Consistency and Uniqueness of combined models of hard jet quenching and soft perfect fluid observables at RHIC and LHC *AND* Non-perturbative Lattice QCD data

Part 1: Perturbative and Nonperturbative Aspects of Jet Tomography
In Ideal Event Averaged A+A Spacetime Geometries

Part 2: Jet Quenching Coupled to Event by Event Fluctuating
Viscous Hydrodynamic "Perfect Fluids"

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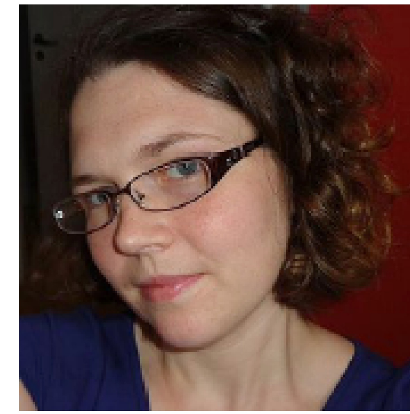
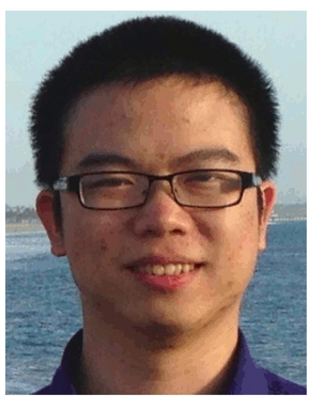
This talk is based on work of many
talented young collaborators. Special thanks to

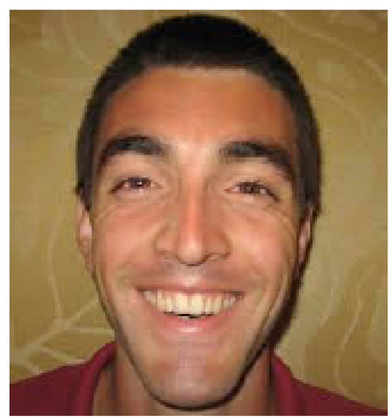

Jiechen Xu

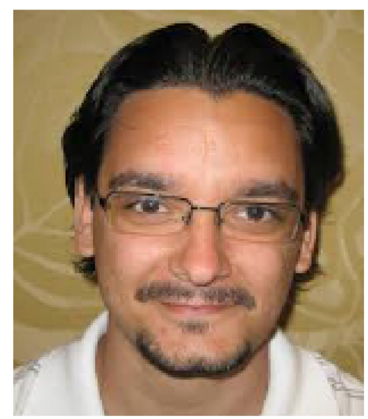

Jinfeng Liao


Jorge Noronha


Jaki Noronha-Hostler


Shuzhe Shi


Alessandro Buzzatti


Andrej Ficnar


Barbara Betz

And to more senior collaborators X.N.Wang, I.Vitev, P.Levai, W. Horowitz, ...

Perturbative vs NonPerturbative Jet Tomography in 2+1D viscous hydrodynamic backgrounds

1) Data on (RAA and v2) at (RHIC&LHC) on high pT (pi, D,B) can be simultaneously "fit" with many different dEdx models combined with different viscous hydrodynamic background models

2) CUJET3 with sQGMonopole plsma parameters constrained by lattice QCD provides a chromo-elec+mag quasi-parton model of qhat(E,T) consistent with RHIC+LHC1+LHC2 data **as well as** perfect fluidity eta/s~ 1/qhat(E~3T, T) ~ 1/4pi at least in smooth VISHNU fields

   Consistency of Perfect Fluidity and Jet Quenching in semi-Quark-Gluon Monopole Plasmas,
   Jiechen Xu , Jinfeng Liao, MG, CPL32 (2015),JHEP(2016); Shuzhe Shi, et al in progress 2017

3) There exists a pQCD/HTL dEdx model coupled to **event by event** viscous hydro consistent with hard&soft data but with qhat(E~3T, T) incompatible with perfect fluidity

   Event-by-event hydrodynamics + jet energy loss: A solution to the $R_{AA} \otimes v_2$ puzzle
   Jacquelyn Noronha-Hostler (Houston U.), Barbara Betz (Frankfurt U.), Jorge Noronha (Sao Paulo U.), Miklos Gyulassy
   PRL116 (2016), PRC95 (2017)

4) See other soft+hard model combinations this week workshop

The Existence of multiple incompatible microscopic descriptions that can account for hard and soft data ***(at similar Chi^2/NDF < 4 level of confidence)*** **remains** an obstacle in drawing objective conclusions about the physics of the the new form(s) of matter produced in AA, pA, pp at RHIC and LHC. This talk outlines our strategy to proceed forward.

How to proceed ?? How can we converge on the physics ??

Can we utilize Soft-Hard Event Engineering (SHEE) to constrain quantitatively

the model parameter-space iso-chi^2 hypersurfaces(s)?

Goal is to put experimental constraint bands on top of Lattice QCD cyber-data !

Does there exist an internally consistent band of description(s) that

can account with reasonable chi^2<4 or better for *all* RHIC & LHC data simultaneously

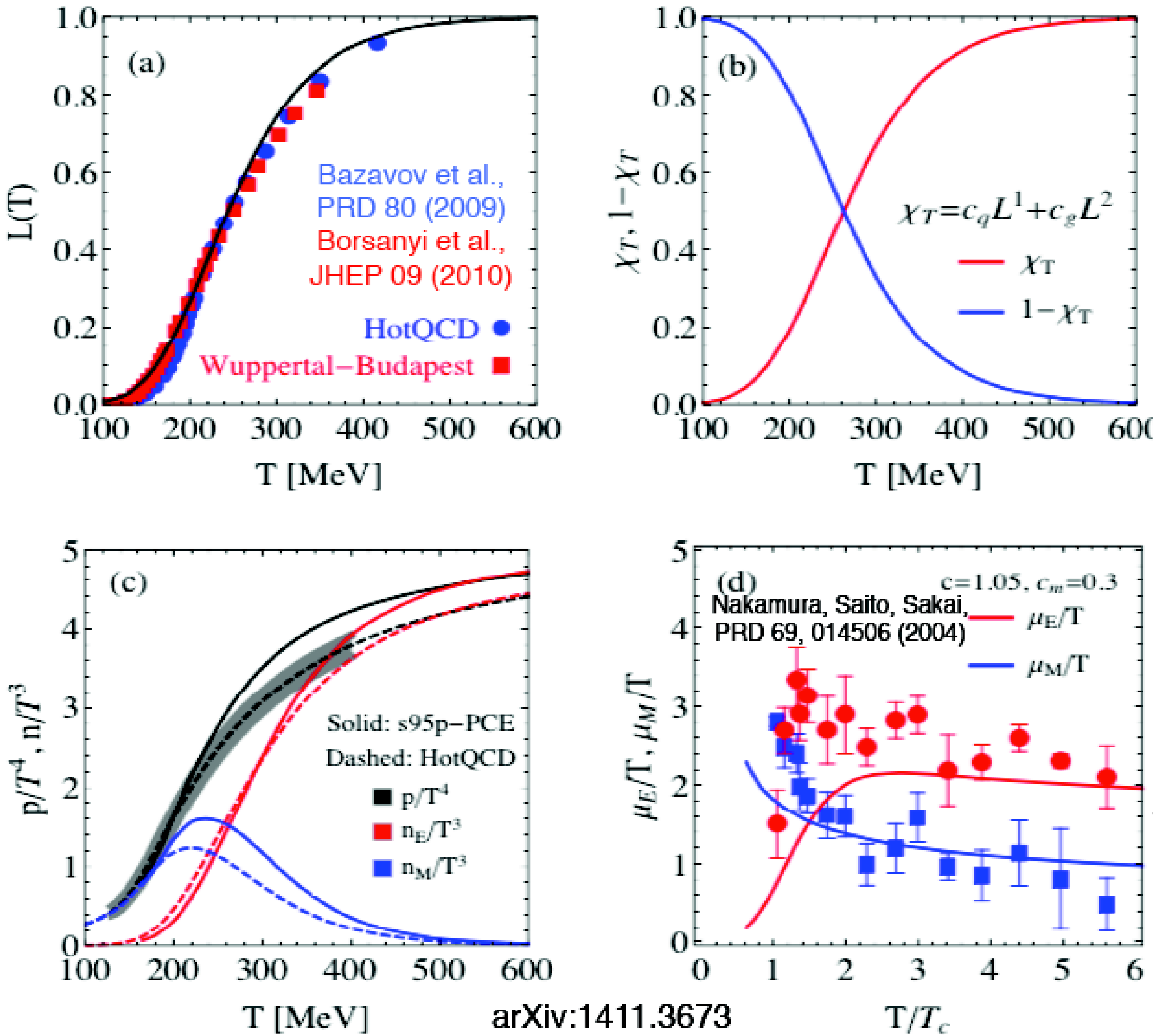
on soft-soft, soft-hard, and hard-hard observed correlations

AND that can predict falsifiable future observables ?

In this talk I review two such models in that band.

Can we eventually put exp. Chi^2 constraint bands on these Thermal Lattice QCD data
And bridge heavy ion phenomenology with the fundamental physics of confinement ??

Lattice Constraints: Polyakov Loop, EOS, E & M Screening Masses



Semi-QGP

The color elec Q + G d.o.f. are Suppressed due to semi confinement

Pisarski etal

Magnetic screen suggests emergent Chromo-Mag Monopole d.o.f. near Tc which could condense T<Tc to explain confinement

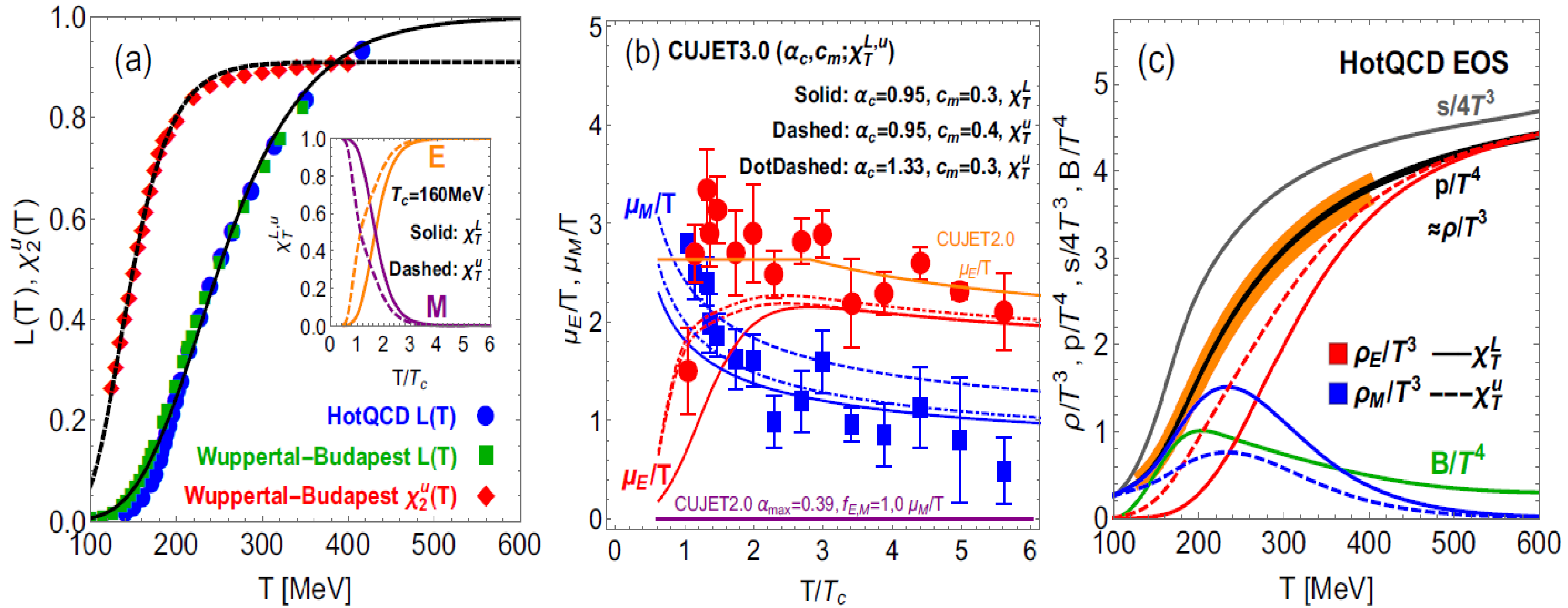
P.Petreczky proposed light quark susceptibility data =>semi-Quark color elec dof may be liberated more quickly than suggested by Polyakov loop suppressed semi-Quarks

As a measure of the sensitivity CUJET3 fits to the assumed color structure of the sQGMP we compare results with Slow quark liberation

$$\chi_T^L = c_q L + c_g L^2$$

to Fast quark liberation

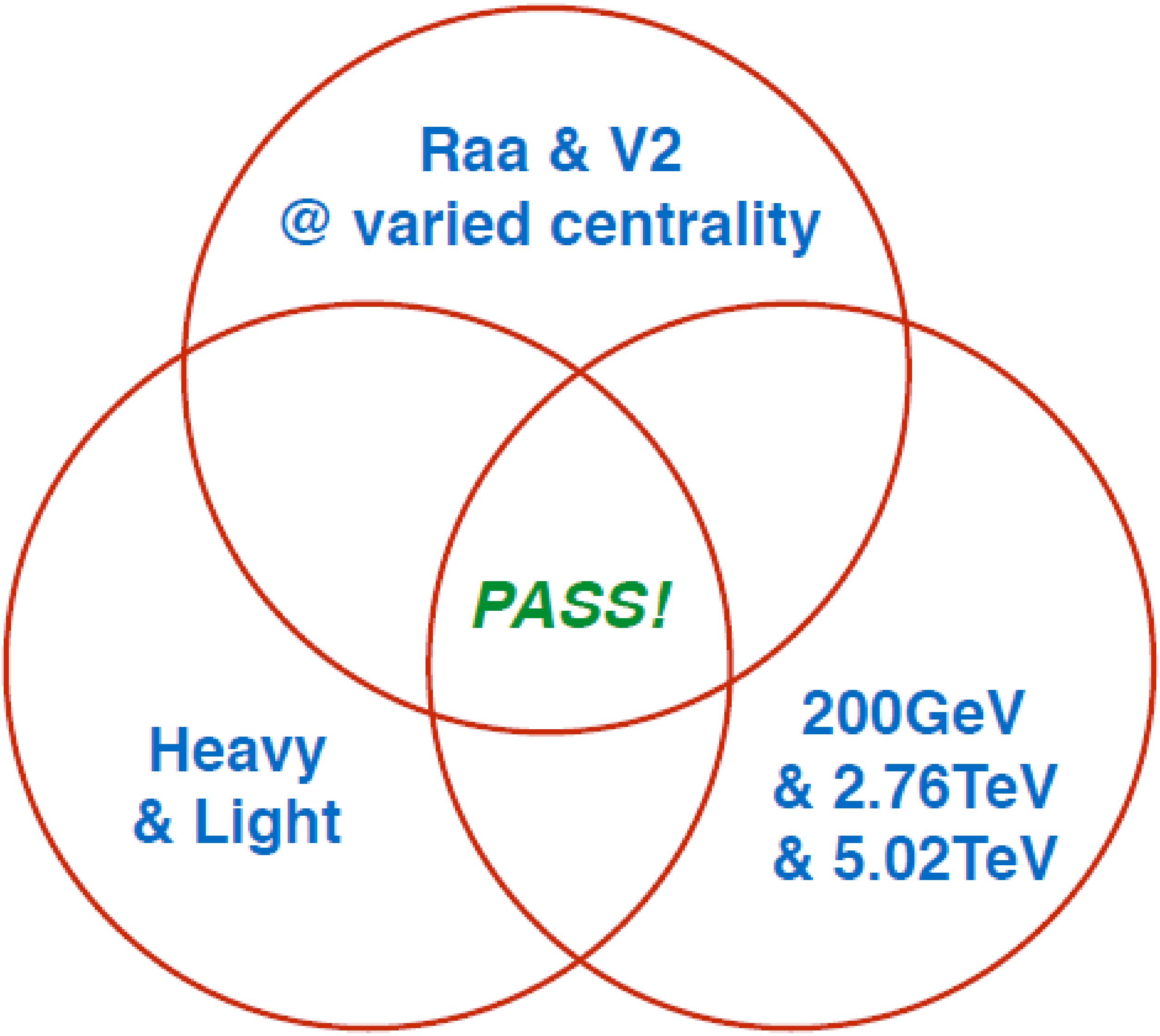
$$\chi_T^u = c_q \chi_2^u(T)/\chi_2^u(\infty) + c_g L^2$$



Our “greedy” goal with CUJET3 and future CUJET4= ebe CUJET3 and SHEE approaches is to try to put experimental (via RAA,v2,v3) Chi^2 constraint bands on the chromo composition/structure of sQGMP quark and gluon color electric quasi-monopoles dof and color magnetic quasi-monopoles dof consistent with
(1) lattice EOS P(T) (2) screening masses, and (3) minimal eta/s~T^3/qhat soft-hard phenom.

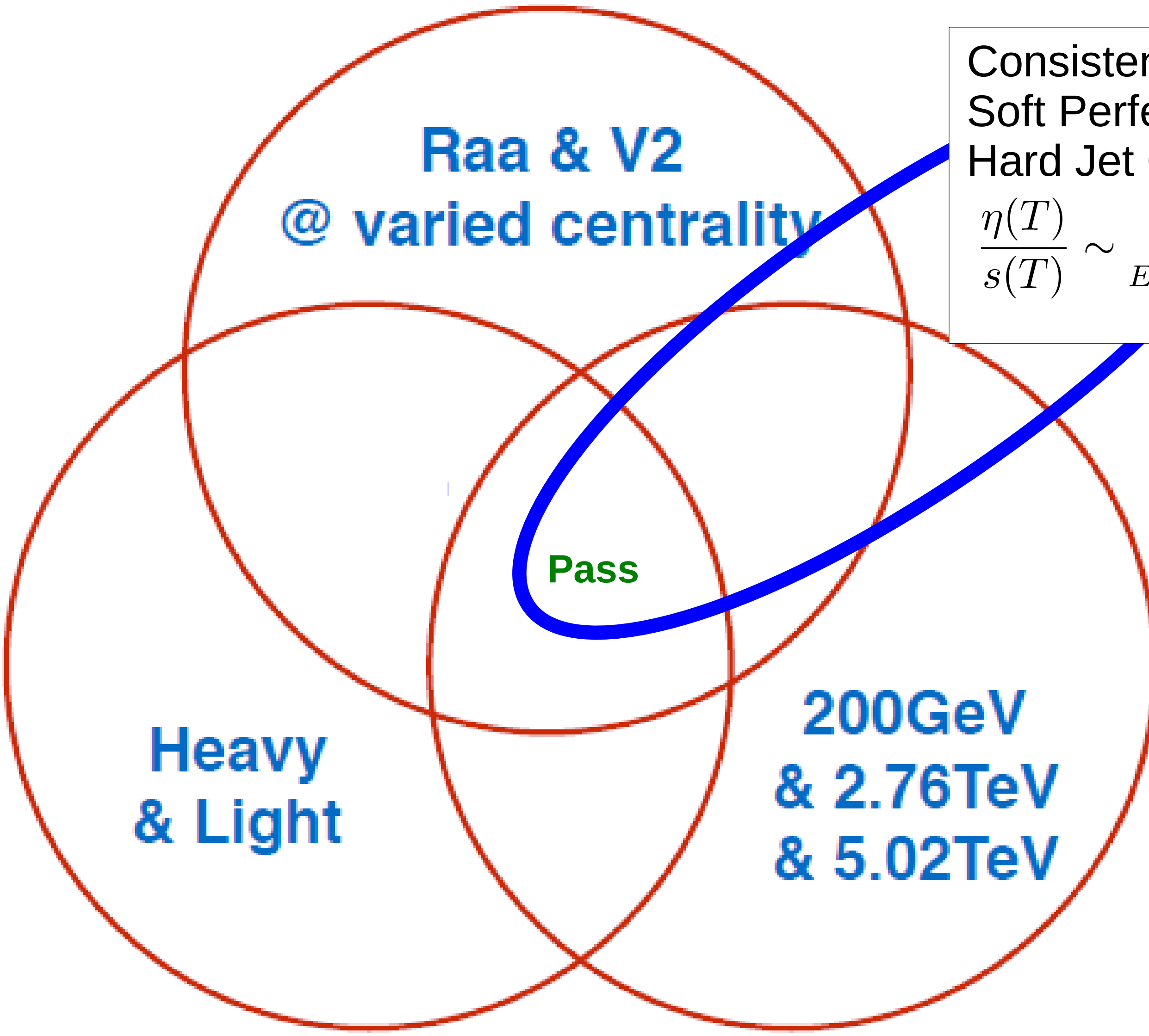
Jinfeng Liao Quark Matter 2017 slide 29

The Challenge to Every Model



My extension 1 of Jinfeng Liao's Quark Matter 2017 slide 29

The Challenge to Every Model

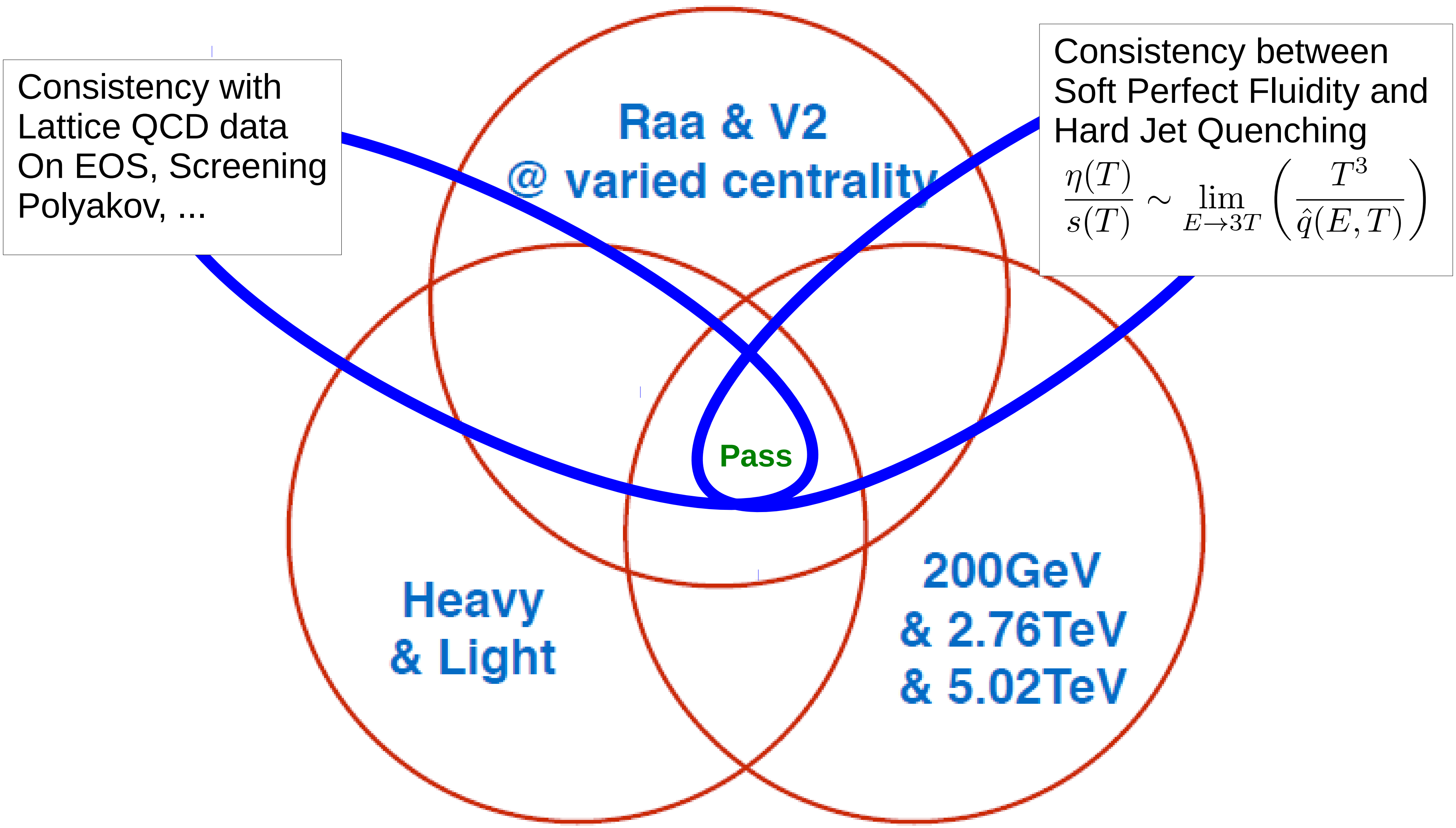


Consistency between
Soft Perfect Fluidity and
Hard Jet Quenching

$$\frac{\eta(T)}{s(T)} \sim \lim_{E \to 3T} \left(\frac{T^3}{\hat{q}(E,T)} \right)$$

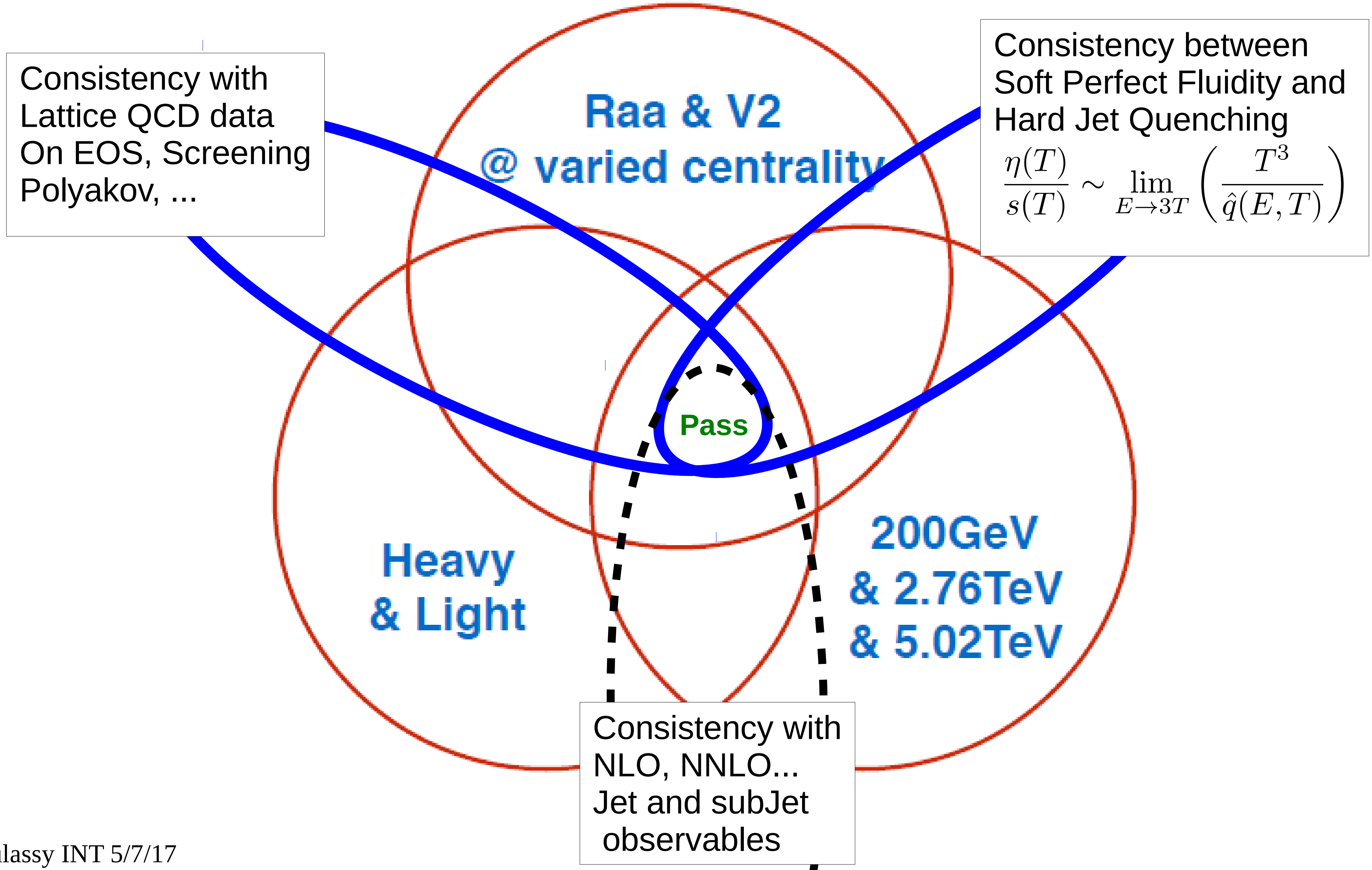
My extension 2 of Jinfeng Liao's Quark Matter 2017 slide 29

The Challenge to Every Model



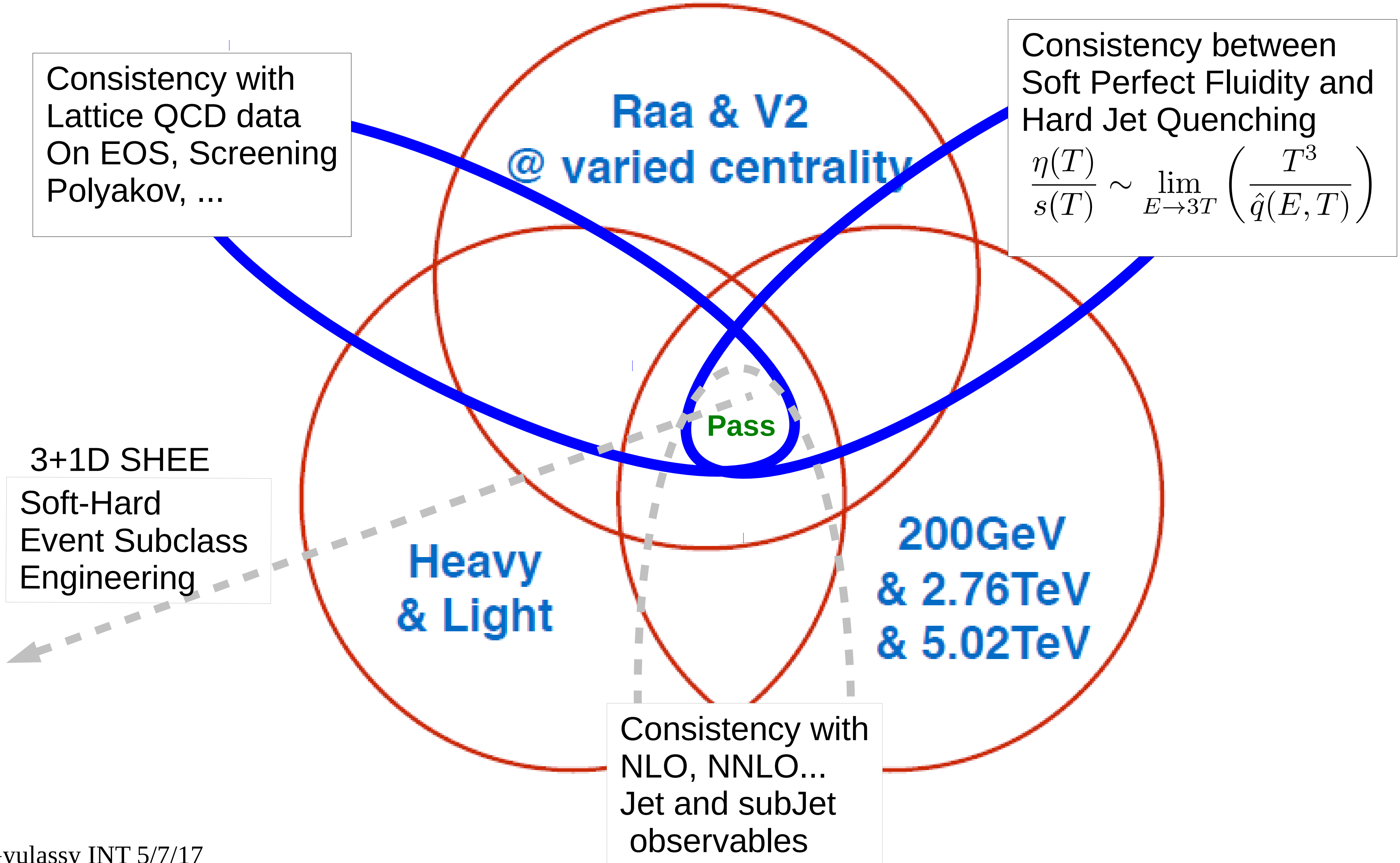
My extension 3 of Jinfeng Liao's Quark Matter 2017 slide 29

The Challenge to Every Model

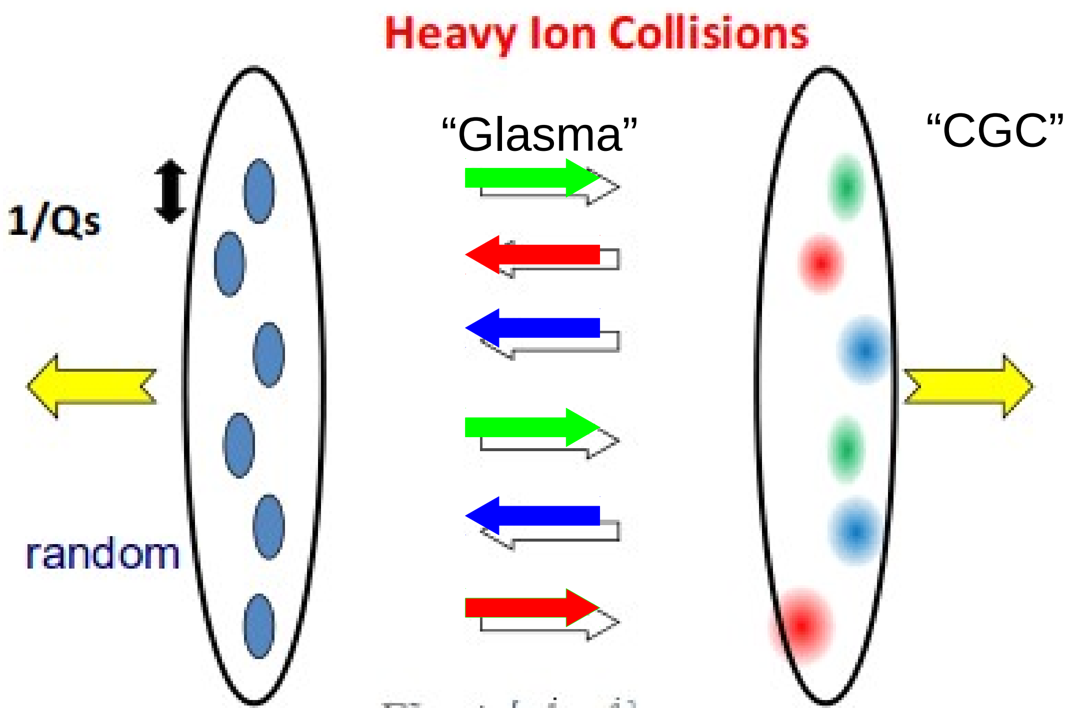


My extension 4 of Jinfeng Liao's Quark Matter 2017 slide 29

The Challenge to Every Model

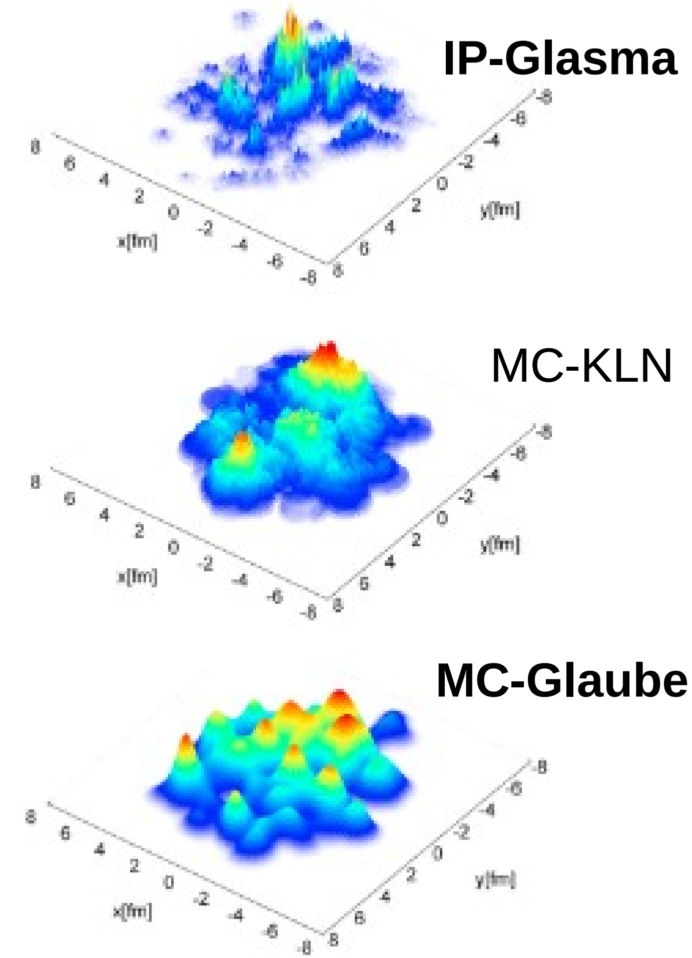


A+B inhomogeneous fluctuating “perfect fluids” &/or “glasmas”:
(L.McLerran, R.Venugopalan 1994. ...B.Schenke et al 2017)



$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

Typical configuration of a single event
just after the collision



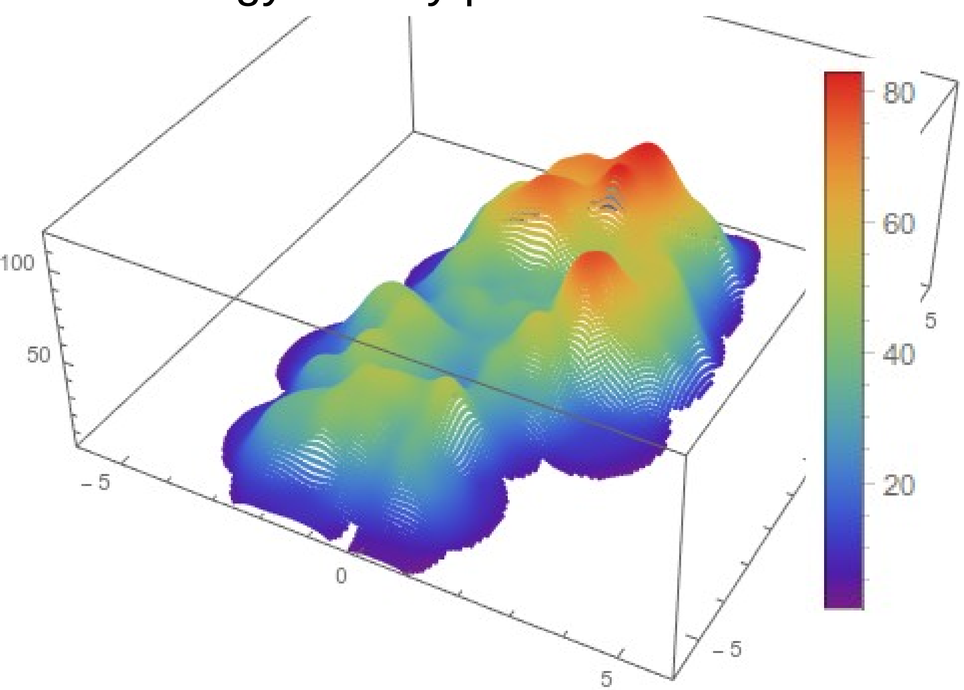
Highly coherent colored fields:
Stringlike in longitudinal direction
Stochastic on scale of inverse saturation momentum in transverse direction
Multiplicity fluctuates as negative binomial distribution

Longitudinal “Glasma” fields generalize ~1fm Lund strings in HIJING
To both electric and magnetic flux tubes of sub nucleon transverse scales 1/Qsat ~ 0.2 fm

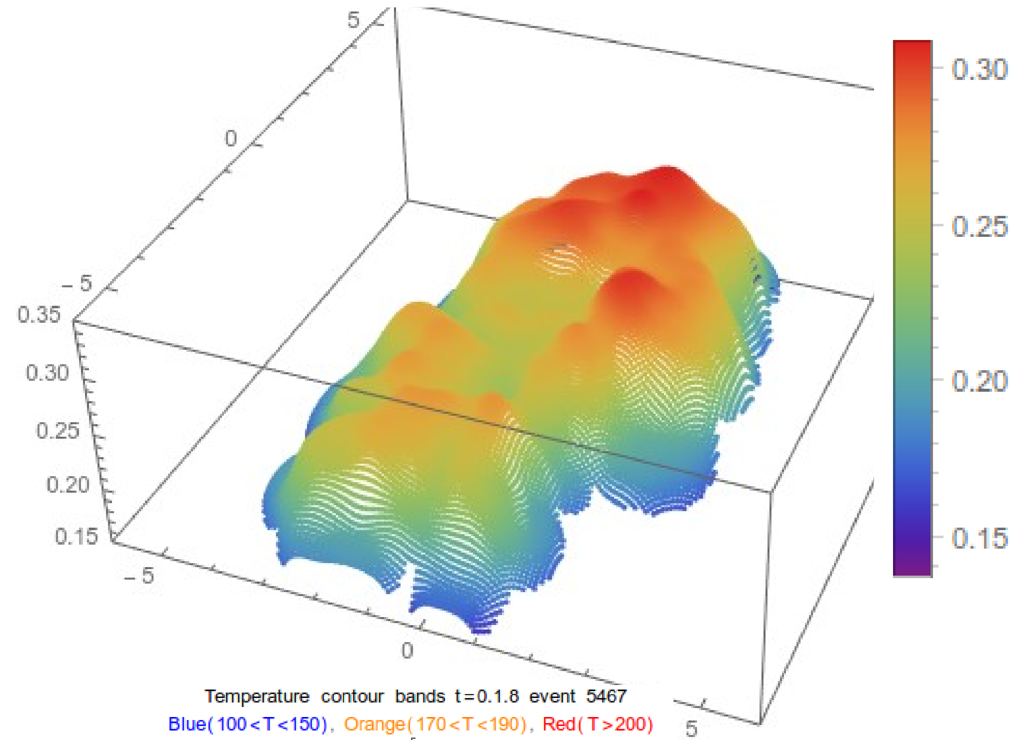
Jacquelyn Noronha-Hostler, et al: PbPb 2.76 20-30% ebe MCKLN v-USPH visc hydrodynamics PRC88 (2013)

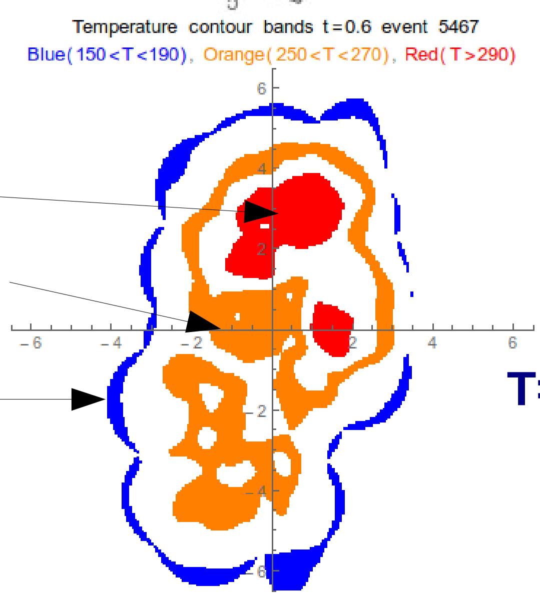
Example of evolution of typical lumpy event with **disconnected isotherm surfaces**

Energy density profile event 5467



Temperature profile event 5467



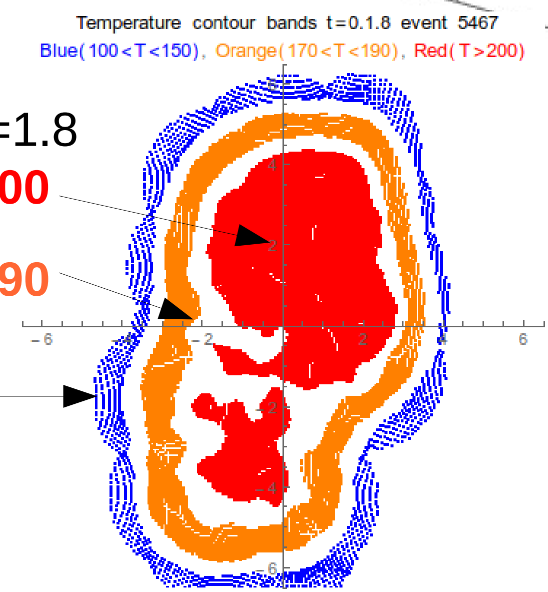


t=0.6

T > 290

T=170-220

T=150-190



t=1.8

T > 200

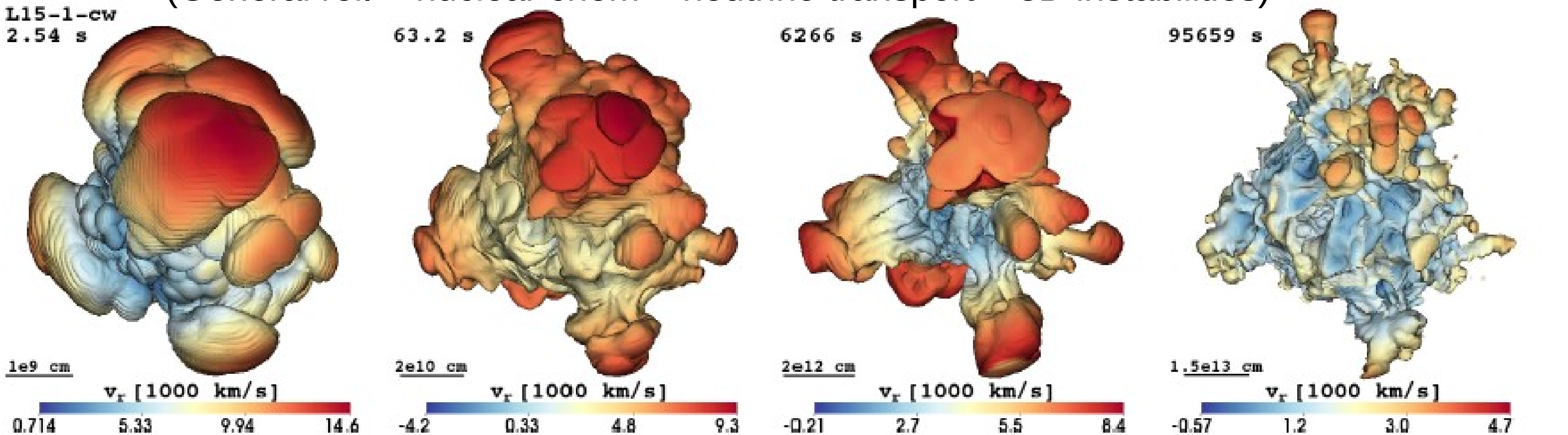
T=170-190

T=100-150

"Hard" jets probe Path Ingegrals of dEdx through such Dynamic "Soft" pT < 2 GeV Matter/Fields

A+A (eta,phi) problem similar to Multi Component problem of 3+1D Supernova Core Collapse

(General rel. + nuclear chem + neutrino transport + 3D instabilities)



A. Wongwathanarat et al.: 3D CCSN simulations A&A 577, A48 (2015)

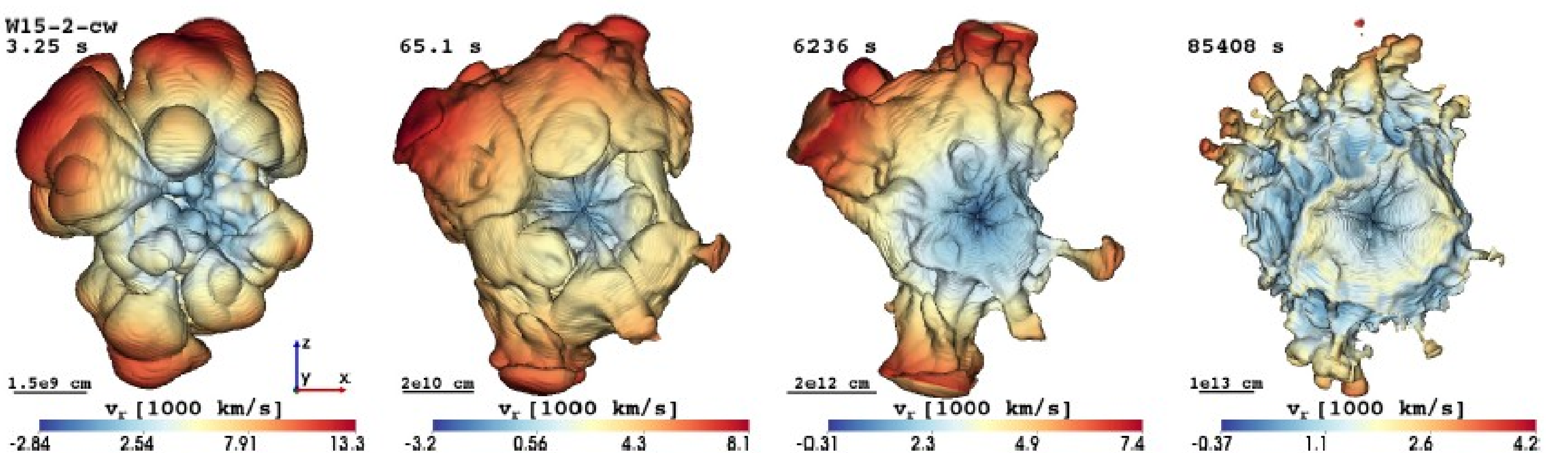
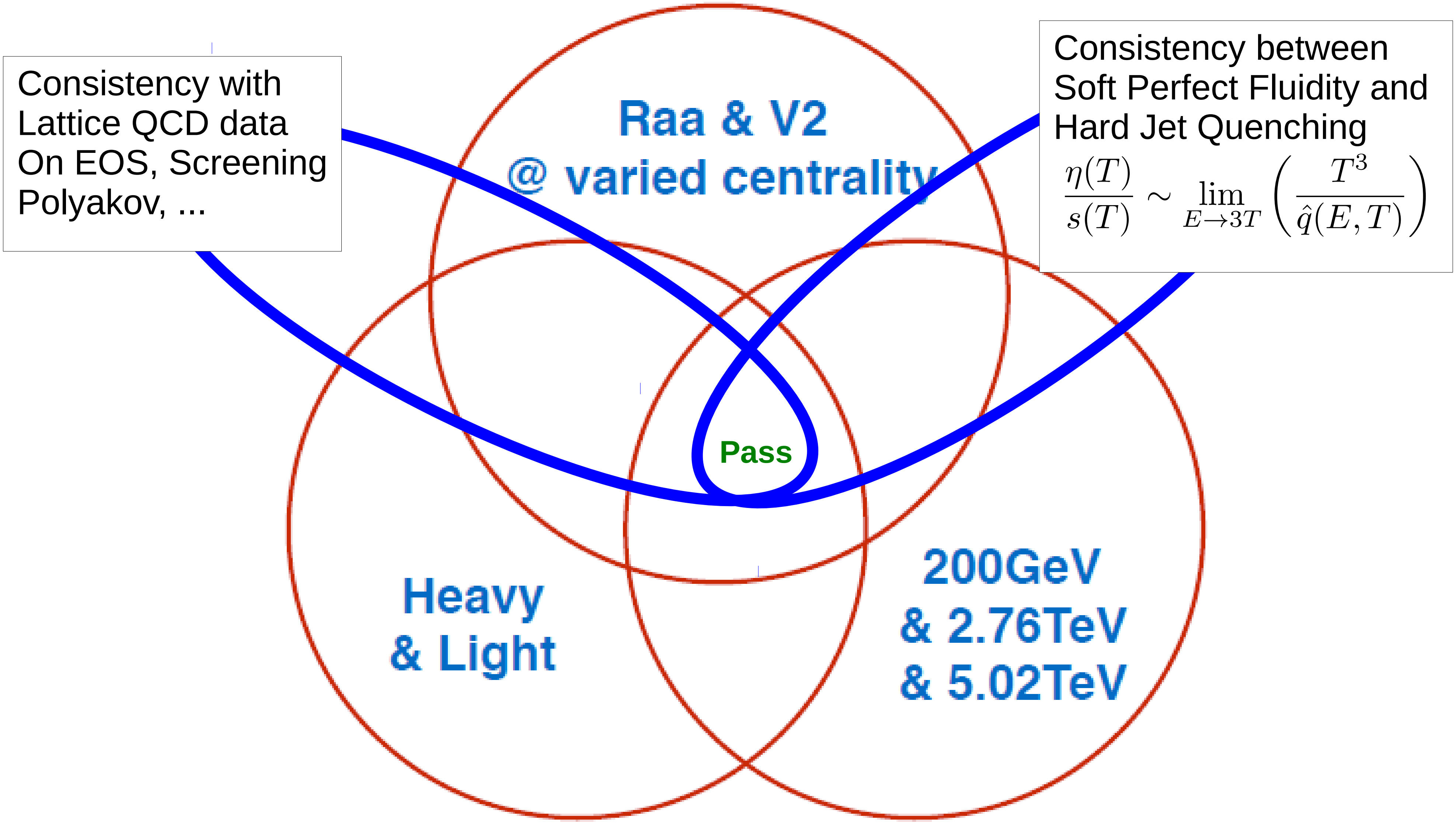


Fig. 7. Snapshots displaying isosurfaces where the mass fraction of ^{56}Ni plus n-rich tracer X equals 3% for model W15-2-cw (*top row*), L15-1-cw (*second row*), N20-4-cw (*third row*), and B15-1-pw (*bottom row*). The isosurfaces, which roughly coincide with the outermost edge of the neutrino-heated ejecta, are shown at four different epochs starting from shortly before the SN shock crosses the C+O/He composition interface in the progenitor star until the shock breakout time. The colors give the radial velocity (in units of km s^{-1}) on the isosurface, with the color coding

The Challenge to Every Model



Review of current progress toward this level with CUJET3.1

DGLV-CUJET framework for describing multi-parton scattering:

$$x_E \frac{dN_g^{n=1}}{dx_E} = \frac{18 C_R}{\pi^2} \frac{4+N_f}{16+9N_f} \int d\tau \; n(\mathbf{z})\Gamma(\mathbf{z}) \int d^2k$$
$$\times \alpha_s\left(\frac{\mathbf{k}^2}{x_+(1-x_+)}\right) \int d^2q \frac{\alpha_s^2(\mathbf{q}^2)}{\mu^2(\mathbf{z})} \frac{f_E^2 \mu^2(\mathbf{z})}{\mathbf{q}^2(\mathbf{q}^2 + f_E^2 \mu^2(\mathbf{z}))}$$
$$\times \frac{-2(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2 + \chi^2(\mathbf{z})} \left[\frac{\mathbf{k}}{\mathbf{k}^2 + \chi^2(\mathbf{z})} - \frac{(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2 + \chi^2(\mathbf{z})}\right]$$
$$\times \left[1 - \cos\left(\frac{(\mathbf{k}-\mathbf{q})^2 + \chi^2(\mathbf{z})}{2x_+ E}\tau\right)\right] \left(\frac{x_E}{x_+}\right) \left|\frac{dx_+}{dx_E}\right| \; . \quad ($$

Original DGLV formalism has only quark/gluon scattering centers

We now include both color-electric and color-magnetic scattering centers.

$$x\frac{dN}{dx} \propto \ldots \int_{q^2} \left[\frac{n\,\alpha_s^2(q^2)\, f_E^2}{q^2(q^2 + f_E^2 \mu^2)}\right] \ldots \quad \longrightarrow \quad \left[\frac{n_e\, (\alpha_s(q^2)\alpha_s(q^2))\, f_E^2}{q^2(q^2 + f_E^2 \mu^2)} + \frac{n_m\, (\alpha^e(q^2)\alpha^m(q^2))\, f_M^2}{q^2(q^2 + f_M^2 \mu^2)}\right]$$

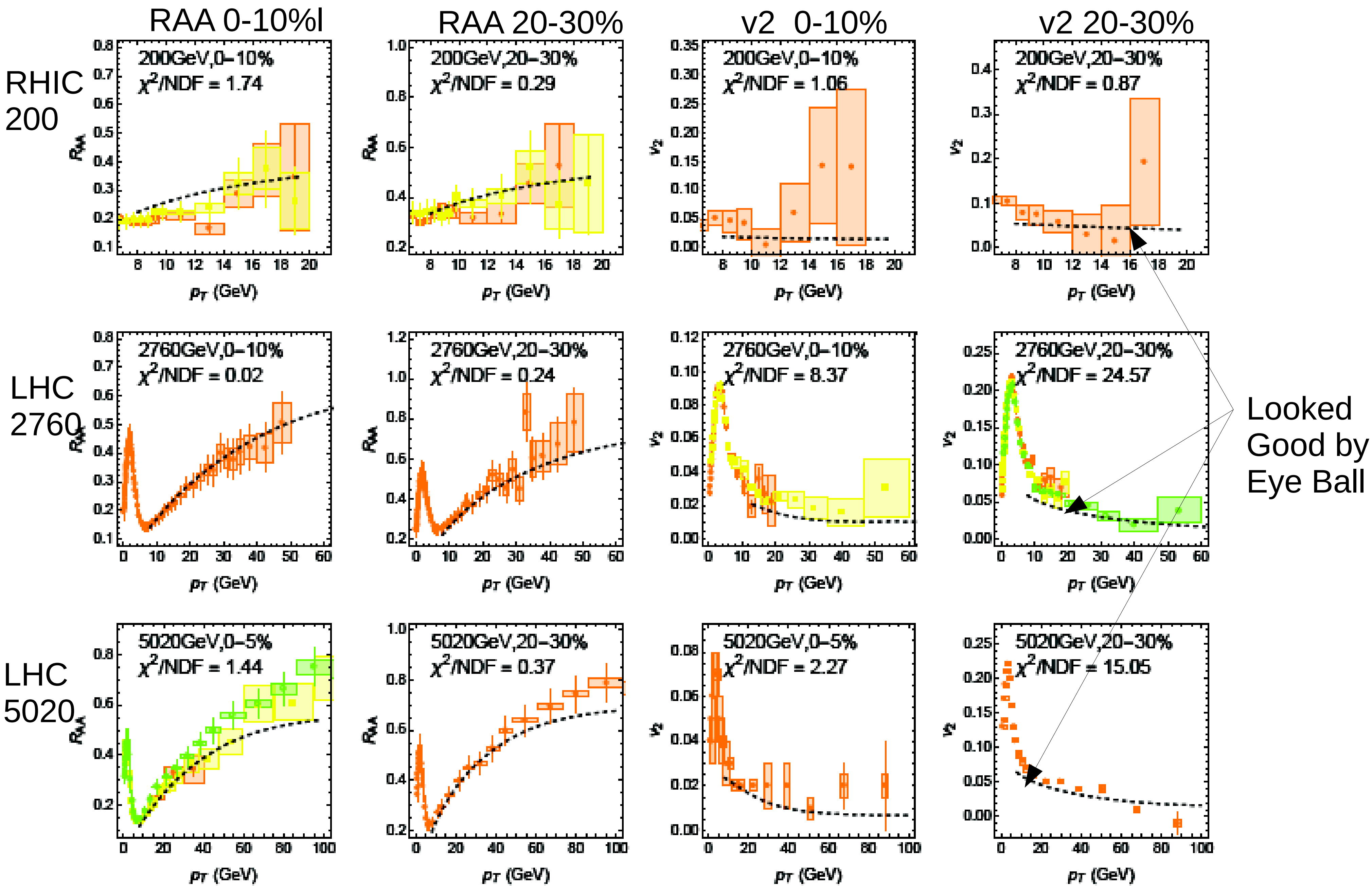
Idea with CUJET3 is to *deform* DGLV HTL kernel with non-perturbative Lattice QCD data, fit (RAA,v2) data with min chi2 to fix max alpha and the ratio of magnetic/electric screen masses, and check if qhat(E->3T,T) extrapolates near 4 pi T^3 with $\frac{\eta(T)}{s(T)} \sim \lim_{E \to 3T} \left(\frac{T^3}{\hat{q}(E,T)}\right)$

Shuzhe Shi 2017

Alessandro Buzzatti, J.Xu, MG, JHEP (2014)

$\alpha_{max} = 0.42$

χ^2/d.o.f for VISH2+1 ⊗ CUJET2.1

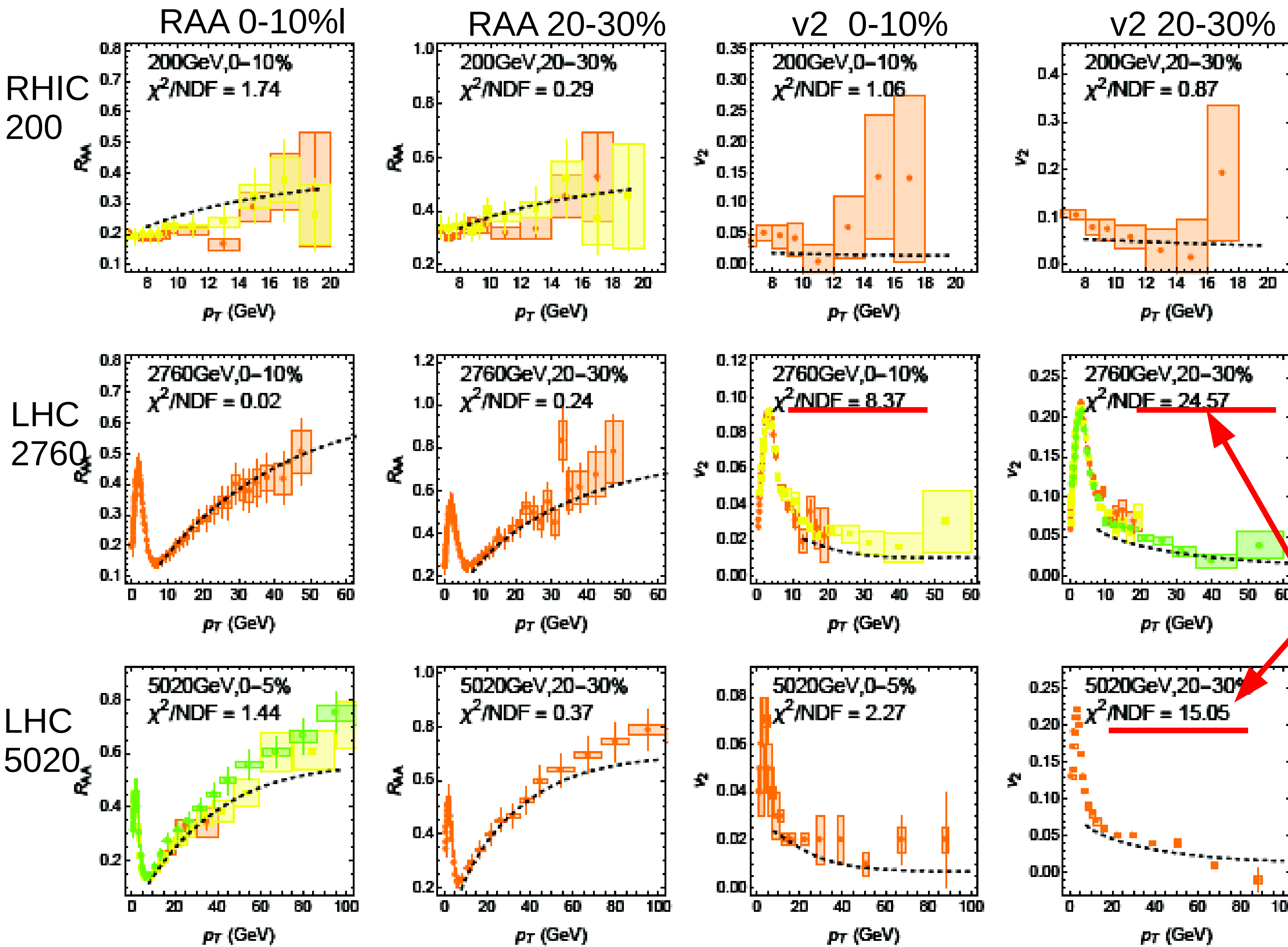


Shuzhe Shi 2017

Alessandro Buzzatti, J.Xu, MG, JHEP (2014)

$\alpha_{max} = 0.42$

χ^2/d.o.f for VISH2+1 $\otimes$ CUJET2.1



However Chi^2>15 Falsified Model !!

CUJET3.0 status at QM15 (J.Xu, J Liao, mg, NPA956 (2016)) improved

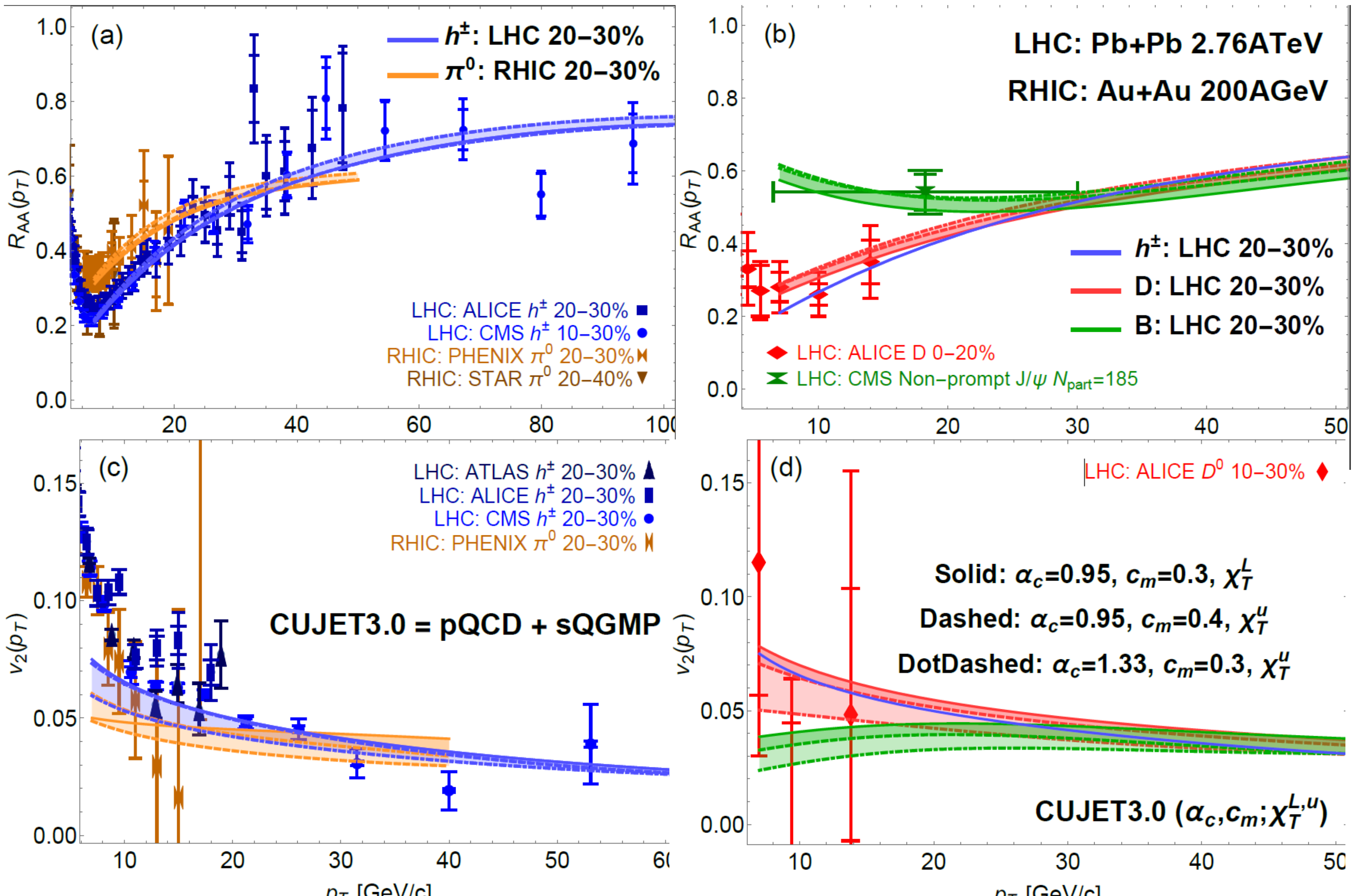


Fig. 2. (Color online) CUJET3.0 results of (a) light hadron (LH, neutral pion π^0 and charge particle $h^{\pm}$)'s R_{AA}, (b) open heavy flavor (HF, B meson and prompt D meson)'s R_{AA}, (c) LH's v_2, and (d) HF's v_2, at high $p_T > 8$GeV in semi-peripheral A+A collisions, compared with data from RHIC and LHC [2]. The variations of predicted jet quenching observables from different schemes within CUJET3.0 suggest that data on high p_T leading hadron R_{AA} and v_2 in heavy-ion collisions can rigorously constrain the nonperturbative chromo-electric and chromo-magnetic structure of the QCD matter near T_c, and provide critical information about color confinement.

CUJET3.0 qhat at QM15 was consistent with Perfect fluiidty near Tc (J.Xu, J Liao, MG (2016))

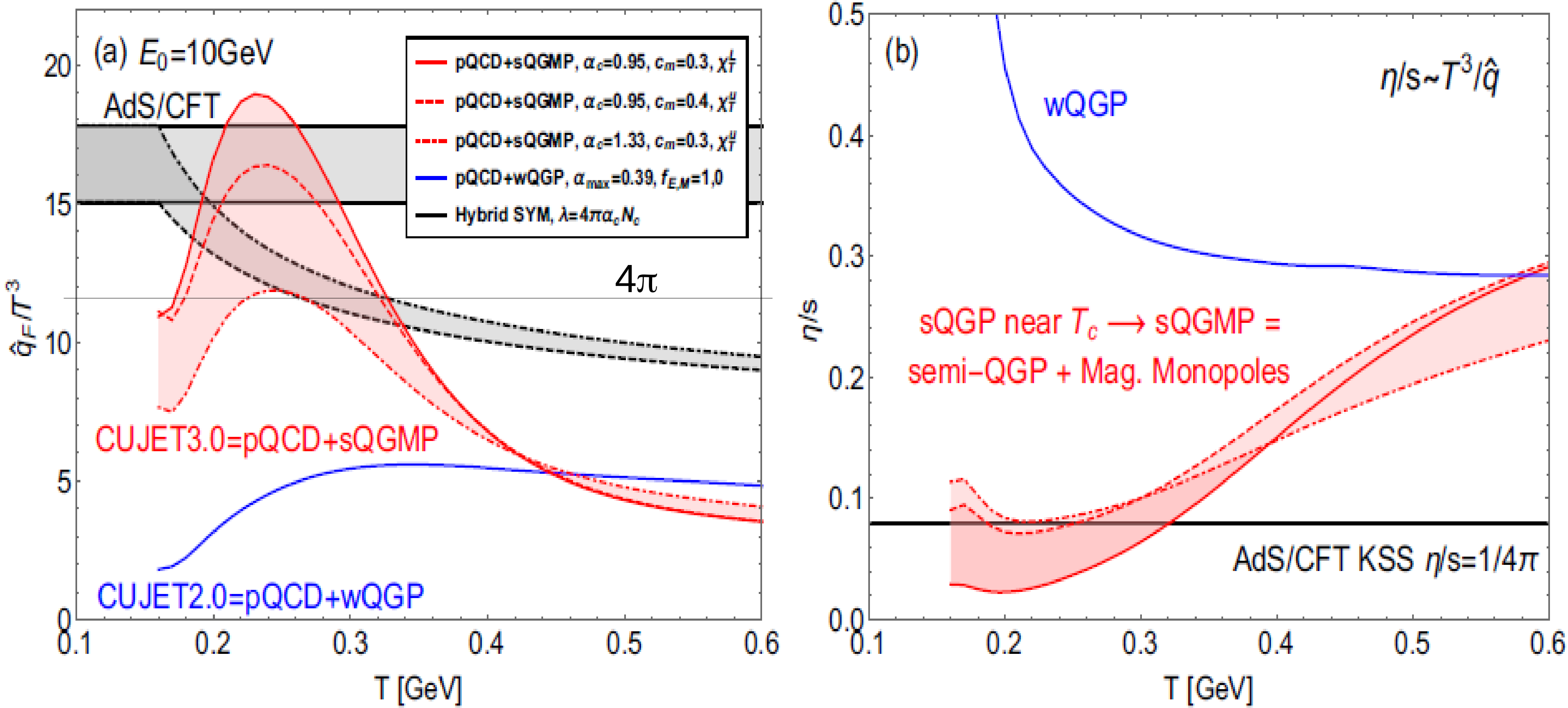


Fig. 3. (Color online) (a) The temperature dependence of the scaled jet transport parameter $\hat{q}/T^3$ for a quark jet (in the fundamental representation F of SU(N_c=3)) with initial energy E_0 = 10 GeV in various schemes within the CUJET3.0 framework, compared with the CUJET2.0 counterpart, as well as $\mathcal{N}$ = 4 Supersymmetric Yang-Mills (SYM) $\hat{q}_{\mathrm{SYM}}$ results from leading order (LO) AdS/CFT calculations ($\hat{q}_{\mathrm{SYM}} = [\pi^{3/2}\Gamma(3/4)/\Gamma(5/4)]\sqrt{\lambda}T^3_{\mathrm{SYM}}$) [15]. Note that $3T^3_{\mathrm{SYM}} \approx T^3$ because of different number of degrees of freedom in N_c = 3 SYM and three-flavor QCD [16]. The gray band with dashed black edges corresponds to using 't Hooft coupling $\lambda = 12\pi\alpha_s(Q^2)$. (b) The shear viscosity to entropy density ratio η/s estimated in the kinetic theory extrapolation $\eta/s \sim T^3/\hat{q}$ from jet quenching parameters in panel (a). Note that T_c = 160 MeV. In CUJET3.0, a $(\hat{q}_F/T^3)_{\max}$ and $(\eta/s)_{\min}$ appear at $T \sim 1.4T_c$ where the scaled number density of emergent chromo-magnetic monopoles near T_c peaks. The $(\eta/s)_{min}$ is influenced by the EM fractions. Its value in both $\chi_T^{L,u}$ schemes converge to approximately the KSS quantum bound $\eta/s = 1/4\pi$ [4]. At high T, the η/s from sQGMP and weakly-coupled QGP (wQGP) coincide because of similar color screening structures.

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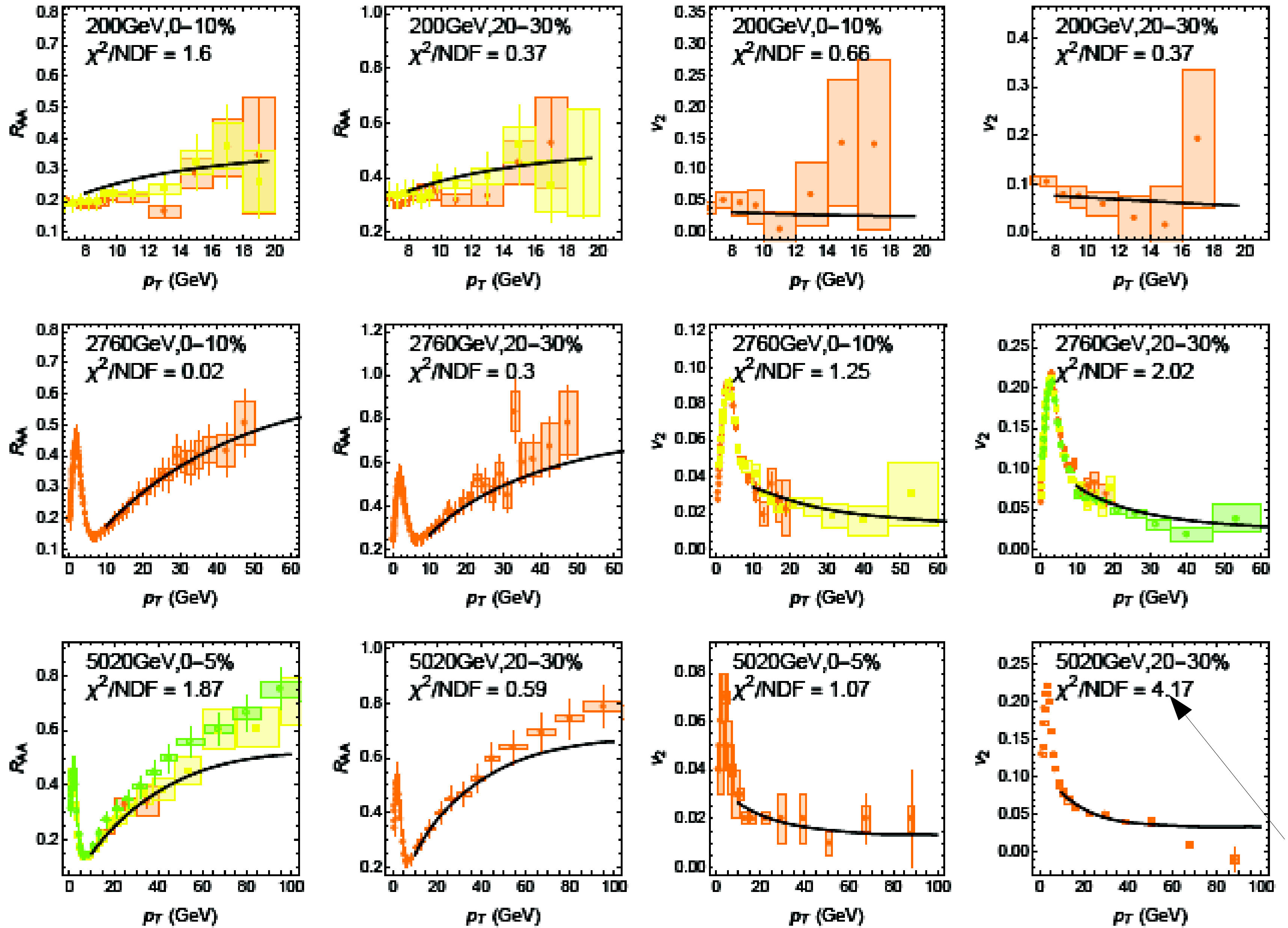
χ^2/d.o.f for VISH2+1 ⊗ **CUJET3.1**

$(\alpha_c, c_m) = (0.9, 0.25)$



Note LHC2 data are much Higher Precision !

V2 CMS challenge now to 1% accuracy?!

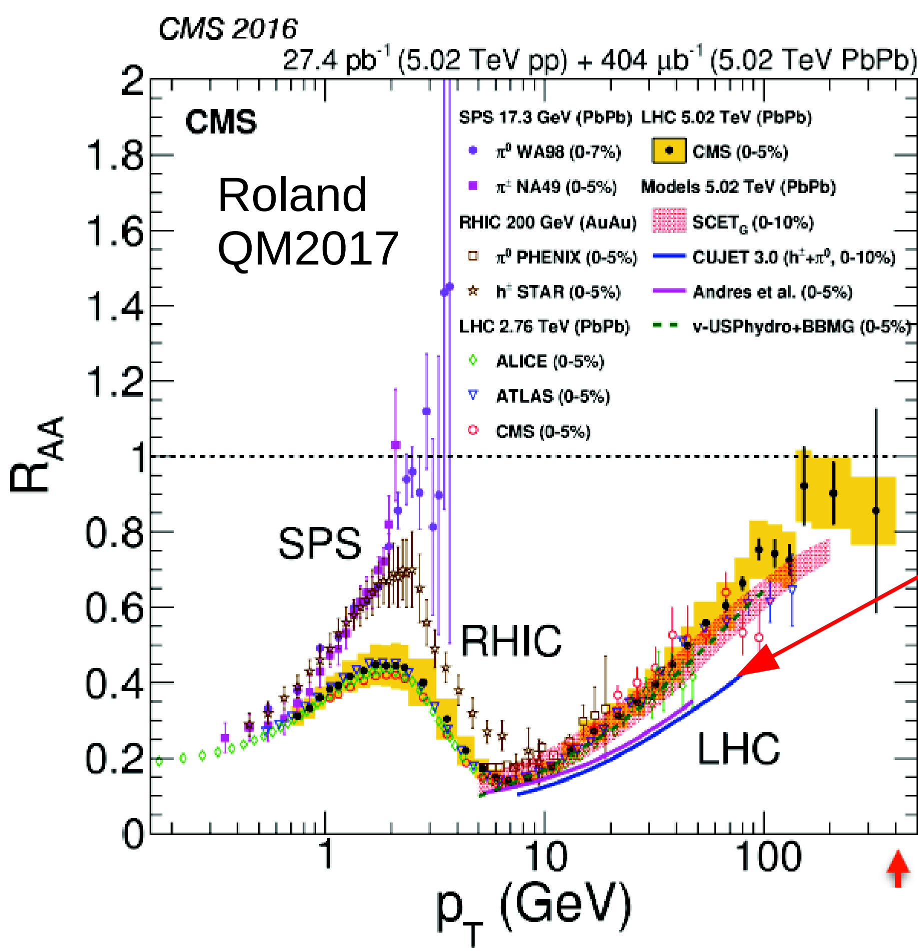
At IS16 and QM17 CMS discrepancies of CUJET3.0 reported for 5ATeV RAA and v2

Shuzhe Shi found 3 bugs in CUJET3.0 and corrected now in CUJET3

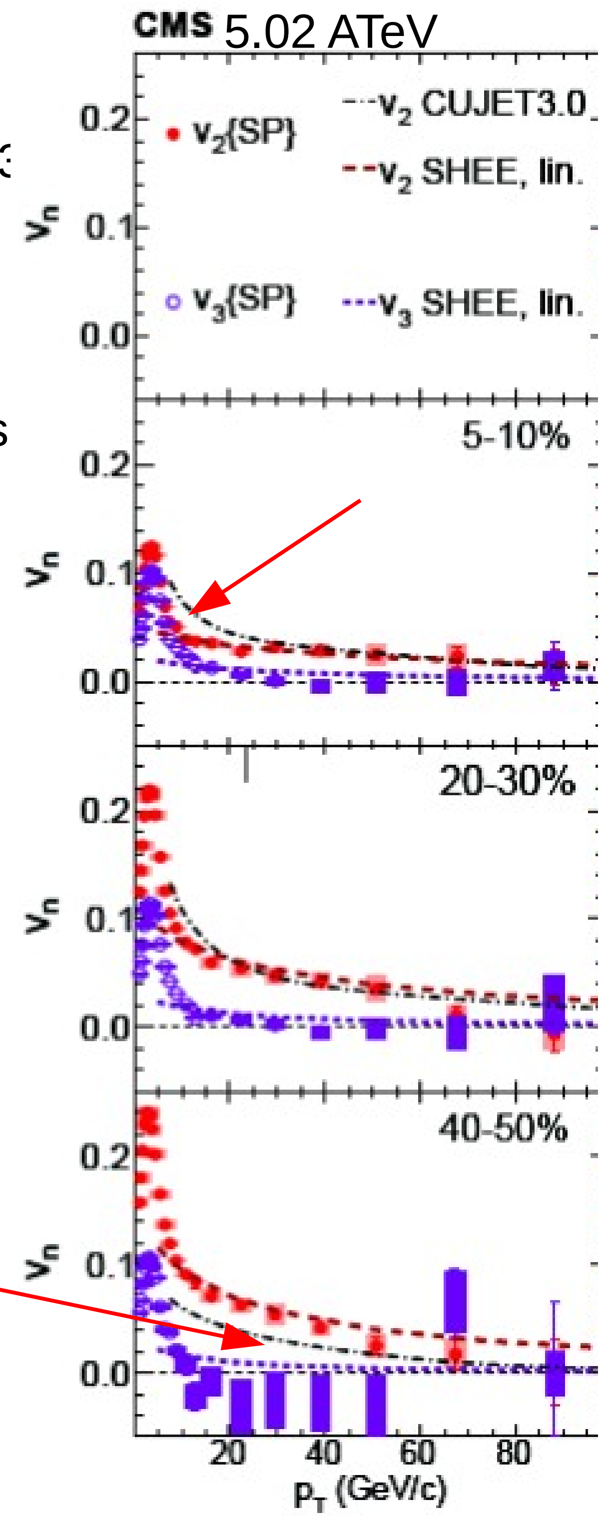
1) Initial parton spectra for 5.02 ATeV were erroneously read from a Pythia file rather than from pQCD Wang code used previously

2) VISHNU hydro fluid grid was misread into CUJET3.0 path integrals

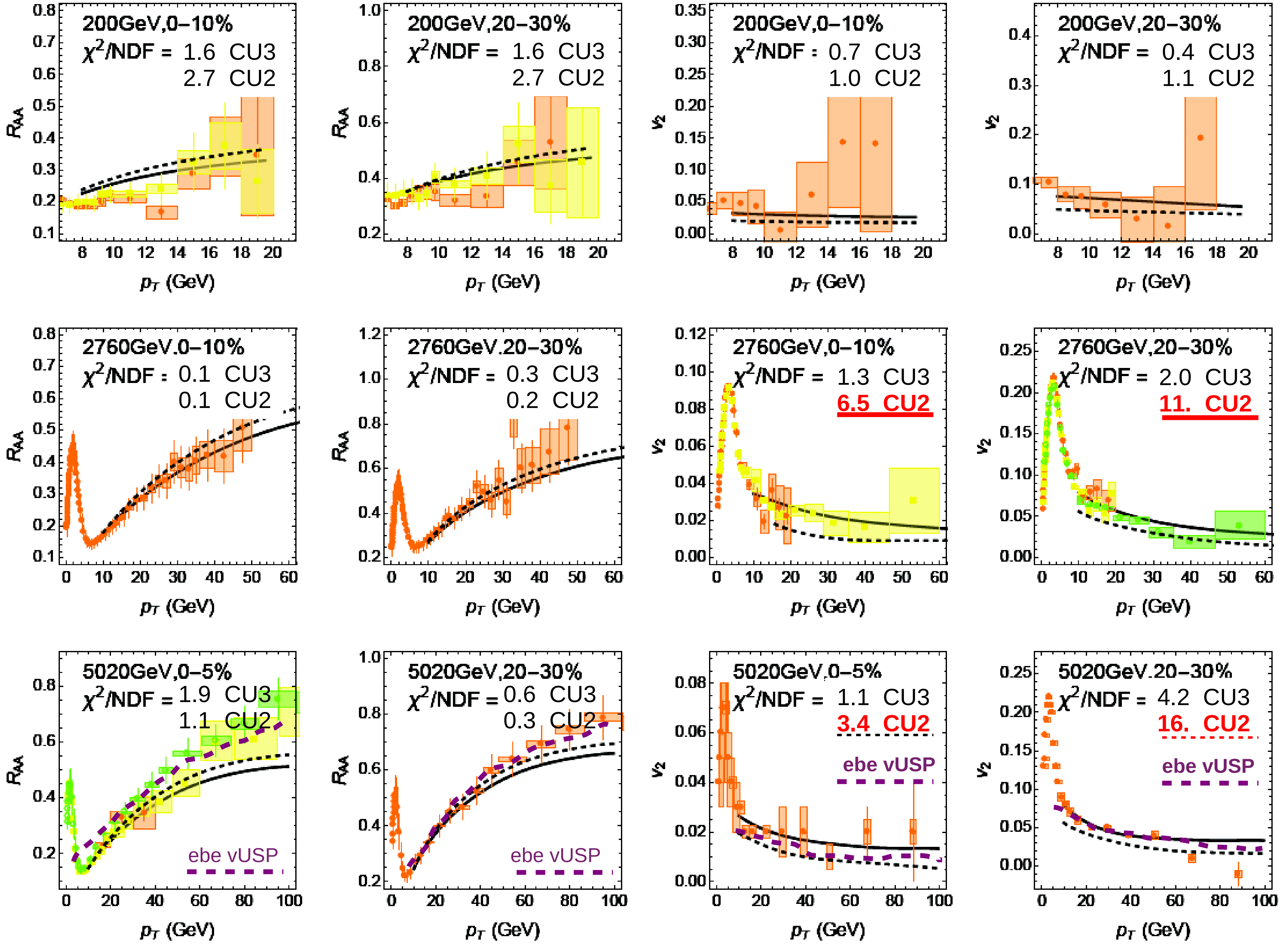
3) Initial parton spectra cut off set at 200 instead of 400 GeV



Bugs led at 5TeV to
1) overquench RAA
2) predict wrong
Centrality dep of v2

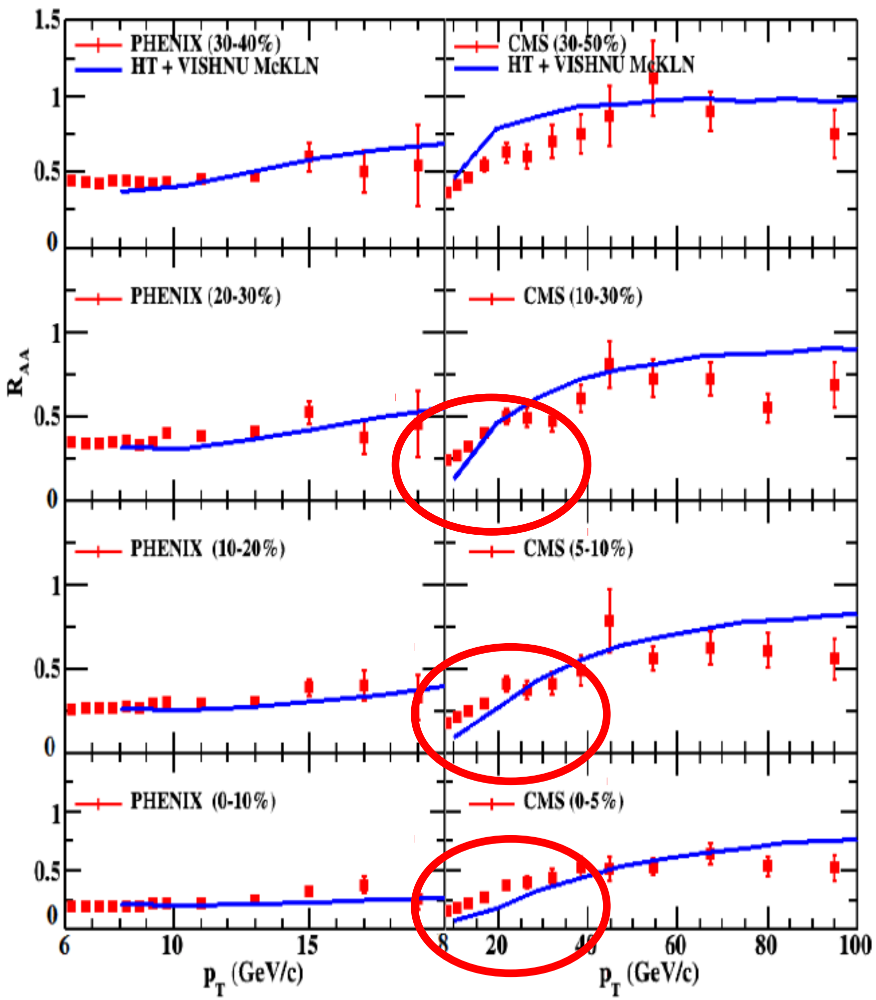


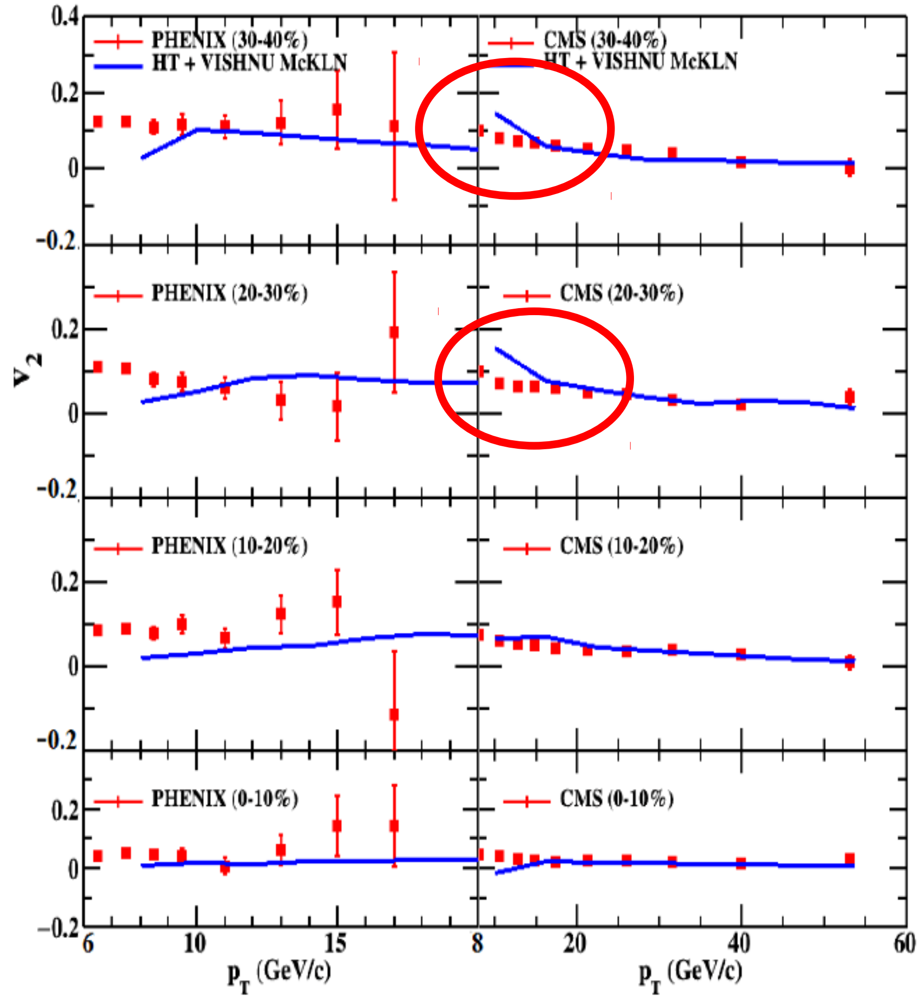
pQGP/CUJET2.1 vs sQGMP/CUJET3.1 vs RHIC&LHC vs ebe/vUSP+BBMG (J.Noronha-Hostler PRC95 (2017)



Recent HigherTwist xG(x,Q2(L)) model should also be compared via Chi^2/dof

E.Bianchi, J.Elledge, A.Kumar, A.Majumder, G.Y.Qin and C.Shen,
``The x and Q^2 dependence of hat{q}, quasi-particles and the JET puzzle" arXiv:1702.00481 [nucl-th]





Appears to over quench LHC RAA(pT<40) in central
And over predict v2(pT<20) in semi-central
Needs functional variation xG(x,Q) to minimize Chi^2(LHC) ?

Shuzhe Shi et al QM 2017
1704.04577 hep-ph

χ^2/d.o.f for VISH2+1 ⊗ **CUJET3.1**

Combined RHIC+LHC1+LHC2 data RAA+v2 fit Chi^2(α_c, c_m)

Assuming slow Polyakov color electric semi-q+g liberation $\chi_T^L = c_q L + c_g L^2$

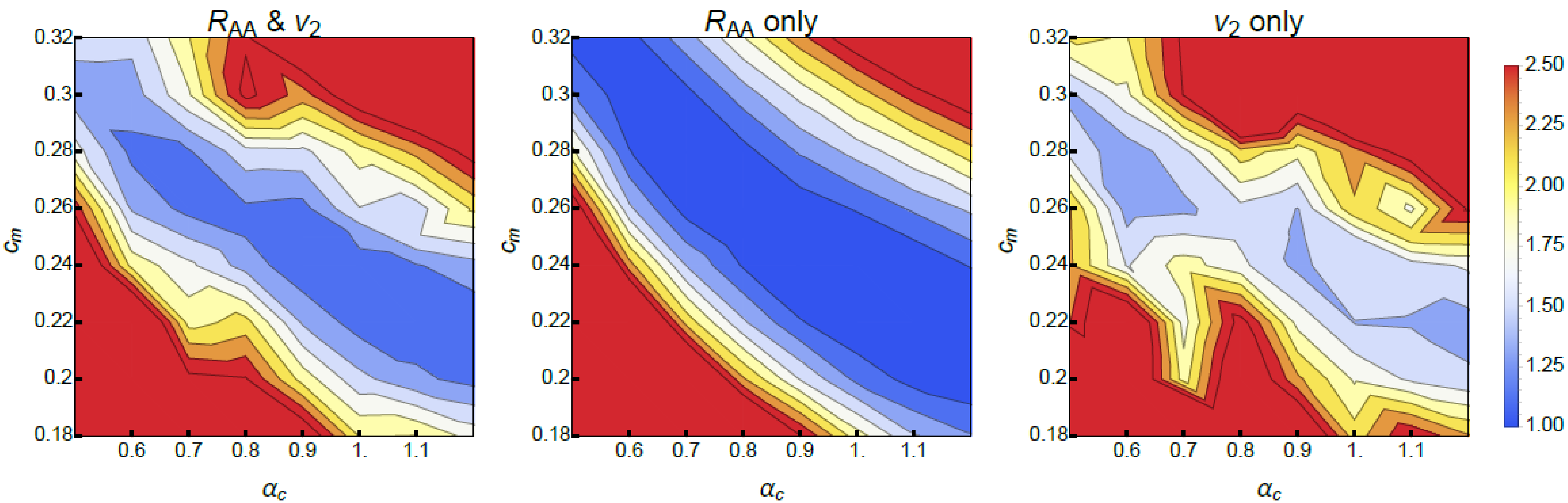


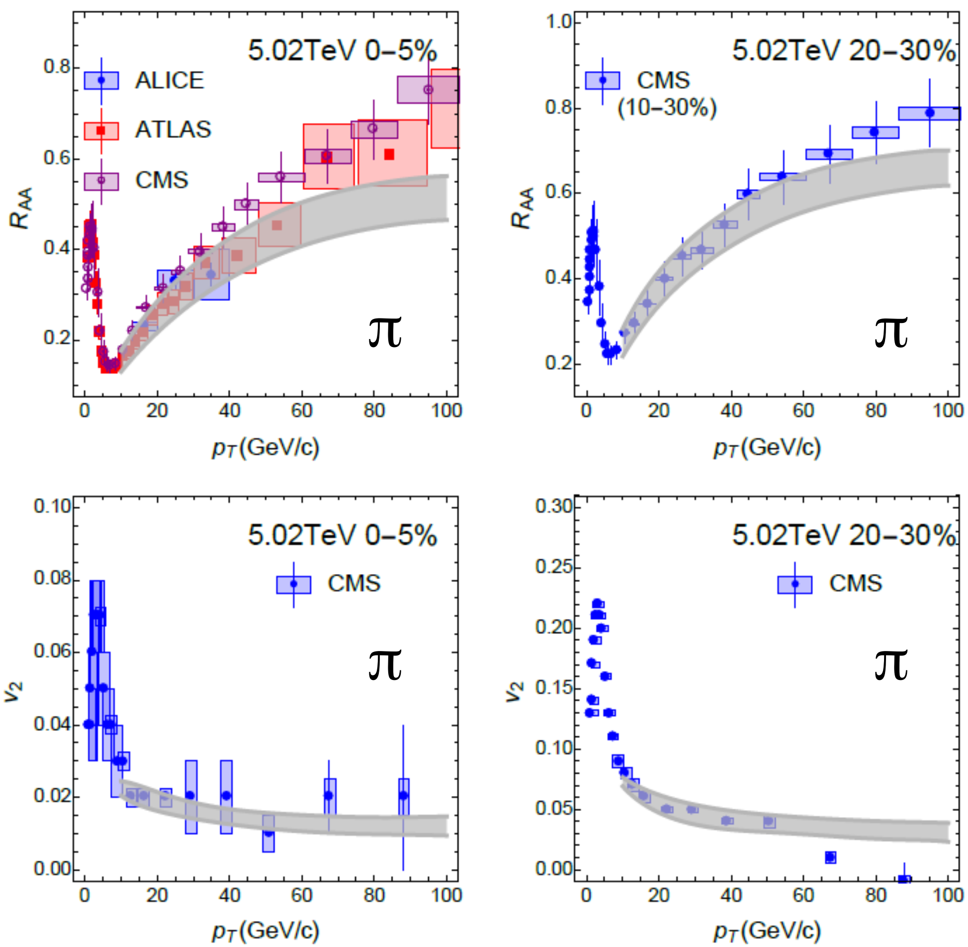
Fig. 1. (color online) The $\chi^2/d.o.f$ distribution on (α_c, c_m) parameter plane, from comparing CUJET3 results for pion high p_T observables with central and semi-central data from RHIC 200GeV, LHC 2.76TeV as well as 5.05TeV collisions: (left) including both R_{AA} and v_2 data; (middle) including only R_{aa}; (right) including only v_2.

The main next open question next is how will inclusion of event-by-event fluctuations
Modify CUJET4.0 = ebe CUJET3.1 predictions ?

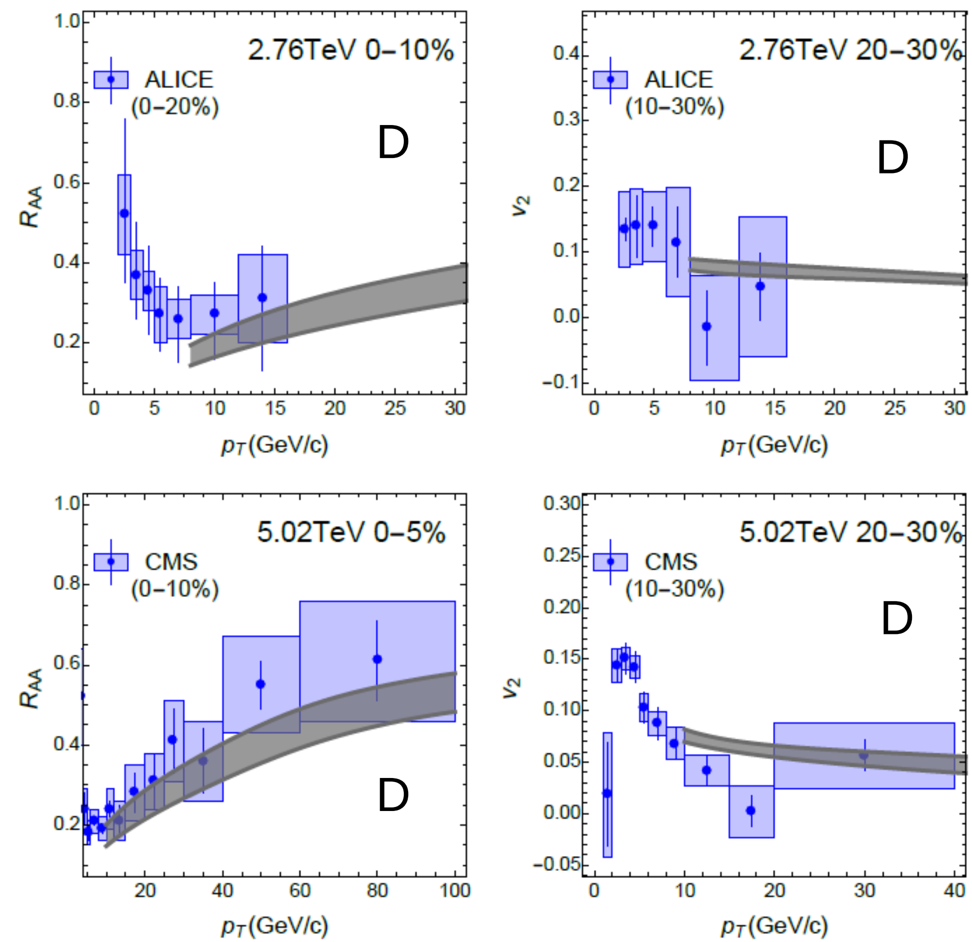
Shuzhe Shi et al QM 2017
1704.04577 hep-ph

VISH2+1 ⊗ **CUJET3.1**

central and semi-central R_{AA} and v_2 of high p_T pions



central and semi-central R_{AA} and v_2 of high p_T D

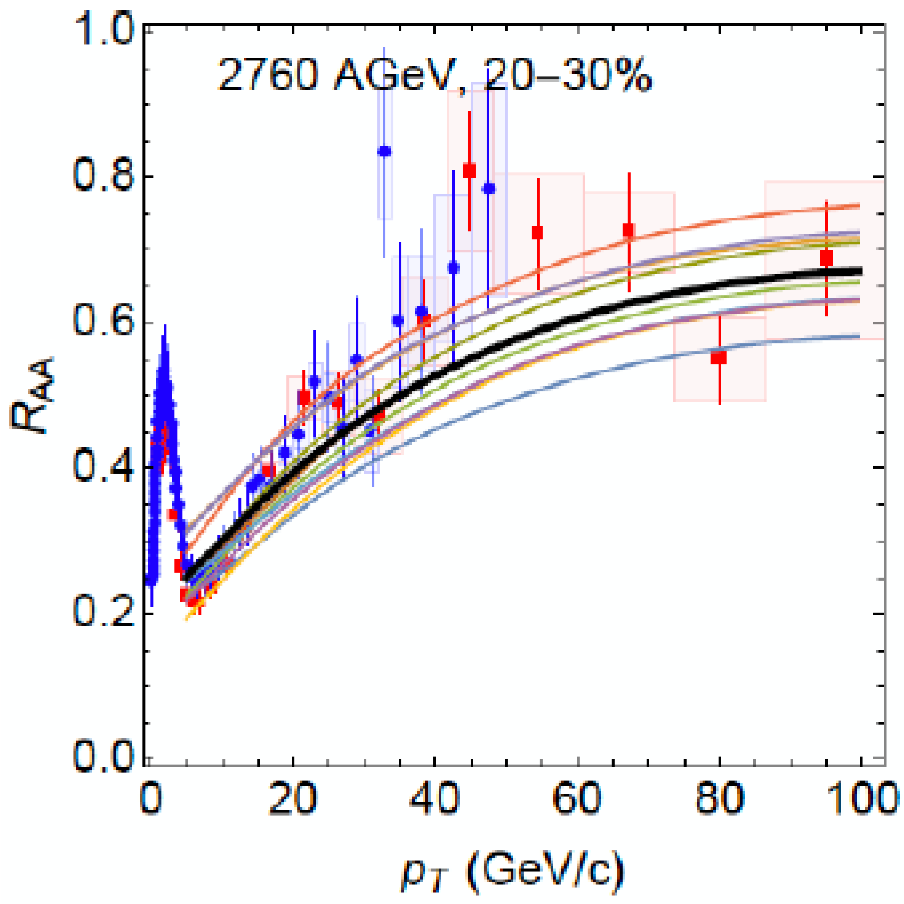


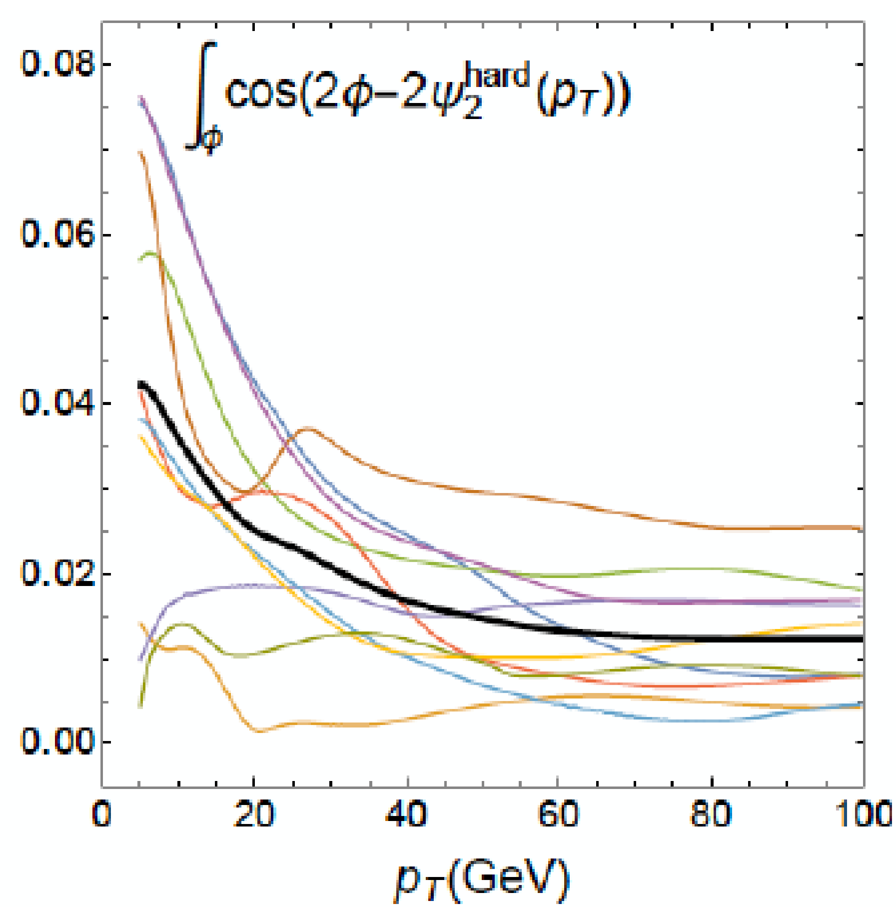
Shuzhe Shi prelim

J.Liao QM17

Event-By-Event Jet Quenching

A first try of e-by-e CUJET3 exercise
(for 10 events —computationally expensive!)





[Hydro background from Jaki Noronha-Holster]

Event-by-event hydrodynamics + jet energy loss: A solution to the $R_{AA} \otimes v_2$ puzzle

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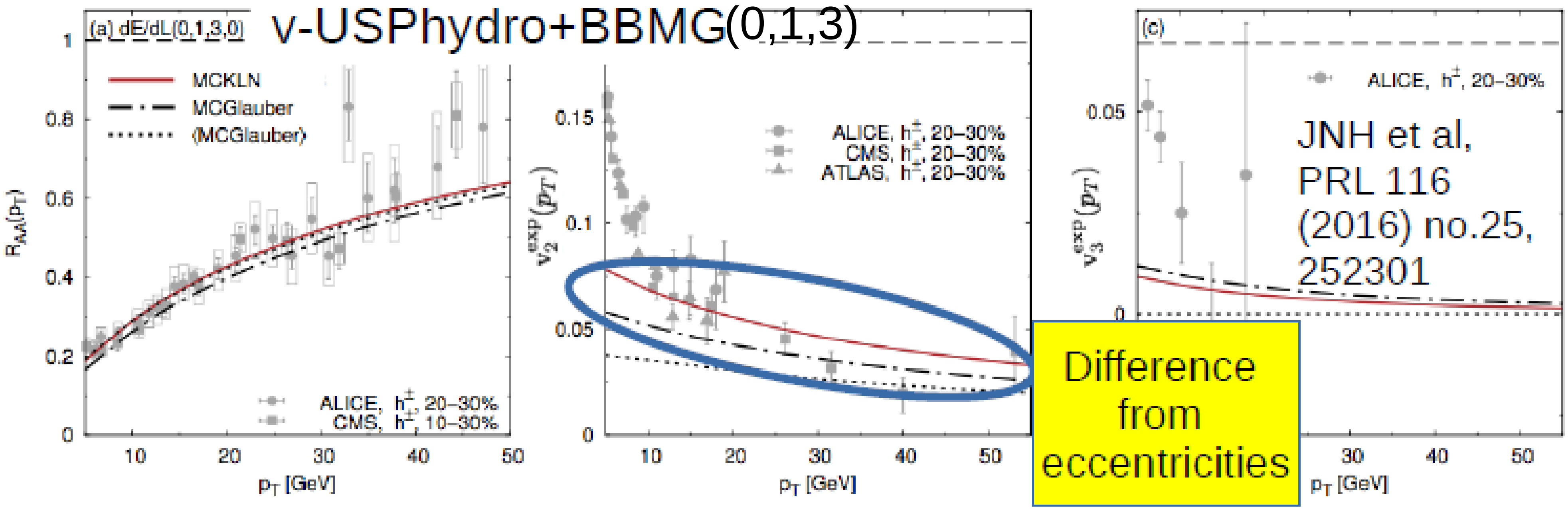


<u>Good fit to RAA+v2+v3! With simple perturbative QCD dE/dx =k L^1 T^3 linear path depend</u>

- Initial Conditions+Hydrodynamics that fit soft v_n's $\rightarrow$ match high p_T flow!

But pQCD qhat(3Tc,Tc) does not extrapolate to 4 pi Tc^3

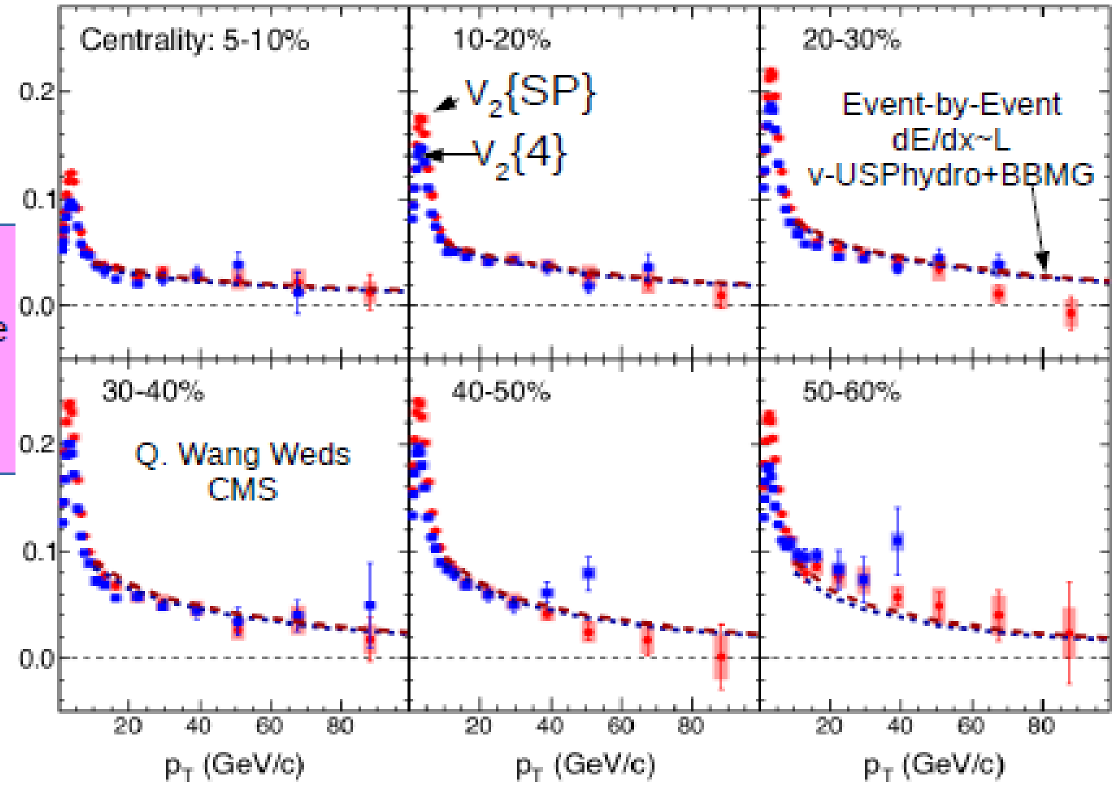
- Other groups currently checking: EKRT+Quenching Weights and v-USPhydro+CUJET3.0

Jacquelyn Noronha-Hostler et al, arXiv:1609.05171 ,Phys.Rev. C95 (2017), 044901

Predictions confirmed with CMS data for LHC Run 2

Over full range of centralities at 5ATeV

First multi-particle cumulants at high pT!



$\frac{v_2\{4\}(p_T)}{v_2\{SP\}(p_T)}$ encodes soft vs. hard fluctuations

References

CMS $v_n m(p_T)$ arXiv:1702.00630; **v-USPhydro+BBMG** JNH, Betz, Gyulassy, Luzum, Noronha, Portillo, Ratti arXiv:1609.05171

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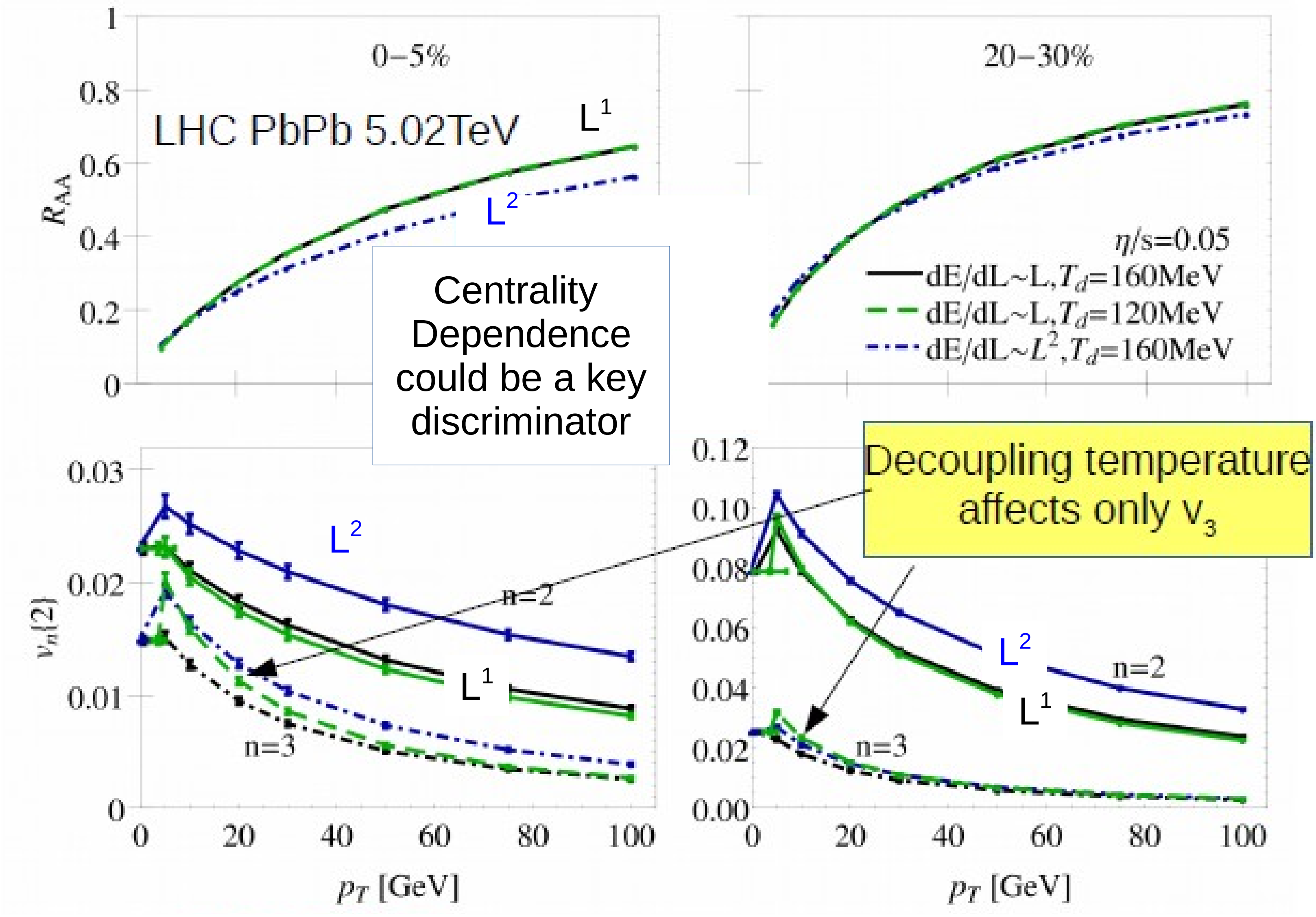
What are R_{AA} and v_n's sensitive to?

Test weak HTL pQCD like dEdx ~ L^1 T^3 versus infinitely coupled AdS like dEdx ~ L^2 T^4

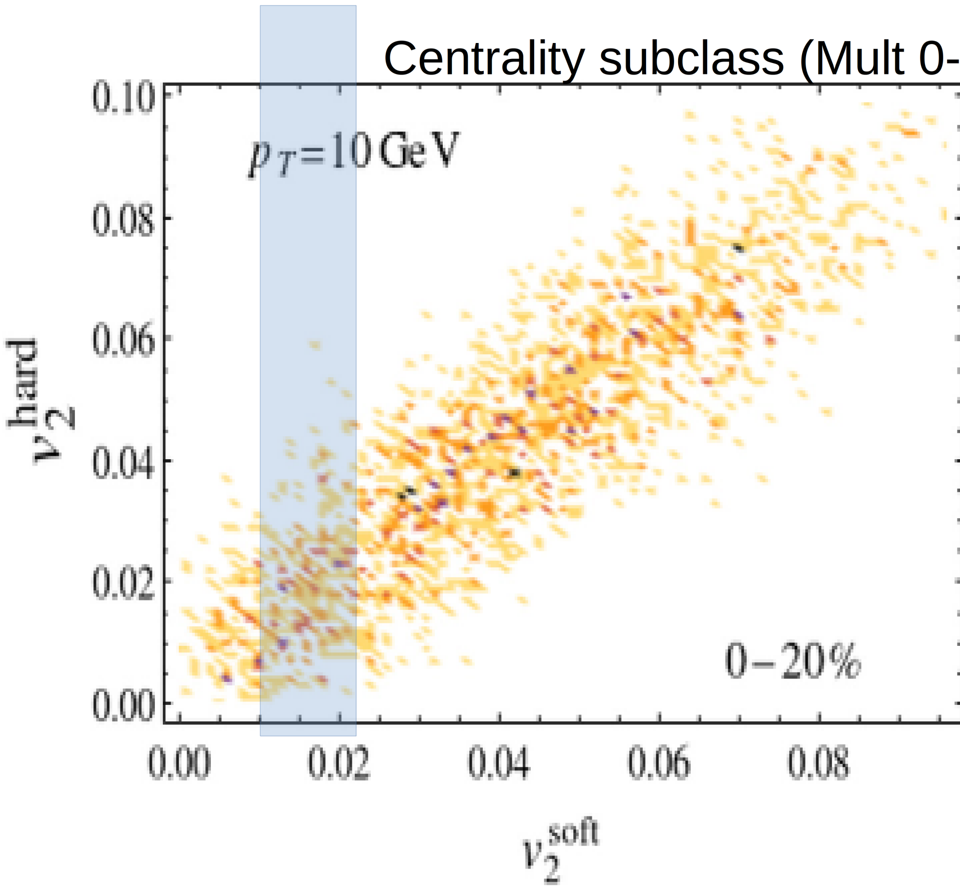


SHEE : Soft-Hard Event Engineering

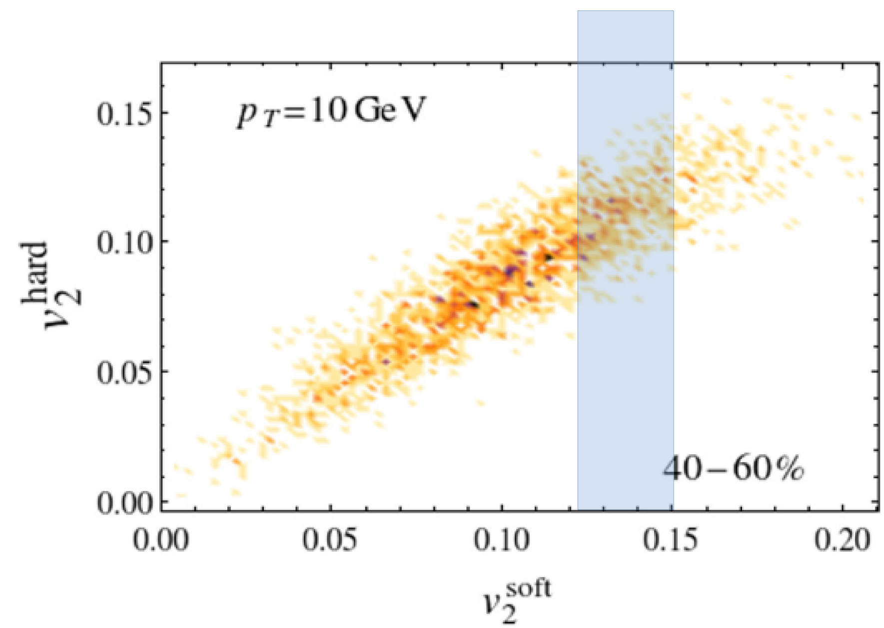
In addition to centrality bins based only on soft Multiplicity or ET binning
more information could be extracted from subclasses of event based on soft v2, v3 .. bins
In which hard jet response is tested subclasses of fluctuating geometries.

PHYSICAL REVIEW C **95**, 044901 (2017)

Centrality subclass (Mult 0-20%, less eccentric v2soft 0.01-0.02)



Centrality subclass
(Mult 40-60%, more eccentric v2soft 0.12-0.15)



Status as of today:

There exists (at least) two combinations of Soft vn +Hard RAA+ Hard vn dynamical models

That are compatible at $\chi^2 < 4$ level with RHIC+LHC1+LHC2 data sets at 0-10% and 20-30%

1) ebe MCKLN+vUSPH+BBMG(L^1) : J.Noronha-Hostler et al, PRL116(2016),PRC95(2017)

2) ave MCKLN+VISH2+1 +CUJET3.1: S.Shi, et al QM17; arXiv:1704.04577;
3.0 : J.Xu et al ; JHEP1602 (2016)

1) is compatible with aexp data including v3, but the weak L^1 jet dynamics qhat(E,T) does not extrapolate to the Perfect Fluidity limit near Tc as E->3Tc.
The jet-medium interaction L^1 does not know about Lattice QCD physics near Tc.

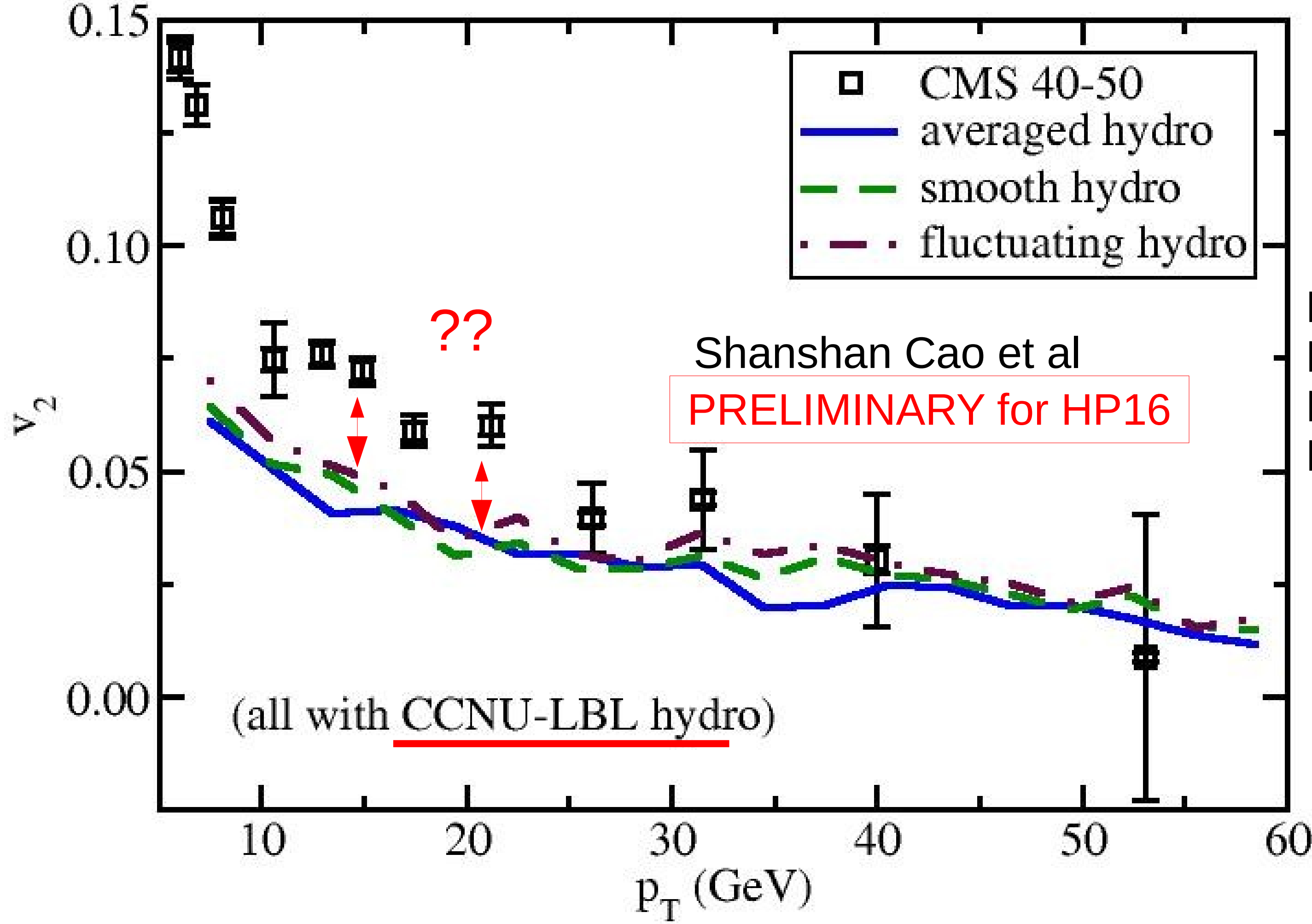
The strong coupling AdS/CFT L^2 version is compatible to Perfect Fluidity but LHC2 CMS hints that maybe they can rule this out! Centrality dependence appears as key observable

2) sQGMP via corrected CUJET3.1 version is also compatible with present data
And builds in all lattice QCD thermal data and does extrapolate near Tc to Perfect fluidity.
However, 3.1 still has not taken into account ebe fluctuations and hence fails on odd vn.
Shuzhe Shi is developing CUJET4 = ebe-vUSPH/VISHNU + CUJET3.1 (numerically challenging)

(Stay tuned)

Averaged: one hydro run on event average IC in 40-50% centrality
Smooth: 20 hydro runs in centrality bin on 20 different bins of soft v2(pT<2)
Fluctuating: Smooth times event fluctuation estimate

IF linear reponse holds $\frac{v_2(p_T)}{\langle v_2^{hard}(p_T)\rangle} \simeq 1 + \frac{1}{2}\left\langle\left(\frac{\delta v_2^{soft}}{\langle v_2^{soft}\rangle}\right)^2\right\rangle - 2\left\langle(\delta\psi_2(p_T))^2\right\rangle$ (J.Noronga-Hostler et al PRL 2016)



Model reproduces RAA well
But still misses Hard jet v2

Assuming linear hard-soft response: v2hard(PT) = χ_{hs}(pT) v2soft = χ_{hs}(pT) $\tilde{\varepsilon}2$

Ebe Fluctuations of soft v2 do not explain hard v2 data in 10-30 GeV range in this moswl

CUJET2.0 = rc DGLV + VISH2+1 at RHIC and LHC and where
VISH is bulk flow pT<2 GeV constrained viscous 2+1 D hydro UHeinz etal

VISH2+1

$$x\frac{dN_{Q->Q+g}}{dx}(\mathbf{x},\phi) = \int d\tau\,\rho_{QGP}(\mathbf{x}+\hat{\mathbf{n}}(\phi)\tau,\tau)\int\frac{d^2\mathbf{q}}{\pi}\frac{\alpha_s^2(\mathbf{q}^2)}{(\mathbf{q}^2+f_E^2\mu^2(\tau))(\mathbf{q}^2+f_M^2\mu^2(\tau)}\int\frac{d^2\mathbf{k}}{\pi}\alpha_s(k_T^2/(x(1-x)))$$

$$\times\frac{12(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)}\cdot\left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)}-\frac{\mathbf{k}}{\mathbf{k}^2+\chi(\tau)}\right)\left(1-\cos\left[\frac{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)}{2x_+E}\tau\right]\right).$$

where $\mu^2(\tau) = 4\pi\alpha_s(4T^2)$ is the local HTL color electric Debye screening mass squared in a pure gluonic plasma with local temperature $T(\tau) \propto \rho_{QGP}^{1/3}(\mathbf{x},\tau)$ along the jet path $\mathbf{x}(\tau)$ through the plasma. Here $\chi(\tau) = M^2x_+^2 + f_E^2\mu^2(T(\tau))(1-x_+)/\sqrt{2}$ controls the "dead cone" and LPM destructive interference effects due to both the finite quark current mass M, and a thermal gluon $m_g = f_E\,\mu(T)/\sqrt{2}$ mass.

Includes effects due to bulk Radial and Elliptic transverse flow of sQGP
as well as boost invariant Bjorken longitudinal flow

These suppress jet v2 by factor of 2 (as in **D. Molnar and D.Sun**, NPA932 (2014))

J.Xu, A.Buzzatti, MG, JHEP 1408 (2014)