Lattice QCD thermodynamics in the presence of the charm quark

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Wuppertal-Budapest collaboration: S. Borsanyi, Z. Fodor, S. Katz, S. Krieg, C. Schröder, K. Szabó

Outline

- update on $N_f = 2 + 1$ EoS
  - $\mu = 0$ continuum limit
  - finite μ EoS at order μ^2
- new results on $N_f = 2 + 1 + 1$ EoS
  - fully dynamical
  - comparison to partial quenching analysis
- introduction of new 4stout action and $N_f = 2 + 1 + 1$ results
- conclusions and outlook

$$N_f = 2 + 1$$

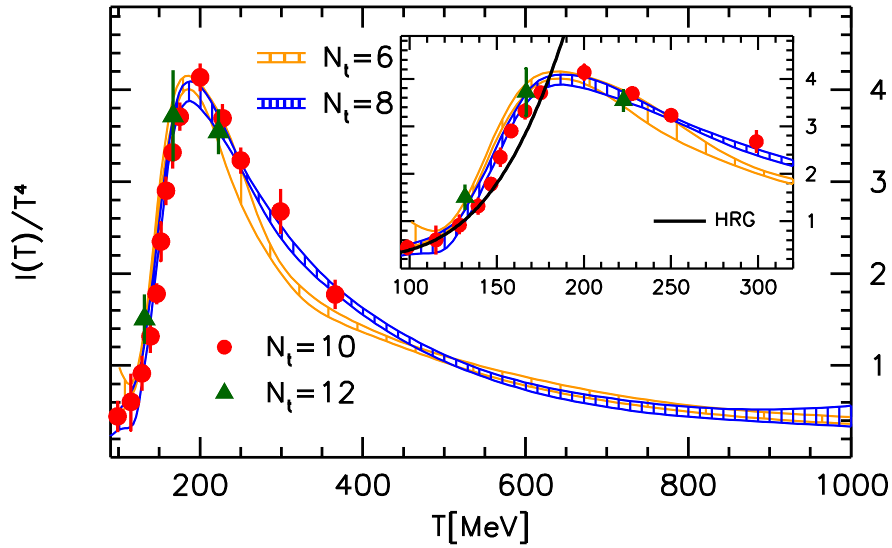
dynamical quark flavors

$$m_s / m_{u,d} \simeq 28$$

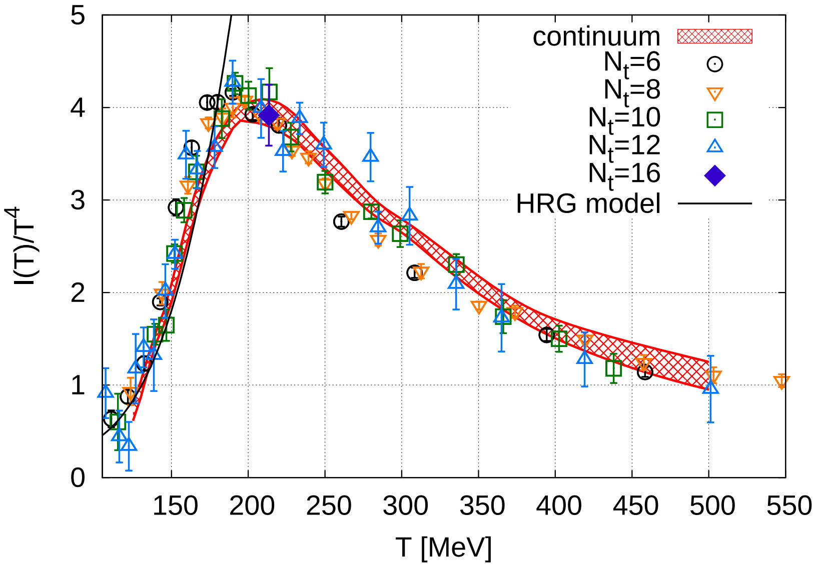
Results: trace anomaly

$$\frac{I(T)}{T^4} = \frac{\epsilon - 3p}{T^4} = T \frac{\partial}{\partial T}(p/T^4)$$

QM 2011



QM 2012

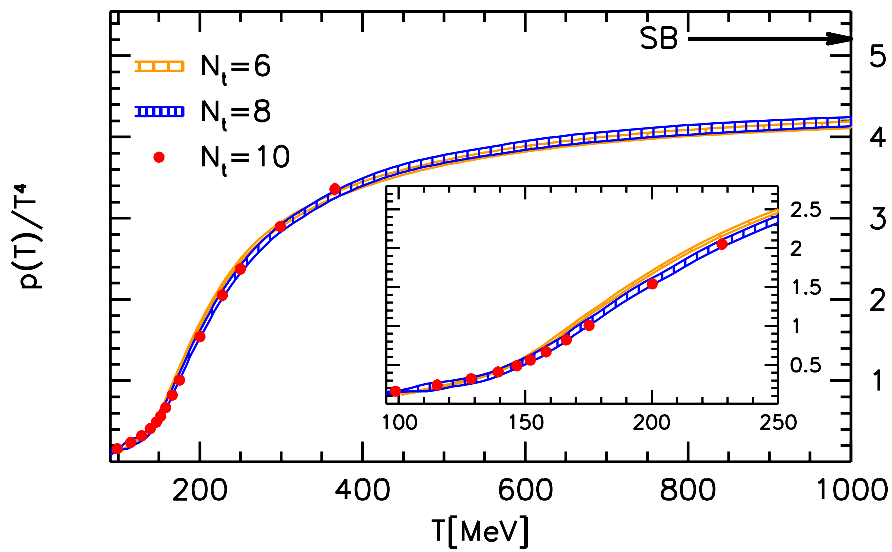


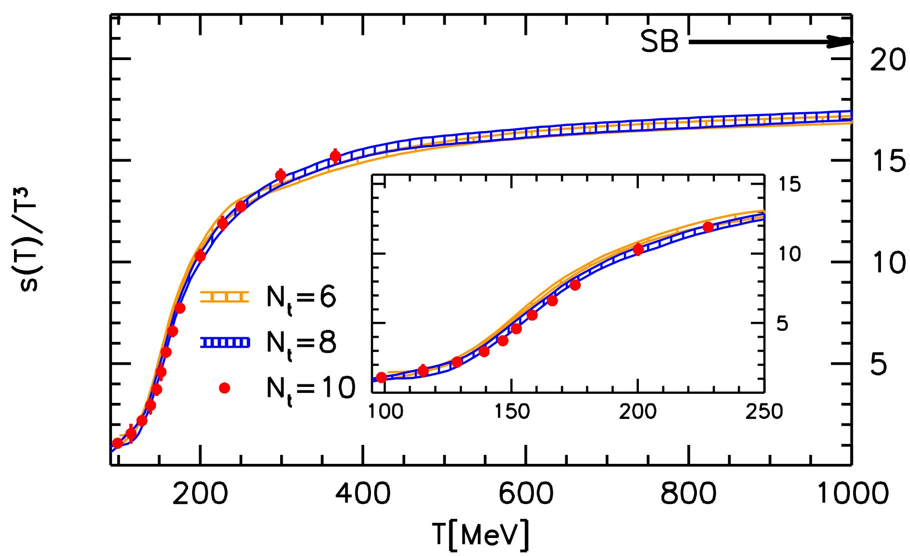
- New $N_t = 12$ points and one $N_t = 16$ check point
- consistent continuum extrapolation

S. Borsanyi *et al.* (Wuppertal-Budapest collaboration): JHEP (2010) and in preparation

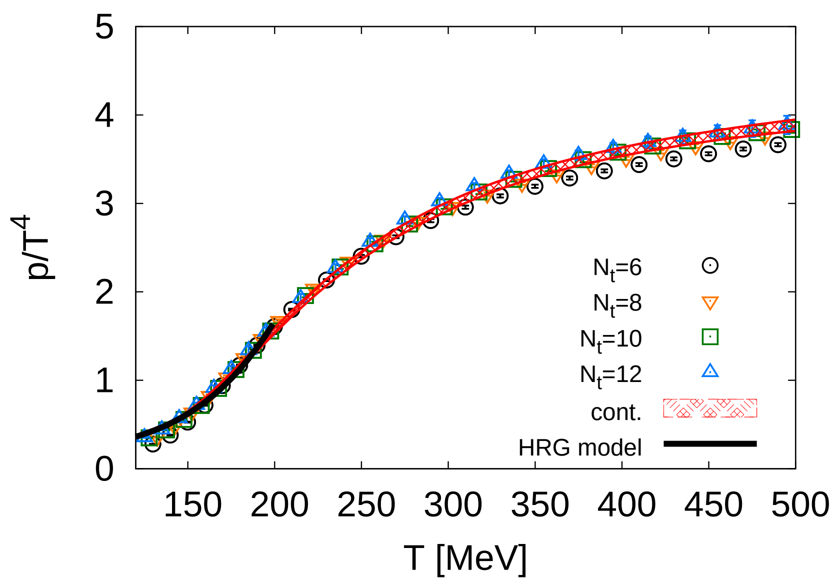
Pressure and entropy density

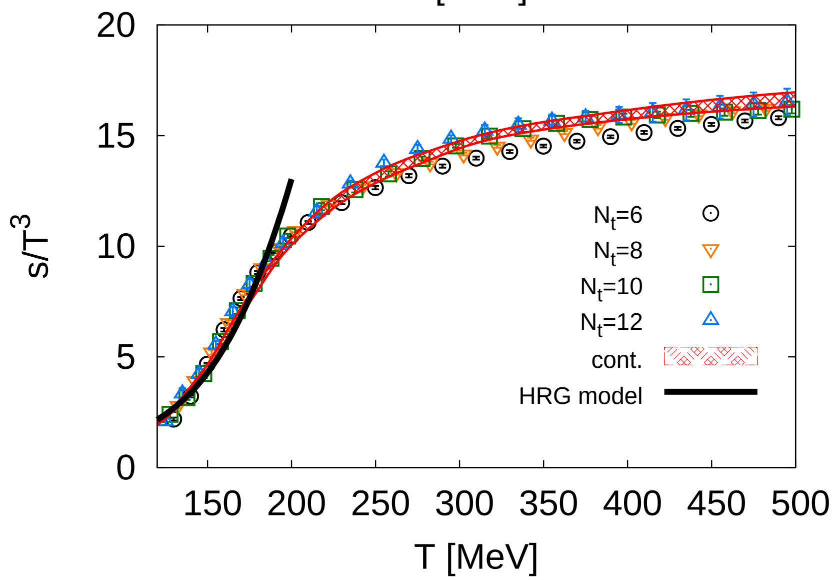
QM 2011



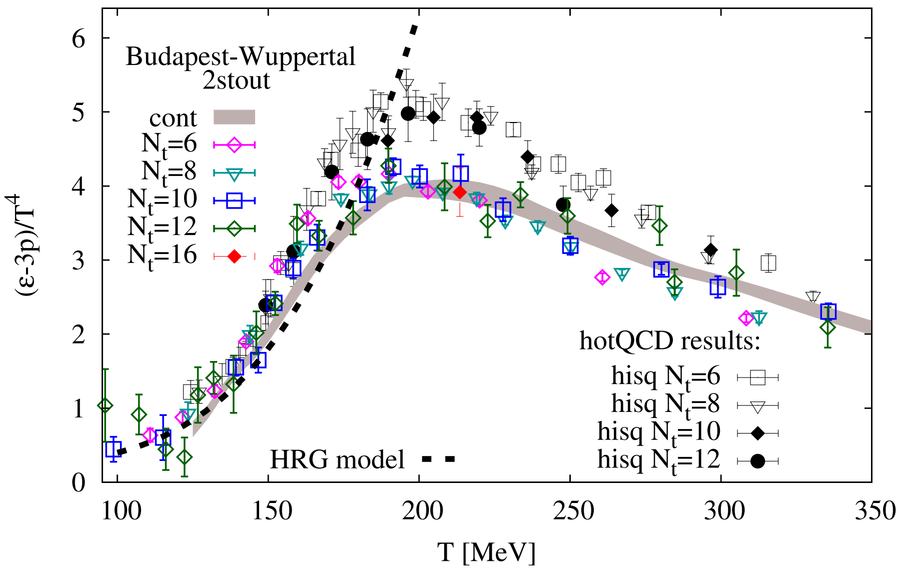


QM 2012





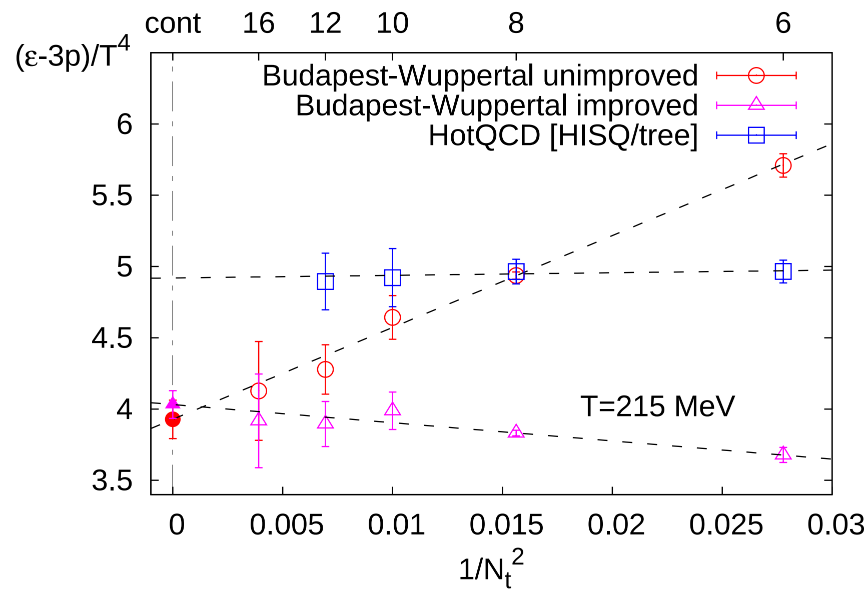
Trace anomaly discrepancy

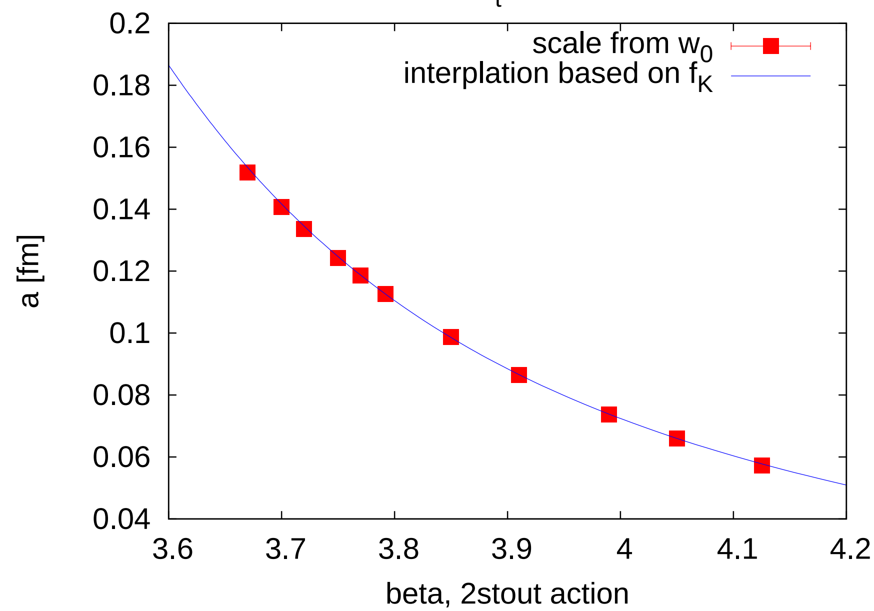


- Discrepancy between 2stout (WB) and hisq (hotQCD) on the trace anomaly
- continuum limits do not seem to converge to the same result

hotQCD: 1005.1131

WB: 1204.0995

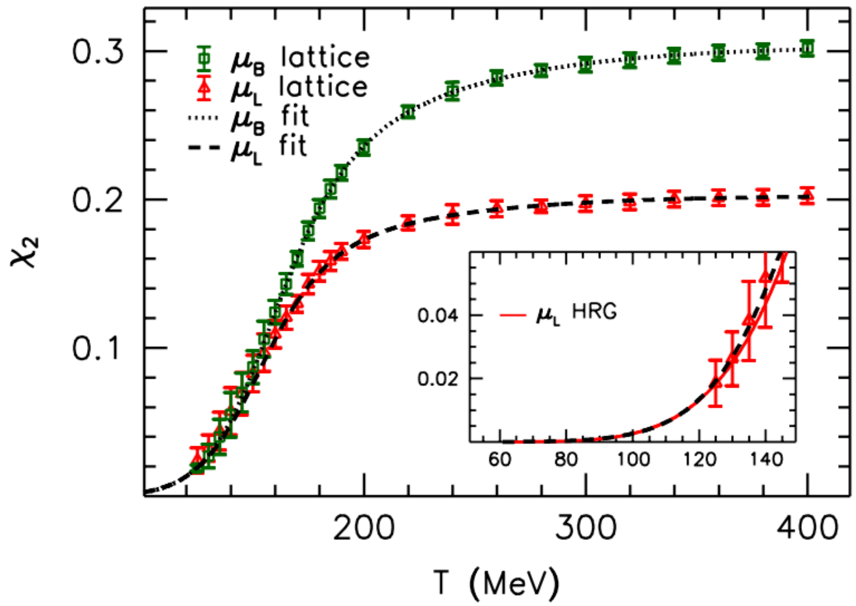




Finite μ EoS at order μ^2

$$\frac{I(T,\mu)}{T^4} = T\frac{\partial}{\partial T}\frac{p(T,\mu)}{T^4} + \frac{\mu^2}{T^2}\chi_2 = \frac{I(T,0)}{T^4} + \frac{\mu^2}{2T}\frac{\partial \chi_2}{\partial T} \qquad \mu_L/3 \equiv \mu_u = \mu_d,$$

$$\frac{p(T,\{\mu_i\})}{T^4} = \frac{p(T,\{0\})}{T^4} + \frac{1}{2}\sum_{i,j}\frac{\mu_i\mu_j}{T^2}\chi_2^{ij} \qquad \chi_2^{ij} \equiv \frac{T}{V}\frac{1}{T^2}\frac{\partial^2 \log}{\partial\mu_i\partial\mu_j}\bigg|_{\mu_i=\mu_j=0}$$



- Simulate the Taylor expansion coefficients at $\mu = 0$

S. Borsanyi *et al.* (Wuppertal-Budapest collaboration): JHEP (2012)

Finite μ EoS at order μ^2

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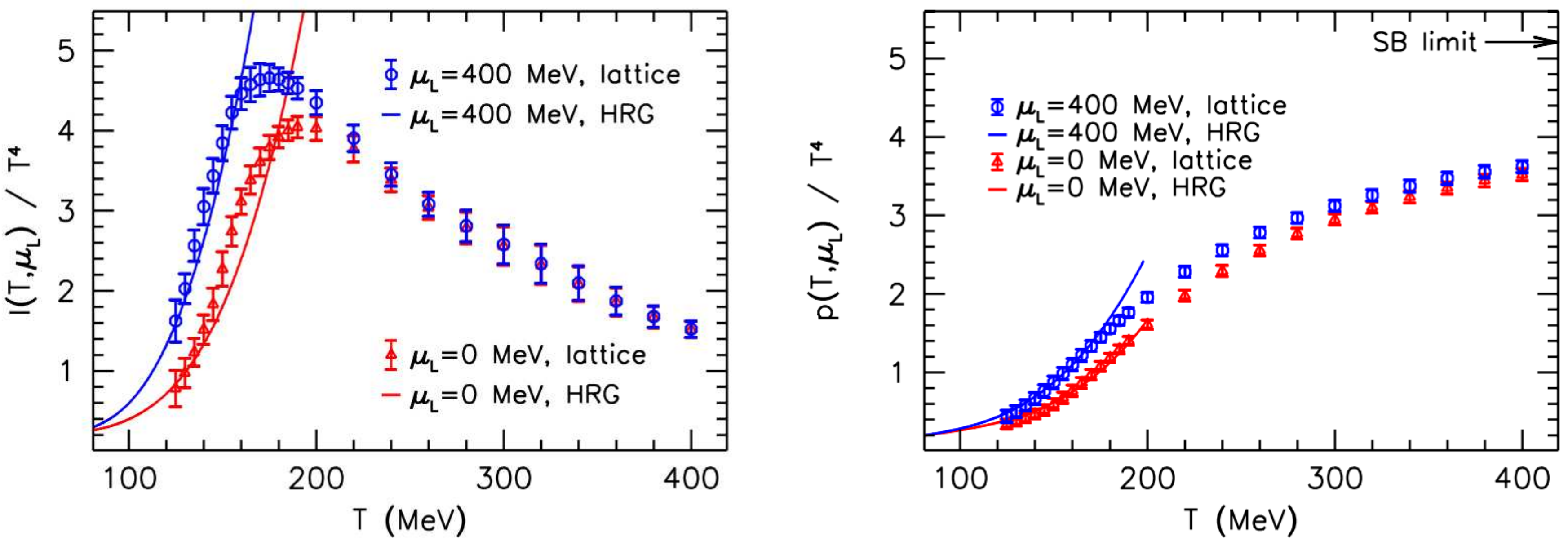
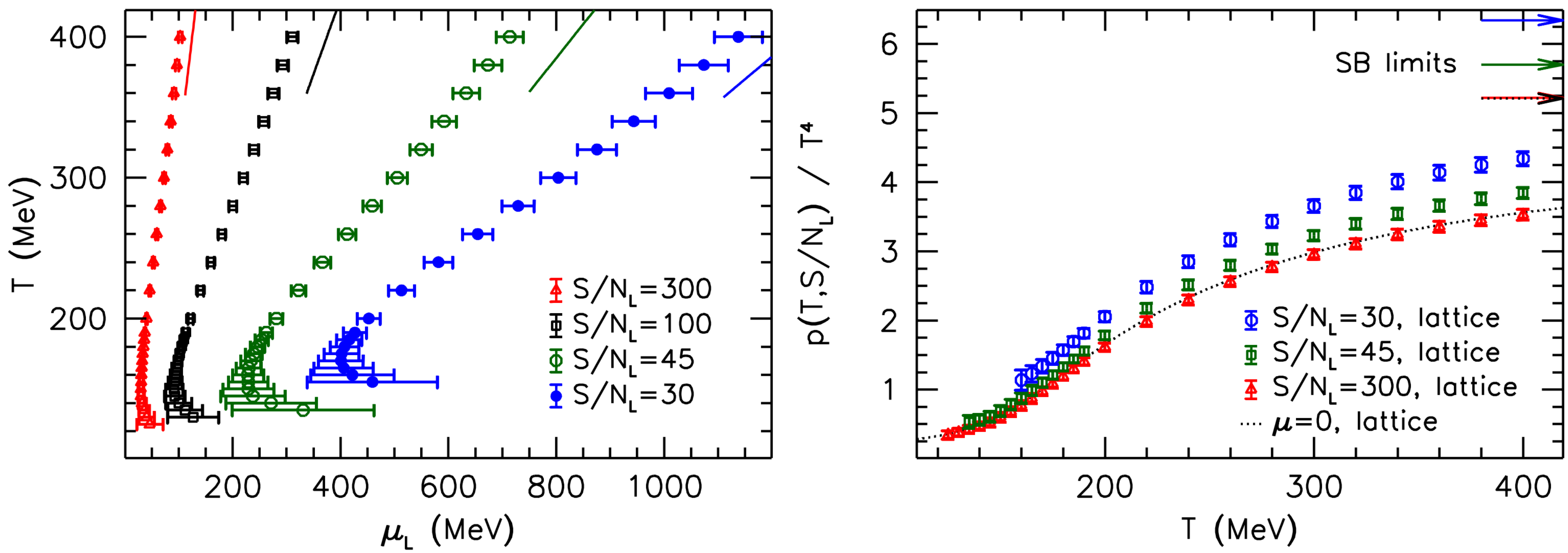


- Obtain the observables at finite μ

S. Borsanyi *et al.* (Wuppertal-Budapest collaboration): JHEP (2012)

Isentropic equation of state



- Isentropic trajectories in the T, μ plane
- Obtain the equation of state along these trajectories

S. Borsanyi *et al.* (Wuppertal-Budapest collaboration): JHEP (2012)

$$N_f = 2 + 1 + 1$$

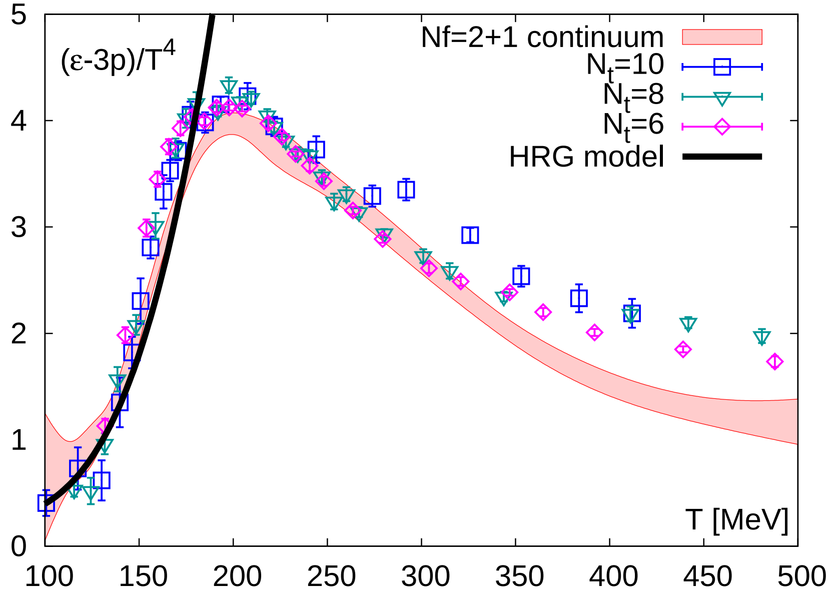
dynamical quark flavors

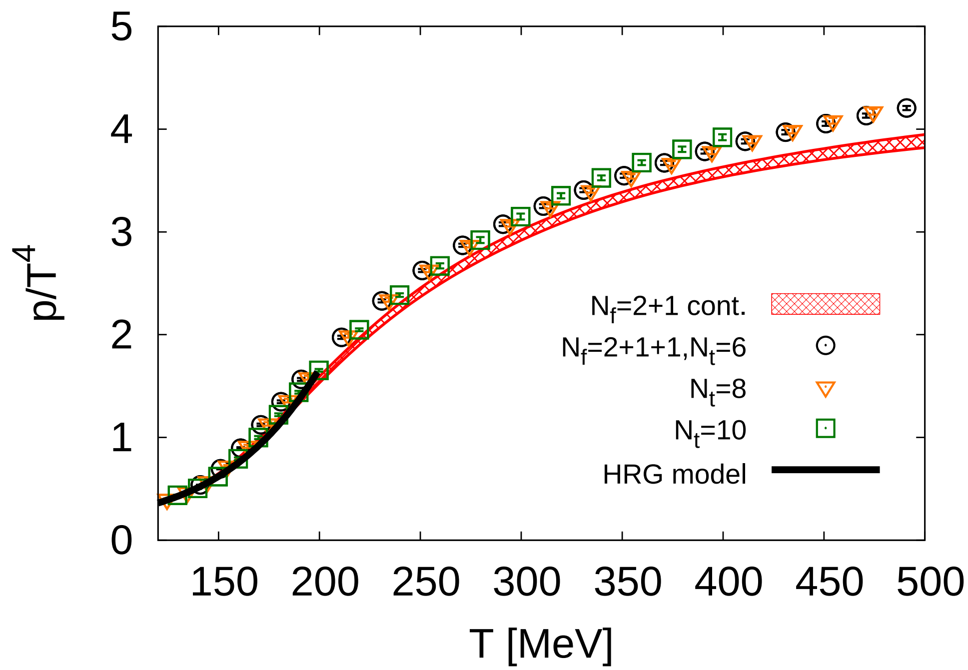
$$m_s / m_{u,d} \simeq 28$$

$$m_c / m_s \simeq 11.8$$

Trace anomaly and pressure

$$\frac{I(T)}{T^4} = \frac{\epsilon - 3p}{T^4} = T\frac{\partial}{\partial T}(p/T^4)$$



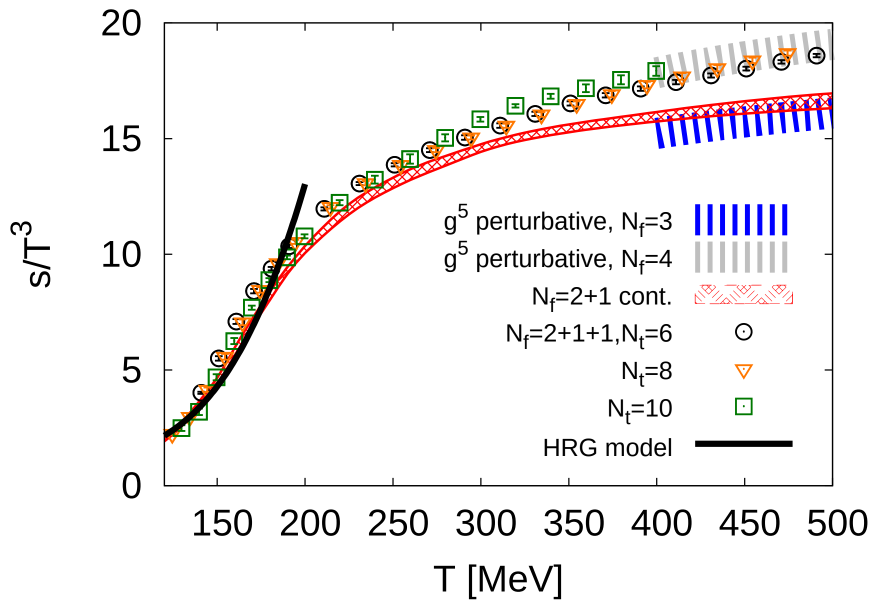


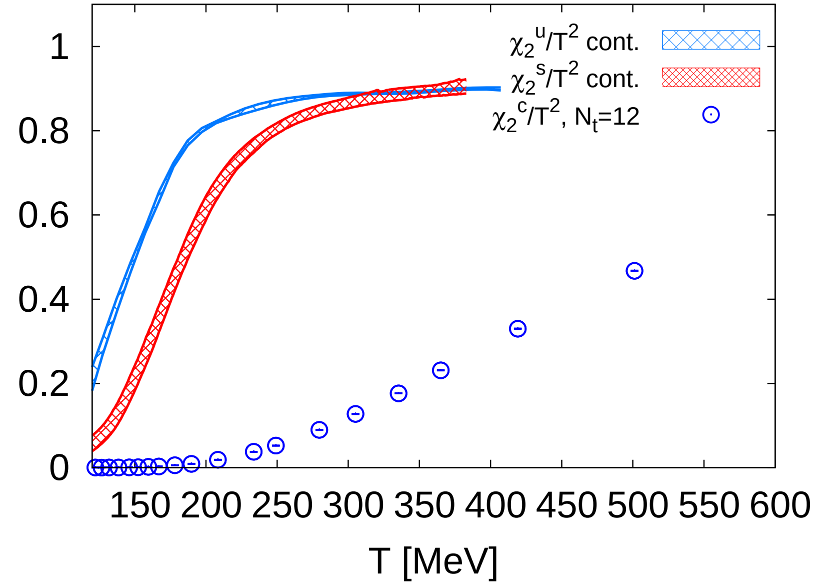
- Effect of charm quark relevant for $T > 250 - 300$ MeV

S. Borsanyi *et al.* (Wuppertal-Budapest collaboration): in preparation

Entropy and charm susceptibility

$$s = \frac{\epsilon + p}{T} \qquad \chi_2^q = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_q \partial\mu_q}\bigg|_{\mu_i=0}$$

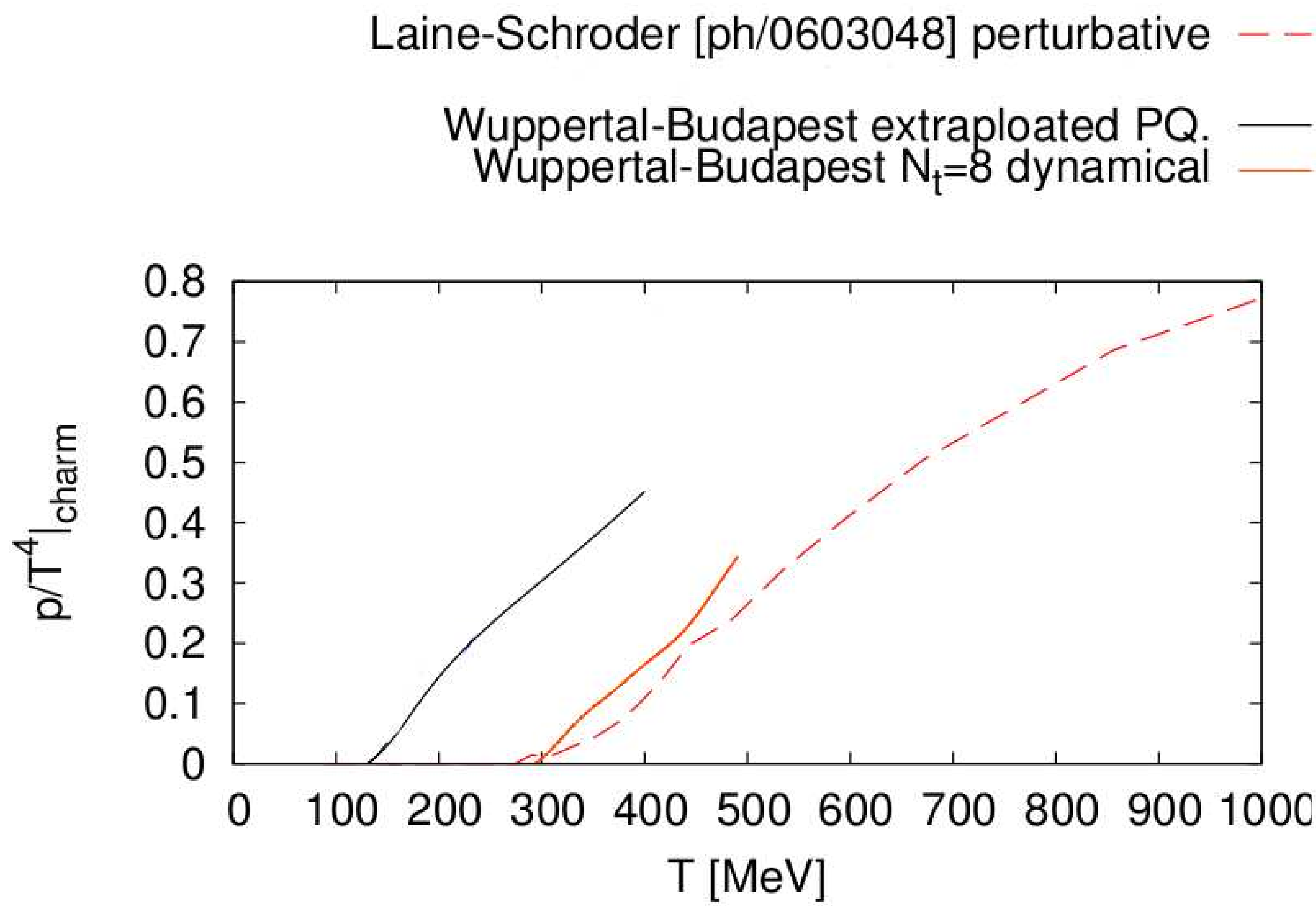




- Effect of charm quark relevant for $T > 250 - 300$ MeV

S. Borsanyi *et al.* (Wuppertal-Budapest collaboration): in preparation

Comparison to partial quenching



- contribution of charm quark moves to higher temperatures when treated fully dynamically
- agreement with perturbative QCD is recovered

Results with

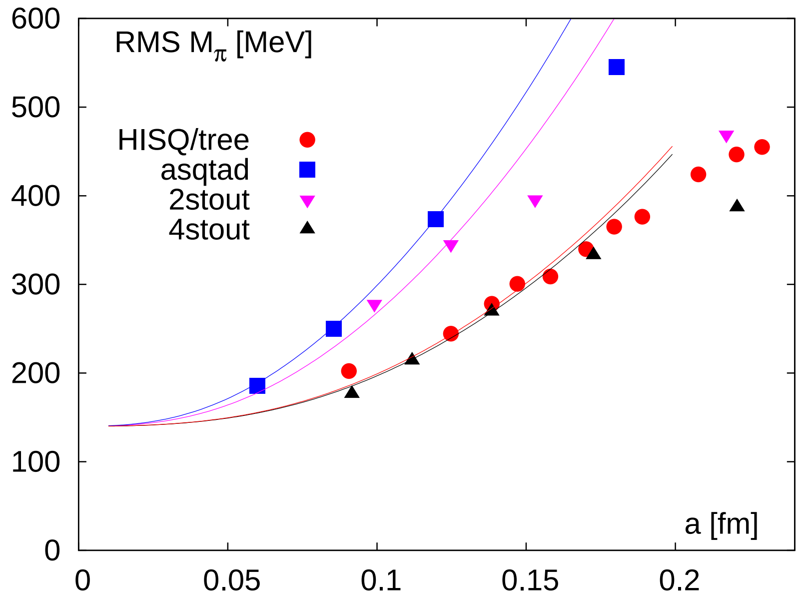
new 4stout action

$$N_f = 2+1+1$$

$$\mathrm{N}_t = 8,\ 10$$

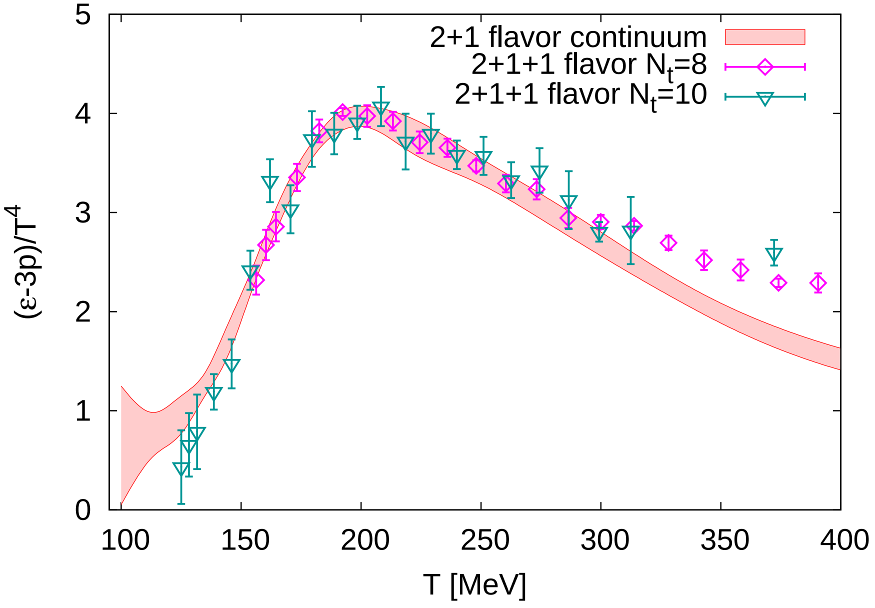
4stout action

- 4-level (stout) smeared improved staggered fermions
- reduced taste symmetry violation comparable to hisq action



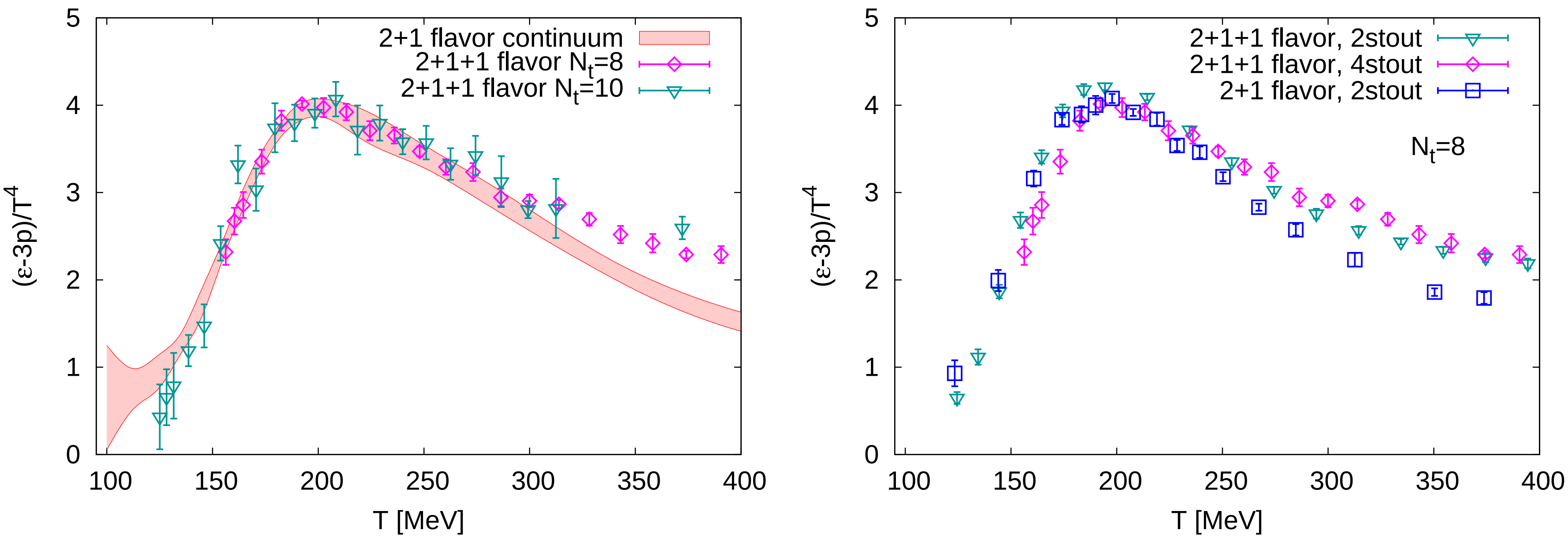
- taste breaking measured for $N_f = 2$ with $m_\pi = 350$ MeV
- taste breaking information is then converted to physical point
- taste breaking measurement at physical point is in progress: we expect above plot to be a good approximation of the physical case

Trace anomaly with 4stout action



- charm quark gives non-negligible contribution for $T > 250 - 300$ MeV

Trace anomaly with 4stout action



- no difference between 2stout and 4stout results
- origin of discrepancy in the trace anomaly between WB and hotQCD does not lie in different taste symmetry violation

Conclusions

- progress in $N_f = 2 + 1$ EoS
- EoS for $N_f = 2 + 1$ at order μ^2
- $N_f = 2 + 1 + 1$ fully dynamical EoS
- introduction of new 4stout action: smaller taste symmetry violation
- results with 4stout action fully agree with 2stout action results

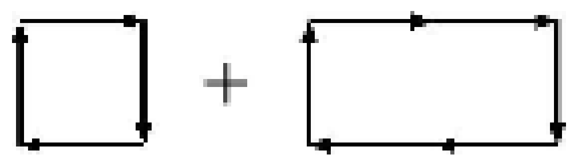
Backup slides

Choice of the action

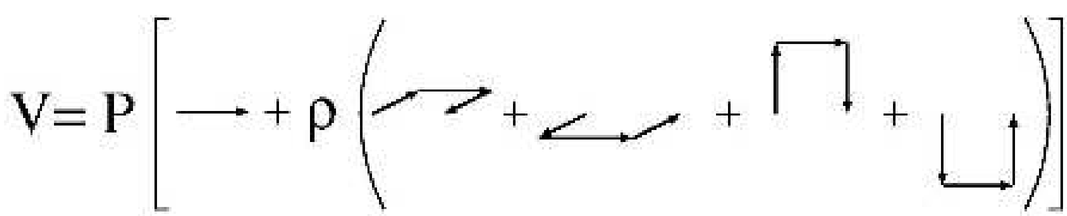
- no consensus: which action offers the most cost effective approach

  Aoki, Fodor, Katz, Szabo, JHEP 0601, 089 (2006)

- our choice tree-level $O(a^2)$-improved Symanzik gauge action

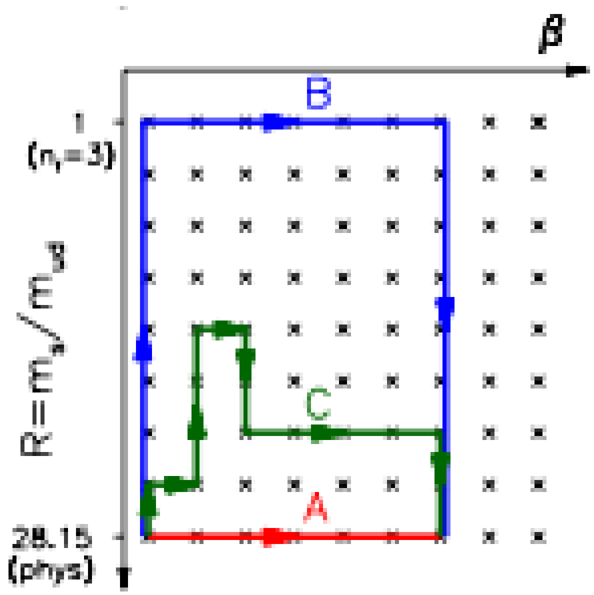


2-level (stout) smeared improved staggered fermions



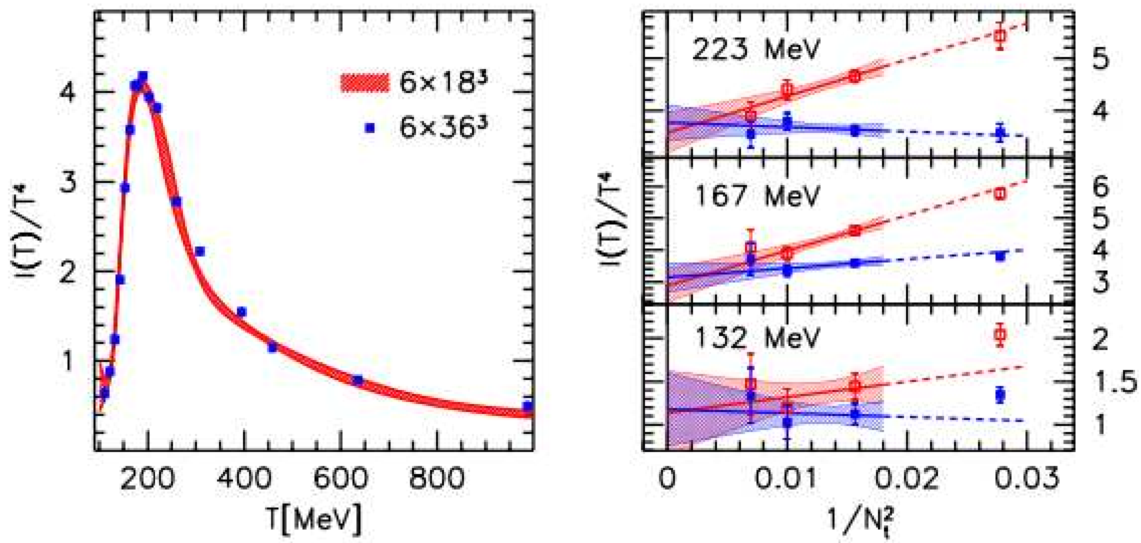
All path approach

- Our goal:
  - determine the equation of state for several pion masses
  - reduce the uncertainty related to the choice of β^0



- conventional path: A, though B, C or any other paths are possible
- generalize: take all paths into account

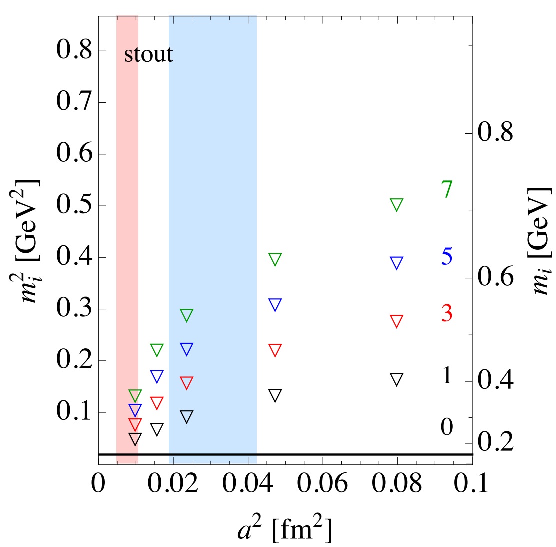
Finite volume and discretization effects

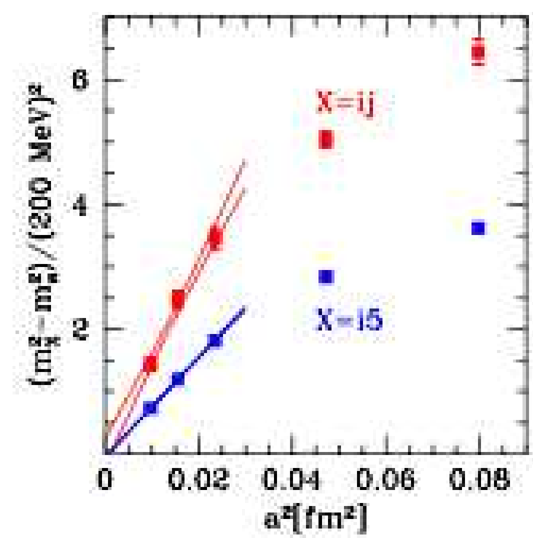


- finite $V : N_s/N_t = 3$ and 6 (8 times larger volume): no sizable difference
- finite a: improvement program of lattice QCD (action observables)
  - tree-level improvement for p (thermodynamic relations fix the others)
  - trace anomaly for three T-s: high T, transition T, low T
  - continuum limit $N_t = 6, 8, 10, 12$: same with or without improvement
- improvement strongly reduces cutoff effects: slope$\simeq 0$ ($1 - 2\sigma$ level)

Pseudo-scalar mesons in staggered formulation

- Staggered formulation: four degenerate quark flavors (‘tastes’) in the continuum limit
- Rooting procedure: replace fermion determinant in the partition function by its fourth root
- At finite lattice spacing the four tastes are not degenerate
  - ➡ each pion is split into 16
  - ➡ the sixteen pseudo-scalar mesons have unequal masses
  - ➡ only one of them has vanishing mass in the chiral limit





- Scaling starts for $N_t \geq 8$.