GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

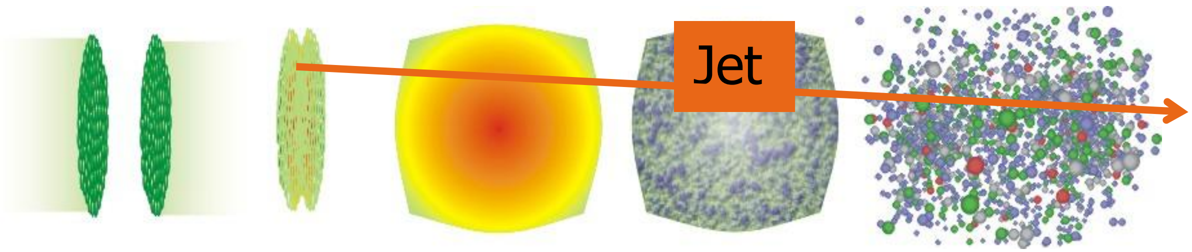
# Constraints on the Jet-Energy Loss from Jet Measurements at RHIC and LHC

Barbara Betz
in collaboration with Miklos Gyulassy

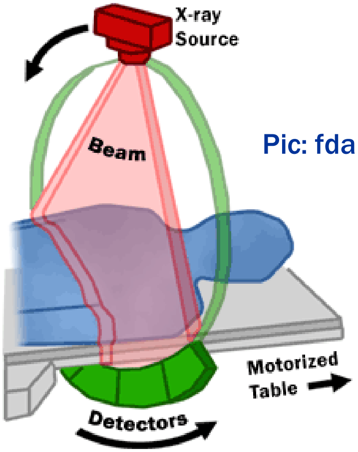
XIth Quark Confinement and the Hadron Spectrum
September 8-12, 2014
Saint-Petersburg State University, Russia

PRC **84**, 024913 (2011); PRC **86**, 024903 (2012);
JHEP **08**, 090 (2014), arXiv:1402.3419; 1407.7436

# Brief reminder on jet quenching



S. Bass, Talk Quark Matter 2001



Pic: fda.gov

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

⇒ What does jet quenching tell us about the jet-medium interaction?

Two observables:

- **jet quenching**: nuclear modification factor parametrizes the jet suppression

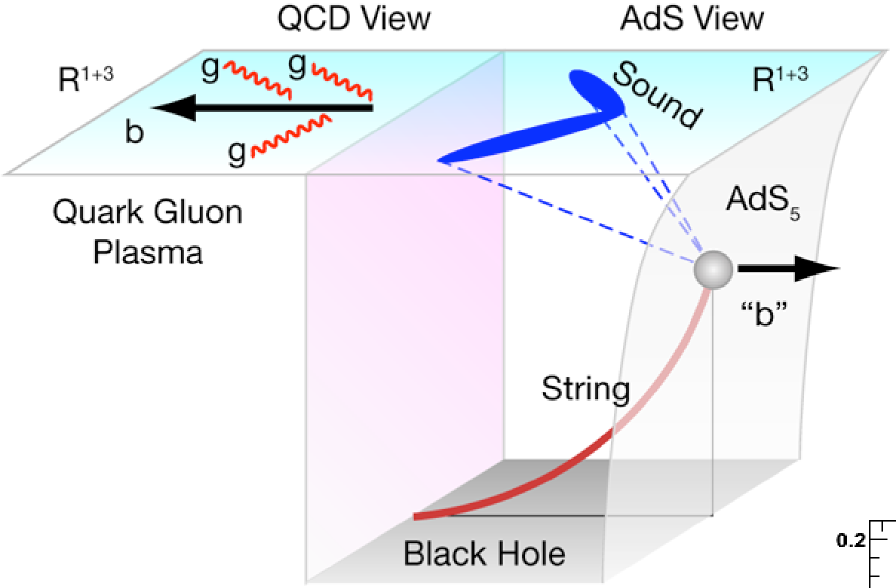
$$R_{\mathrm{AA}}(p_T) = \frac{dN_{\mathrm{AA}}/dp_T}{N_{\mathrm{coll}} dN_{\mathrm{pp}}/dp_T}$$

number of binary collisions

- **elliptic flow**: flow induced by high-$p_T$ particles

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

# Jet quenching in pQCD vs. AdS/CFT



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

Long-standing question:

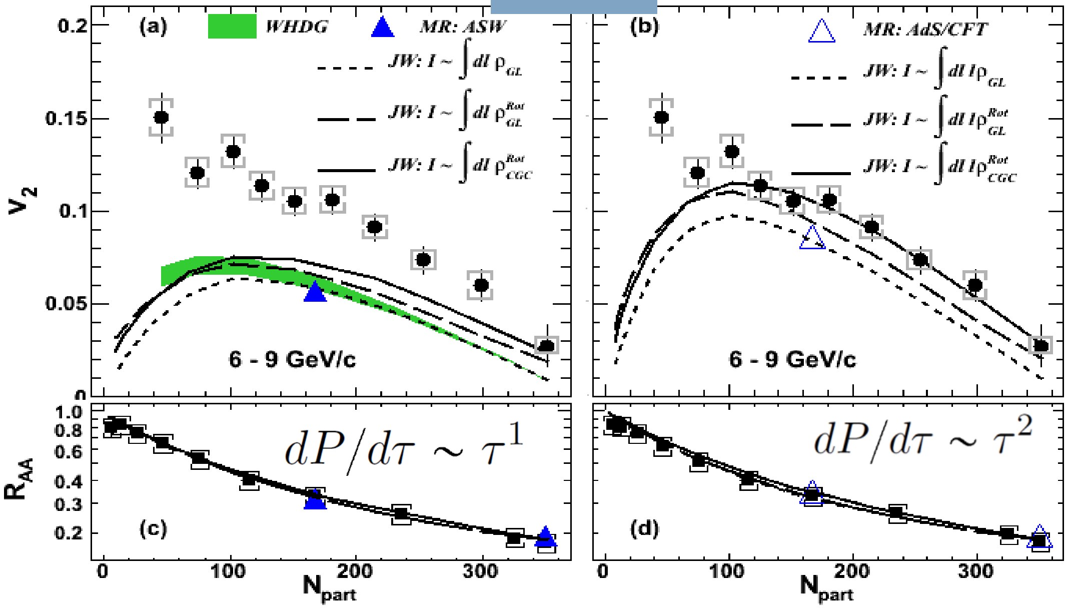
Can the jet-energy loss be described by pQCD or does one need an AdS/CFT prescription?

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

pQCD-like

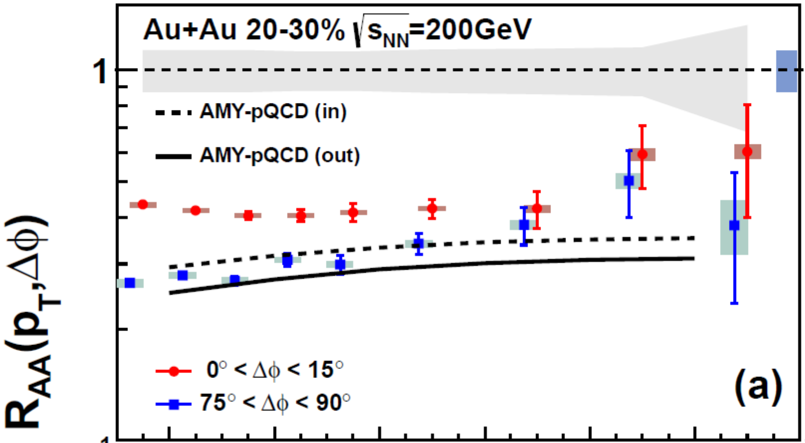
RHIC

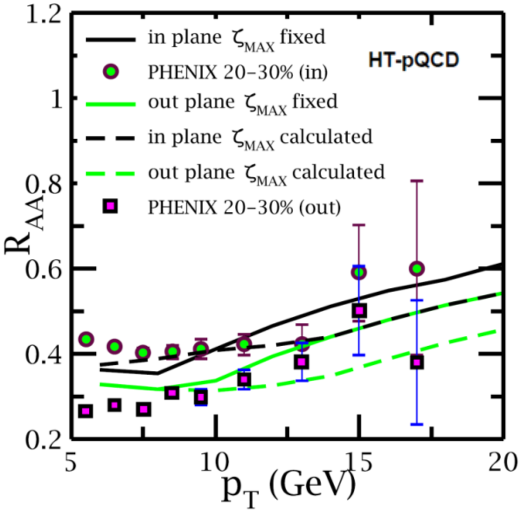
AdS/CFT-like



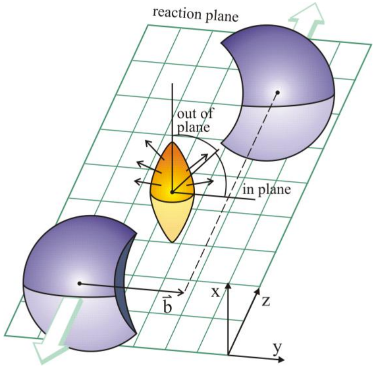
PHENIX, PRL **105**, 142301 (2010)

# pQCD vs. AdS/CFT @RHIC

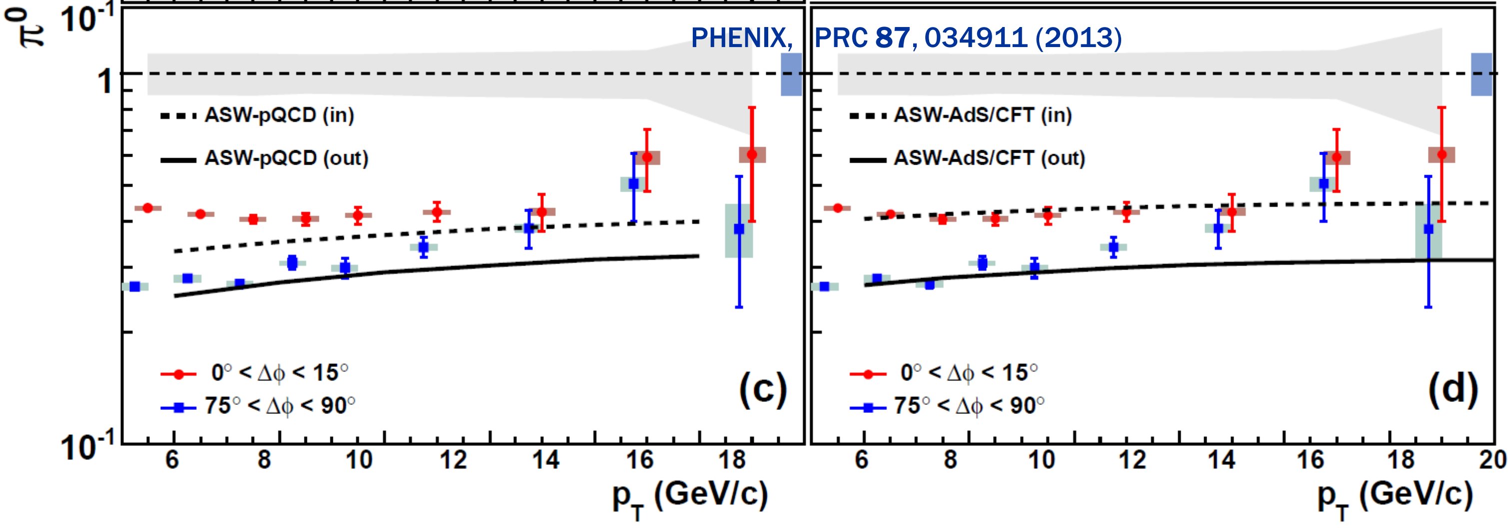




Majumder et al., PRL **109**, 202301 (2012)



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



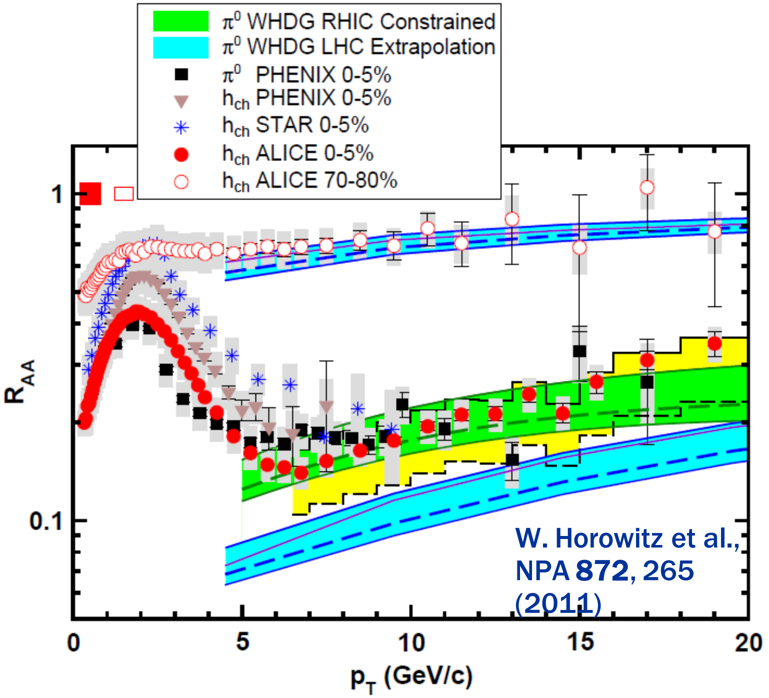
PHENIX, PRC **87**, 034911 (2013)

$$R_{AA}^{\rm in} = R_{AA}(1+2v_2)$$
$$R_{AA}^{\rm out} = R_{AA}(1-2v_2)$$

RHIC results seem to prefer AdS-inspired models

# Overquenching @LHC

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

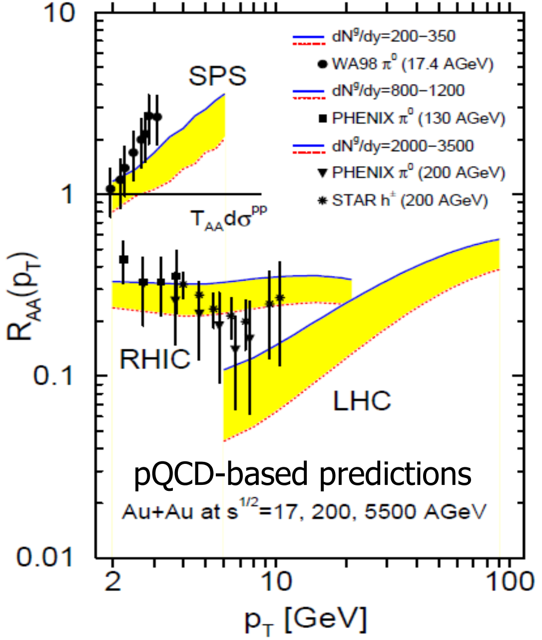


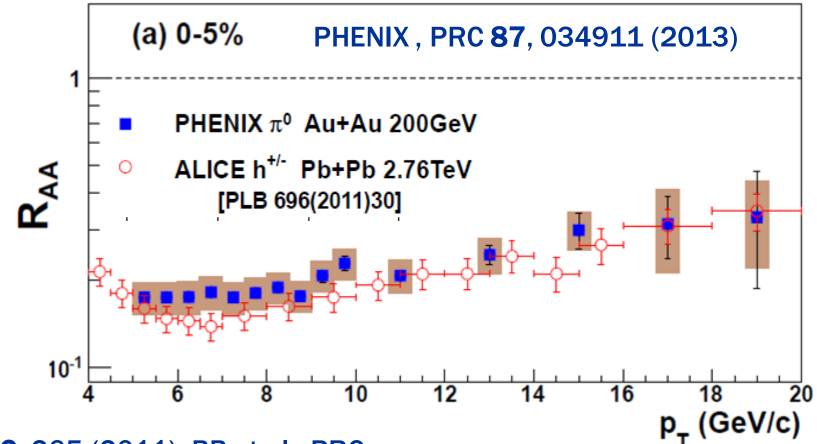
**W. Horowitz et al., NPA 872, 265 (2011)**

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

**W. Horowitz et al., NPA 872, 265 (2011) ;BB et al., PRC 86, 024903 (2012) ; S. Pal et al., PLB 709, 82 (2012)**

**Vitev et al., PRL 89, 252301 (2002)**





**PHENIX , PRC 87, 034911 (2013)**

# Energy-loss mechanism

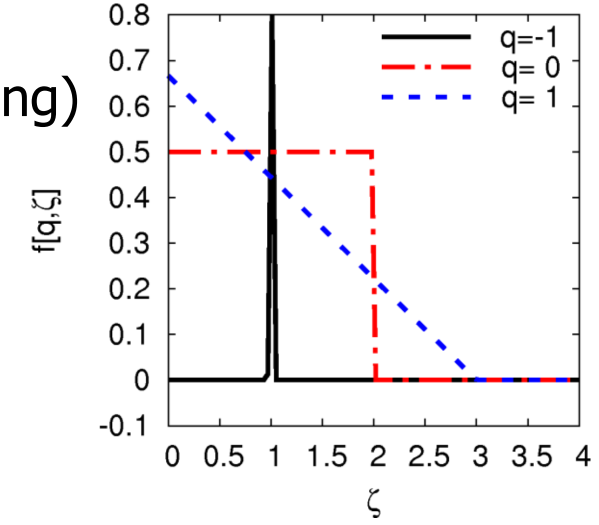
Generic model of jet-energy loss:

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

BB et al., PRC **86**, 024903 (2012); JHEP **80**, 090 (2014)

including more realistic fluctuations of the jet-energy loss about its path averaged mean via $\zeta_q$ and fragmentation for "averaged scenarios"

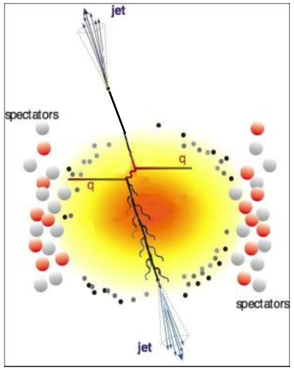
- **Bullet #1**: $R_{AA}$@RHIC & LHC (overquenching & reduction of jet-medium coupling)
- **Bullet #2**: $v_2$@RHIC & LHC (transverse expansion)
- **Bullet #3**: path-length dependence (pQCD vs. AdS/CFT)
- **Bullet #4**: jet-energy dependence
- **Bullet #5**: different initial conditions



energy-loss fluctuation distribution

$$f(q,\zeta_q) = \frac{1+q}{(q+2)^{1+q}}\,(q+2-\zeta_q)^q$$

# Energy-loss mechanism



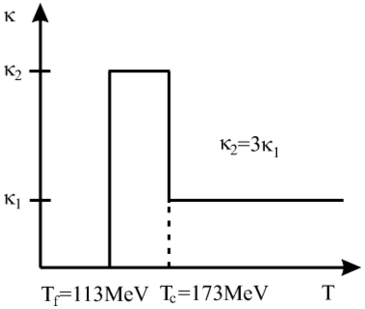
Generic model of jet-energy loss:

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

calculate $R^{in}_{AA}$ and $R^{out}_{AA}$ @RHIC & $R_{AA}$ and $v_2$ @LHC for:

BB et al., JHEP **80**, 090 (2014)

- 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)



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

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 et al., PRC **78**, 034915 (2008); PRL **103**, 262302 (2009).

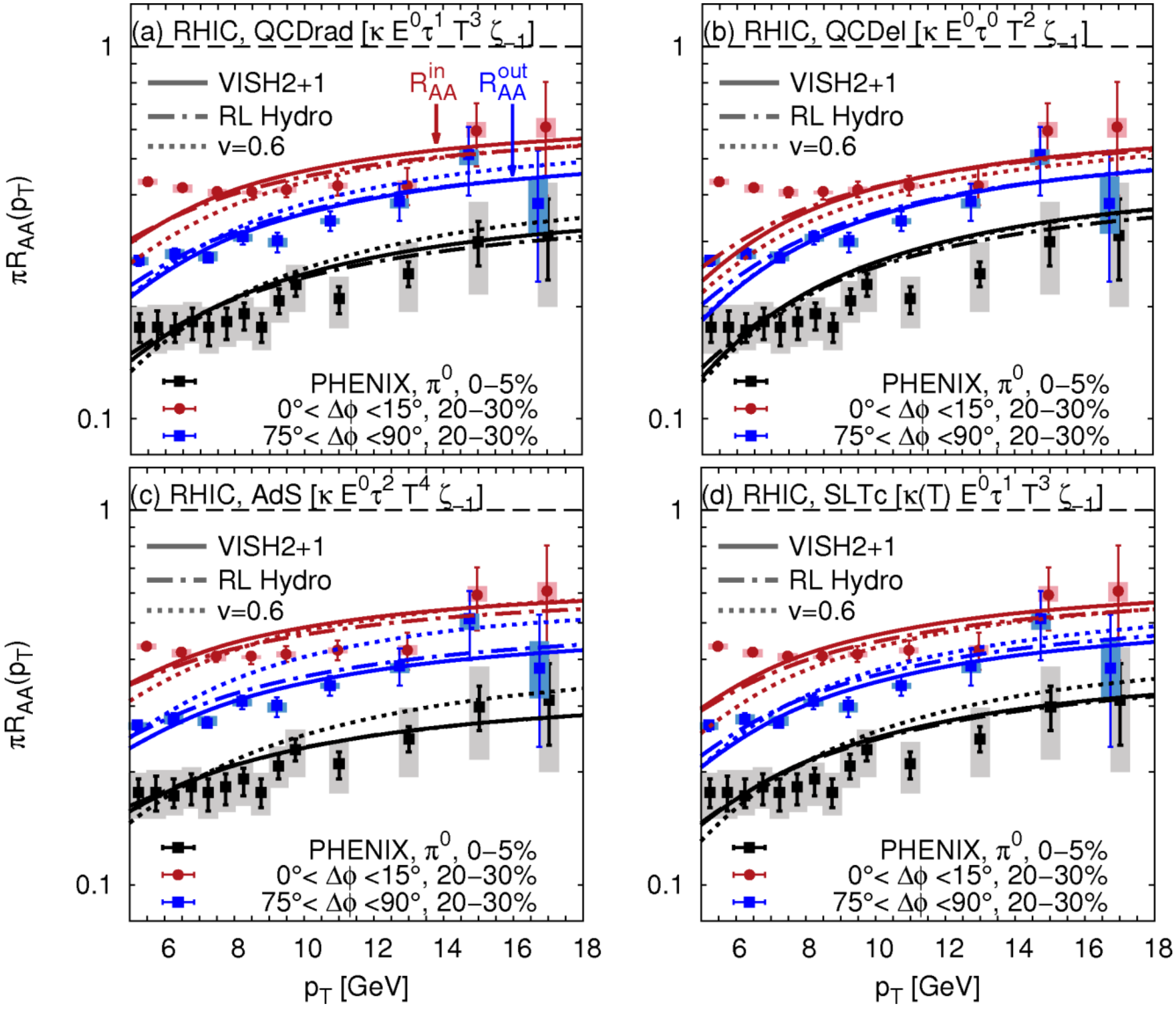
We asked for hydro expansions that reproduce the bulk properties. For the results used, some parameters (viscosity, ...) differ between RHIC and LHC.

# Survey of results

BB et al., JHEP 80, 909 (2014)

| name | fluct. | $(z,c,q)$ | temp. profile | RHIC | | | LHC | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $R^{\mathrm{centr}}_{\mathrm{AA}}$ | $R^{\mathrm{in,periph}}_{\mathrm{AA}}$ | $R^{\mathrm{out,periph}}_{\mathrm{AA}}$ | $R^{\mathrm{centr}}_{AA}$ | $R^{\mathrm{periph}}_{AA}$ | $v_2^{\mathrm{periph}}$ |
| QCDrad | no | $(1,3,-1)$ | VISH2+1 | ✓ | ✓ | ✓ | ✓ | ✓ | (✓) |
| QCDrad | no | $(1,3,-1)$ | RL Hydro | ✓ | ✓ | ✓ | (✓) | ✓ | ✓ |
| QCDrad | no | $(1,3,-1)$ | $v=0.6$ | ✓ | ✓ | no | (✓) | ✓ | no |
| QCDel | no | $(0,2,-1)$ | VISH2+1 | ✓ | ✓ | ✓ | no | ✓ | no |
| QCDel | no | $(0,2,-1)$ | RL Hydro | ✓ | ✓ | ✓ | no | (✓) | no |
| QCDel | no | $(0,2,-1)$ | $v=0.6$ | ✓ | no | ✓ | no | (✓) | no |
| AdS | no | $(2,4,-1)$ | VISH2+1 | ✓ | (✓) | ✓ | no | no | ✓ |
| AdS | no | $(2,4,-1)$ | RL Hydro | ✓ | (✓) | ✓ | no | no | ✓ |
| AdS | no | $(2,4,-1)$ | $v=0.6$ | (✓) | (✓) | no | no | no | (✓) |
| SLTc | no | $(1,3,-1)$ | VISH2+1 | ✓ | ✓ | ✓ | no | no | no |
| SLTc | no | $(1,3,-1)$ | RL Hydro | ✓ | ✓ | ✓ | ✓ | ✓ | (✓) |
| SLTc | no | $(1,3,-1)$ | $v=0.6$ | (✓) | ✓ | (✓) | no | no | no |
| QCDrad | yes | $(1,3,+1)$ | VISH2+1 | ✓ | ✓ | ✓ | ✓ | (✓) | (✓) |
| QCDel | yes | $(0,2,+1)$ | VISH2+1 | ✓ | ✓ | no | ✓ | no | (✓) |
| AdS | yes | $(2,4,+1)$ | VISH2+1 | ✓ | ✓ | ✓ | no | no | ✓ |
| ncAdS | no | $(2,4,-1)$ | VISH2+1 | ✓ | no | ✓ | ✓ | (✓) | ✓ |
| ncAdS | yes | $(2,4,+1)$ | VISH2+1 | ✓ | ✓ | ✓ | ✓ | (✓) | ✓ |
| $\kappa(\phi)$ QCDrad | yes | $(1,3,0)$ | VISH2+1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $\kappa(\phi)$ QCDrad | yes | $(1,3,0)$ | RL Hydro | ✓ | ✓ | ✓ | (✓) | (✓) | ✓ |
| exp. $\kappa(T)$ QCDrad | no | $(1,3,-1)$ | VISH2+1 | ✓ | no | (✓) | ✓ | ✓ | ✓ |
| exp. $\kappa(T)$ QCDrad | yes | $(1,3,0)$ | VISH2+1 | ✓ | ✓ | ✓ | ✓ | (✓) | ✓ |
| exp. $\kappa(T)$ ncAdS | no | $(2,4,-1)$ | VISH2+1 | ✓ | no | (✓) | (✓) | ✓ | ✓ |
| exp. $\kappa(T)$ ncAdS | yes | $(2,4,0)$ | VISH2+1 | ✓ | ✓ | ✓ | (✓) | (✓) | ✓ |

# $R_{AA}^{in}$ and $R_{AA}^{out}$ @RHIC, no fluctuations

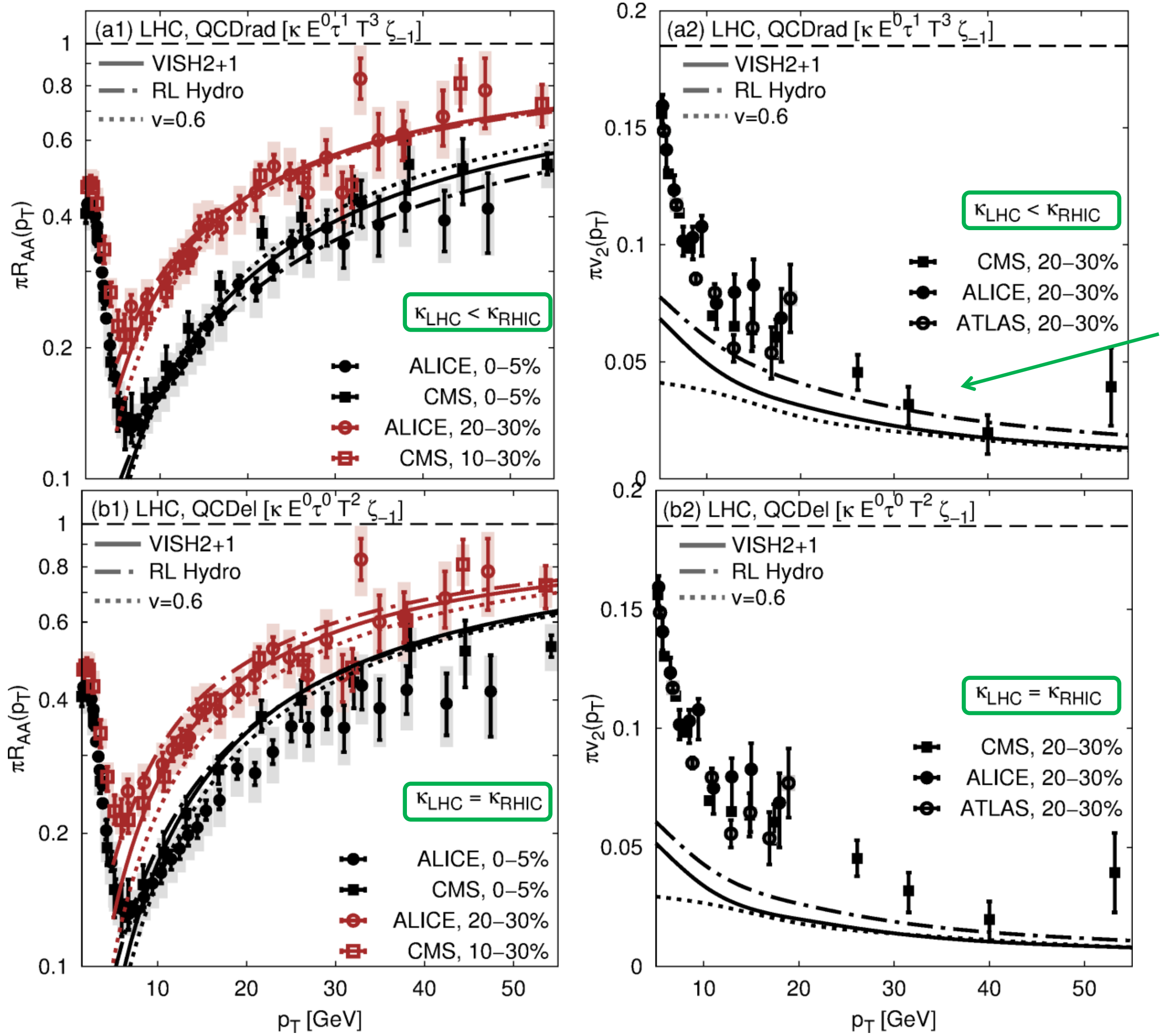


All scenarios based on (visc.) hydro background account for $p_T$>8 GeV data, while blast wave model (v=0.6) fails

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

More similar to new HT results.

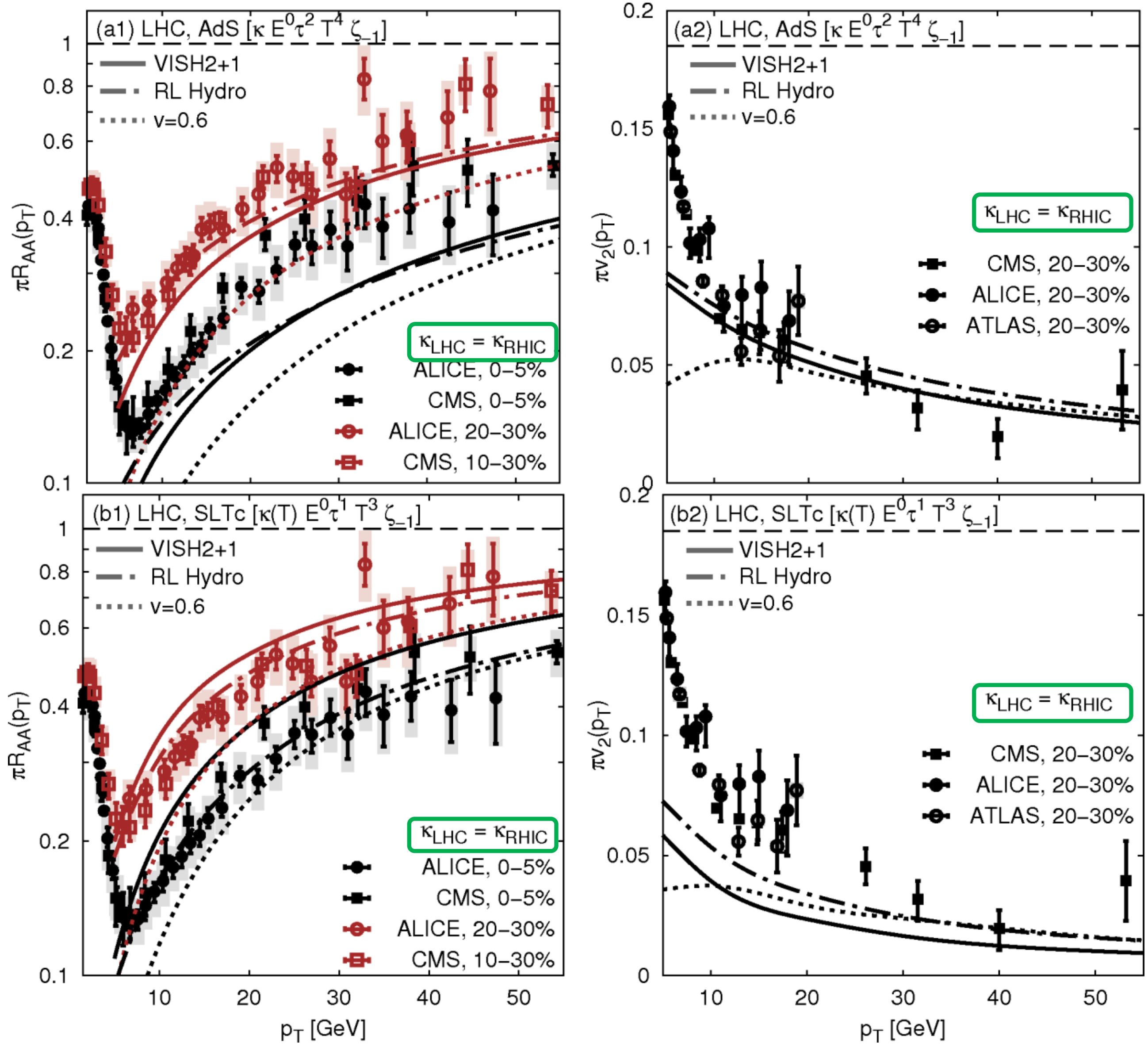
# pQCD-like models @LHC, no fluctuations



$dE^{rad}/dx \sim E^0\tau^1T^3$ reproduces BOTH $R_{AA}$ and $v_2$ within the uncertainties of bulk space time evolution (IC, $\eta/s$, $\tau_0$)

Running coupling radiative QCDrad ($\sim E^0\tau^1$) appears to be preferred over running coupling QCDel ($\sim E^0\tau^0$).

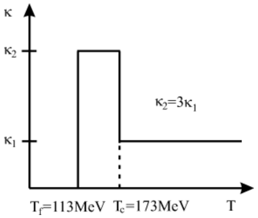
# Non-perturb. models @LHC, no fluctuations



The conformal AdS scenario overquenches for a fixed coupling @LHC

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

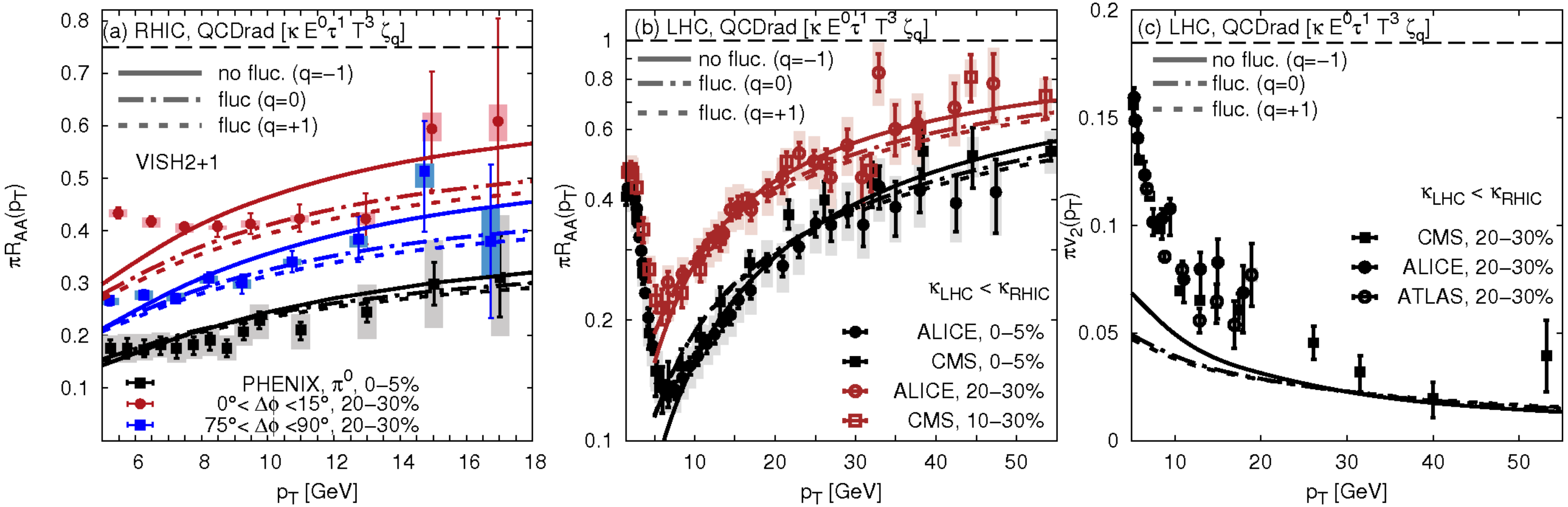
SLTc κ(T) closer to the LHC data, depending on the background.



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

# QCDrad with jet-energy loss fluctuations

Including more realistic fluctuations of the jet-energy loss about its path-averaged mean:

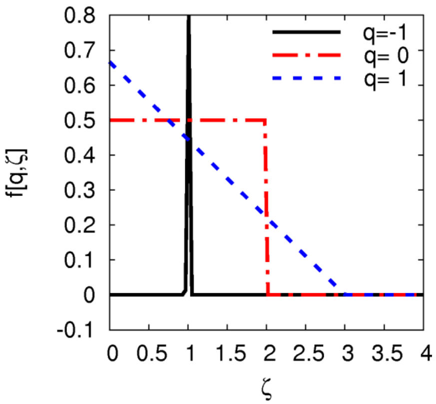


⟹ $R_{AA}$ gets smaller, $v_2$ less affected, $v_2$@LHC too low

Background impacts results ($v_2$@LHC larger for RL hydro)

energy-loss fluctuation distribution

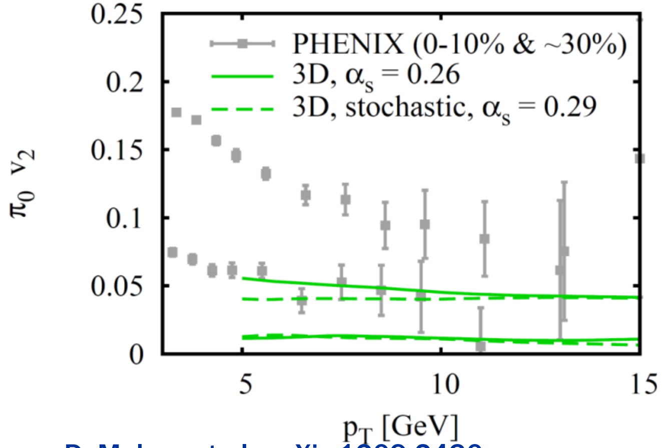
$$f(q,\zeta_q) = \frac{1+q}{(q+2)^{1+q}}\,(q+2-\zeta_q)^q$$



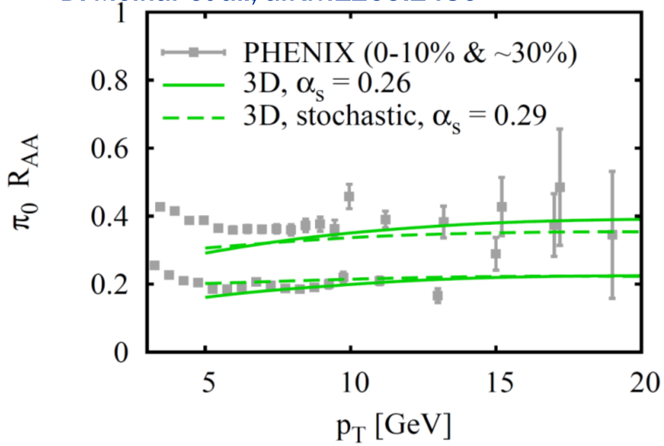
# The high-$p_T$ $v_2$ problem

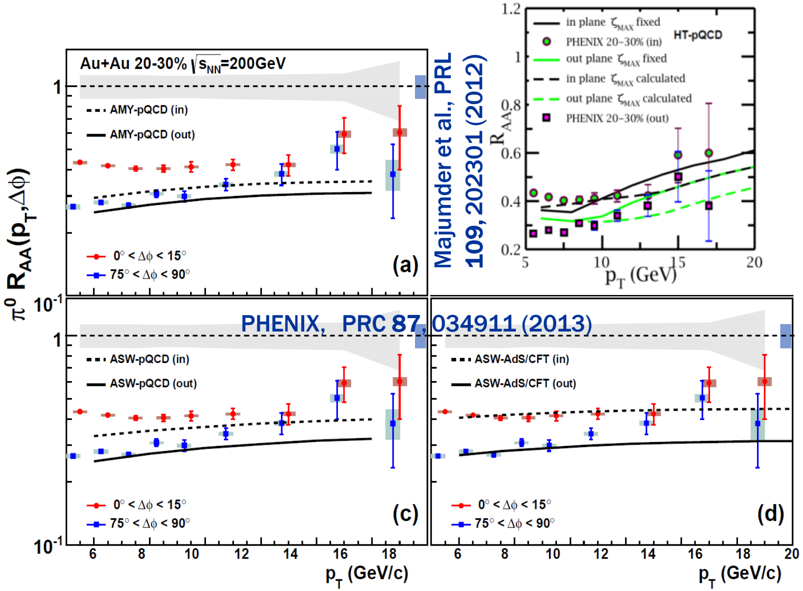
# The high-$p_T$ $v_2$ problem of pQCD models

RHIC



D. Molnar et al., arXiv:1209.2430

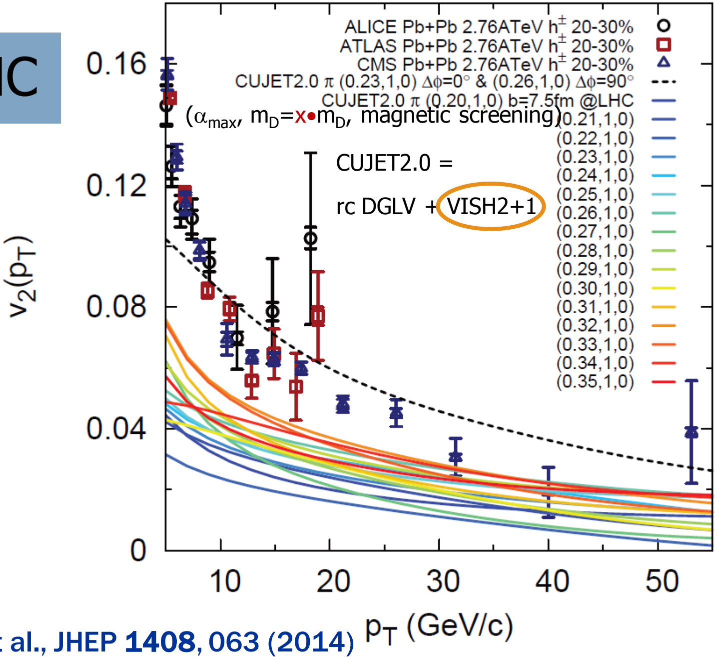




Majumder et al., PRL 109, 202301 (2012)

PHENIX, PRC **87**, 034911 (2013)

LHC



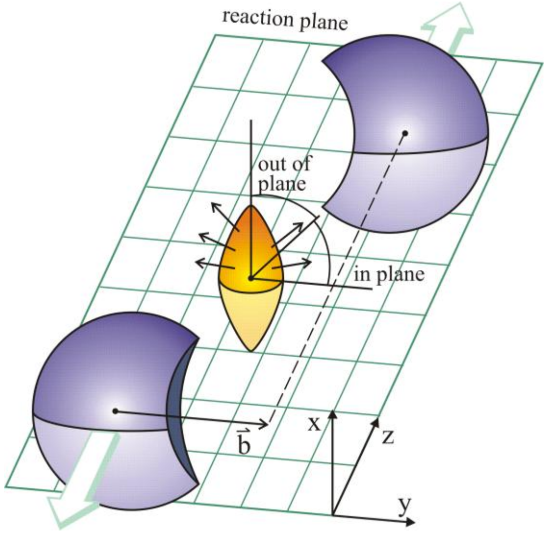
J. Xu et al., JHEP **1408**, 063 (2014)

- High-$p_T$ $v_2$ is about a factor of 2 too small for D. Molnar, HT, and ASW
- Yield of CUJET2.0 $v_2$ depends on $\alpha_{max}$

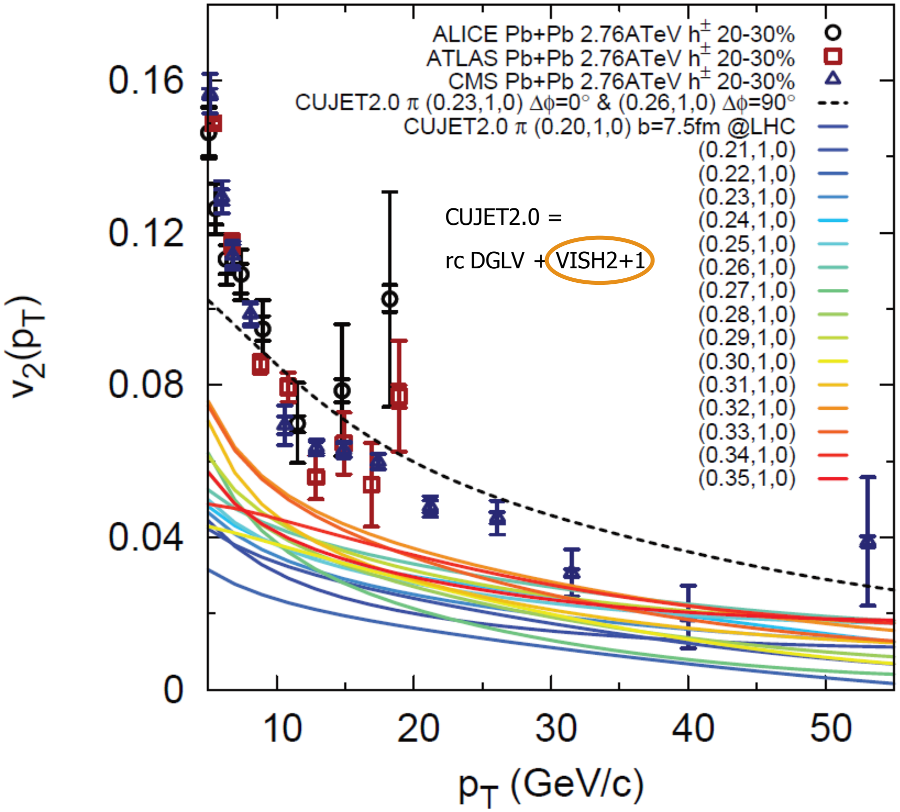
# Path-variation of the jet-medium coupling

Ansatz to solve the high-$p_T$ $v_2$-puzzle:

J. Xu et al., JHEP **1408**, 063 (2014)



Assume a modest (~10%) variation of the jet-medium coupling in- vs. out-of-plane, $\alpha_{max}$ (out-of-plane) > $\alpha_{max}$ (in-plane)



Empirical result,
may be due to a combination of various effects from $\alpha$(T,Q=momentum transfer) and T(x,y,t)

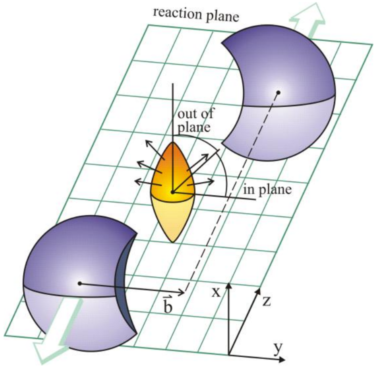
# Path-variation of the jet-medium coupling

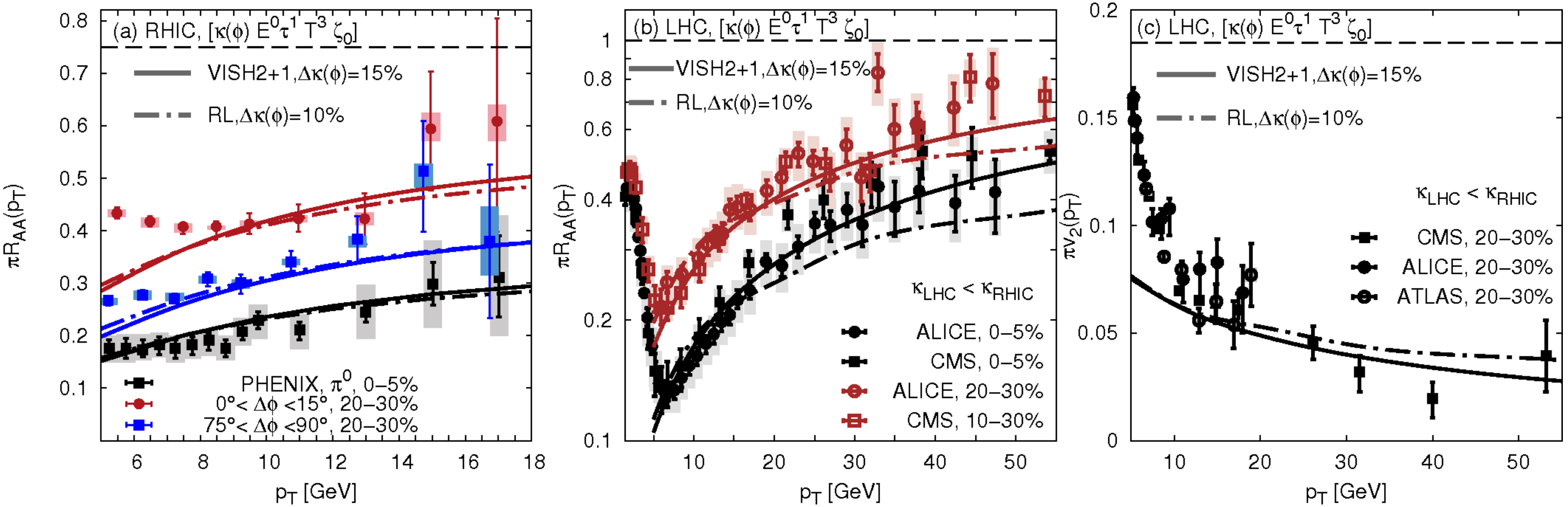
To mimic this ansatz with

$\alpha_{max}$ (out-of-plane) $>$ $\alpha_{max}$ (in-plane)

we assume an increase of the jet-medium coupling out-of-plane

$\kappa(\phi) = \kappa \cdot (1 + |\sin(\phi)| \cdot X)$ X: value in percentage

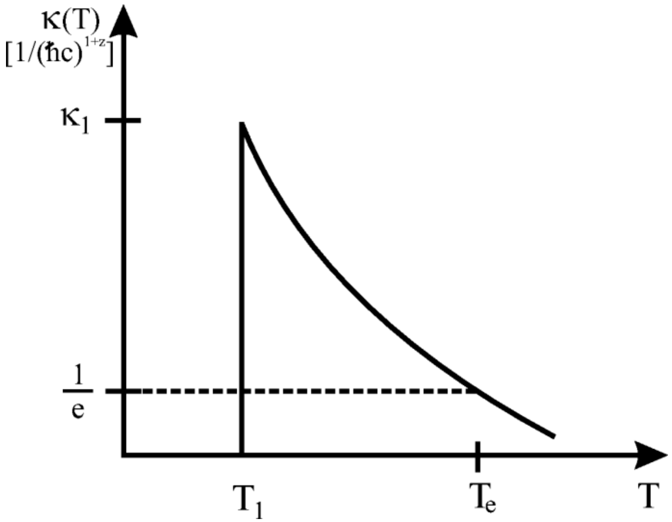




⟹ $R_{AA}$ and $v_2$ can be described BOTH @RHIC & @LHC, assuming running coupling and a fluctuating, pQCD-like $dE^{rad}/dx \sim E^0\tau^1T^3$

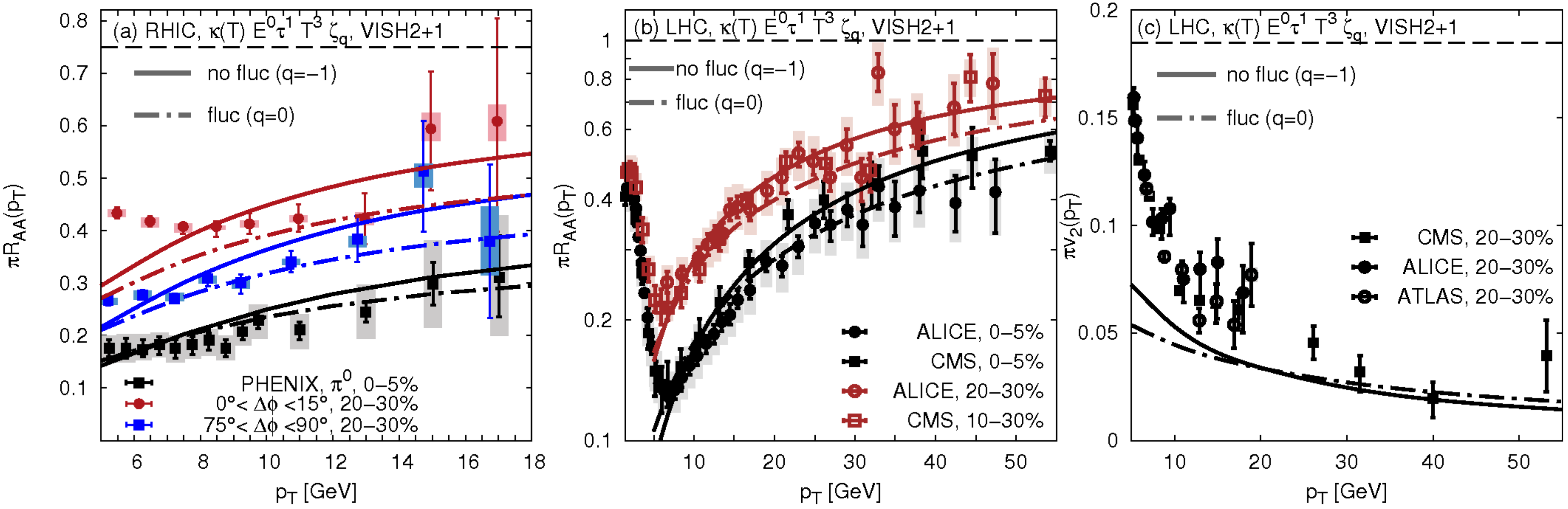
# Exponential κ(T) ansatz

Inspired by the SLTc model,
we consider an exponential ansatz:



$$\kappa(T) = \kappa_1 e^{-b(T-T_1)}$$

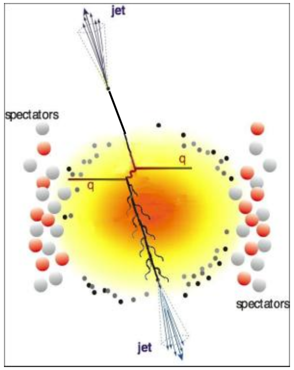
⇒ One possible ansatz to describe the LHC transparency.



⇒ Data are fairly described.

# The Flowing Medium

# The flow factor



The generic model of jet-energy loss discussed above

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

BB et al., PRC **86**, 024903 (2012); JHEP **80**, 090 (2014)

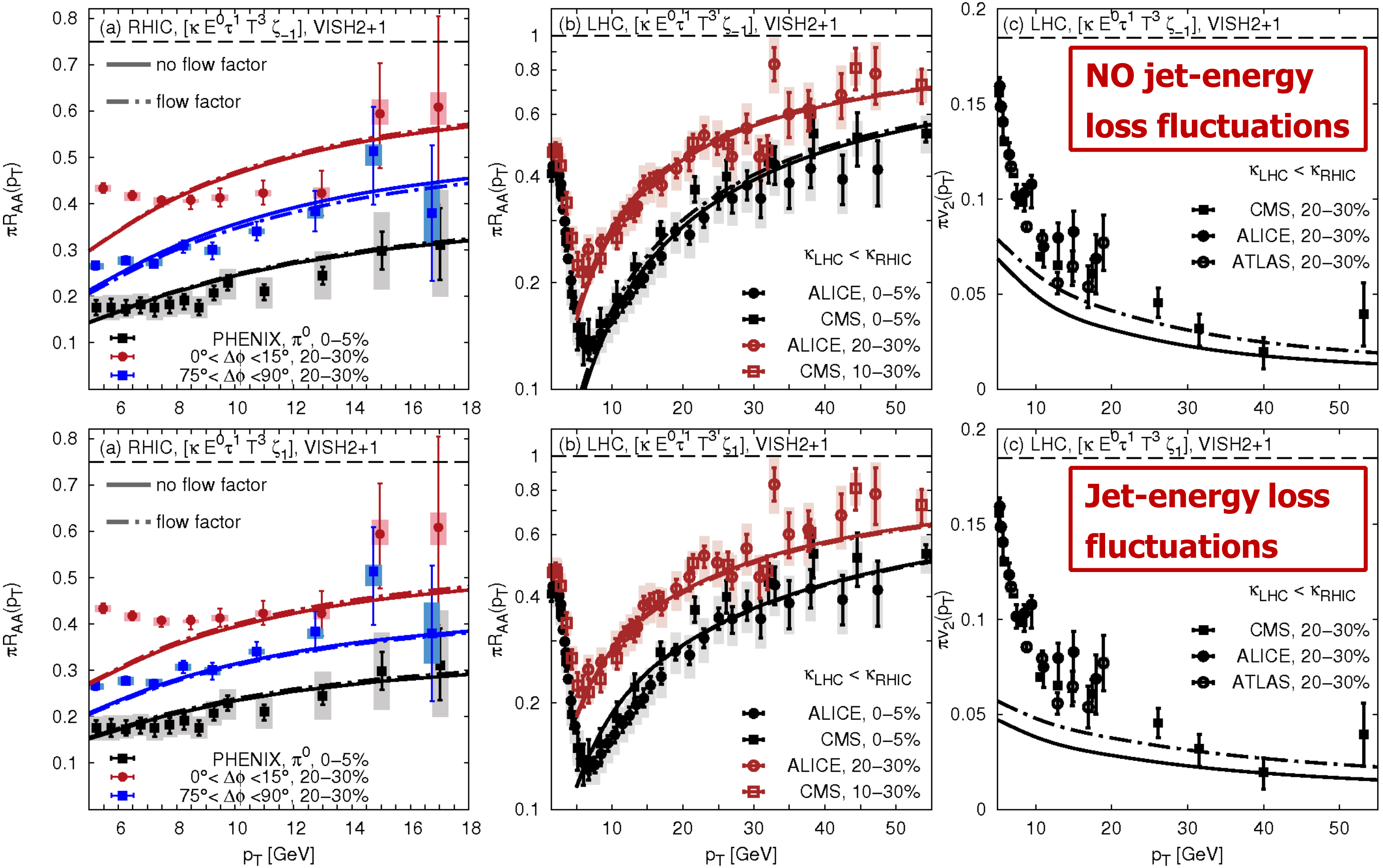
did **NOT** consider the effect of transverse flow on the jet-energy loss.

For that, one needs to include a flow factor

Liu et al., JHEP **0703**, 066 (2007); Baier et al., PLB **649,** 147-151 (2007); Renk et al., PRC **72**, 044901 (2005); Armesto et al., PRC **72,** 064910 (2005)

$$\frac{dP^{\mathrm{flow}}}{d\tau} = \frac{dP}{d\tau}\underbrace{\gamma_f\left[1 - v_f\cos(\phi_{\mathrm{jet}} - \phi_{\mathrm{flow}})\right]}_{\text{flow factor}}$$

# The flow factor



**NO jet-energy loss fluctuations**

**Jet-energy loss fluctuations**

⇒ Including the flow factor, $v_2$ increases @LHC, $R_{AA}$ described @RHIC & LHC

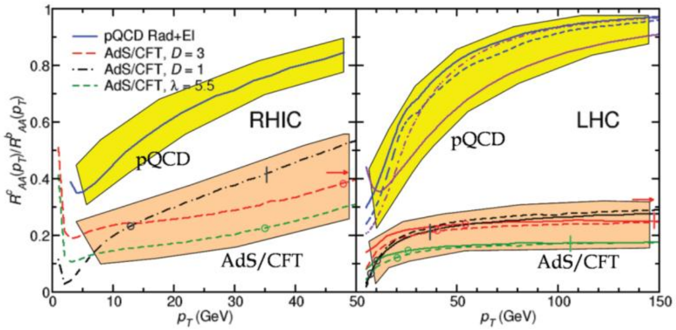
# (Non-conformal) AdS/CFT

# Non-conformal holography @LHC

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

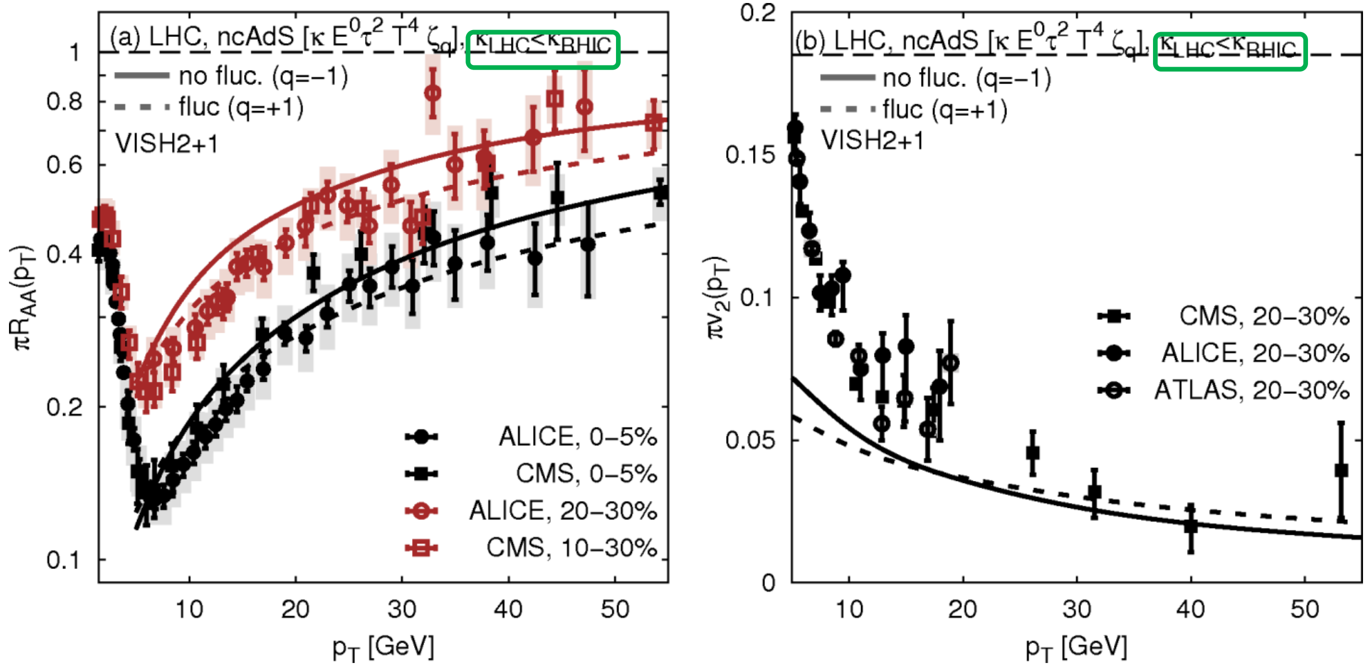
Using conformal AdS, a flat $R_{AA}(p_T)$@LHC was predicted, in contrast to measured data

W. A. Horowitz et al., PLB **666**, 320-323 (2008)



Allowing for **non-conformal, non-standard AdS** (i.e. $dE/dx \sim E^0\tau^2T^4$ with a red. coupling @LHC):

A. Ficnar et al., arXiv: 1311.6160



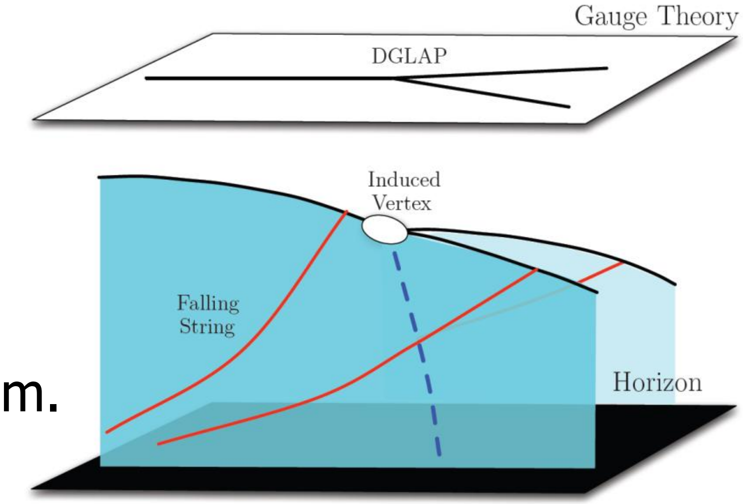
$\Rightarrow$Only conformal AdS fails to describe the ($R_{AA}$ & $v_2$) data BOTH @RHIC & LHC

# A Hybrid Strong/Weak Approach

# Hybrid Strong/Weak Approach

J. Casalderrey-Solana et al., arXiv: 1405.3864

Any partons of the jet propagating in the plasma may suffer hard splittings (weak coupling), described by DGLAP.
Additionally, these partons possess soft fields that interact strongly with the medium.



Energy loss based on falling strings by Chesler et al.:

P. Chesler et al., PRD **90**, 025033 (2014)

$$\frac{1}{E_{\text{in}}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\text{stop}}^2}\frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}$$

$$x_{\text{stop}}^{q,g} = \frac{1}{2\kappa_{\text{sc}}^{(g)}}\frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

$$\kappa_{\text{sc}}^{g} = \kappa_{\text{sc}}\left(\frac{C_A}{C_F}\right)^{1/3}$$

The main difference to our generic energy loss model is the square root.

# Hybrid Strong/Weak Approach

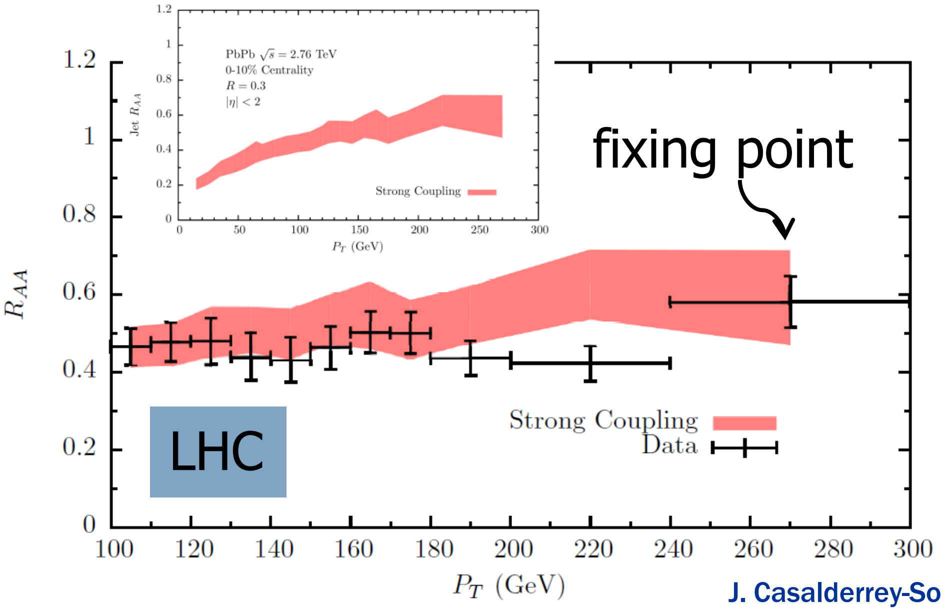
Procedure:

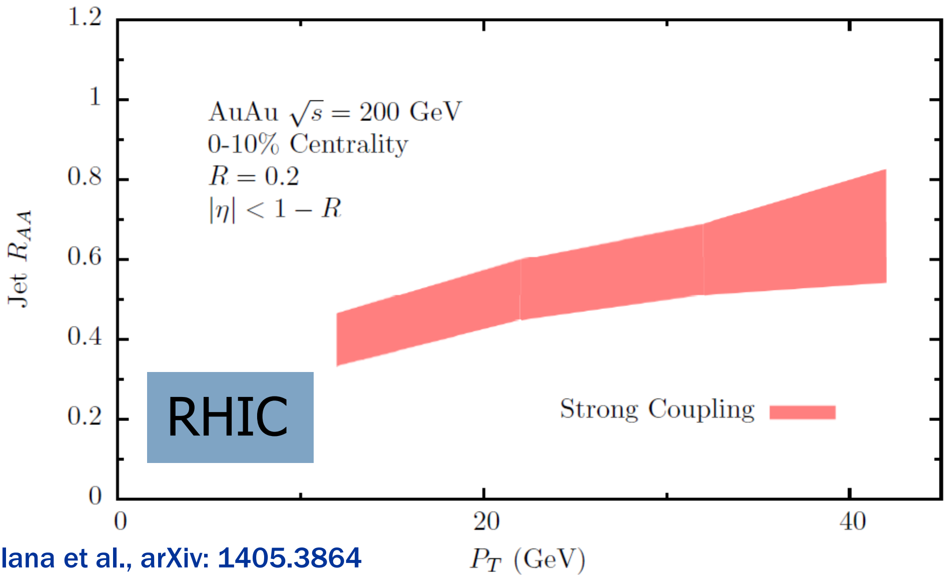
- Create showers with PHYTHIA until $\tau_{hydro}$=0.6fm
- Embed jets in (3+1)d ideal hydro

T. Hirano et al., PRC **84**, 011901 (2011)

- Calculate the energy loss
- Determine the reconstructed jets with FASTJet

M. Cacciari et al., Eur. Phys. J. C **72**, 1896 (2012)





J. Casalderrey-Solana et al., arXiv: 1405.3864

⟹ Using **the same coupling** $\kappa_{SC}$ the yield of the Jet $R_{AA}$ @RHIC & LHC is reproduced

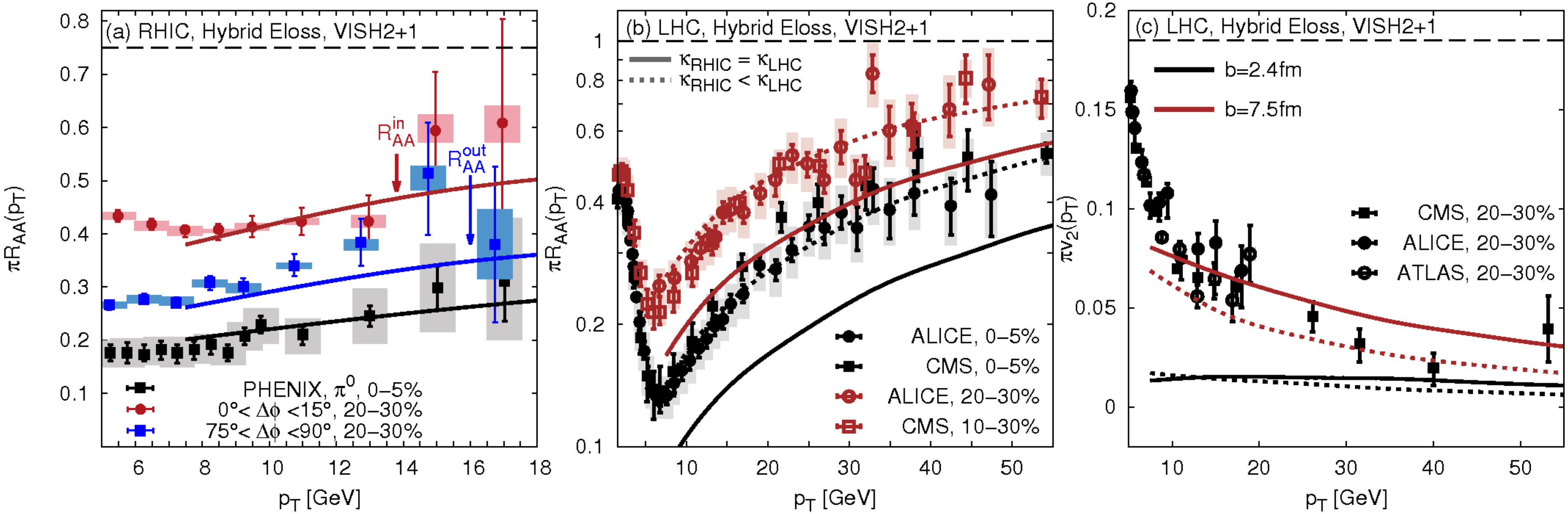
# Hybrid Strong/Weak Approach

Using the falling strings energy loss ansatz

P. Chesler et al., PRD **90**, 025033 (2014)

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\rm stop}^2}\frac{1}{\sqrt{x_{\rm stop}^2 - x^2}}$$

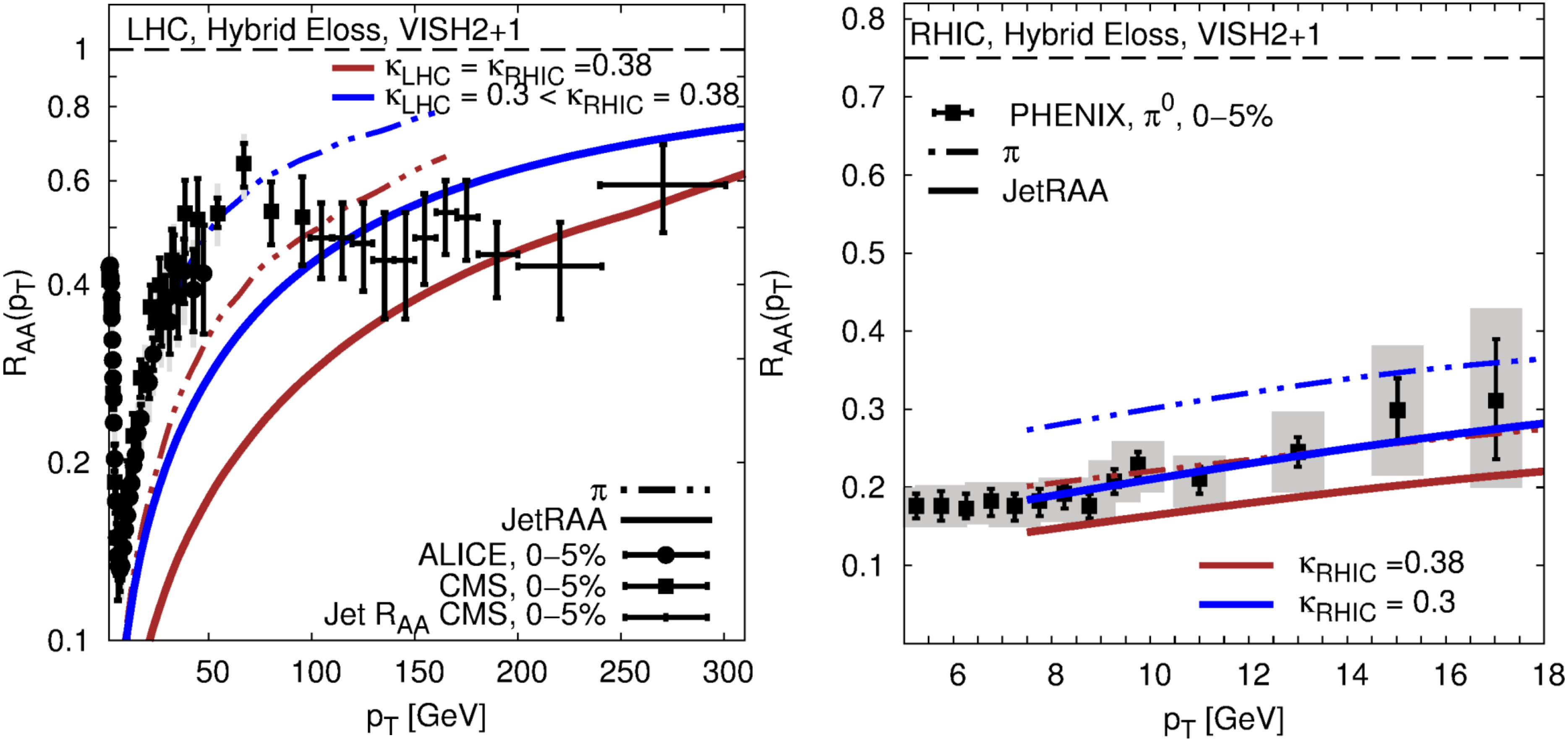
in our model for the VISH2+1 background, we need a reduction from $\kappa_{RHIC}=0.38$ to $\kappa_{LHC}=0.3$ to describe the $R_{AA}$ !!



# Hybrid Strong/Weak Approach

Casalderrey-Solana et al. plotted **Jet $R_{AA}$** NOT **$\pi$ $R_{AA}$** for $p_T$ > 100 GeV:

We assume $\text{Jet}\,R_{AA}(p_T) \;=\; \dfrac{R^g_{AA}(p_T)d\sigma_g(p_T) + R^q_{AA}(pT)d\sigma_q(p_T)}{d\sigma_g(p_T) + d\sigma_q(p_T)}$



⇒ Never compare apples and oranges!

# Summary

**Never compare apples and oranges!**

**Running coupling is essential to describe $\pi$ data @LHC**
An additional flow factor might be needed to describe v2

**Conformal AdS seems to be ruled out**
However, non-conformal generalizations of AdS may provide an alternative

**There is a high degeneracy of solutions**
- $dE^{rad}/dx \sim E^0\tau^1T^3$ without fluctuations,
- $dE^{rad}/dx \sim E^0\tau^1T^3$ with an SLTc $\kappa(T)$,
- $dE^{rad}/dx \sim E^0\tau^1T^3$ with jet-energy loss fluctuations and $\kappa(\phi)$,
- $dE^{rad}/dx \sim E^0\tau^1T^3$ with an exponential $\kappa(T)$,
- and non-conformal $dE/dx \sim E^0\tau^2T^4$

⇒ Path-length exponent cannot be constrained narrower than z=[0-2]
⇒ New jet observables and reduced experimental errors are needed

The evolution of the bulk medium influences the jet-energy loss &
**all details** of both bulk evolution and jet-energy loss **matter equally!**

# Backup

# Energy-loss mechanism

$R_{AA}$ is a ratio of jets 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: $v_2^\pi(N_{part}) = \dfrac{\int d\phi \cos\{2\phi\}\; R^\pi_{AA}(N_{part},\phi)}{\int d\phi\, R^\pi_{AA}(N_{part},\phi)}$

# Energy-loss mechanism with fluctuations

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

$$= \frac{g_{\rm r=q,g}[P_0(P_f)]}{g_{\rm r}(P_f)}\frac{dP_0^2}{dP_f^2}$$

Thus, without fluctuations

$$R_{\rm AA}^{\rm r=q,g} = \frac{g_{\rm r}[P_f+\Delta E(\vec{x}_0,\phi)]}{g_{\rm r}(P_f)}\frac{dP_0^2}{dP_f^2}$$

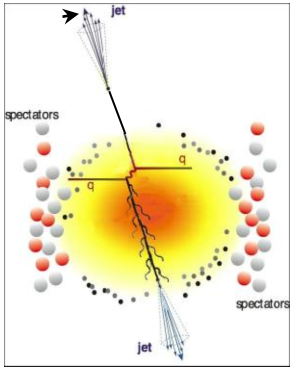
However, with fluctuations

$$R_{\rm AA}^{\rm r,\zeta} = \frac{\int d\zeta f(q,\zeta) g_{\rm r}[P_f+\zeta\overline{\Delta E}(\vec{x}_0,\phi)]}{g_{\rm r}(P_f)}\frac{dP_0^2}{dP_f^2}$$

applying skewed fluctuations of jet-energy loss about its path-averaged mean using a scaling factor $0 < \zeta < q+2$

$$f(q,\zeta) = \frac{1+q}{(q+2)^{1+q}}(q+2-\zeta)^q$$

# Energy-loss mechanism



Generic model of jet-energy loss:

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

- 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: lower bound of power a in falling string scenario

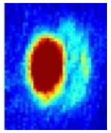
  A. Ficnar, PRD **86** , 046010 (2012)

- a=1, z=2: “AdS/CFT” model

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

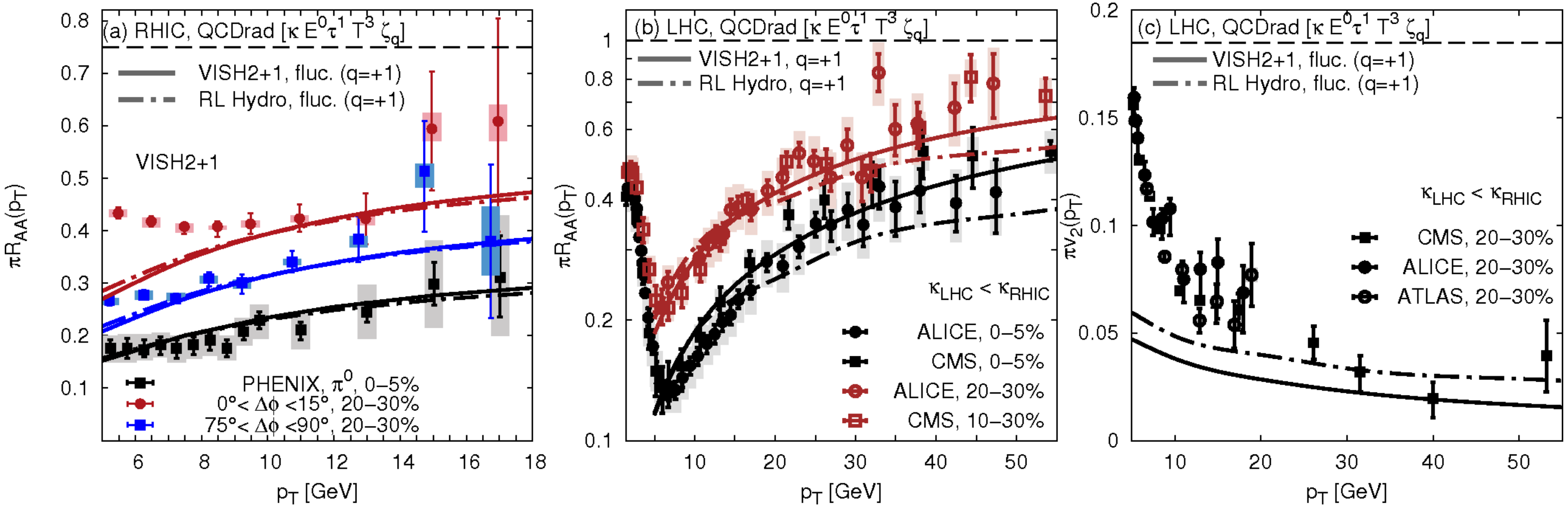
- a<0, z=0: cold atoms Y. Nishida, PRA **85**, 053643 (2012)

  Boltzmann eq. with 2 and 3-body scatterings.



# QCDrad with fluctuations, diff. background

Including more realistic fluctuations of the jet-energy loss shows the impact of different hydrodynamic backgrounds



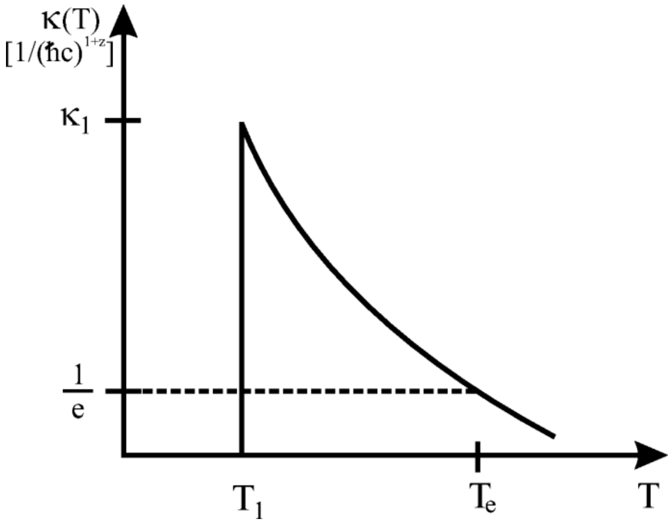
⟹ $R_{AA}$ @LHC more affected for RL Hydro

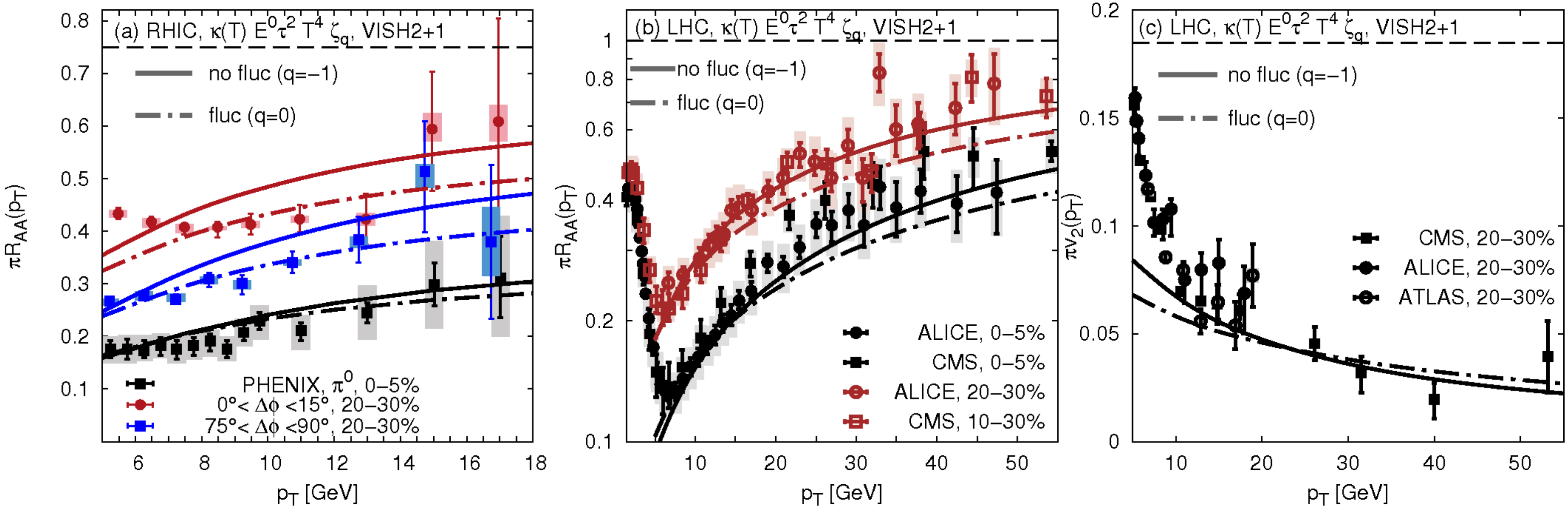
# Exponential κ(T) ansatz, ncAdS

Inspired by the SLTc model,
we consider an exponential ansatz:

$$\kappa(T) = \kappa_1 e^{-b(T-T_1)}$$

⇒ One possible ansatz to describe the LHC transparency.

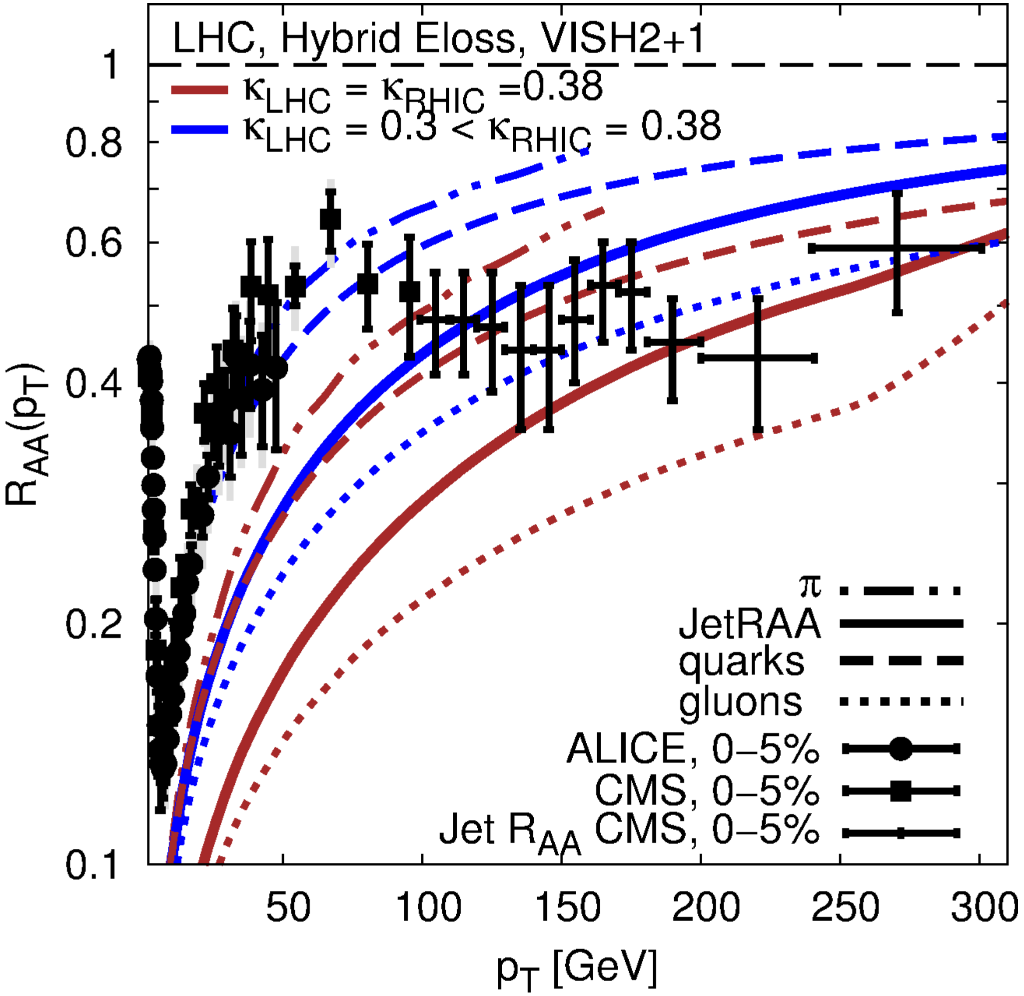




⇒ Data are fairly described.

# Hybrid Strong/Weak Approach

We assume $\text{Jet}\,R_{AA}(p_T) = \dfrac{R^g_{AA}(p_T)d\sigma_g(p_T) + R^q_{AA}(pT)d\sigma_q(p_T)}{d\sigma_g(p_T) + d\sigma_q(p_T)}$

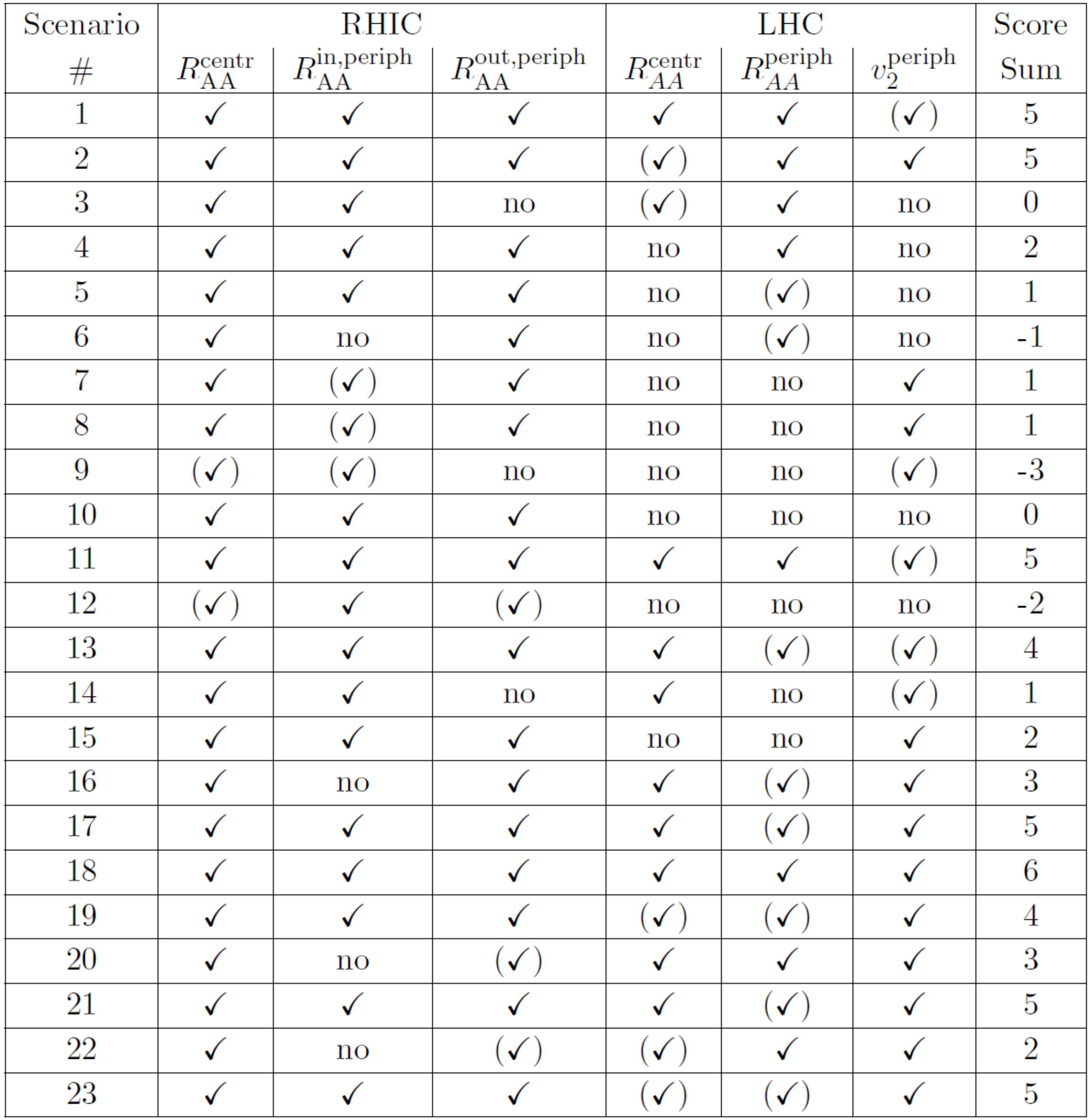


# Survey of results

BB et al., JHEP **80**, 090 (2014)

| # | name | fluct. | $(z, c, q)$ | temp. profile | $\kappa_{\rm RHIC}$ | $\kappa_{\rm LHC}$ | Fig. # |
|---|---|---|---|---|---|---|---|
| 1 | QCDrad | no | $(1, 3, -1)$ | VISH2+1 | 0.970 | 0.834 | 1,4,5 |
| 2 | QCDrad | no | $(1, 3, -1)$ | RL Hydro | 0.505 | 0.485 | 1,4 |
| 3 | QCDrad | no | $(1, 3, -1)$ | $v = 0.6$ | 3.338 | 2.135 | 1,4 |
| 4 | QCDel | no | $(0, 2, -1)$ | VISH2+1 | 2.266 | 2.266 | 1,4 |
| 5 | QCDel | no | $(0, 2, -1)$ | RL Hydro | 1.497 | 1.497 | 1,4 |
| 6 | QCDel | no | $(0, 2, -1)$ | $v = 0.6$ | 5.91 | 5.221 | 1,4 |
| 7 | AdS | no | $(2, 4, -1)$ | VISH2+1 | 0.382 | 0.382 | 1,9 |
| 8 | AdS | no | $(2, 4, -1)$ | RL Hydro | 0.168 | 0.168 | 1,9 |
| 9 | AdS | no | $(2, 4, -1)$ | $v = 0.6$ | 1.781 | 1.781 | 1,9 |
| 10 | SLTc | no | $(1, 3, -1)$ | VISH2+1 | 0.408 | 0.408 | 1,9 |
| 11 | SLTc | no | $(1, 3, -1)$ | RL Hydro | 0.334 | 0.334 | 1,9 |
| 12 | SLTc | no | $(1, 3, -1)$ | $v = 0.6$ | 1.552 | 1.552 | 1,9 |
| 13 | QCDrad | yes | $(1, 3, +1)$ | VISH2+1 | 1.859 | 1.358 | 2,5 |
| 14 | QCDel | yes | $(1, 3, +1)$ | VISH2+1 | 4.236 | 4.039 | 2,5 |
| 15 | AdS | yes | $(2, 4, +1)$ | VISH2+1 | 0.703 | 0.703 | 2,10(a,b) |
| 16 | ncAdS | no | $(2, 4, -1)$ | VISH2+1 | 0.382 | 0.210 | 2,10(c,d) |
| 17 | ncAdS | yes | $(2, 4, +1)$ | VISH2+1 | 0.703 | 0.417 | 2,10(c,d) |
| 18 | $\kappa(\phi)$ QCDrad | yes | $(1, 3, 0)$ | VISH2+1 | 1.475 | 1.203 | 8 |
| 19 | $\kappa(\phi)$ QCDrad | yes | $(1, 3, 0)$ | RL Hydro | 0.854 | 0.710 | 8 |
| 20 | exp. $\kappa(T)$ QCDrad | no | $(1, 3, -1)$ | VISH2+1 | $\kappa_1$=2.057 | $\kappa_1$=2.057 | 12 |
| 21 | exp. $\kappa(T)$ QCDrad | yes | $(1, 3, 0)$ | VISH2+1 | $\kappa_1$=3.609 | $\kappa_1$=3.609 | 12 |
| 22 | exp. $\kappa(T)$ ncAdS | no | $(2, 4, -1)$ | VISH2+1 | $\kappa_1$=0.849 | $\kappa_1$=0.849 | 13 |
| 23 | exp. $\kappa(T)$ ncAdS | yes | $(2, 4, 0)$ | VISH2+1 | $\kappa_1$=1.529 | $\kappa_1$=1.529 | 13 |

# Survey of results



| Scenario | RHIC | | | LHC | | | Score |
|---|---|---|---|---|---|---|---|
| # | $R_{AA}^{\text{centr}}$ | $R_{AA}^{\text{in,periph}}$ | $R_{AA}^{\text{out,periph}}$ | $R_{AA}^{\text{centr}}$ | $R_{AA}^{\text{periph}}$ | $v_2^{\text{periph}}$ | Sum |
| 1 | ✓ | ✓ | ✓ | ✓ | ✓ | (✓) | 5 |
| 2 | ✓ | ✓ | ✓ | (✓) | ✓ | ✓ | 5 |
| 3 | ✓ | ✓ | no | (✓) | ✓ | no | 0 |
| 4 | ✓ | ✓ | ✓ | no | ✓ | no | 2 |
| 5 | ✓ | ✓ | ✓ | no | (✓) | no | 1 |
| 6 | ✓ | no | ✓ | no | (✓) | no | -1 |
| 7 | ✓ | (✓) | ✓ | no | no | ✓ | 1 |
| 8 | ✓ | (✓) | ✓ | no | no | ✓ | 1 |
| 9 | (✓) | (✓) | no | no | no | (✓) | -3 |
| 10 | ✓ | ✓ | ✓ | no | no | no | 0 |
| 11 | ✓ | ✓ | ✓ | ✓ | ✓ | (✓) | 5 |
| 12 | (✓) | ✓ | (✓) | no | no | no | -2 |
| 13 | ✓ | ✓ | ✓ | ✓ | (✓) | (✓) | 4 |
| 14 | ✓ | ✓ | no | ✓ | no | (✓) | 1 |
| 15 | ✓ | ✓ | ✓ | no | no | ✓ | 2 |
| 16 | ✓ | no | ✓ | ✓ | (✓) | ✓ | 3 |
| 17 | ✓ | ✓ | ✓ | ✓ | (✓) | ✓ | 5 |
| 18 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 6 |
| 19 | ✓ | ✓ | ✓ | (✓) | (✓) | ✓ | 4 |
| 20 | ✓ | no | (✓) | ✓ | ✓ | ✓ | 3 |
| 21 | ✓ | ✓ | ✓ | ✓ | (✓) | ✓ | 5 |
| 22 | ✓ | no | (✓) | (✓) | ✓ | ✓ | 2 |
| 23 | ✓ | ✓ | ✓ | (✓) | (✓) | ✓ | 5 |

BB et al., JHEP **80**, 090 (2014)

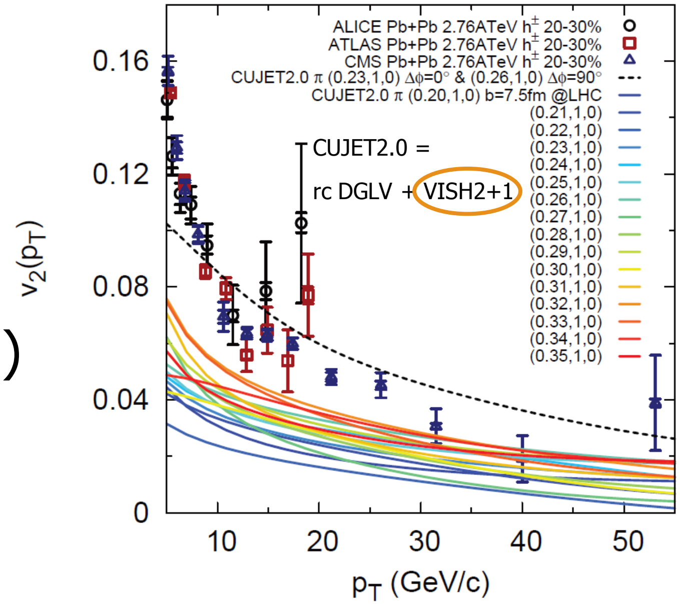
# Path-variation of the jet-medium coupling

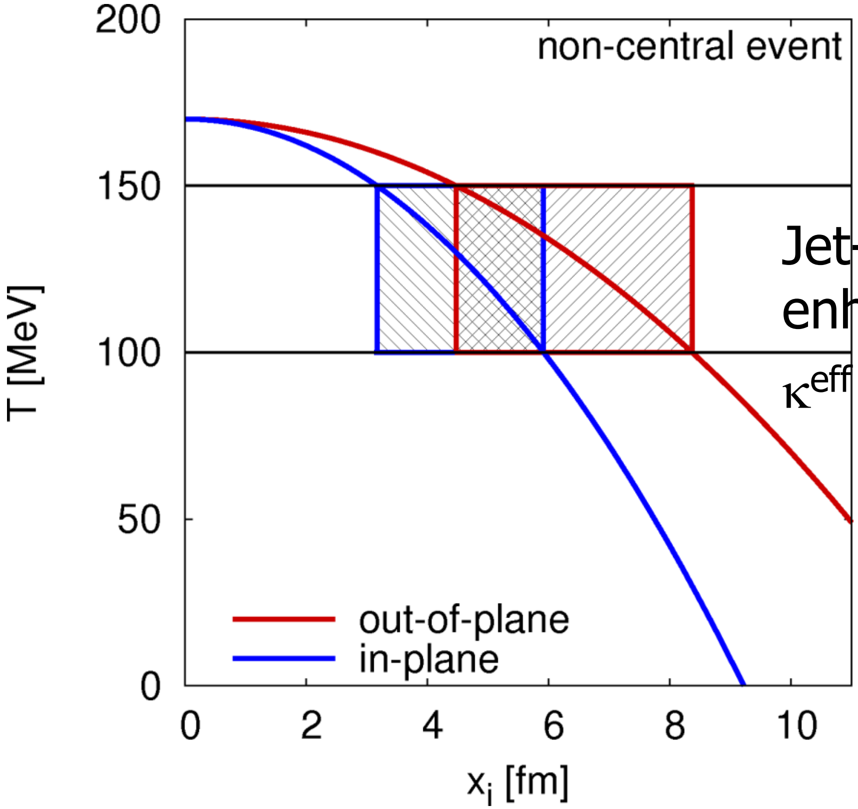
Ansatz to solve the high-$p_T$ $v_2$-puzzle:

Assume a modest variation of the jet-medium coupling in- and out-of-plane, corresponding to a temperature dependence of $\alpha_{max}$.

Effectively, $\alpha_{max}$ (out-of-plane) $>$ $\alpha_{max}$ (in-plane)

J. Xu et al., JHEP **1408**, 063 (2014)





Jet-medium coupling enhanced for 100<T<150 MeV

$\kappa^{eff}$ (out-of-plane) $>$ $\kappa^{eff}$ (in-plane)