Round Table Discussion

Field theory at finite temperature : EFTs and lattice methods

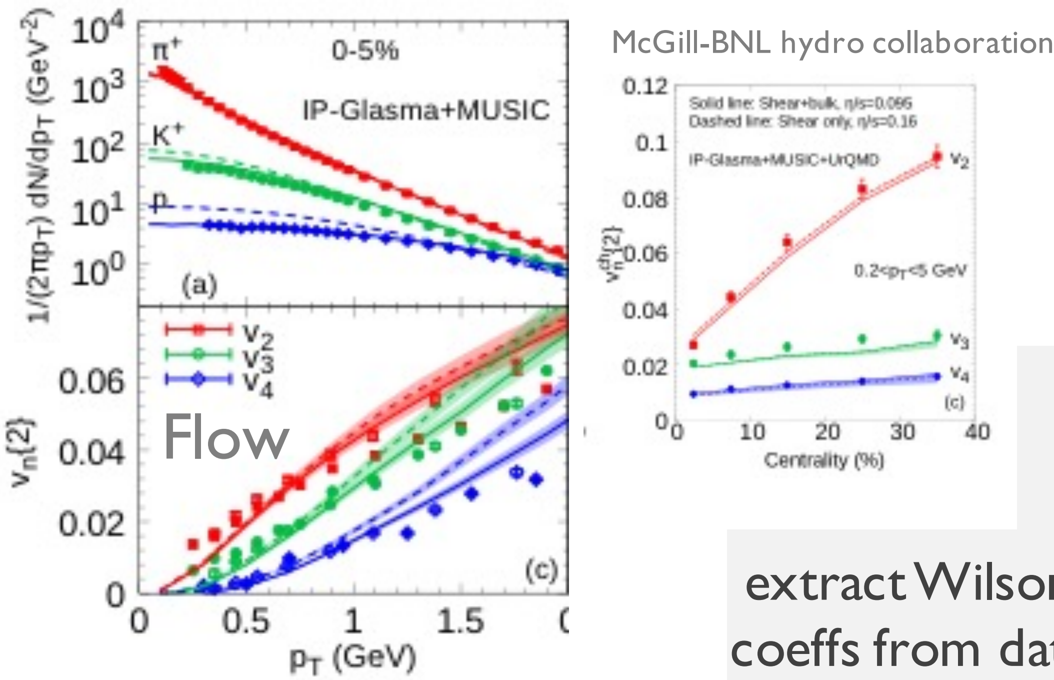
Chair N. Brambilla, Members:
H. Meyer, P. Petreczky, A. Rothkopf, J. Soto, A. Vairo

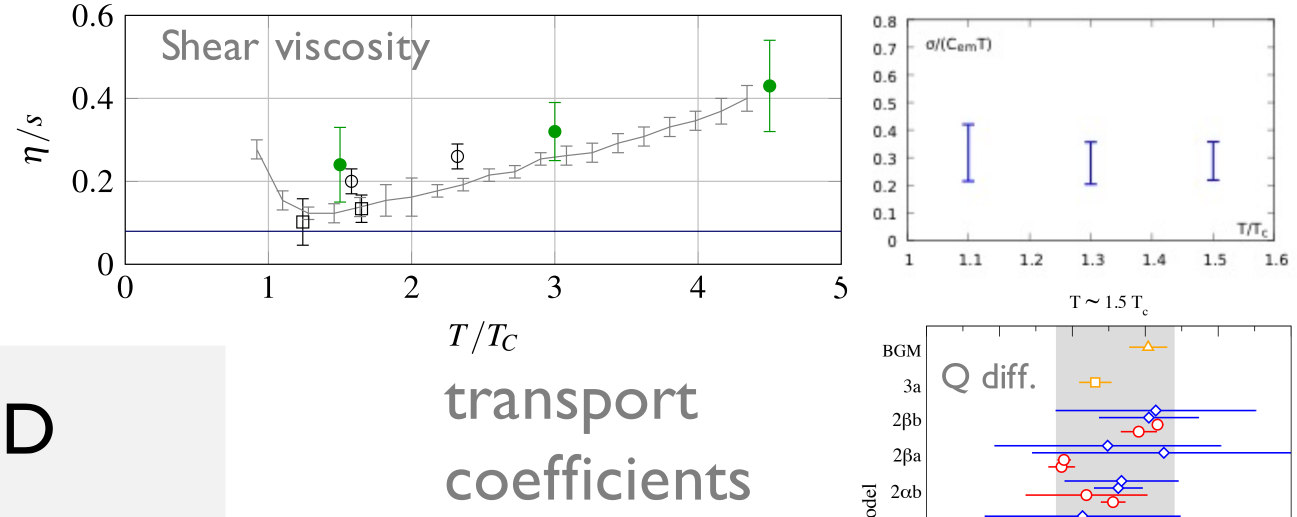
First: set the stage!

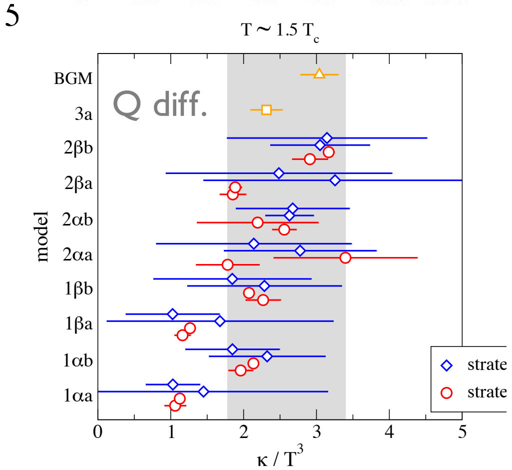
An outstanding application of these techniques is the case of the study of quark gluon plasma formation in heavy ion collisions at LHC : what are the physical conditions (temperature, energy density..) and what are the observables?

How can we interpret/calculate these observables in EFT/lattice?

Experimental data: How do we gain insight?







QCD

extract Wilson coeffs from data

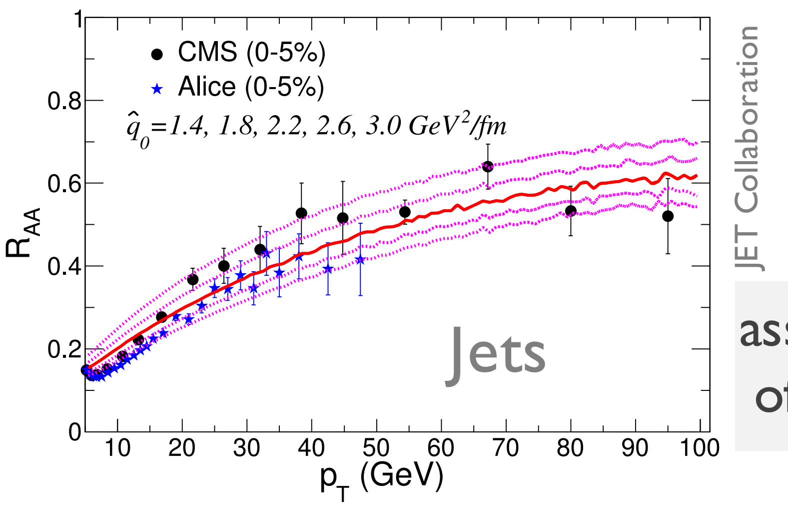
compute QCD Wilson coeffs

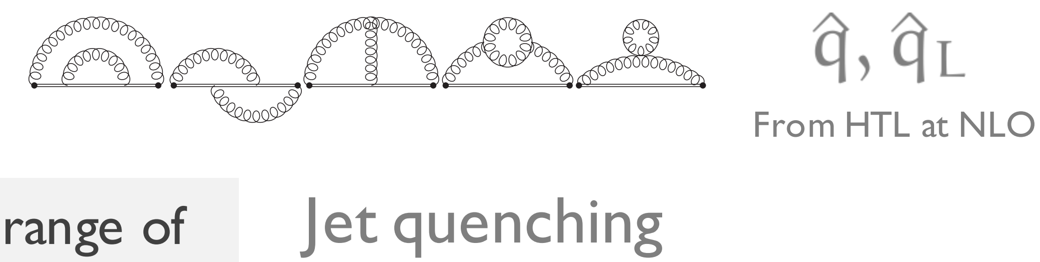
EFT's
((p)NRQCD,SCET, Hydro,..)

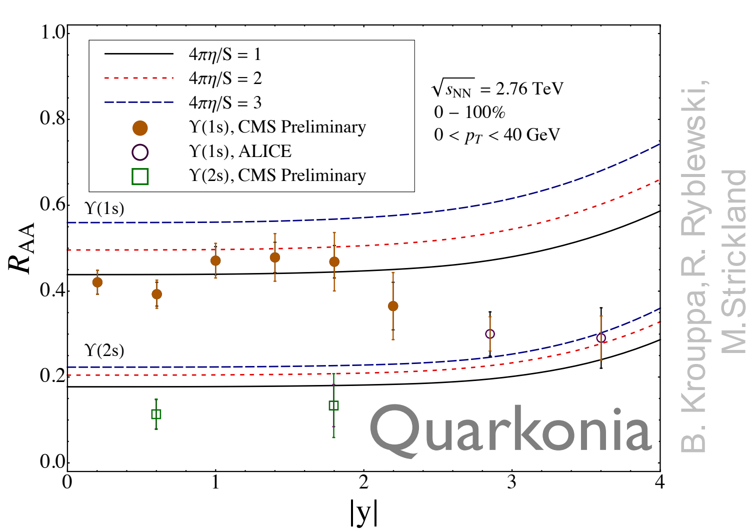
assume validity of EFT/model

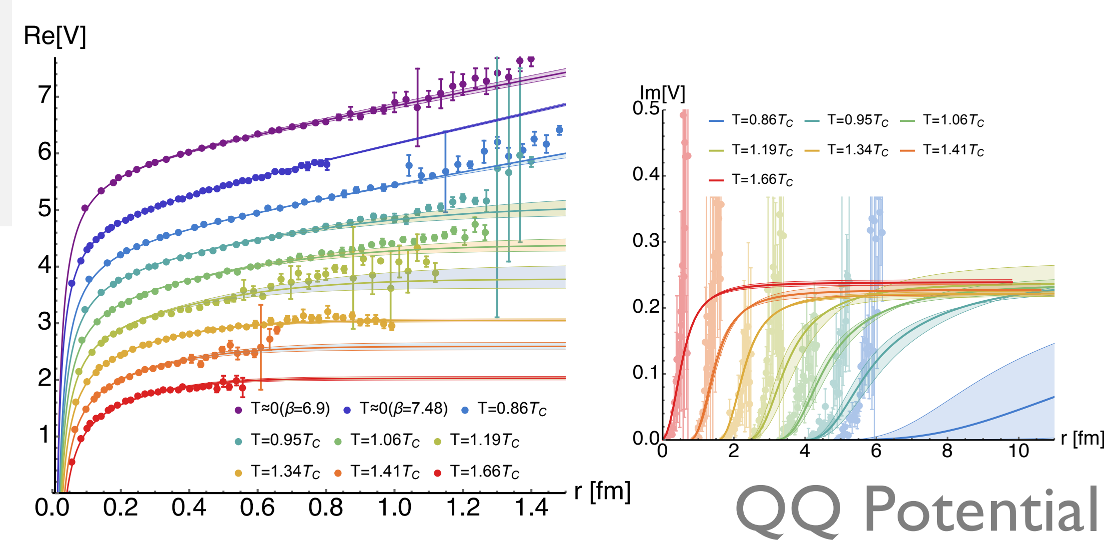
test range of validity of EFT

Data





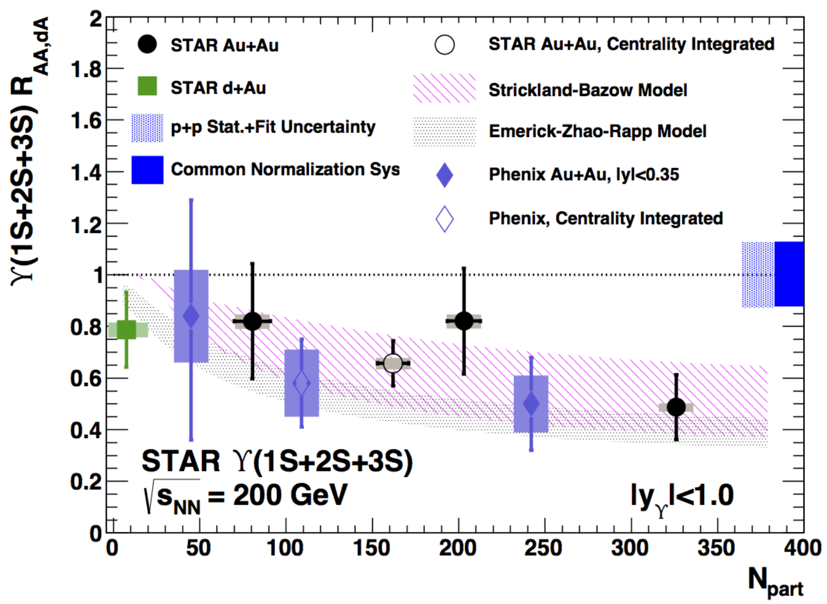




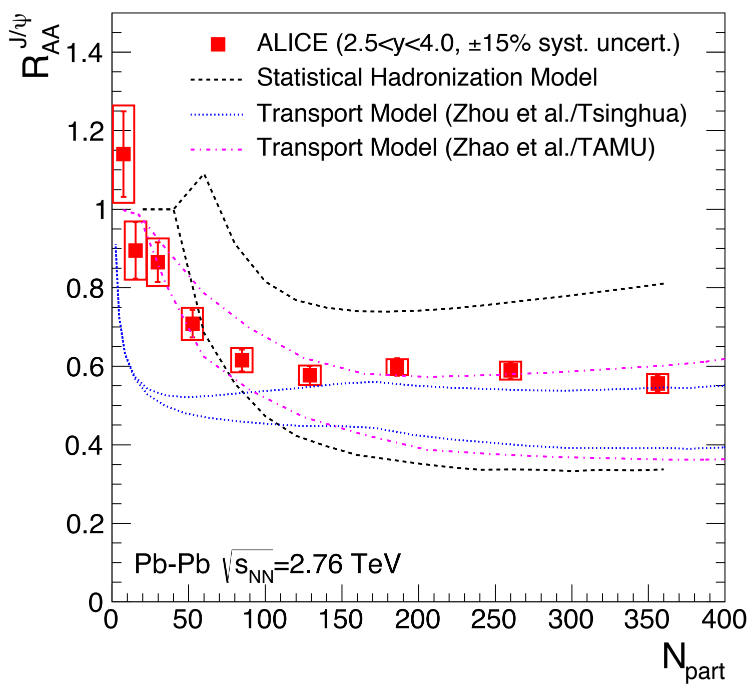
LHC heavy-ion data: Where do we stand?

Dawn of the highest LHC Pb+Pb energies: 2.76TeV → 5.06TeV

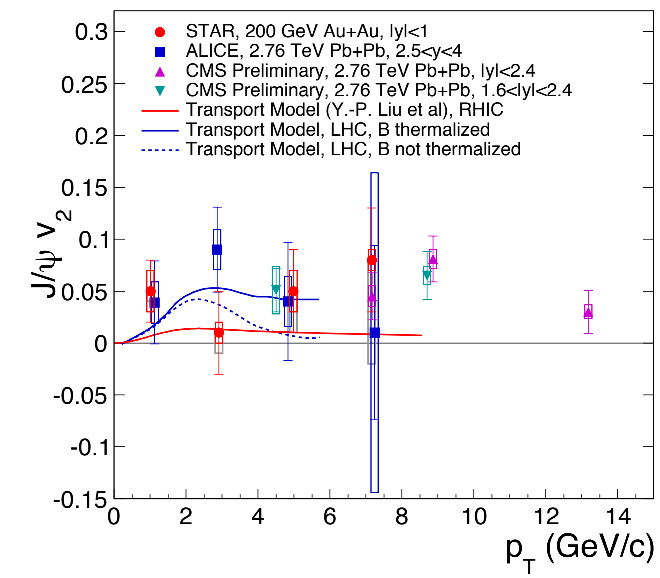
Bottomonium R_{AA}



Charmonium R_{AA}



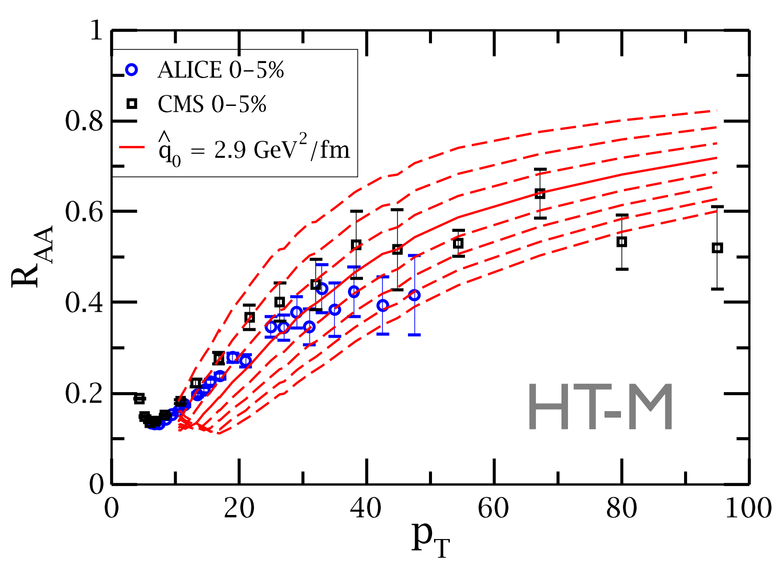
Charmonium Flow

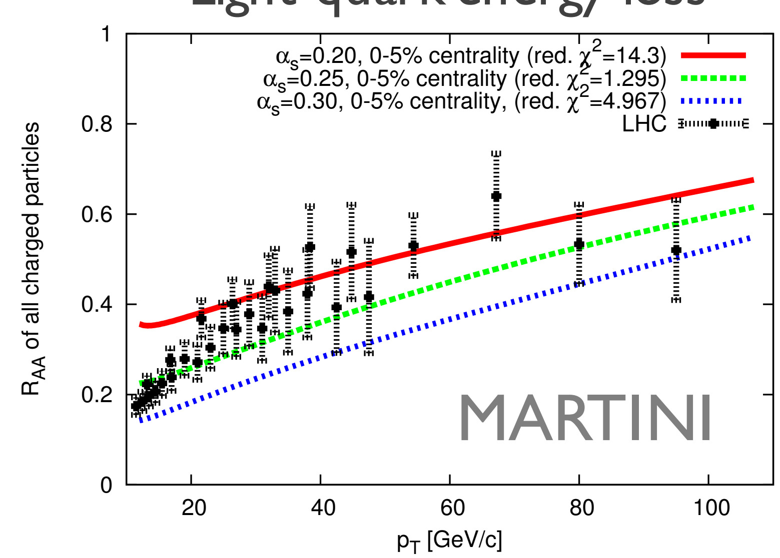


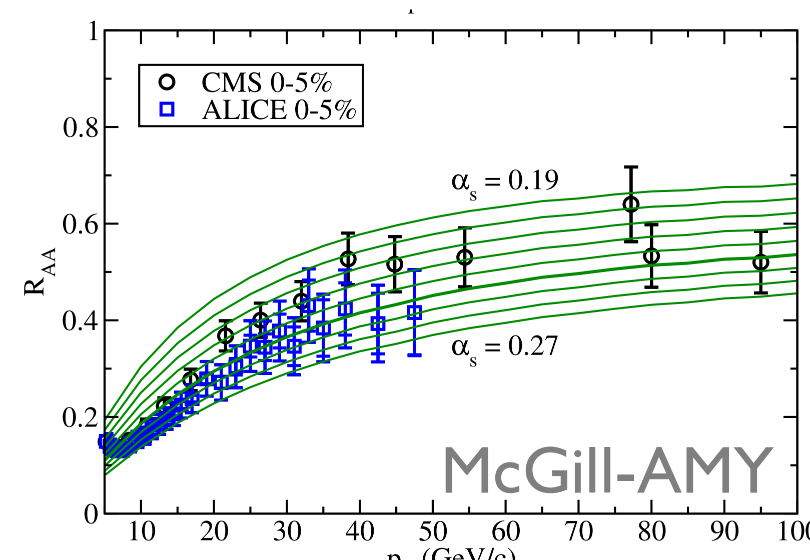
Many models describe current data almost equally well:

How can EFT/LQCD help to constrain further? Need different observables?

Light quark energy loss



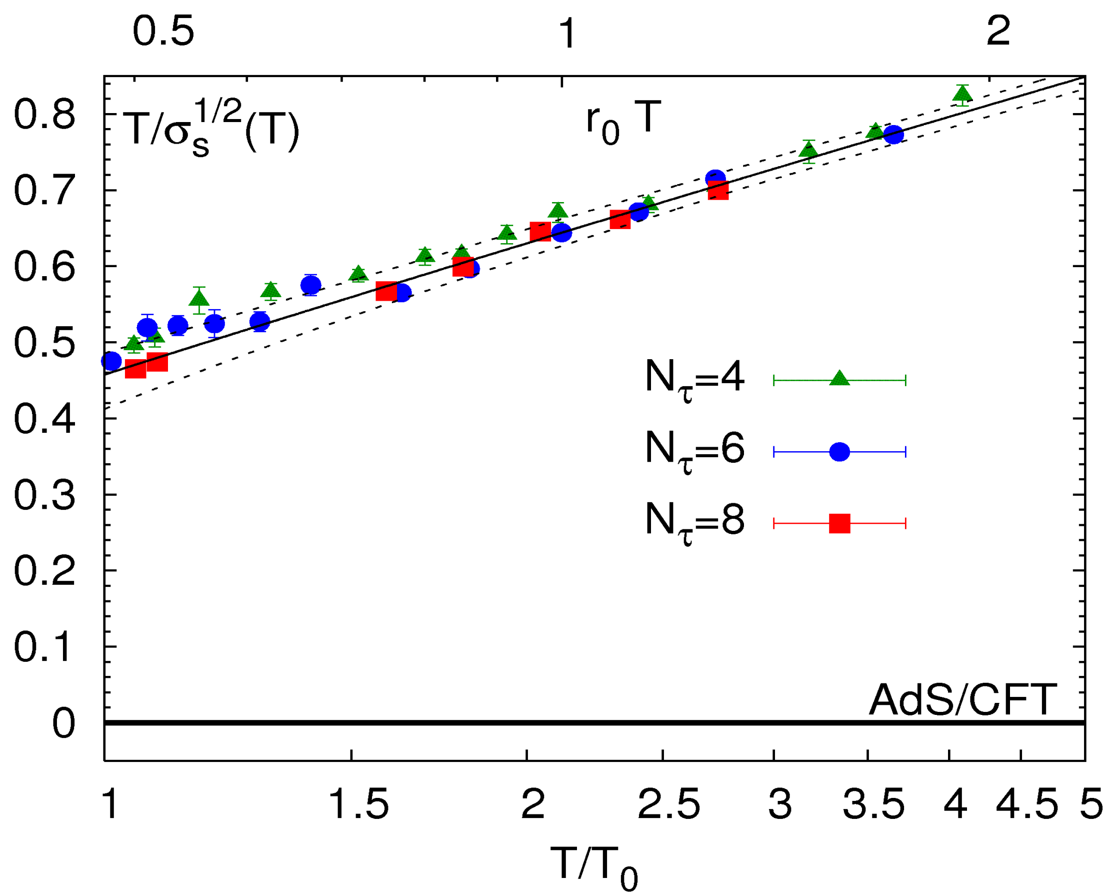


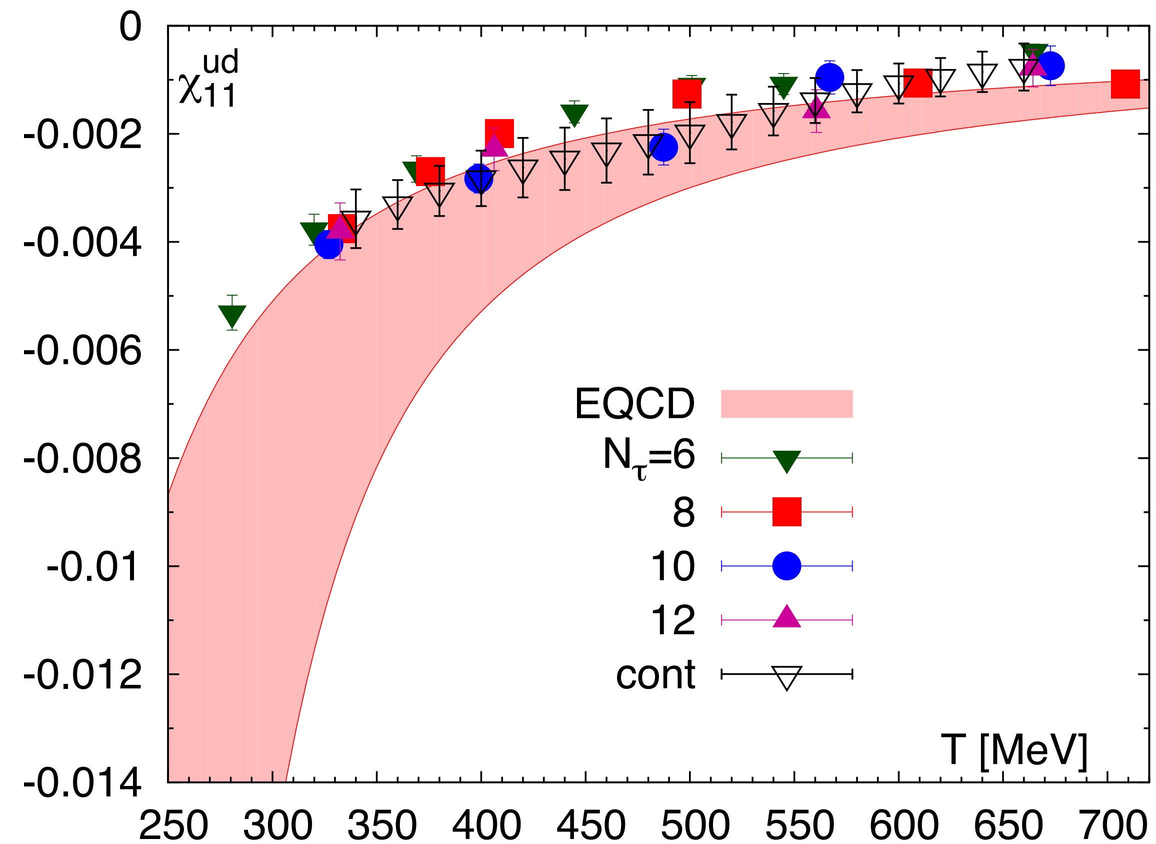


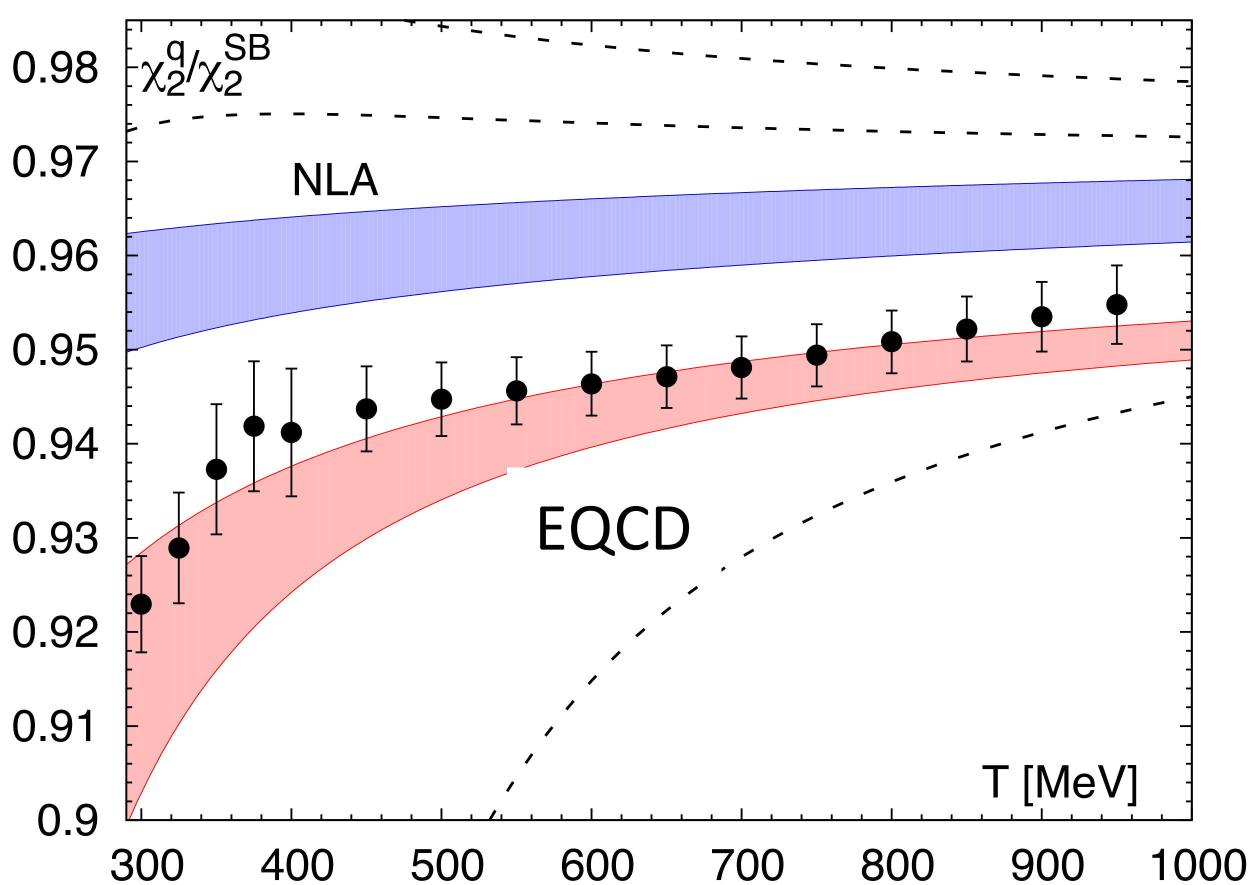
Questions:

- Resummed perturbative calculations of important quantities like the pressure, the Polyakov loop/free energy, Polyakov loop correlation, transport coefficients are performed within EFTs (HTL, EQCD, NRQCD and pNRQCD at finite T) . The same quantities are calculated on the lattice: do the two calculations agree or match? in which cases yes and when not? why? how can we exploit this?

EQCD at work



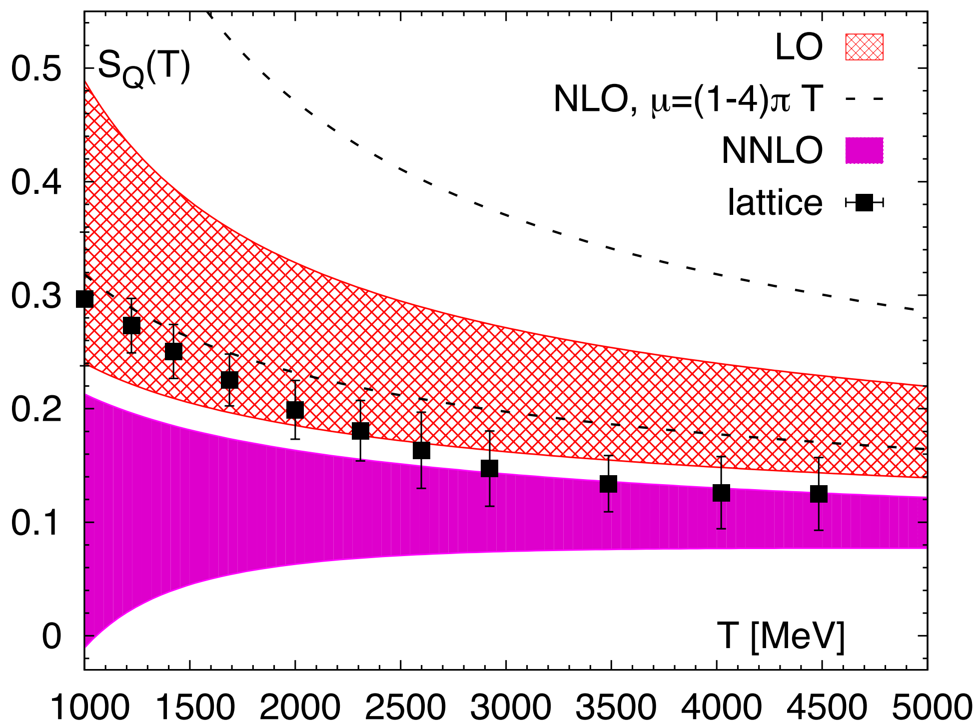


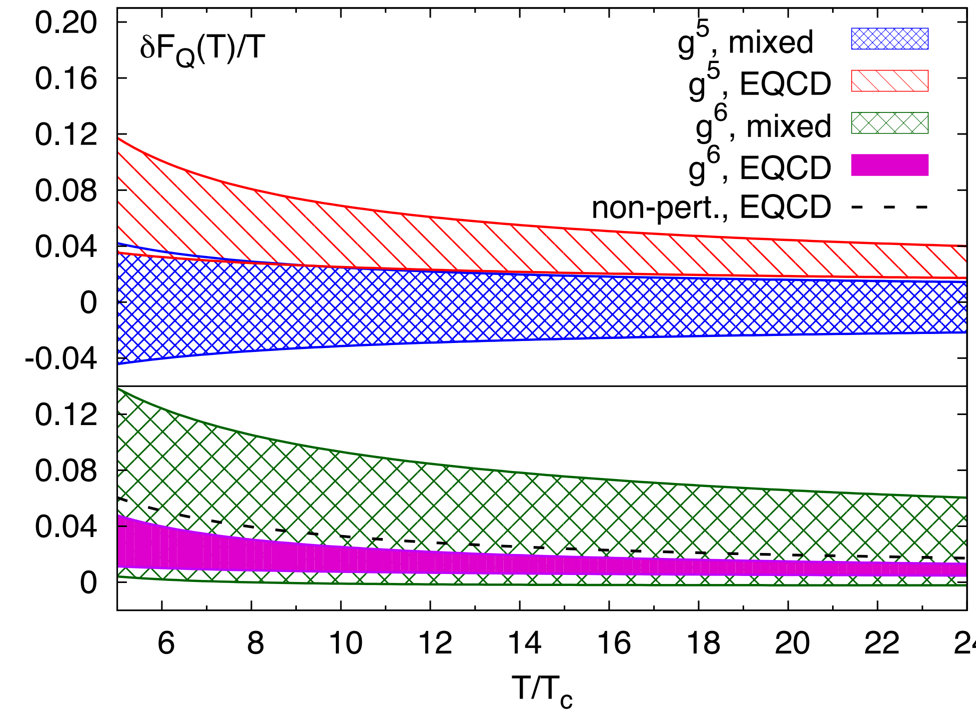


EQCD works for spatial string tension and quark number correlations (purely chromo-magnetic observables)

EQCD works for quark number susceptibility maybe because it is dominated by scale T and the contribution electro-static sector is s mall $m_D \sim g\, T\, \mu / (2\pi)$ magnetic sector does not contribute

EQCD work less well …

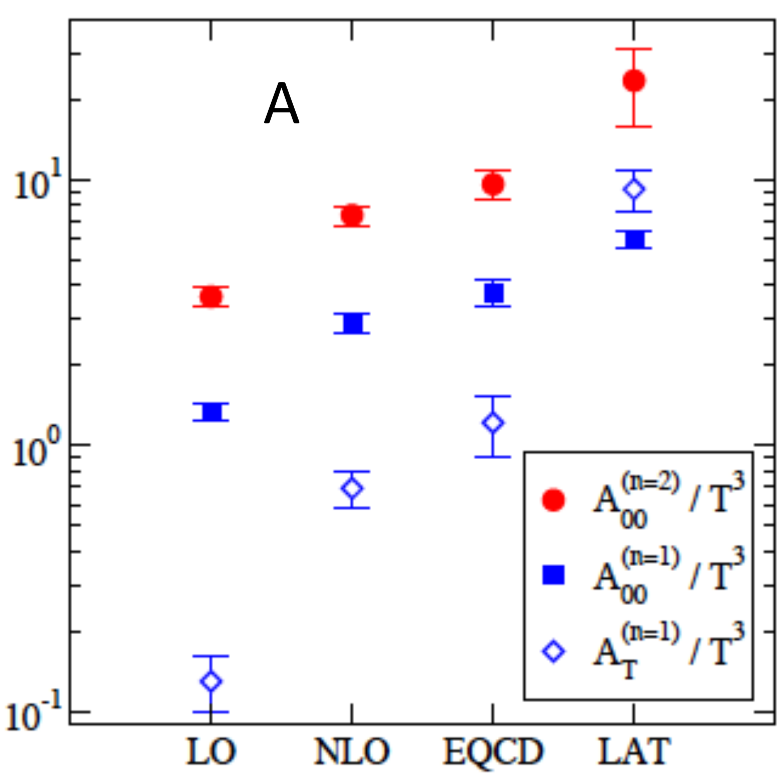




EQCD works only for T>2GeV for the static quark free energy/entropy even-though magnetic contribution is small, subtle interplay between scale *T* and *gT* contributions ? Large g^6 contribution from scale *T* ? Need full g^6 calculation …

Spatial Meson correlation functions

EQCD

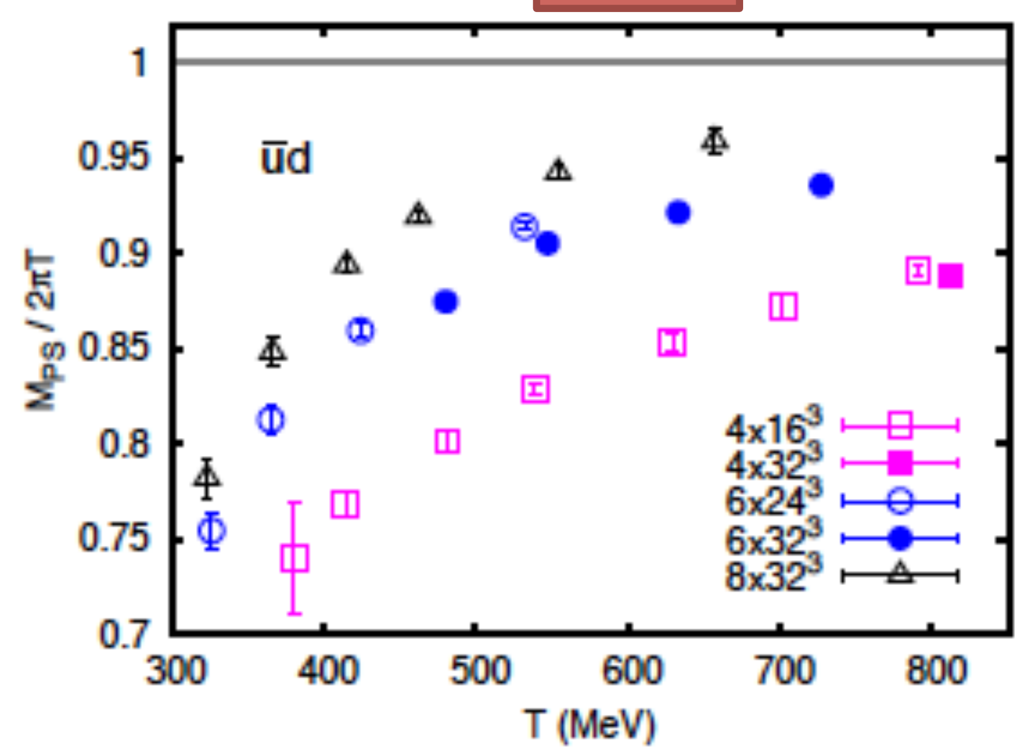


$$G(z) = A\exp(-Mz)$$

Cheng et al, EPJC 71 (2011) 1564

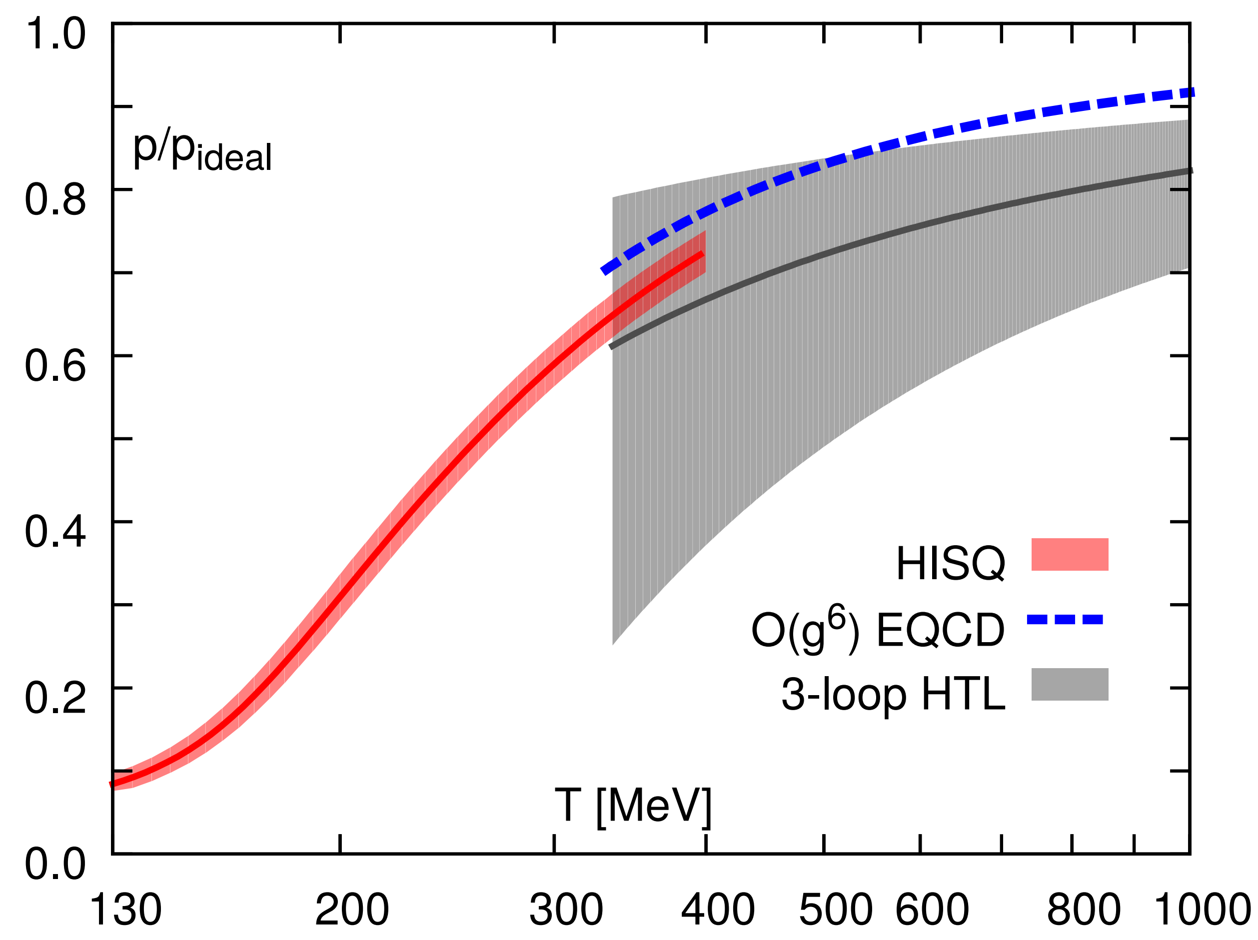
Brandt et al, JHEP 1405 (2014) 117

Need continuum at High T and improved EQCD calculations !



Weak coupling without EQCD:

Large scale dependence !



Other open issues:

Power law corrections (Λ_{QCD}/T)^m ?

Polyakov loop/Wilson loops at short distances vs. pNRQCD and EQCD ?
(at what distances screening sets in ?)

ChiPT at T>0 ?

Questions:

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- **Q2**: How to use the EFTs combined with lattice to define and calculate objects of great physical importance like:

the qqbar potential at finite T (give evolution in real time)
R_AA
q_hat and jet quenching
transport coefficients

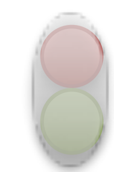
Complex in-medium inter-quark potential

- EFT definition of V: matching of pNRQCD wavefunction correlator to QCD Wilson loop

Relativistic thermal field theory

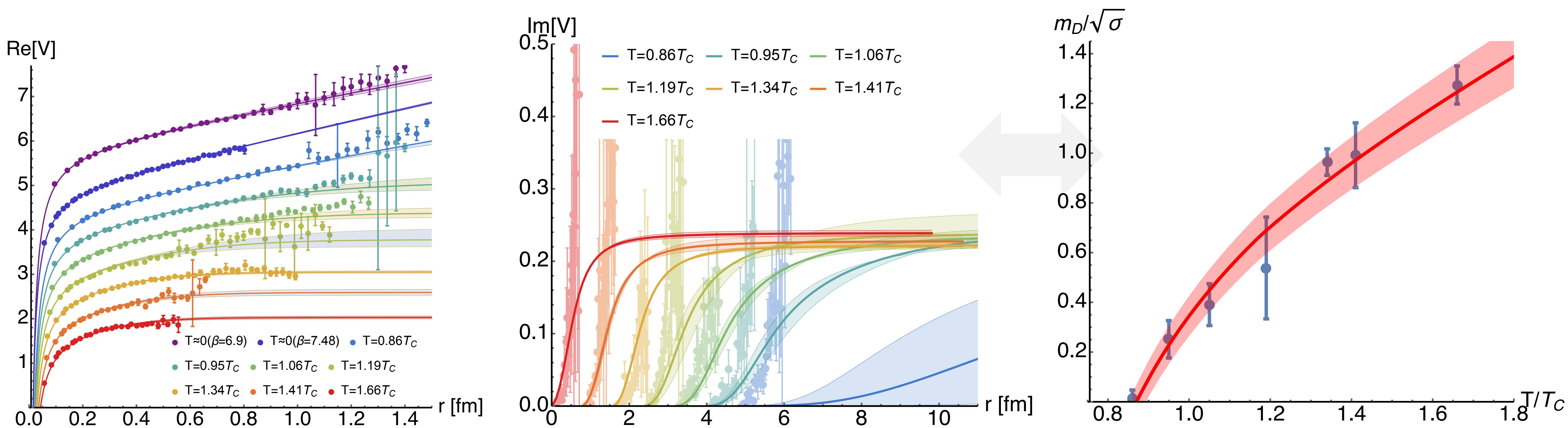
QCD	NRQCD	pNRQCD
Dirac fields	Pauli fields	Singlet/Octet
$\bar{Q}(x), Q(x)$	$\chi^\dagger(x), \chi(x)$	$\psi_S(R,t), \psi_O(R,t)$
$\bar{q}(x), q(x), A^\mu(x)$		$i\partial_t\psi_S = \left(V^{QCD}(R) + \mathcal{O}(m_Q^{-1})\right)\psi_S$

Quantum mechanics



- Re[V] and Im[V] encoded in spectrum of Wilson line correlators (Bayesian inference)

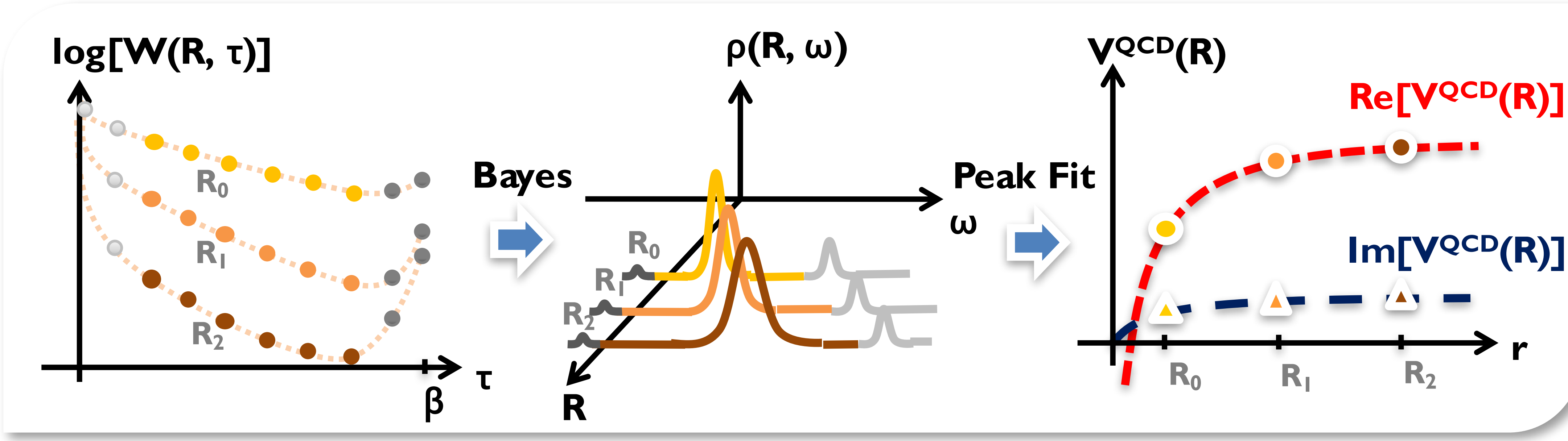
Y. Burnier, O. Kaczmarek, A.R.
JHEP 1512 (2015) 101



- Single temperature dependent parameter m_D seems to govern the in-medium modification

Complex in-medium inter-quark potential

- EFT definition of V: matching of pNRQCD wavefunction correlator to QCD Wilson loop



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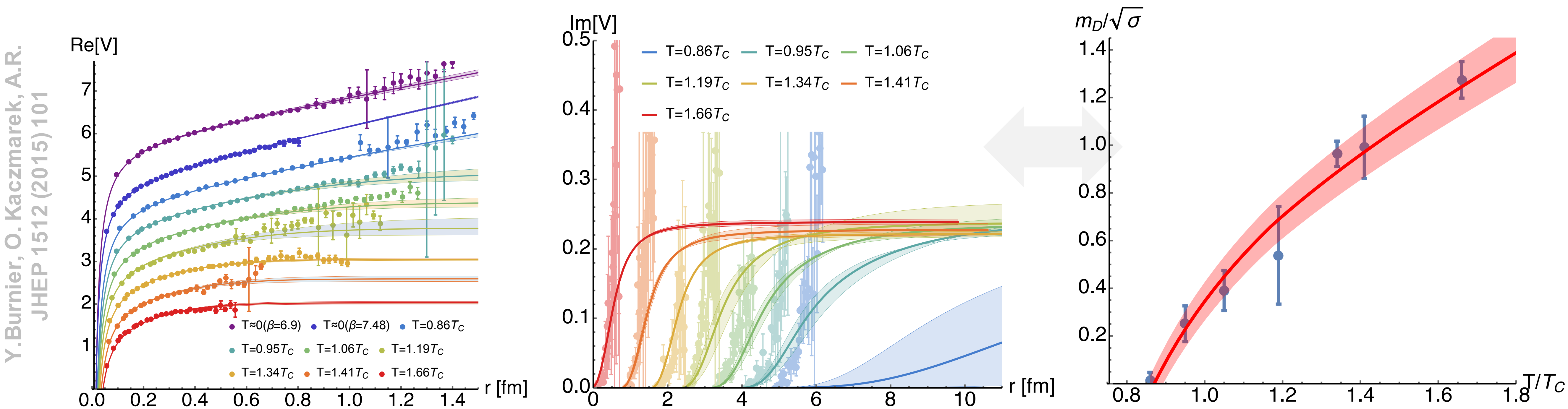
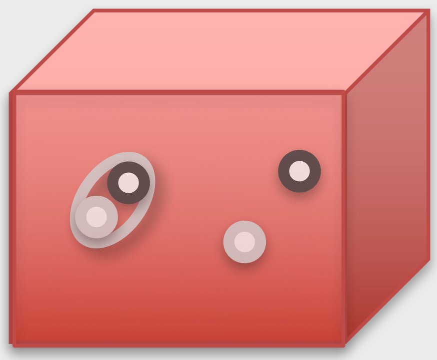


- Single temperature dependent parameter m_D seems to govern the in-medium modification

In-medium $Q\bar{Q}$ yields from EFTs on the lattice

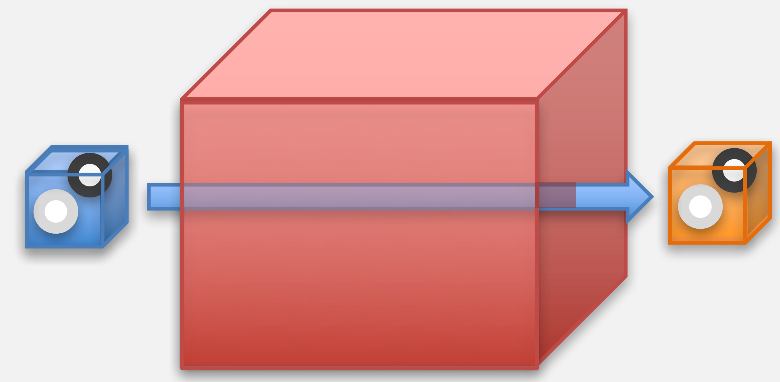


In-medium bound states identified by di-lepton emission, related to T>0 spectral function

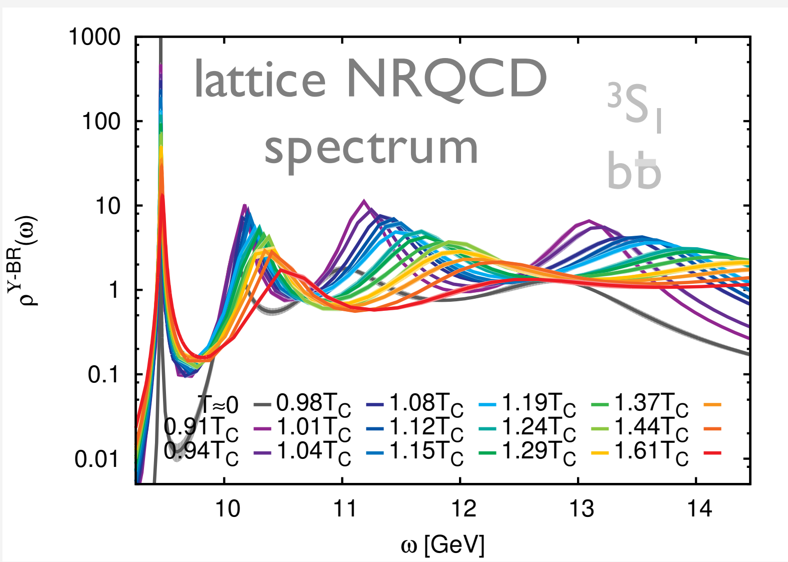
Full kinetic thermalization

vs.

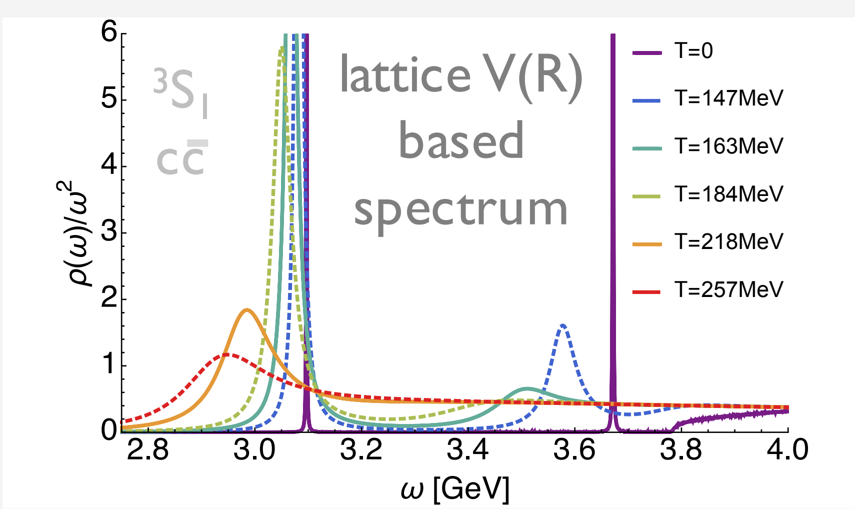
Survival of vacuum states in the QGP from a real-time Schrödinger equation



Open-quantum system in a QGP

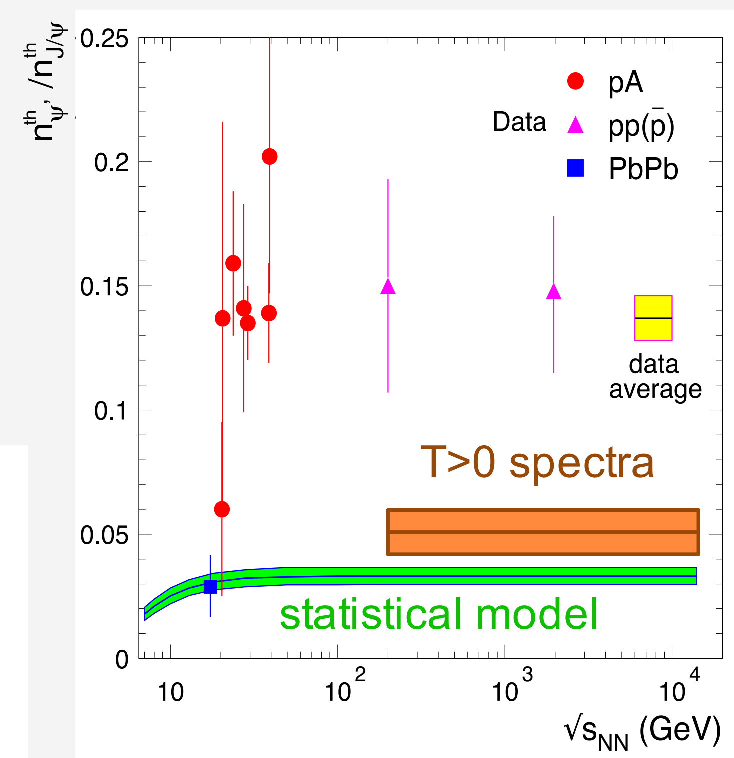


S.Kim, P.Petreczky, A.R. PRD 91 (2015) 054511

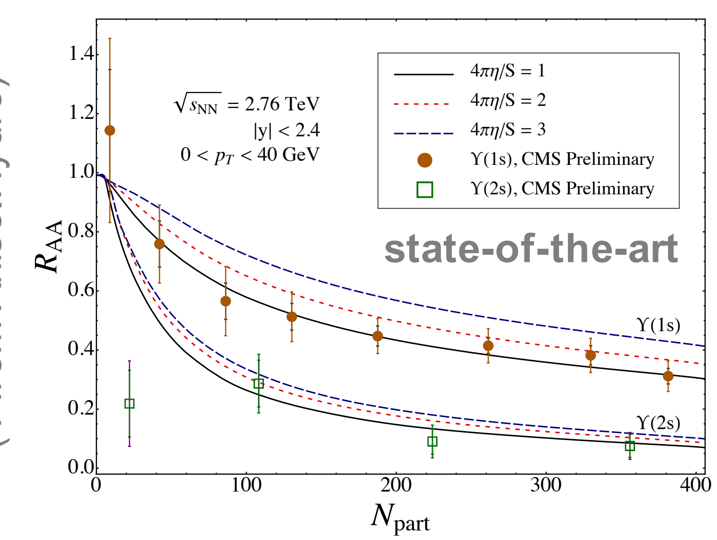


Y.Burnier, O. Kaczmarek, A.R. JHEP 1512 (2015) 101

ψ' to J/ψ ratio

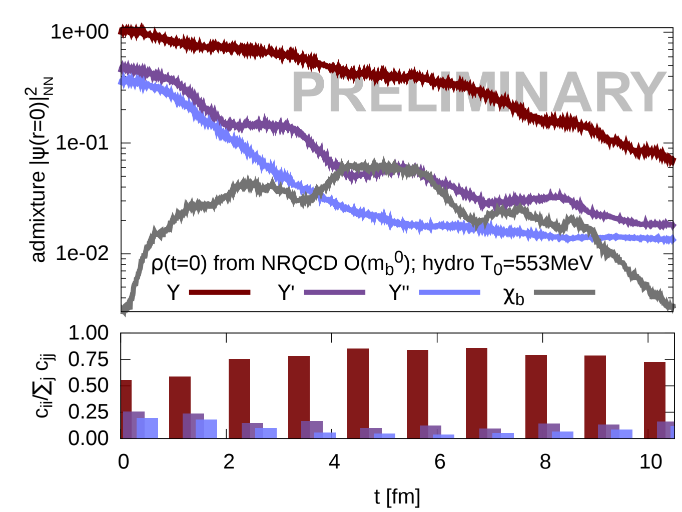


ImV as S→O (T from Aniso.Hydro)



B. Krouppa, R. Ryblewski, M.Strickland PRCC 92, 061901 (2015)

ImV as stochastic noise (T from conv. Hydro)



Y.Akamatsu, J.Casalderrey-Solana, C. Nonaka, A.R. work in progress

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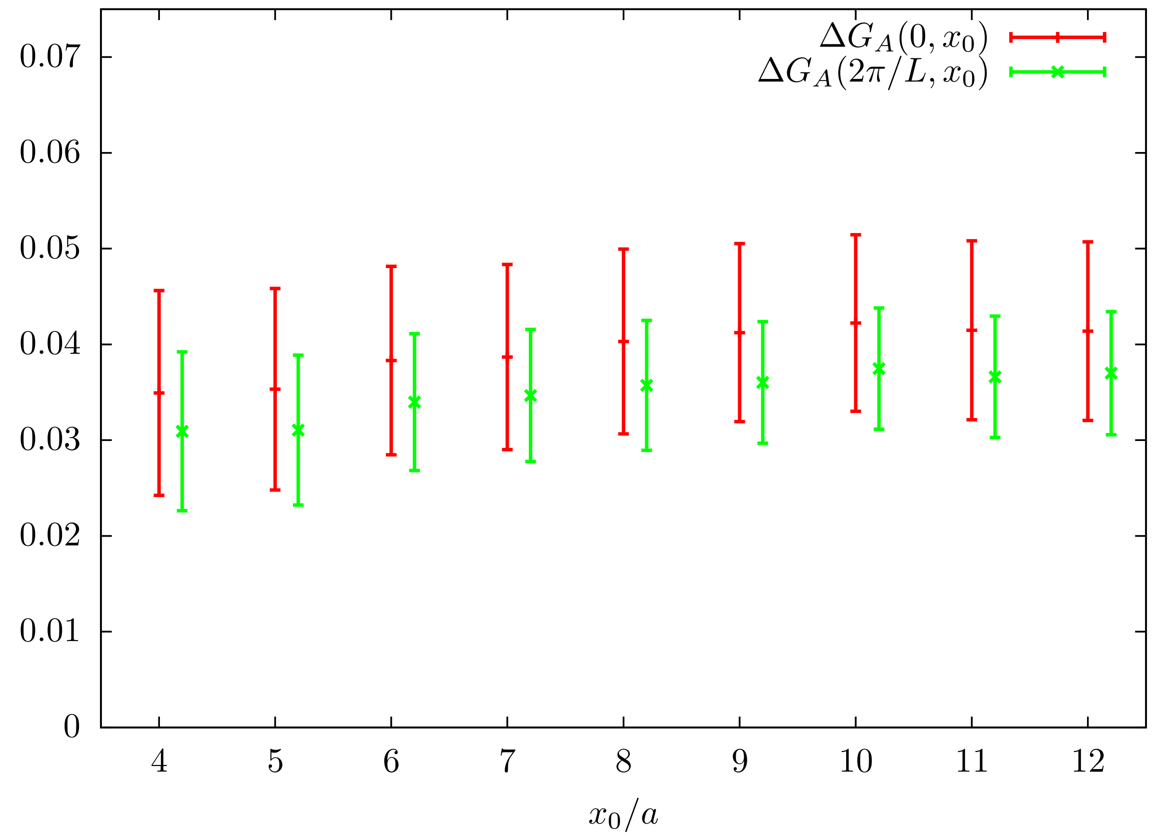
- **Q2**: How to use the EFTs combined with lattice to define and calculate objects of great physical importance like

- **Q3**: How to use lattice combined with EFTs to obtain determinations of out of equilibrium quantities ?

Correlator of $A_0^a = \bar{\psi}\gamma_0\gamma_5\frac{\tau^a}{2}\psi$ corresponding to $\rho(\omega,T) - \rho(\omega,0)$:
$(T = 170\text{MeV} < T_c)$



$T = 0$: pion mass $= 267(2)$ MeV

$\swarrow \qquad \searrow$

$T = 169\text{MeV}$: quasiparticle mass $= 223(4)\text{MeV}$ screening mass $= 303(4)\text{MeV}$.

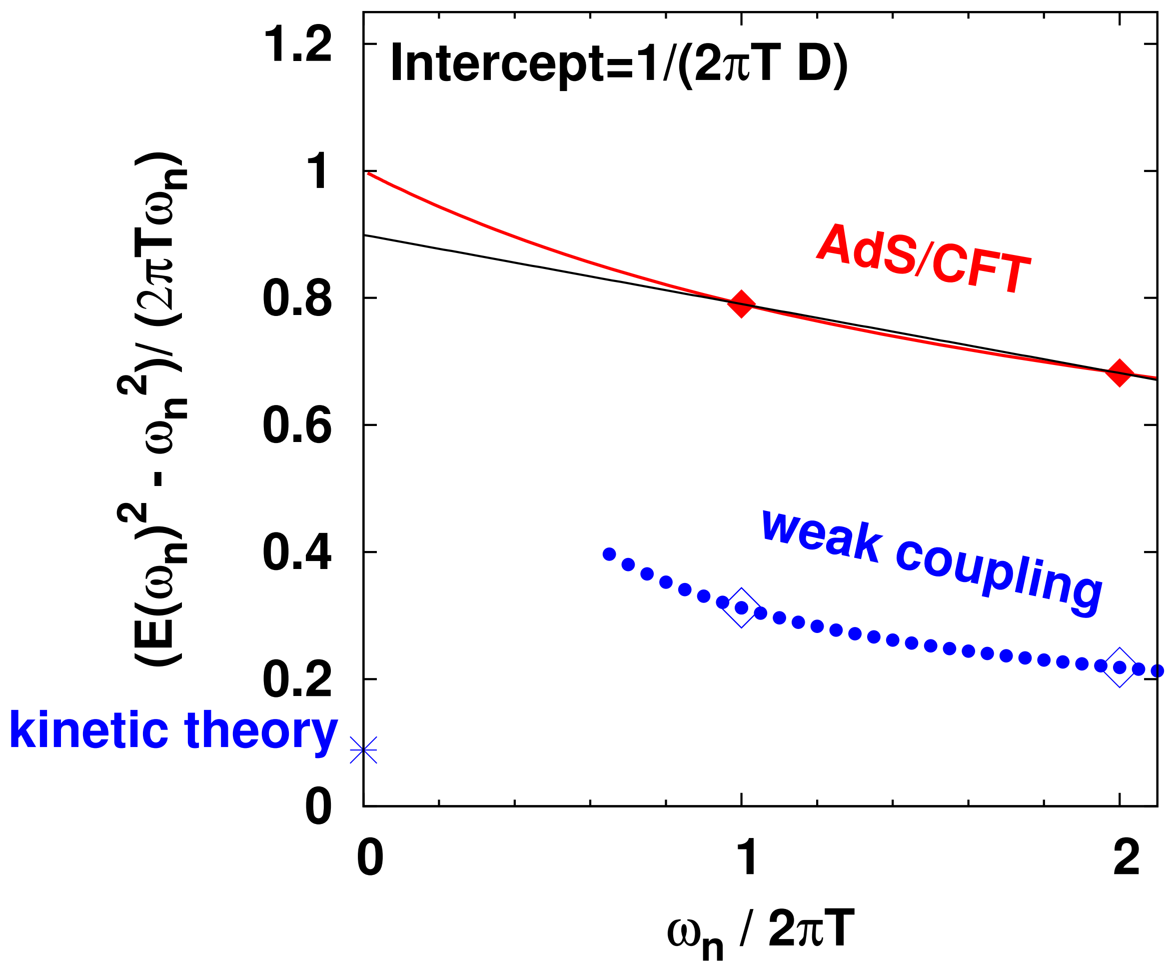
Implications for the hadron resonance gas model!?

Non-static screening masses and transport coefficients

Linear response along with a constitutive equation for the vector current $\boldsymbol{J}$ $\Rightarrow$

$$G_E^{J_0 J_0}(\omega_n, k) \overset{\omega_n, k\to 0}{=\!=\!=} \frac{\chi_s D k^2}{\omega_n + D k^2} \qquad \Rightarrow \qquad E(\omega_n)^2 \overset{\omega_n \to 0}{\sim} \frac{\omega_n}{D}.$$

χ_s = static susceptibility, D = diffusion coefficient, $E(\omega_n)$ = screening mass in sector ω_n



In the limit $T \to \infty$, extrapolating the screening masses in the lowest Matsubara sectors to $\omega_n = 0$ gives the correct result, $1/(T\,D) = 0$.

Brandt, Francis, Laine, HM 1408.5917; Kinetic theory: Arnold, Moore & Yaffe hep-ph/0111107

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- **Q4**: can these results and techniques be impactful on other fields: e.g. cosmology and the physics of early universe; condensed matter..