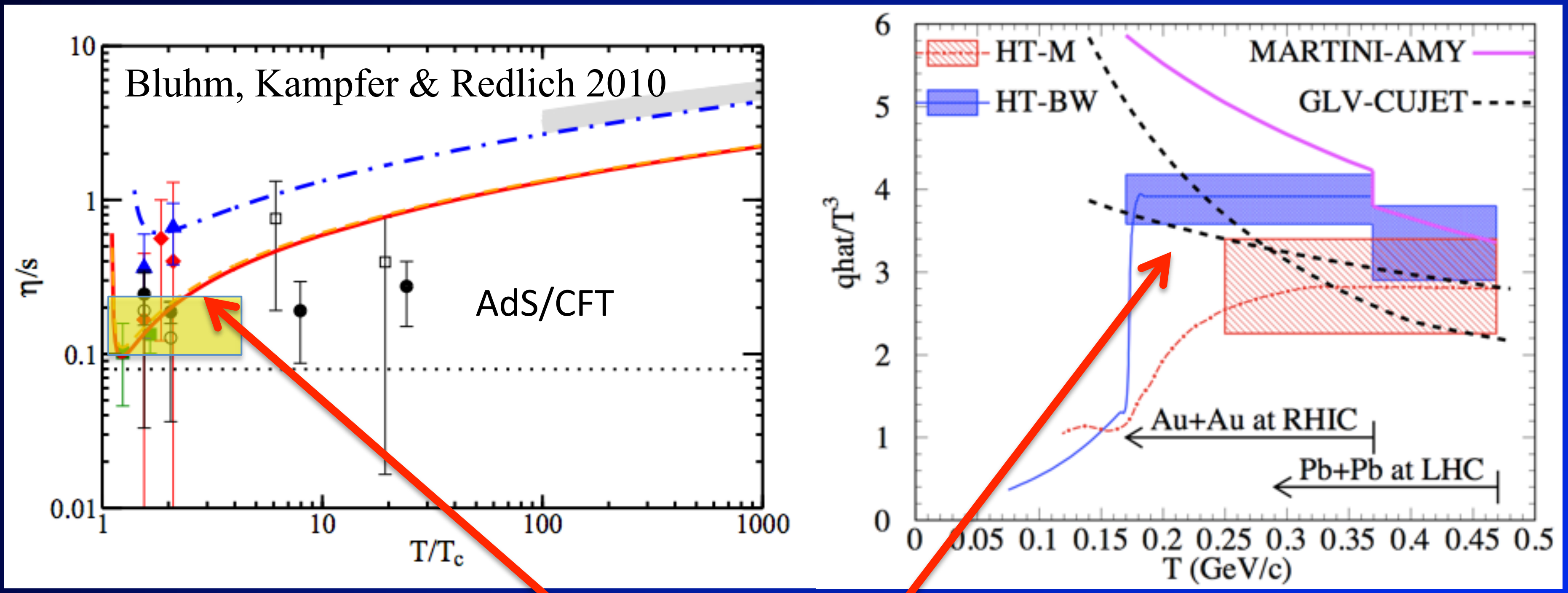
$$\frac{\partial}{\partial\ln\mu_f^2}T_{qg}(x_B,0,0,\mu_f^2) = \frac{\alpha_s}{2\pi}\int_{x_B}^{1}\frac{dx}{x}\left[\mathcal{P}_{qg\to qg}\otimes T_{qg} + P_{qg}(\hat{x})T_{gg}(x,0,0,\mu_f^2)\right].$$

$$\hat{q}\Longrightarrow\hat{q}(E,Q^2)$$ Casalderrey-Solana & XNW (2007)

Summary

EM emissions, quarkonium, jet quenching & collective flows: 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)