QUARK MATTER ANNECY 2011

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Higher Harmonic Jet Tomography as a Probe of Fluctuating Initial Condition Geometries in A+A

Barbara Betz

Miklos Gyulassy and Giorgio Torrieri

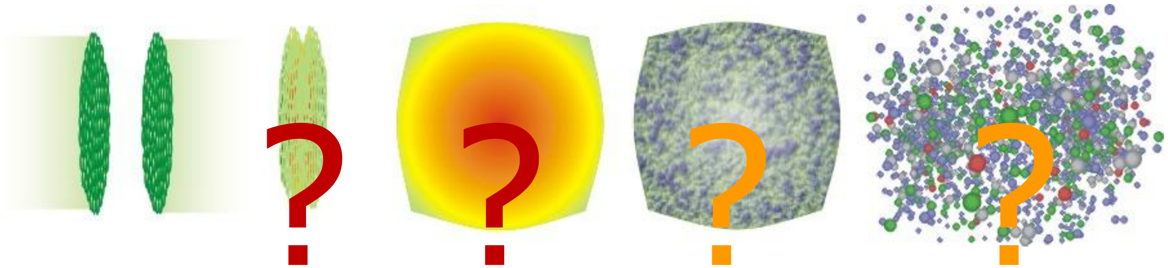
arXiv:1102.5416 [nucl-th]

Unterstützt von / Supported by

Alexander von Humboldt Stiftung/Foundation

JET Collaboration

Motivation



S. Bass, Talk Quark Matter 2001

→ Two basic questions:

- Is the medium weakly-coupled (pQCD) or strongly-coupled (AdS/CFT)?
- What are the initial conditions (Glauber or CGC)?

→ Two observables characterizing the medium:

- jet quenching: signal for creation of opaque matter (QGP)

  defined via: $R_{\mathrm{AA}}(p_{\mathrm{T}}) = \dfrac{1/\sigma_{\mathrm{A+A}}\, d\sigma^{\mathrm{A+A}}/dp_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle/\sigma_{\mathrm{p+p}}\, d\sigma^{p+p}/dp_{\mathrm{T}}}$

- elliptic flow: signal for creation of a (nearly) perfect fluid

  defined via: $\dfrac{dN}{d\phi} = \dfrac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi)\right]$

The Connection

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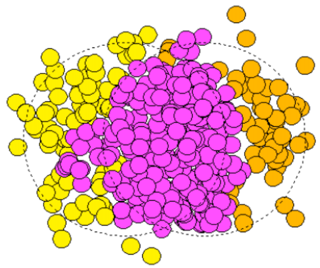
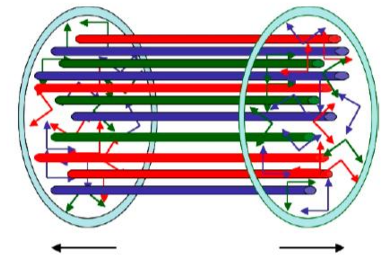
- Glauber Model and CGC differ by:
  - initial temperature gradients
  - initial high-p_T parton distribution
  - distance travelled by each parton

  leading to a different opacity estimate



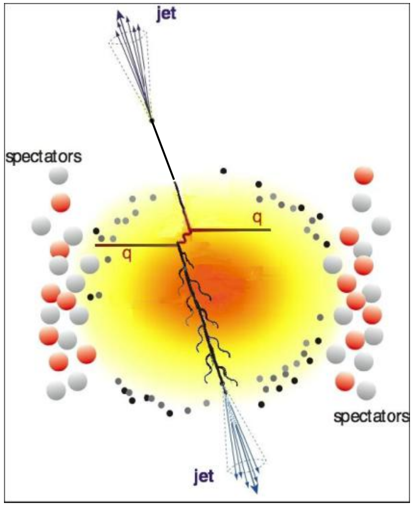


- Elliptic flow is sensitive to the path length dependence of energy loss, scaling as $dE/dx \sim l^z$:

  z=1 : pQCD
  M. Gyulassy et. al., PRL **85** (2000), 5535

  z=2 : AdS/CFT (on-shell partons)

  z>2 : AdS/CFT (off-shell partons)
  S. Gubser et. al., JHEP **0810** (2008), 052;
  P. Chesler et.al., PRD **79** (2009) 125015



Energy-Loss Mechanisms

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- First investigation of $R_{AA}(N_{part})$ and $v_2(N_{part})$ for $p_T > 5$ GeV hadrons is based on

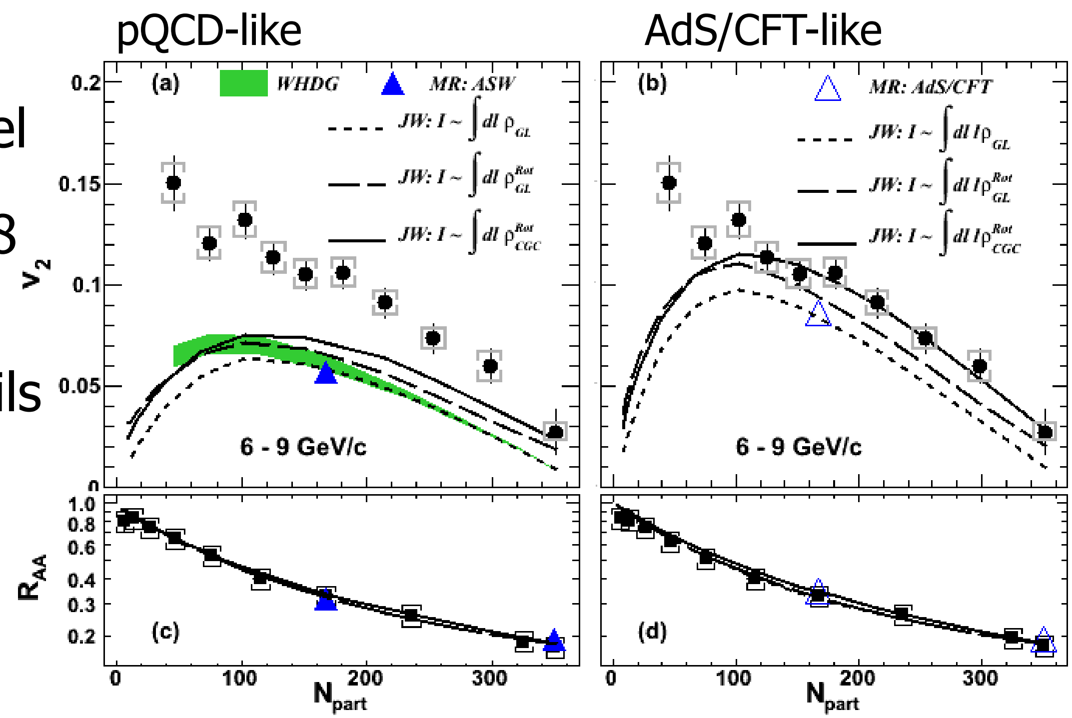
J. Jia et. al., PRC **82** (2010), 024902

$$R_{AA}(N_{part}) = \langle e^{-\kappa I_m} \rangle \qquad I_m = \int_0^\infty dl\, l^{m-1} \rho(\vec{r} + l\hat{v}), m = 1, 2, ...$$

$$v_2 = \langle e^{-\kappa I} \cos 2\,(\phi - \Psi_{\rm part}) \rangle$$

→ simple jet absorption model

- Once $R_{AA}(N_{part}=350) \sim 0.18$ for 0-5% π^0 data
  - pQCD-like energy loss fails to reproduce $v_2(N_{part})$
  - AdS/CFT-like energy loss describes data for CGC initial conditions



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

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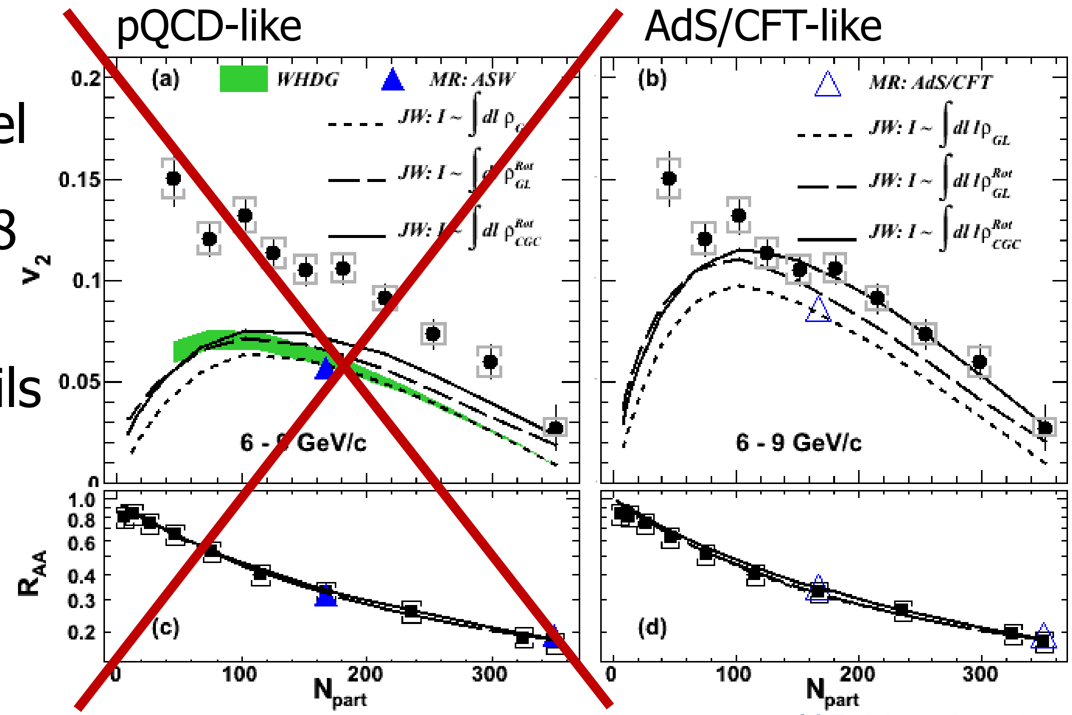

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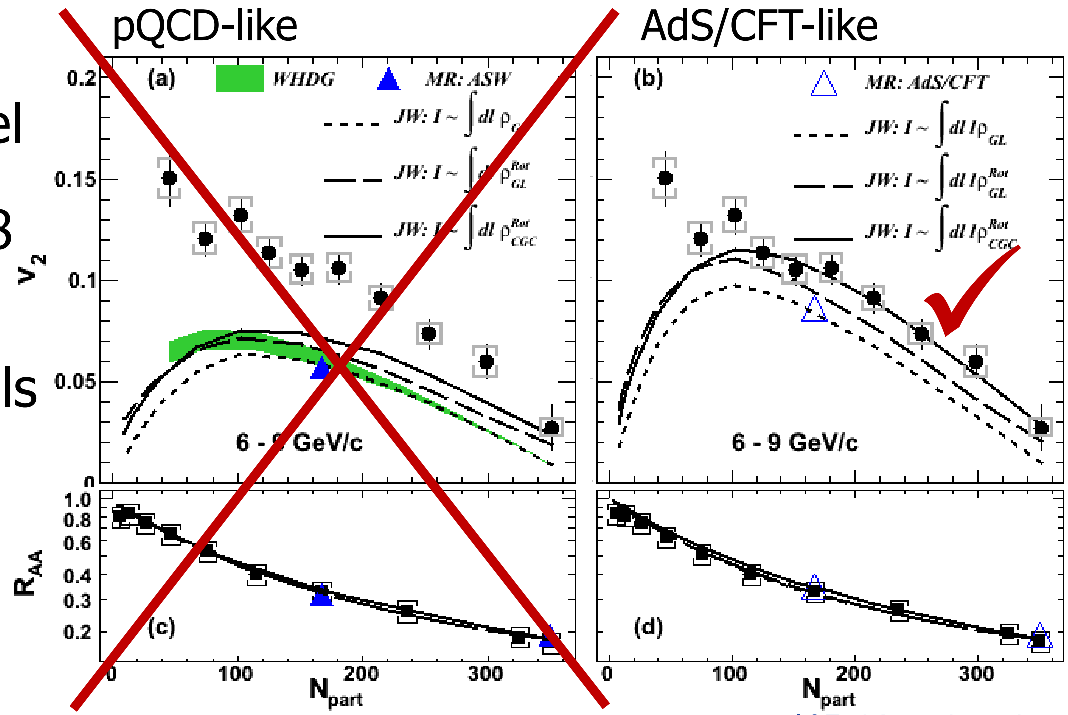

A. Adare et al, Phys. Rev. Lett. **105**, 142301 (2010)

Generic Energy Loss Model

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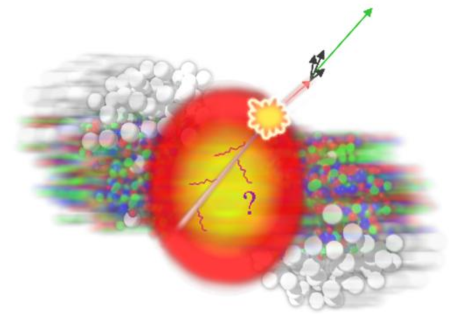
Choosing an ansatz for the energy loss

$$\frac{dE}{dx}(\vec{x}_0, \phi, \tau) \; = \; -\kappa P^a \tau^z T^{z-a+2}[\vec{x}_0 + \hat{n}(\phi)\tau, \tau]$$



P: momentum of the jet(s)

a,z: parameters controlling the jet-energy and path-length dependence

κ: being fixed thus that $R_{AA}(N_{part}=350) \sim 0.18$ for most central data

and considering Bjorken expansion via

$$T(\vec{x}, \tau) = T_0(\vec{x}) \left(\frac{\tau_0}{\tau}\right)^{1/3}$$

τ_0 = 1fm, one can determine the $R_{AA}(N_{part})$ & $v_n(N_{part})$

Glauber: B.Betz et.al., arXiv:1102.5416 [nucl-th]
CGC/KLN: H. Drescher et. al., PRC **76** (2007) 024905

R_{AA} and v_2

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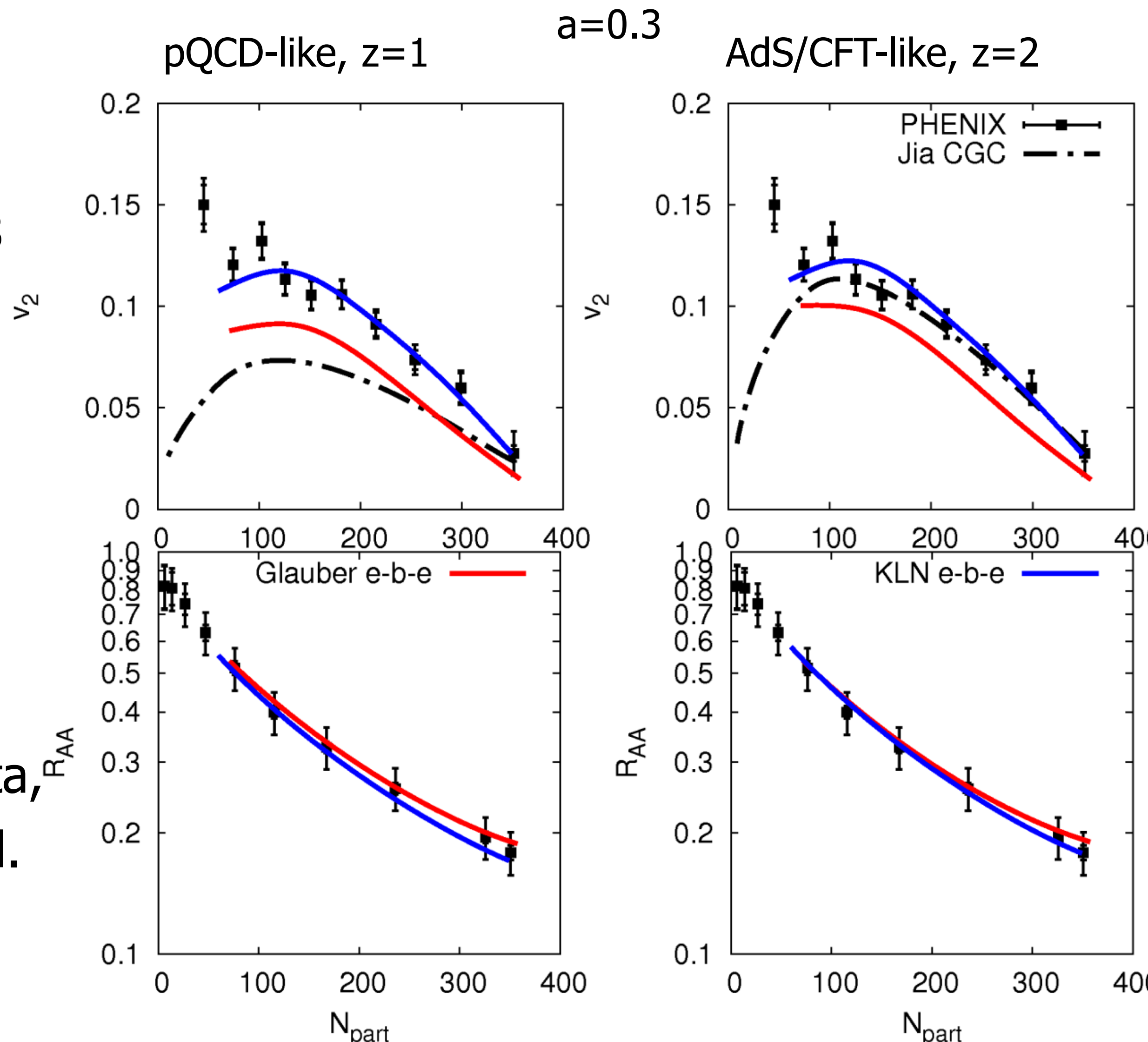
→ Having fixed κ for
$R_{AA}(N_{part}=350) \sim 0.18$
$R_{AA}(N_{part})$ can be reproduced

→ z=1: CGC in. cond. close to data
z=2: CGC in. cond. still describe data, Glauber in. cond. getting closer



⇒ NO striking big difference between pQCD and AdS/CFT

B.Betz et.al., arXiv:1102.5416 [nucl-th]

R_{AA} and v_2

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- → Having fixed κ for $R_{AA}(N_{part}=350) \sim 0.18$ $R_{AA}(N_{part})$ can be reproduced

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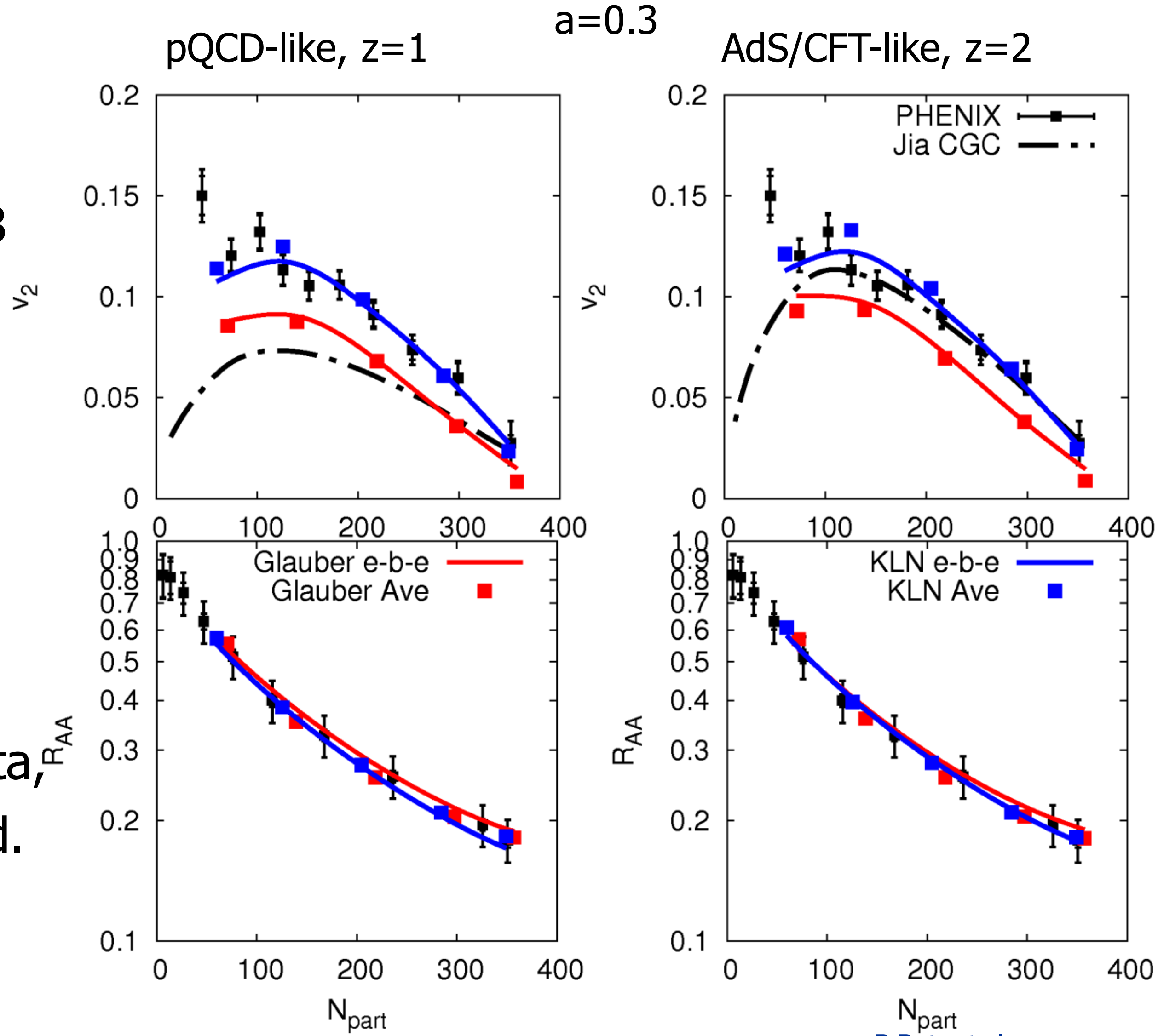

⇒ Similar results for event-by-event and averaged scenarios!

B.Betz et.al., arXiv:1102.5416 [nucl-th]

Differences

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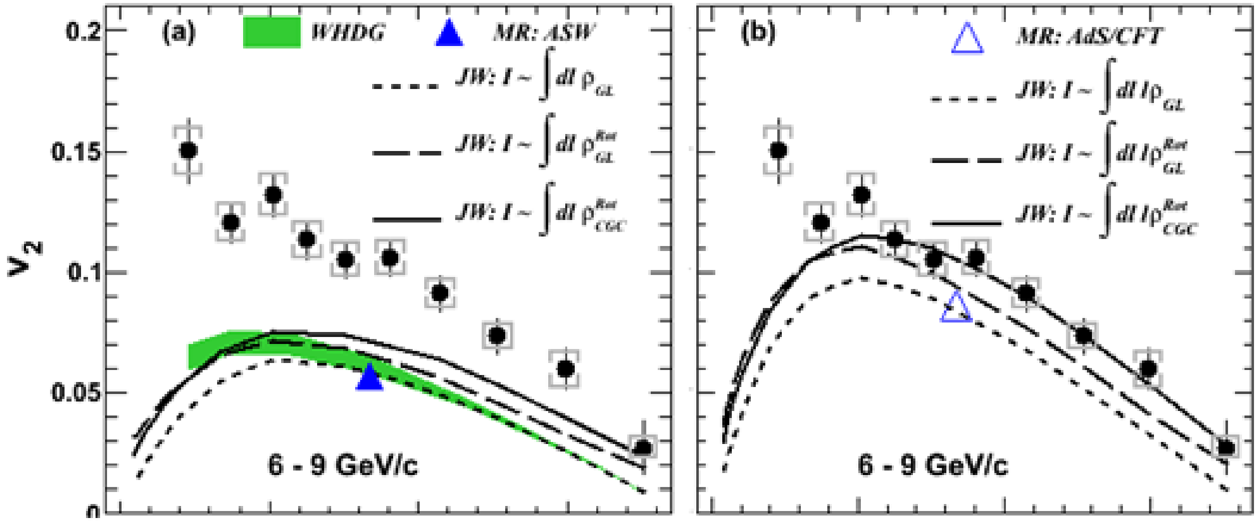
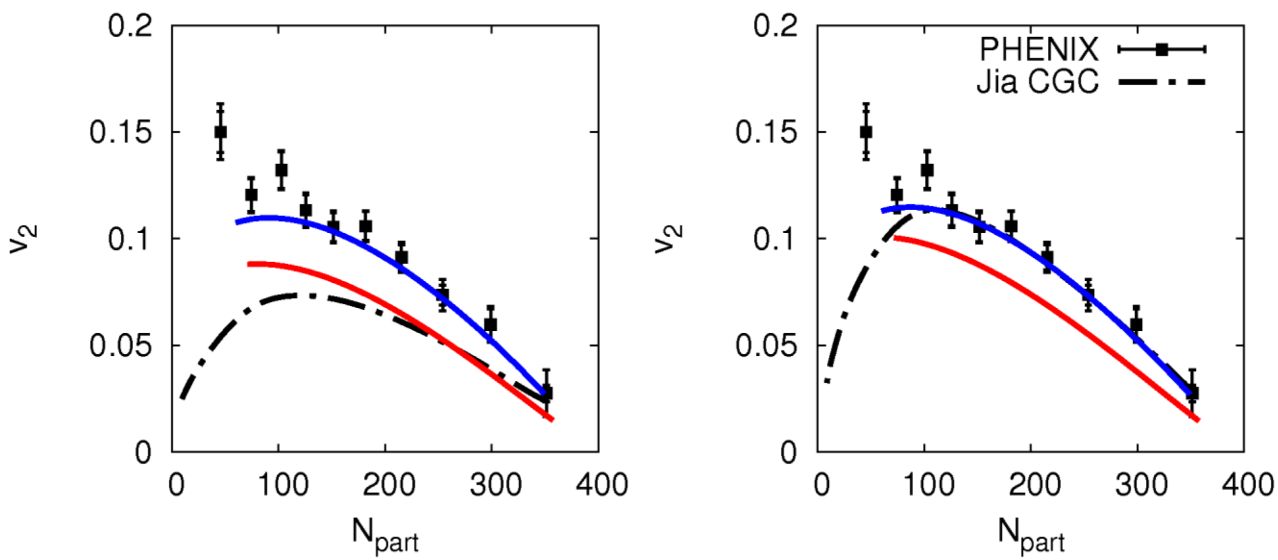
pQCD-like

AdS/CFT-like

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



B.Betz et.al., arXiv:1102.5416 [nucl-th]



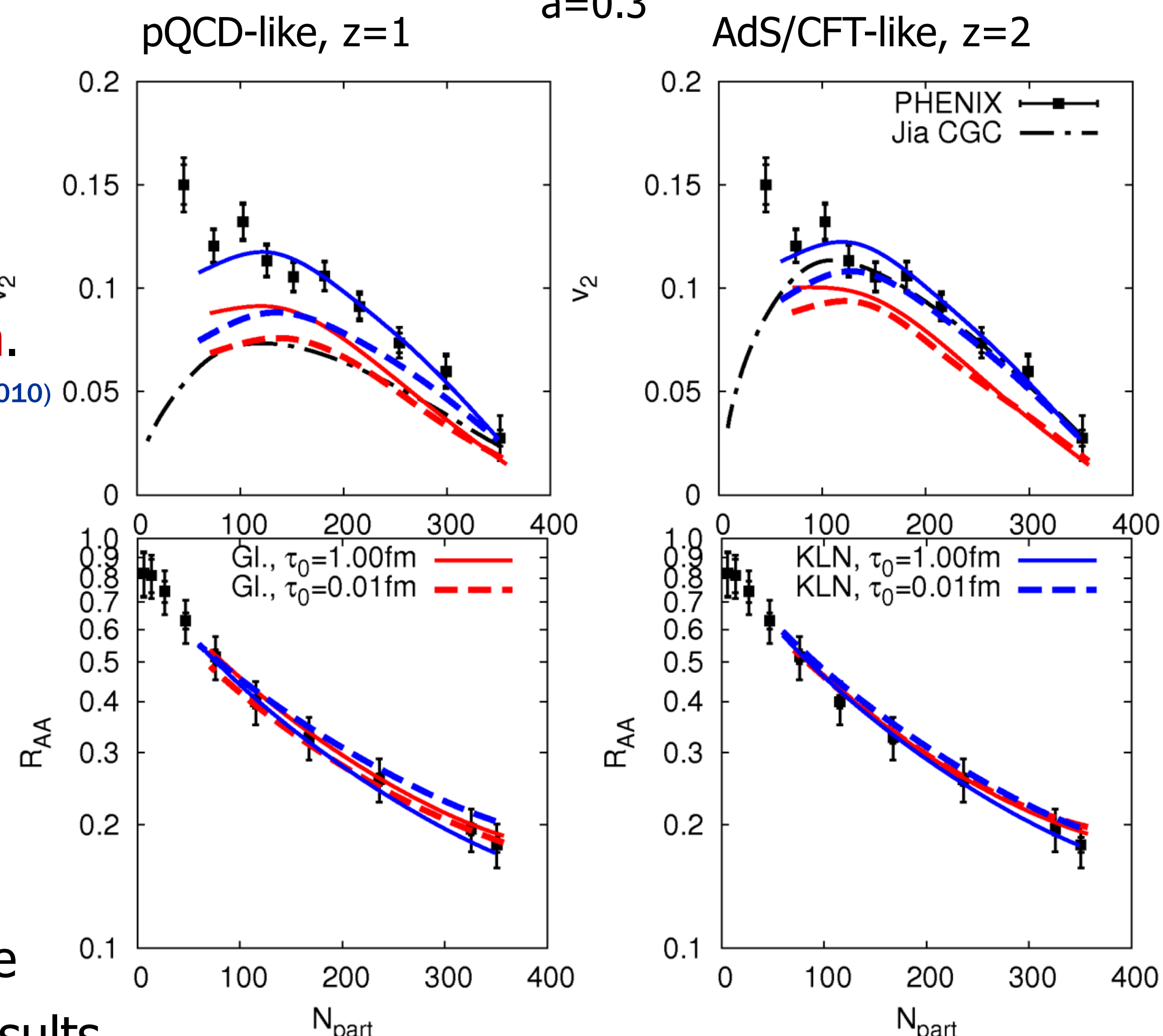
Initial time

- We chose τ_0 = 1fm.
  H. Song et.al., arXiv:1011.2783[nucl-th]

- Jia's model has τ_0 = 0fm.
  A. Adare et al, Phys. Rev. Lett. **105**, 142301 (2010)

⟹ A smaller τ_0 reduces the $v_2(N_{part})$ for both pQCD-like and AdS/CFT-like energy loss and increases the difference between the pQCD and AdS/CFT results

a=0.3



B.Betz et.al., in preparation

The role of τ_0

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τ_0 = 1fm $\longrightarrow$ 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)

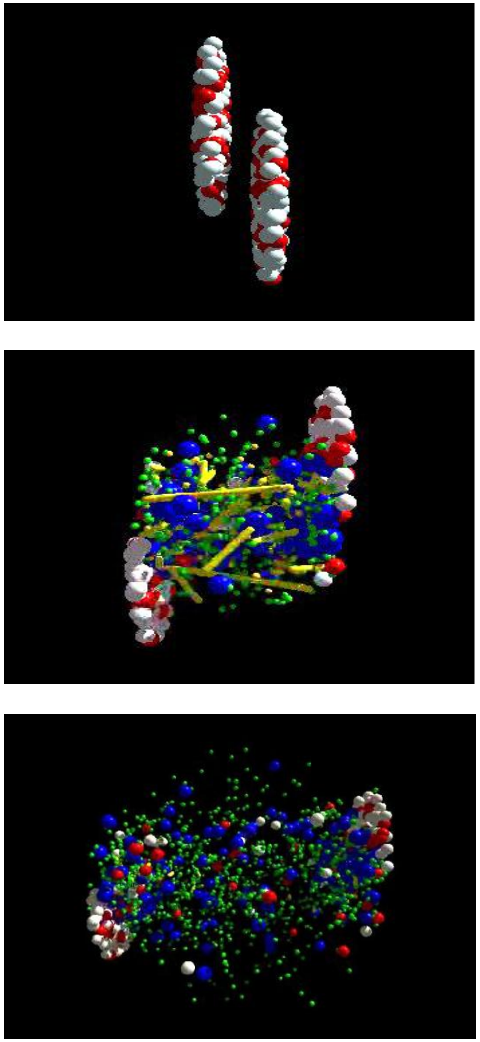
- describes formation time of hydrodynamics
  → no pressure at early times, everything is free flow

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

- AdS/CFT: $dE/dx \sim l^2$ accounts for absense of energy loss < 1fm.

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

⇒ Only the corona is seen!

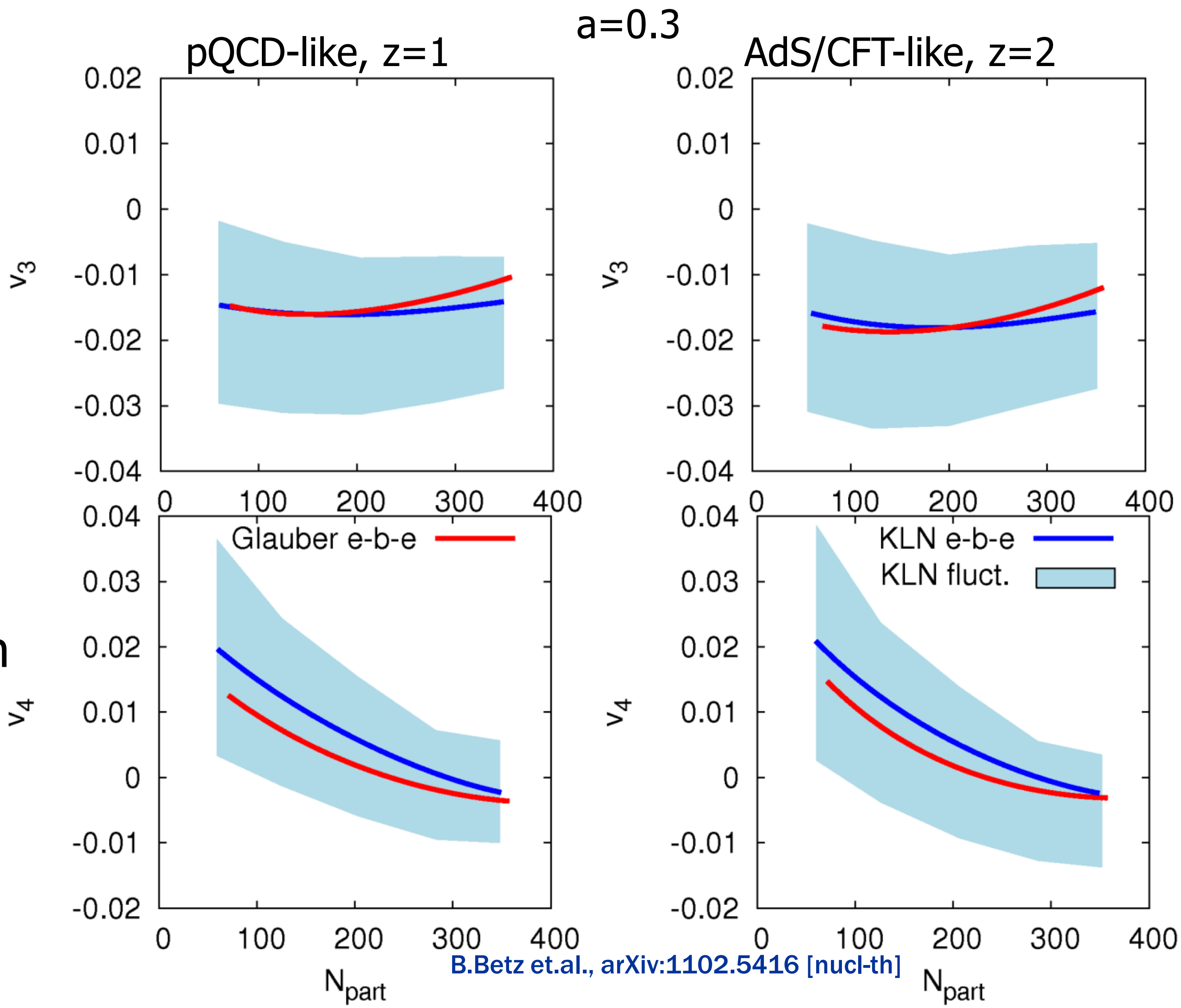


UrQMD Simulartion, H. Weber

Higher Harmonics

v_3 and v_4 similar for Glauber and KLN initial conditions

→ Not suitable to distinguish between Glauber and CGC initial conditions



B.Betz et.al., arXiv:1102.5416 [nucl-th]

→ Higher harmonics are more sensitive to local gradients, but also to event-by-event fluctuations → larger $v_{3,4}$ fluctuations

Fragmentation

Nuclear modification factor

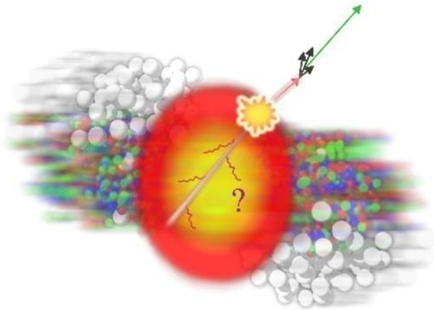
$$R^{\pi}_{AA}(p_\pi) = \frac{\sum\limits_{\alpha=q,g} \int\limits_{z_{min}}^{1} \frac{dz}{z}\, d\sigma_\alpha\left(\frac{p_\pi}{z}\right) R^{\alpha}_{AA}\left(\frac{p_\pi}{z}\right) D_{\alpha\to\pi}\left(z, \frac{p_\pi}{z}\right)}{\sum\limits_{\alpha=q,g} \int\limits_{z_{min}}^{1} \frac{dz}{z}\, d\sigma_\alpha\left(\frac{p_\pi}{z}\right)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

z : momentum of the observed pion

p_π : fractional momentum of the quarks and gluons

$d\sigma_\alpha\left(\frac{p_\pi}{z}\right)$: fitted pQCD cross-sections for quarks and gluons

$D_{\alpha\to\pi}\left(z, \frac{p_\pi}{z}\right)$: fragmentation functions for quarks and gluons



R_{AA} and v_2 for π's

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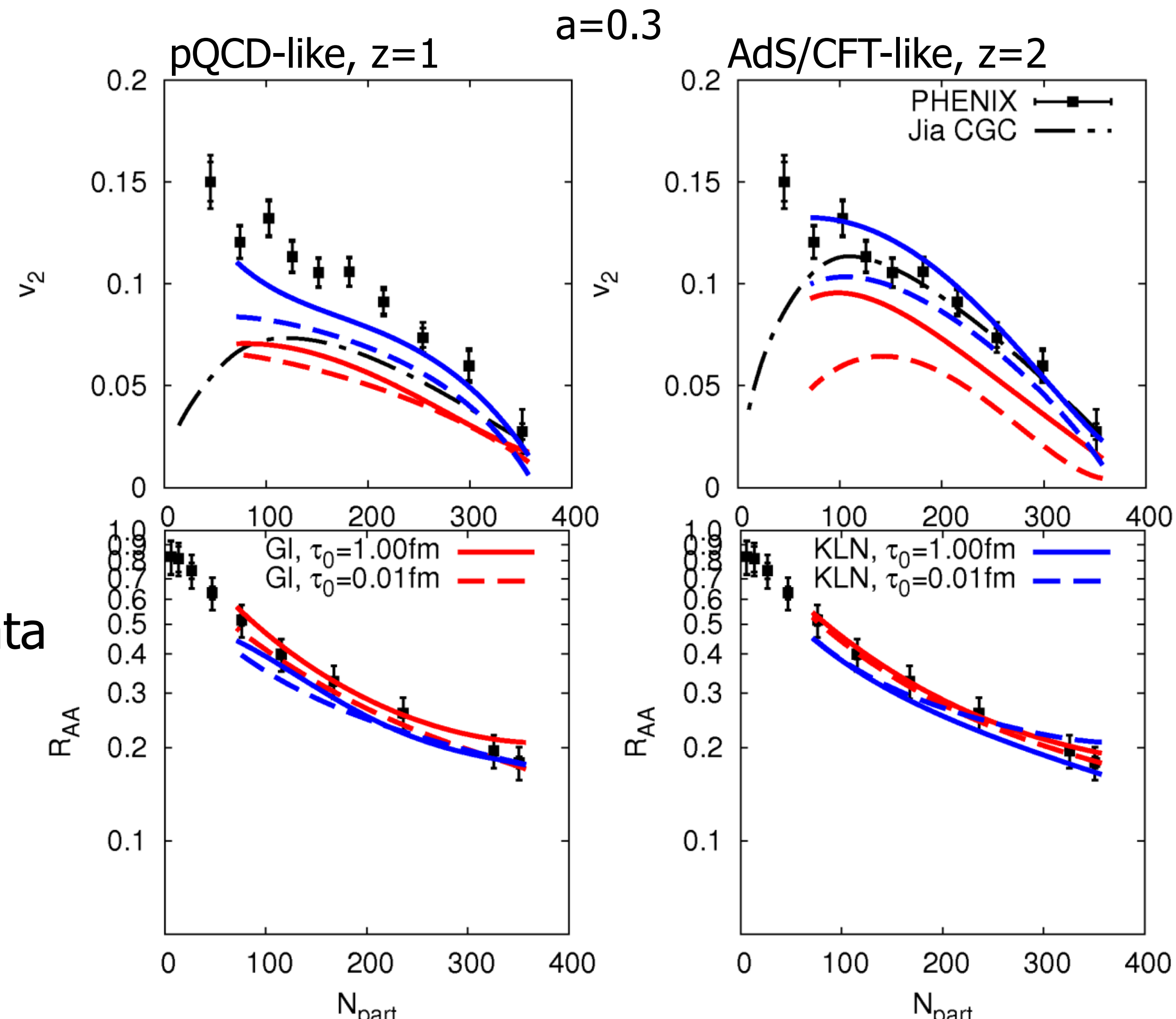


→ $R_{AA}(N_{part})$ can be described

→ z=1: CGC in. cond. close to data, Glauber fails to describe v_2 data

⇒ A smaller τ_0 reduces the $v_2(N_{part})$

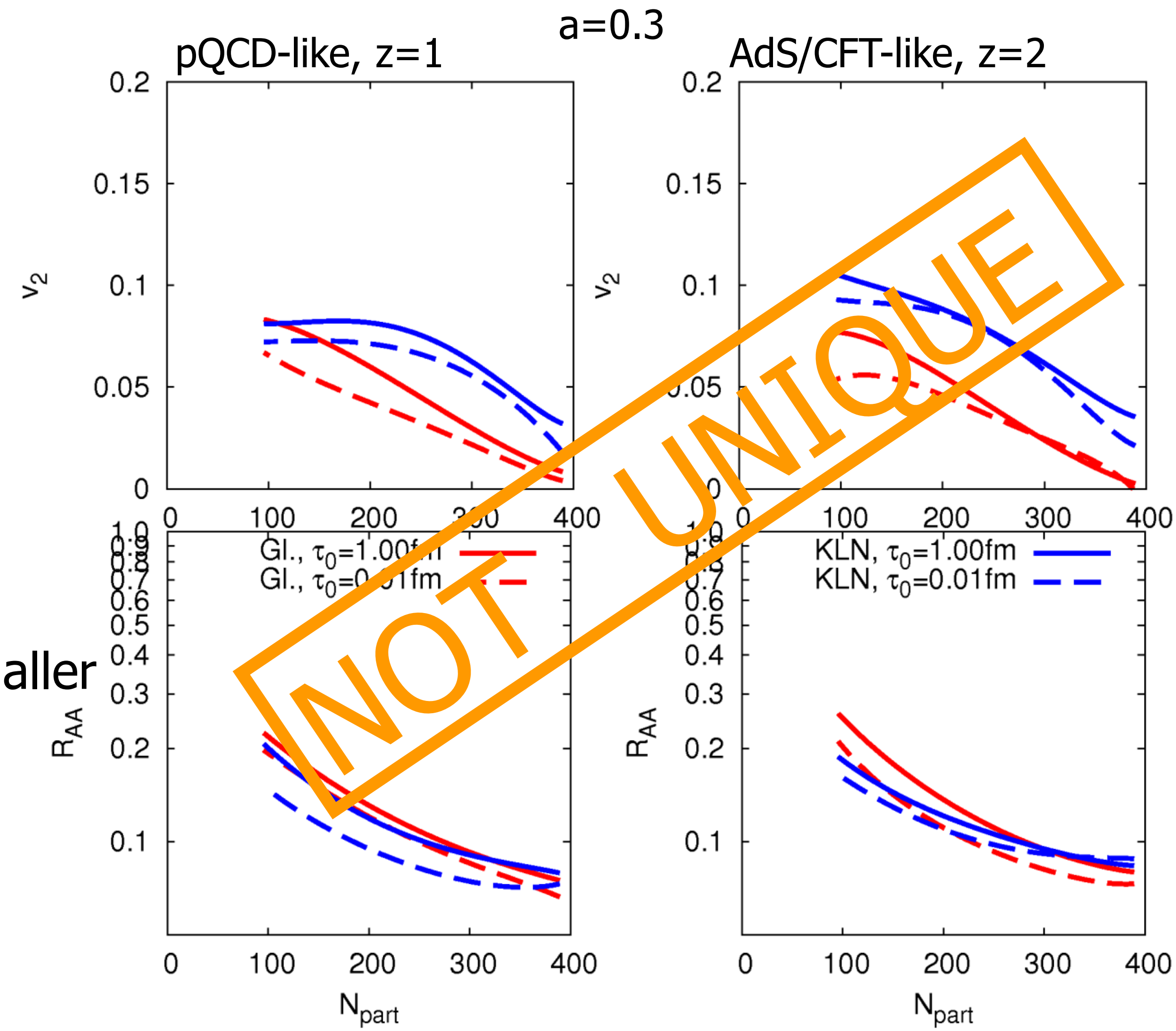
⇒ For τ_0=1fm and CGC initial conditions, pQCD and AdS/CFT-like energy loss close to the data

B.Betz et.al., in preparation

LHC conditions for π's

- → $R_{AA}(N_{part})$ decreases as a function of energy

- → CGC in. cond. lead to larger v_2
- → CGC-v_2 flattens for smaller N_{part}



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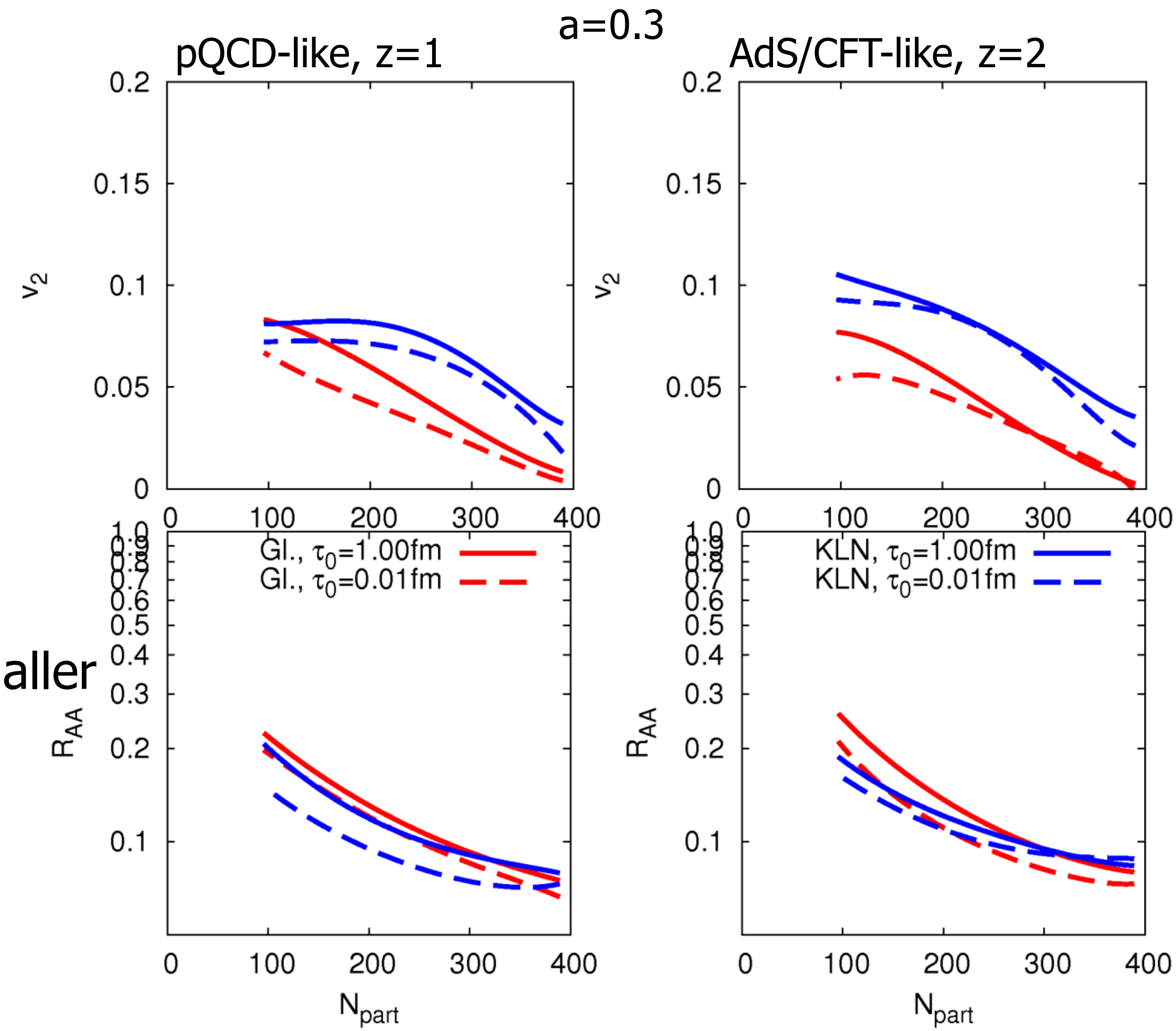


B.Betz et.al., in preparation

LHC conditions for π's

ALICE:

R. Snellings, v_2\{SP\}, p.17

H. Appelshäuser, $\pi^{+/-}$, p.24

ATLAS:

J. Jia, $h^{+/-}$, p.10

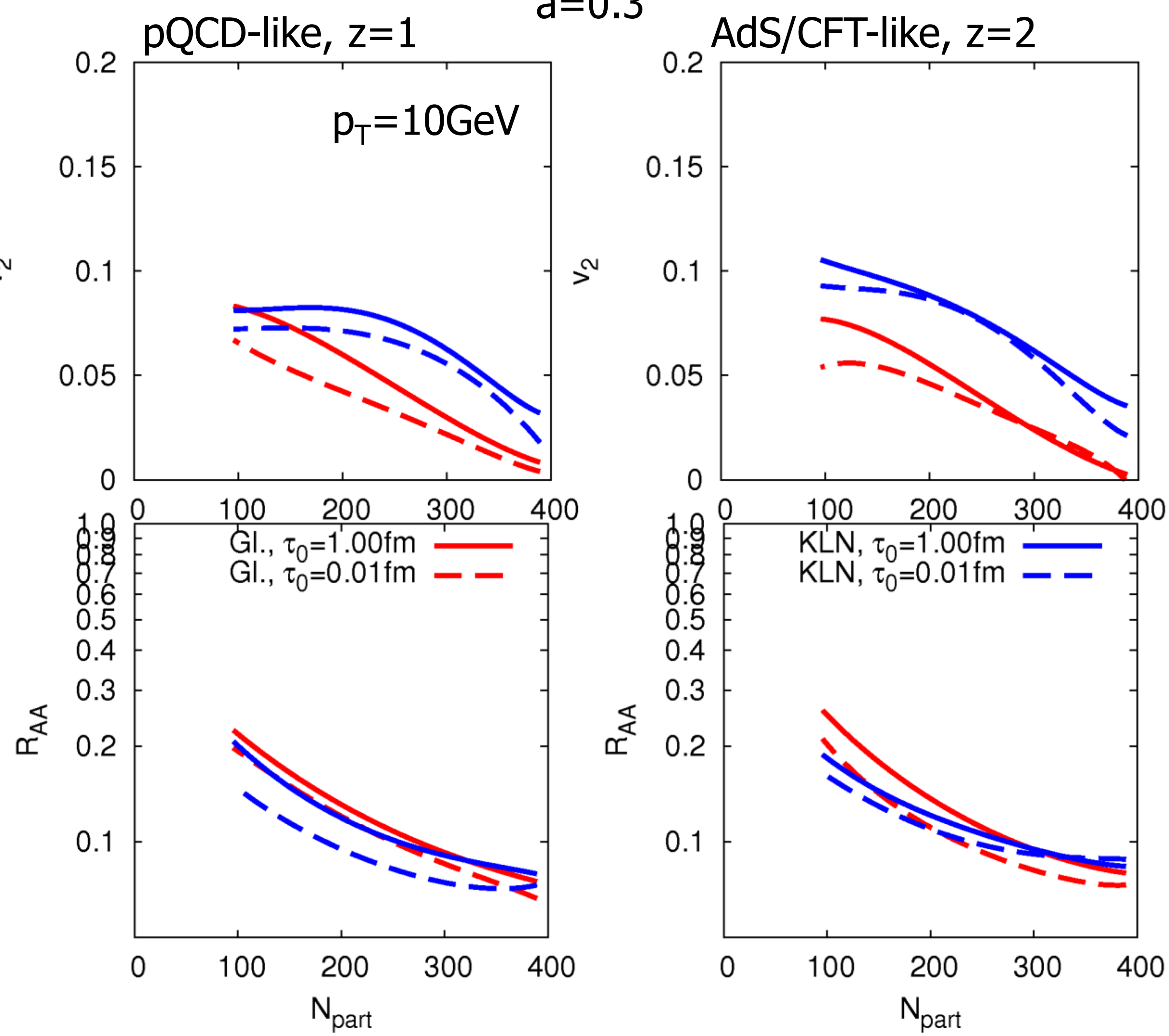
CMS:

J. Velkovska, v_2\{EP\}, p.8

Y.-J. Lee, $h^{+/-}$, p.26

p_T~9.5GeV

a=0.3



B.Betz et.al., in preparation

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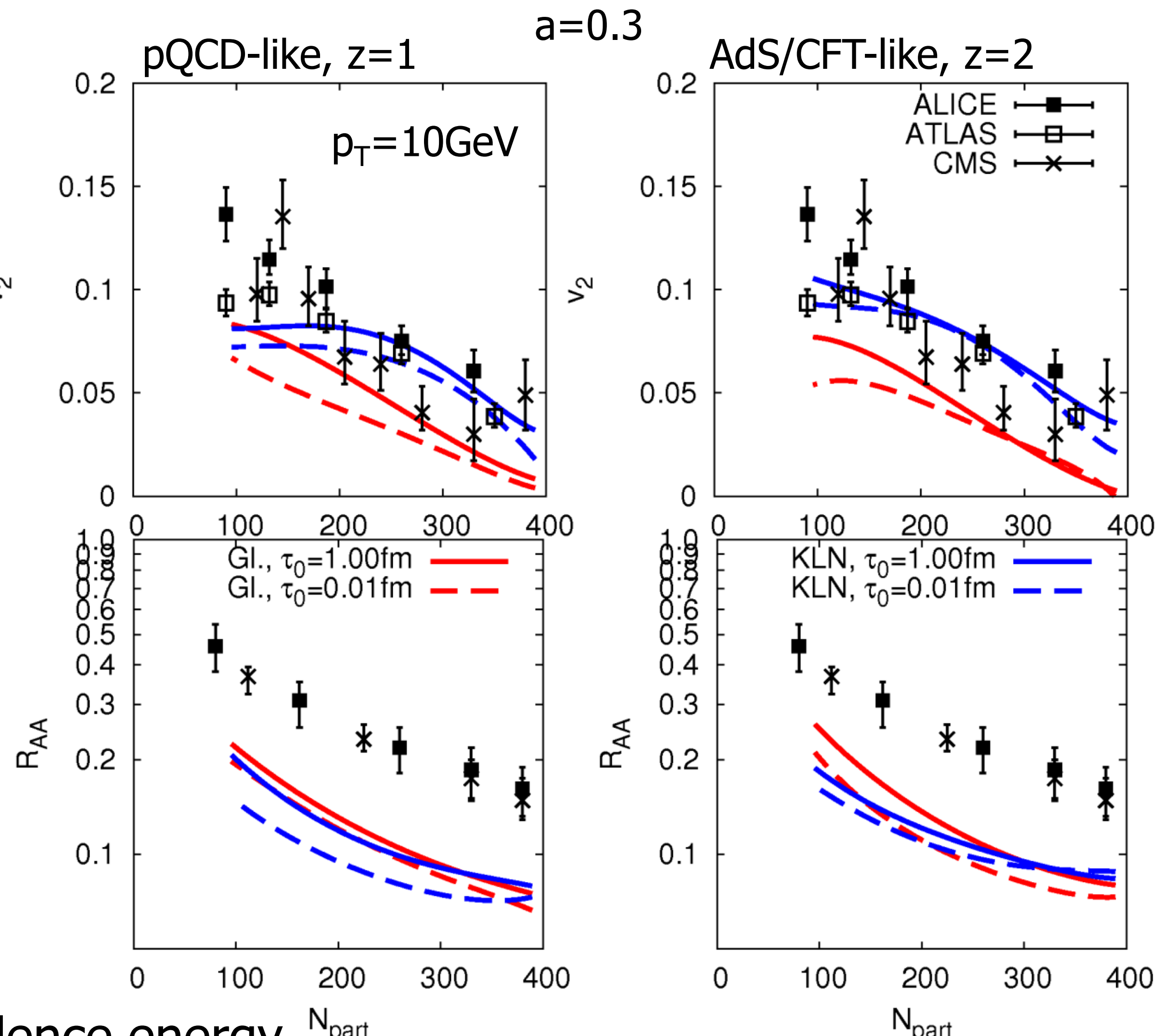

⟹ Puzzle: Density dependence energy loss fails to describe R_{AA} (WHDG/DGLV)

B.Betz et.al., in preparation

Talk W. Horowitz, QM 2011

W. Horowitz et. al., arXiv:1104.4958[hep-ph]

Conclusions

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- Introduced a generic energy loss model, exploring dE/dx ~ P^a and l^z with a dimensionless coupling κ

- gets close to the $v_2(N_{part})$ data in the pQCD-case for KLN initial conditions for τ_0=1fm at RHIC energies, even after fragmentation

- Discussed the role of the initial time τ_0

  ➔ v_2(high- p_T) @ RHIC is sensitive to short distance properties < 1fm,

  ➔ suggesting that either weak coupling + τ_0 ~ 1fm or strong coupling

  ↳ features energy loss suppression at early times

➔ Only the corona is seen (RHIC)

➔ Puzzle: Density dependence energy loss fails to describe R_{AA} @LHC

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Backup

Generic Energy Loss Model

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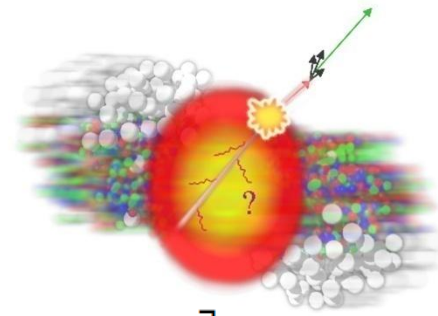
Nuclear modification factor



$$R_{AA}(\vec{x}_0, \phi, N_{part}) = \exp[-\chi(\vec{x}_0, \phi, P_f)]$$

with

$$\chi(\vec{x}_0, \phi, P_f) = \left(\frac{1+a-n}{1-a}\right) \ln\left[1 - \frac{K}{P_0^{1-a}} I(a, z, \phi, \vec{x}_0)\right]$$

$$I(a, z, \phi, \vec{x}_0) = \int\limits_{\tau_0}^{\infty} \tau^z T^{z-a+2}[\vec{x}_0 + \hat{n}(\phi)\tau, \tau] d\tau$$

n ~ 6: spectral index

K = κ (1-a)

$$R_{AA}(N_{part}) = \frac{\int R_{AA}(\vec{x}_0, \phi)\, T_{AA}(\vec{x}_0) d\vec{x}_0\, d\phi/(2\pi)}{\int T_{AA}(\vec{x}_0) d\vec{x}_0}$$

T_{AA} : Glauber

$T_{AA} = \rho^2 / P_0^2$: CGC

H. Drescher et. al., PRC **76** (2007) 024905

Generic Energy Loss Model

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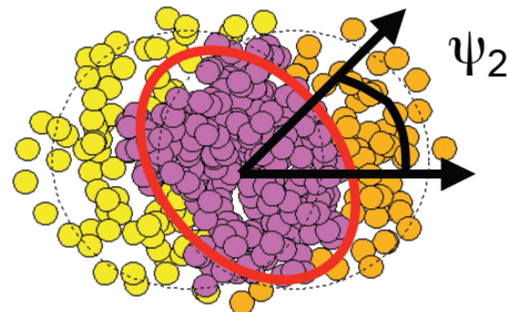
Having fixed κ, the harmonics can be calculated

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



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

determining the angle with the reaction plane

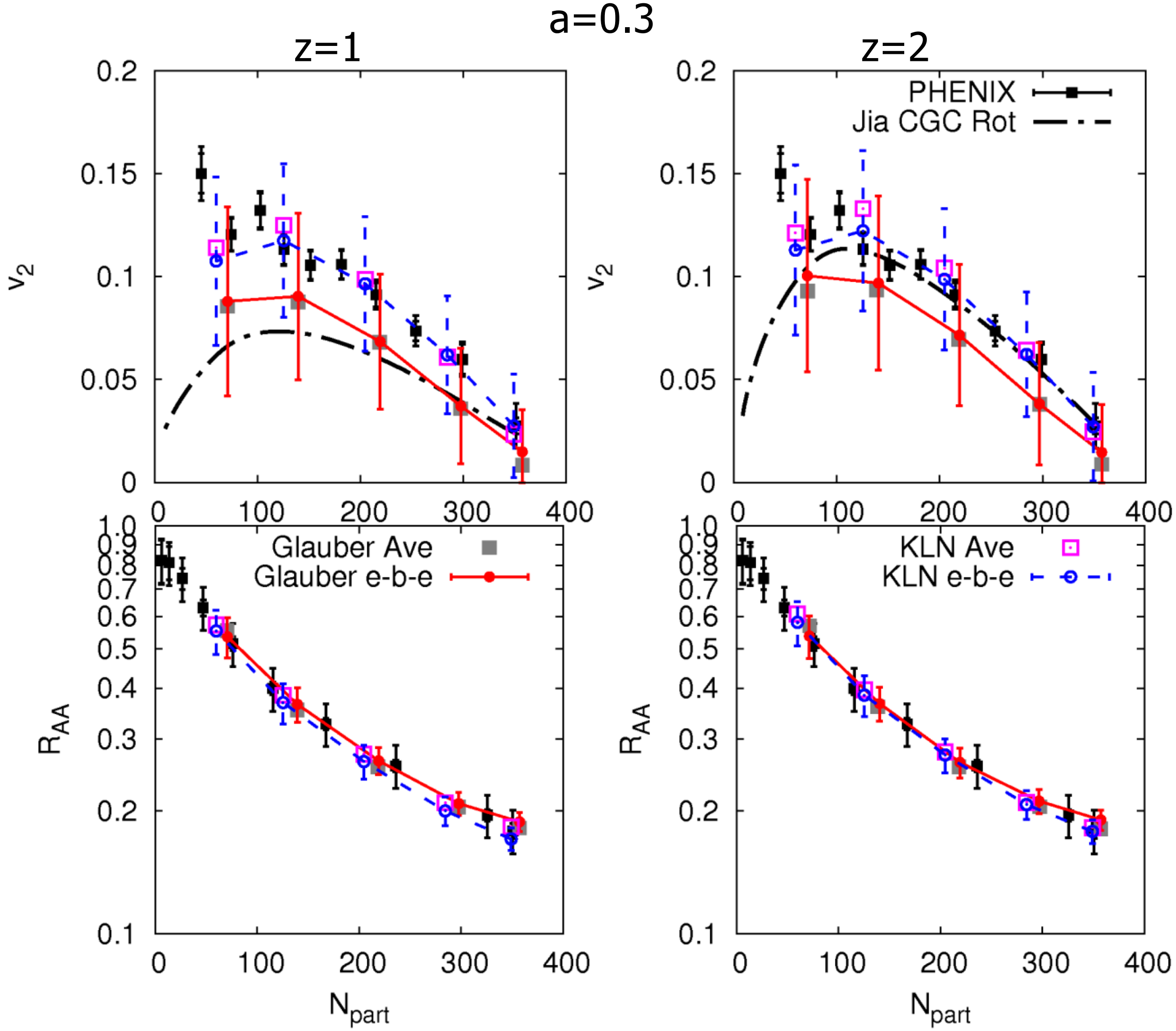
$$\psi_n(t) = \frac{1}{n} \tan^{-1} \frac{\langle r \sin(n\phi)\rangle}{\langle r \cos(n\phi)\rangle}$$

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

- Having fixed κ for $R_{AA}(N_{part}=350) \sim 0.18$
  $R_{AA}(N_{part})$ can be reproduced
- z=1: CGC in. cond.
  close to data
  z=2: Glauber in. cond.
  getting closer
- Small fluctuations for $R_{AA}(N_{part})$
  large fluctuations for $v_2(N_{part})$
- Not straightforward
  to distinguish between initial conditions



B.Betz et.al., arXiv:1102.5416 [nucl-th]

R_{AA} vs. I_{AA}, and v_n vs. v_n^{IAA}

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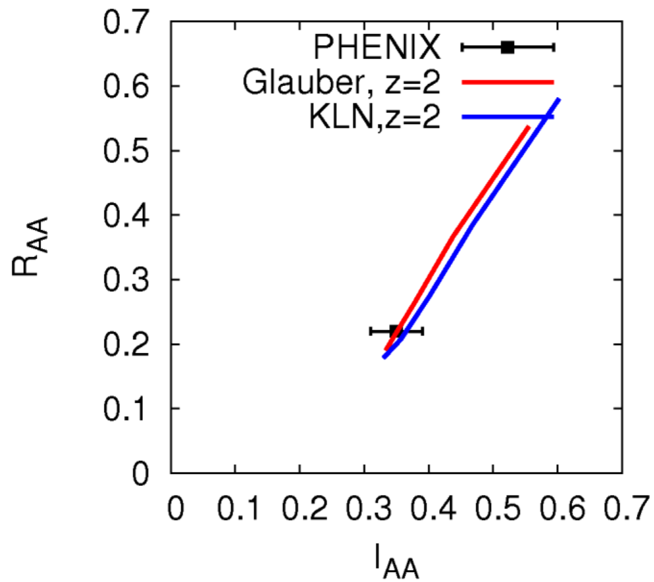
- Extend to dijet analysis,

  but considering $\kappa_{away} = \kappa$

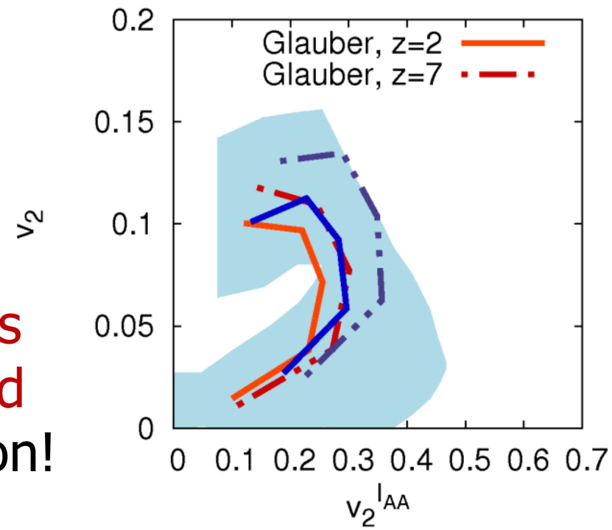
→ In contrast to Jia's model, we fit the R_{AA} vs. I_{AA}

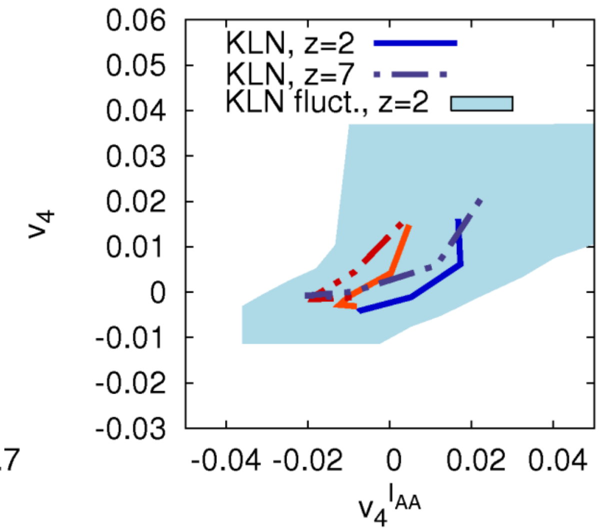
J. Jia et.al., arXiv:1101.0290 [nucl-th]



- v_n vs. v_n^{IAA}:
  - clear shift between Glauber and CGC model

- It is necessary to always determine the mean and the width of a correlation!





B.Betz et.al., arXiv:1102.5416 [nucl-th]

Path-length dependence

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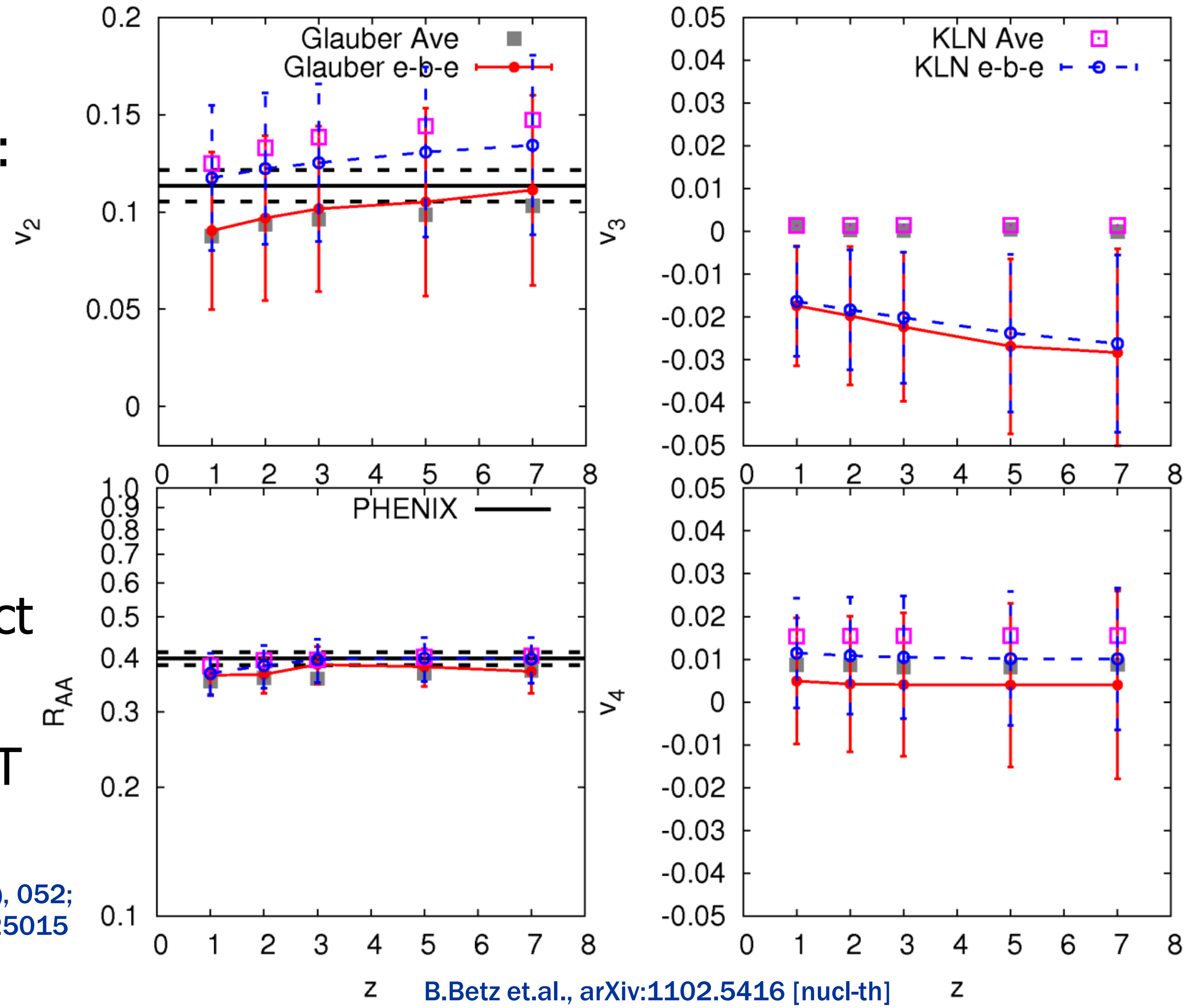
- Study the path-length dependence at b=8fm:
  - Once R_{AA} is fixed via κ,
  - sensitivity remains mostly for v_2 and v_3

➔ small saturation effect occurs for larger z

⟶ described by AdS/CFT **off-shell** partons

S. Gubser et. al., JHEP **0810** (2008), 052;
P. Chesler et.al., PRD **79** (2009) 125015



B.Betz et.al., arXiv:1102.5416 [nucl-th]

Insensitivity of higher v_n's

- Why are the v_n's at high-p_T so insensivite to initial conditions while the v_n's of soft particles are?
  - viscous forces are driven by *local gradients*
  - jet absorption is driven by *global differences* in the integrated $\left\langle -\kappa P^a \tau^z T^{z-a+2} \right\rangle$

→ These two effects are different, especially event-by-event

- Glauber and CGC in. cond. are tuned to reproduce the observed multiplicites

→ <T> is *similar*, even if *local gradients* of T are different

➡ Hydrodynamics and tomography lead to very different results.

Differences

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Nuclear modification factor for the generic energy loss model

$$R_{AA} = \Big\{1 - \frac{K}{P_0^{1-a}} \underbrace{\int_{\tau_0}^{\infty} \tau^z T^{z-a+2}[x_0 + \hat{n}(\phi)\tau, \tau_0] d\tau}_{I} \Big\}^{(n-1-a)/(1-a)}$$

K = κ (1-a), leads to the line integral (a=0, z=1)

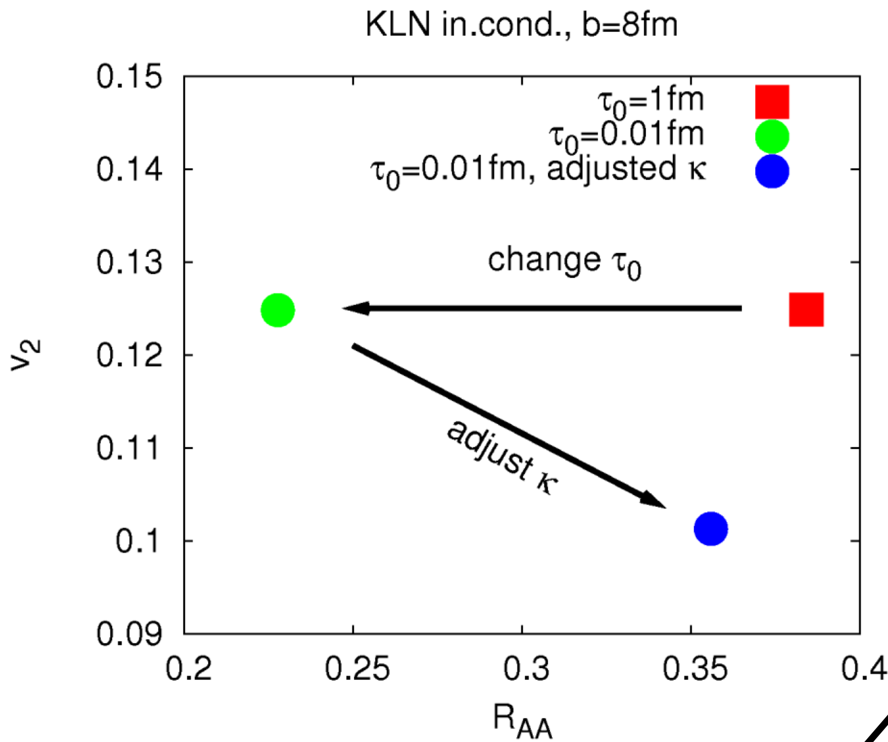
$$I = \int_{\tau_0}^{\infty} T_0^2[x_0 + \hat{n}(\phi)\tau] d\tau = \int_{\tau_0}^{\infty} \rho_0^{2/3}[x_0 + \hat{n}(\phi)\tau] d\tau$$

→ The powers matter!

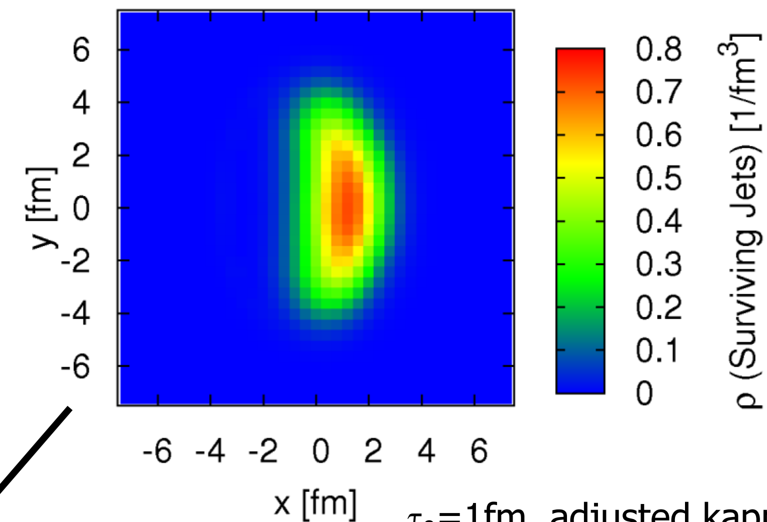
Line integral according to A. Adare et al, PRL **105**, 142301 (2010)

$$I_{m=1} = \int_{\tau_0}^{\infty} dl\, \rho(\vec{r} + l\vec{v})$$

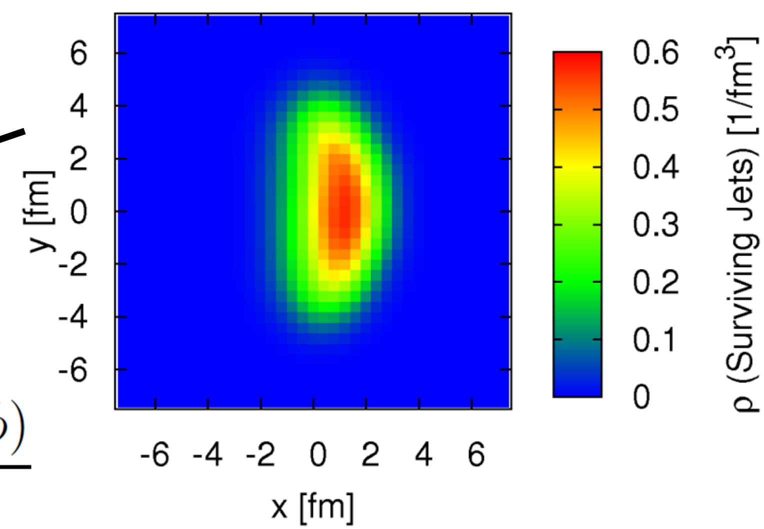
Differences



τ_0=1fm



τ_0=1fm, adjusted kappa



$R_{AA}(\phi)$ changes

↓

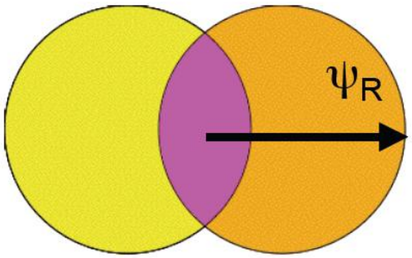
$$v_n(N_{part}) = \frac{\int d\phi \cos\{n[\phi - \psi_n]\}\, R_{AA}(\phi)}{\int d\phi\, R_{AA}(\phi)}$$

Initial Fluctuations I

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Glauber initial conditions:

P. Sorensen J. Phys. G **37**, 094011 (2010),
B. Alver et al., Phys. Rev. C **81**, 054905 (2010)



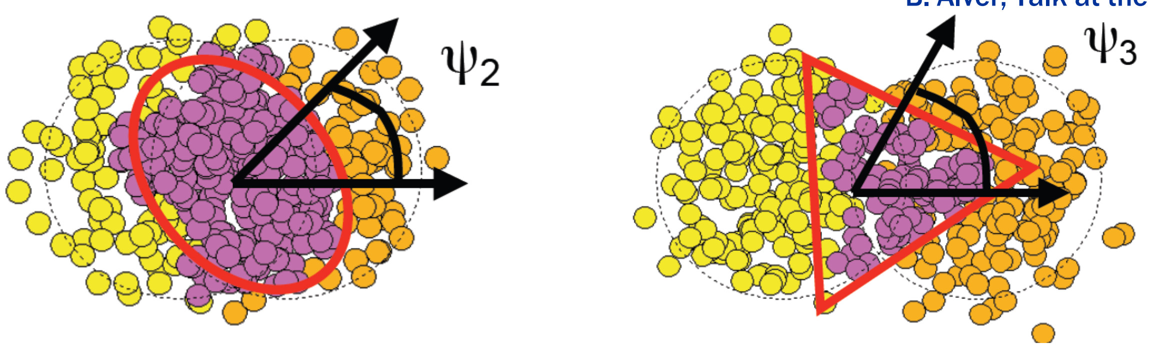
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_R)\right)\right\rangle$$
$$v_3 = 0$$

→ due to symmetry, odd Fourier components vanish

Fluctuating initial conditions:

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



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle$$

$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right)\right\rangle$$

→ higher Fourier components may occur