Lattice 2012
Cairns, Australia

High Temperature QCD

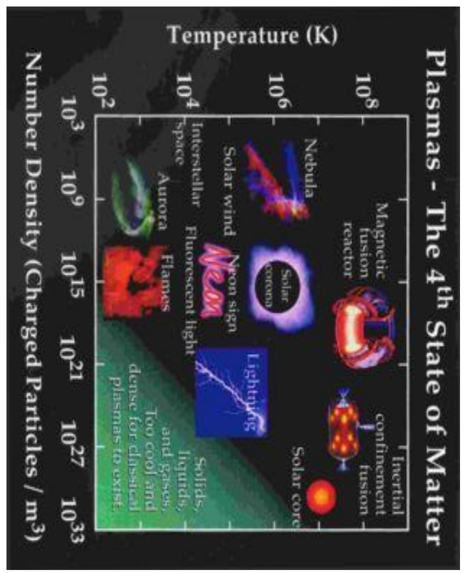
Maria Paola Lombardo

From here to high temperature QCD

Here : 330 Kelvin

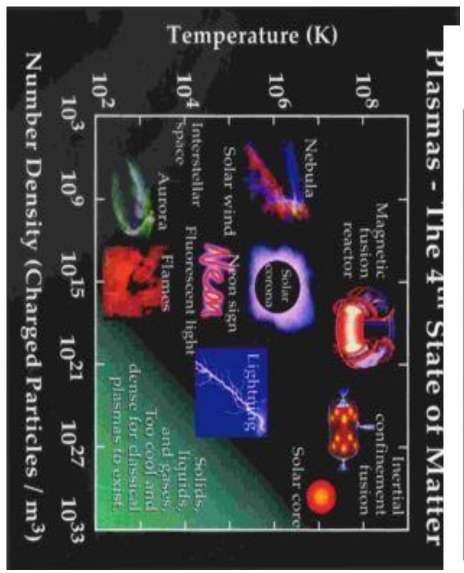
From here to high temperature QCD

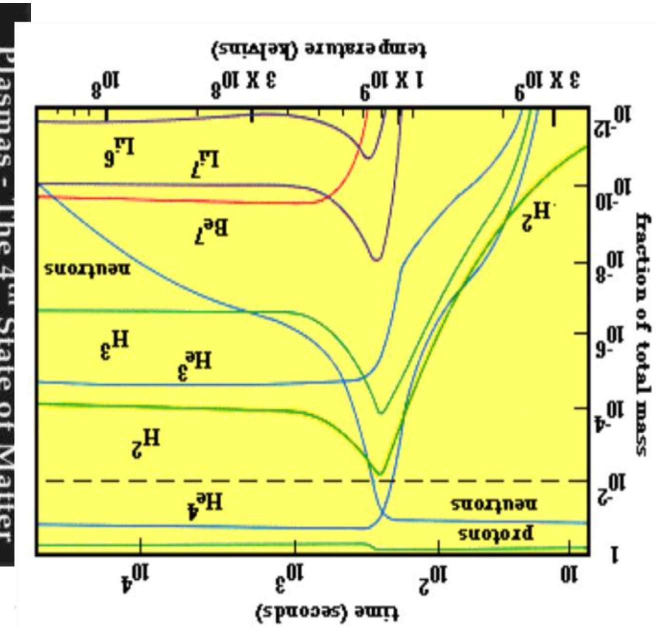
Here : 330 Kelvin 10^3—10^8 Kelvin : EM Plasma



From here to high temperature QCD

Here : 330 Kelvin 10^3—10^8 Kelvin : EM Plasma 10^8 – 10^10 K : Nucleosynthesis-





From here to high temperature QCD

Hadronic word : 10^10 K -- .2 10^12 K

Quark Gluon Plasma

EW transition O(100) GeV

Tc sim 200 MeV
= .2 10^12 K

High temperature QCD

High T χPT - Hadron Gas

Critical region

Quark Gluon Plasma

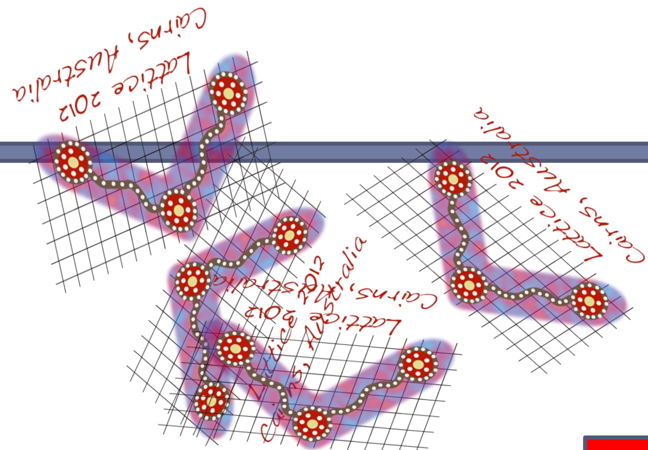
10^-2 Tc < T < Tc

Tc sim 200 MeV
Sim Λ QCD

Tc < T < 10^3 Tc

High temperature QCD @Lattice 2012

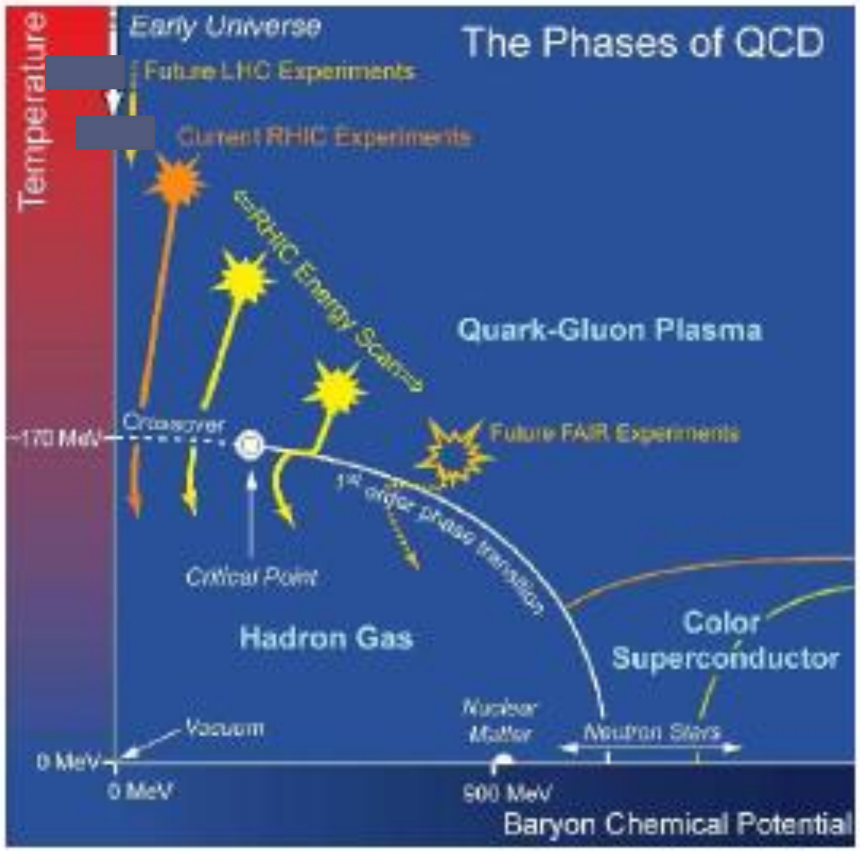
Critical region   Quark Gluon Plasma



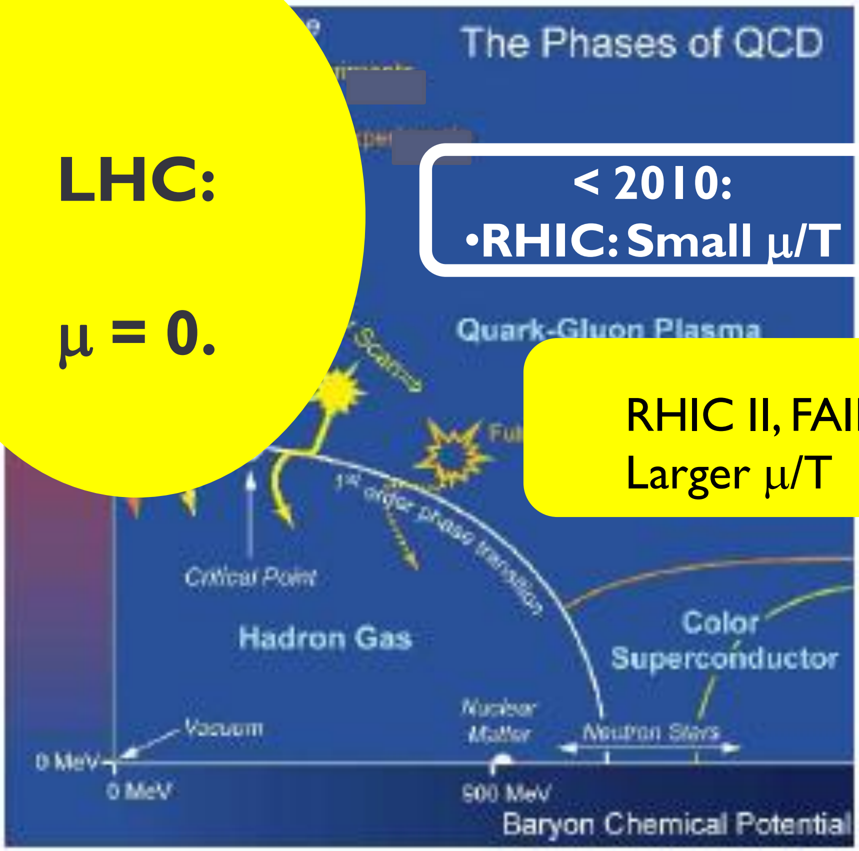
QCD with (nearly) physical quark masses

Pure YM, large N, models.

High Temperature QCD @ Colliders



High Temperature QCD @ Colliders Past, present,future



LHC:

$\mu = 0.$

< 2010:

•RHIC: Small μ/T

RHIC II, FAIR
Larger μ/T

Non-zero μ :
Gert Aarts 's Talk

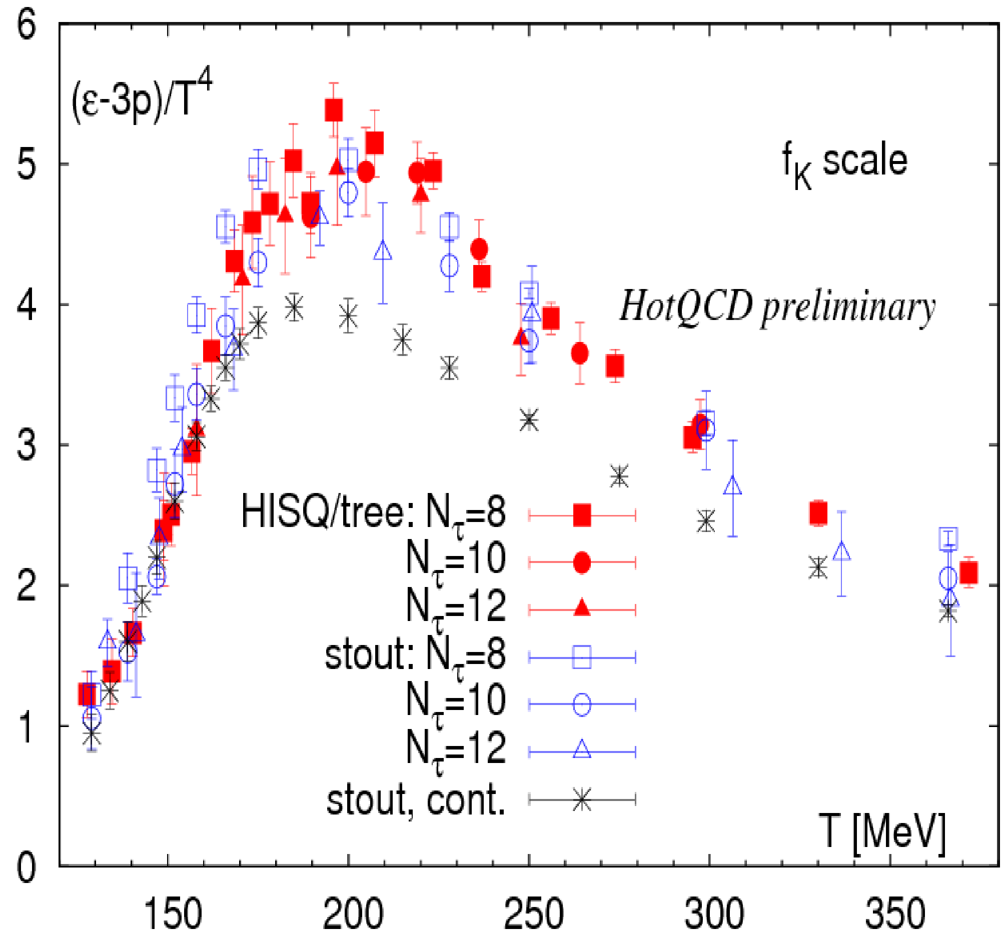
Thermodynamics: from hadronic phase to QGP

Eos – Conformal Anomaly – Transport

Equation of State: HISQ and Stout

P. Petreczki (HotQCD) Monday

- HISQ: HotQCD Lat2012
- Stout : Borsanyi et al. 1204.6710
- Nf = 2+1
- Physical Quark Masses
- Nt =10, 12 no significant difference between stout and HISQ

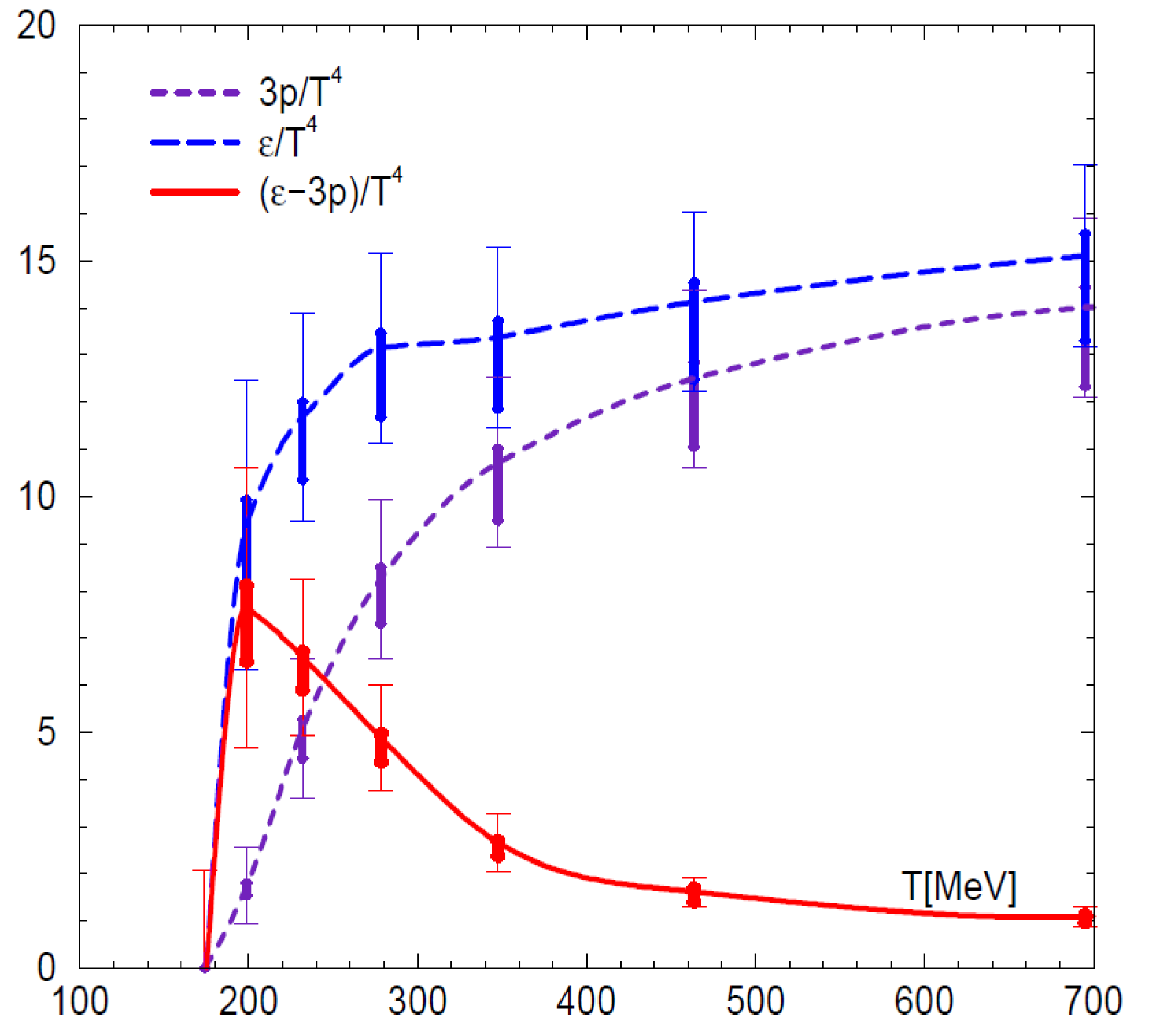


Plot courtesy P.Petreczki

Equation of state: Wilson fermions

Umeda (WHotQCD) Monday

- ❑Nf = 2+1
- ❑Physical Strange mass
- ❑M π / m ρ = 0.63
- ❑ Np improved Wilson
- ❑Iwasaki improved glue



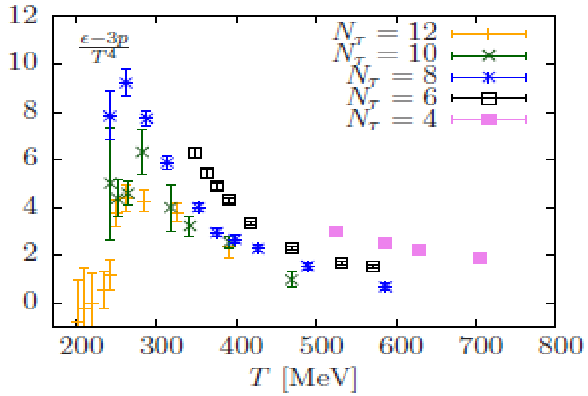
Plot courtesy Umeda

Equation of state: Wilson at maximal twist

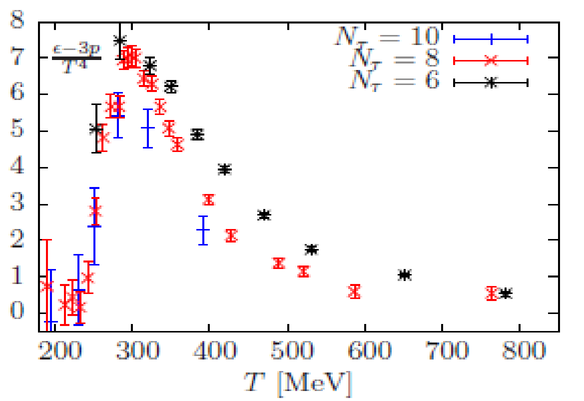
Burger (tmft) Monday

uncorrected

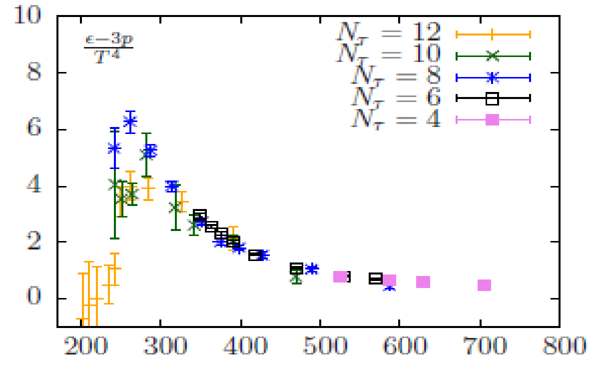
$m_\pi \approx 400$ MeV:



$m_\pi \approx 700$ MeV:



corrected



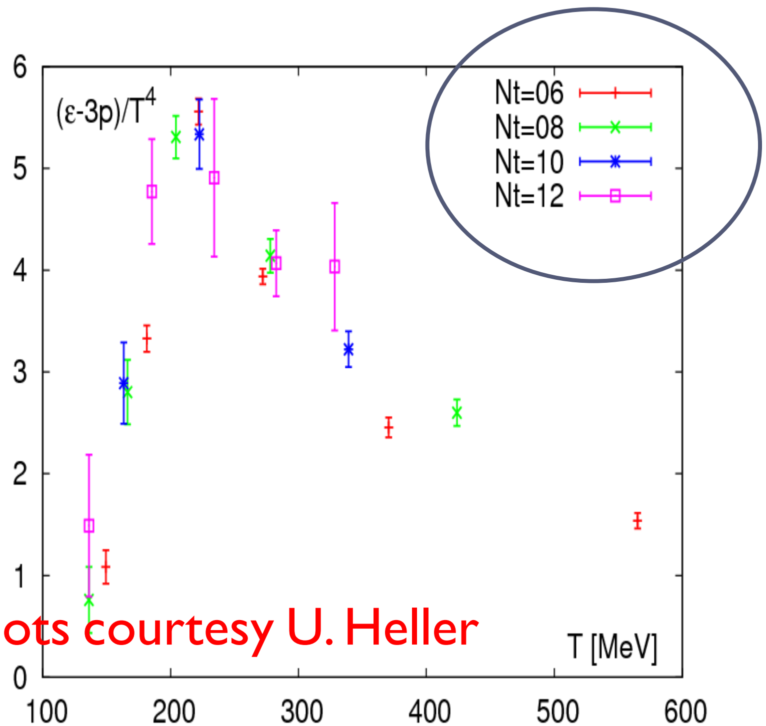
- Nf = 2
- Pion masses 400-700MeV
- Wilson,maximal twist

EoS for Nf = 2+1+1

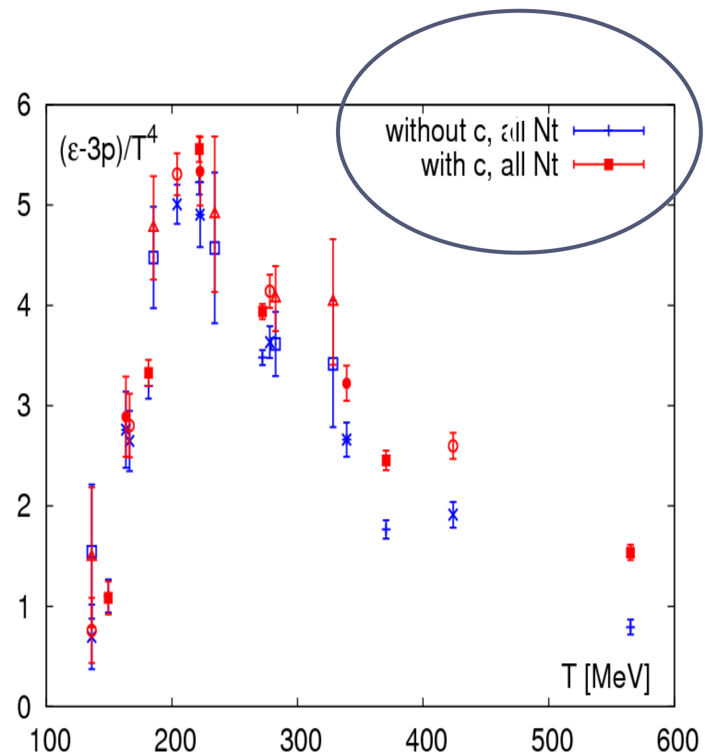
Heller (HotQCD) Monday

- HISQ 2 + 1 +1
- Lines of constant physics
- Physical charm and strange masses
- ml = ms/5 most likely ininfluent above peak

Early onset of charm contribution : T ≈350 MeV predicted by effective theory [Laine Schroeder 2006]

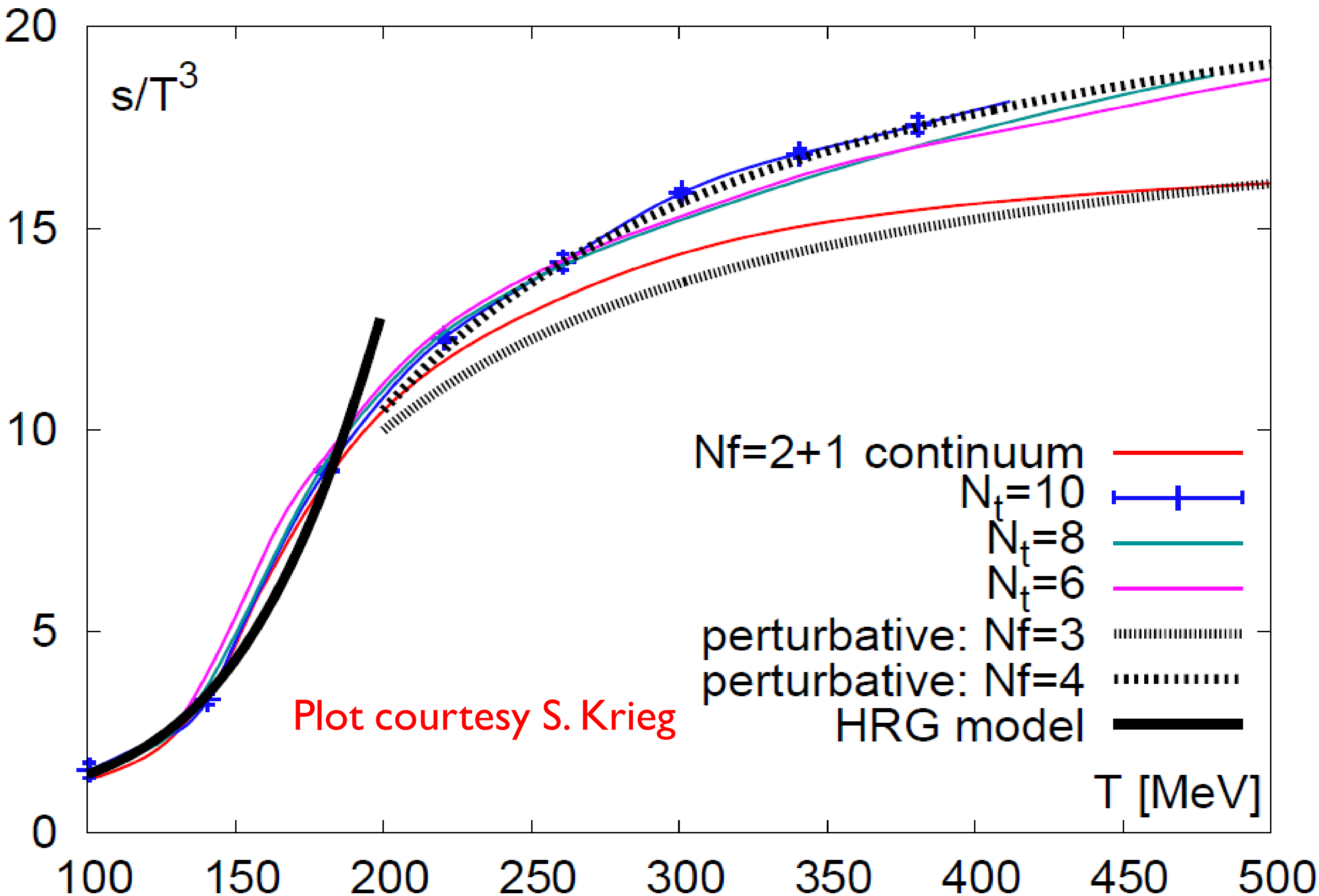


Plots courtesy U. Heller



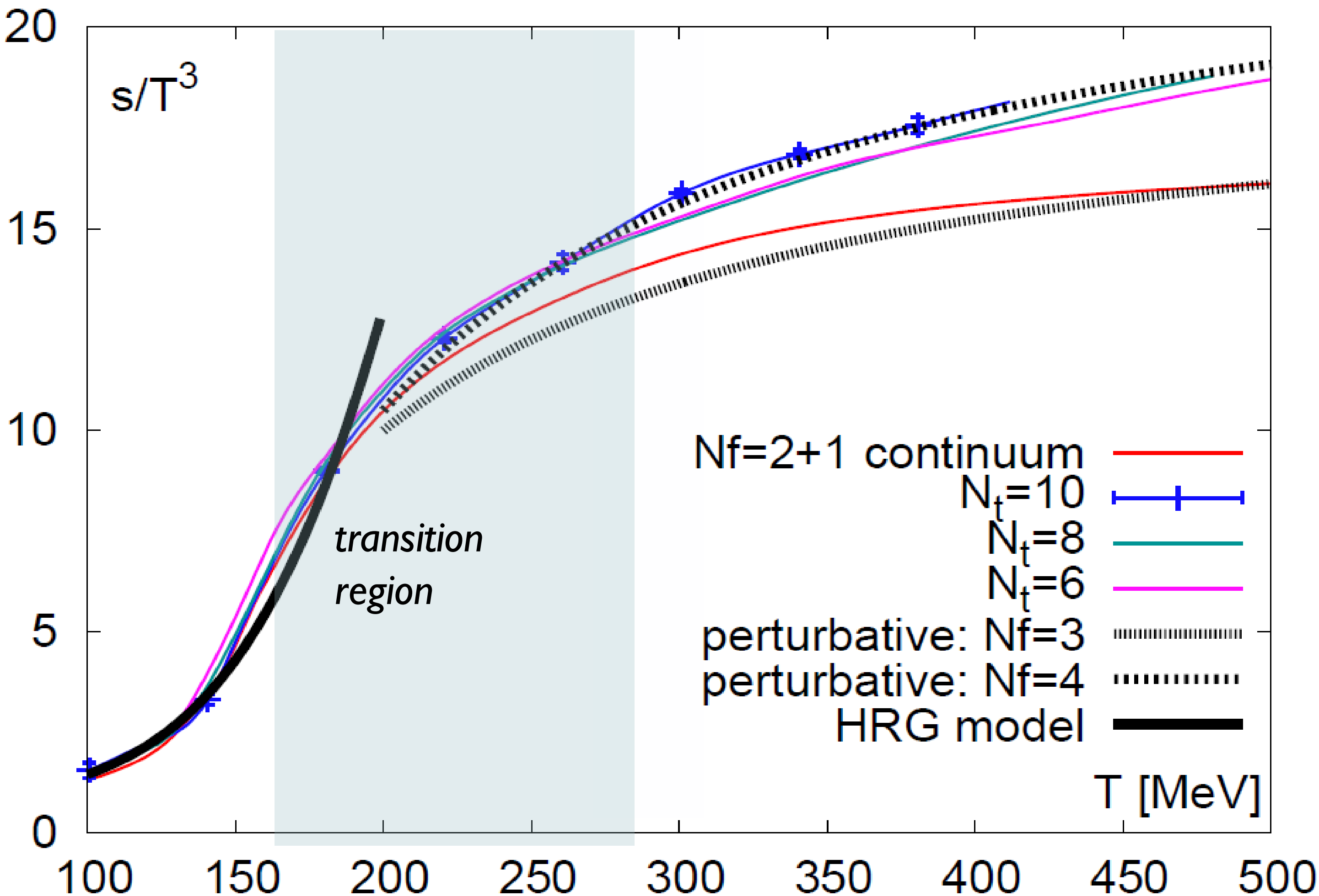
EoS for Nf = 2+1+1

Krieg Monday

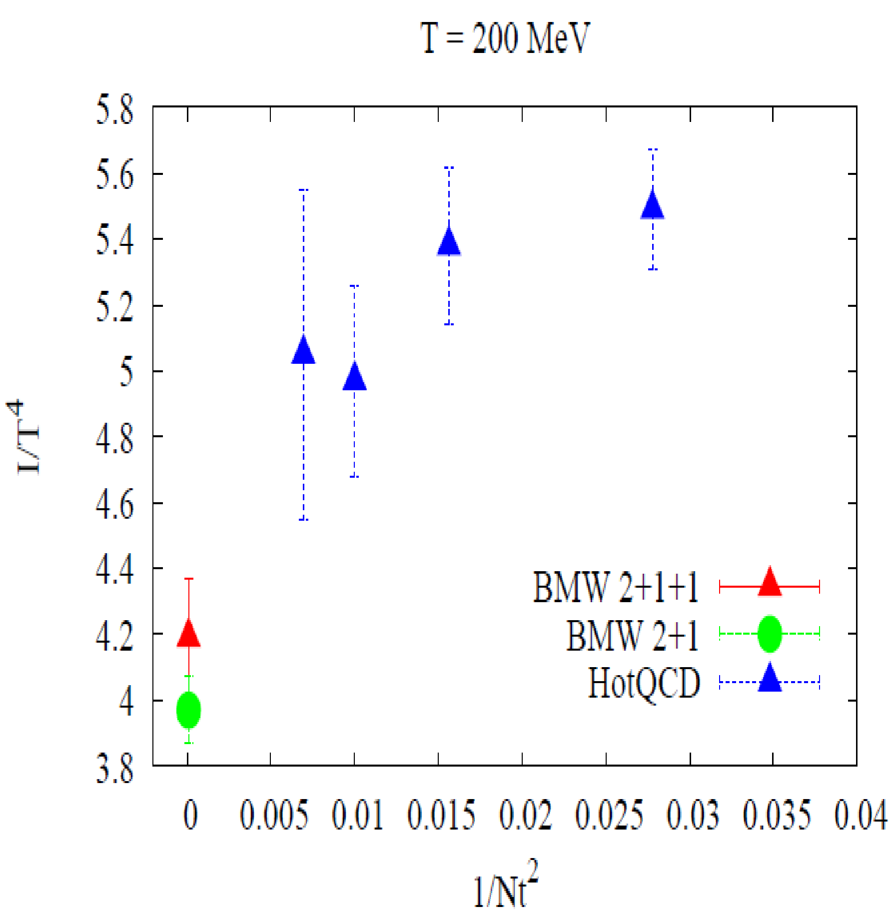


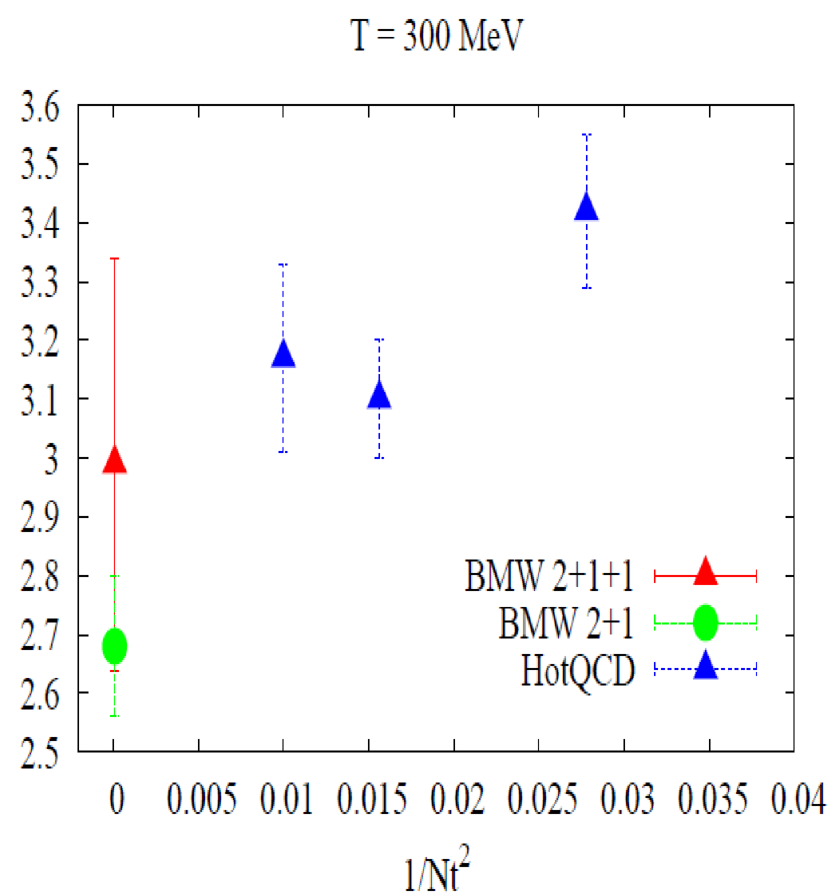
EoS for Nf = 2+1+1

Krieg Monday

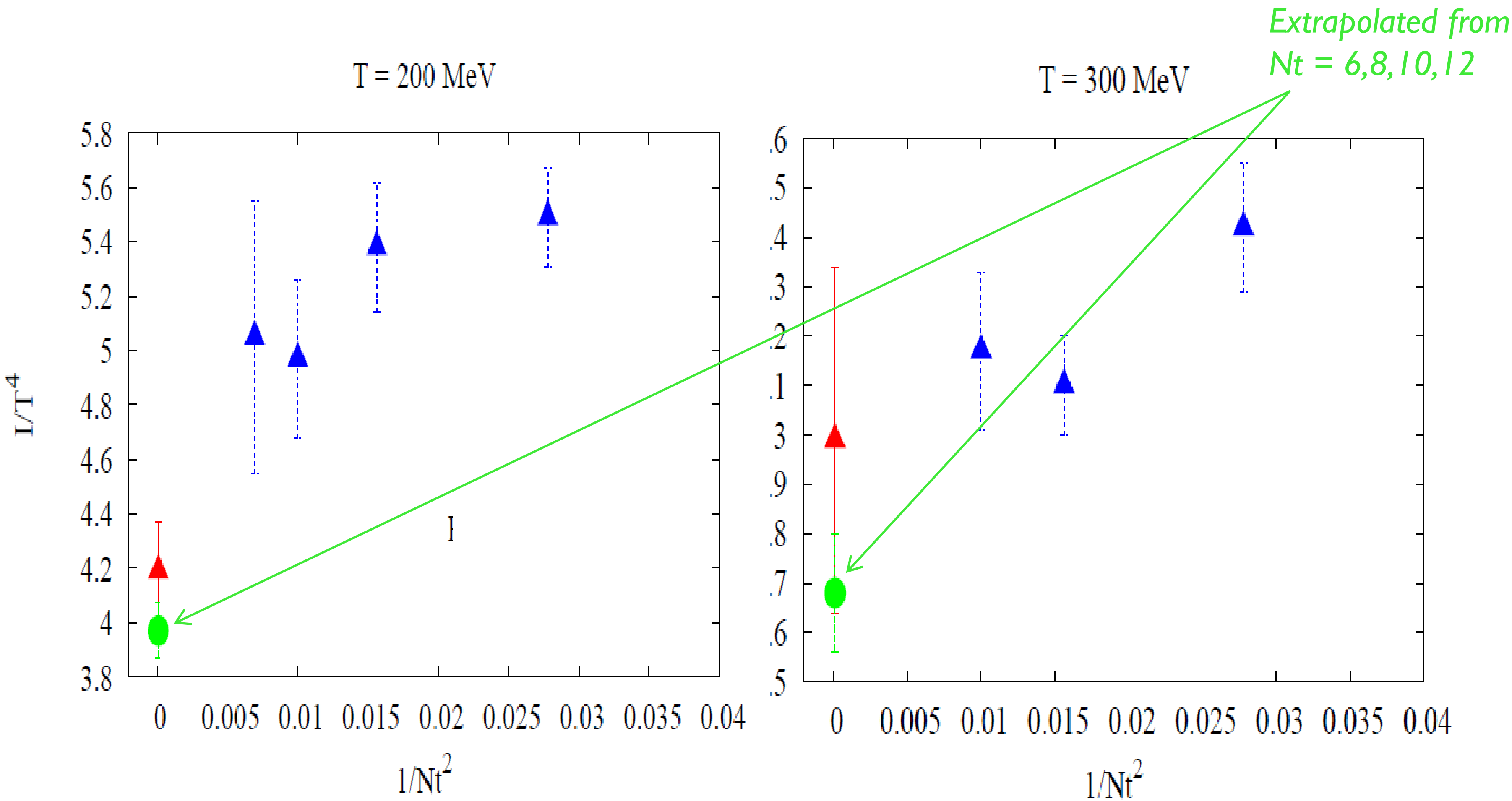


EoS : Detailed comparison between Stout and HISQ

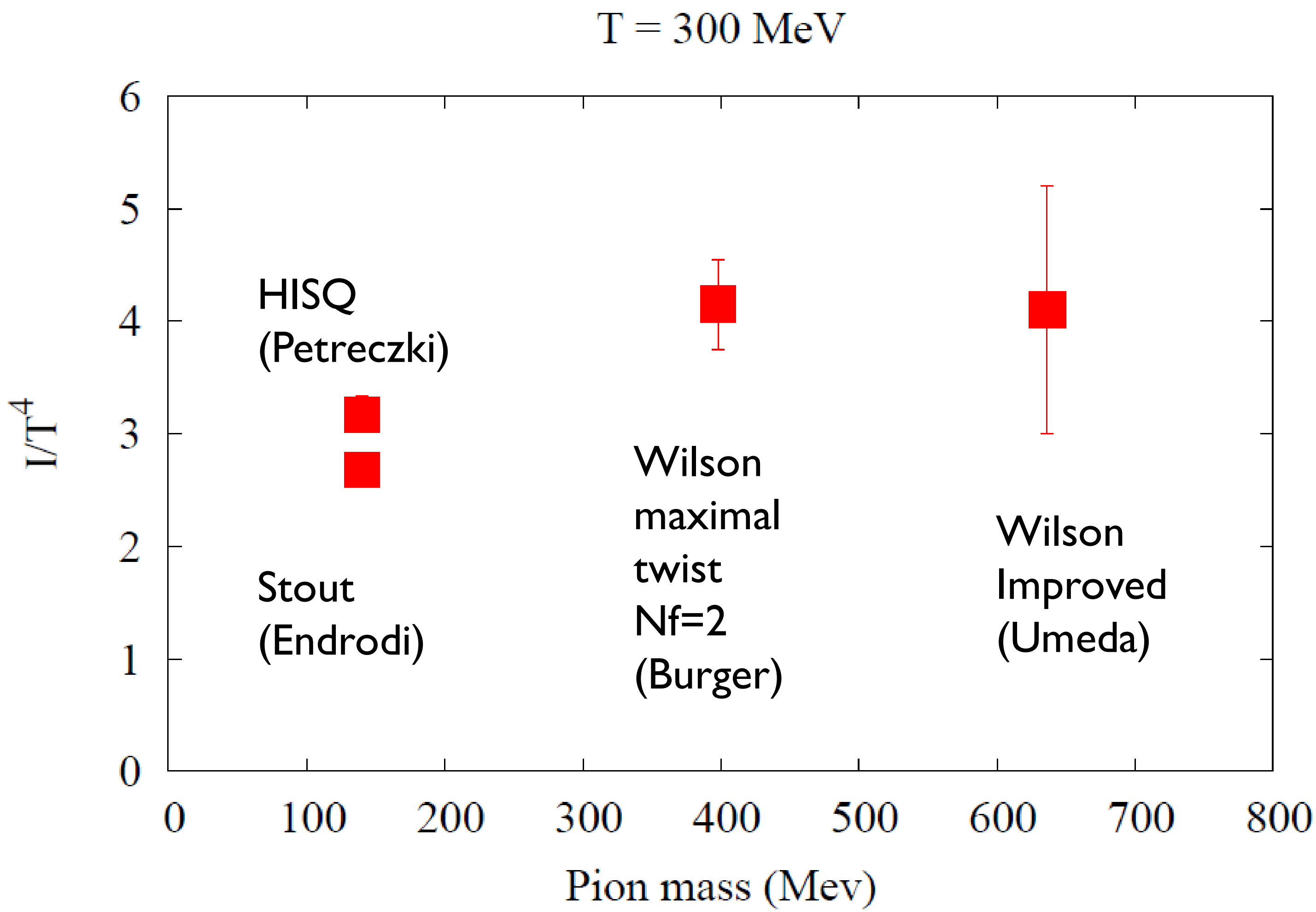




EoS – ‘discrepancy’ a matter of extrapolation?

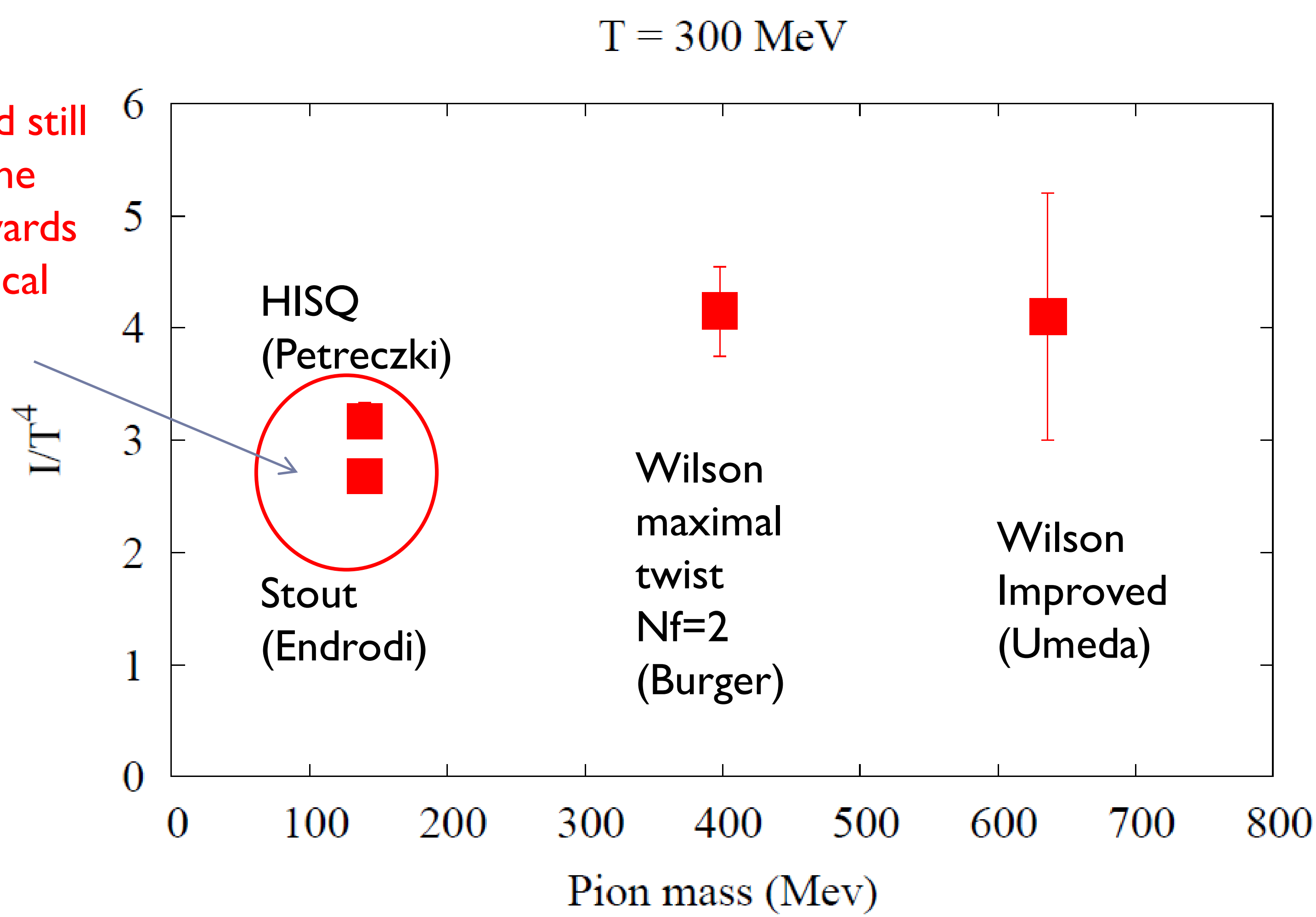


EoS for T = 300 MeV



EoS for T = 300 MeV

Staggered still leading the race towards the physical point



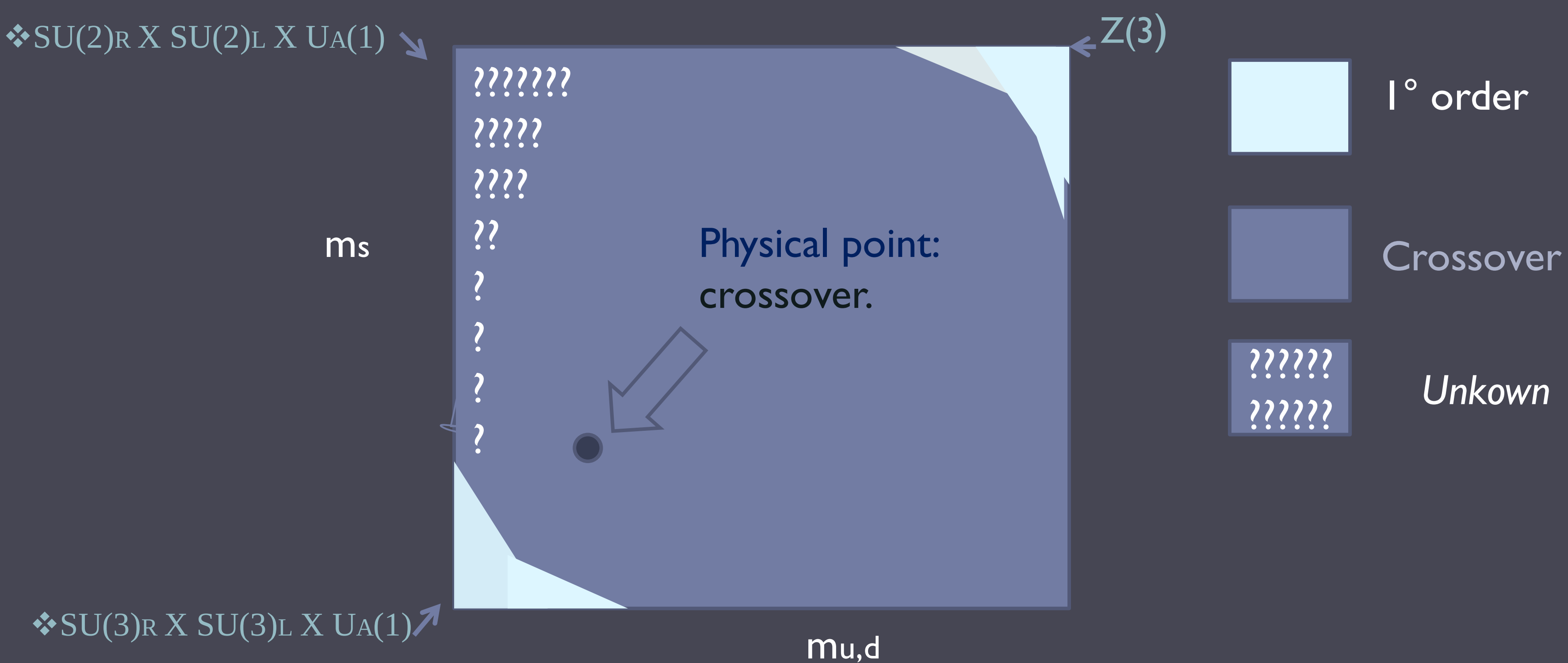
The transition region

Order Parameters

Symmetry aspects of the chiral transition

Fate of the UA(1) symmetry

The critical region



QCD Symmetries and lattice fermions

High T

$$SU(Nf)_R \text{ X } SU(Nf)_L \text{ X } U_A(1)$$

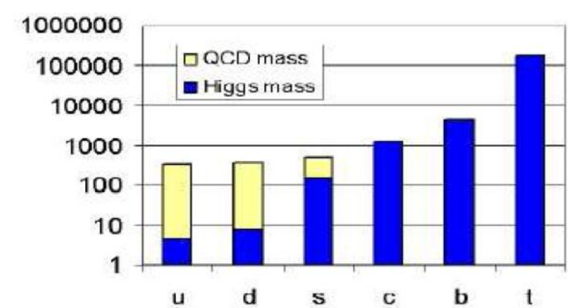
Dynamically broken at low T

Broken by anomaly

$$SU(Nf)_V \text{ X } \cancel{U_A(1)}$$

Low T

Possibility to study the effects of the anomaly at high T

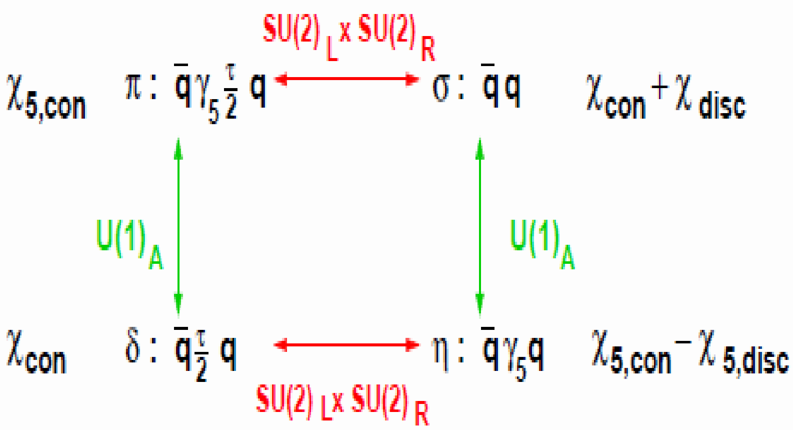


Nf=2,3

	SU(N)XSU(N)	$U_A(1)$
Staggered	Remnant U(1)	Broken
Wilson	Broken	Broken
Domain Wall	Exact (for L $\rightarrow \infty$)	Exact (for L $\rightarrow \infty$)
Overlap	Exact	Exact

Patterns of Symmetries

1996: The MILC Plot



2000: Cohen, Lee-Hatsuda, Cohen,....

If:

$\langle \bar{q}q \rangle = 0$

Then :

$$\chi\pi - \chi\delta \propto m^{(Nf-2)}$$

New Developments

Aoki Monday

Singlet susceptibility at high T

$$\lim_{m\to 0}\chi^{\pi-\eta} = \lim_{m\to 0}\lim_{V\to\infty}\frac{N_f^2}{m^2V^2}\langle Q(A)^2\rangle_m = 0$$

Both Cohen and Lee-Hatsuda are inaccurate.

This, however, does not mean U(1)_A symmetry is recovered at high T.

$$\lim_{m\to 0}\chi^{\pi-\eta} = 0$$

is necessary but NOT “sufficient” for the recovery of U(1)_A .

2000: Cohen, Lee-Hatsuda, Cohen,....

If:

$\langle\bar{q}q\rangle = 0$

Then :

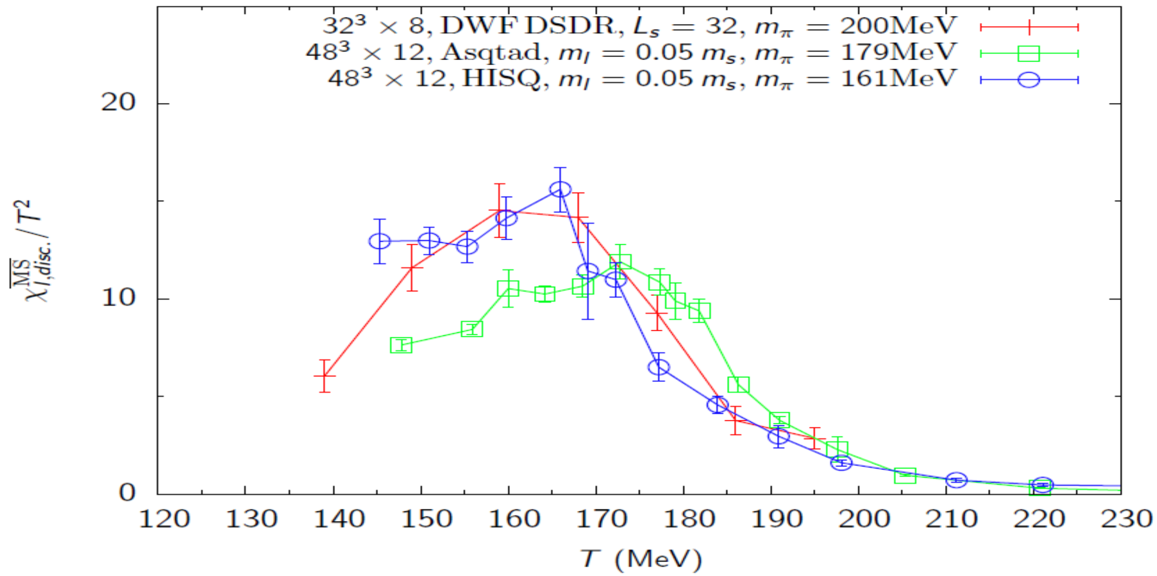
$$\chi\pi - \chi\delta \propto \cancel{m}^{(N_f-2)} \quad 1/V^2$$

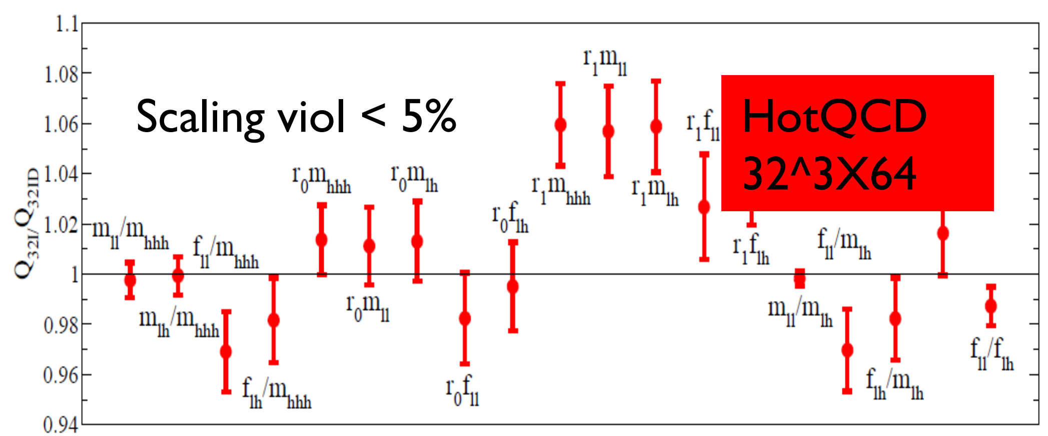
Slide courtesy S.Aoki

Lin, (RGB/HotQCD) Wedsnday
Bazavov et al, HotQCD 1205.3535

Domain wall fermions

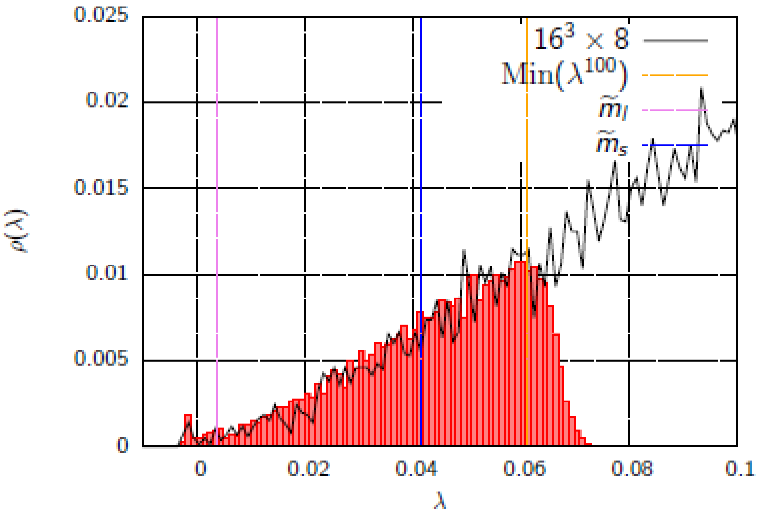
- Nf = 2+1
- L5 = 96 ←
- 16^3X8 HOTQCD
- 32^3 X8 RBC/LLNL
- 64^3X8 (ongoing)
- Kaon 'almost physical'
- Physical pion planned

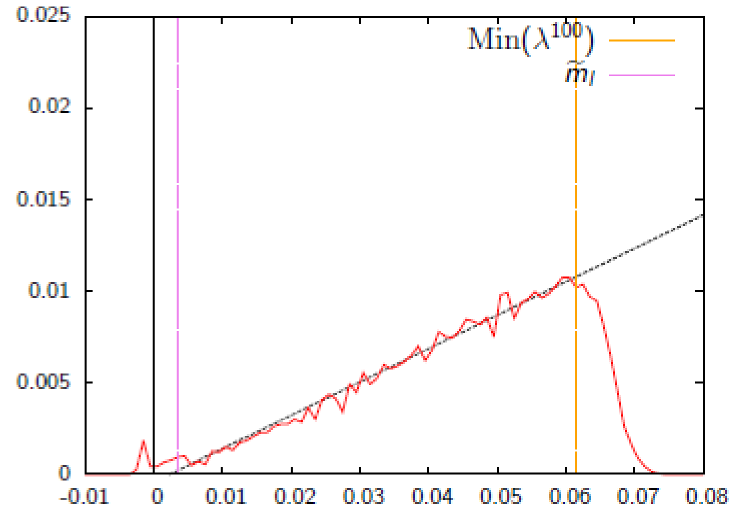




Plots courtesy N. Christ and J.Lin

Eigenvalue Distrubition at 177 MeV





- Intercept has become 0.
- Assume $\rho(\lambda)$ is composed of two parts, $\rho(\lambda) = c_1\delta(\lambda) + c_2\lambda$
- c_1: number of "zero modes", renormalization invariant
- c_2: slope of the distribution

UA(1) order parameter $$\chi_\pi - \chi_\delta = \int_0^\infty \mathrm{d}\lambda \frac{4\widetilde{m}^2\rho(\lambda)}{(\widetilde{m}^2+\lambda^2)^2}$$

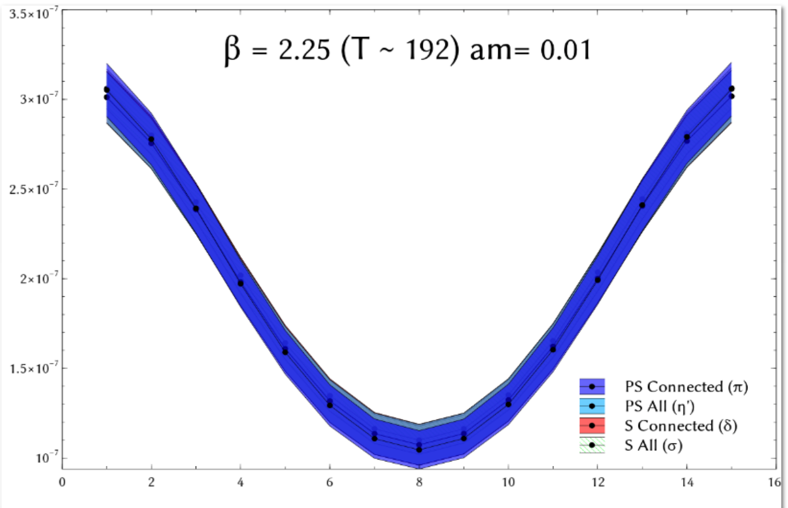
$$\frac{\chi_\pi - \chi_\delta}{T^2} = 48.72{+}9.70 = 36(14)(\text{Correlator measurement of } 16^3{\times}8)$$

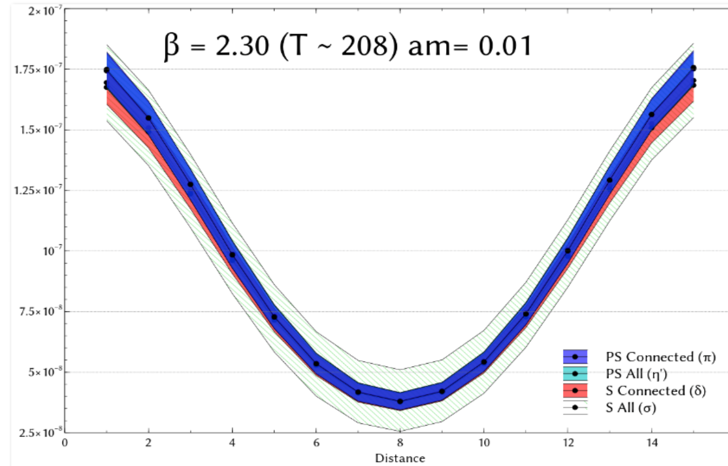
- Axial symmetry breaking: $\sim 83\%$ from near zero modes; $\sim 17\%$ from linear part

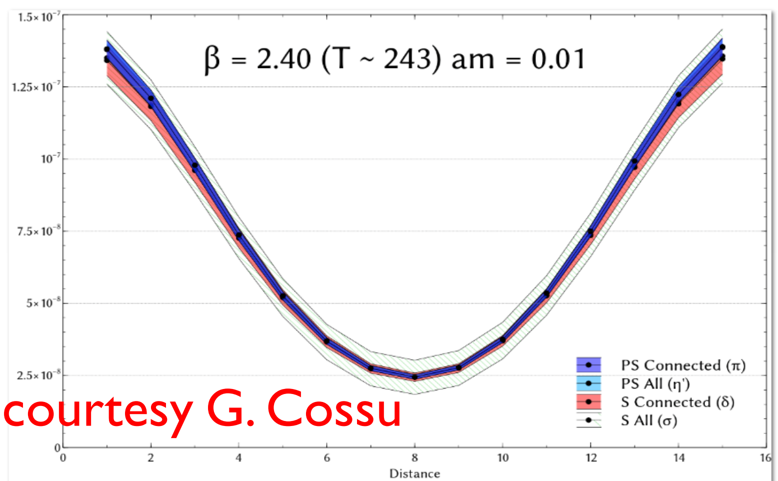
Slide from Jasper Lin ' s talk

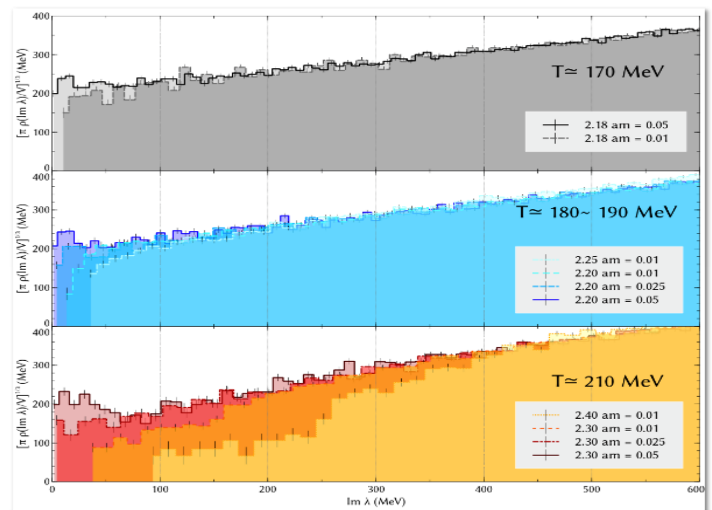
Overlap Fermions
Nf=2 mπ = 200 MeV

Cossu (JLQCD) Monday





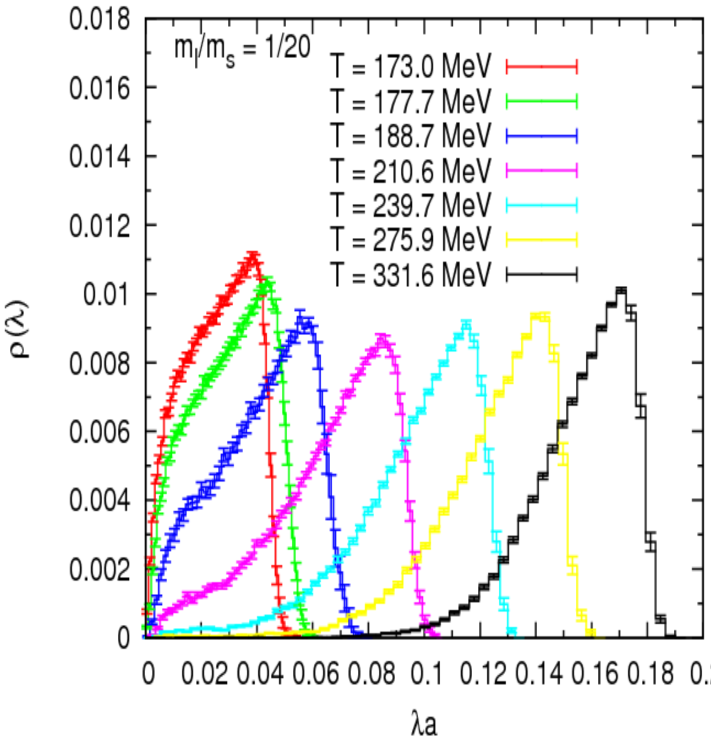


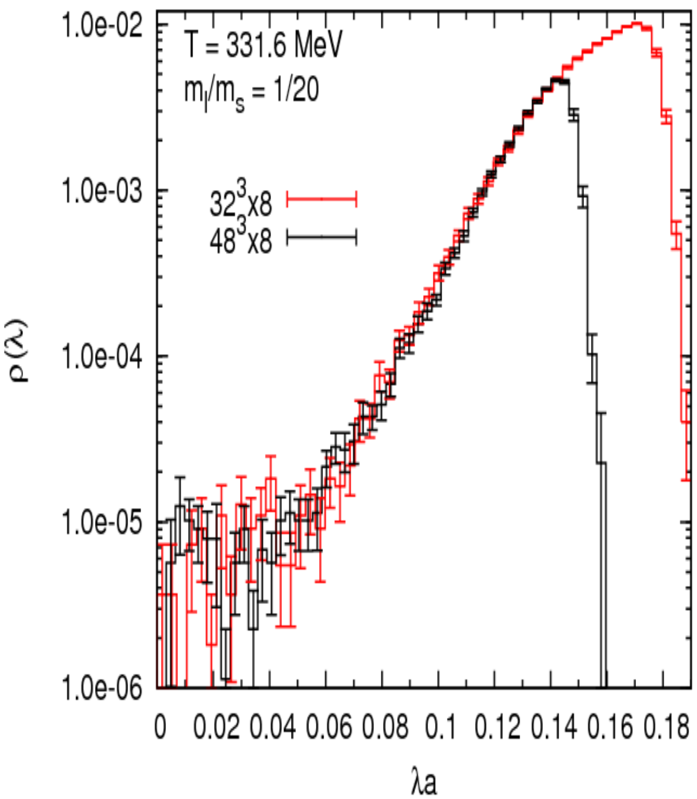


Plots courtesy G. Cossu

HISQ Fermions
Nf = 2+ 1 mπ =115–230 Mev

Ohno Thuersday





Plots courtesy H. Ohno

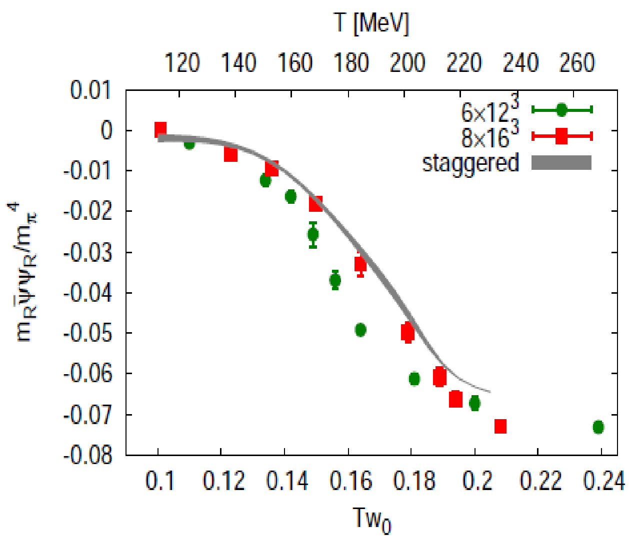
More to expect from chiral fermions

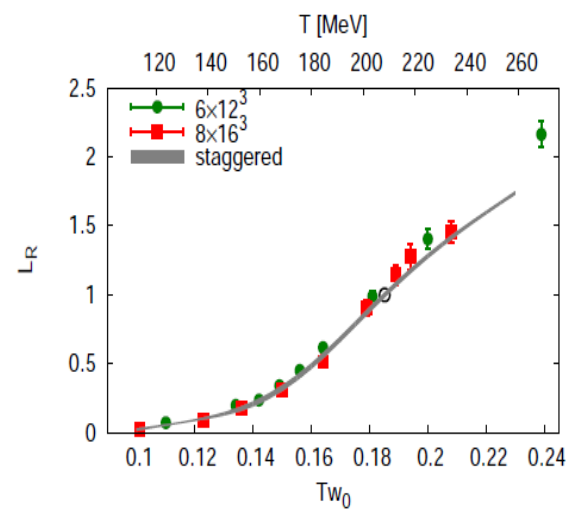
Hsieh Tuesday
Krieg Monday and
Borsanyi et al 1204.4889

- Domain Wall Fermions
- 2 flavors
- Hsieh, Tuesday

(TWQCD Collaboration)

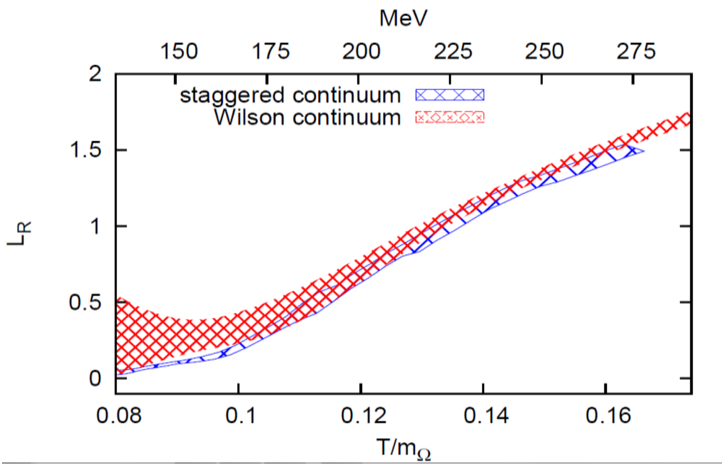
- Overlap
- Krieg, Monday
- Topology Fixing (JLQCD)
- Nf=2 mπ = 350 MeV

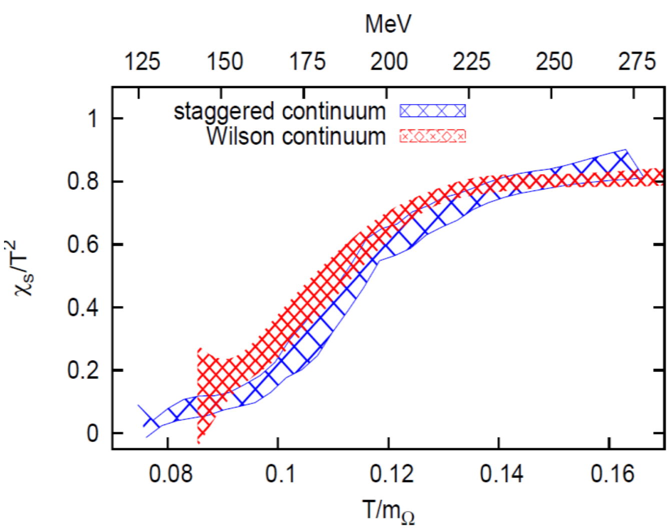




Wilson fermions Nf=2+1

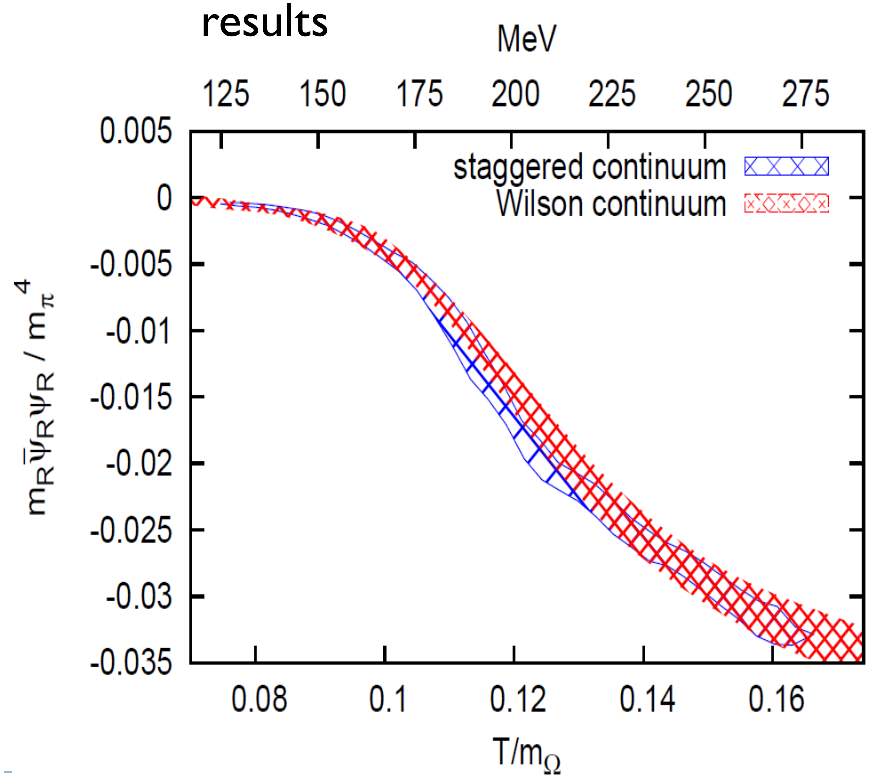
Borsany et al. 1205.0440
Nogradi Monday





$M\pi$ = 125-275 MeV

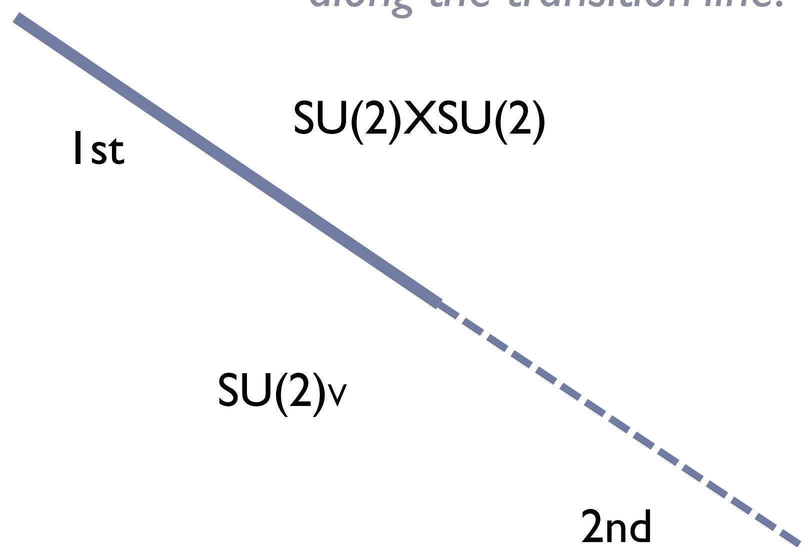
Agreement with continuum staggered results



QCD symmetries and order of transition

- Nf = 3 : I° order
- Nf = 0 : I° order (deconfinament)
- Nf = 2: order of the transition depends on coefficients : dynamical issue!

The order migh change along the transition line!



$$\mathcal{L}_{U(N_f)} = \mathrm{Tr}(\partial_\mu \Phi^\dagger)(\partial_\mu \Phi) + r\,\mathrm{Tr}\,\Phi^\dagger\Phi + \frac{u_0}{4}\left(\mathrm{Tr}\,\Phi^\dagger\Phi\right)^2 + \frac{v_0}{4}\,\mathrm{Tr}\left(\Phi^\dagger\Phi\right)^2$$

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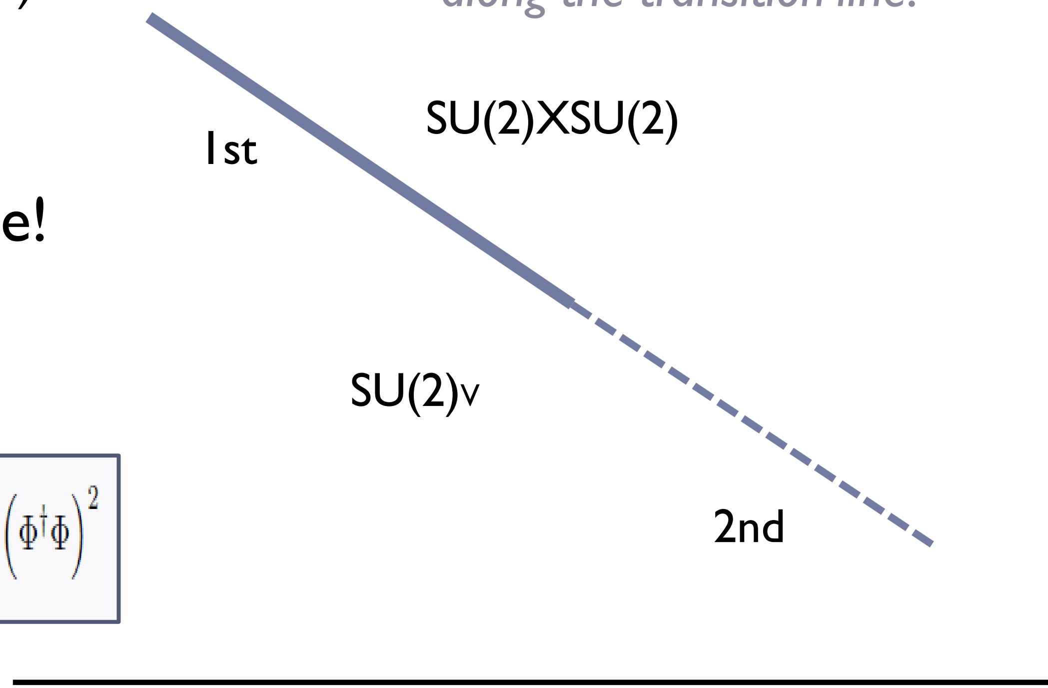

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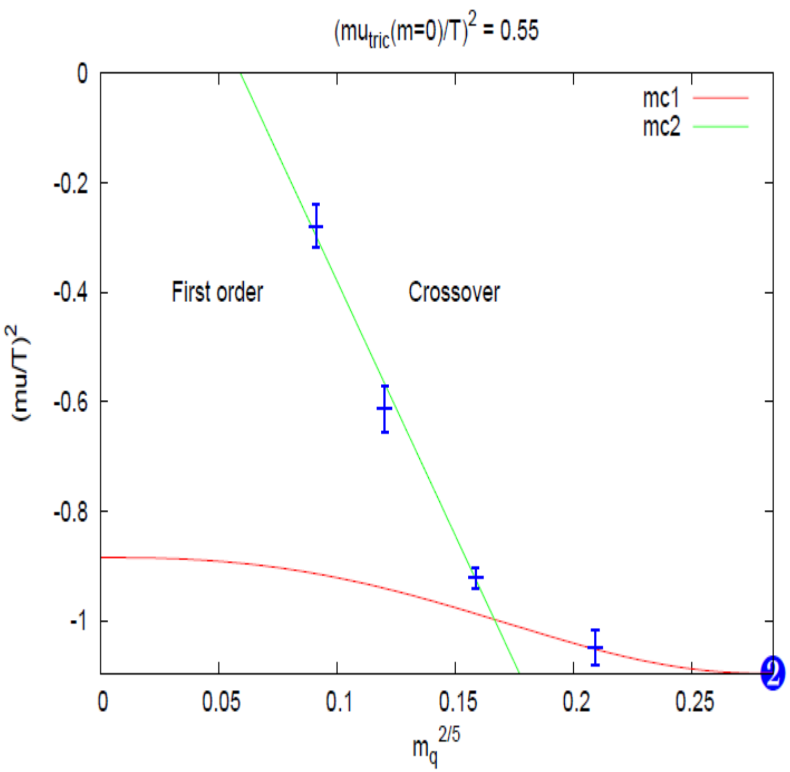
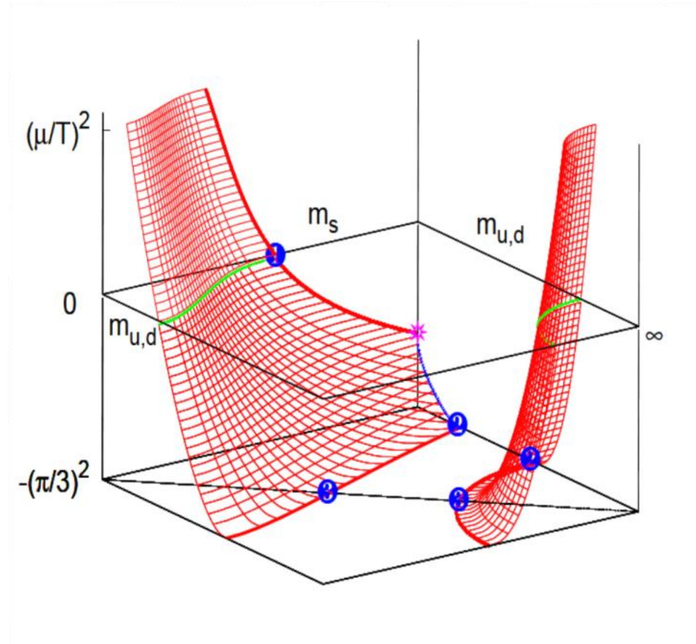
For instance as a function Of chemical potential

μ^2

Order changes with μ^2

Bonati , D'Elia, de Forcrand
Sanfilippo, Philipsen 2012





Staggered Nt=4

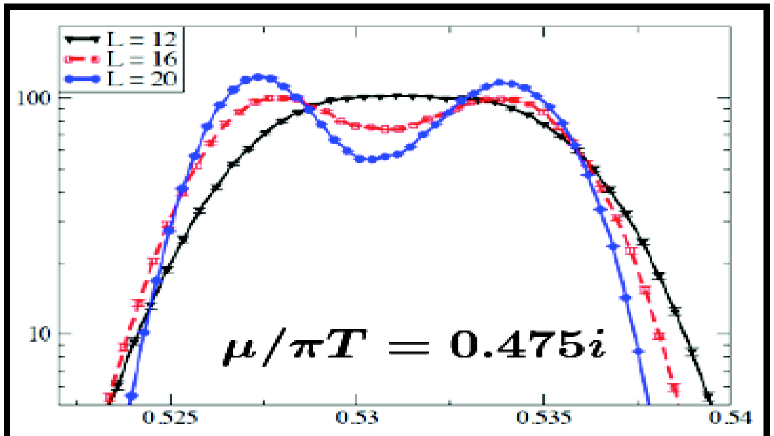
Plots courtesy of Ph. De Forcrand

D. Cosmai et al 1202.5700
Cosmai, Monday

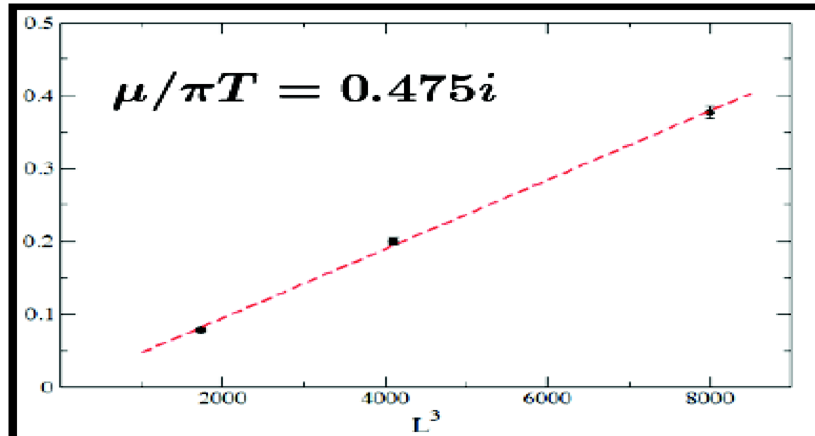
Order changes with μ^2

SU(3) n_f=2 staggered am=0.05

The transition becomes first order for large enough imaginary chemical potentials, but before one reaches the RW-like transition $(\mu/\pi T|_{RW} \simeq 0.5i)$



Normalized plaquette distributions at the pseudocritical coupling for different spatial lattice sizes

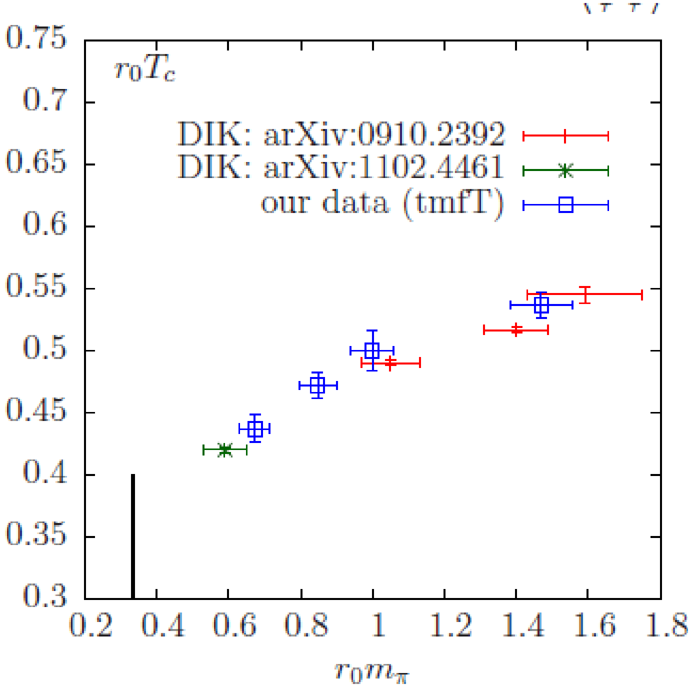


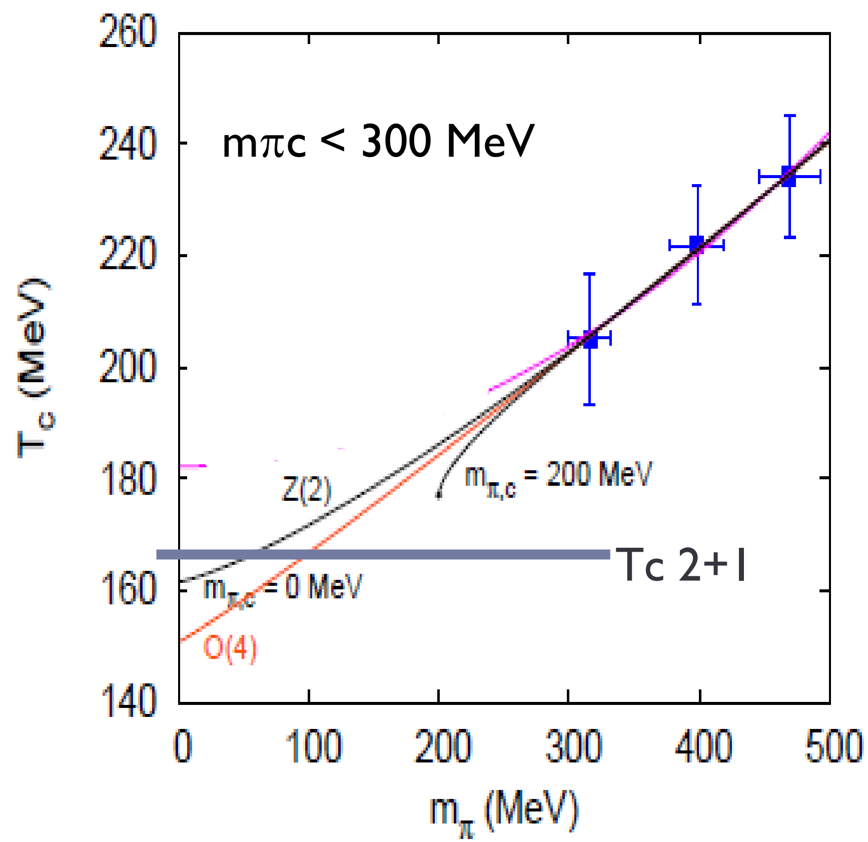
Maxima of the plaquette susceptibility scale linearly with the spatial volume

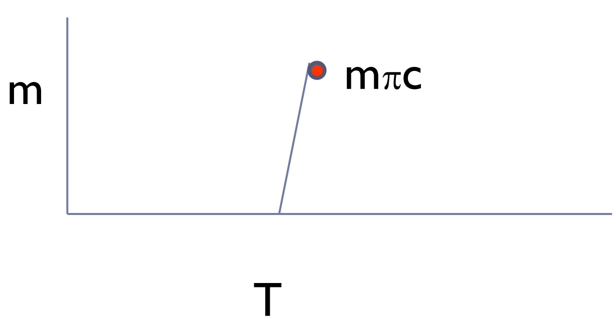
Plots courtesy M. D'Elia

Wilson Nf= 2 – Status of the transition in the continuum

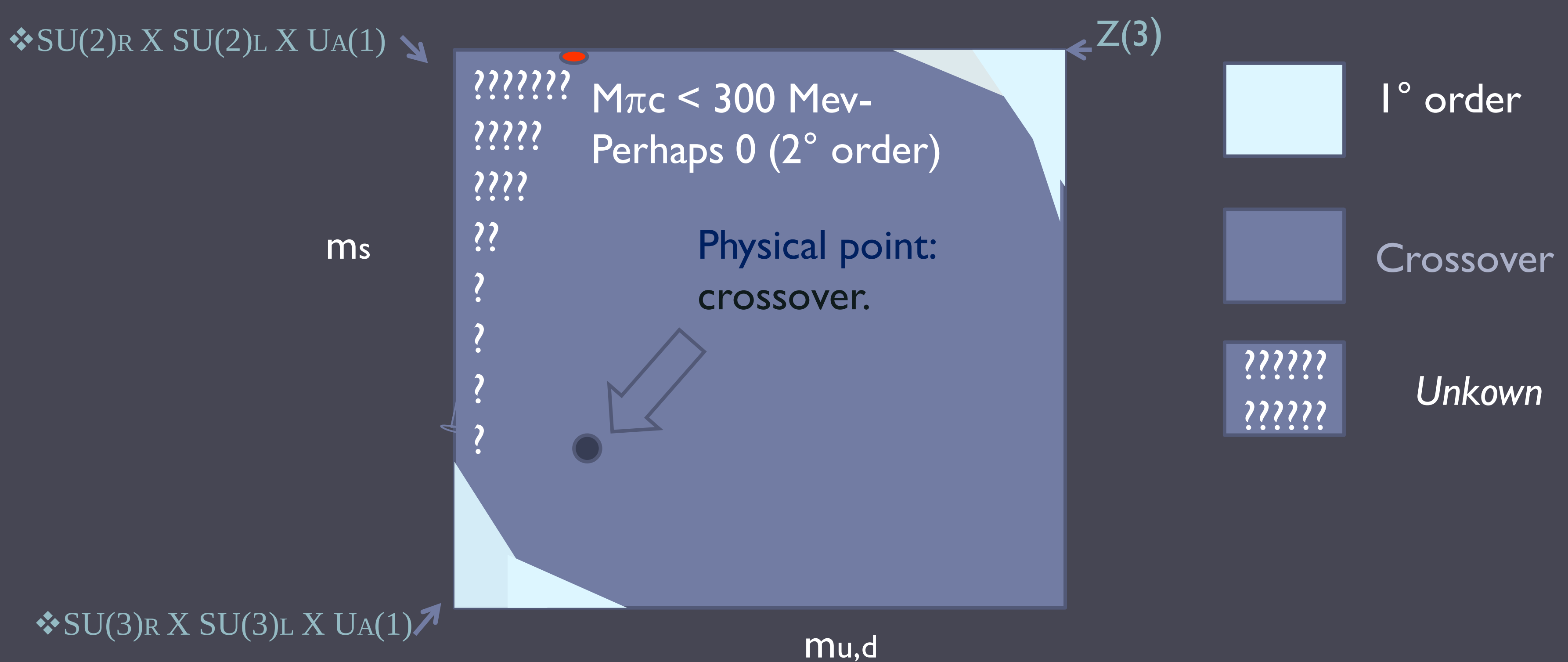
F. Burger (tmfT) Monday







Status of the Columbia plot



The transition region-II

Nf=0, Confinement
Large Nf
Q vacuum
External Magnetic field

Nf=0 : SU(N) theories and effective U(1) -> monopoles

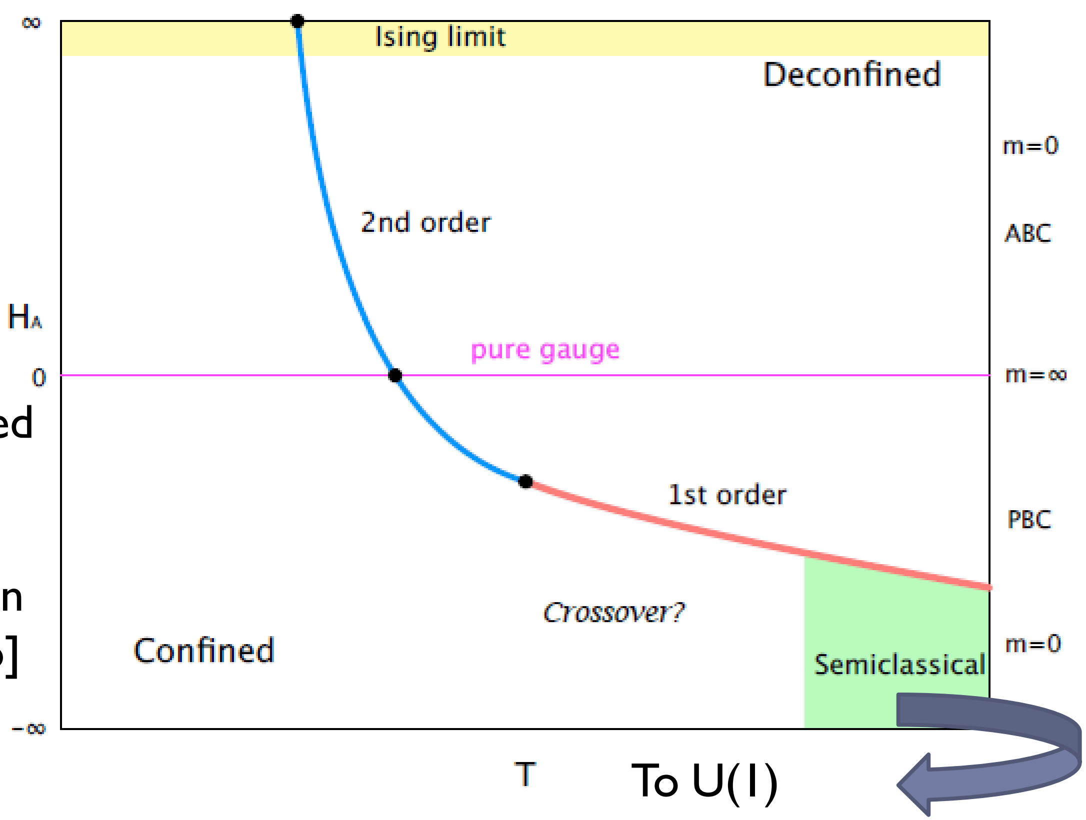
Ogilvie Wednsday

U(1) : confinement /deconfinement monopole condensation.

Enlarge space : find continuous path between confined phase of SU(2) and monopole dominated phase of U(1) .

Lattice simulations in progress [M. Panero]

SU(2) phase diagram $S \to S - \int d^3x\, H_A \,|Tr_F P|^2$



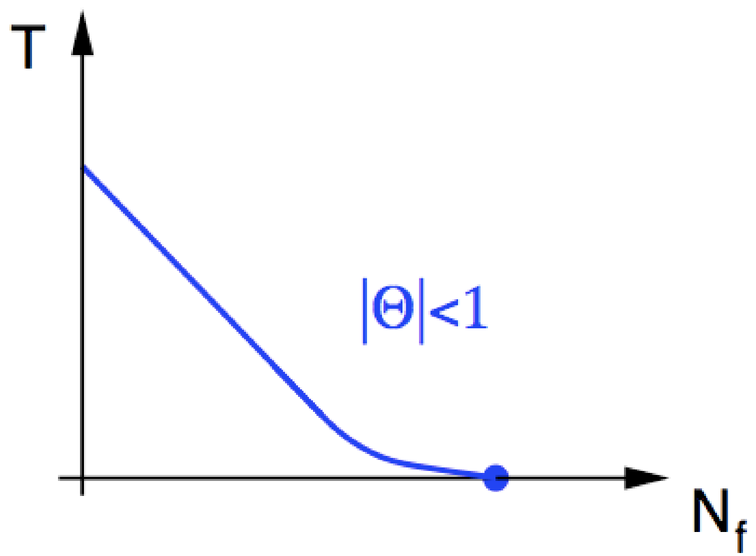
Nf =0, 2, 2+1,2+1+1, Many…
The fate of the transition at large Nf

$$T_c(N_f) = K|N_f - N_f^c|^{-1/\theta} .$$

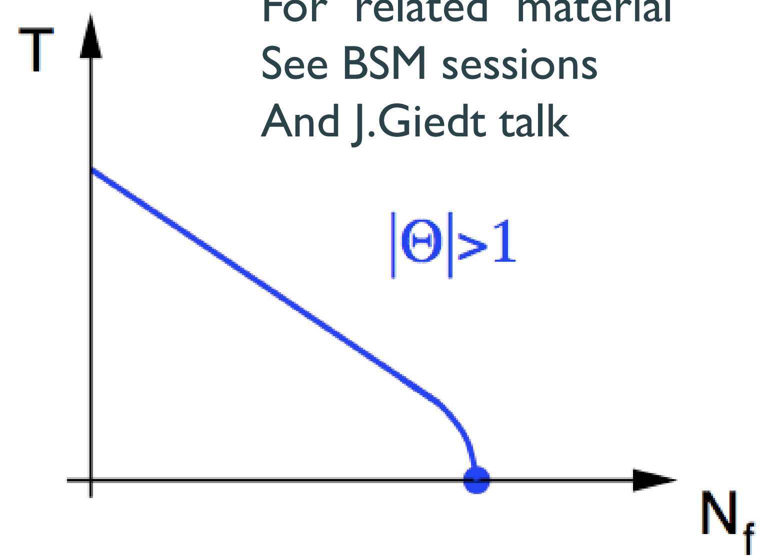
Braun, Gies 2006-2010

Recent lattice studies below Nfc

Deuzeman et al. 2008 Nf = 8
Jin and Mawhinnehy, 2009, Nf=8
Miura et al. 2011, Nf =4,6



For related material
See BSM sessions
And J.Giedt talk

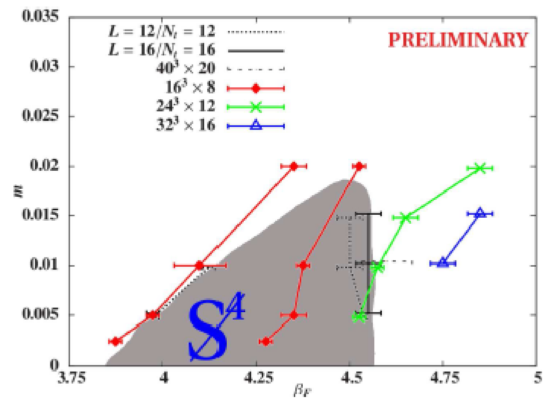


Schaich Monday

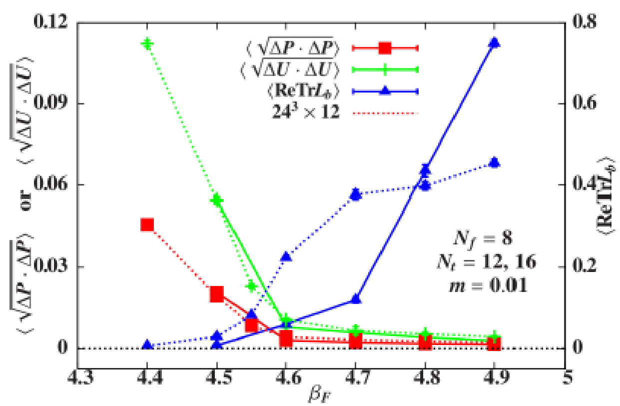
New results for Nf=8

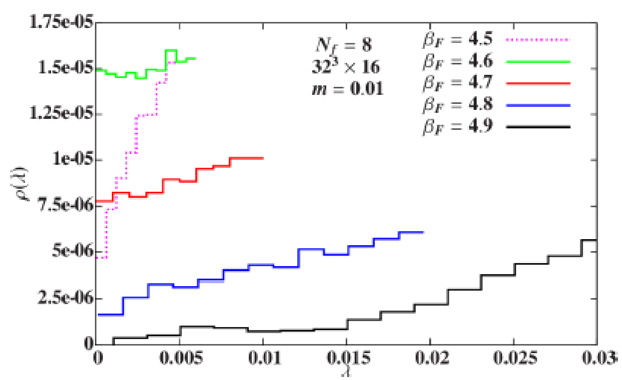
Slide courtesy D. Schaich

$N_F = 8$ finite-temp. transitions pass through $\not{S}^4$ lattice phase



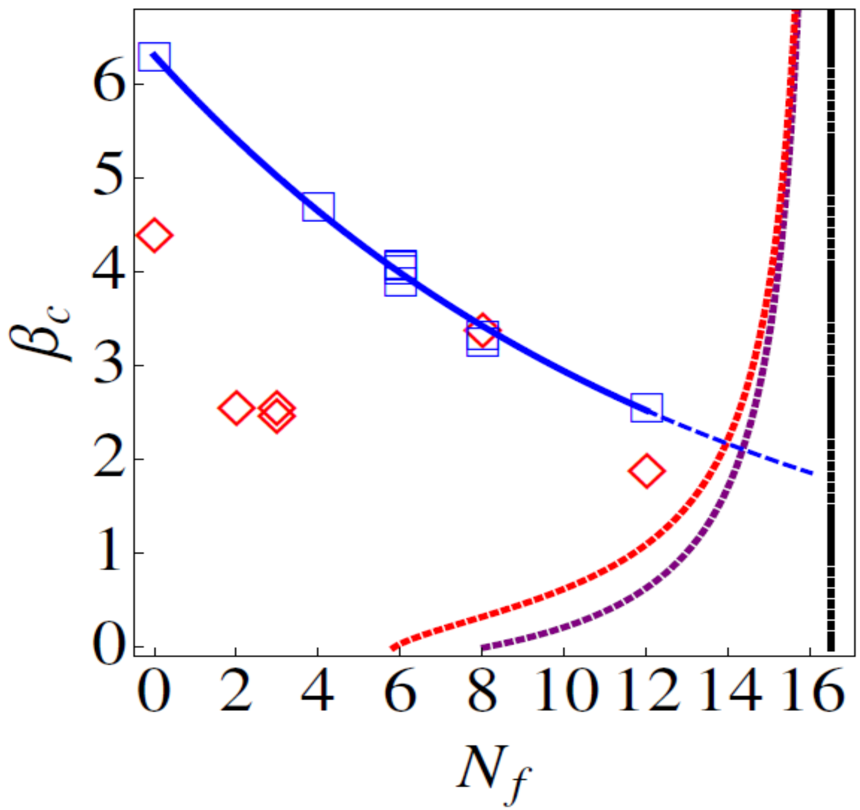
$\not{S}^4$ phase signalled by order parameters (red and green, left)
Transitions signalled by Polyakov loop (left) and eigenvalues (right)

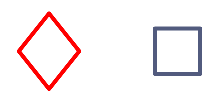




The strength of the plasma with Nf

Liao and Shuryak 1206.3989



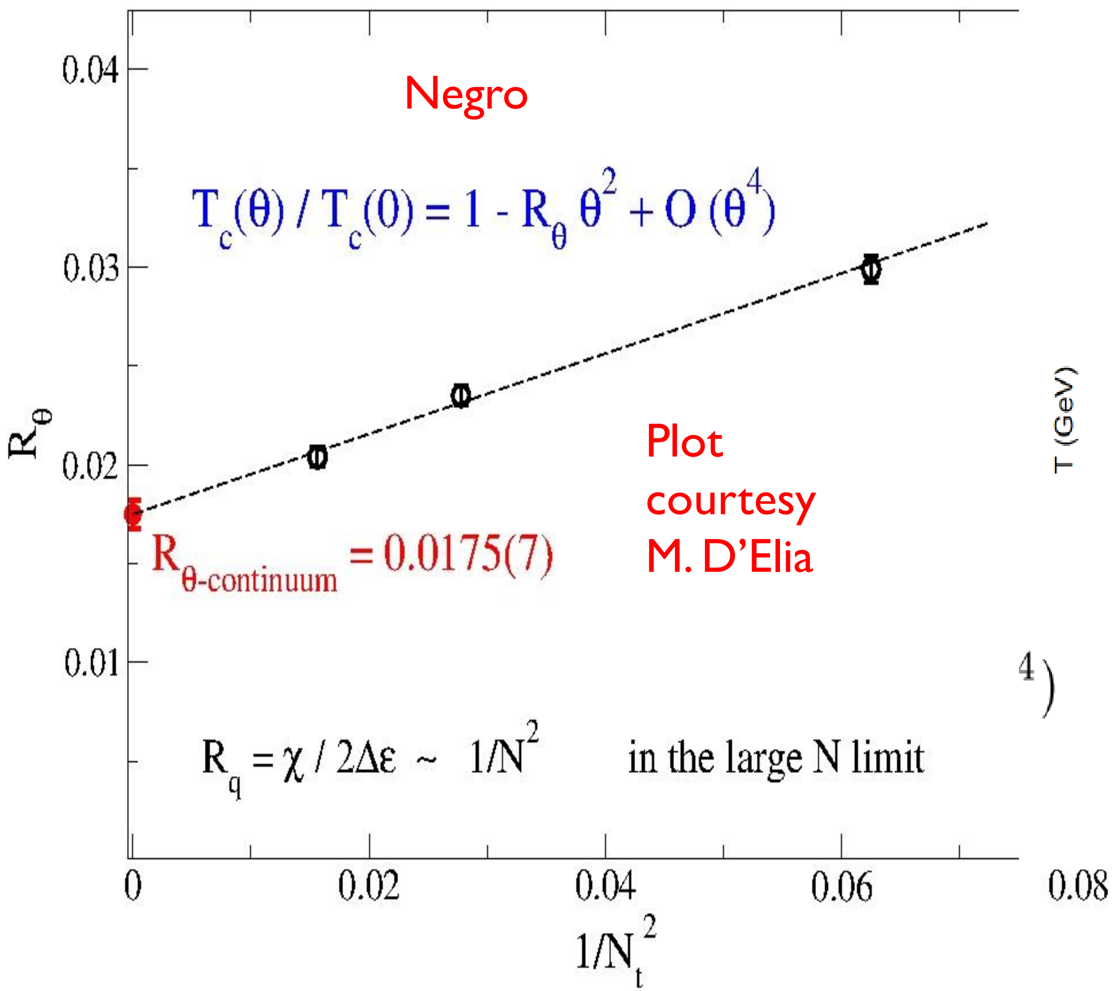


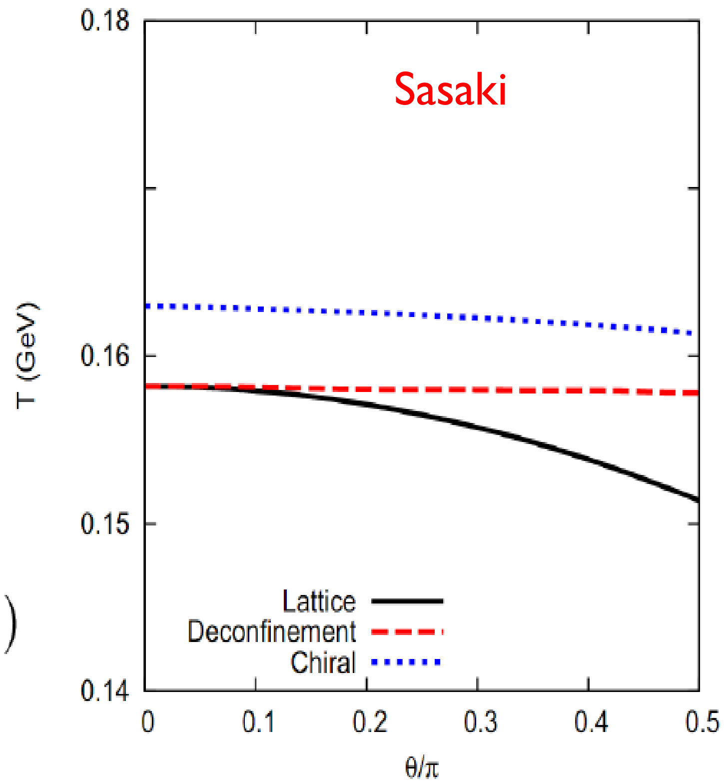
: Lattice data

Theta vacuum

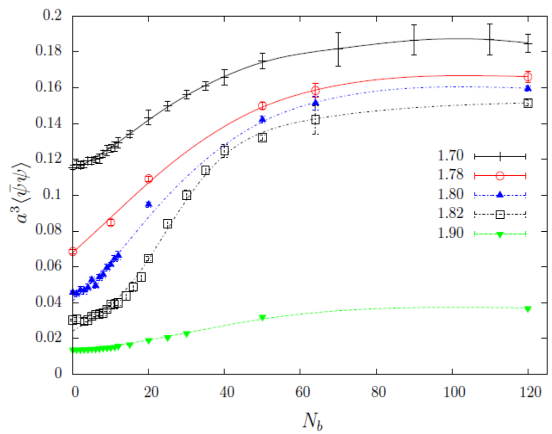
$S = S_{QCD} + S_\theta\,(-\theta\, Q\,)$

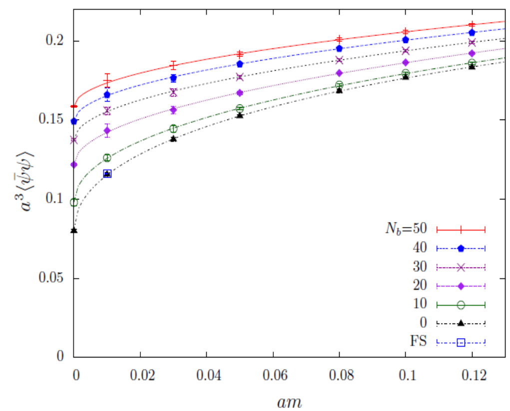
D'Elia and Negro 1205.0538
Negro Tuesday
Sasaki Tuesday





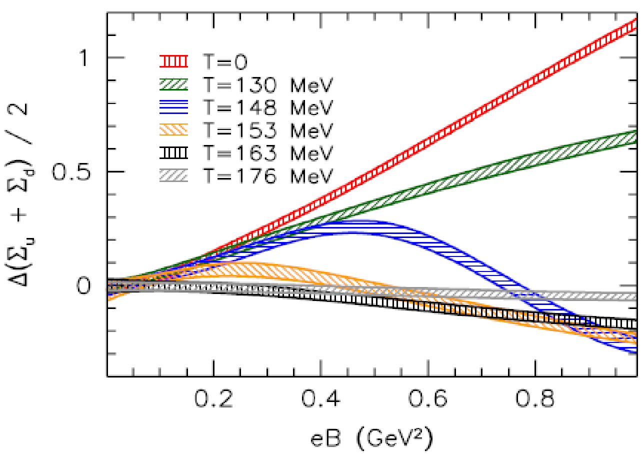
Chiral Magnetic Effect:
B =10^14 Tesla at QCD transition and Heavy Ion collisions!

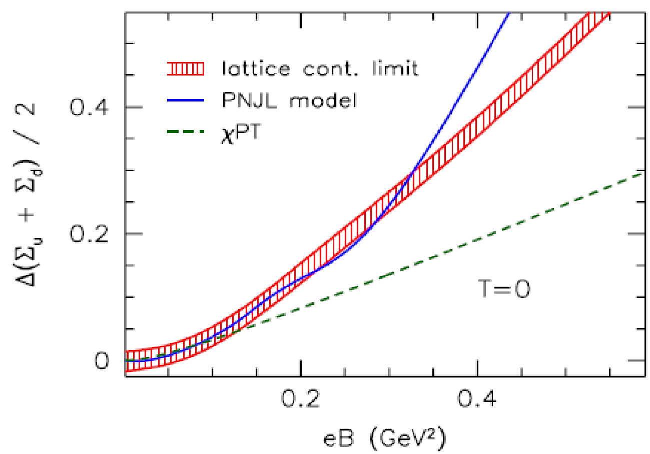




Ilgenfritz et al.
1203.3360

G. Bali et al.
1206.4205



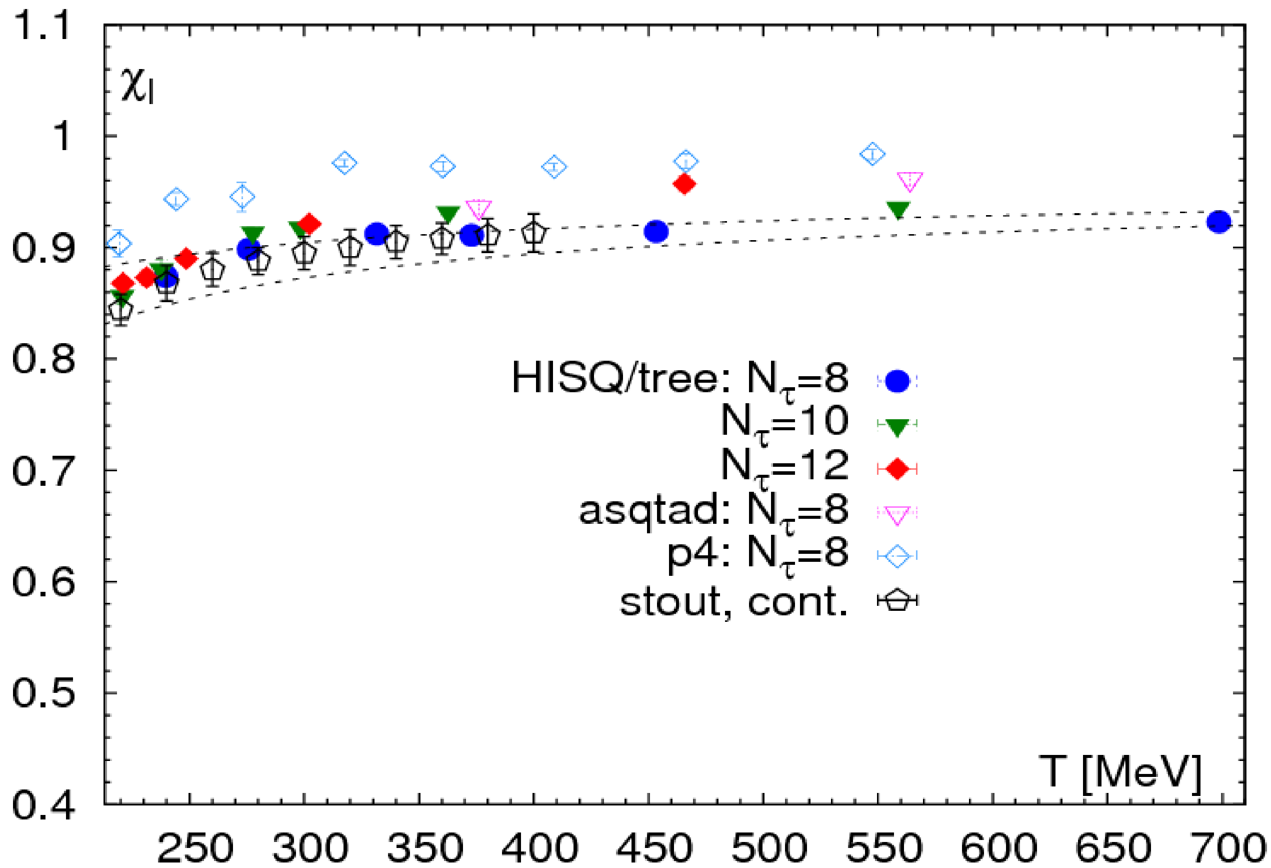


Fluctuations

Results&comparison with analytic work

Model studies

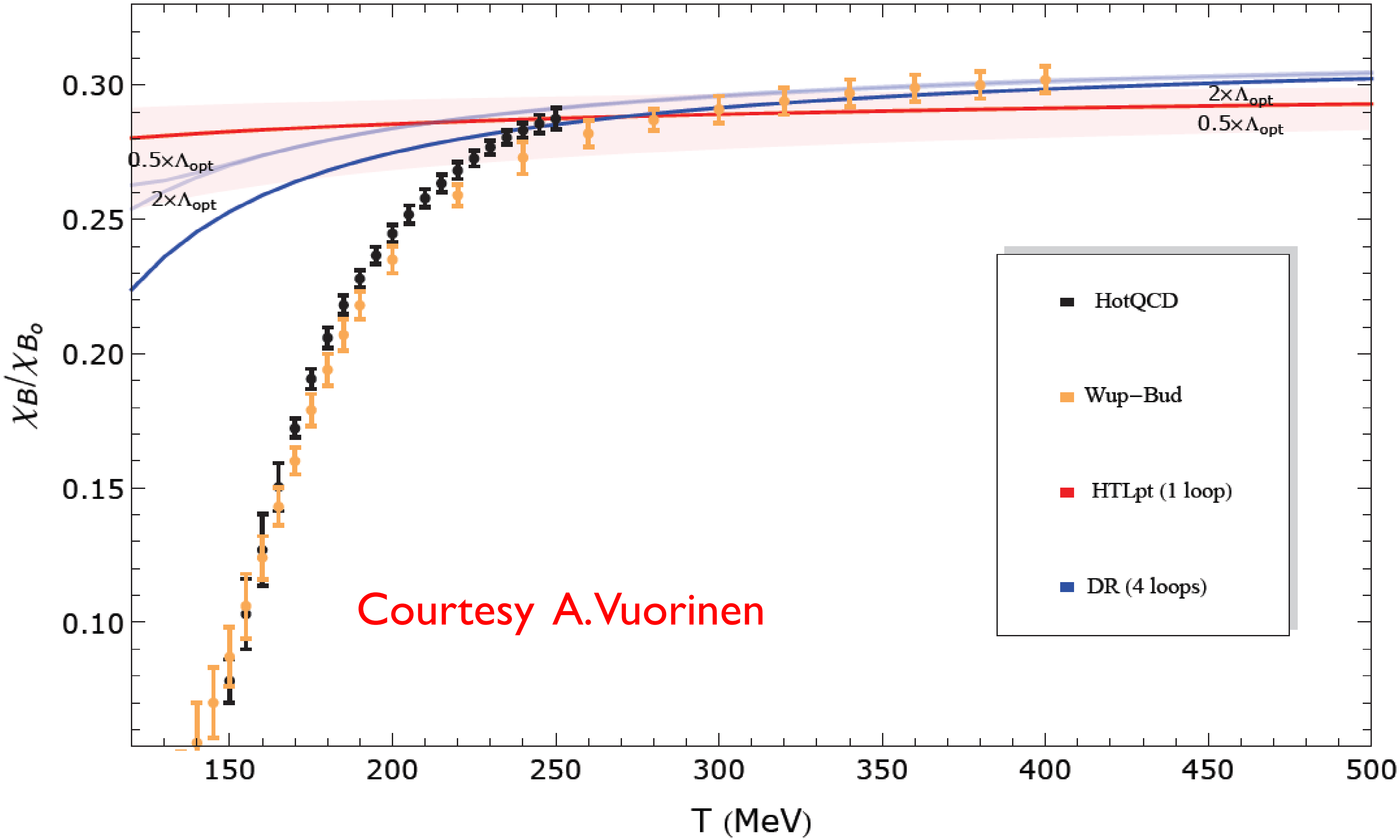
Lattice meets HT pertubation theory



Courtesy P.Petreczky

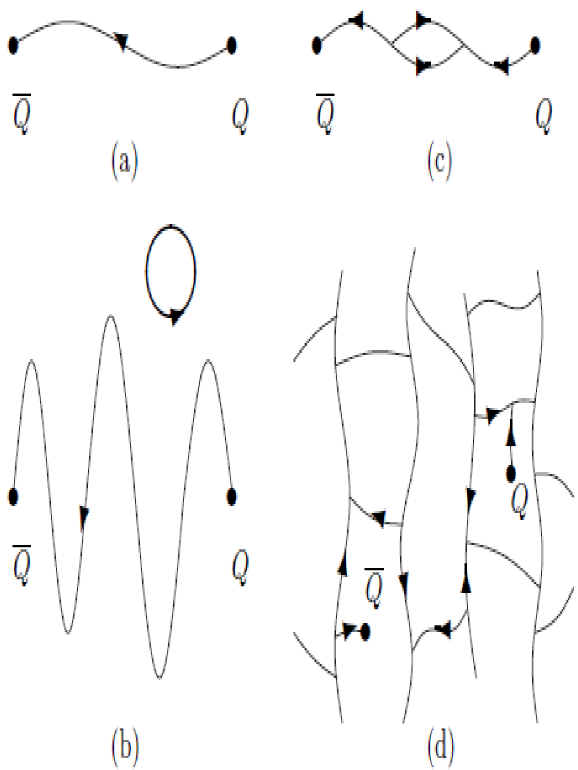
Lattice meets HT perturbation theory

Nf=2+1, perturbation theory vs. lattice data; Andersen, Mogliacci, Su, Vuorinen (in preparation).



Flux tube model

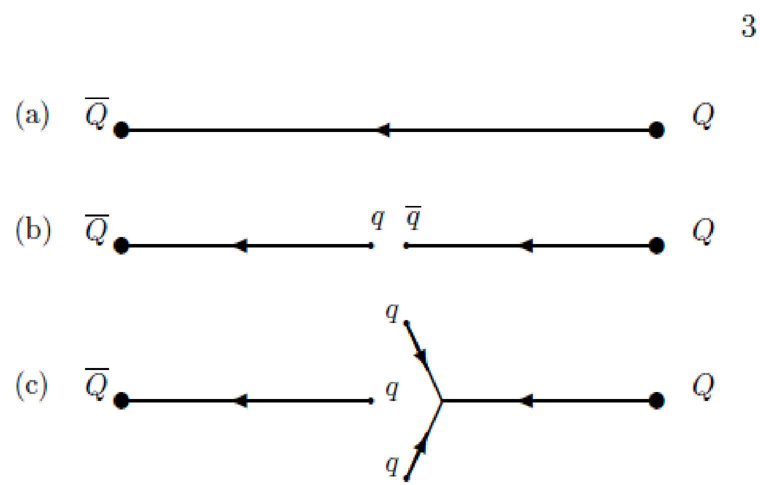
Patel, Friday
A. Patel 1111.0177



Visualise gauge field dynamics in position space.

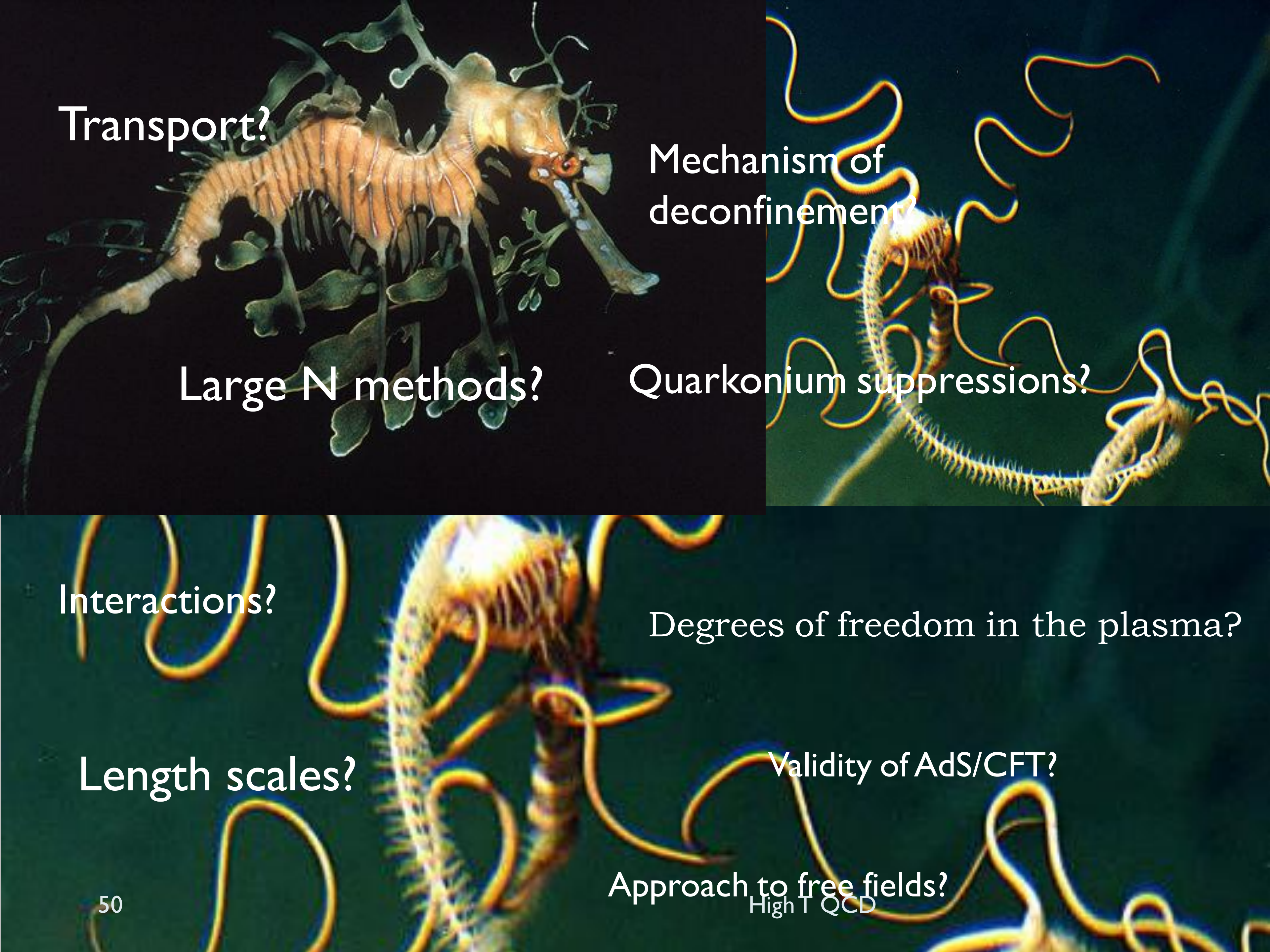
Can study multicorrelation particles which are useful for phenomenology

Nb : non sign problem at finite density



Quark Gluon Plasma

Exploring uncharted territories



Transport?

Mechanism of deconfinement?

Large N methods?

Quarkonium suppressions?

Interactions?

Degrees of freedom in the plasma?

Length scales?

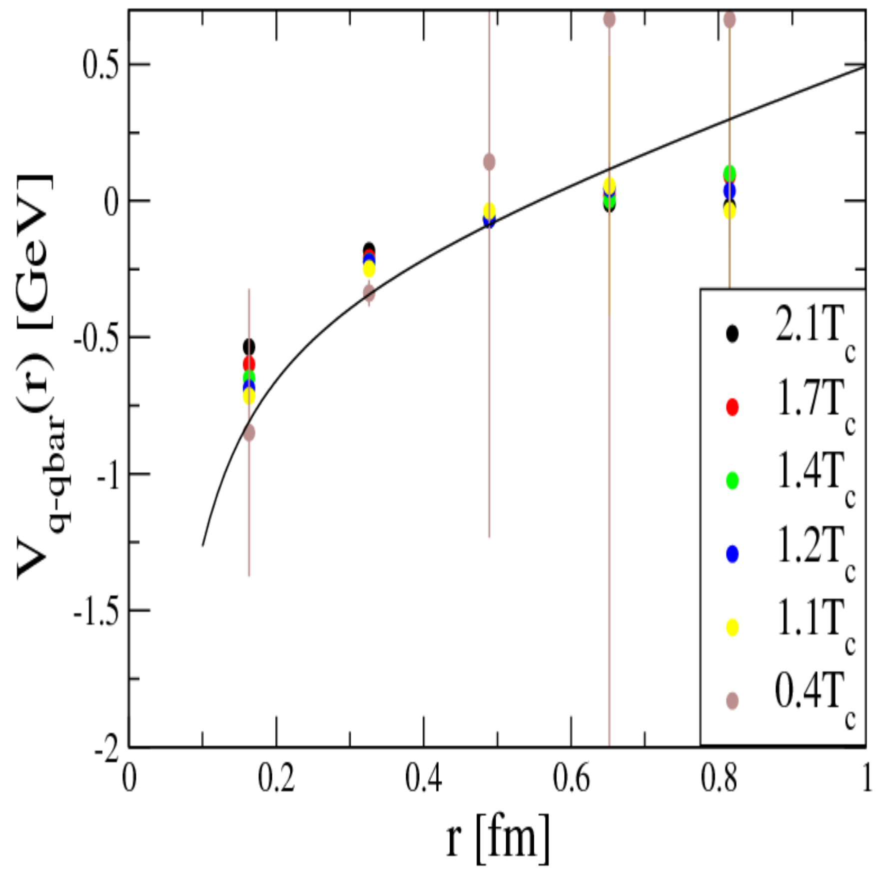
Validity of AdS/CFT?

Approach to free fields?

Potential&Quarkonia

C. Allton Wedsnday

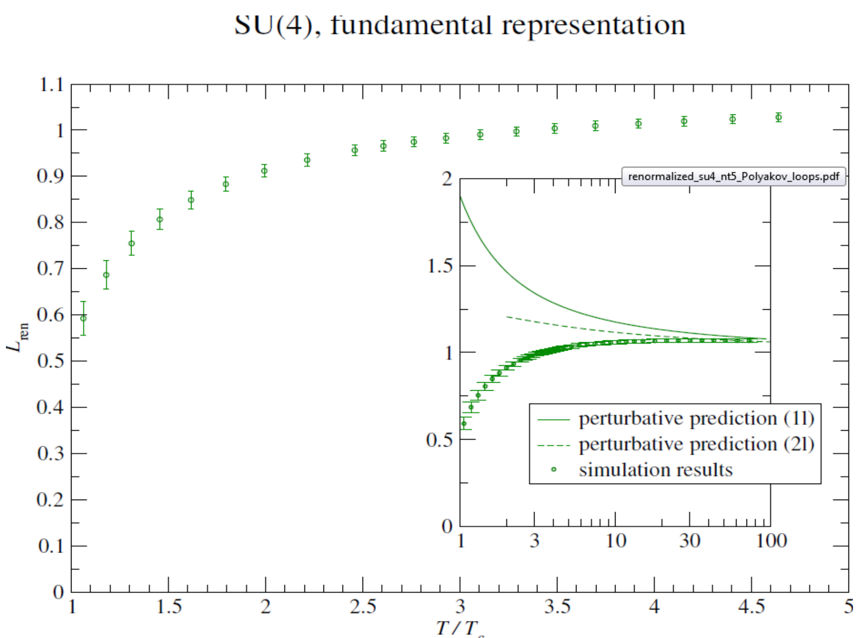
- New Results for Nf = 2
- Schroedinger equation approach : extract potential from wavefunction
- Spectral functions measured as well
- Possible comparison of spectral functions and potential in analogous conditions – from same set of gauge fields

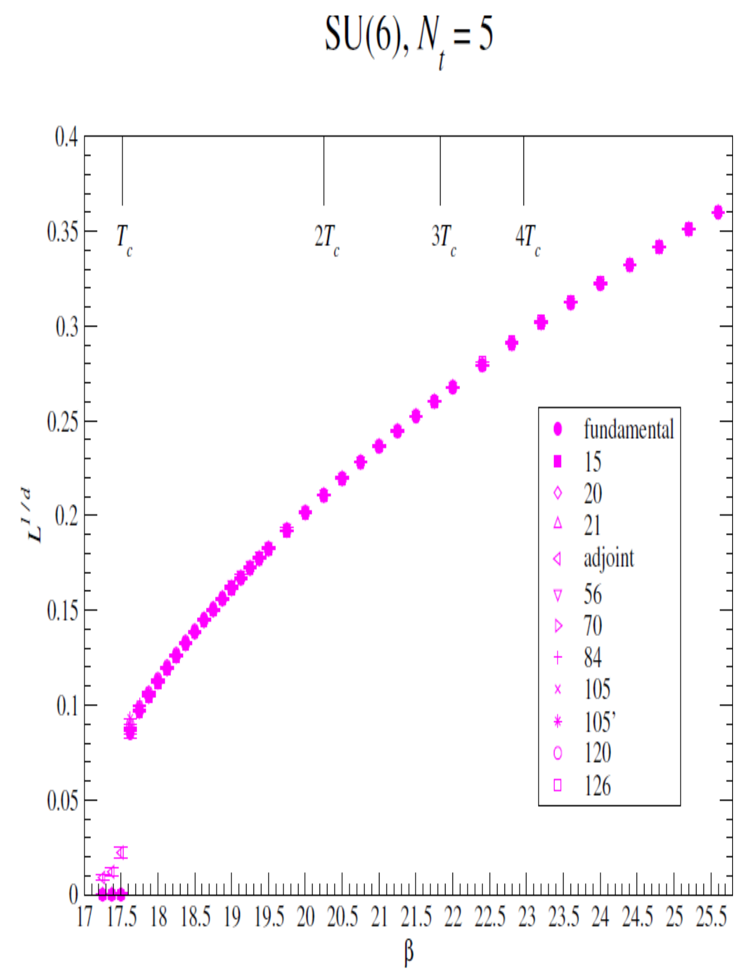


Large Nc

M. Panero Tuesday (Review)
Mikkanen et al. JHEP 1205 (2012)

Analogous behaviour for different Nc lends support to large Nc approach to the QCD high T phase



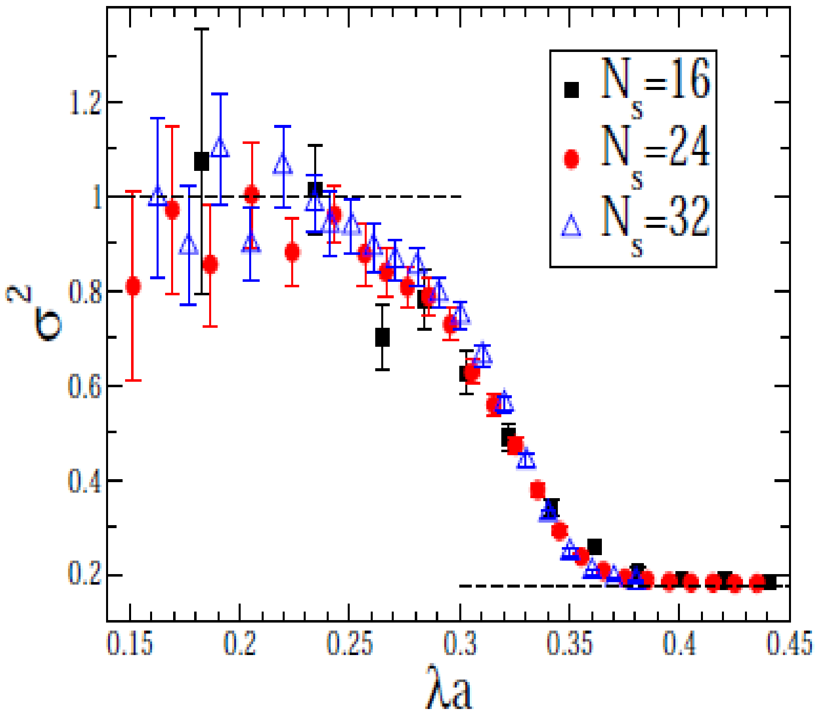


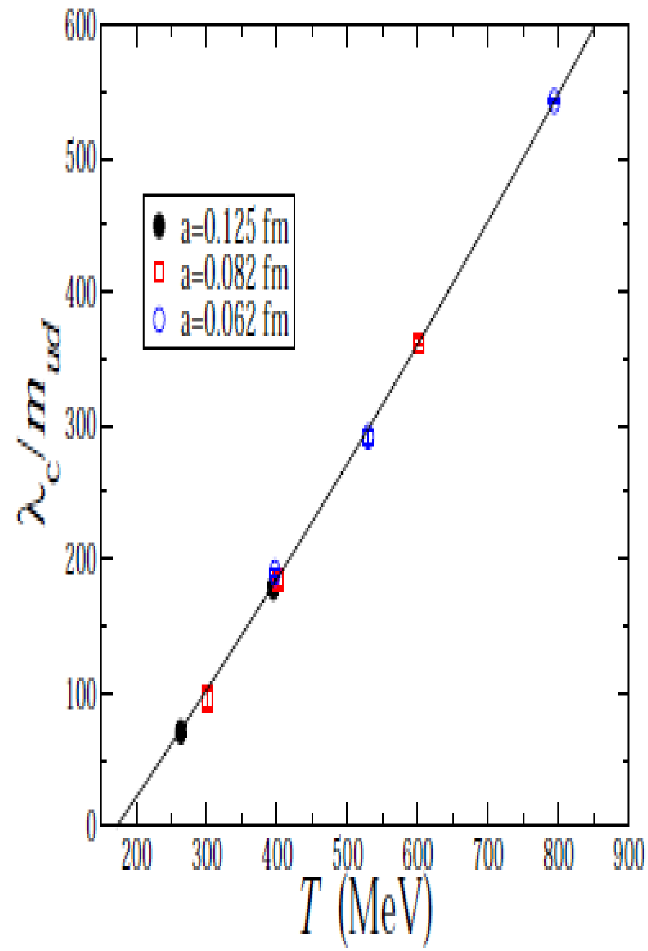
Plots courtesy M. Panero

A new scale in the QGP

Eigenvalue distribution follow different distributions at low and high frequency: separation

λc : mobility edge





Metastable states and Polyakov Loop Dynamics

Deka at al. 2011

- Z3 metastable states with dynamical fermions might have an important influence on the system behaviour (bubble formations, etc.)
- New study : find that metastable states become relevant for T > 750 MeV

Pure gauge High T: Three Z3 equivalent vacua for the Polyakov loop

With dynamical fermions: one true vacuum other two metastable

Polyakov loop dynamics: rigorous approach (YM)

Diakonov et al. 1243.3217

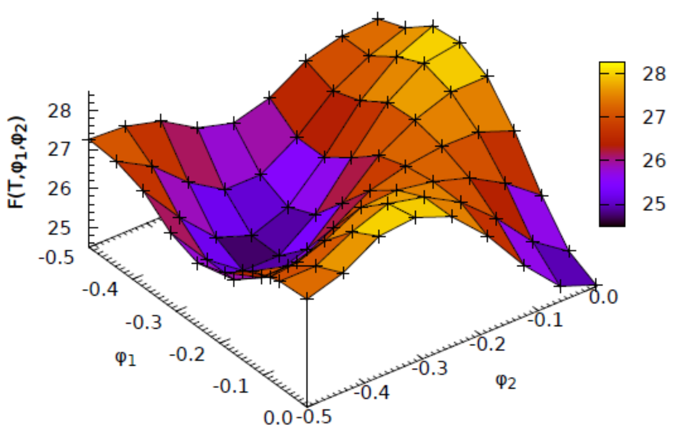
Free energy for untraced Polyakov loop X

$$P = \frac{1}{V_3}\sum_{\vec{x}} \mathrm{Tr} \prod_{t=1}^{N_t} U_4(\vec{x},t) = \mathrm{Tr}\, X\,,$$

:

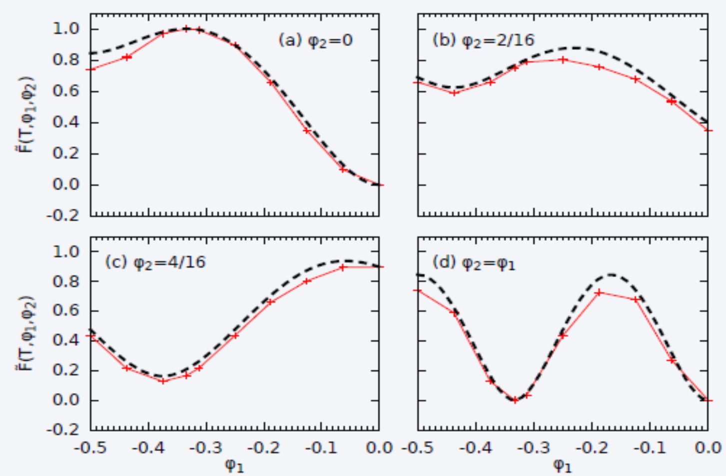
$$\mathcal{F}(T,X) = T\int_0^{\beta} d\beta' \,\langle S\rangle_{T,X,\beta'}$$

$$\langle S\rangle_{T,X,\beta'} = -\frac{\partial}{\partial\beta'}\ln \mathcal{Z}(T,X,\beta')$$



T = 1460 MeV

Excellent comparison with Pt.



Tc

$\approx$200MeV

340 –380 MeV RHIC AuAu 200 GeV	420-480 MeV LHC 2.76 TeV	500- 600MeV LHC hot spots 2.76 TeV	→	**1 GeV LHC 7 TeV**
		[U. Heinz 2012]		[Expected]

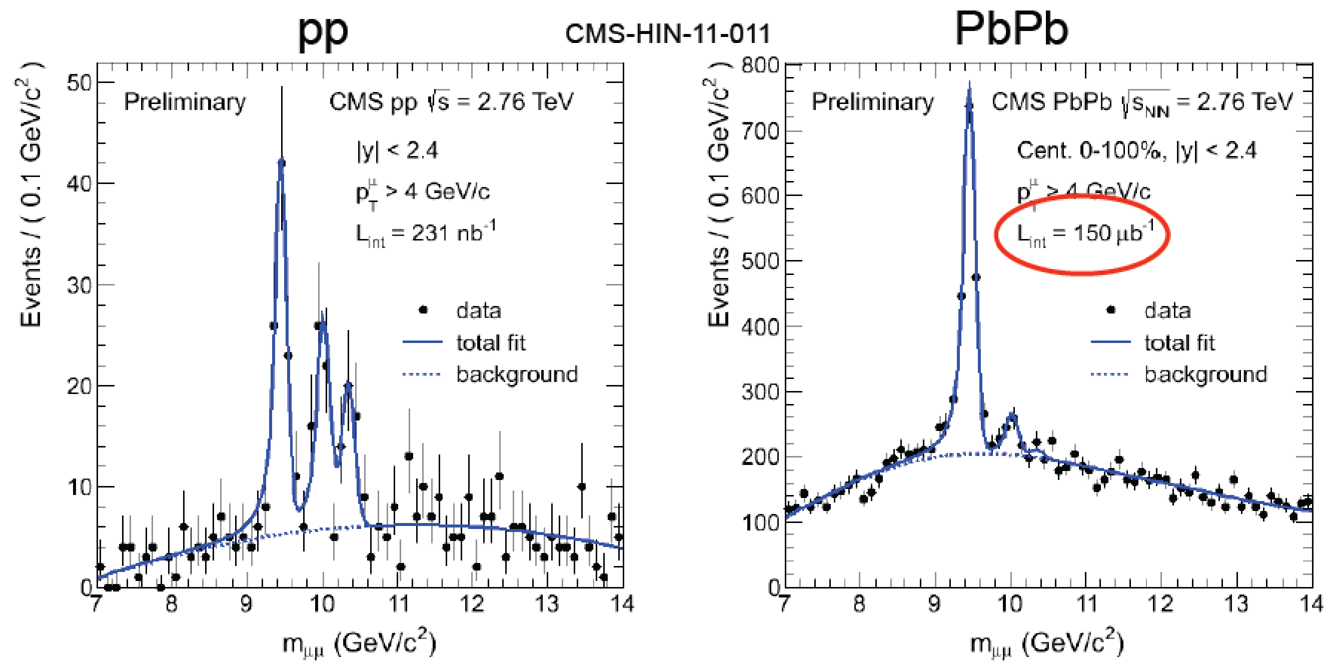
Quark Gluon Plasma & Colliders

Quarkonia

Transport

T. Dahms CMS Hard Probes 2012

Bottomonia: with 2011 data



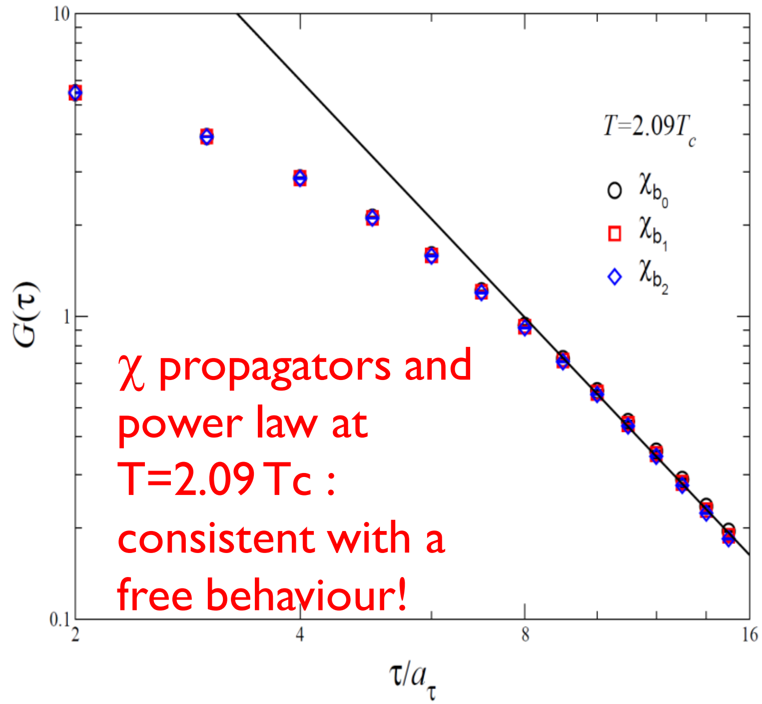
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

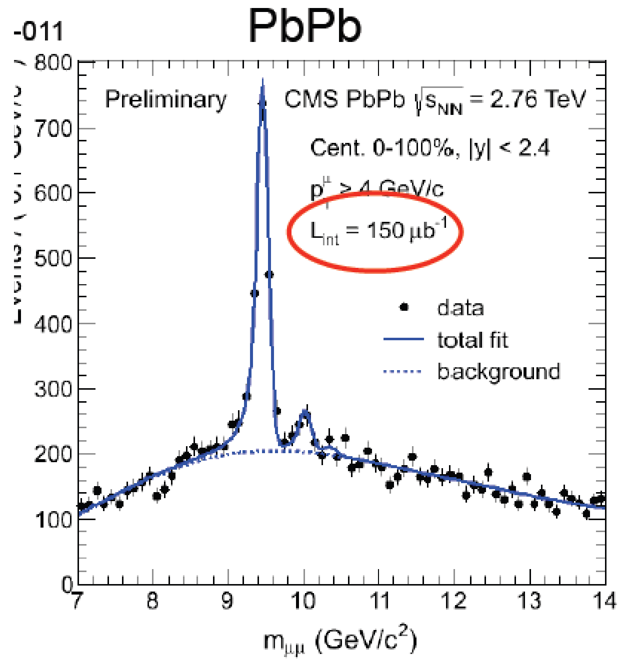
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

Ratios not corrected for acceptance and efficiency

Hard Probes 2012, Calgiari, 27 May – 1 June 2011 11

Bottomonia: with 2011 data





$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}} = 0.12 \pm 0.03 \pm 0.01$$

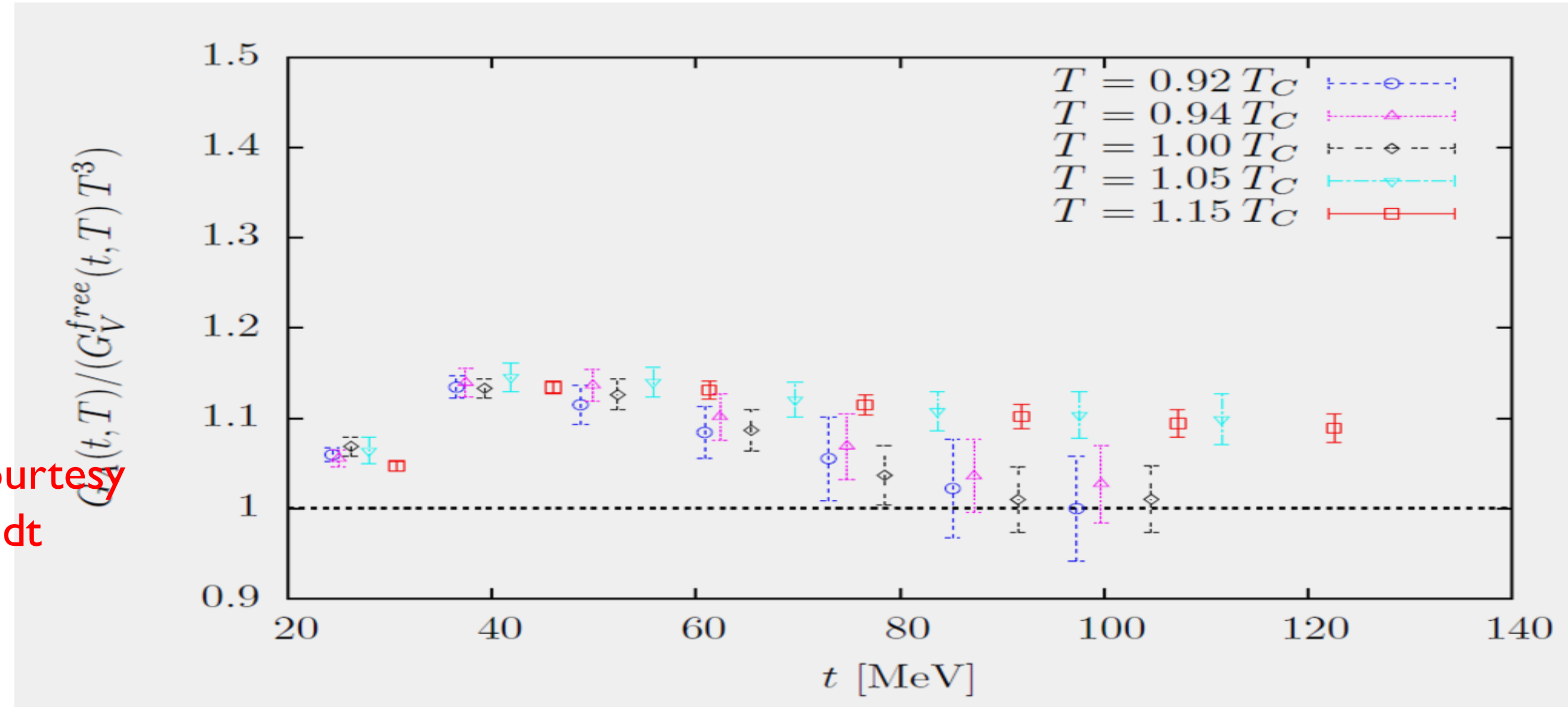
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}} < 0.07$$

Ratios not corrected for acceptance and efficiency

Hard Probes 2012, Calgiari, 27 May – 1 June 2011 11

Brandt Tuesday

A look at propagators in real time



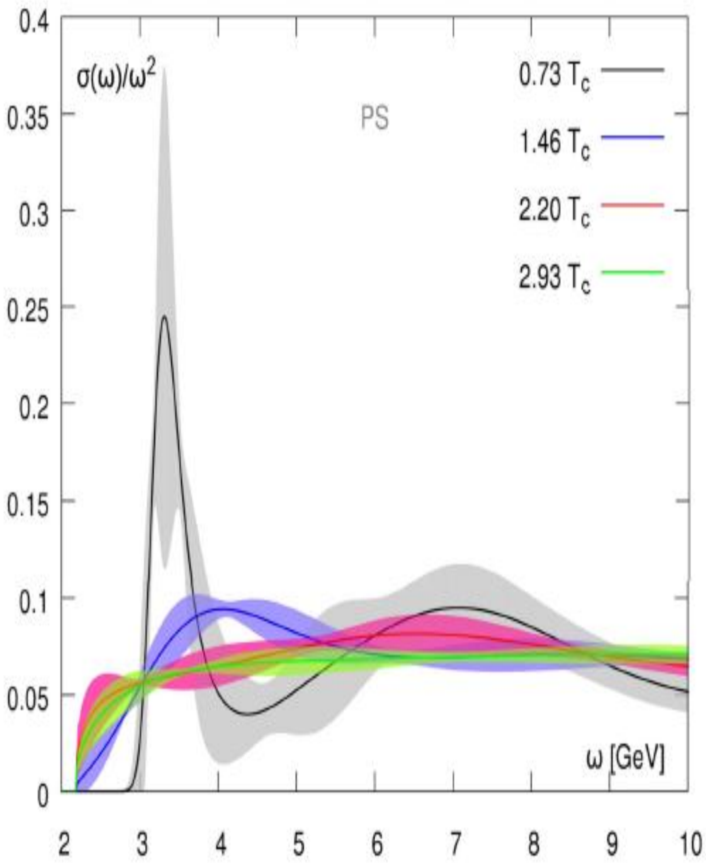
Plot courtesy
B. Brandt

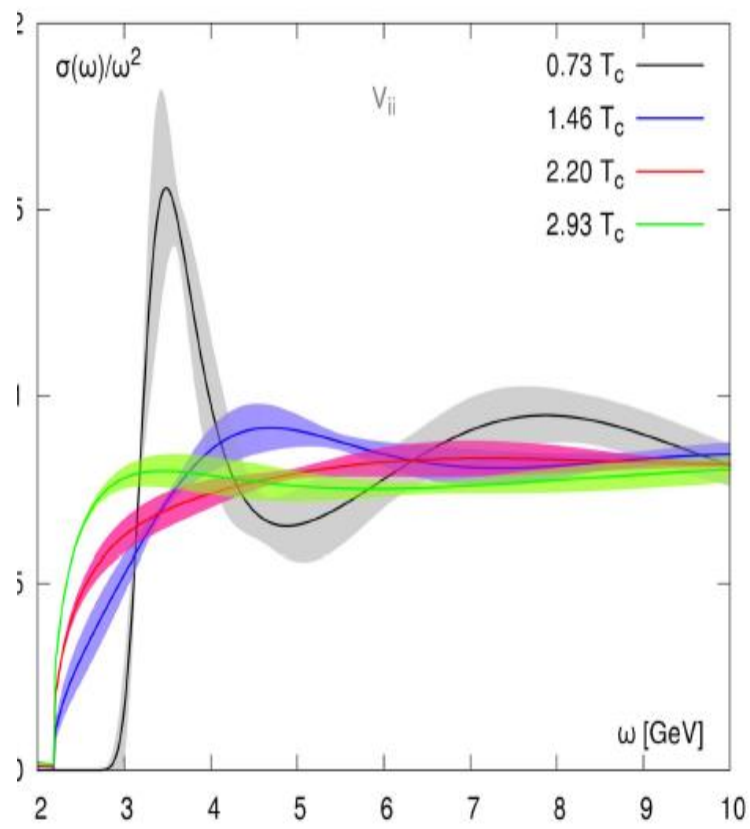
From Euclidean propagators to spectral functions via MEM: new method

Rhotkopf Friday

Charmonium

Ding et al. 2012 1204.4945





Kim Wedsnday

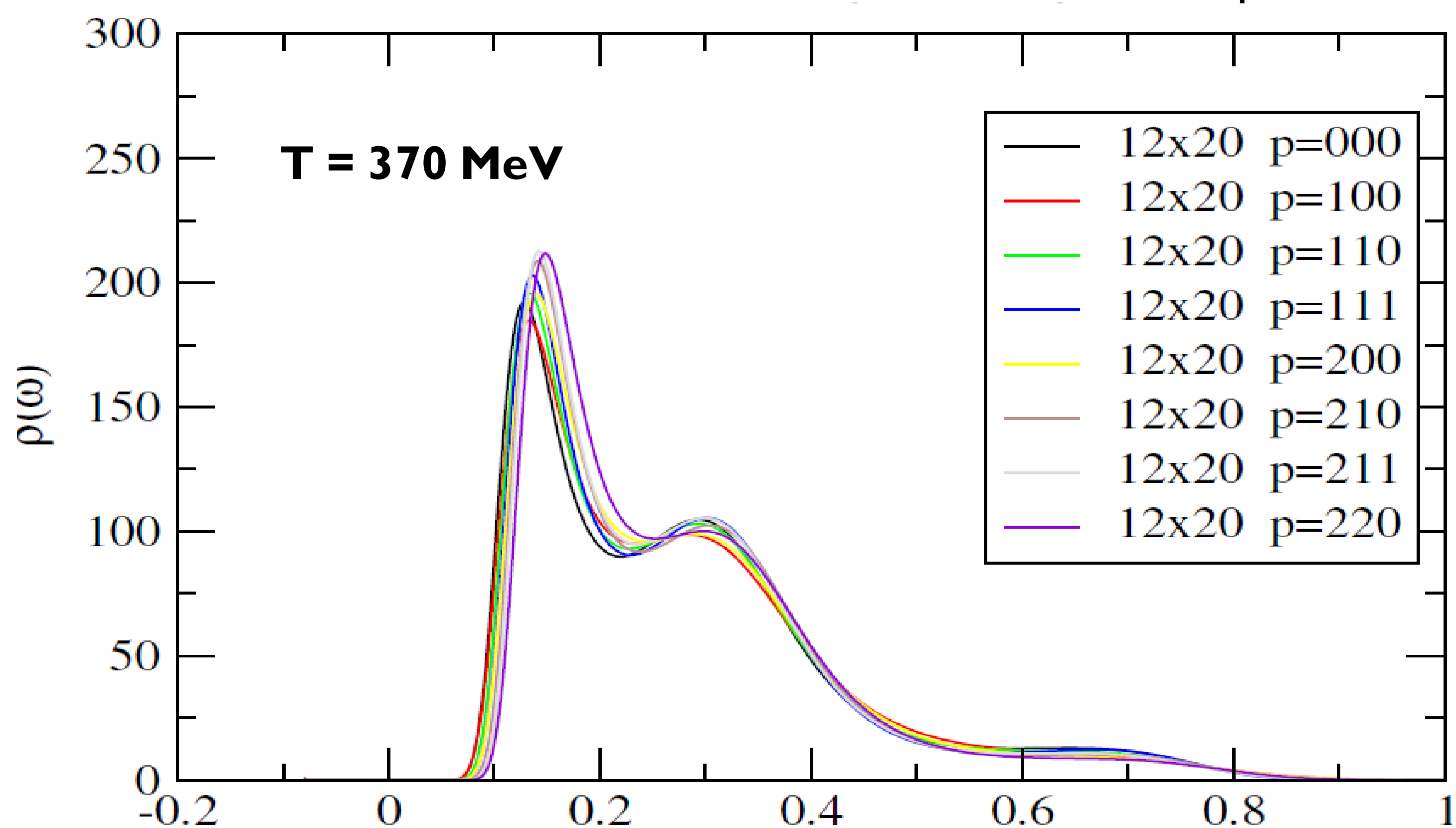
Bottomonium

NRQCD for bottom

Two light flavors

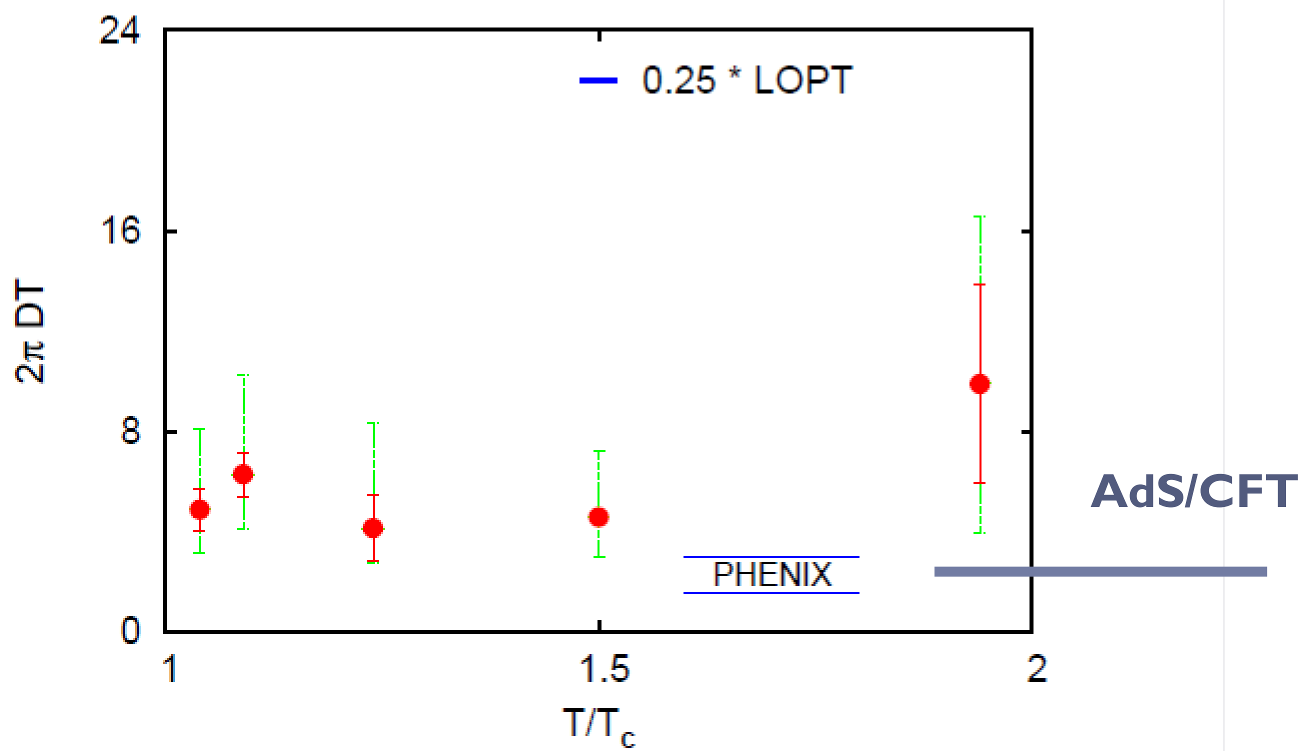
Momentum dependence : v^2 sim 0.3. Visible on poles, not on width.

Heavy mass dependence consistent with potential models



Heavy Quark Momentum Diffusion Coefficient

S. Datta Thuersday



Summary – Hot QCD @ Lattice2012

- Bulk Thermodynamics : result in the continuum and at the physical point for staggered results well into the current LHC region are in good control. Residual discrepancies seem minor.
- Wilson fermions becoming competitive.Continuum limit (with largish masses).
- New analytic studies in the high T regime compare well with numerical results, building further confidence in the numerical results. Contact with free limits also established
- New high quality results for domain wall and overlap fermions, large scale simulations are being planned.
- Good chiral properties togheter with further theoretical insight trigger activity on axial symmetry.
- Details of QCD dynamics extremely important around the phase transitions: fate of the axial anomaly, order for Nf=2 , response to magnetic field, and to Θ therm are still unclear
- (Strongly coupled) Quark Gluon Plasma theoretical laboratory inspiring studies and contacts with other fields
- Lattice results for trasport and quarkonia compare well with RHIC and LHC experiments.