

Aktuelle Entwicklungen in der Theorie II

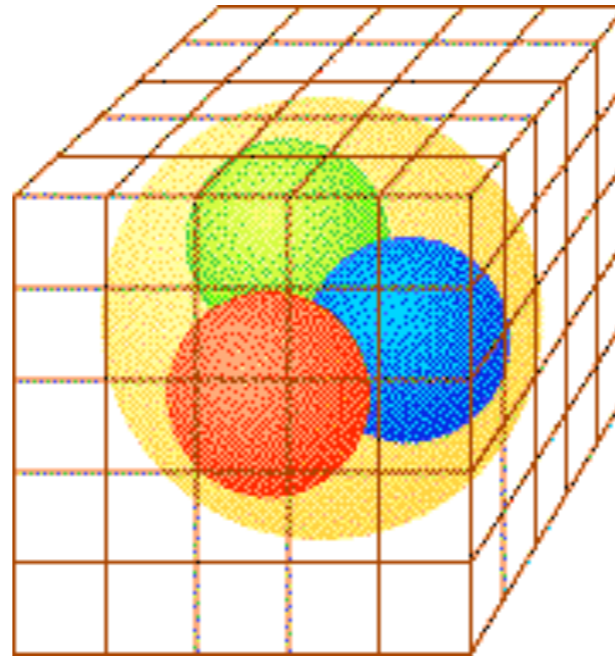
Owe Philipsen



- Lattice QCD at $T=0$
- Lattice QCD at finite temperature and density
- Continuum work relevant for heavy ion collisions

Disclaimer: -list of activities **incomplete!**
-choices by interests, awareness,....

Lattice at $T=0$

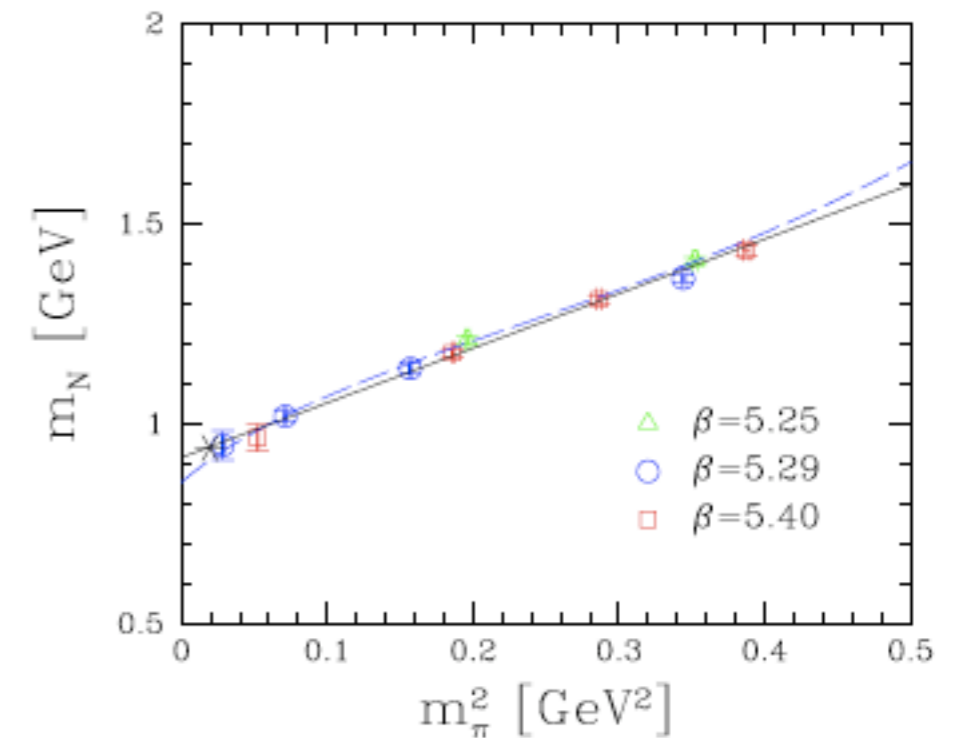
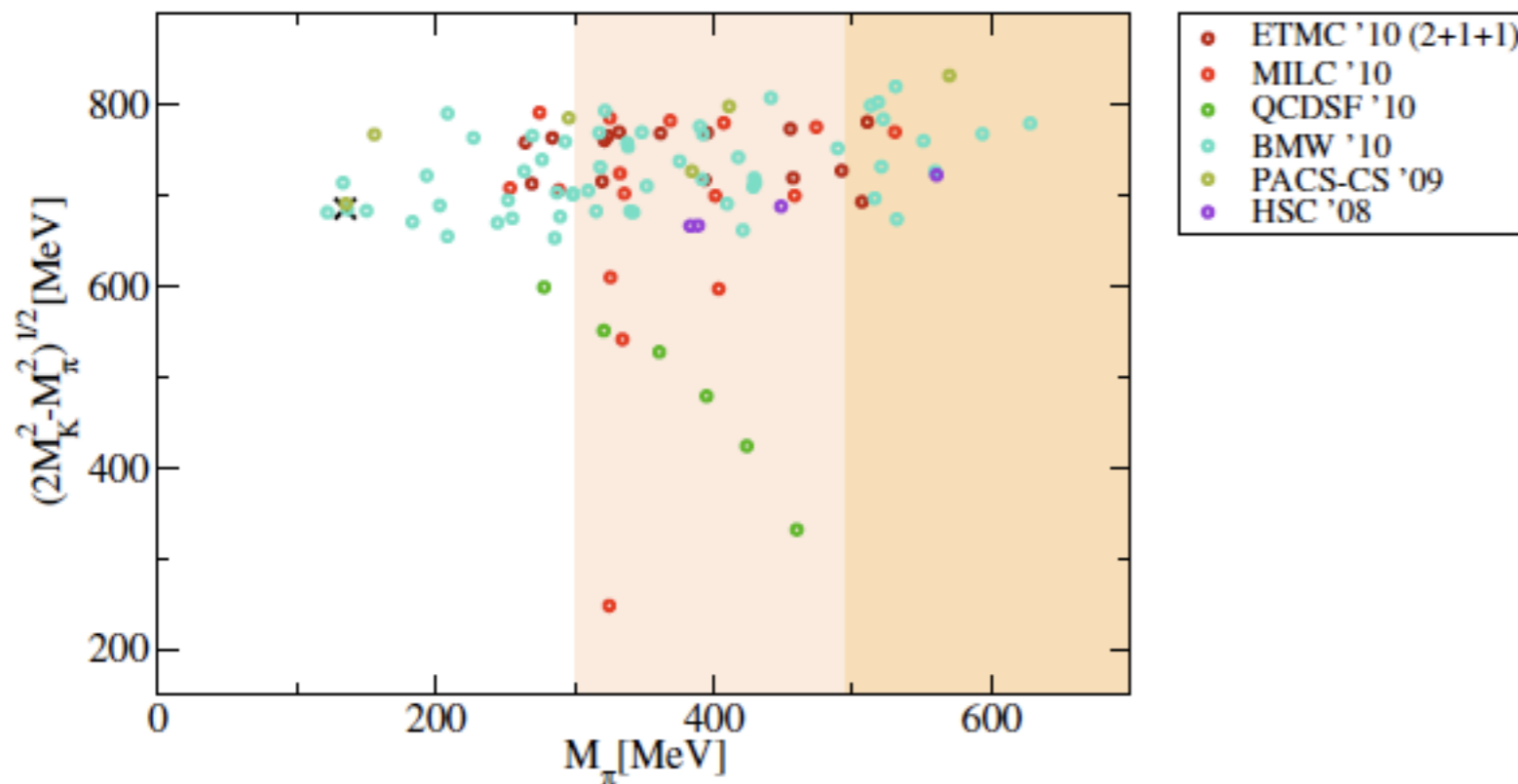


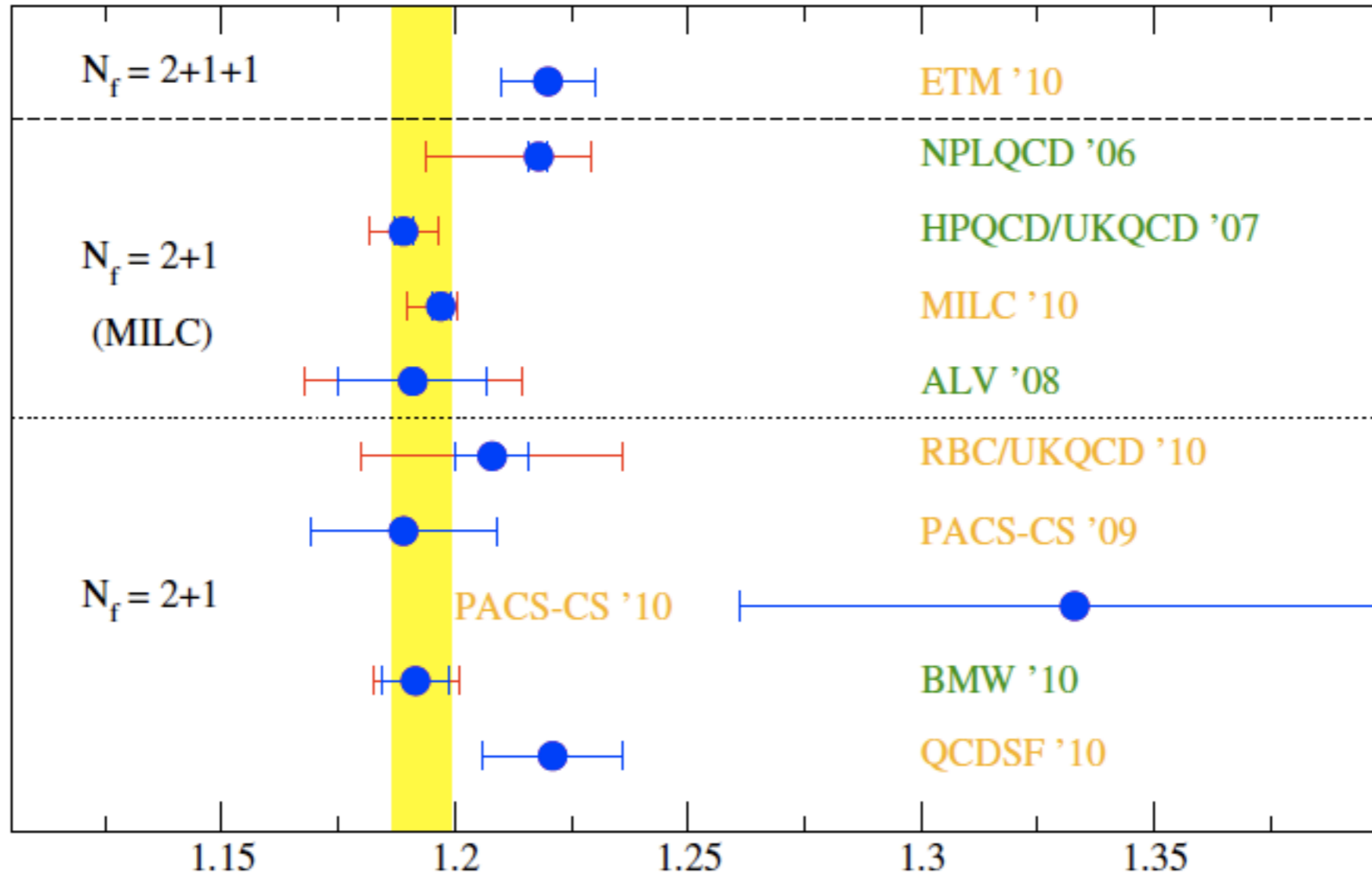
Light hadron properties

- Physical light quark masses can be simulated (staggered) or reliably extrapolated to (Wilson)
- Step from $N_f=2$ to $N_f=2+1$ or $2+1+1$ is made

Simulation landscape [Hoelbling, LAT 2010](#)

$N_f=2$ Wilson [QCDSF](#)

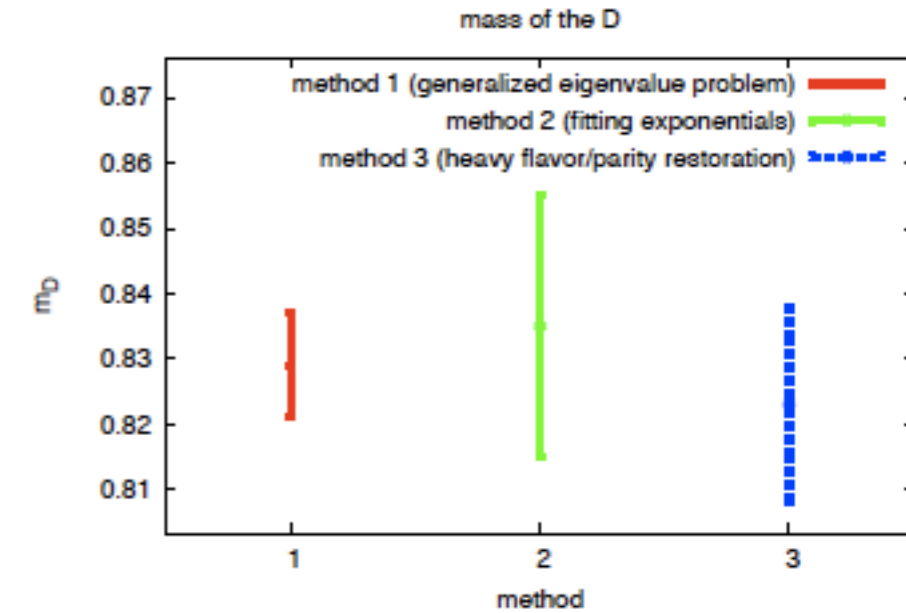
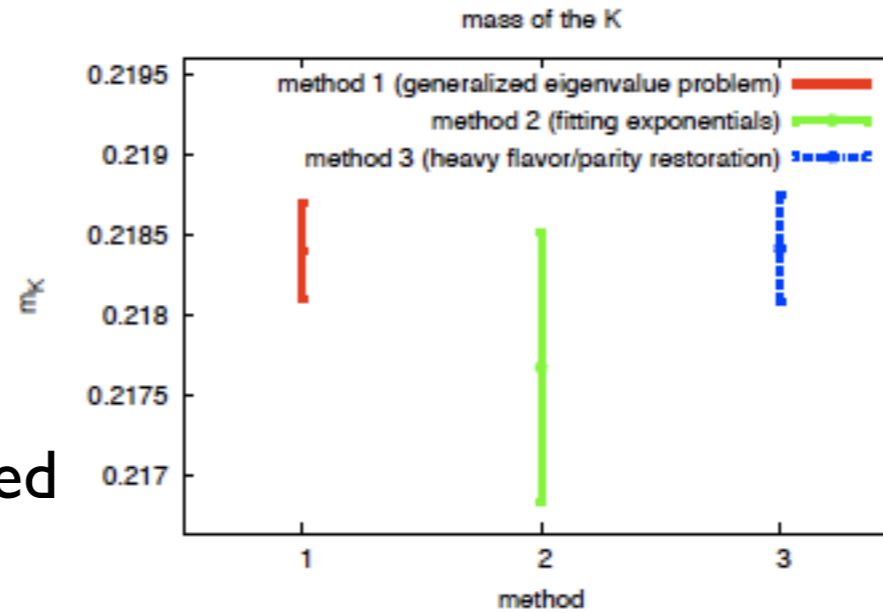


F_K/F_π Summary

Light hadron properties

ETMC, BMW

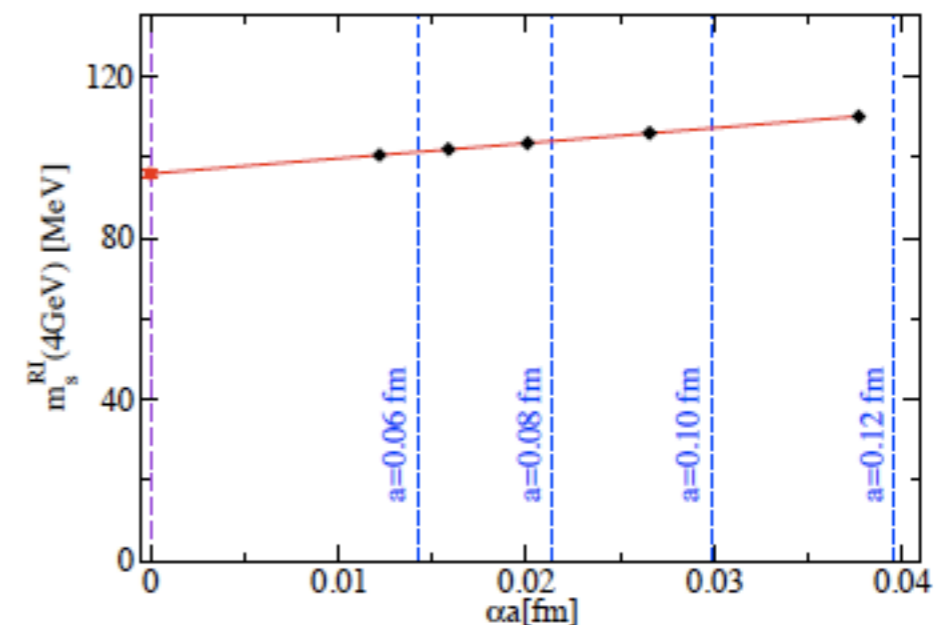
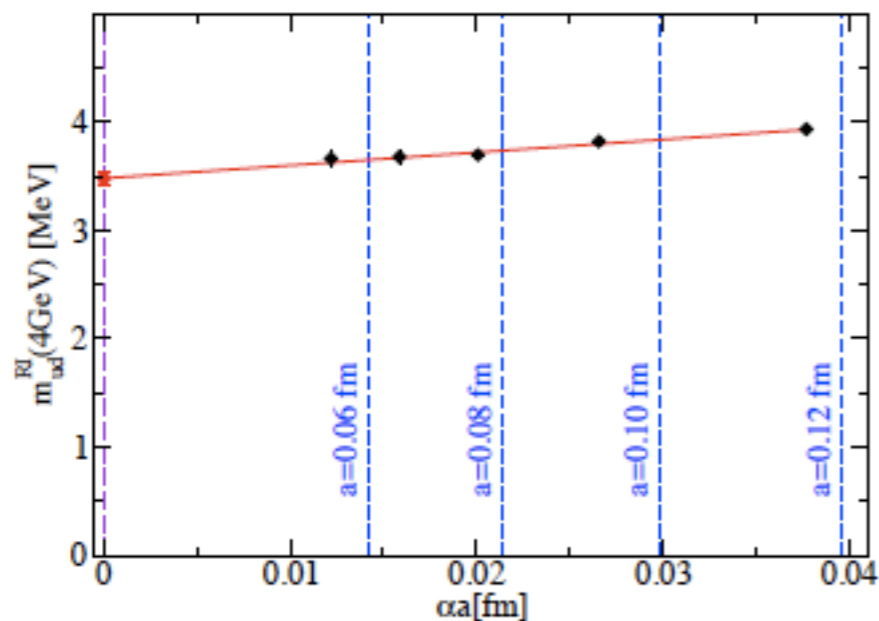
- 2+1+1 twisted mass
- Parity and heavy flavour symmetry broken by twist, spectroscopy complicated
- Feasibility test: K, D- mesons



Baron et al., arxiv:1009.2074

Non-perturbative light quark masses in RI-MOM scheme

Dürr et al., arxiv:1011.2403

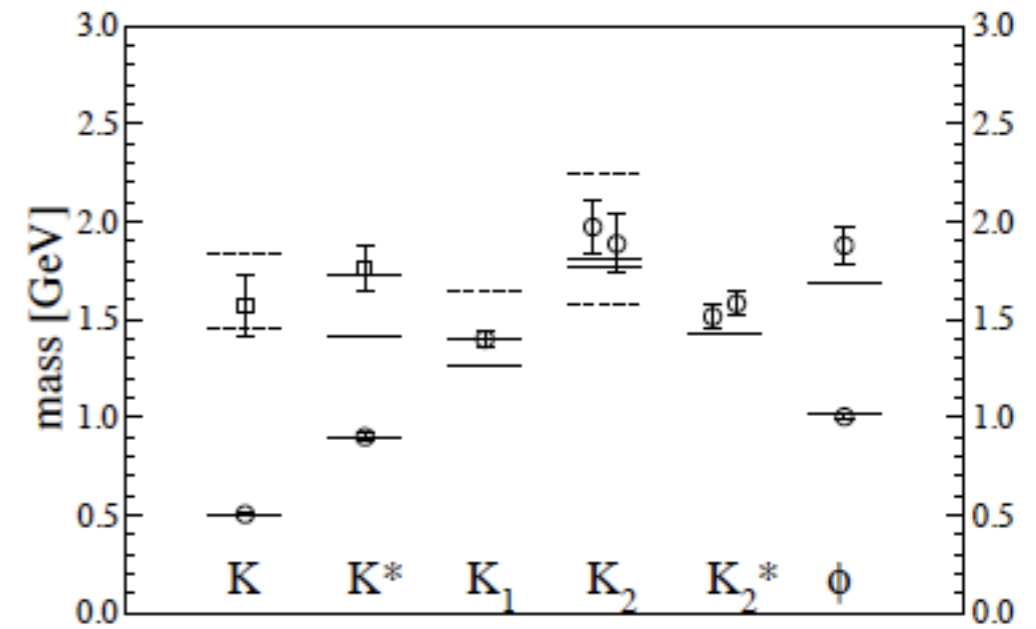
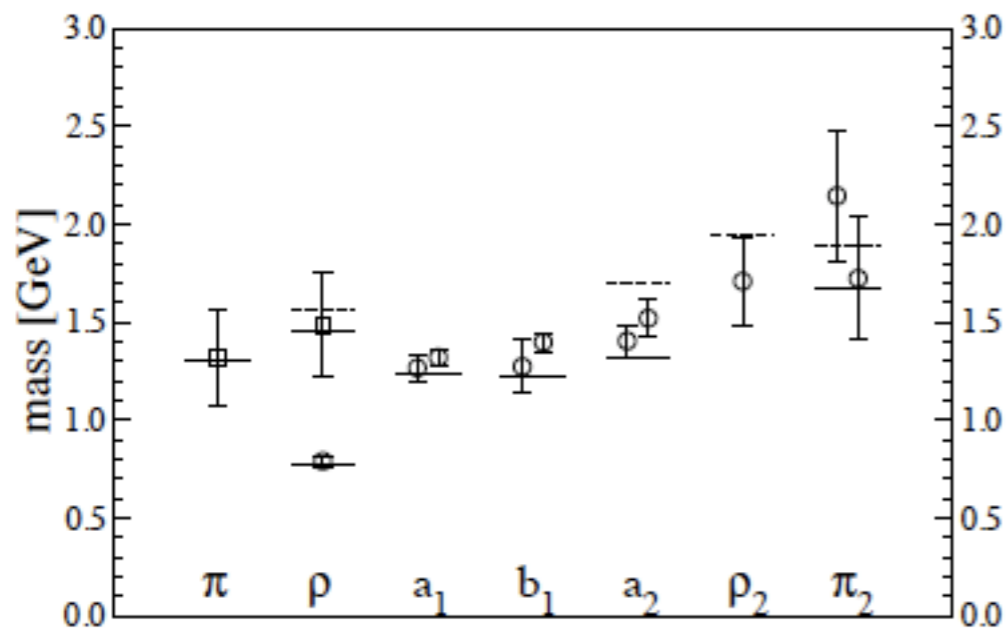
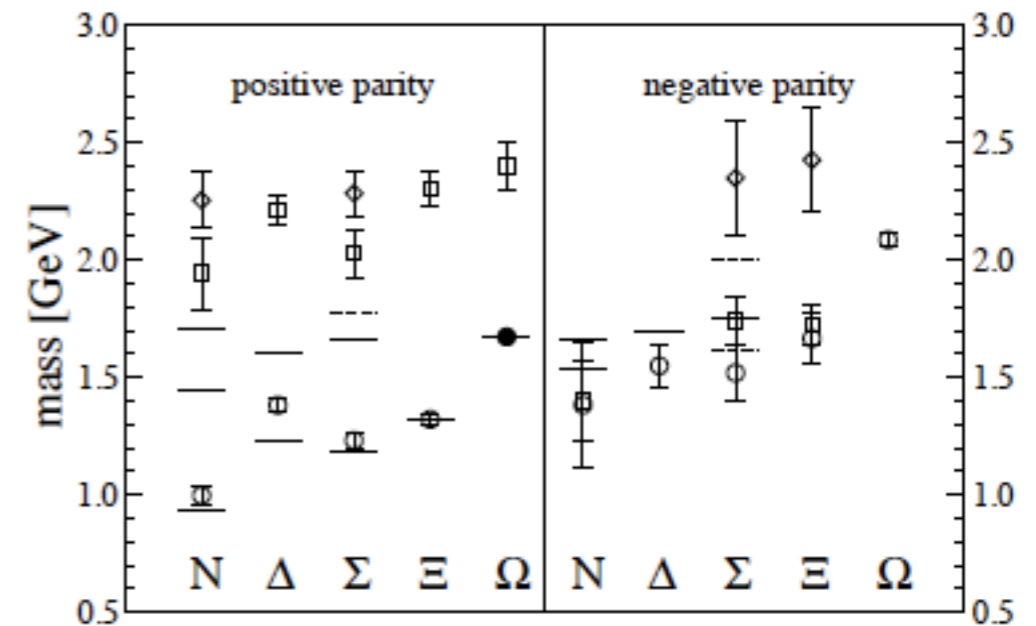


Challenge: m_u/m_d from $\Upsilon(4S) \rightarrow h_b \pi^0(\eta)$ Guo, Hanhardt, Meissner, PRL 105 (2010) 162001

(Excited) hadron states

Bern-Graz-Regensburg

- $N_f=2$, $a=0.15$ fm, chirally impr. action
- Variational method, operator basis
- Good ground states
- Weak signals for excited and scattering states



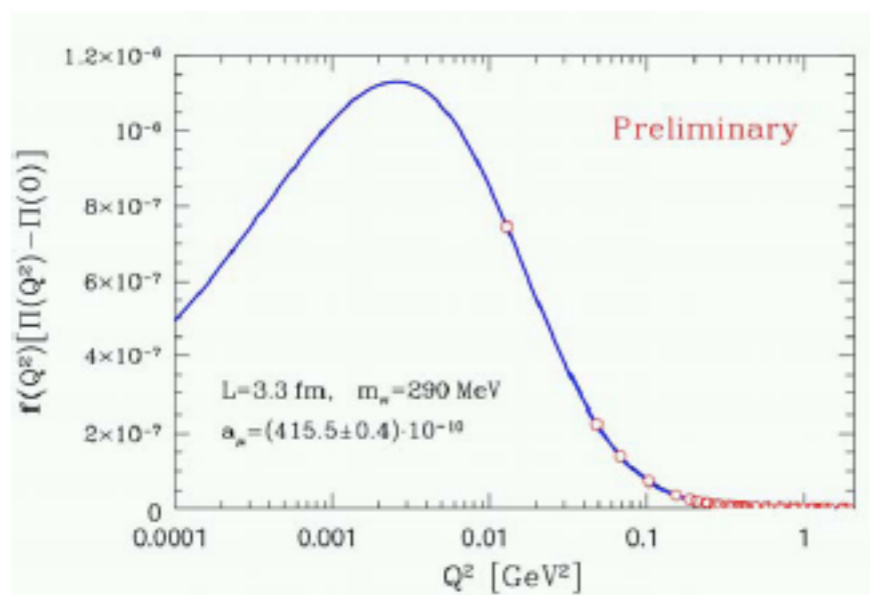
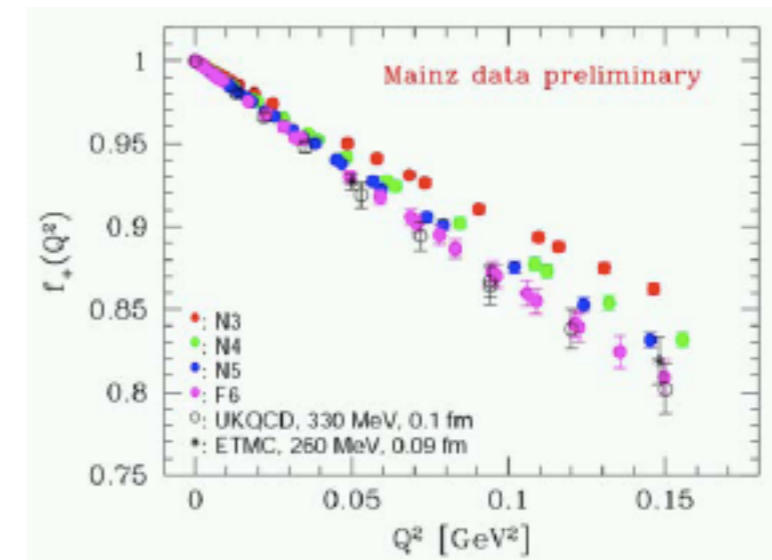
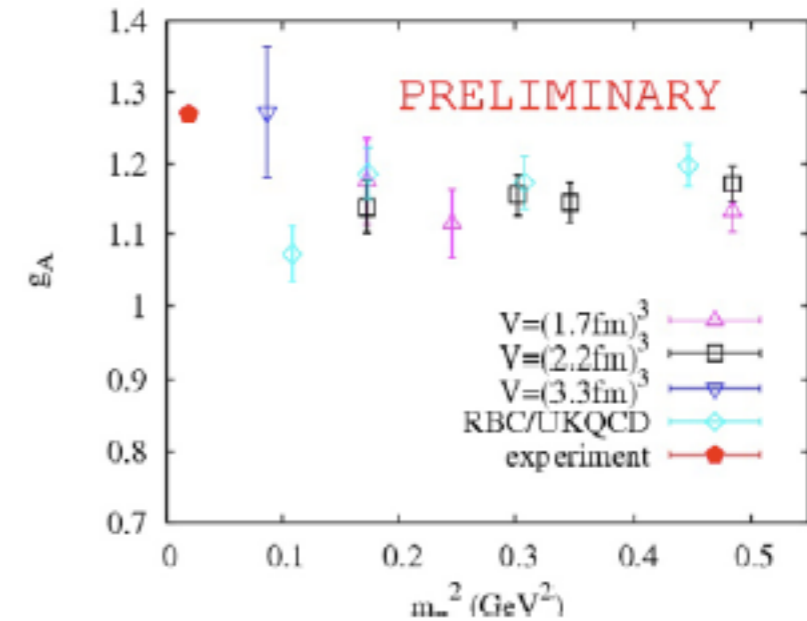
Engel et al., arxiv:1010.2366

Nucleon properties

Mainz

- Some lattice form factors do not reproduce exp. values, Q -dependence; systematics!
- New methods to control contaminations from excited states, “summed insertions”
- Axial charge: three lattice spacings $a=0.08, 0.07, 0.05$ fm
- Twisted b.c. to tune momentum; Pion form factor with better accuracy

Capitani et al., arxiv:1011.1358



- Twisted b.c. to stabilise polarisation amplitude $\Pi(q^2)$
- Disconnected diagrams estimated to lead to 10% decrease, convolution for $(g - 2)_\mu$

Brandt et al., arxiv:1010.3290

Nucleon properties

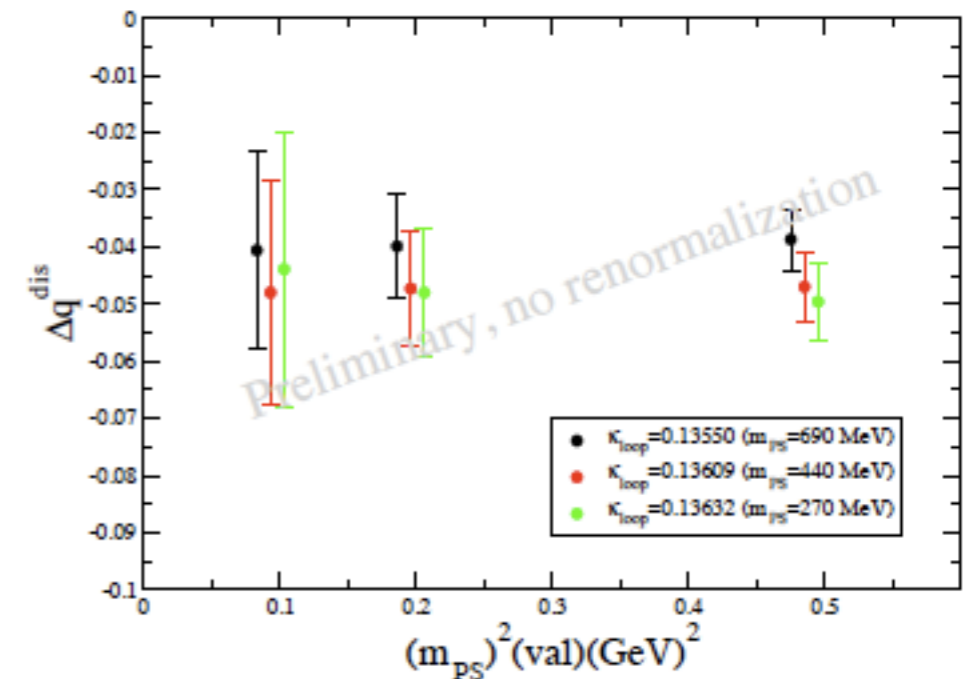
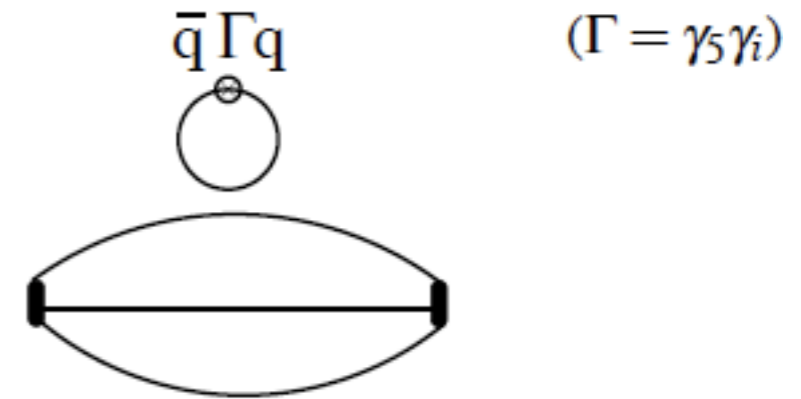
QCDSF

- Disconnected diagrams important for many matrix elements, e.g. quark contribution to nucleon spin

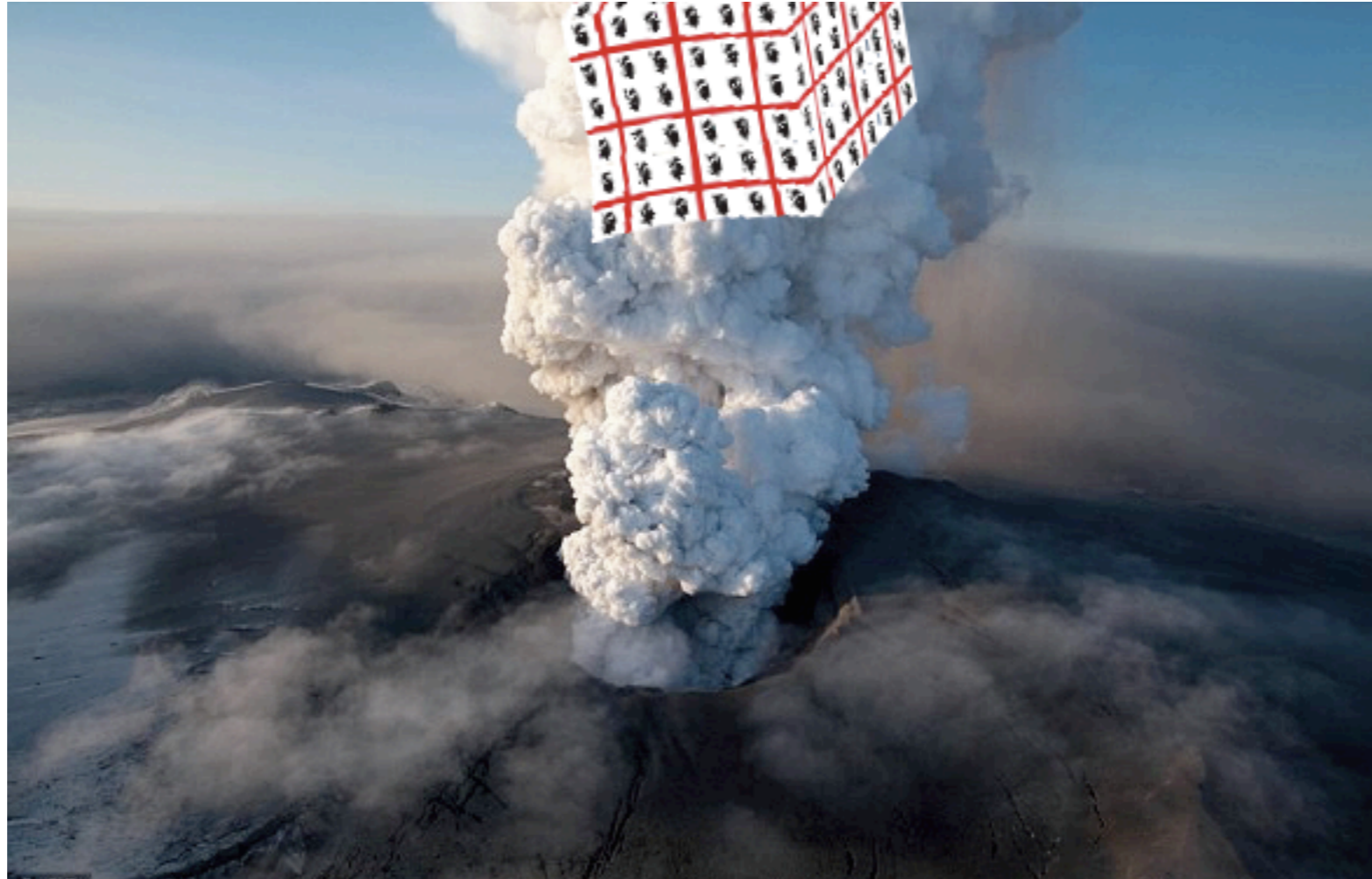
$$\langle N, s | \bar{q} \gamma_\mu \gamma_5 q | N, s \rangle = 2m_N s_\mu \frac{\Delta q}{2}$$

- $O(V)$ more expensive than connected, calculational methods needed
- Combination of stochastic estimators and hopping expansion for noise reduction

Collins et al., arxiv:1011.2194



Lattice at finite temperature and density

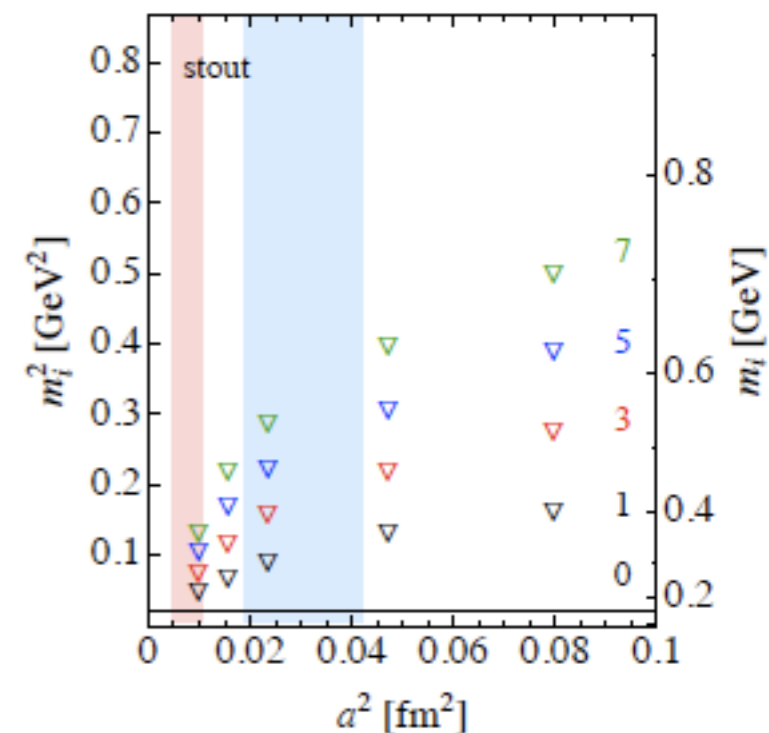
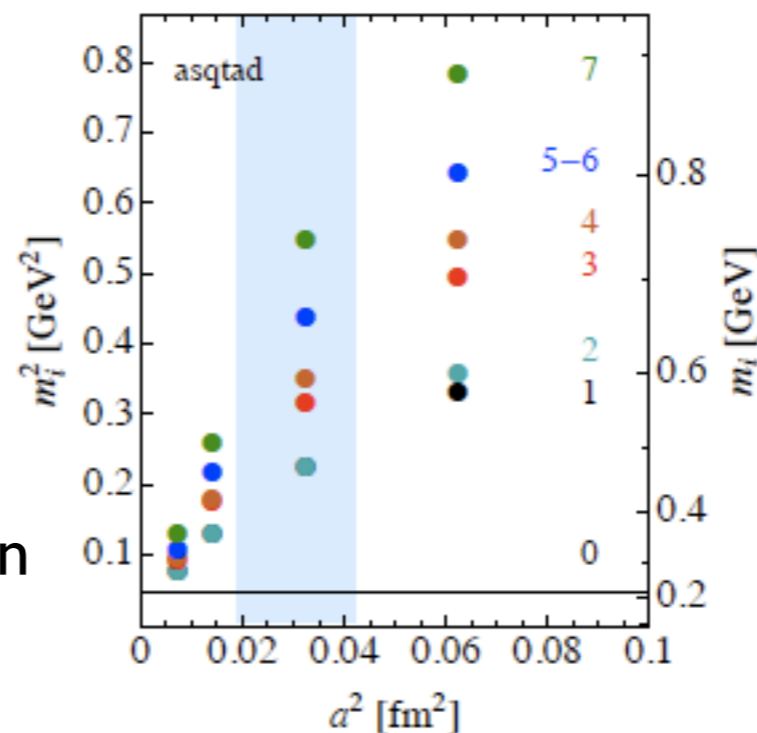


The critical temperature

Budapest-Wuppertal
hotQCD (Brookhaven, Riken, Bielefeld)

Resolution of the “ T_c -crisis”:

- Staggered fermions: pion-taste splitting
- Effect larger for asqtad-, p4- than stout actions
- Tune pion by average, rather than lightest taste



- Comparison chiral condensates:

- BW:

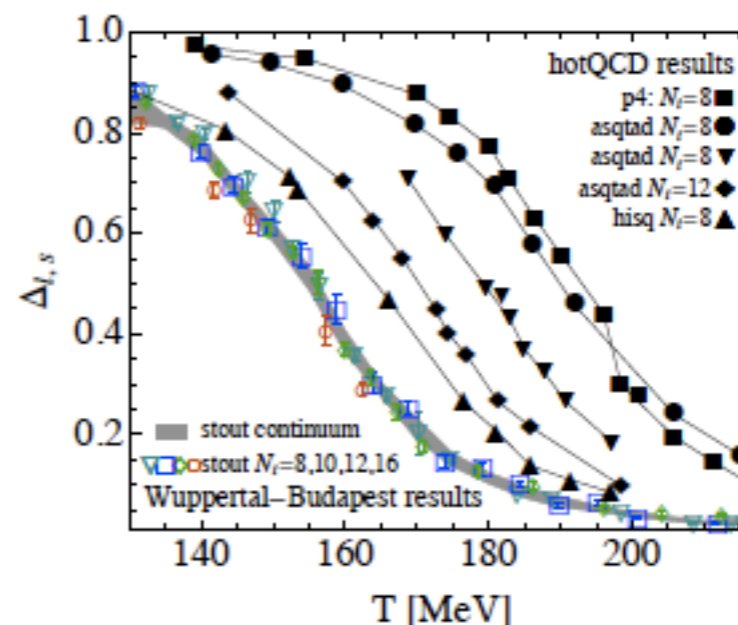
$$m_\pi = 135 \text{ MeV}$$

- hotQCD:

$$m_\pi = 220, 160 \text{ MeV}$$

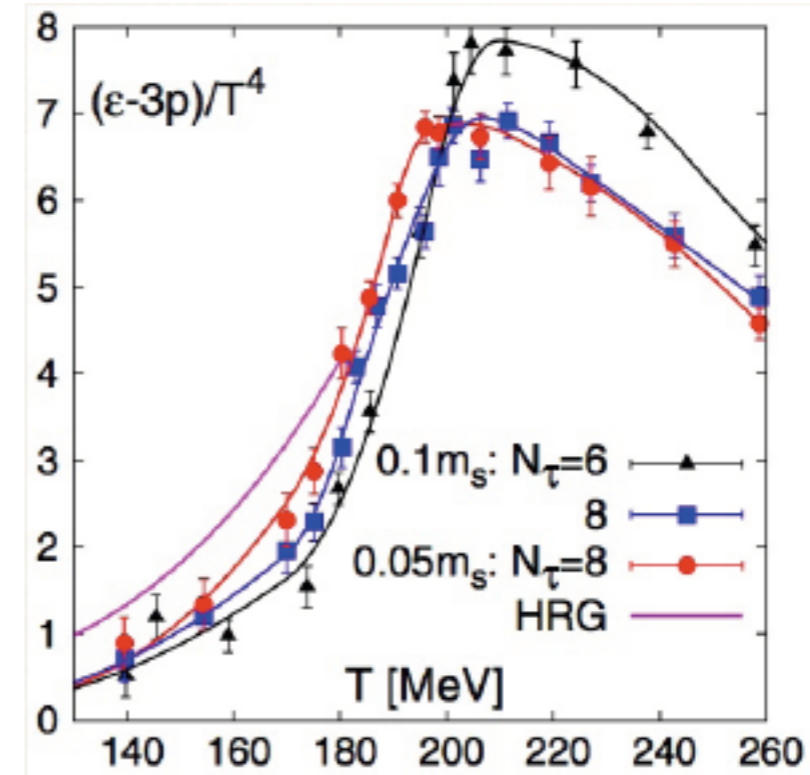
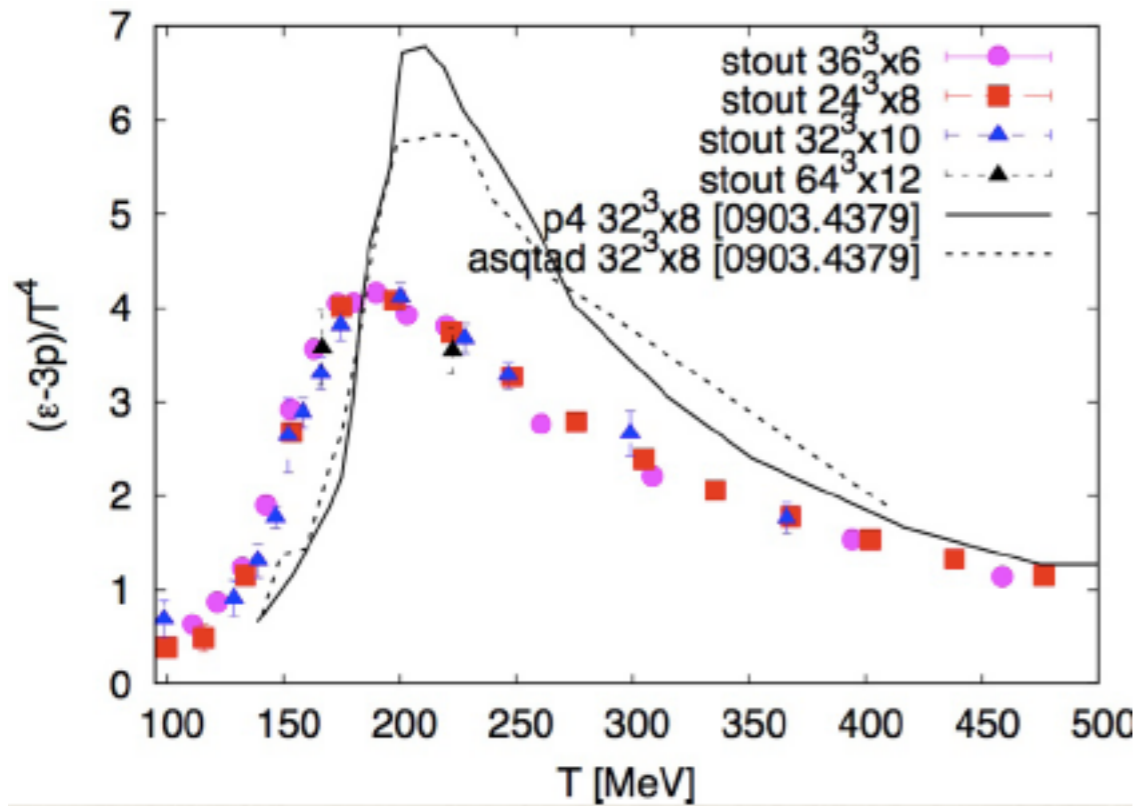
$$T_c = \begin{matrix} 147(2)(3) & \text{chiral susceptibility} \\ 165(5)(3) & \text{strange quark number} \end{matrix}$$

Borsanyi et al., arxiv:1005.3508



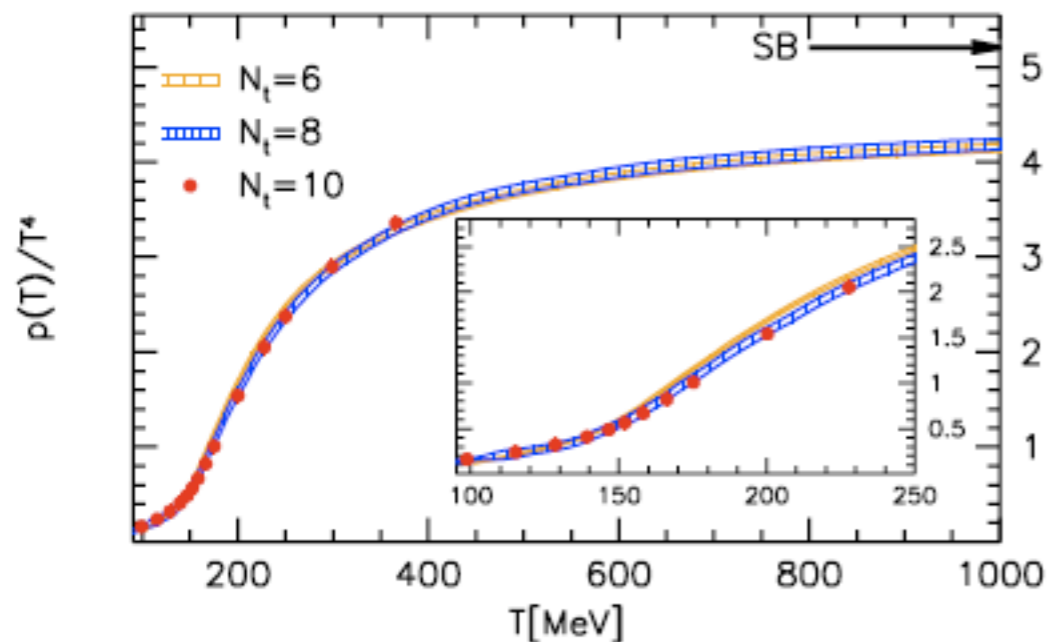
Equation of state

BW, hotQCD



Borsanyi et al., arxiv:1011.4229

Cheng et al., PRD 81 (2010) 054504



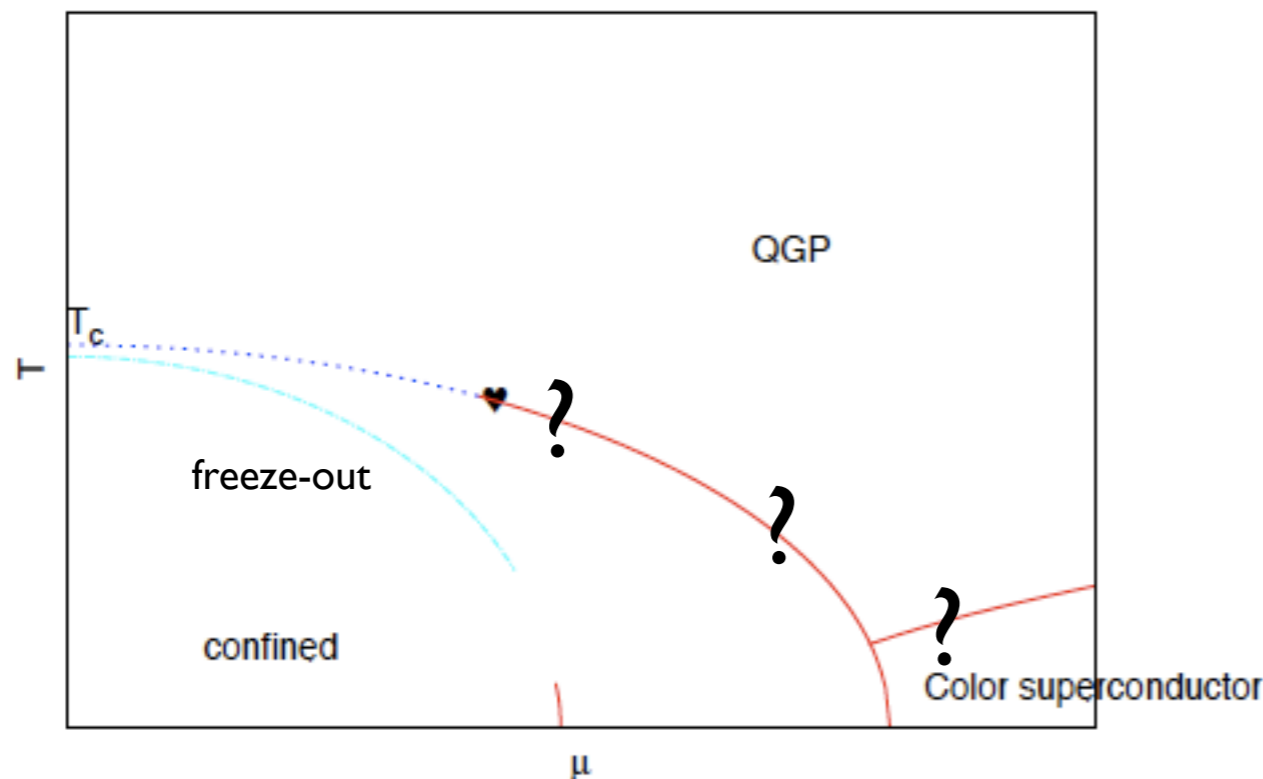
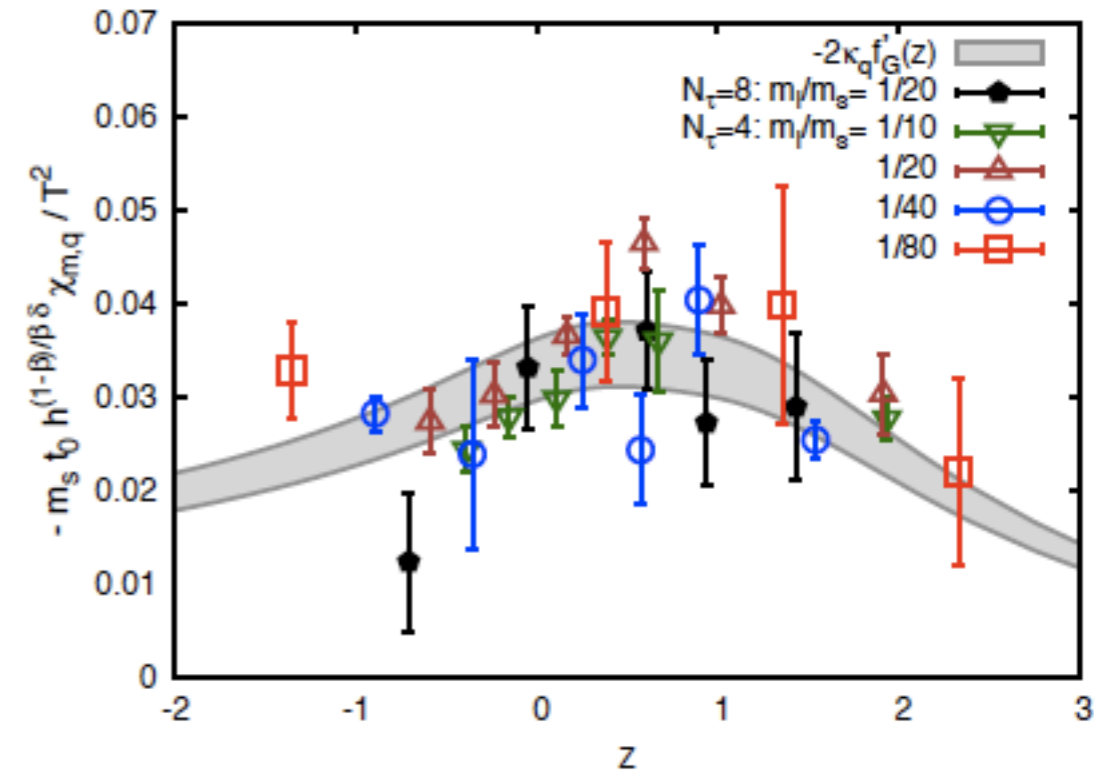
- Note remaining interactions!
- Contact with pQCD possible

Phase boundary at finite density

hotQCD

Kaczmarek et al., arxiv:1011.3130

- Curvature of crit. line from Taylor expansion
2+1 flavours, $m_l/m_s = 1/10 \dots 1/80$ $N_t = 4, 8$
- Extrapolation to chiral limit assuming
 $O(4), O(2)$ scaling
- No continuum limit, but cut-off effects small
- Consistent with determinations at finite
mass with imag. chem. pot.



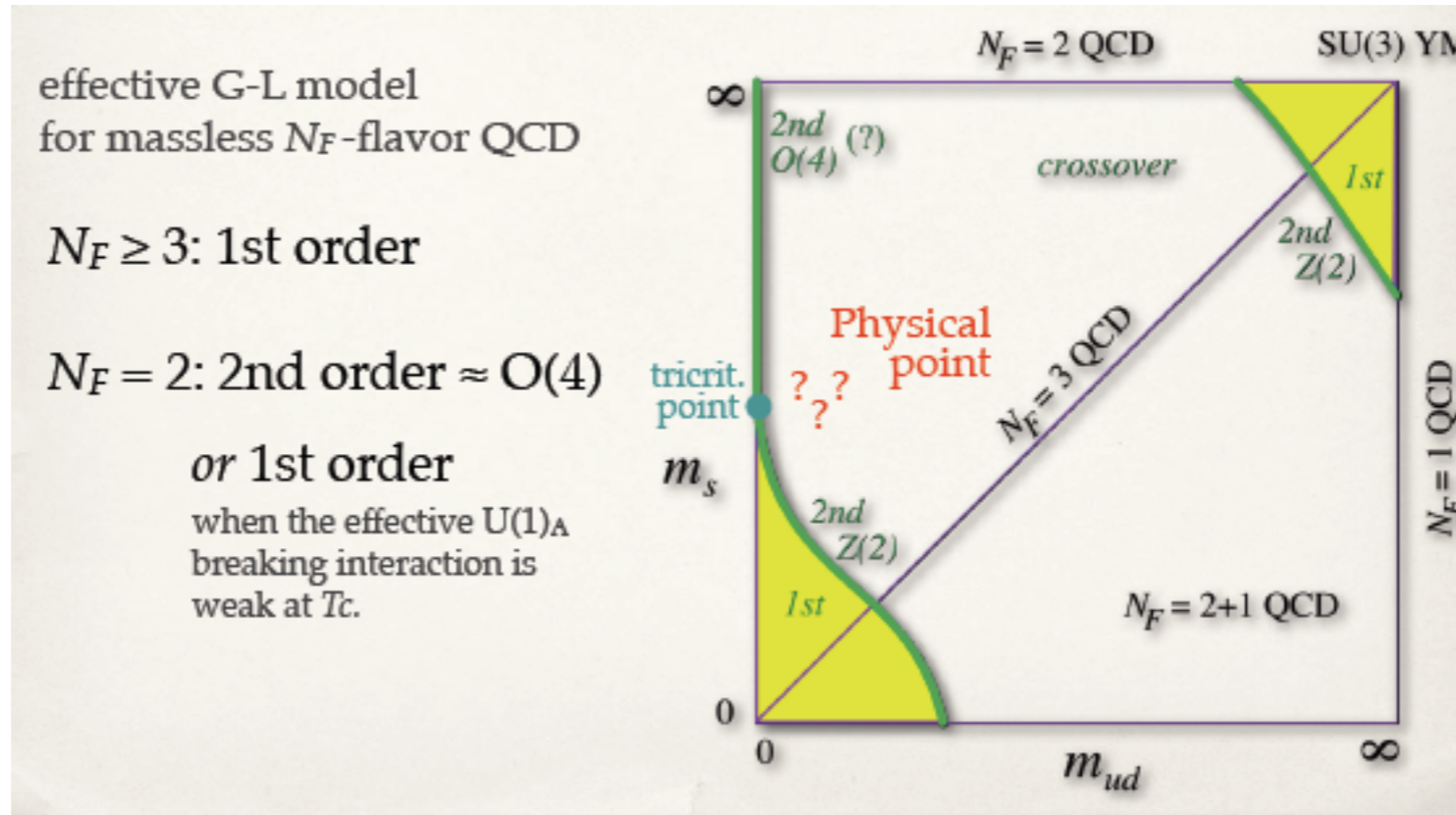
$$\frac{T_c(\mu)}{T_c(0)} = 1 - 0.059(2)(4) \left(\frac{\mu}{T}\right)^2 + O\left(\left(\frac{\mu}{T}\right)^4\right)$$

Freeze-out curvature 3-4 times larger:

$$\frac{T_f(\mu)}{T_f(0)} = 1 - 0.21(2) \left(\frac{\mu}{T}\right)^2 + O\left(\left(\frac{\mu}{T}\right)^4\right)$$

(Cleymans et al., PRC 73 (2006) 034905)

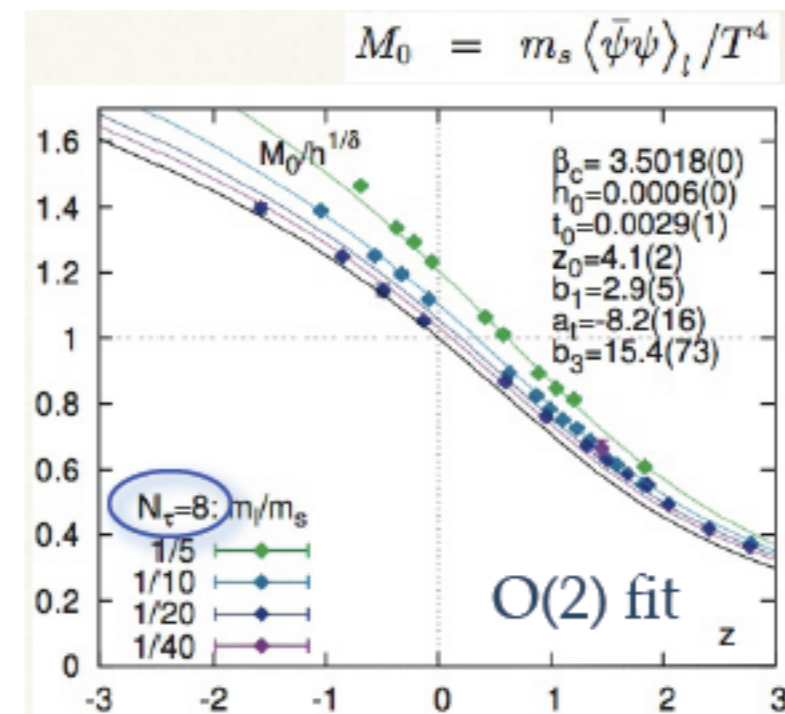
Order of the QCD phase transition



- old Wilson $N_f=2$ preferred $O(4)$
(with too heavy pions...)
- old staggered $N_f=2$ preferred 1st order
- **hotQCD**: 2+1 flavours

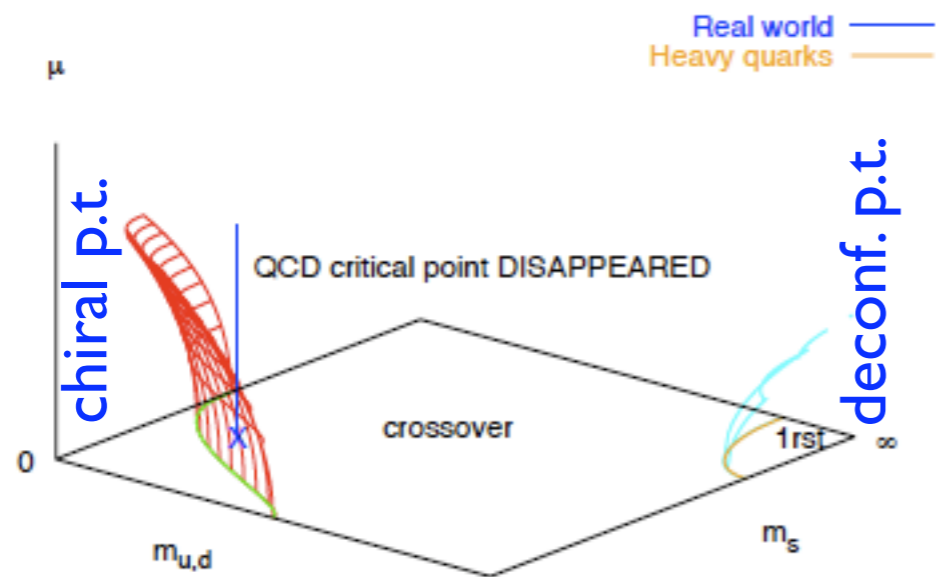
$$m_t/m_s = 1/10 \dots 1/80 \quad N_t = 4, 8$$

consistent with $O(4)/O(2)$,
deviations with larger masses



Order of p.t. at finite chemical potential

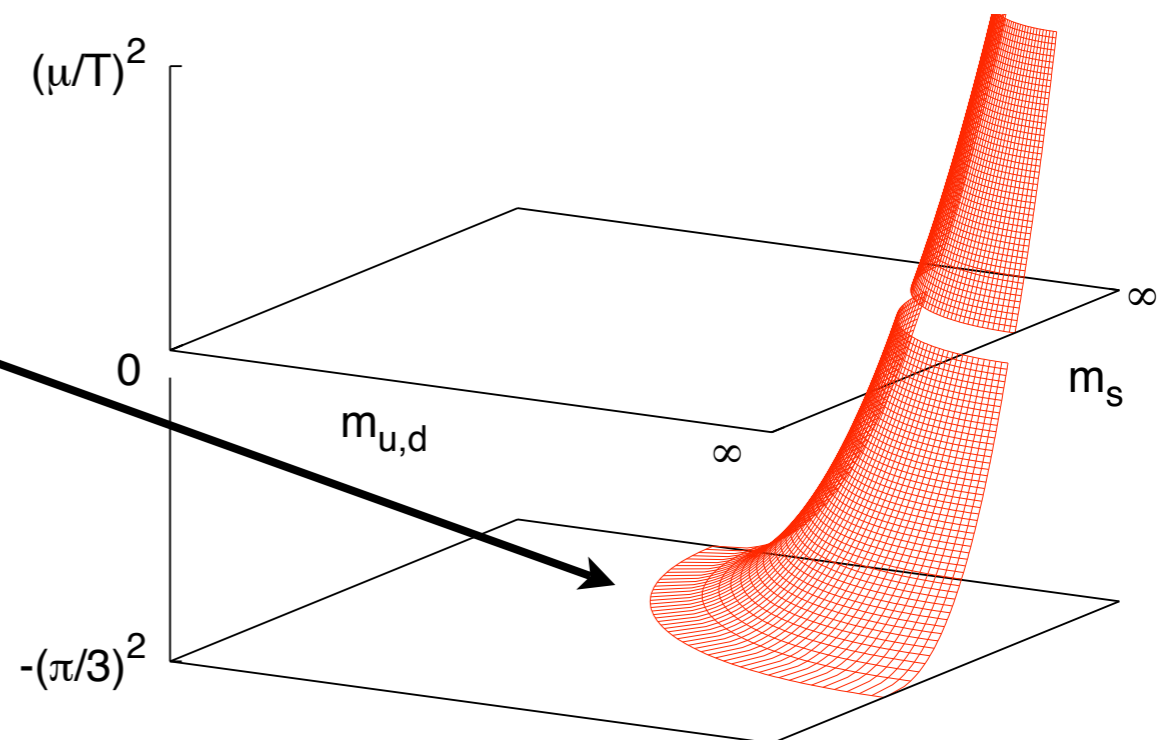
Frankfurt



$$\frac{m_c(\mu)}{m_c(0)} = 1 + \sum_{k=1} c_k \left(\frac{\mu}{\pi T}\right)^{2k}$$

- Previous finding on $N_t=4$: $c_1 = -3.3(3)$
Preliminary $N_t=6$: $c_1 = -10(5)$
- Chiral p.t. weakens with real chem. pot.!
- Same for deconfinement p.t. heavy quarks, same for isospin chem. pot.

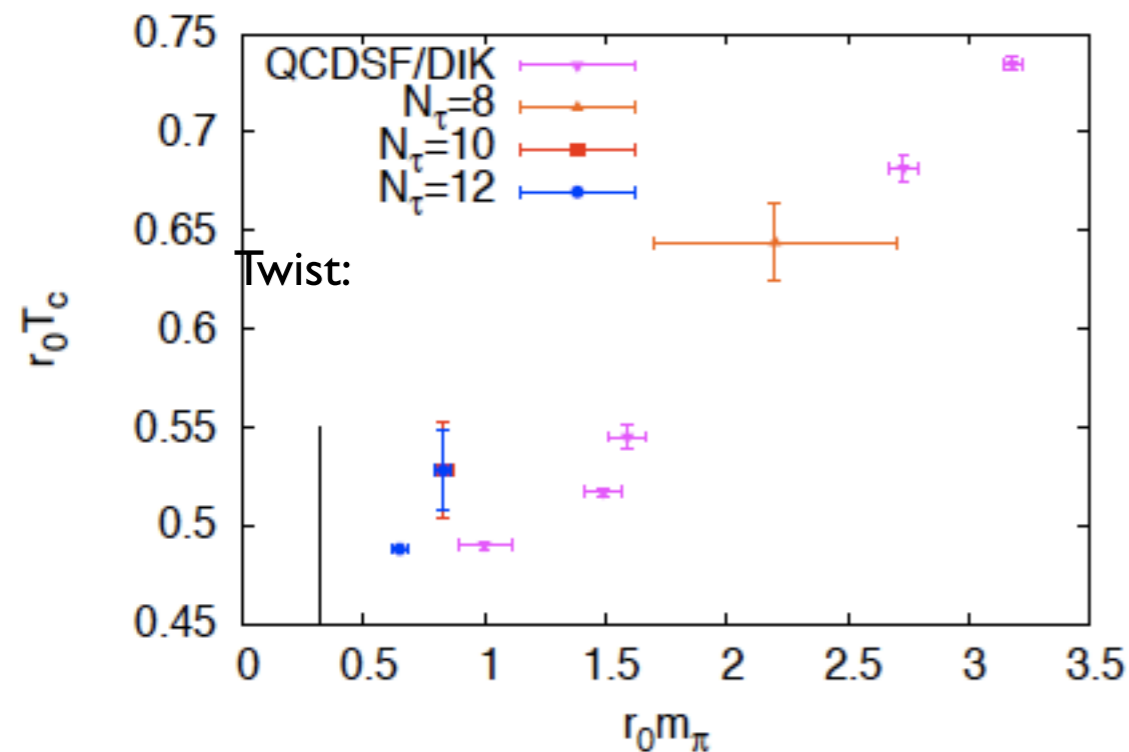
- Continuation to imaginary chem. pot. (no sign problem)
- Crit. surfaces end in tri-critical lines
- Shape of deconfinement surface (sign of curvature) determined by tri-critical scaling!



de Forcrand, O.P., PRL 105 (2010) 152001

Wilson fermions at finite temperature

- + No roots of fermion determinant needed
- + No taste-splitting
- No remnant chiral symmetry
- Expensive, just at the beginning



$$T_c(m_\pi) > 200 \text{ MeV}$$

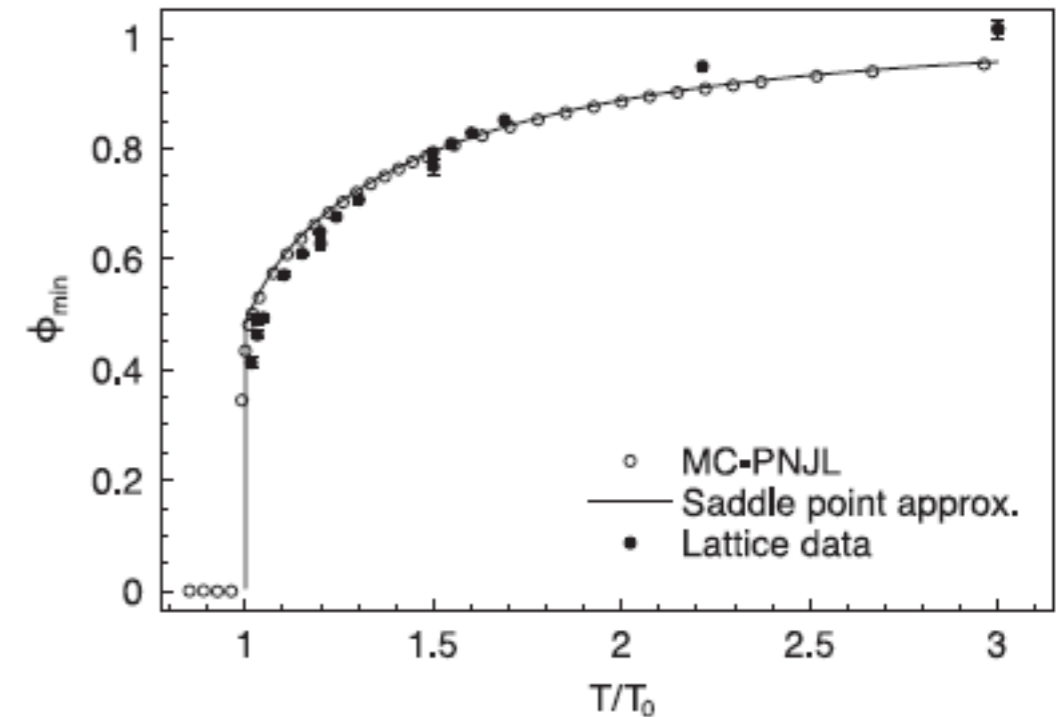
- Clover-improved
QCDSF, Mainz+Frankfurt
- Twisted mass
HU Berlin+Bonn+Frankfurt
- pion masses $m_\pi \geq 300 \text{ MeV}$,
 $N_t = 10 - 16$

Bornyakov et al., PRD 82 (2010) 014504;

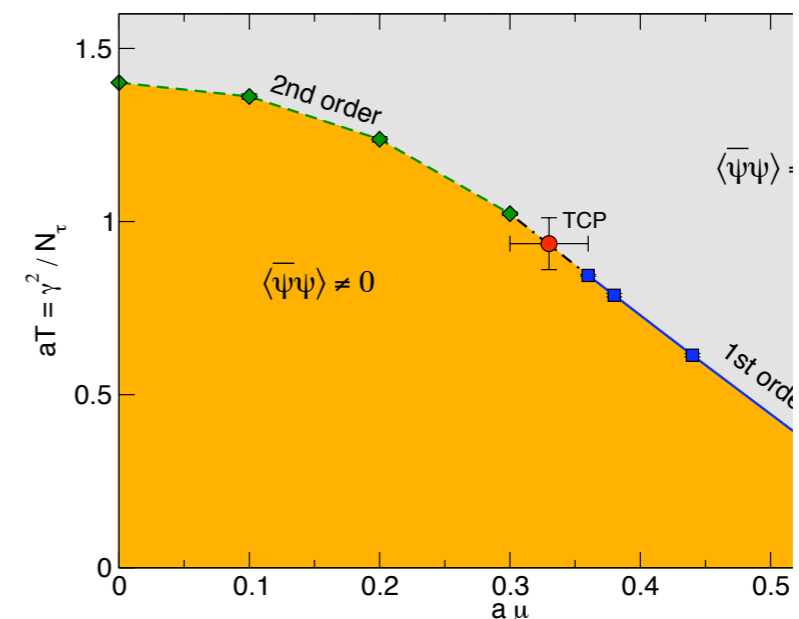
Burger et al., arxiv:1009.3758; Brandt et al., arxiv:1011.6172

Continuum

- PNJL: check sensitivity on mean field
- Monte Carlo of PNJL
- Litte change in evaluation, fluctuations improve fits to lattice data
Christoforetti et al., PRD 81 (2010) 114017
- P-quark-meson model beyond mean field, RG
Herbst, Pawłowski, Schaefer, arxiv:1008.0081
- Generalised models:
NJL + spin models (for gauge d.o.f.)
- Fundamental and adj. fermions,
Polyakov loops
- Phase diagram and its dependence on reps.,
number of colours etc.

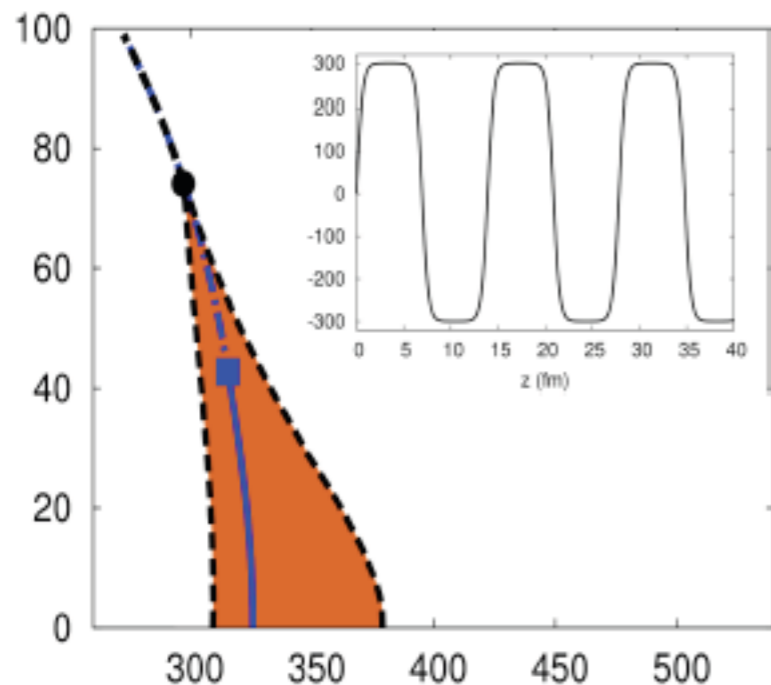
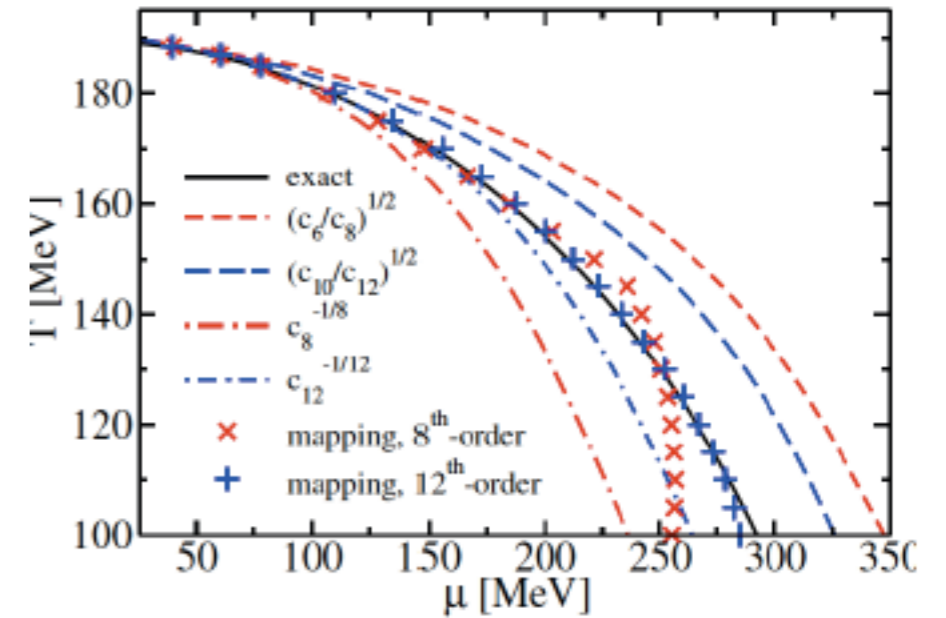


- Nf=1 QCD in strong coupling limit,
detailed nuclear physics



- RG methods in P-sigma models for interplay chiral transition/deconfinement transition
- Testbed for lattice methods, Crit. point from radius of convergence

Friman, Morita, Skokov, Redlich



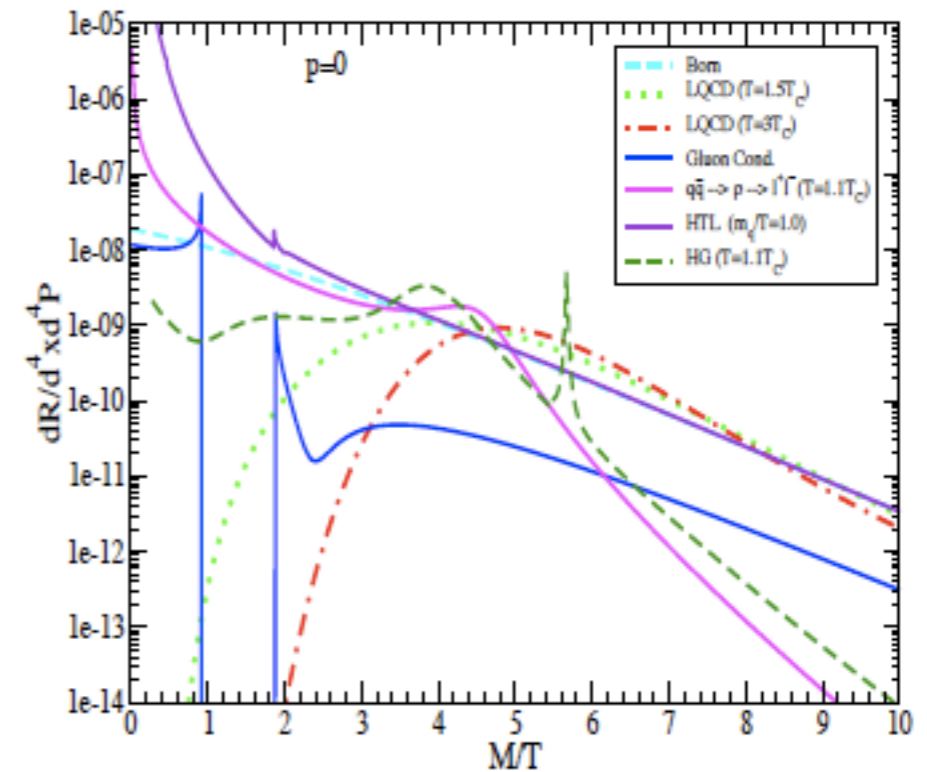
- Inhomogeneous phases: Spatially varying condensate $\langle \bar{\psi}\psi \rangle(\mathbf{x})$
- Critical region covered by inhomogeneous phase, delimited by 2nd. O. p.t.

Carignano, Nickel, Buballa

Quarkonia in medium

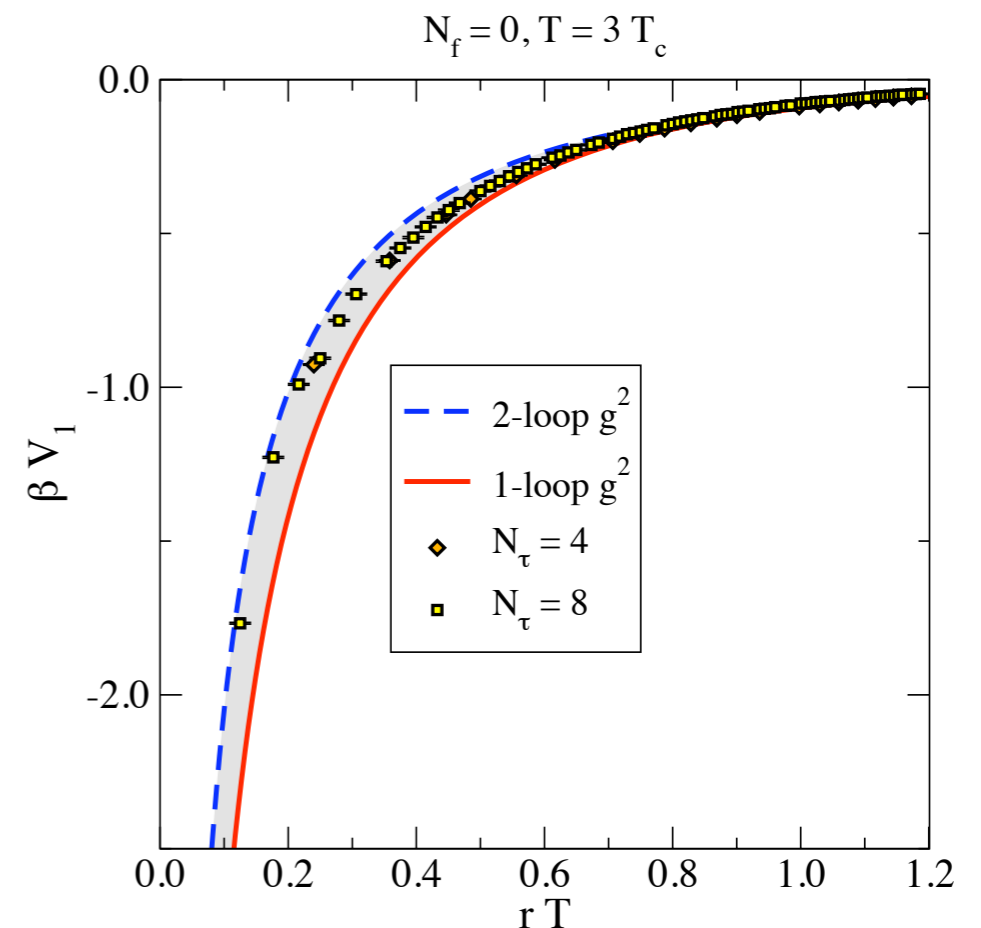
- Lattice: no direct dynamical quantities, only MEM
- HTL-resummed perturbation theory
- Modelling with condensates, HRG etc. in non-perturbative regime

Greiner et al., arxiv:1010.2169



- Comparison: static quark free energy in Coulomb gauge
- Convergence very reasonable
- Resummed p.t. for quarkonia in

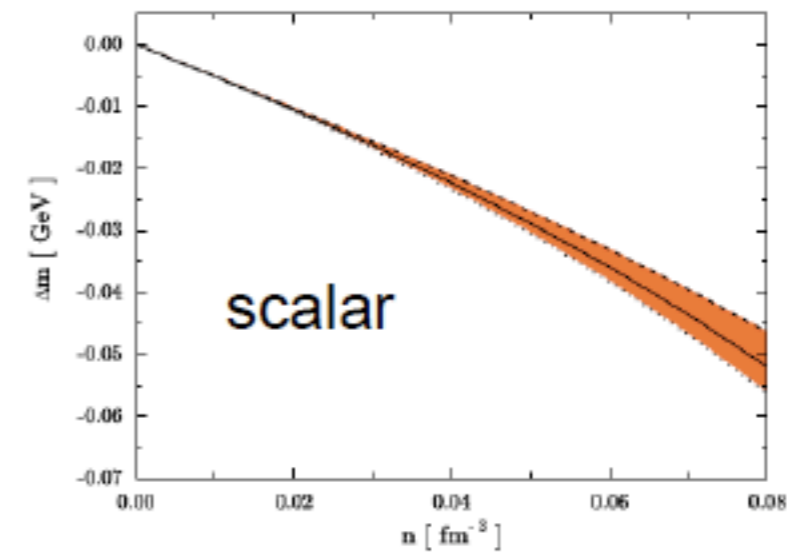
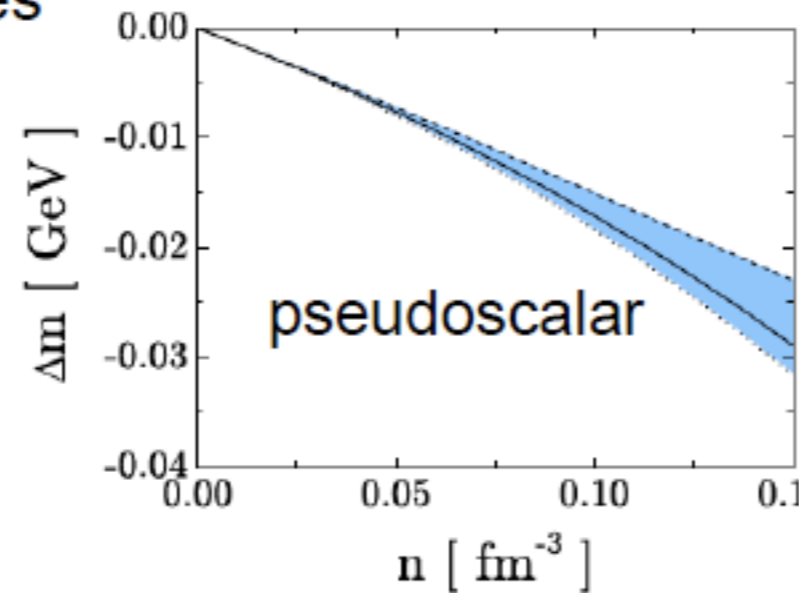
Burnier, Laine, Vepsalainen JHEP 01 (2010) 54



1. $D - \bar{D}$ mass splitting in nuclear matter

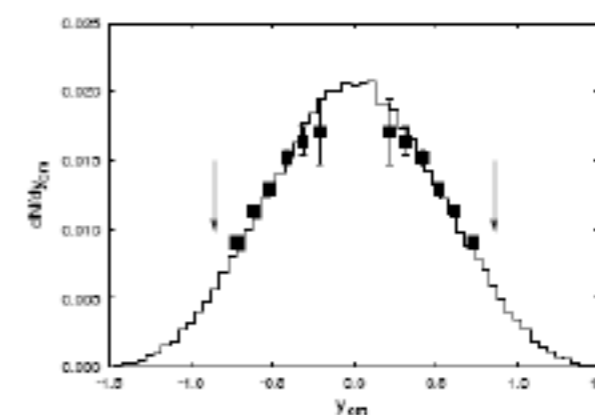
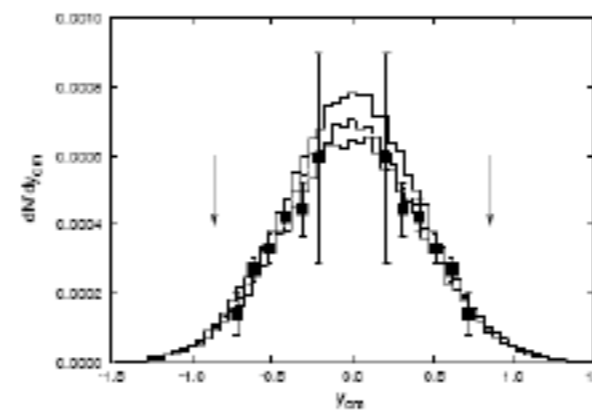
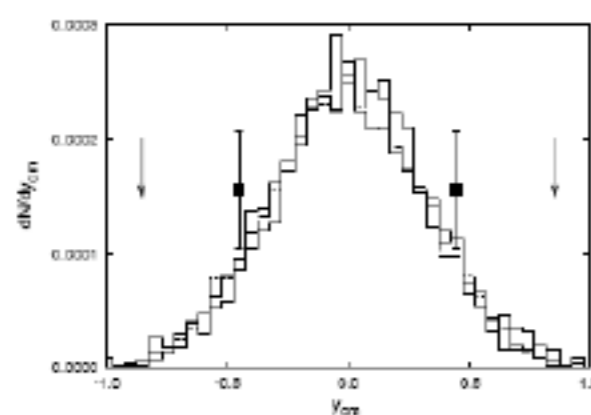
QCD sum rules
depend on
 $m_c \langle q\bar{q} \rangle$

Hilger-Kämpfer, J. Phys. G 37 (2010), Nucl. Phys. B PS (2010)



2. ϕ, K^-, K^+ production in rel. HICs

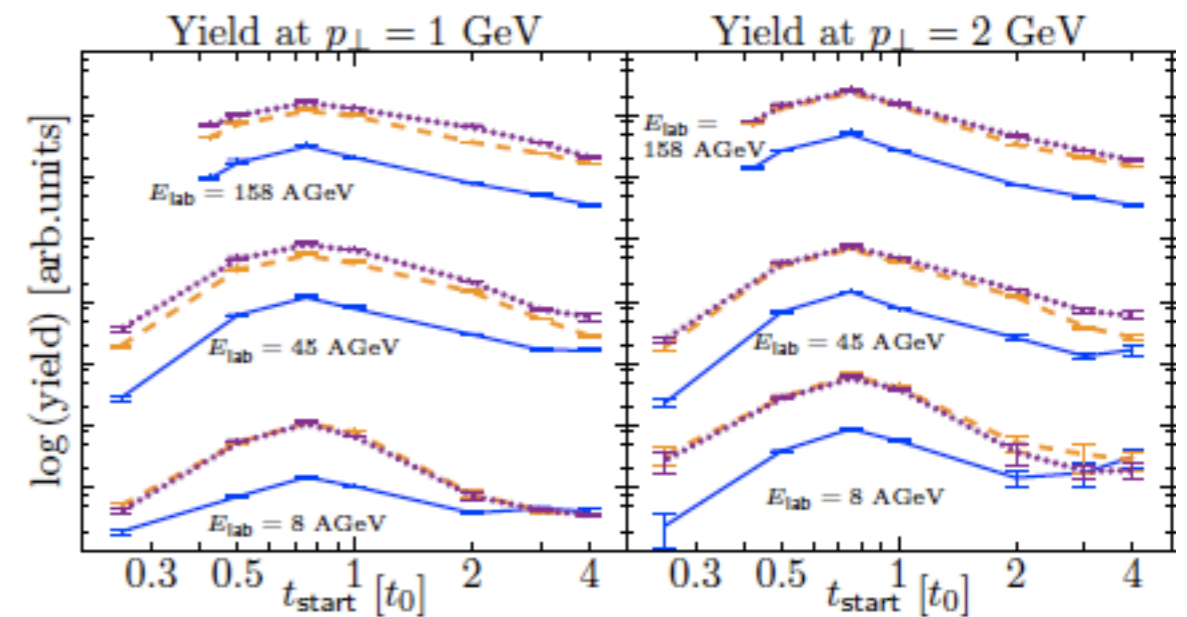
Schade-Kämpfer, Phys. Rev. C 81 (2010), BUU transport with in-medium potentials



HADES data 2010
Ar(1.76 AGeV) + KCl

Modelling and simulating heavy ion dynamics

- Hybrid approach
- Early and late stages by UrQMD (hadron and string d.o.f., PYTHIA)
- Intermediate stages by hydrodynamics + HRG, MIT-Bag Equations of state
- Dependence of direct photon yield on start time of hydro
- Other applications: dileptons, bulk properties of hadrons (multiplicities, spectra, flow)



Baeuchle et al., PRC 81 (2010); Santini et al., PLB 687 (2010)

Conclusions

- Lattice calculations for $T=0$ reach maturity, **physics!**
- Lattice calculations for finite T now understand **systematics**, only small baryon densities possible
- Beginning **overlap** between **analytic** and **lattice** approaches!