Quantifying a Possibly Reduced Jet-Medium Coupling of the sQGP at the LHC

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Miklos Gyulassy

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PRC 84, 024913 (2011); PRC 86, 024903 (2012)

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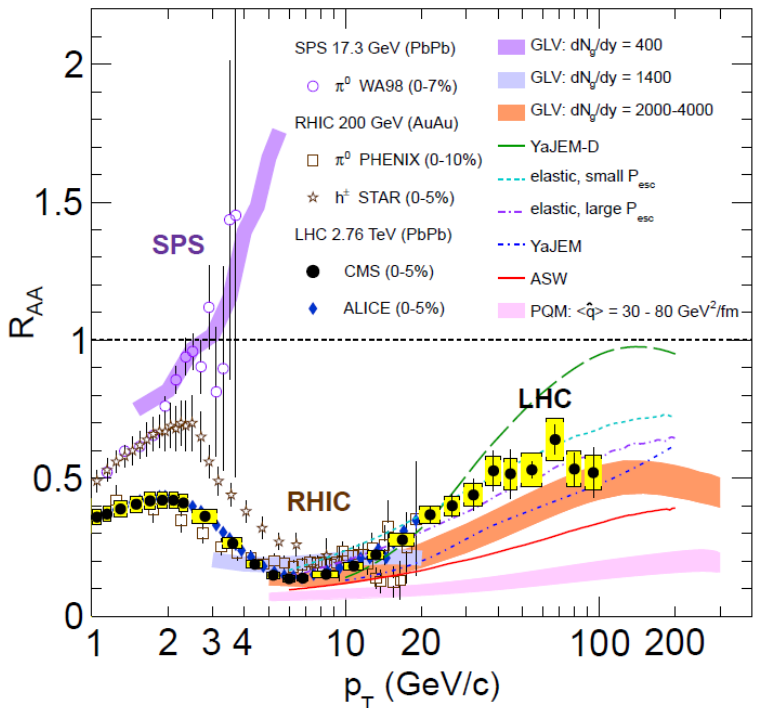
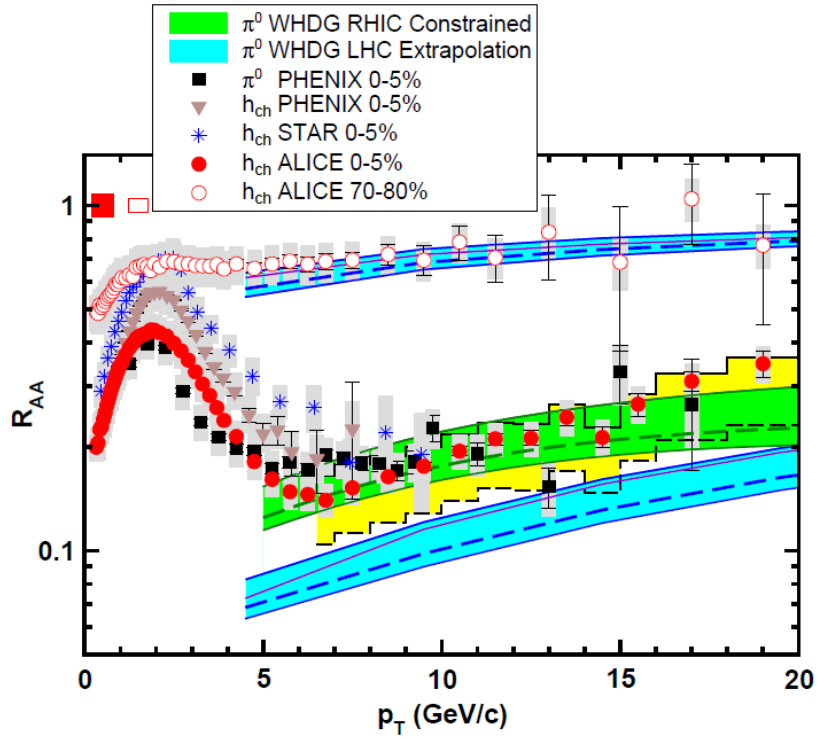
Transparency of the QGP



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



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

- Remarkable similarity of jet quenching at RHIC and LHC
- p_T-rise in data readily understood from generic perturbative physics

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

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

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

$$\epsilon_{\rm CGC} = f \cdot \epsilon_{\rm Gl} \qquad f = 1.2 \pm 0.1$$

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

see A. Ficnar QM'12 Poster
A. Ficnar, arXiv: 1201.1780

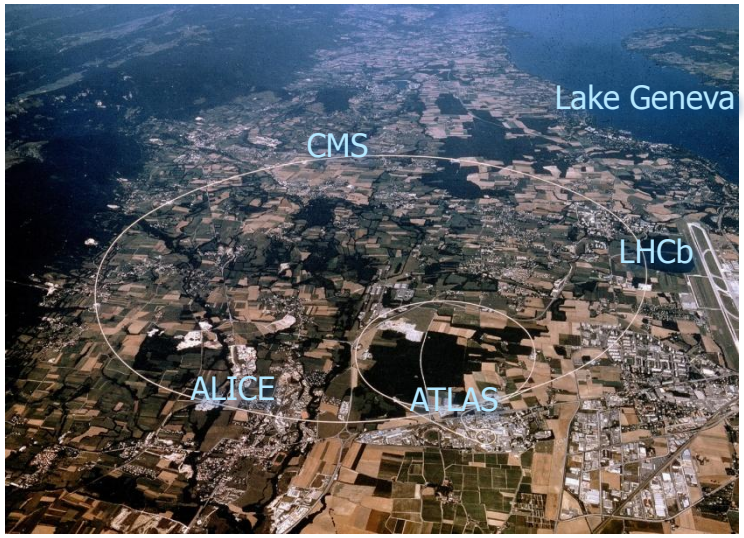
pure binary collisions for a=1
J. Jia et al., PRC **82** (2010), 024902

RHIC


RHIC
BOOSTER
LINAC
AGS
HTB
TANDEMS
HITL

vs.

LHC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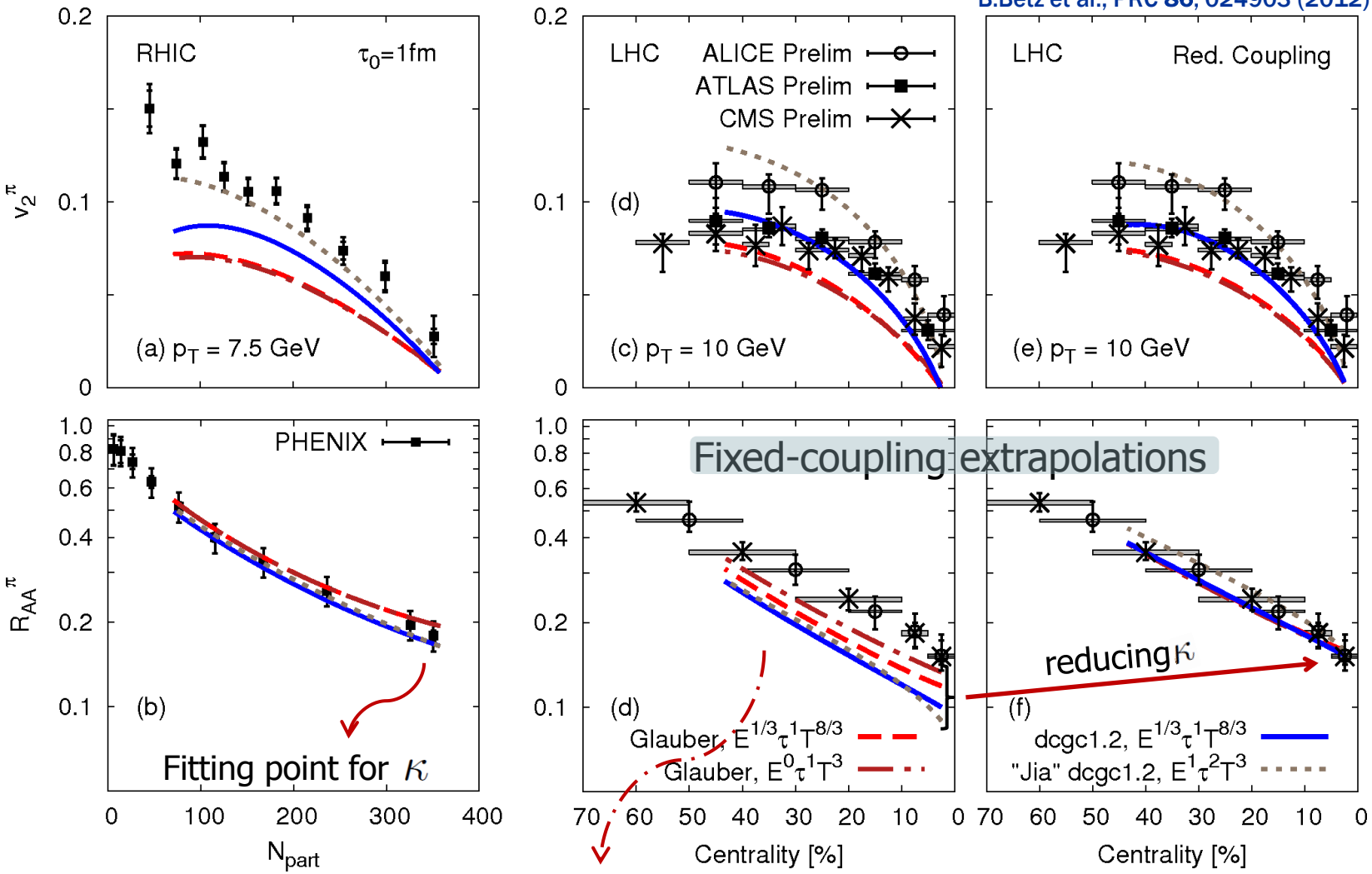
CMS
LHCb
ALICE
ATLAS

R_{AA} and v_2 at RHIC vs. LHC

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

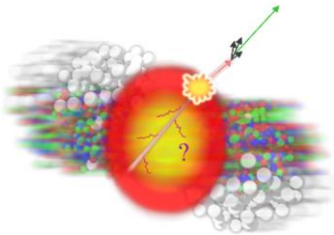


Extrapolation from RHIC to LHC energies leads to an overquenching of the R_{AA} at LHC energies

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

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)

⟹ Reasonable moderate reduction of the running coupling

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

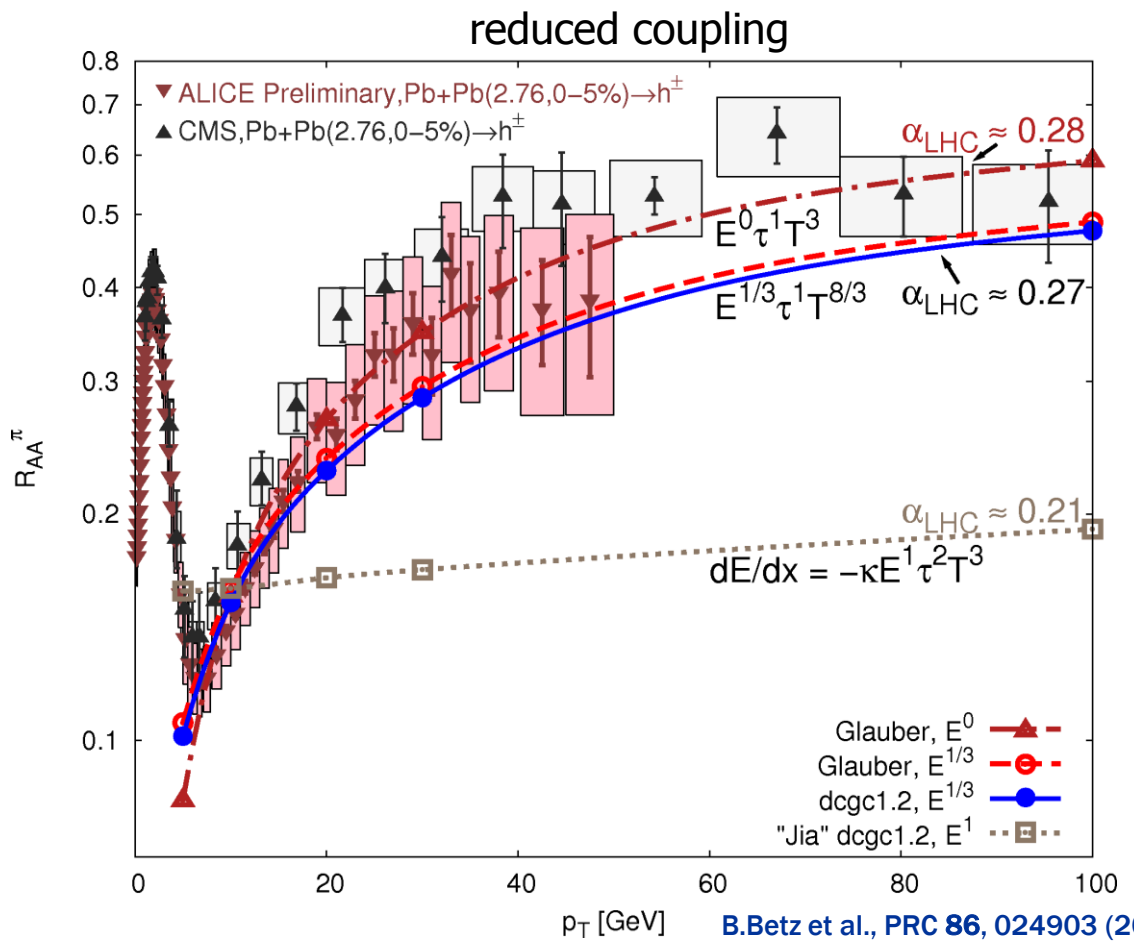
$$\lambda_{\rm LHC} = (\kappa_{\rm LHC}/\kappa_{\rm RHIC})^2\,\lambda_{\rm RHIC} \qquad \lambda_{\rm RHIC} \sim 20$$ (heavy quarks)

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

Non-conformal gravity dual generalizations are under construction (Mia, Ficnar, Noronha, ...)

$R_{AA}(p_T)$ at the LHC



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

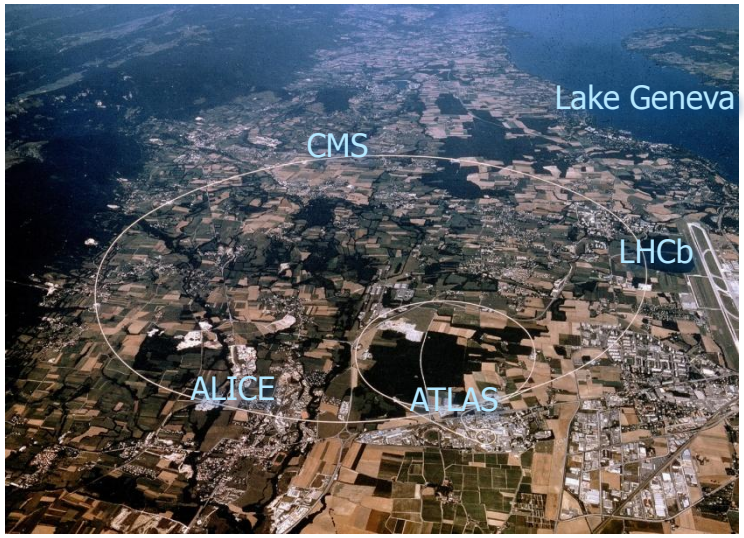
- ⇒ Linear p_T-dependent (a=1) model describes RHIC p_T<10 GeV data well but is falsified at LHC
- ⇒ Rapid rise of $R_{AA}(p_T)$ rules out any model with $dE/dx \sim E^{a>1/3}$

RHIC


RHIC
BOOSTER
LINAC
AGS
HTB
TANDEMS
HITL

vs.

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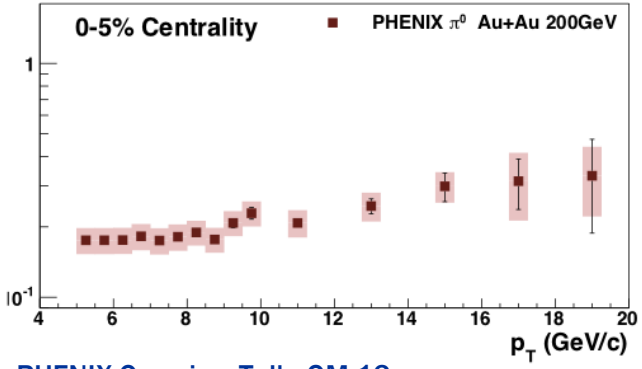
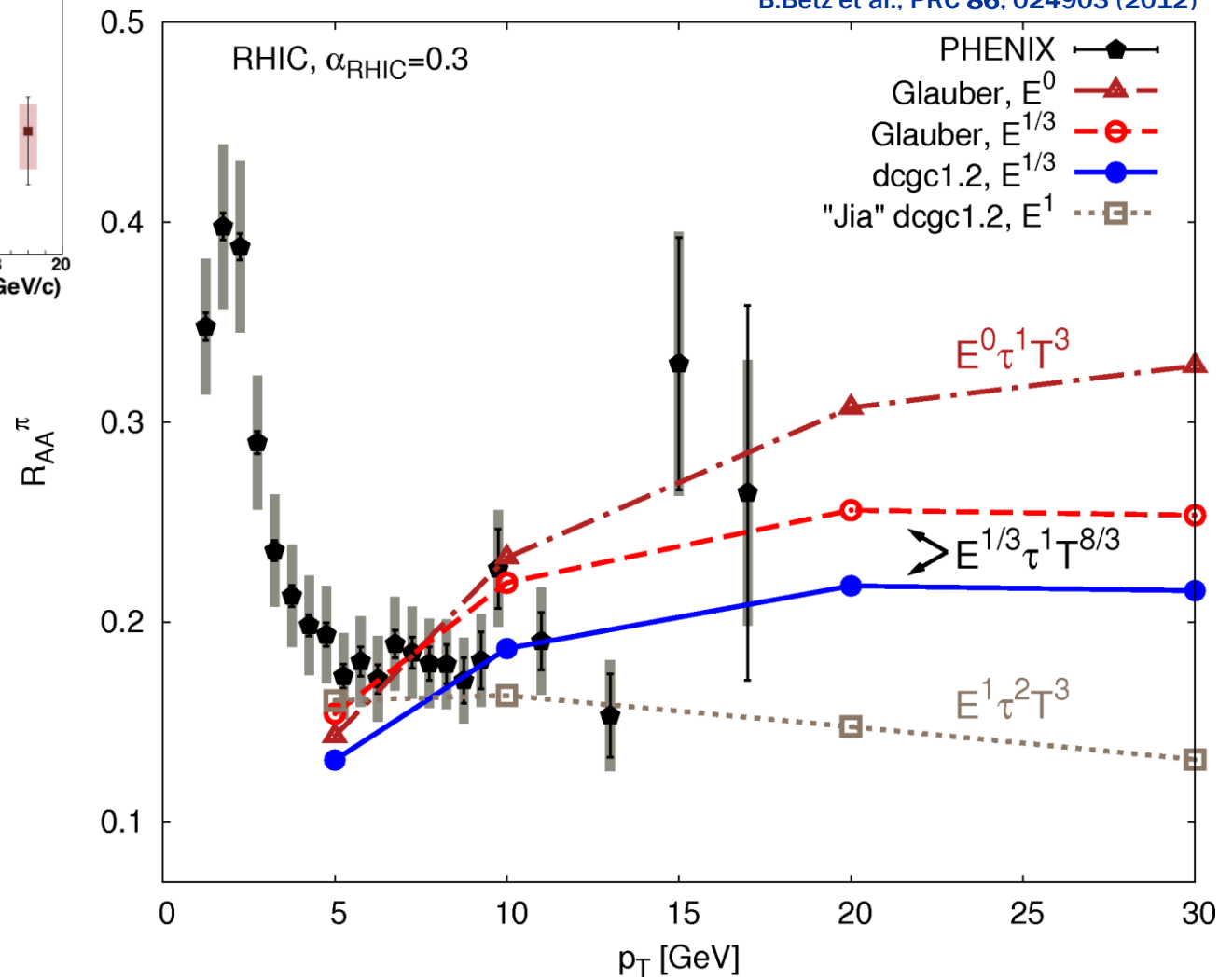
$R_{AA}(p_T)$ at RHIC



PHENIX Overview Talk, QM 12

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



- a= 0 and a=1/3 energy exponents are consistent with data within error bars

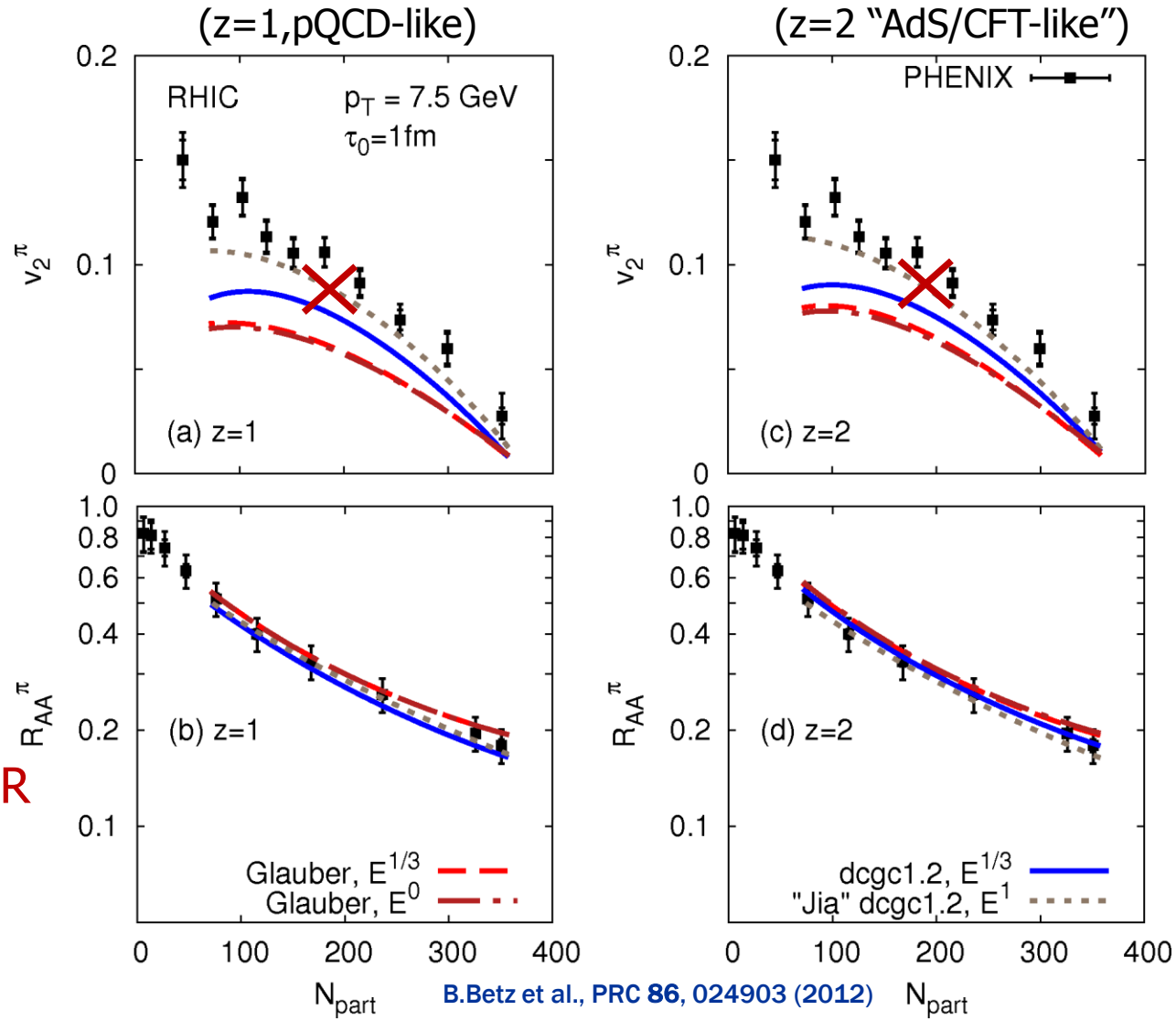
⇒ Higher statistics measurements at RHIC with $5 < p_T < 30$ GeV are needed

sPHENIX Upgrade Concept, arXiv:1207.6378

R_{AA} and v_2 at RHIC

- "Jia" dcgc1.2 model is excluded by the p_T-dependence of the R_{AA} at LHC
- a=0, 1/3 scenarios fail to describe the v_2(Centr.)

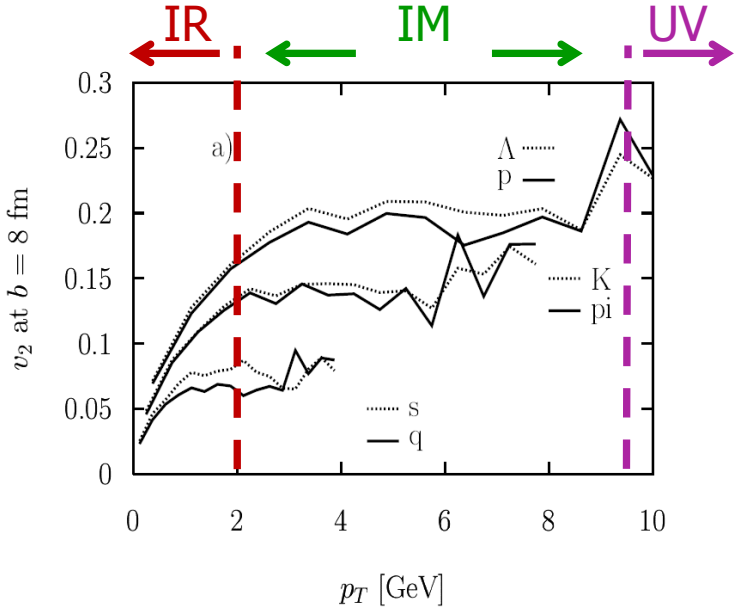
⇒ Disagreement with v_2 data at RHIC FOR THIS intermediate p_T-regime

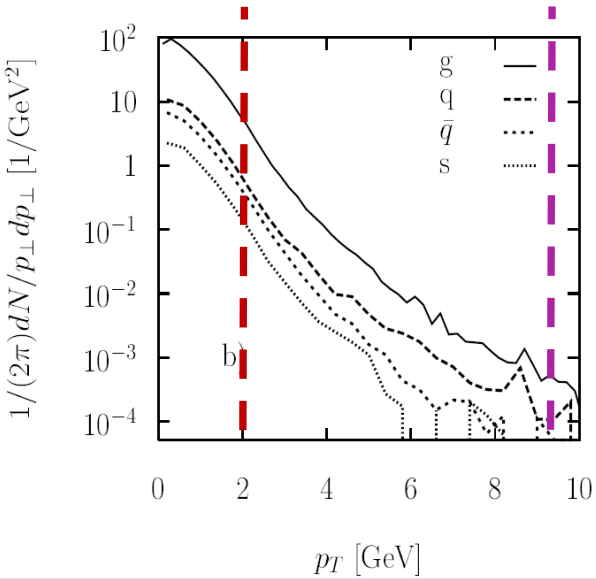


B.Betz et al., PRC **86**, 024903 (2012)

⇒ SMALL difference between path-length dependence z=1 and z=2

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





While hadronization via $1 parton \rightarrow 1\pi$ 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)

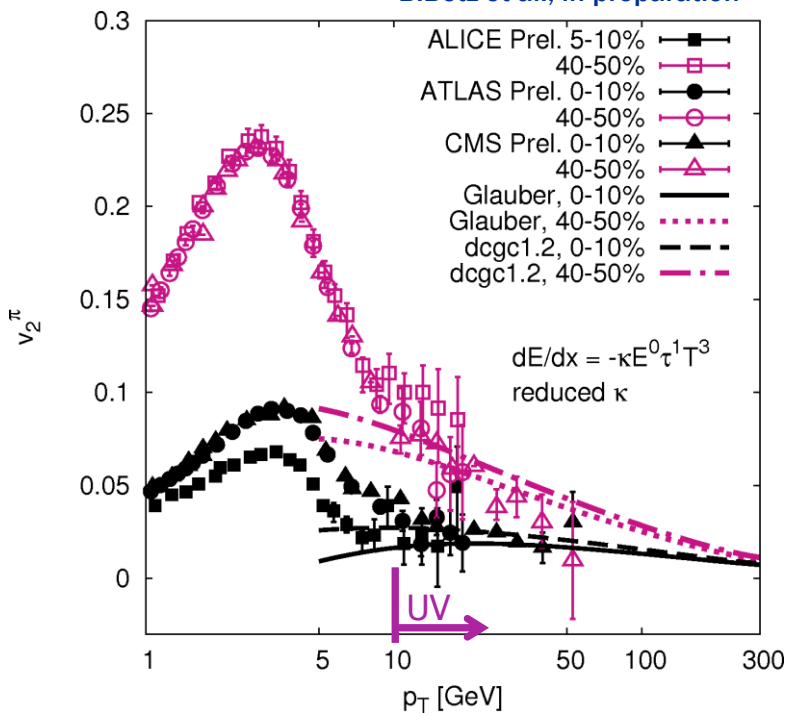
- ⇒ parts of the v_2(intermediate p_T) could originate from bulk tails

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

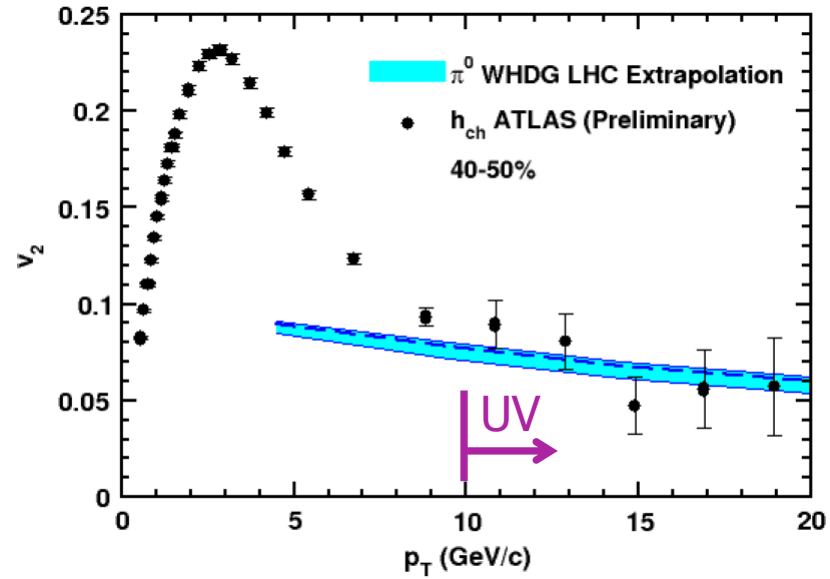
- ⇒ pure jet fragmentation and absorption models should NOT be expected to fully describe the intermediate p_T -range

$v_2(p_T$, Centrality) at LHC

B.Betz et al., in preparation



W. Horowitz et al., J. Phys. G **38**, 124064 (2011)

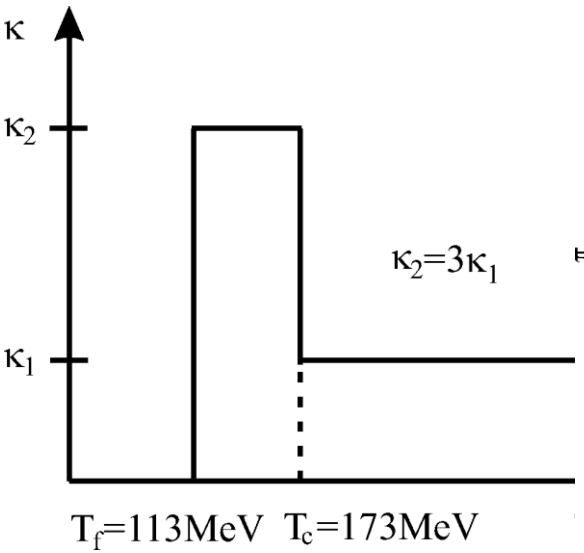


- Unlike the intermediate p_T, the deep ultraviolet p_T>10 GeV is much better explained by standard jet tomography at LHC
- For 1< p_T< 5 GeV, it is difficult to separate the jet contribution to v_2 from the high-p_T tails of the bulk QGP elliptic flow

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

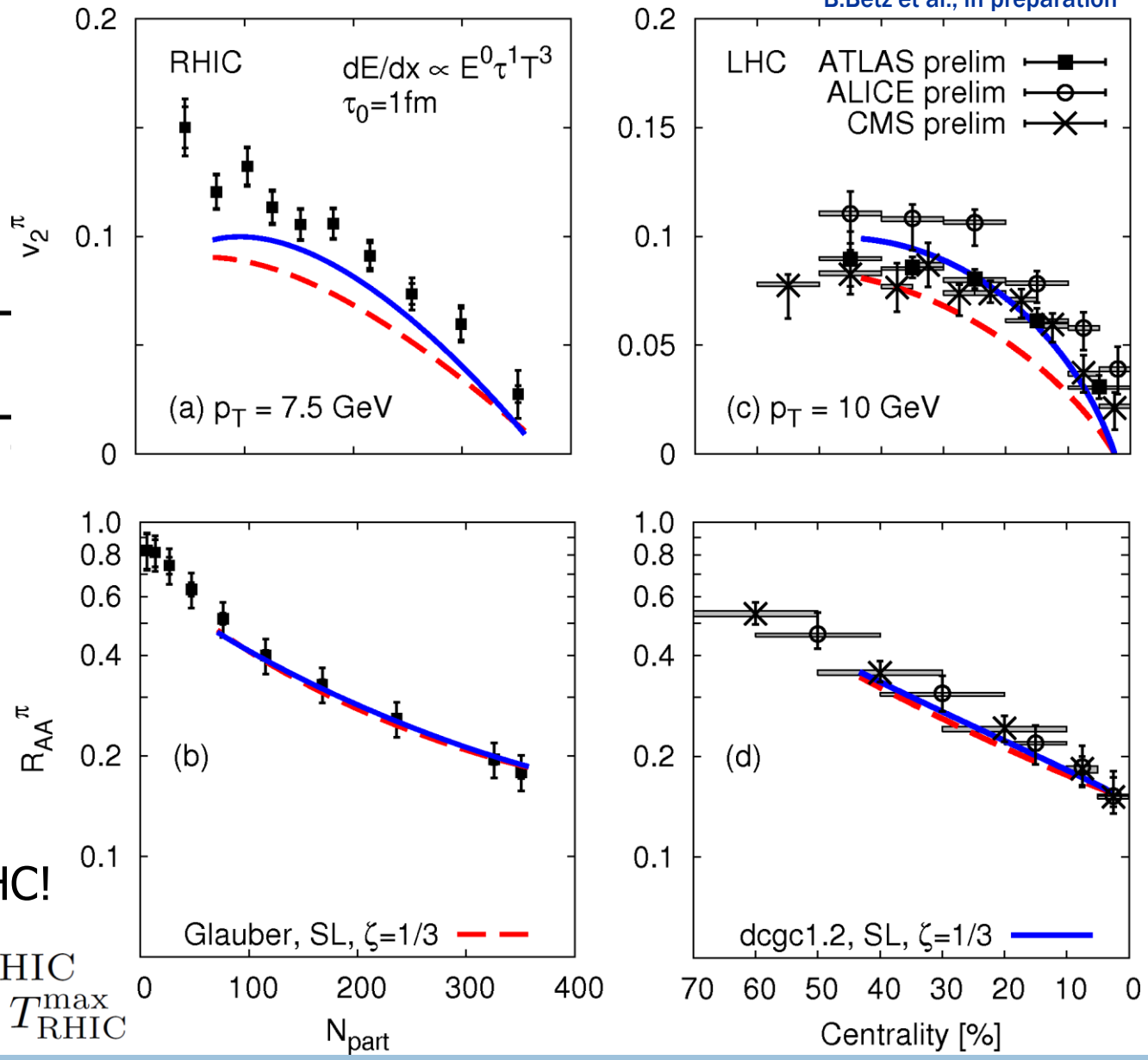
Fixed vs. Temperature-Dependent Coupling

Temperature-dependent Coupling



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

B.Betz et al., in preparation

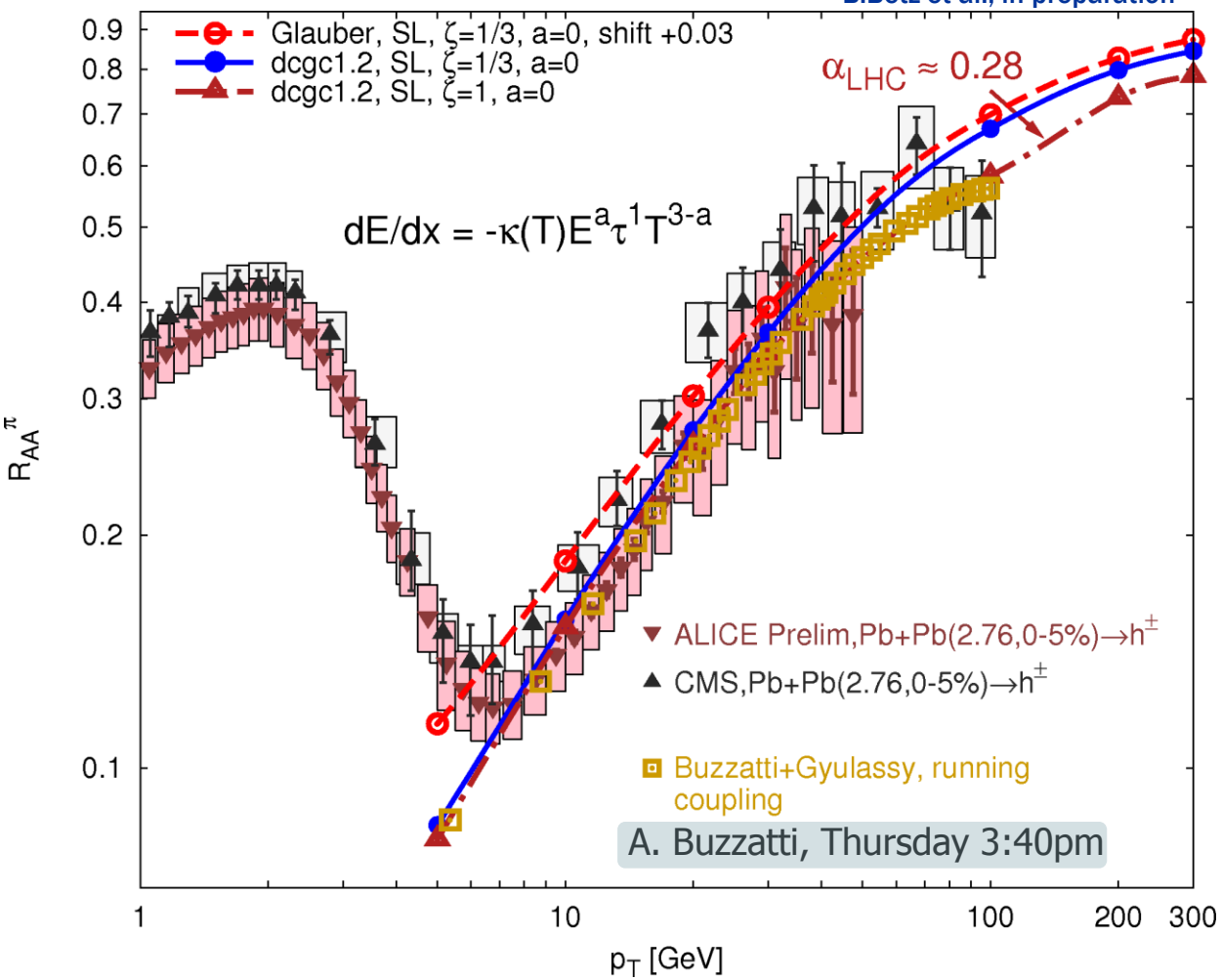


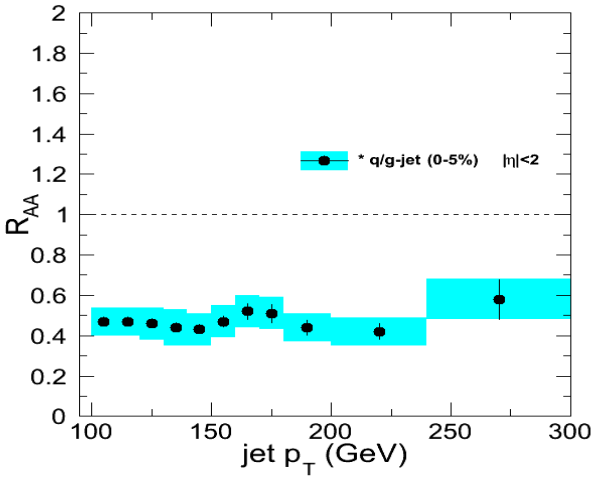
$$\zeta = \kappa_1 / \kappa_2$$

- ⇒ Assumes the same κ(T) at RHIC and LHC!
- ⇒ eff $\kappa_{\rm LHC} <$ eff $\kappa_{\rm RHIC}$ because $T^{\rm max}_{\rm LHC} \sim 1.3\, T^{\rm max}_{\rm RHIC}$

$R_{AA}(p_T)$ at LHC

B.Betz et al., in preparation



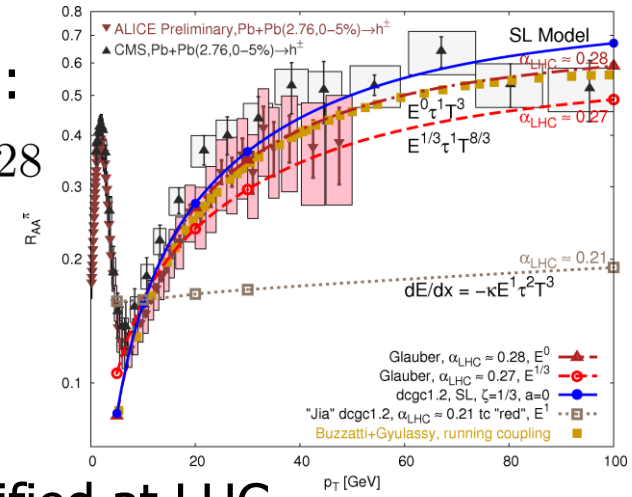


CMS Overview Talk, QM 12

- Temperature-dependent and reduced couplings lead to similar $R_{AA}(p_T)$
- Running coupling CUJET and SL a=0 ζ=1/3,1 all similar for p_T >10 GeV

Summary & Open Problems

- Puzzle of overquenching R_{AA} @LHC can be solved:
  - reduced jet-medium coupling at LHC, $\alpha \sim 0.27 - 0.28$
  - running coupling A. Buzzatti, Thursday 3:40pm
  - temperature-dependent jet-medium coupling
  - or a combination



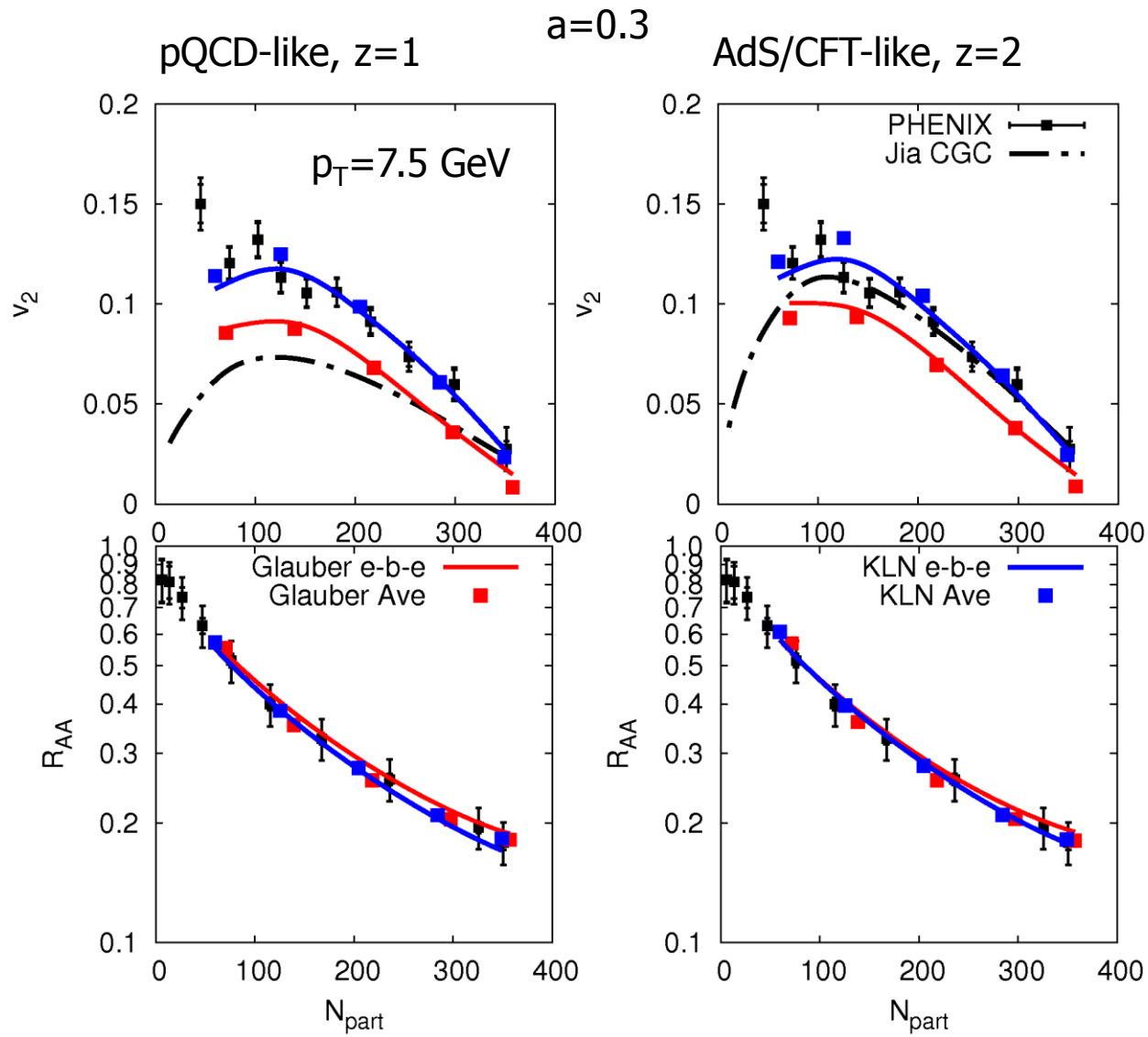
- $dE/dx \sim E^{a=1}$ best describing RHIC data but is falsified at LHC
- Rapid rise of $R_{AA}(p_T)$ rules out any model with $dE/dx \sim E^{a>1/3}$
- An energy loss with $dE/dx \sim E^{a=0}$ is slightly favoured over $dE/dx \sim E^{a=1/3}$
- Disentangling of initial conditions with high-p_T v_2 difficult once the coupling is fixed to a single R_{AA} reference point
- Unlike the intermediate p_T, the deep ultraviolet $v_2(p_T>10$ GeV) is much better explained by standard jet tomography at LHC

⟹ Cross checking RHIC vs. LHC at all combinations of available data is essential to test consistency of all models

Backup

R_{AA} and v_2 at RHIC

Similar results for event-by-event and averaged scenarios



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

Initial time

We set τ_0 = 1fm

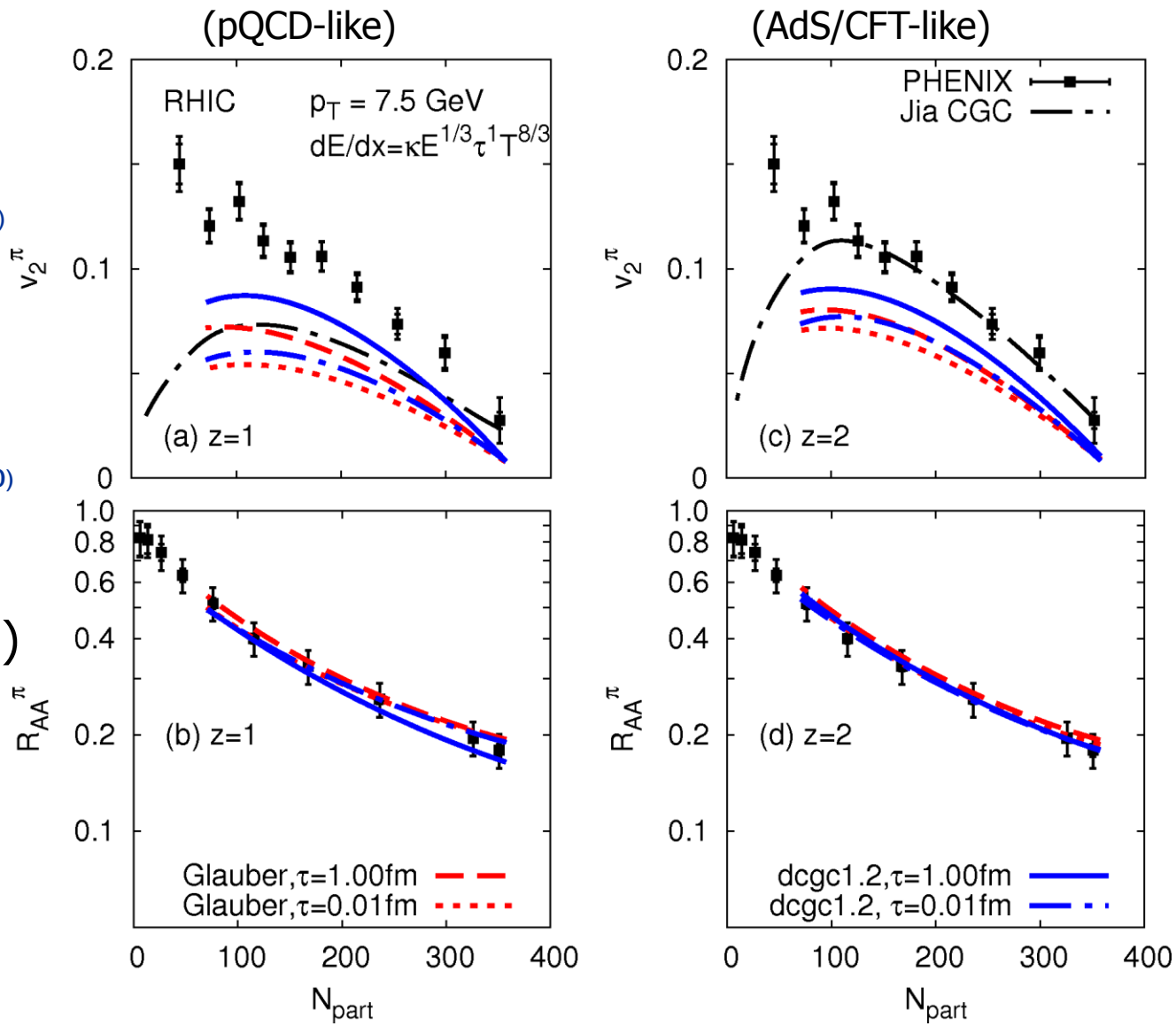
H. Song et al., PRL **106**, 192391 (2011)

Jia's model has

τ_0 = 0fm

A. Adare et al., PRL **105**, 142301 (2010)

⇒ A smaller τ_0 reduces the v_2(Centr.) and increases the difference between the pQCD and AdS/CFT results



Initial time

τ_0 = 1fm ⟶ Assumption: NO energy loss within 1fm

- pQCD does not give excuse for this ansatz, τ_0 = 0fm most natural assumption

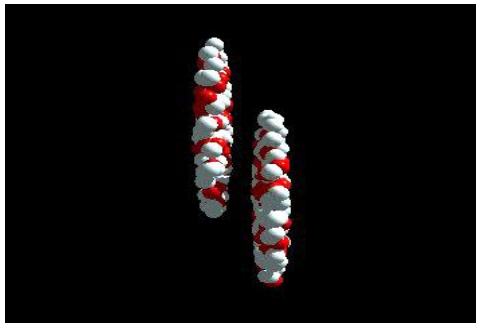
Adare et al, Phys. Rev. Lett. **105**, 142301 (2010)

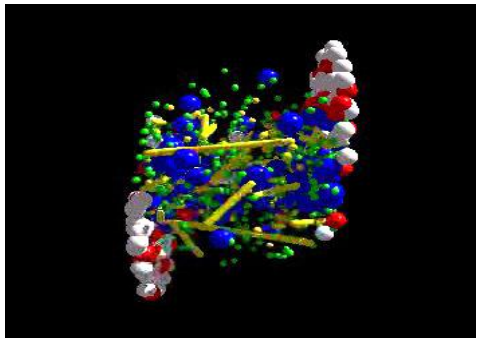
- describes formation time of hydrodynamics
  → no pressure at early times, everything is free flow

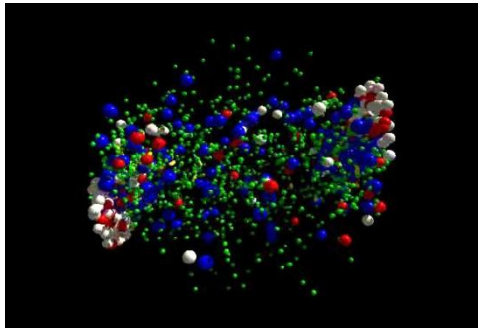
τ_0 = 1fm ⟶ essentially equivalent to AdS/CFT energy loss suppression of early times

⇒ v_2(high- p_T) not sensitive to long distance dE/dx ~ l^1 vs. dE/dx ~ l^2, but to short distance properties < 1fm!

⇒ We cannot access the center of the collision!



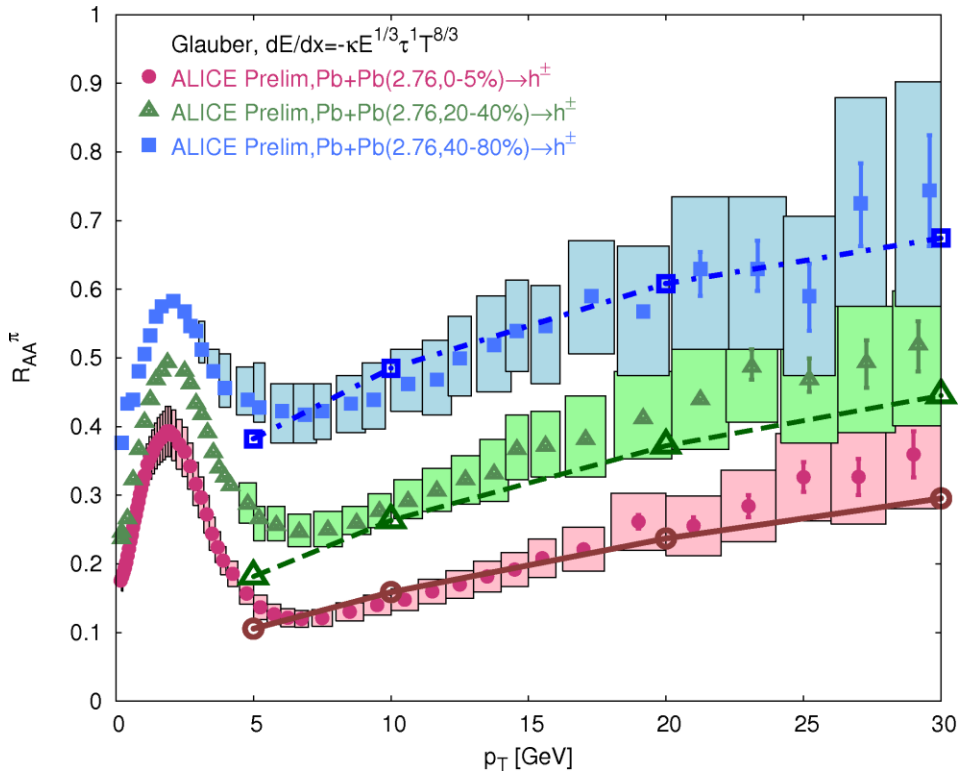


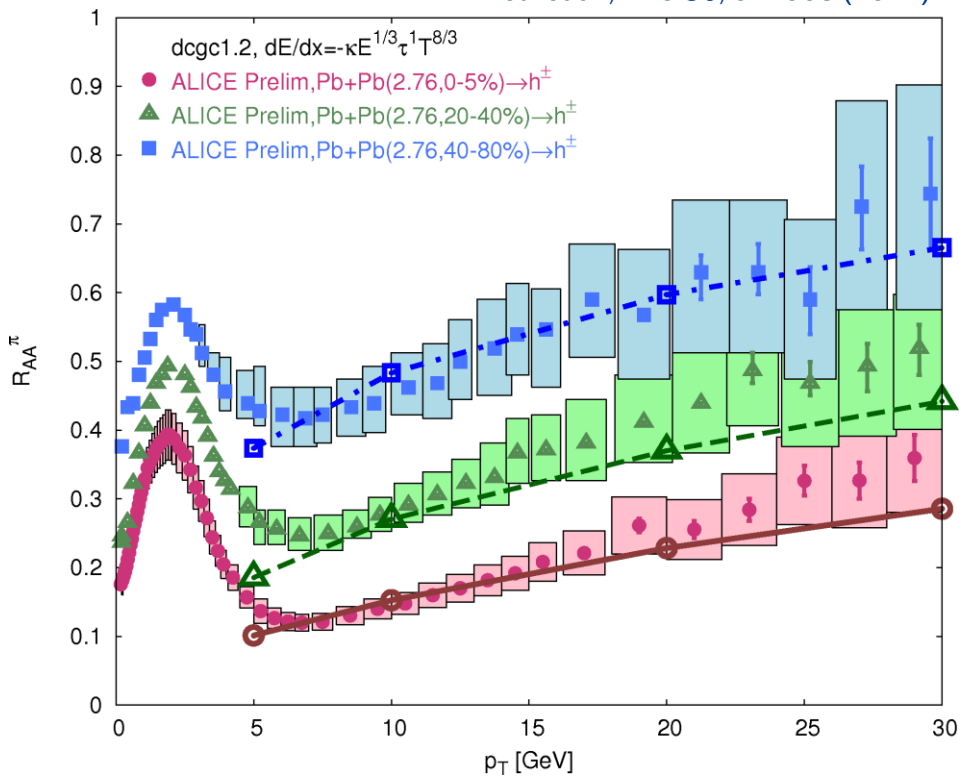


UrQMD Simulartion, H. Weber

$R_{AA}(p_T$, Centrality) at LHC

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





Remarkably insensitive to the initial conditions

⇒ It's NOT sufficient to just study ONE variable!

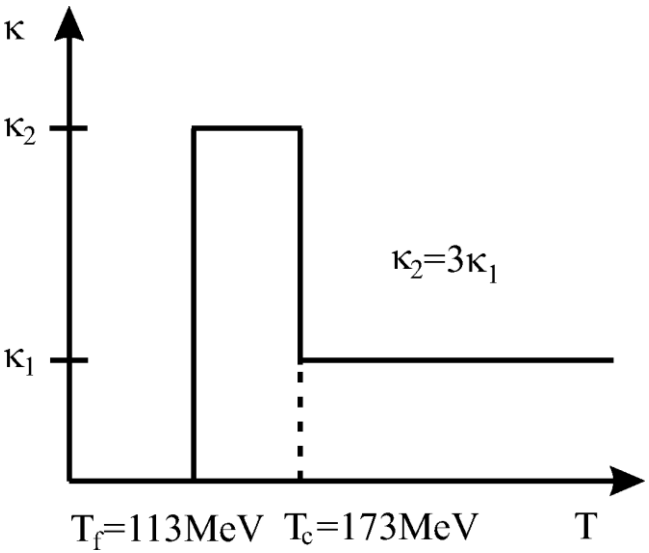
Reduced Jet-Medium Coupling

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

Effective Coupling κ assuming $\tau_0 = 1.0$ fm/c					
$\sqrt{s}$	Glauber a=1/3 z=1	dcgc1.2 a=1/3 z=1	Glauber a=1/3 z=2	Glauber a=0 z=1	"Jia" a=1 z=2
0.20	0.93	1.09	0.55	3.30	0.057
2.76	0.66	0.66	0.33	2.72	0.017
LHC/RHIC	0.71	0.61	0.60	0.82	0.33

Effective Coupling κ assuming $\tau_0 = 0.01$ fm/c			
$\sqrt{s}$	Glauber z=1	dcgc1.2 z=1	Glauber z=2
0.20	0.60	0.58	0.44
2.76	0.45	0.43	0.26
LHC/RHIC	0.75	0.74	0.59

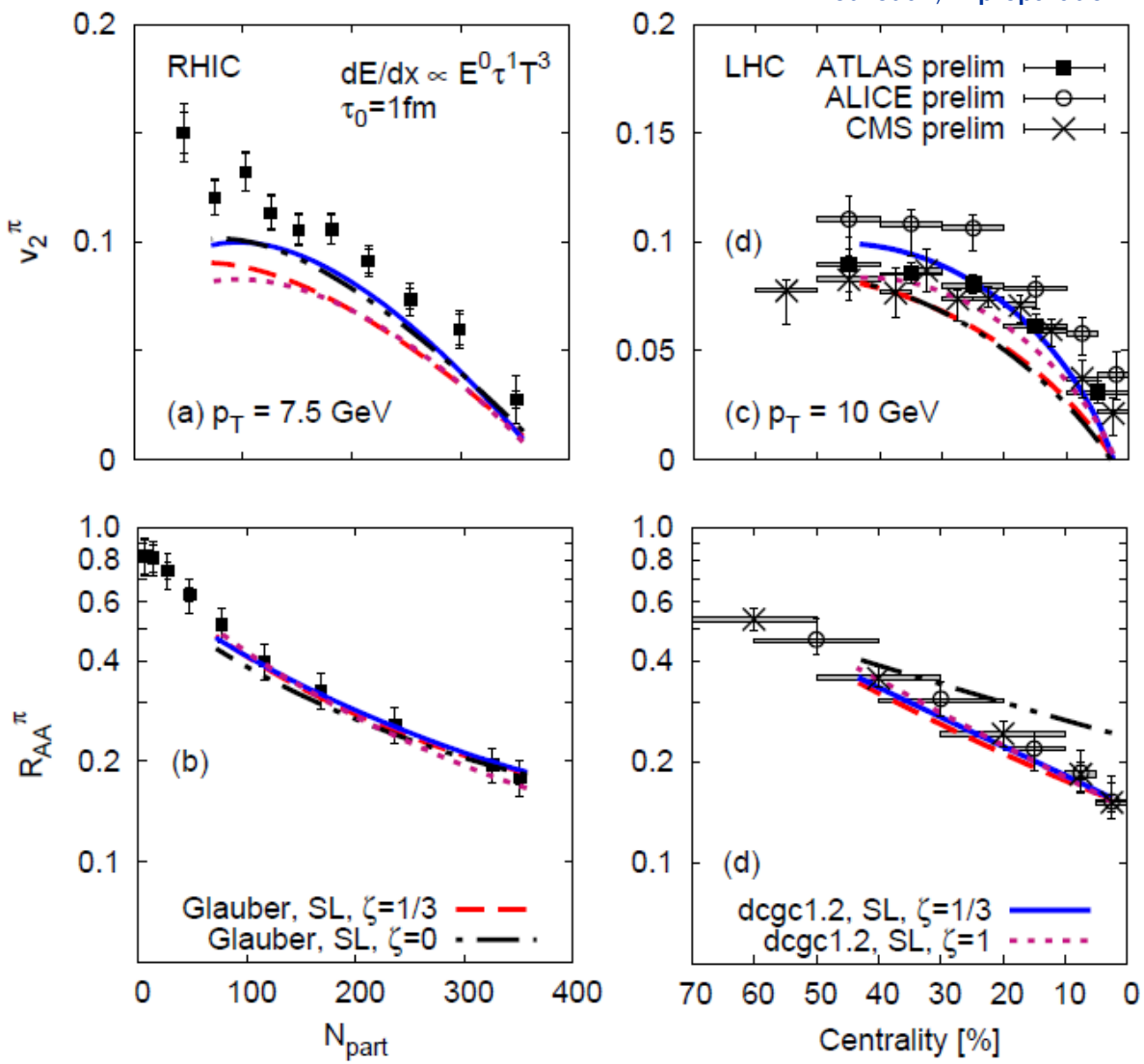
Temperature-dependent Coupling



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

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

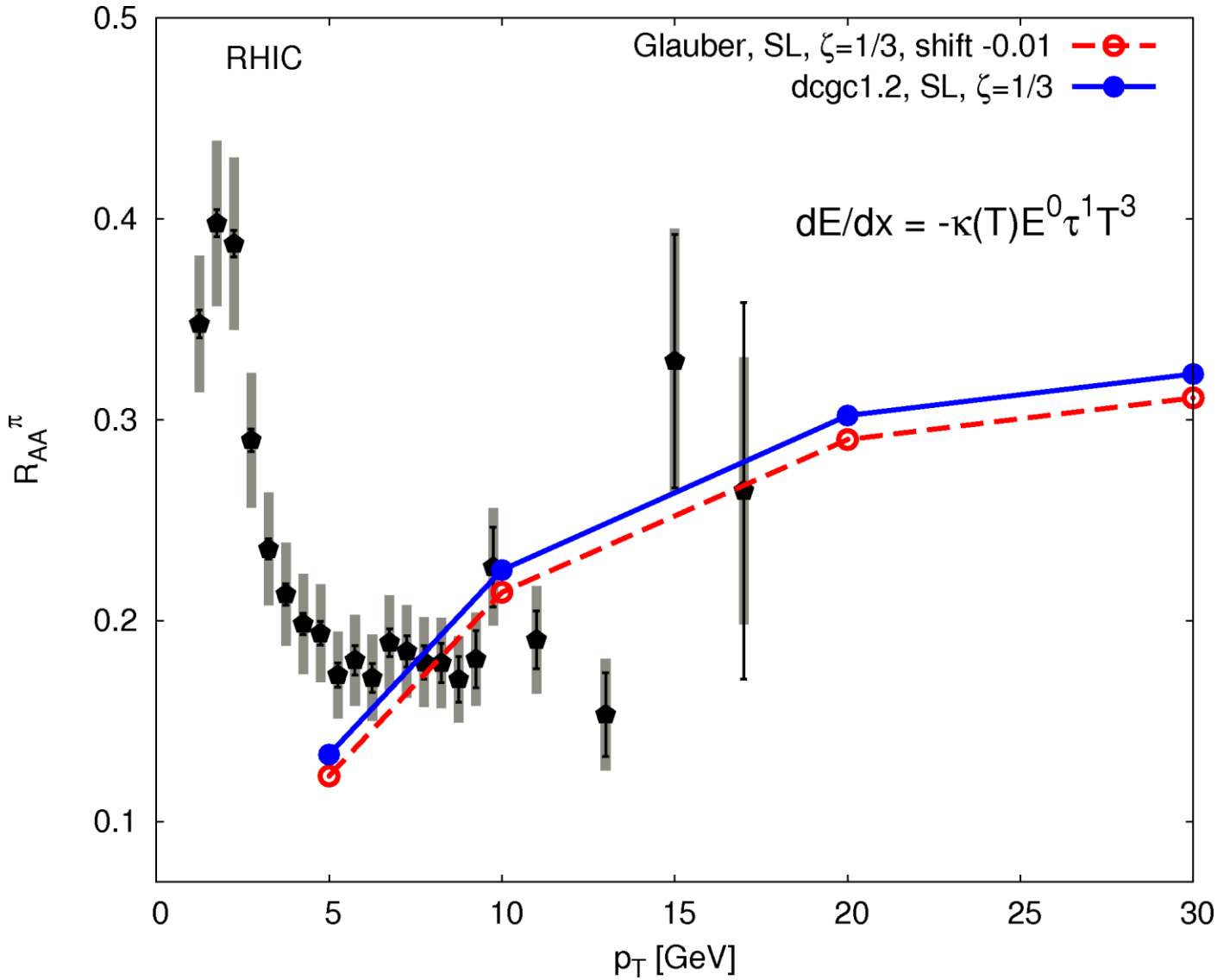
B.Betz et al., in preparation



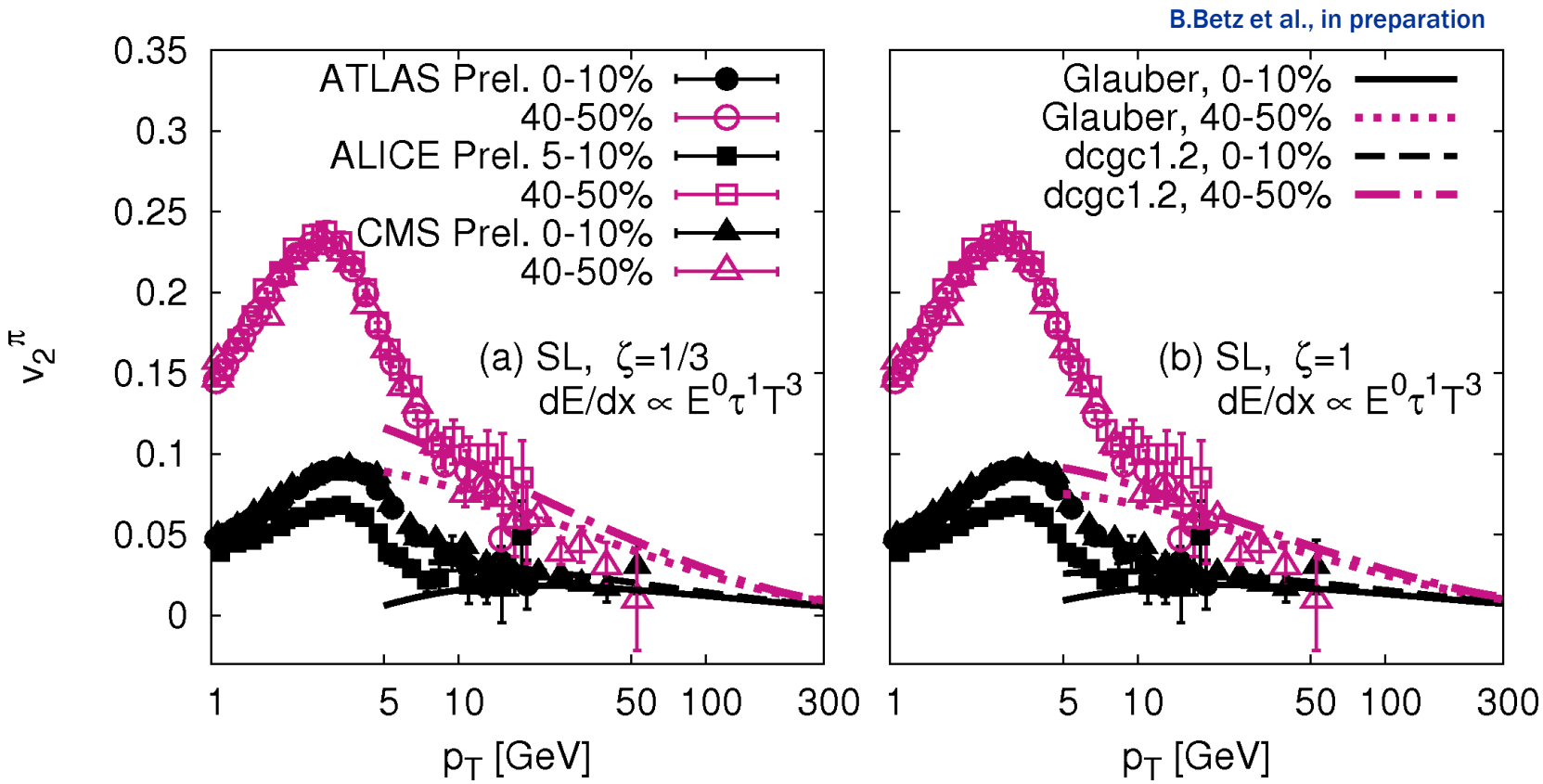
$R_{AA}(p_T)$ at RHIC, LS model

B.Betz et al., in preparation

ζ=1/3 scenario consistent with RHIC data on $R_{AA}(p_T)$



$v_2(p_T$, Centrality) at LHC, LS model



Small difference between ζ=1/3 and ζ=1

Effective Coupling in the LS Model

Effective Coupling κ assuming $\tau_0 = 1.0$ fm/c				
$\zeta = \kappa_1/\kappa_2$	in. cond.	$\sqrt{s}$	κ_1	κ_2
1/3	Glauber	RHIC&LHC	1.82	5.47
1/3	dcgc1.2	RHIC&LHC	1.75	5.45
0	Glauber	RHIC&LHC	0.0	7.65
1	dcgc1.2	RHIC	3.80	$\kappa_2 = \kappa_1$
1	dcgc1.2	LHC (red.)	2.66	$\kappa_2 = \kappa_1$

B.Betz et al., in preparation

The "Geometric Optics" Limit

For the generic energy-loss model

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

the initial parton momentum depends on the final parton momentum

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

For a=1, this leads to a pure exponential dependence of the initial parton momentum

$$P_0(P_f) = P_f\ e^{\chi_{z,c}}$$

with the jet-energy independent effective opacity

$$\chi_{z,c}(\phi) = \kappa C_2 \int_{\tau_0}^{\tau_f} d\tau \tau^z T^c(\tau, \phi)$$

This corresponds to a generalized "geometric optics" limit.

Falling String Scenario

A. Ficnar, arXiv: 1201.1780

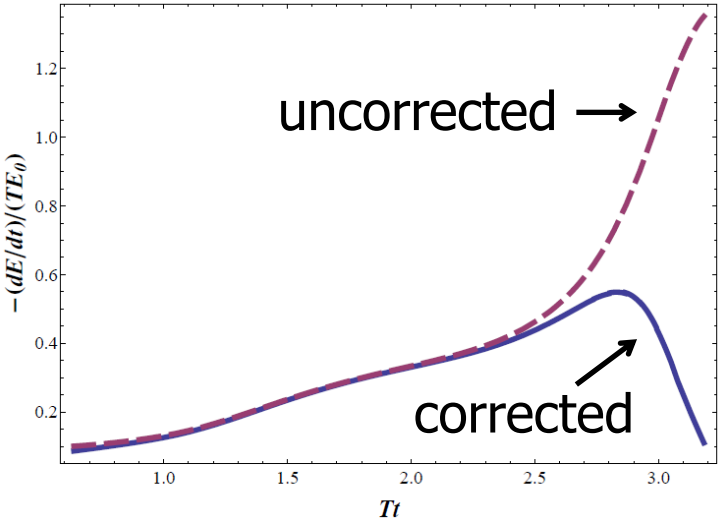


FIG. 1. Comparison of the (normalized) instantaneous energy loss as a function of time with and without the correction in (4.8). The dashed red curve shows the (uncorrected) dp_0/dt in the radial $\sigma = r$ parametrization, while the solid blue curve is the actual energy loss $d\tilde{p}_0/dt$, as given by (4.8). The energy loss was evaluated at points at a fixed spatial distance from the string endpoint, chosen in such a way that the correction in (4.8) appears clearly. The normalization constant E_0 is the energy of half of the string and $T = 1/(\pi r_h)$ is the temperature. The numerical parameters used are $r_h = 1$, $A = 50$ and $r_c = 0.1$.

The reason is the following. If, from the solid blue curve in Figure 1, we can roughly conclude that the energy loss is linear in time, $dE/dt \sim t^1$, and we know that $(\Delta x)_{max} \sim E^{1/3}$, it can be shown that this is actually the typical qualitative behavior of energy loss of light quarks in pQCD in the strong LPM regime [18]. This suggests a tempting idea that the phenomenon of light quark jet quenching may have a roughly universal qualitative character, regardless of whether we are dealing with a strongly or a weakly coupled medium.

Furthermore, a known generic feature of pQCD energy loss in the strong LPM regime is the rise of R_{AA} at high transverse momenta p_T, a qualitative behavior exhibited by the LHC data for light quarks [18]. And if we can roughly conclude that here we have the same qualitative behavior of energy loss as in pQCD, there is hope that an R_{AA} computed from a falling string energy loss would yield the same characteristic rise at high p_T. However, if there was a pronounced late-time Bragg peak in the energy loss (the dashed red curve in Figure 1), then the energy loss would scale more like $dE/dt \sim t^2$ and would not yield the same behavior as in pQCD, and therefore might not result in an R_{AA} rising at high p_T [18].