GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Jet-Medium Coupling in Heavy-Ion Collisions

Barbara Betz

in collaboration with Miklos Gyulassy and Giorgio Torrieri

2013 RHIC & AGS Annual Users' Meeting
Brookhaven National Laboratory

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

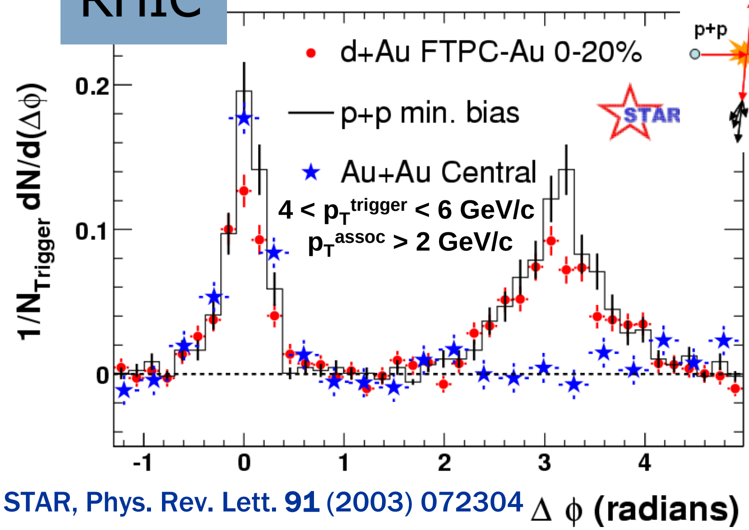
HIC for FAIR
Helmholtz International Center

Jet Quenching

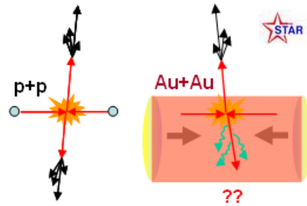
Jet Quenching is a way of learning about the opacity of a system

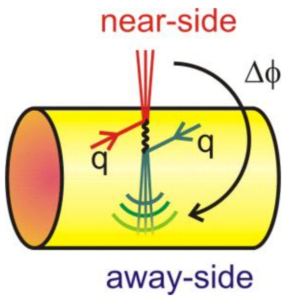
Idea: Jet moving through dense matter, depositing its energy should eventually disappear

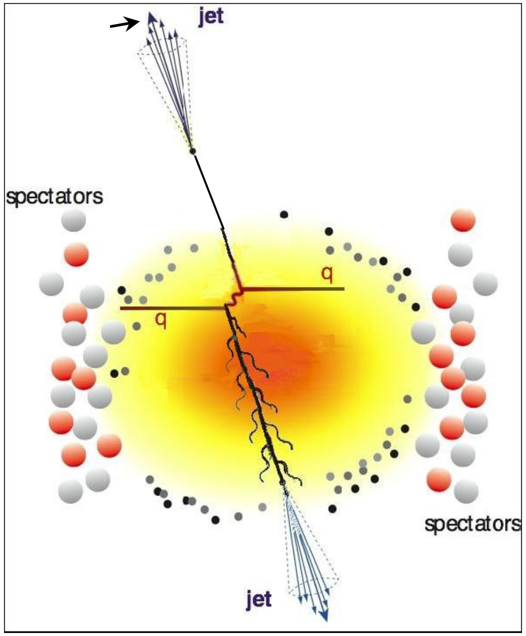
RHIC



STAR, Phys. Rev. Lett. **91** (2003) 072304



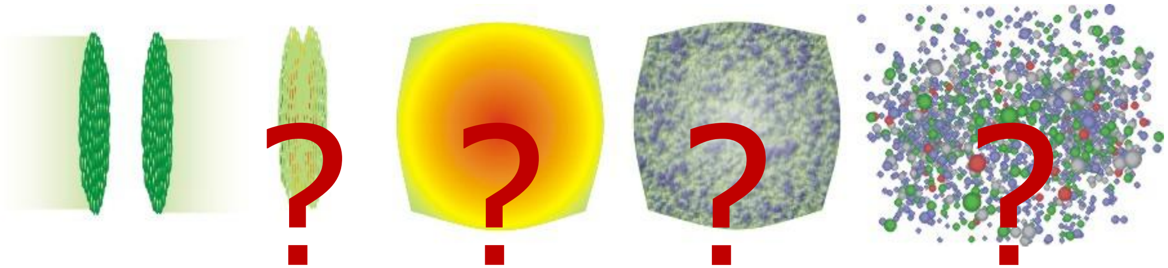




→ Signal for creation of an opaque matter (Quark-Gluon Plasma)

→ What does this tell us about the jet-medium coupling?

Open Problems in HIC



S. Bass, Talk Quark Matter 2001

Some basic questions in HIC (an incomplete list):

What are the initial conditions (Glauber vs. CGC/KLN)?

Is the medium weakly or strongly-coupled (pQCD vs. AdS/CFT)?

How viscous is the medium created?

How big is the jet-medium coupling?

How does the jet-energy loss look like?

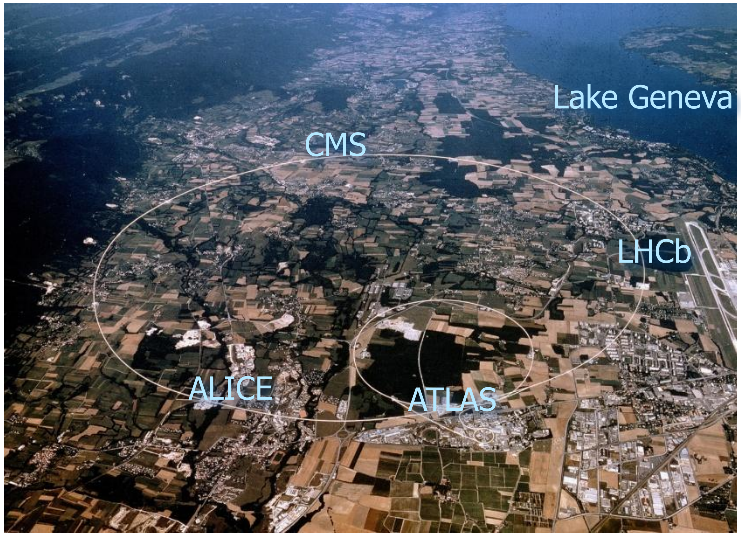
What is the correct description of the freeze-out/fragmentation into particles?

RHIC

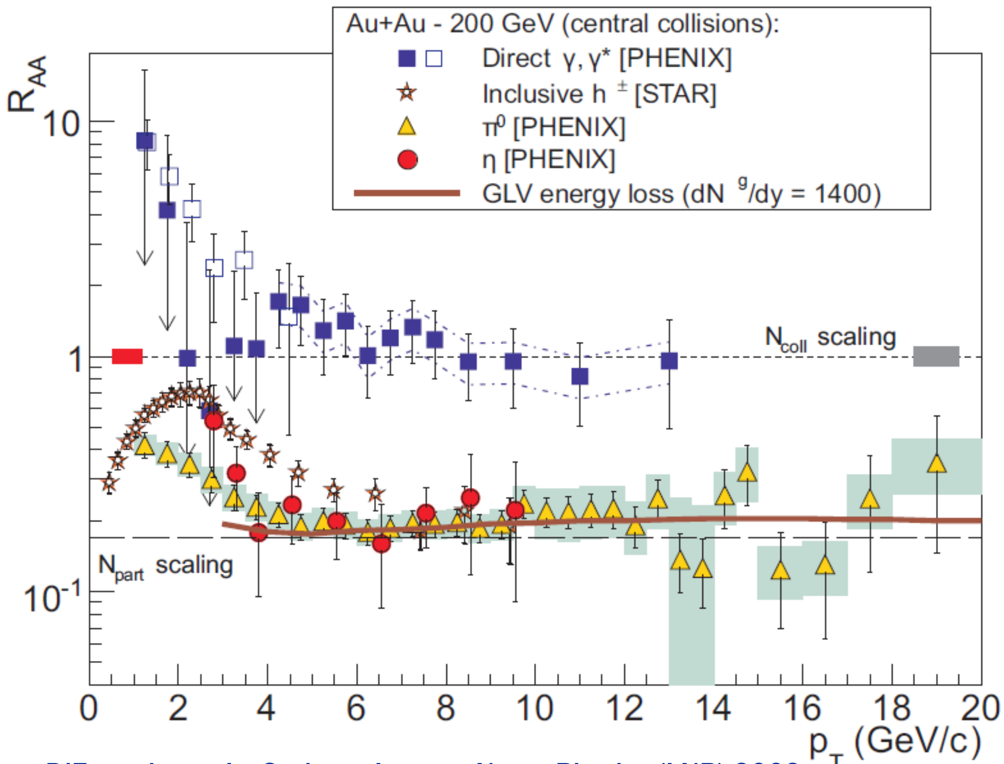

RHIC
BOOSTER
LINAC
AGS
HTB
TANDEMS
HITL

vs.

LHC

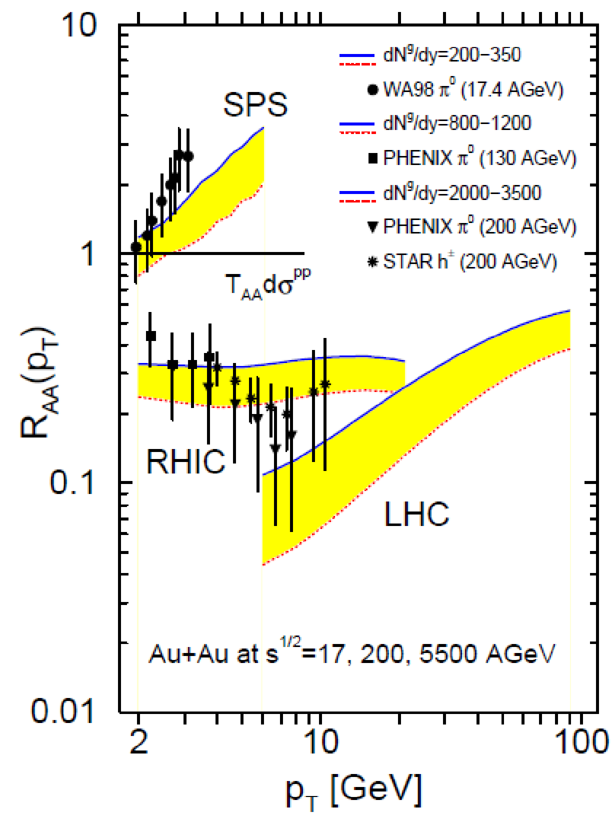

Lake Geneva
CMS
LHCb
ALICE
ATLAS

RHIC & LHC



D'Enterria et al., Springer Lecture Notes Physics (LNP) 2009

2002 prediction based on pQCD



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

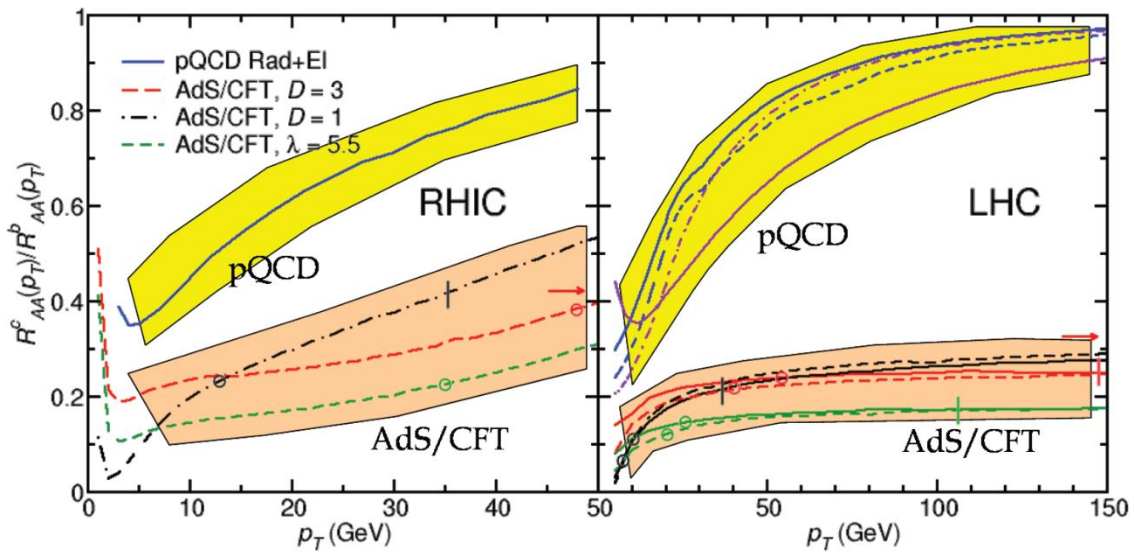
- ⇒ R_{AA}@RHIC is flat, R_{AA}@LHC strongly increases with p_T
- ⇒ p_T<20 GeV: R_{AA}@LHC < R_{AA}@RHIC

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

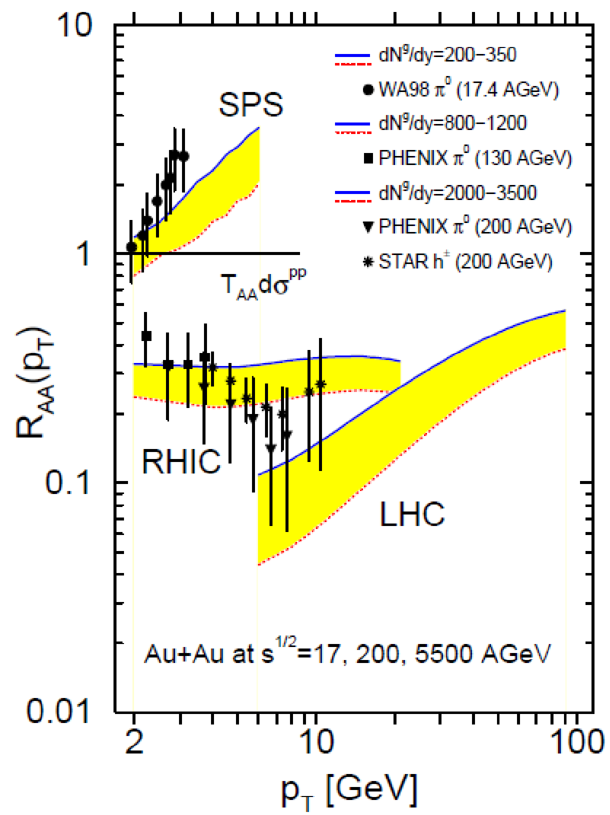
The Nuclear Modification Factor

RHIC & LHC

2002 prediction based on pQCD



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

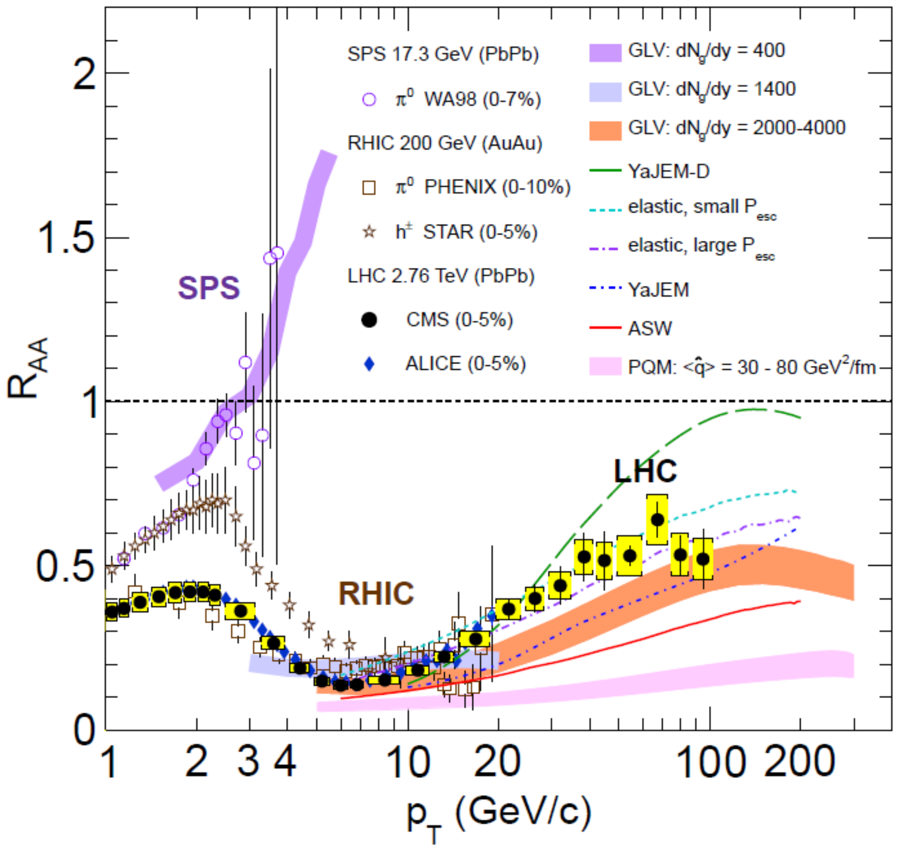


Vitev et al., Phys. Rev. Lett. **89**, 252301 (2002)

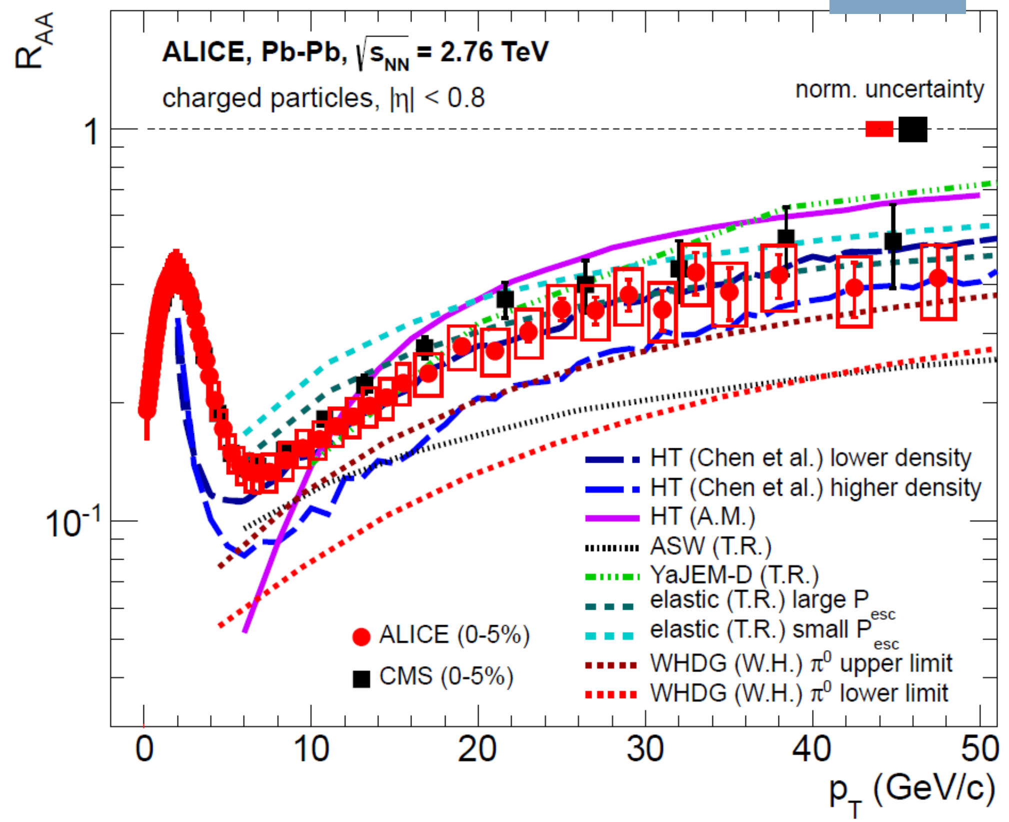
⇛ 2008: An AdS/CFT-like energy loss will lead to a flat $R_{AA}(p_T)$@LHC

LHC Jet-Quenching: Experiment

LHC



CMS Collaboration, Eur. Phys. J C **72**, 1945 (2012)



ALICE Collaboration, Phys. Lett. B **720**, 52 (2013)

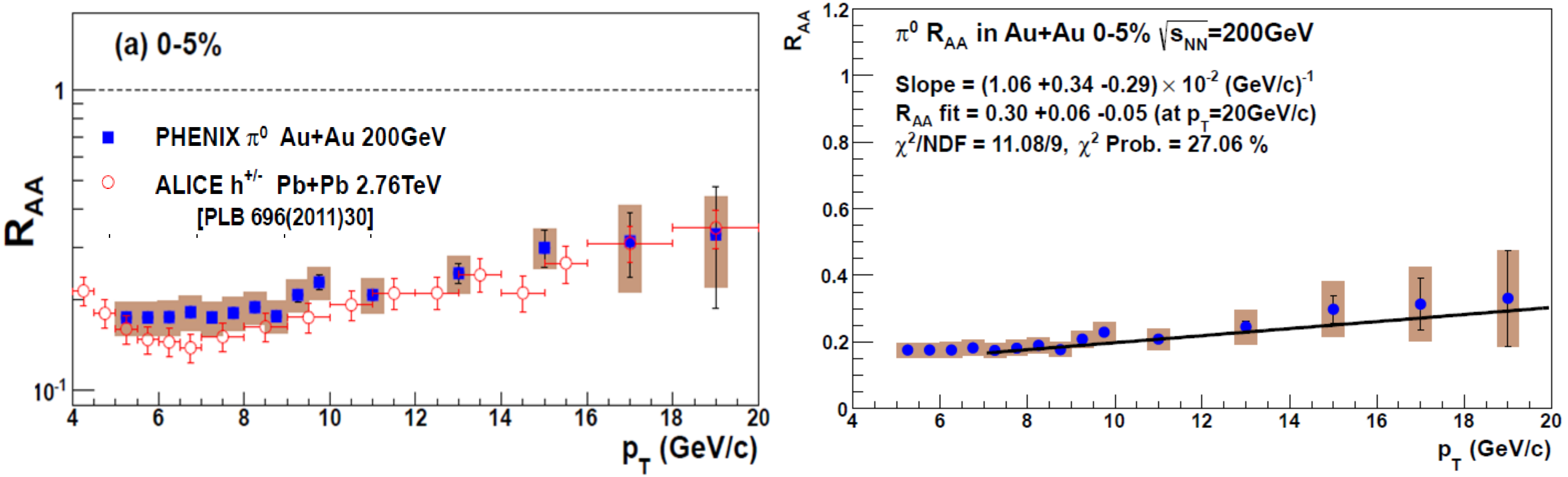
⇒ $R_{AA}(p_T)$@LHC: Does that rule out an AdS-like energy loss?

⇒ R_{AA} @LHC not as small as predicted

⇒ Wide variety of models that might or might not describe the data

New PHENIX results

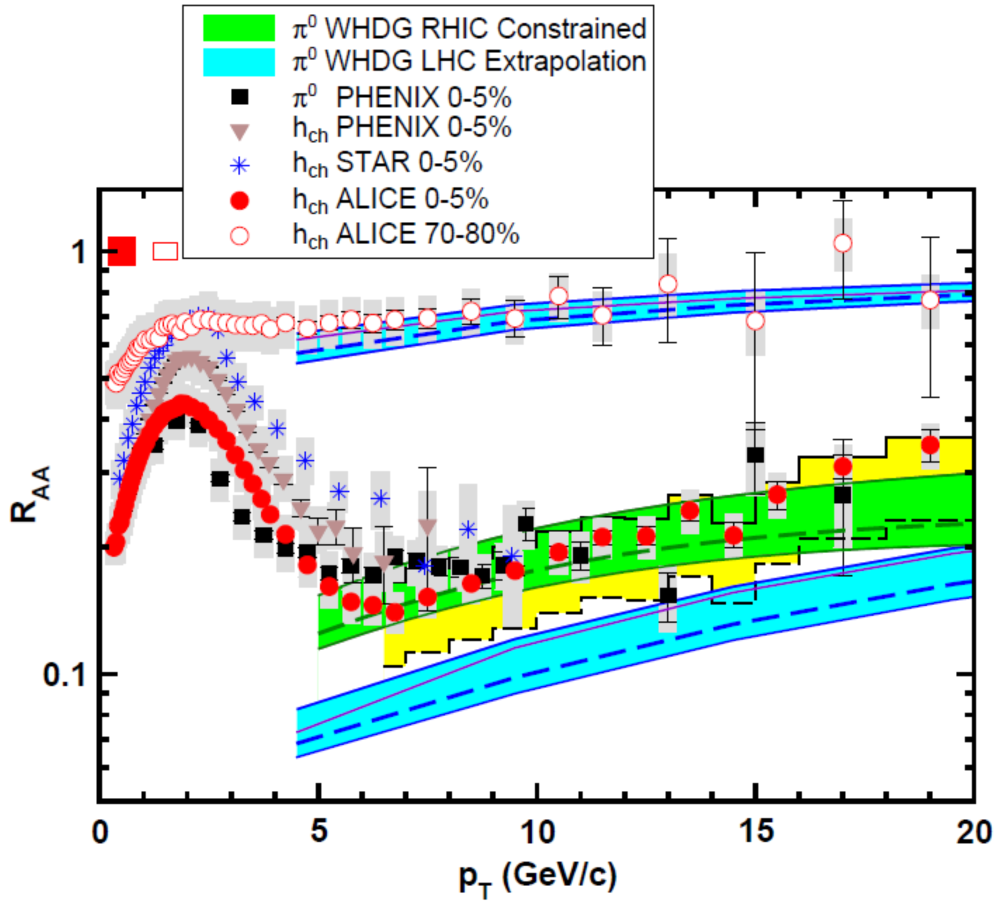
RHIC



PHENIX Collaboration, arXiv: 1208.2254

- ⟹ New PHENIX (higher precision & larger p_T) indicate rising R_{AA} @RHIC
- ⟹ p_T>15 GeV: remarkable similarity of RHIC & LHC results, in contrast to predictions

LHC Jet-Quenching: Theory



RHIC & LHC

Puzzle: RHIC constrained models tend to overquench R_{AA} @LHC

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

Is the jet-medium coupling at LHC weaker? By how much?

⇒ Quantify the reduction of the jet-medium coupling @LHC

Energy-Loss Mechanisms

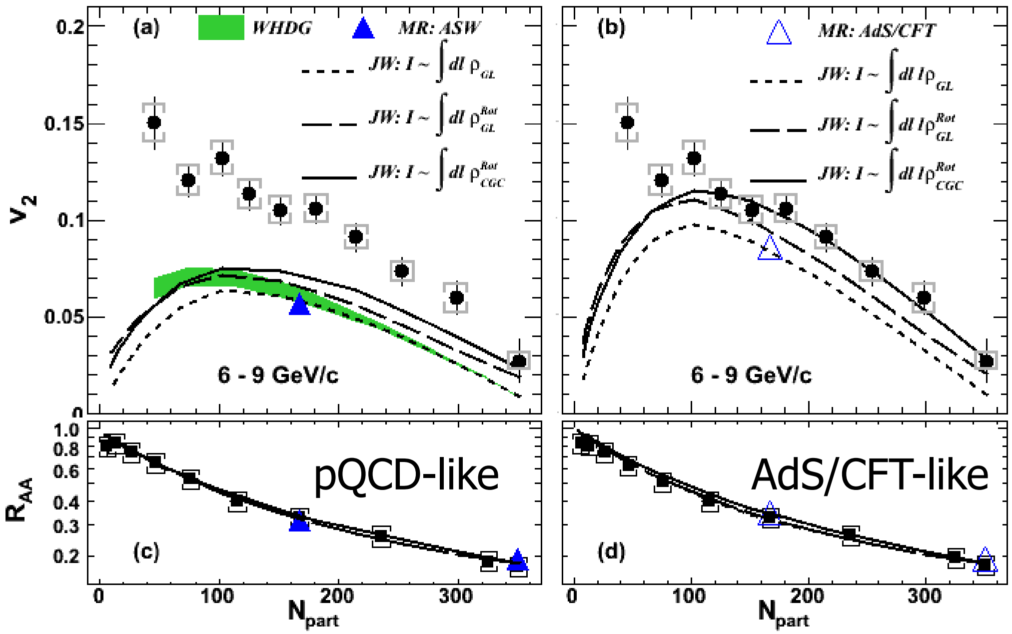
Generic model of jet-energy loss:

RHIC & LHC

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

including fragmentation, and examining an "averaged scenario" for Glauber and CGC-like inital conditions

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



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

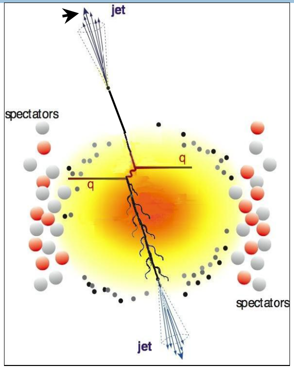
generalized from Jia's survival model

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

Energy-Loss Mechanisms II

Generic model of jet-energy loss:

RHIC & LHC



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

- a=1, z=0: Bethe-Heitler limit

  energy loss of charged particles passing through matter, based on the Dirac equation and the Born approximation for the interaction of the particle with the field of a nucleus.

- a~0, z~1: Landau-Pomeranchuk Migdal (LPM) pQCD

  quantum interferences between successive scatterings (LPM effect) leads to a suppression of the radiation spectrum compared to Bethe-Heitler.

- a=1/3, z=1: DGLV (logarithmic) jet-energy dependence & a=1/3 is lower bound of power a in falling string scenario
- a=0,1, z=2: "AdS/CFT" model

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

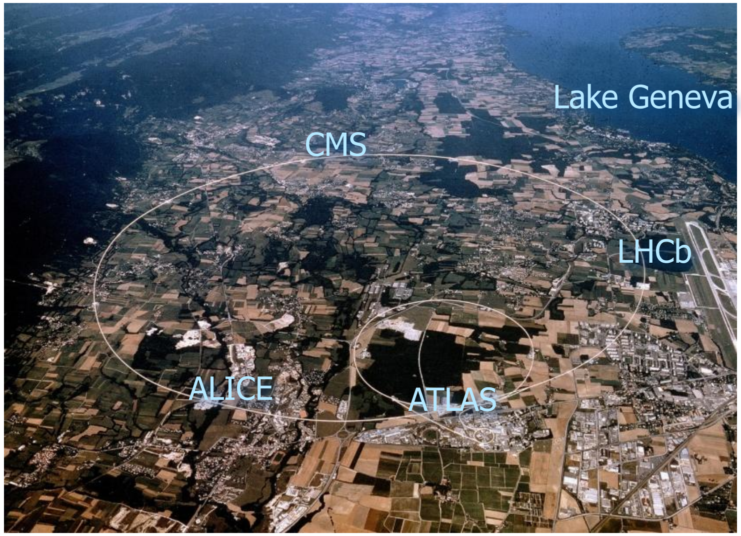
a	z	c	In. Cond.
0	1	3	Glauber
1/3	1	8/3	Glauber dcgc1.2
1	2	3	„Jia" dcgc1.2
0	2	4	AdS

A. Ficnar, arXiv: 1201.1780

RHIC

vs.

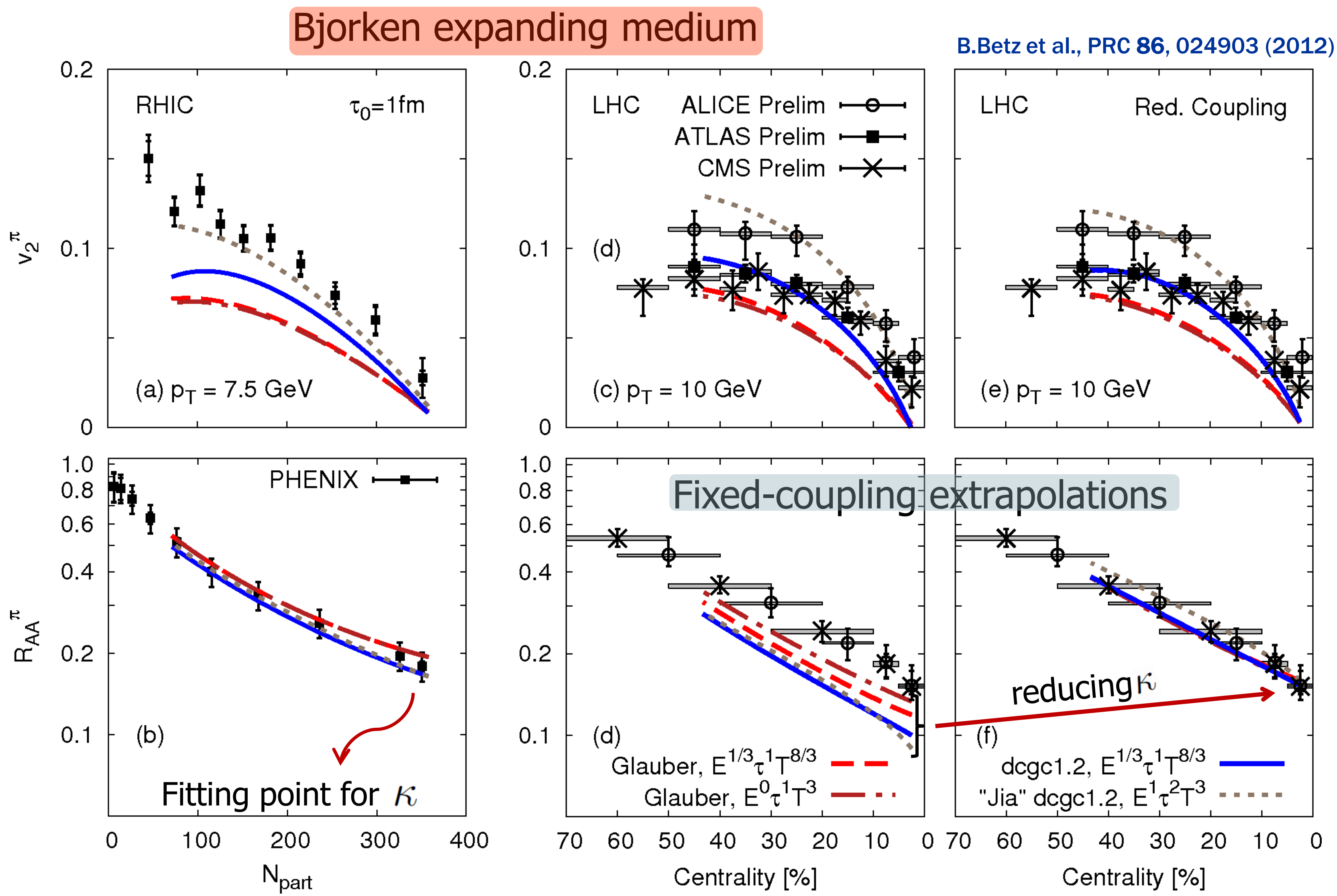
LHC



pure Bjorken expansion

R_{AA} and v_2 at RHIC vs. LHC

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



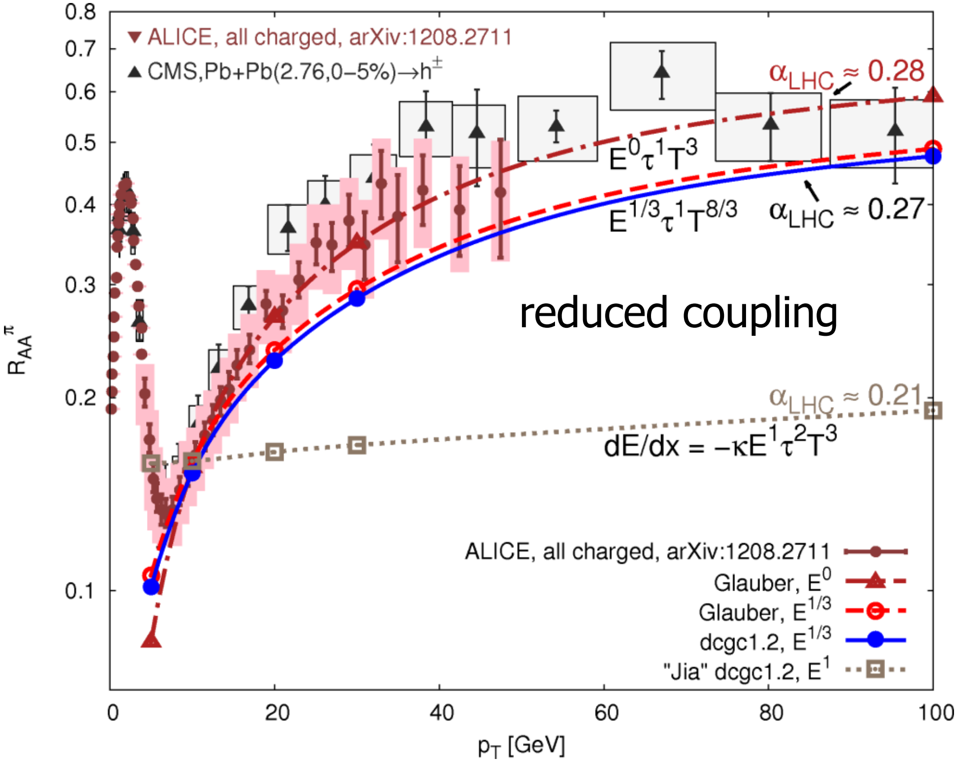
⇒ Moderate reduction of the running coupling: $\alpha_{\mathrm{LHC}} \sim 0.24 - 0.28$

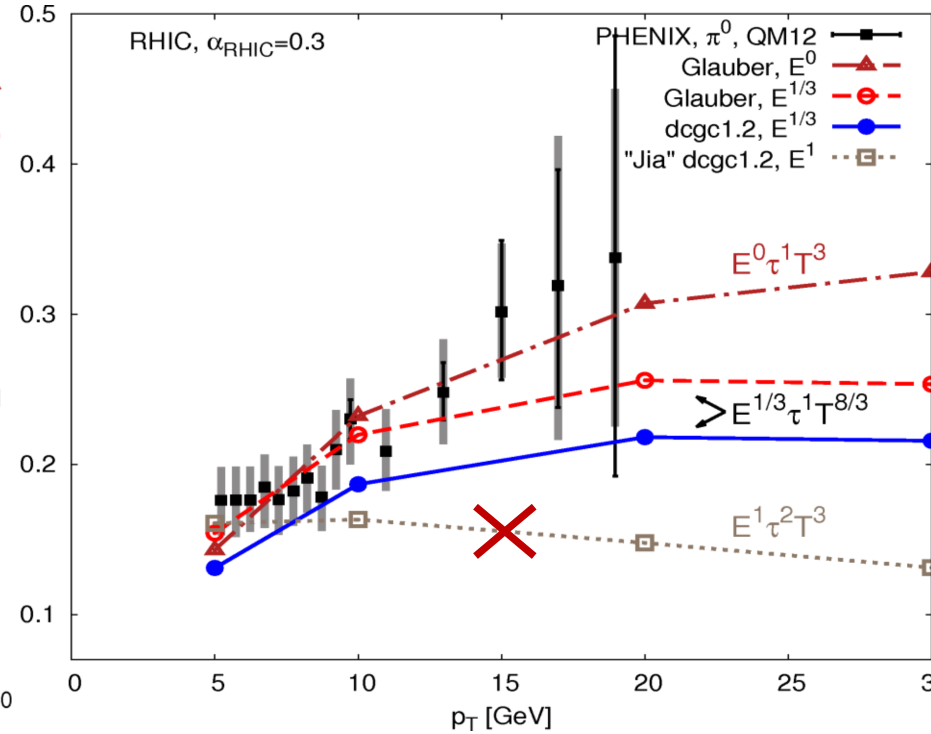
$R_{AA}(p_T)$ at LHC & RHIC

LHC

Bjorken expanding medium

RHIC





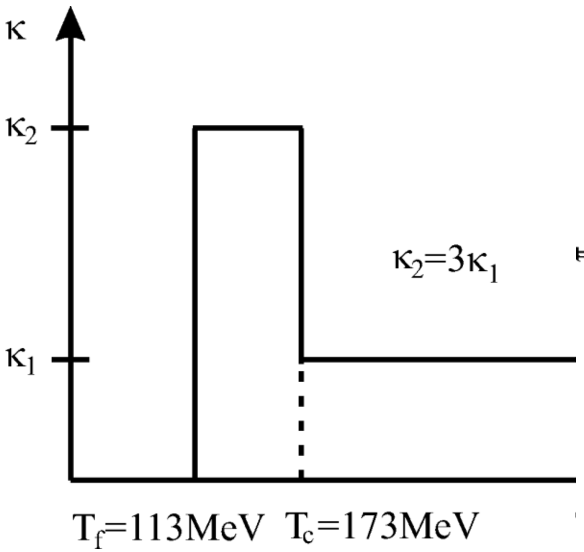
⇒ Linear p_T -dependent (a=1) model describes RHIC p_T<10 GeV data well but is falsified at LHC

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

Fixed vs. Temperature-Dependent Coupling

pure Bjorken expansion

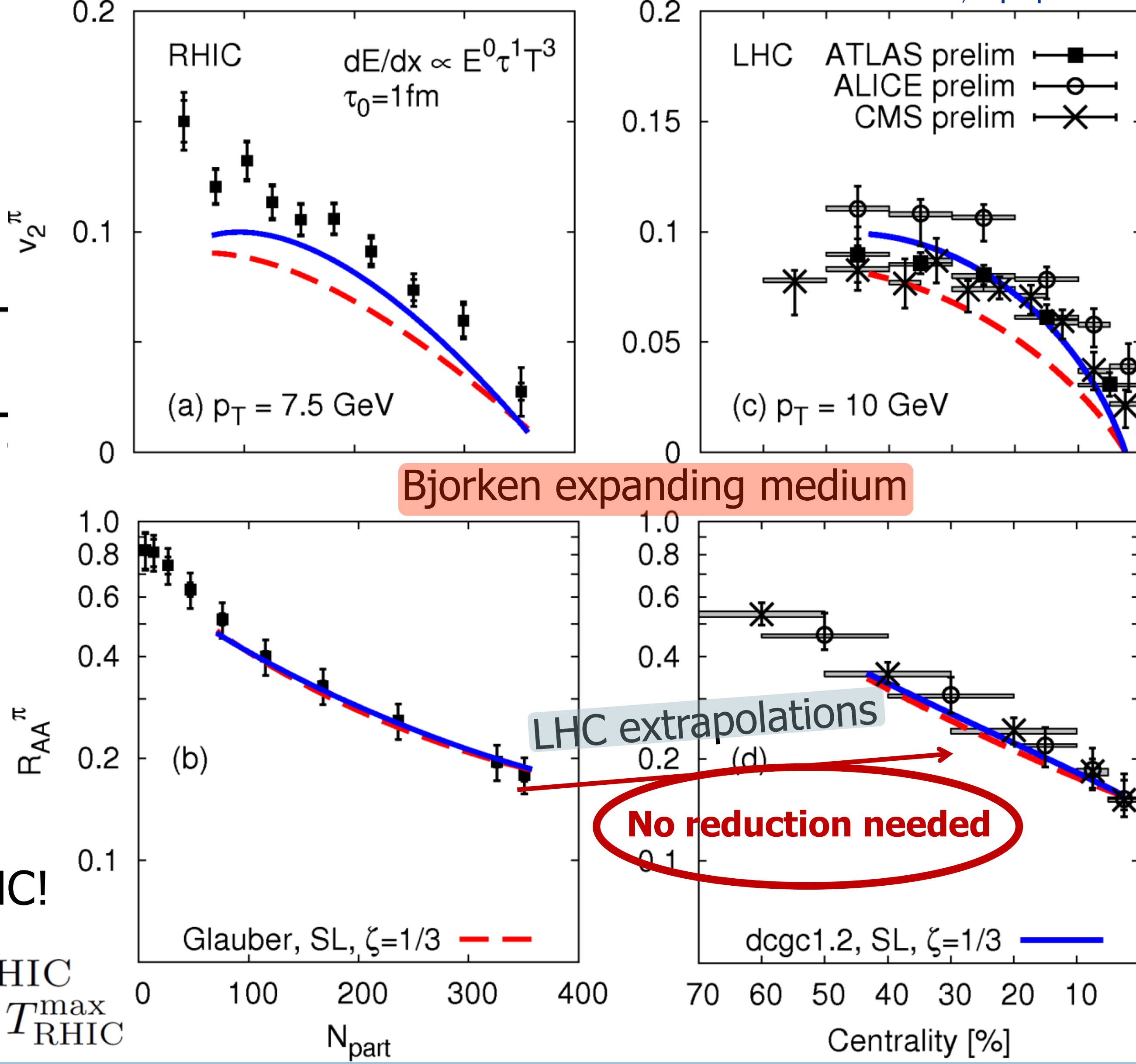
Temperature-dependent Coupling



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

$$\zeta = \kappa_1 / \kappa_2$$

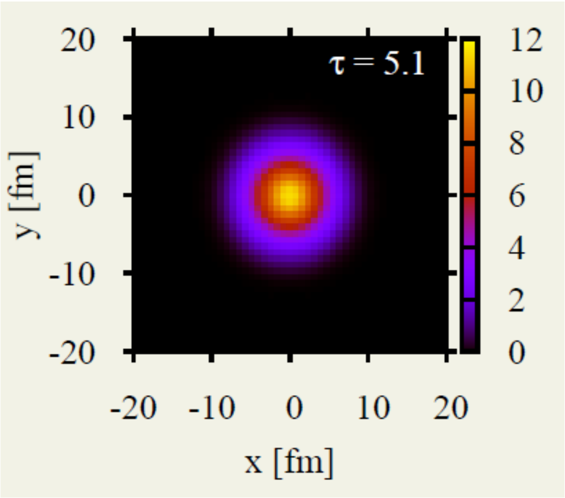
B.Betz et al., in preparation



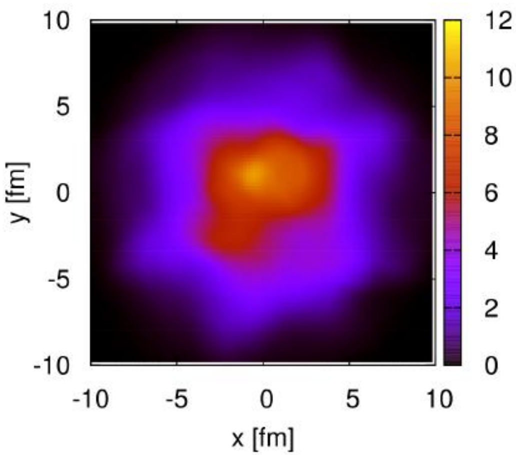
⇛ Assumes the same κ(T) at RHIC and LHC!

⇛ eff κ_{LHC} < eff κ_{RHIC} because $T_{LHC}^{max} \sim 1.3\, T_{RHIC}^{max}$

Transverse expansion

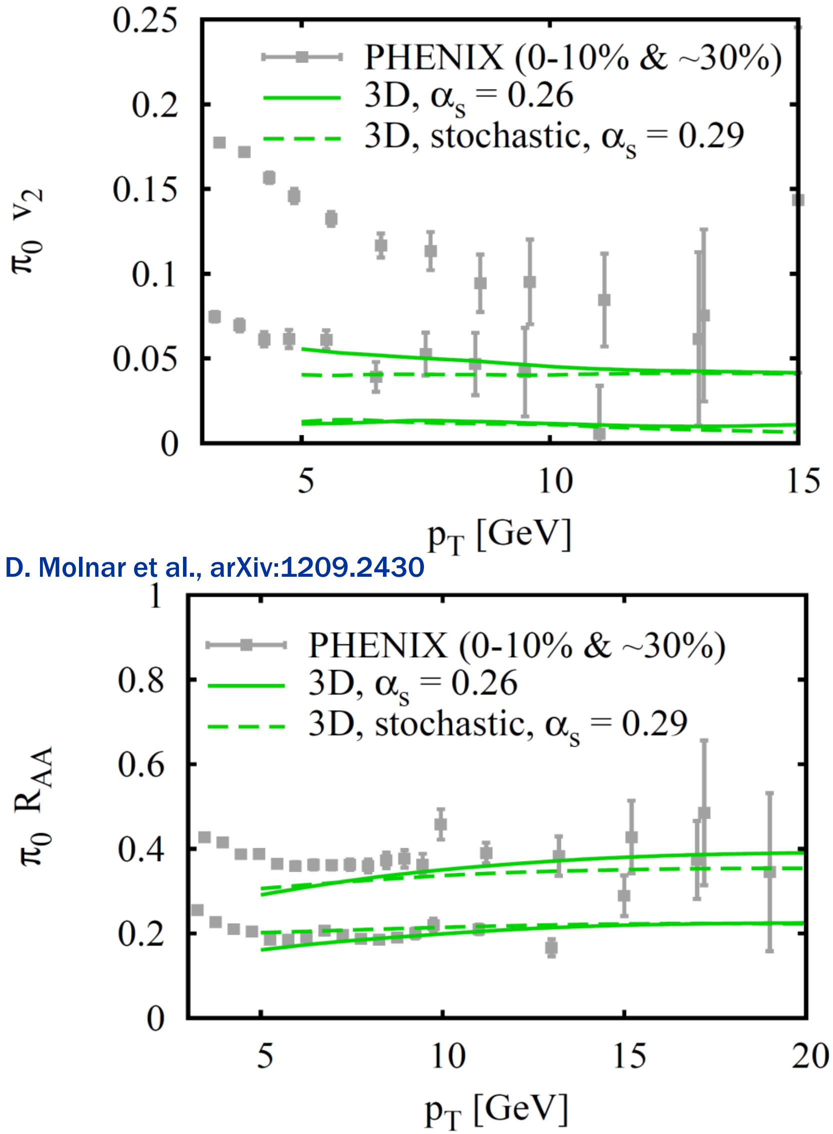


D. Molnar



B. Schenke

MPC 3D Twist



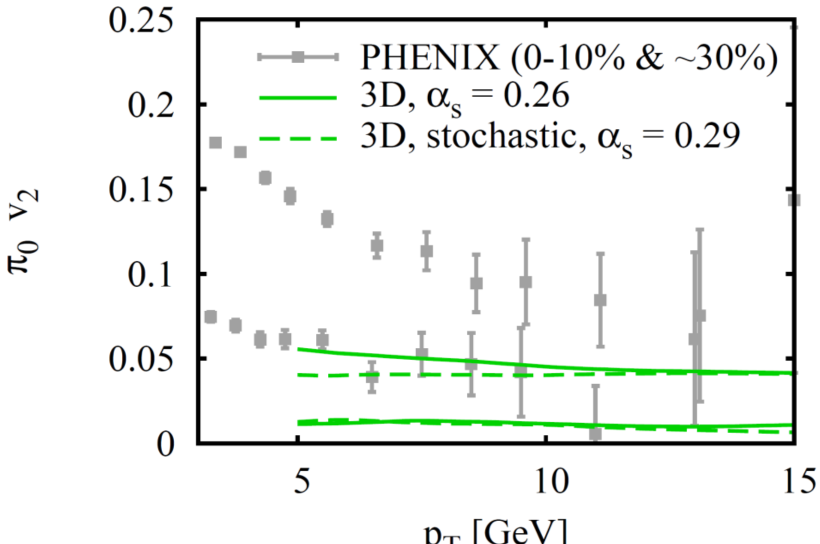
D. Molnar et al., arXiv:1209.2430

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

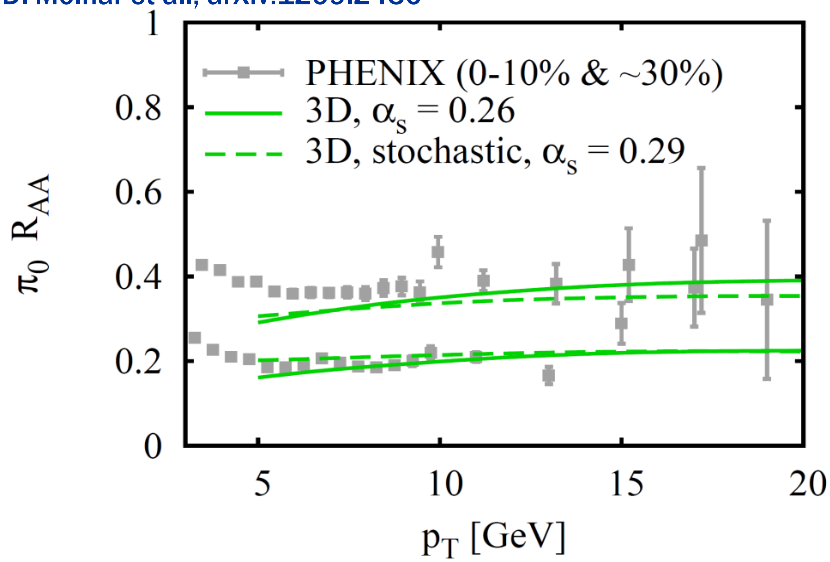
D. Molnar et al., Phys. Rev. C **62**, 054907 (2000)

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

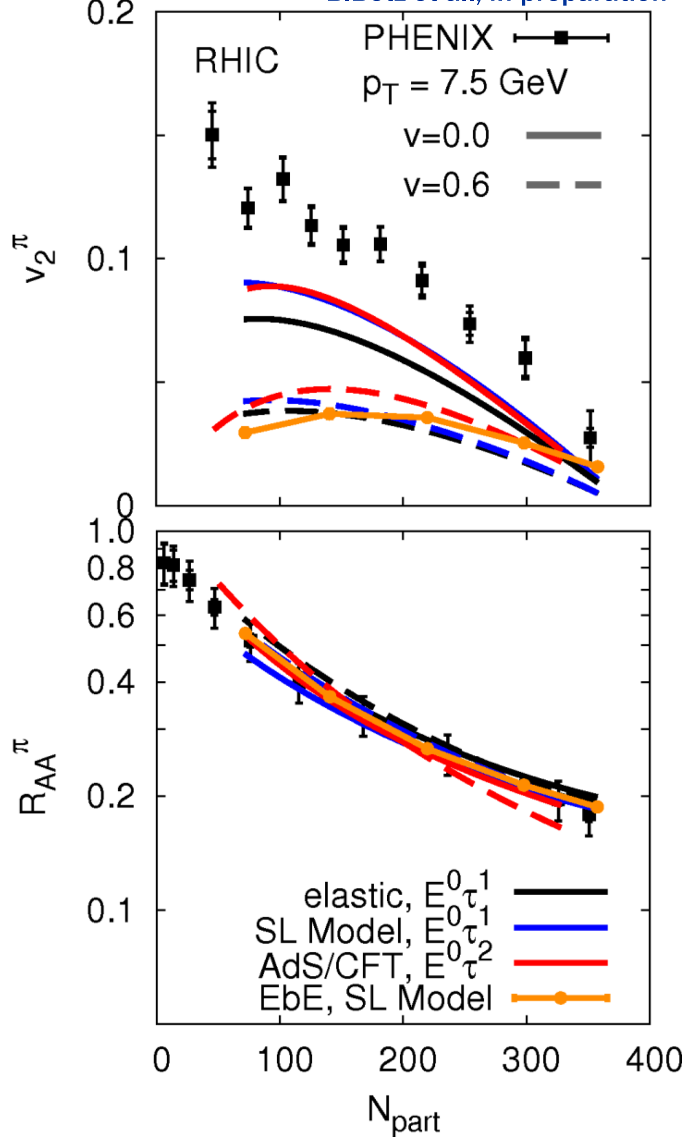
Check with simple 3d blast wave model



D. Molnar et al., arXiv:1209.2430



B.Betz et al., in preparation

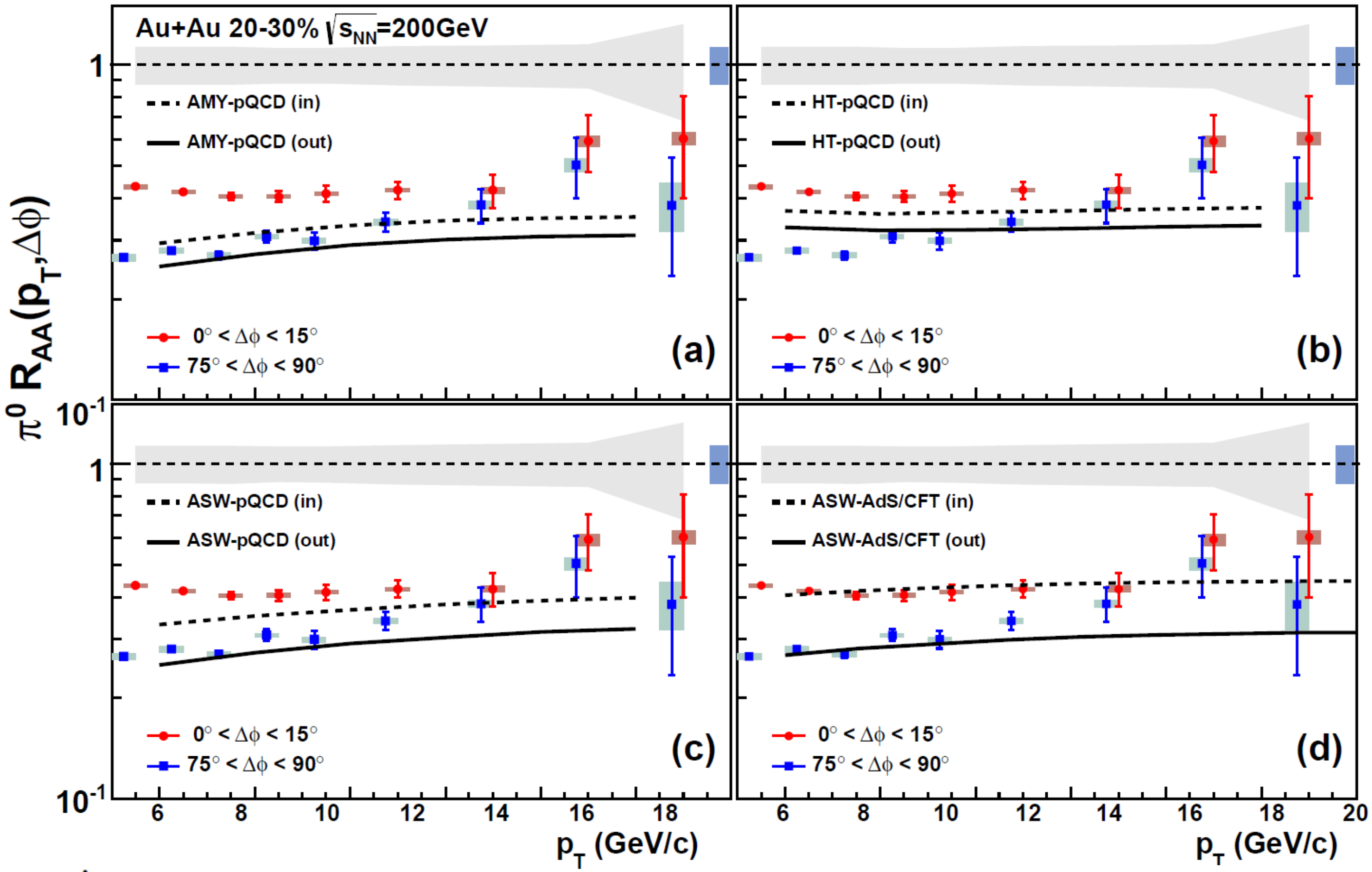


⟹ Reduction of the pion v_2 by a factor of 2 considering **transverse expansion**

R_{AA}^{in} and R_{AA}^{out} at RHIC and LHC

PHENIX R_{AA}^{in} and R_{AA}^{out}

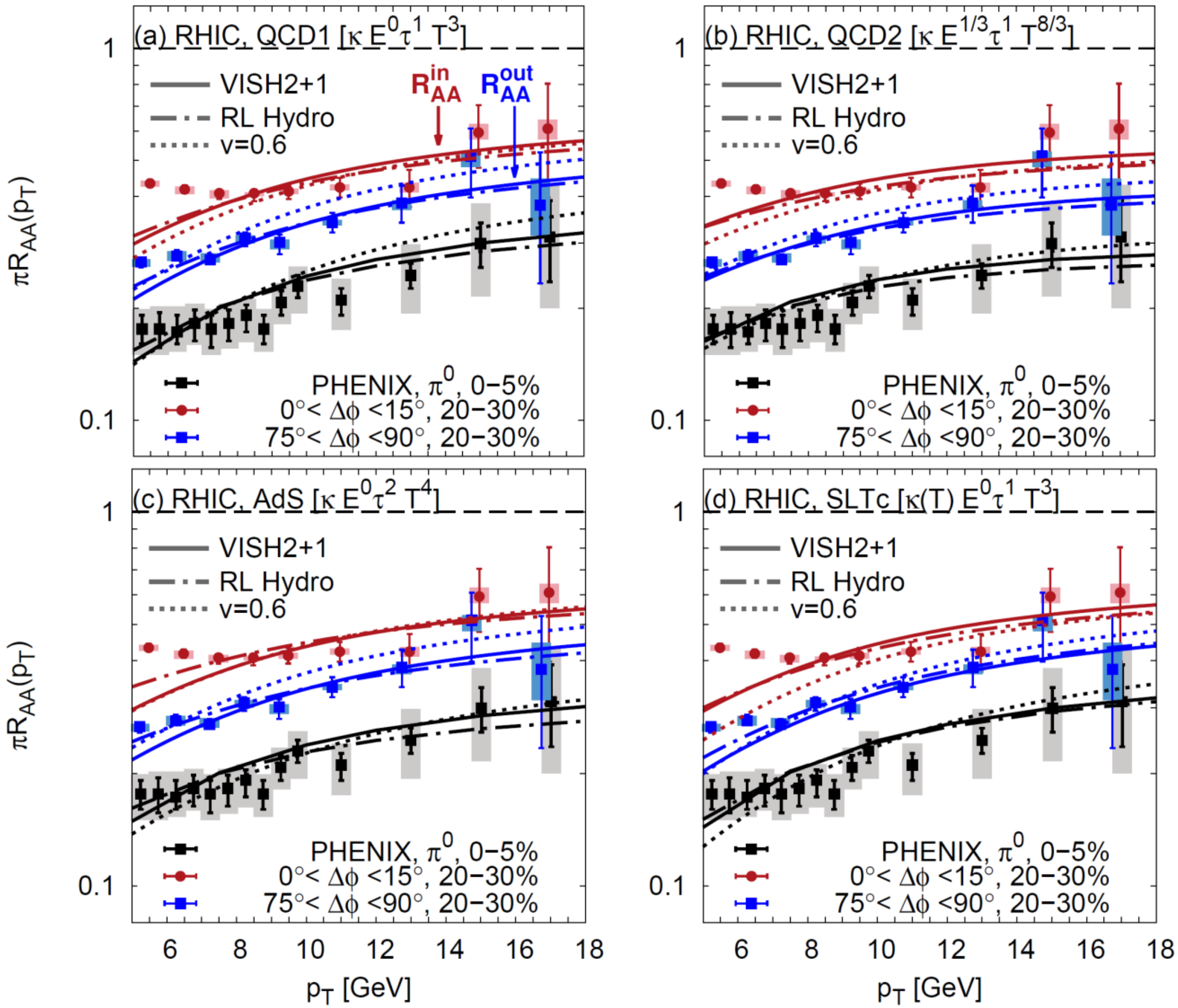
A. Adare et al., arXiv:1208.2254



→ $R_{AA}^{in} = R_{AA}(1 + 2v_2)$ and $R_{AA}^{out} = R_{AA}(1 - 2v_2)$ provide information about both R_{AA} and v_2

⇒ Conclusion: Only ASW-AdS/CFT can describe both R_{AA}^{in} and R_{AA}^{out} for a 3d expanding medium

R_{AA}^{in} and R_{AA}^{out} at RHIC



B. Betz et al., arXiv:1305.6458

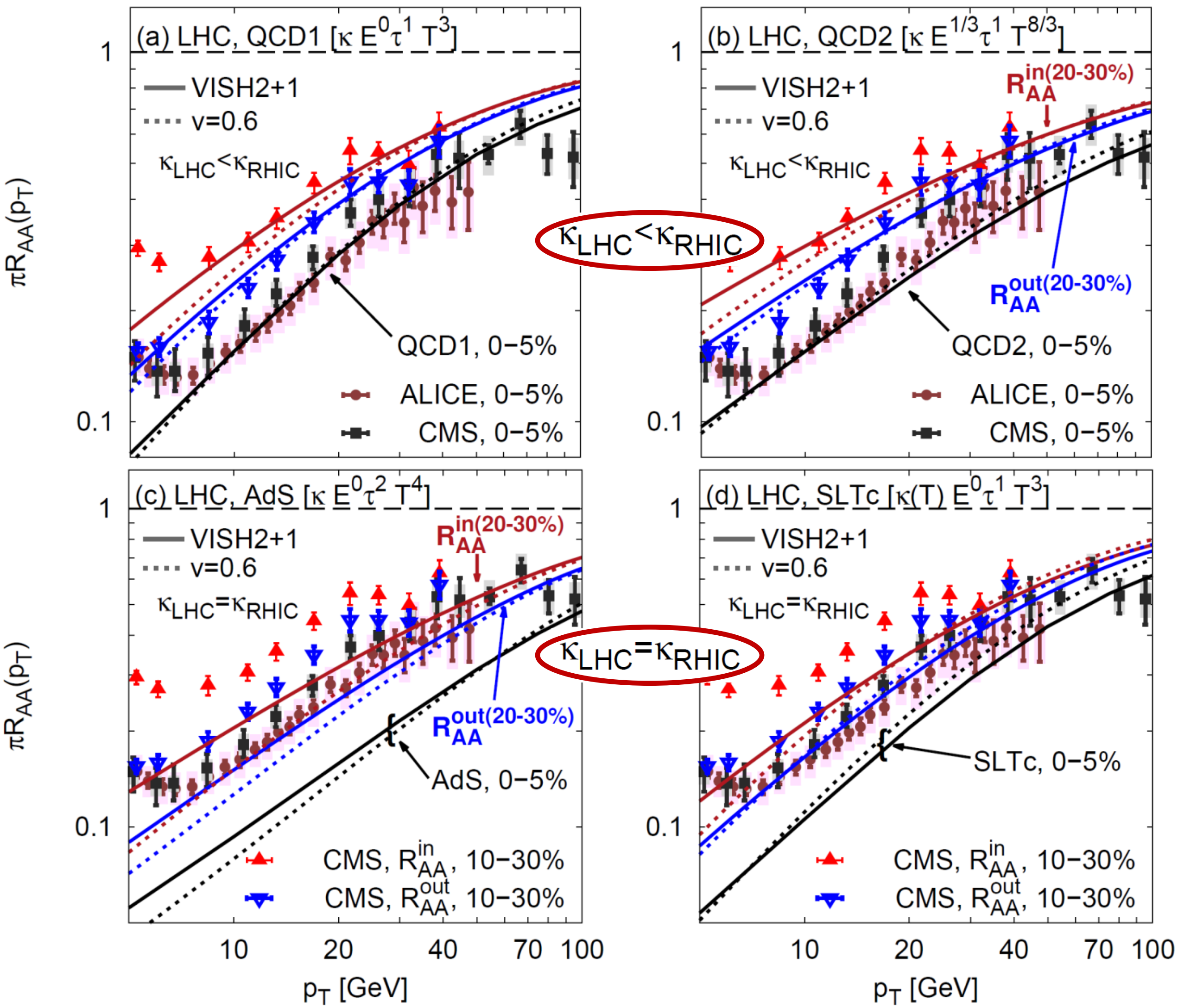
Blast wave model (v=0.6) fails to describe the data

⟹ v_2 is too small

Ideal and viscous hydro that reproduce the bulk properties succeed in describing the data

Qualitative difference to PHENIX results: Hydro code in PHENIX plot uses a hydro code with a Bag model EoS (vanishing speed of sound)

R_{AA}^{in} and R_{AA}^{out} at the LHC



B. Betz et al., arXiv:1305.6458

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 QCD1 scenario describes best the data both at RHIC and at LHC

Summary & Open Problems

Comparison of recent R_{AA}@RHIC and @LHC with

- pQCD-like, AdS/CFT-inspired, and a T_C-dominated energy-loss model (SLTc)
- in a pure longitudinal (Bjorken) expanding vs.
  a (2+1)d transverse expanding medium (hydro vs. bast wave)

A pure Bjorken expanding medium can describe both RHIC & LHC data
BUT
inclusion of transverse expansion requires a realistic (hydro) medium.

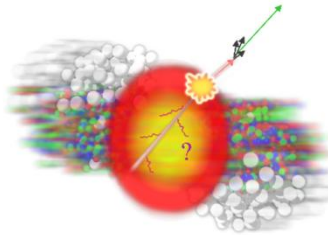
$\Longrightarrow$ The evolution of the bulk medium influences the jet-energy loss!

A running coupling pQCD-like energy loss seems to be favored.

The intermediate region ($2<p_T<8$ GeV) is underpredicted by all jet-quenching models considered. A proper theory of jet quenching in this non-equilibrium intermediate range is still needed.

Backup

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!

$\Longrightarrow$ Reasonable moderate reduction of the running coupling

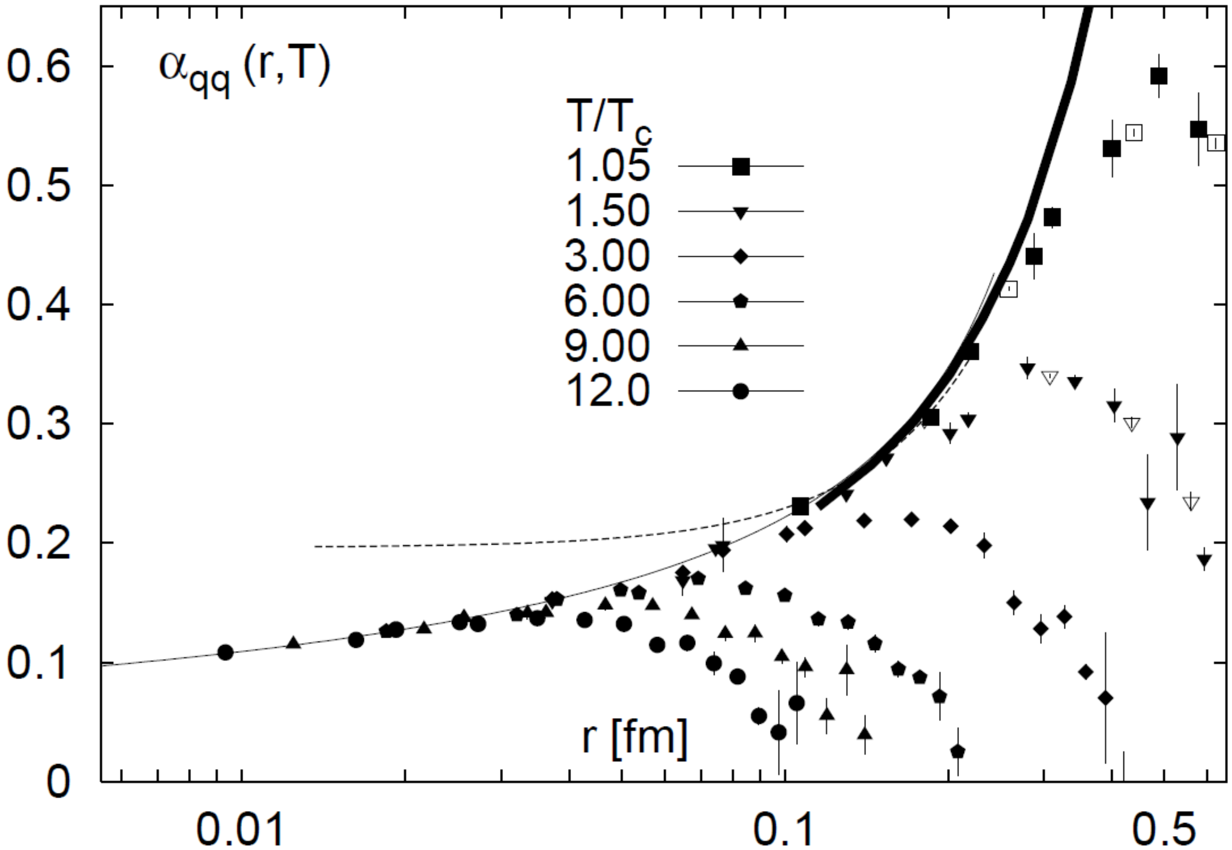
AdS/CFT: $\kappa \propto \sqrt{\lambda}$ ← t'Hooft coupling

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

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

$\Longrightarrow$ 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**,(2004) 074505

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)

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

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

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

	$\kappa_{LHC}/\kappa_{RHIC}$	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	-	-

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** (2010), 024902

considering Bjorken expansion for τ_0 = 1fm, including fragmentation, and examining an "averaged scenario" for Glauber and CGC-like in. cond.
B.Betz et al., PRC **84**, 024913 (2011)

CGC-like, deformed Glauber in. cond. (dcgc1.2):
B.Betz et al., PRC **86**, 024903 (2012)

$$x \to s_x x, \quad y \to s_y y$$

$$s_x = \sqrt{\frac{\langle x^2\rangle_{\rm CGC}}{\langle x^2\rangle_{\rm Gl}}}, \quad s_y = \sqrt{\frac{\langle y^2\rangle_{\rm CGC}}{\langle y^2\rangle_{\rm Gl}}}$$

with the assumption

$$\epsilon_{\rm CGC} = f\cdot\epsilon_{\rm Gl} \qquad f = 1.2\pm0.1$$

Jet-energy and path-length dependencies (4 main scenarios):

a	z	c	in. cond.
0	1	3	Glauber
1/3	1	8/3	Glauber dcgc1.2
1	2	3	"Jia" dcgc1.2

⇓ **pure binary collisions** for a=1
J. Jia et al., PRC **82** (2010), 024902

Energy-Loss Mechanisms

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

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

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:

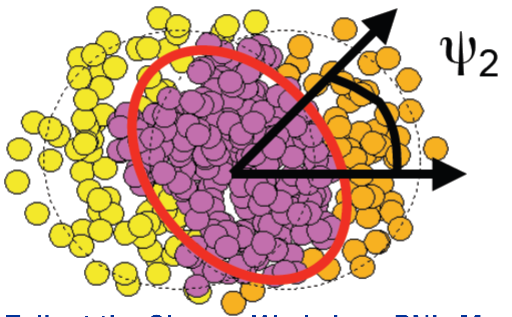
momentum of the observed pion — pQCD cross-sections — fragmentation functions

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

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

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

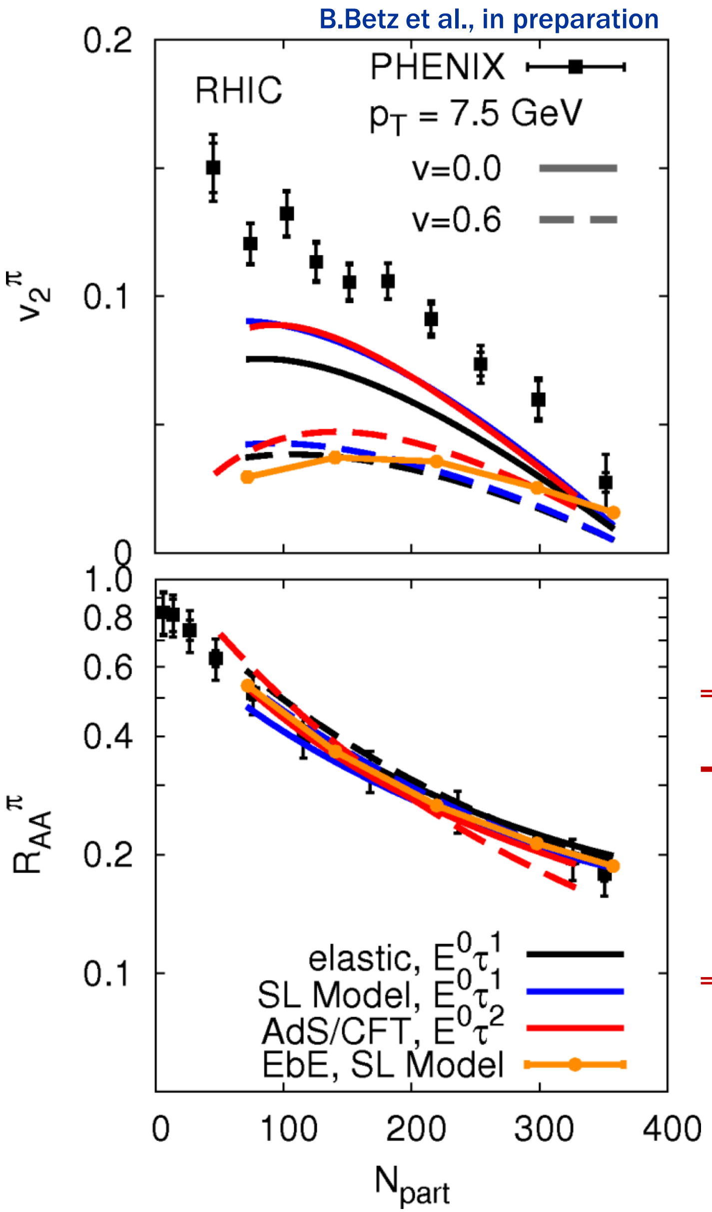
determining the angle with the reaction plane

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

and the Fourier density components are given by

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

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

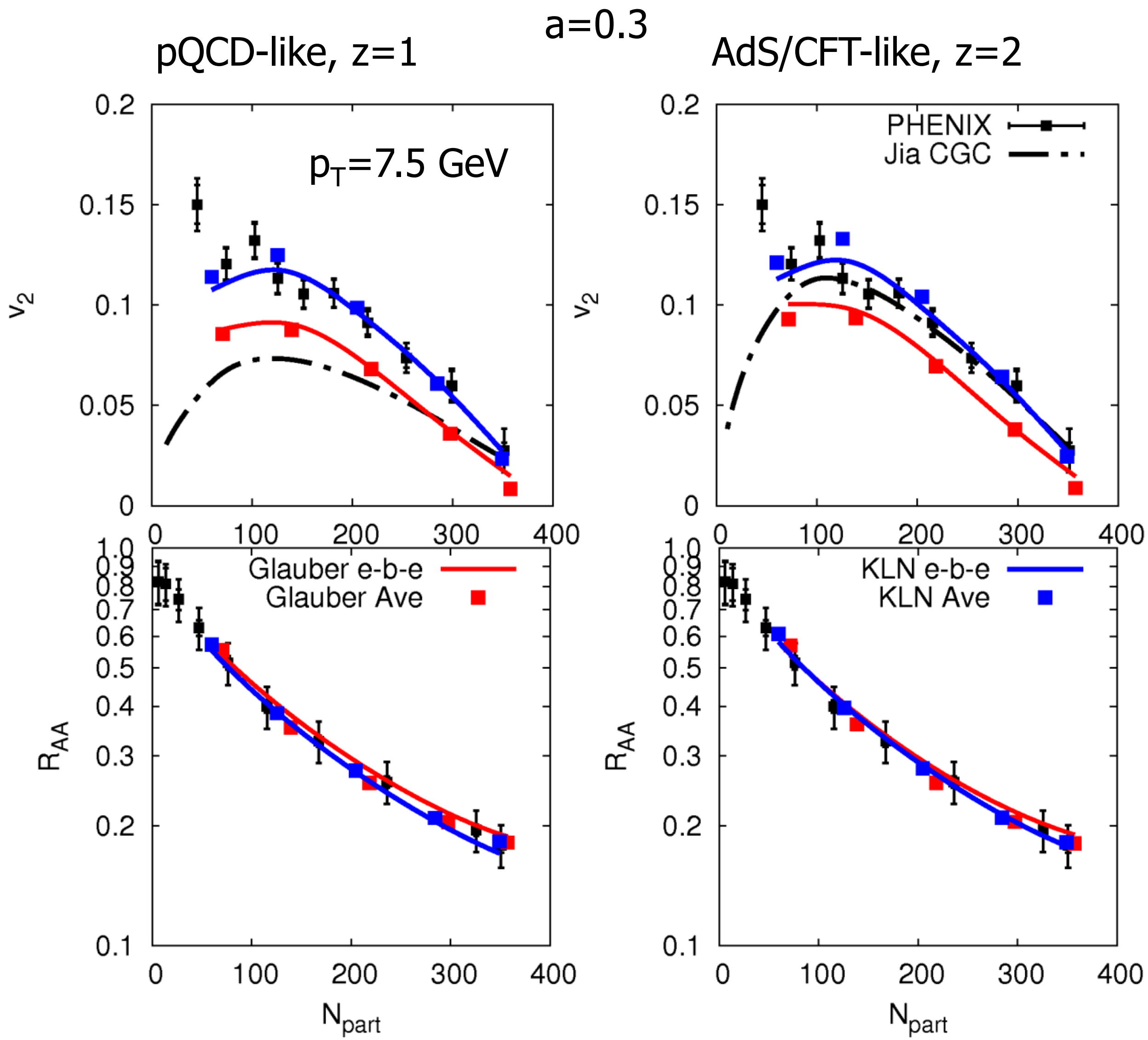
⟹ Pre-Conclusion: It is impossible to describe R_{AA} and v_2 simultaneously!

R_{AA} and v_2 at RHIC

Similar results for

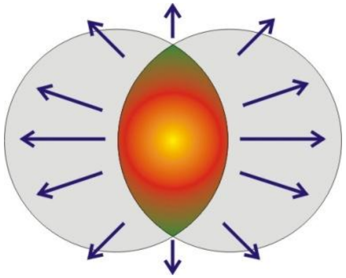
event-by-event and

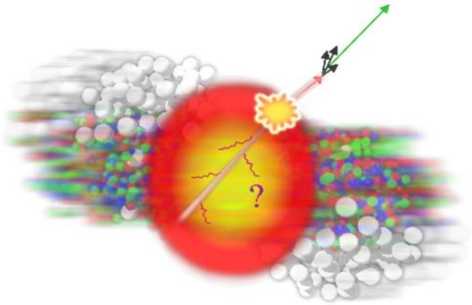
averaged scenarios



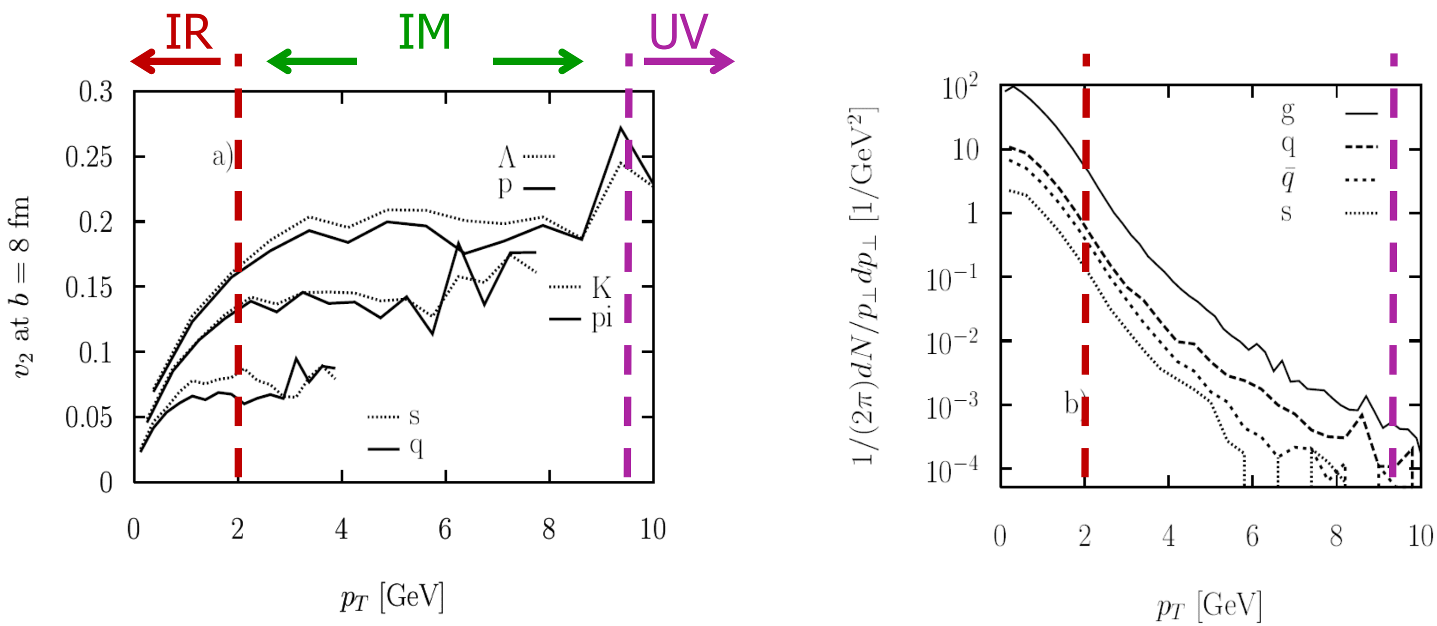
B.Betz et al., PRC **84**, 024913 (2011)

The intermediate p_T-range





Intermediate $v_2(p_T)$ range ($2<p_T<10$ GeV)



While hadronization via $1parton \to 1\pi$ or independent fragmentation approximately preserves elliptic flow at high $2 < p_\perp < 6$ GeV [3], parton coalescence enhances v_2 two times for mesons and three times for baryons. Hence, the same hadron elliptic flow can be reached from $2-3$ times smaller parton v_2, i.e., with smaller parton densities and/or cross sections.

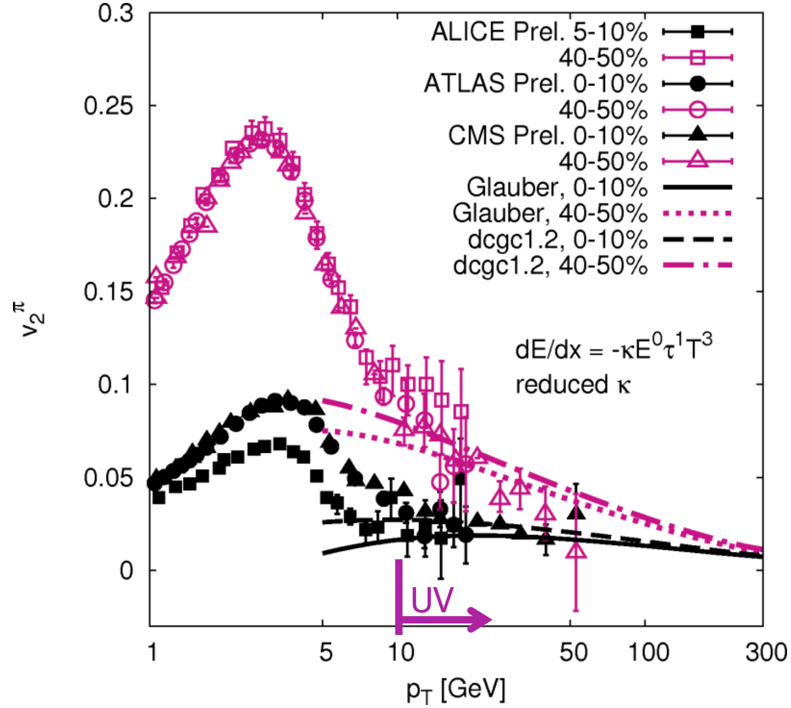
D. Molnar, J. Phys. G **30**, S235 (2004)

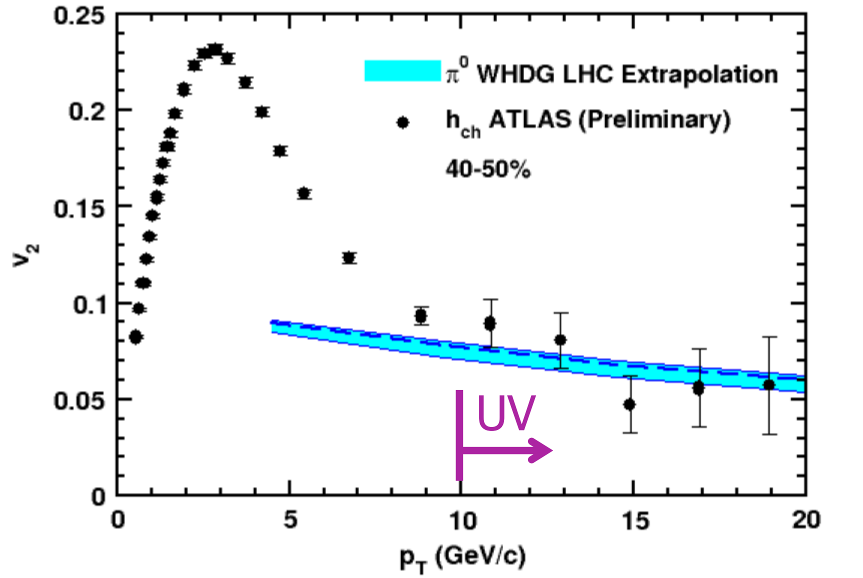
⇒ parts of the v_2(intermediate p_T) could originate from bulk tails

see Eqs. (16) – (18) in M. Gyulassy et al., Phys. Rev. Lett. **86**, 2537 (2001)

⇒ pure jet fragmentation and absorption models should NOT be expected to fully describe the intermediate p_T -range

$v_2(p_T$, Centrality) at LHC





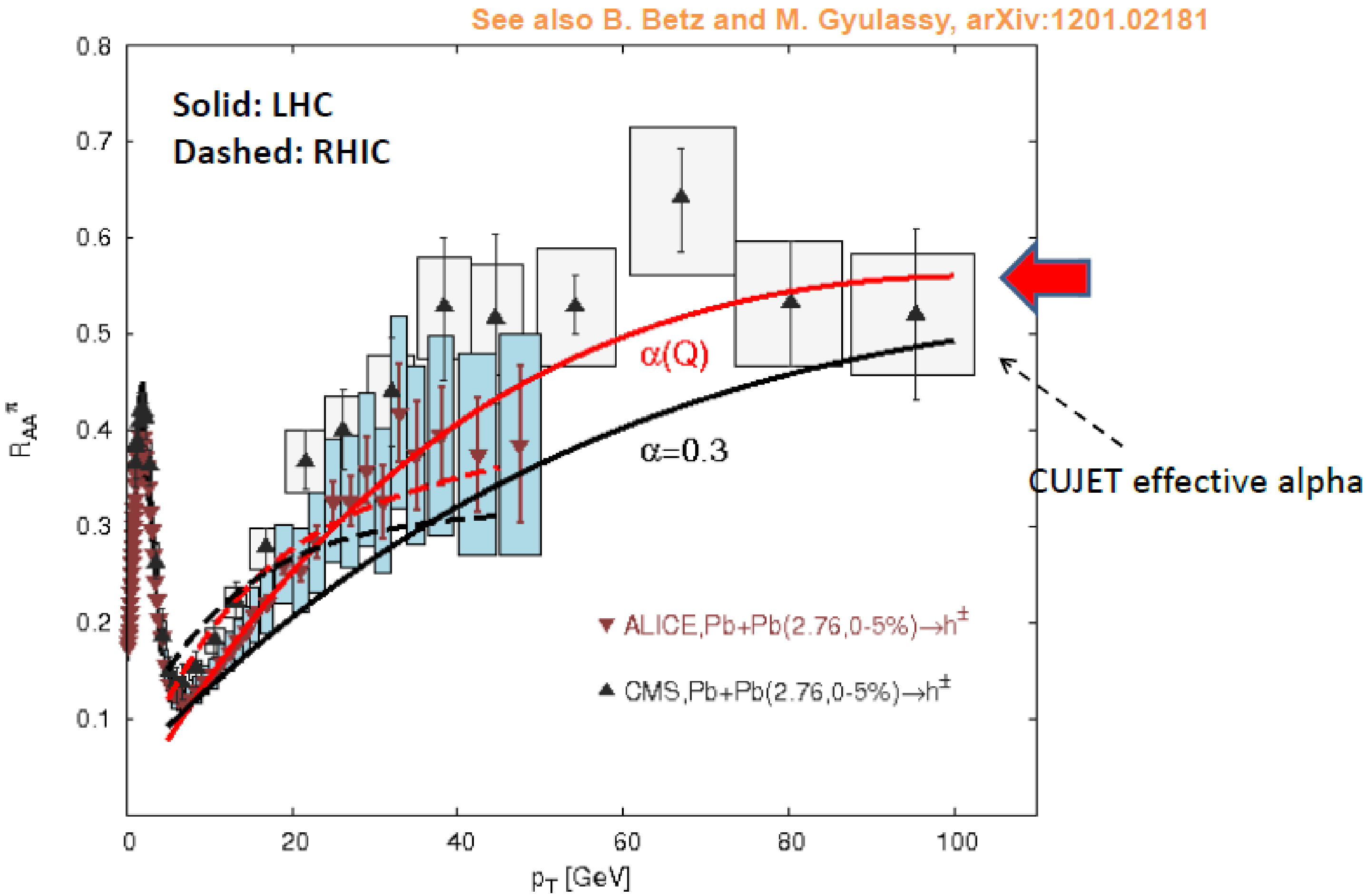
– Unlike the intermediate p_T, the deep ultraviolet p_T>10 GeV is much better explained by standard jet tomography at LHC

– For 1< p_T< 5 GeV, it is difficult to separate the jet contribution to v_2 from the high-p_T tails of the bulk QGP elliptic flow

⇒ Very high p_T>10 GeV v_2 is rather insensitive to 20% variations in the eccentricity between Glauber and CGC

Running Coupling rc-CUJET

LHC Pions

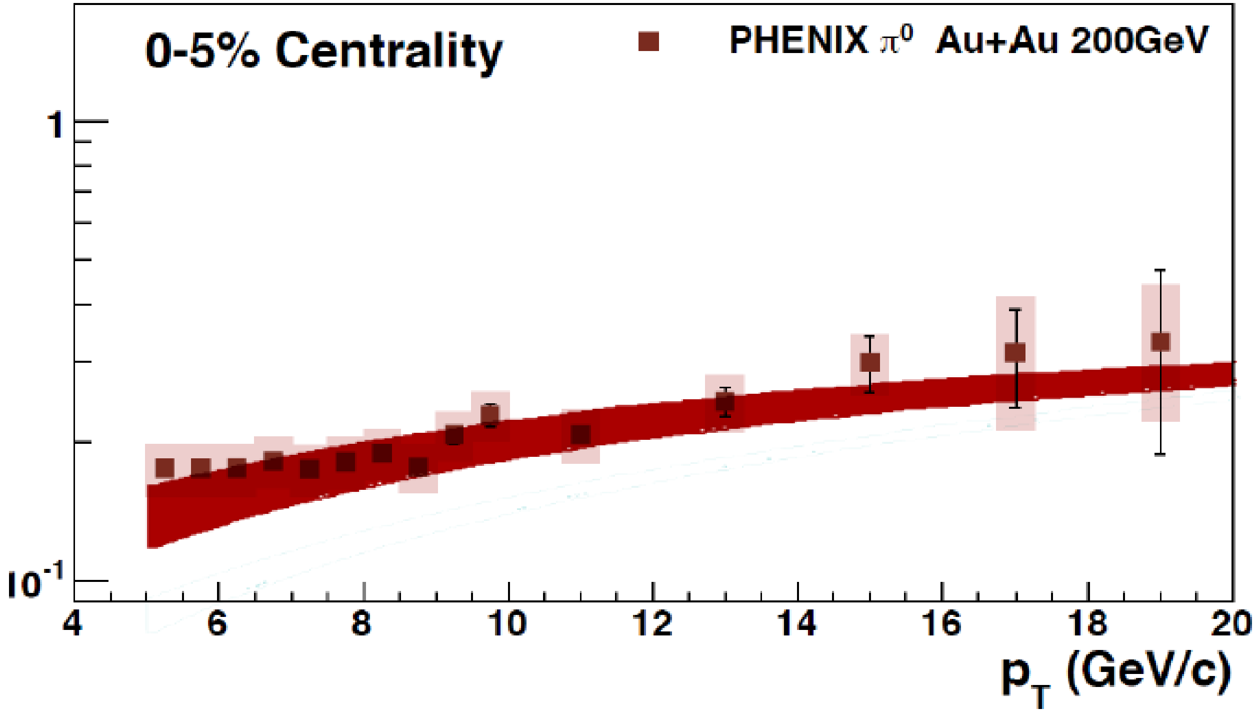


August 16st, 2012 – Quark Matter 2012, Washington DC   Alessandro Buzzatti – Columbia University   19

Running Coupling rc-CUJET

PHENIX Pions

PHENIX Collaboration



August 16st, 2012 – Quark Matter 2012, Washington DC
Alessandro Buzzatti – Columbia University
22