GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Azimuthal Jet Tomography at RHIC and LHC

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in collaboration with Miklos Gyulassy

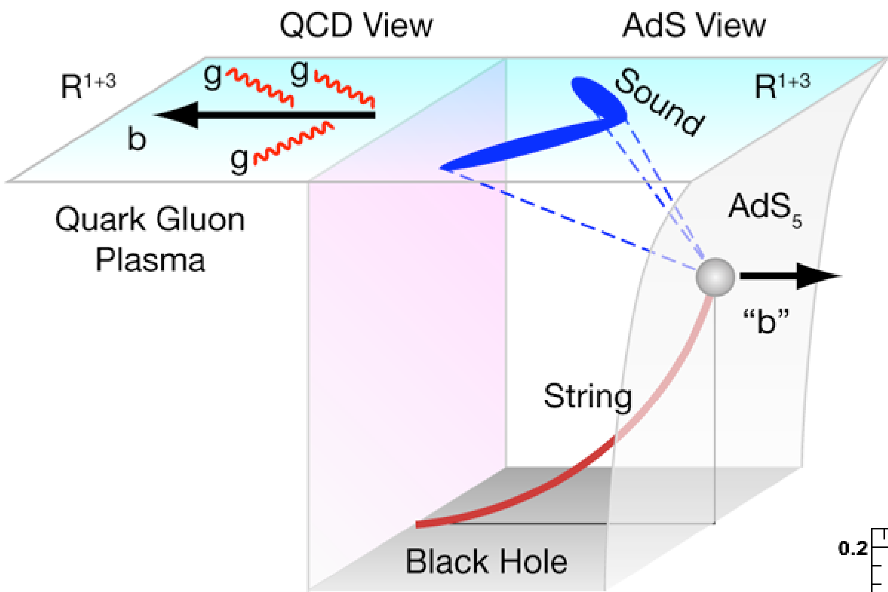
PRC **84**, 024913 (2011); PRC **86**, 024903 (2012);
arXiv: 1305.6458; 1402.3419; 1404.6378

Survey of results

BB et al., arXiv: 1404.6378

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

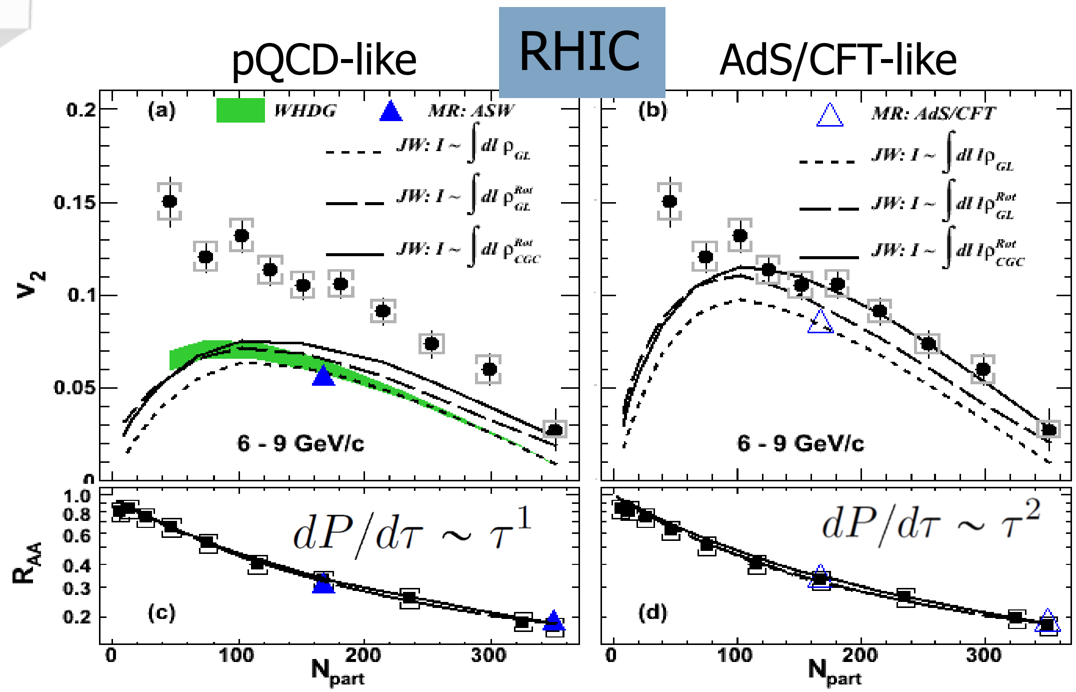
Jet quenching in pQCD vs. AdS/CFT



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?

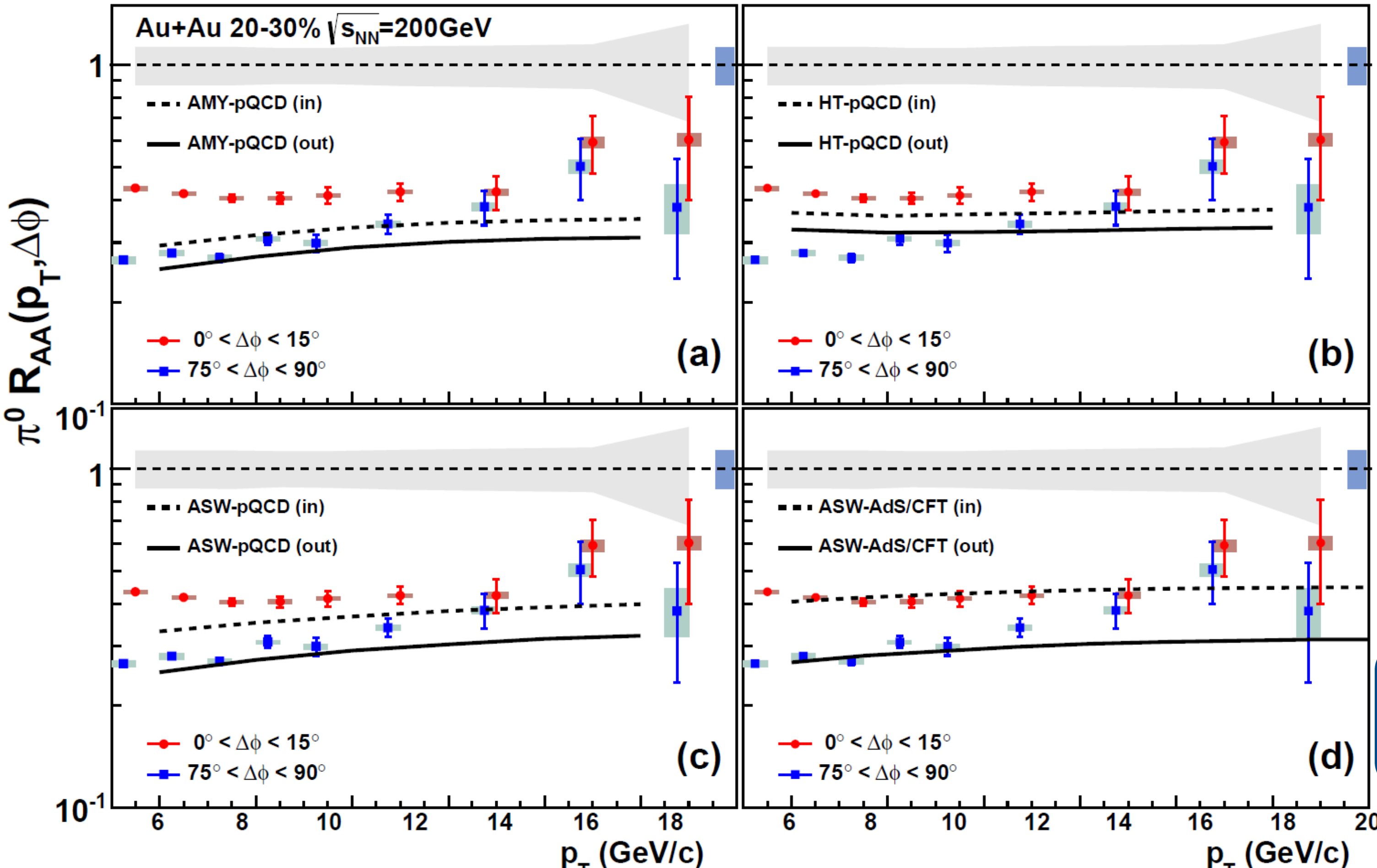


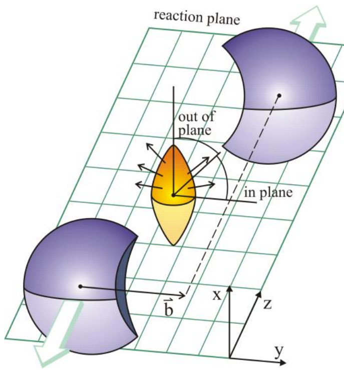
PHENIX results seem to indicate an AdS/CFT-inspired energy-loss???

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

pQCD vs. AdS/CFT @RHIC

A. Adare et al., Phys. Rev. C **87**, 034911 (2013)





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

$$\boxed{\begin{aligned} R_{AA}^{in} &= R_{AA}(1+2v_2) \\ R_{AA}^{out} &= R_{AA}(1-2v_2) \end{aligned}}$$

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

Caveat: Result may depend on analysis method R. Lacey, Phys. Rev. C **80**, 051901 (2009)

Energy-loss mechanism

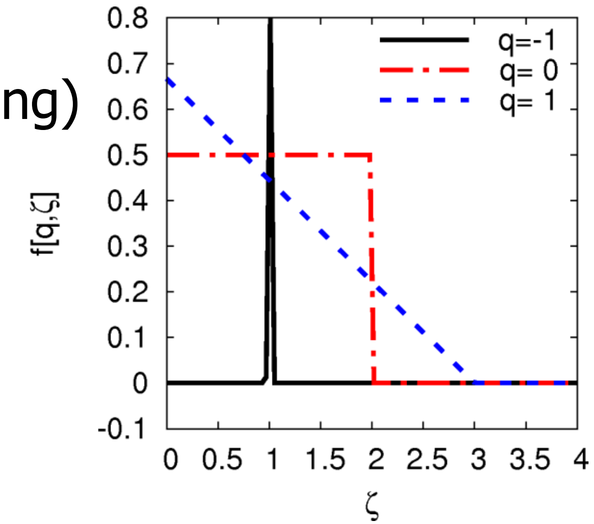
Generic model of jet-energy loss:

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

BB et al., PRC **86**, 024903 (2012); arXiv:1404.6378

including more realistic fluctuations of the jet-energy loss about its path averaged mean via ζ_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

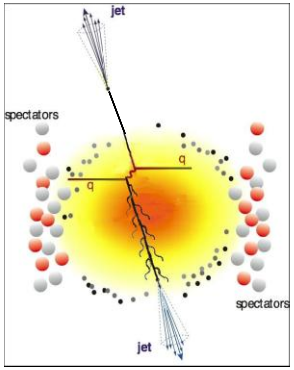


energy-loss fluctuation distribution

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

Energy-loss mechanism

Generic model of jet-energy loss:



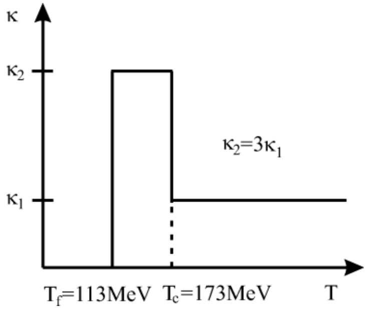
M. Gyulassy et al,. PRL **86**, 2537 (2001)

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

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

BB et al., arXiv: arXiv:1404.6378

- 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)

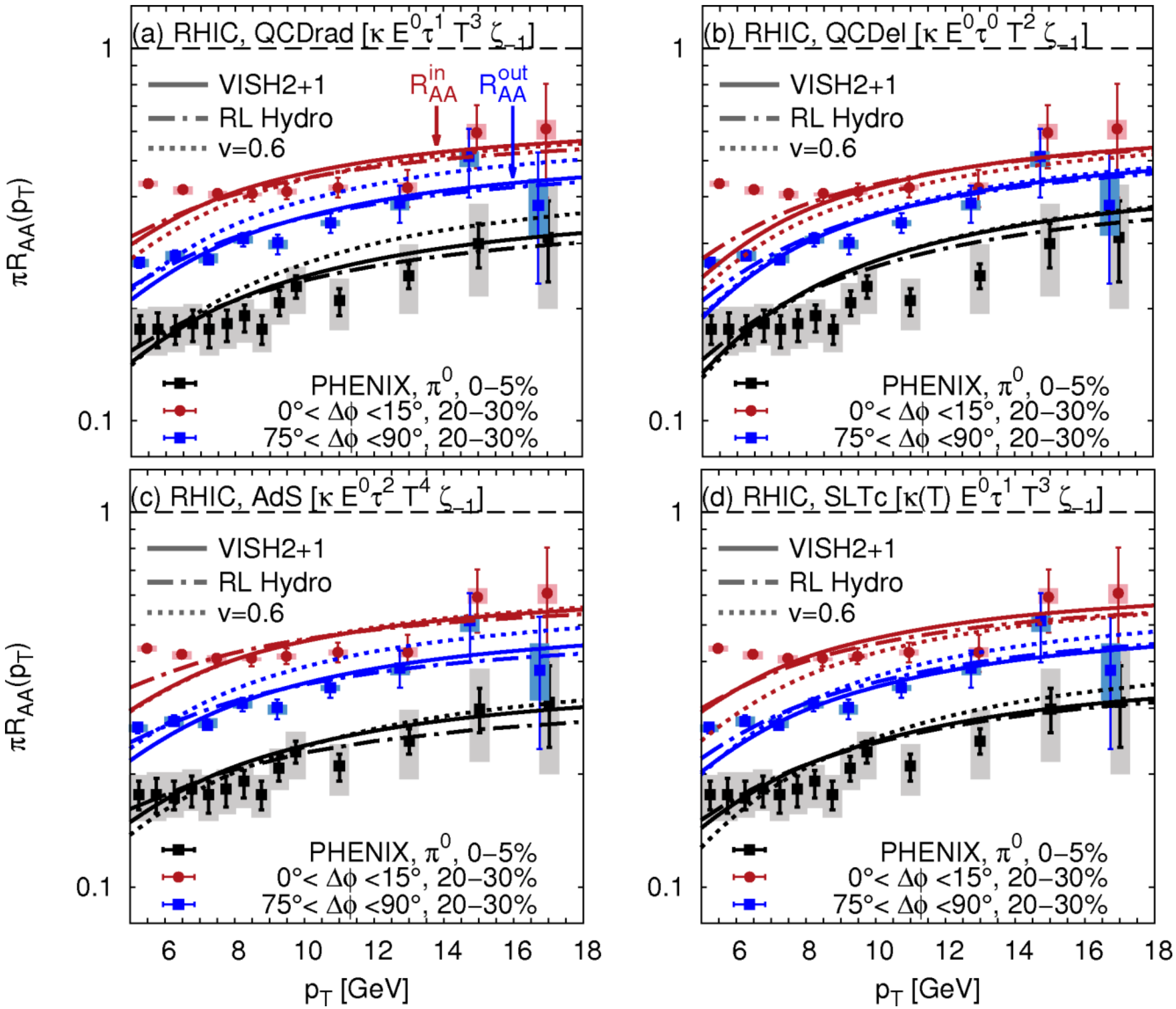


J.Liao et al., PRL **102** , 202302 (2009)

- 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.

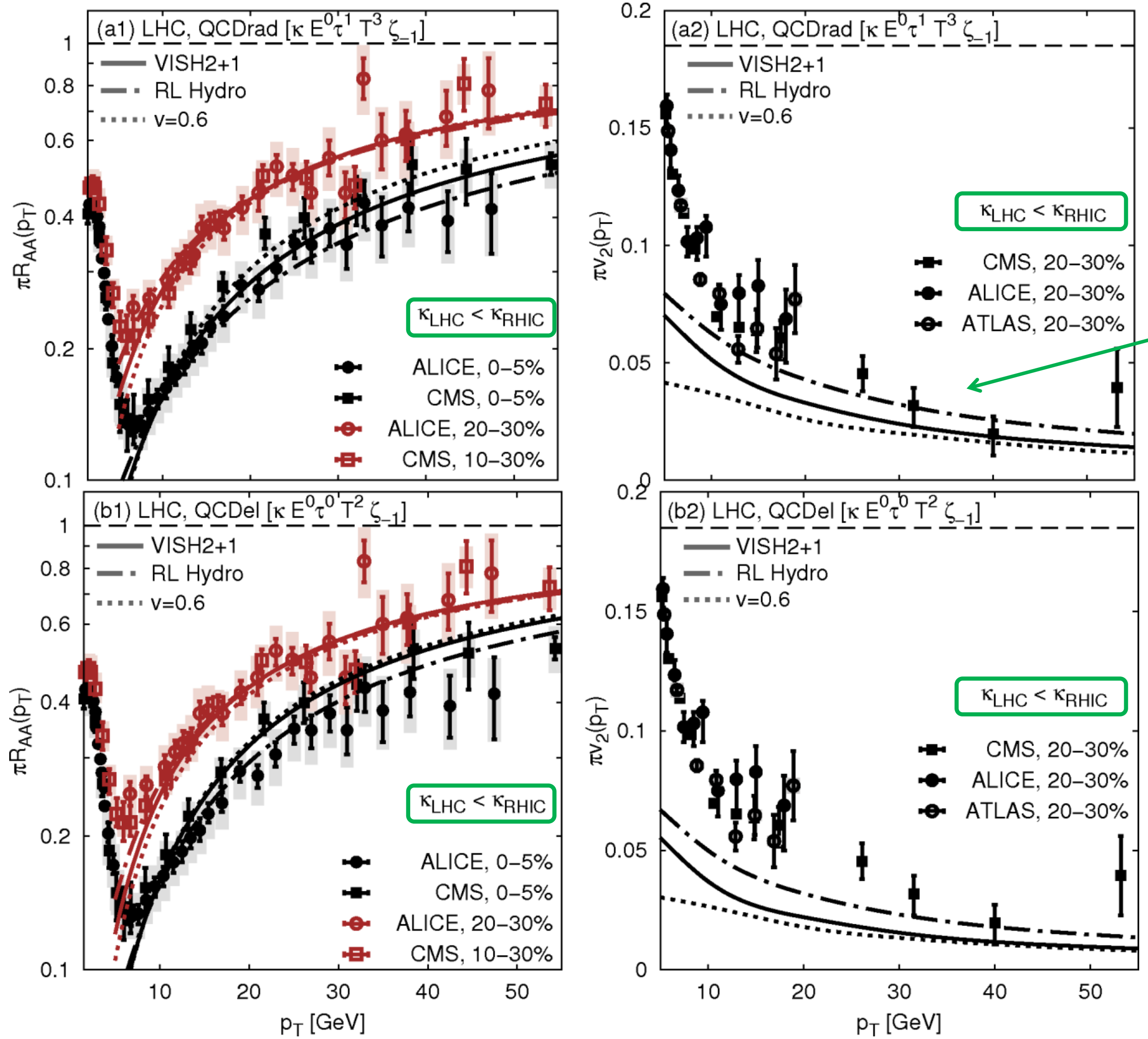
R_{AA}^{in} and R_{AA}^{out} @RHIC, no fluctuations



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.

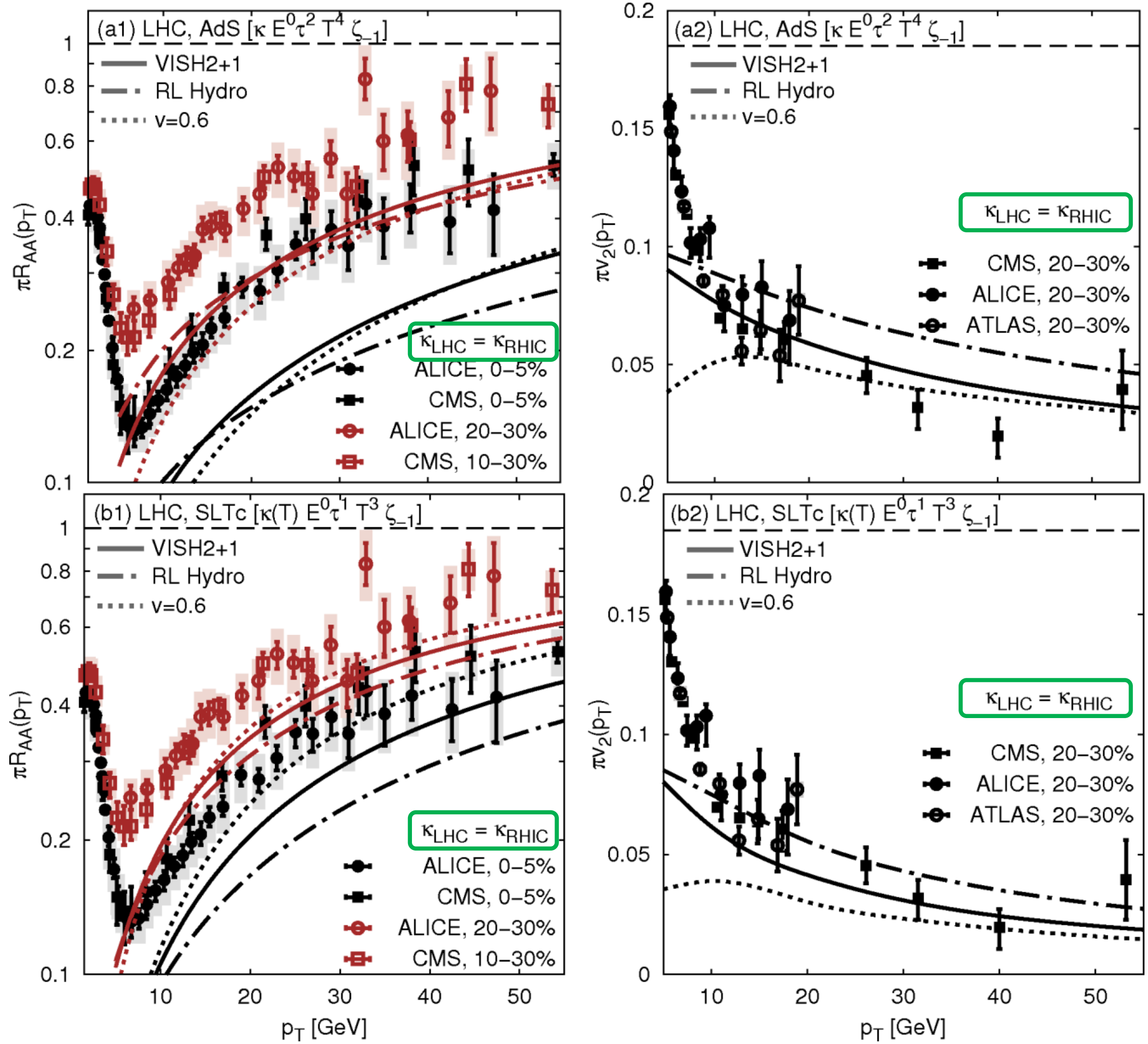
pQCD-like models @LHC, no fluctuations



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

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

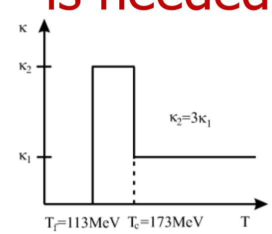
Non-perturb. models @LHC, no fluctuations



The conformal AdS and the SLTc model overquench for a fixed coupling @LHC

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

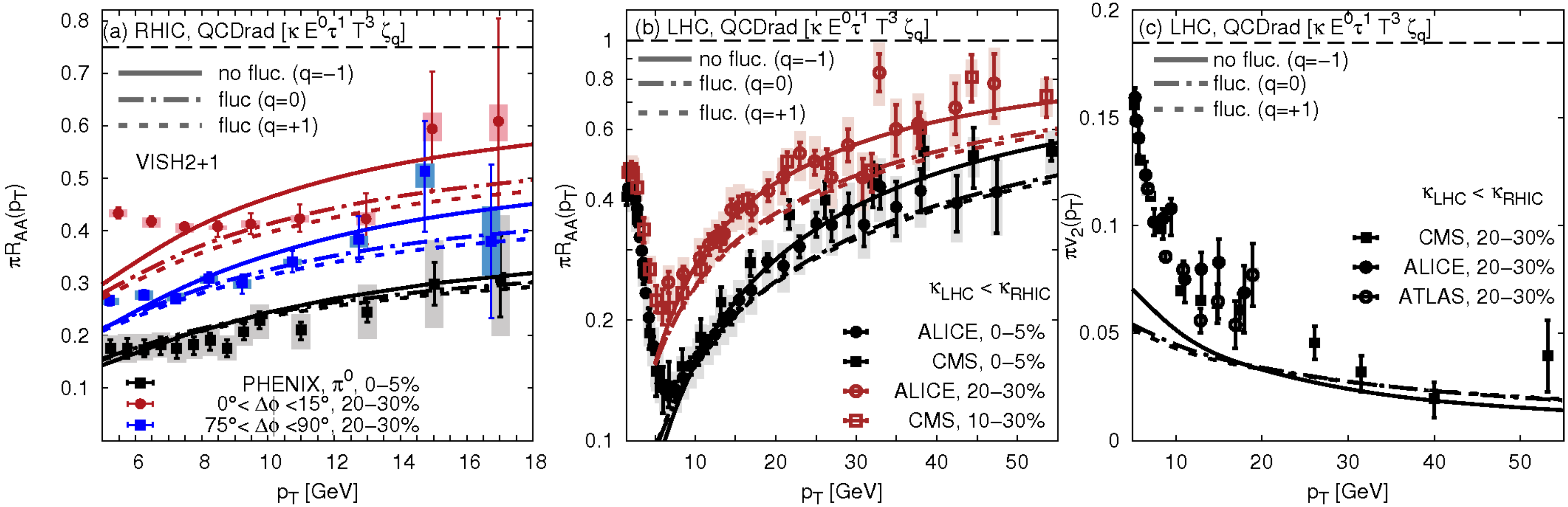
SLTc $\kappa(T)$ is not enough to describe the LHC data, more running is needed.



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:

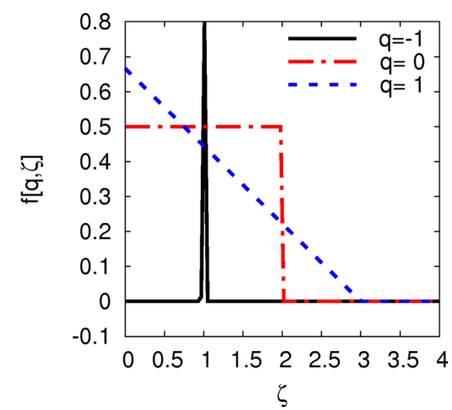


⟹ R_{AA} gets smaller, v_2 less affected, v_2@LHC too low

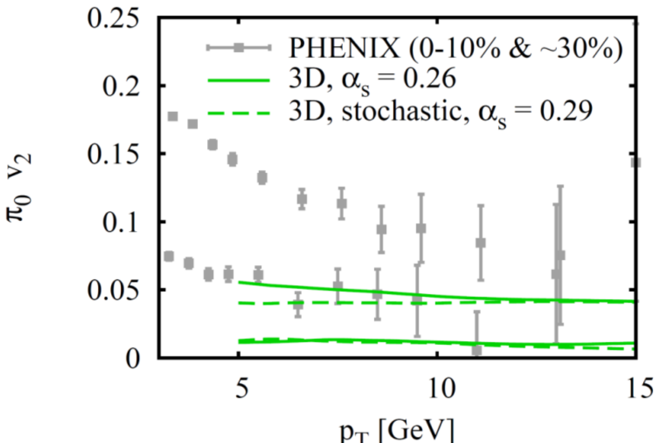
Background impacts results (v_2@LHC larger for RL hydro)

energy-loss fluctuation distribution

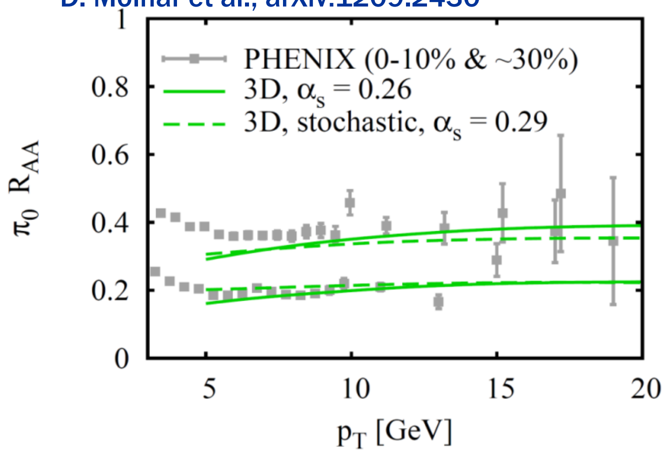
$$f(q,\zeta_q) = \frac{1+q}{(q+2)^{1+q}}\,(q+2-\zeta_q)^q$$



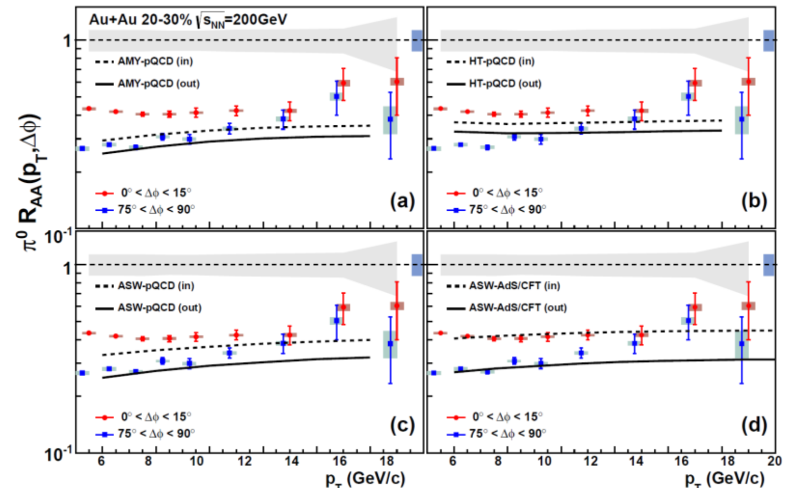
The high-p_T v_2 problem of pQCD models



D. Molnar et al., arXiv:1209.2430

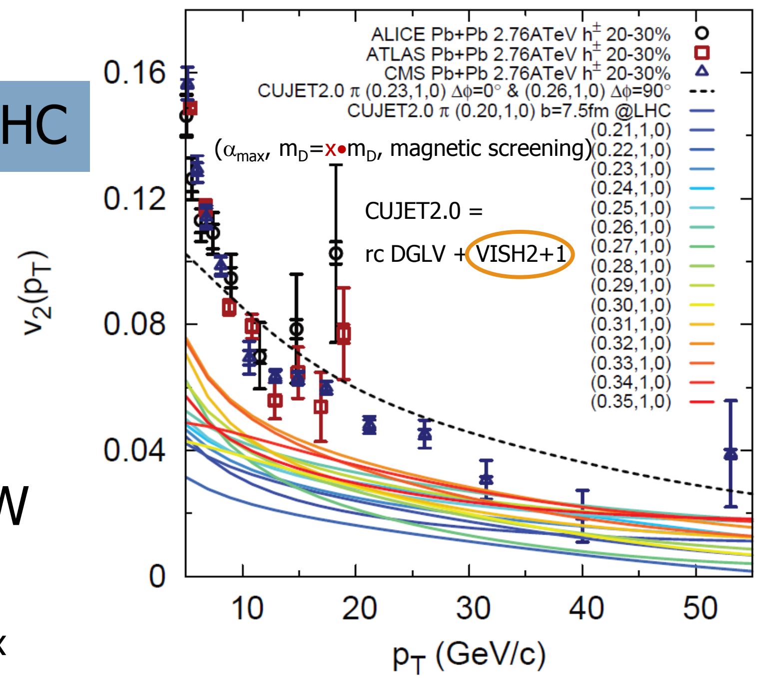


RHIC



A. Adare et al., PRC **87**, 034911 (2013)

LHC



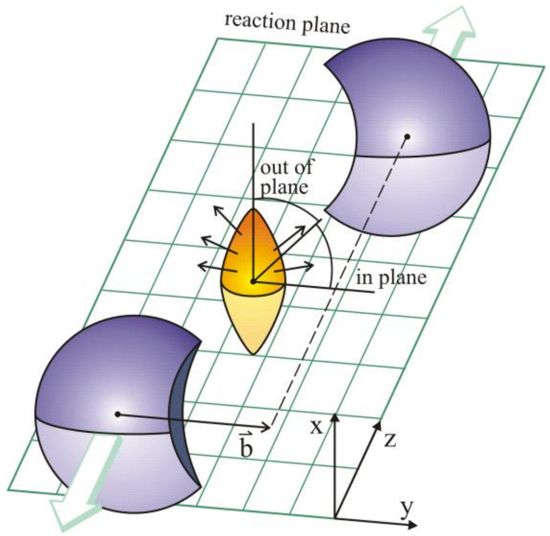
J. Xu et al., arXiv:1402.2956

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

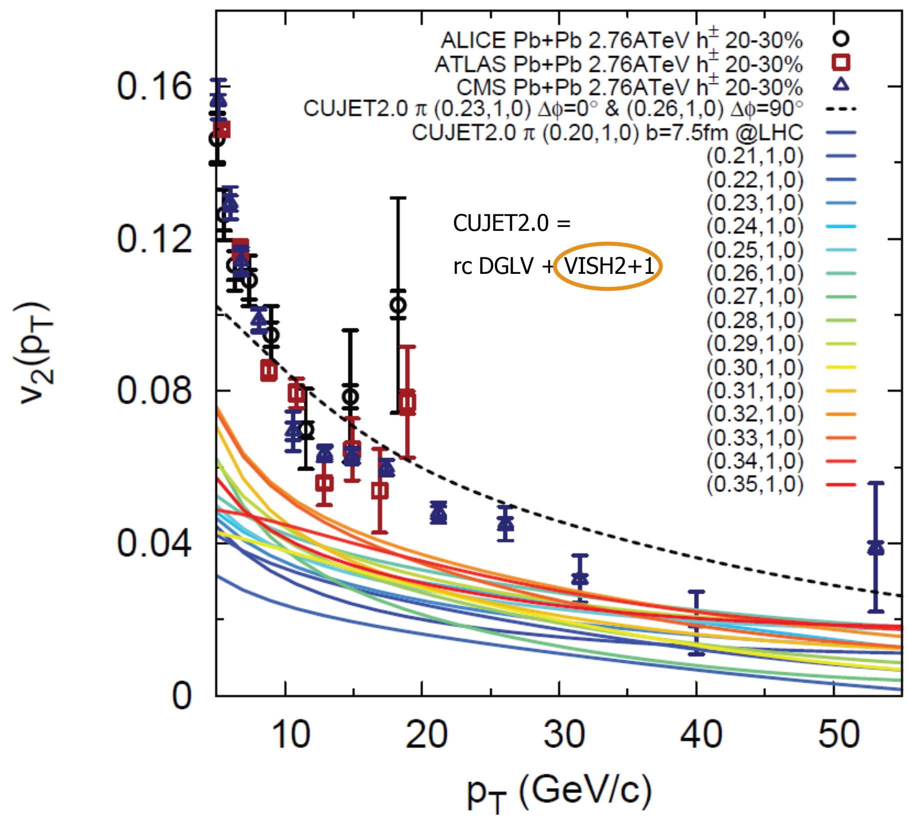
Path-variation of the jet-medium coupling

Ansatz to solve the high-p_T v_2-puzzle:

J. Xu et al., arXiv:1402.2956



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



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

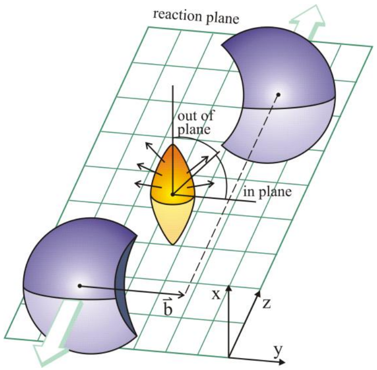
Path-variation of the jet-medium coupling

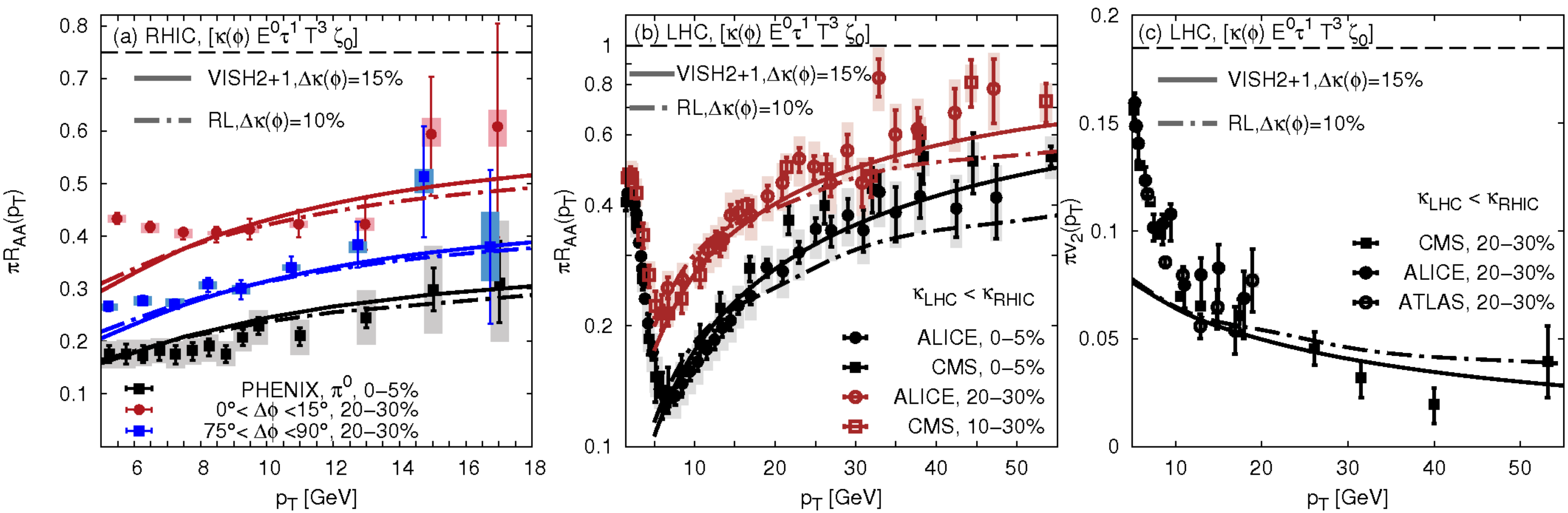
To mimic this ansatz with

α_{max} (out-of-plane) > α_{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





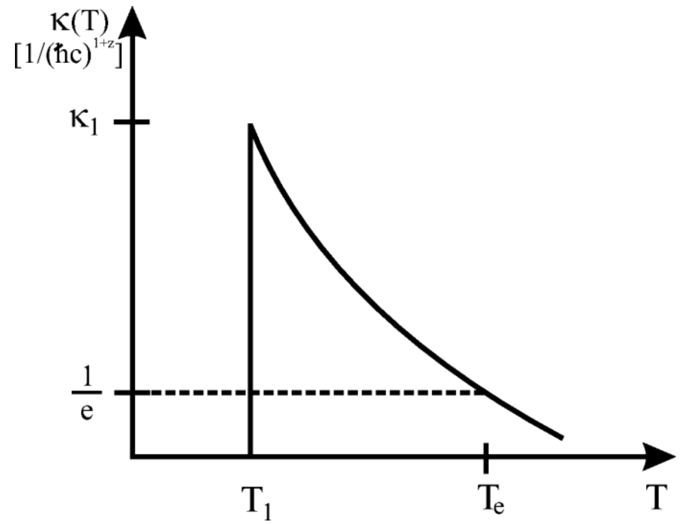
⇒ R_{AA} and v_2 can be described BOTH @RHIC & @LHC, assuming running coupling and a fluctuating, pQCD-like $dE^{rad}/dx \sim E^0\tau^1T^3$

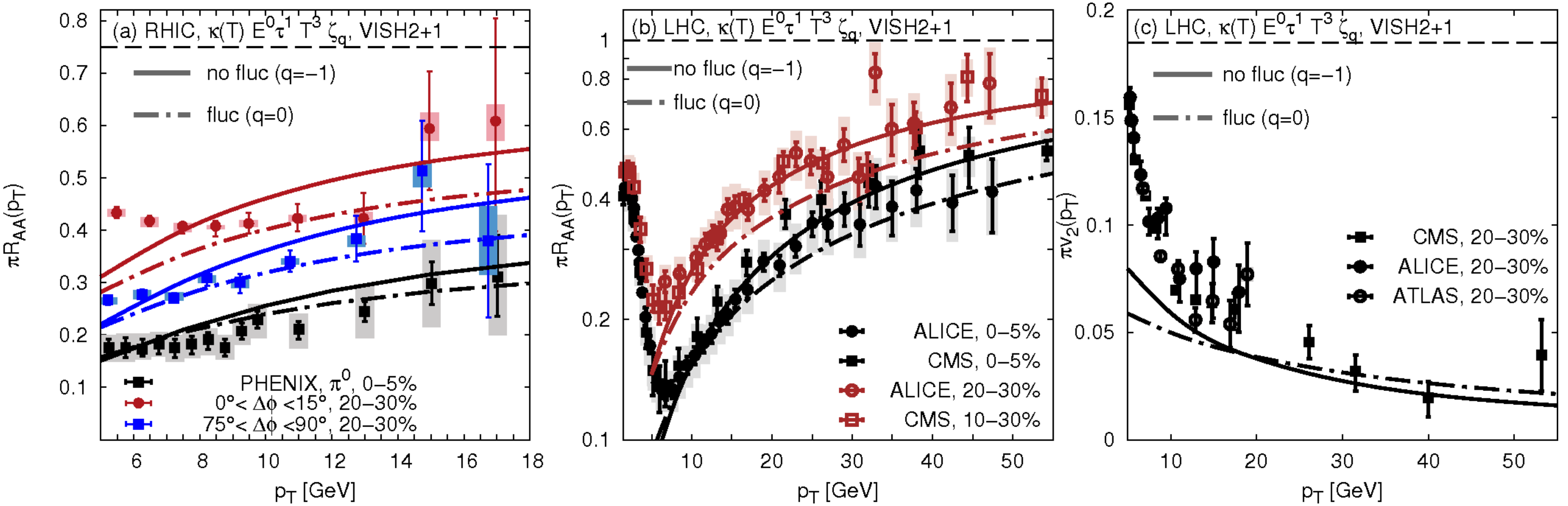
Exponential κ(T) ansatz

Inspired by the SLTc model that did NOT reproduce opacity of the LHC medium, we consider an exponential ansatz:

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

⇒ One possible ansatz to describe the LHC transparency.





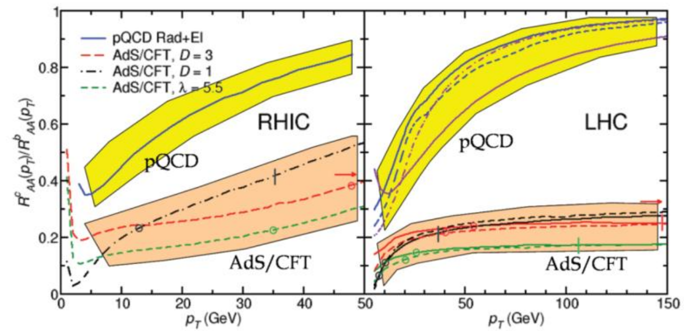
⇒ Data are fairly described.

Non-conformal holography @LHC

Conformal AdS: scale cannot change,

i.e. the coupling cannot run

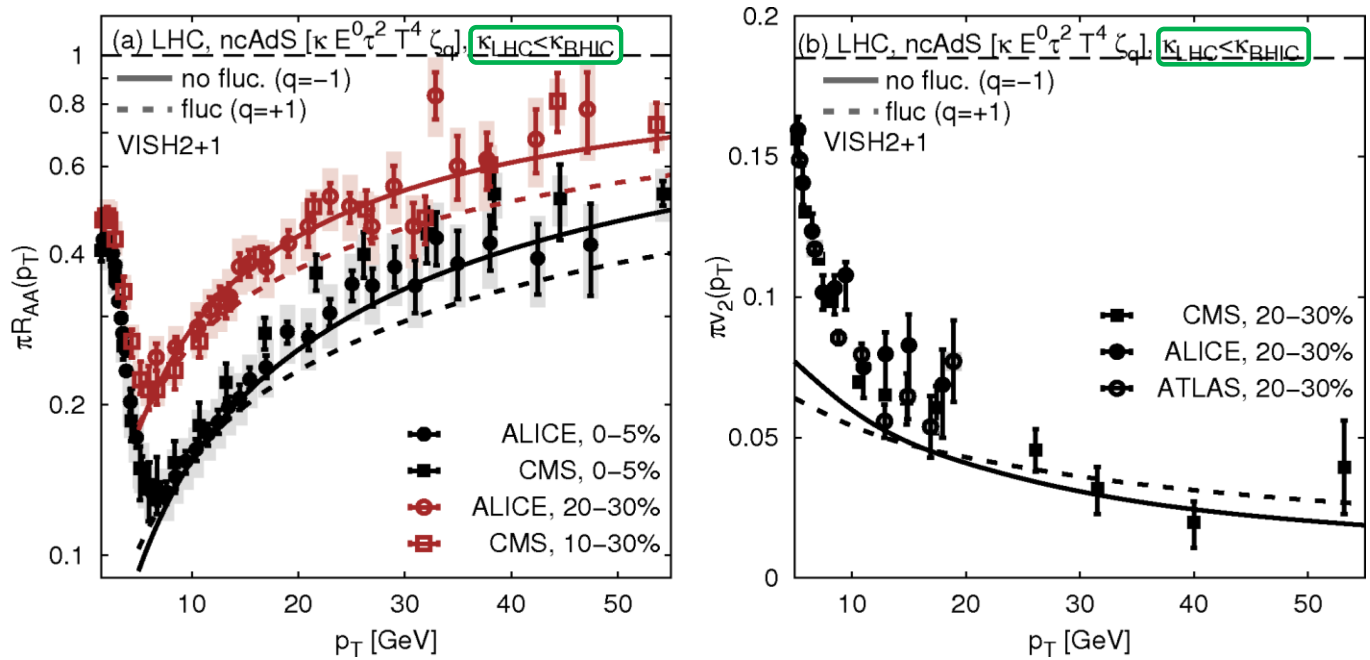
W. A. Horowitz et al., PLB **666**, 320-323 (2008)



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

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



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

Summary

Comparison of R_{AA} & v_2 @RHIC & LHC with pQCD & AdS/CFT-inspired energy-loss models for various hydrodynamic backgrounds shows:

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

Running coupling is essential to describe data @LHC

There is a high degeneracy of solutions
- $dE^{rad}/dx \sim E^0\tau^1T^3$ or $dE^{el}/dx \sim E^0\tau^0T^2$ without fluctuations,
- $dE^{rad}/dx \sim E^0\tau^1T^3$ 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 $dE/dx \sim E^0\tau^2T^4$

provide a decent description to BOTH RHIC & LHC data.

$\Rightarrow$ Path-length exponent cannot be constrained narrower than z=[0-2]
$\Rightarrow$ 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!**

Backup

Energy-loss mechanism

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

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

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 mechanism with fluctuations

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

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

Thus, without fluctuations

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

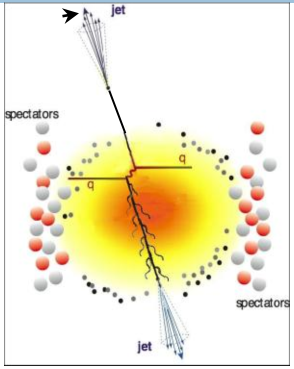
However, with fluctuations

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

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

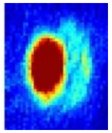
  A. Ficnar, arXiv: 1201.1780

- a=1, z=2: "AdS/CFT" model

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

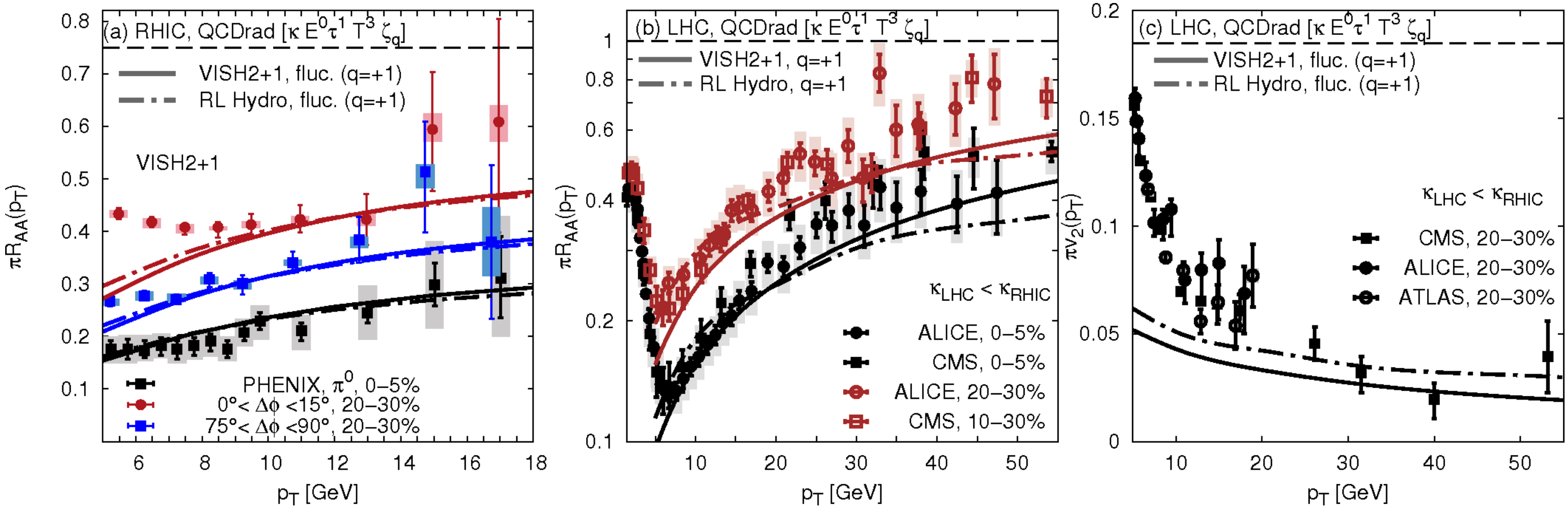
- a<0, z=0: cold atoms Y. Nishida, arXiv: 1110.5926

  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

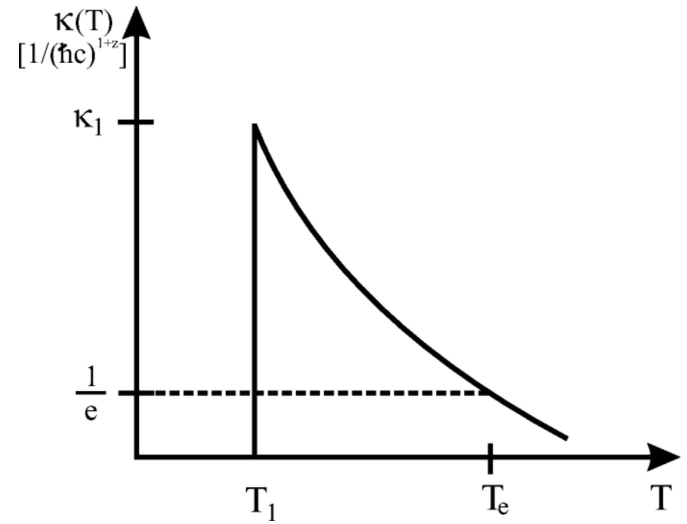


⟹ R_{AA} @LHC more affected for RL Hydro

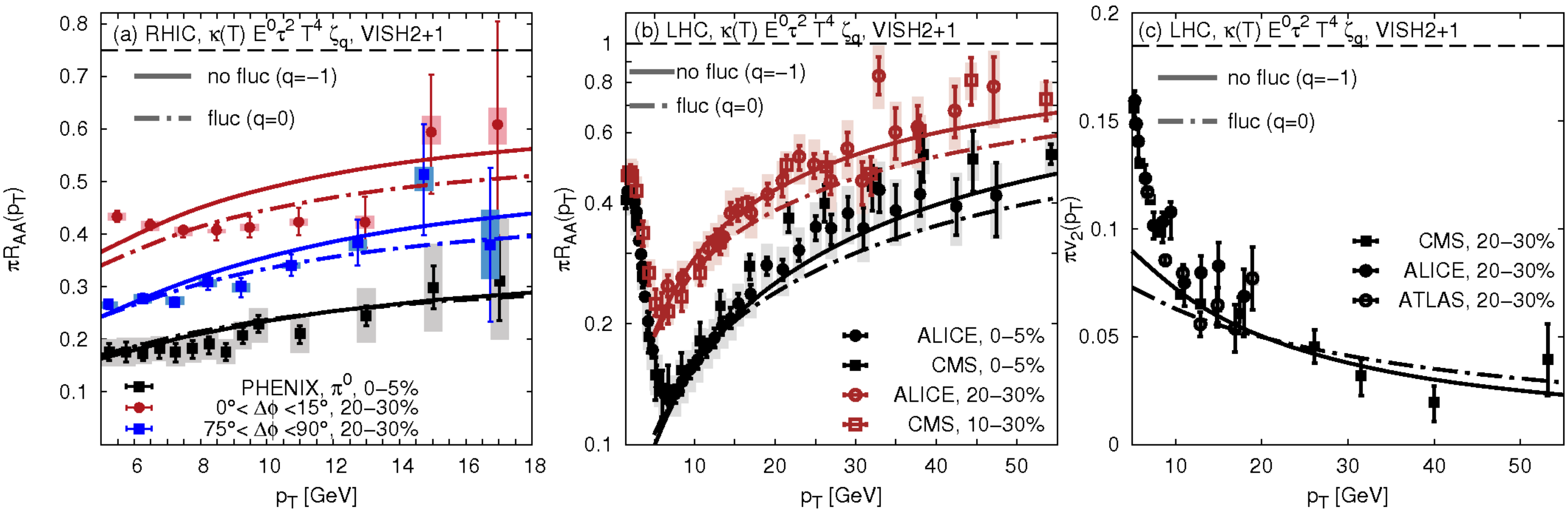
Exponential κ(T) ansatz, ncAdS

Inspired by the SLTc model that did NOT reproduce opacity of the LHC medium, we consider an exponential ansatz:

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



$\Longrightarrow$ One possible ansatz to describe the LHC transparency.



$\Longrightarrow$ Data are fairly described.

Survey of results

#	name	fluct.	(z, c, q)	temp. profile	κ_{RHIC}	κ_{LHC}	Fig. #
1	QCDrad	no	$(1, 3, -1)$	VISH2+1	0.380	0.167	1,4,5
1a	QCDrad	no	$(1, 3, -1)$	VISH2+1	0.380	0.136	1,6
2	QCDrad	no	$(1, 3, -1)$	RL Hydro	0.477	0.241	1,4
3	QCDrad	no	$(1, 3, -1)$	$v = 0.6$	3.182	2.096	1,4
4	QCDel	no	$(0, 2, -1)$	VISH2+1	0.887	0.483	1,4
5	QCDel	no	$(0, 2, -1)$	RL Hydro	1.497	0.906	1,4
6	QCDel	no	$(0, 2, -1)$	$v = 0.6$	5.713	5.024	1,4
7	AdS	no	$(2, 4, -1)$	VISH2+1	0.092	0.092	1,9
8	AdS	no	$(2, 4, -1)$	RL Hydro	0.145	0.145	1,9
9	AdS	no	$(2, 4, -1)$	$v = 0.6$	1.911	1.911	1,9
10	SLTc	no	$(1, 3, -1)$	VISH2+1	0.167	0.167	1,9
11	SLTc	no	$(1, 3, -1)$	RL Hydro	0.330	0.330	1,9
12	SLTc	no	$(1, 3, -1)$	$v = 0.6$	1.591	1.591	1,9
13	QCDrad	yes	$(1, 3, +1)$	VISH2+1	0.718	0.349	2,5
13a	QCDrad	yes	$(1, 3, +1)$	VISH2+1	0.718	0.269	2,6
14	QCDel	yes	$(1, 3, +1)$	VISH2+1	1.615	1.024	2,5
15	AdS	yes	$(2, 4, +1)$	VISH2+1	0.283	0.283	2,10(a,b)
16	ncAdS	no	$(2, 4, -1)$	VISH2+1	0.092	0.047	2,10(c,d)
17	ncAdS	yes	$(2, 4, +1)$	VISH2+1	0.283	0.111	2,10(c,d)
18	$\kappa(\phi)$ QCDrad	yes	$(1, 3, 0)$	VISH2+1	0.543	0.235	8
19	$\kappa(\phi)$ QCDrad	yes	$(1, 3, 0)$	RL Hydro	0.776	0.345	8
20	exp. $\kappa(T)$ QCDrad	no	$(1, 3, -1)$	VISH2+1	κ_1=1.281	κ_1=1.281	12
21	exp. $\kappa(T)$ QCDrad	yes	$(1, 3, 0)$	VISH2+1	κ_1=2.134	κ_1=2.134	12
22	exp. $\kappa(T)$ ncAdS	no	$(2, 4, -1)$	VISH2+1	κ_1=0.589	κ_1=0.589	13
23	exp. $\kappa(T)$ ncAdS	yes	$(2, 4, 0)$	VISH2+1	κ_1=0.956	κ_1=0.956	13

BB et al., arXiv:1404.6378

Survey of results

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

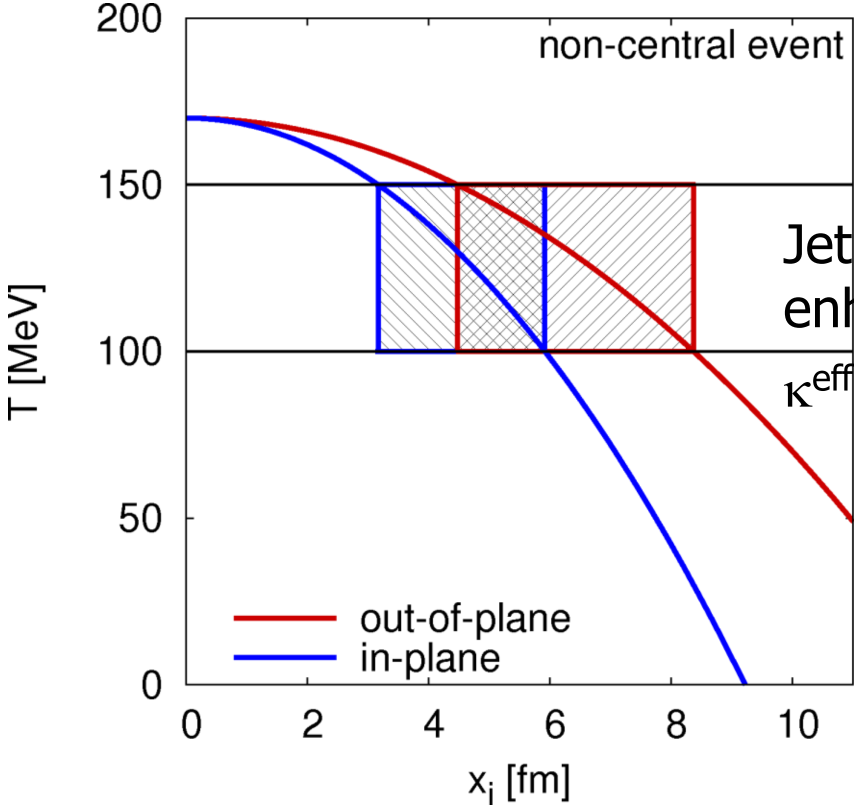
BB et al., arXiv:1404.6378

Path-variation of the jet-medium coupling

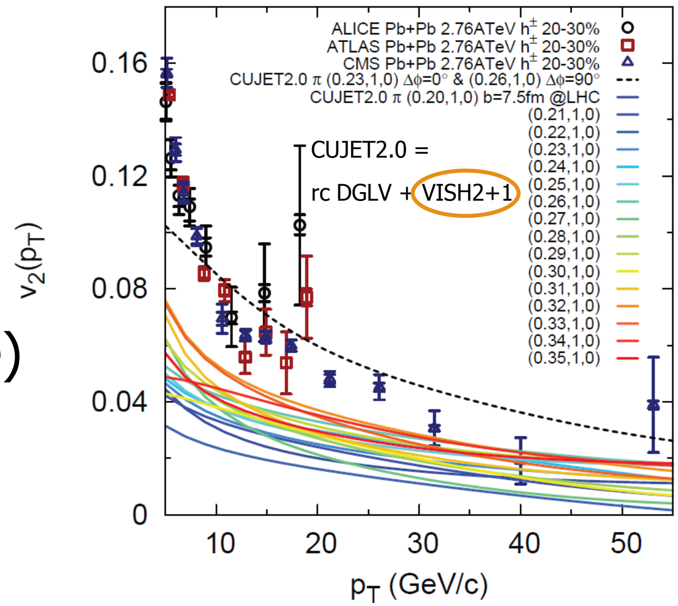
Ansatz to solve the high-p_T v_2-puzzle:

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

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



J. Xu et al., arXiv:1402.2956



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

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