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Azimuthal Jet Tomography at RHIC and LHC

Barbara Betz

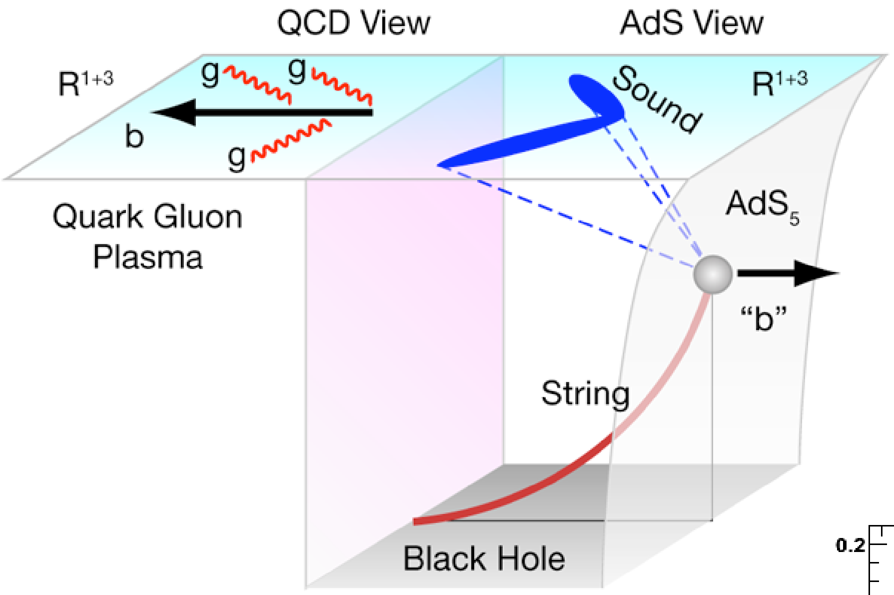
in collaboration with Miklos Gyulassy

Hard Probes 2013
Stellenbosch, South Africa

PRC **84**, 024913 (2011); PRC **86**, 024903 (2012);
arXiv: 1305.6458

HIC for FAIR
Helmholtz International Center

Jet Quenching in pQCD vs. AdS/CFT



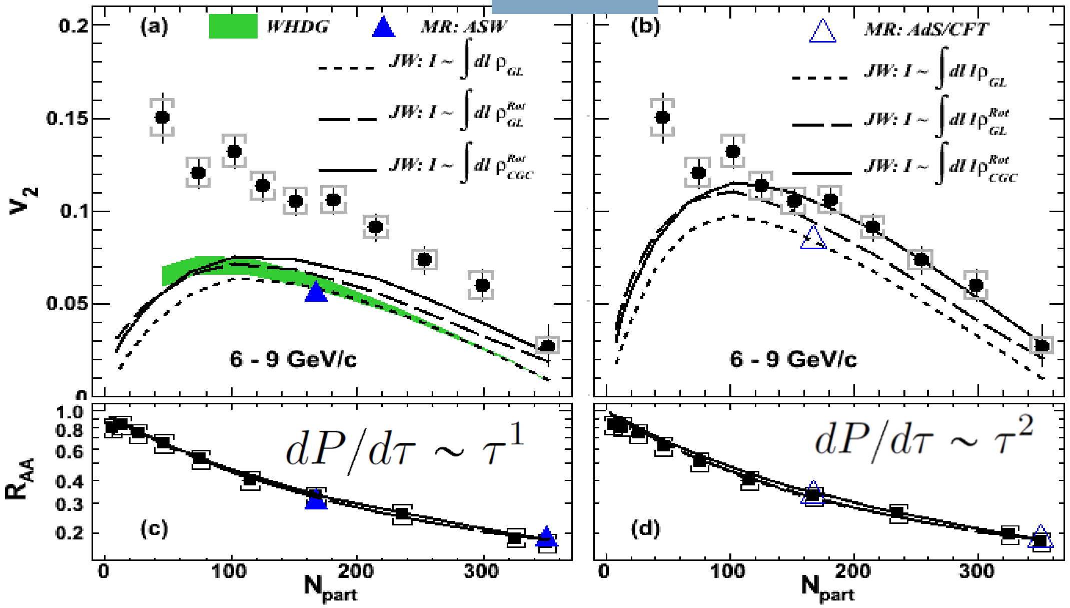
M. Gyulassy Physics **2**, 107 (2009)

Long-standing question:

Can the jet-energy loss be described by pQCD or does one need an AdS/CFT prescription?

PHENIX results seem to indicate an AdS/CFT-inspired energy-loss???

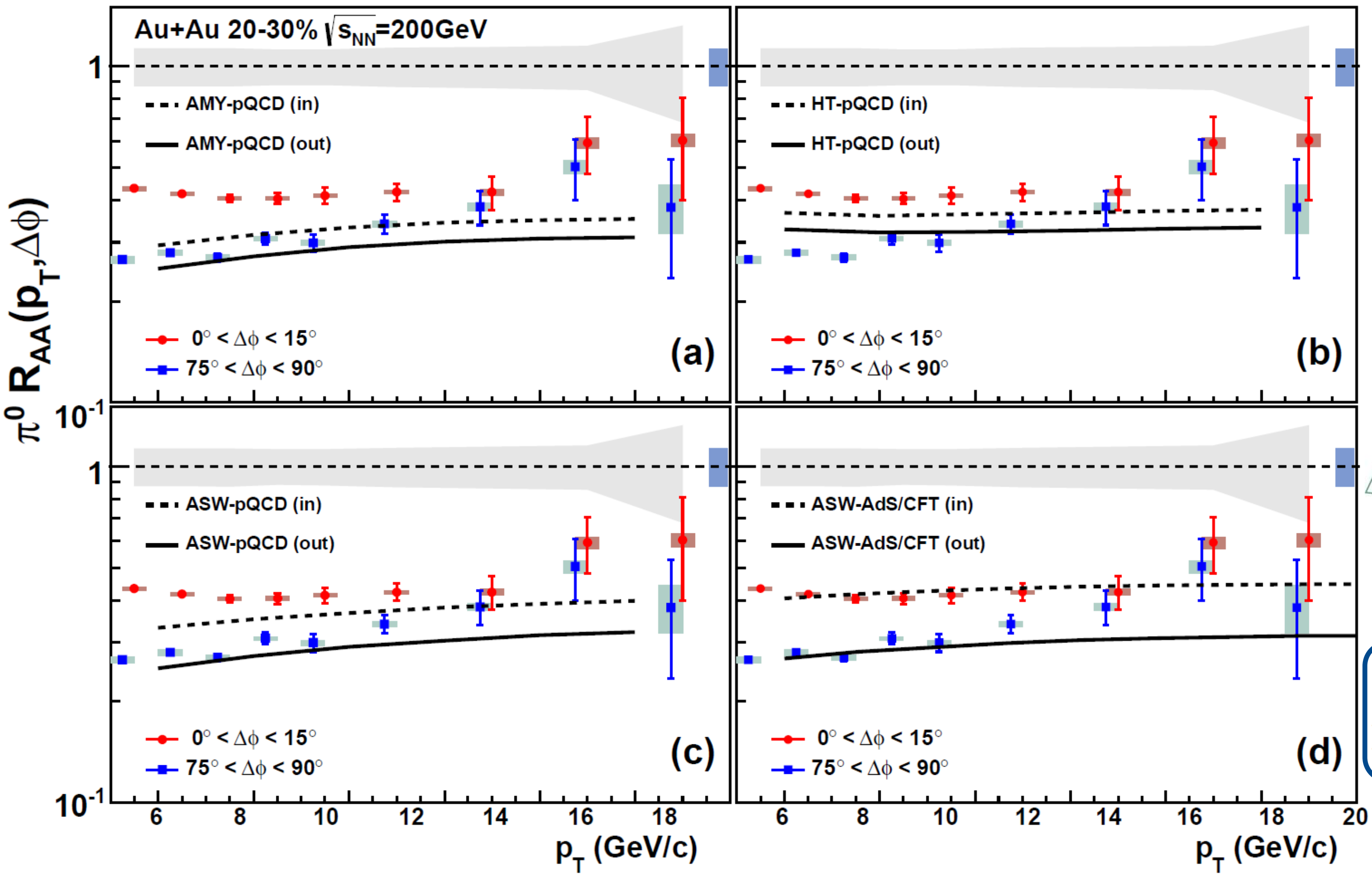
pQCD-like RHIC AdS/CFT-like

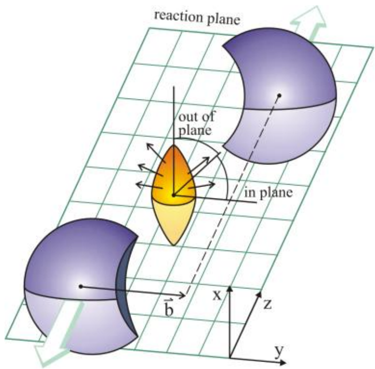


A. Adare et al, Phys. Rev. Lett. **105**, 142301 (2010)

pQCD vs. AdS/CFT @RHIC

A. Adare et al., arXiv:1208.2254





$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{coll} dN_{pp}/dp_T}$$

$$R_{AA}^{in} = R_{AA}(1 + 2v_2)$$

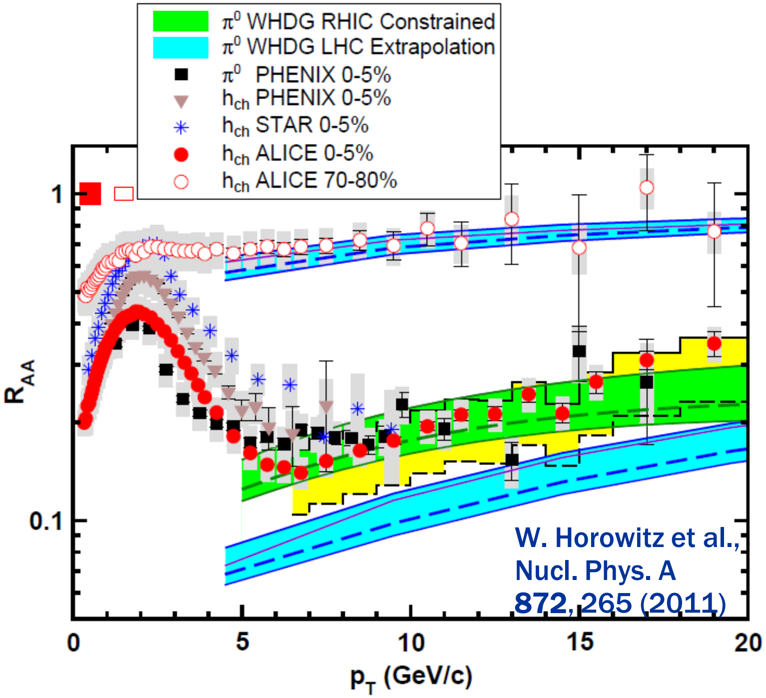
$$R_{AA}^{out} = R_{AA}(1 - 2v_2)$$

PHENIX results strongly suggest that pQCD-based jet tomography fails at RHIC and only AdS-inspired models explain jet asymmetry

In contrast to conclusion from R. Lacey et al. R. Lacey, Phys. Rev. C **80**, 051901 (2009)

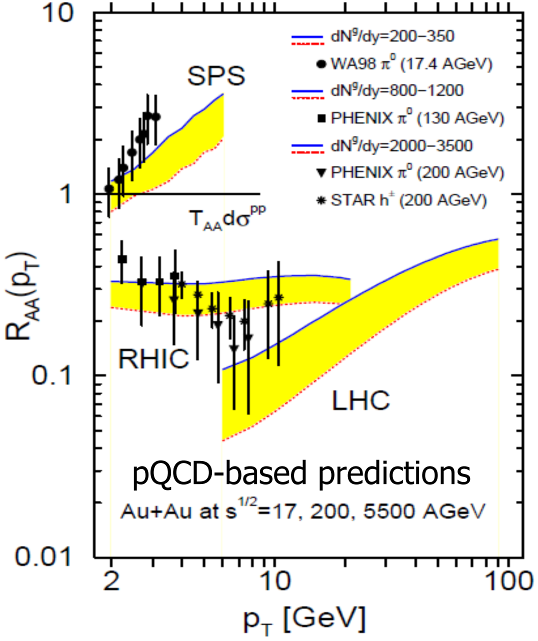
Overquenching @LHC

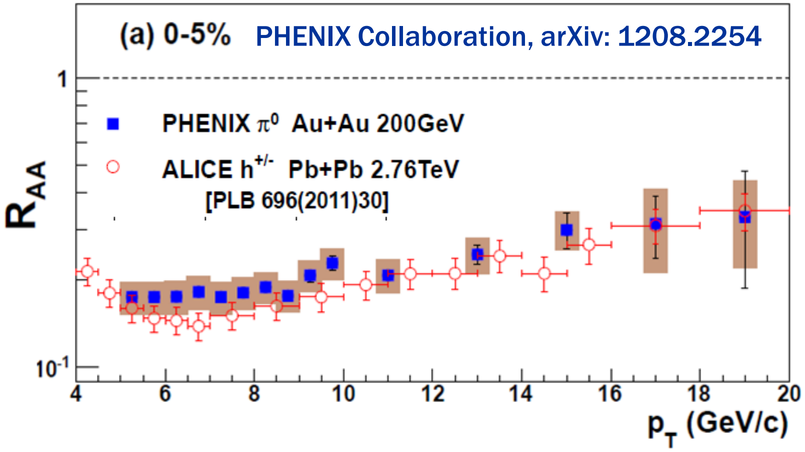
In contrast to predictions: remarkable similarity of RHIC & LHC results at p_T>15 GeV



W. Horowitz et al., Nucl. Phys. A **872**, 265 (2011)

Vitev et al., Phys. Rev. Lett. **89**, 252301 (2002)





PHENIX Collaboration, arXiv: 1208.2254

⇒ The jet-medium coupling @LHC seems to be smaller than @RHIC (points to a running-coupling effect consistent with pQCD).

Energy-Loss Mechanisms

Generic model of jet-energy loss:

$$\frac{dP}{d\tau}(\vec{x}_0,\phi,\tau) = -\kappa P^a(\tau)\,\tau^z\,T^{c=2-a+z}[\vec{x}_\perp(\tau),\tau,b]$$

generalized from Jia‘s survival model

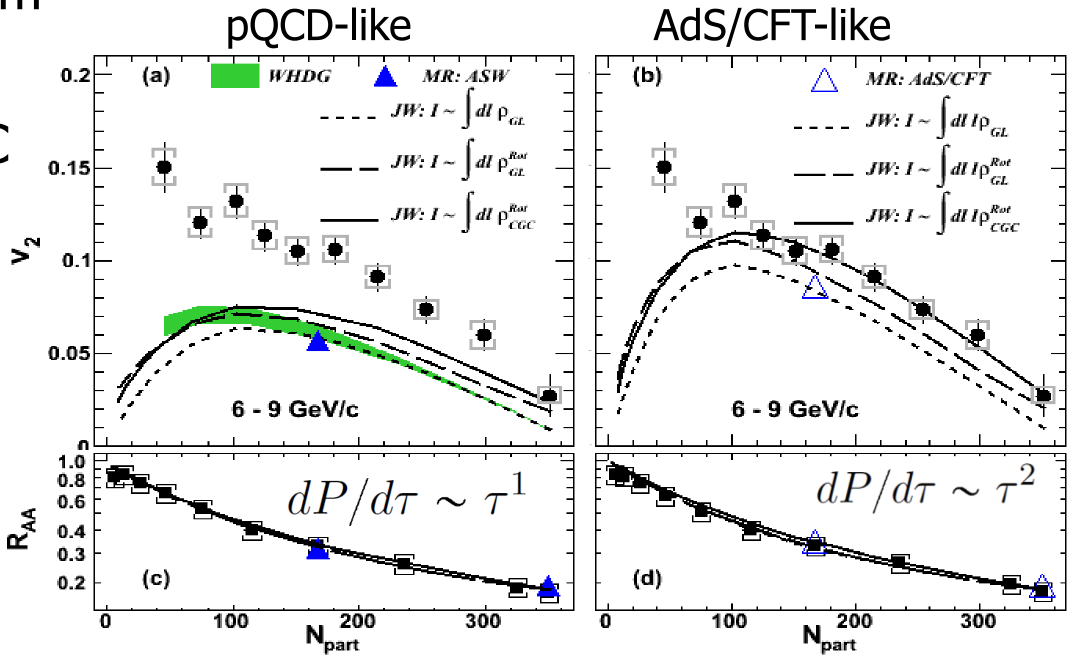
J. Jia et al., PRC **82**, 024902 (2010)

including fragmentation and examining an “averaged scenario” to study:

B.Betz et al., PRC **84**, 024913 (2011)

- **Bullet #1**: R_{AA}@RHIC & LHC (overquenching & jet-medium coupling reduction)
- **Bullet #2**: v_2@RHIC & LHC (transverse expansion)
- **Bullet #3**: path-length dependence (pQCD vs. AdS/CFT?)

+ the energy-dependence
+ different initial conditions (Glauber and CGC-like)

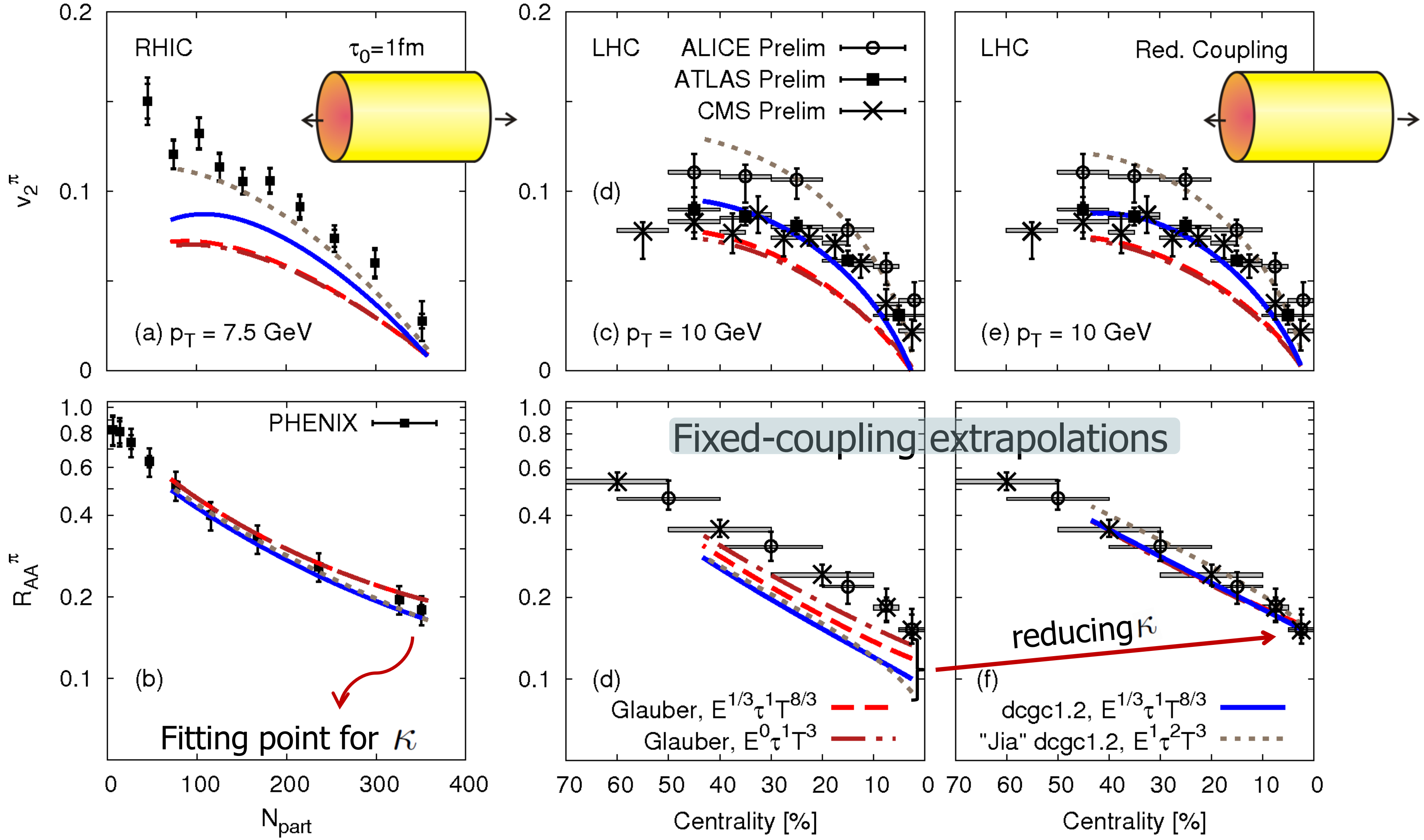


A. Adare et al, Phys. Rev. Lett. **105**, 142301 (2010)

Bullet #1: R_{AA} and v_2 at RHIC vs. LHC

Bjorken expanding medium

B.Betz et al., PRC **86**, 024903 (2012)



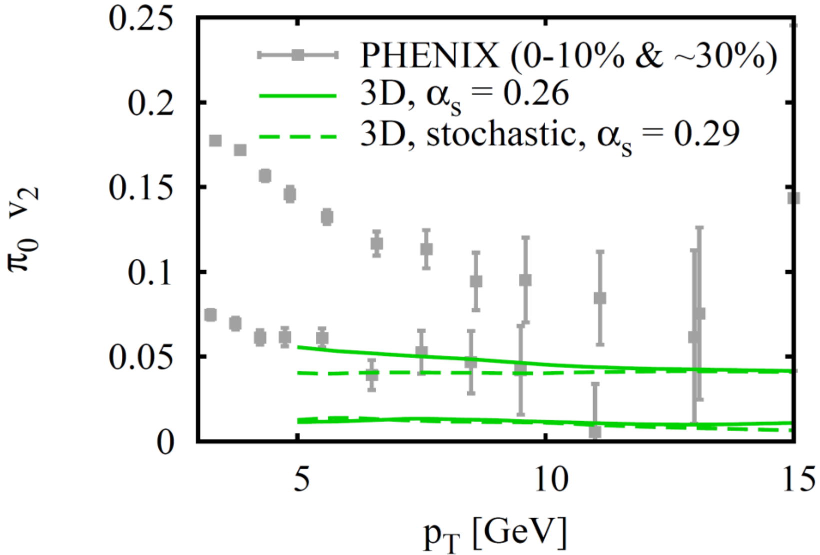
Fixed-coupling extrapolations

⟹ Moderate reduction of the running coupling: $\alpha_{\rm LHC} \sim 0.24 - 0.28$

similar for all scenarios

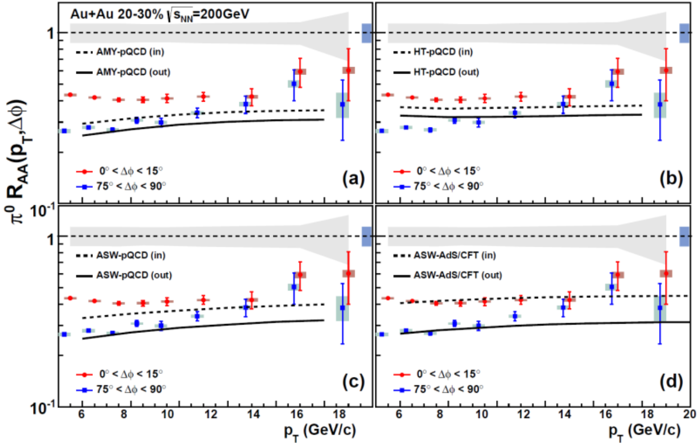
Similar: Pal et al., PLB **709**, 012027 (2012); R. Lacey et al., arXiv: **1202.5537**

Bullet #2: Transverse expansion

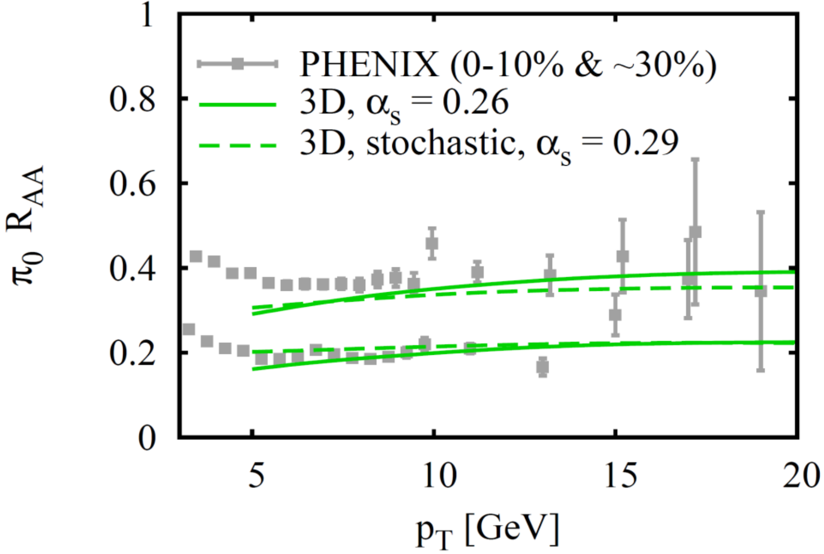


RHIC

A. Adare et al., arXiv:1208.2254



D. Molnar et al., arXiv:1209.2430



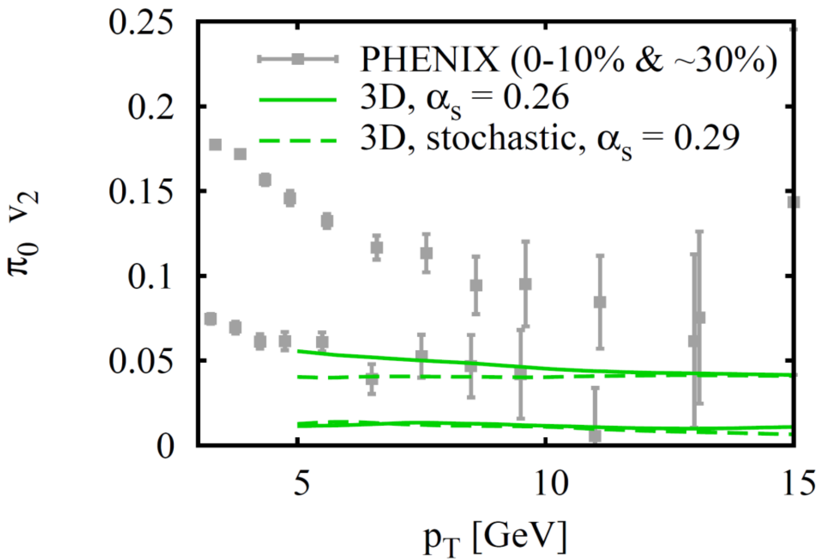
Considering a combination of (D)GLV and the parton transport model (MPC) and a 3d expansion

D. Molnar et al., Phys. Rev. C **62**, 054907 (2000)

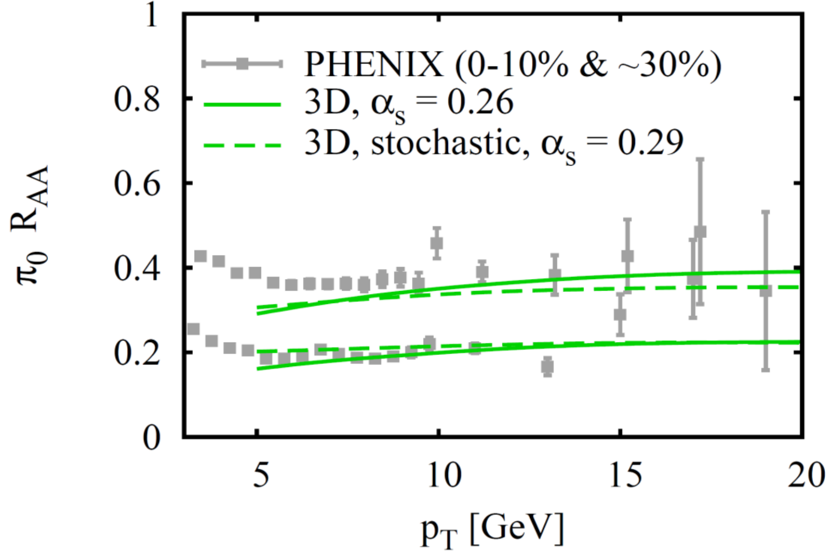
⟹ The pion v_2 at RHIC energies is a factor of 2 too small

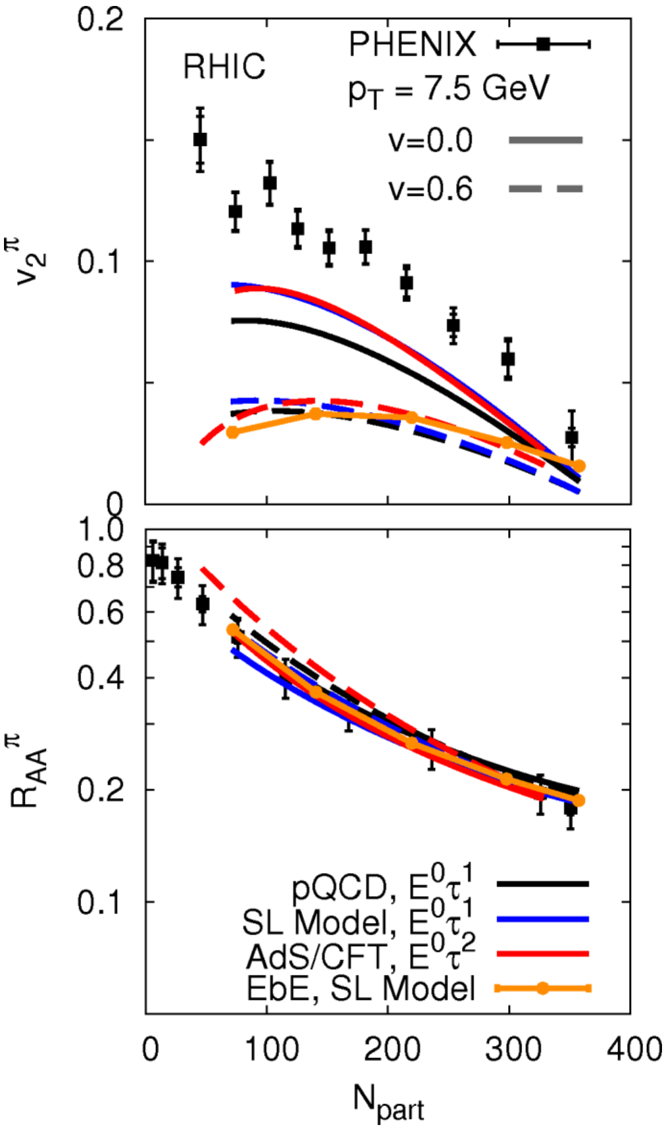
Bullet #2: Transverse expansion

RHIC



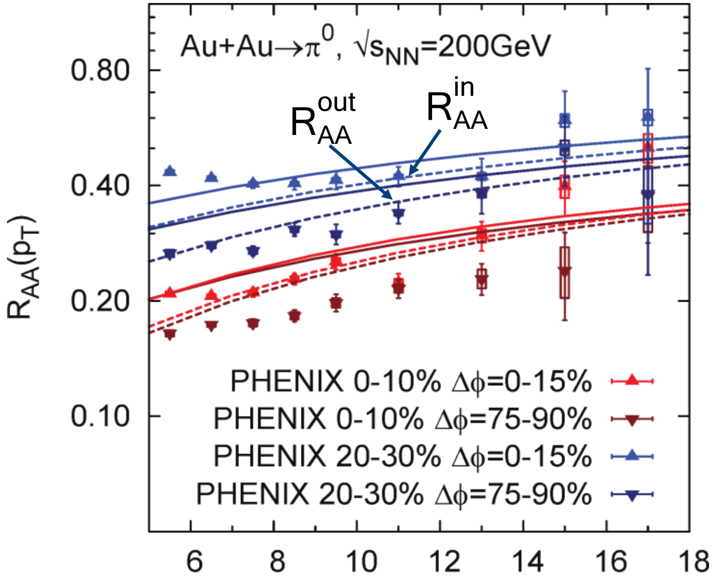
D. Molnar et al., arXiv:1209.2430





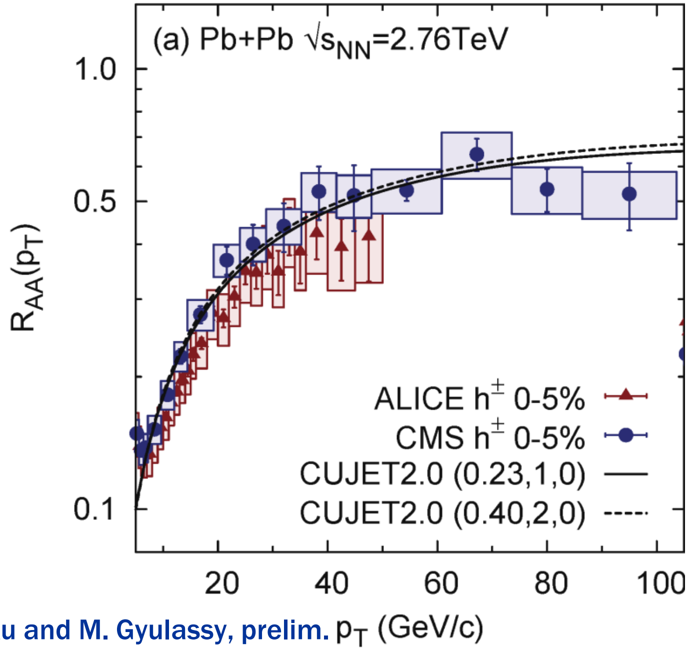
⇒ Reduction of the pion v_2 by a factor of 2 considering **transverse expansion**

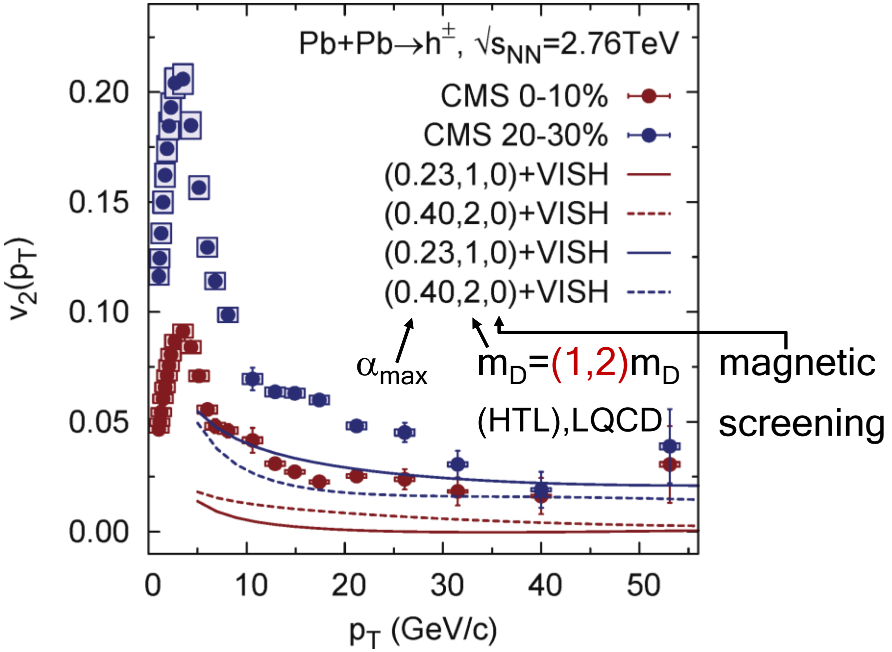
CUJET2.0 = DGLV (run. coupl.) + VISH2.1 ($\eta/s=0.08$)



v_2 is about a factor of 2 too small, consistent with D. Molnar's and our results considering a blast wave background

see Jiechen Xu's
talk, today 17:40
(heavy flavor session)



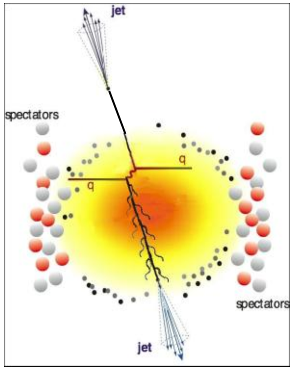


Jichen Xu and M. Gyulassy, prelim.

Energy-Loss Mechanisms 2.0

Generic model of jet-energy loss:

RHIC & LHC



$$\frac{dP}{d\tau}(\vec{x}_0,\phi,\tau) = -\kappa P^a(\tau)\,\tau^z\,T^{c=2-a+z}[\vec{x}_\perp(\tau),\tau,b]$$

Calculate R_{AA}^{in} and R_{AA}^{out}/R_{AA} and v_2 @ RHIC & LHC for:

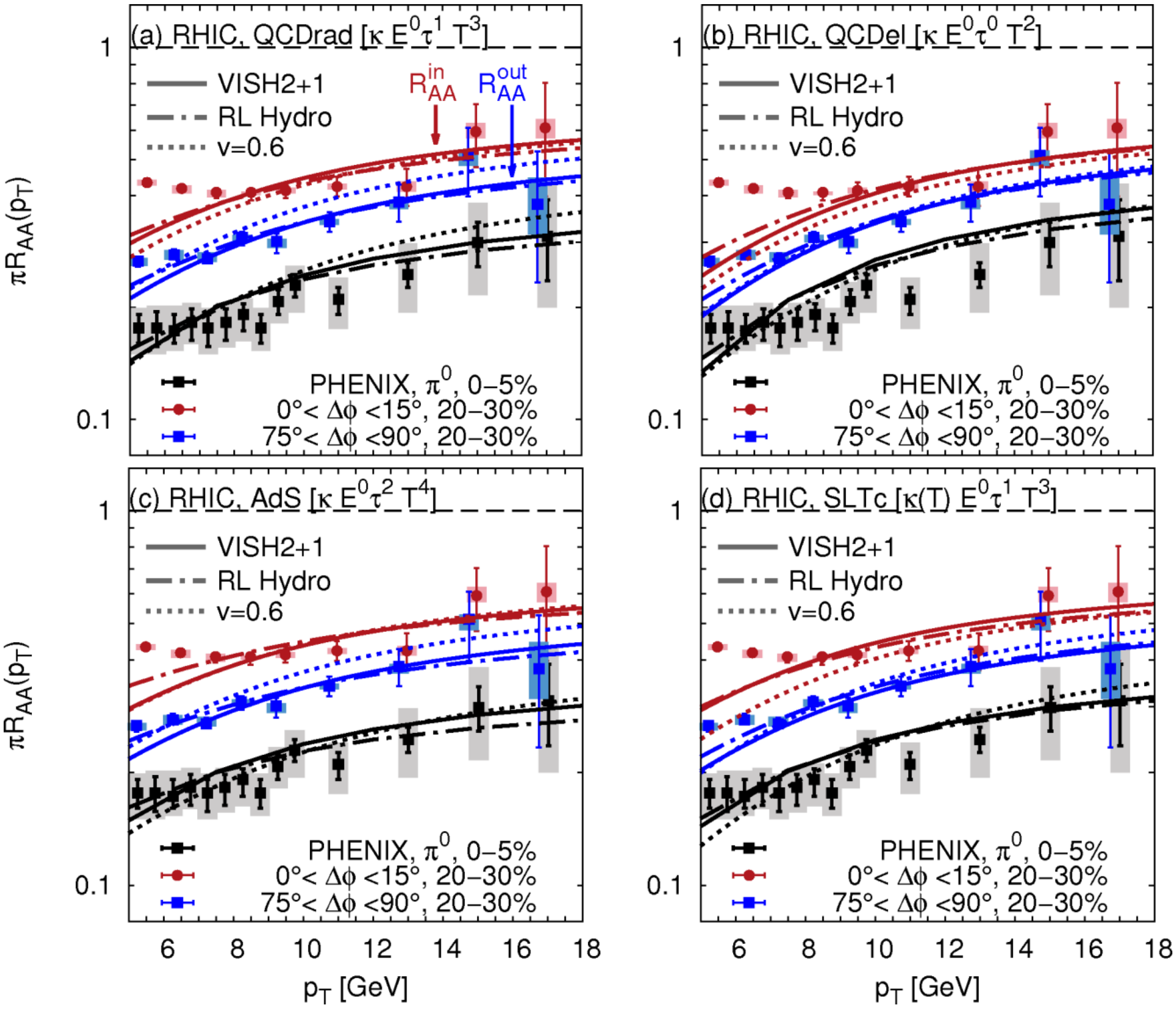
- QCDrad: a=0, z=1, const. κ
- QCDel: a=0, z=0 , const. κ
- AdS: a=0, z=2 , const. κ
- SLTc: a=0, z=1, κ(T)

M. Gyulassy et al, PRL **86**, 2537 (2001)

- Blast wave model: v=0.6
- VISH2+1 C. Shen et al. , PRC **82**, 054904 (2010); PRC **84**, 044903 (2011)
- RL Hydro M. Luzum and P. Romatschke, PRC **78**, 034915 (2008); [Erratum-ibid. C **79**, 039903 2009)]; PRL **103**, 262302 (2009).

We asked for hydro expansions that reproduce the bulk properties. For the results used, some parameters (viscosity, ...) differ between RHIC and LHC.

R^{in}_{AA} and R^{out}_{AA} at RHIC



B. Betz et al., arXiv:1305.6458

QCDrad ~ rc CUJET1.1

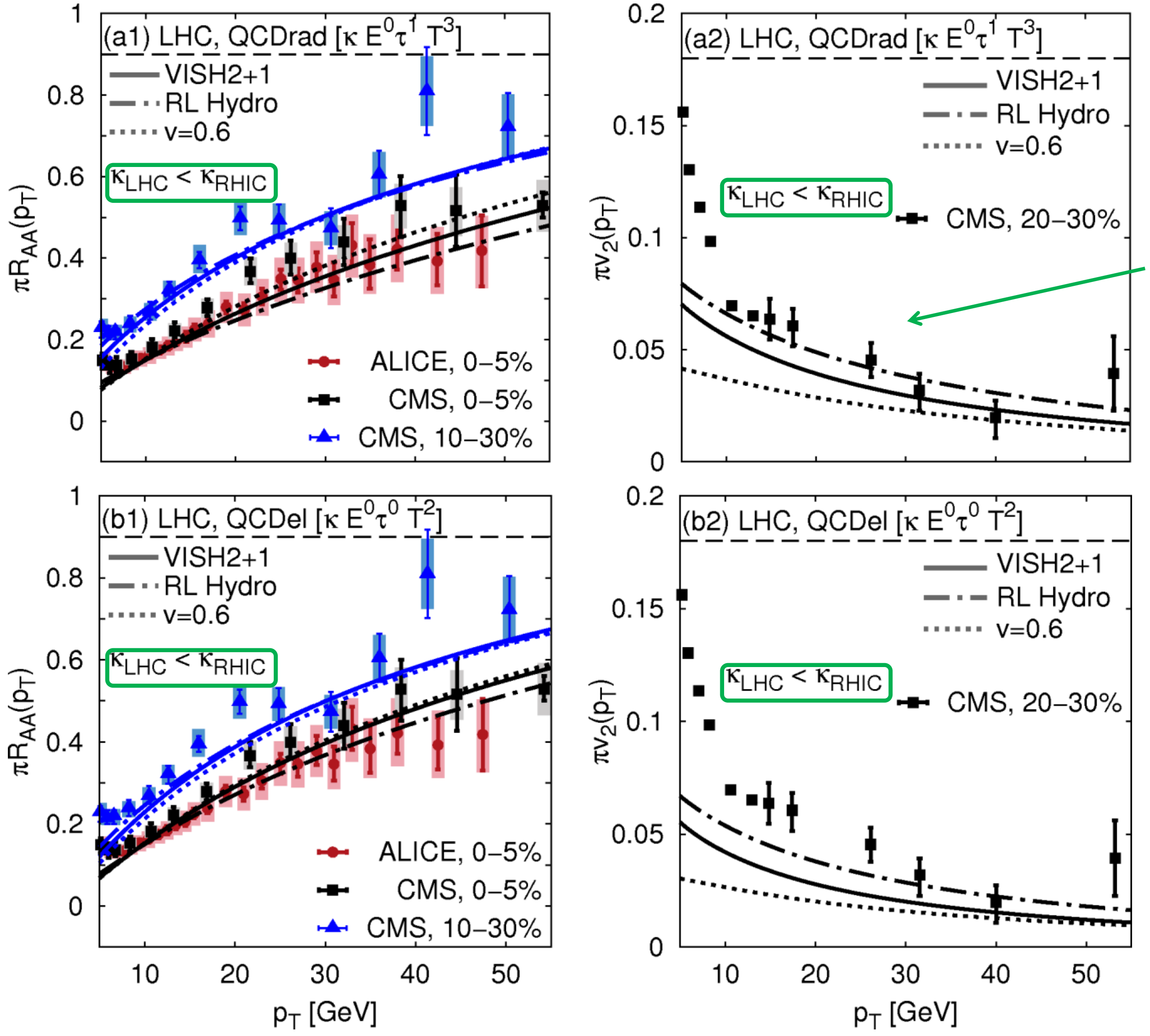
AdS ~ fixed t'Hooft conformal falling string

SLTc ~ temperature-dependent coupling

All scenarios based on (visc.) hydro background account for p_T>8 GeV data, while blast wave model (v=0.6) fails

Qualitative difference to PHENIX results to due details of hydro simulation and jet-energy loss.

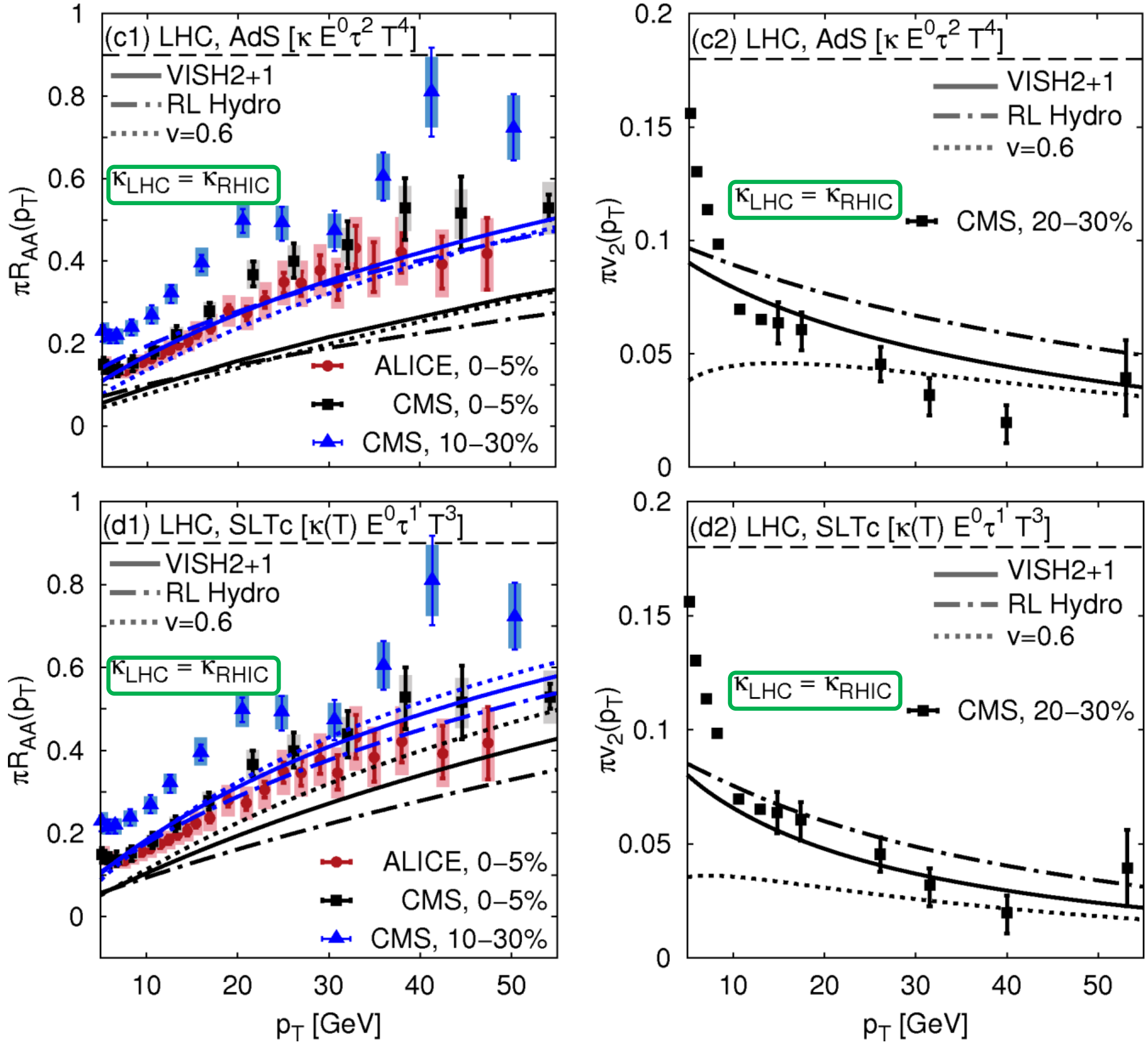
R_{AA} and v_2 at the LHC



dE/dx ~ $E^0\tau^1T^3$ reproduces BOTH R_{AA} and v_2 within the uncertainties of bulk space time evolution (IC, η/s, τ_0)

Running coupling radiative QCDrad appears to be preferred over running coupling QCDel.

R_{AA} and v_2 at the LHC



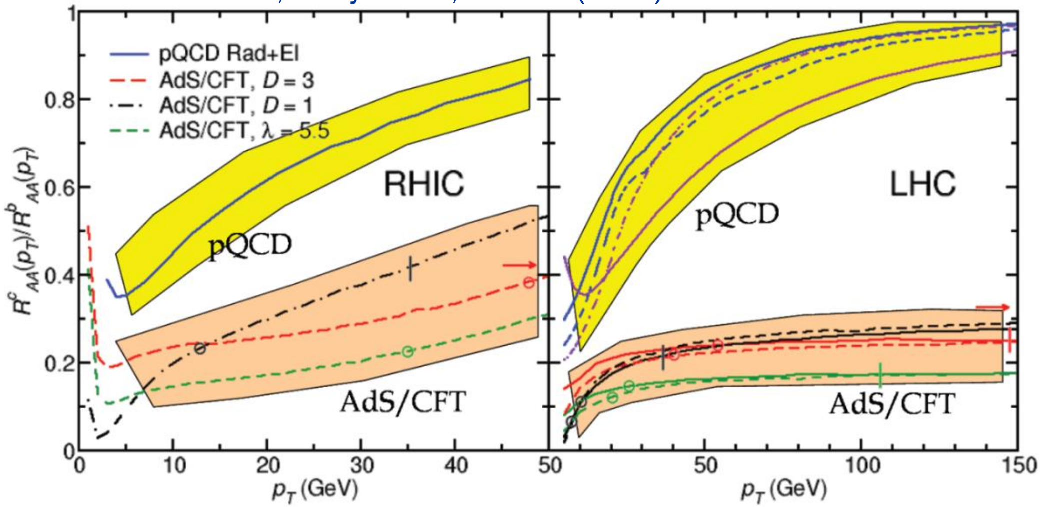
Conformal AdS and the SLTc model considered for a fixed coupling overquench at the LHC.

⇒ Conformal AdS is ruled out by the rapid rise of the $R_{AA}(p_T)$

Bullet #3: The path-length dependence

Conformal AdS: scale cannot change, i.e. coupling cannot run.

Using conformal AdS, Horowitz et al. predicted a flat $R_{AA}(p_T)$@LHC in constrast to measured data



W. A. Horowitz, J. Phys. G **35**, 044025 (2008)

Using non-standard AdS, A. Ficnar et al. found:

A. Ficnar, Tue, 14:50

$$dE/dx = \kappa T^2 [T_c\, z0(T) + xT]^2$$

$z0(T)$: Initial "radial" jet-production point

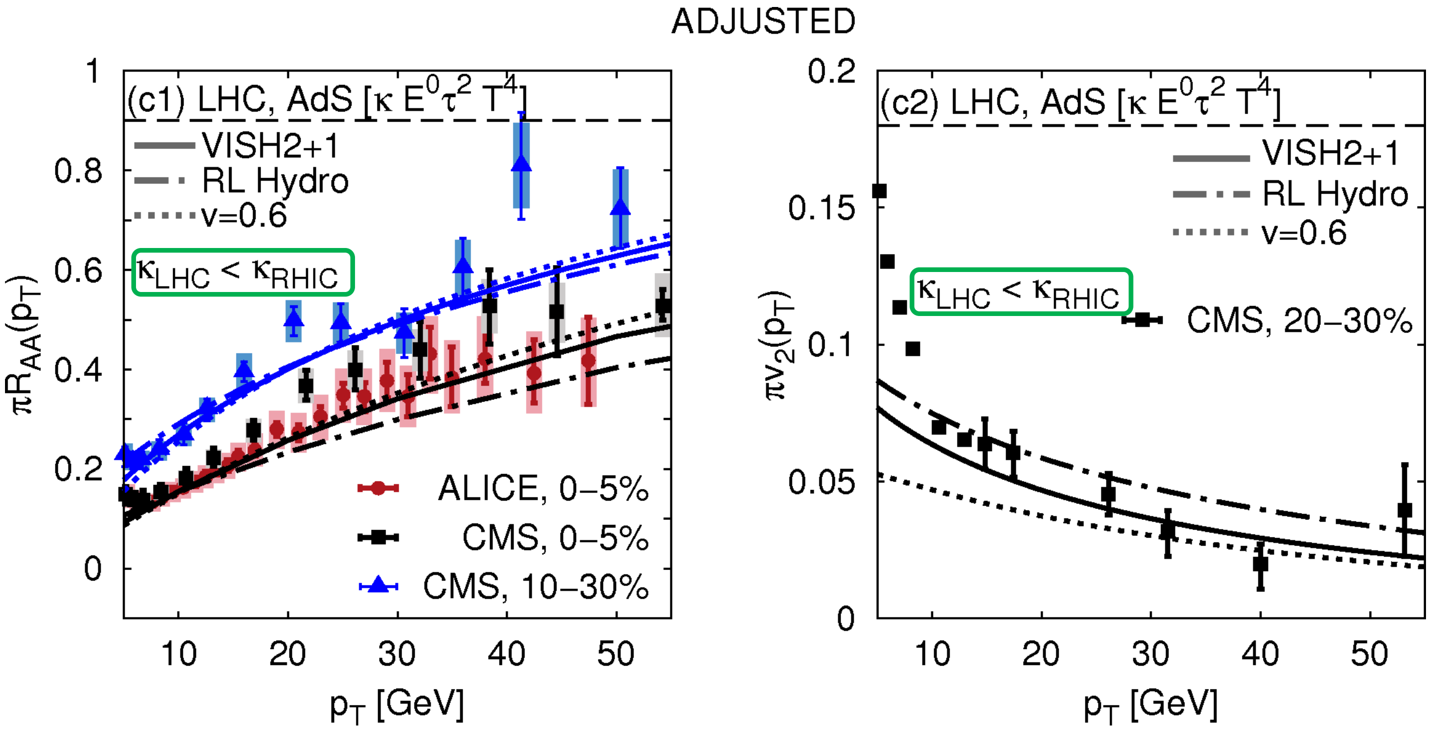
leading to a temperature-dependent path-length dependence, interpolating between the above discussed cases (extremes) QCDel and AdS:

$$T_c\, z0(T) \gg xT \quad : \quad dE/dx = \kappa [T_c\, z0(T)]^2 T^2 = \kappa_1(T) E^0 x^0 T^2$$

$$T_c\, z0(T) \ll xT \quad : \quad dE/dx = \kappa x^2 T^4$$

R_{AA} and v_2 at the LHC for *nCF AdS*

Allowing the coupling to vary, all of the above discussed models will reproduce the measured data (note: QCDel dE/dx~ $E^0\tau^0T^2$ is less preferred):



Only conformal AdS fails to describe the data (R_{AA} and v_2) BOTH @RHIC & LHC

Summary

Comparison of recent R_{AA} and v_2 @RHIC and @LHC with pQCD-like, AdS/CFT-inspired, and a T_C-dominated energy-loss model

Bullet #1:
The overquenching @LHC points to a moderate reduction of the running coupling.

Bullet #2:
In a (2+1)d transverse + Bjorken expanding medium, the high-p_T v_2-values tends to be too low in various models (Molnar, CUJET2.0, AMY, ASW, HT). However, our idealized $dE^{rad}/dx \sim E^0 \tau^1 T^3$ seems to fit best the data both @RHIC and @LHC.

Bullet #3:
While conformal AdS string-like jet holography appears to be ruled out by the LHC data, novel non-conformal generalizations of AdS string models (Ficnar et al.) may provide an alternative description.

The evolution of the bulk medium influences the jet-energy loss!

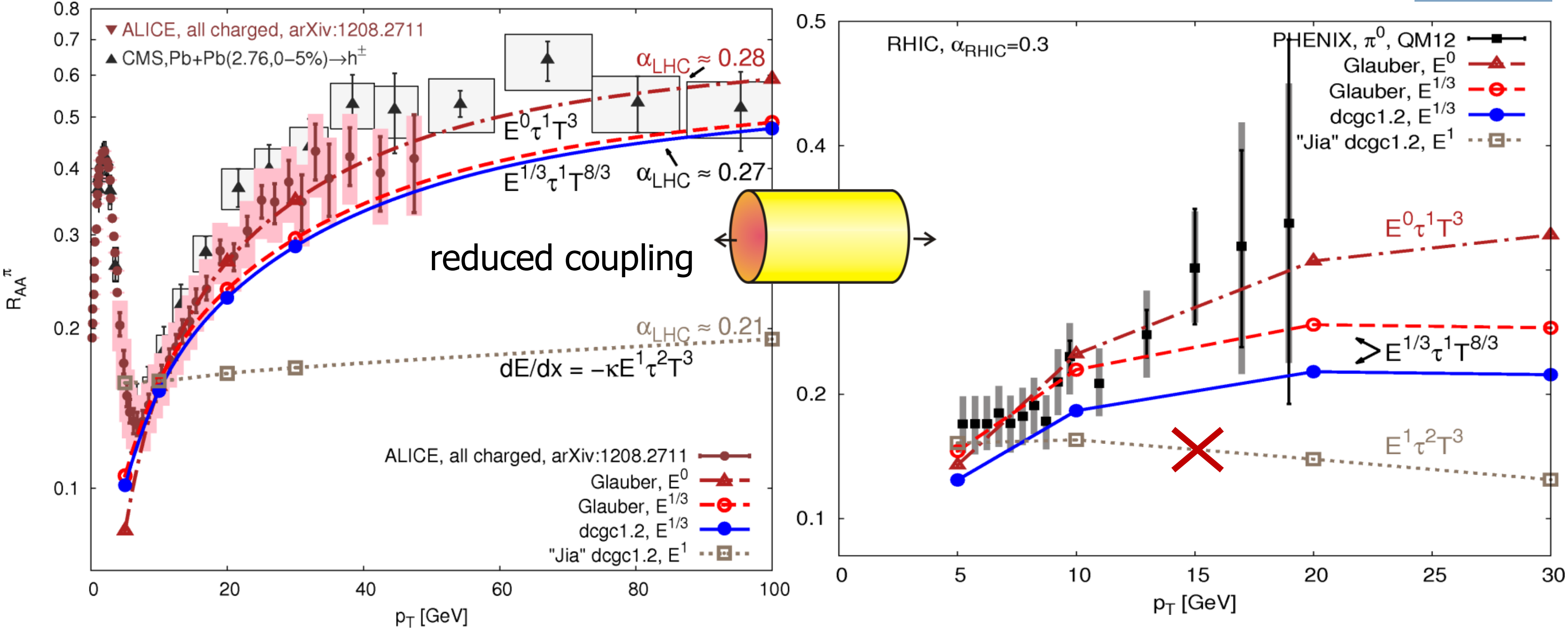
Backup

$R_{AA}(p_T)$ at LHC & RHIC

LHC

Bjorken expanding medium

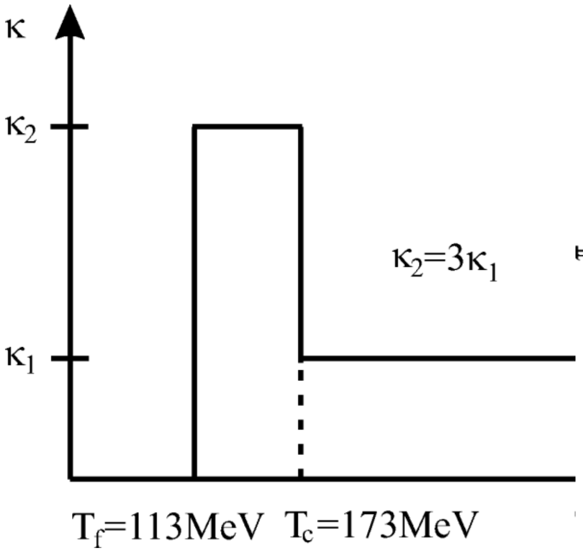
RHIC



B.Betz et al., Nucl. Phys. A **904**, 717c (2013)

⟹ Rapid rise of $R_{AA}(p_T)$ rules out any model with dE/dx ~ $E^{a>1/3}$

Temperature-dependent Coupling

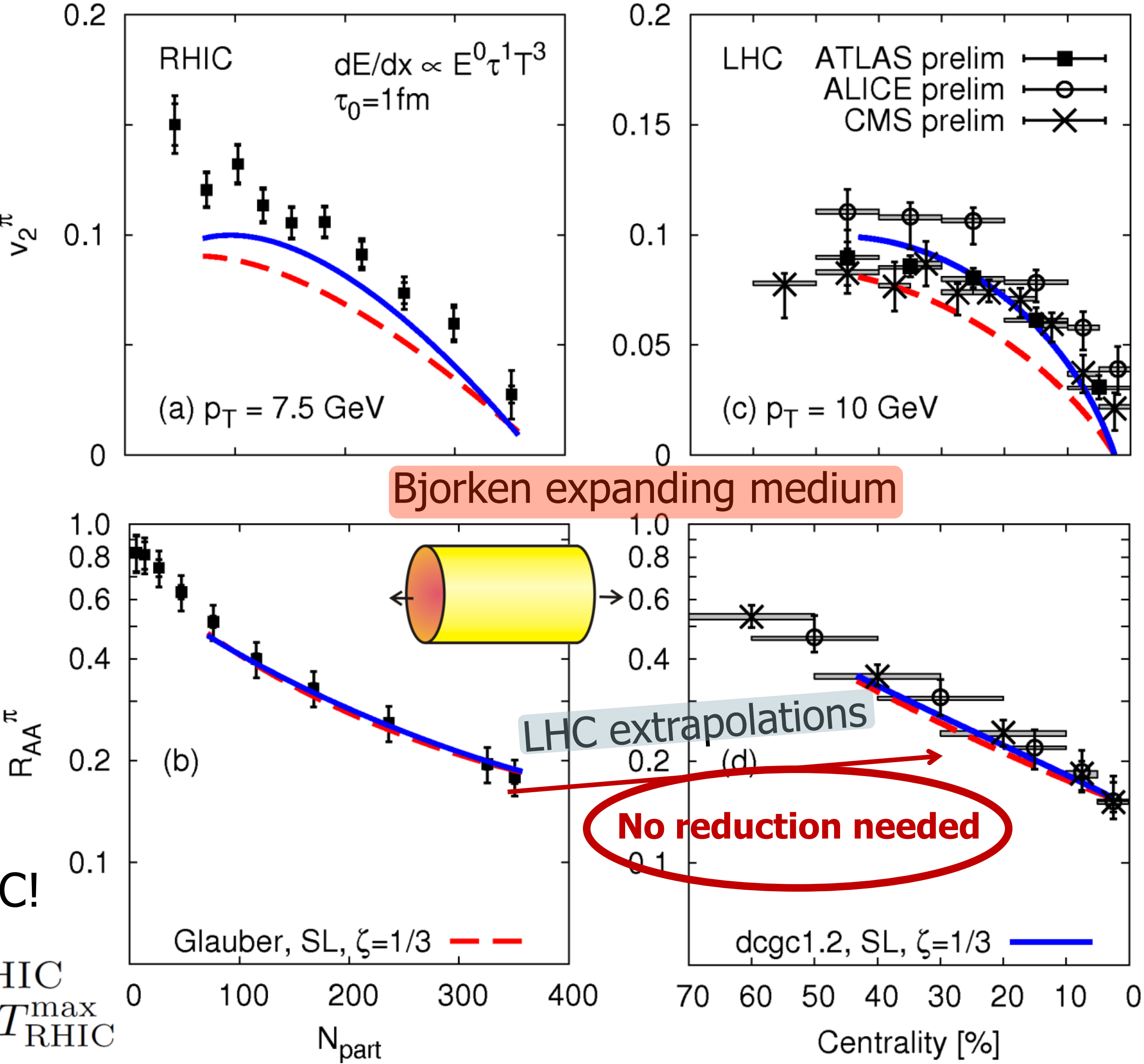


J.Liao et al,. PRL **102** (2009) 202302

$$\boxed{\zeta = \kappa_1/\kappa_2}$$

⇒ Assumes the same κ(T) at RHIC and LHC!

⇒ eff $\kappa_{\mathrm{LHC}} <$ eff κ_{RHIC} because $T^{\mathrm{max}}_{\mathrm{LHC}} \sim 1.3\, T^{\mathrm{max}}_{\mathrm{RHIC}}$



Bjorken expanding medium

LHC extrapolations

No reduction needed

Energy-Loss Mechanisms

R_{AA} is a ratio of jet penetrating a QGP to the initial jet spectrum

$$R_{AA}^{q,g}(P_f,\vec{x}_0,\phi) = \frac{dN^{jet}_{QGP}(P_f)}{dy\,d\phi\,dP_f^2} \Big/ \frac{dN^{jet}_{vac}(P_f)}{dy\,d\phi\,dP_0^2} = \frac{dP_0^2}{dP_f^2}\,\frac{dN^{jet}_{vac}[P_0(P_f)]}{dy\,d\phi\,dP_0^2} \Big/ \frac{dN^{jet}_{vac}(P_f)}{dy\,d\phi\,dP_0^2}$$

One needs to determine the $P_0(P_f)$ from the $dP/d\tau$ ansatz

$$P_0(P_f) = \left[P_f^{1-a} + K\int_{\tau_0}^{\tau_f} \tau^z T^c[\vec{x}_\perp(\tau),\tau]\,d\tau\right]^{\frac{1}{1-a}}, \qquad K = (1-a)\kappa C_2$$

Fragmentation:

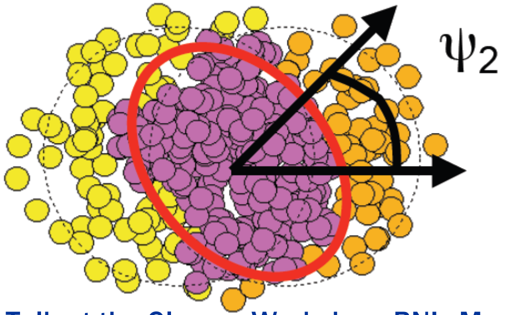
momentum of the observed pion   pQCD cross-sections   fragmentation functions

$$R^\pi_{AA}(p_\pi,\phi,N_{part}) = \frac{\left\langle \sum\limits_{\alpha=q,g}\int\limits_{z_{min}}^{1} \frac{dz}{z}\, d\sigma_\alpha\left(\frac{p_\pi}{z}\right) R^\alpha_{AA}\left(\frac{p_\pi}{z},\phi\right) D_{\alpha\to\pi}\left(z,\frac{p_\pi}{z}\right)\right\rangle_{\vec{x}_0,N_{part}}}{\sum\limits_{\alpha=q,g}\int\limits_{z_{min}}^{1} \frac{dz}{z}\, d\sigma_\alpha\left(\frac{p_\pi}{z}\right) D_{\alpha\to\pi}\left(z,\frac{p_\pi}{z}\right)}$$

Elliptic Flow: $$v_2^\pi(N_{part}) = \frac{\int d\phi\cos\{2\phi\}\; R^\pi_{AA}(N_{part},\phi)}{\int d\phi\, R^\pi_{AA}(N_{part},\phi)}$$

Energy-Loss Mechanisms

Having fixed κ, the harmonics can be calculated



B. Alver, Talk at the Glasma Workshop, BNL, May 2010

$$v_n(N_{part}) = \frac{\int d\phi \cos\{n\,[\phi-\psi_n]\}\; R_{AA}(\phi)}{\int d\phi\, R_{AA}(\phi)}$$

determining the angle with the reaction plane

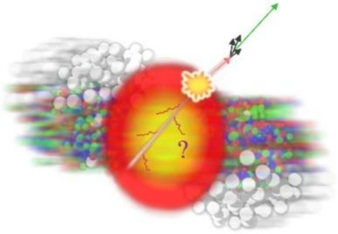
$$\psi_n(t) = \frac{1}{n}\tan^{-1}\frac{\langle r\sin(n\phi)\rangle}{\langle r\cos(n\phi)\rangle}$$

and the Fourier density components are given by

$$e_n(t) = \frac{\sqrt{\langle r^2\cos(n\phi)\rangle^2 + \langle r^2\sin(n\phi)\rangle^2}}{\langle r^2\rangle}$$

Reduced Jet-Medium Coupling

What is the physical meaning of a reduced coupling?



pQCD: $\kappa \propto \alpha^3$

$$\alpha_{\rm LHC} = (\kappa_{\rm LHC}/\kappa_{\rm RHIC})^{1/3}\alpha_{\rm RHIC} \qquad \alpha_{\rm RHIC} \sim 0.3$$

fit to LHC most central data: $\alpha_{\rm LHC} \sim 0.24 - 0.28$

(independent of initial time)

B.Betz et al., PRC **86**, 024903 (2012)

IF α is reduced at the LHC, κ is reduced as well!

⟹ Reasonable moderate reduction of the running coupling

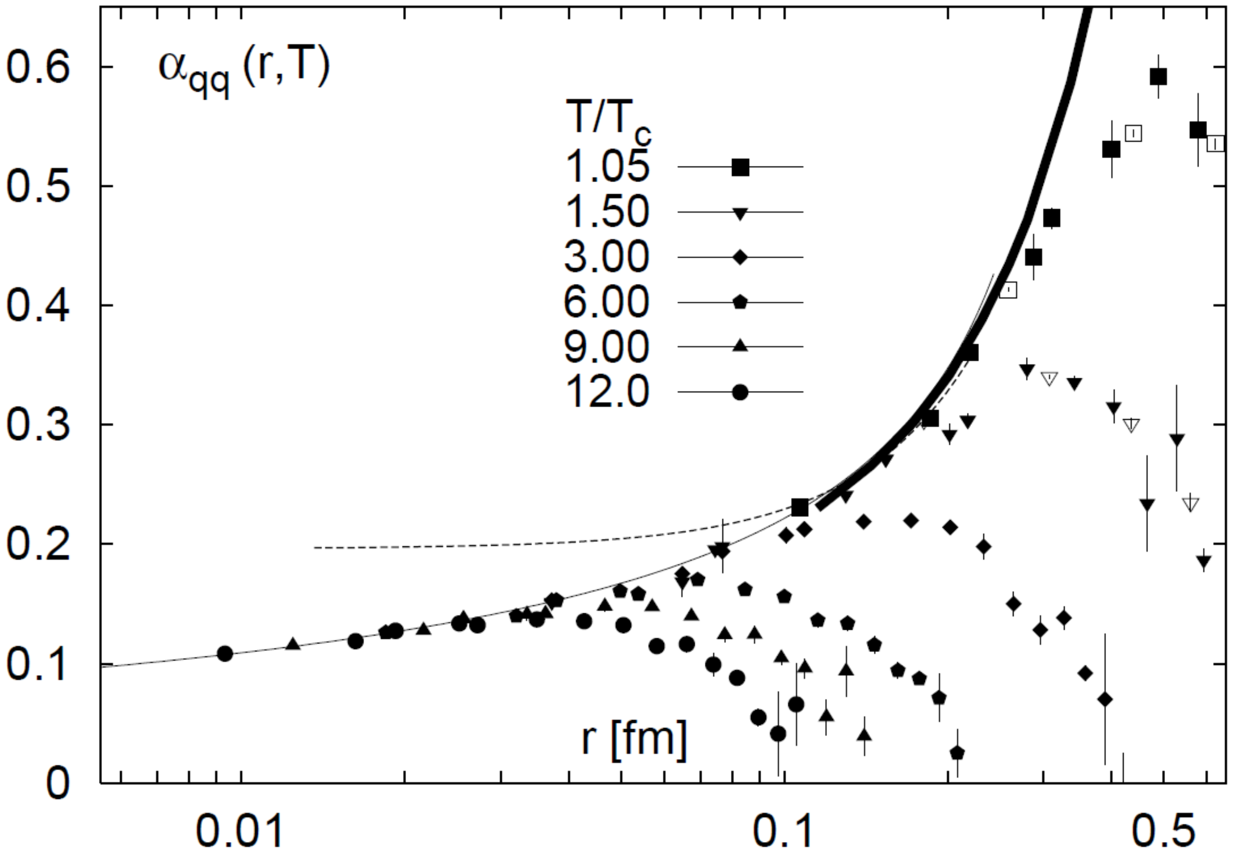
AdS/CFT: $\kappa \propto \sqrt{\lambda}$ ← t'Hooft coupling

$$\lambda_{\rm LHC} = (\kappa_{\rm LHC}/\kappa_{\rm RHIC})^2\,\lambda_{\rm RHIC} \qquad \lambda_{\rm RHIC} \sim 20$$ (heavy quarks)

with the values used: $\lambda_{\rm LHC} \sim 5 - 10$

⟹ Rather strong conformal symmetry breaking over a narrow temperature interval (1-2)T_C is required

Lattice QCD running coupling



O. Kaczmarek et al., Phys. Rev. D **70**, 074505 (2004)

We found that the reduction of κ needed to fit the LHC data is larger in a transverse expanding medium.

This points to a temperature-dependent running coupling as predicted by Lattice QCD

Jet-medium coupling, transverse expansion

pQCD mode (a=0, z=1)

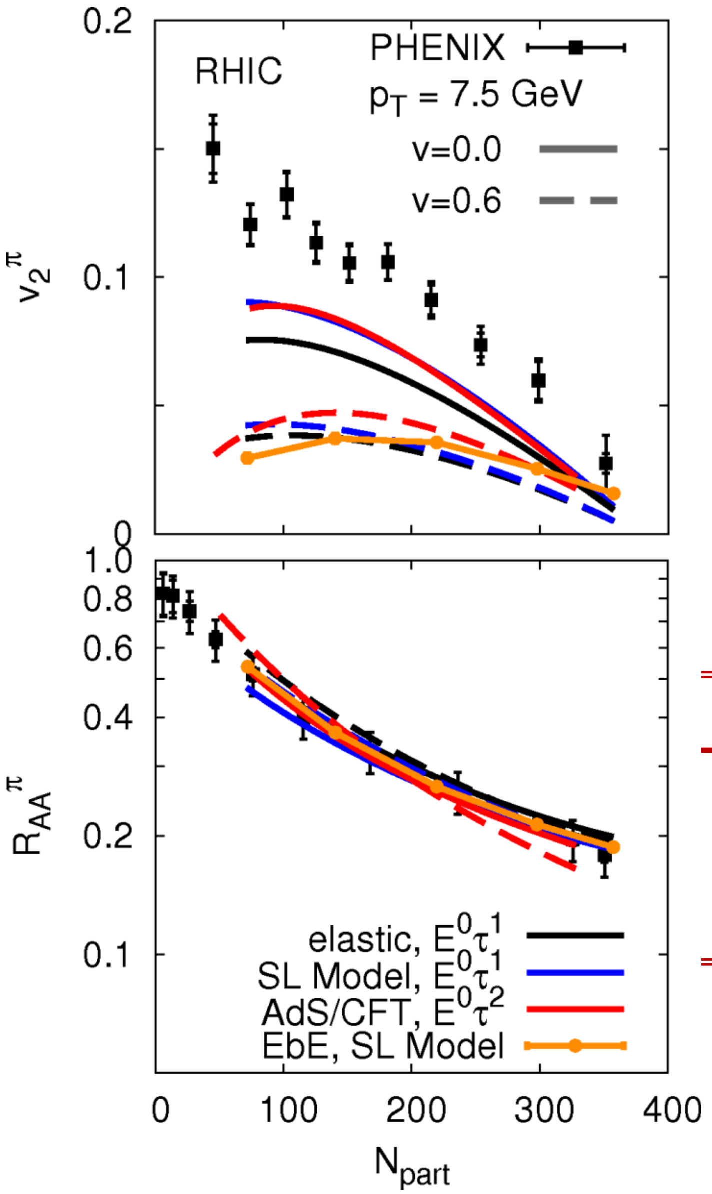
$$\frac{dP}{d\tau}(\vec{x}_0,\phi,\tau) = -\kappa P^a(\tau)\,\tau^z\, T^{c=2-a+z}[\vec{x}_\perp(\tau),\tau,b]$$

$$\kappa \propto \alpha^3$$

$$\alpha_{\rm LHC} = (\kappa_{\rm LHC}/\kappa_{\rm RHIC})^{1/3}\alpha_{\rm RHIC} \qquad \alpha_{\rm RHIC} \sim 0.3$$

	$\kappa_{LHC}/\kappa_{RHIC}$	α_{LHC}
$v_T = 0.0$	0.82	0.28
$v_T = 0.6$	0.66	0.26
$v_T = 0.9$	0.608	0.25
VISH2+1	0.43	0.23
Romatschke	0.504	0.24

R_{AA} and v_2 at RHIC for a 3d expansion



Mimicking a transverse expansion by a blast wave model:

$$\rho^{\text{eff}} = \rho\left[\left(\frac{x_{\text{jet}}(t)}{rx(t)}, \frac{y_{jet}(t)}{ry(t)}\right)\right] \Big/ \left[rx(t)ry(t)\right]$$

$$rx(t) = \sqrt{1 + (v_x^T t)^2/(\text{rms}_x)^2}$$

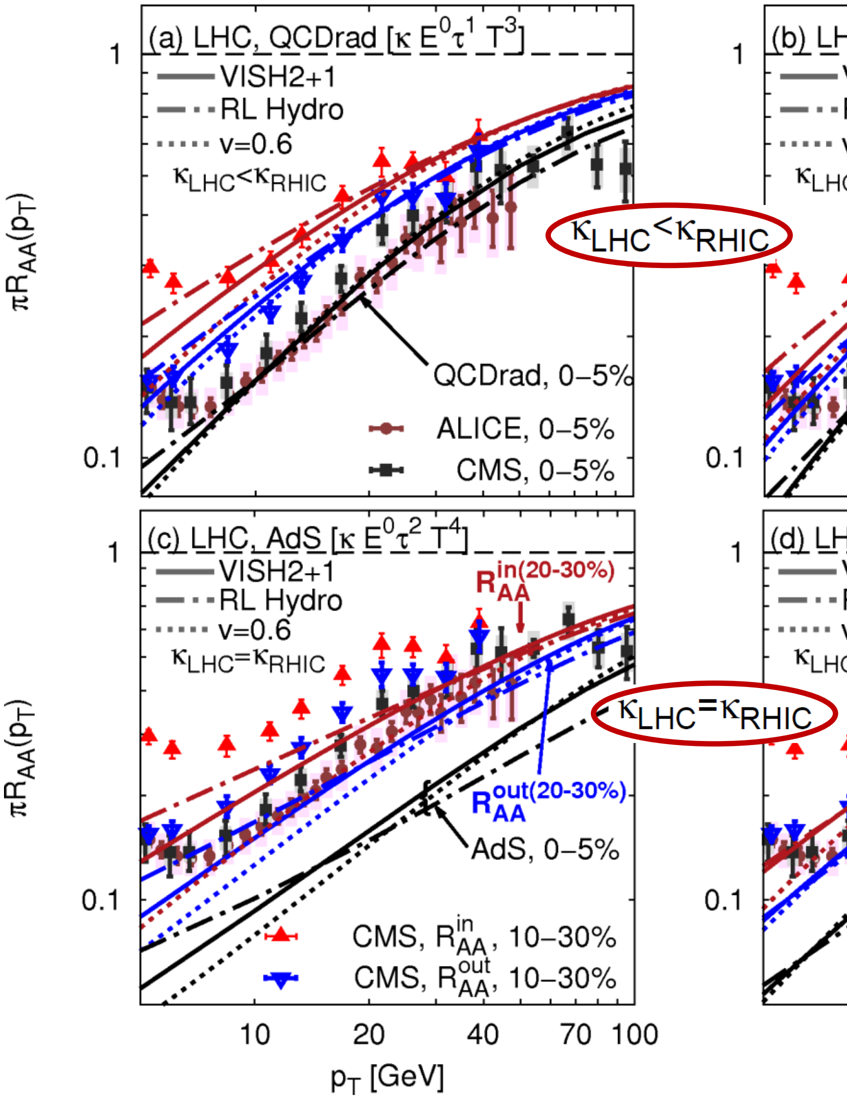
$$ry(t) = \sqrt{1 + (v_y^T t)^2/(\text{rms}_y)^2}$$

⟹ Reduction of the pion v_2 by a factor of 2

⟶ Independent of κ(T), pQCD or AdS/CFT-like energy-loss

⟹ Pre-Conclusion: It is impossible to describe R_{AA} and v_2 simultaneously!

R^{in}_{AA} and R^{out}_{AA} at the LHC



Like at RHIC energies, the blast wave model fails to describe the data

The AdS and the SLTc model (assuming no running coupling) also fail to describe the data

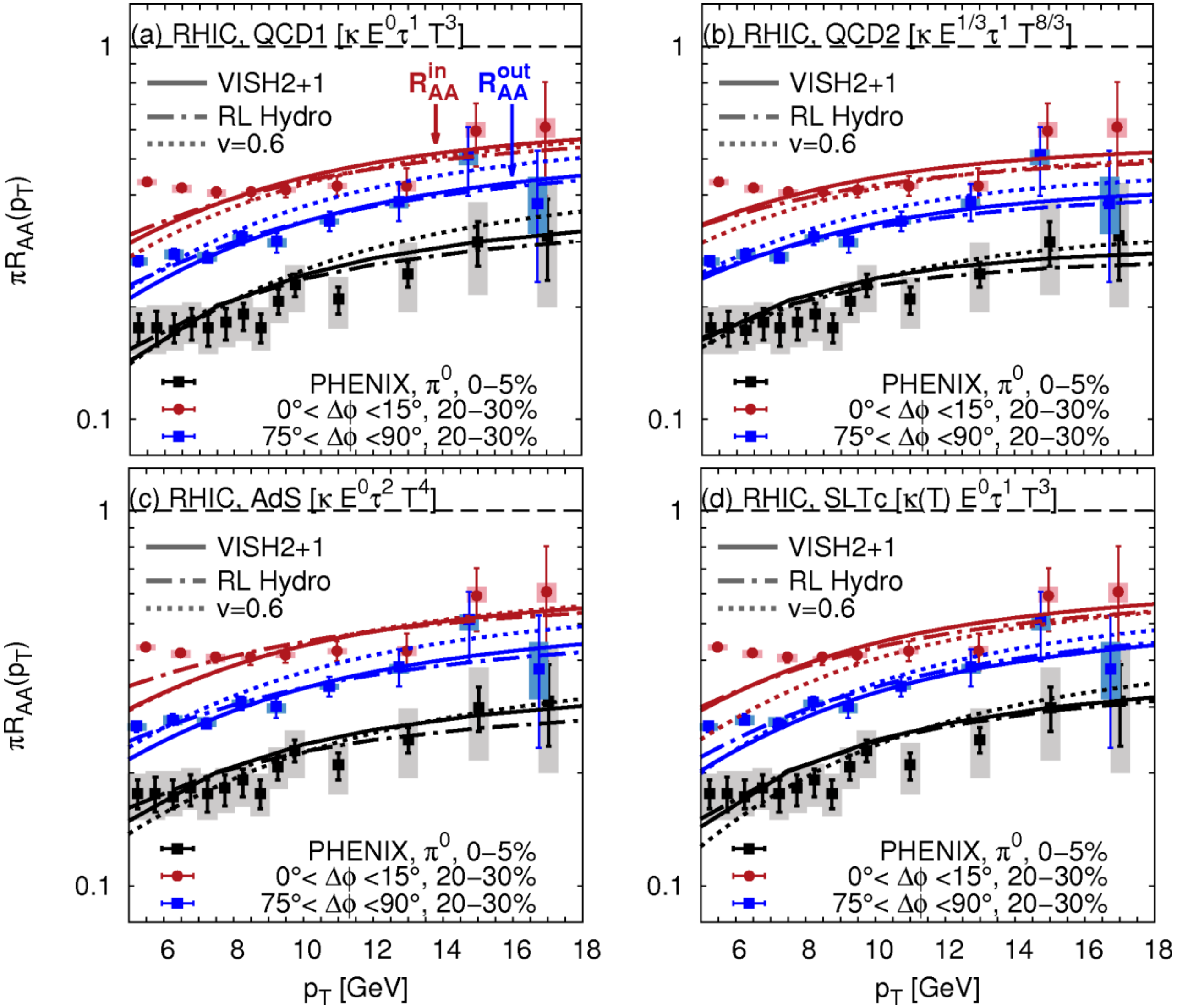
The pQCD-based scenarios describe the data both at RHIC and at LHC

$$\Longrightarrow \alpha_{LHC} \sim 0.23 - 0.26$$

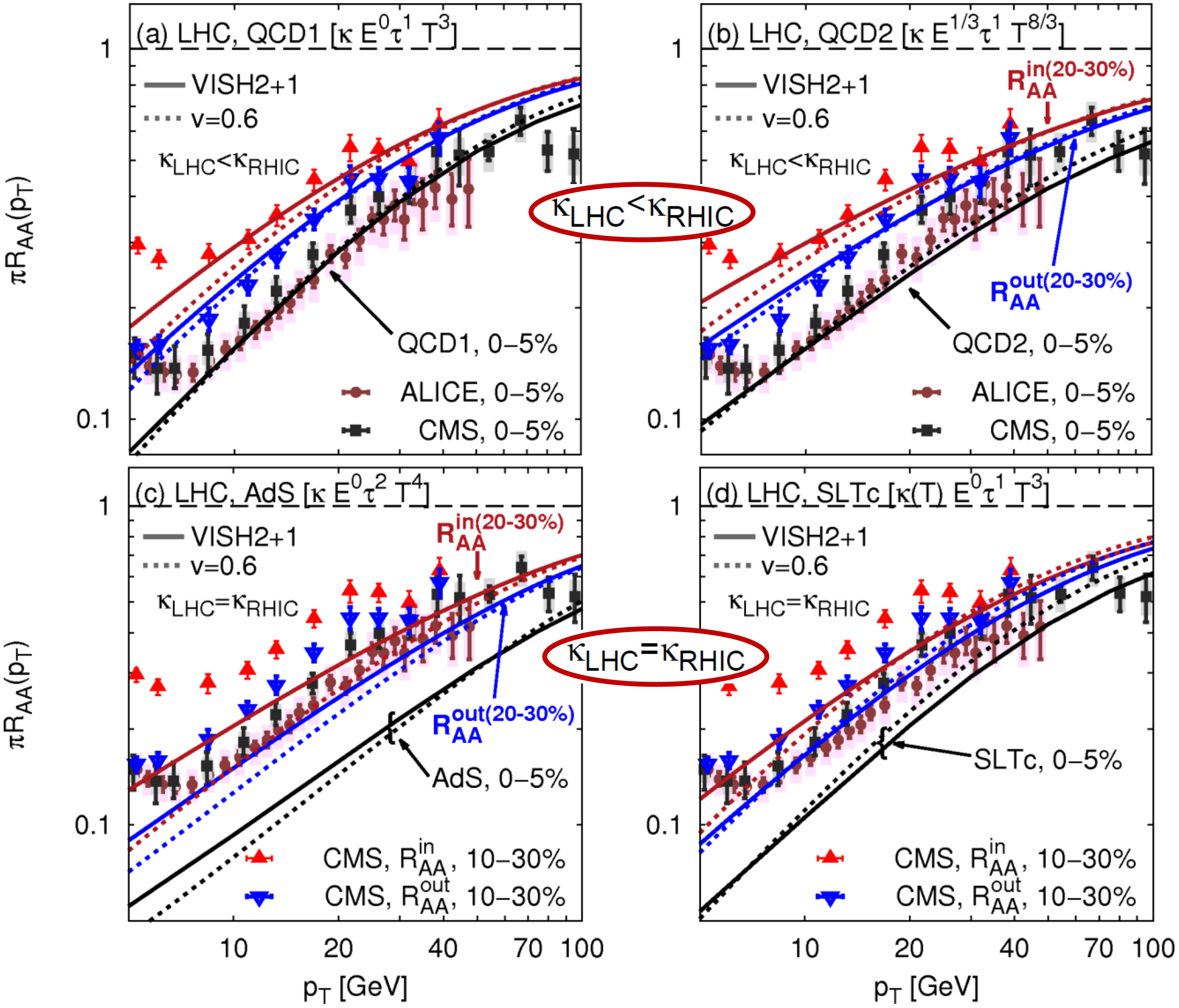
Caution: Hydro parameters may differ between RHIC & LHC

AMPT: $\alpha_{LHC} \sim 0.24$ S. Pal et al., PLB **709**, 012027 (2012)

R_{AA}^{in} and R_{AA}^{out} at RHIC – $E^{1/3}$-dependence



R^{in}_{AA} and R^{out}_{AA} at LHC – $E^{1/3}$-dependence



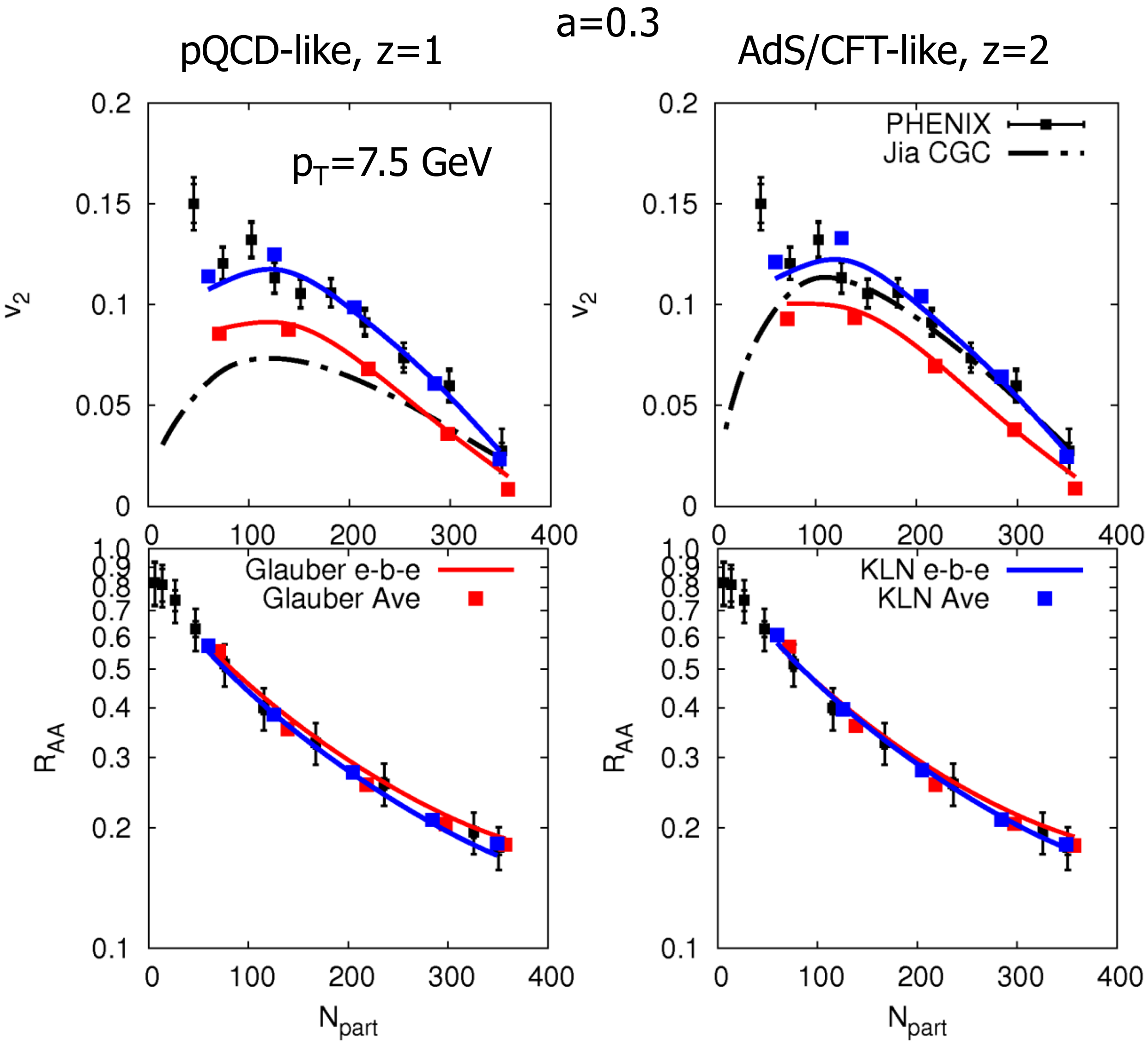
$\kappa_{LHC}<\kappa_{RHIC}$

$\kappa_{LHC}=\kappa_{RHIC}$

B. Betz et al., arXiv:1305.6458

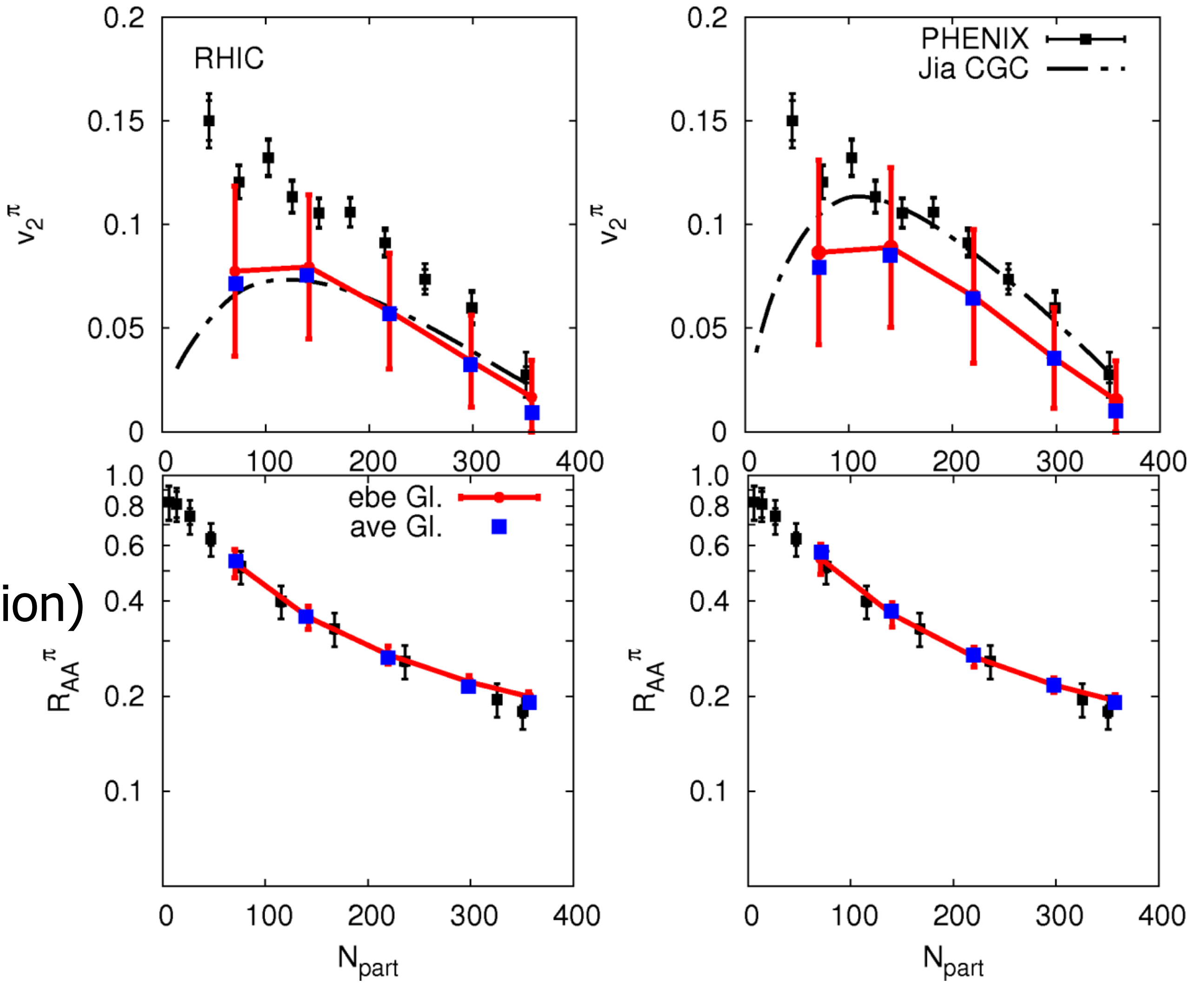
R_{AA} and v_2 at RHIC

Similar results for event-by-event and averaged scenarios (no fragmentation)



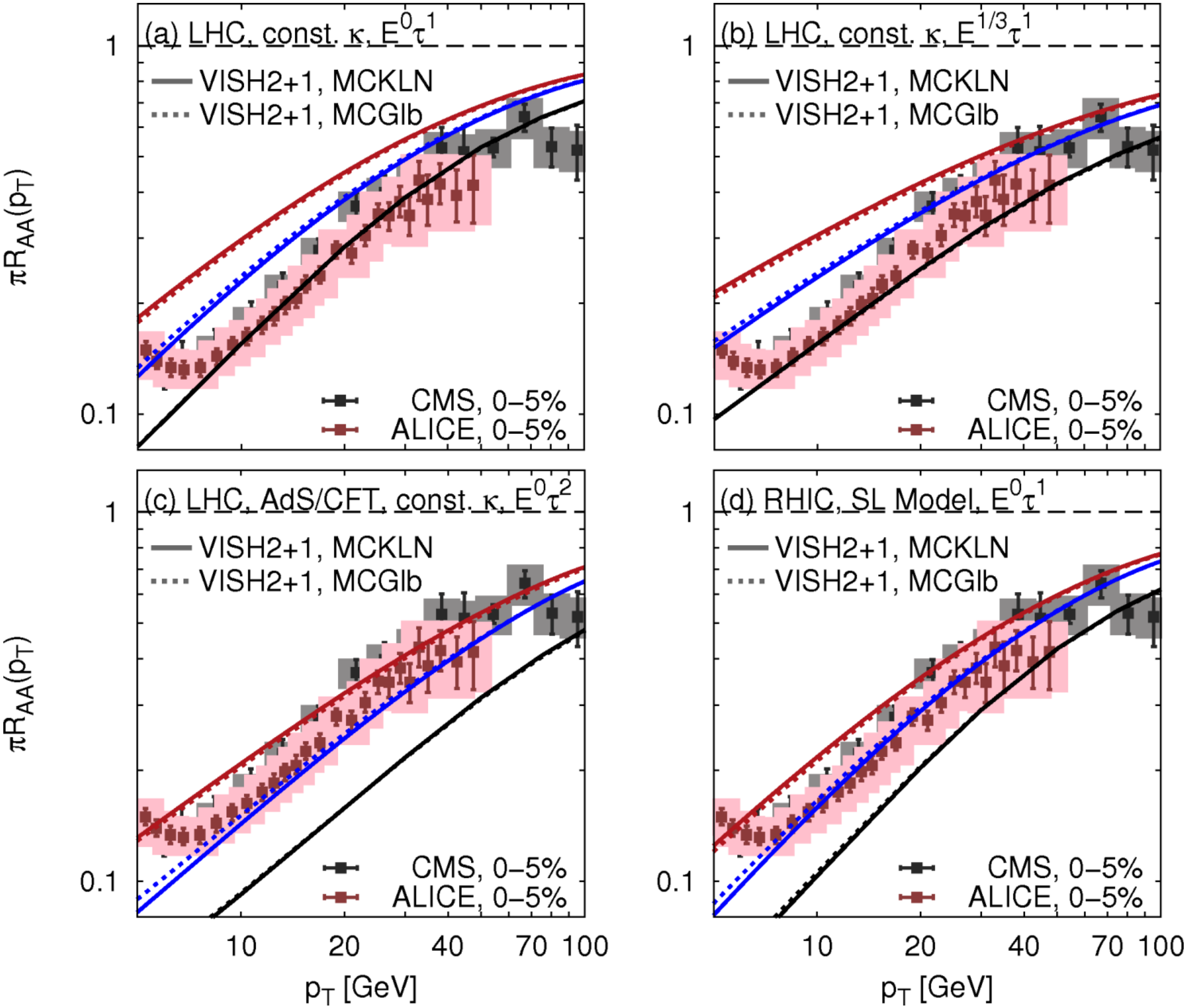
B.Betz et al., PRC **84**, 024913 (2011)

R_{AA} and v_2 at RHIC



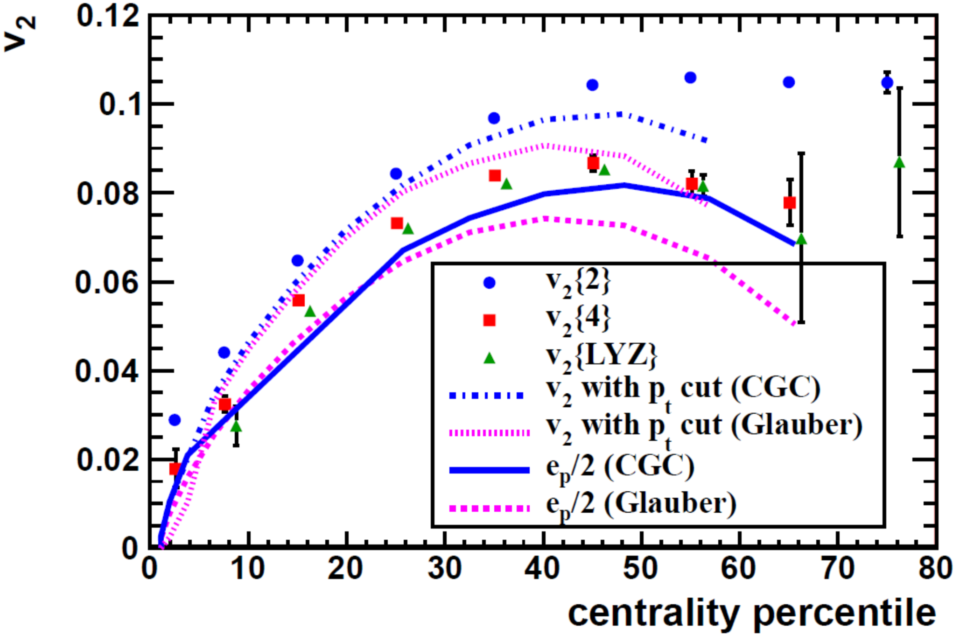
Similar results for
event-by-event and
averaged scenarios
(including fragmentation)

Initial Conditions

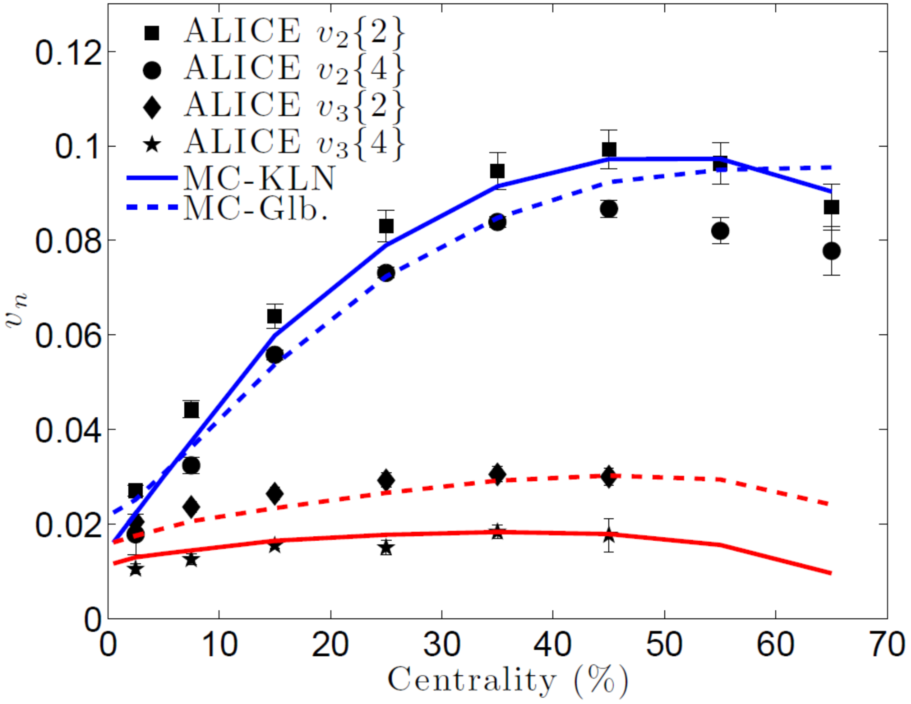


Bulk properties RL Hydro & VISH2+1

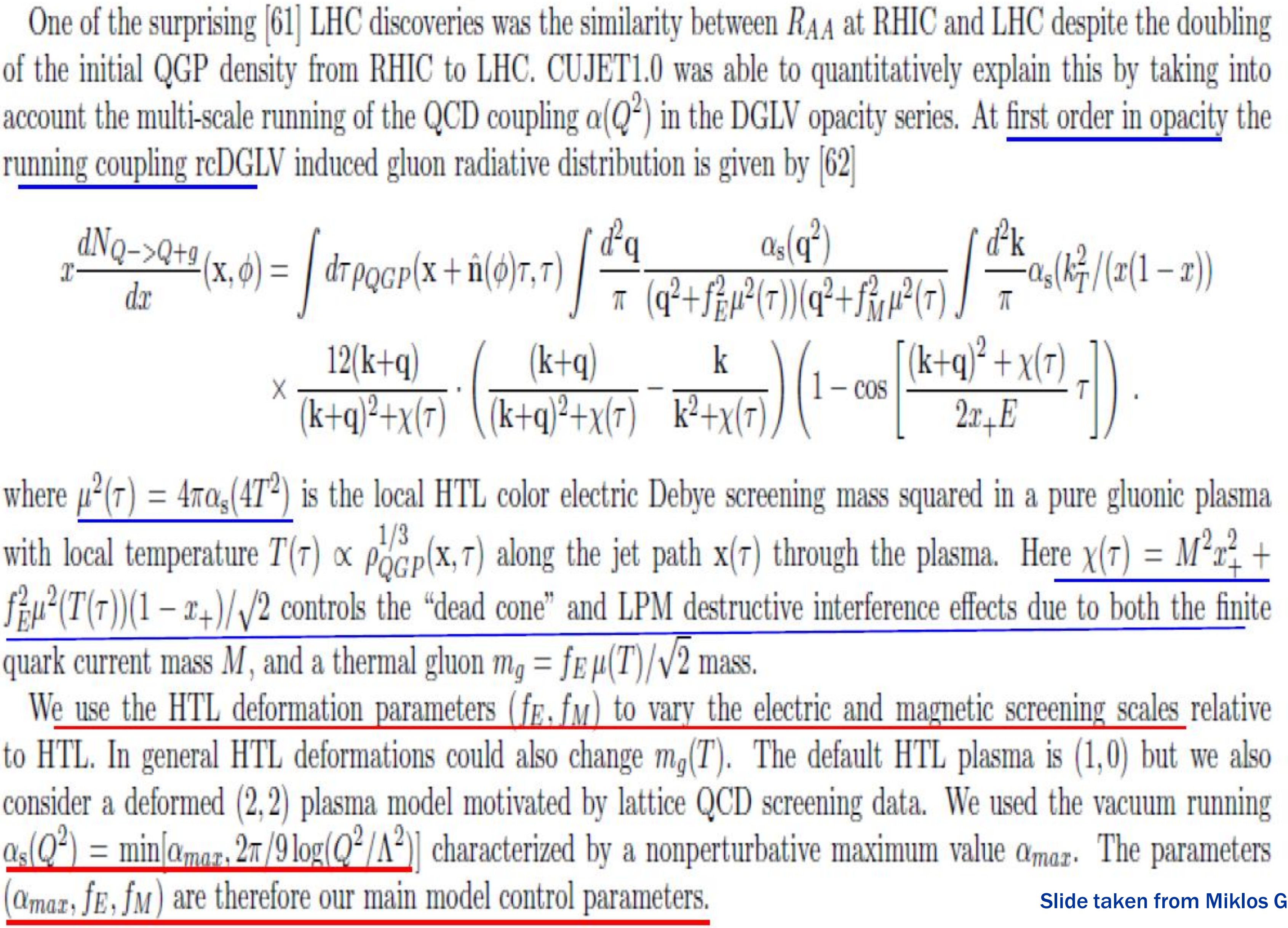
M. Luzum, Phys. Rev. C **83**, 044911 (2011)



Z. Qiu et al., Phys. Lett. B **707**, 151 (2012)



CUJET 2.0



One of the surprising [61] LHC discoveries was the similarity between R_{AA} at RHIC and LHC despite the doubling of the initial QGP density from RHIC to LHC. CUJET1.0 was able to quantitatively explain this by taking into account the multi-scale running of the QCD coupling $\alpha(Q^2)$ in the DGLV opacity series. At first order in opacity the running coupling rcDGLV induced gluon radiative distribution is given by [62]

$$x\frac{dN_{Q->Q+g}}{dx}(\mathbf{x},\phi) = \int d\tau\,\rho_{QGP}(\mathbf{x}+\hat{\mathbf{n}}(\phi)\tau,\tau)\int\frac{d^2\mathbf{q}}{\pi}\frac{\alpha_s(\mathbf{q}^2)}{(\mathbf{q}^2+f_E^2\mu^2(\tau))(\mathbf{q}^2+f_M^2\mu^2(\tau))}\int\frac{d^2\mathbf{k}}{\pi}\alpha_s(k_T^2/(x(1-x))$$

$$\times\frac{12(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)}\cdot\left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)}-\frac{\mathbf{k}}{\mathbf{k}^2+\chi(\tau)}\right)\left(1-\cos\left[\frac{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)}{2x_+E}\tau\right]\right).$$

where $\mu^2(\tau) = 4\pi\alpha_s(4T^2)$ is the local HTL color electric Debye screening mass squared in a pure gluonic plasma with local temperature $T(\tau) \propto \rho_{QGP}^{1/3}(\mathbf{x},\tau)$ along the jet path $\mathbf{x}(\tau)$ through the plasma. Here $\chi(\tau) = M^2x_+^2 + f_E^2\mu^2(T(\tau))(1-x_+)/\sqrt{2}$ controls the "dead cone" and LPM destructive interference effects due to both the finite quark current mass M, and a thermal gluon $m_g = f_E\,\mu(T)/\sqrt{2}$ mass.

We use the HTL deformation parameters (f_E, f_M) to vary the electric and magnetic screening scales relative to HTL. In general HTL deformations could also change $m_g(T)$. The default HTL plasma is (1,0) but we also consider a deformed (2,2) plasma model motivated by lattice QCD screening data. We used the vacuum running $\alpha_s(Q^2) = \min[\alpha_{max}, 2\pi/9\log(Q^2/\Lambda^2)]$ characterized by a nonperturbative maximum value α_{max}. The parameters (α_{max}, f_E, f_M) are therefore our main model control parameters.

Slide taken from Miklos Gyulassy

CUJET 2.0 $\hat{q}$-solution

$\hat{q}(E,T)/T^3 \neq$ const.

⇒ $\hat{q}(E,T)/T^3 =$ const.
(as used by e.g. ASW, ...)
is not supported by a full
pQCD-calculation & realistic
(EoS, ...) hydro evolution.