

Critical endpoint of 4-flavor QCD with non-perturbatively $O(a)$ -improved Wilson quarks

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in collaboration with

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Introduction

- Finite temperature phase transition of $N_f = 3$ QCD

- expected to be 1st order at $m = 0$ R. D. Pisarski and F. Wilczek, PRD 29 (1984) 338
- 2nd order critical endpoint $m = m_E$
- crossover $m > m_E$ e.g.)

e.g.)

L. Varnhorst, PoS LATTICE2014 (2015) 193

X.-Y. Jin *et al.*, PRD 91 (2015) 014508

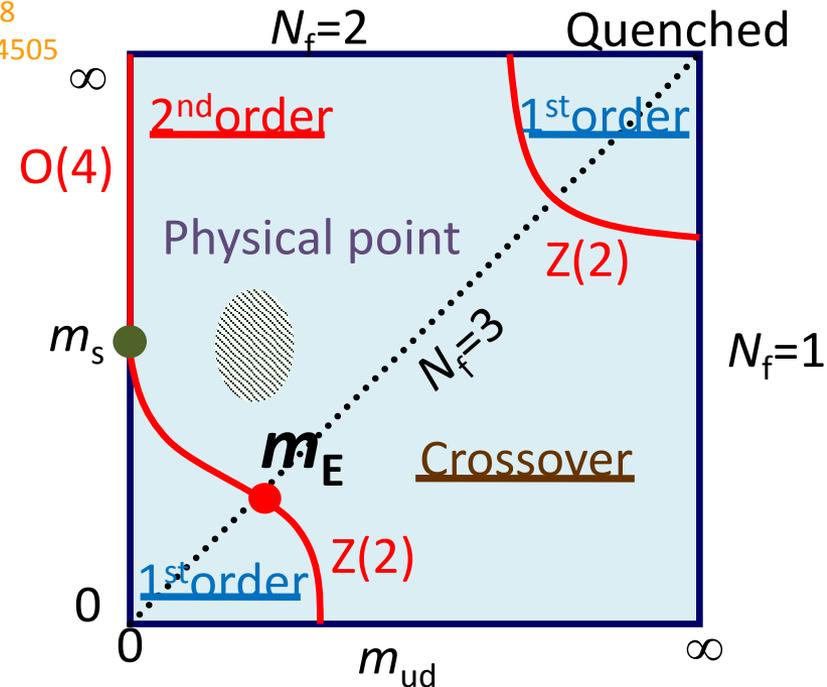
A. Bazavov *et al.*, PRD 95 (2017) 074505

- Lattice studies so far

- m_E keeps decreasing for more improved actions and as $a \rightarrow 0$
- Different scaling btw. Wilson and staggered
- **m_E in $a \rightarrow 0$ is still not conclusive**

- $N_f = 4$ QCD

- also expected to be 1st order at $m = 0$, which would be stronger than $N_f = 3$
- larger m_E = numerically less expensive
- better comparison btw. Wilson and staggered since no rooting is needed
- **a good analog to understand the $N_f = 3$ results**

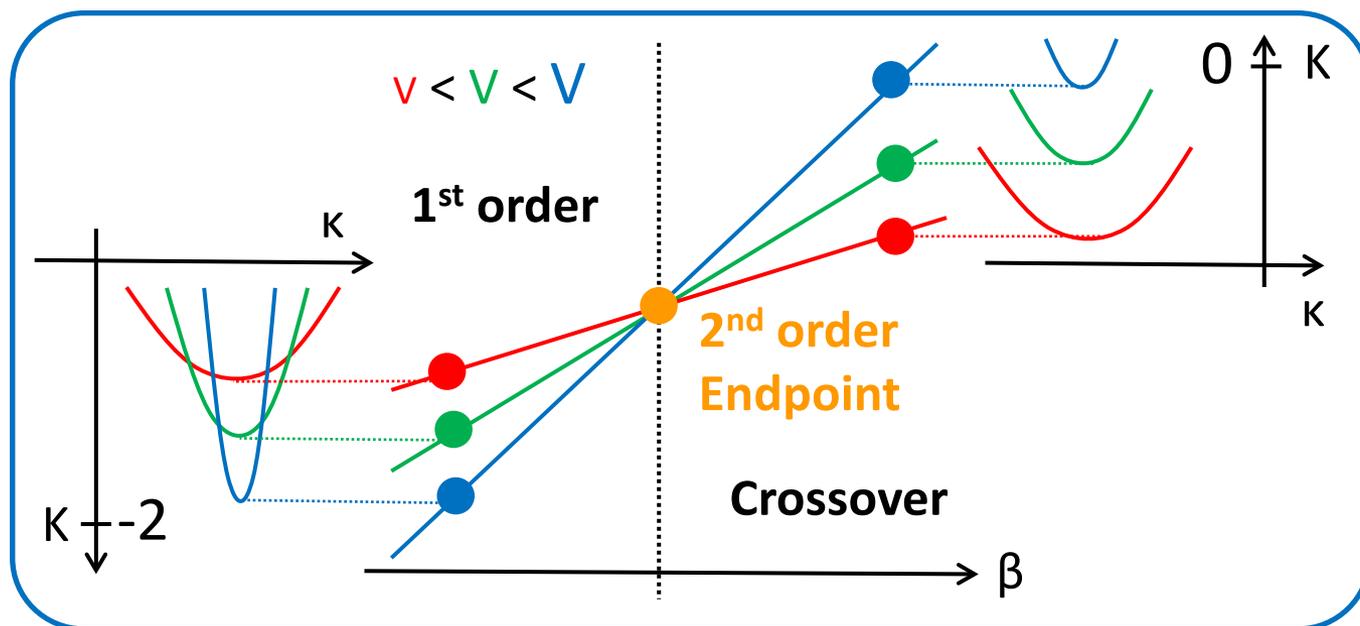


Simulation setup (1)

- Iwasaki gauge + $O(a)$ -improved Wilson quarks with 4 degenerate flavors
 - C_{sw} has been non-perturbatively determined in $N_f = 4$
- Three different cutoffs towards the continuum limit
 - $N_t = 4, 6$ and 8
 - $N_t = 8$ results are still very preliminary
- Three different β values at each N_t
 - $\beta = 1.60, 1.62$ and 1.64 at $N_t = 4$
 - $\beta = 1.67, 1.68$ and 1.69 at $N_t = 6$
 - $\beta = 1.66, 1.675$ and 1.68 at $N_t = 8$
- Five different κ values at each β
- Zero temperature simulations also have been done on a $16^3 \times 32$ lattice to determine t_0 and m_{PS}

Simulation setup (2)

- Chiral condensate and its cumulants
 - Up to 4th order, i.e. susceptibility, skewness and kurtosis
 - Traces, e.g. $\text{Tr}D^{-n}$ for $n = 1, 2, 3$ and 4, measured with 10 noises
- Multi-ensemble reweighting for κ
- The kurtosis intersection method to find critical endpoints



An example of cumulants at $N_t = 4$

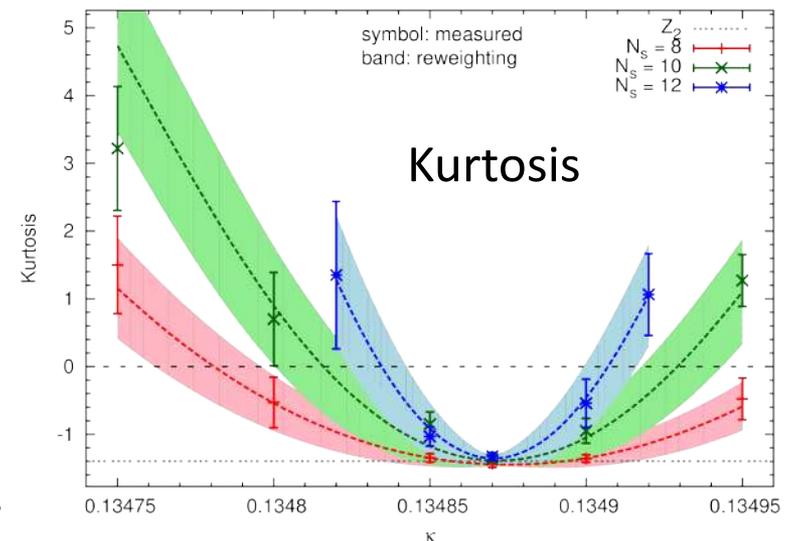
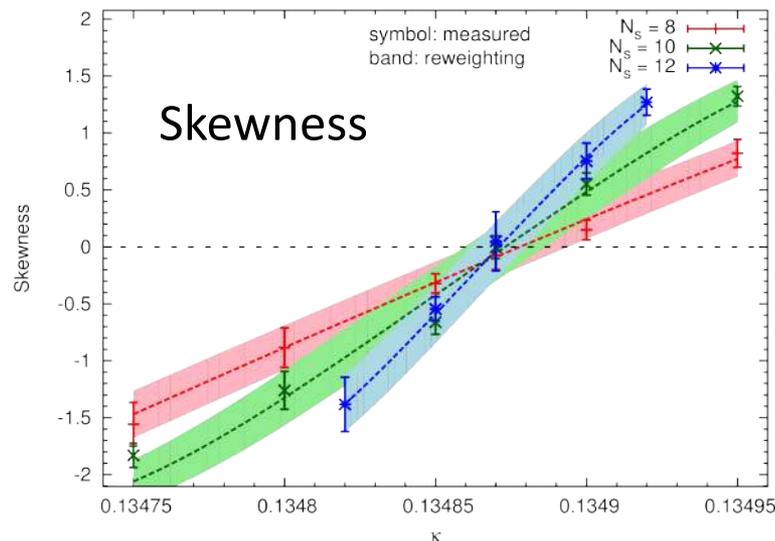
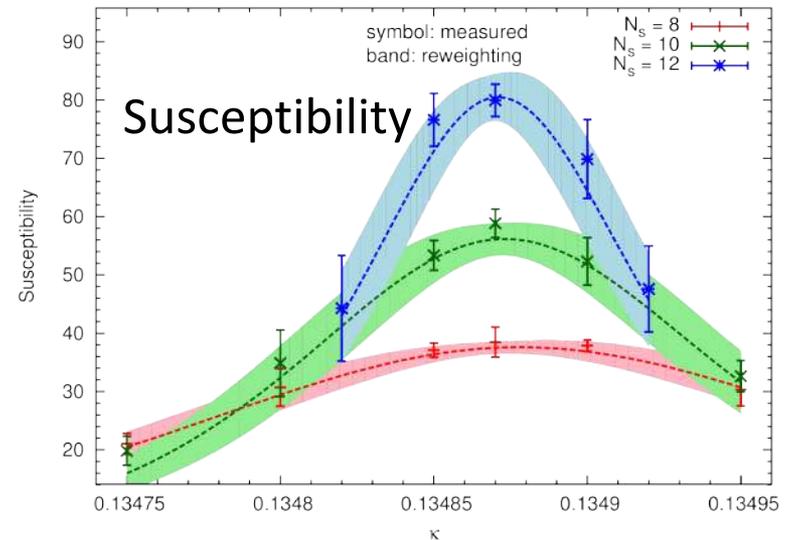
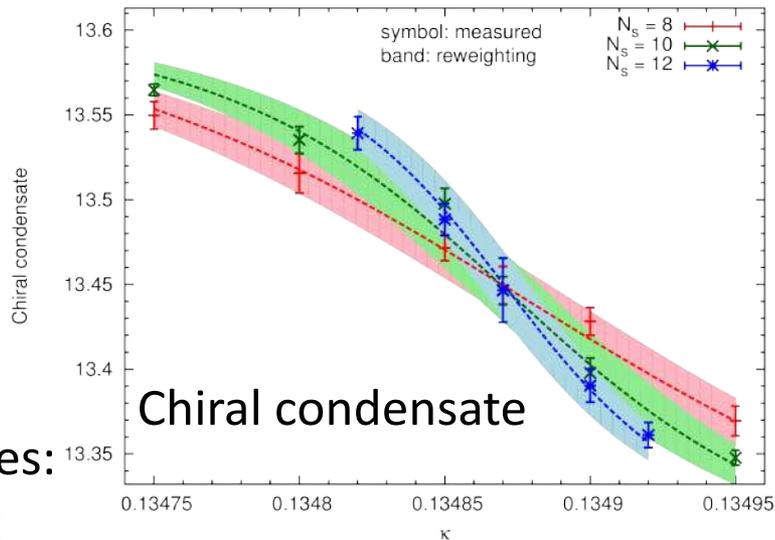
$\beta = 1.62$

$N_s = 8$

$N_s = 10$

$N_s = 12$

dotted curves:
reweighting



An example of cumulants at $N_t = 6$

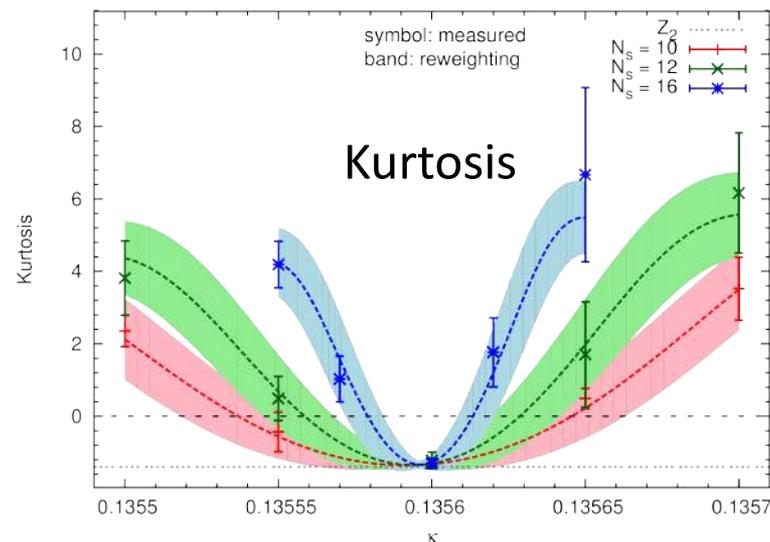
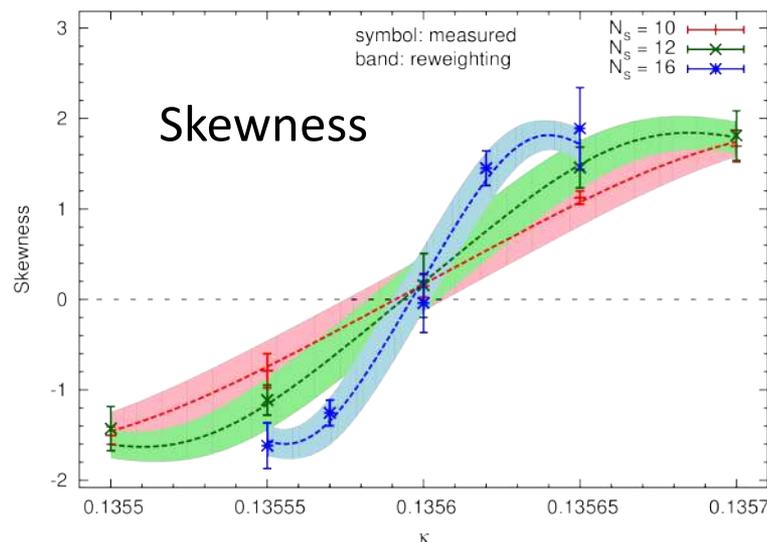
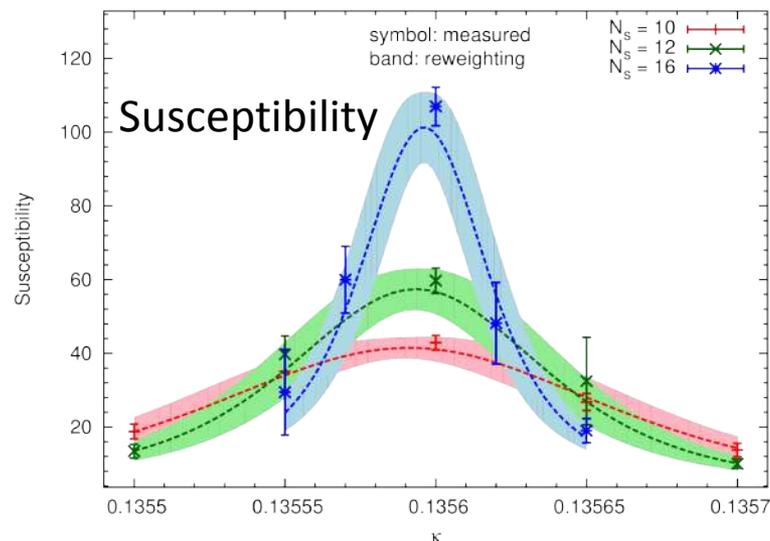
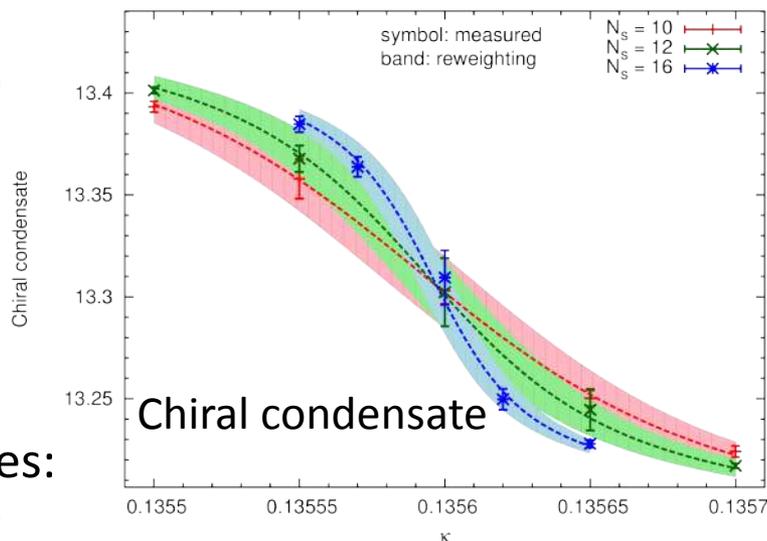
$\beta = 1.68$

$N_s = 10$

$N_s = 12$

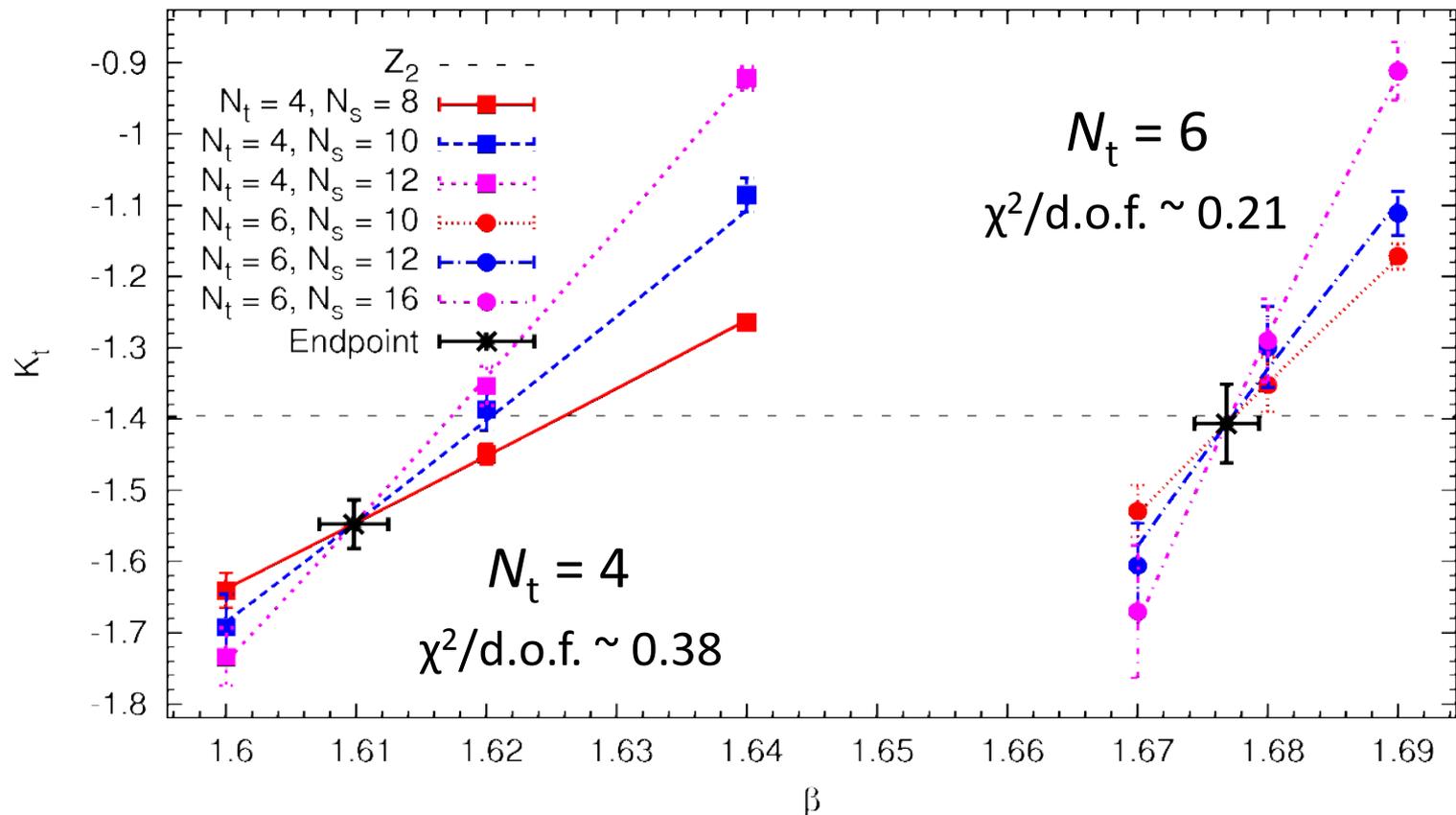
$N_s = 16$

dotted curves:
reweighting



Results of kurtosis intersections

$$\text{Fit ansatz: } K_t(\beta) = K_E + aN_s^{1/\nu}(\beta - \beta_E) + b \left[N_s^{1/\nu}(\beta - \beta_E) \right]^2$$

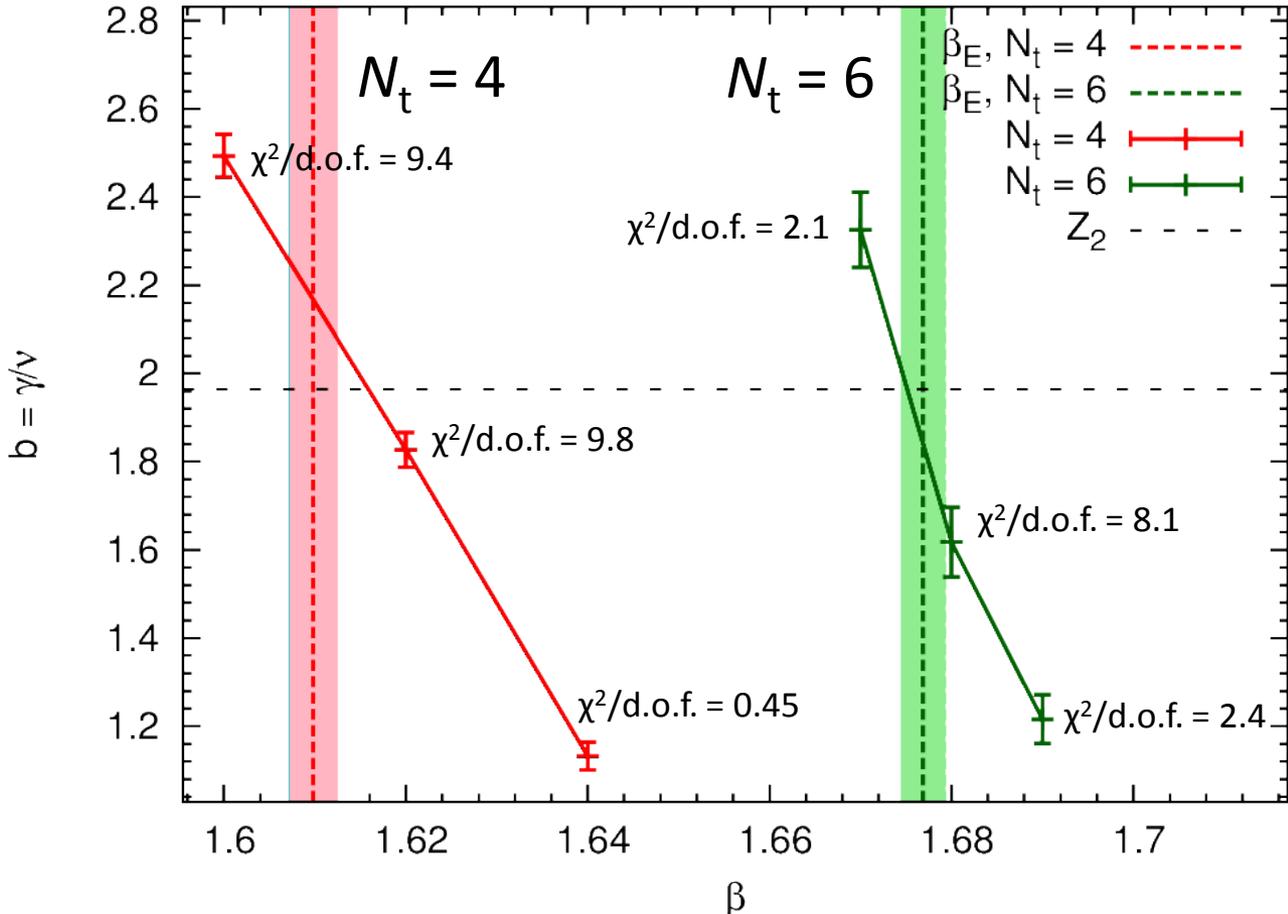


The quadratic term is almost irrelevant.

K_E is smaller than that of Z_2 at $N_t = 4$ while they are consistent with each other at $N_t = 6$.
 $\nu = 0.54(6)$ and $0.60(15)$ at $N_t = 4$ and 6 , respectively. Cf) $\nu = 0.630$ for Z_2

Further universality check with susceptibilities

Fit ansatz: $\chi_t(N_s) = aN_s^b$



b at the endpoint is larger than that of Z_2 at $N_t = 4$ while they are consistent with each other at $N_t = 6$.

Preliminary results at $N_t = 8$

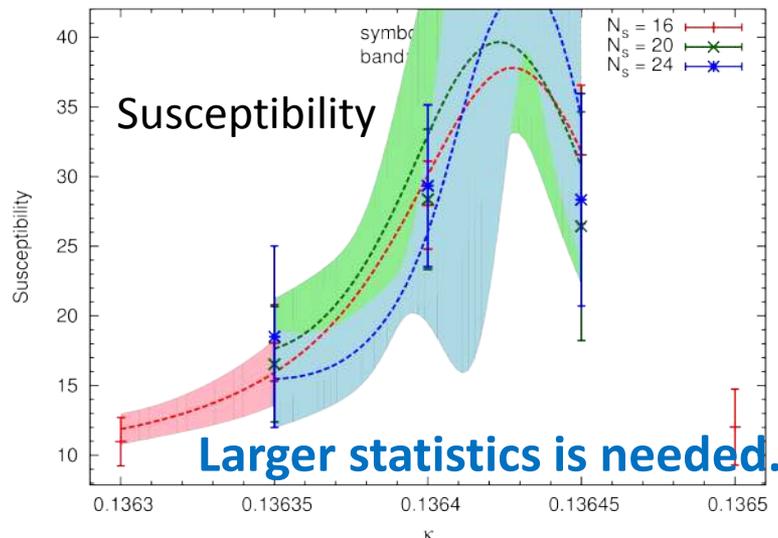
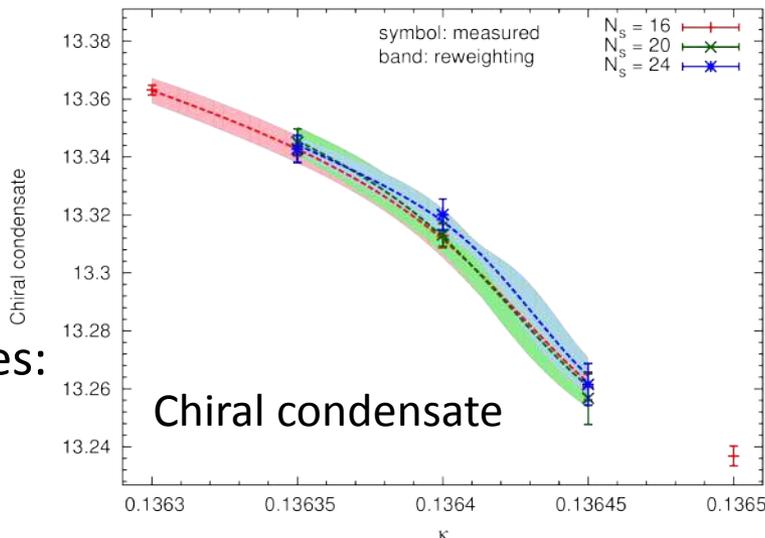
$\beta = 1.675$

$N_s = 16$

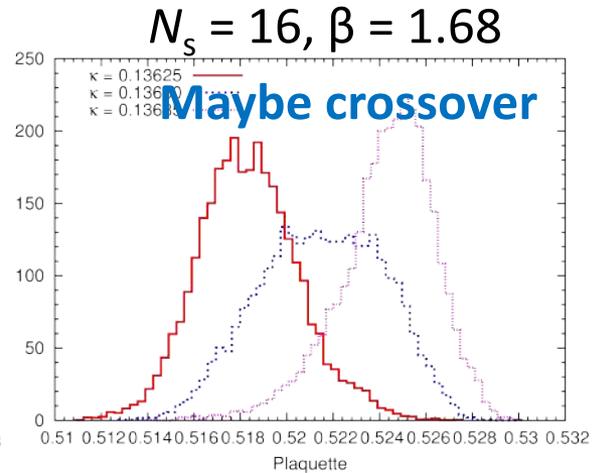
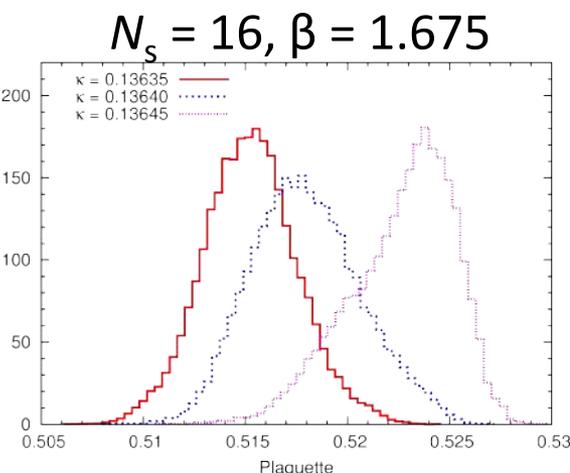
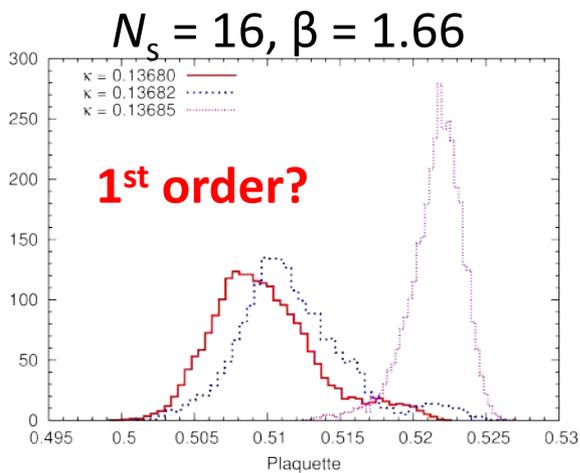
$N_s = 20$

$N_s = 24$

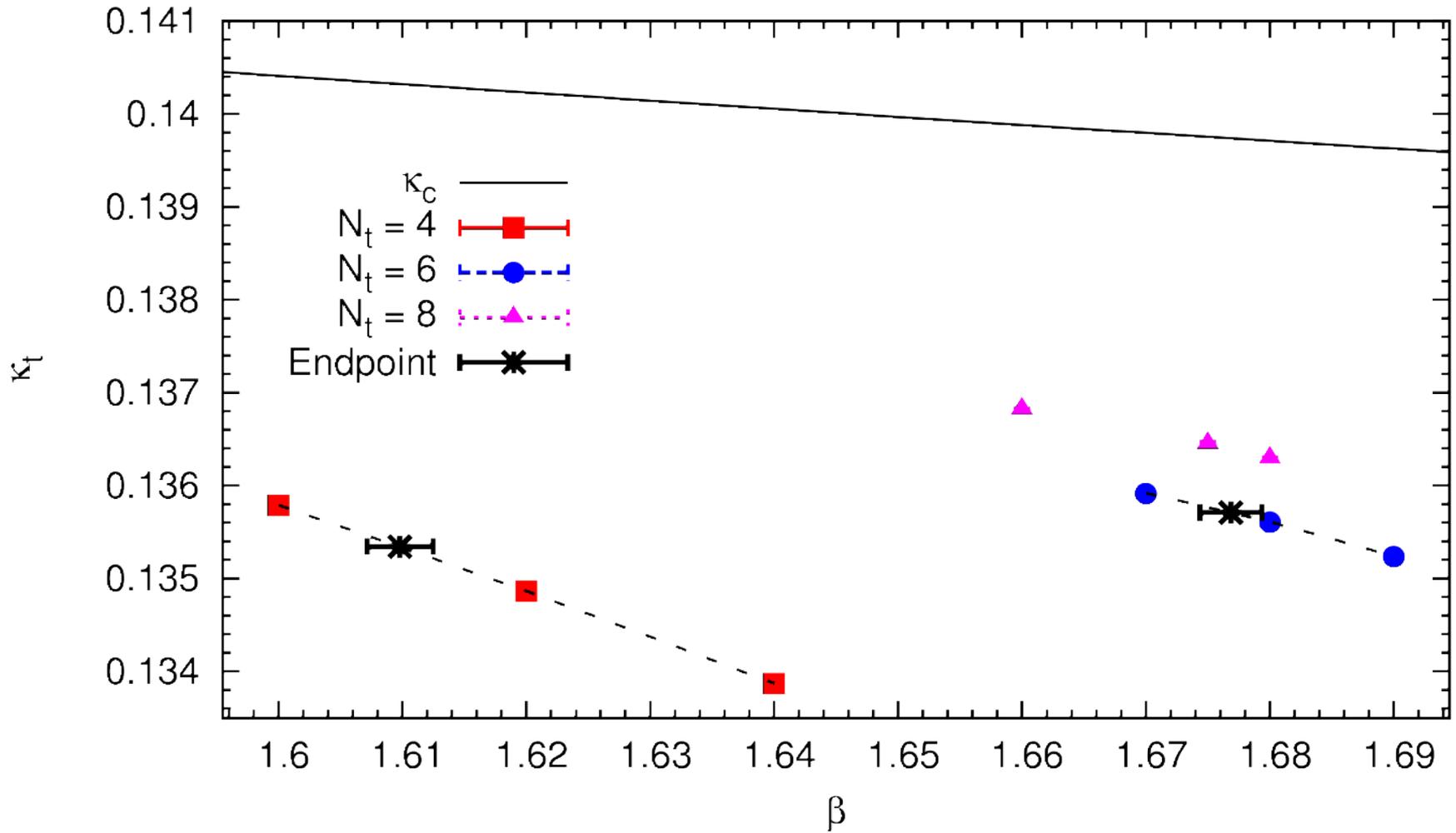
dotted curves:
reweighting



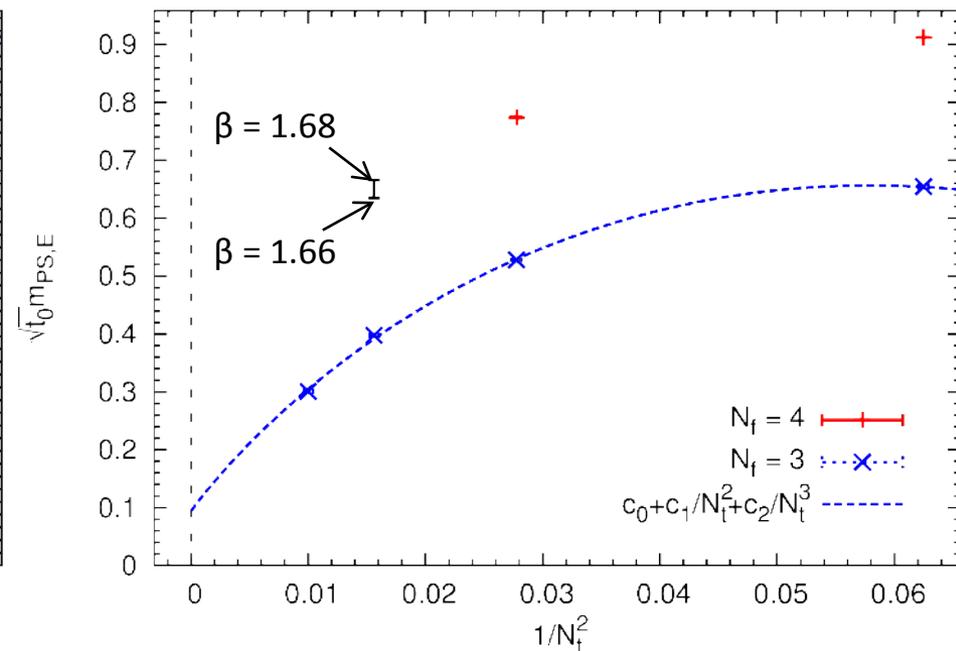
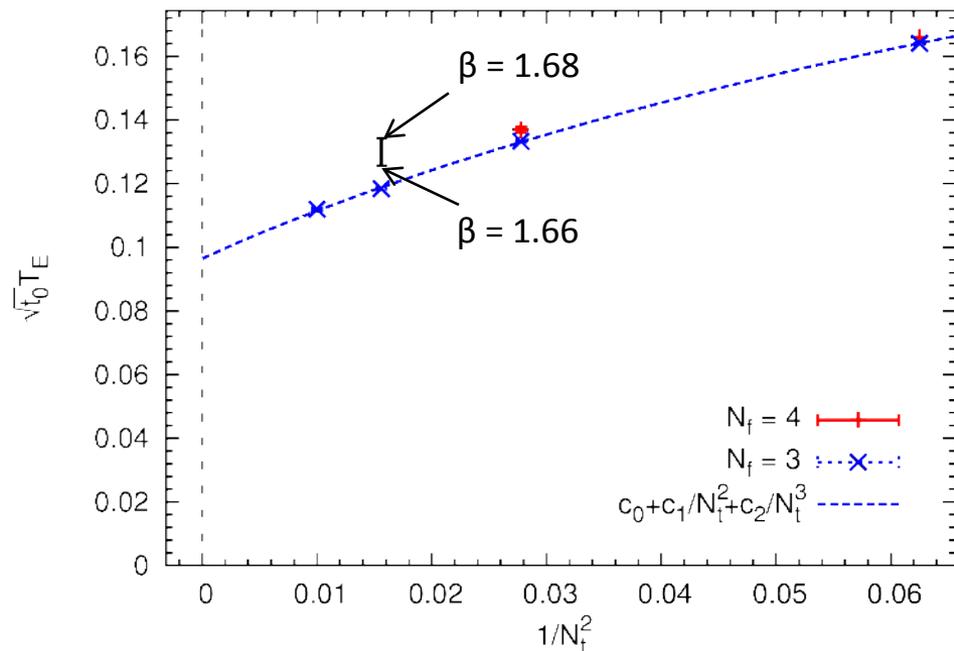
Plaquette histogram



Critical endpoints in $N_f = 4$ QCD



Cutoff dependence of critical endpoints



$N_f = 3$ results: X.-Y. Jin *et al.*, arXiv:1706.01178 [hep-lat]

(See also S. Takeda's talk on Tue.)

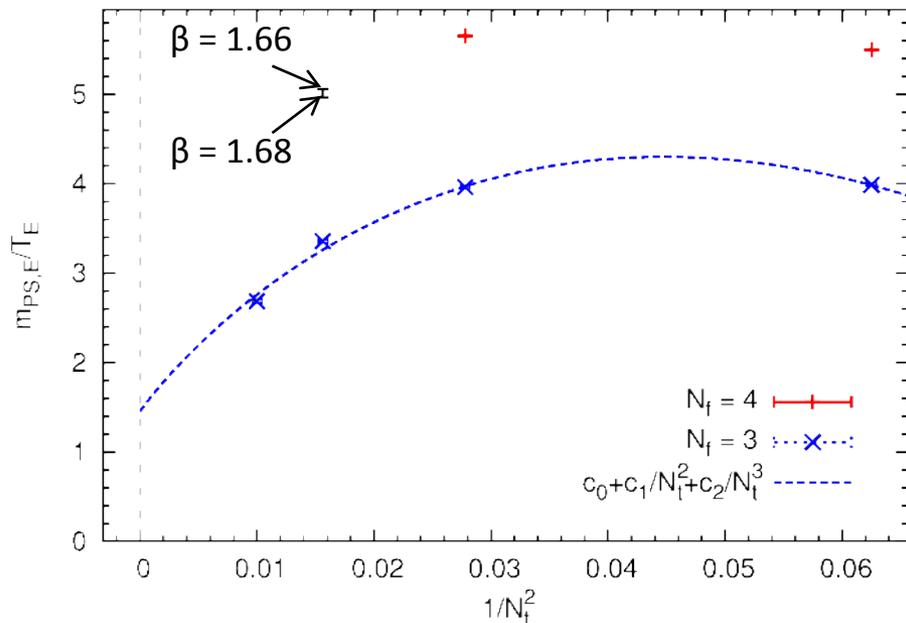
So far, a possible β_E range is given between 1.66 and 1.68 at $N_t = 8$ assuming $\beta = 1.66$ is 1st order.

$N_f = 4$ results have similar cutoff dependence as those of $N_f = 3$.

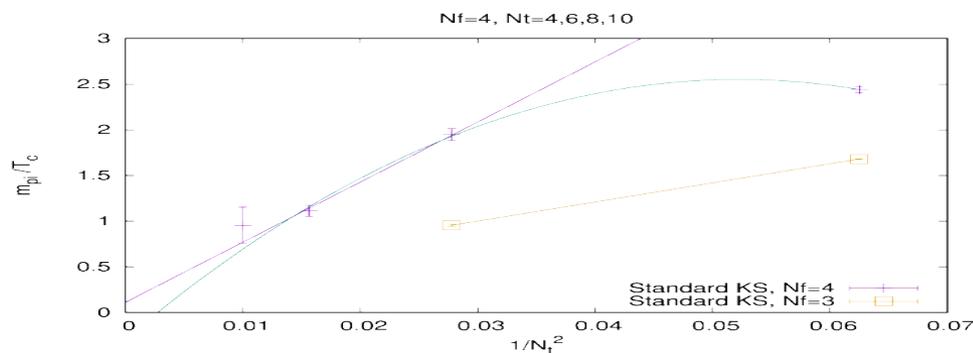
$m_{PS,E}$ in $N_f = 4$ is larger than in $N_f = 3$.

Further studies at $N_t = 8$ and even larger N_t data are needed for the reliable continuum limit.

Comparison with staggered quark results



Staggered results:
 P. de Forcrand and M. D'Elia,
 PoS LATTICE2016 (2017) 081



Similarly to the $N_f = 3$ case, there are different scaling behaviors to the continuum limit between the Wilson and staggered quarks in $N_f = 4$.

Summary and outlook

- Critical endpoints in $N_f = 4$ QCD has been studied.
- Larger $m_{PS,E}$ has been observed in $N_f = 4$ than in $N_f = 3$.
- We found a similar scaling behavior to $a \rightarrow 0$ as shown in $N_f = 3$.
- The scaling behavior is also different from that of the staggered quarks.
- Further studies are needed for the reliable continuum limit.
 - More statistics at $N_t = 8$
 - Simulations at larger N_t

End

Backup slides

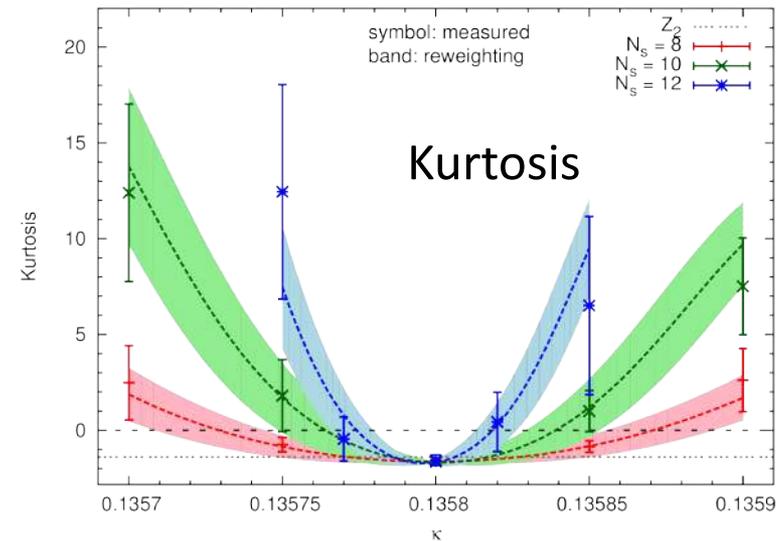
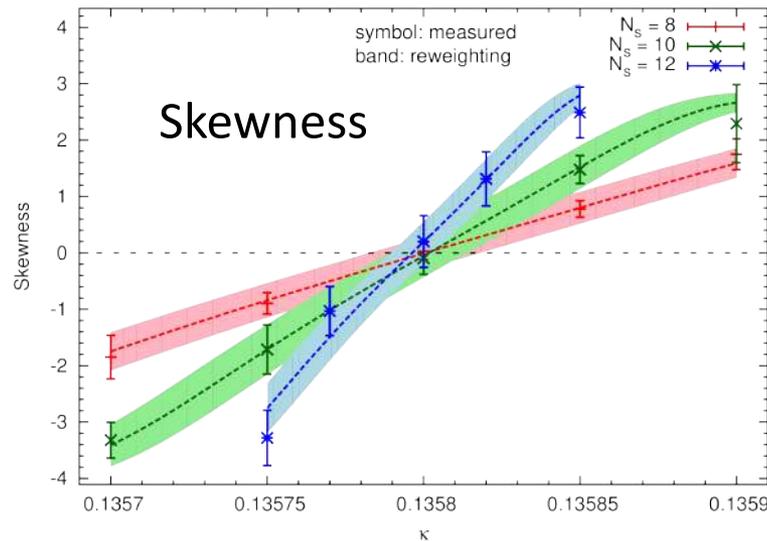
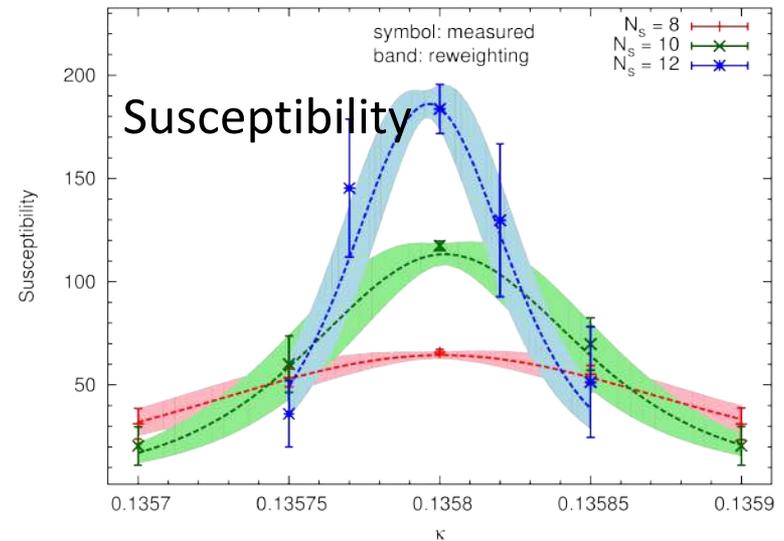
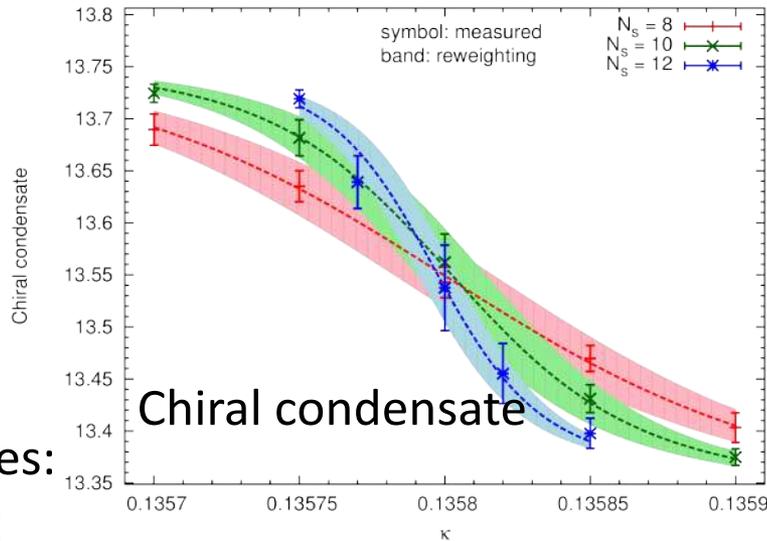
Cumulants at $N_t = 4, \beta = 1.60$

$N_s = 8$

$N_s = 10$

$N_s = 12$

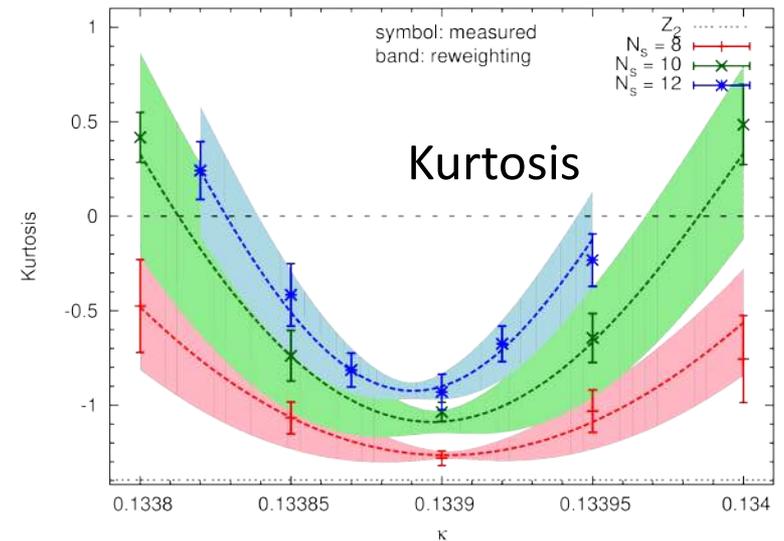
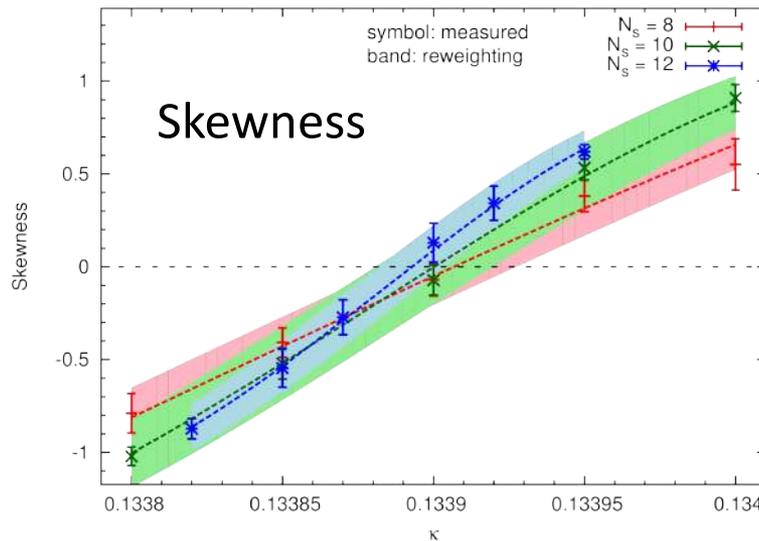
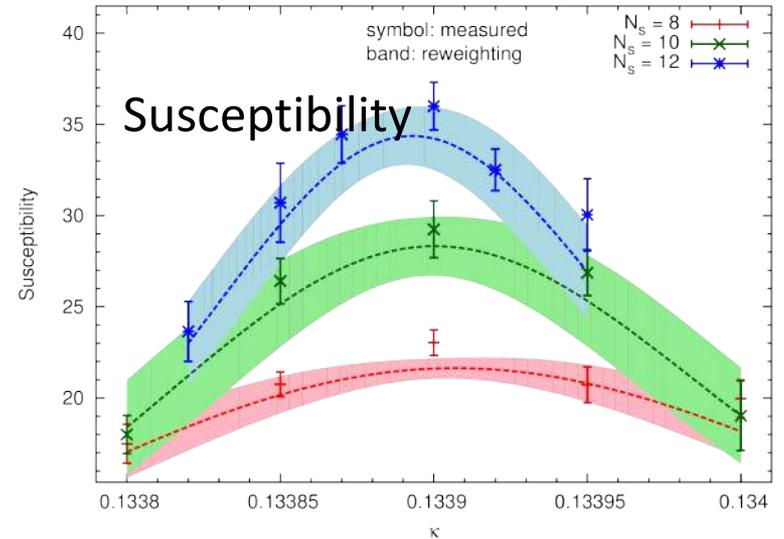
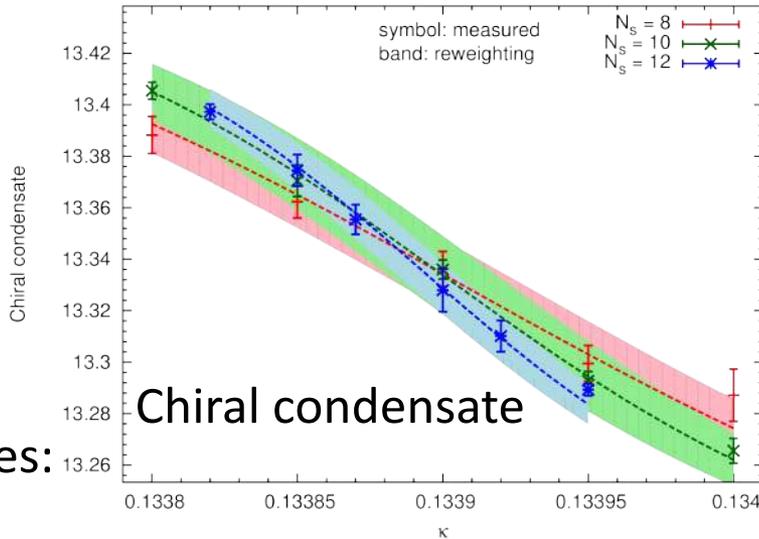
dotted curves:
reweighting



Cumulants at $N_t = 4, \beta = 1.64$

$N_s = 8$
 $N_s = 10$
 $N_s = 12$

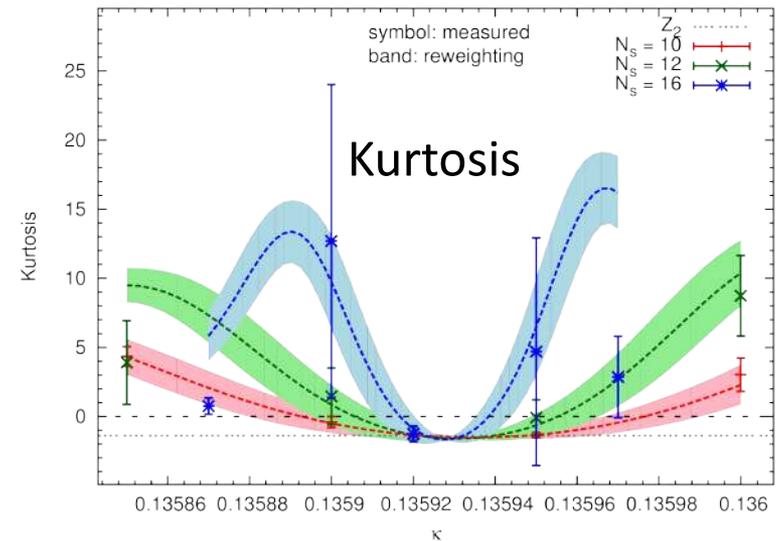
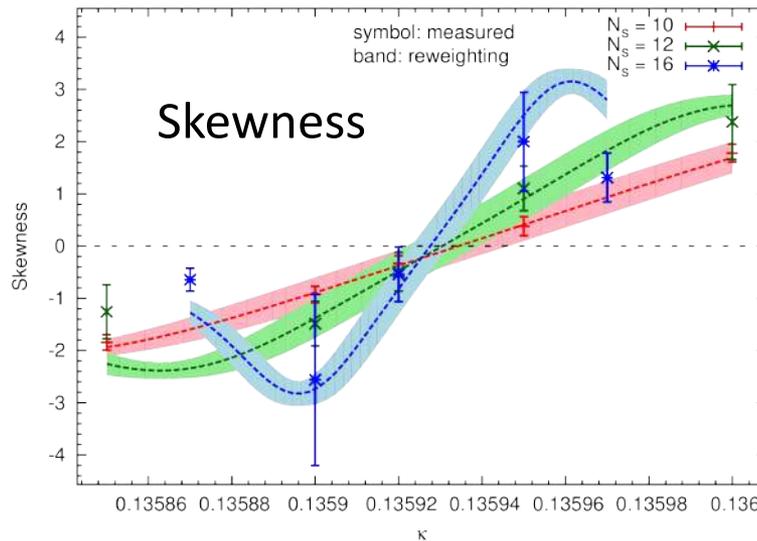
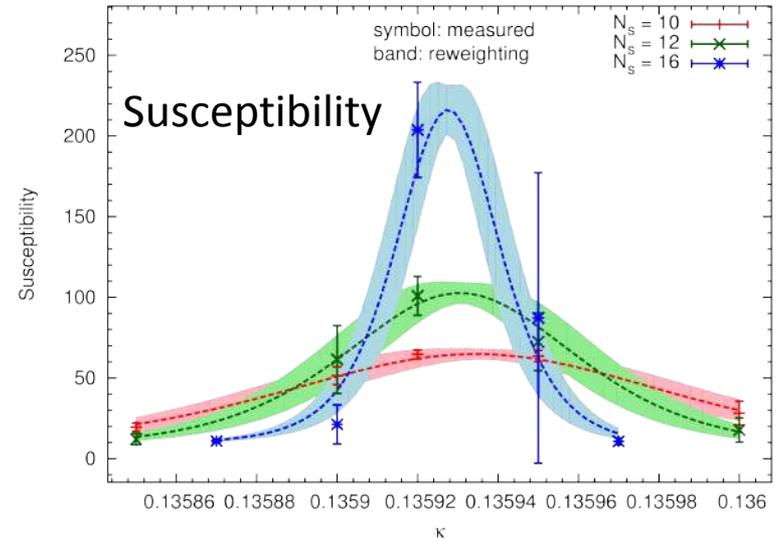
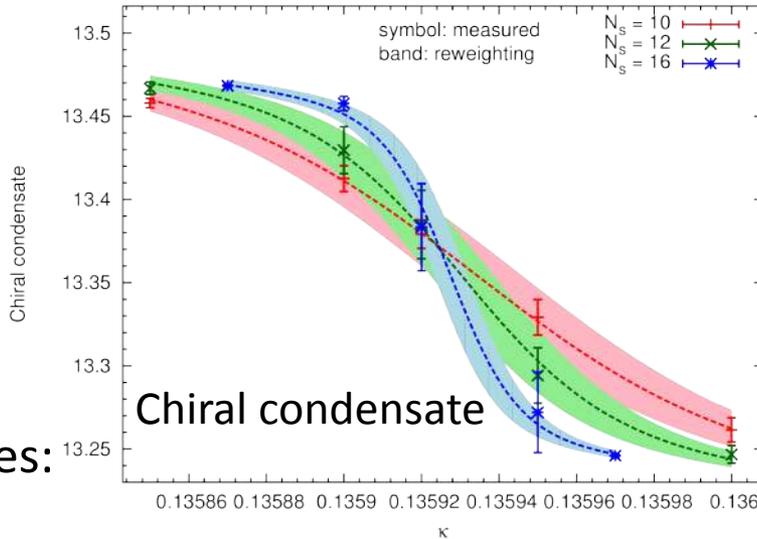
dotted curves:
reweighting



Cumulants at $N_t = 6, \beta = 1.67$

$N_s = 10$
 $N_s = 12$
 $N_s = 16$

dotted curves:
reweighting



Cumulants at $N_t = 6, \beta = 1.69$

$N_s = 10$

$N_s = 12$

$N_s = 16$

dotted curves:
reweighting

