ATHIC 2008, Tsukuba (Oct. 13-15)

ATHIC
Asian Triangle Heavy Ion Conference

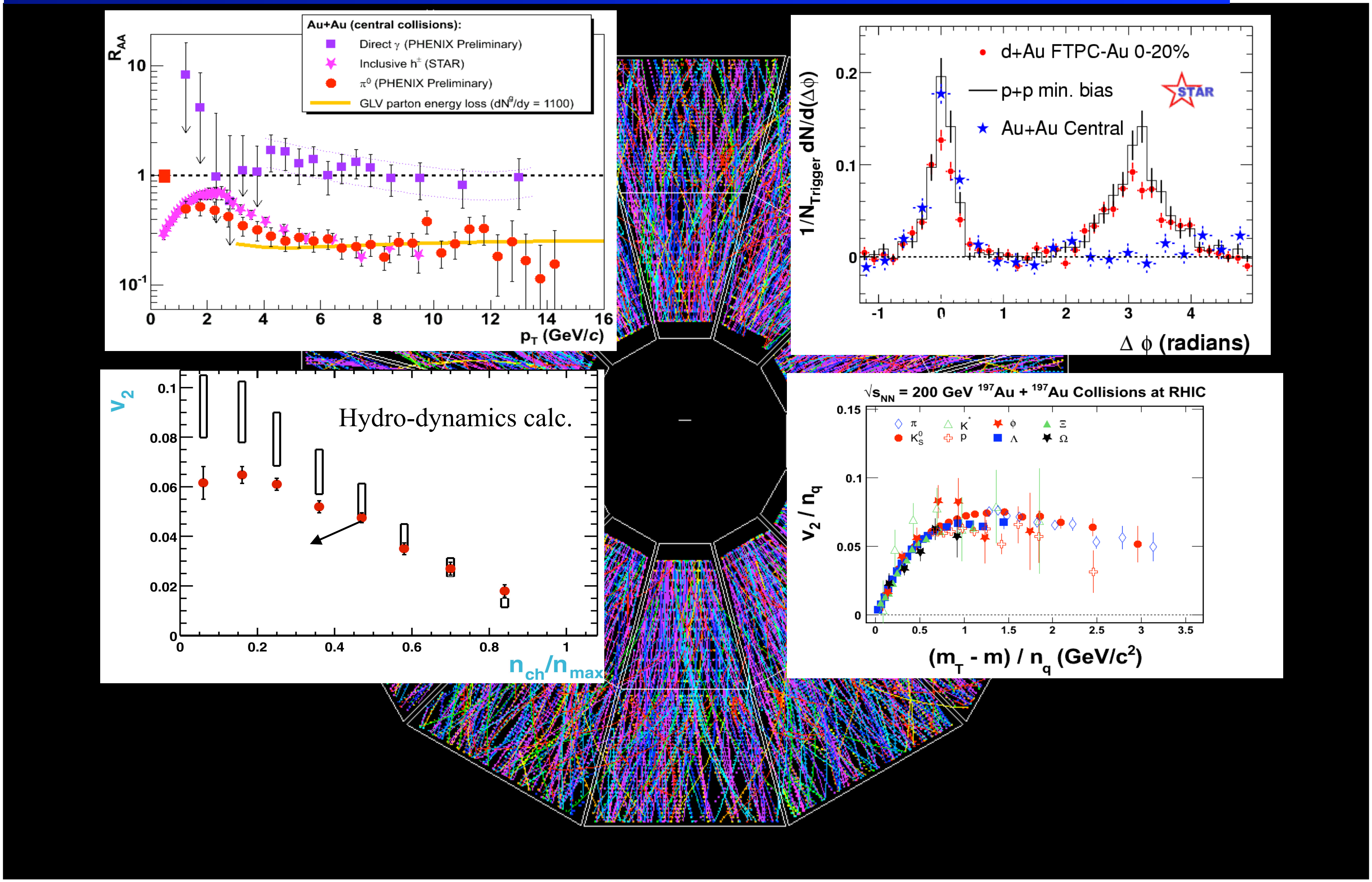
筑波大学
University of Tsukuba

QGP and Jets

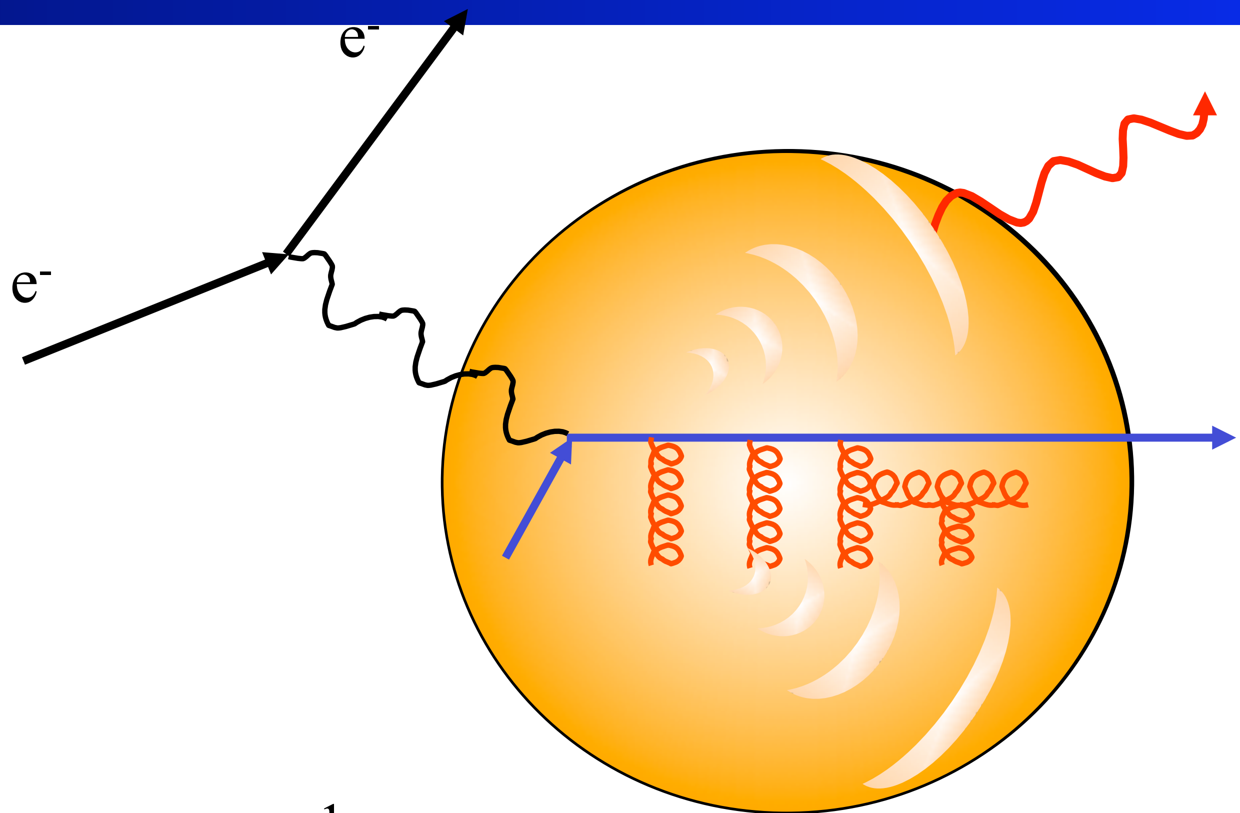
王新年

Xin-Nian Wang
Lawrence Berkeley National Laboratory
China Central Normal University

Empirical Evidence of sQGP at RHIC



Hard Probes & Structure of Dense Matter



Photon, Dilepton Emission

J/Ψ suppression

Medium response

Jet quenching

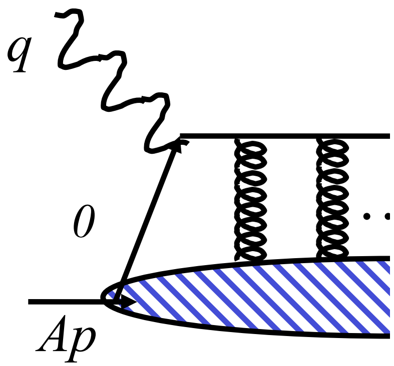
$\Delta D(z, k_\perp)$

$\frac{dE}{dx}$ $\hat{q}$

$$W_{\mu\nu}(q) = \frac{1}{4\pi}\int d^4x e^{iq\cdot x}\langle A | j_\mu^{em}(0) j_\nu^{em}(x) | A\rangle = -e_T^{\mu\nu}F_1(x_B) + e_L^{\mu\nu}F_2(x_B)$$

$$x_B = \frac{Q^2}{2p\cdot q}$$

Jet transport in medium



Belitsky, Ji & Yuan'03

$$L_{\|}^{\dagger}(-\infty,0;\vec{0}_{\perp}) = \exp\left[-ig\int_{0}^{-\infty} d\xi^{-} A^{+}(\xi^{-},\vec{0}_{\perp})\right]$$

"Leading-twist" or eikonal approx

Liang, XNW & Zhou'08

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

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

Jet transport in medium

"Leading-twist" or eikonal approx

Liang, XNW & Zhou'08

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

Jet Transport Operator

$$\vec{W}_\perp(y^-,\vec{y}_\perp)\equiv i\vec{D}_\perp(y)+g\int_{-\infty}^{y^-}d\xi^-L_{\parallel}^{\dagger}(\xi^-,y)\vec{F}_{+\perp}(\xi)L_{\parallel}(\xi;y)\,|_{\vec{\xi}_\perp=\vec{y}_\perp}$$

Classical correspondence: $$\frac{d\vec{p}_\perp}{d\tau}=g\vec{F}_{\perp\mu}v^\mu$$

Collinear q-g matrix elements → All quark k_T distr. info.

Jet transport parameter & medium

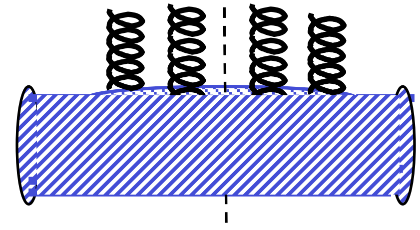
$$\sim \left[L_A \frac{g^2 \rho_A}{p^+} \langle N | F_{+\perp}(0) F_{+\perp}(\xi) | N \rangle \right]^n \sim \left[\alpha_s L_A \rho_A \, x G_N(x)|_{x\approx 0} \right]^n$$

$$\left\langle\left\langle \left[g \int_{-\infty}^{y^-} d\xi F_{+\perp}(\xi) \right]^{2n} \right\rangle\right\rangle_A$$

$$f_A^q(x,k_\perp) \approx A f_N^q(x) \frac{1}{\pi\Delta} \exp\left[-\frac{k_\perp^2}{\Delta} \right]$$

$$\Delta \equiv \langle k_\perp^2 \rangle = \int_A d\xi_N^- \hat{q}_F(\xi_N, 0) \approx \langle W_\perp^2(0, \vec{0}_\perp) \rangle_A$$

$$\left\langle\left\langle \vec{W}_\perp(y^-, \vec{y}_\perp)^{2n} \right\rangle\right\rangle_A$$



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

Solution of diffusion eq.

$$\frac{d\vec{p}_\perp}{d\tau} = g \vec{F}_\mu v^\mu$$

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

$$\hat{q}_F(\xi_N, x) \equiv \frac{4\pi^2 \alpha_s C_F}{N_c^2 - 1} \rho_A(\xi_N) x G_N(x)$$

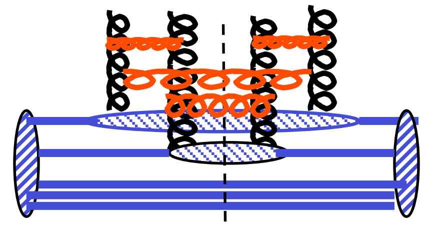
Jet transport parameter

Jet transport parameter & medium

$$\hat{q}_F(\xi_N, x) \equiv \frac{4\pi^2\alpha_s C_F}{N_c^2 - 1}\rho_A(\xi_N)xG_N(x)$$

Jet transport parameter

Multi-gluon correlation: $\hat{q}(1/\xi_\perp^2) \Leftrightarrow xG_N(x, 1/\xi_\perp^2)$



Gluon saturation

$$\hat{q}_A L_A \to Q_{sat}^2 = \frac{4\pi^2\alpha_s C_A}{N_c^2 - 1}L_A\rho_A(\xi_N)xG_N(x, Q_{sat}^2)|_{x\approx 0}$$

Casalderrey-Salana, XNW'07

Kochegov & Mueller'98
McLerran & Venugapolan'95

Gluon saturation in QGP

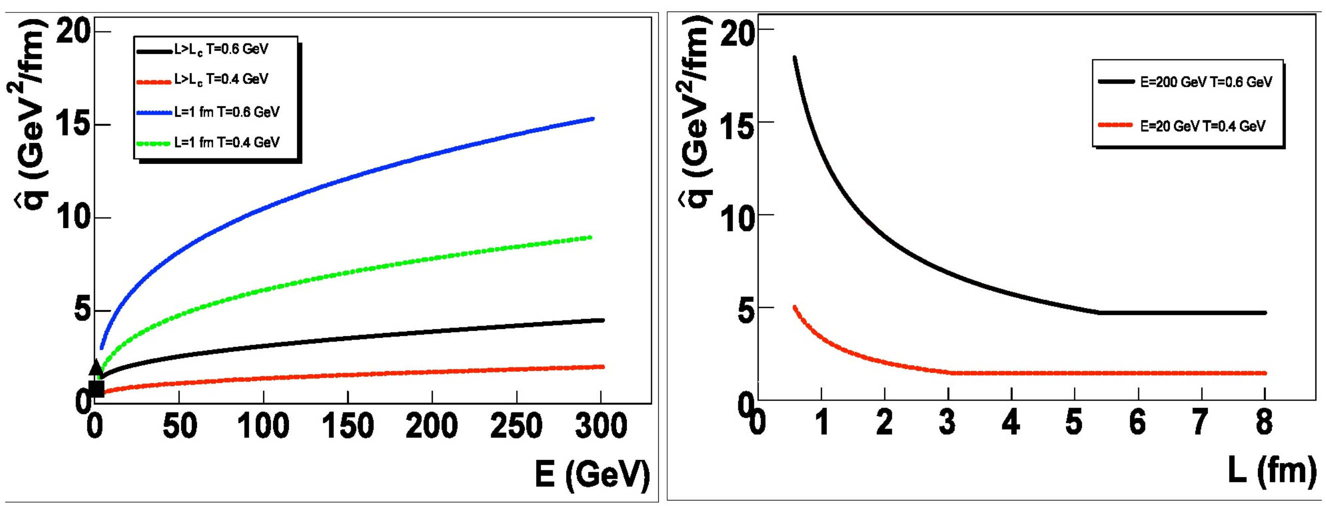
Gluon distr. from HTL at finite-T (gluon gas)

$$xG_N(x,\mu^2) \approx C_A \frac{\alpha_s}{\pi} \frac{\pi^2}{12\zeta(3)} \left[\frac{3}{2} \ln \frac{\mu^2}{\mu_D^2} + \frac{1}{3} \ln \frac{\mu_D}{xT} \right]$$

Casalderrey-Salana, XNW'07

DGLAP evolution in linearized regime

$$Q_s^2(x) = \frac{4\pi^2 \alpha_s C_A}{N_c^2 - 1} \rho_A(\xi_N) x G_N(x, Q_s^2) \min(L, L_c) \quad (L_c = 1/xT)$$

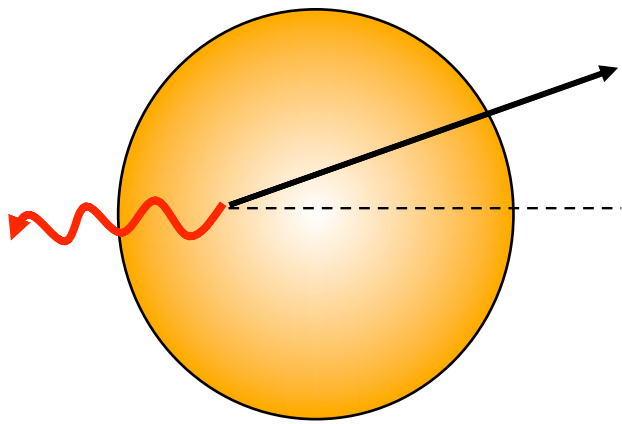


Direct Measurement of qhat

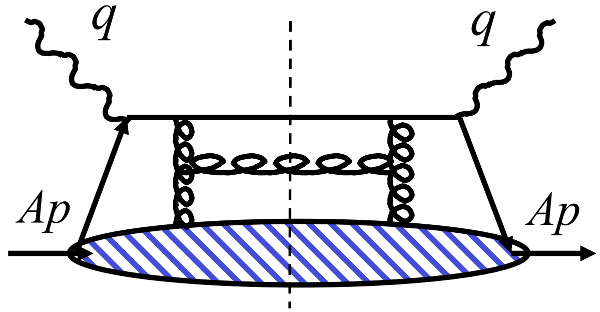
Strong coupling SYM: $\hat{q} \sim \sqrt{\lambda} T^3$

Liu, Rajagopal & Wiedemann'06

$$\left\langle k_\perp^2 \right\rangle = \int d\xi_N^- \hat{q}_F(\xi_N, 0)$$



Radiated & elastic energy loss



$$x_L = \frac{\ell_\perp^2}{2Ep^+ z(1-z)}$$

Gyulassy & XNW'04
BDMPS'96
LCPI:Zakharov'96
GLV: Gyulassy, Levai & Vitev'01
ASW: Wiedemann'00
HT: Guo & XNW'00
AMY: Arnold, Moore & Yaffe'03

$$\frac{dN_g}{dz d\ell_\perp^2} = \int d\xi \frac{\alpha_s N_c}{\pi} \frac{1+(1-z)^2}{z\ell_\perp^4} \left[c(x_L)\hat{q}(\xi,0) + \hat{q}(\xi,x_L) \right] \left[1-\cos(x_L p^+ \xi_N^-) \right]$$

$$\hat{q}(\xi,x) \sim \alpha_s \rho(\xi) xG(x) \qquad xG(x) \sim \delta(x-1) + \alpha_s \log \alpha_s$$

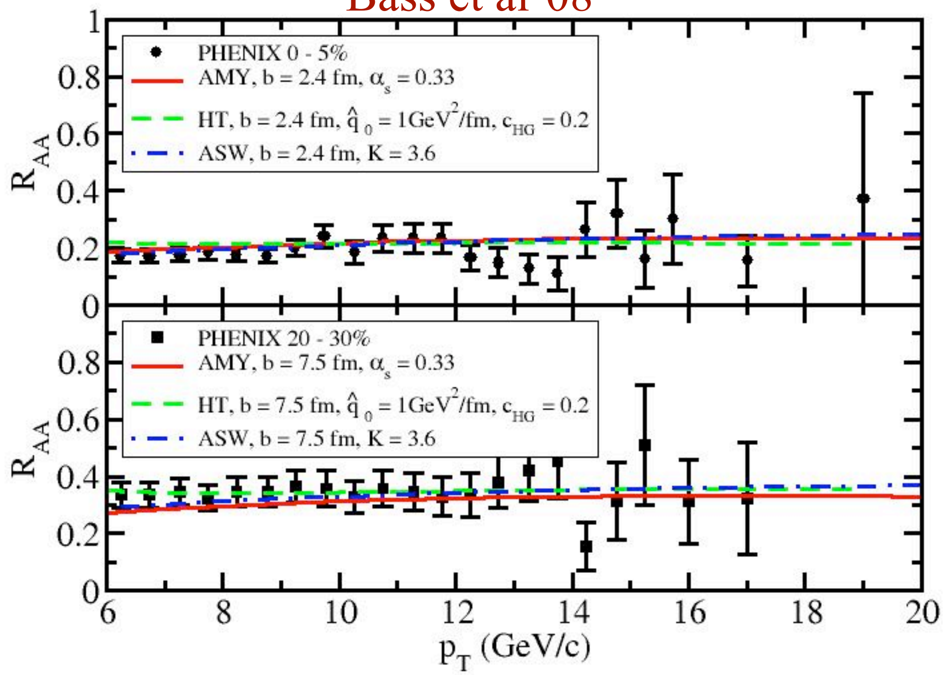
$$\Delta E_{el} = \left\langle \frac{1}{2\omega} \right\rangle \int d\xi \hat{q}(\xi) \left[1-\cos(\xi/\bar{\tau}_f) \right]$$

$$\frac{\Delta E_{el}}{\Delta E_{rad}} \simeq 0.1$$

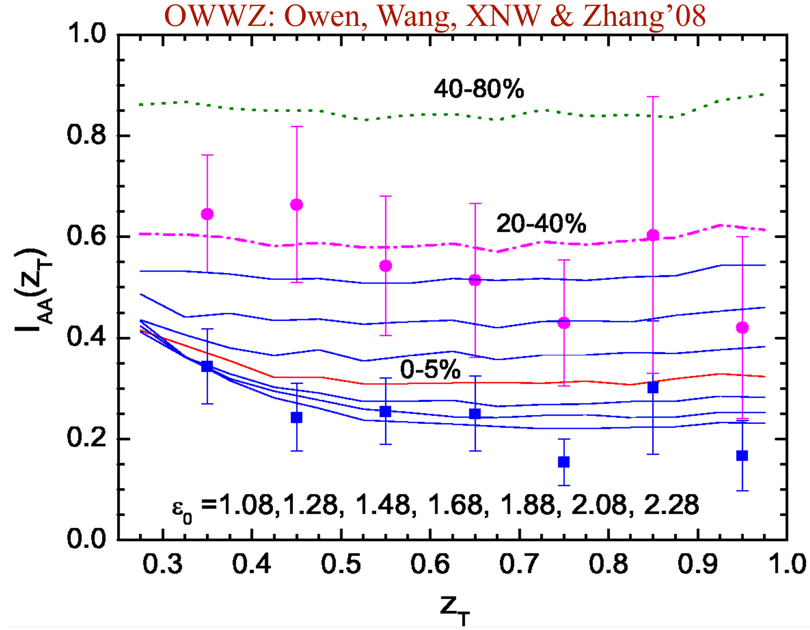
Wicks et al'06
Djordjevic et al'06
Vitev'06
XNW'06
Qin, et al'08

Hadron suppression & medium properties

Bass et al'08



OWWZ: Owen, Wang, XNW & Zhang'08



$$\hat{q}_0\tau_0 \approx 1-5\ \mathrm{GeV}^2 / fm$$

Cold nuclear matter in DIS

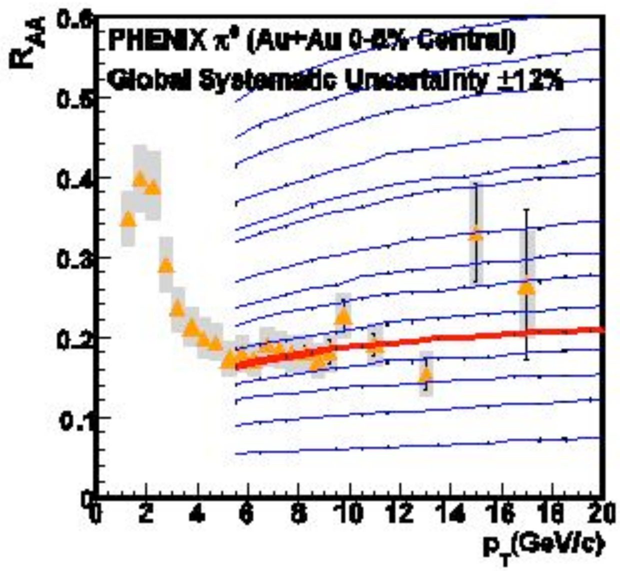
$$\hat{q}_N \approx 0.01\ \ \mathrm{GeV}^2 / fm$$

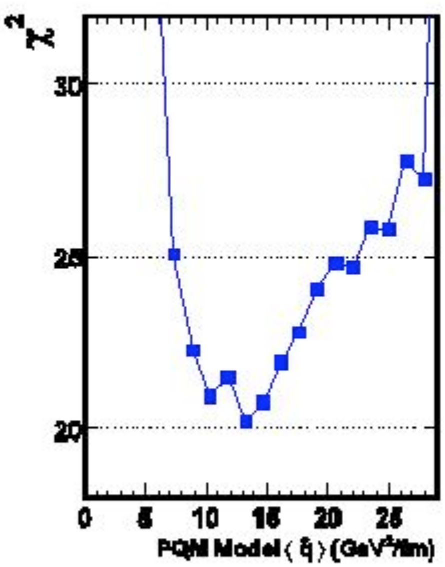
Wang & XNW'01

Jet Quenching phenomenology

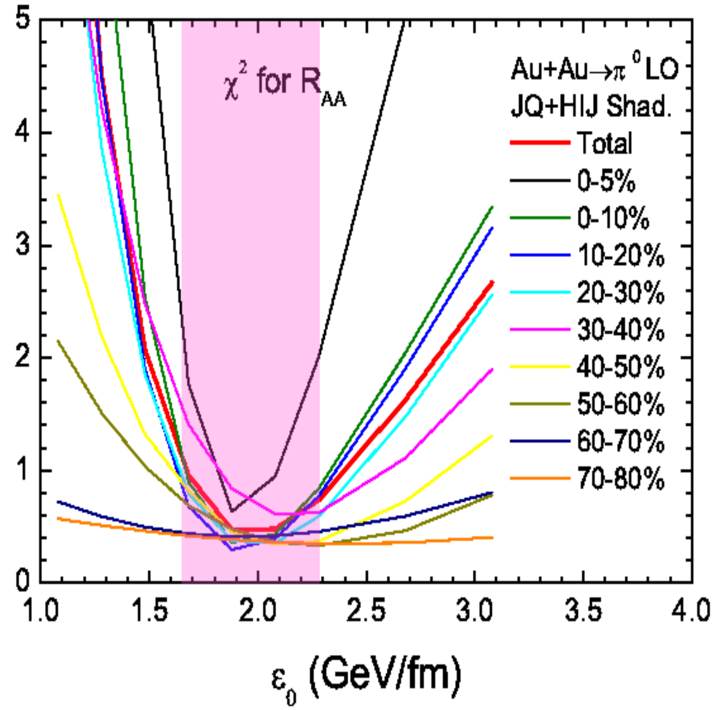
χ^2 -fit to single hadron Raa in Au+Au at all centralities at RHIC energy

Phenix'08,





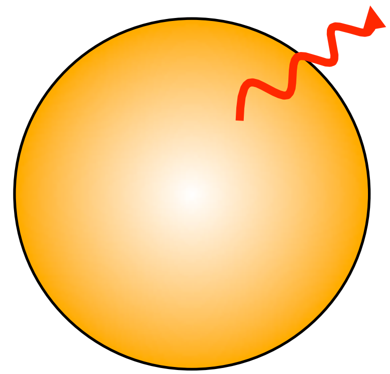
OWWZ'08



TECHQM $\Delta E_q \approx \left\langle \frac{dE}{dL} \right\rangle_{1d} \int_{\tau_0}^{\tau_0+L} d\tau \, \frac{\tau - \tau_0}{\tau_0 \rho_0} \rho_g(\tau, \vec{b}, \vec{r} + \vec{n}\tau)$

Direct photons

Arnold, Moore & Yaffe'01, Baym et al'07
Fries et al'03, Turbide et al'06, Arleo'07, Vitev'08,
Majumder et al'08



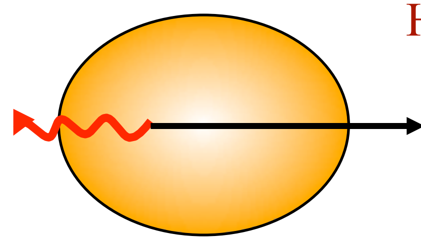
Fragmentation γ and its suppression
Medium induced γ (⟶ v2)

See talks by: Sangyang Jeon and Fuming Liu

Gamma-jet Correlation

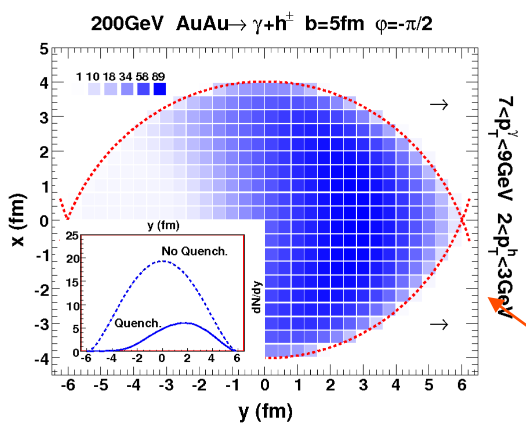
See talk by H. Zhang

HSW: Huang, Sarcevic & XNW'96

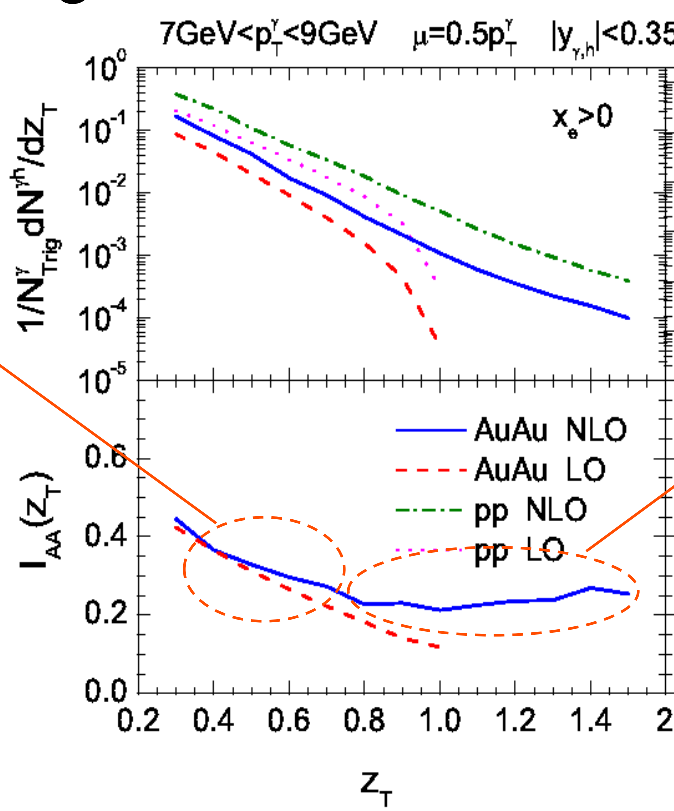


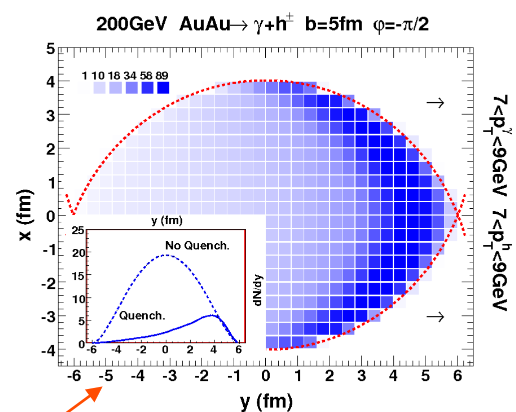
Isolated photons as tags:

OWWZ'08



Renk'06



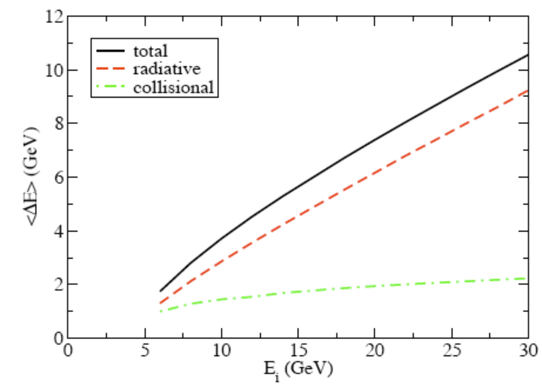


Volume emission for small z_T

Surface emission for large z_T>1

Theoretical improvements

Qin, et al ''08

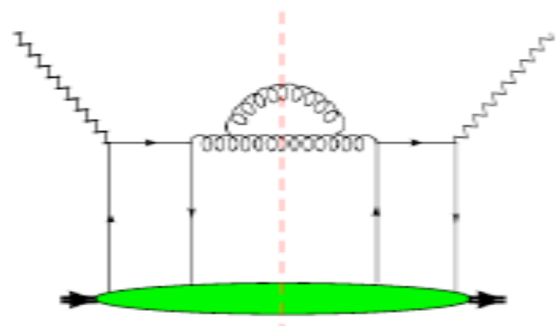


- Elastic vs radiative: for finite E & L

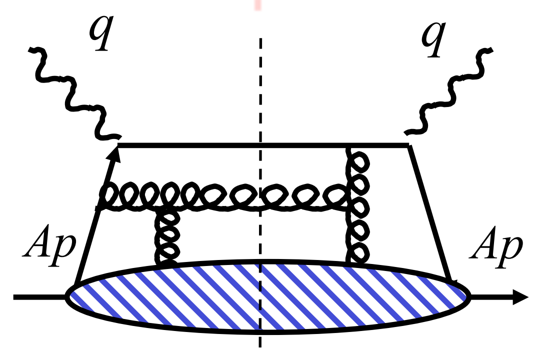
$$\frac{\Delta E_{rad}}{\Delta E_{el}} \simeq \frac{9\xi(3)N_c}{2\pi^2}\alpha_s LT \ln\frac{EL}{11}$$

- Recoil in radiative process:

$$\frac{dN_g}{dz d\ell_\perp^2} \sim c(x_L)\hat{q}(\xi,0) + \hat{q}(\xi,x_L) \sim 2\hat{q}(\xi,0) + O(\frac{\ell_\perp^2}{Q^2})$$



- Quark-annihilation
  Flavor changing process $O(\frac{\ell_\perp^2}{Q^2})$



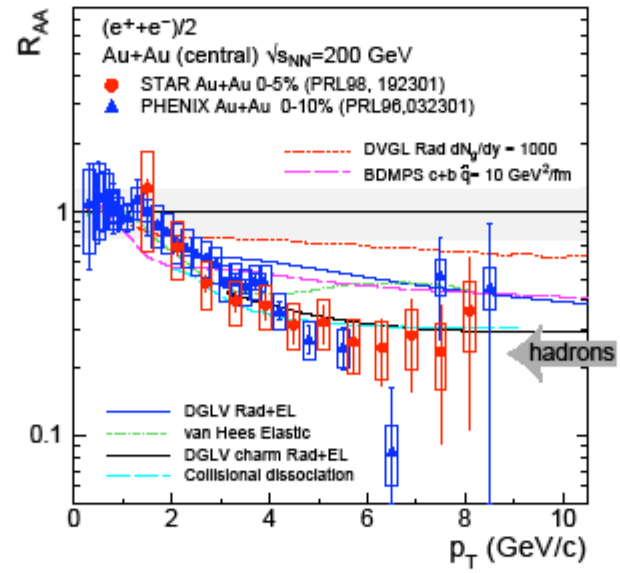
- NLO corrections to LO collinear factorized contribution

- Mass correction for heavy quarks $O(\frac{M_Q^2}{Q^2})$

Heavy Quarks

Wicks et al'06,Djordjevic et al'06

$\Delta E_{el} / \Delta E_{rad}$ for heavy quark
is larger than light quarks



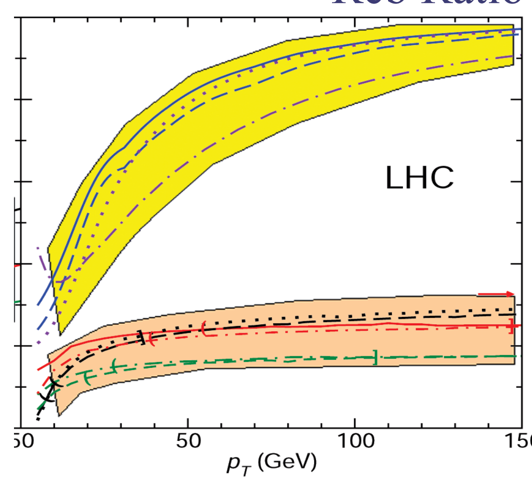
Langevin Eq. for v<<1 Moore & Teaney'05

$$\frac{d\vec{p}}{dt} = -\eta_D \vec{p} + \vec{\xi}$$

Talk by Y. Akamatsu

pQCD $\eta_D \sim \frac{T^2}{M} \alpha_s^2 \log \frac{T}{\mu_D}$

Rcb Ratio



Strong coupling SYM

$$\eta_D = \frac{T^2}{M} \frac{\pi}{2} \sqrt{\lambda}$$

Casalderrey-Solana & Teaney'06
Gubser'06, Herzog et al'06

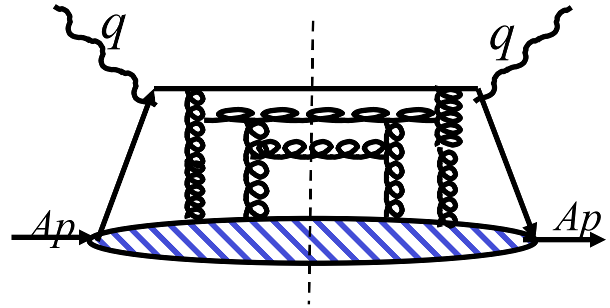
Horowitz & Gyulassy'08

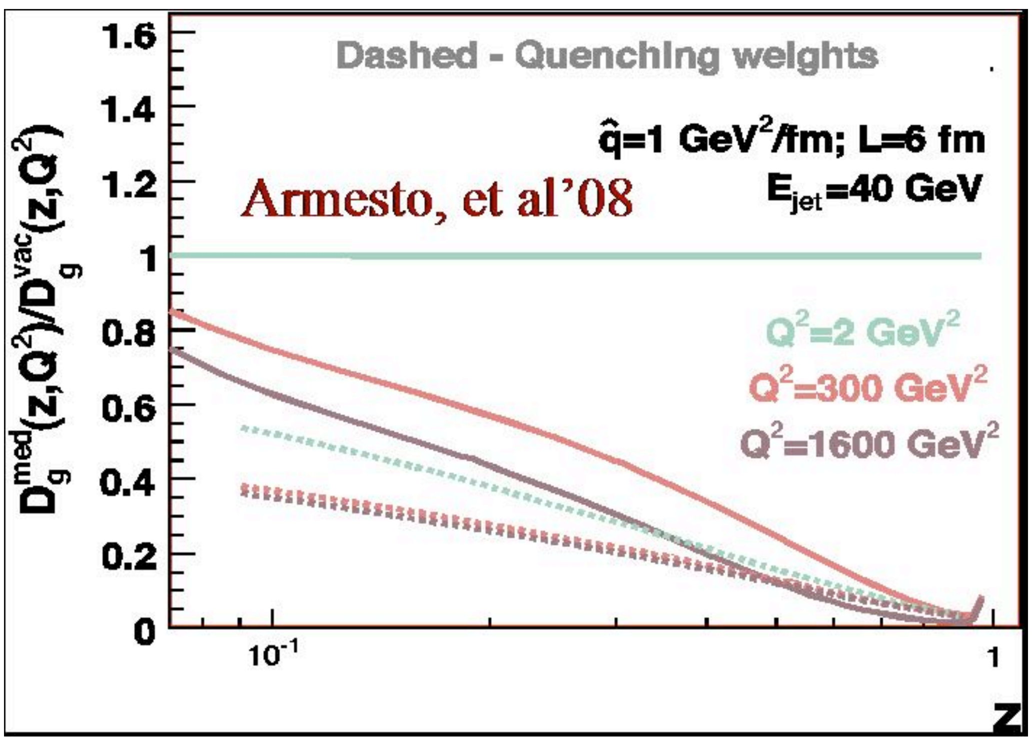
Inclusion of multiple gluon emission

Modified DGLAP Evolution Eq. Guo & XNW'00

$$\frac{\partial D(z,Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\int \frac{dy}{y}\left[P(y) + \Delta P(y,Q^2)\right] D(\frac{y}{z},Q^2)$$

$$\Delta P(z,\ell_\perp^2) \equiv \ell_\perp^2 \frac{dN_g}{dz d\ell_\perp^2}$$





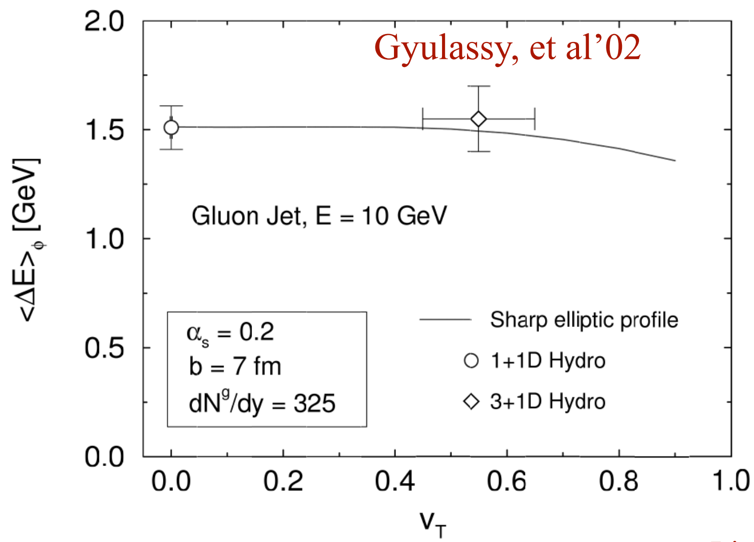
Armesto, et al'08
Renk'08
Zapp et al'08

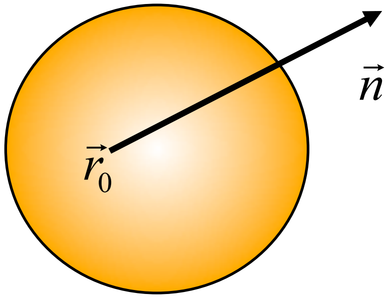
Effects of hydrodynamics

$$\Delta E \sim \int d\tau \hat{q}(\tau, \vec{r}_0 + \tau \vec{n})$$

1D vs. 2+1D

Faster decrease in ρ
but increased duration





Effect of flow $\hat{q} = \hat{q}_0 \frac{u \cdot p}{p_0}$ $\frac{\langle \hat{q} \rangle_{flow}}{\langle \hat{q} \rangle_{no-flow}} \approx 0.9$

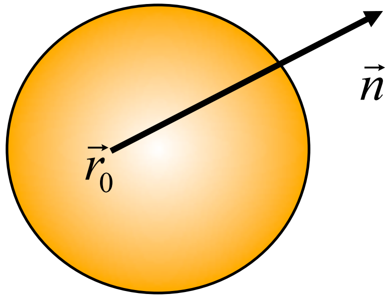
Liu, Rajagopal & Wiedemann'06

Baier, Mueller &Schiff'06

Talk by T. Hirano

Effects of hydrodynamics

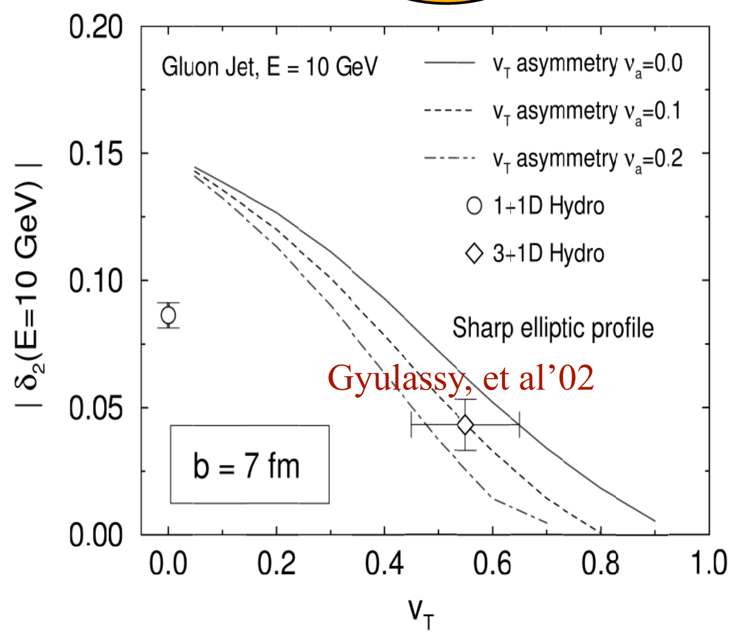
$$\Delta E \sim \int d\tau \hat{q}(\tau, \vec{r}_0 + \tau \vec{n})$$



Some decrease in anisotropy of ΔE in 1+2D without effect of flow

Viscous hydro, 3-D haydro: effects are expected to be small

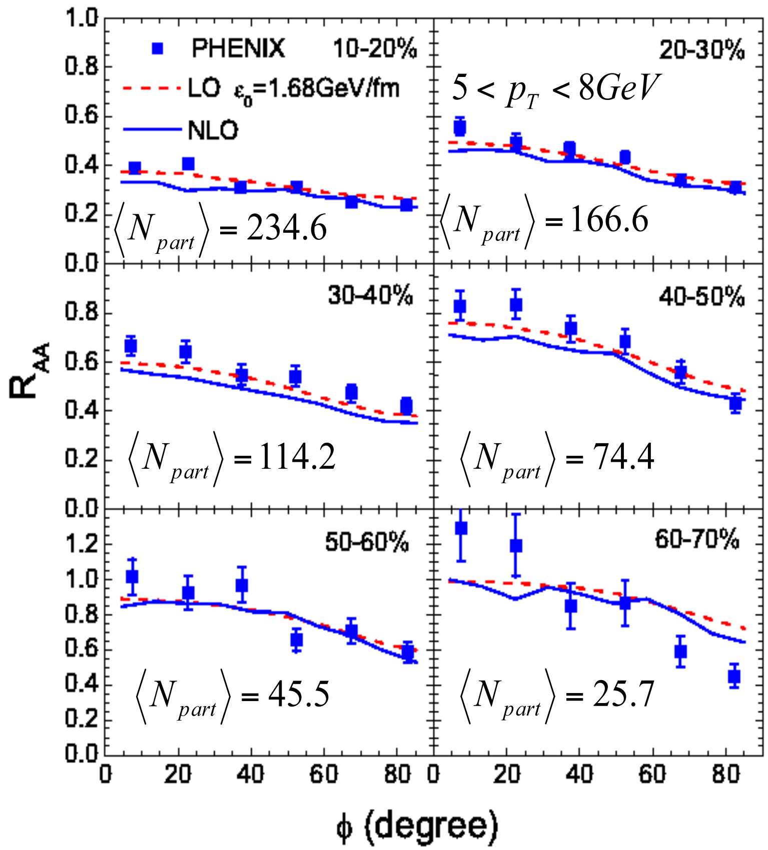
TECHQM for 3-D viscous hydro



Azimuthal anisotropy

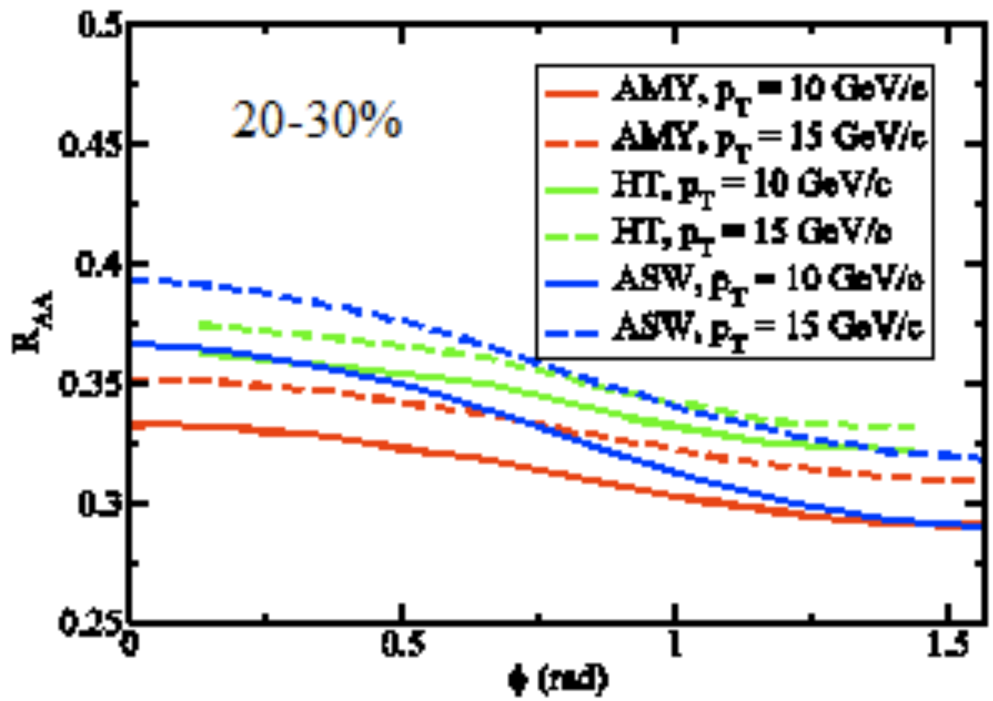
OWWZ' 2008

1+1D Bjorken



Bass et al'08

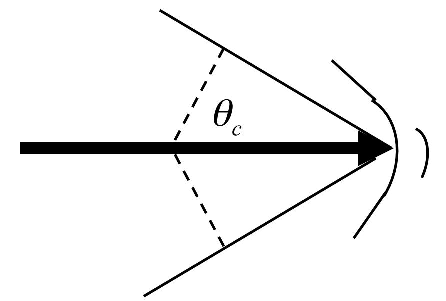
1+2D hydro



Medium response to jets

Sonic mach cones induced by propagating jets

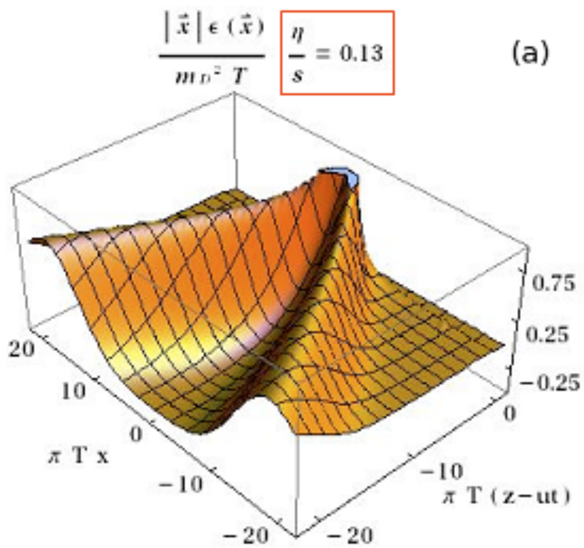
Stocker'05, Casaderrey-Solana, Shuryak & Teaney'05



Mach cone angle: $\cos\theta_c = \frac{c_s}{v}$

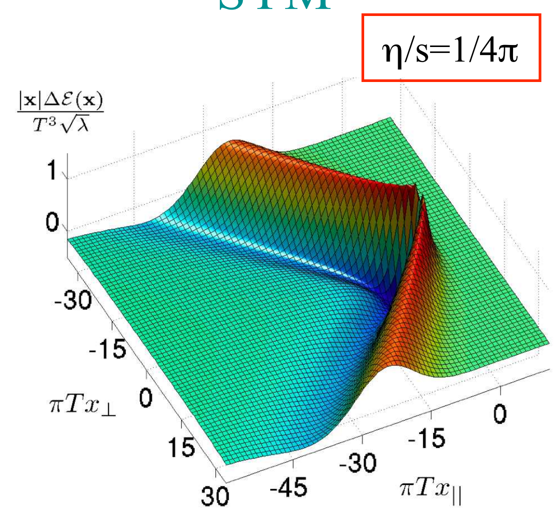
Sound attenuation → with of the cone structure: $\frac{\eta}{sT}$

pQCD



Neufeld, Muller & Ruppert'08

SYM



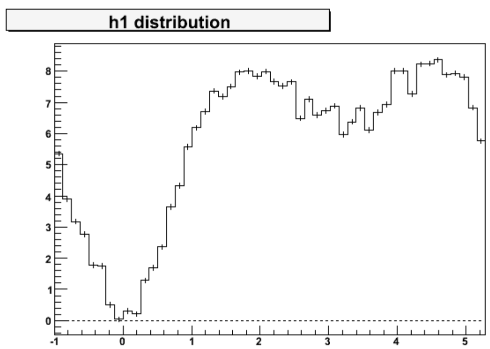
Chesler & Yaffe;07

Fries et al'07

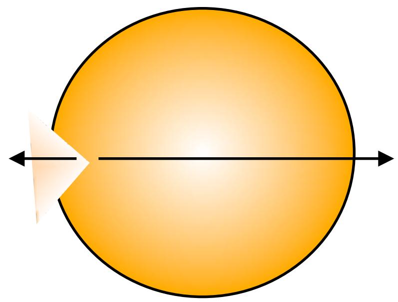
Cone & ridge in parton cascade

Double peak structure was seen in AMPT simulation Ma, et al ‘06

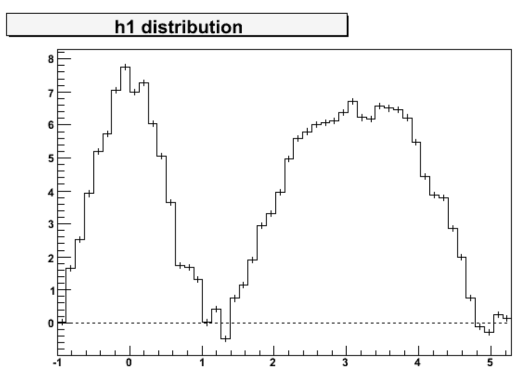
Soft hadrons associated with a jet



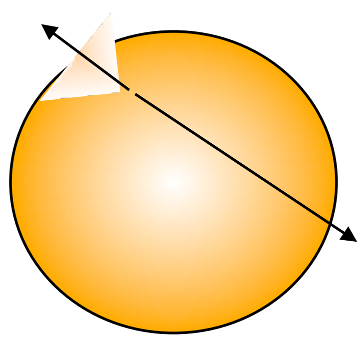
punch-through jets



p_T=0~1GeV/c



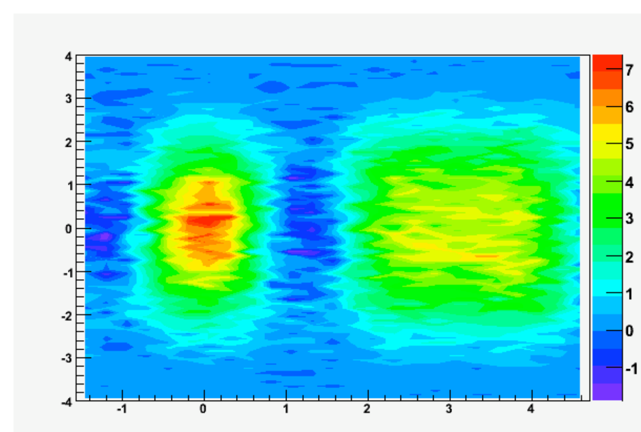
tangential jets



Minimum distance required

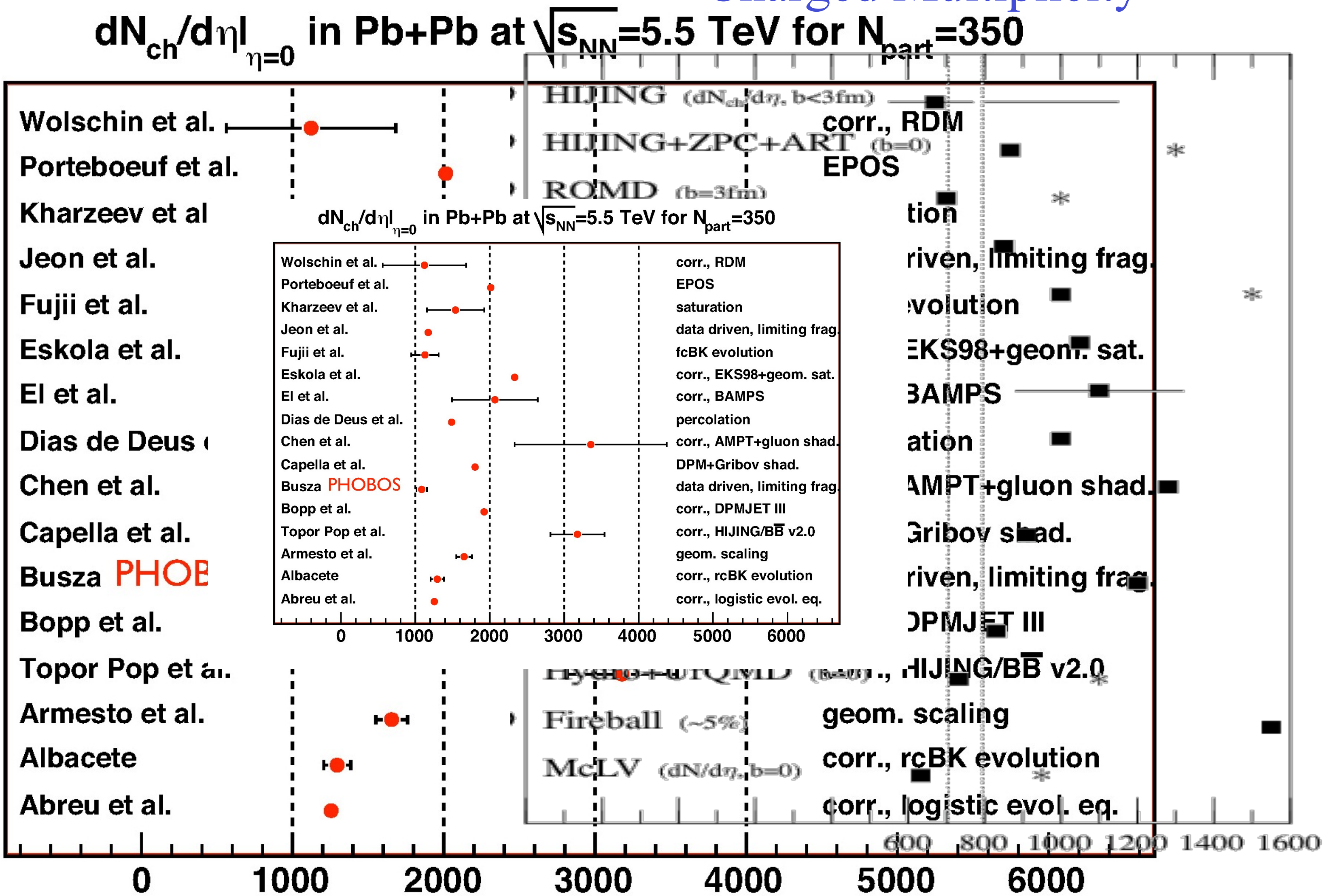
Ridge along tangential jets

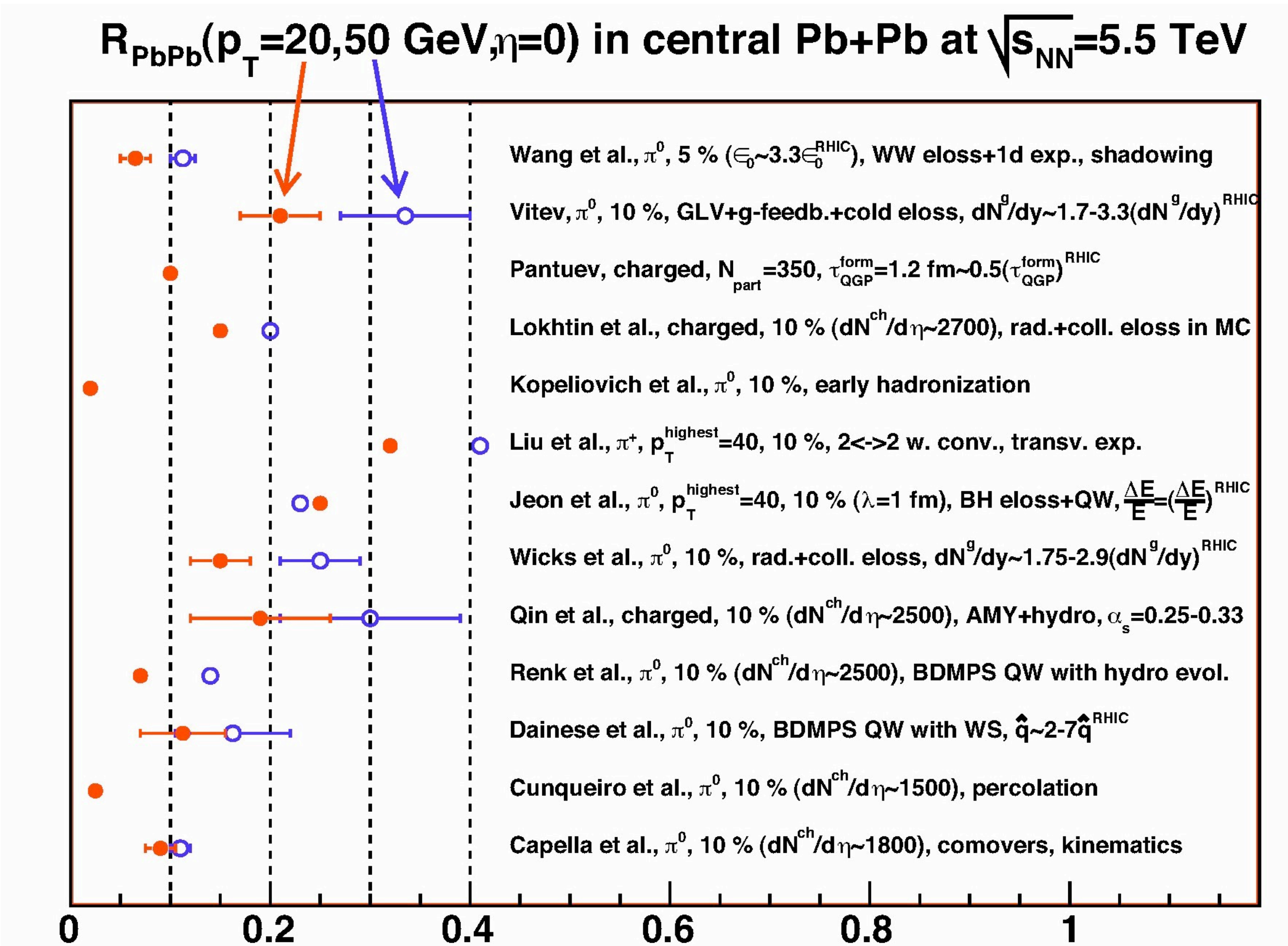
Longitudinal flow (Armesto et al’05)
Longitudinal field (Majumder et al’07)
Recombination (Hwa’05, Wong’ 07)



Predictions for LHC

Charged Multiplicity




R_PbPb(p_T=20,50 GeV,η=0) in central Pb+Pb at √s_NN=5.5 TeV
Wang et al., π0, 5 % (∈0~3.3∈0RHIC), WW eloss+1d exp., shadowing
Vitev, π0, 10 %, GLV+g-feedb.+cold eloss, dNg/dy~1.7-3.3(dNg/dy)RHIC
Pantuev, charged, Npart=350, τQGPform=1.2 fm~0.5(τQGPform)RHIC
Lokhtin et al., charged, 10 % (dNch/dη~2700), rad.+coll. eloss in MC
Kopeliovich et al., π0, 10 %, early hadronization
Liu et al., π+, pThighest=40, 10 %, 2<->2 w. conv., transv. exp.
Jeon et al., π0, pThighest=40, 10 % (λ=1 fm), BH eloss+QW, ΔE/E=(ΔE/E)RHIC
Wicks et al., π0, 10 %, rad.+coll. eloss, dNg/dy~1.75-2.9(dNg/dy)RHIC
Qin et al., charged, 10 % (dNch/dη~2500), AMY+hydro, αs=0.25-0.33
Renk et al., π0, 10 % (dNch/dη~2500), BDMPS QW with hydro evol.
Dainese et al., π0, 10 %, BDMPS QW with WS, q̂~2-7q̂RHIC
Cunqueiro et al., π0, 10 % (dNch/dη~1500), percolation
Capella et al., π0, 10 % (dNch/dη~1800), comovers, kinematics
0
0.2
0.4
0.6
0.8
1

Summary

- Jets in QGP provide unprecedented information about the dense matter produced in heavy-ion collisions
- Jet quenching studies have become quantitative both in theory and phenomenology
- Identified jets and gamma-jets offer more discriminating information
- Study the response of medium in terms of sonic mach cone and ridge becoming a reality
- LHC : expect to see the same trend. Most uncertainty comes from initial conditions. But it will be measured.

Thank you !

ありがとう！

당신을 감사하십시오 !

谢谢！