XQCD 26-28 June 2017 Pisa (IT)

Chiral phase transition of three flavor QCD with nonzero magnetic field

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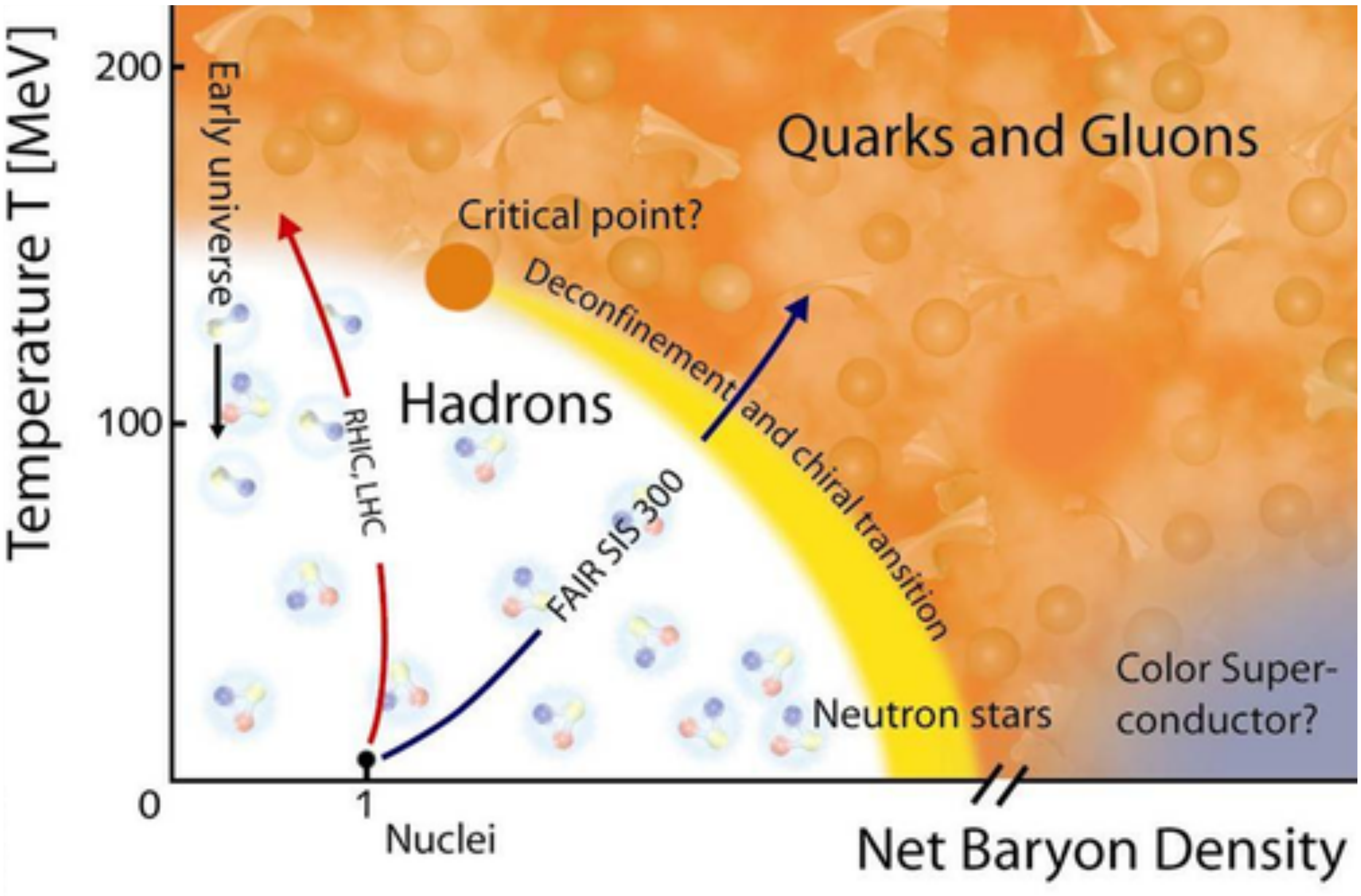
Collaborate with:
- Heng-Tong Ding
- Swagato Mukherjee
- Christian Schmidt
- Xiao-Dan Wang

Background & Motivation

QCD phase transition at physical mass is crossover



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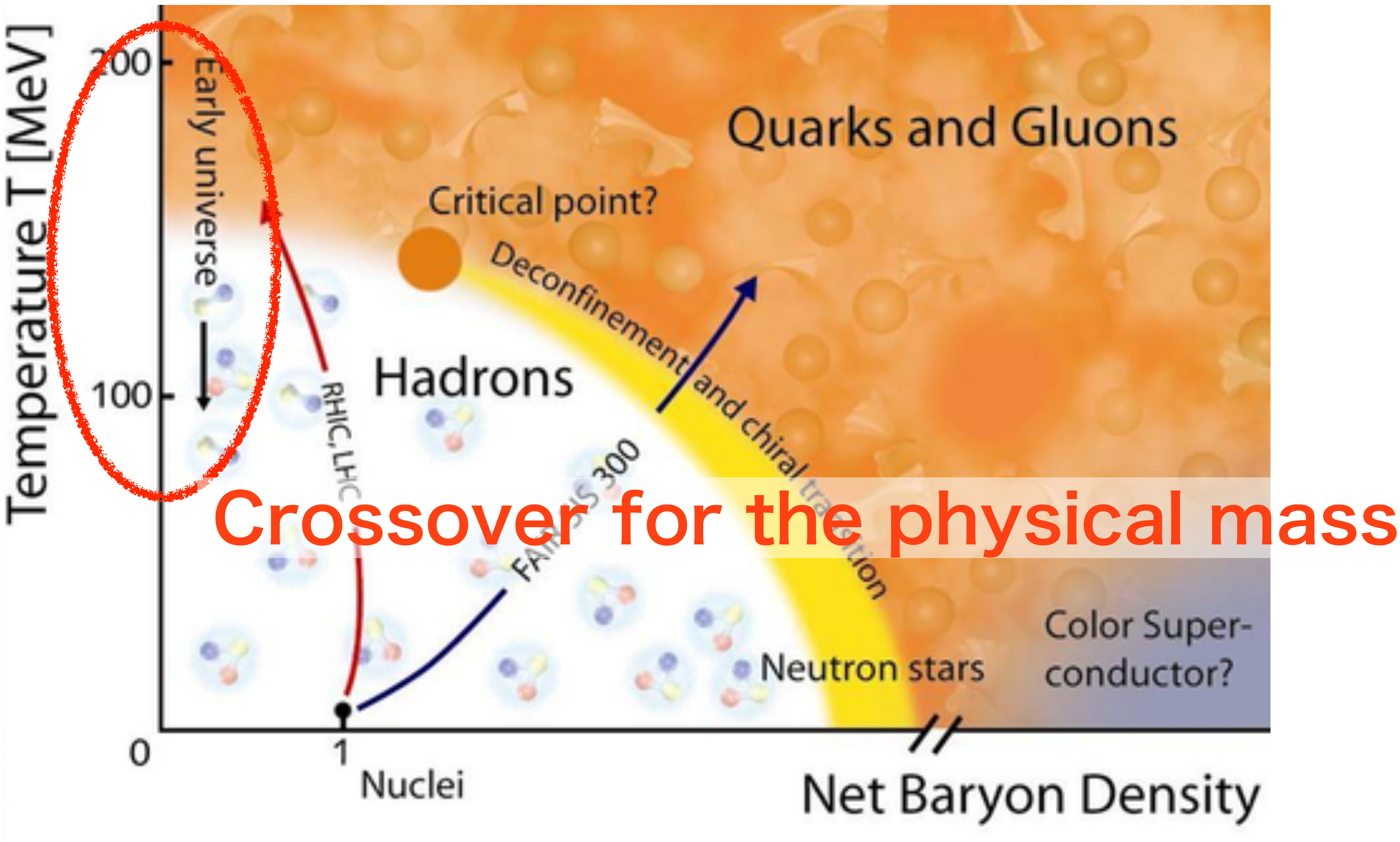

Background & Motivation

QCD phase transition depends on Magnetic field?

Colombia plot : the order of QCD phase transition

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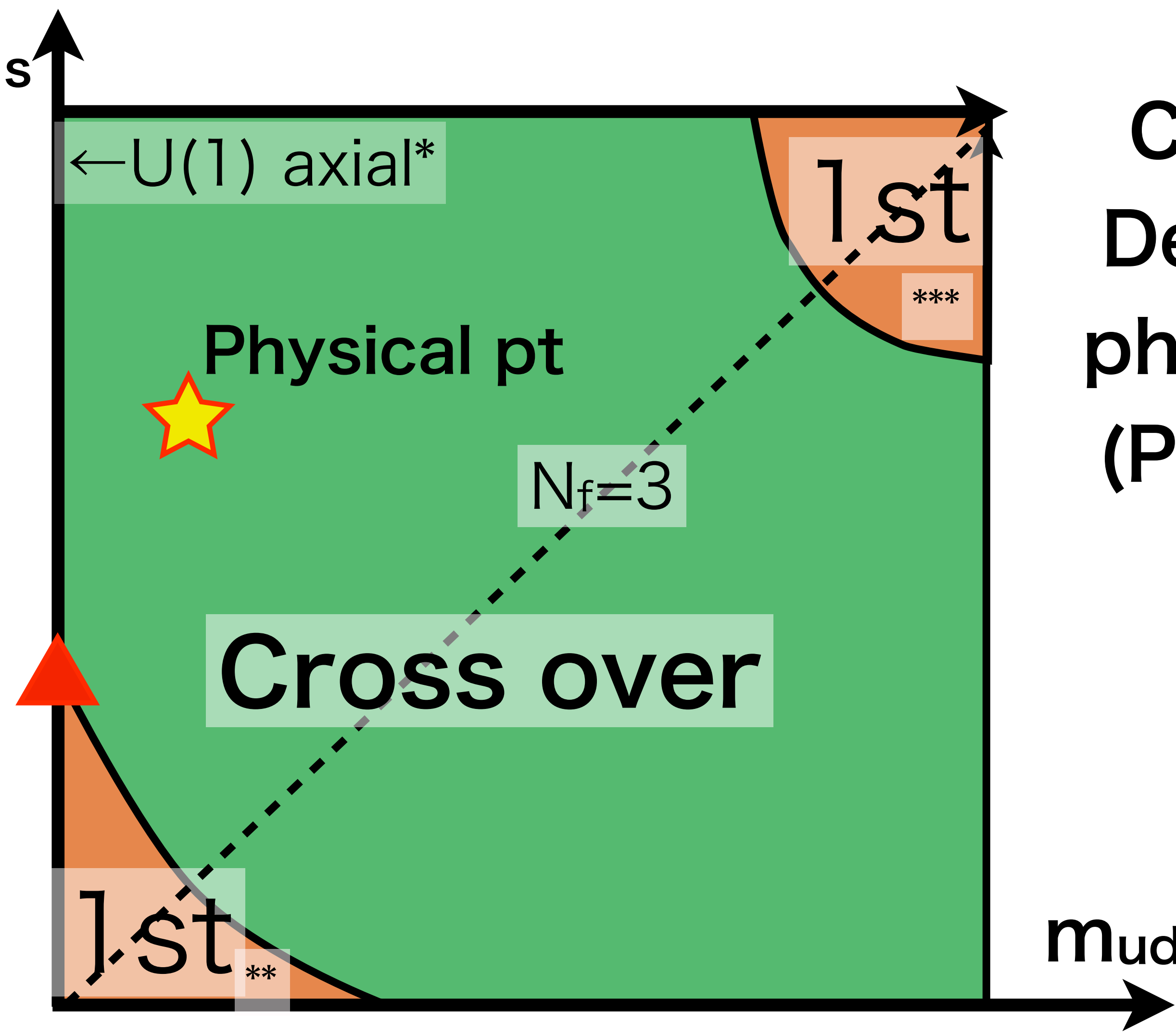
QCD phase transition depends on Magnetic field?

Colombia plot : the order of QCD phase transition

*A. Tomiya et al. 1612.01908
S. Sharma et al. 1510.03930



Tri. Crit.

Chiral phase transition (Chiral cond.)

Confinement/ Deconfinement phase transition (Polyakov loop)

** Xiao-Yong Jin et al. 1706.01178
*** H. Saito et al. 1106.0974

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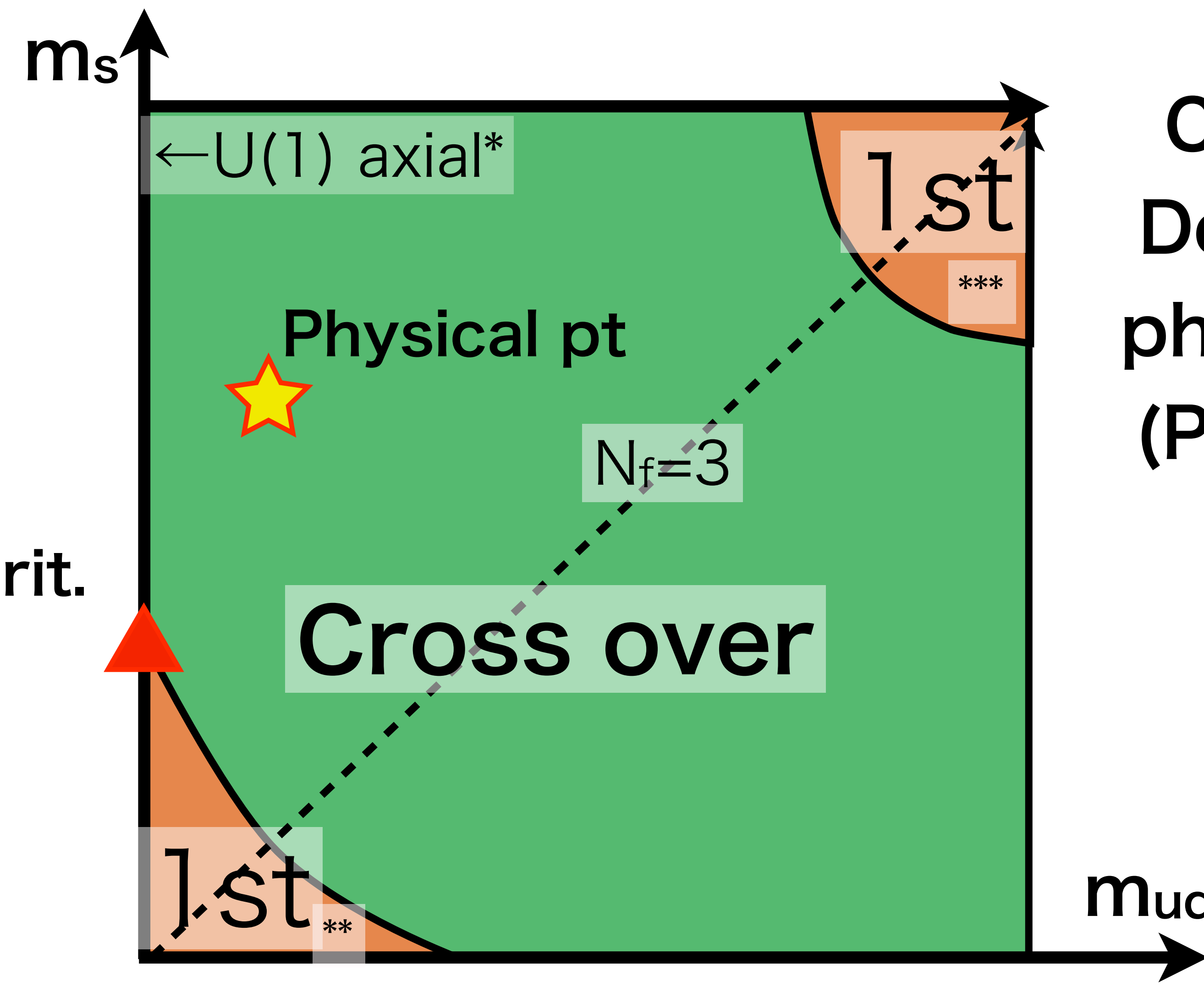

Confinement/ Deconfinement phase transition (Polyakov loop)

Chiral phase transition (Chiral cond.)

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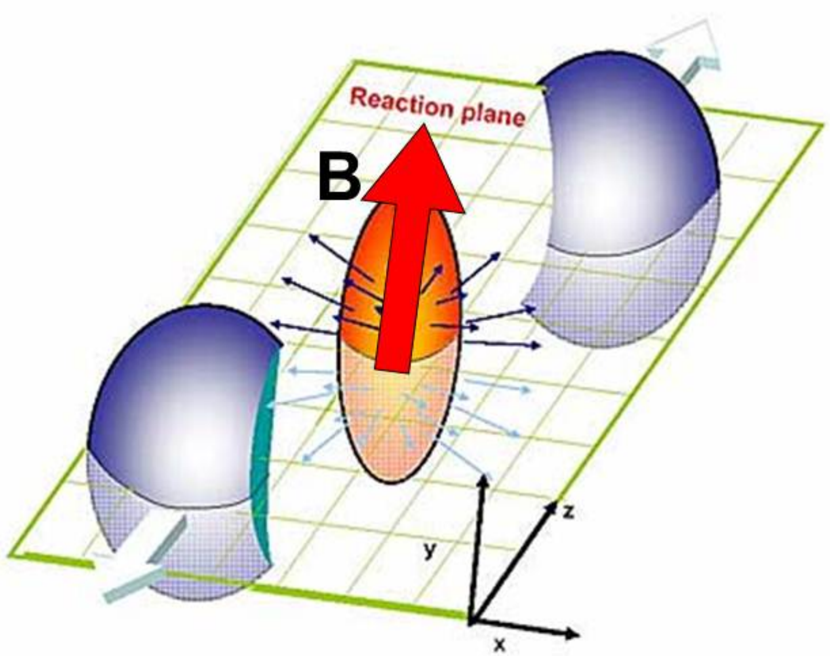
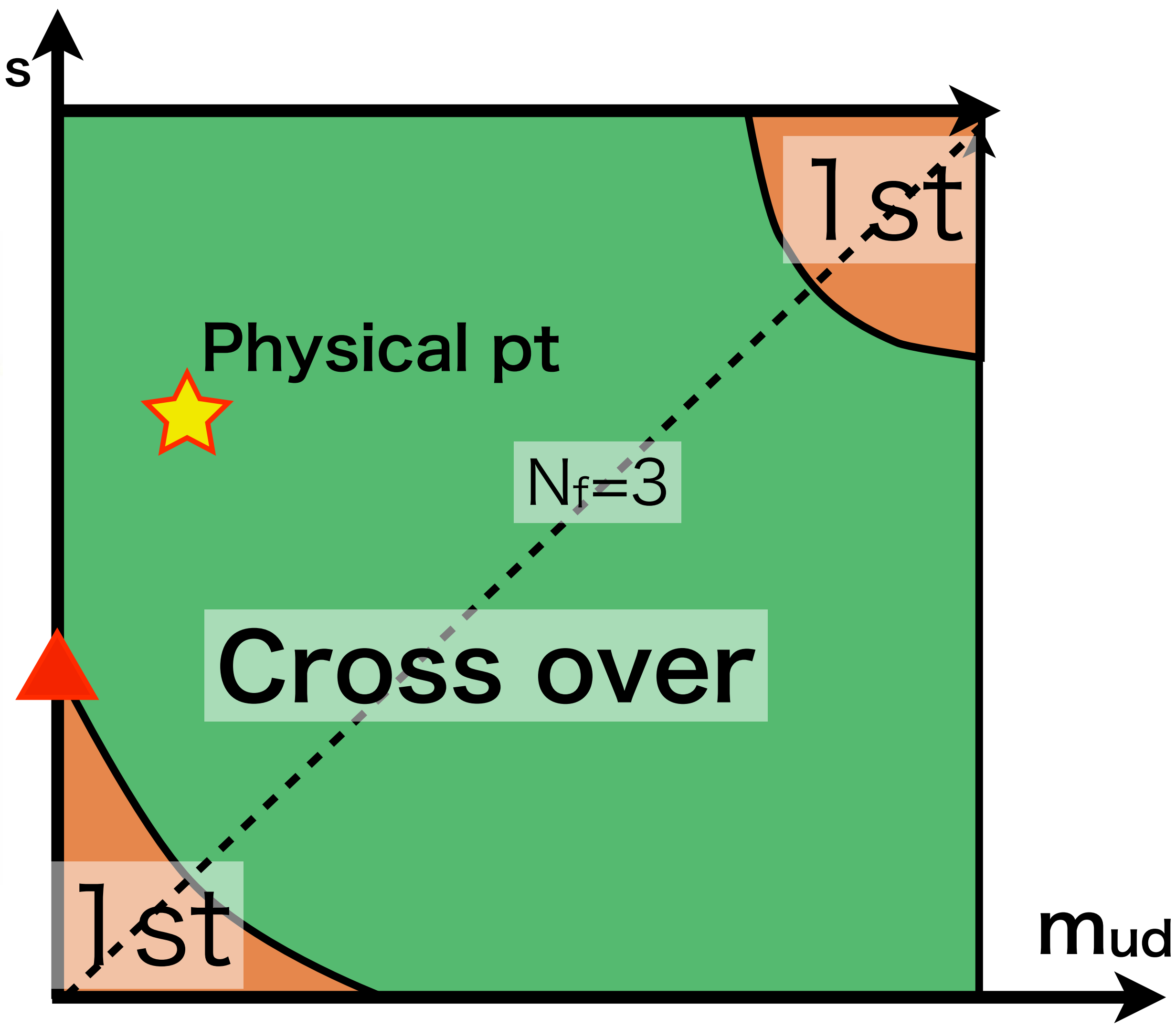
Other than the physical point info. is useful for model building

Background & Motivation

QCD phase transition depends on Magnetic field?

Colombia plot : <u>the order of </u>QCD phase transition





*V. V. SKOKOV
et al(arXiv:0907.1396)

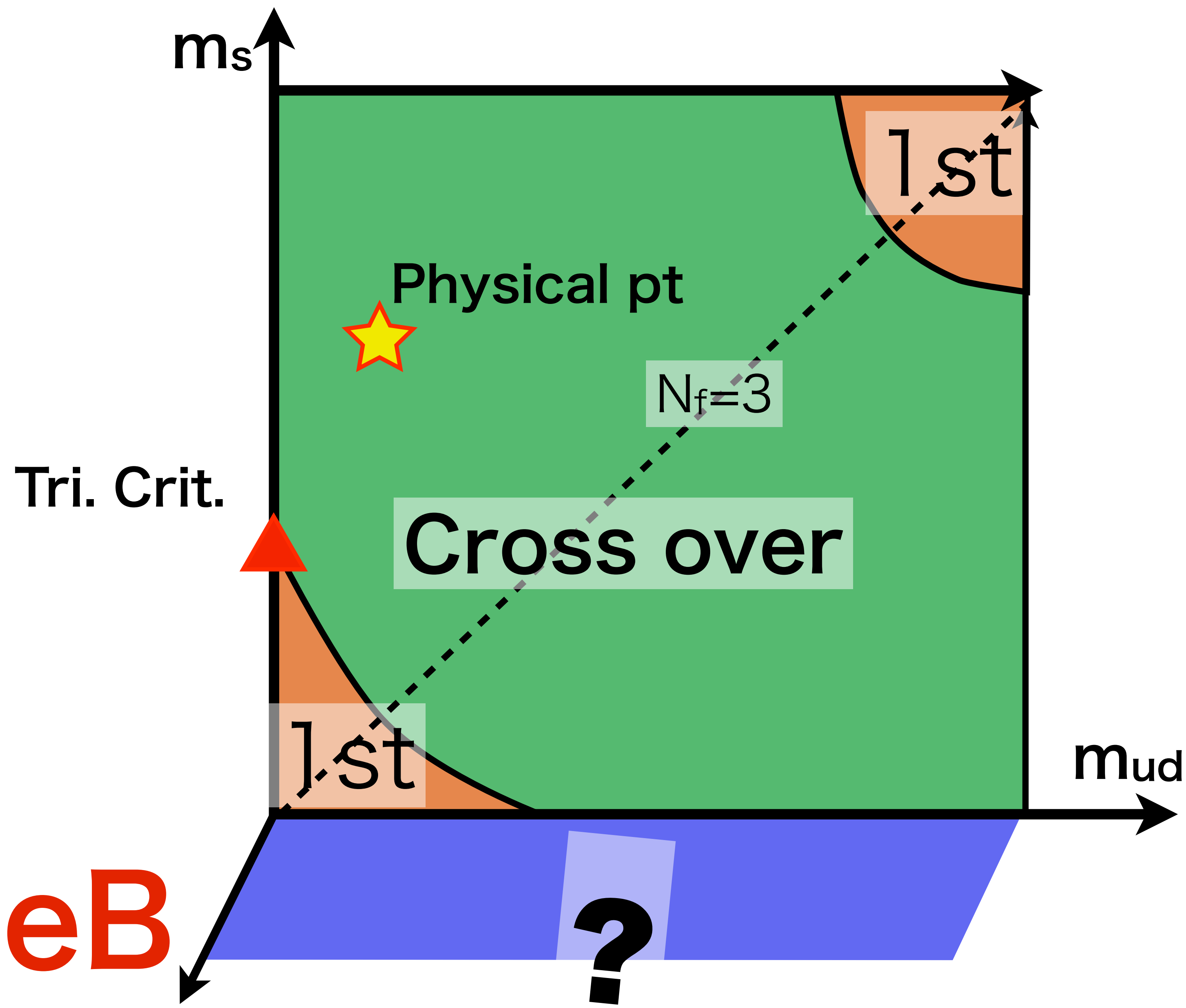
Off-central AA collisions generate huge magnetic field(15mπ*)

<u>Does it affect phase structure?</u>

Background & Motivation

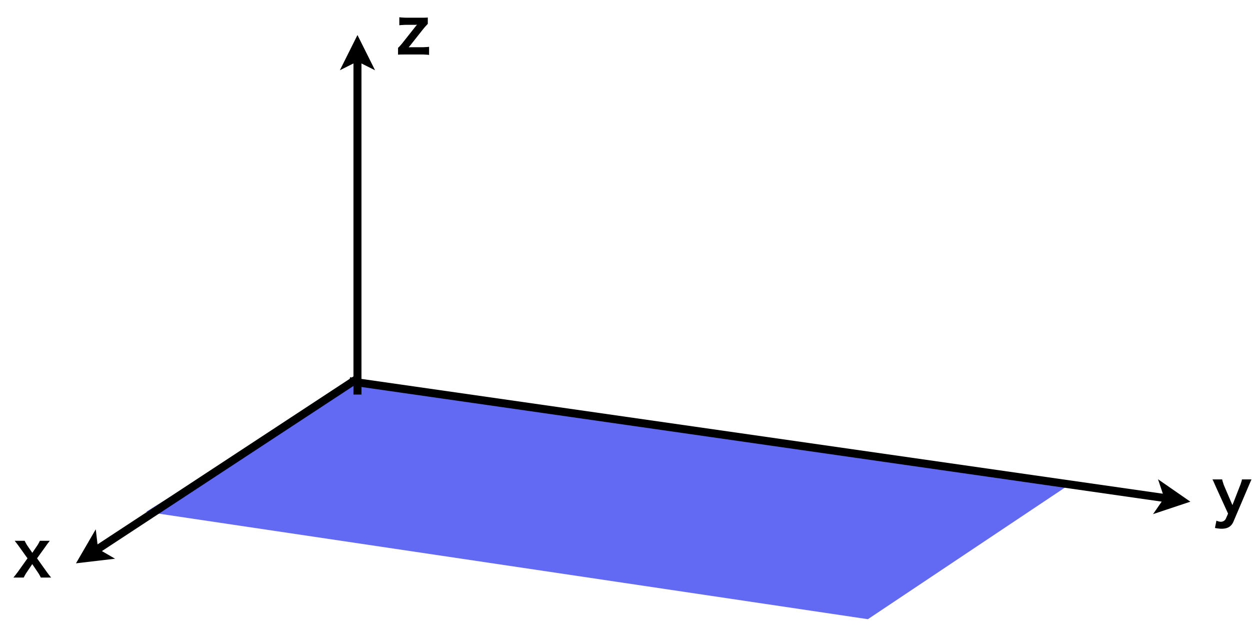
QCD phase transition depends on Magnetic field?

Colombia plot : the order of QCD phase transition



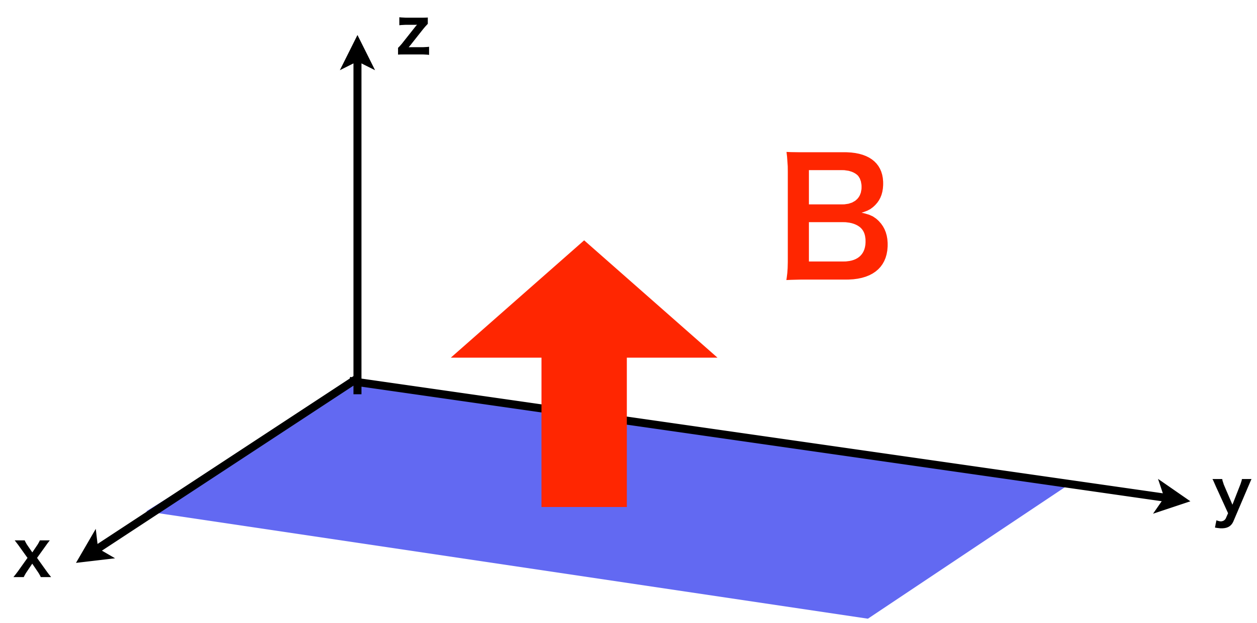
Background & Motivation

Magnetic field breaks symmetries



Background & Motivation

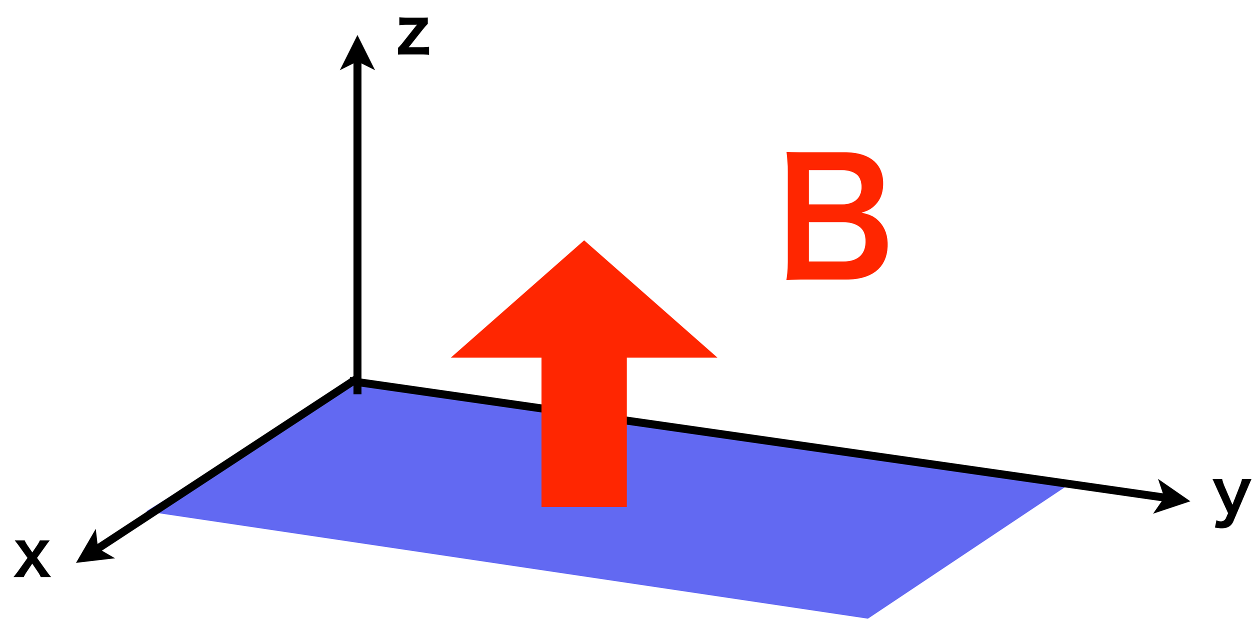
Magnetic field breaks symmetries



U(1) mag. $a_\mu = (0, xB, 0, 0)$

Background & Motivation

Magnetic field breaks symmetries



U(1) mag. $a_\mu = (0, xB, 0, 0)$

Magnetic field breaks:
- Lorentz symmetry
- Flavor symmetry
- Time reversal

Phase diagram will change

Outline

1. Introduction (Background)
2. Previous studies (5 studies as example)
3. Setup
4. Preliminary results
5. Summary

Background & Motivation

Previous studies: Model & Lattice

Previous studies: Model & Lattice

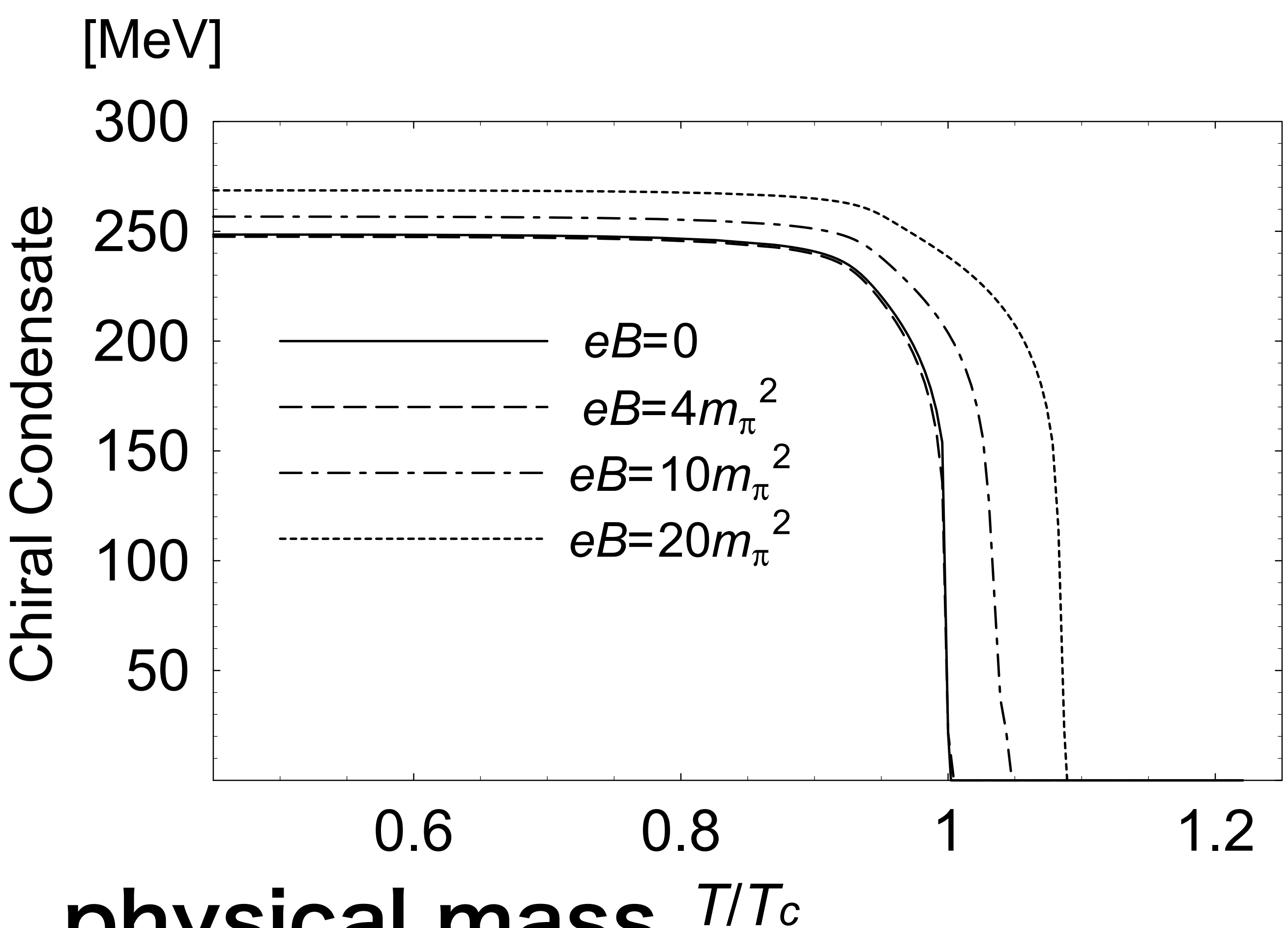
Model Kenji Fukushima et al (arXiv: 1003.0047)
N. O. Agasian et al (arXiv: arXiv: 0803.3156)
Jens Braun et al (arXiv: 1412.6025)
Lattice Massimo D'Elia et al (arXiv: 1005.5365)
Gergely Endrődi 2015 (arXiv: 1504.08280)

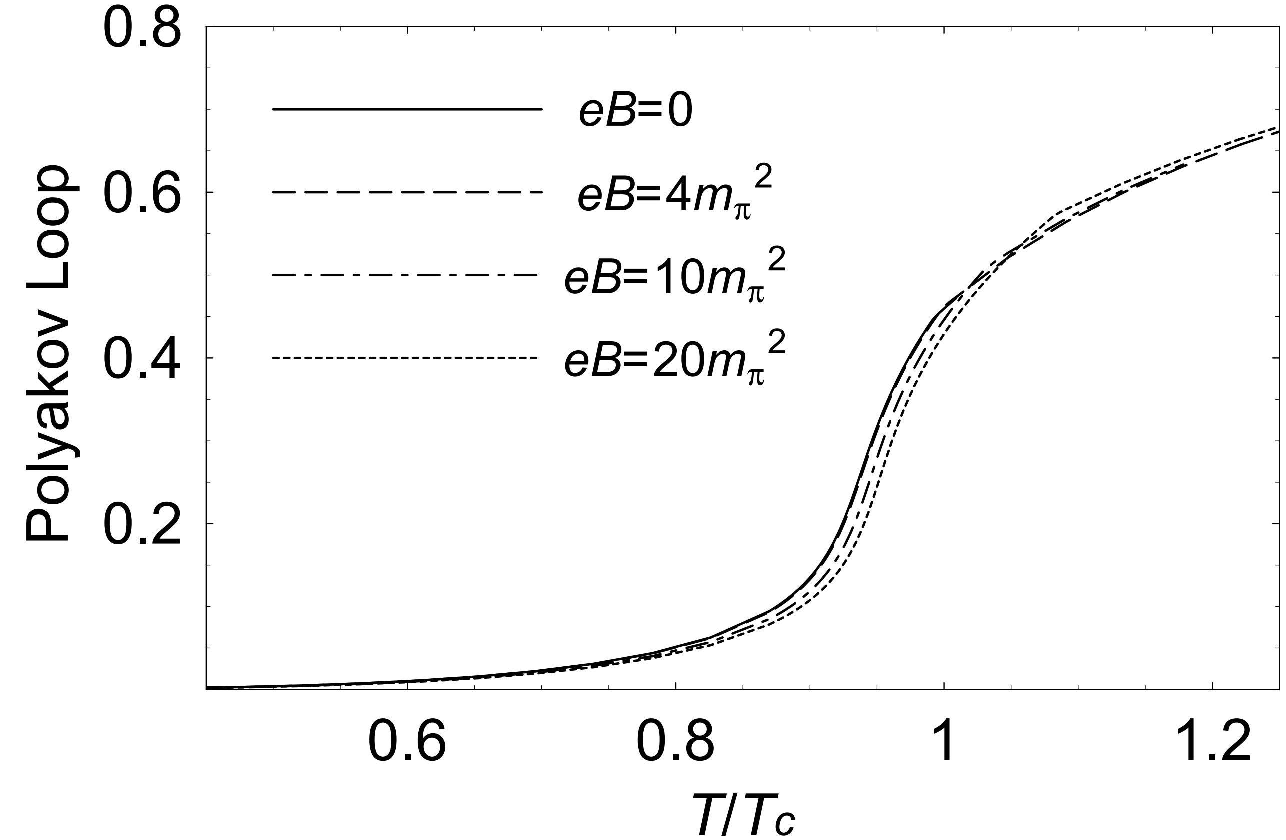
Background & Motivation

Previous studies: Model & Lattice 1/5

Model(1/3) : PNJL (Nf=2)

Kenji Fukushima, Marco Ruggieri, Raoul Gatto 2010 (arXiv: 1003.0047)





physical mass

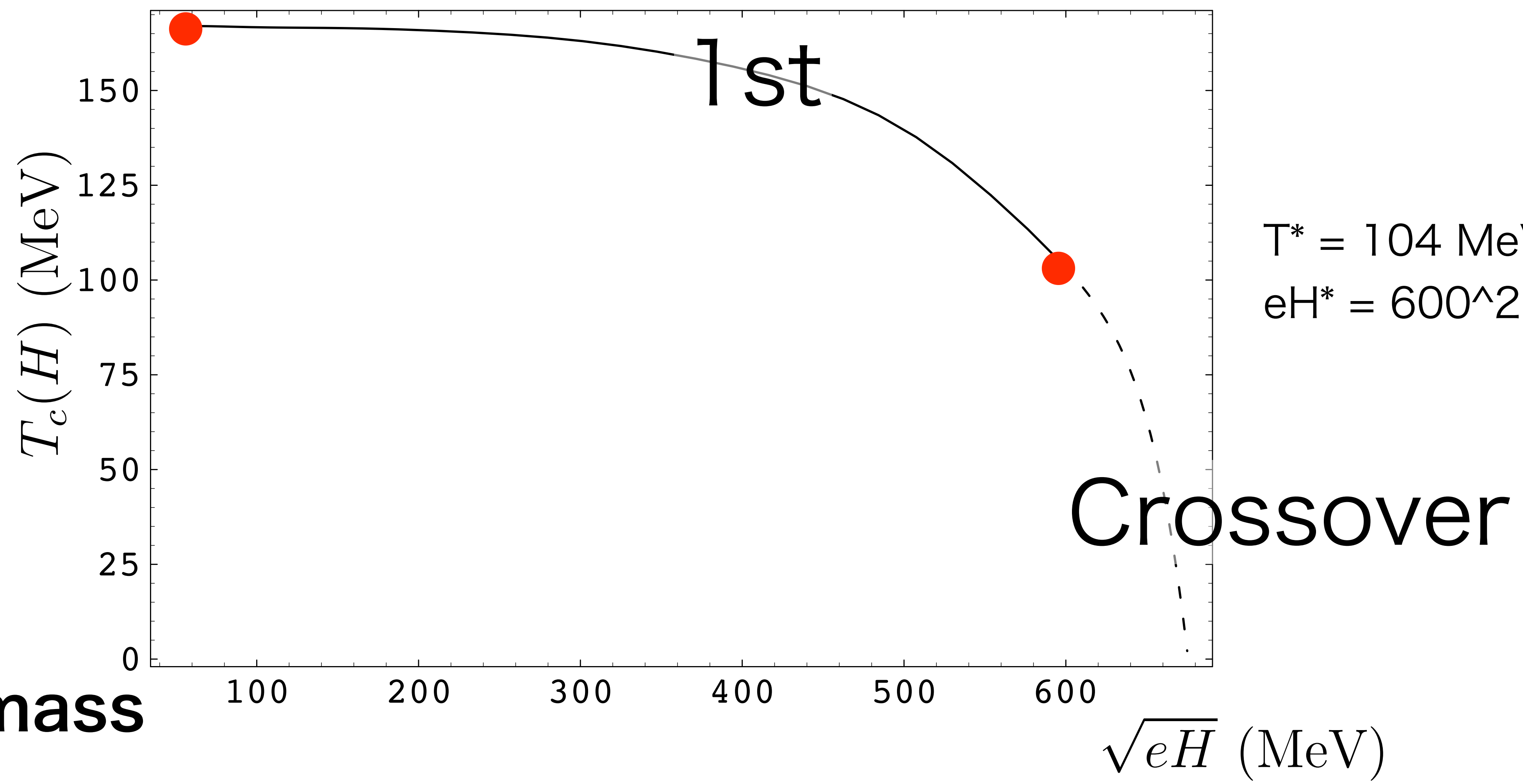
- Tc goes **up** along with mag. field.
- Order does not depend on eB? (not discussed)

Background & Motivation

Previous studies: Model & Lattice 2/5

Model(2/3) : ChPT (Nf=2) + gluon

N. O. Agasian and S. M. Fedorov 2008 (arXiv: 0803.3156)



T* = 104 MeV

eH* = 600^2 MeV^2

physical mass

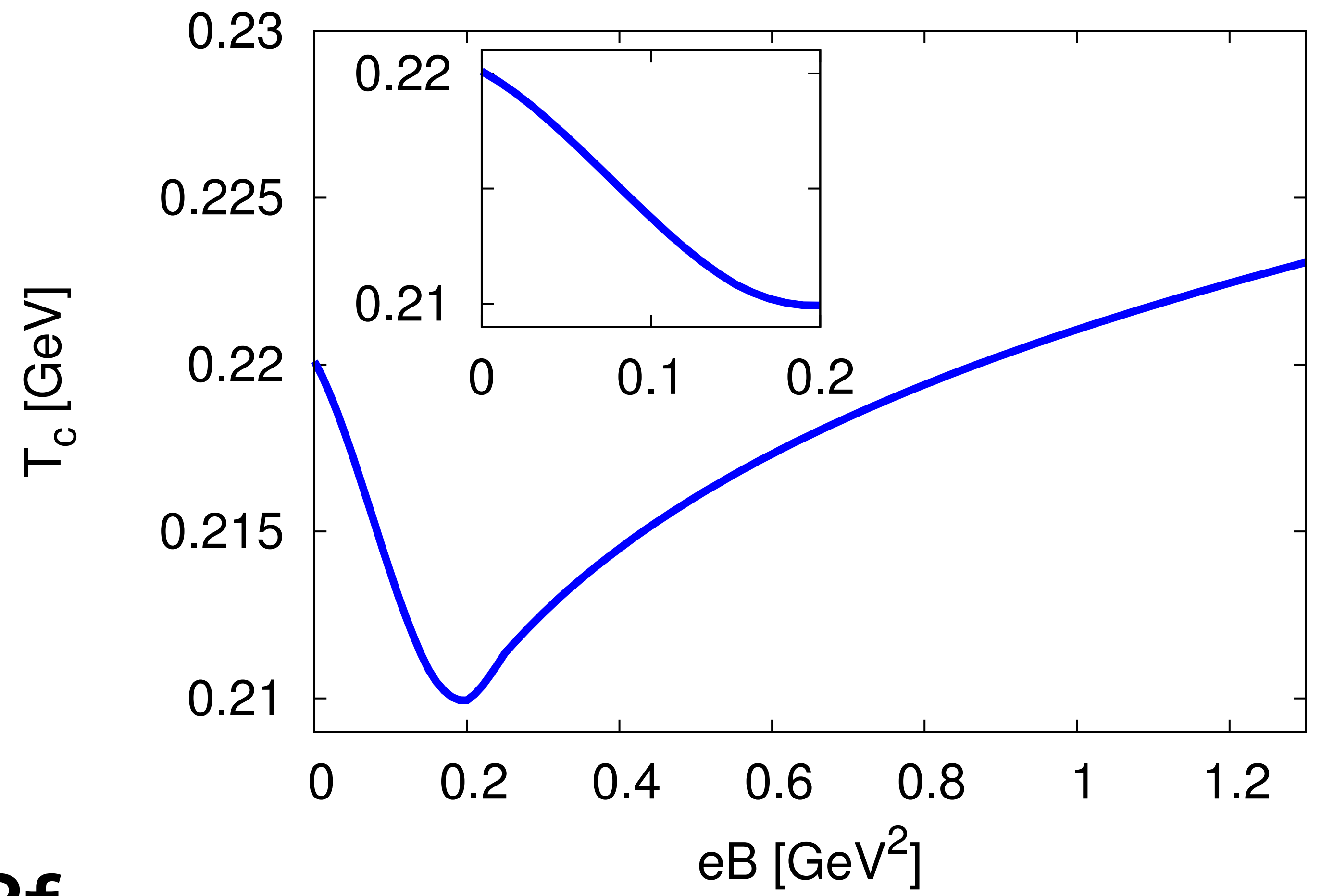
- Tc goes **down** along with mag. field.
- Order depends on eB(1st to crossover)

Background & Motivation

Previous studies: Model & Lattice 3/5

Model(3/3) : QCD + 4-fermi intr. + Renormalization Group

Jens Braun, Walid Ahmed Mian, Stefan Rechenberger 2014 (arXiv: 1412.6025)



Massless 2f

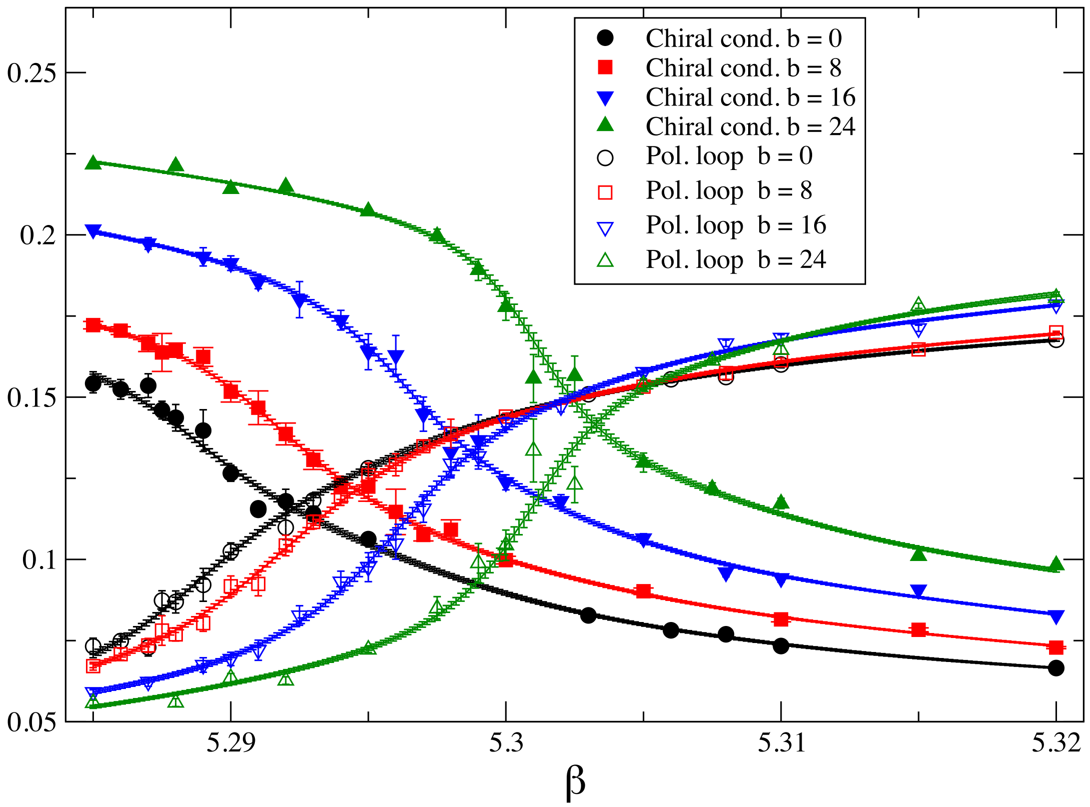
- Tc goes **down** and **up** along with mag. field.
- Order is not discussed

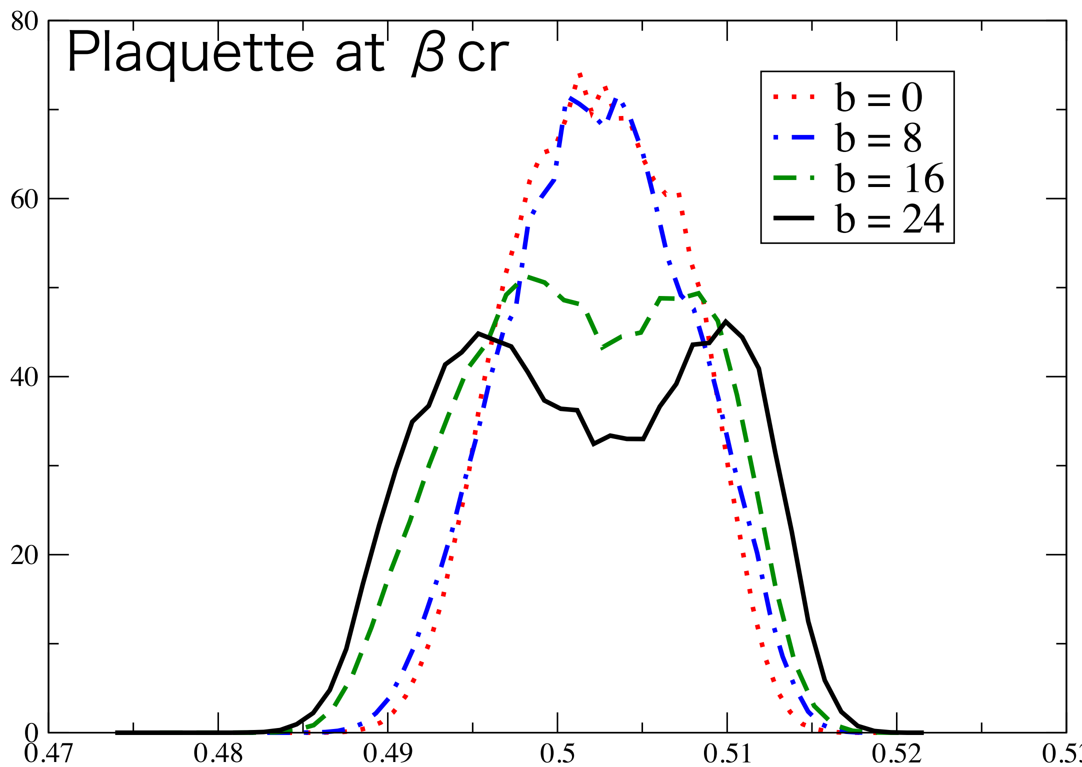
Background & Motivation

Previous studies: Model & Lattice 4/5

Lattice(1/2): Nf=2, standard KS

Massimo D'Elia, Swagato Mukherjee and Francesco Sanfilippo (arXiv: 1005.5365)





$m_\pi \approx$ 275 MeV

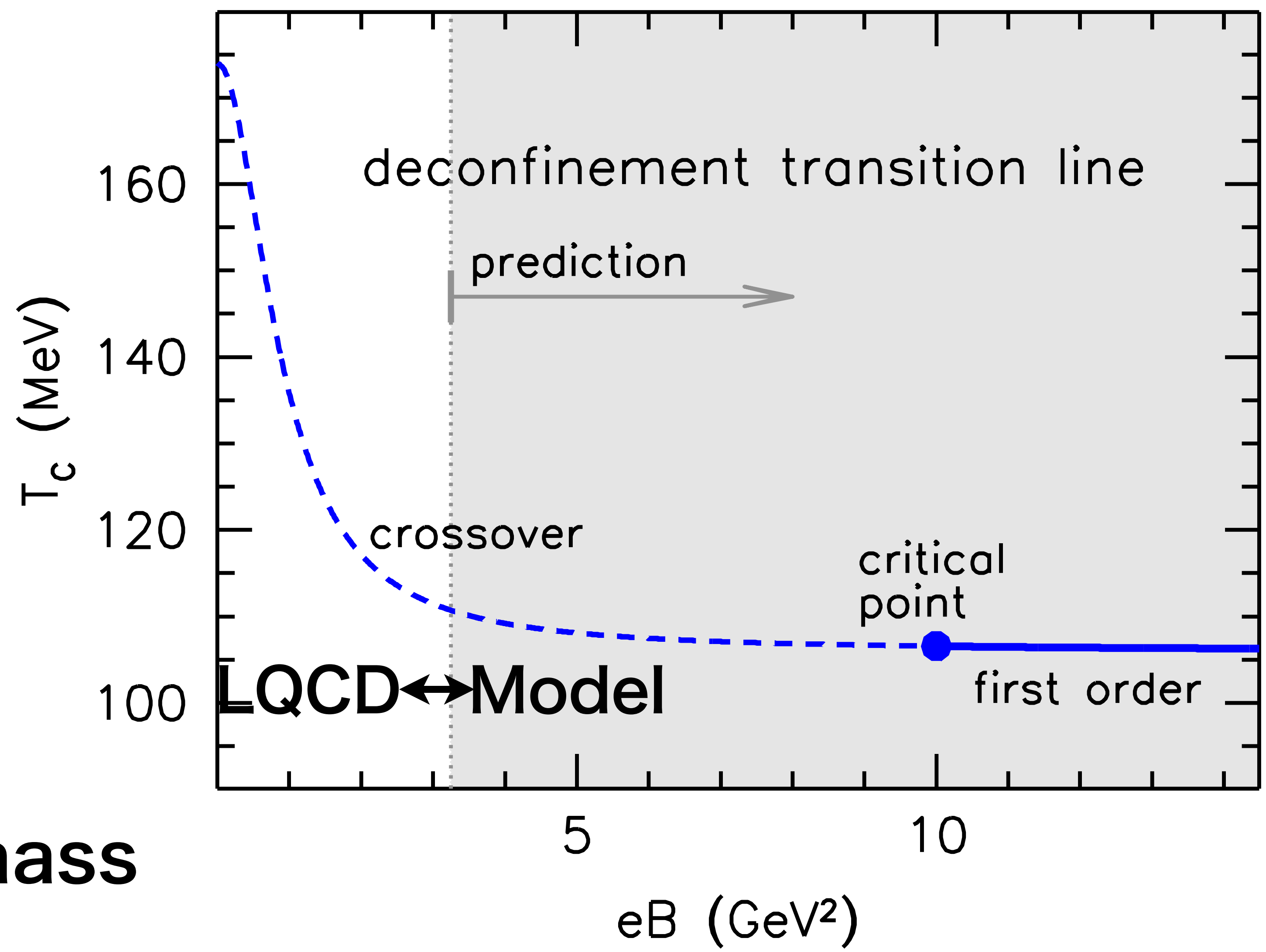
- Tc goes **up** along with mag. field.
- Order depends on eB (Crossover to strong 1st)

Background & Motivation

Previous studies: Model & Lattice 5/5

Lattice(2/2) + model: Nf =3, stout KS, physical mass

Gergely Endrődi 2015 (arXiv: 1504.08280)



Physical mass

- Tc goes **down** along with mag. field.
- Order depends on eB (crossover to 1st by a model)

Background & Motivation

Tc and order

QCD phase transition with external U(1) magnetic field has been investigated for long years, from J. Schwinger(1951)

Author(s)	Ref.	Method	Tc w/ eB	Order w/ eB
Kenji Fukushima et al	arXiv: 1003.0047	PNJL(2f) at m_{phys}	Increase	No change?
N. O. Agasian et al	arXiv: 0803.3156	ChPT(2f) at m_{phys}	Decrease	1st to crossover
Jens Braun et al	arXiv: 1412.6025	RG, massless 2f	Decrease and increase	?
Massimo D'Elia et al	arXiv: 1005.5365	KS(2f)	Increase	Crossover to strong 1st
Gergely Endrődi	arXiv: 1504.08280	Stout KS (3f) at m_{phys} + model	Decrease	Crossover to 1st (model)

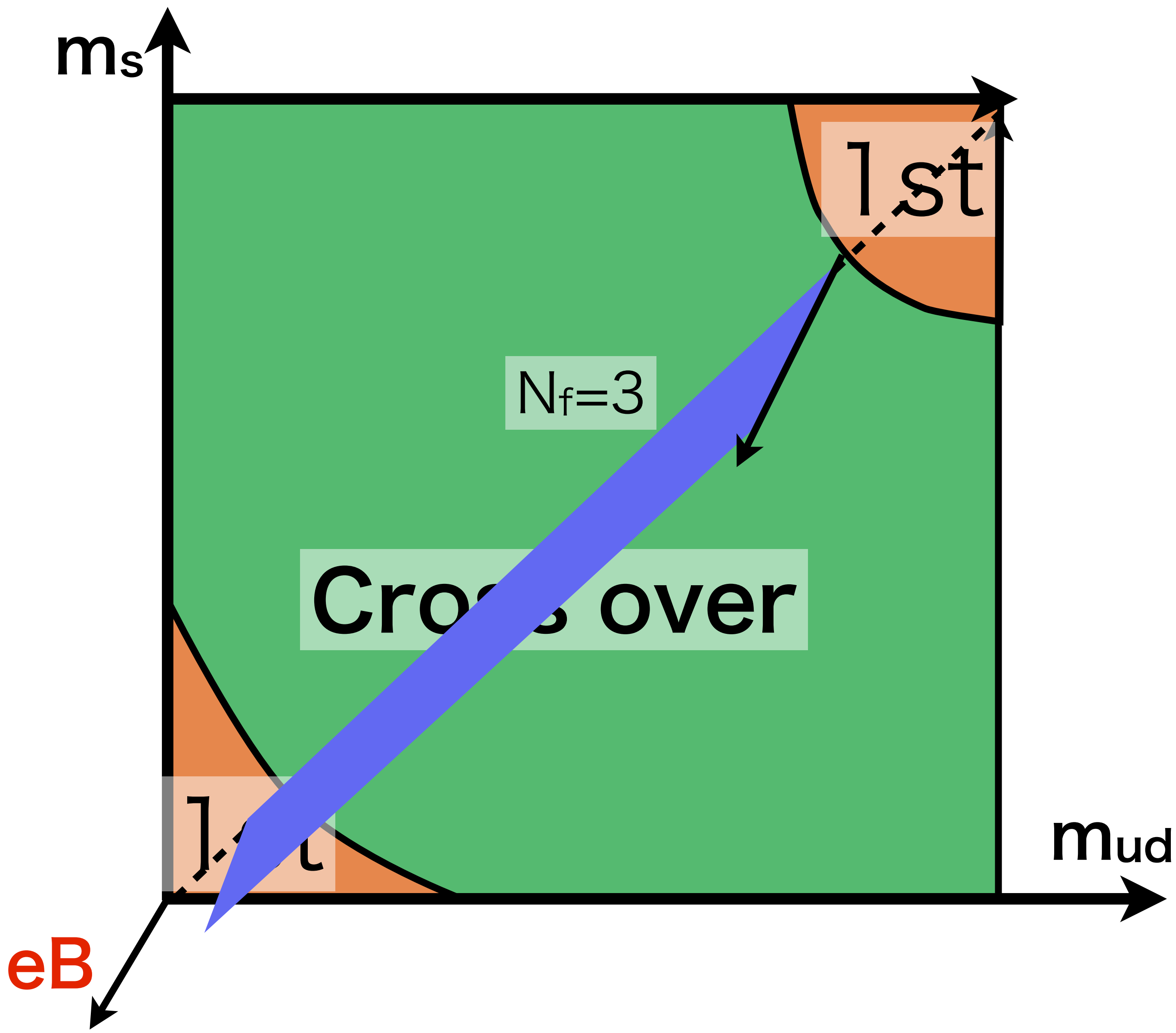
Ref. 1208.0917, 1209.0374, 1411.7176 and there in

We examine dependence of the order of phase transition on quark mass and external magnetic field

What we have done

Dependence of order of transition on ma and eB

Mass degenerated 3 flavor QCD with magnetic field



ma = 0.024(1st order), 0.028(~critical pt), 0.2, 0.4, 0.8
Check the order of phase transition on eB

Setup

3Flavor Standard staggered + Wilson plaq. action

Setup: 3 Flavor degenerated mass staggered fermion (same as *)

4th rooted RHMC, Observables: chiral condensates, Polyakov loop

Resource: Fermi-lab GPU cluster

	m_q a	Size	β range	Nb (Magnetic flux)	#Conf.
Light	0.024(1st order for Nb=0*)	24^3x4 (16^3x4)	5.128-5.160	0-56	O(2000)
Light	0.028(Critical for Nb = 0*)	16^3x4	5.130-5.170	0-56	O(1500)
Heavy	0.2	16^3x4	5.10-5.65	0-56	O(500)
Heavy	0.4	16^3x4	5.35-5.65	0-56	O(500)
Heavy	0.8	16^3x4	5.35-5.85	0-56	O(700)

* Dominik Smith et al 2010 (arXiv: 1109.6729)

$$qBa^2 = \frac{2\pi N_b}{N_x N_y}$$

Nb: Number of magnetic flux

Mass vs magnetic field

Magnetic field changes eigenvalues

$$\mathcal{L} = \overline{\psi}(\gamma_\mu(\partial_\mu - iq\underline{a_\mu}) + \underline{m})\psi$$

U(1) gauge field affects as “mass” to the system
then we can estimate a “comparable mass” as,

$$a\sqrt{eB} = \sqrt{\frac{2\pi N_b}{N_x N_y |q|}} = am_{N_b}$$

q=2/3 Nx=Ny=16 case,

N_b	1	4	17	24	32	56	64
am_{N_b}	0.19	0.38	0.79	0.9	1.1	1.4	1.5

For each Nb is consider to be compatible with the quark mass

We choose ma=0.2, 0.4, 0.8 to see effect of quark mass and the magnetic field

Preliminary Results

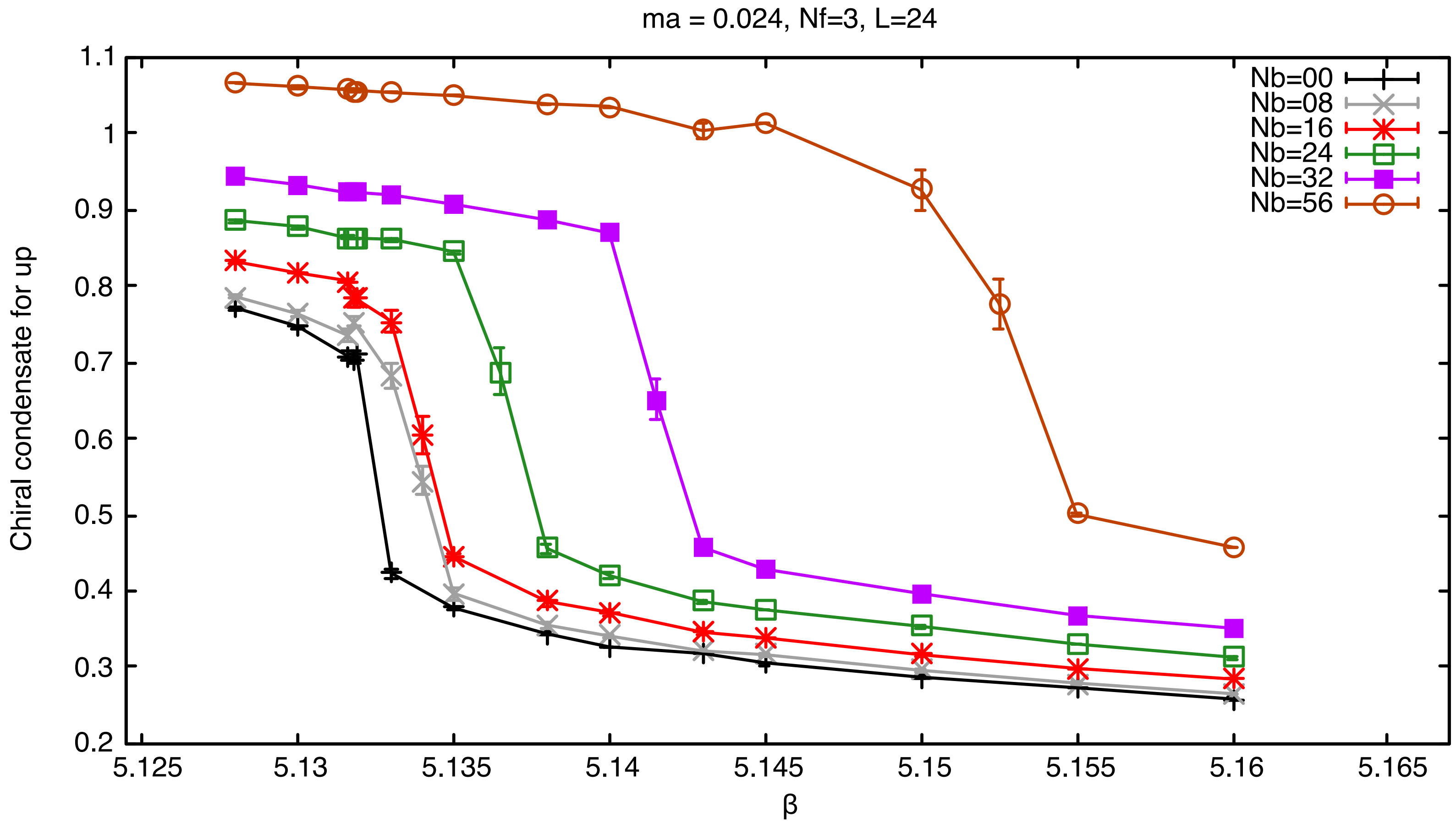
For 5 quark mass points:
ma = 0.024 (1st order),
ma = 0.028 (just above the critical pt, crossover regime),
ma = 0.2 (comparable with magnetic field Nb=1)
ma = 0.4 (comparable with magnetic field Nb=5)
ma = 0.8 (comparable with magnetic field Nb=24)

Preliminary Result (1/5)

am = 0.024(1st for Nb=0): 1st becomes stronger?

L=24^3x4

Up quark cond.



Tc increases Nb -> Large

Preliminary Result (1/5)

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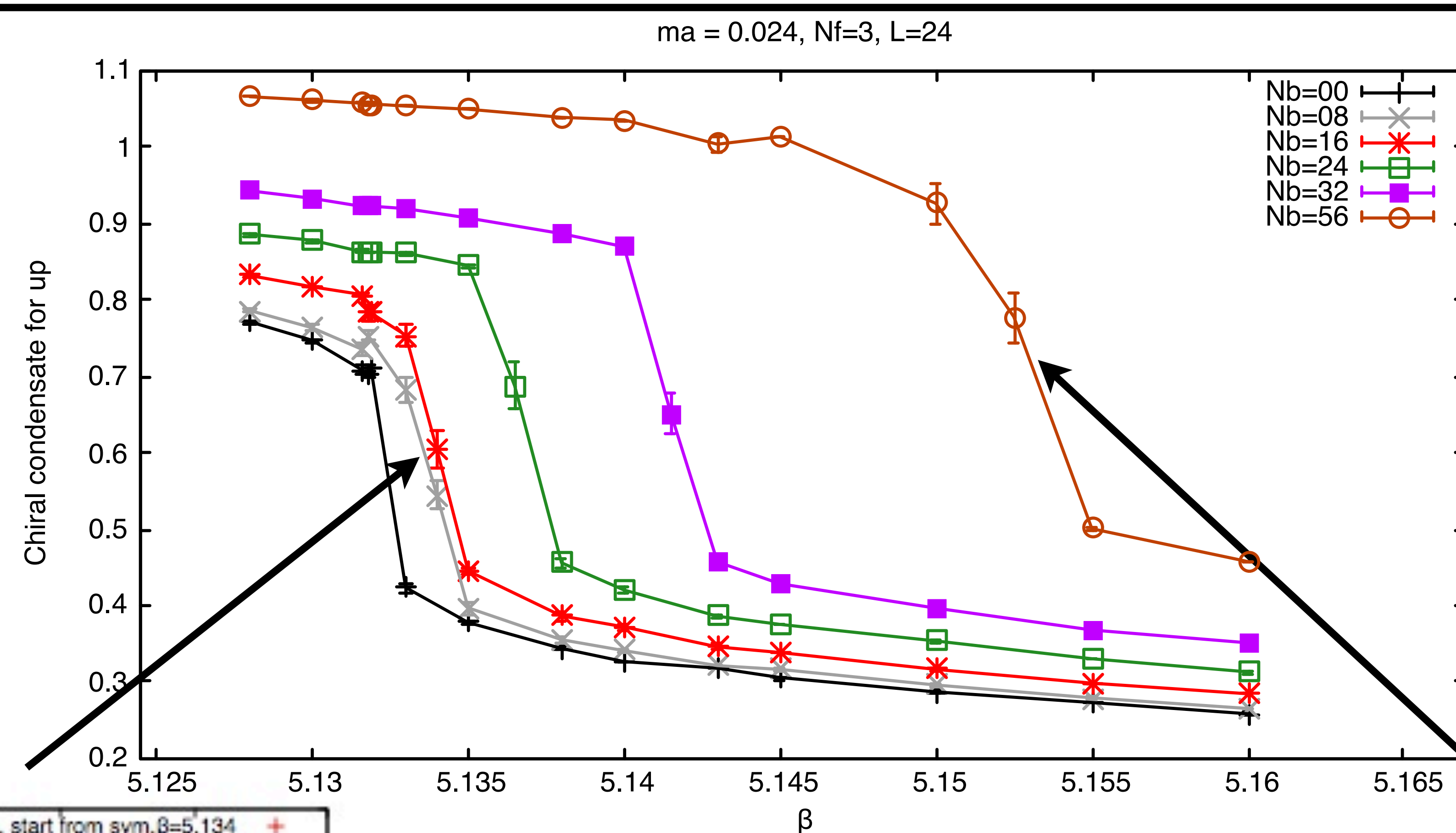
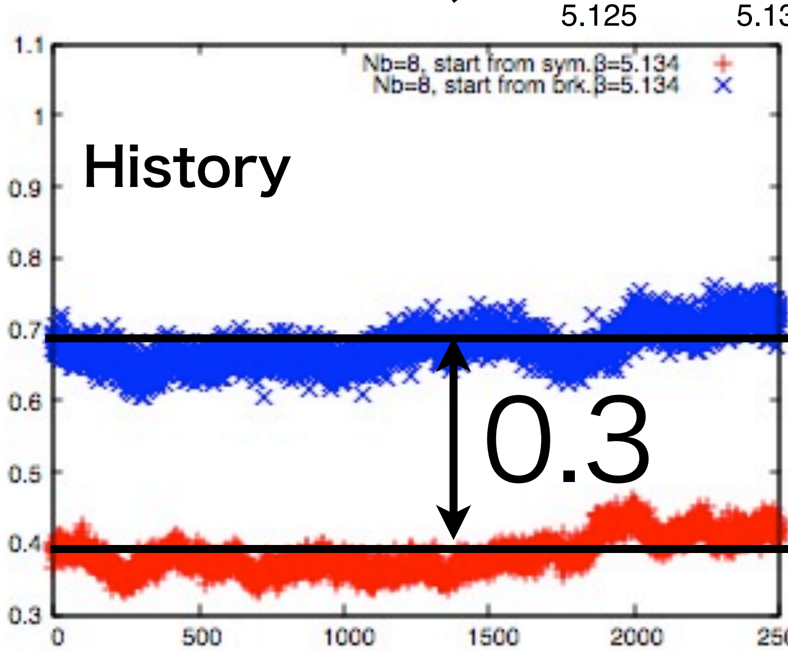
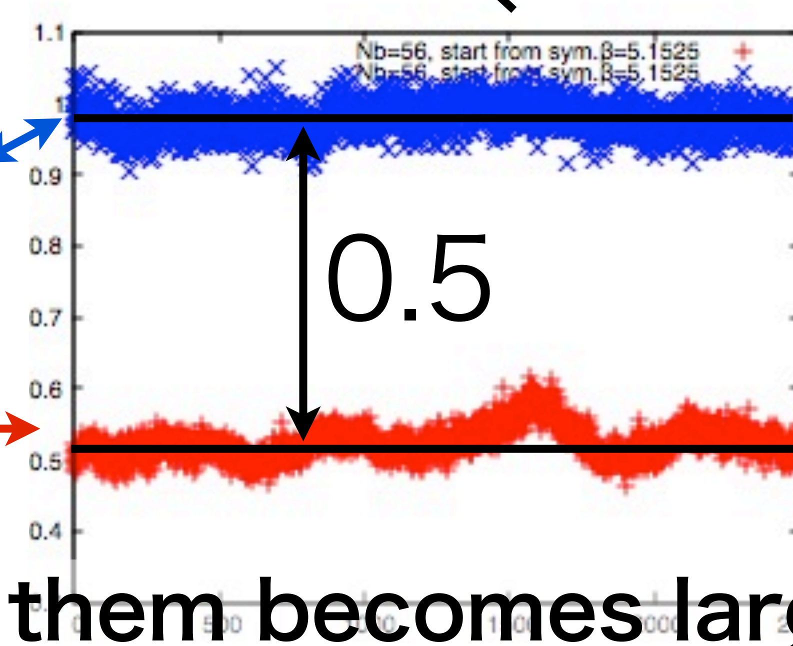


Tc increases
Nb -> Large



Start from broken phase

Start from sym. phase



Hysteresis (=1st order) and the gap of them becomes larger

Preliminary Result (1/5)

am = 0.024(1st for Nb=0): 1st becomes stronger?

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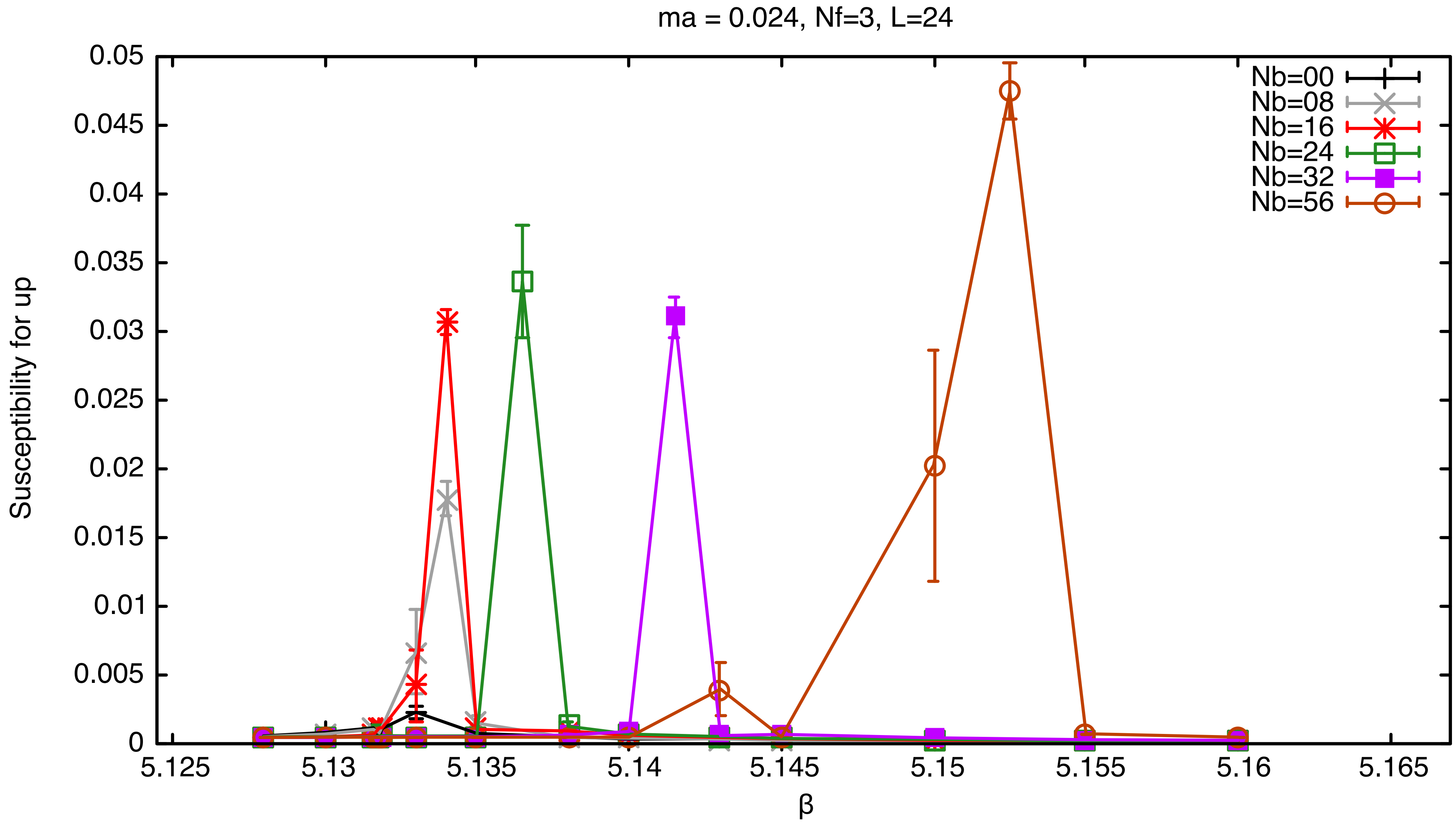
Up quark cond.



Tc increases

Nb -> Large

The Binder ratio(cumulant)

B4 = 1: 1st. B4 ~ 1.6: 2nd(Z2). B4 = 3: Crossover

The Binder cumulant is defined as ratio of 4th order cumulant with square of 2nd oder cumulant,

$$B_4(x) \;=\; \frac{\langle \left(\delta M(x)\right)^4 \rangle}{\langle \left(\delta M(x)\right)^2 \rangle^2}$$

M: order parameter

This quantity can distinguish the order of phase transition

$$B_4 \begin{cases} = 1 & \text{First order} \\ \sim 1.6 & \text{Second with } Z_2 \\ \sim 3 & \text{Crossover} \end{cases}$$

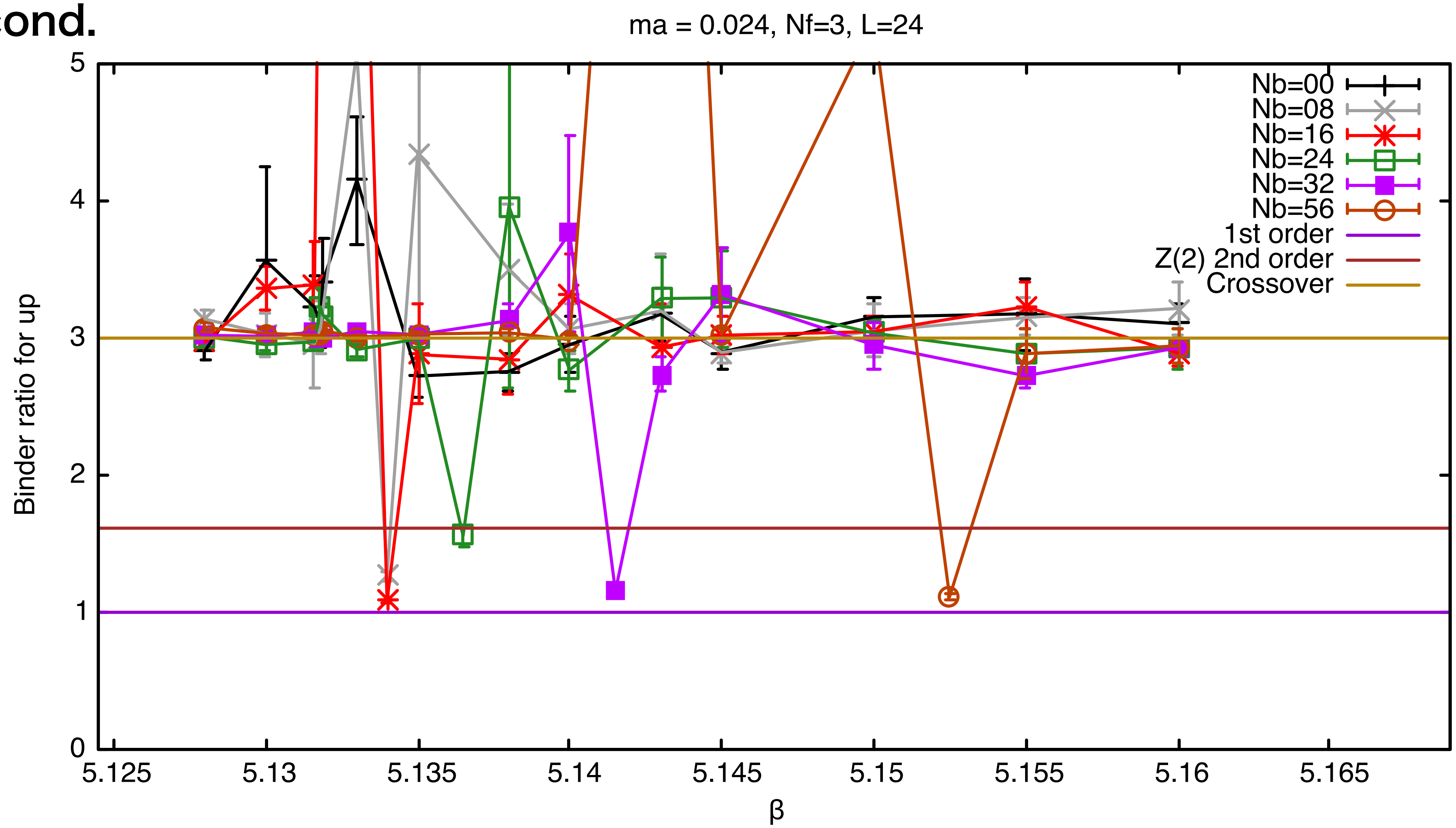
But higher statistics are demanded

Preliminary Result (1/5)

am = 0.024(1st for Nb=0): 1st becomes stronger?

L=24^3x4

Up quark cond.



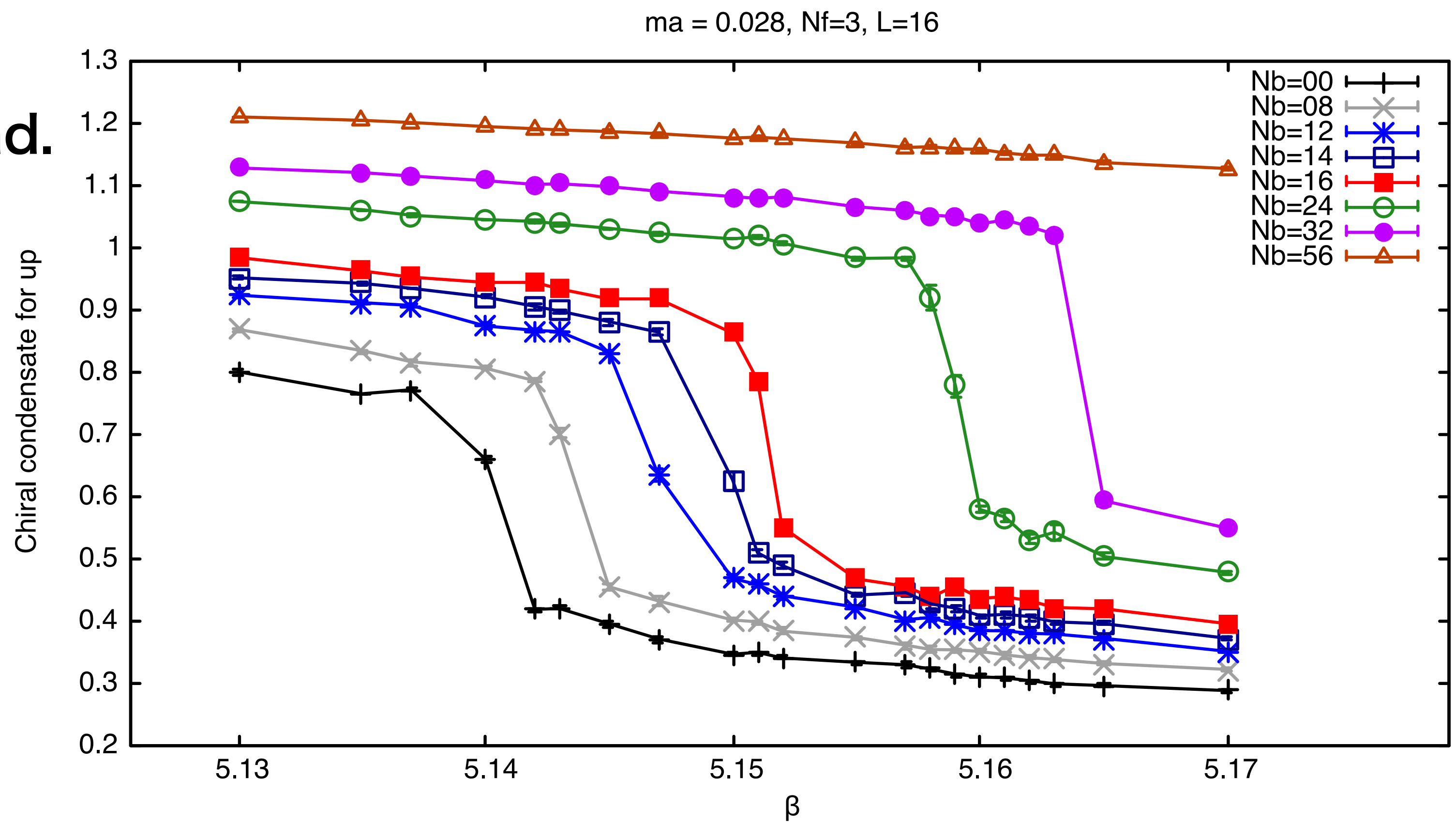
(For Nb-0, 1st order is already confirmed in Dominik Smith & Christian Schmidt 2010)
Statistics is not enough

Preliminary Result (2/5)

am = 0.028(crossover for Nb=0): crossover to 1st

L=16^3x4

Up quark cond.



Tc increases

Nb -> Large

Preliminary Result (2/5)

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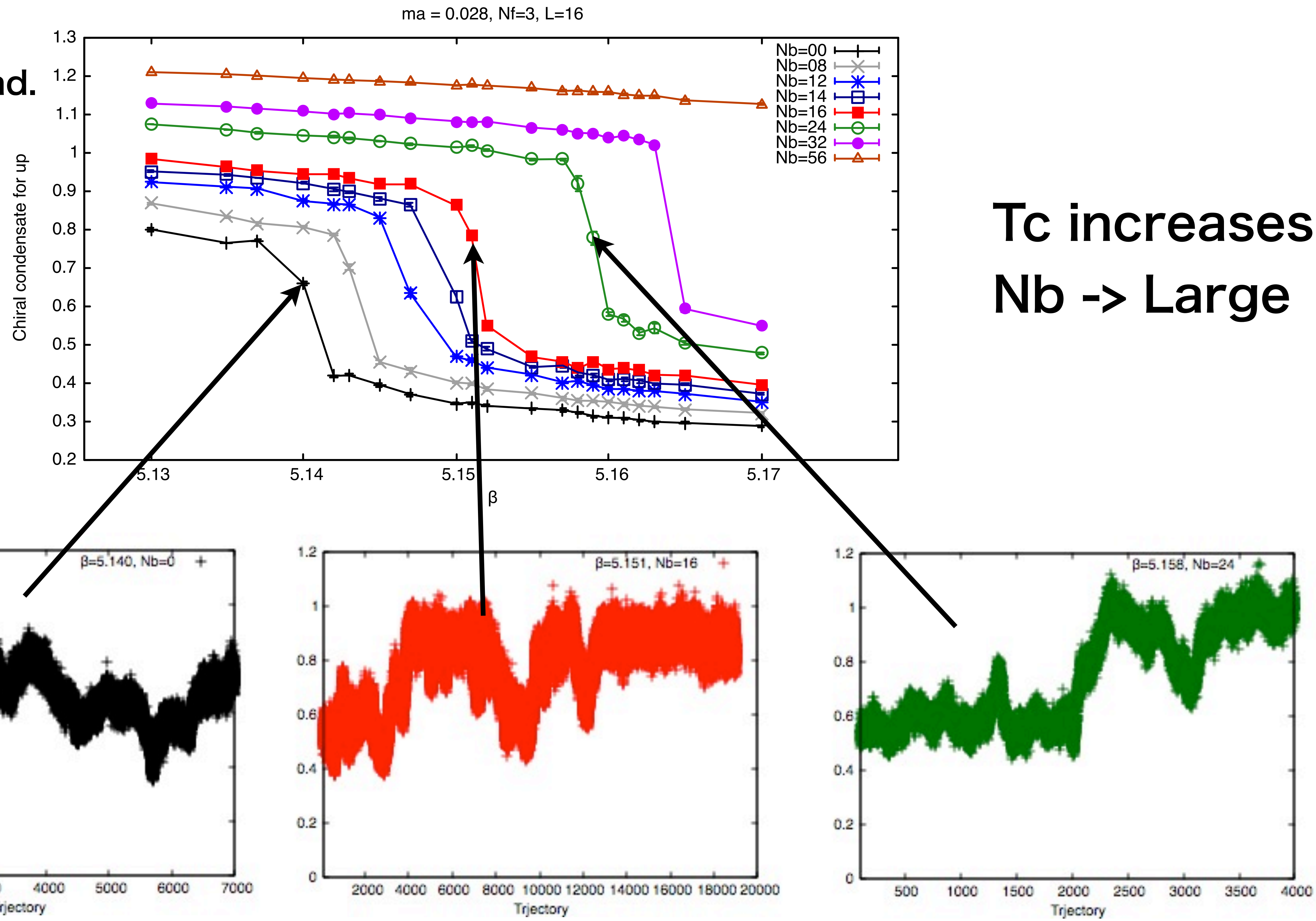
L=16^3x4

Up quark cond.



Tc increases Nb -> Large

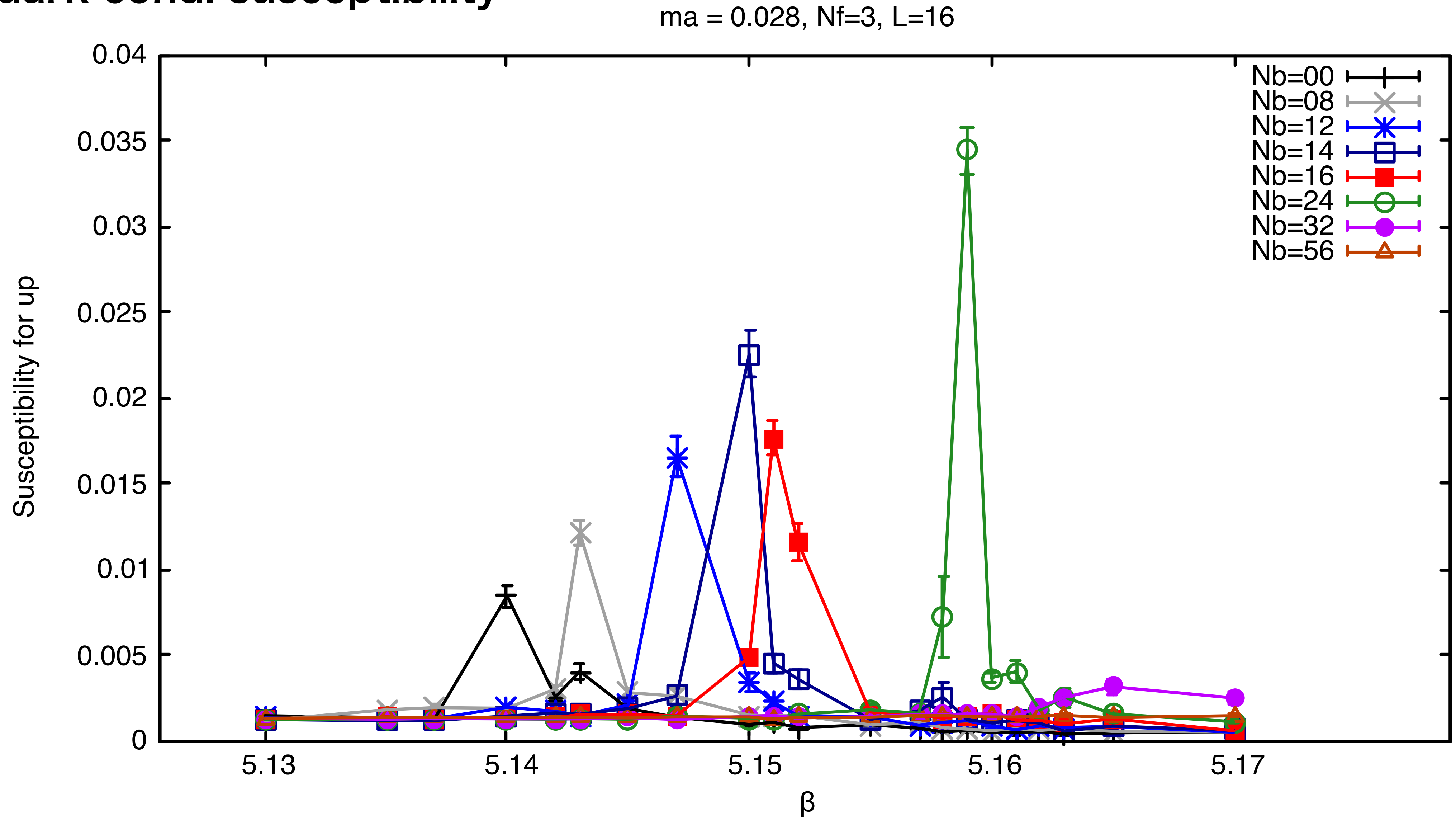
A. Tomiya CCNU

Preliminary Result (2/5)

am = 0.028(crossover for Nb=0): crossover to 1st

L=16^3x4

Up quark cond. susceptibility



Tc increases

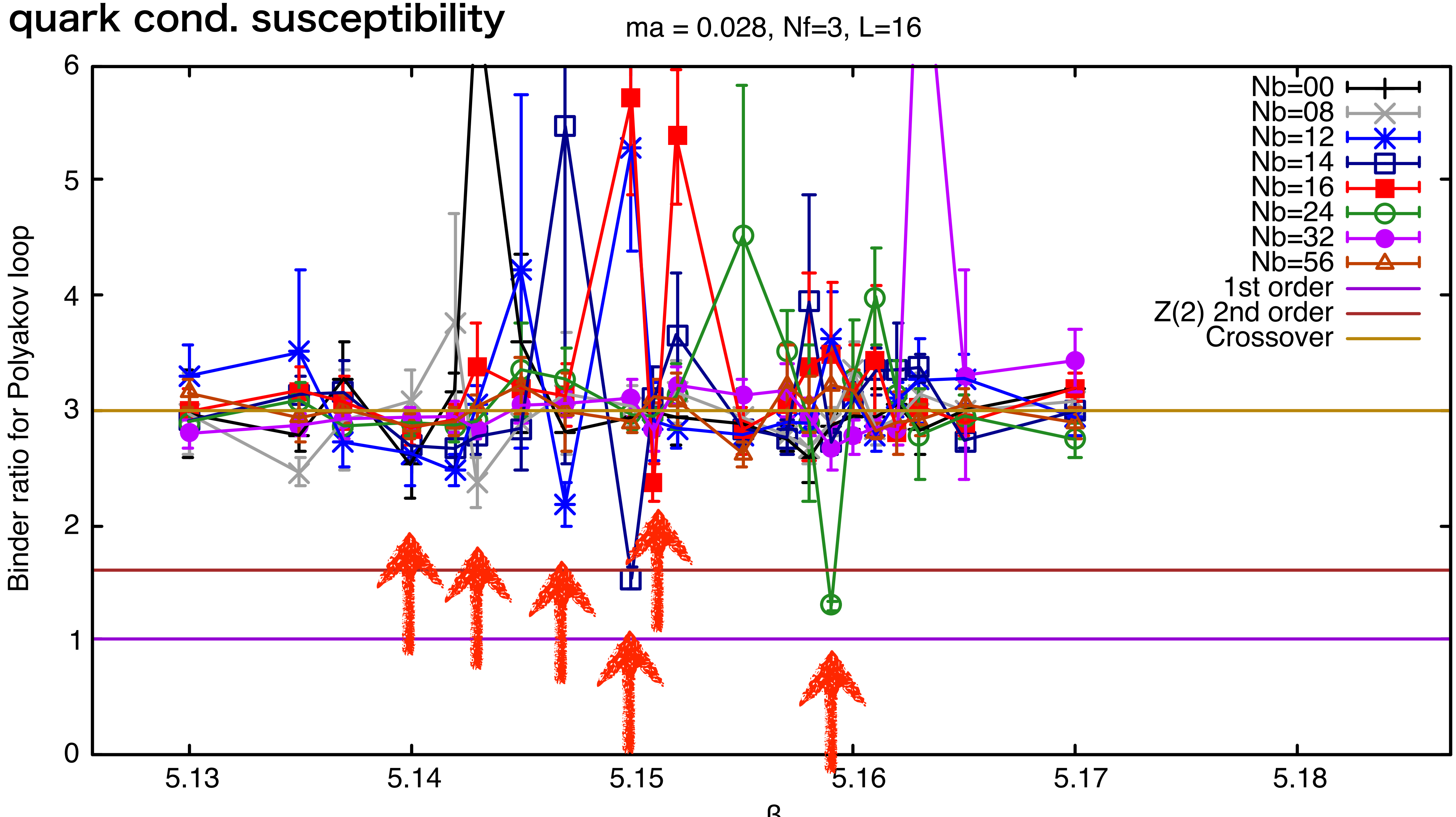
Nb -> Large

Preliminary Result (2/5)

am = 0.028(crossover for Nb=0): crossover to 1st

L=16^3x4

Up quark cond. susceptibility



Nb -> Large,

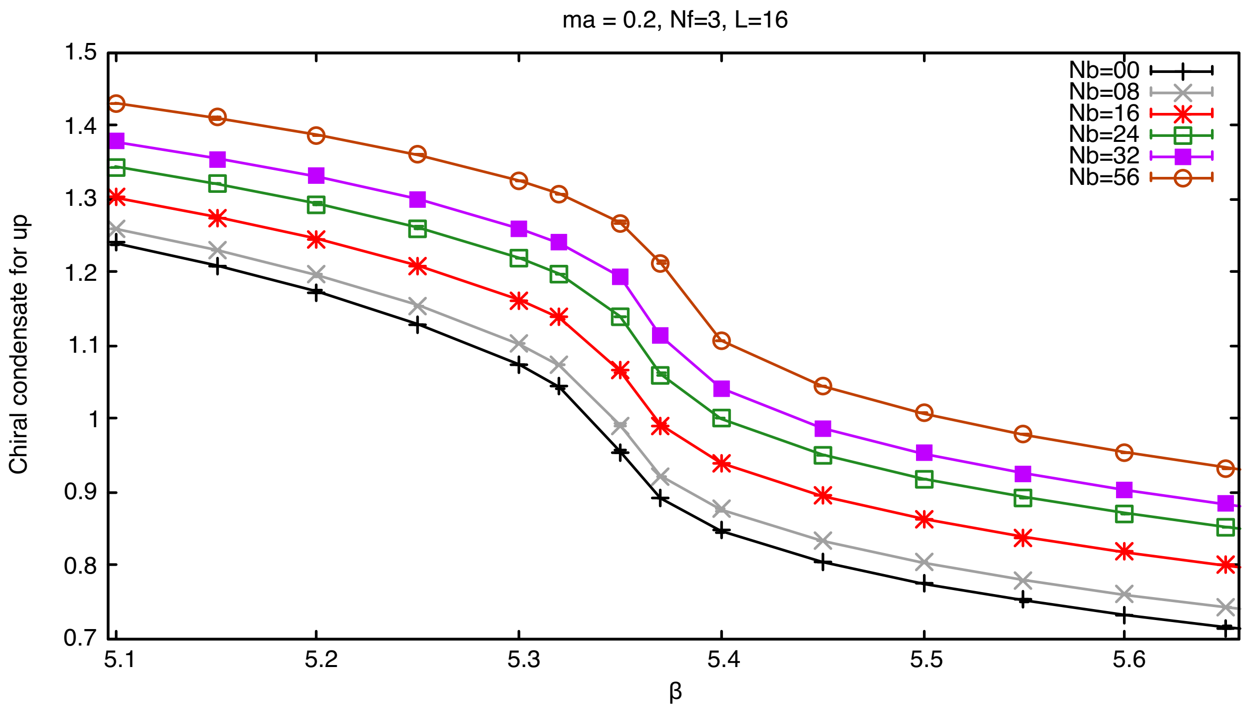
B -> 1? Statistics is not enough

Preliminary Result (3/5)

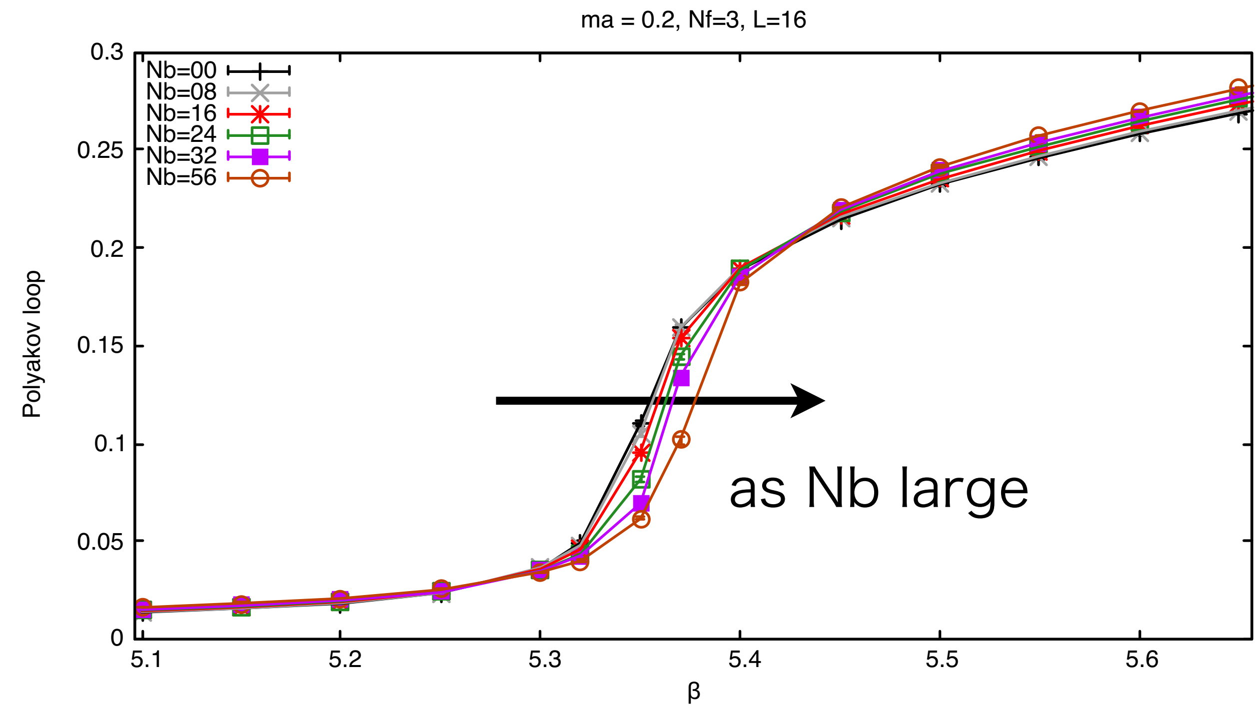
am = 0.2: Tc goes up

L=16^3x4

Up quark condensate



Polyakov loop



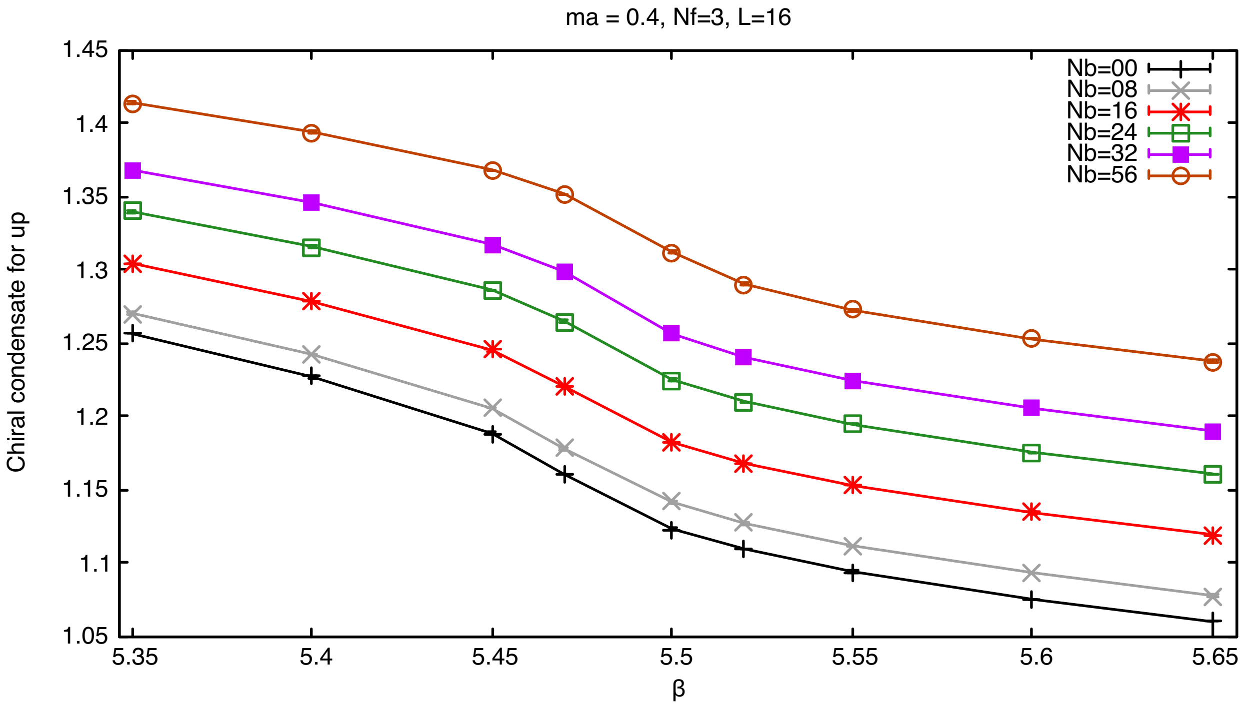
- Chiral condensate does not show phase transition for Nb = 0-56
- Behavior of the Polyakov loop is similar to that in PNJL results
- Tc for deconf/conf trans. goes up for increasing Nb (not clear)

Preliminary Result (4/5)

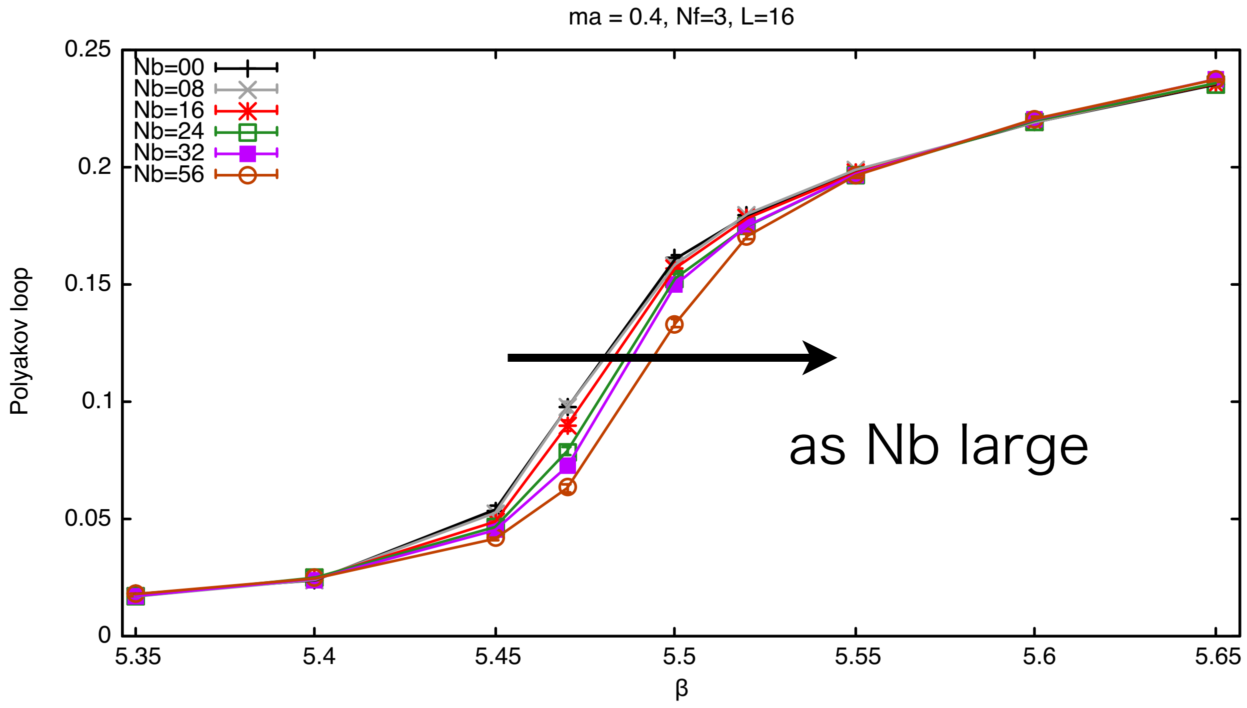
am = 0.4: No clear signal yet but Tc goes up

L=16^3x4

Up quark condensate



Polyakov loop



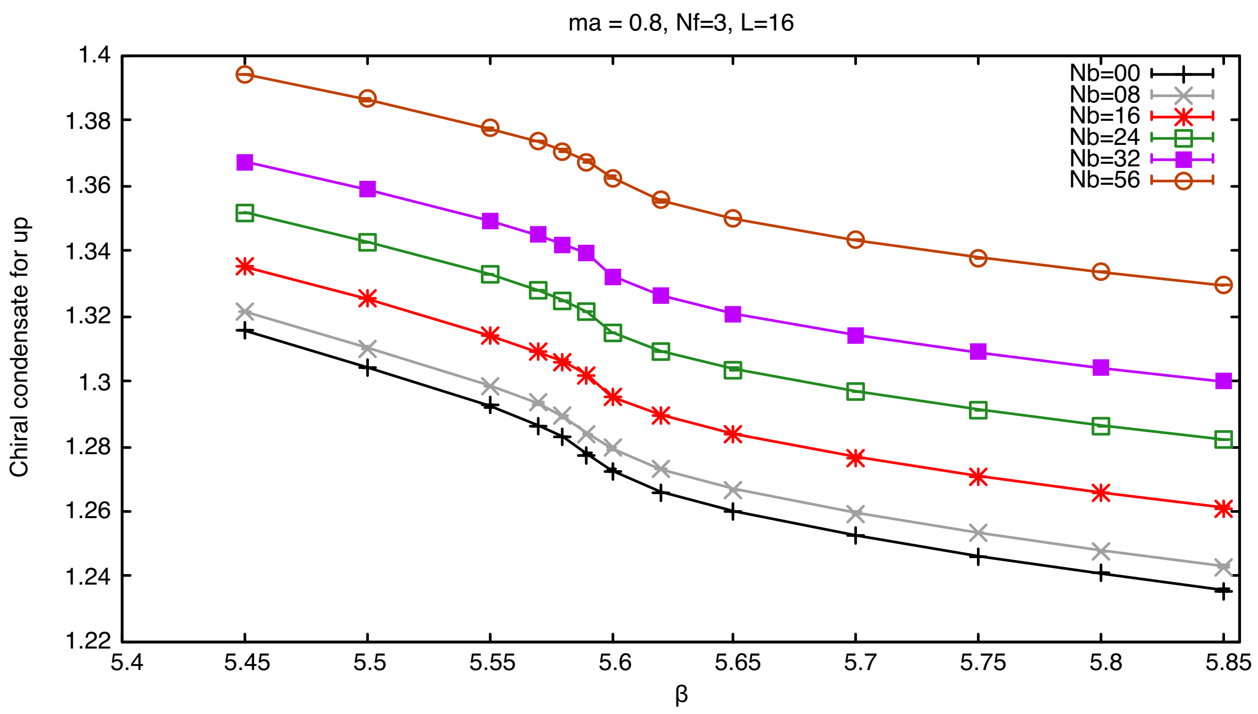
- Chiral condensate does not show phase transition (trivially scaled)
- Behavior of the Polyakov loop is similar to that in PNJL results
- Tc for deconf/conf trans. goes up for increasing Nb (not clear)

Preliminary Result (5/5)

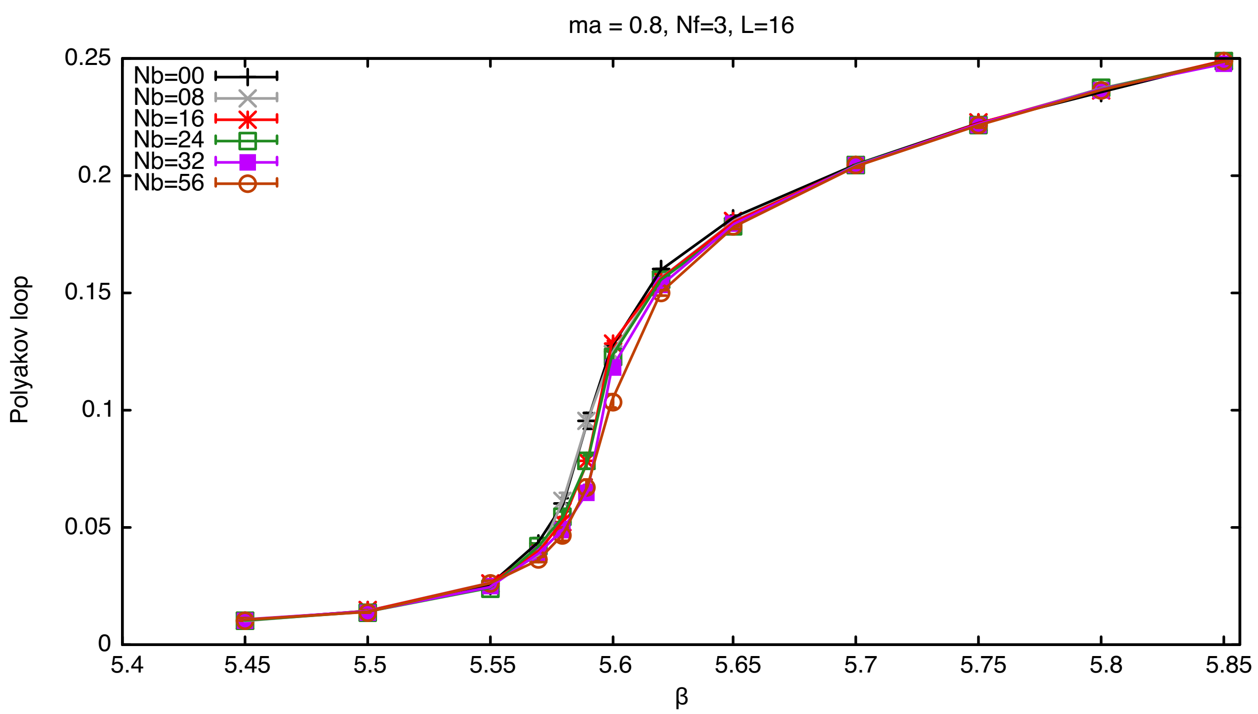
am = 0.8: No clear signal (1st order like for conf.)

L=16^3x4

Up quark condensate



Polyakov loop



- Chiral condensate does not show phase transition (trivially scaled)
- Conf/deconf. transition is not changed for Nb=0 to 56 (expected)

Summary of preliminary results

Tc goes up

am_q	Tc(chiral) dep. on Nb	Order(Chiral) dep. on Nb	Tc(Confinement) dep. on Nb	Order(Confinement) dep. on Nb
0.024 (1st order for Nb=0)	**Increase**	1st to strong 1st?	**Increase**	1st to strong 1st?
0.028 (Crossover for Nb = 0)	**Increase**	crossover to1st	**Increase**	crossover to 1st
0.2	no critical behavior	-	**Increase**	crossover like
0.4	no critical behavior	-	**Increase**	crossover like
0.8	no critical behavior	-	Increase?	1st ?

Summary

QCD phase transition depends on Magnetic field

Summary:

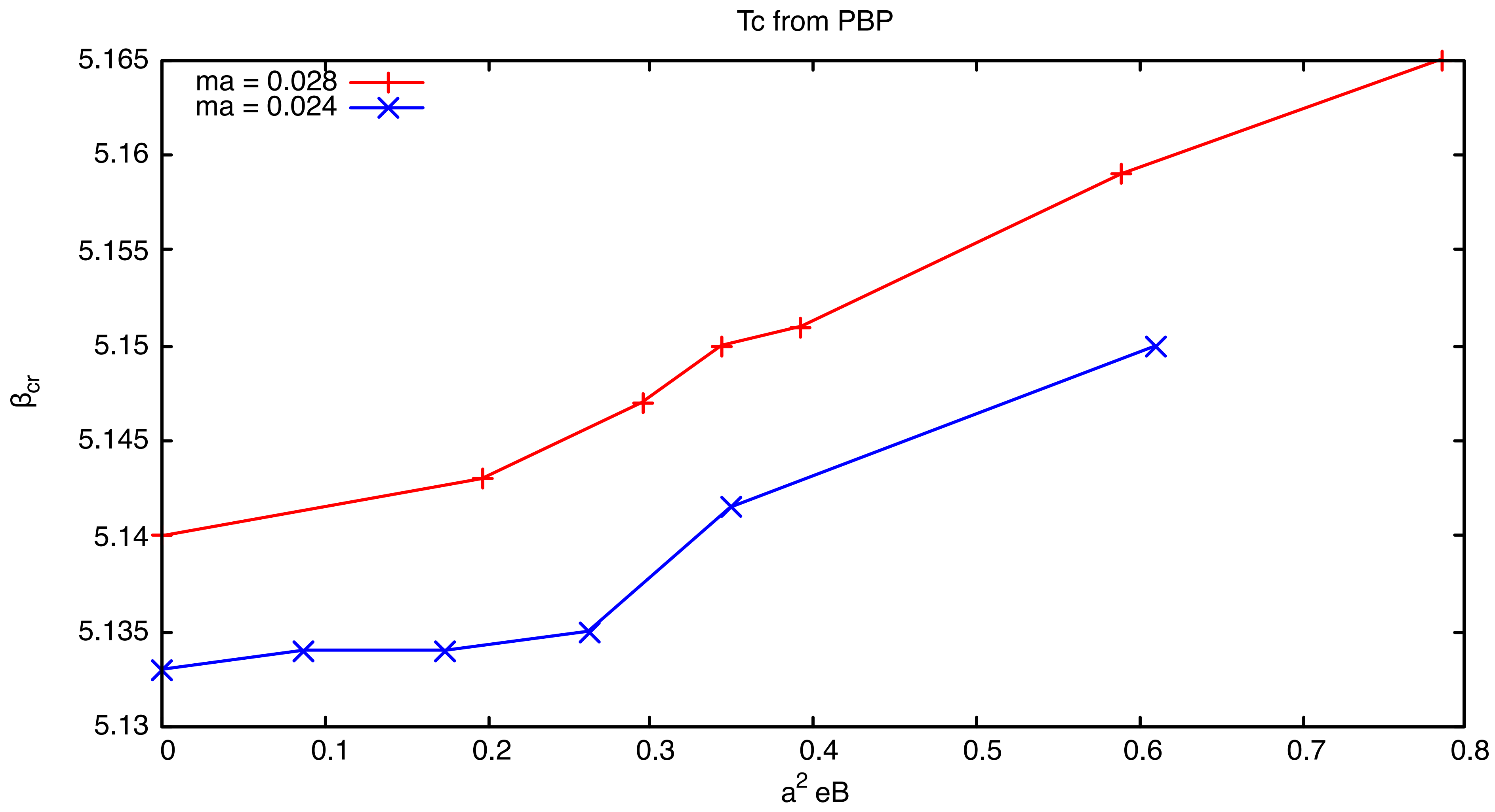
1. We investigate 3 flavor QCD with U(1) external magnetic field for various mass using standard staggered fermion with $N\sigma$=16(24), Nt=4
2. We observed strengthening of order of phase transition in light mass regime
3. Except for ma=0.8, Tc goes up. ma = 0.8, no clear response to Nb.

Tasks:

1. Increasing statistics
2. Improve resolution of beta
3. Scaling analysis to determine the order
5. Determination of the order of phase transition from the Binder ratio
6. Scale setting
7. Other cutoff scheme to check the cutoff effect on Tc vs Nb

Backup

Tc for
ma = 0.024(1st for Nb=0)
ma = 0.028(crossover for Nb=0)



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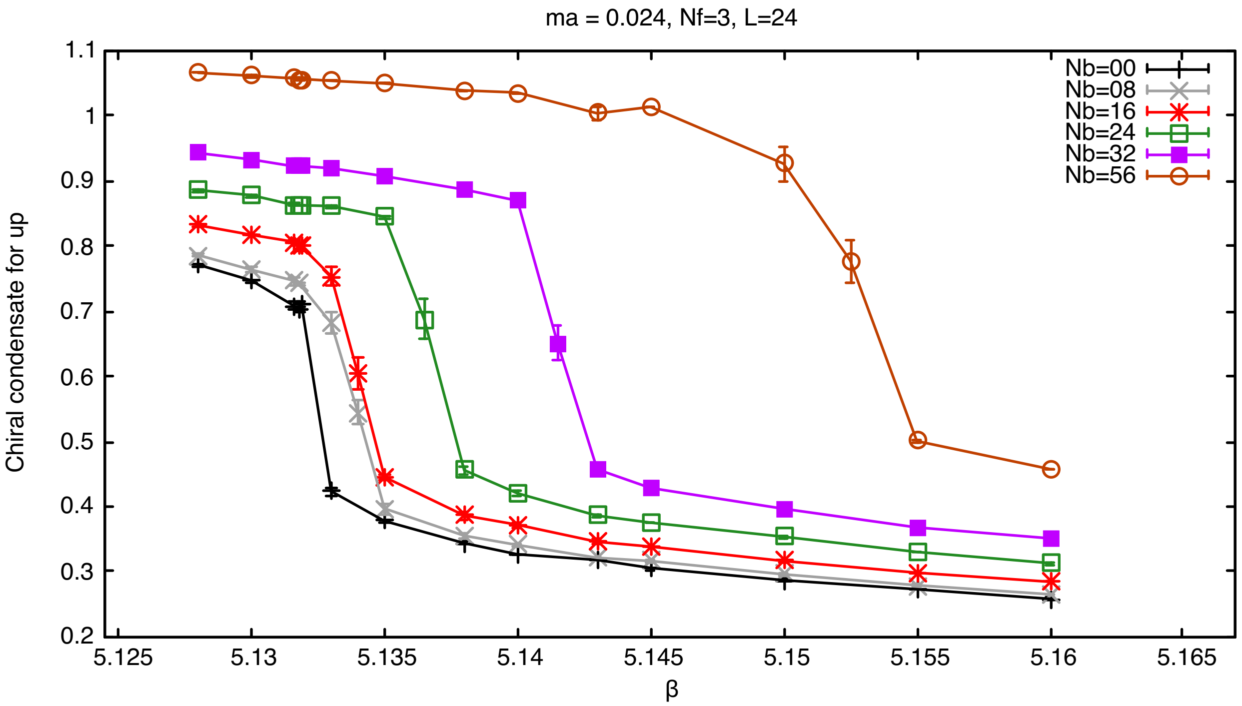
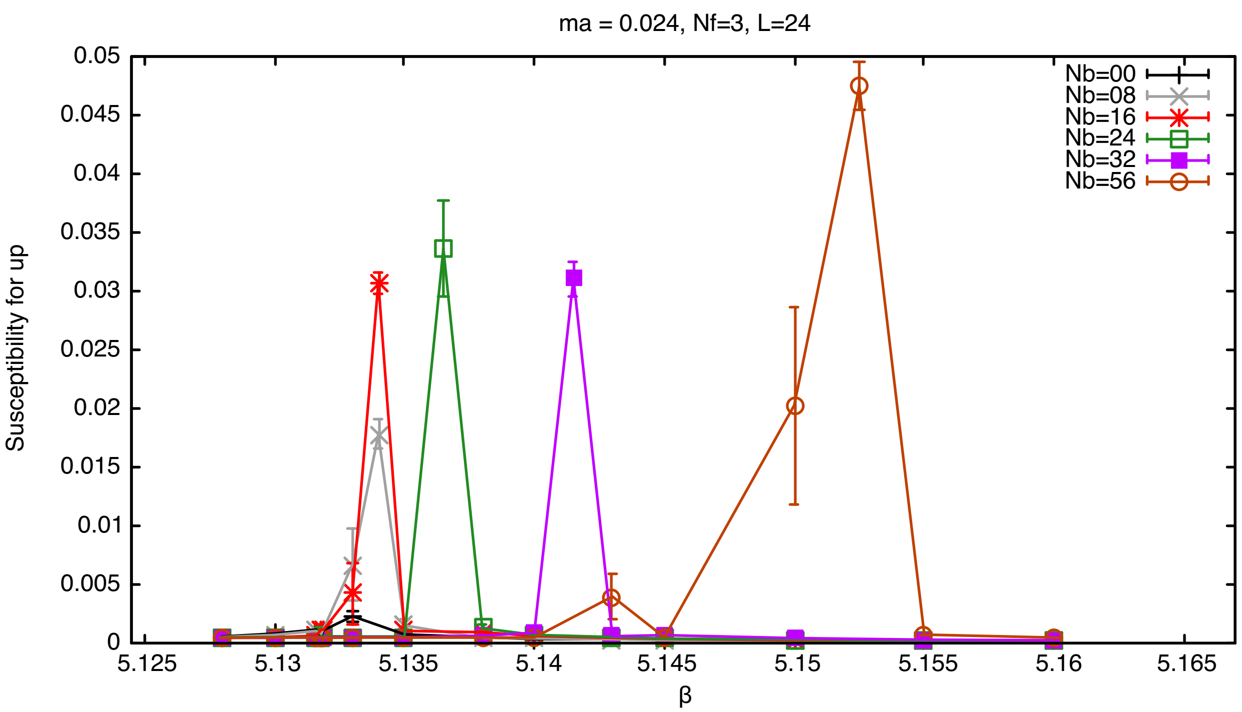
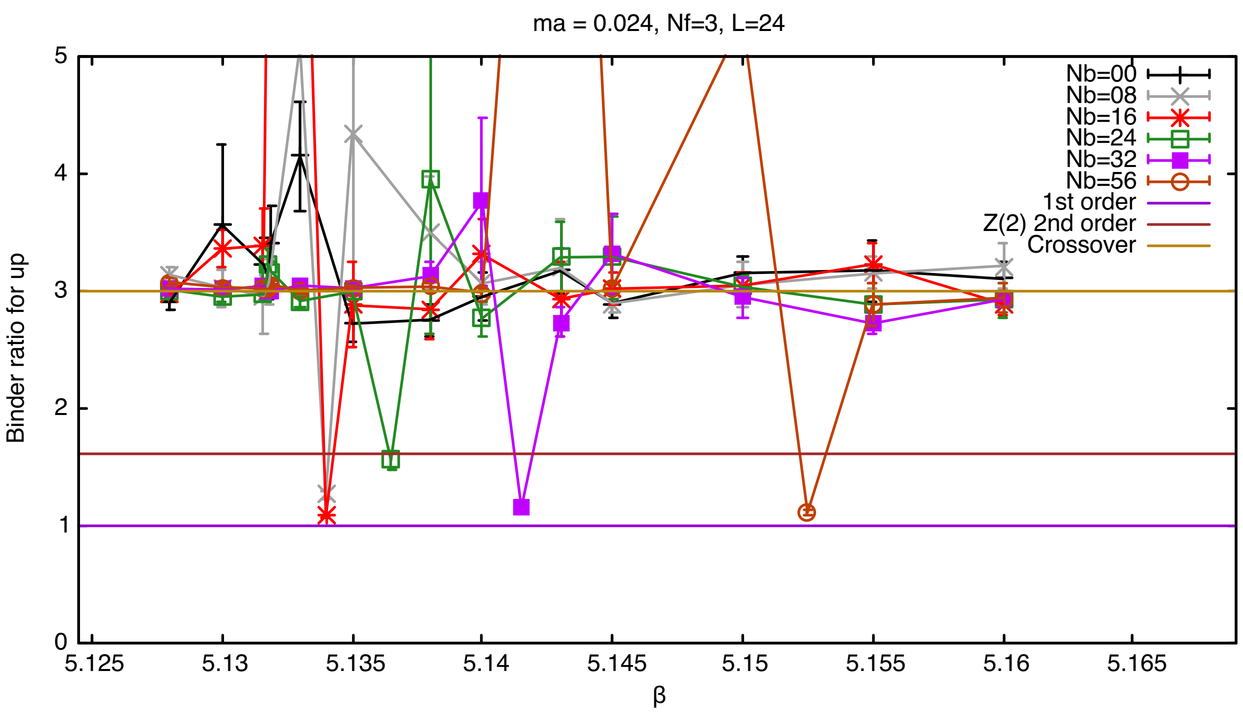
ma = 0.024(1st for Nb=0) Up quark condensates



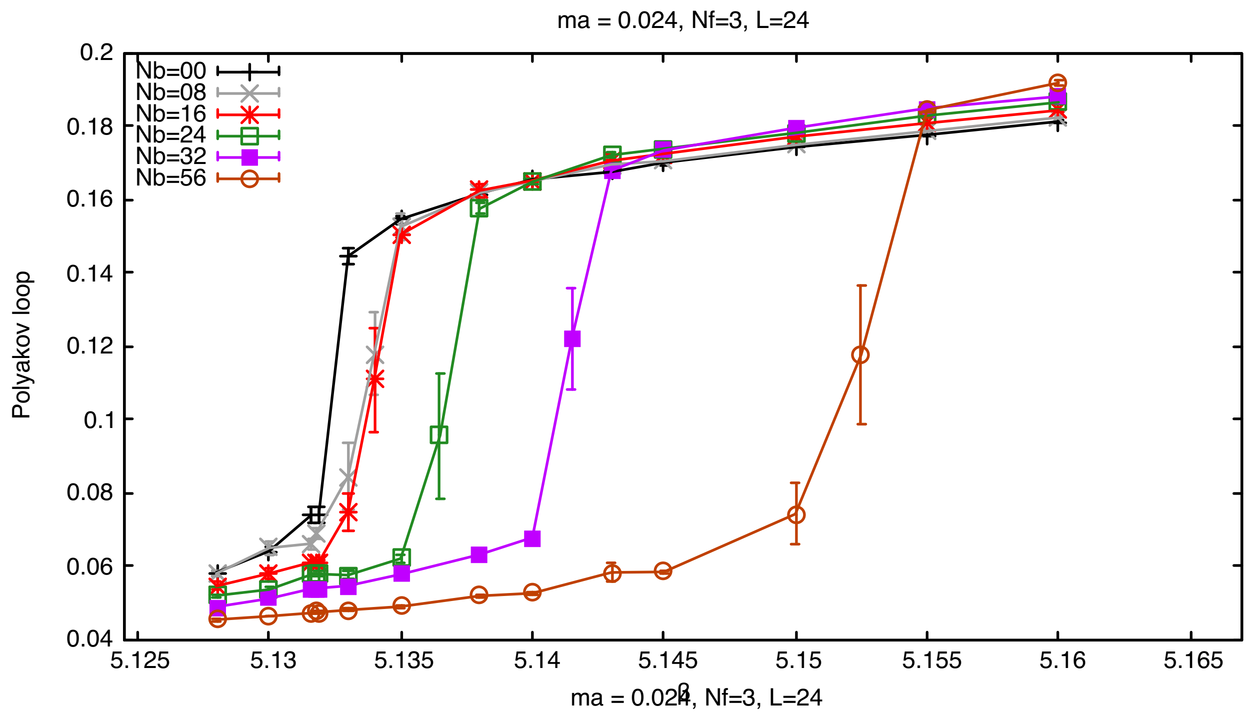
Consistent with
1st order



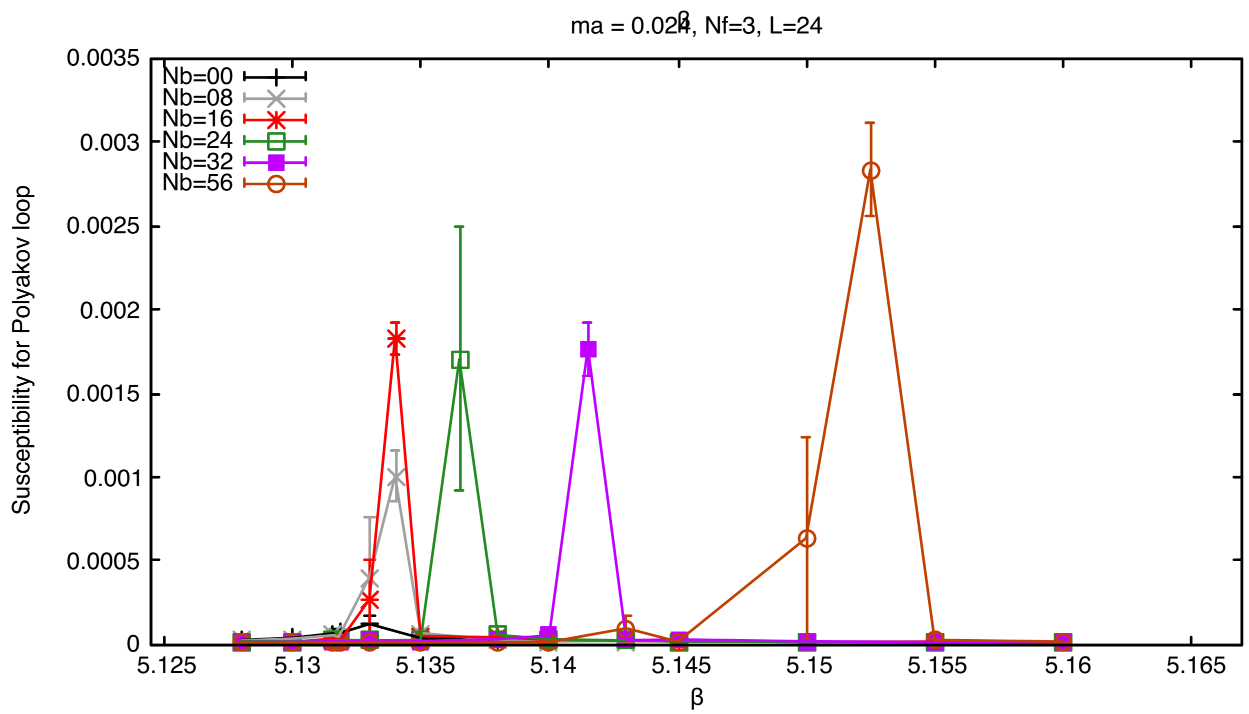


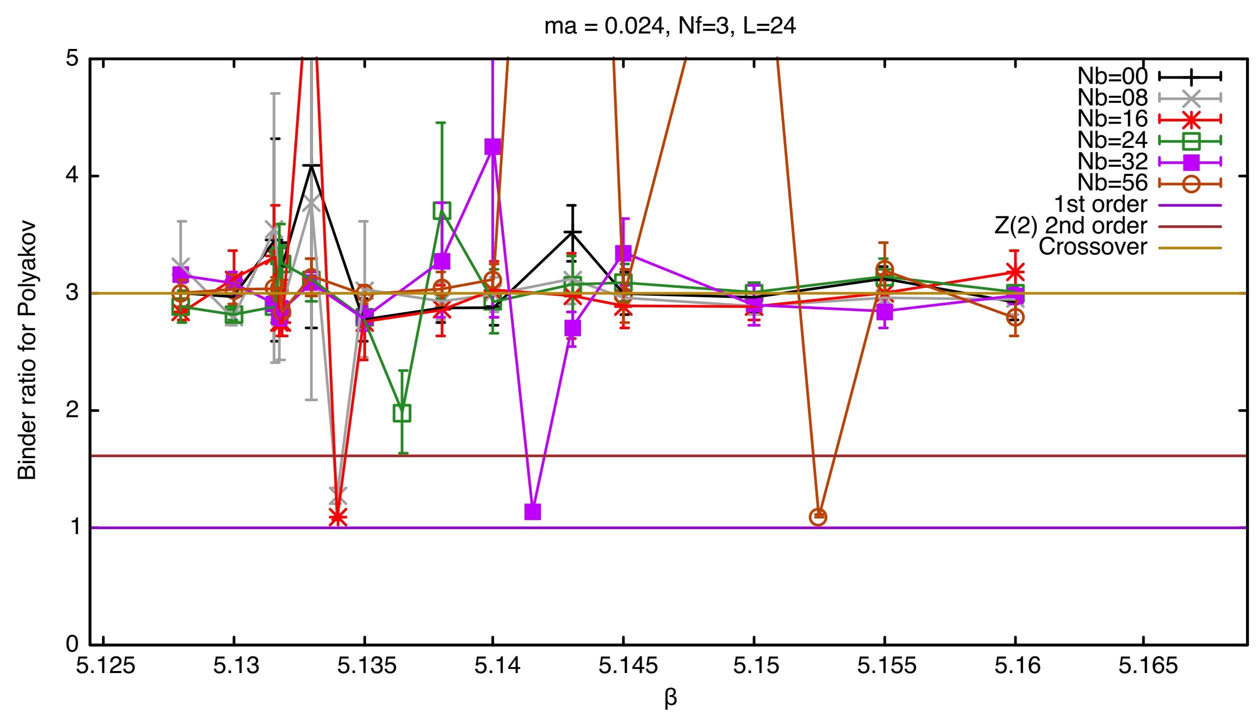
A. Tomiya CCNU

ma = 0.024(1st for Nb=0) Polyakov loop



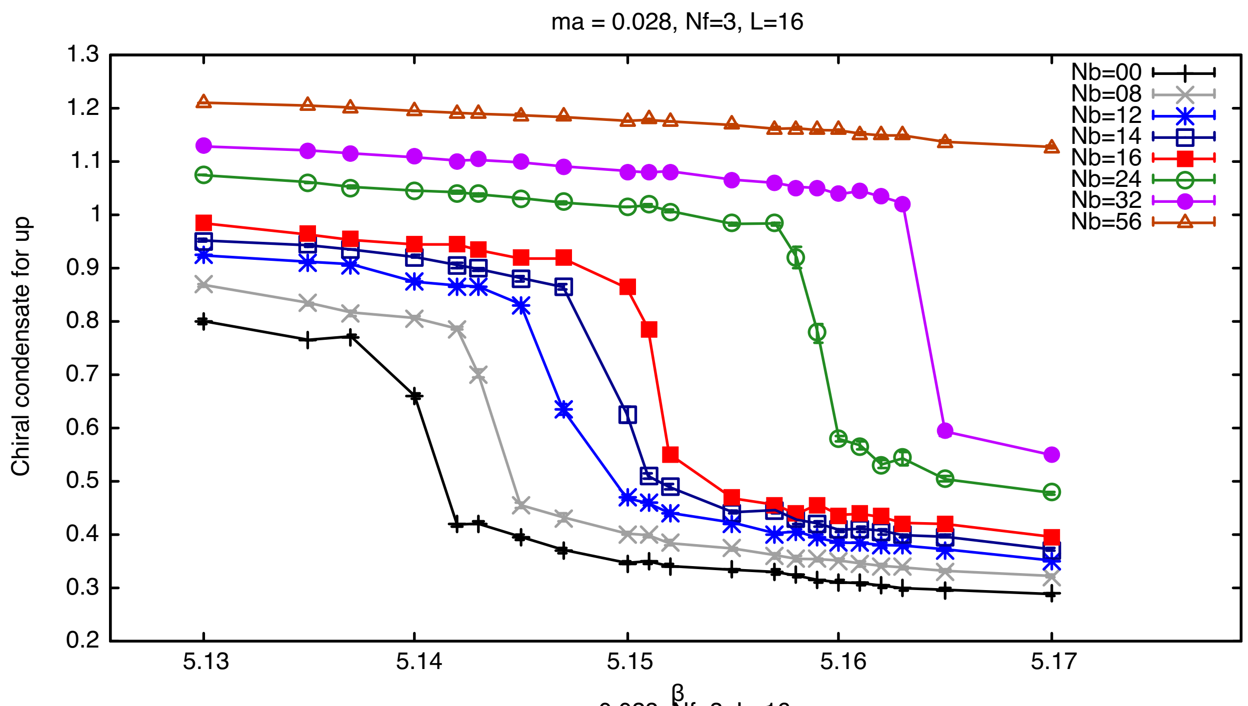
Consistent with
1st order

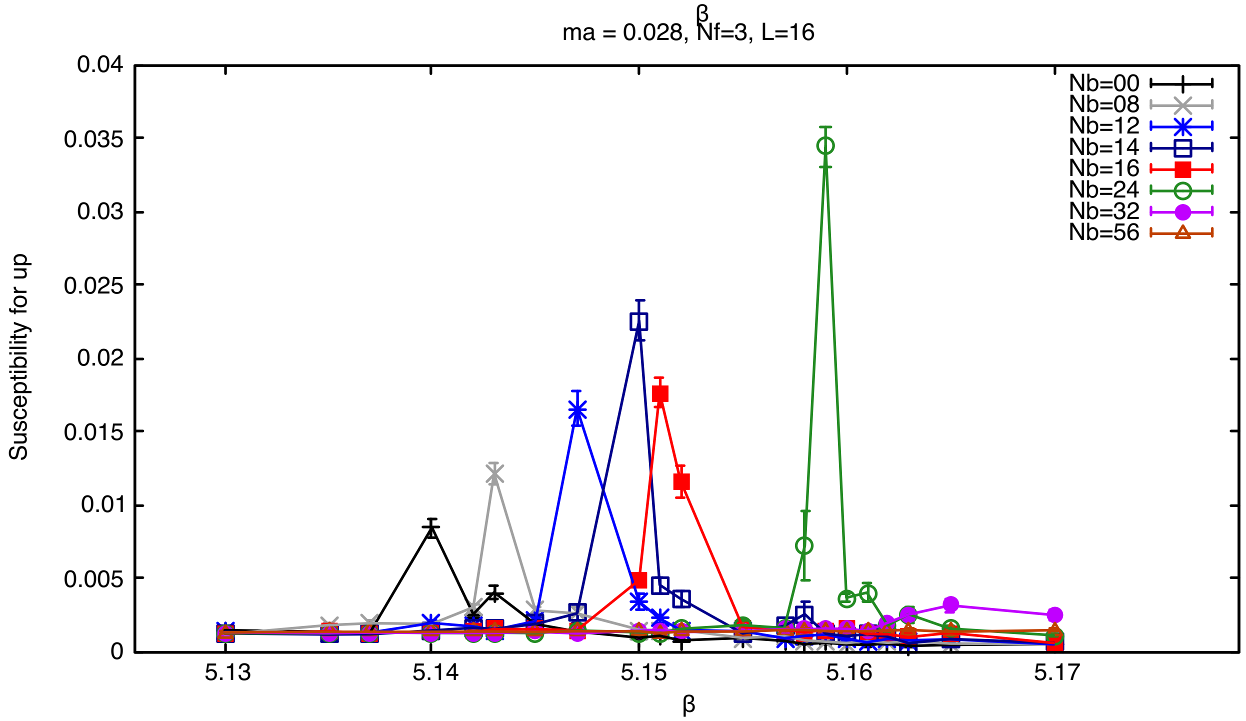


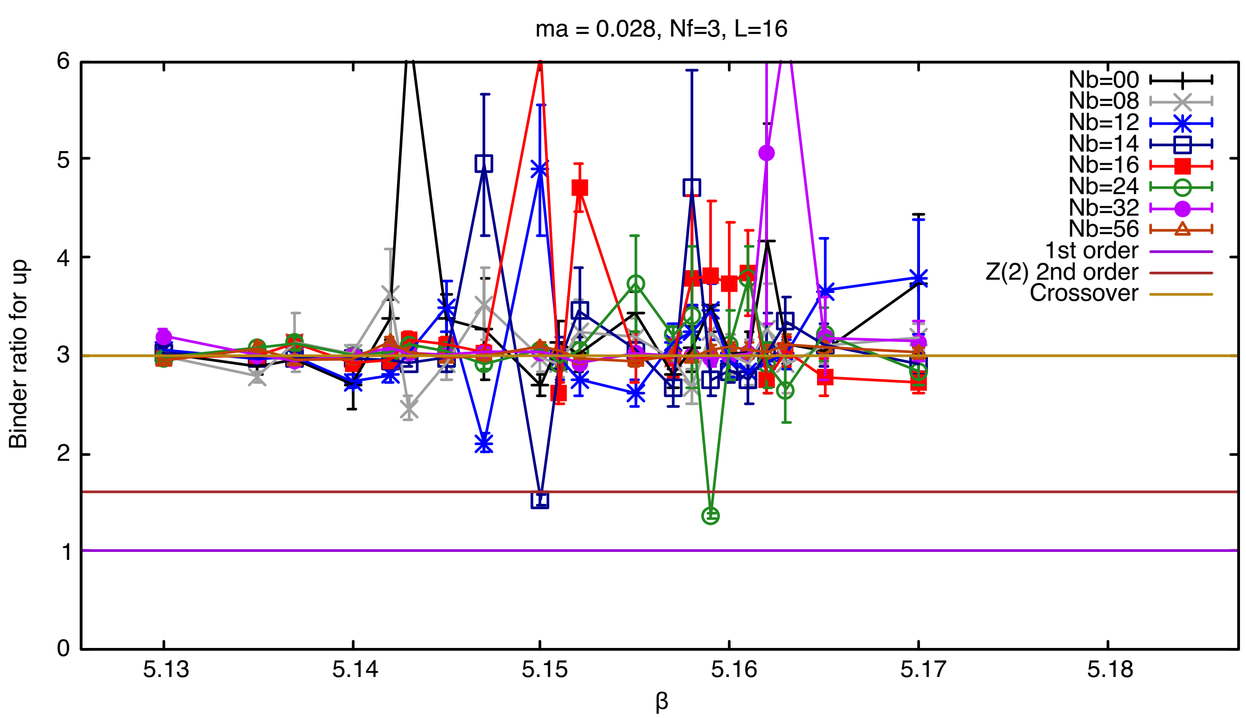


A. Tomiya CCNU

ma = 0.028(crossover for Nb=0) Up quark condensates



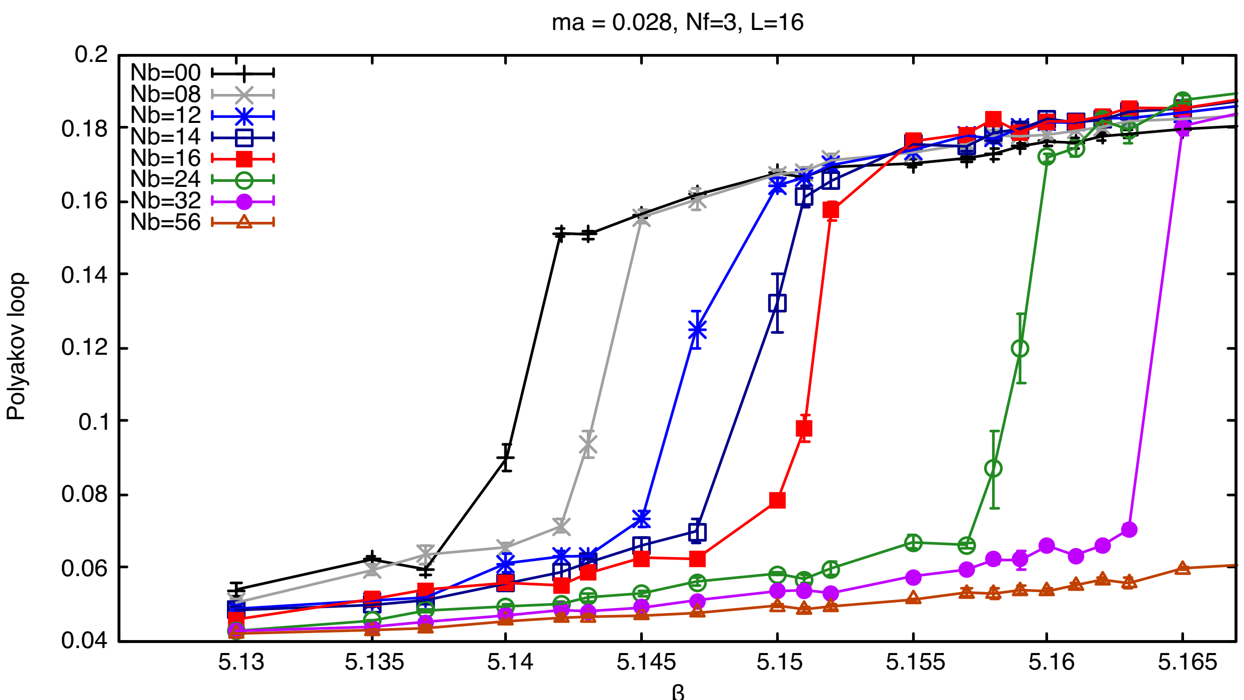


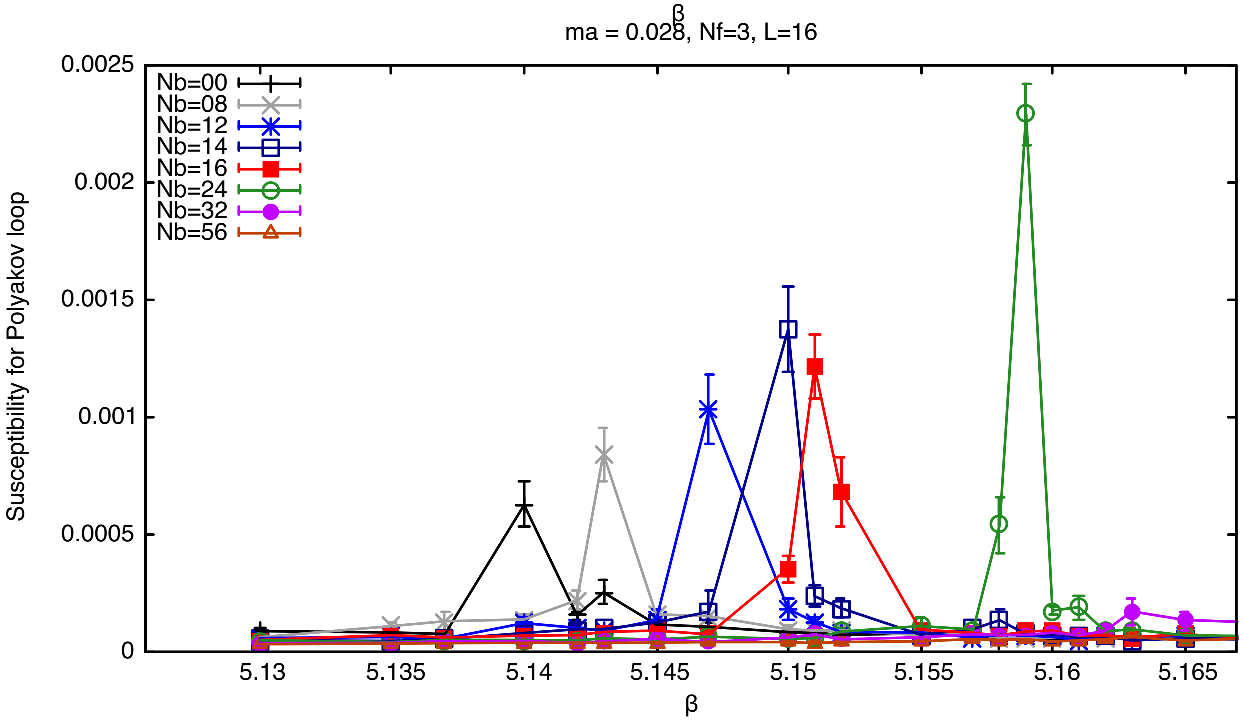


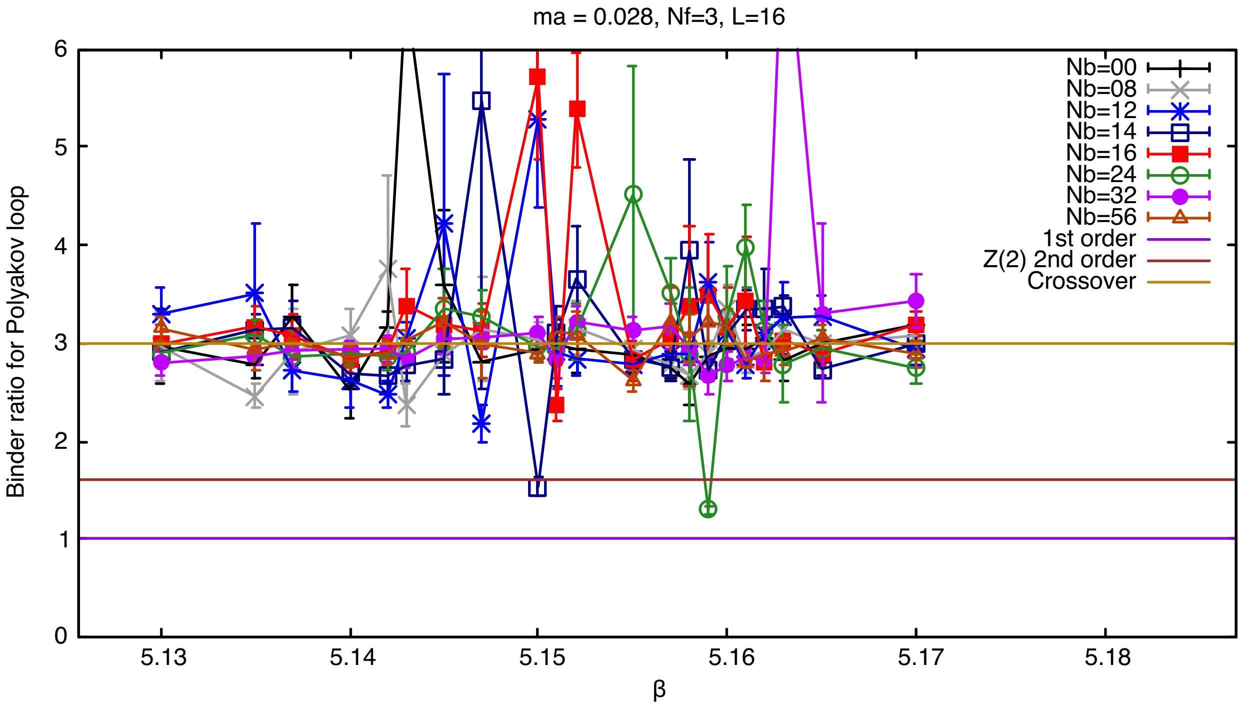
Nb=14 is “critical” eB*

A. Tomiya CCNU

ma = 0.028(crossover for Nb=0) Polyakov loop

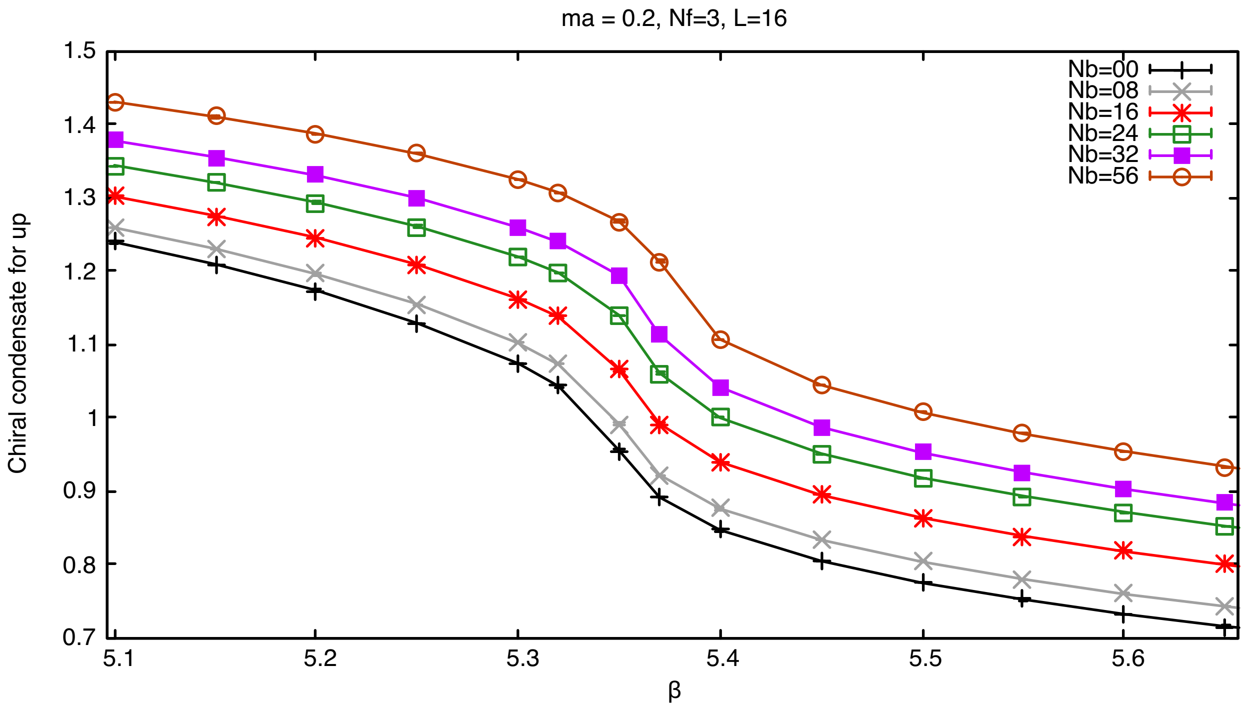




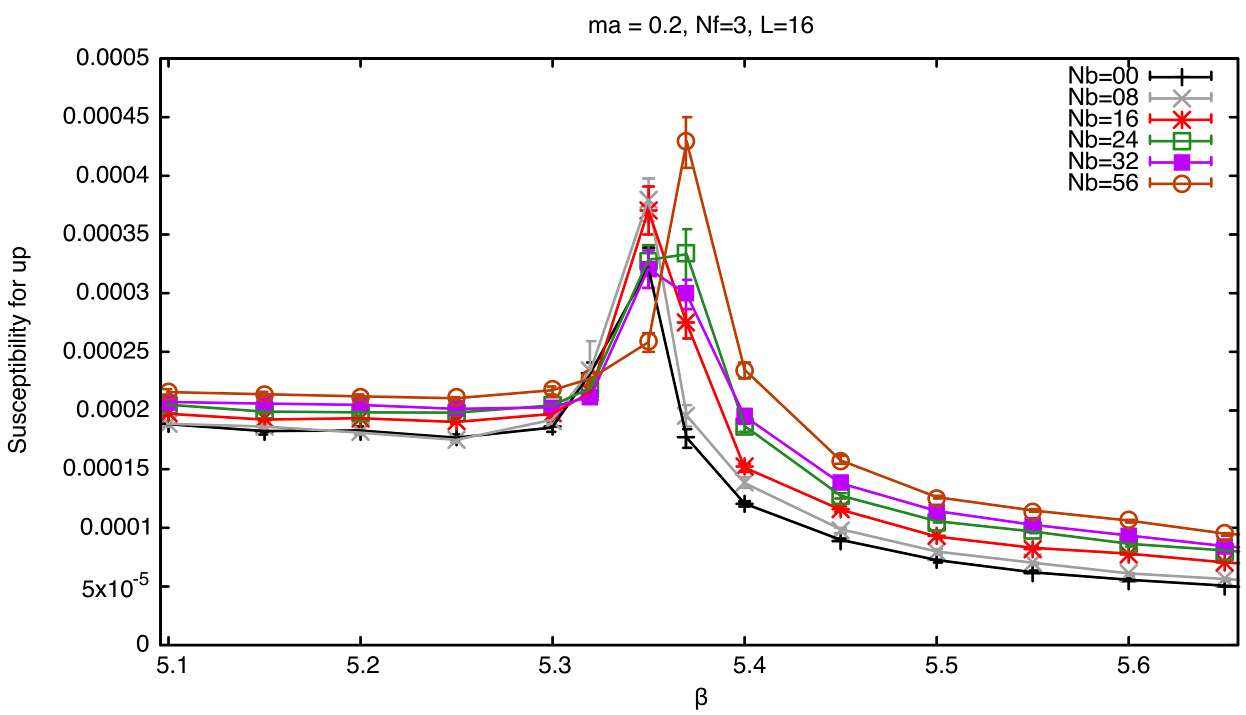


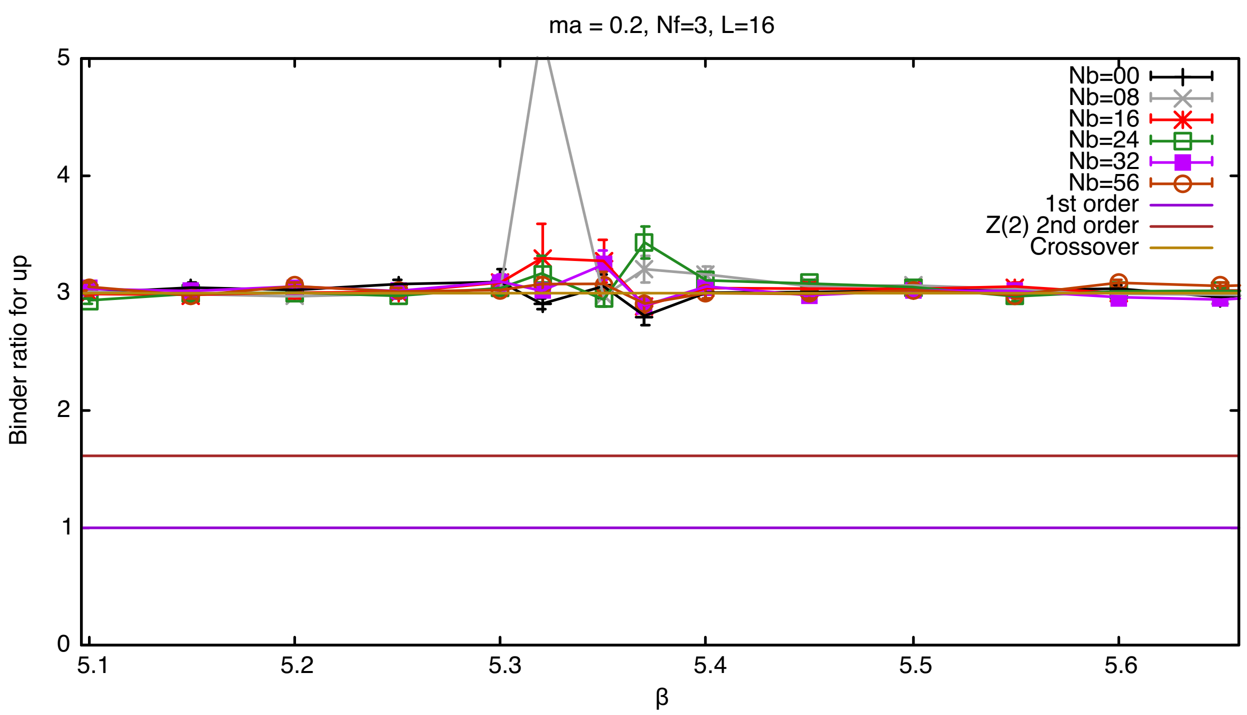
Nb=14 is critical eB*

ma = 0.2(crossover for Nb=0) Up quark condensate



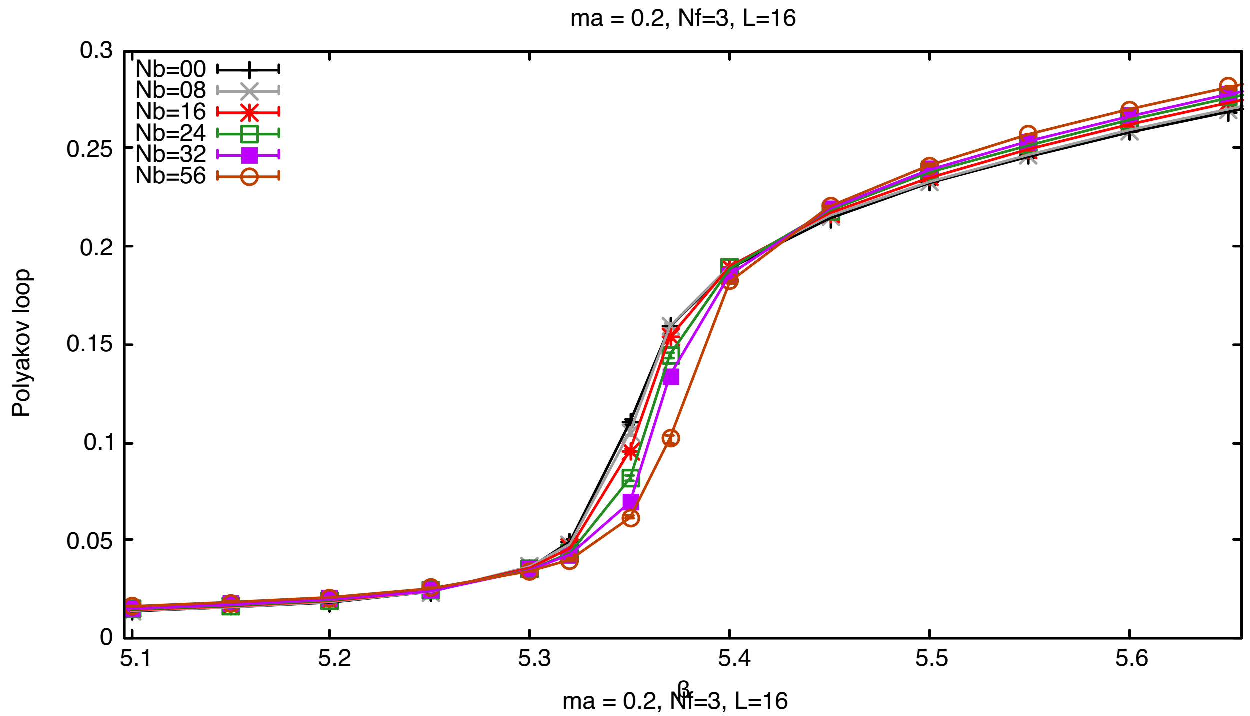
No criticality

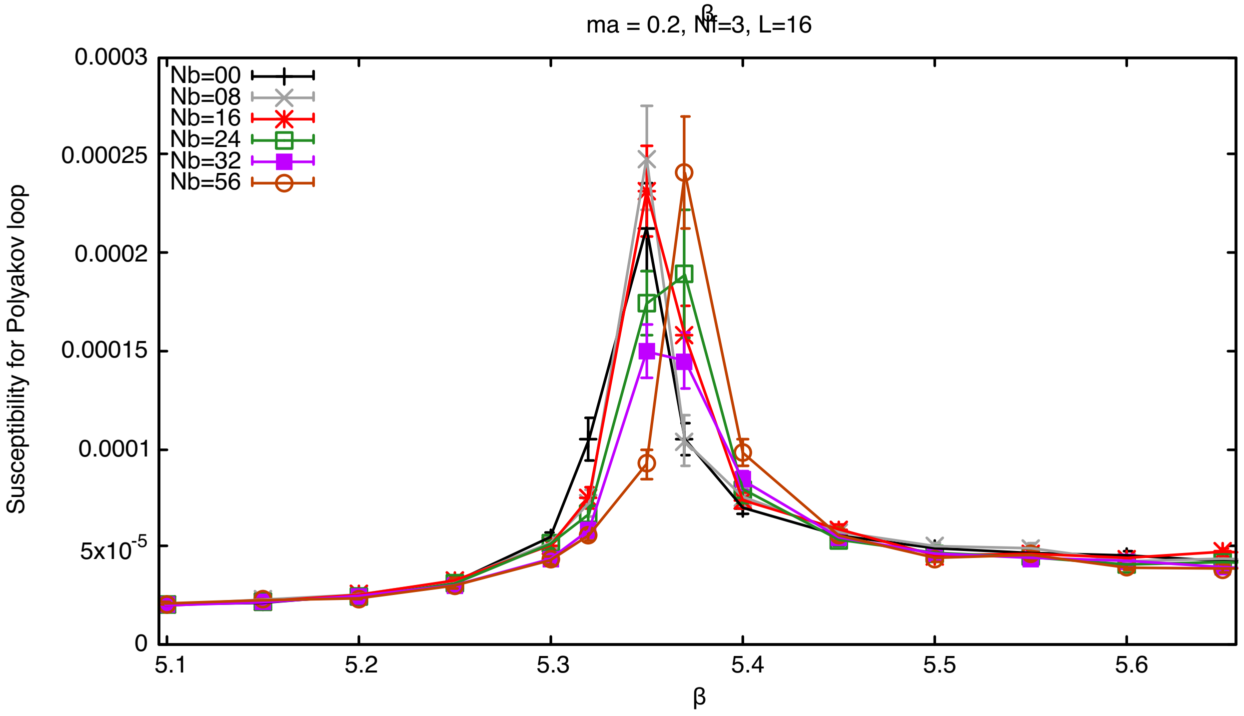


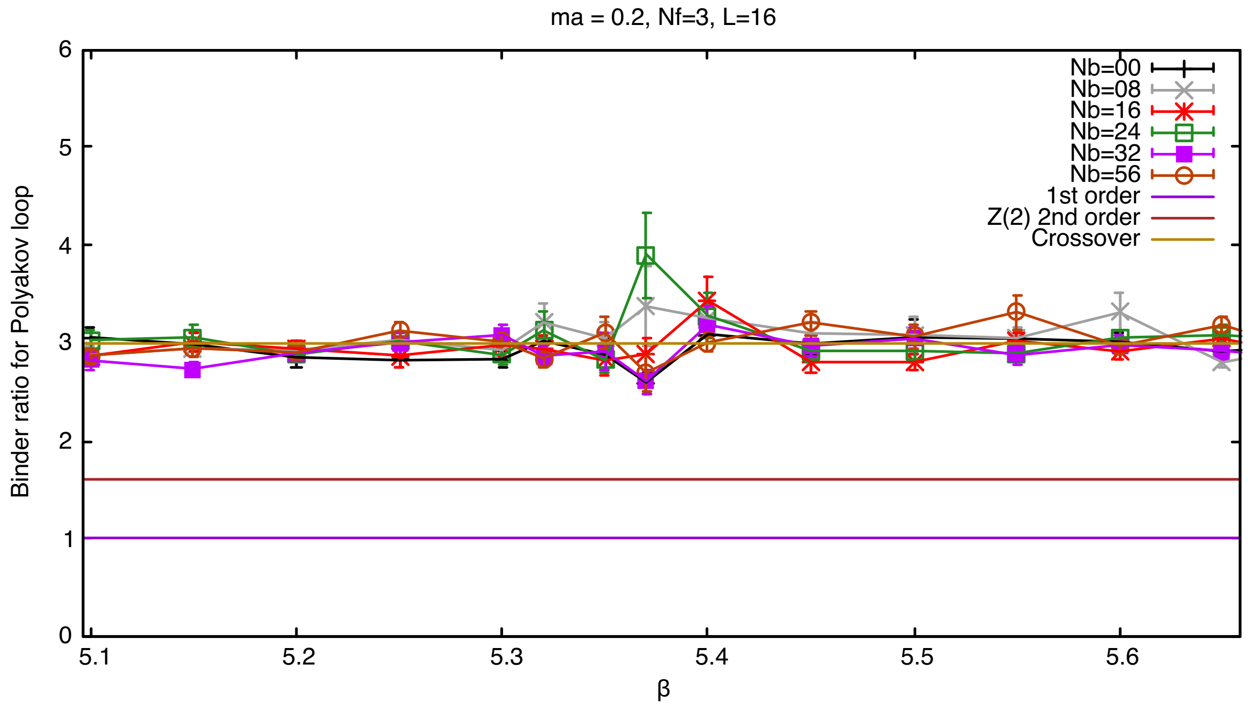


A. Tomiya CCNU

ma = 0.2(crossover for Nb=0) Polyakov loop

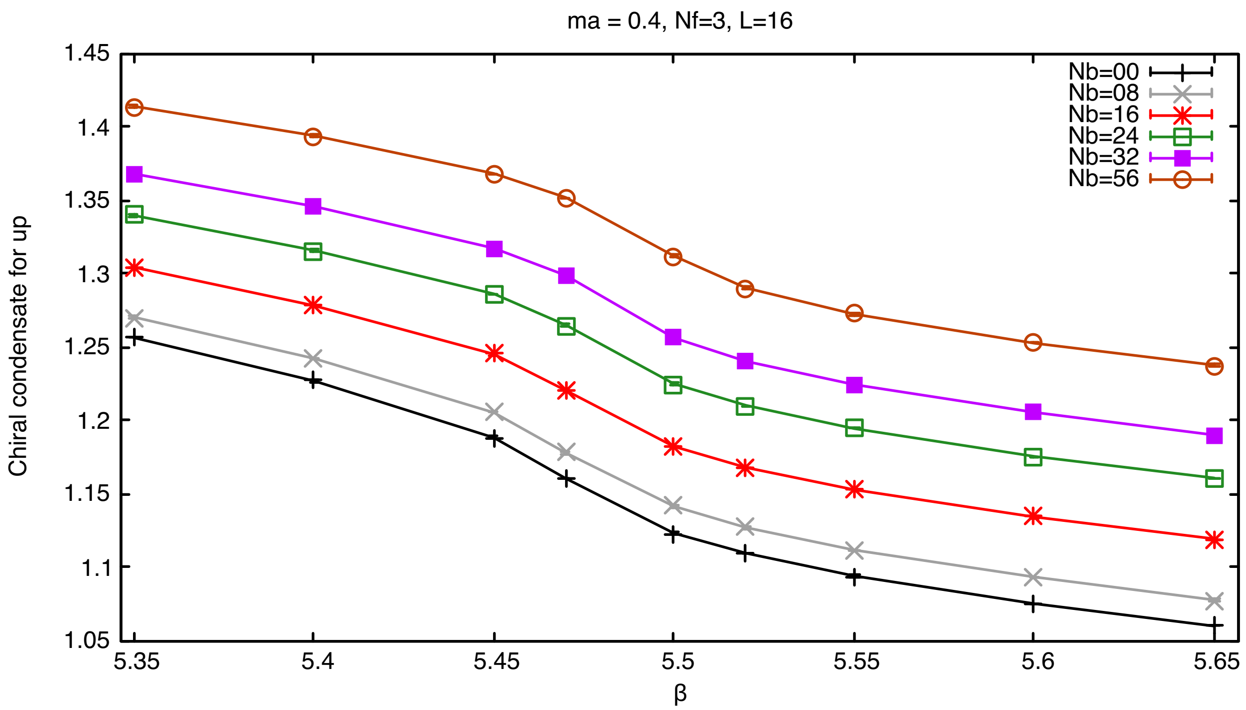




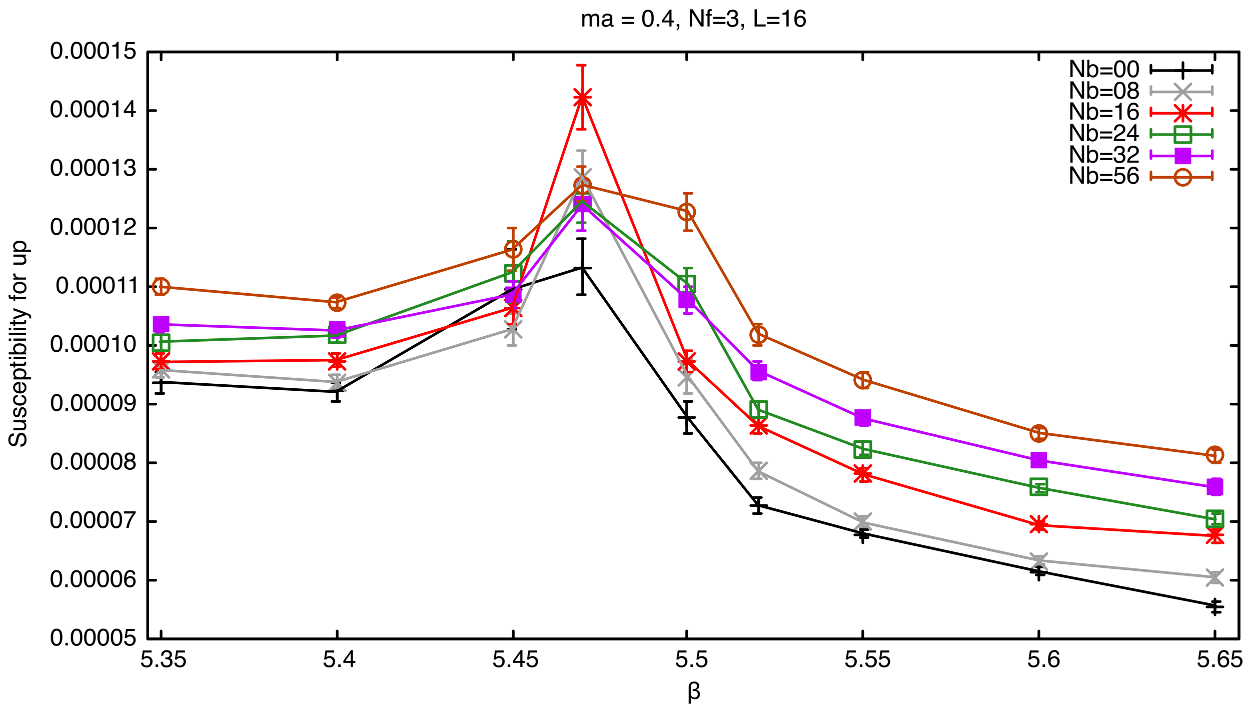


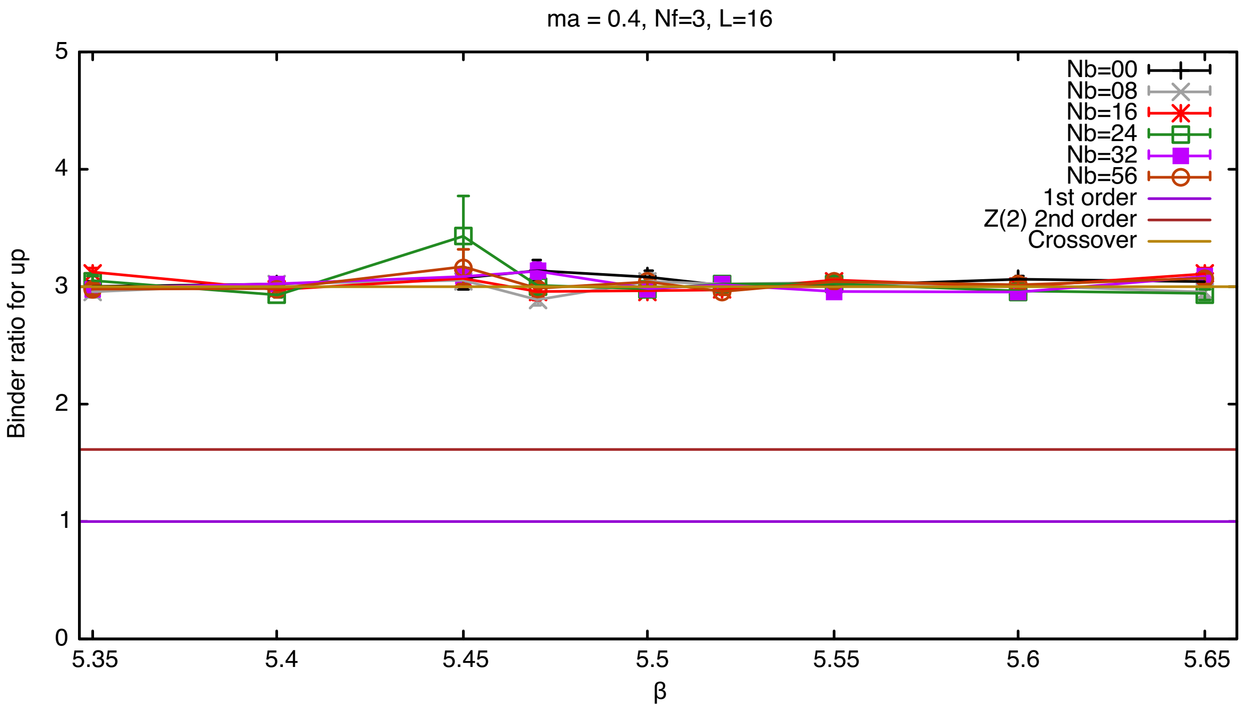
A. Tomiya CCNU

ma = 0.4(crossover for Nb=0) Up quark condensate



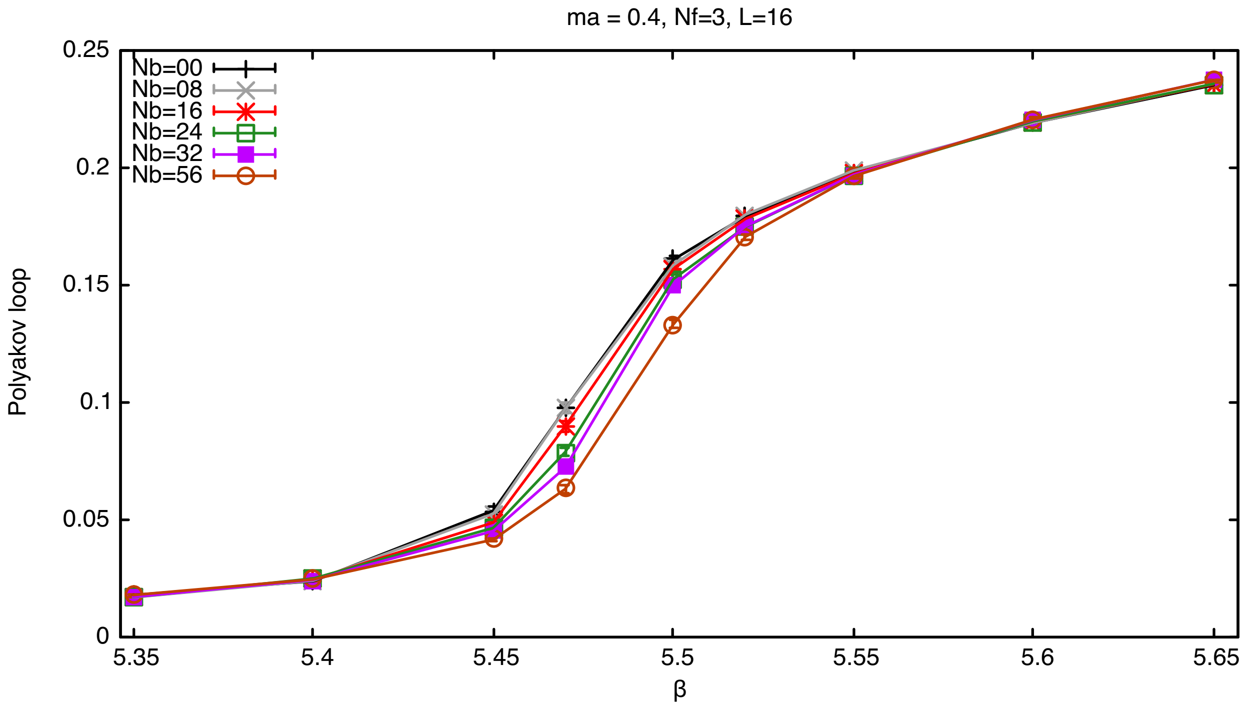
No criticality

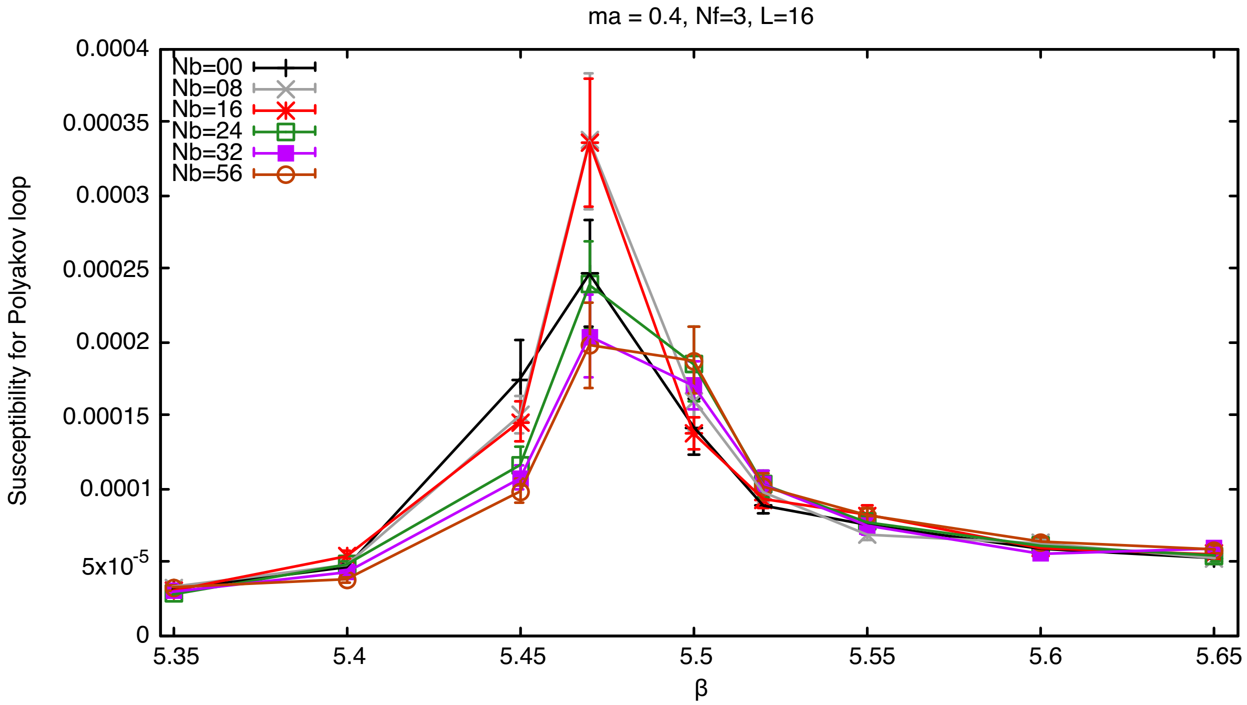


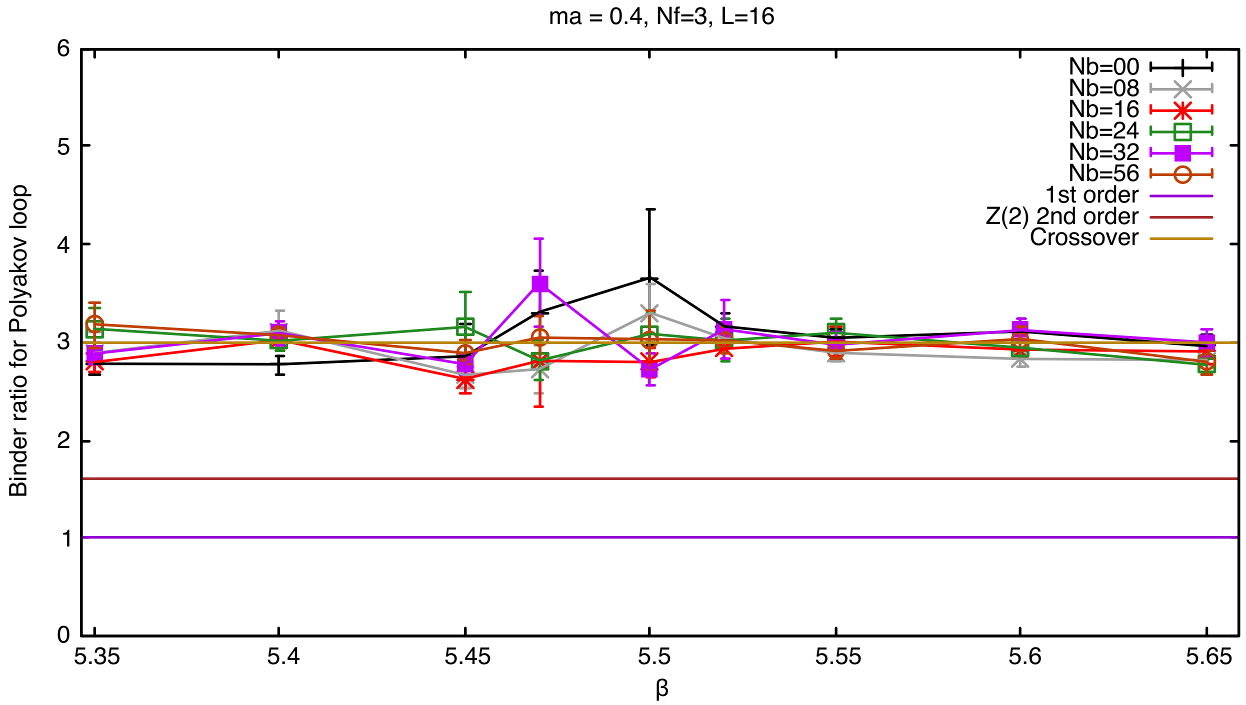


A. Tomiya CCNU

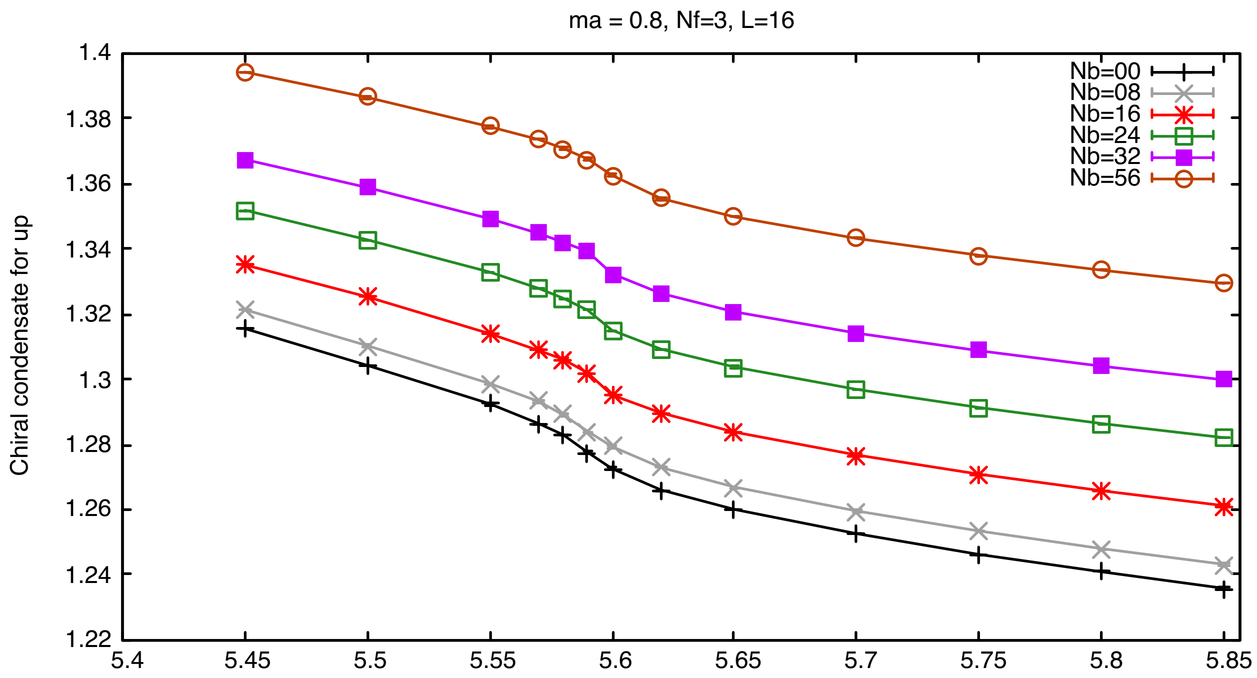
ma = 0.4(crossover for Nb=0) Polyakov loop



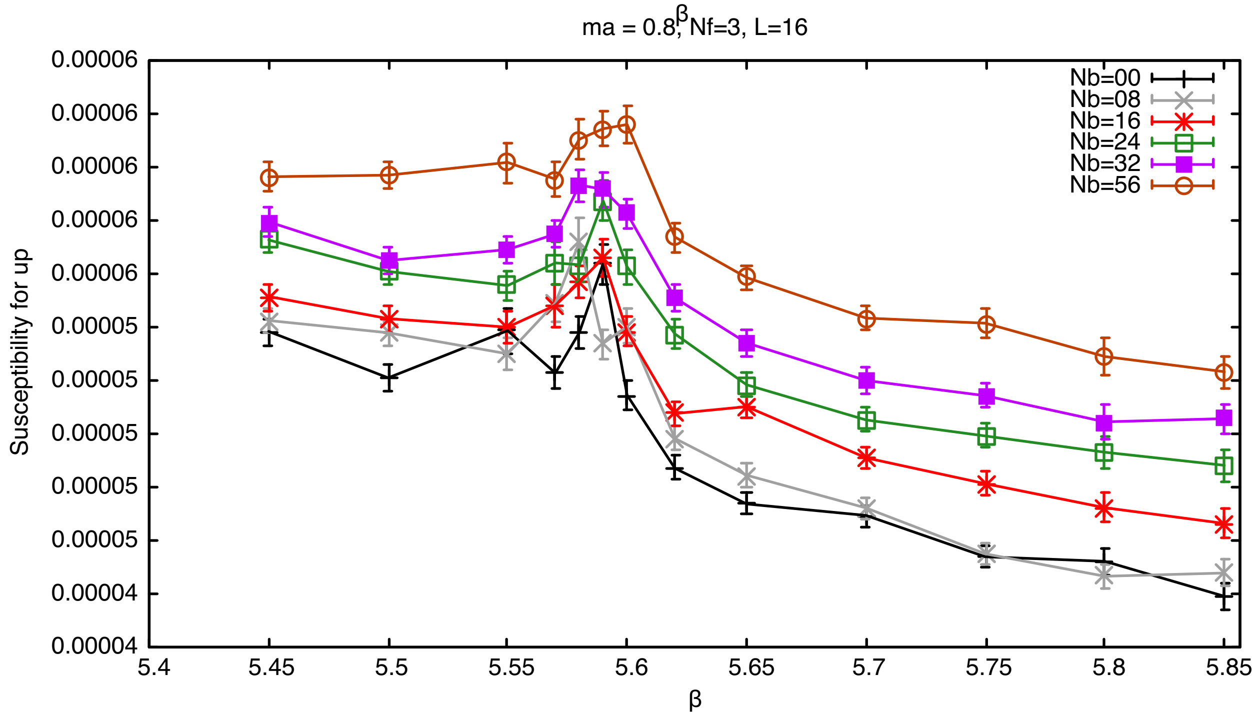


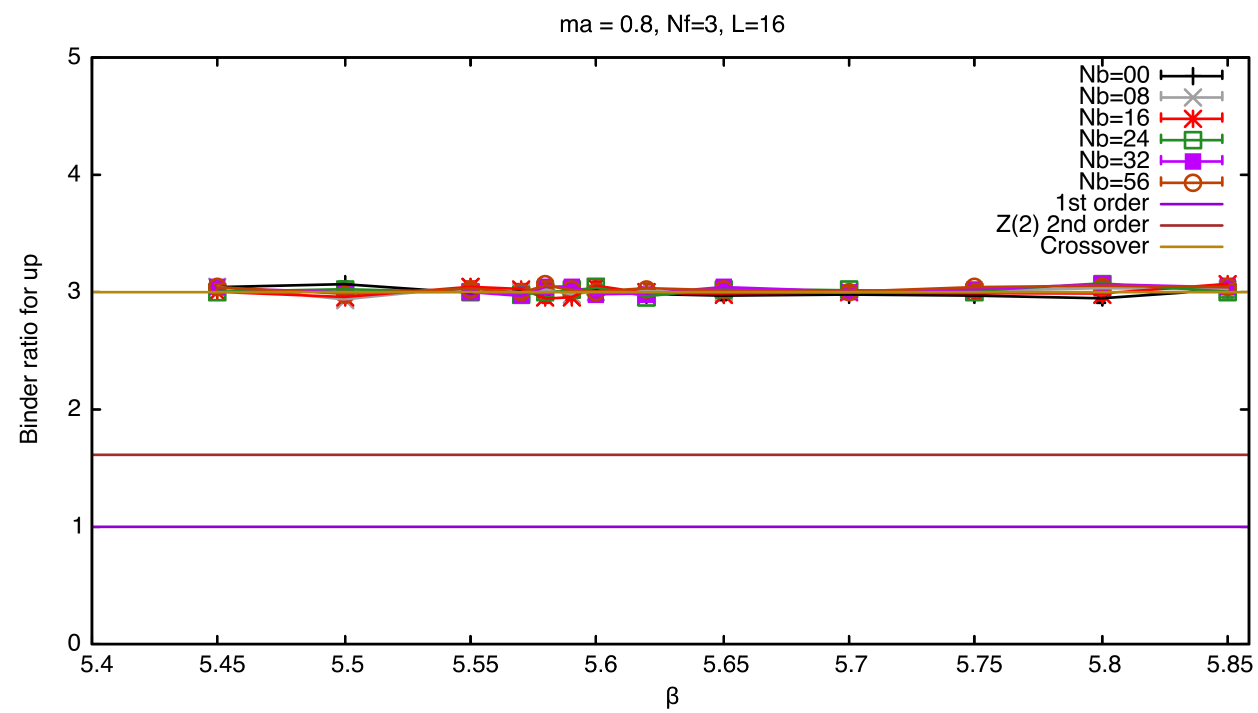


ma = 0.8 Up quark condensate

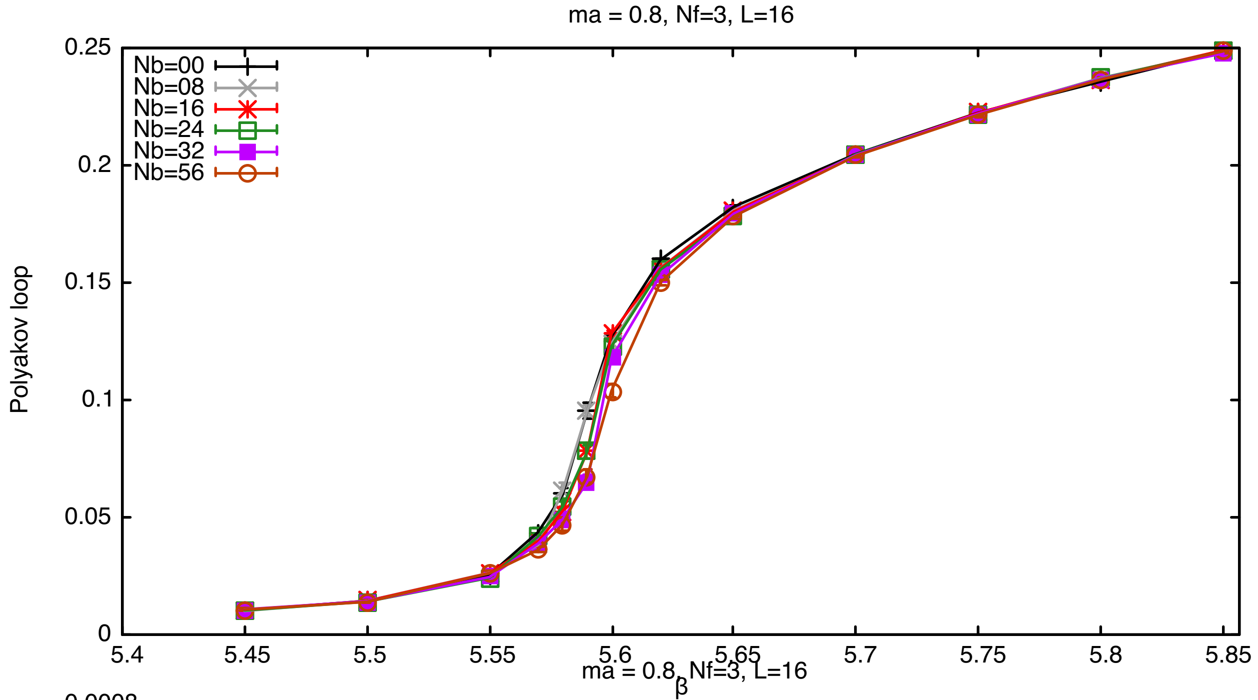


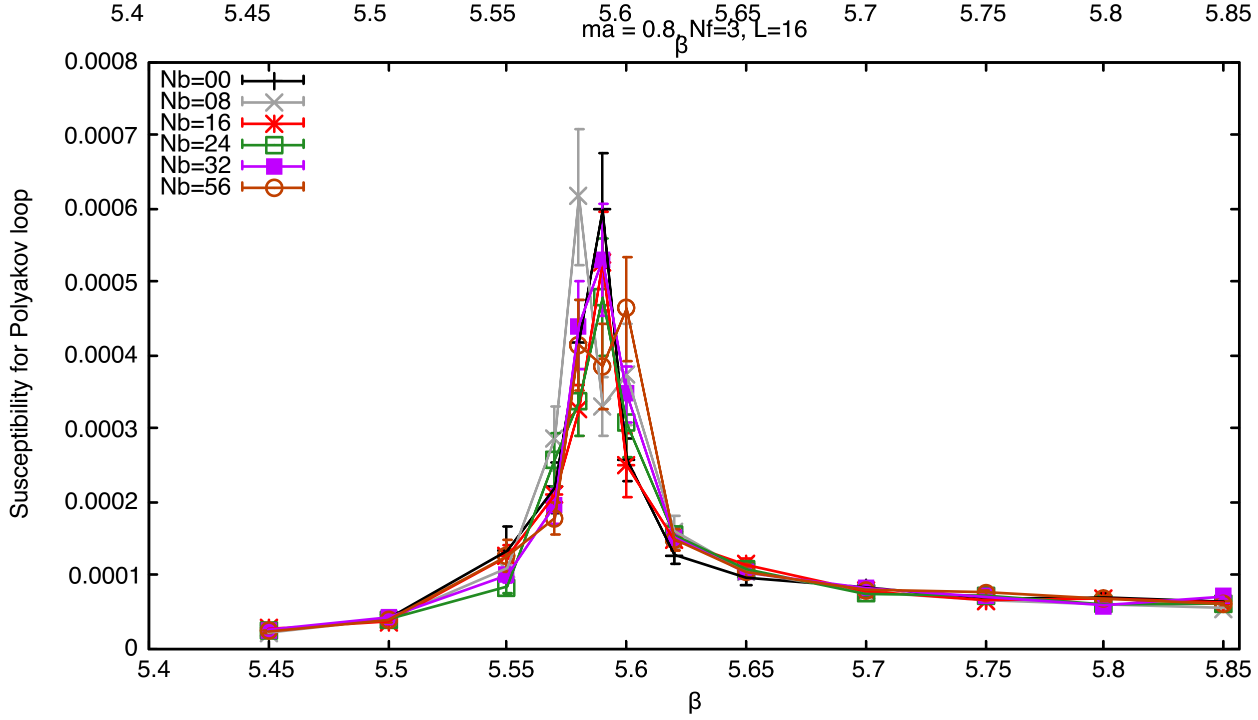
No criticality

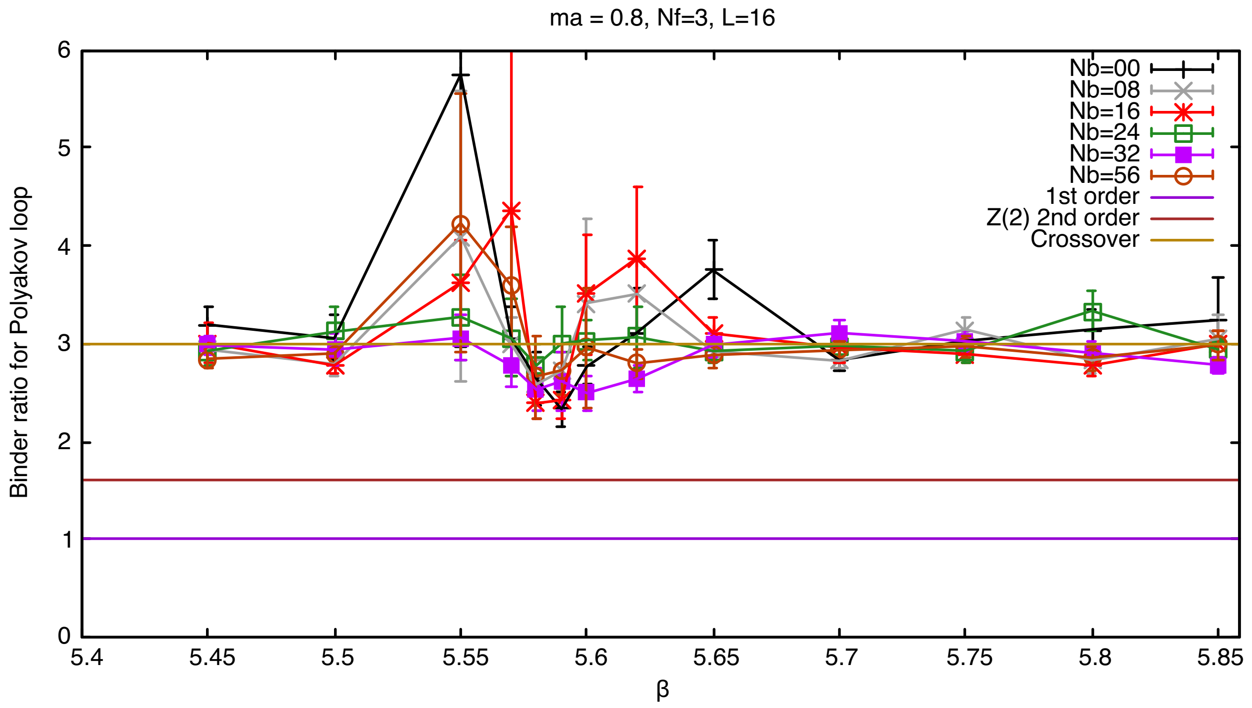




ma = 0.8 Polyakov loop







A. Tomiya CCNU