SCGT14Mini

Sakata Memorial KMI Mini-Workshop on

"Strong Coupling Gauge Theories Beyond the Standard Model"

(SCGT14Mini)

How many scales in many-flavor QCD ?

March 6 2014

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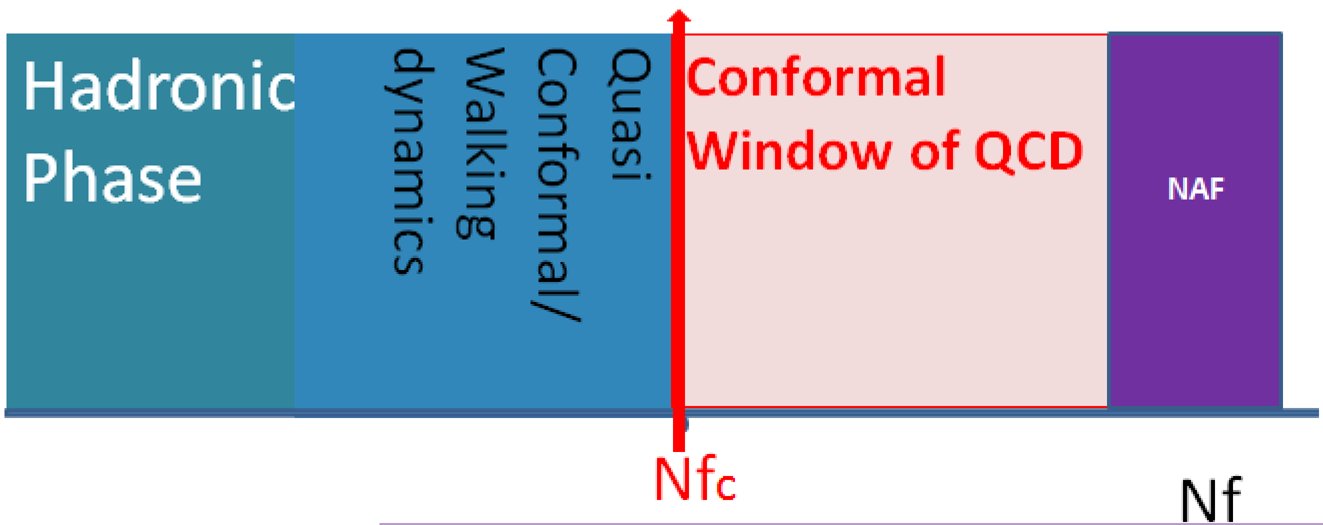
We study Nc=3,
Fundamental fermions :

Nf = 0 --
Nf = 4 --
Nf = 6 --
Nf = 8 --
Nf = 12 --
Nf = 16 --

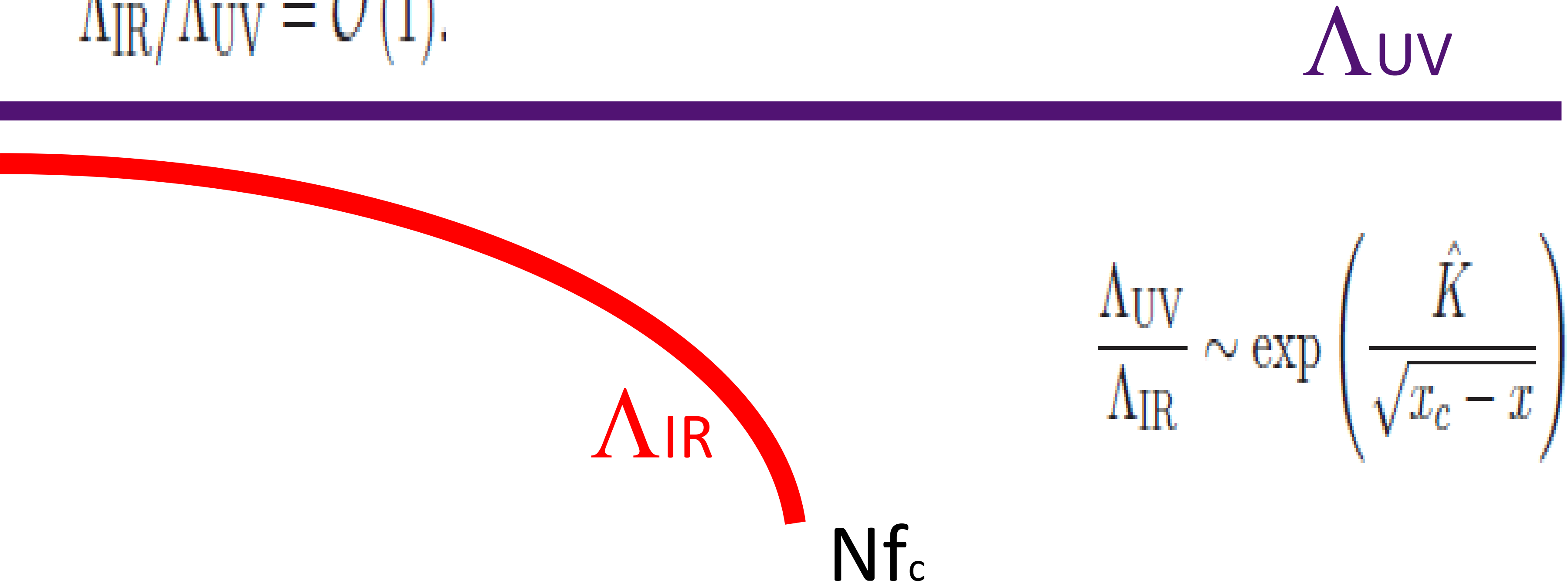
At zero and non-zero temperature.



MpL,KM,TndS,EP : work in progress
Talk by KM at Lat2013
Talk by TndS at Lat2013
KM,MpL **Nuclear Physics B 871 (2013)**

From UV to IR

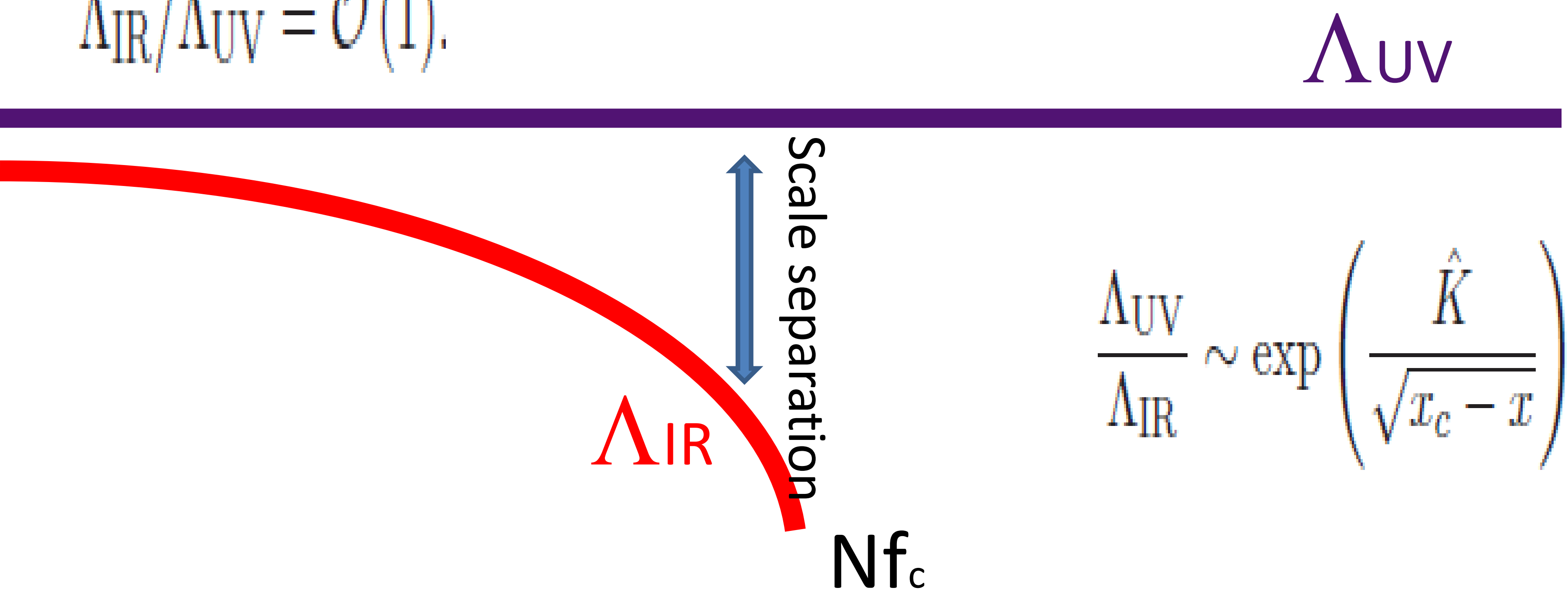
$$\Lambda_{\mathrm{IR}}/\Lambda_{\mathrm{UV}} = \mathcal{O}(1).$$



$$\frac{\Lambda_{\mathrm{UV}}}{\Lambda_{\mathrm{IR}}} \sim \exp\left(\frac{\hat{K}}{\sqrt{x_c - x}}\right)$$

From UV to IR

$$\Lambda_{\mathrm{IR}}/\Lambda_{\mathrm{UV}} = \mathcal{O}(1).$$



$$\frac{\Lambda_{\mathrm{UV}}}{\Lambda_{\mathrm{IR}}} \sim \exp\left(\frac{\hat{K}}{\sqrt{x_c - x}}\right)$$

Physical scales & Lattice scales

- ✓ Lattice introduces two further technical scales a and L obscuring the UV and IR behaviour respectively

- ✓ Ratios of homogeneous quantities

  R = O1/O2

  useful: Help controlling a and L systematic effects Display scale hierarchy with no need to fix the scale across different theories

- ✓ When **O2** is an UV quantity – non critical at Nfc -- taking the ratio is de facto a scale fixing procedure for O1

Plan

- Critical temperature : Nf = (0,4,6,8)
- String tension: Nf = 6,8
- Wilson flow: Nf = 6,8

- Spectrum and anomalous dimension: Nf=12

THE (PSEUDO) CRITICAL TEMPERATURE

Lattice setup

All simulations :

--Gauge Action: one loop Symanzyk improved
--Fermion Action: Tadpole improved AsqTad

m = 0.02 : only one mass

Scaling for essential singularities

Nogada, Hasegawa, Nemoto,PRL 2012

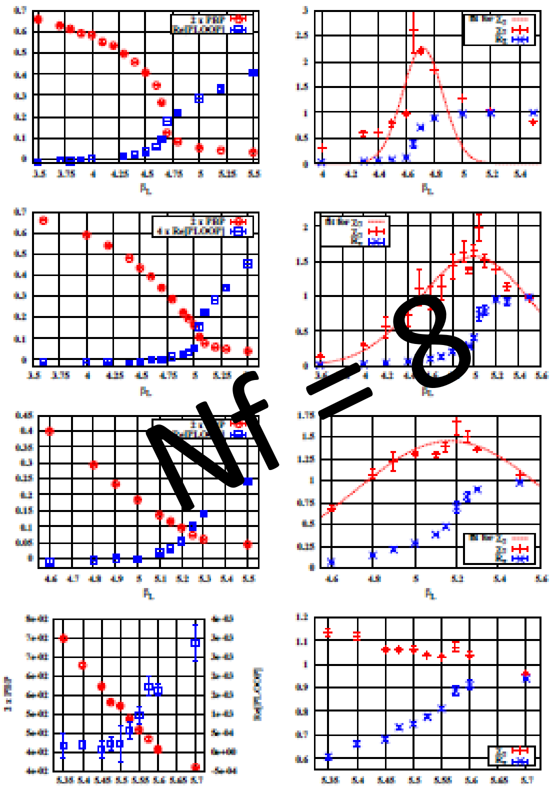
$$g(t,h,N^{-1}) = b^{-1}\hat{g}(e^{-(t/t_0)^{-x_t}}b, hb^{y_h}, N^{-1}b).$$

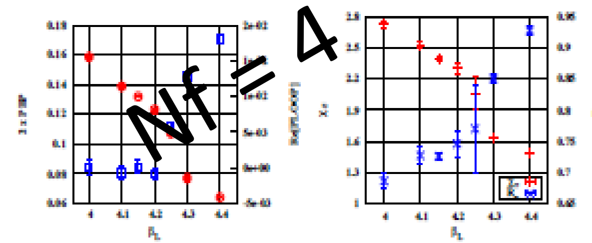
$$m \propto \begin{cases} e^{-(1-y_h)(t/t_0)^{-x_t}} & \text{for } he^{y_h(t/t_0)^{-x_t}} \ll 1 \\ h^{y_h^{-1}-1} & \text{for } he^{y_h(t/t_0)^{-x_t}} \gg 1 \end{cases}$$

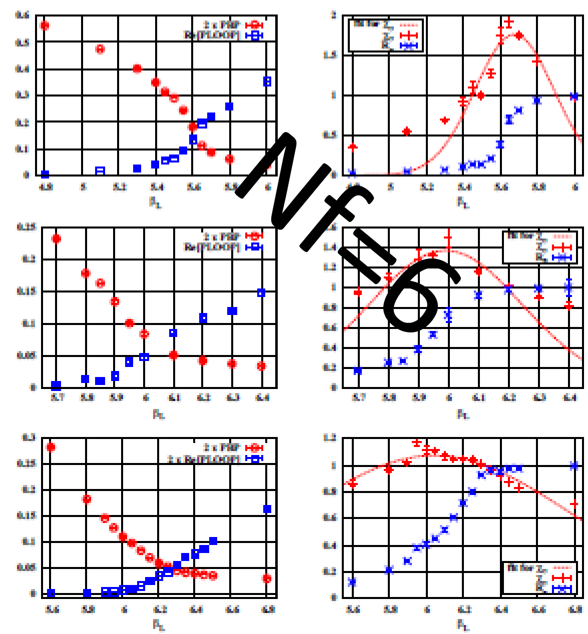
m <-> Chiral Condensate
h <-> bare mass
t <-> Nc - Nfc

Within the scaling window data at finite mass contain information on the critical behaviour . They can can be approximativelydescribed as zero mass ones, but with a larger apparent critical point.

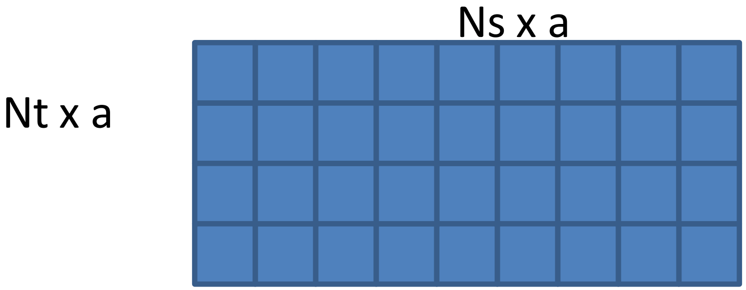
We studied the thermal transition for several Nf and several Nt







All simulations :
Gauge Action one loop Sym.
Tadpole improved AsqTad



From the Lattice..

$$T \equiv \frac{1}{a(\beta_{\mathrm{L}}) \cdot N_t} \, ,$$

..to the continuum

Via old fashioned asymptotic scaling

$$\Lambda_{\mathrm{L}} \; a(\beta_{\mathrm{L}}) = \left(\frac{2 N_c b_0}{\beta_{\mathrm{L}}} \right)^{-b_1/(2b_0^2)} \exp\left[\frac{-\beta_{\mathrm{L}}}{4 N_c b_0} \right] .$$

$$\frac{1}{N_t} = \boxed{\frac{T_c}{\Lambda_{\mathrm{L}}}} \times \left(\Lambda_{\mathrm{L}} \; a(\beta_{\mathrm{L}}^{c}) \right) .$$

Must be approx. constant for several Nt

The quest for continuum limit

$$\frac{T_c}{\Lambda_{L/E}} = \frac{R(g_{L/E})}{N_t} = (b_0 g_{L/E}^2)^{-b_1/(2b_0^2)} \exp\left[\frac{-1}{2b_0}\right],$$

Explore different prescriptions for Tc/Λ

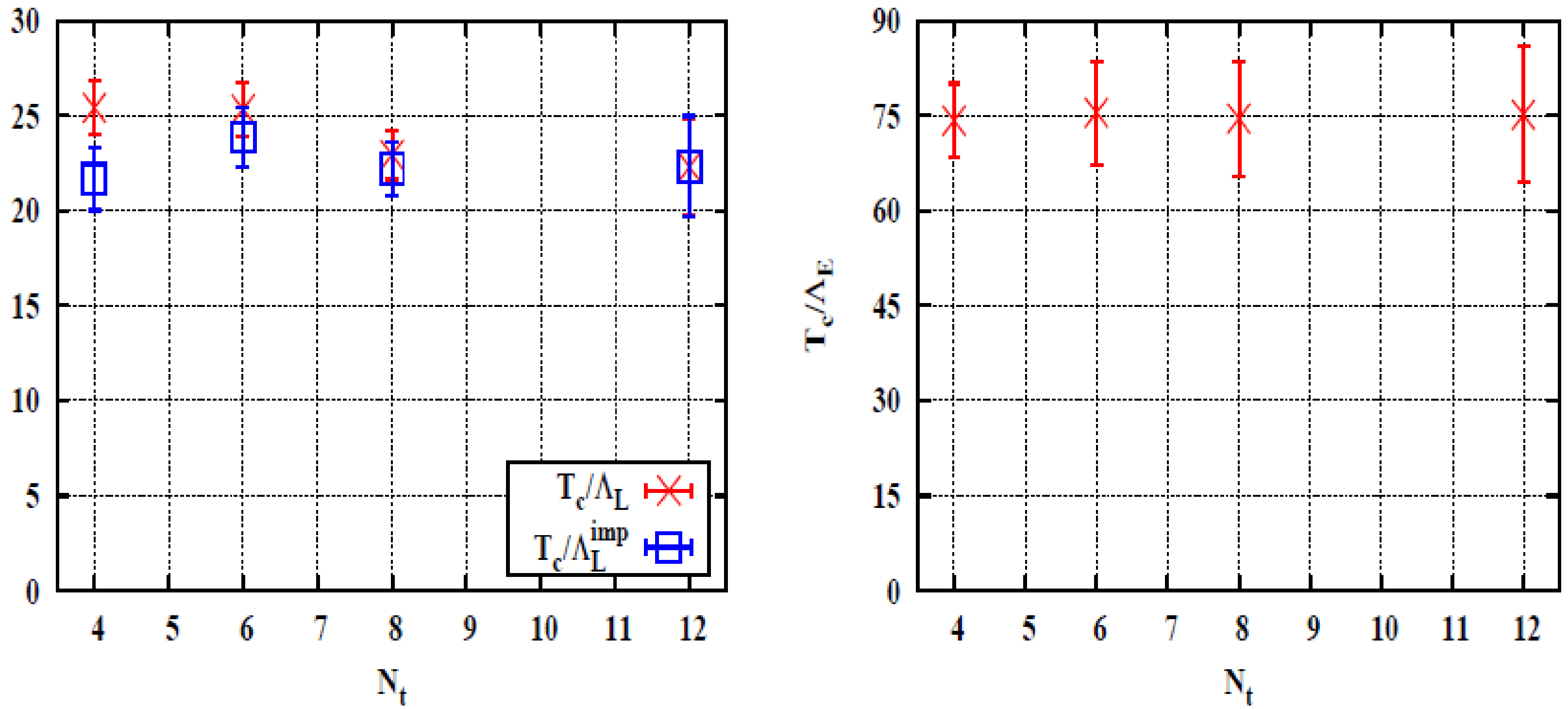
$$R(g_{L/E}) \equiv a(g_{L/E})\Lambda_{L/E} = (b_0 g_{L/E}^2)^{-b_1/(2b_0^2)} \exp\left[\frac{-1}{2b_0 g_{L/E}}\right]$$

$$g_E = \sqrt{3(1 - \langle P \rangle(g_L))}$$

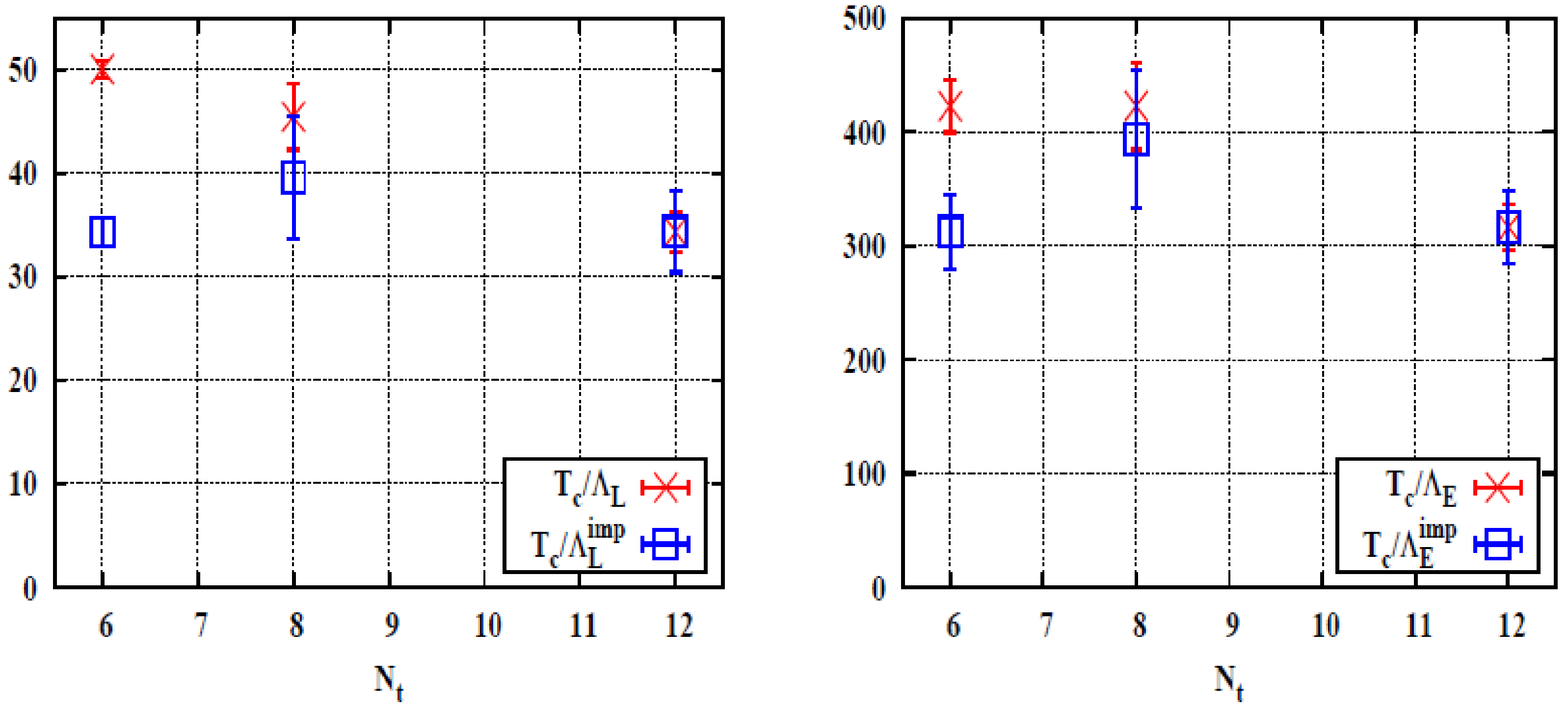
$$R^{\mathrm{imp}}(\beta_{L/E}) = \Lambda_{L/E}^{\mathrm{imp}}\, a(\beta_{L/E}) \equiv \frac{R(\beta_{L/E})}{1+h} \times \left[1 + h\,\frac{R^2(\beta_{L/E})}{R^2(\beta_0)}\right],$$

C. Allton, 2007

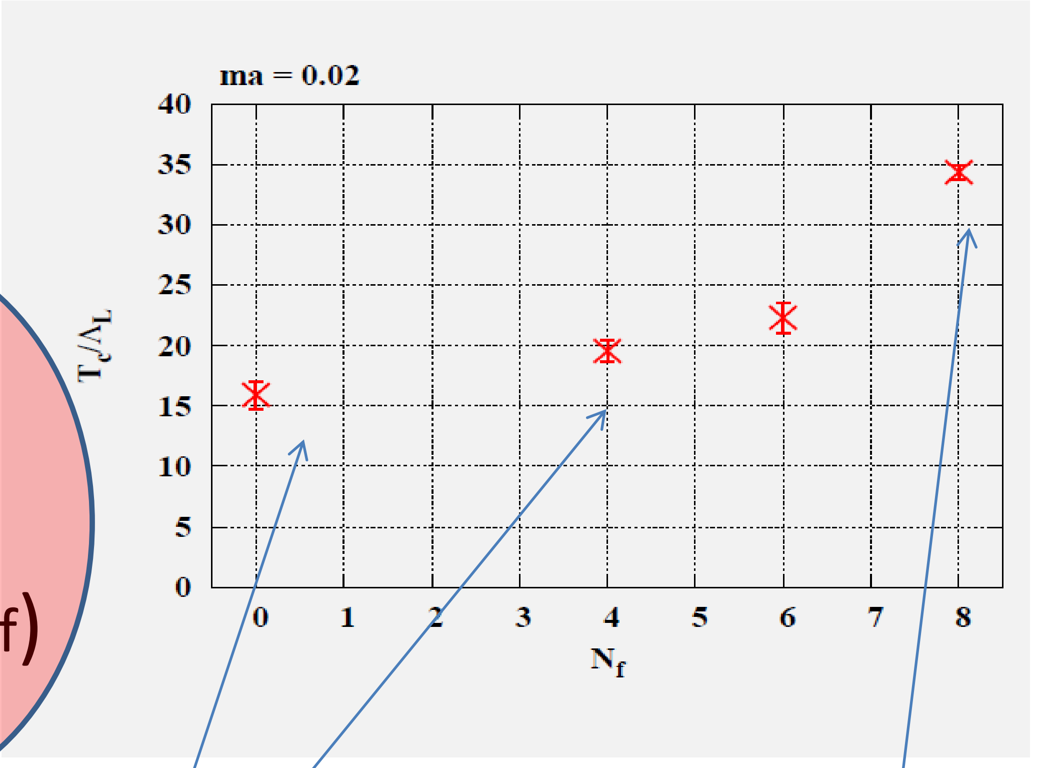
Nf = 6, asympt. scaling



Nf = 8, asympt scaling



Tc/Λ as a function of Nf



Tc/Λ

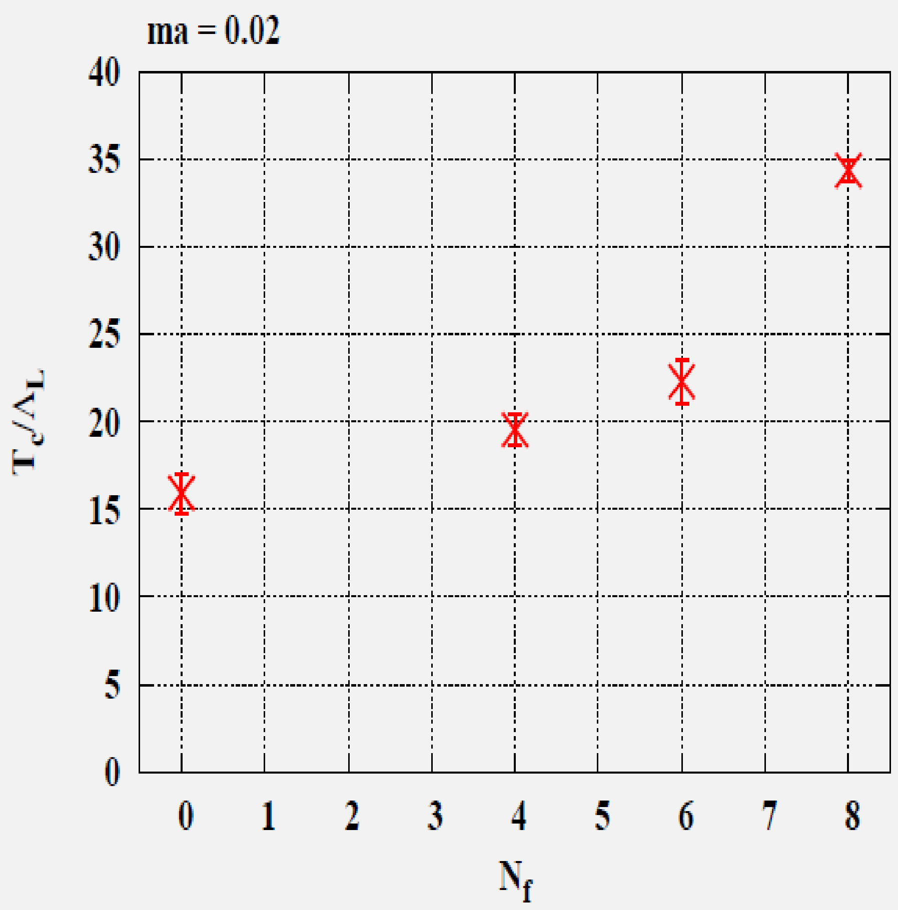
Λ = Λ(Nf)

Scale separation ?

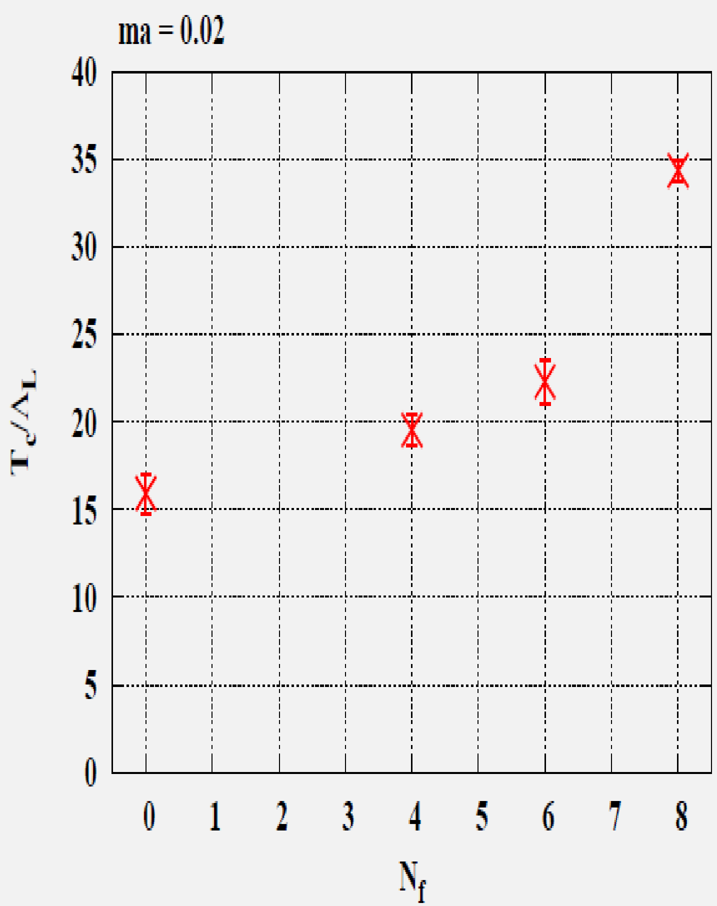
Nf

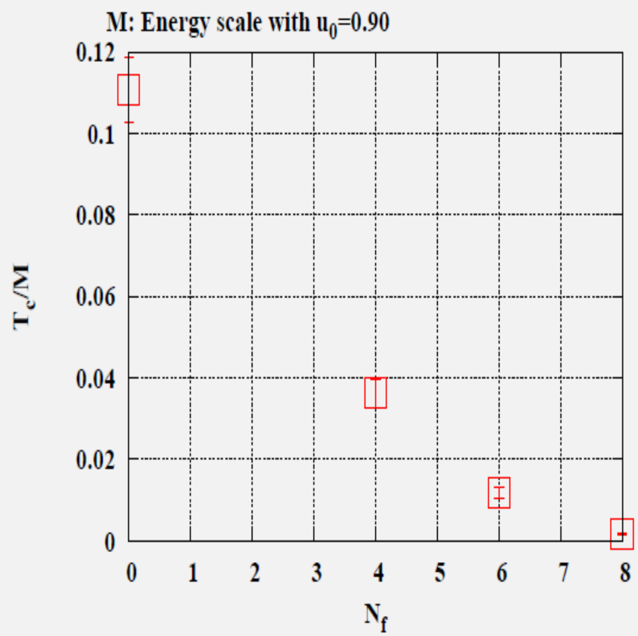
Conventional running

Puzzle??



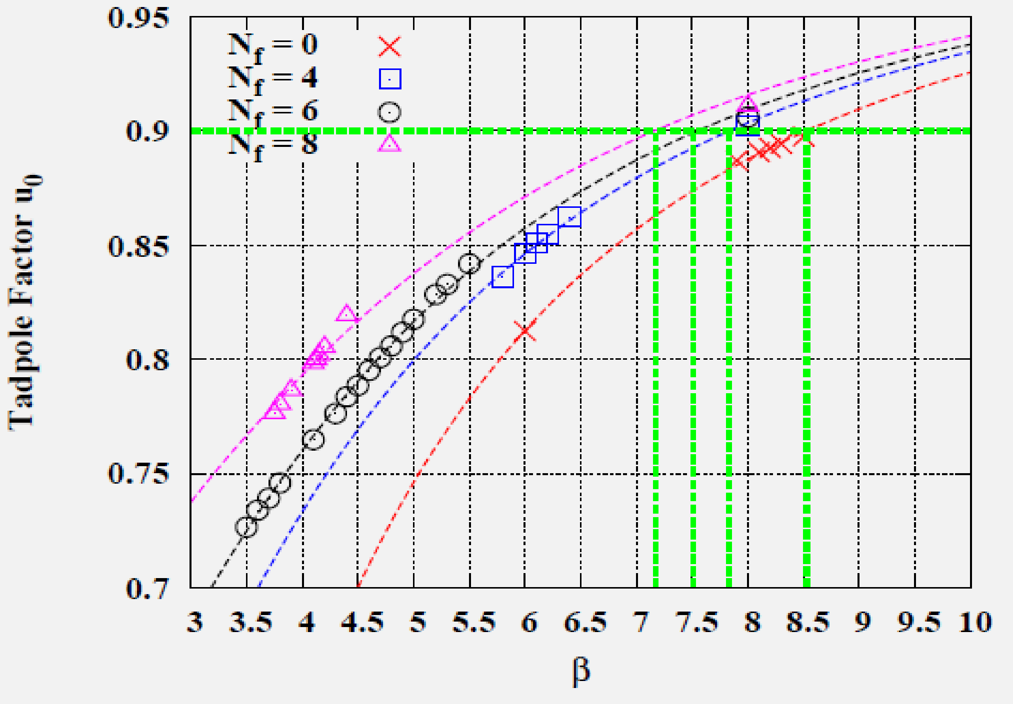
Solution: Λ = Λ (Nf) ; use UV scale





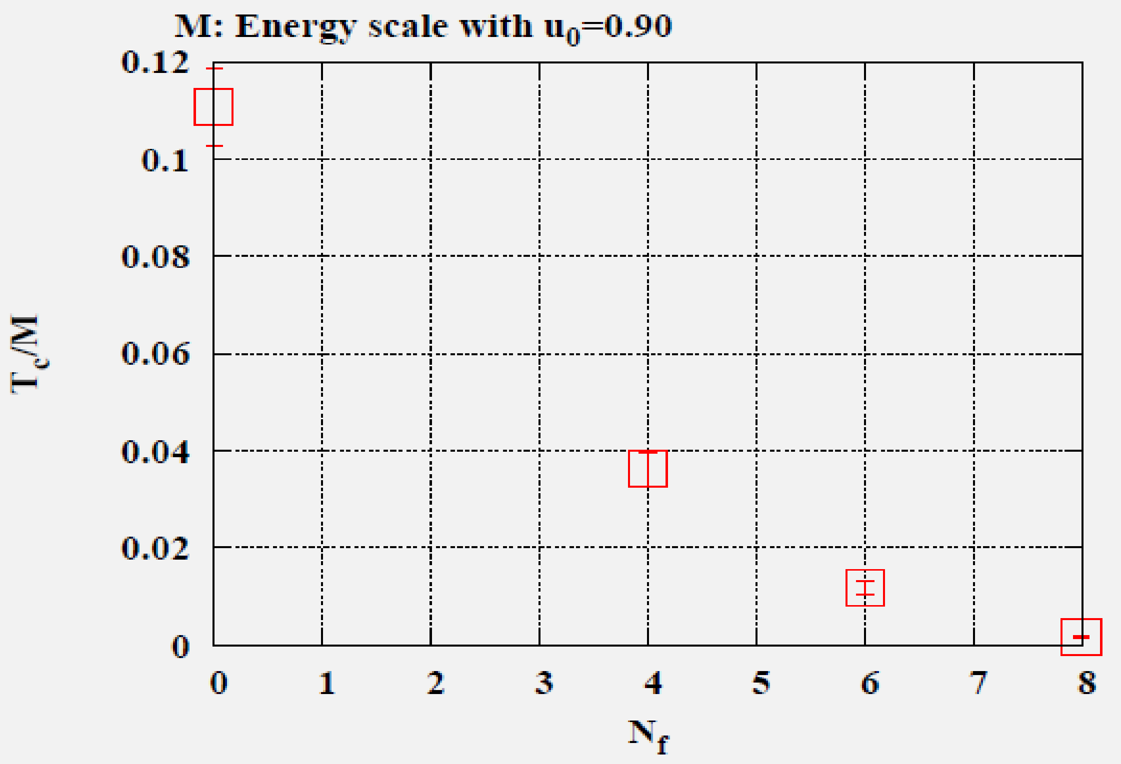
$$\frac{T_c}{M} = \frac{1}{N_t} \exp\left[\int_{g_{\mathrm{ref}}}^{g_c} \frac{dg}{B(g)}\right].$$

Fixing an UV scale



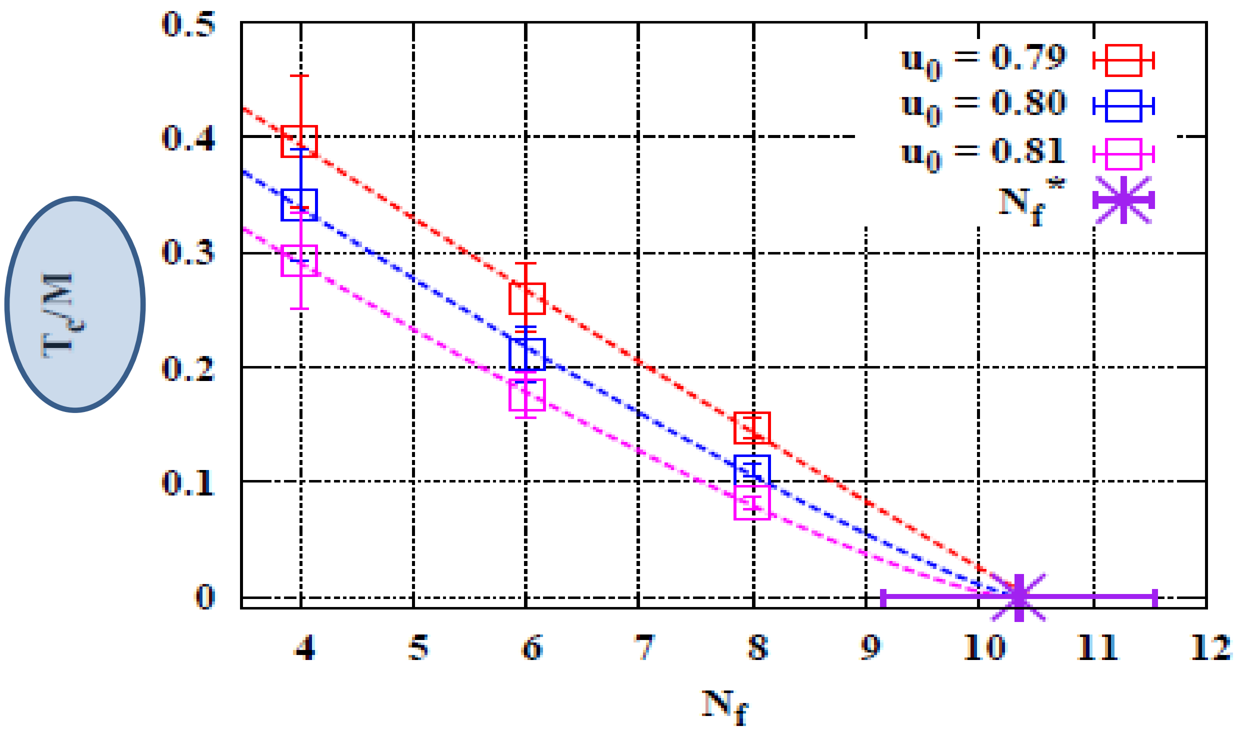
- We have measured the tadpole factosr $u_0 = \langle \Box \rangle^{1/4}$ at $T = 0$.
- We use the couplings obtained by the constant u_0 line to define a UV reference scale M.

Tc/MUV



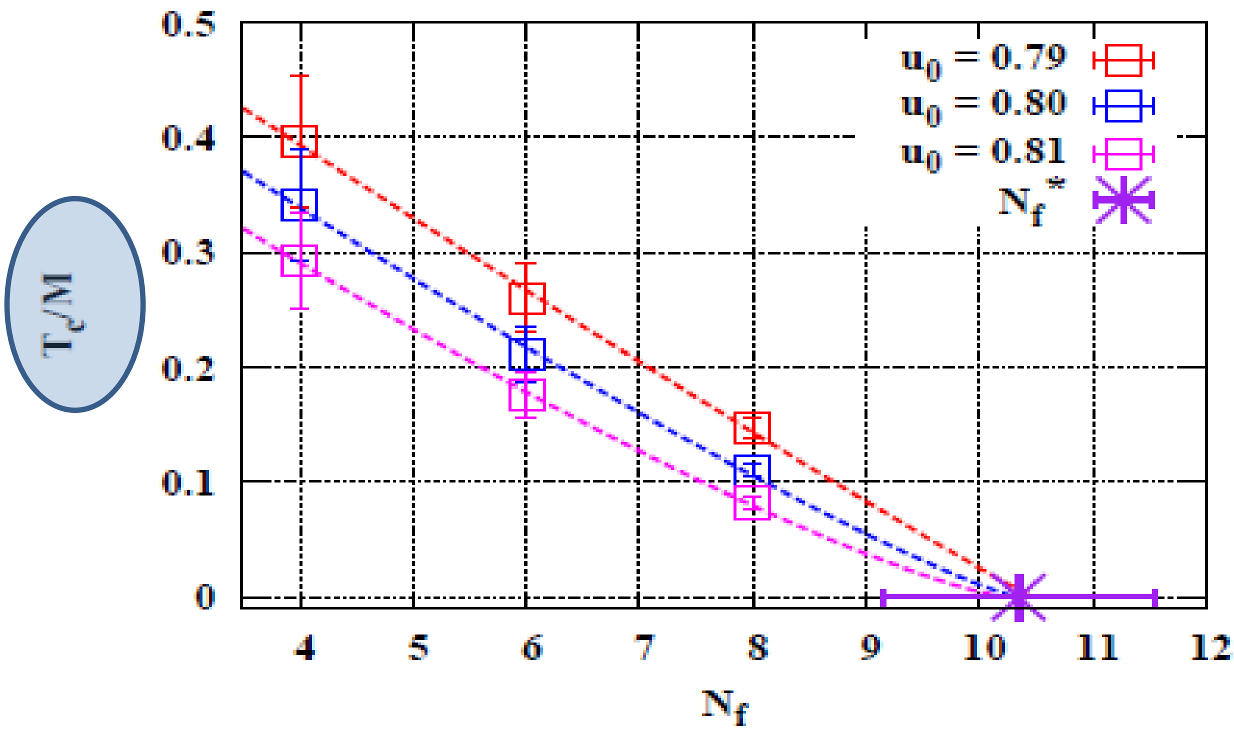
$$\frac{T_c}{M} = \frac{1}{N_t} \exp\left[\int_{g_{ref}}^{g_c} \frac{dg}{B(g)}\right] .$$

Tc/M extrapolates to zero for Nf* ~ 10.5



Tc/M extrapolates to zero for Nf ~ 10.5*

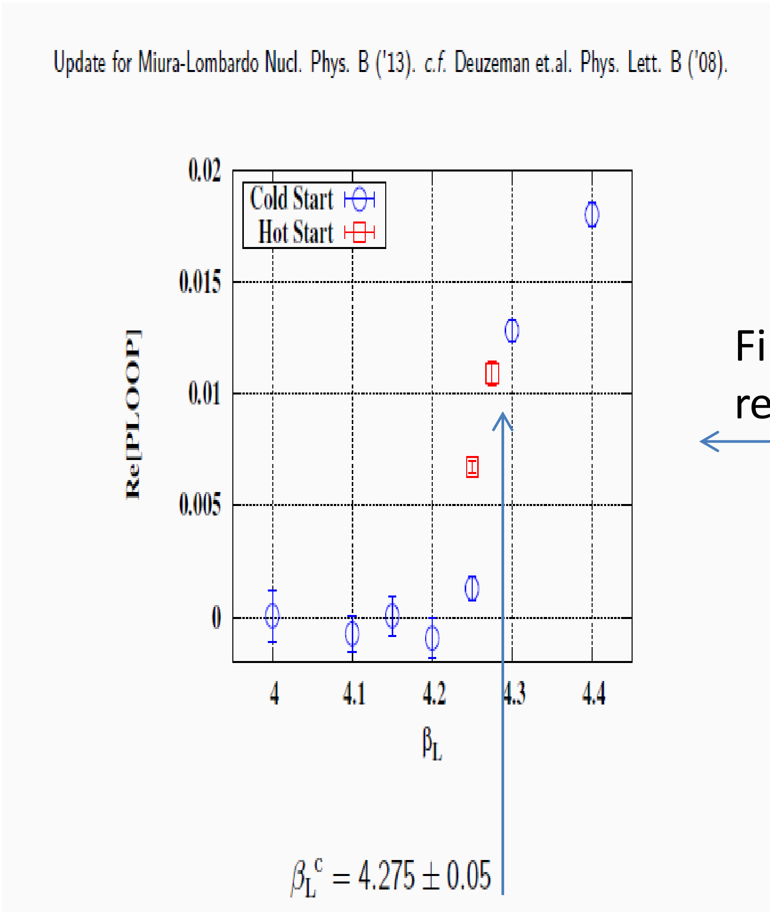
M fixed with the help of perturbation theory



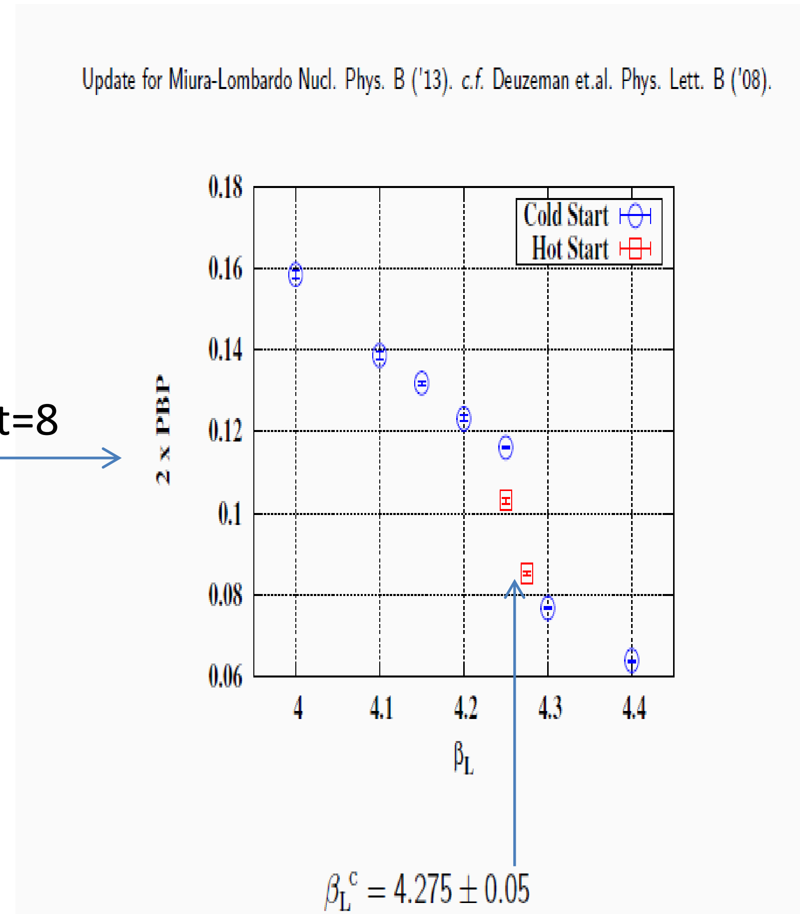
Talk by K. Miura@Lattice2013

THE STRING TENSION

Lattice setup: β for Nf=8

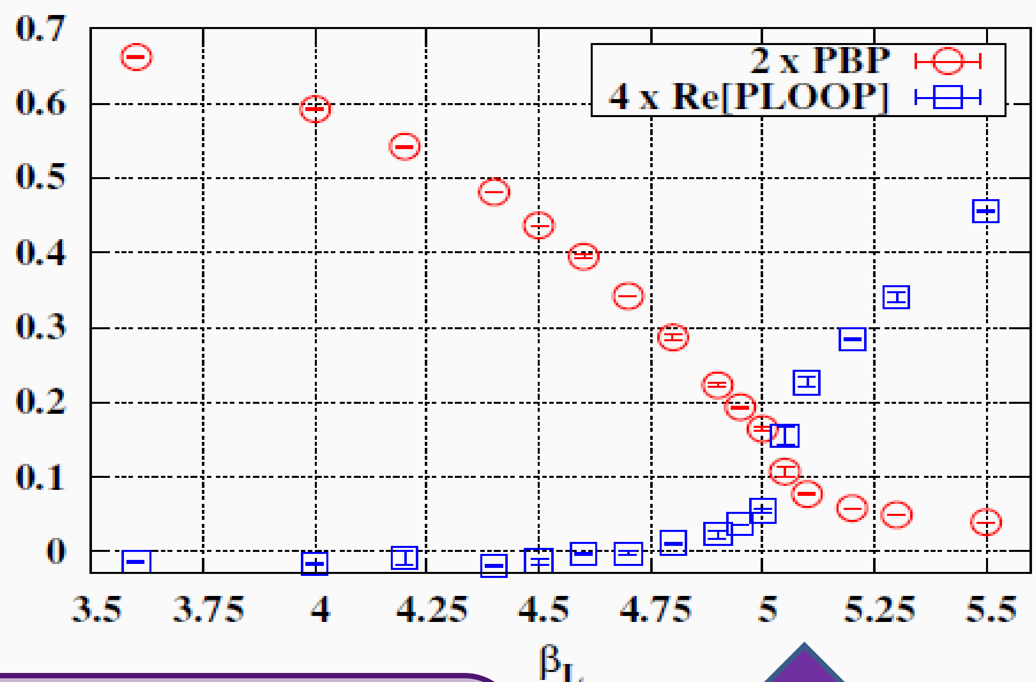


Finite T results Nt=8



Choice for the T=0 simulation

Lattice setup: β for Nf=6

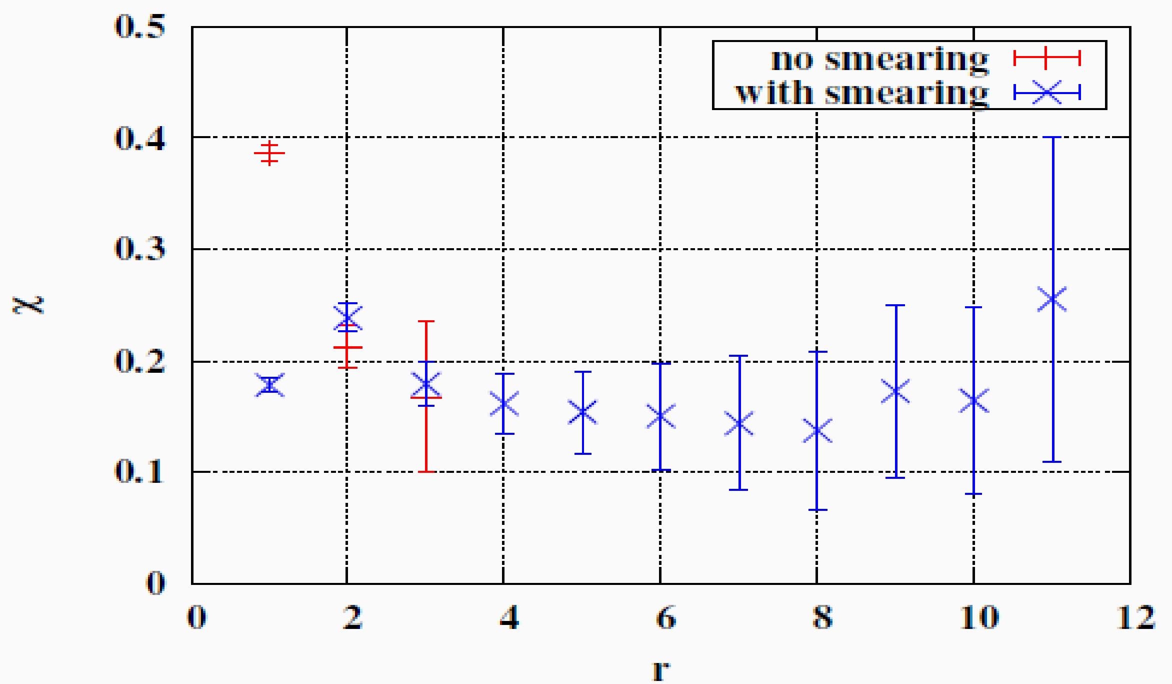


Finite temperature, Nt=6 results

βc = 5.025:
Choice for the T=0 simulations

Nf=8: Creutz ratios

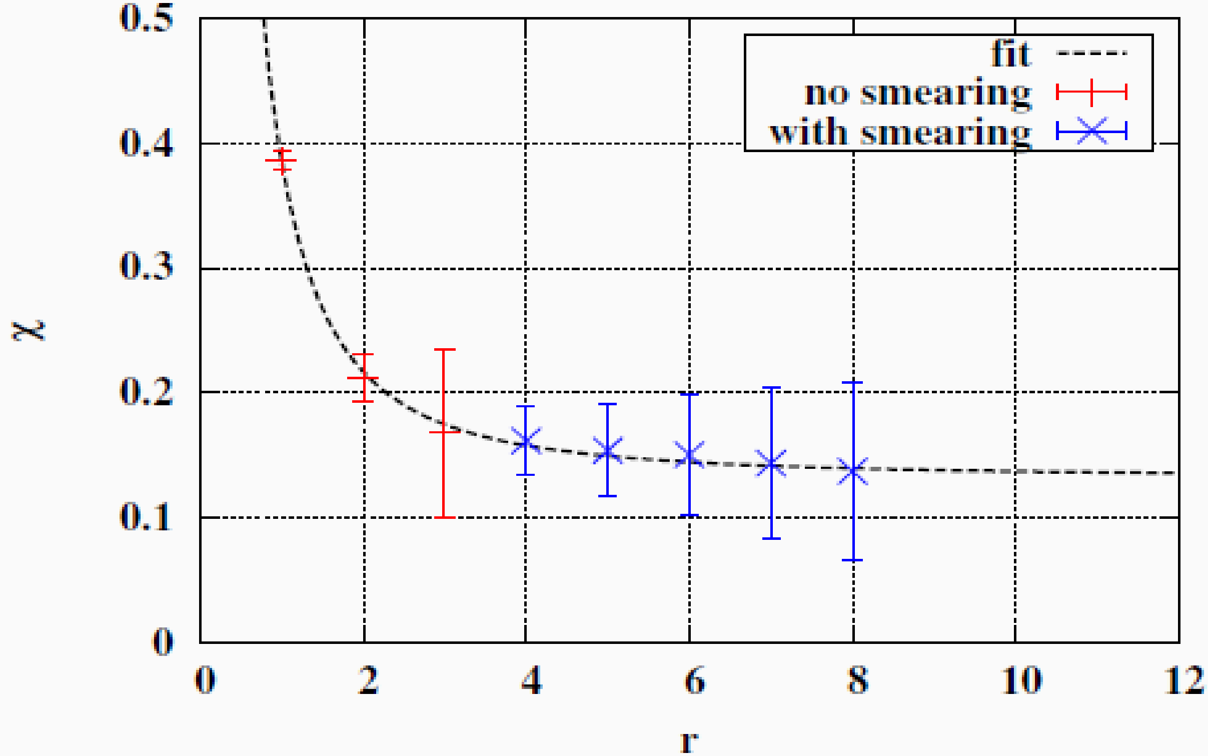
Preliminary, $\beta = \beta_L{}^c = 4.275$, $ma = 0.02$, $32^3 \times 64, t = 3$



$$\chi_{r,t} = -\log\left[\frac{W_{r,t}W_{r+1,t+1}}{W_{r,t+1}W_{r+1,t}}\right] = \frac{\alpha}{\hat{r}(\hat{r}+1)} + \hat{\sigma} \ .$$

Nf = 8 : String tension

Preliminary



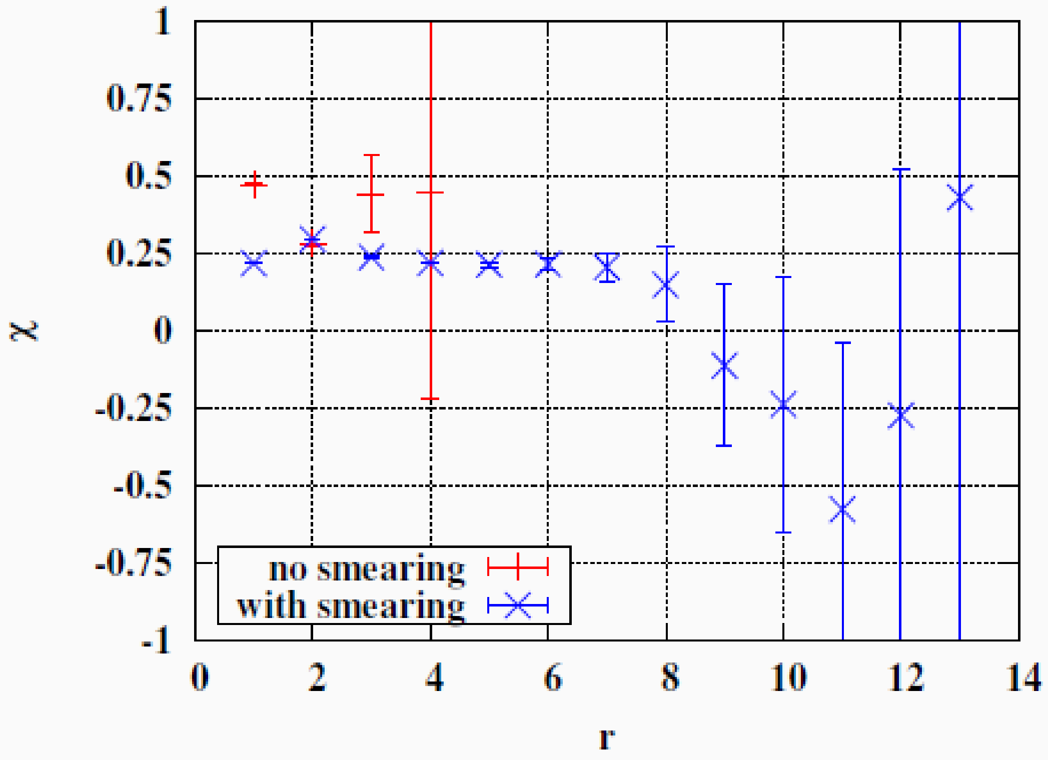
$$\alpha = 0.506821 \pm 0.005149 \quad (1.016\% \quad \text{error}) ,$$

$$\boxed{\hat{\sigma} = 0.132381 \pm 0.002283} (1.724\% \quad \text{error}) ,$$

$$X^2/\text{d.o.f.} = 0.0203838 .$$

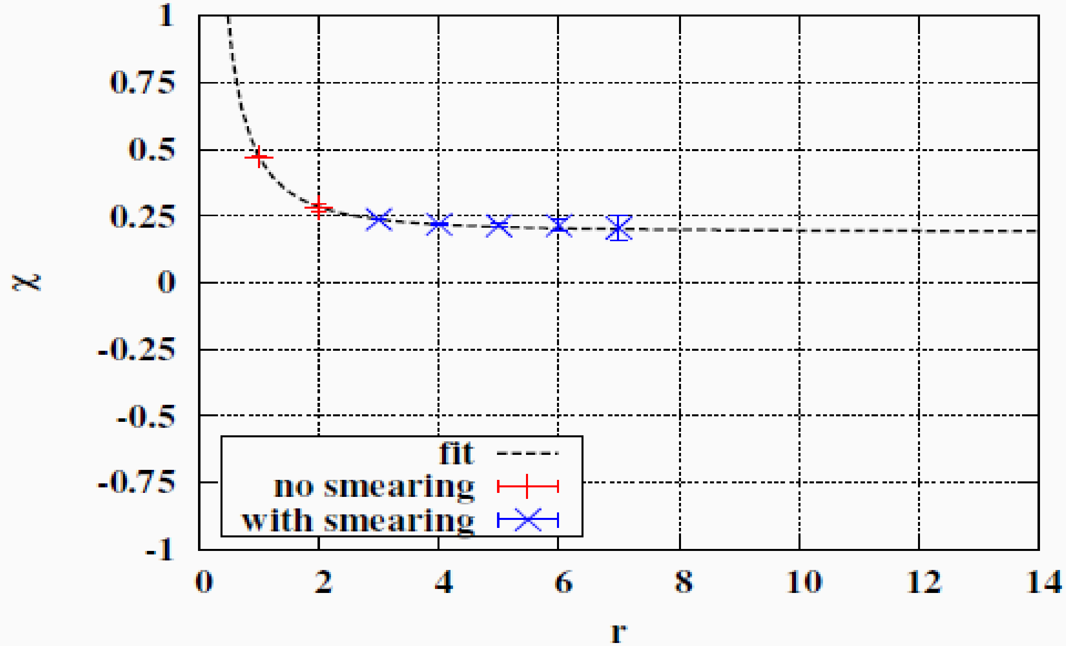
Nf=6: Creutz ratios

Preliminary, $\beta = \beta_{\mathrm{L}}^{\mathrm{c}} = 5.025$, $ma = 0.02$, $32^3 \times 64, t = 3$



Nf=6 String tension

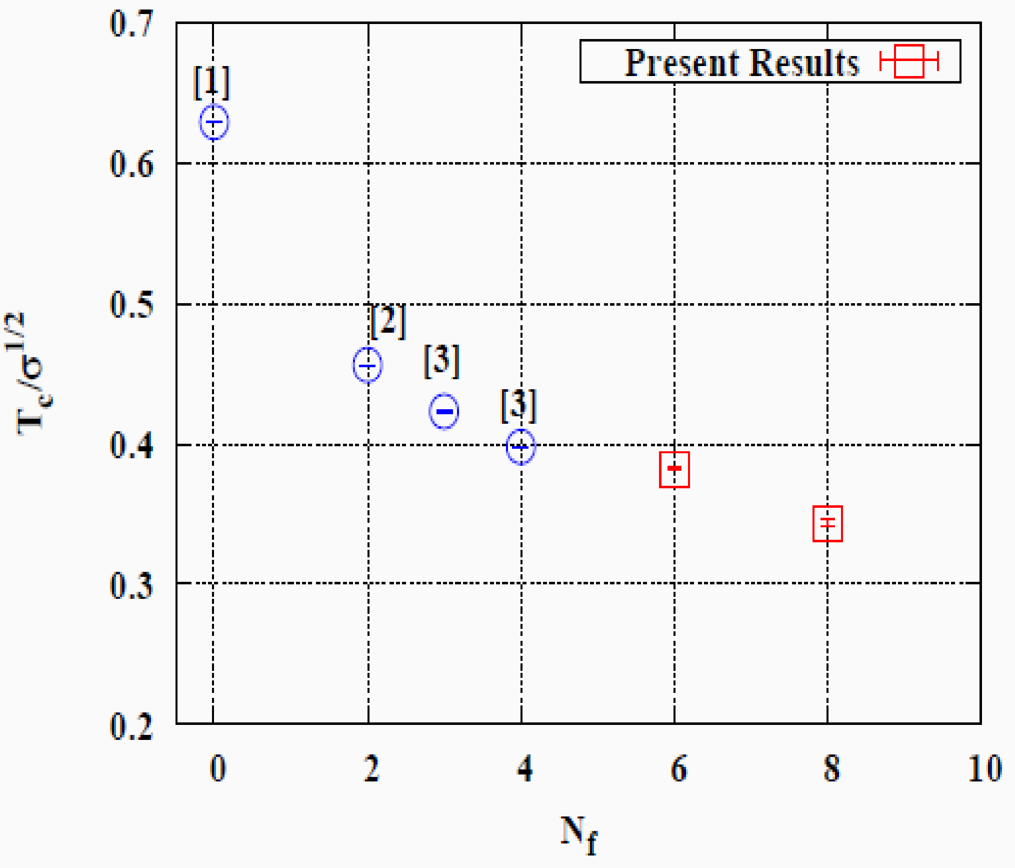
Preliminary



$$\alpha = 0.563763 \pm 0.002853 \quad (0.506\% \quad \text{error}) \,,$$
$$\hat{\sigma} = 0.190117 \pm 0.0006817 \quad (0.3586\% \quad \text{error}) \,,$$
$$X^2/\text{d.o.f.} = 0.184966 \,.$$

Tc/√ σ

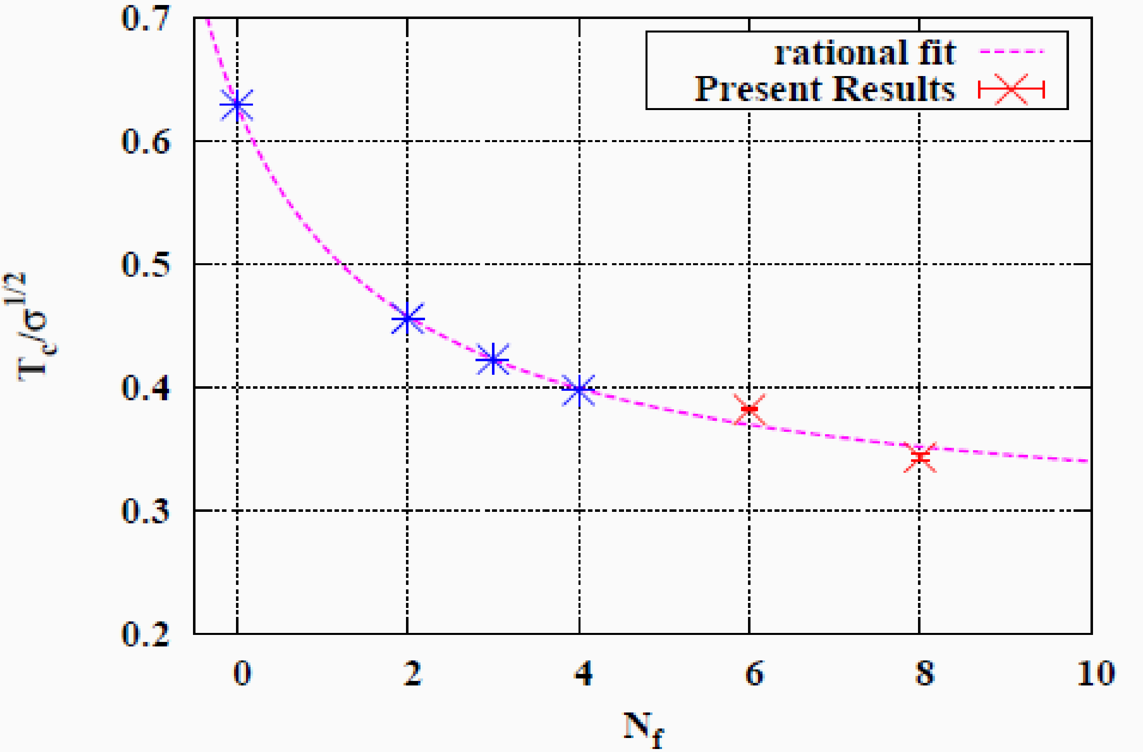
Preliminary



[1] E.Laermann, Nucl.Phys.B, '96, [2] F.Karsch and E.Laermann, Nucl.Phys.B, '01, [3] Engels, Nucl.Phys.B, '97.

Lim Nf -> Nfc Tc/√ σ = Const.

Preliminary



$$\frac{T_c}{\sqrt{\sigma}}(N_f) = C \cdot \frac{1 + D \cdot N_f}{1 + E \cdot N_f} \ .$$

RESULTS FOR W0

Wilson flow

$$\mathcal{E}(t) = t^2\langle E(x,t)\rangle\,, \quad E(x,t) \equiv -\frac{1}{2}\,\mathrm{tr}\,G_{\mu\nu}(x,t)G_{\mu\nu}(x,t)$$

$$w_0\ :\ w_0^2\mathcal{E}'(w_0^2) = 0.3\,.$$

✓Computationally easy

✓Naturally smooth

✓Well behaved at short distance

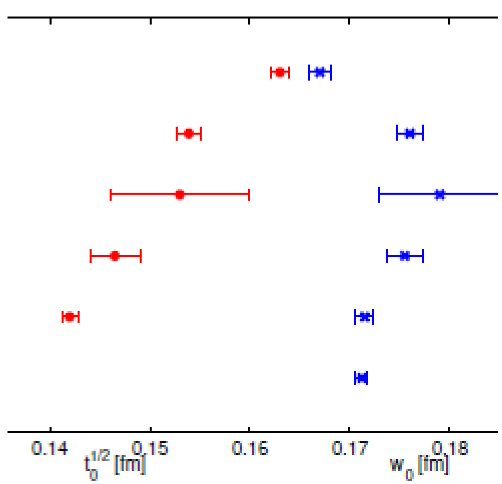
W0 vs r0

R. Sommer@Lat2013

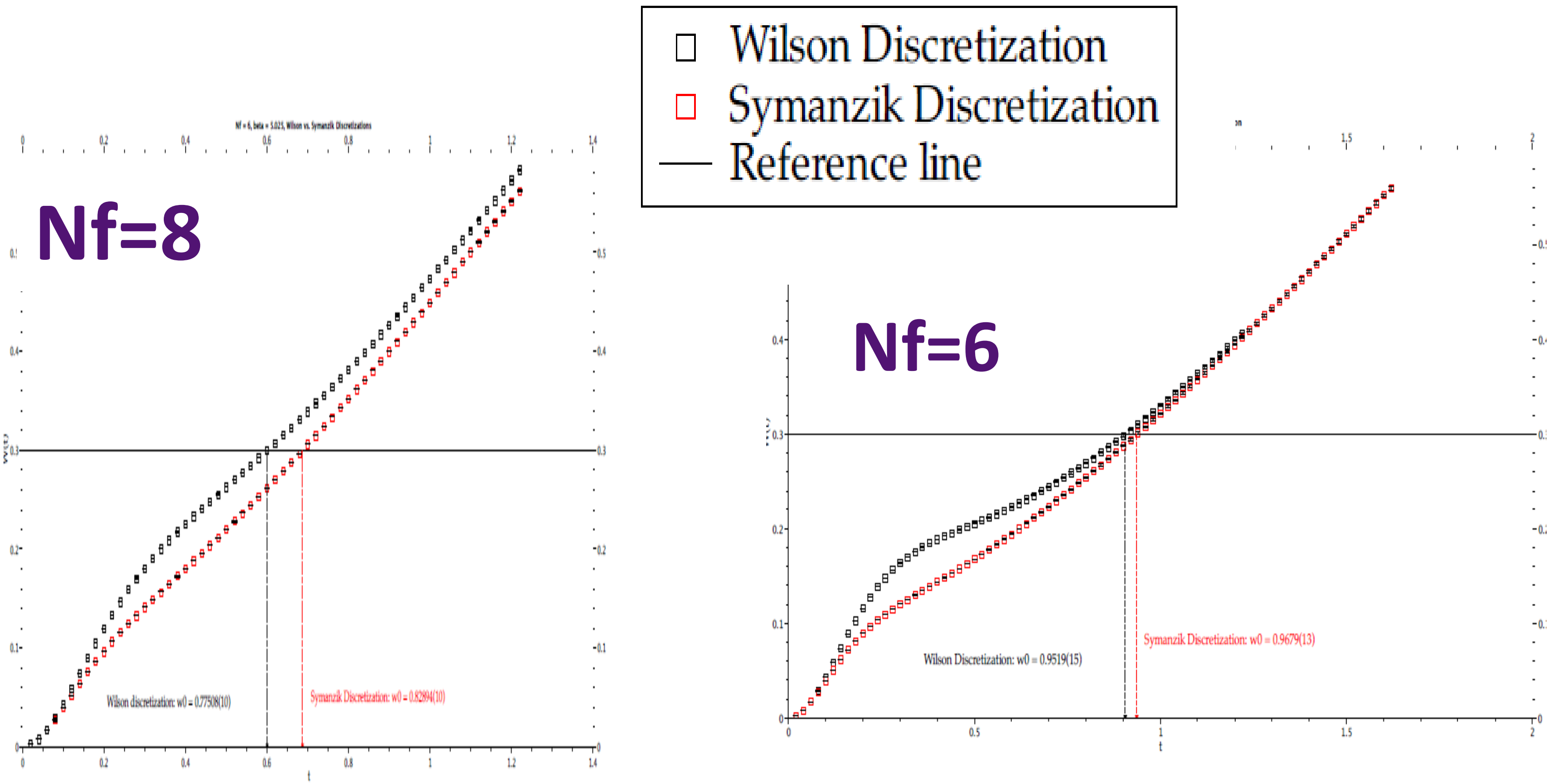
Wilson, $N_f = 2$			tmQCD, $N_f = 2$			$N_f > 2$				
r_0[fm]	from		r_0[fm]	from		N_f	r_0[fm]	r_1[fm]	from	
$0.503(10)$	f_K	[14]	$0.438(14)$	f_K	[38]	2+1	$0.466(4)^a$	$0.313(2)$	div.	[39]
$0.491(\ 6)^c$	f_K	[9]				2+1		$0.321(5)$	Υ	[1]
$0.485(\ 9)^c$	f_π	[9]	$0.420(20)$	f_π	[40]	2+1	$0.470(4)$	$0.311(2)$	f_π	[41, 42]
$0.501(15)^b$	m_p	[43]	$0.465(16)$	m_p	[44]	2+1	$0.492(10)^b$		m_Ω	[11]
$0.471(17)$	m_Ω	[13]				2+1	$0.480(11)$	$0.323(9)$	m_Ω	[10]
						2+1+1		$0.311(3)$	f_π	[45]

[a] with r_0/r_1 and r_1/a from [46]   [c] preliminary, at this conference

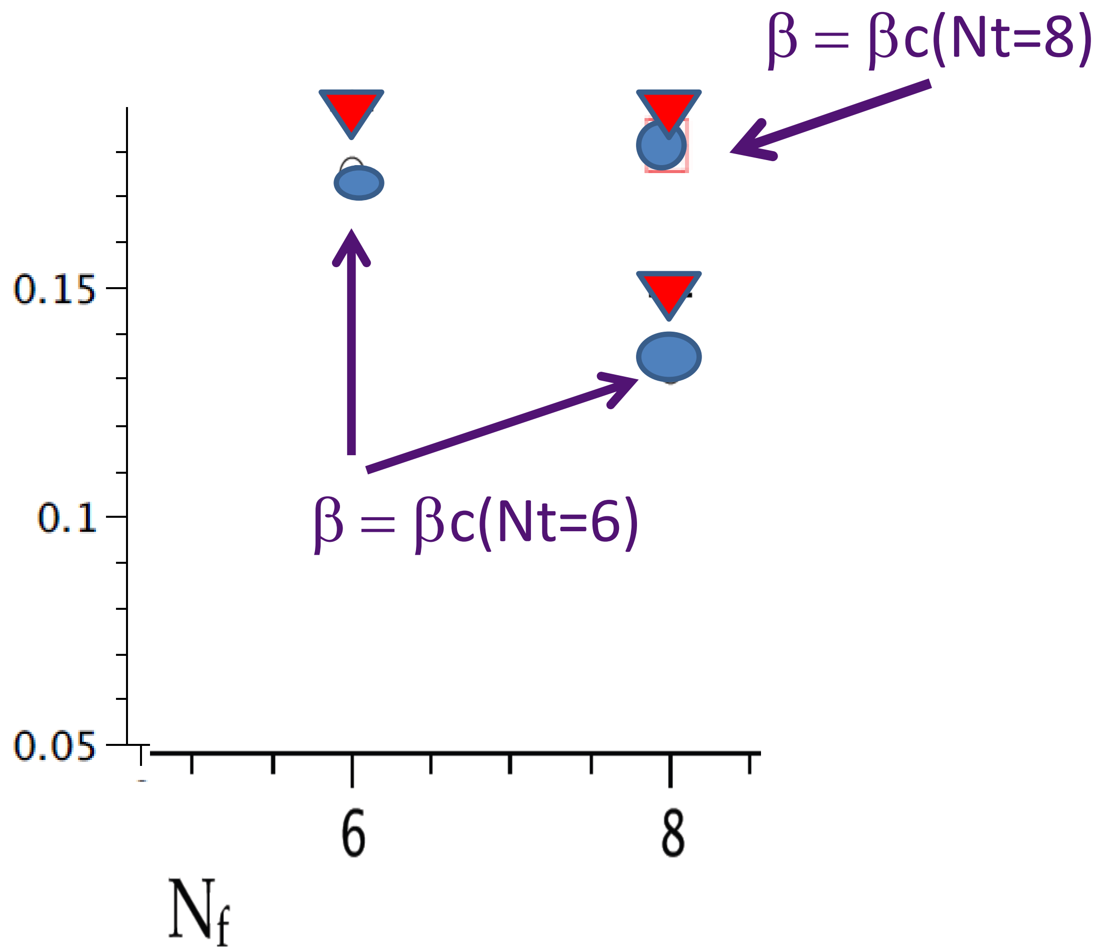
N_f	$\sqrt{t_0}$ [fm]	w_0 [fm]	from
0	0.1638(10)	0.1670(10)	$r_0 = 0.49$ fm [35, 30]
2	0.1539(12)	0.1760(13)	f_K [35, 9]
3	0.153 (7)	0.179 (6)	m_p[47]
3	0.1465(25)	0.1755(18)	m_Ω [33]
4	0.1420(8)	0.1715(9)	f_π [45]
4		0.1712(6)	f_π [34]



With and without improvement



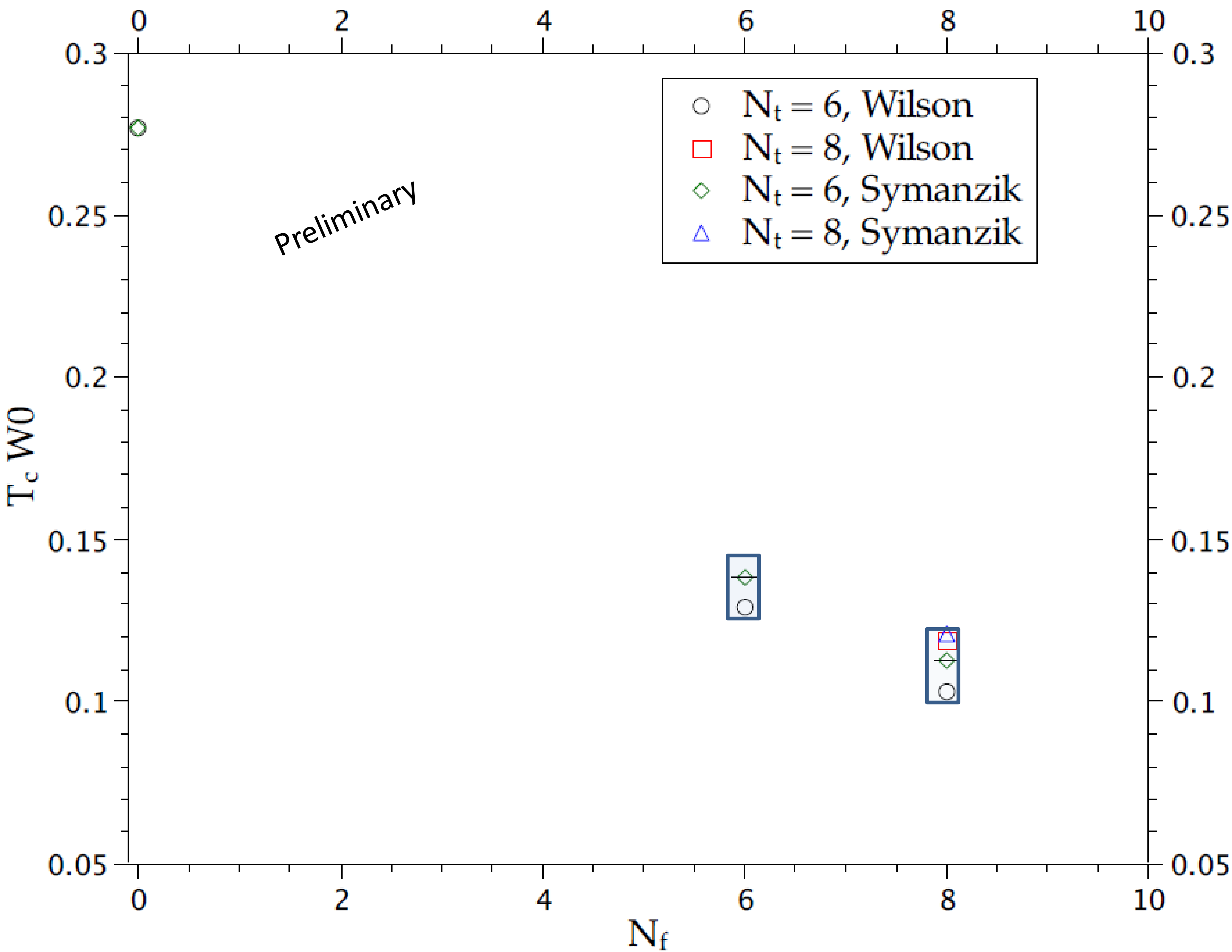
Results for w0 – improved and unimproved



Control on the continuum limit:

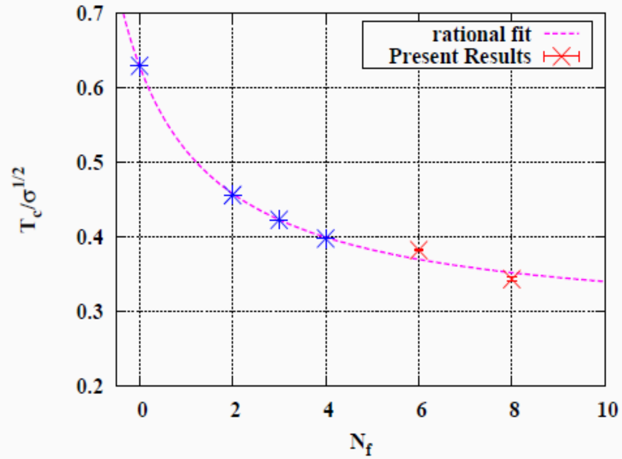
Improved and unimproved

Two different β in the more challenging Nf=8 model

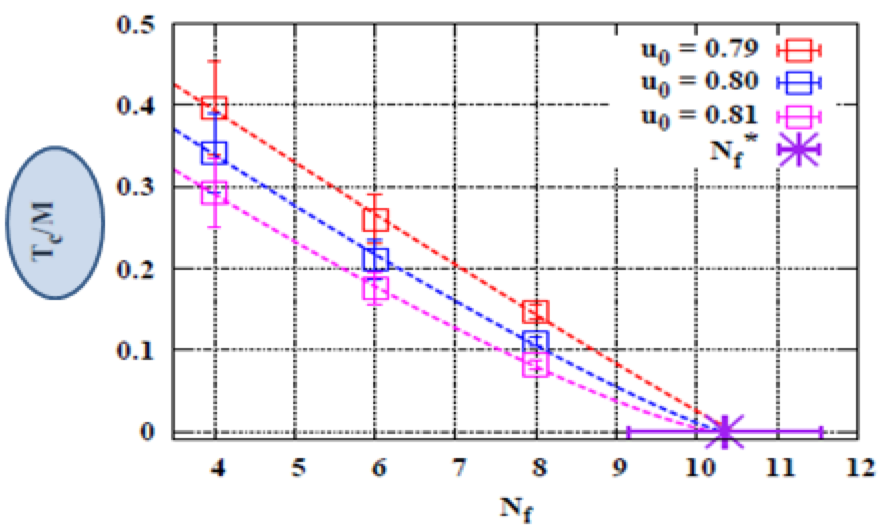


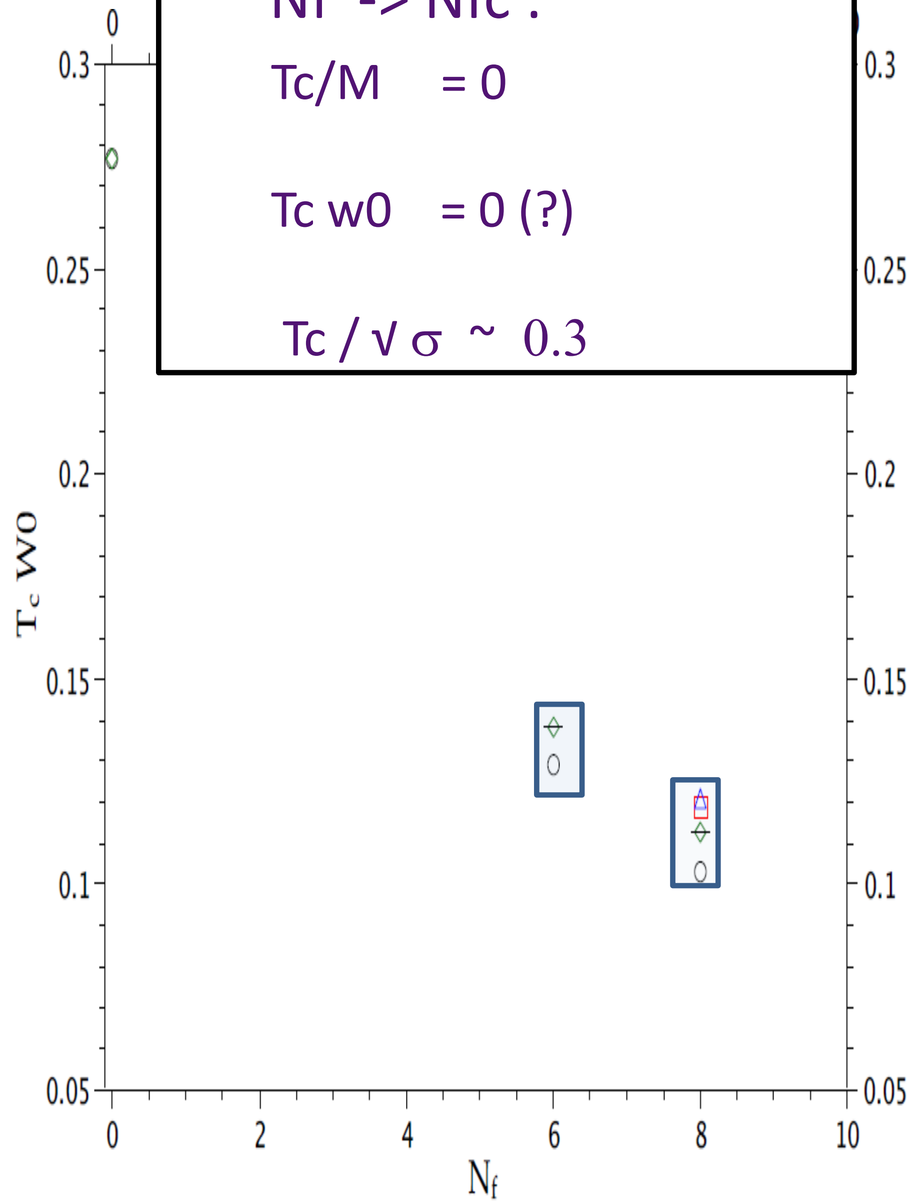
Preliminary
$N_t = 6$, Wilson
$N_t = 8$, Wilson
$N_t = 6$, Symanzik
$N_t = 8$, Symanzik
T_c W0
N_f
0
2
4
6
8
10
0.05
0.1
0.15
0.2
0.25
0.3

Preliminary



$$\frac{T_c}{\sqrt{\sigma}}(N_f) = C \cdot \frac{1 + D \cdot N_f}{1 + E \cdot N_f} \; .$$





Nf -> Nfc :

Tc/M = 0

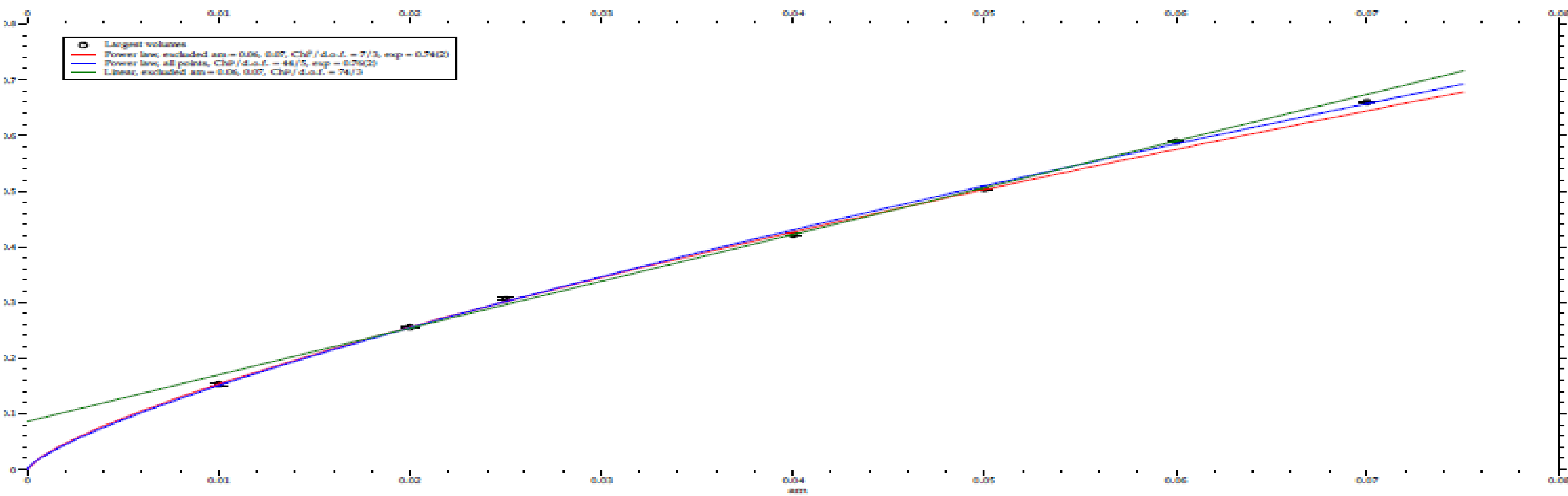
Tc w0 = 0 (?)

Tc / √ σ ~ 0.3

T.Nunes da Silva, Talk@Lattice 2013 (update of previous results)

NF=12 SPECTRUM

Nf = 12 – Pion



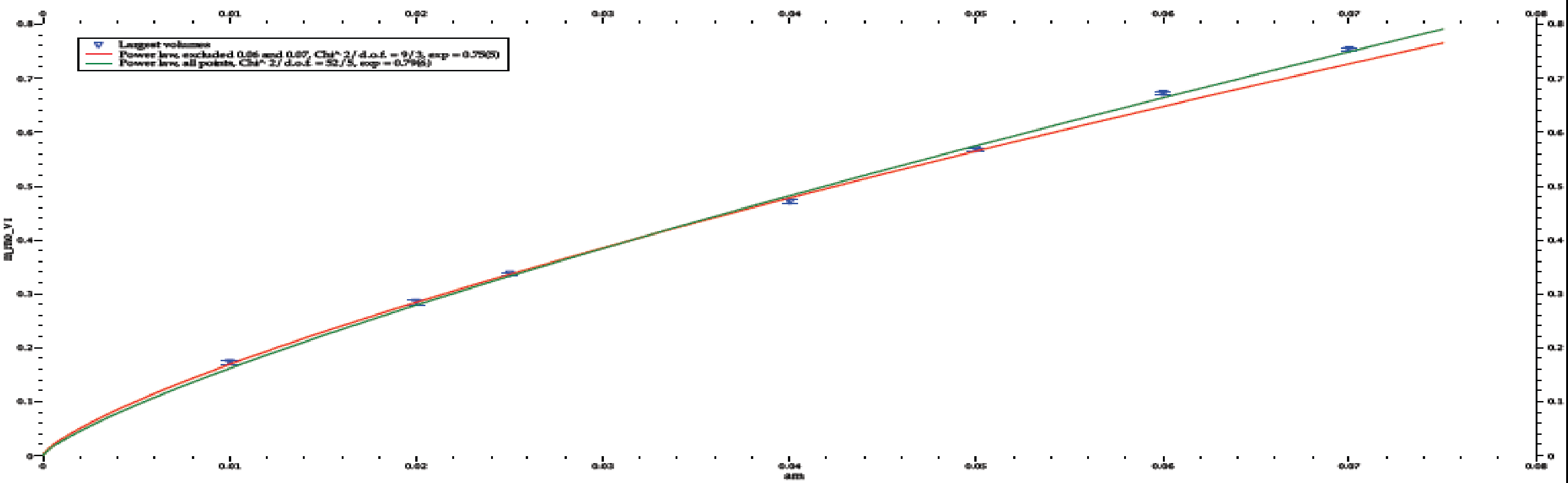
○ Largest volumes

Power law, excluded am = 0.06, 0.07, Chi^2 / d.o.f. = 7 / 3, exp = 0.74(2)

Power law, all points, Chi^2 / d.o.f. = 44 / 5, exp = 0.76(2)

Linear, excluded am = 0.06, 0.07, Chi^2 / d.o.f. = 74 / 3

Nf=12- Rho



Largest volumes

Power law, excluded 0.06 and 0.07, Chi^ 2/ d.o.f. = 9 / 3, exp = 0.75(5)

Power law, all points, Chi^ 2/ d.o.f. = 52 / 5, exp = 0.79(6)

Nf=12 Mass anomalous dimension

γ = 0.33 (2)(rho) ; 0.35(3) (pion)
at β=3.9

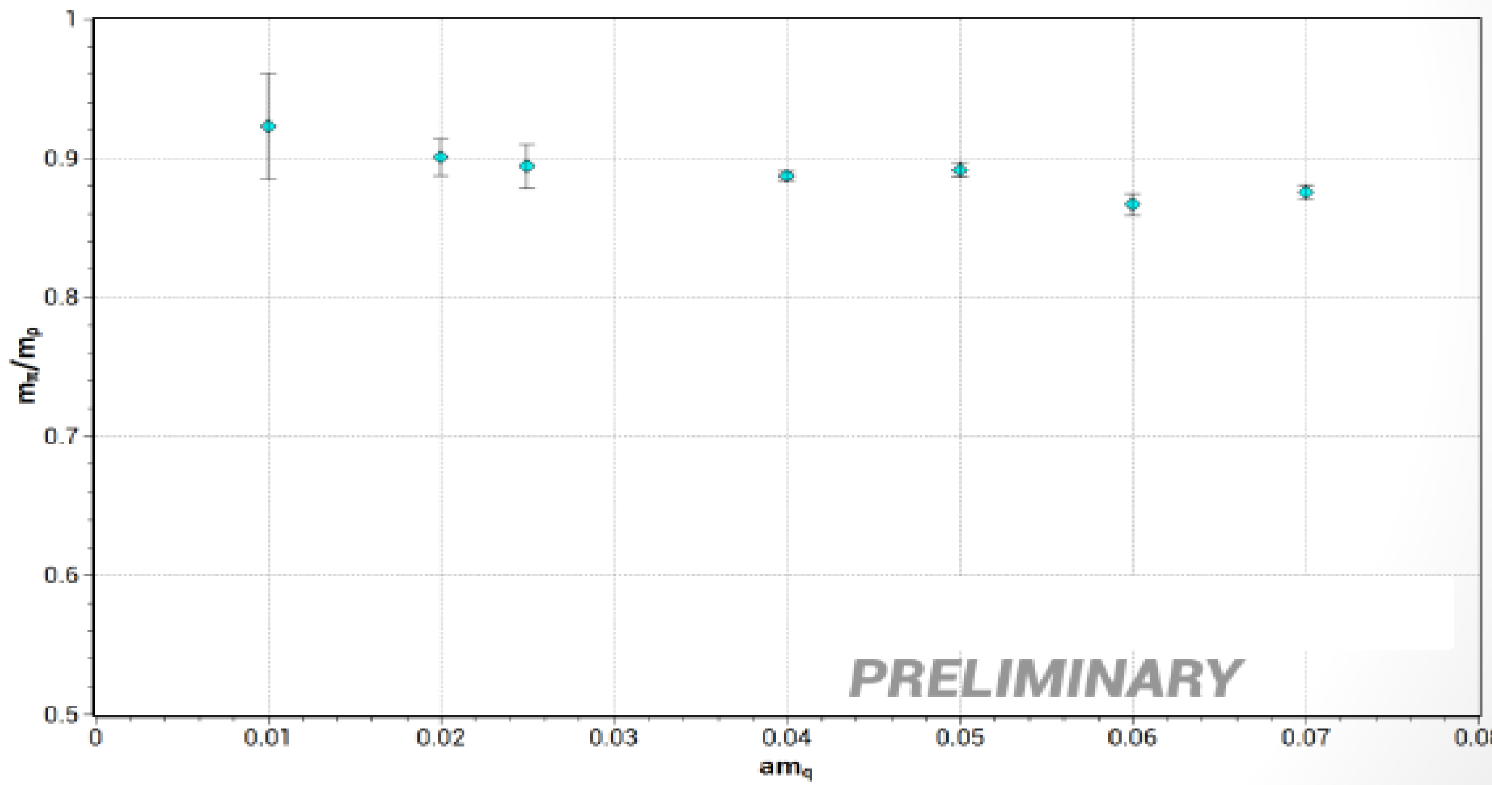
E.Itou Lat2013

	γ_g^*	γ_m^*
2 loop	0.36	0.77
4 loop (MS bar)	0.28	0.25
Step scaling (SF scheme) Ref. [15]	0.13(3)	
hyperscaling I (mCGT) Ref. [21]		0.403(13)
hyperscaling II (mCGT) Ref. [22]		0.35(23)
hyperscaling III (mCGT) Ref. [23]		0.4 − 0.5
hyperscaling IV (Dirac eigenmode) Ref. [10]		0.32(3)
Step scaling (our result) Ref. [1], [40]	0.57(35)	$0.044^{+0.062}_{-0.040}$

B.Schrock 2013

3	10	2.21	0.764	0.815
3	11	1.23	0.578	0.626
3	12	0.754	0.435	0.470
3	13	0.468	0.317	0.337
3	14	0.278	0.215	0.224
3	15	0.143	0.123	0.126
3	16	0.0416	0.0397	0.0398

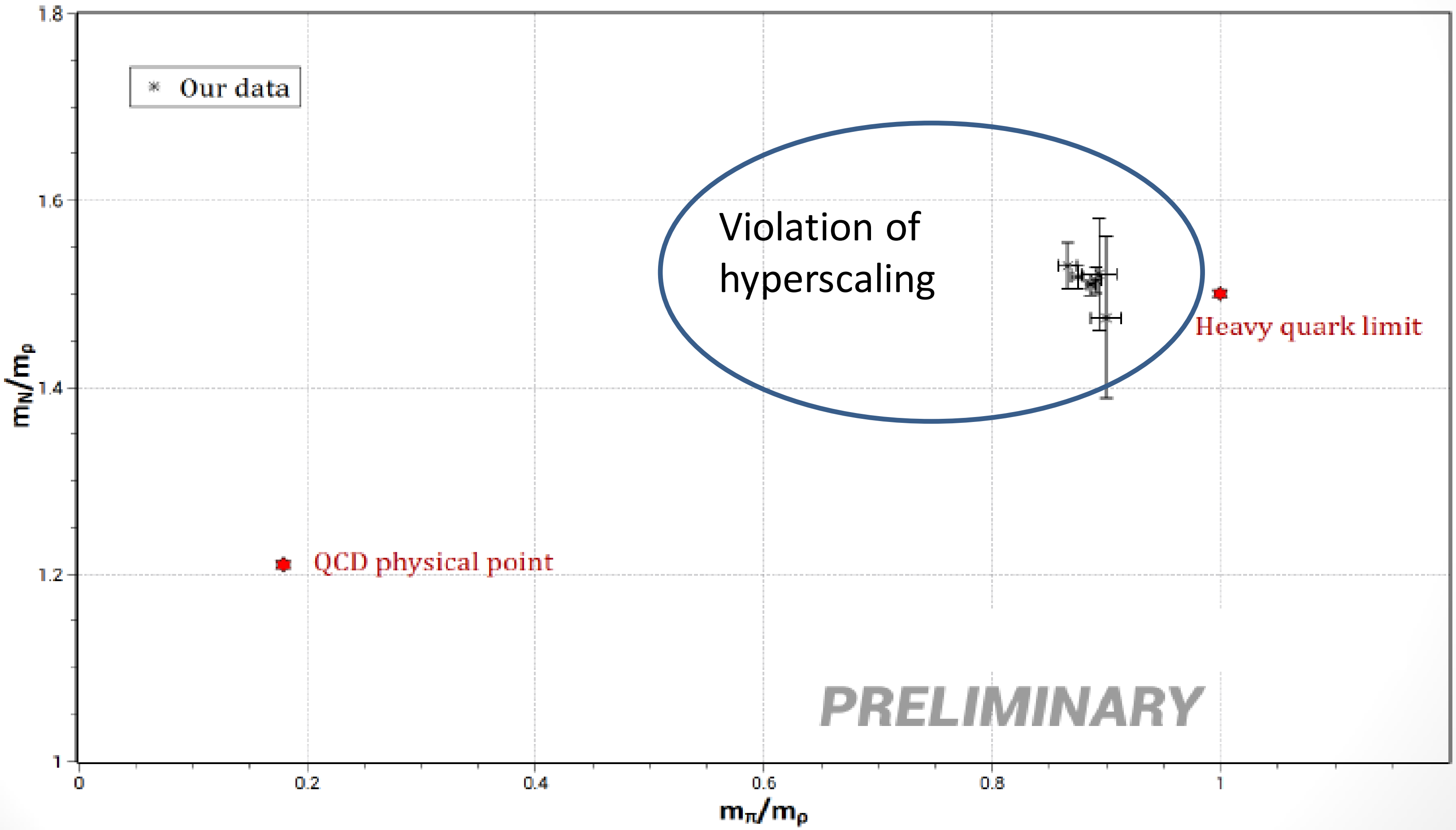
$m\pi/m\rho$



1
0.9
0.8
0.7
0.6
0.5
m_π/m_ρ
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
am_q
PRELIMINARY

the Edinburgh plot

... A simple test of hyperscaling



Summary

Indication of preconformality for Nf=8:

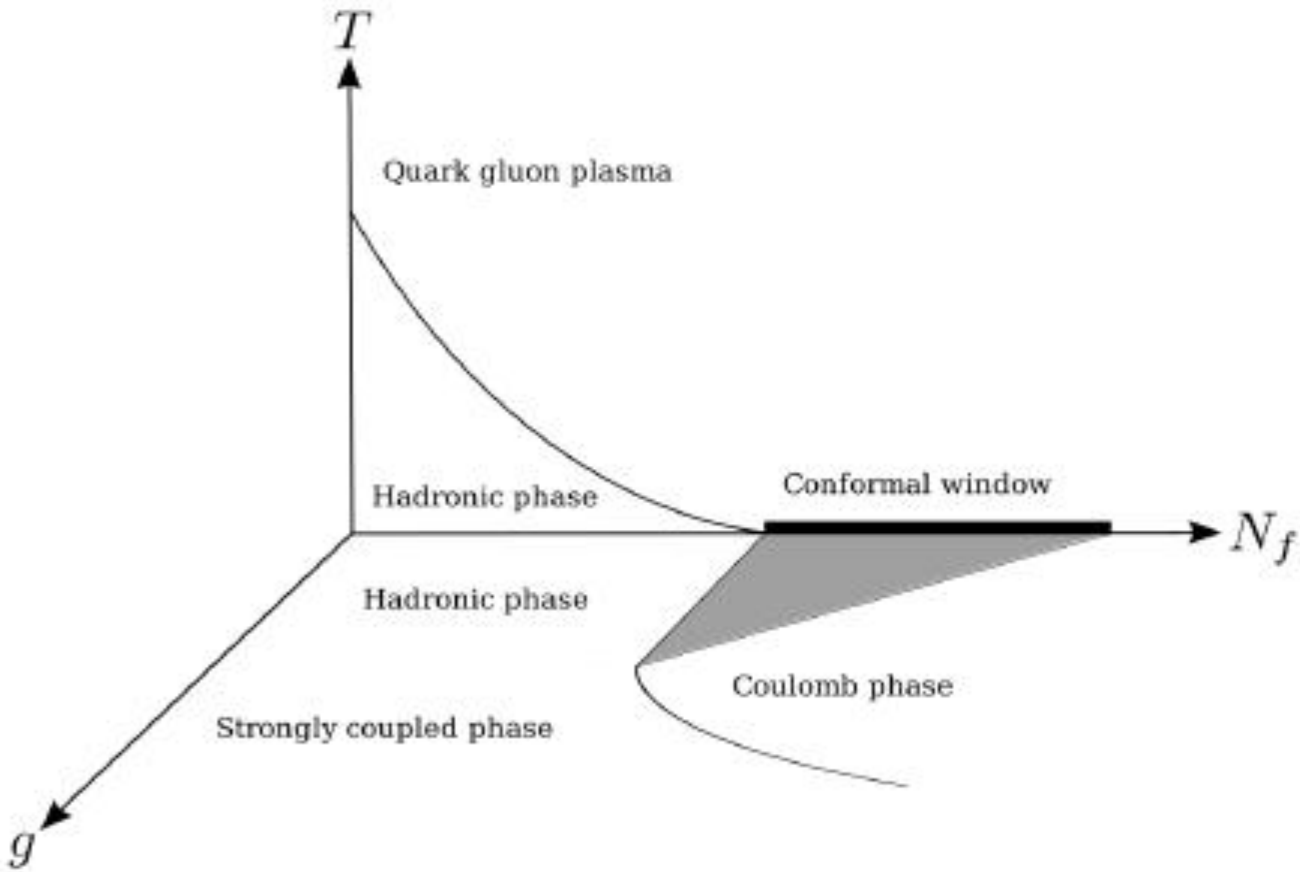
--Scale separation

-- Tc measured on a UV scale approaches 0

Tc and the string tension have a similar sensitivity to the IRFP . Their ratio is weakly dependent on Nf

Anomalous dimension $\gamma = 0.35(5)$ for Nf=12 (Indication of violation of hyperscaling)

- Backup slides


T
Quark gluon plasma
Hadronic phase
Conformal window
N_f
Hadronic phase
Coulomb phase
Strongly coupled phase
g

Thermal coupling and IRFP

We consider the critical coupling at the temperature scale 1/Nt

$$R(g_L^c, g_T^c) = 1/N_t \,,$$

$$\bar{R}(g_L{}^c, g_L{}^{\mathrm{ref}}) \equiv \frac{M(g_L{}^{\mathrm{ref}})}{a^{-1}(g_L{}^c)} = \exp\left[\int_{g_L{}^c}^{g_L{}^{\mathrm{ref}}} \frac{dg_L}{\beta(g_L)}\right]$$

$$\simeq \left(\frac{(g_L{}^c)^2}{(g_L{}^c)^2 b_1 + b_0} \frac{(g_L{}^{\mathrm{ref}})^2 b_1 + b_0}{(g_L{}^{\mathrm{ref}})^2}\right)^{-b_1/(2b_0^2)}$$

$$\times \exp\left[\frac{1}{2b_0}\left(\frac{1}{(g_L{}^{\mathrm{ref}})^2} - \frac{1}{(g_L{}^c)^2}\right)\right],$$

$$M(g_L{}^{\mathrm{ref}}) = 1/N_t \, a(g_L^c).$$

And we match it with the phenomenological zero temperature critical coupling

IRFP from couplings