Strong Interactions in the LHC Era

Physikzentrum Bad Honnef

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Evidence for scale separation in many-flavor QCD

Maria Paola Lombardo

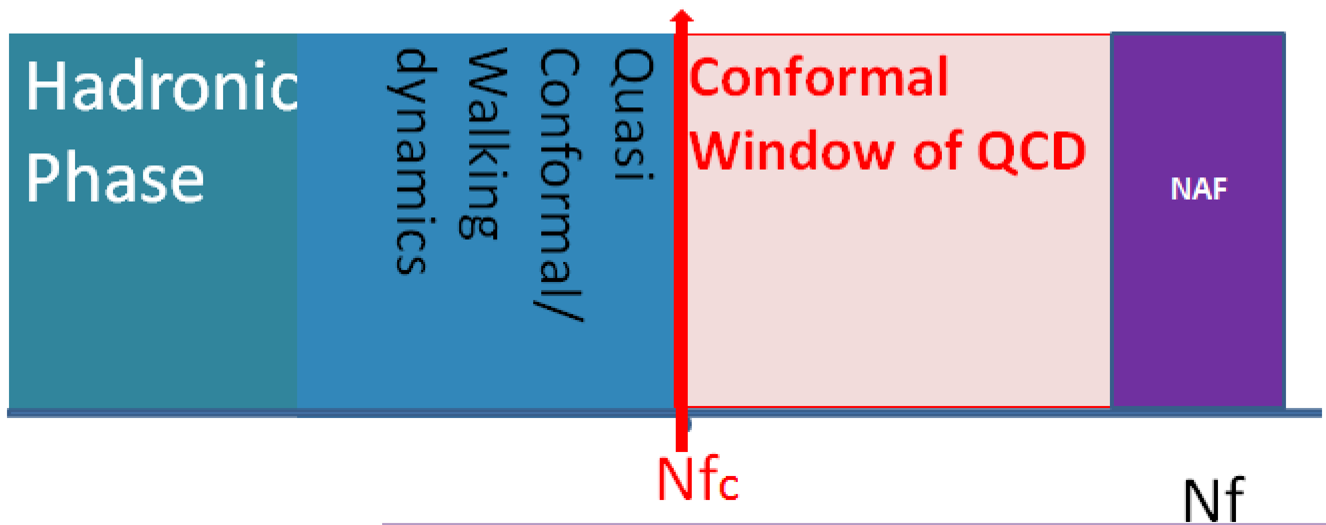
INFN

Maria Paola Lombardo — *INFN, Italy*
Kohtaroh Miura — *KMI, Nagoya University, Japan*
Elisabetta Pallante — *University of Groningen, Netherlands*
Tiago Nunes da Silva — *University of Groningen, Netherlands*

We study Nc=3,
Fundamental fermions :

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

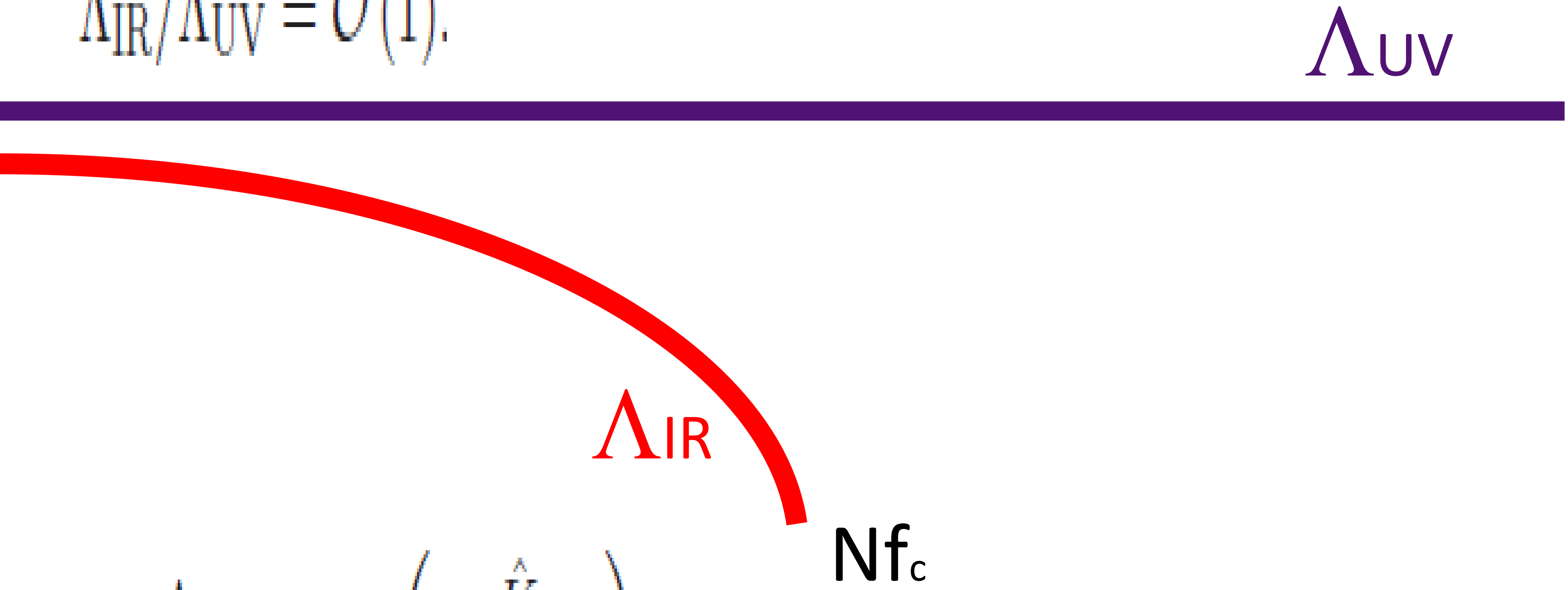
At zero and non-zero temperature.



MpL,KM,TndS,EP:
arXiv:1410.0298
arXiv:1410.2036
arXiv:1411.1657

From UV to IR

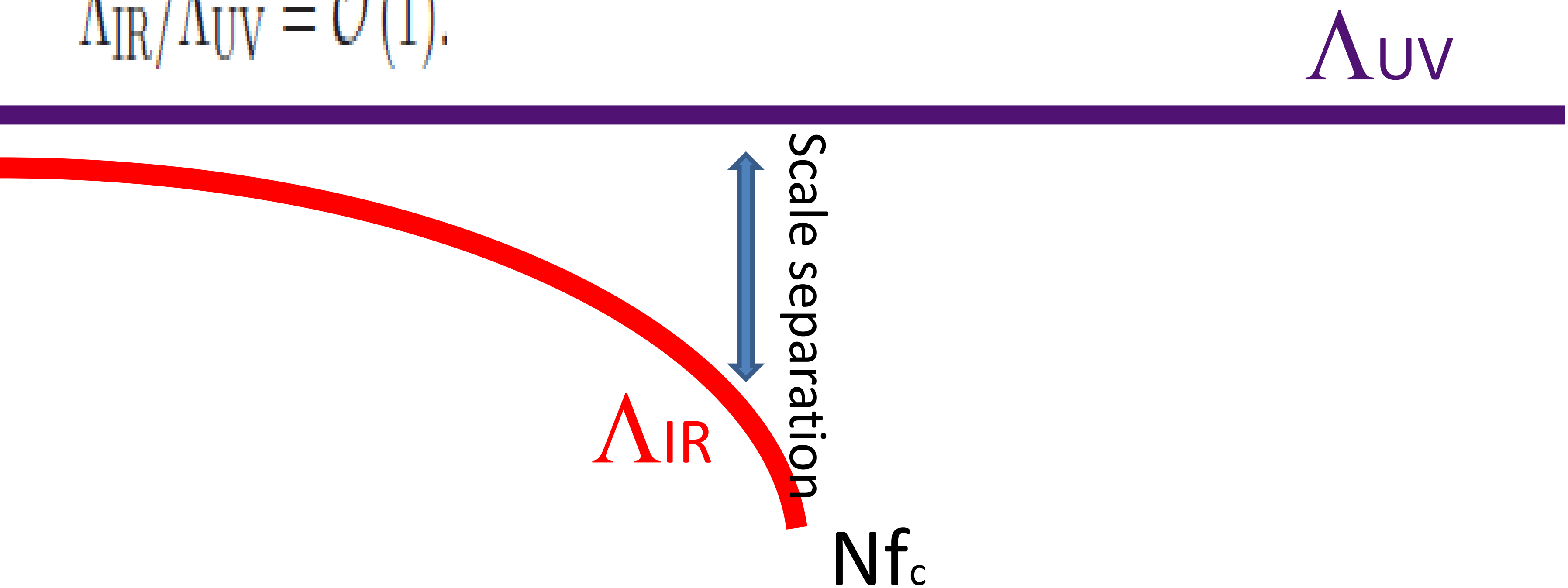
$$\Lambda_{\rm IR}/\Lambda_{\rm UV} = \mathcal{O}(1).$$



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

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

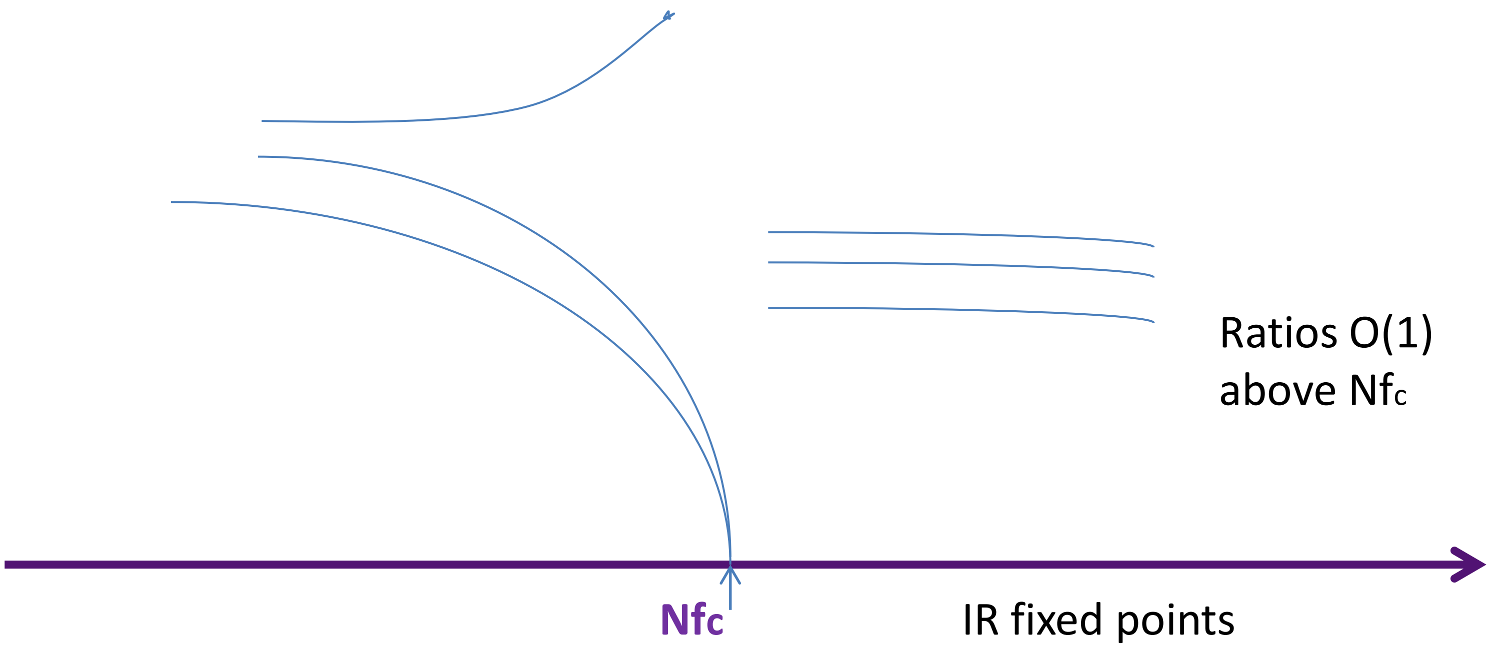
  R = O1/O2

  Miranski , Yamawaki
  Braun, Gies
  Kiritsis et al

  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**

Adimensional ratios below and above Nf_c



$O(Nf,m) = c_o(Nf)\, m^{\wedge}\delta(Nf)$

Plan

Conformal scaling and anomalous dimension (Nf=12)

Pre-conformal behaviour (Nf=6,8)

NF=12 CONFORMAL SCALING AND ANOMALOUS DIMENSION

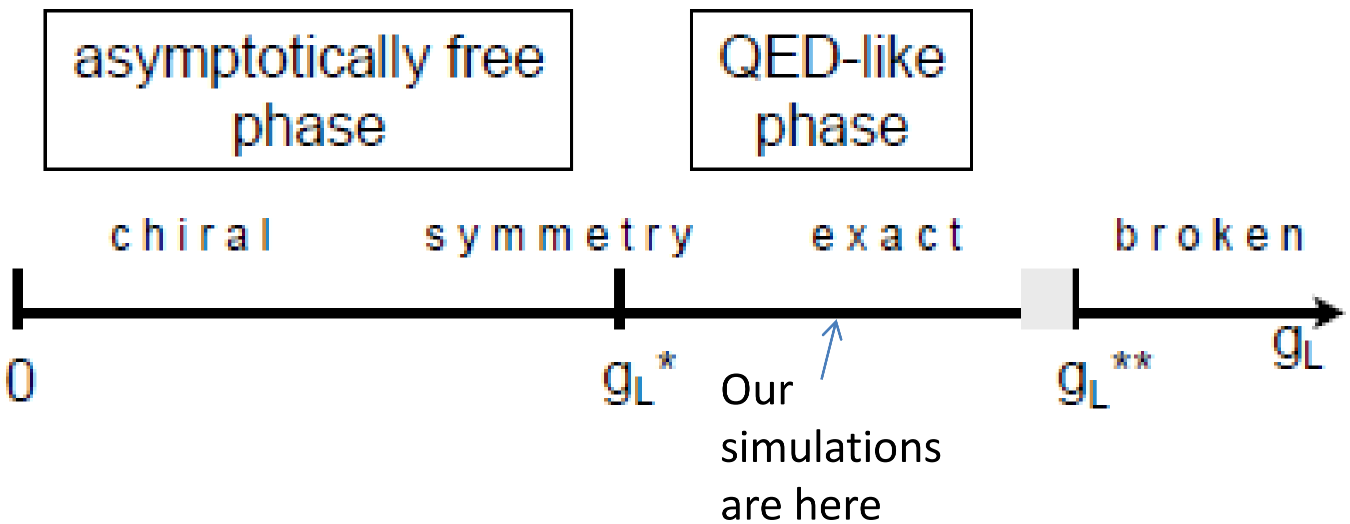
Lattice corrections to conformal scaling

1: Size $M_H = L^{-1} f_H(x)$ $x \equiv Lm^{1/y_m}$

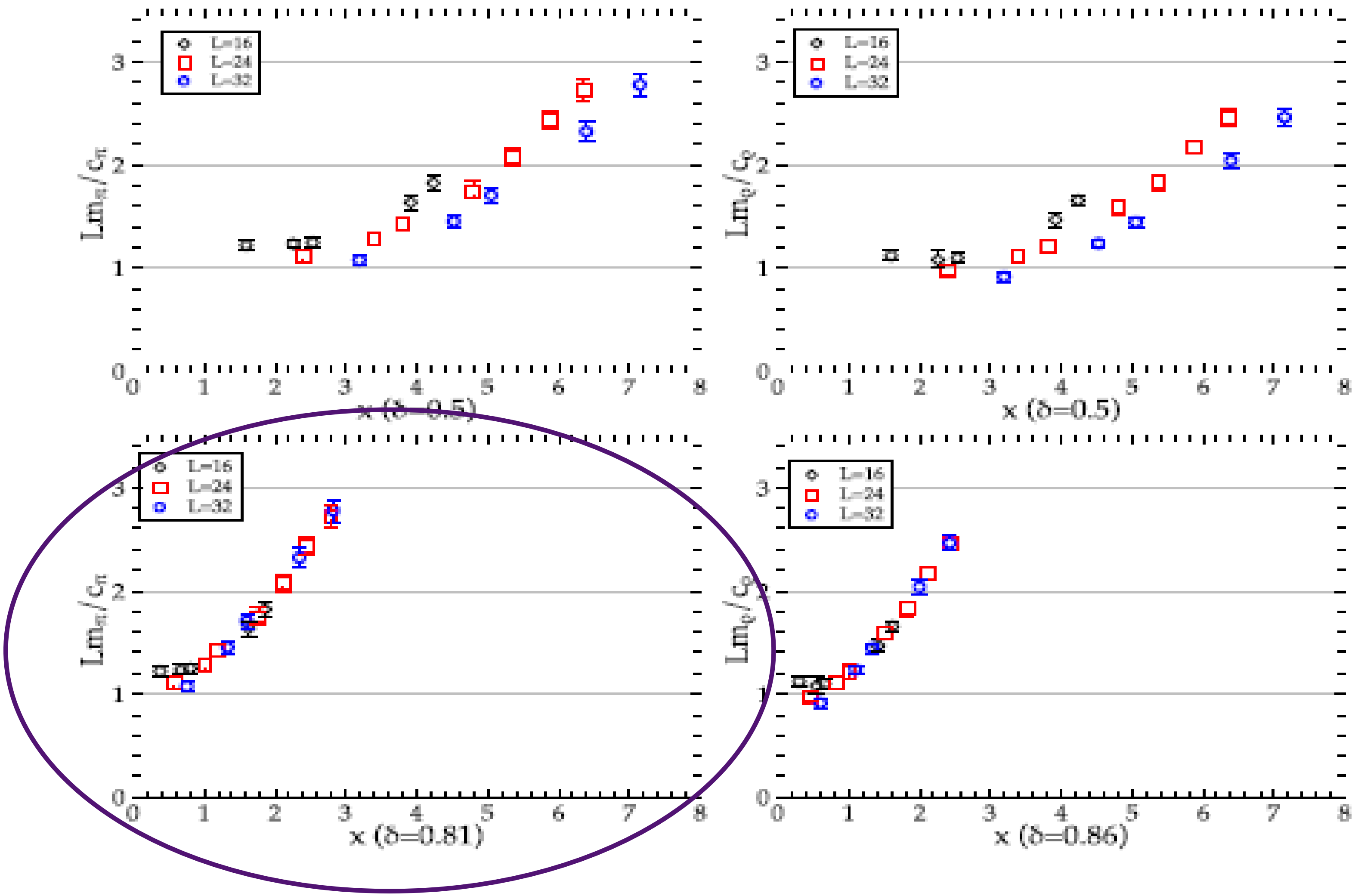
2: Coupling $M_H = L^{-1} f_H\left(x, g_0 m^{\omega}\right)$

Del Debbio, Zwicky;
Hasenfratz et al;
MpL, da Silva, Miura, Pallante

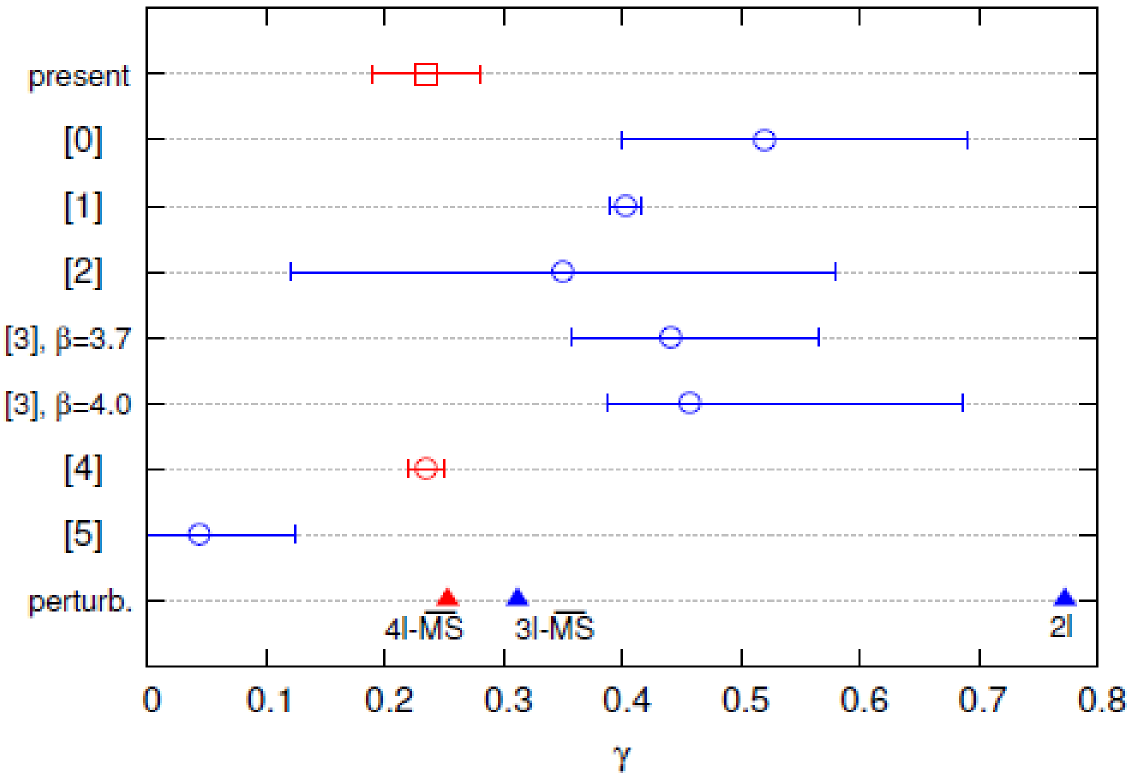
$$LM_H = F_H(x)\left\{1 + g_0 m^{\omega} G_H(x) + \mathcal{O}\left(g_0^2 m^{2\omega}\right)\right\}$$

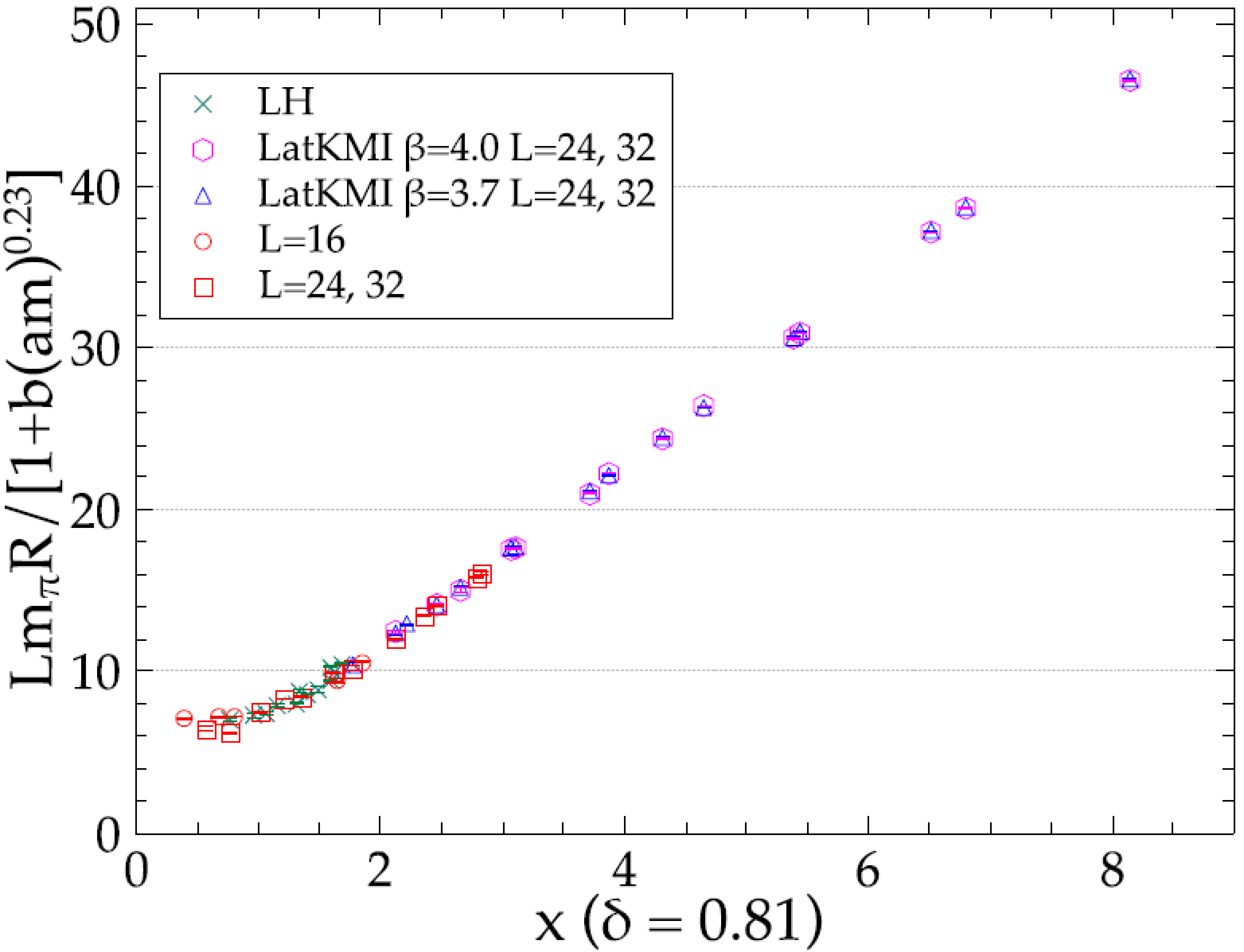


Anomalous dimension from the QED phase?



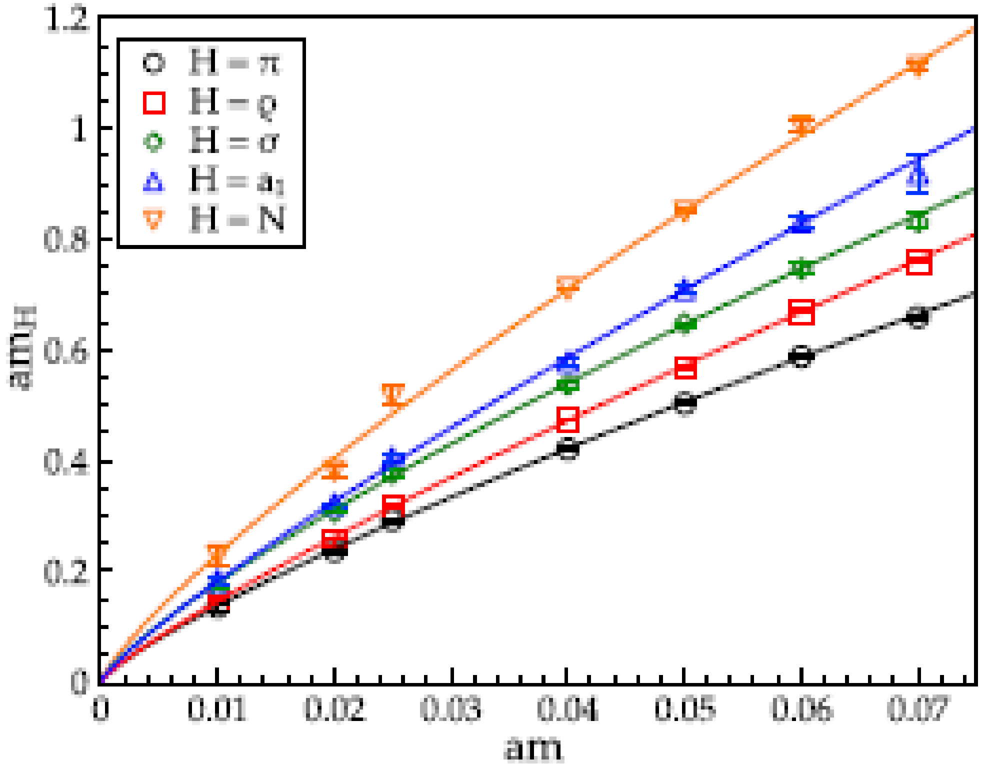
Summary of the results: accidental agreement??



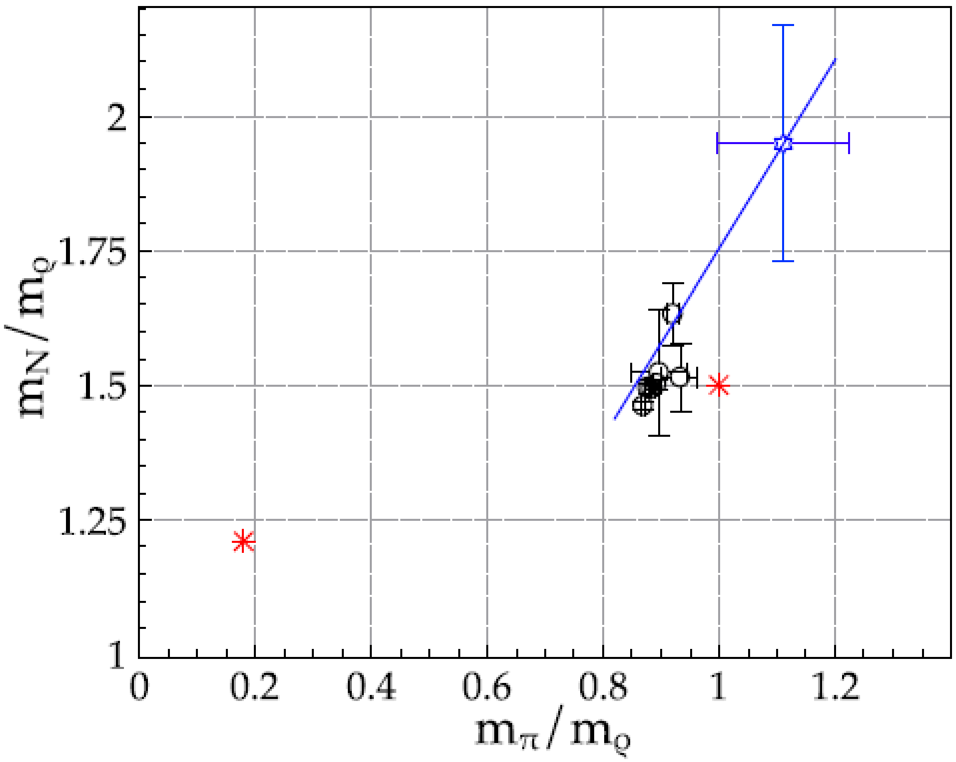


LH
LatKMI β=4.0 L=24, 32
LatKMI β=3.7 L=24, 32
L=16
L=24, 32
$Lm_\pi R / [1+b(am)^{0.23}]$
x (δ = 0.81)
0
10
20
30
40
50
0
2
4
6
8

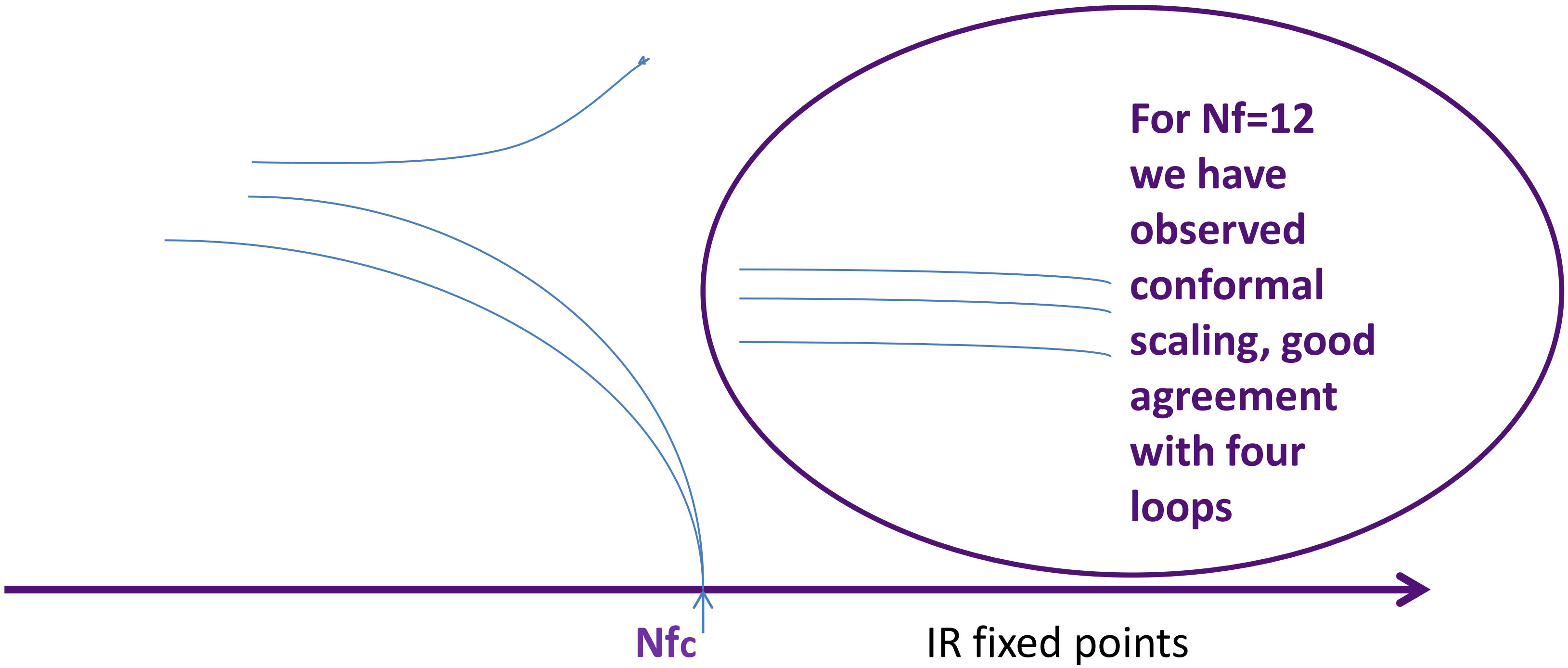
Hadron spectrum



Ratios in the conformal window at a glance: the Edinburgh plot



Adimensional ratios below and above Nfc



O(Nf,m) = c_o(Nf) m^δ(Nf)

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

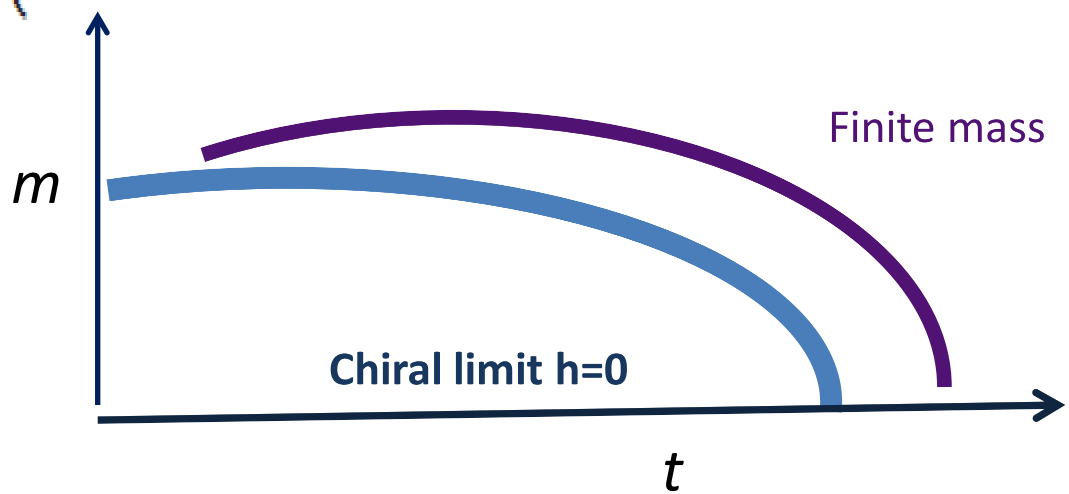
Scaling for essential singularities

Nogada, Hasegawa, Nemoto,PRL 2012

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

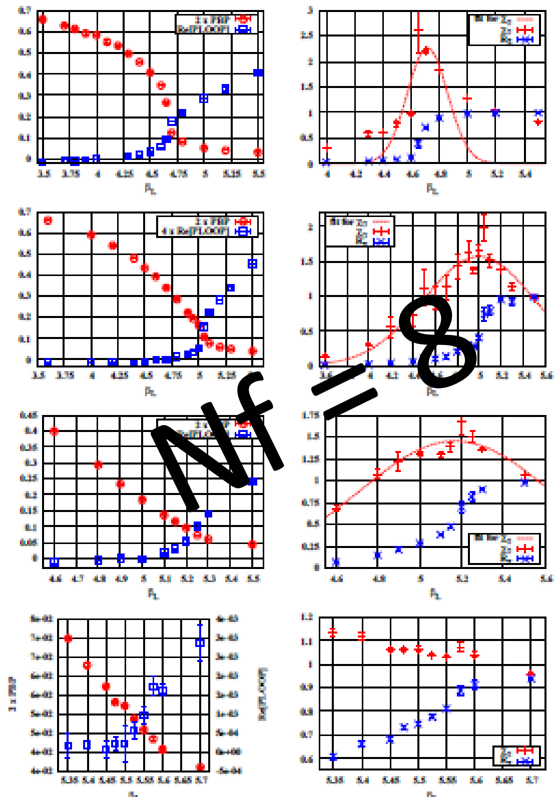
$$m \propto \begin{cases} e^{-(1-y_h)(t/t_0)^{-x_t}} & \text{for } he^{y_h(t/t_0)^{-x_t}} \ll 1 \\ h^{y_h^{-1}-1} & \text{for } he^{y_h(t/t_0)^{-x_t}} \gg 1 \end{cases}$$

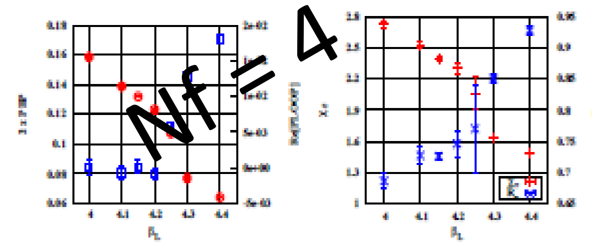
m <-> Chiral Condensate
h <-> bare mass
t <-> Nfc – Nc

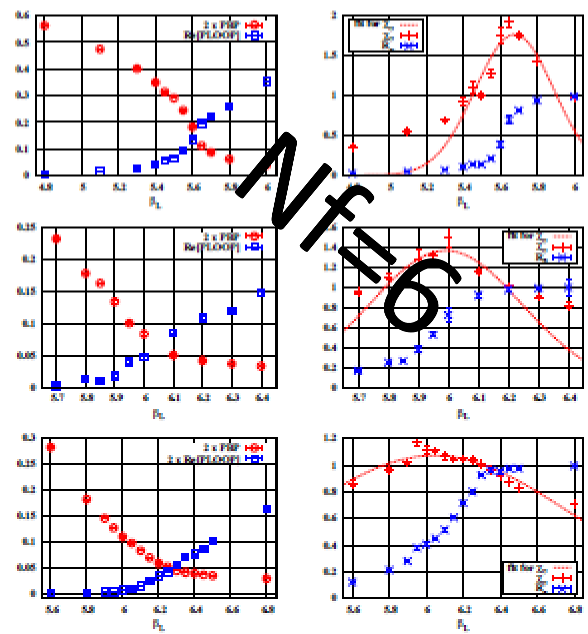


Within the scaling window data at finite mass contain information on the critical behaviour . They can can be approximativelydescribed as zero mass ones, but with a larger apparent critical point.

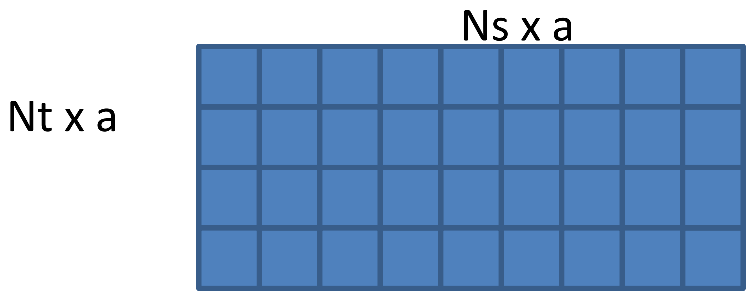
We studied the thermal transition for several Nf and several Nt







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

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

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

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

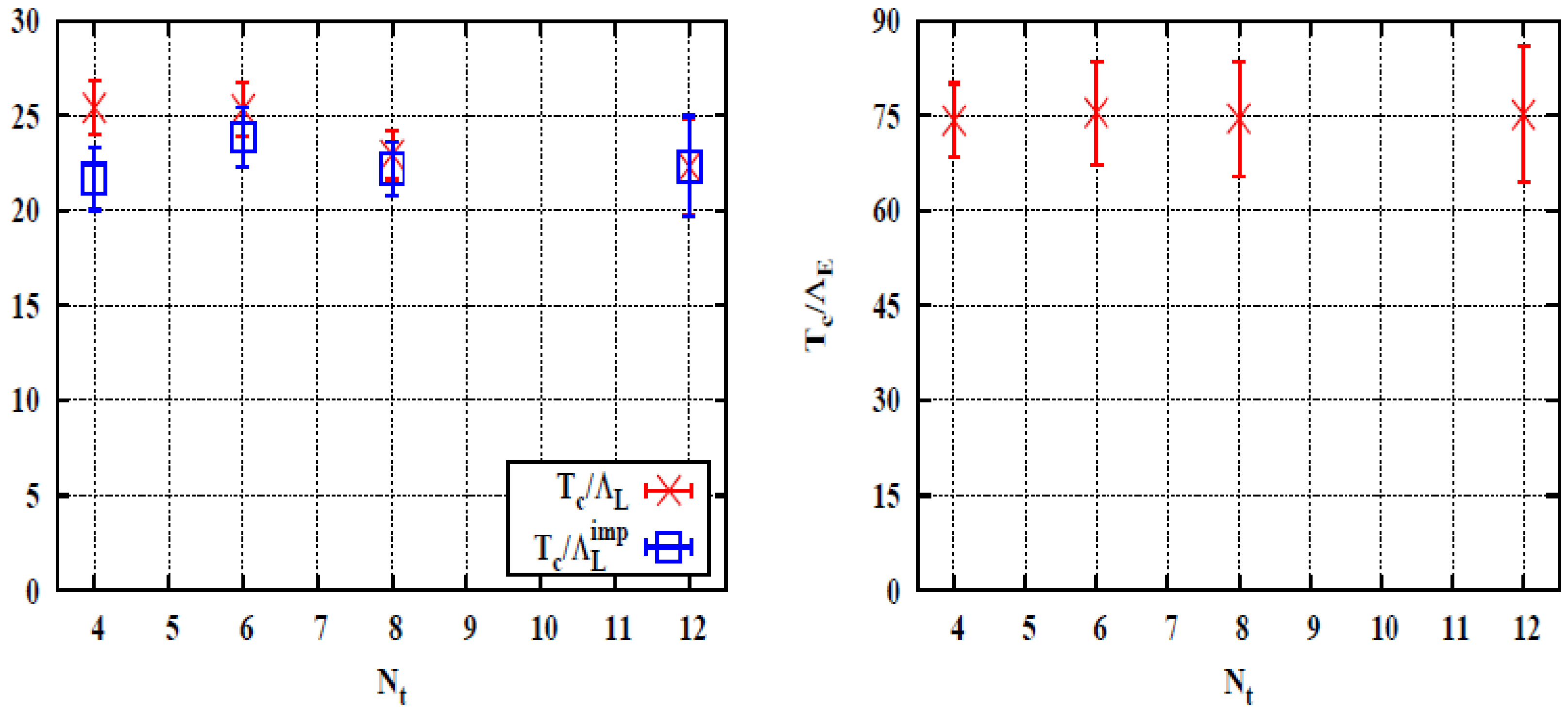
$$R(g_{L/E}) \equiv a(g_{L/E})\Lambda_{L/E} = (b_0 g_{L/E}^2)^{-b_1/(2b_0^2)} \exp\left[\frac{-1}{2b_0 g_{L/E}}\right]$$

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

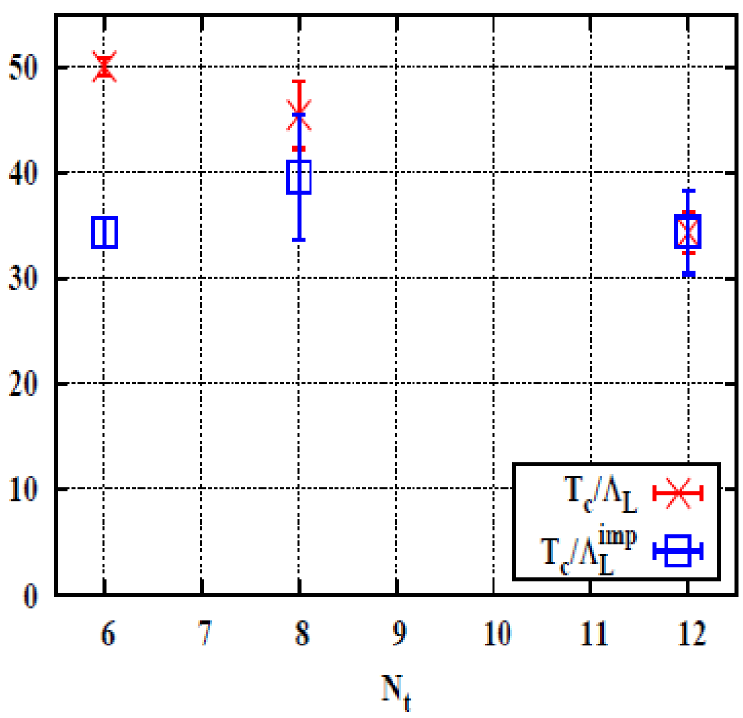
$$R^{imp}(\beta_{L/E}) = \Lambda_{L/E}^{imp}\, a(\beta_{L/E}) \equiv \frac{R(\beta_{L/E})}{1+h} \times \left[1 + h\frac{R^2(\beta_{L/E})}{R^2(\beta_0)}\right],$$

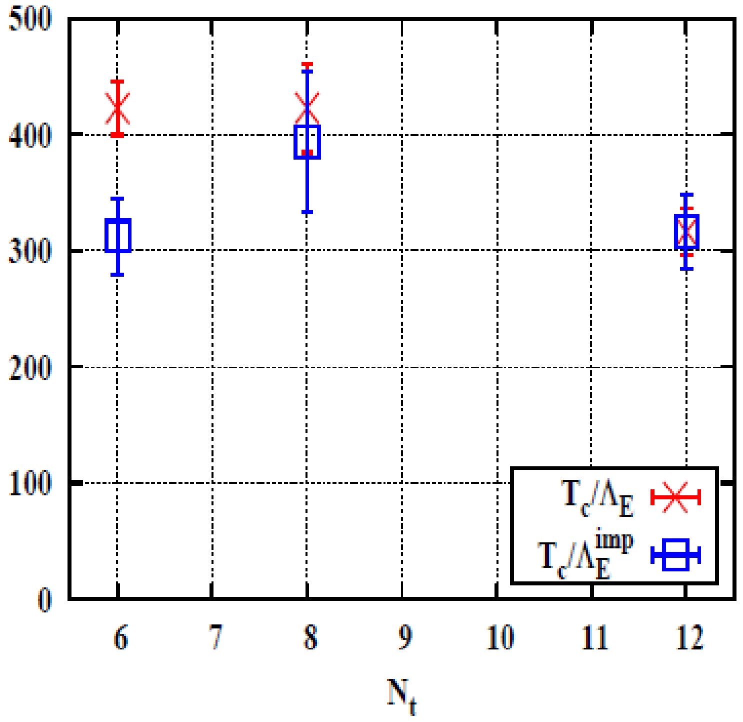
C. Allton, 2007

Nf = 6, asympt. scaling

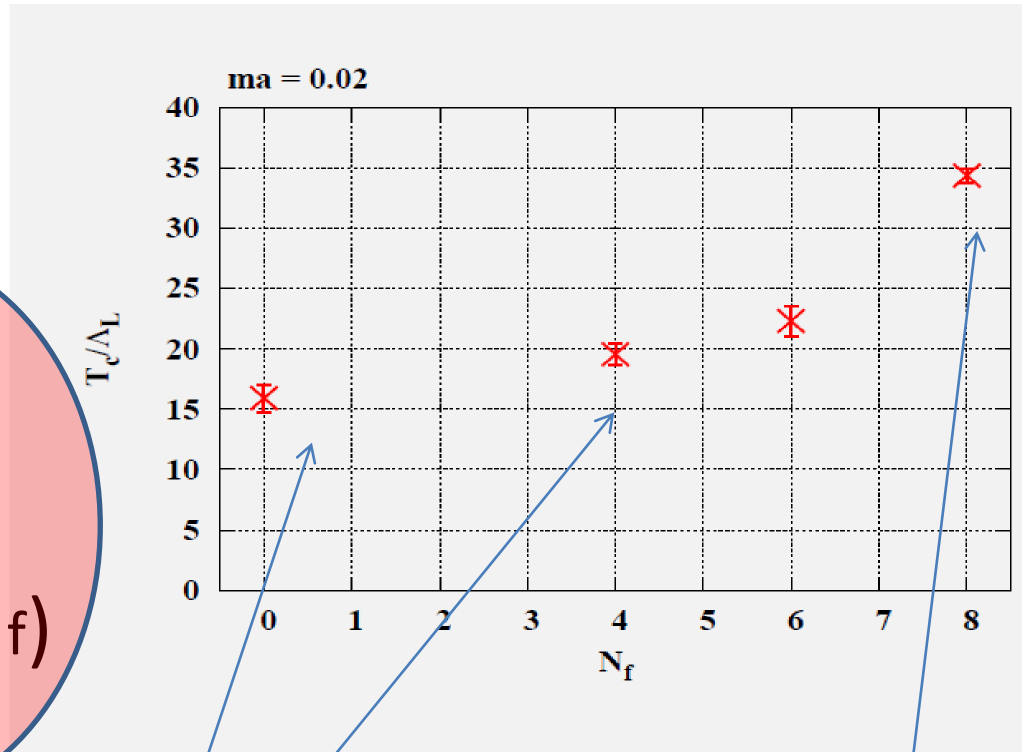


Nf = 8, asympt scaling





Tc/Λ as a function of Nf



Tc/Λ

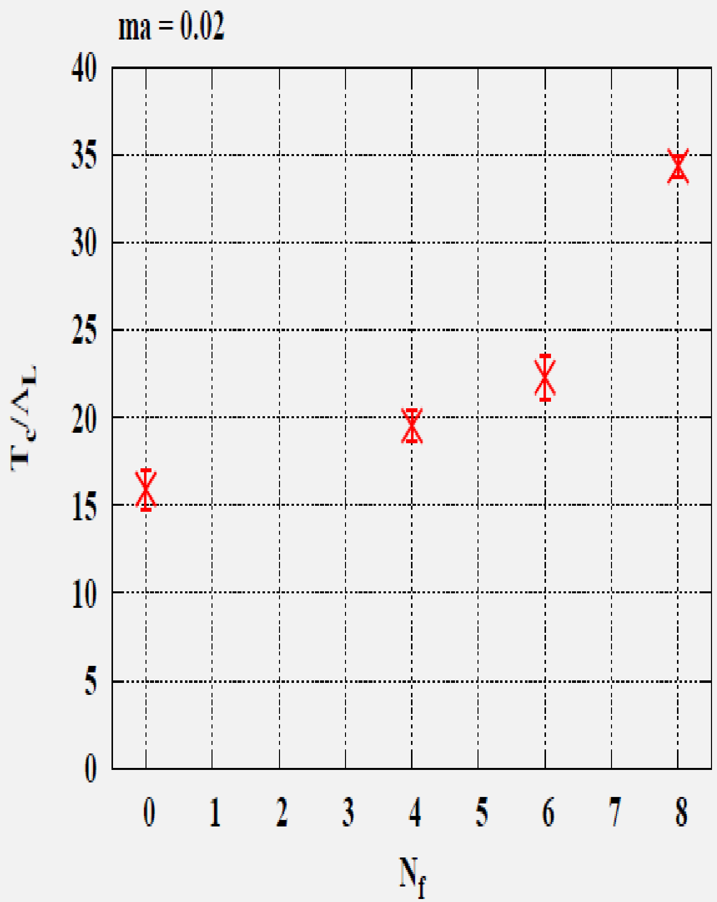
$\Lambda = \Lambda(Nf)$

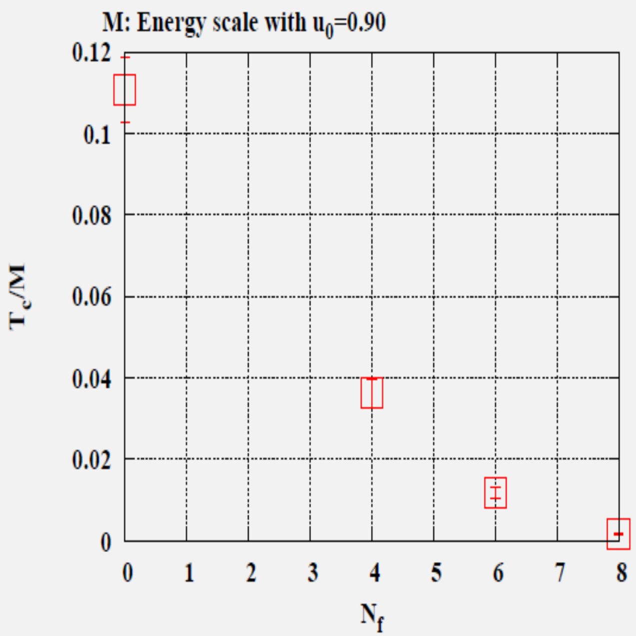
Scale separation ?

Nf

Conventional running

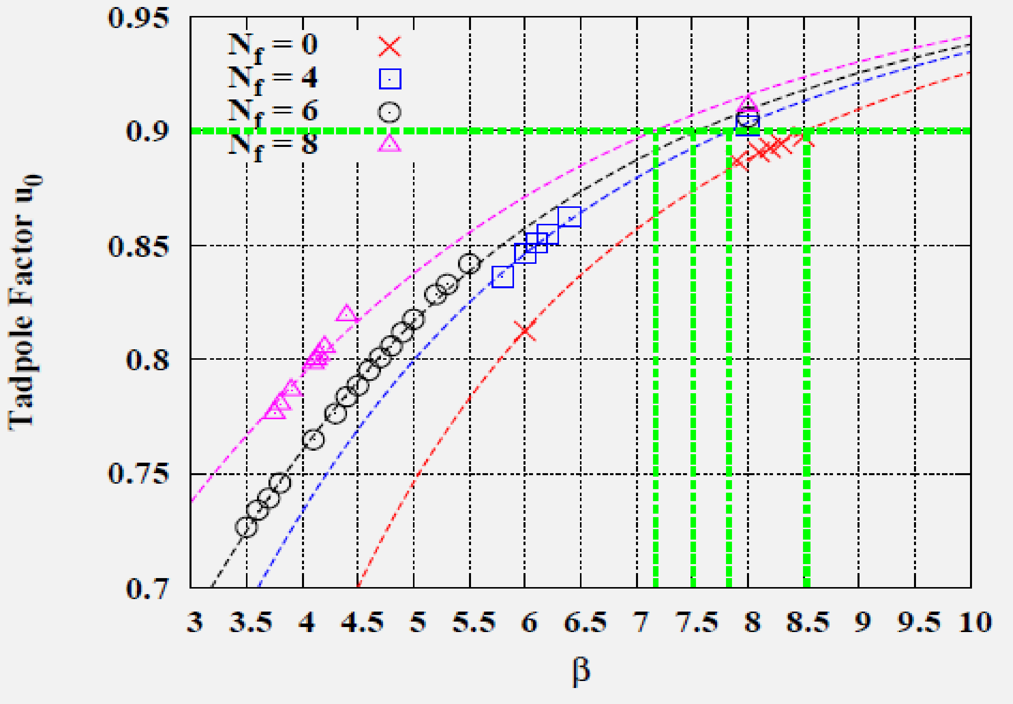
Solution: $\Lambda = \Lambda\,(N_f)$; use UV scale





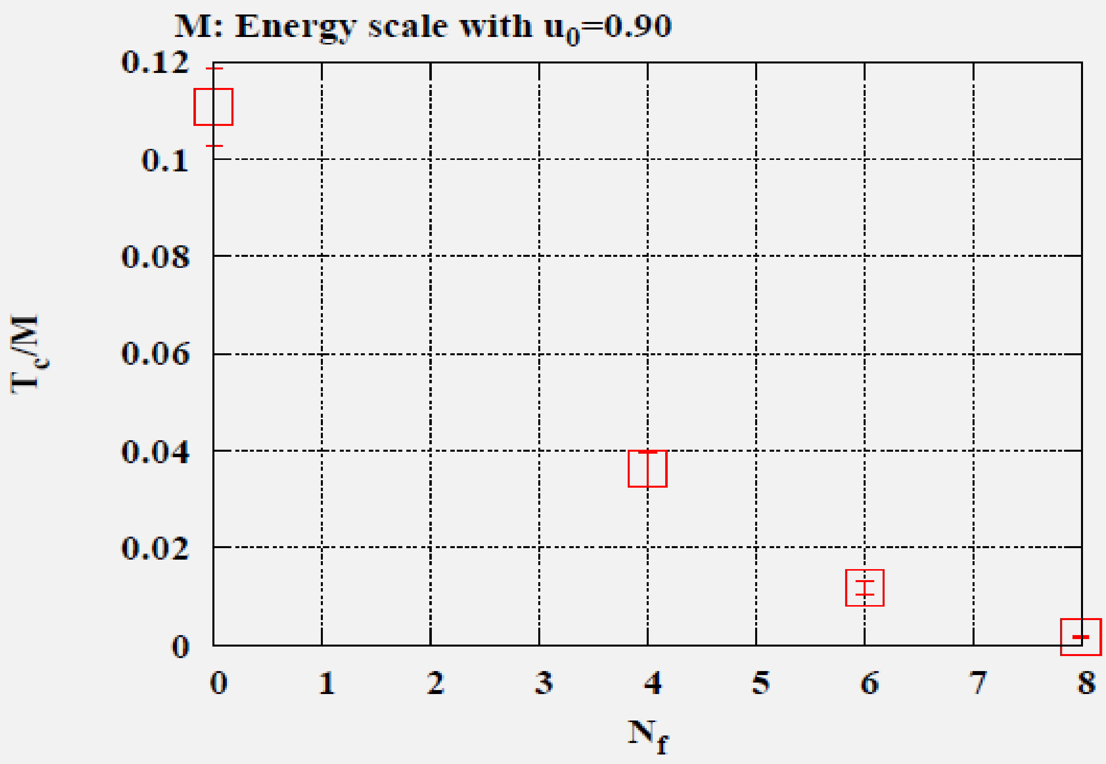
$$\frac{T_c}{M} = \frac{1}{N_t}\exp\left[\int_{g_{\mathrm{ref}}}^{g_c}\frac{dg}{B(g)}\right].$$

Fixing an UV scale



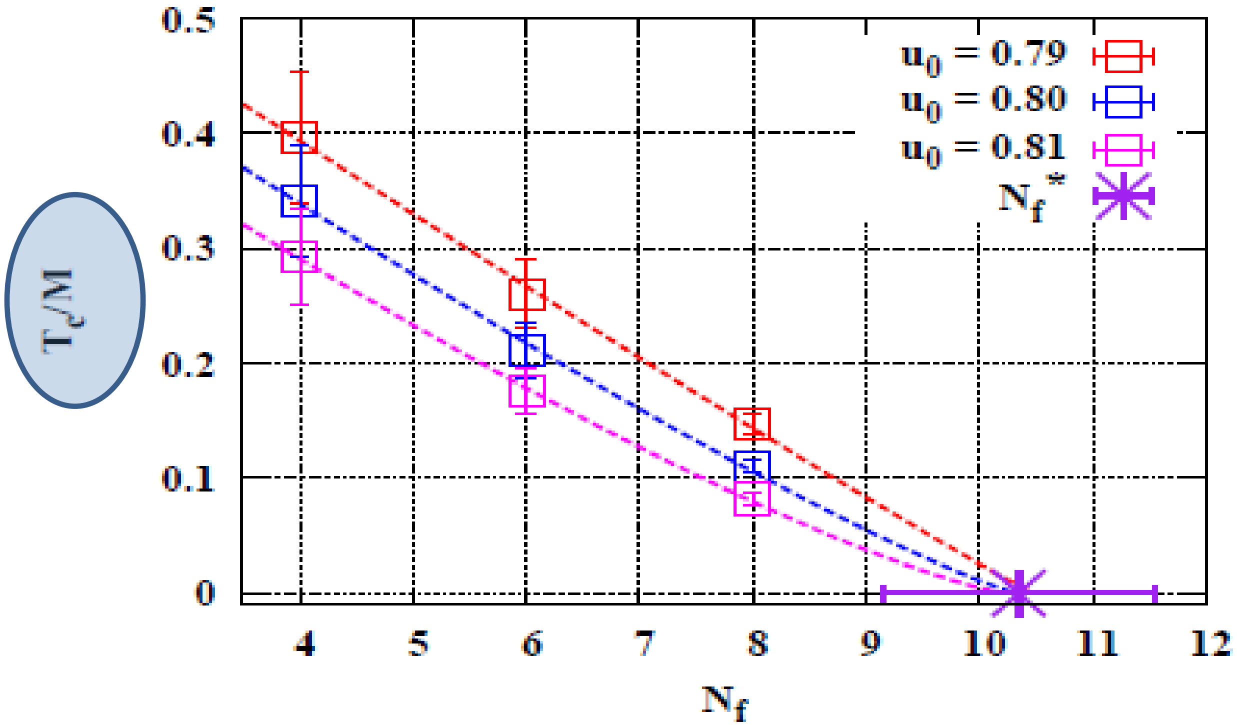
- We have measured the tadpole factosr $u_0 = \langle \Box \rangle^{1/4}$ at $T = 0$.
- We use the couplings obtained by the constant u_0 line to define a UV reference scale M.

Tc/M_{UV}



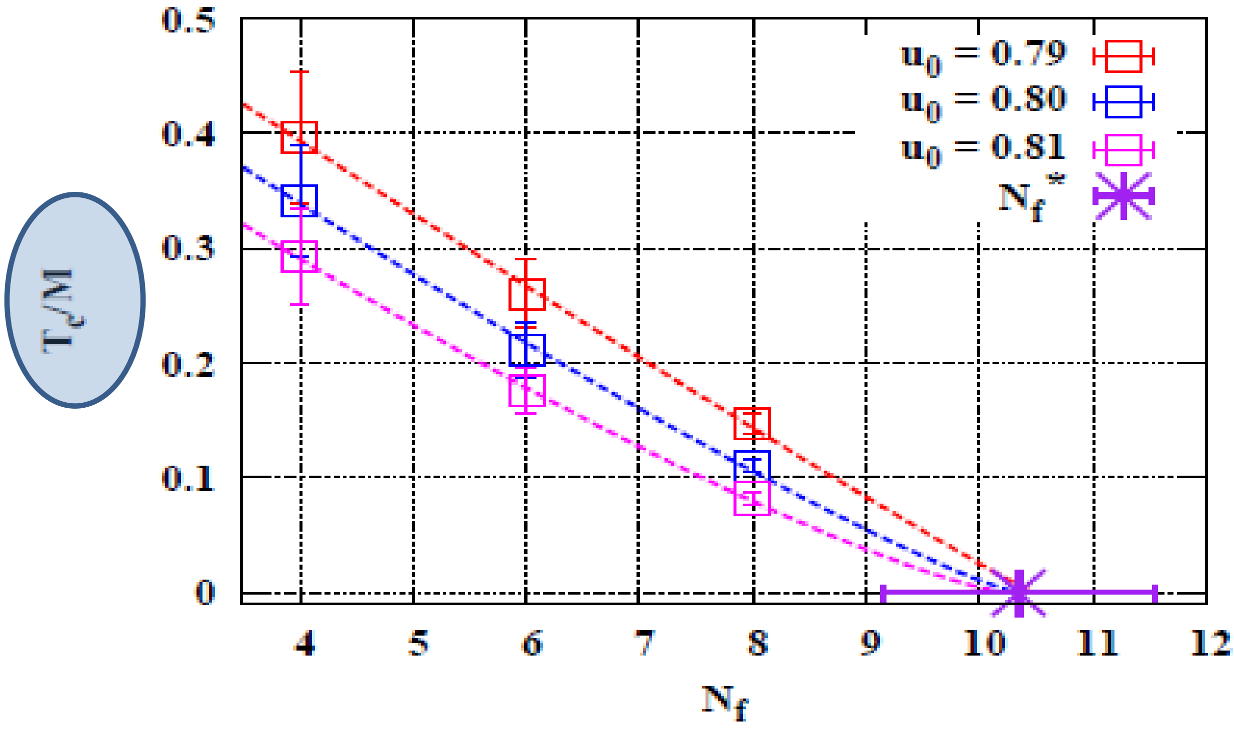
$$\frac{T_c}{M} = \frac{1}{N_t} \exp\left[\int_{g_{\rm ref}}^{g_c} \frac{dg}{B(g)}\right] .$$

Tc/M extrapolates to zero for Nf ~ 10.5*



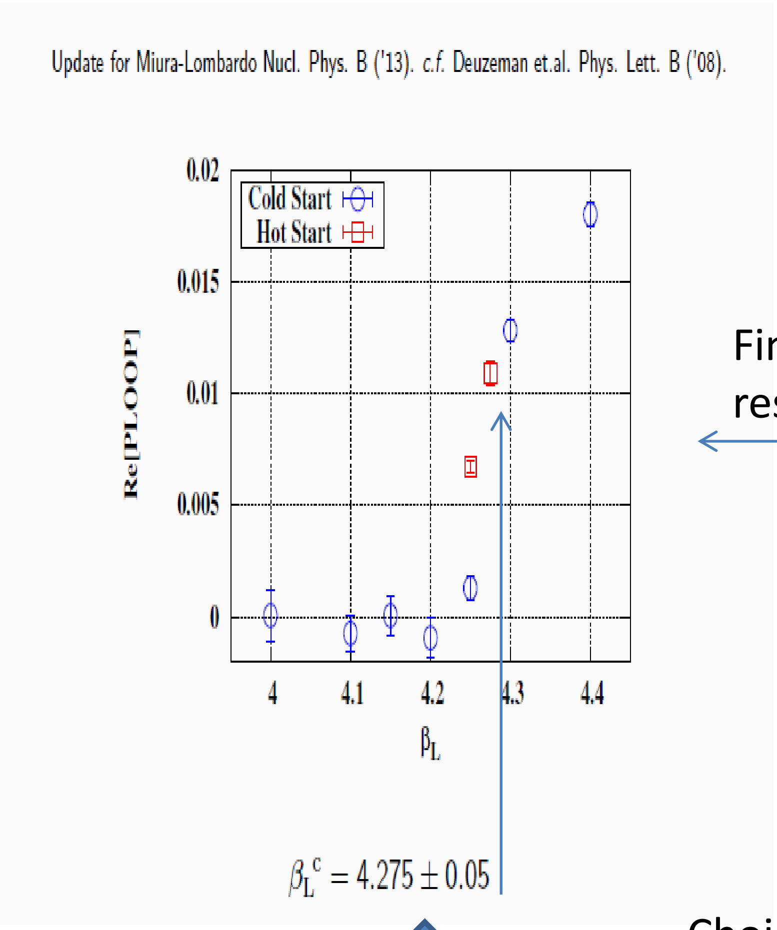
Tc/M extrapolates to zero for Nf ~ 10.5*

M fixed with the help of perturbation theory

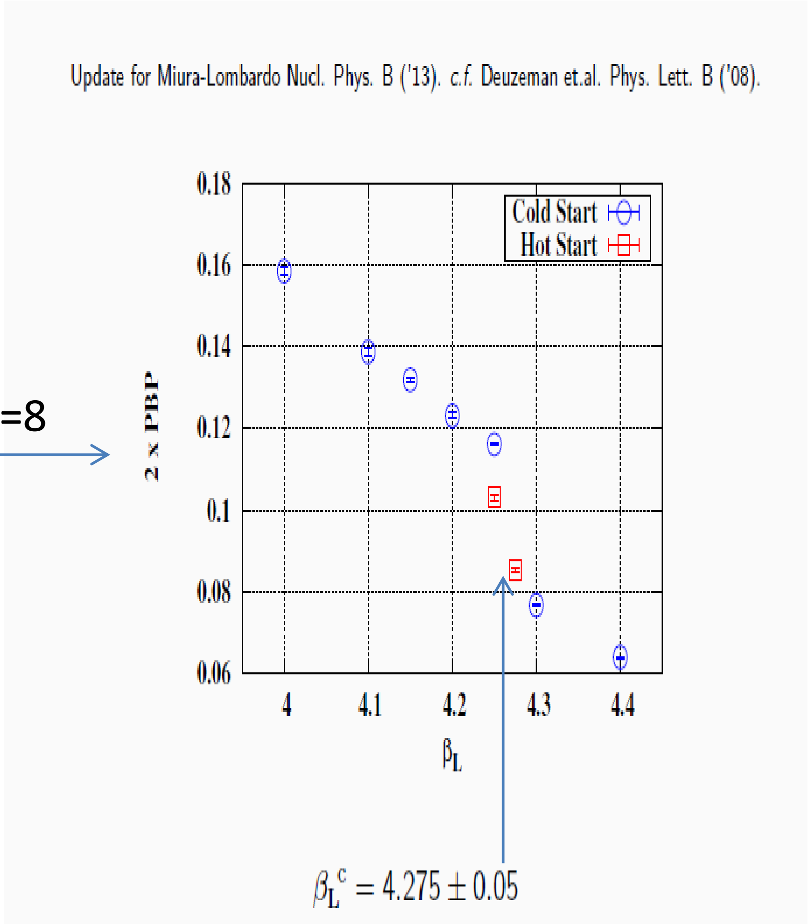


THE STRING TENSION AND W0

Lattice setup: β for Nf=8

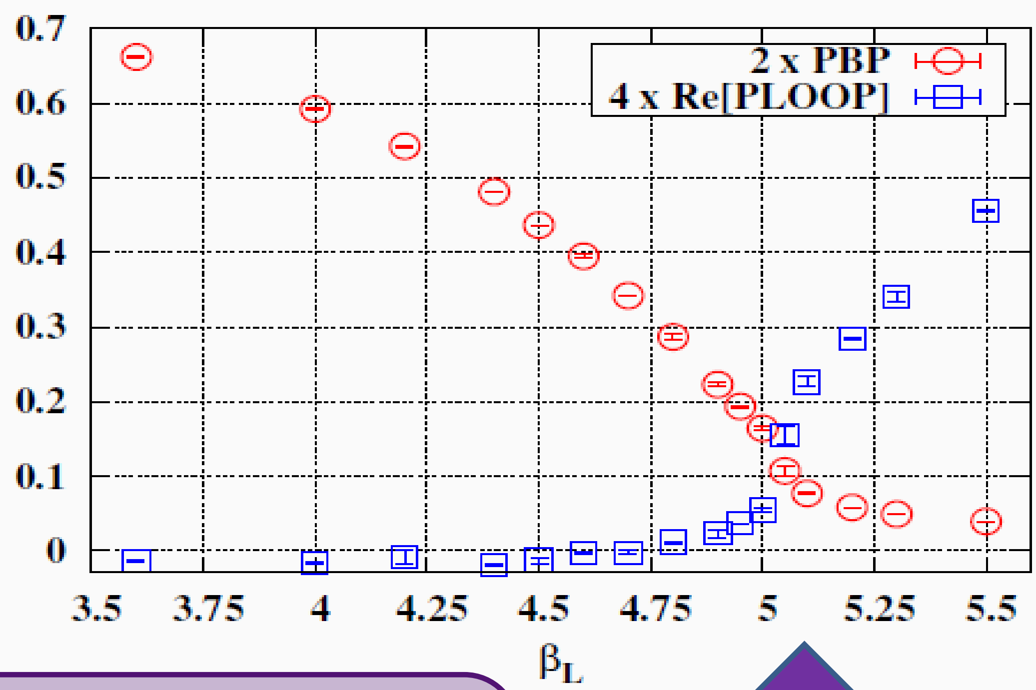


Finite T results Nt=8



Choice for the T=0 simulation

Lattice setup: β for Nf=6



Finite temperature, Nt=6 results

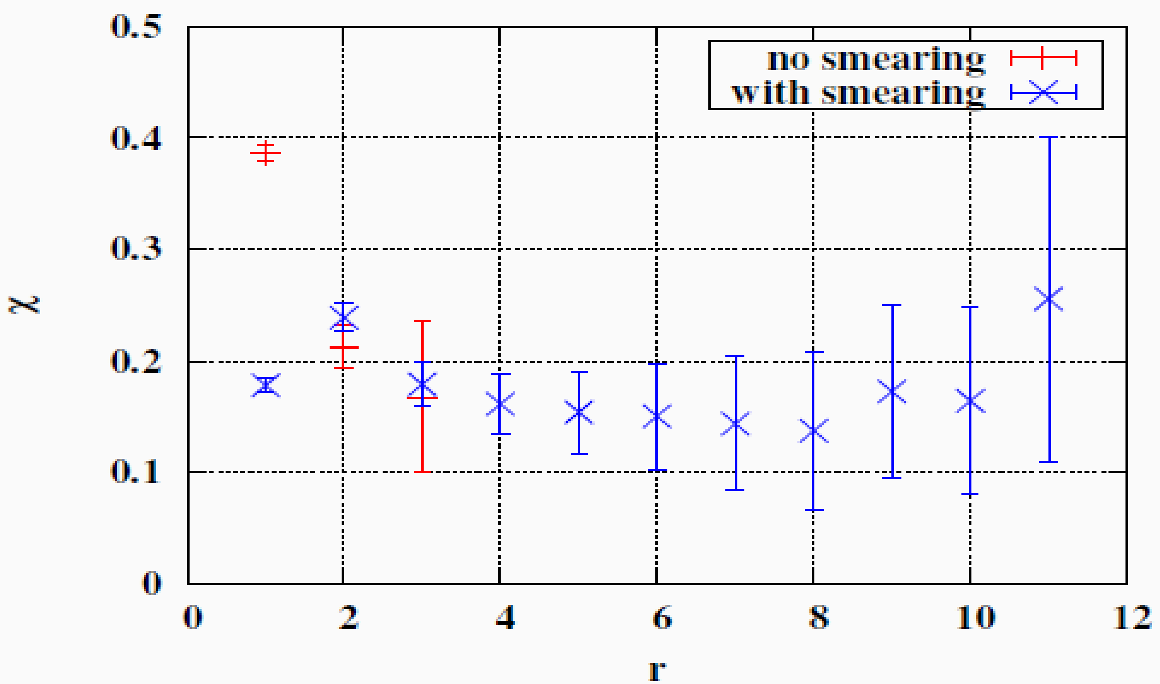
$\beta c = 5.025$: Choice for the T=0 simulations

And analogously for Nt=8

Nf=8: Creutz ratios

Measurements' code by M. Wagner and collaborators

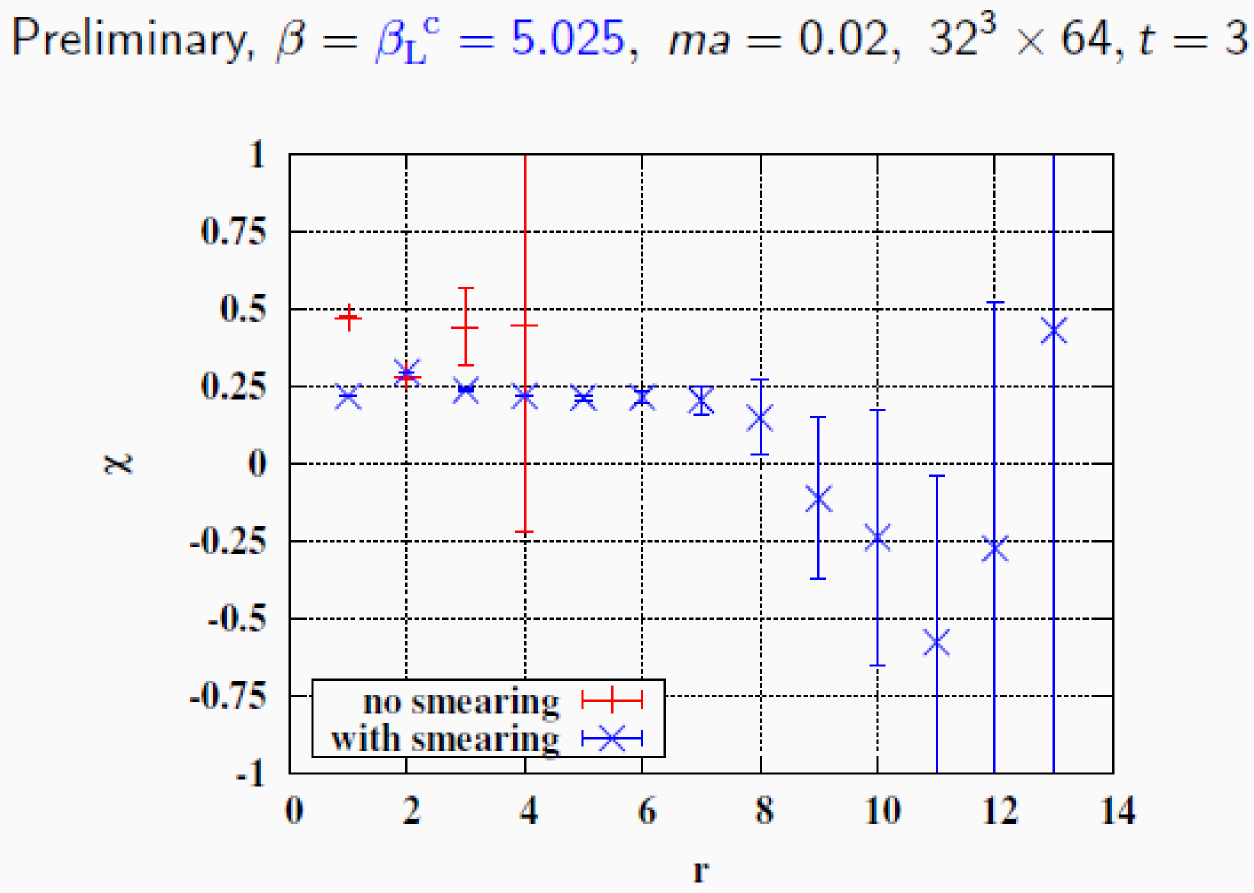
Preliminary, $\beta = \beta_{\mathrm{L}}{}^{\mathrm{c}} = 4.275,\ \ ma = 0.02,\ \ 32^3 \times 64, t = 3$



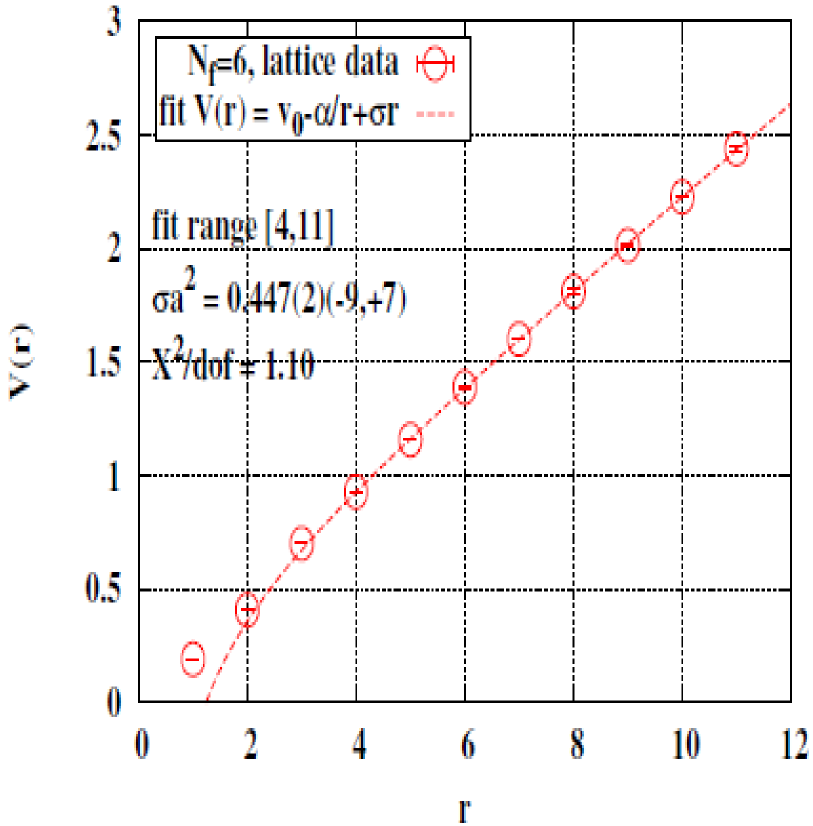
$$\chi_{r,t} = -\log\left[\frac{W_{r,t}W_{r+1,t+1}}{W_{r,t+1}W_{r+1,t}}\right] = \frac{\alpha}{\hat{r}(\hat{r}+1)} + \hat{\sigma}\ .$$

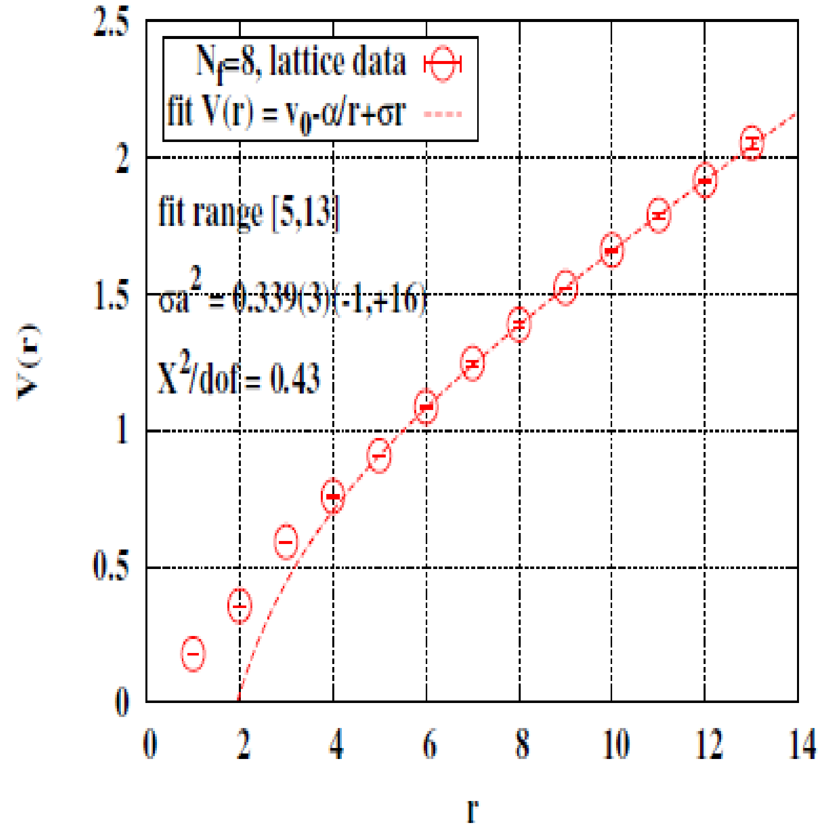
Nf=6: Creutz ratios

Measurements' code by M. Wagner and collaborators



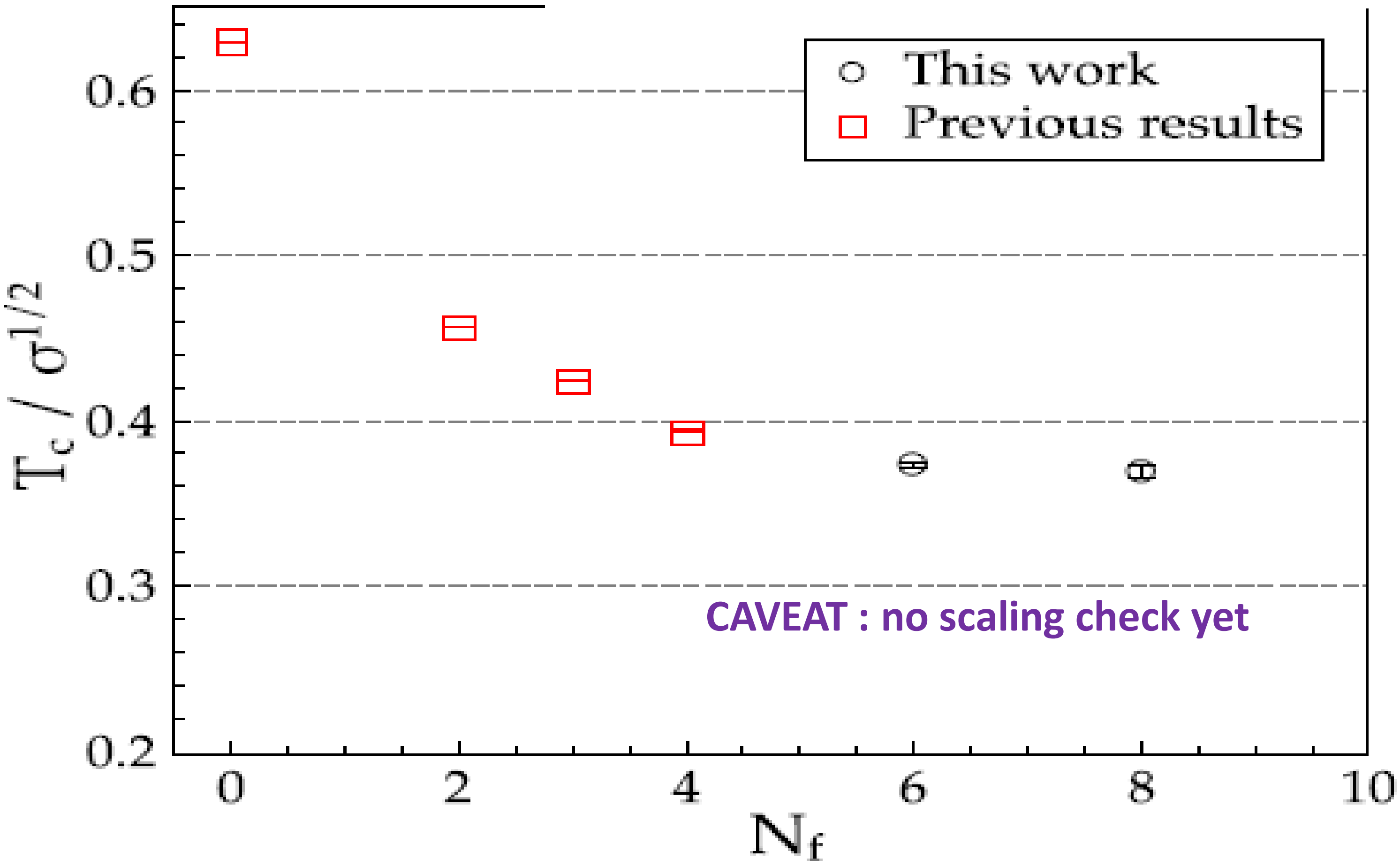
Heavy Quark Potential



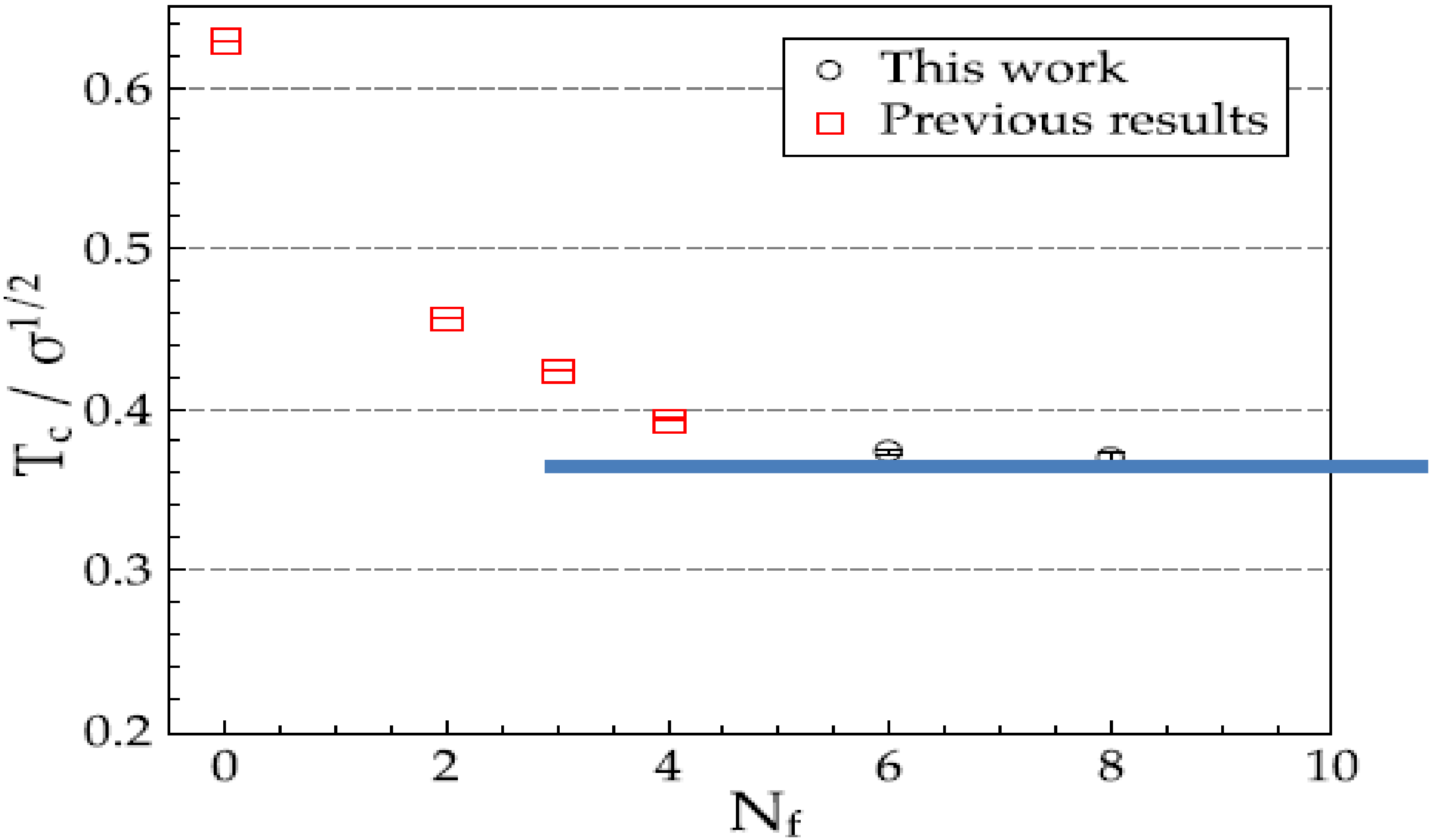


Tc/√ σ

$$T_c/\sqrt{\sigma} = \begin{cases} 0.373(2)(+5,-6), & N_f = 6, \beta = 5.025, \\ 0.369(4)(+1,-5), & N_f = 8, \beta = 4.275. \end{cases}$$



Lim Nf -> Nfc Tc/√ σ = Const?



Wilson flow

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

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

✓Computationally easy

✓Naturally smooth

✓Well behaved at short distance

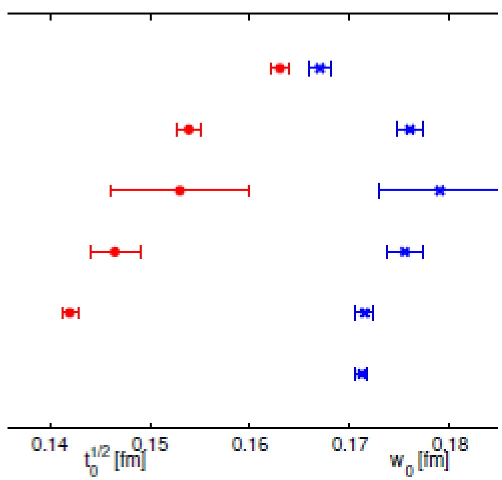
W0 vs r0

R. Sommer@Lat2013

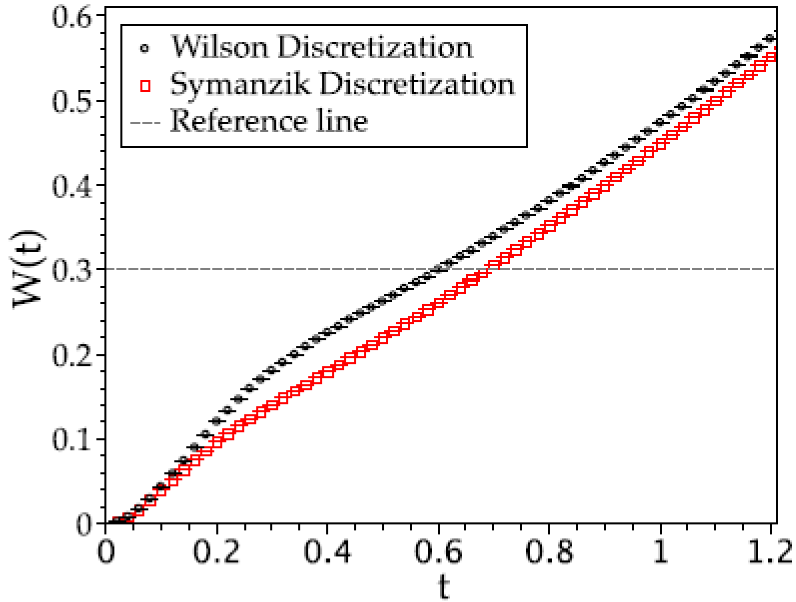
Wilson, $N_f = 2$			tmQCD, $N_f = 2$			$N_f > 2$				
r_0[fm]	from		r_0[fm]	from		N_f	r_0[fm]	r_1[fm]	from	
0.503(10)	f_K	[14]	0.438(14)	f_K	[38]	2+1	0.466(4)[a]	0.313(2)	div.	[39]
0.491(6)[c]	f_K	[9]				2+1		0.321(5)	Υ	[1]
0.485(9)[c]	f_π	[9]	0.420(20)	f_π	[40]	2+1	0.470(4)	0.311(2)	f_π	[41, 42]
0.501(15)[b]	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

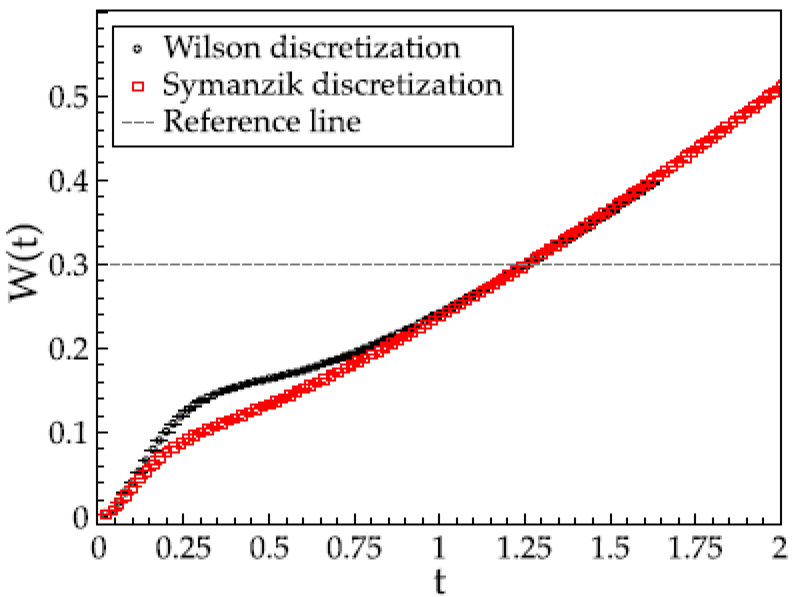
N_f	$\sqrt{t_0}$ [fm]	w_0 [fm]	from
0	0.1638(10)	0.1670(10)	$r_0 = 0.49$ fm [35, 30]
2	0.1539(12)	0.1760(13)	f_K [35, 9]
3	0.153 (7)	0.179 (6)	m_p[47]
3	0.1465(25)	0.1755(18)	m_Ω [33]
4	0.1420(8)	0.1715(9)	f_π [45]
4		0.1712(6)	f_π [34]



Scale from the flow, Nf=6

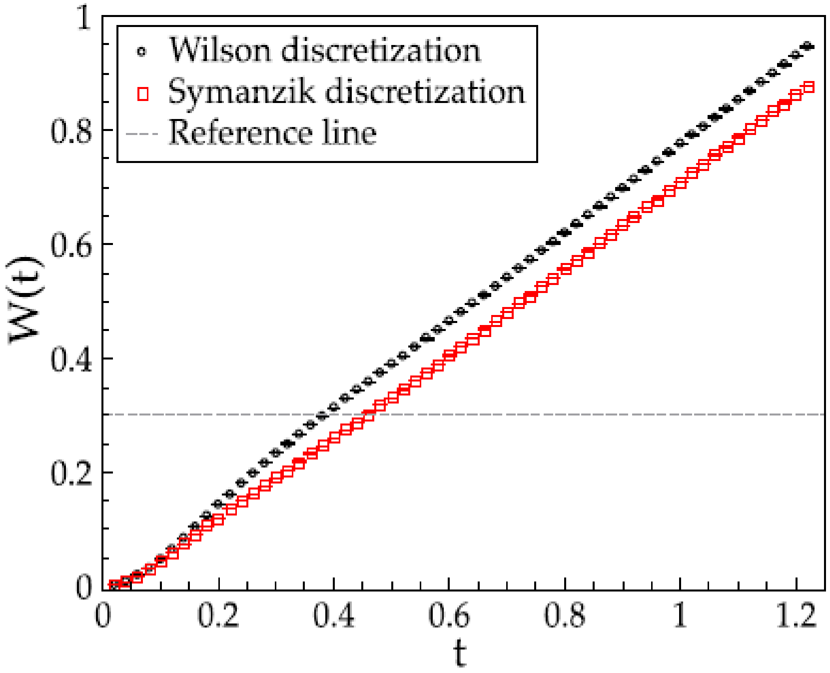


$\beta = 5.025$

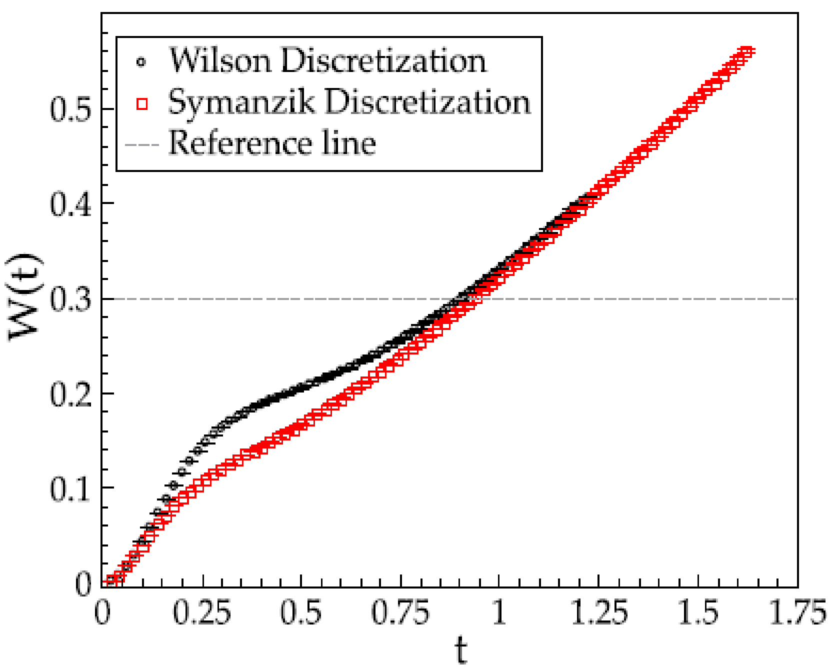


$, \beta = 5.200$

Scale from the flow, Nf=8

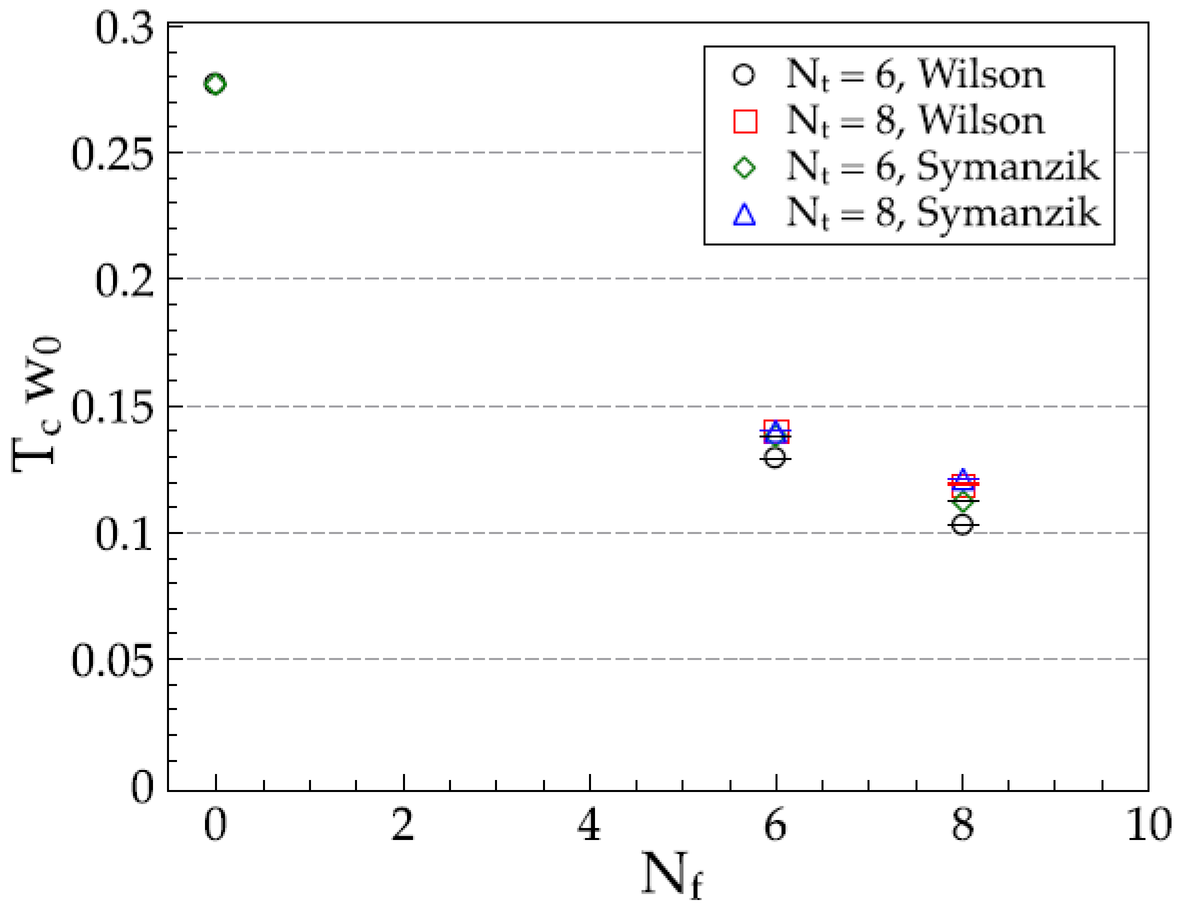


$,\beta = 4.1125$

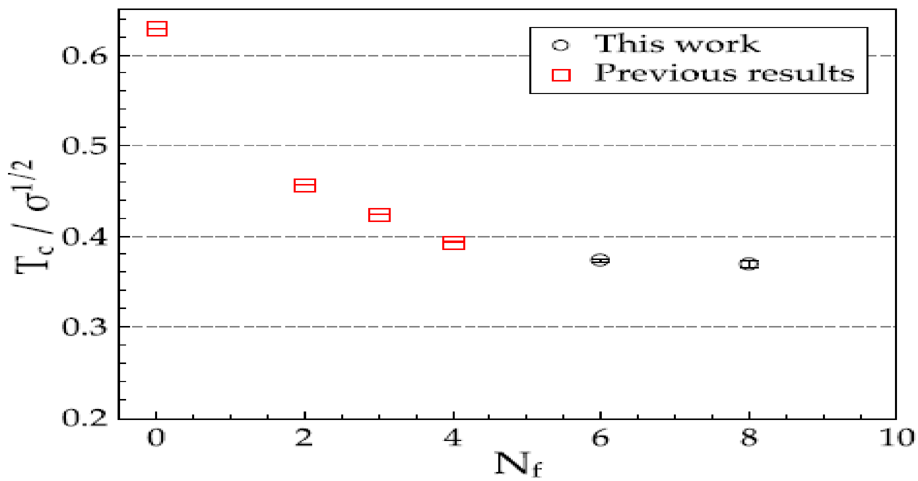


$,\beta = 4.275$

Results for Tc on the 1/w0 scale



DIFFERENT SCALES

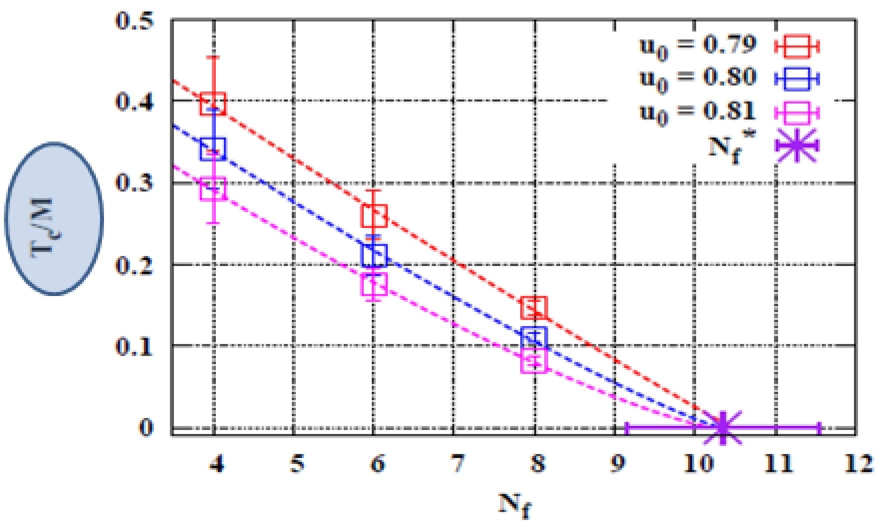


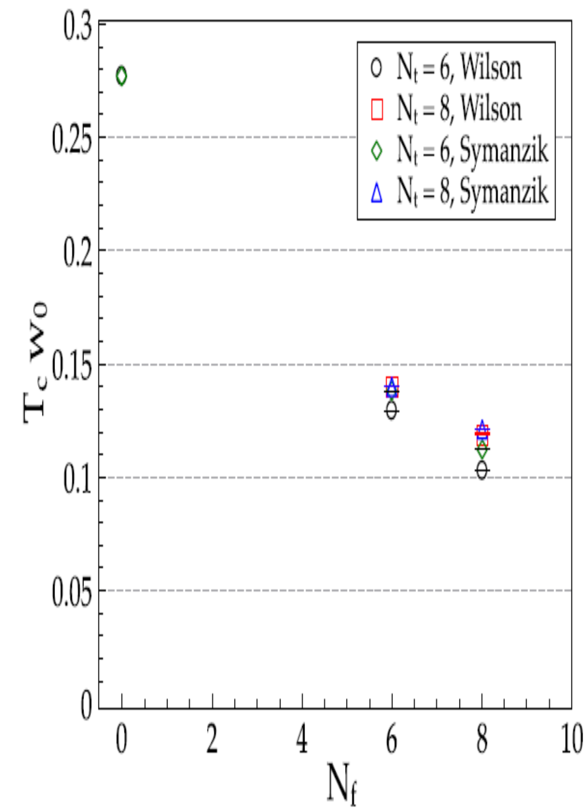
Nf -> Nfc :

Tc/M = 0

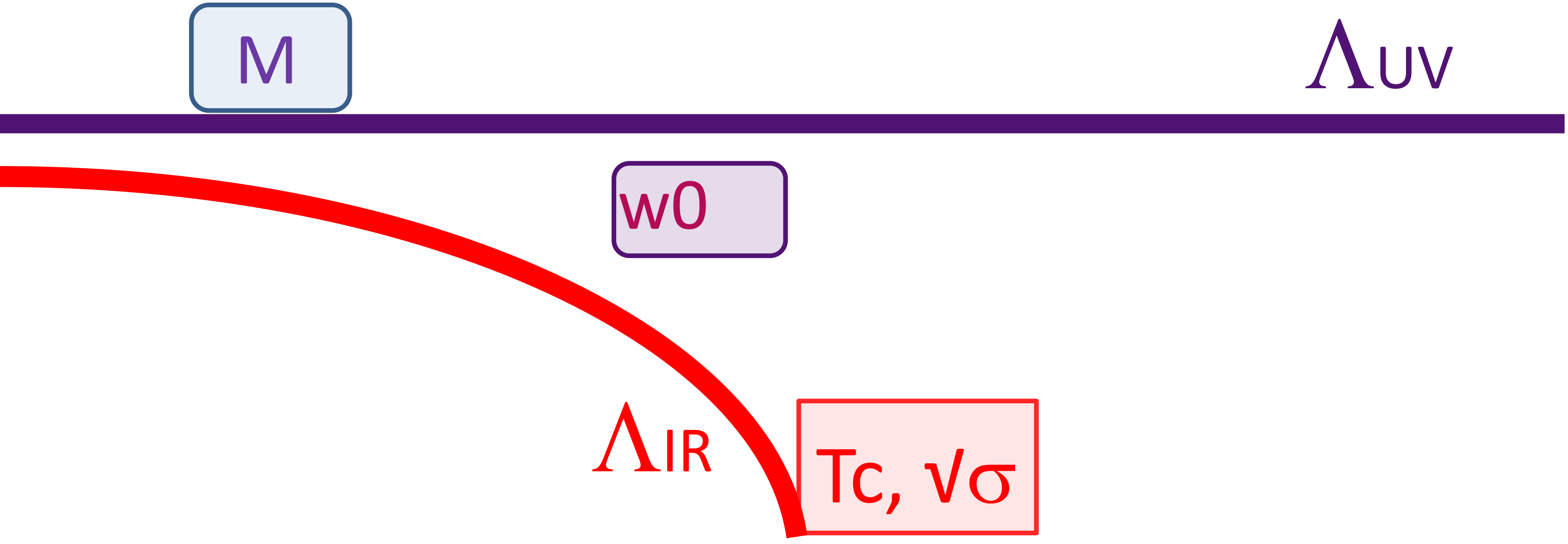
Tc w0 = 0 (?)

Tc / √ σ ~ 0.3



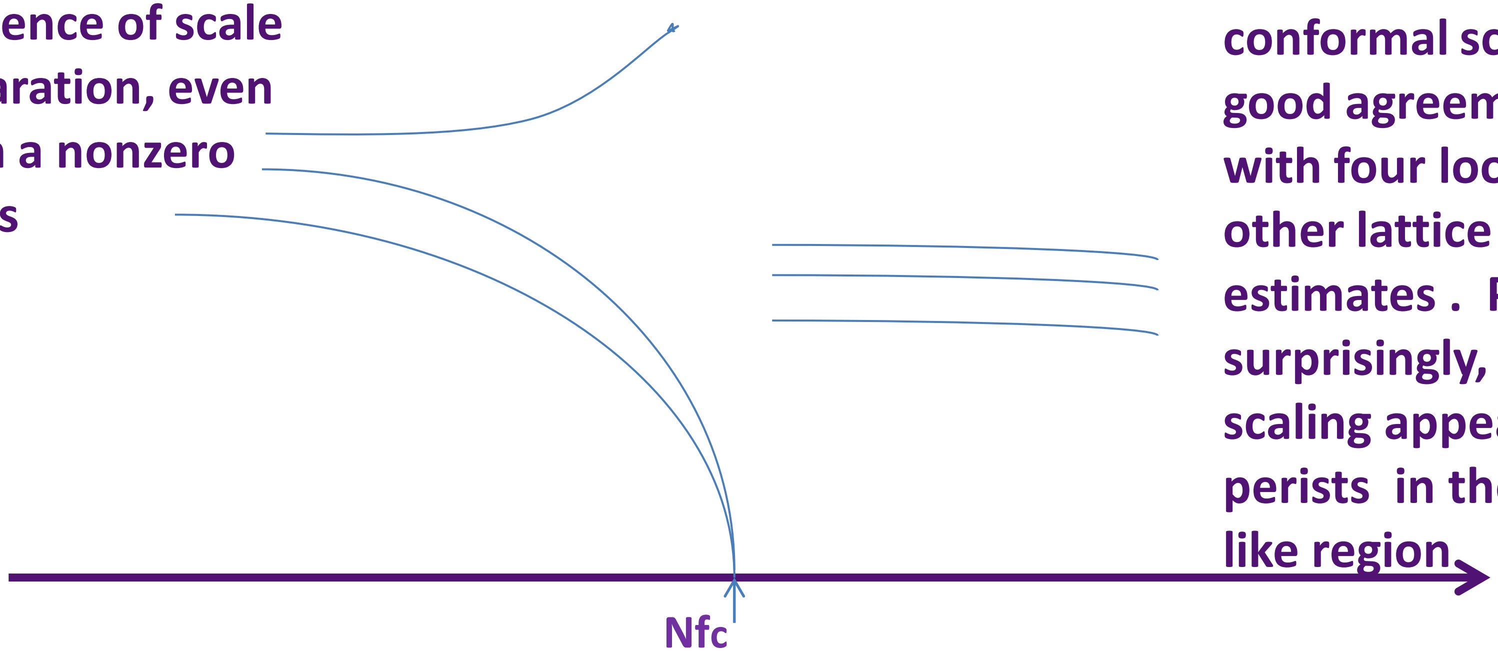


Different scales



Summary

For Nf=8 we have observed some evidence of scale separation, even with a nonzero mass



For Nf=12 we have measured conformal scaling, in good agreement with four loops and other lattice estimates . Perhaps surprisingly, the scaling appears to perists in the QED-like region

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 $\gamma = 0.235(46)$ for Nf=12:

Four loops 'almost exact'?

Next

- **Better developed scaling for essential singularities maybe using models as a guidance**
- **Running coupling in the QCD phase from the potential and the flow**
- Studies of mass dependence in the pre-conformal region
- Explicit check of conformal scaling and corrections with more masses and sizes in the conformal window