

# Chiral phase transition of three flavor QCD with nonzero magnetic field



**Akio Tomiya**

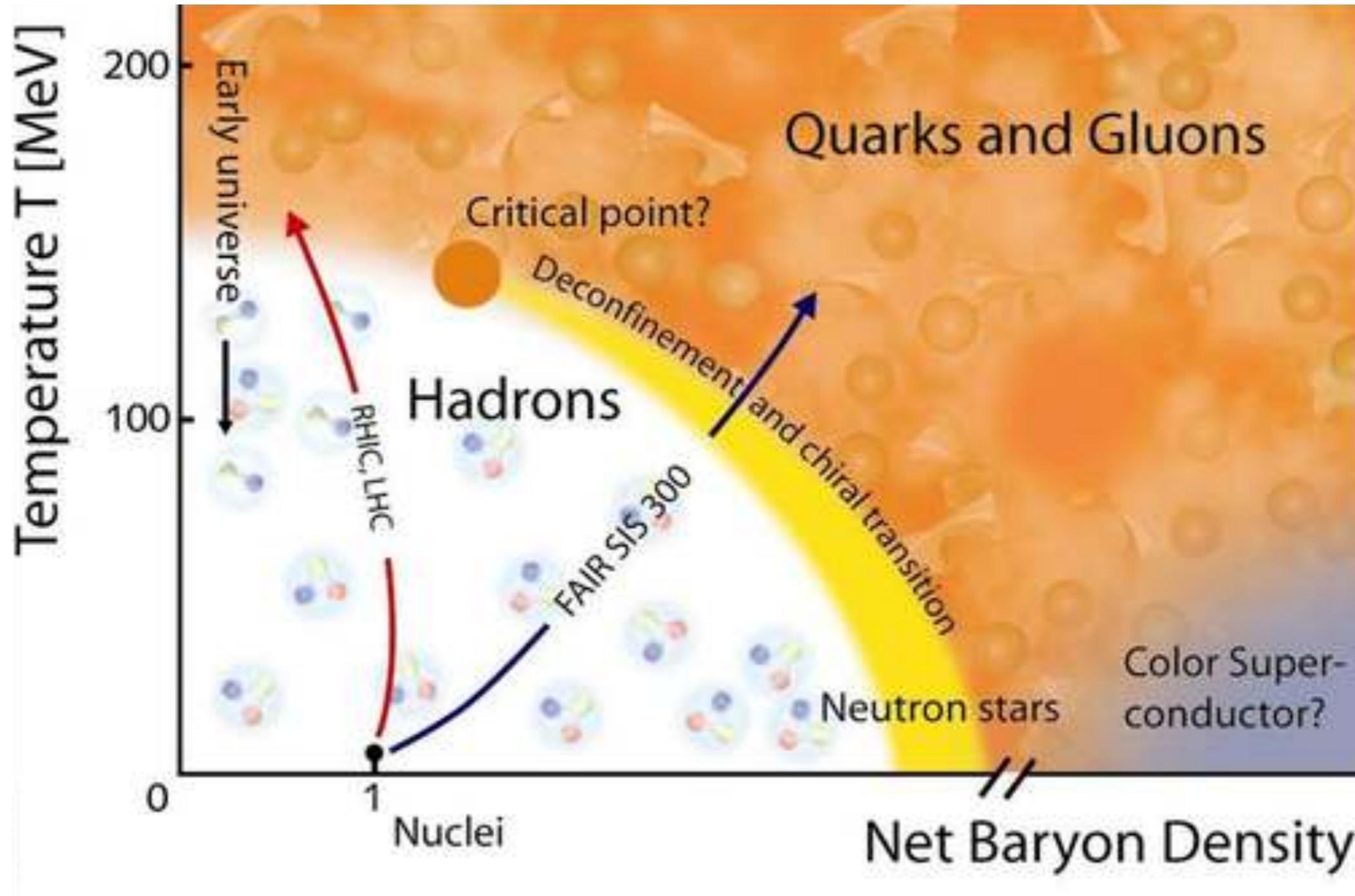
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Collaborate with:

- Heng-Tong Ding
- Swagato Mukherjee
- Christian Schmidt
- Xiao-Dan Wang

# Background & Motivation

QCD phase transition at physical mass is crossover





# Background & Motivation

## QCD phase transition depends on Magnetic field?

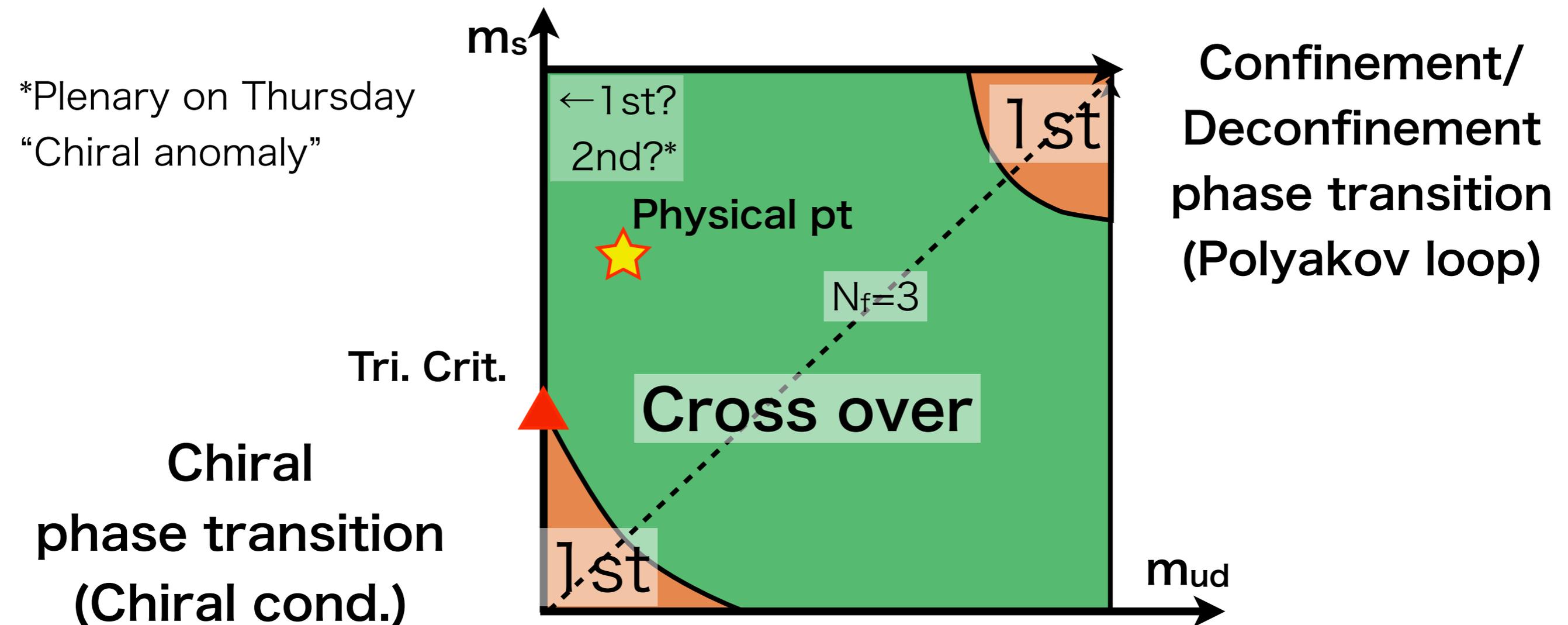
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Colombia plot : the order of QCD phase transition

# Background & Motivation

## QCD phase transition depends on Magnetic field?

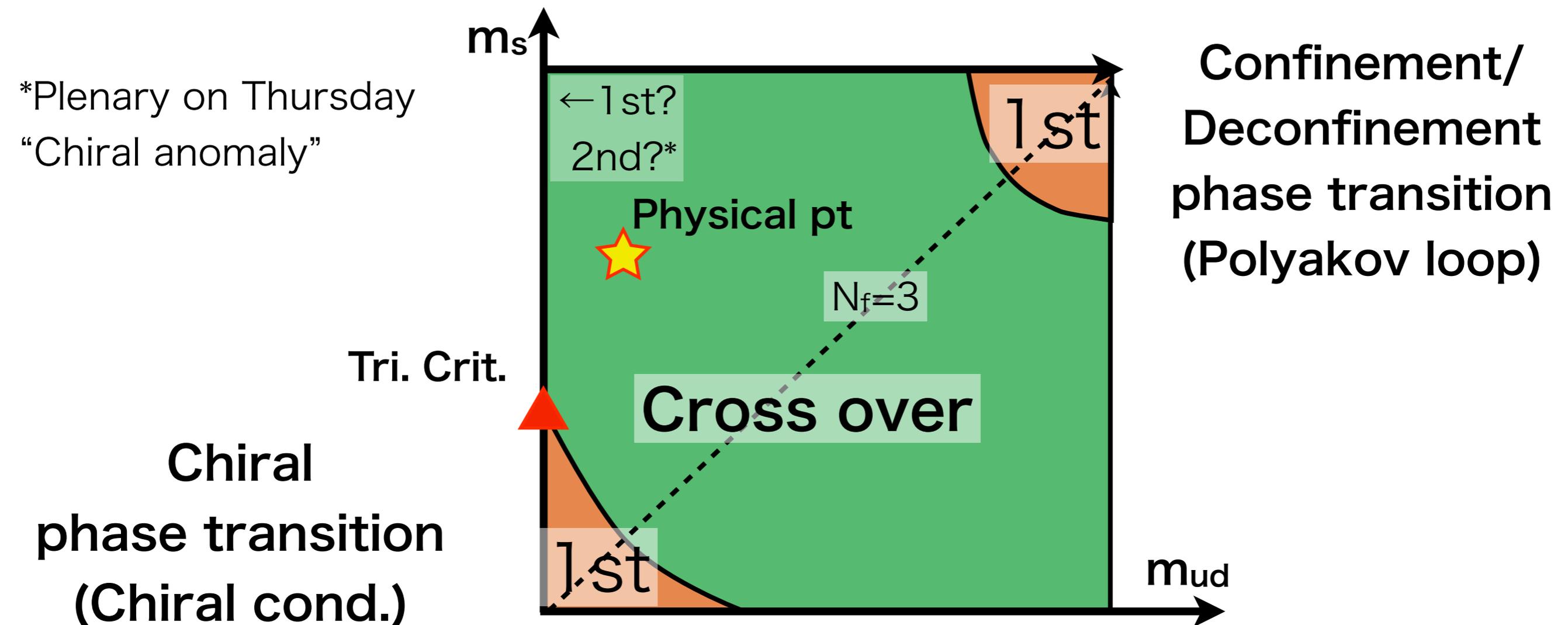
Colombia plot : the order of QCD phase transition



# Background & Motivation

## QCD phase transition depends on Magnetic field?

Colombia plot : the order of QCD phase transition

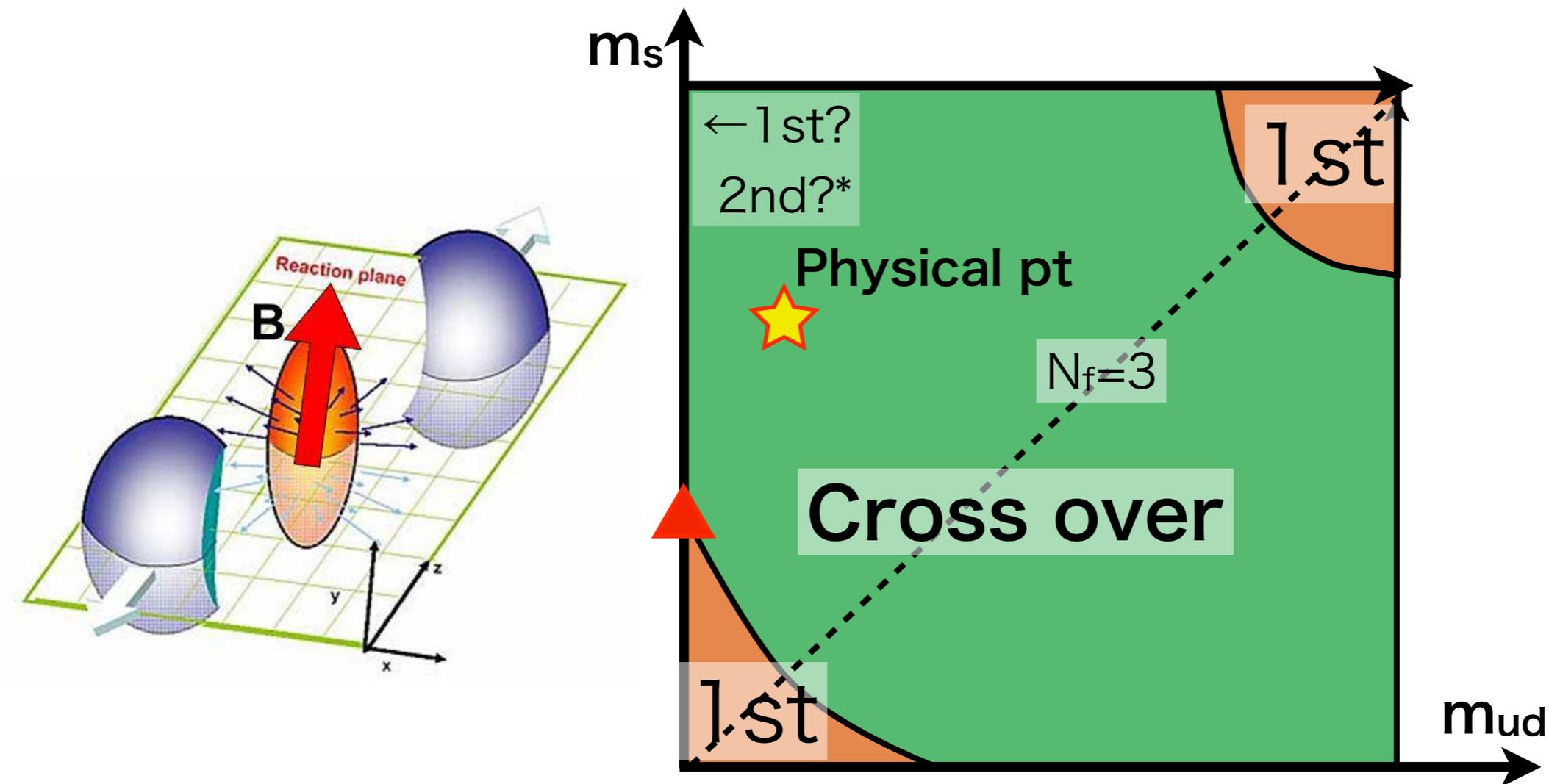


Other than the physical point info. is useful for model building

# Background & Motivation

## QCD phase transition depends on Magnetic field?

Colombia plot : the order of QCD phase transition



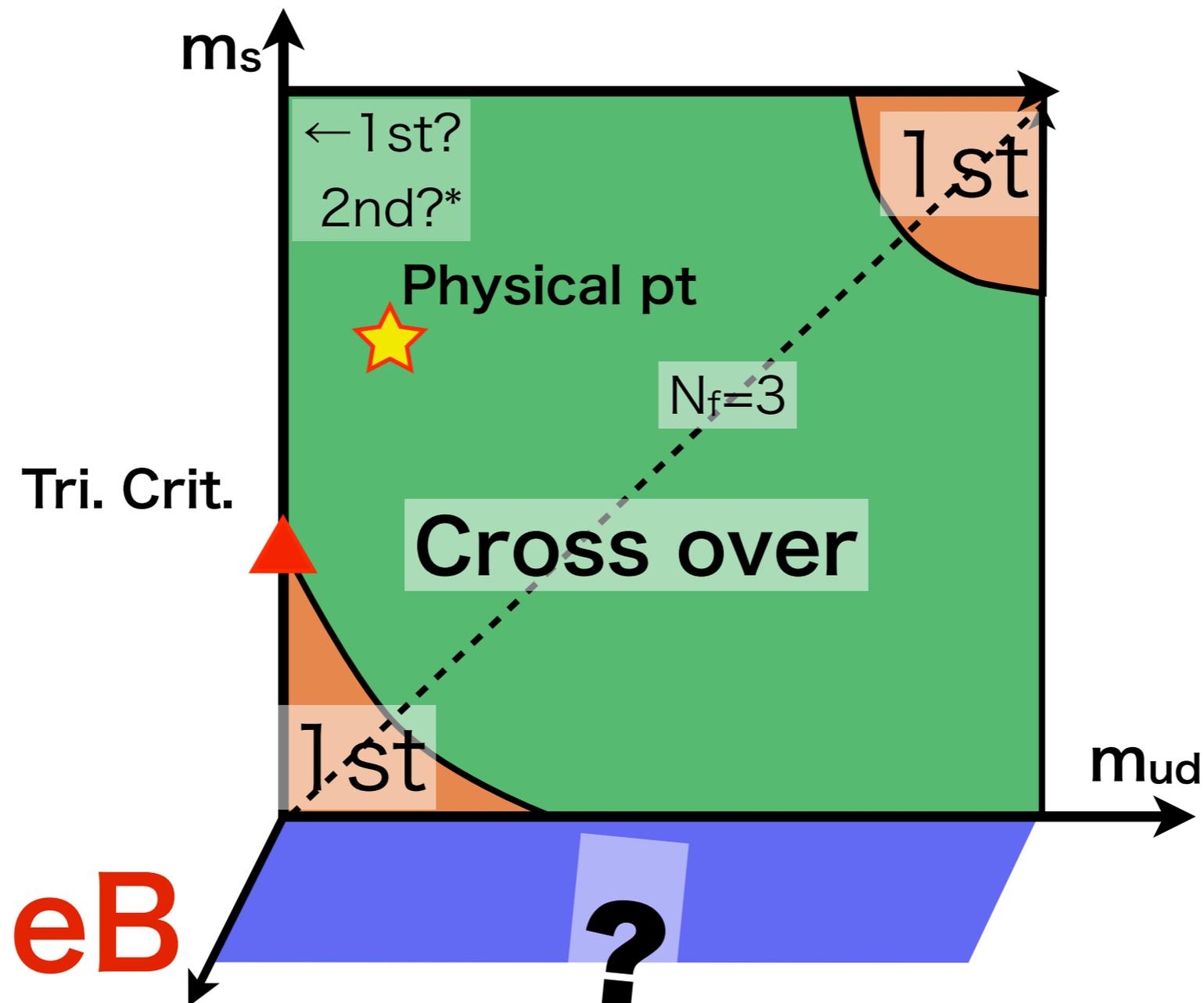
Off-central AA collisions generate huge magnetic field ( $15m\pi^*$ )

Does it affect phase structure?

# Background & Motivation

## QCD phase transition depends on Magnetic field?

Colombia plot : the order of QCD phase transition



# Background & Motivation

## Previous studies: Model & Lattice

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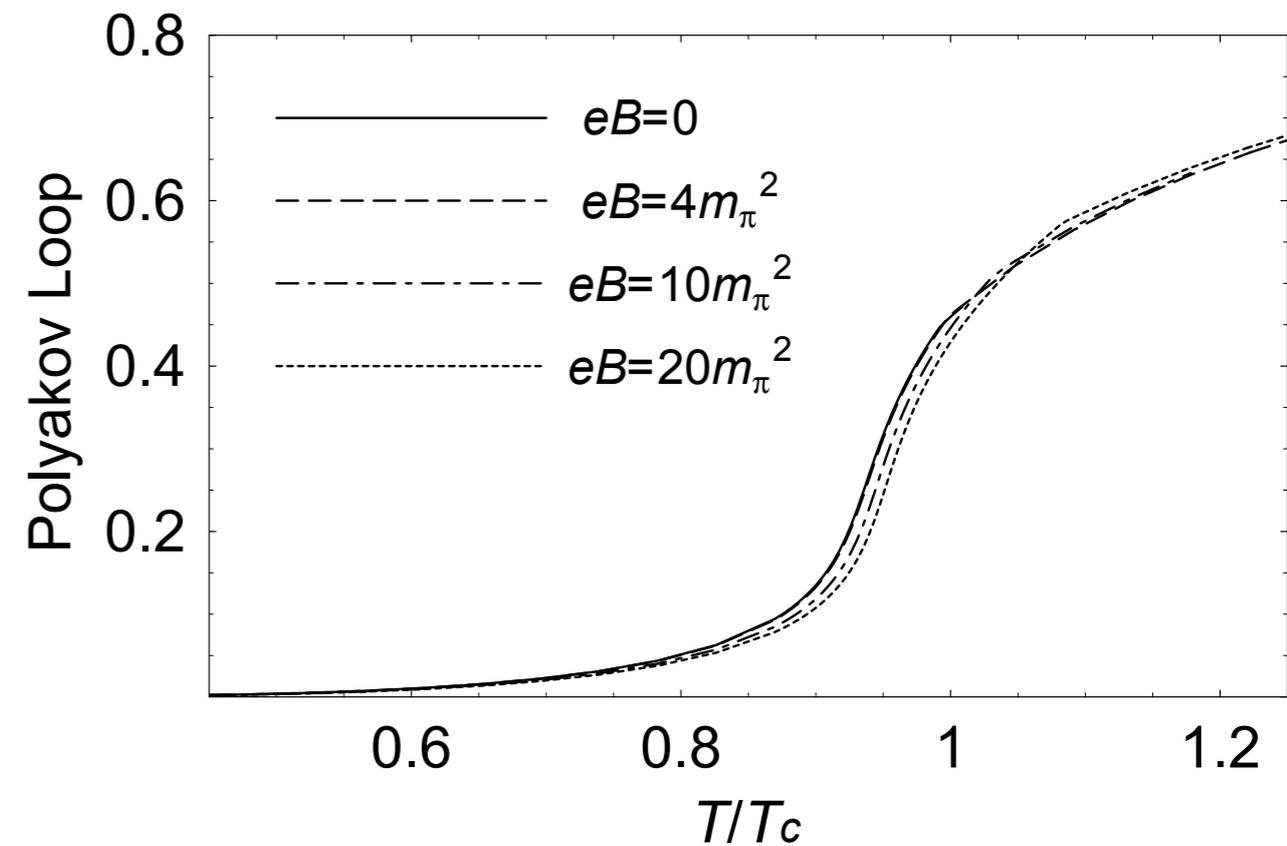
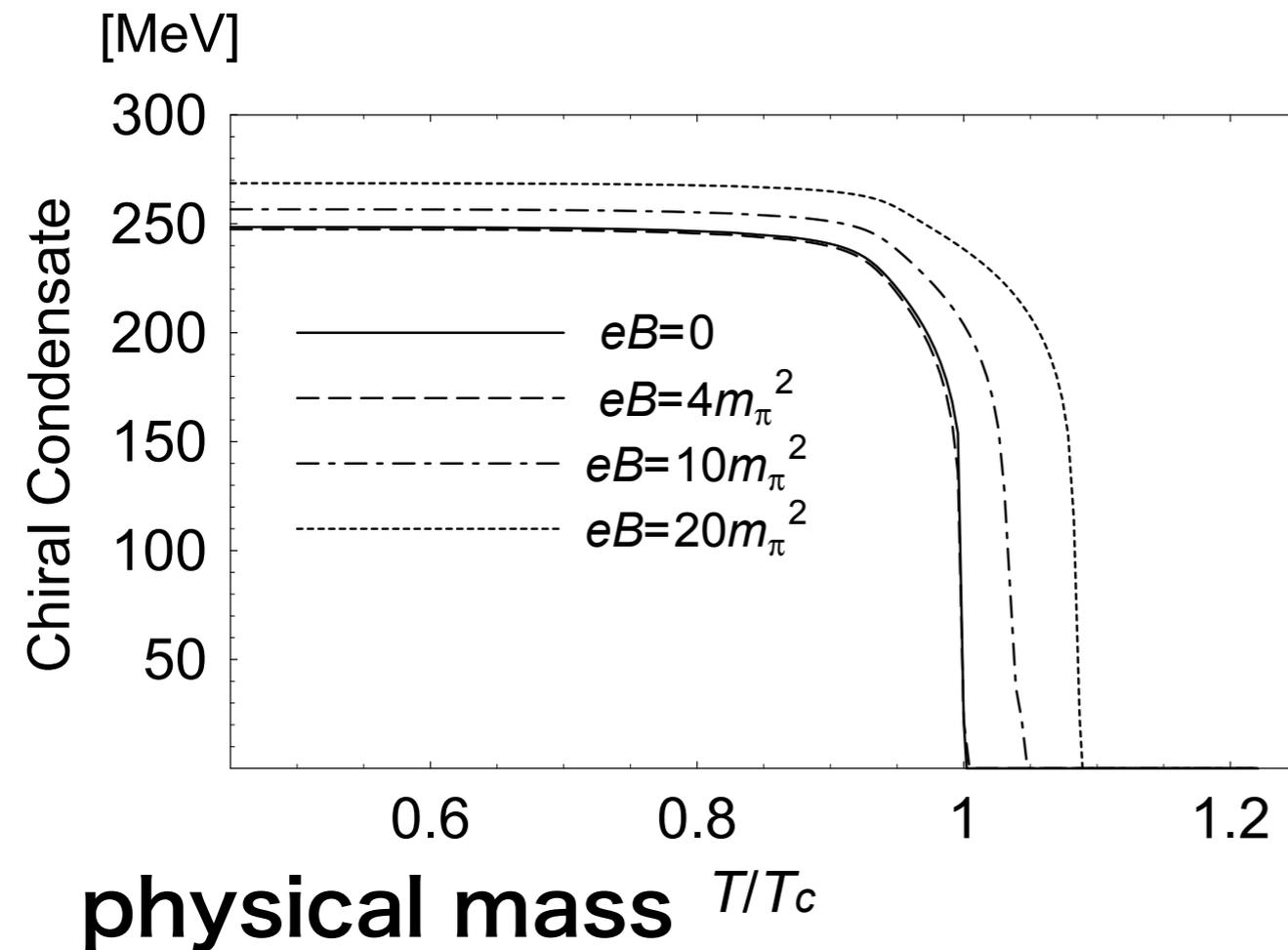
Model	Kenji Fukushima et al (arXiv: 1003.0047) N. O. Agasian et al (arXiv: arXiv: 0803.3156) Jens Braun et al (arXiv: 1412.6025)
Lattice	Massimo D'Elia et al (arXiv: 1005.5365) Gergely Endrődi 2015 (arXiv: 1504.08280)

# Background & Motivation

## Previous studies: Model & Lattice 1/5

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

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



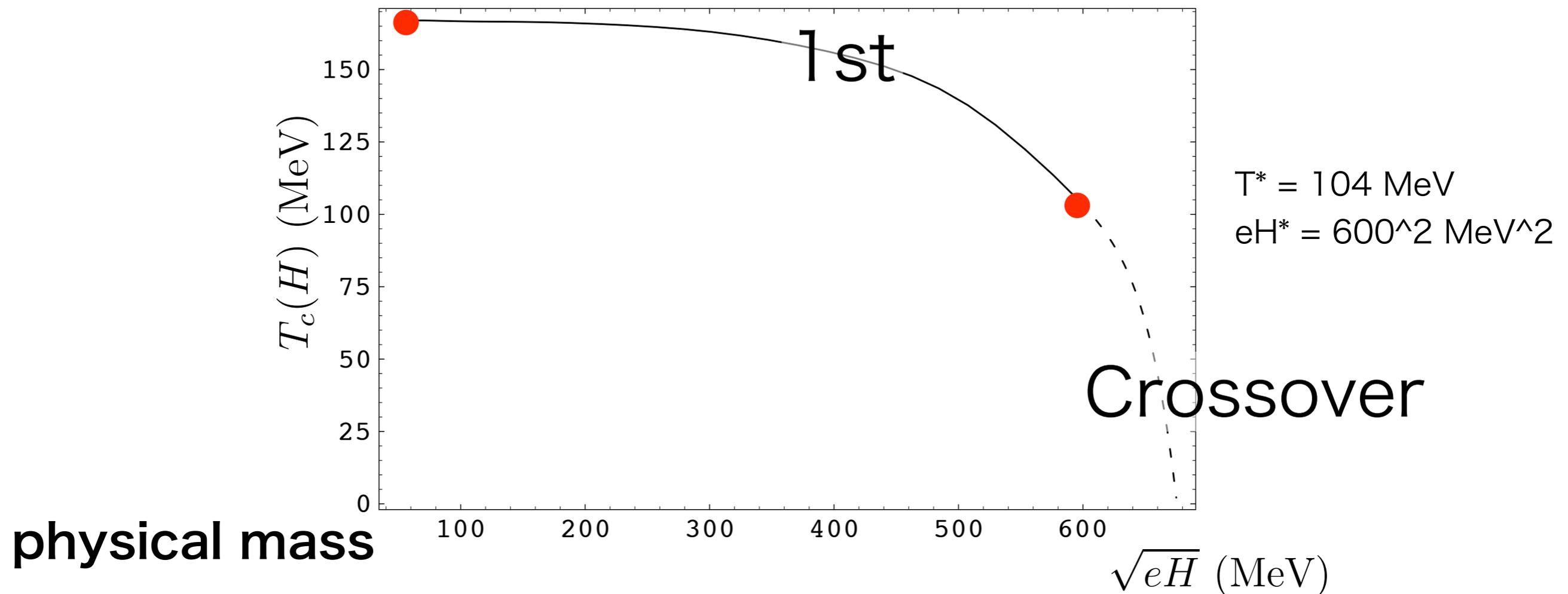
- $T_c$  goes **up** along with mag. field.
- Order does not depend on  $eB$ ? (not discussed)

# 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)



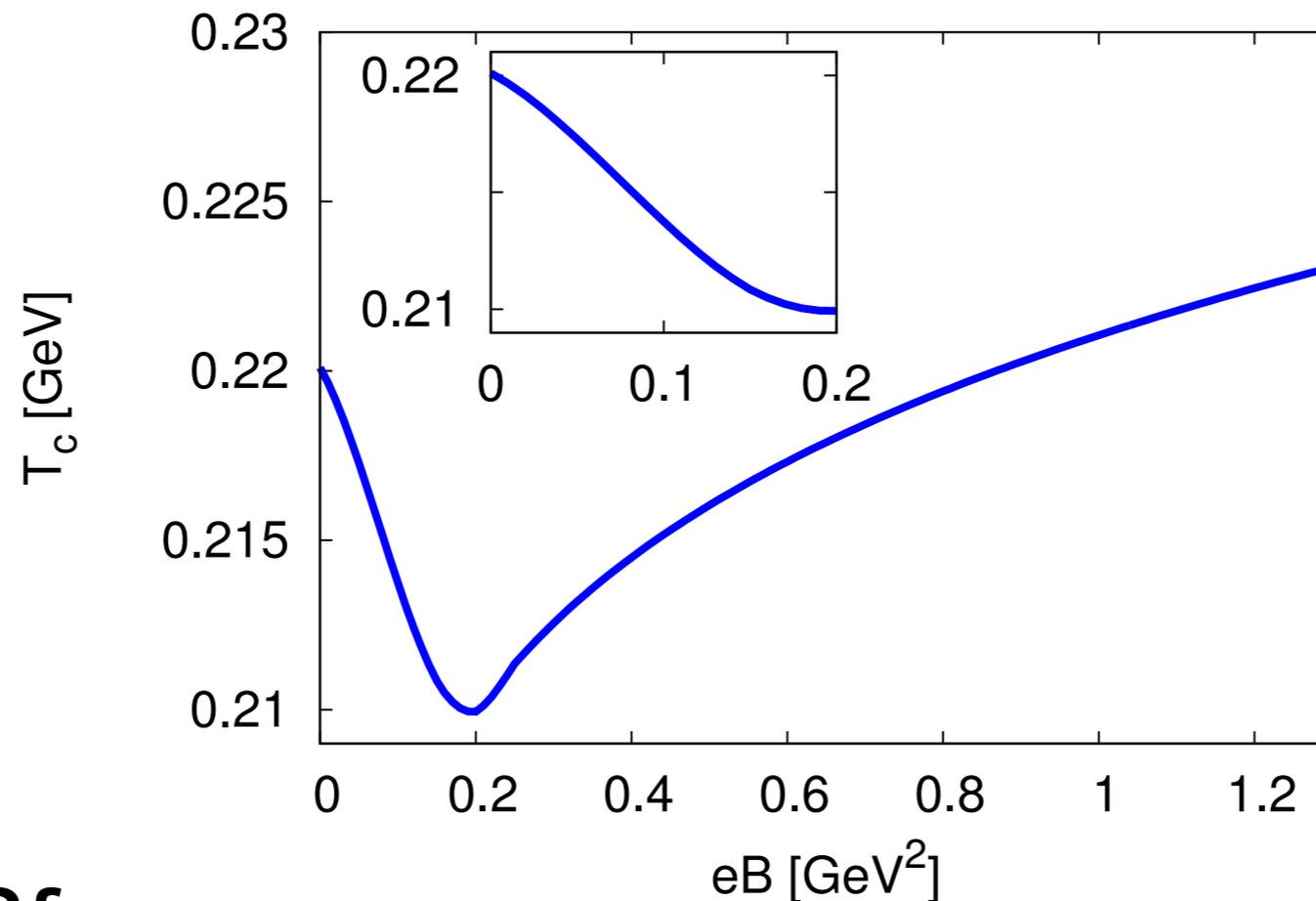
- $T_c$  goes **down** along with mag. field.
- Order depends on  $eB$  (1st to crossover)

# 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

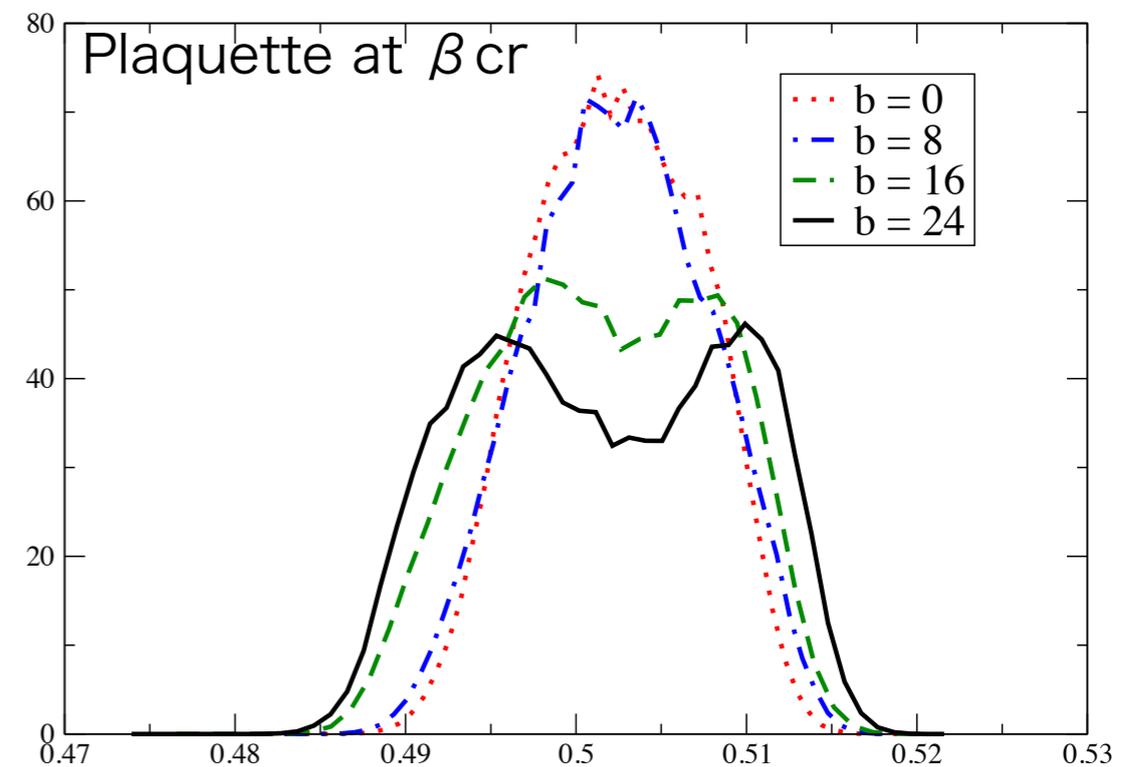
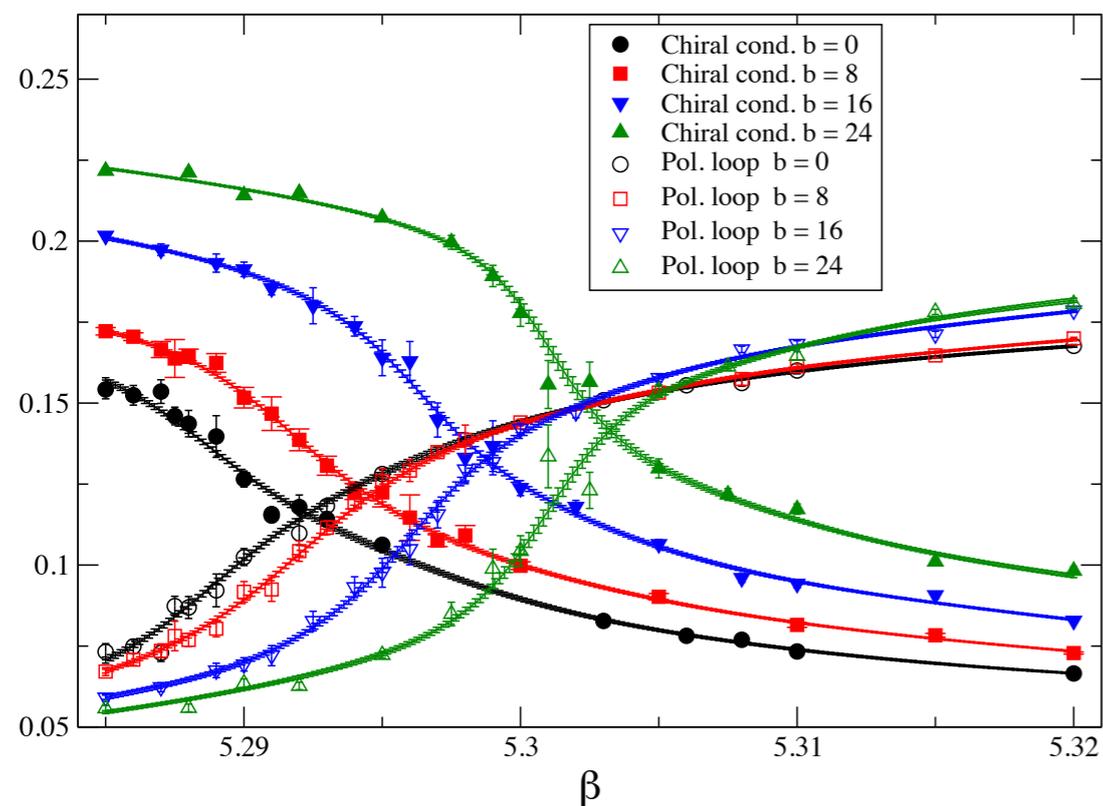
- T<sub>c</sub> goes **down** and **up** along with mag. field.
- Order is not discussed

# Background & Motivation

## Previous studies: Model & Lattice 4/5

### Lattice(1/2): $N_f=2$ , standard KS

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



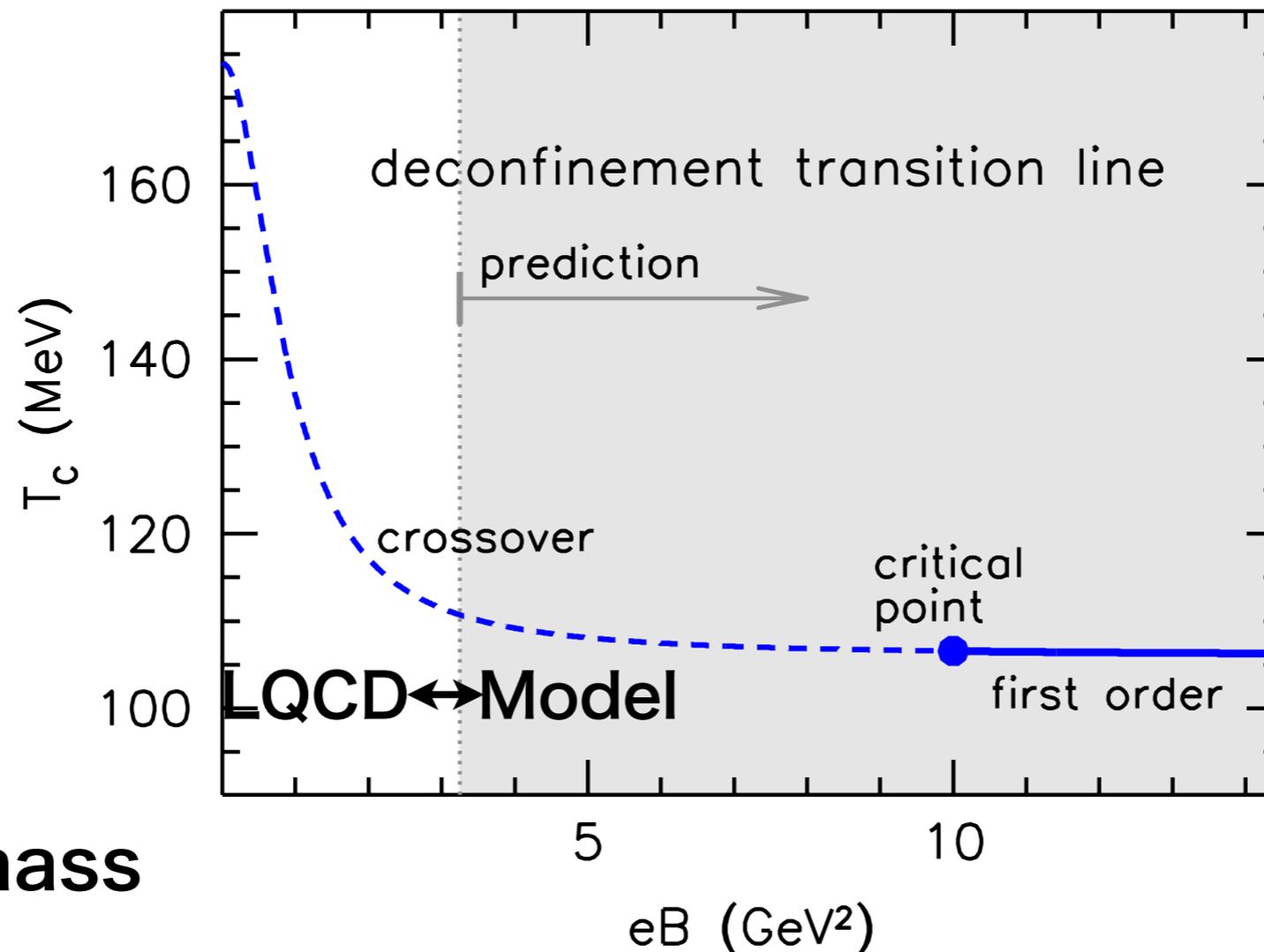
$m_\pi \approx 275 \text{ MeV}$

- $T_c$  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:  $N_f = 3$ , stout KS, physical mass  
 Gergely Endrődi 2015 (arXiv: 1504.08280)



### Physical mass

- $T_c$  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 $m_{\text{phys}}$	<b>Increase</b>	No change?
N. O. Agasian et al	arXiv: 0803.3156	ChPT(2f) at $m_{\text{phys}}$	<b>Decrease</b>	1st to crossover
Jens Braun et al	arXiv: 1412.6025	RG, massless 2f	<b>Decrease and increase</b>	?
Massimo D'Elia et al	arXiv: 1005.5365	KS(2f)	<b>Increase</b>	Crossover to strong 1st
Gergely Endrődi	arXiv: 1504.08280	Stout KS (3f) at $m_{\text{phys}}$ + model	<b>Decrease</b>	Crossover to 1st (model)

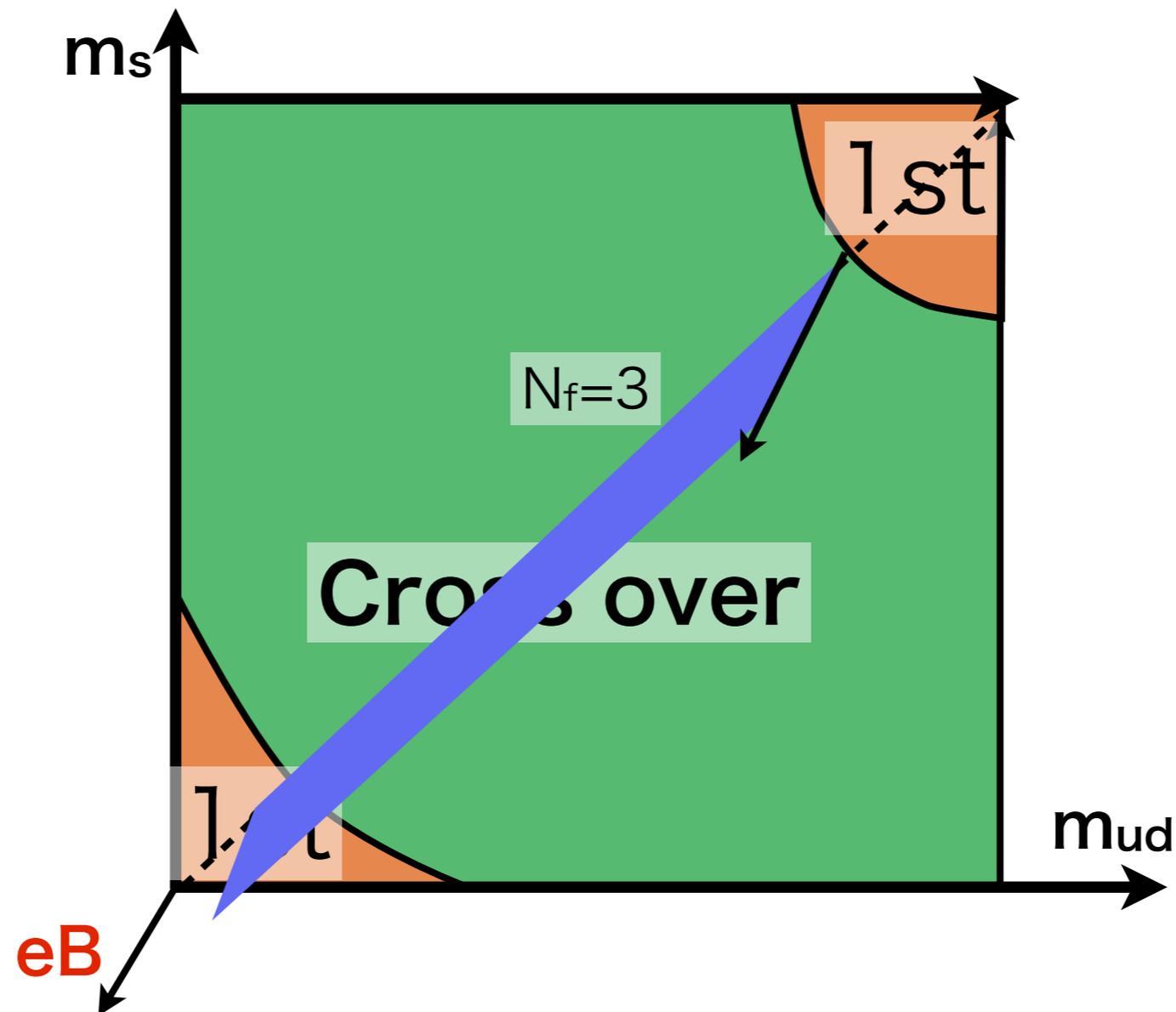
Ref. 1208.0917, 1209.0374, 1411.7176 and there in

**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

## 3 Flavor Standard staggered + Wilson plac. 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	$\beta$ range	Nb (Magnetic flux)	#Conf.
Light	0.024(1st order for Nb=0*)	$24^3 \times 4$ ( $16^3 \times 4$ )	5.128-5.160	0-56	O(2000)
	0.028(Critical for Nb = 0*)	$16^3 \times 4$	5.130-5.170	0-56	O(1500)
Heavy	0.2	$16^3 \times 4$	5.10-5.65	0-56	O(500)
	0.4	$16^3 \times 4$	5.35-5.65	0-56	O(500)
	0.8	$16^3 \times 4$	5.35-5.85	0-56	O(700)

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

\* C. Schmidt et al 2010 (arXiv: 1109.6729)

Nb: Number of magnetic flux

# Mass vs magnetic field

## Magnetic field shifts eigenvalues

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

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  $N_b$  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  $Nb=5$ )

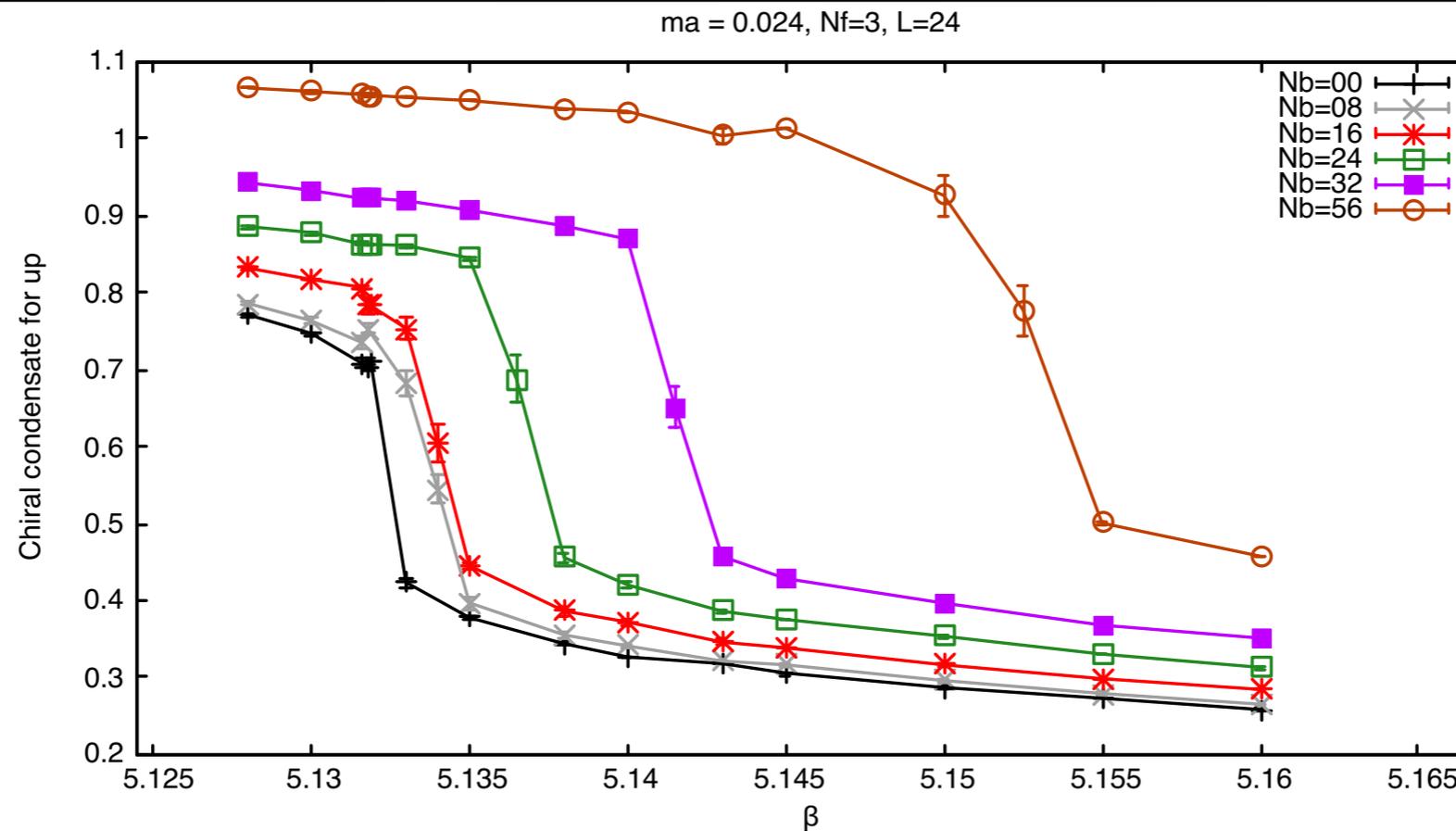
$ma = 0.8$  (comparable with magnetic field  $Nb=24$ )

# Preliminary Result (1/6)

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

$L=24^3 \times 4$

Up quark cond.



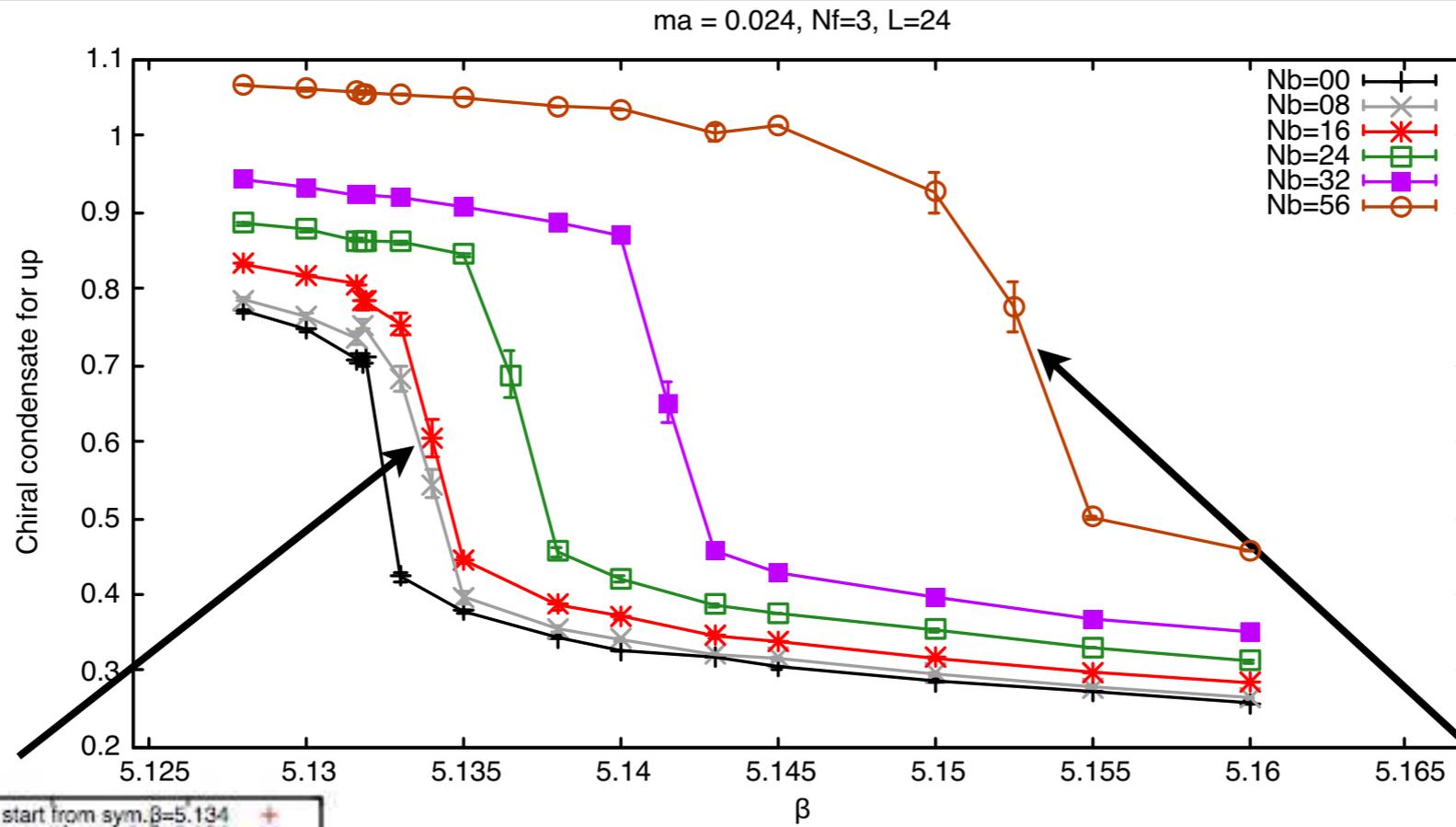
**Tc increases  
Nb → Large**

# Preliminary Result (1/6)

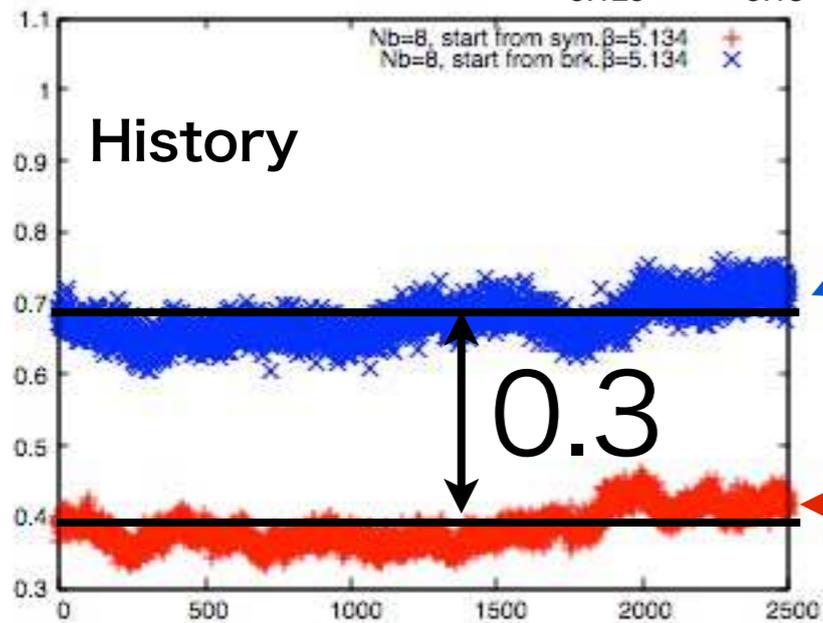
$am = 0.024$  (1st for  $Nb=0$ ): 1st becomes stronger?

$L=24^3 \times 4$

Up quark cond.

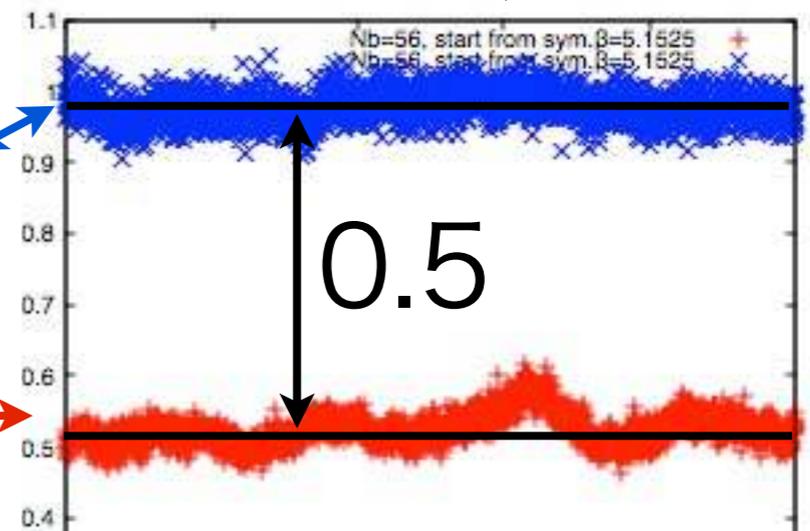


**Tc increases  
Nb -> Large**



Start from broken phase

Start from sym. phase



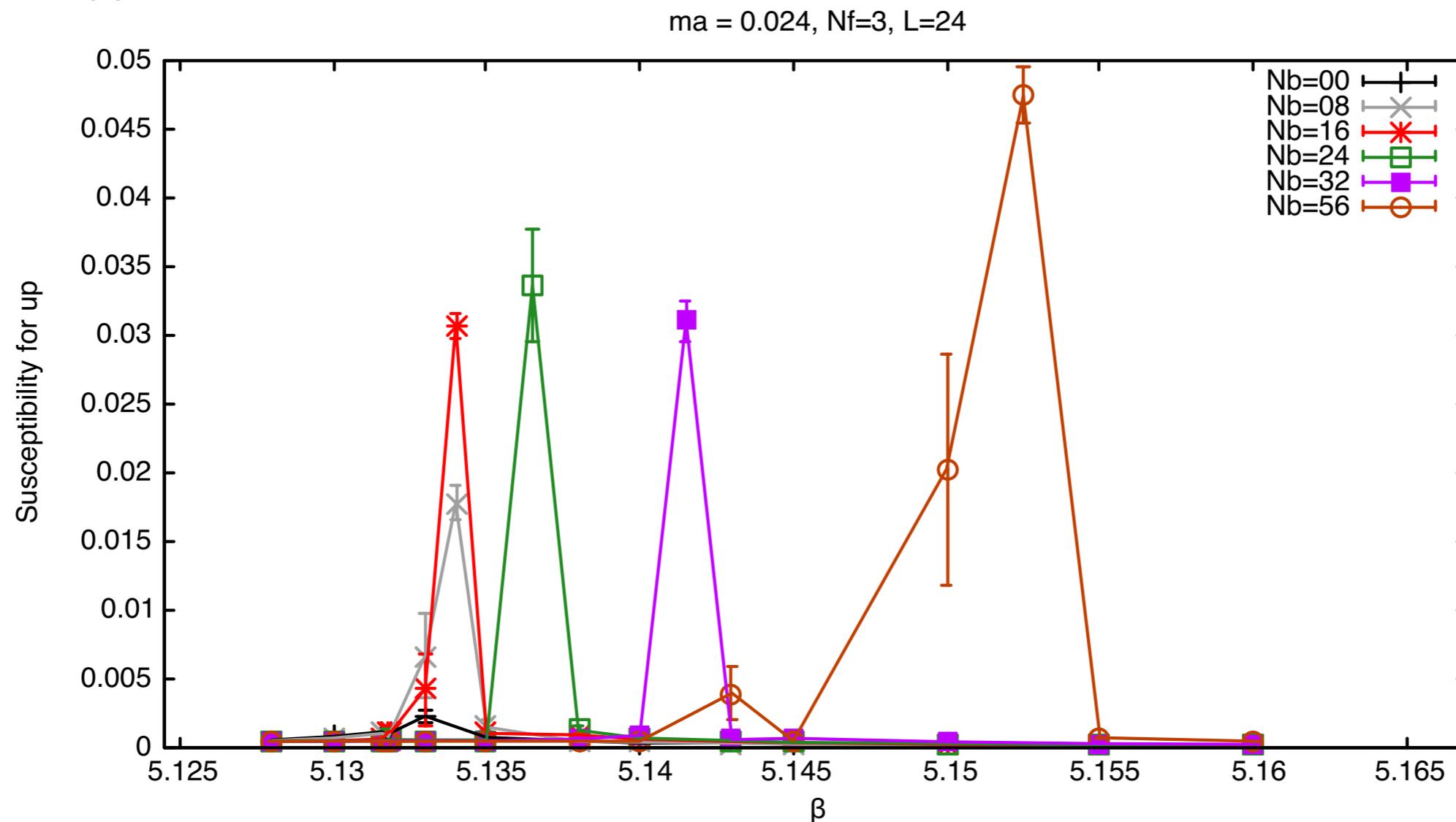
**Hysteresis (=1st order) and the gap of them becomes larger**

# Preliminary Result (1/6)

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

$L=24^3 \times 4$

Up quark cond.



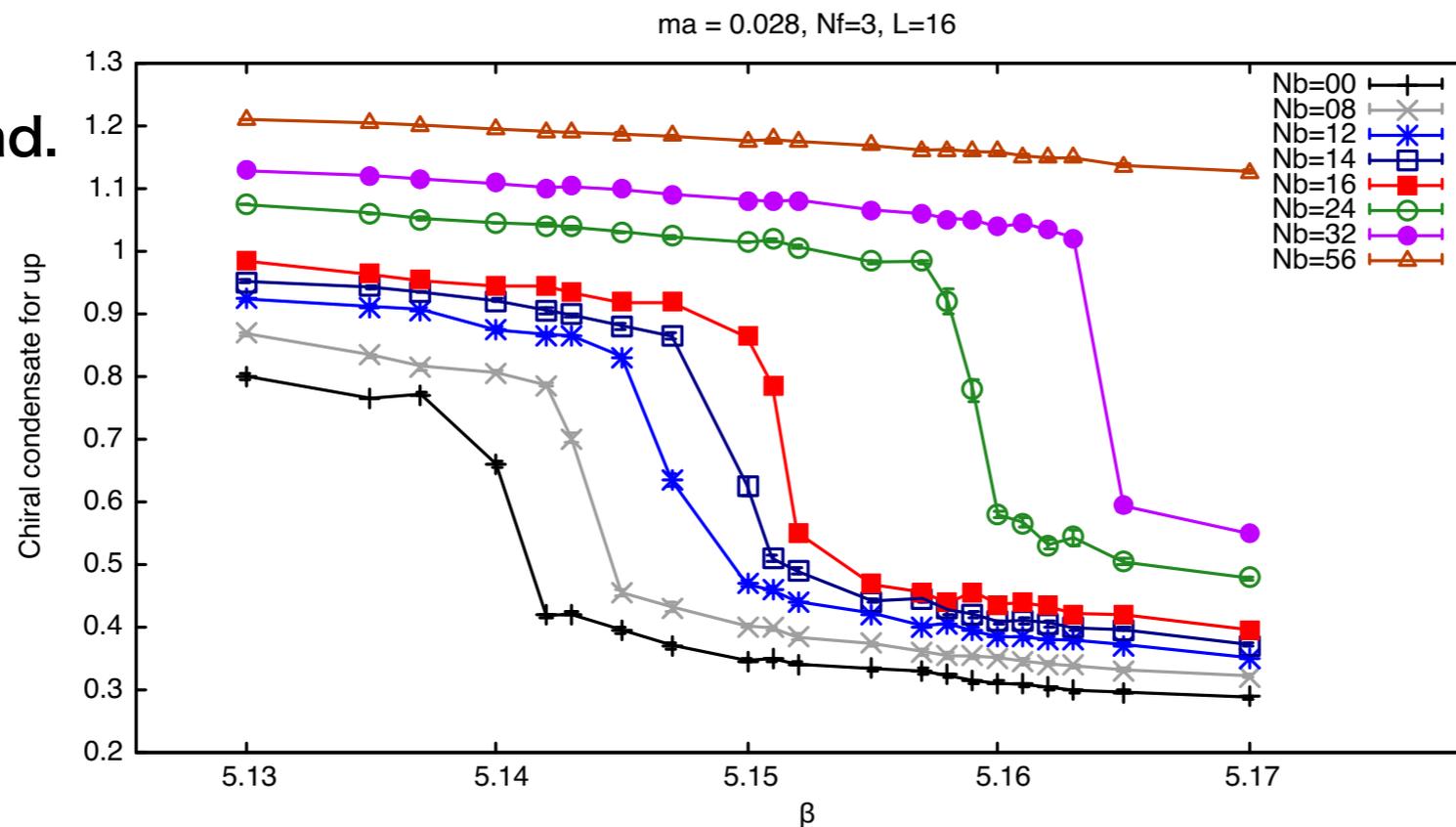
**Tc increases**  
**Nb  $\rightarrow$  Large**

# Preliminary Result (2/6)

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

$L=16^3 \times 4$

Up quark cond.



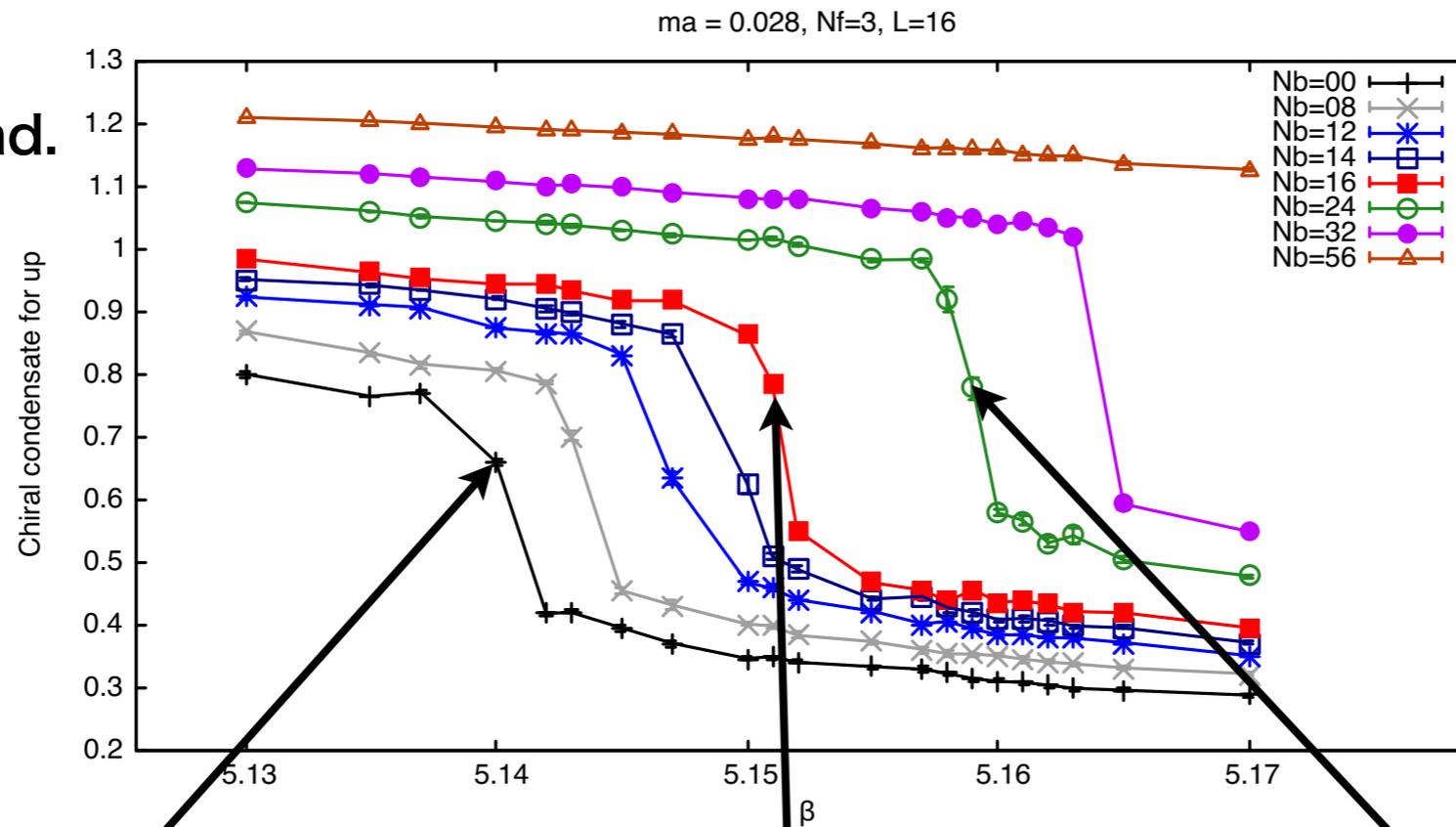
**$T_c$  increases  
Nb  $\rightarrow$  Large**

# Preliminary Result (2/6)

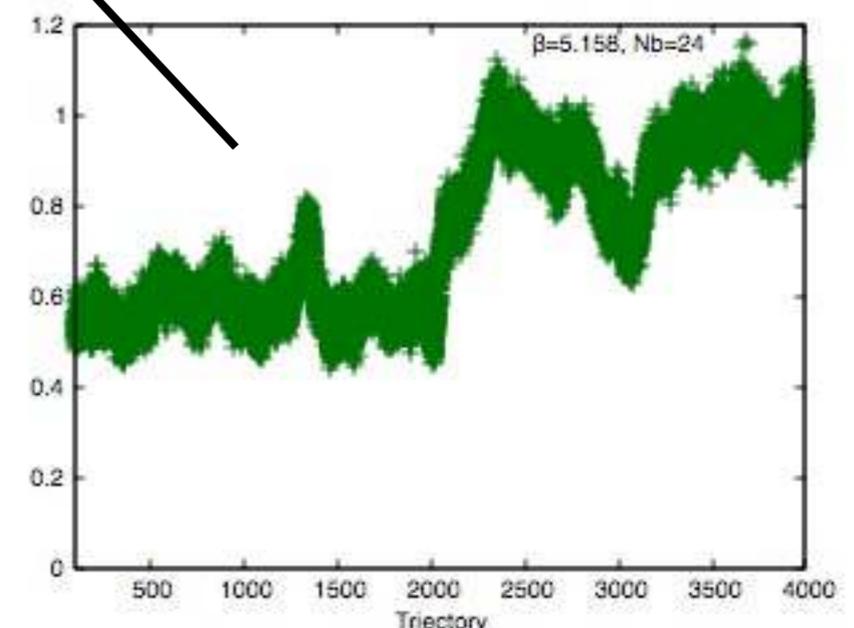
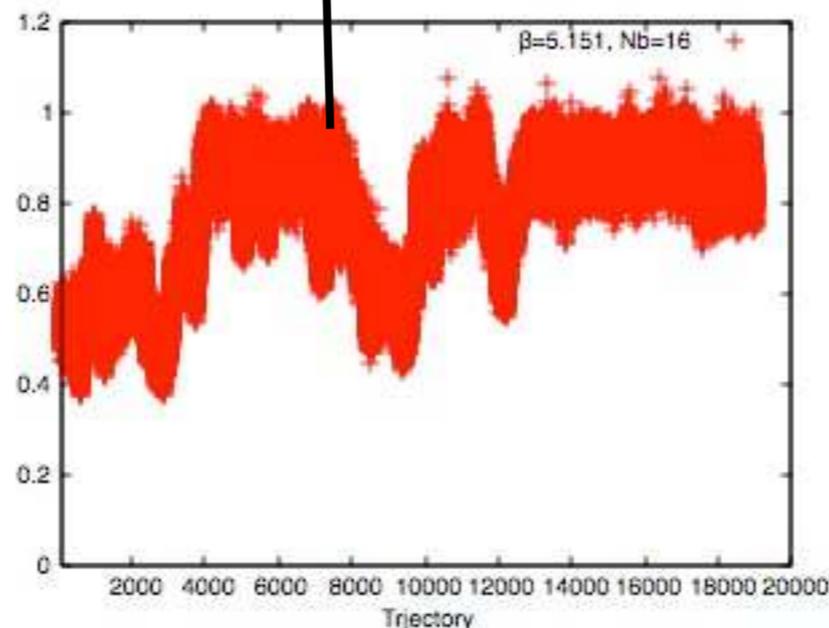
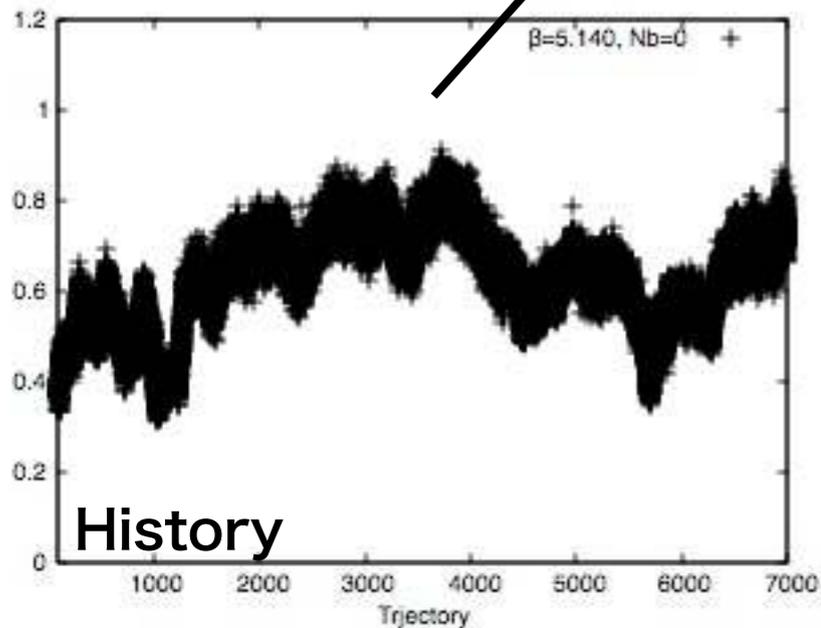
$am = 0.028$  (crossover for  $N_b=0$ ): crossover to 1st

$L=16^3 \times 4$

Up quark cond.



Tc increases  
Nb -> Large



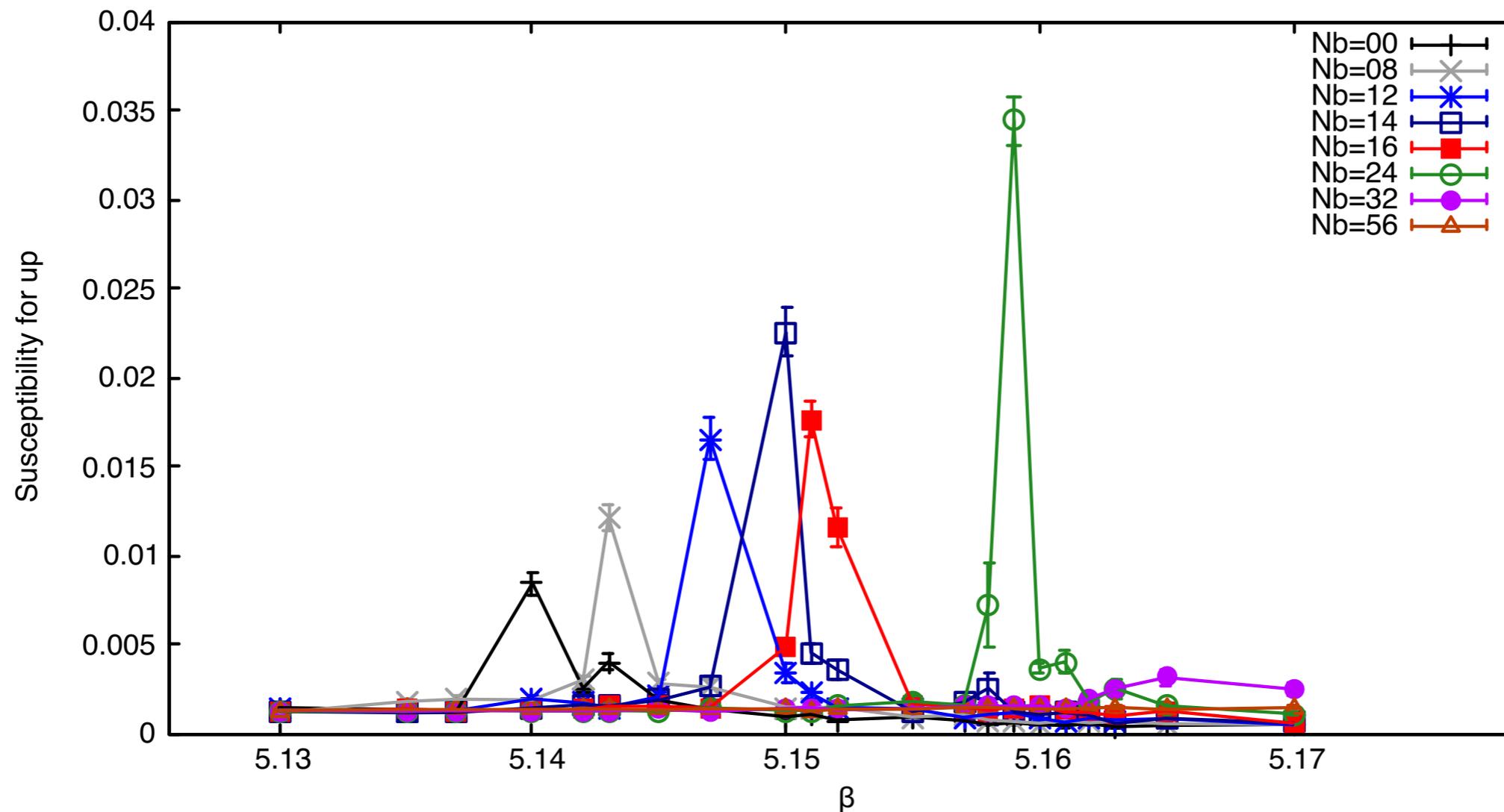
# Preliminary Result (2/6)

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

$L=16^3 \times 4$

Up quark cond. susceptibility

ma = 0.028, Nf=3, L=16



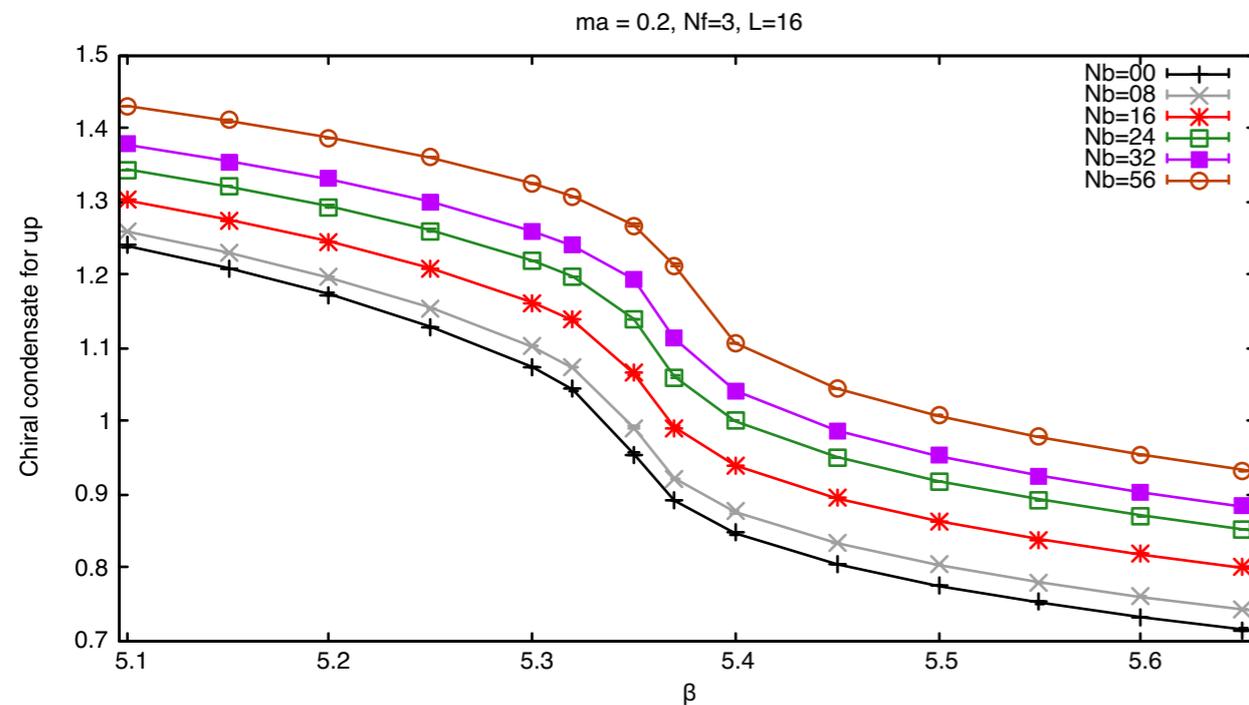
**Tc increases  
Nb -> Large**

# Preliminary Result (3/5)

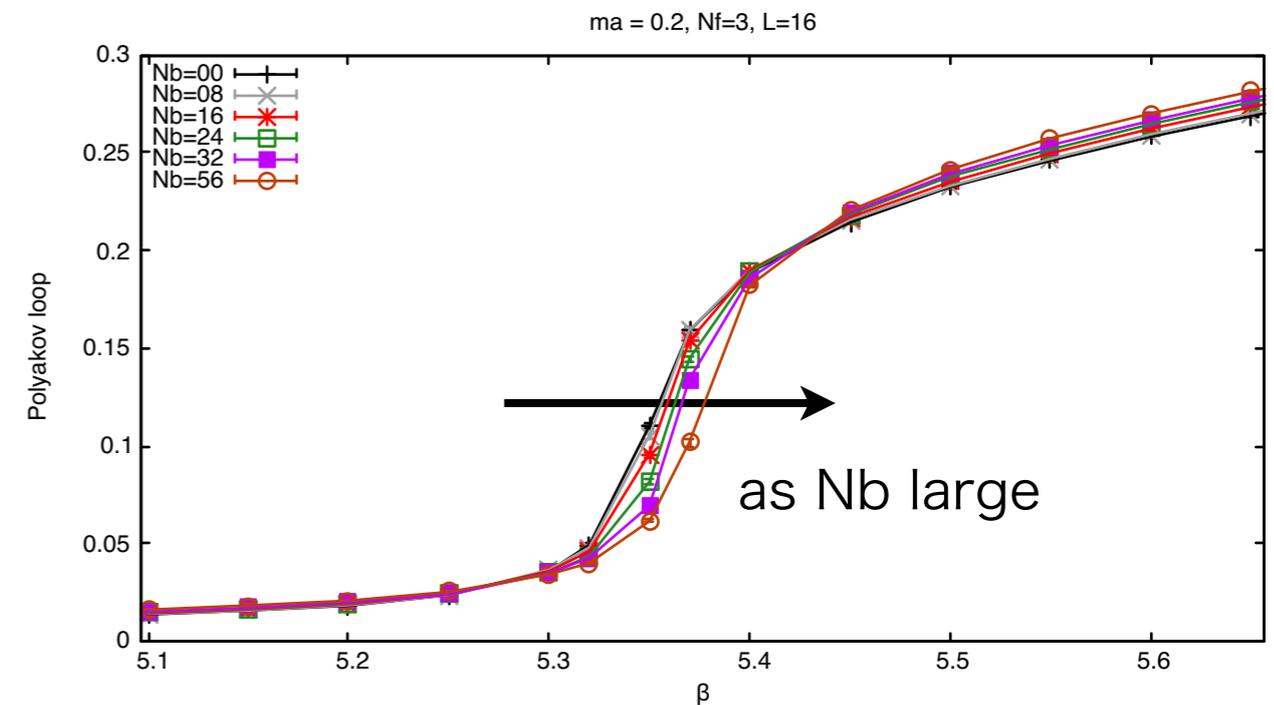
## am = 0.2: Tc goes up

L=16<sup>3</sup>x4

### Up quark condensate



### Polyakov loop



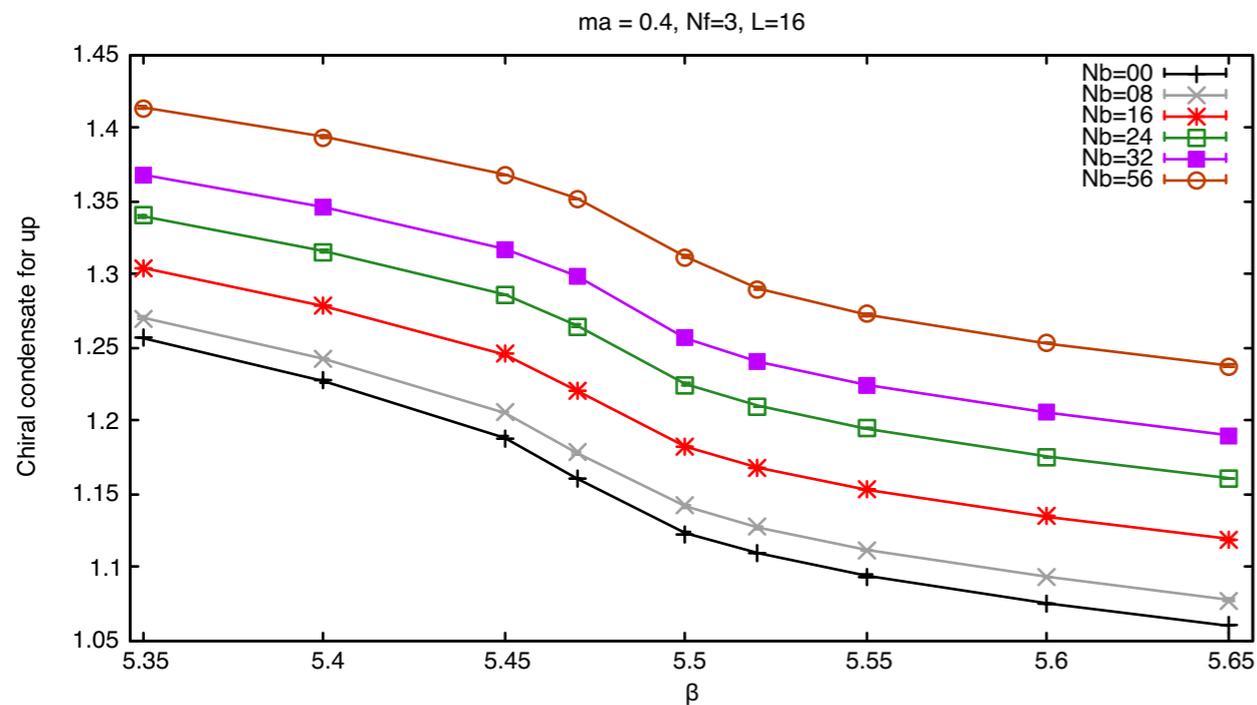
- Chiral condensate does not show phase transition for Nb = 0-56
- Behavior of the Polyakov loop is similar to that in PNJL results
- Tc for deconf/conf trans. goes up for increasing Nb (not clear)

# Preliminary Result (4/5)

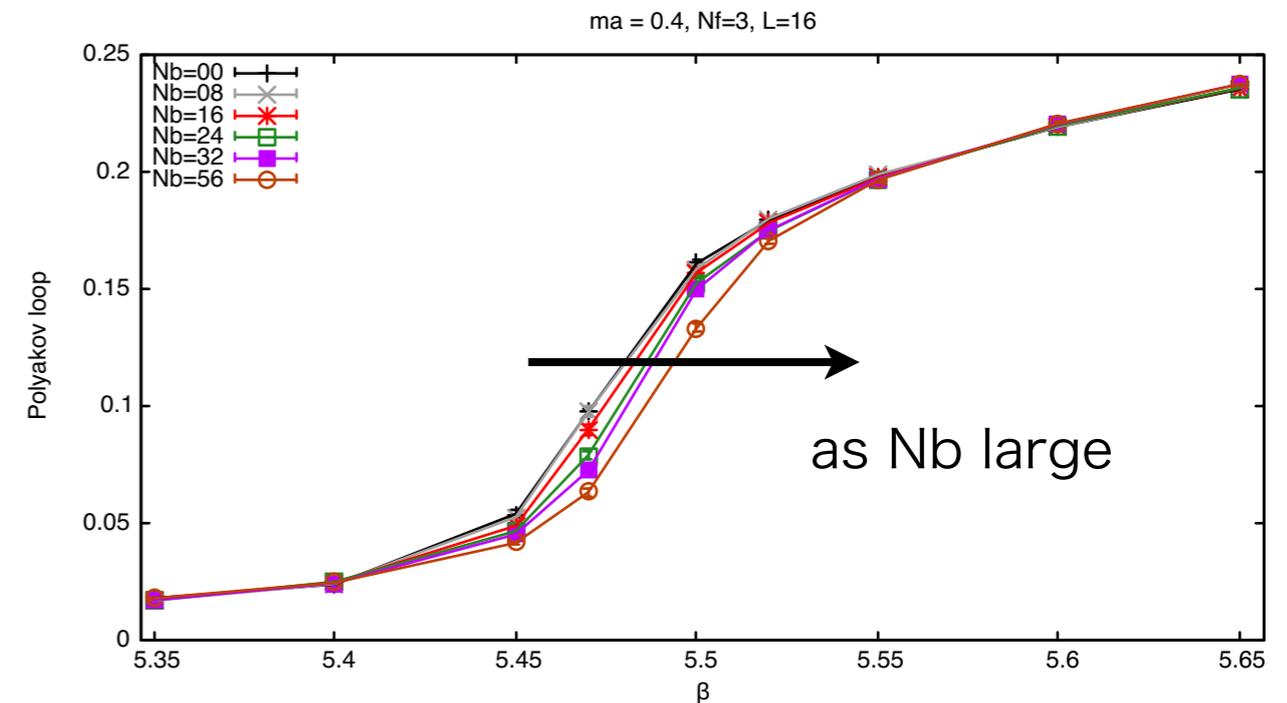
## am = 0.4: No clear signal yet but Tc goes up

$L=16^3 \times 4$

### Up quark condensate



### Polyakov loop



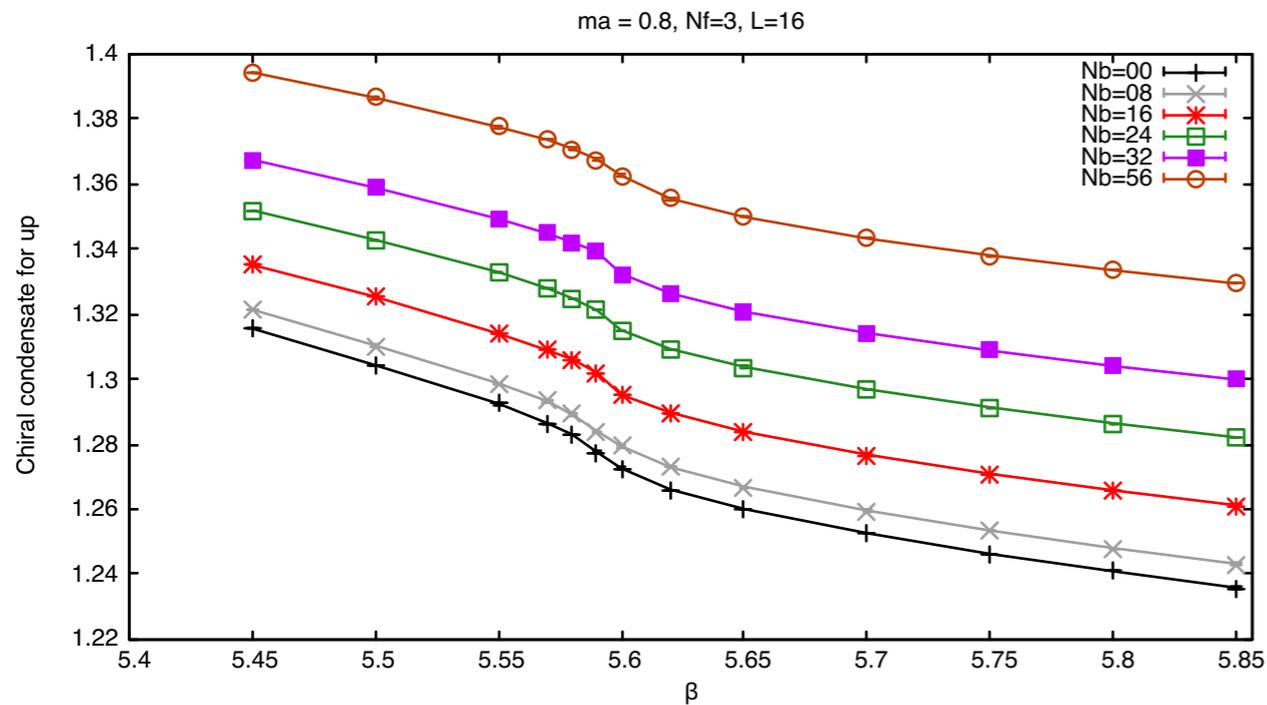
- Chiral condensate does not show phase transition (trivially scaled)
- Behavior of the Polyakov loop is similar to that in PNJL results
- Tc for deconf/conf trans. goes up for increasing Nb (not clear)

# Preliminary Result (5/5)

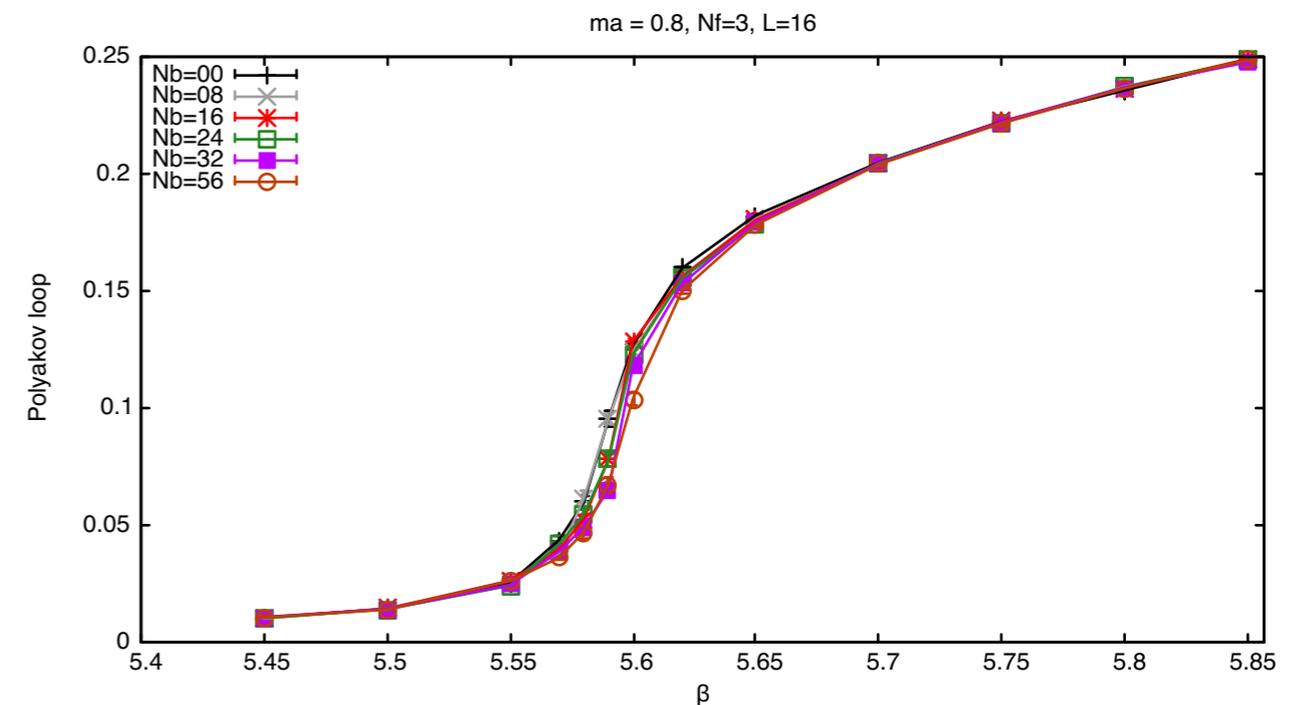
## am = 0.8: No clear signal (1st order like for conf.)

$L=16^3 \times 4$

### 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)	<b>Increase</b>	1st to strong 1st?	<b>Increase</b>	1st to strong 1st?
0.028 (Crossover for Nb = 0)	<b>Increase</b>	crossover to 1st	<b>Increase</b>	crossover to 1st
0.2	no critical behavior	-	<b>Increase</b>	crossover like
0.4	no critical behavior	-	<b>Increase</b>	crossover like
0.8	no critical behavior	-	Increase?	1st ?

# Summary

## QCD phase transition depends on Magnetic field

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### Summary:

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

### Tasks:

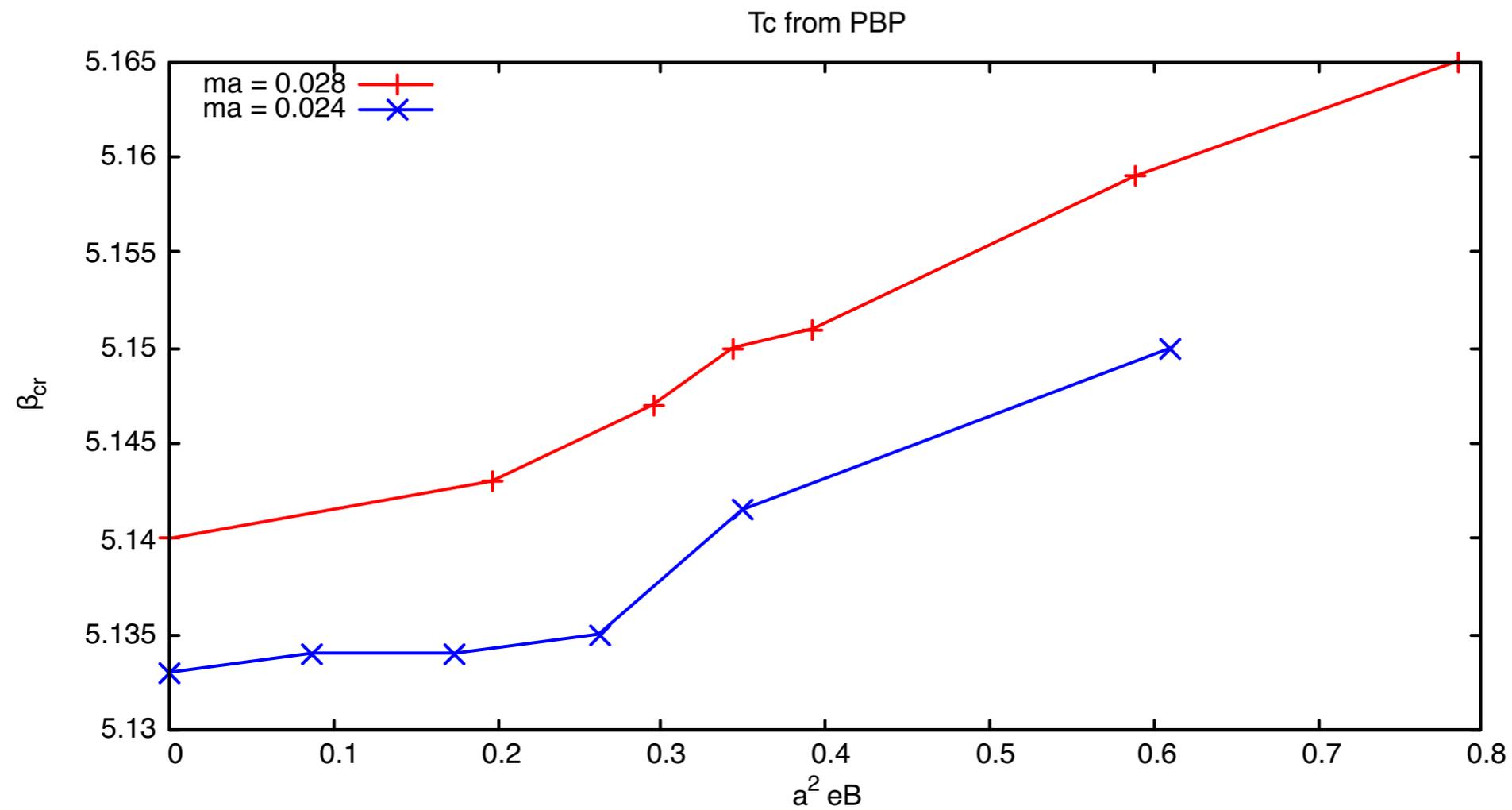
1. Increasing statistics
2. Improve resolution of beta
3. Scaling analysis to determine the order
5. Determination of the order of phase transition from the Binder ratio
6. Scale setting
7. Other cutoff scheme to check the cutoff effect on  $T_c$  vs  $N_b$

# Backup

Tc for

$ma = 0.024$  (1st for  $N_b=0$ )

$ma = 0.028$  (crossover for  $N_b=0$ )



# The Binder ratio(cumulant)

**$B_4 = 1$ : 1st.  $B_4 \sim 1.6$ : 2nd( $Z_2$ ).  $B_4 = 3$ : Crossover**

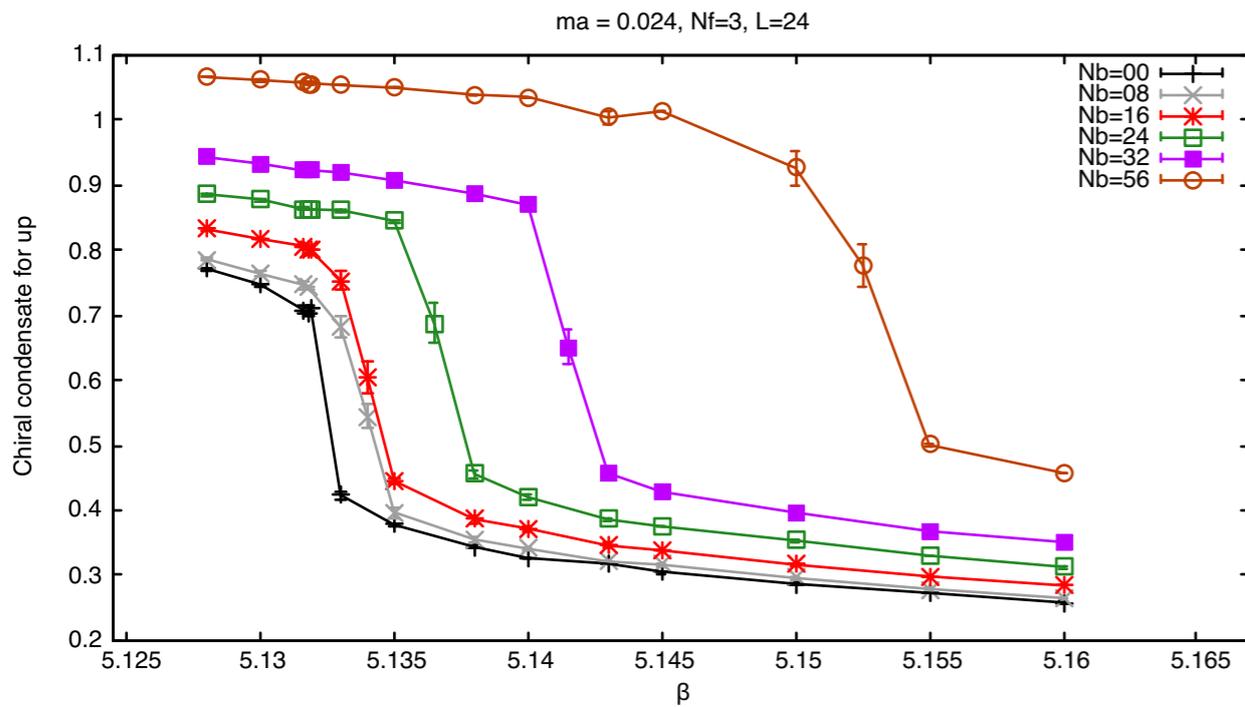
The Binder cumulant is defined as ratio of 4th order cumulant with square of 2nd order cumulant,

$$B_4(x) = \frac{\langle (\delta M(x))^4 \rangle}{\langle (\delta M(x))^2 \rangle^2} \quad \text{M: order parameter}$$

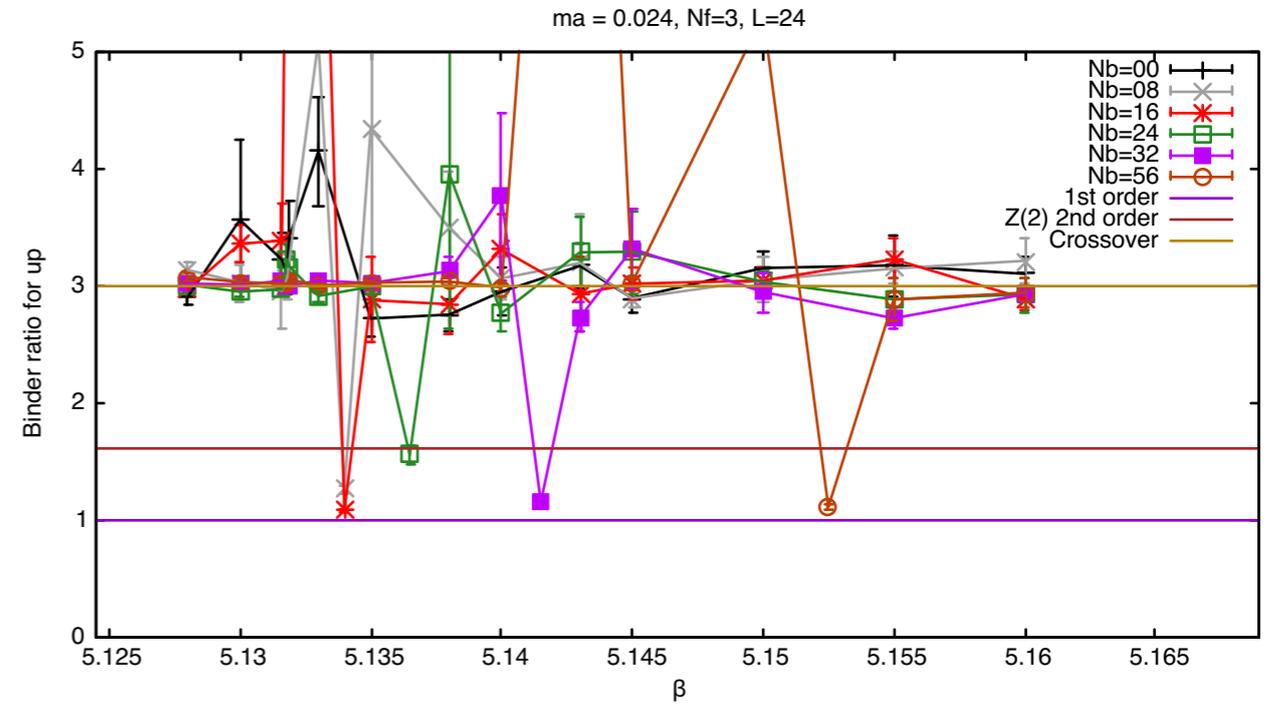
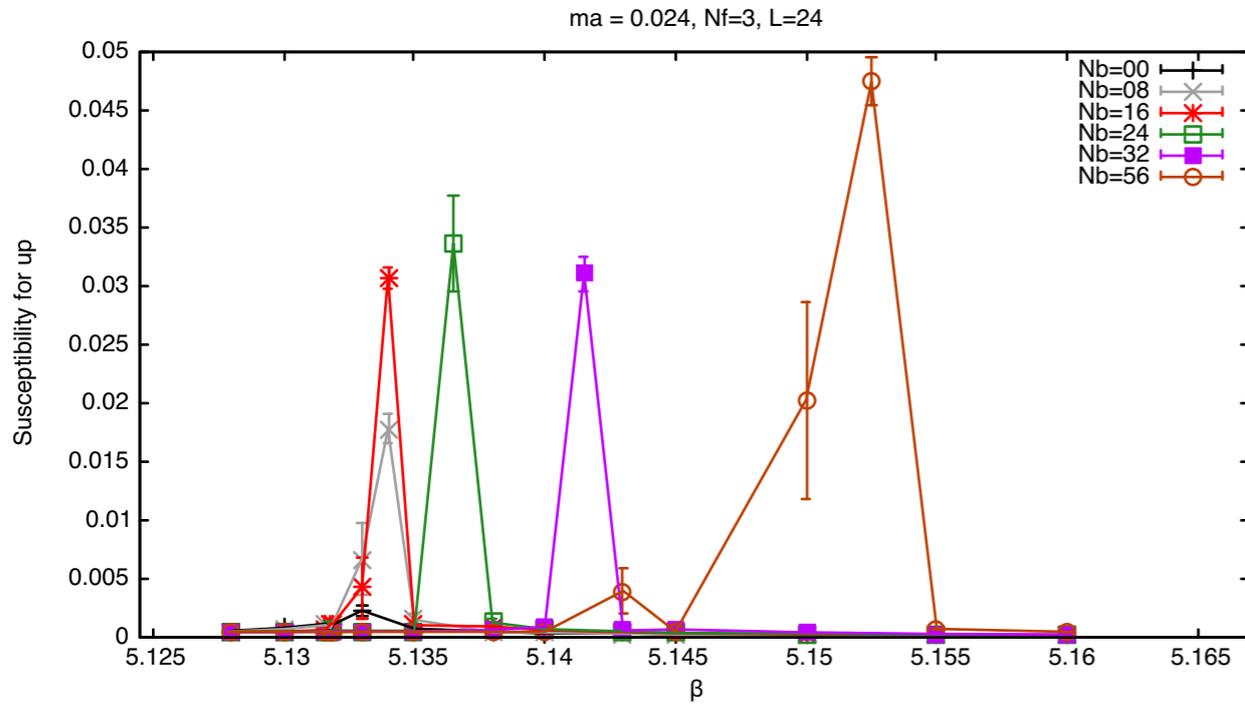
This quantity can distinguish the order of phase transition

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

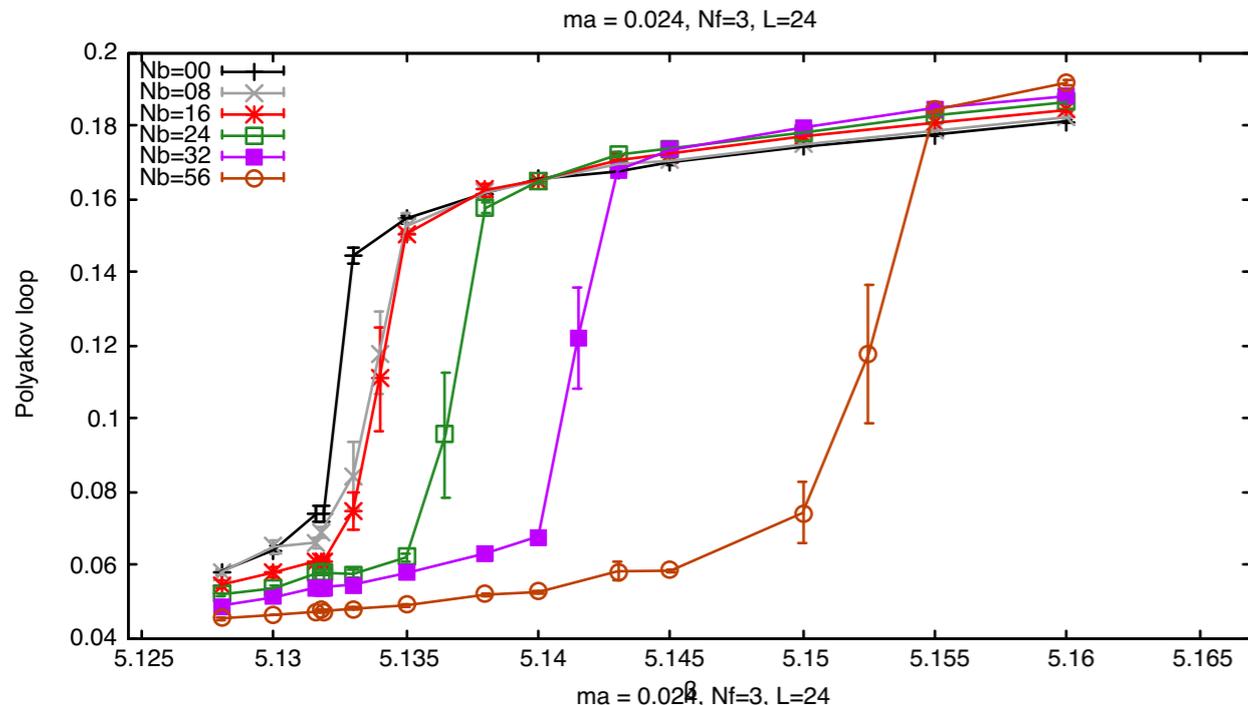
# ma = 0.024(1st for Nb=0) Up quark condensates



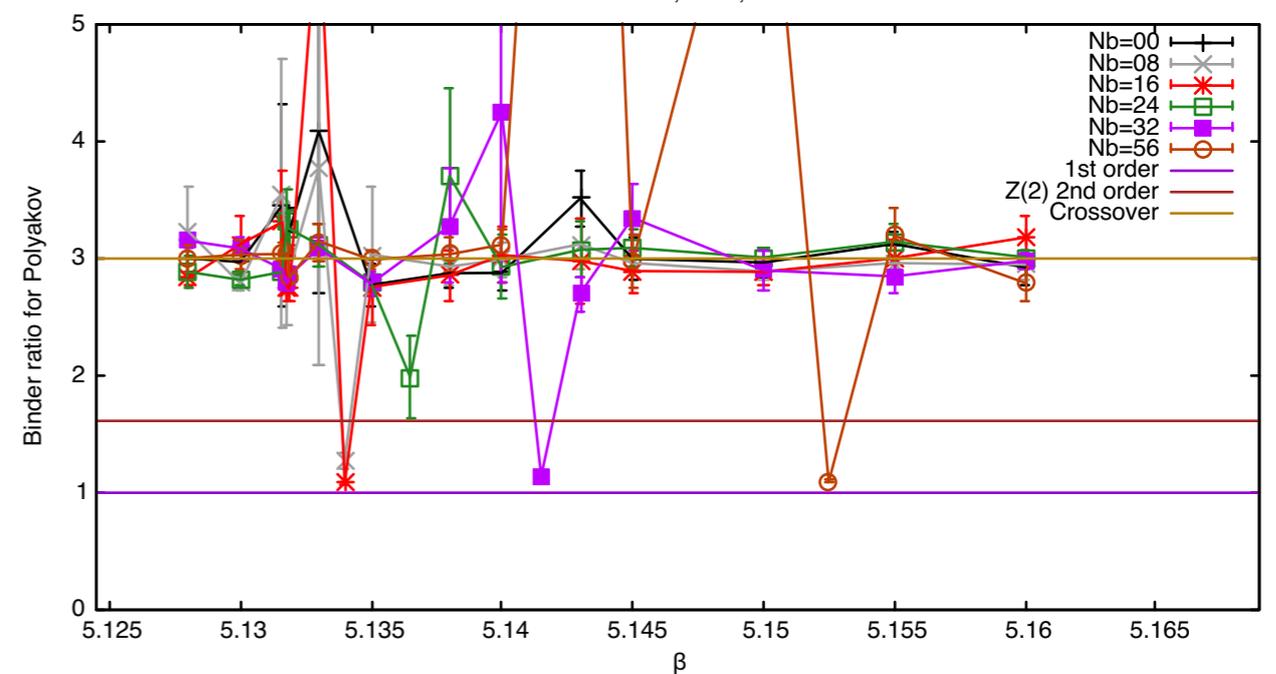
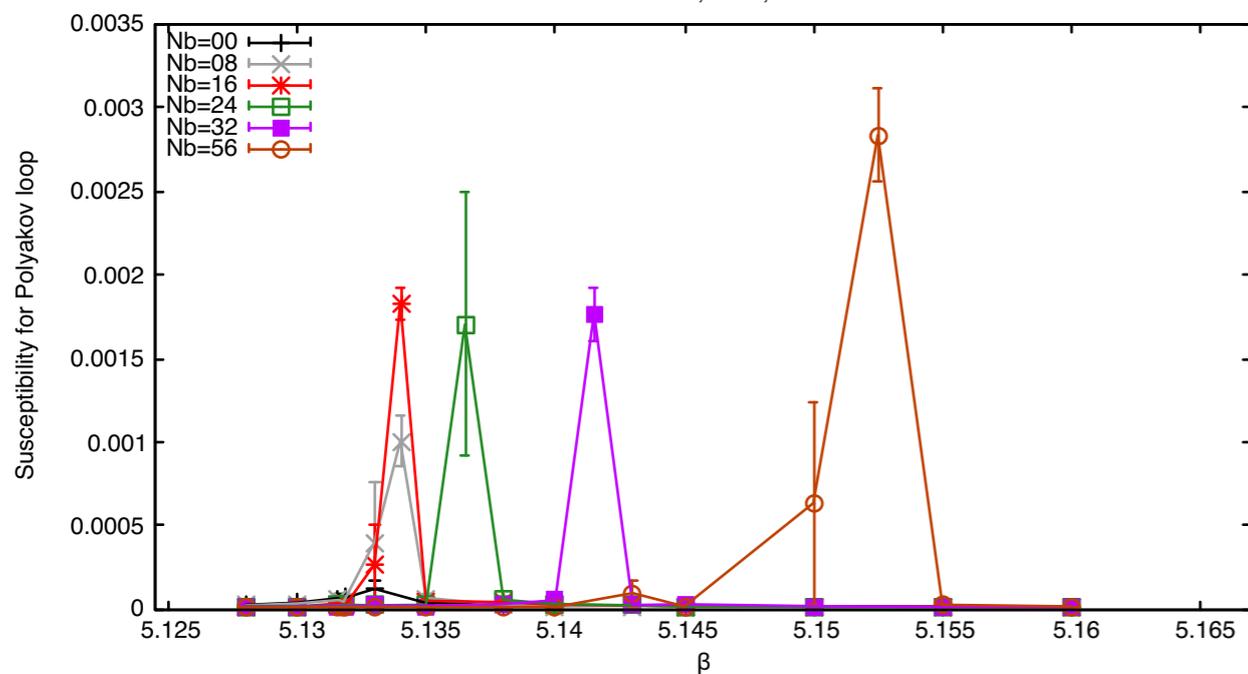
Consistent with  
1st order



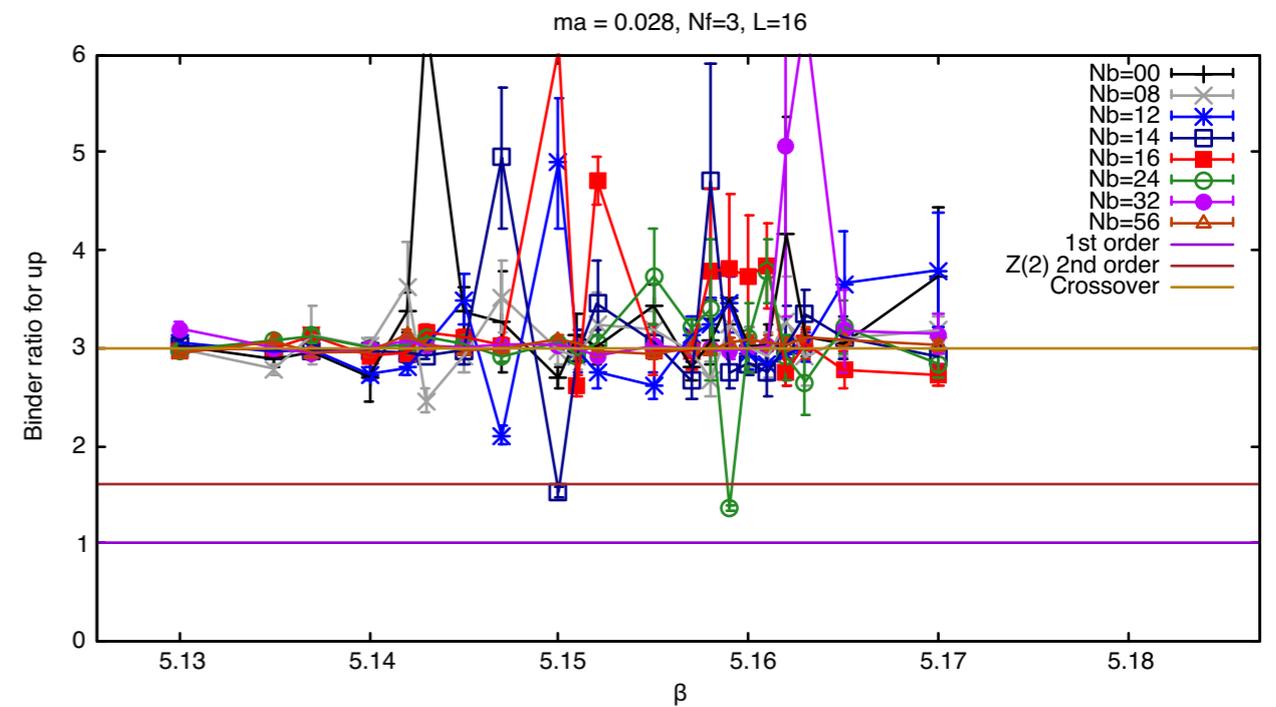
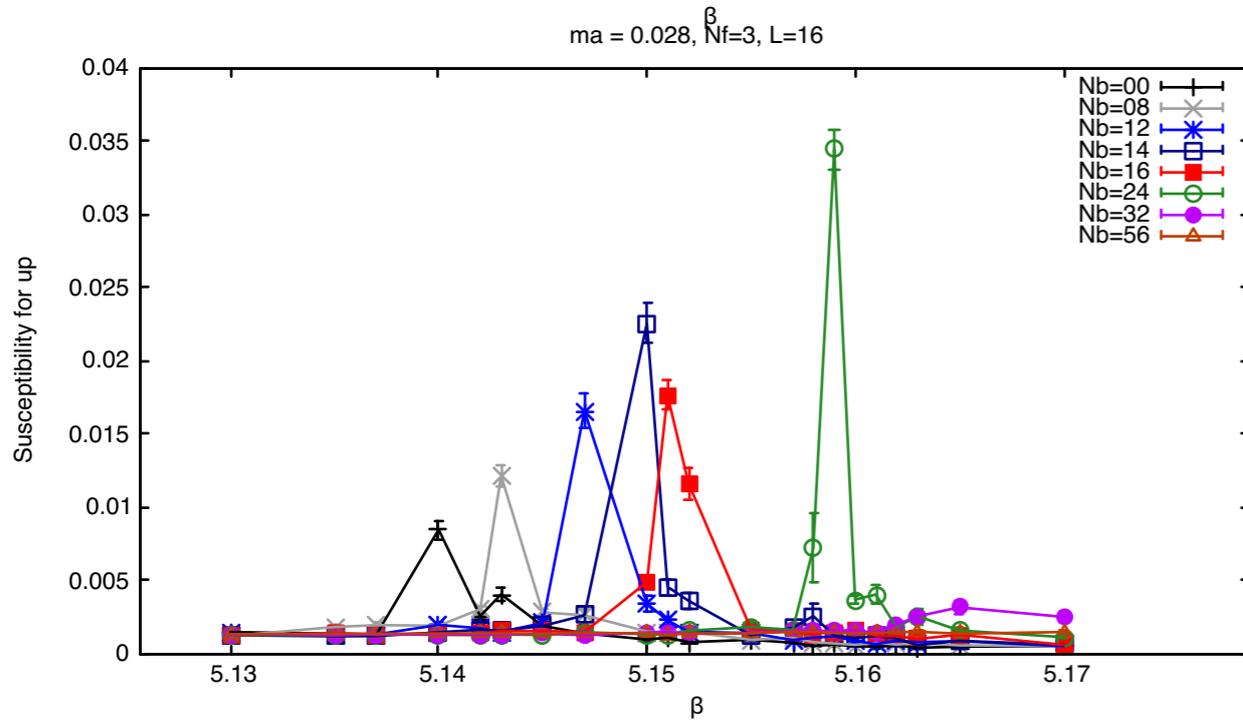
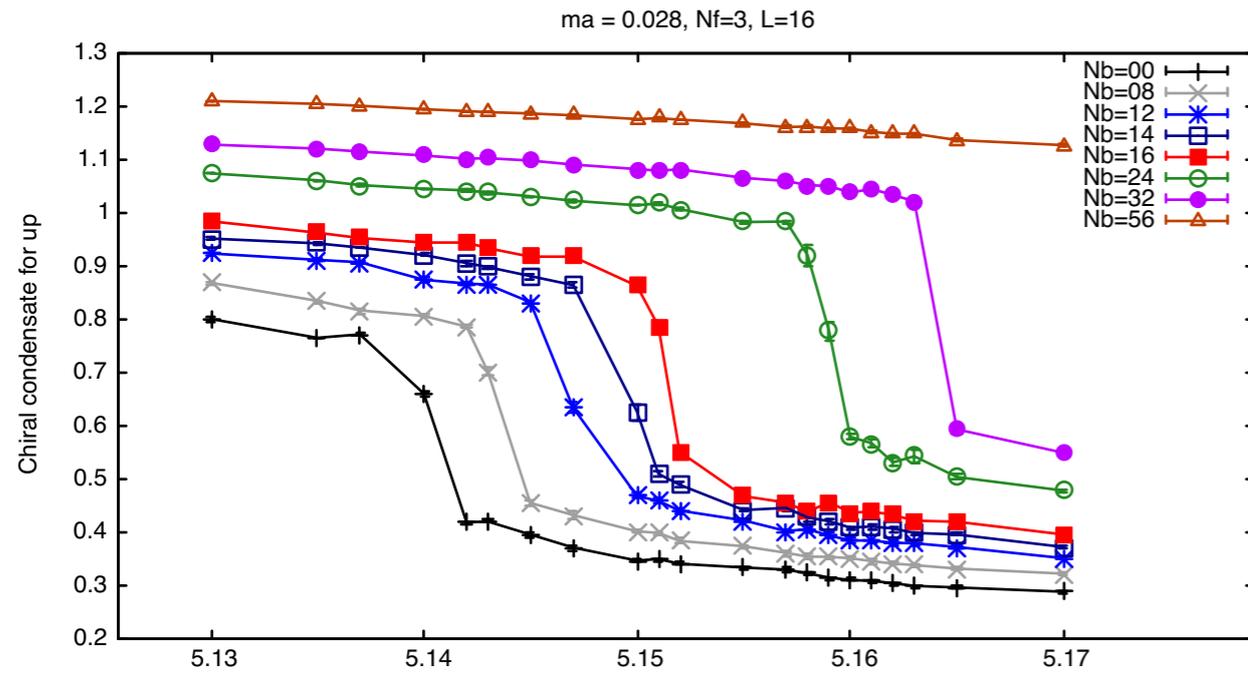
# ma = 0.024(1st for Nb=0) Polyakov loop



Consistent with  
1st order

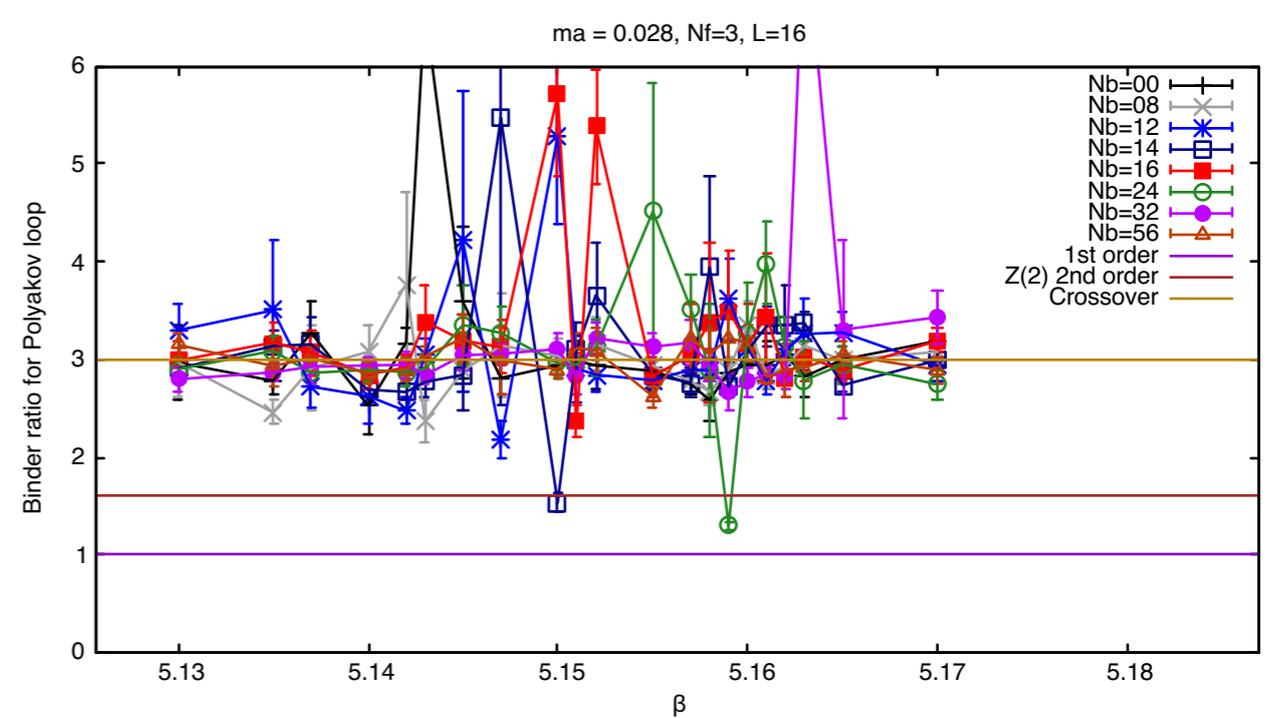
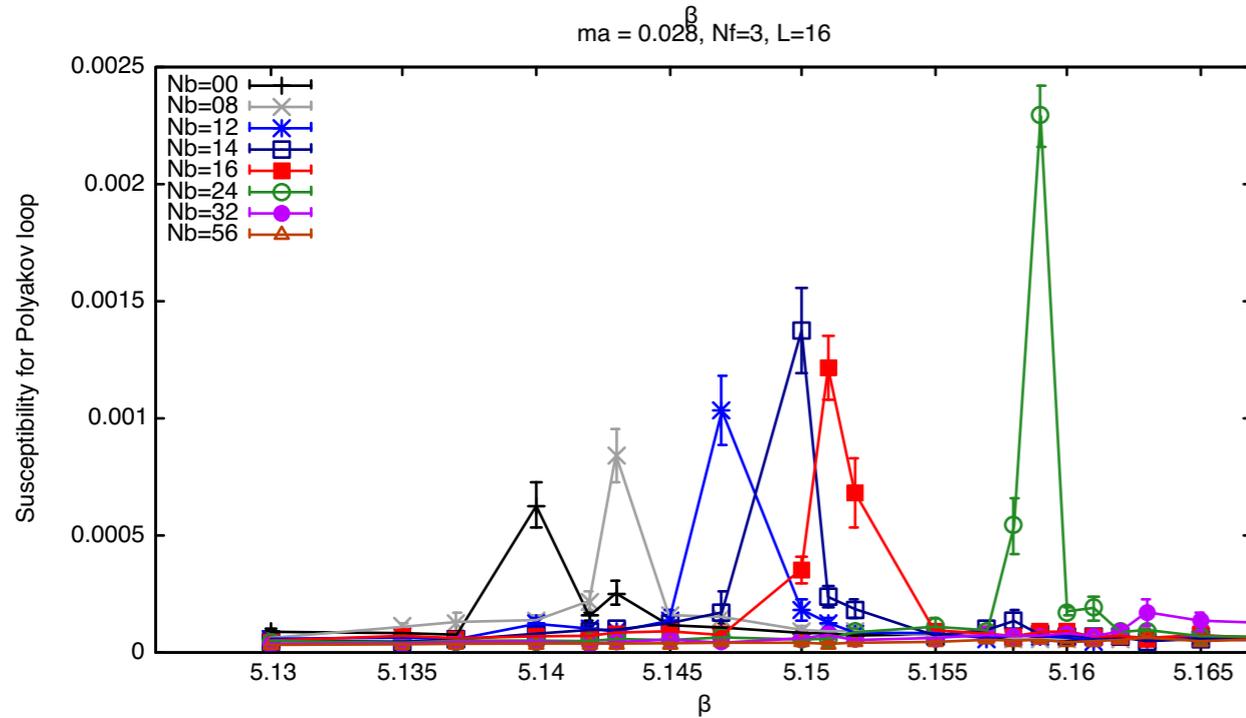
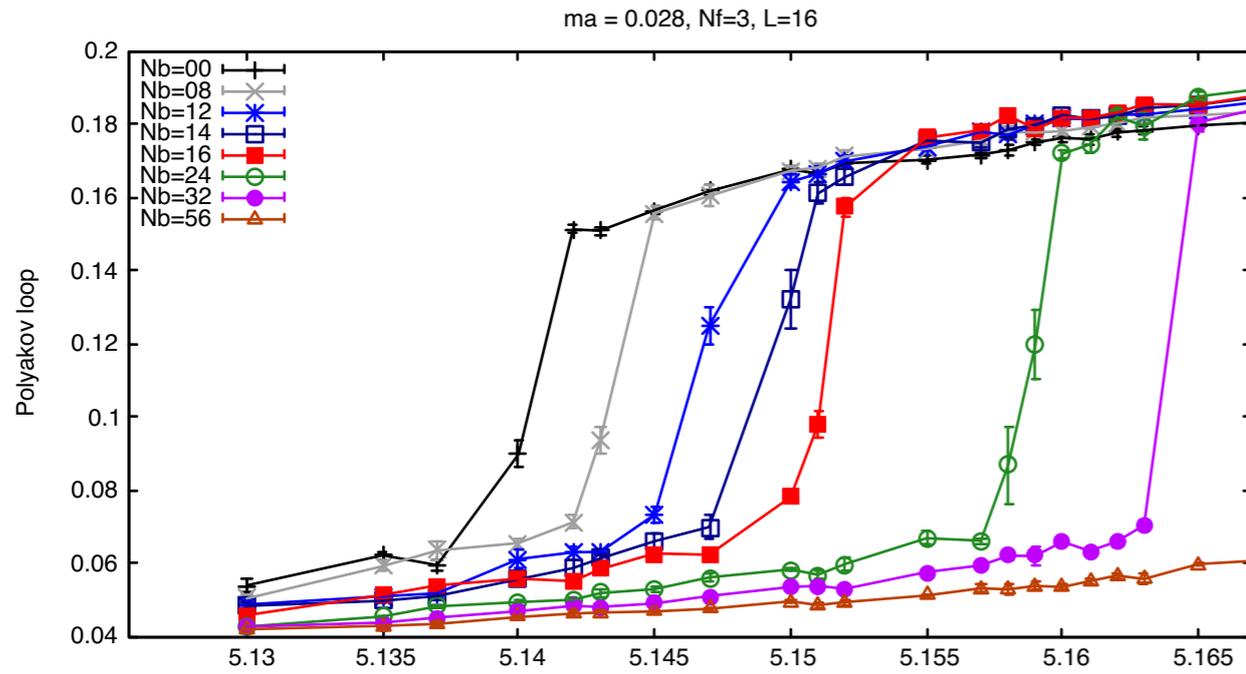


# ma = 0.028(crossover for Nb=0) Up quark condensates



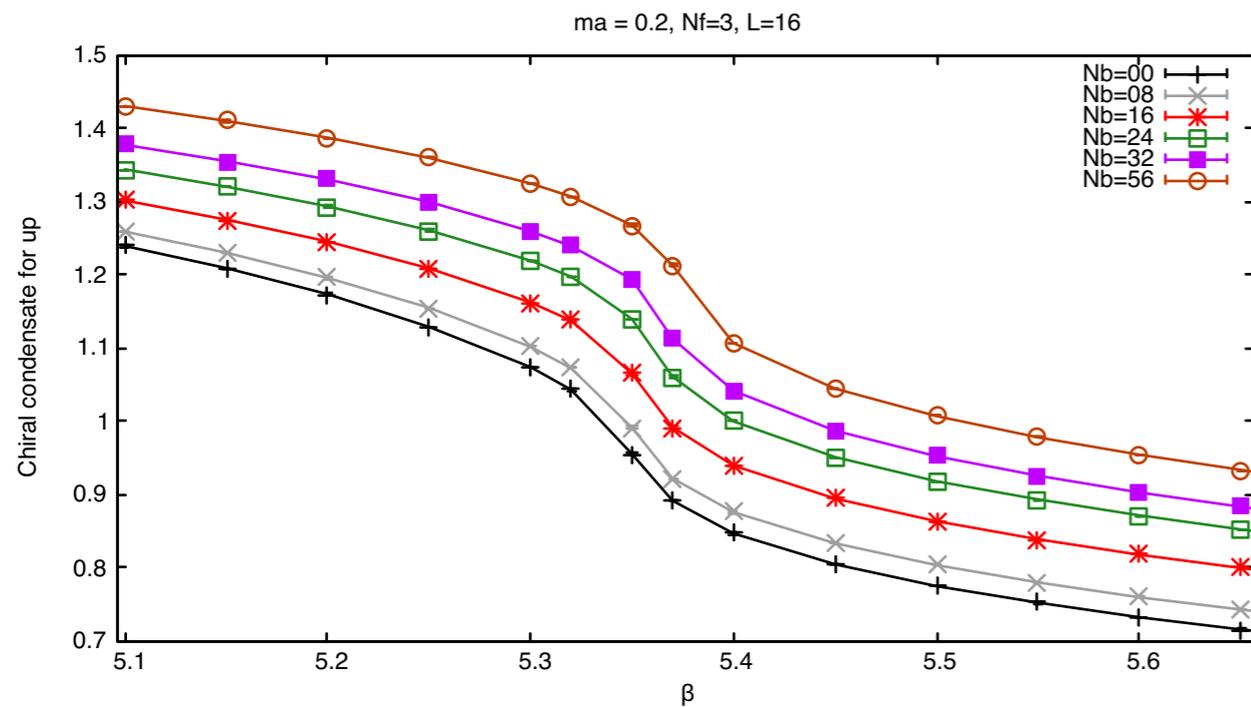
Nb=14 is "critical" eB\*

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

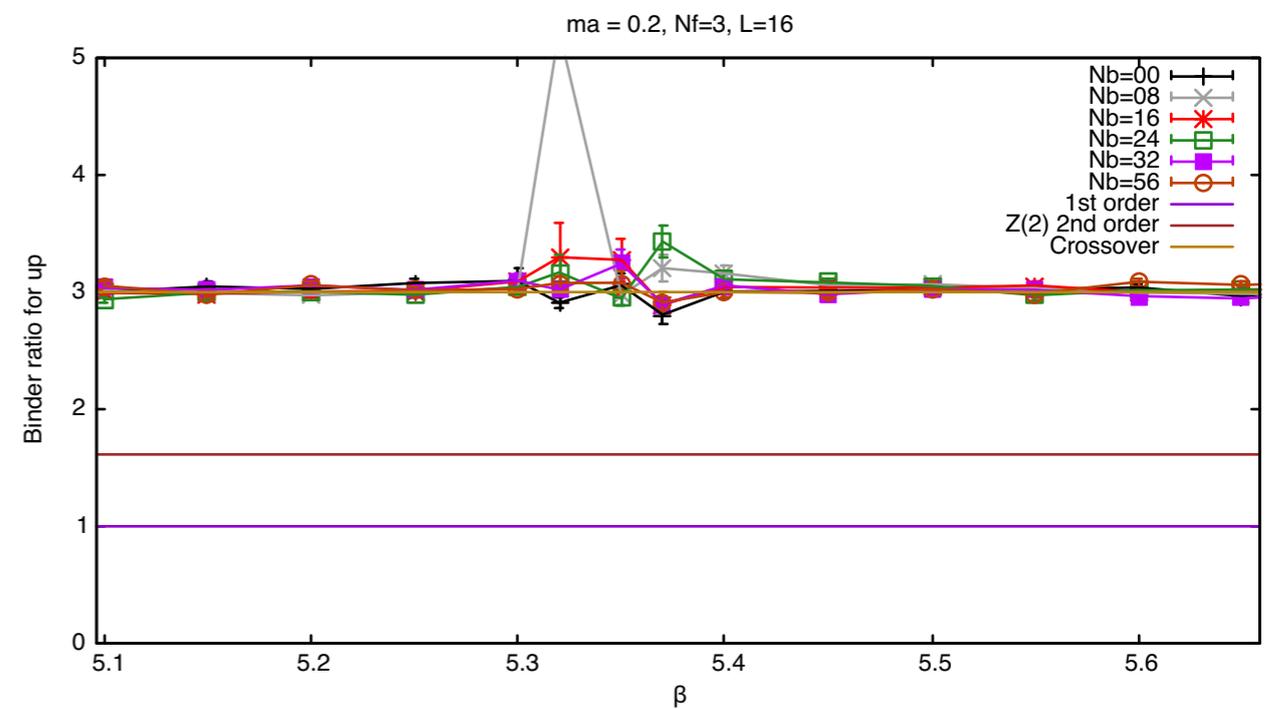
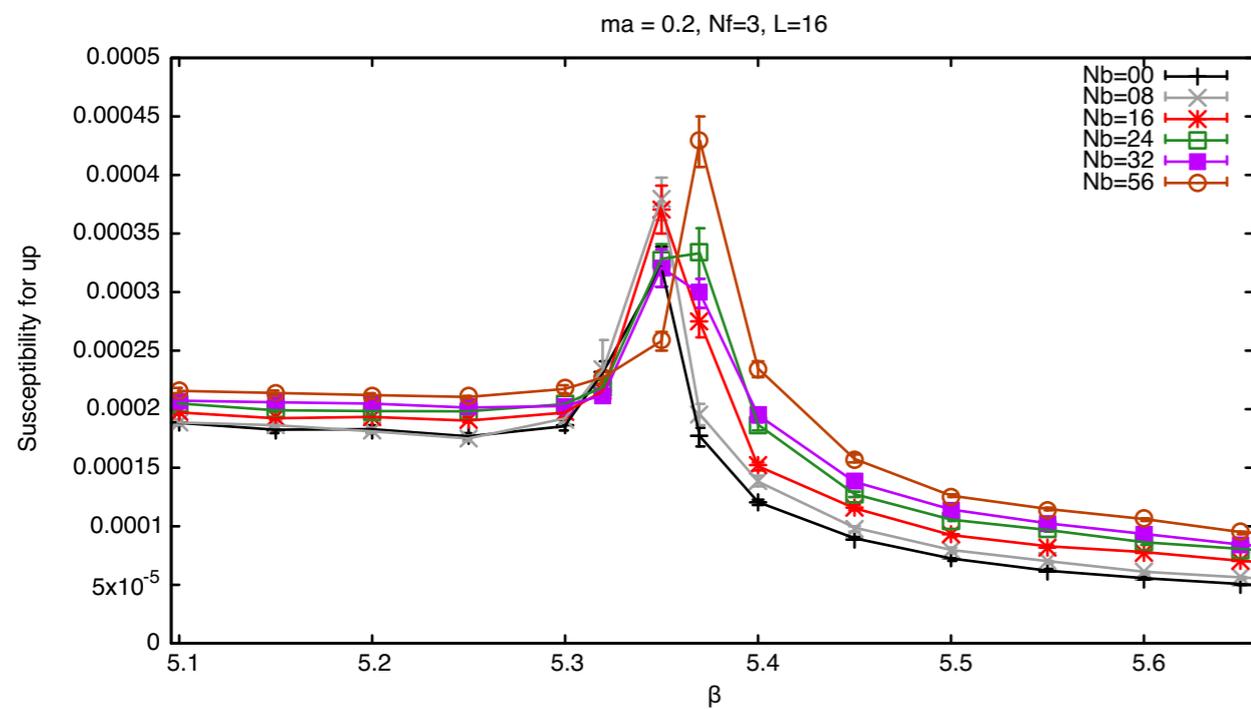


Nb=14 is critical eB\*

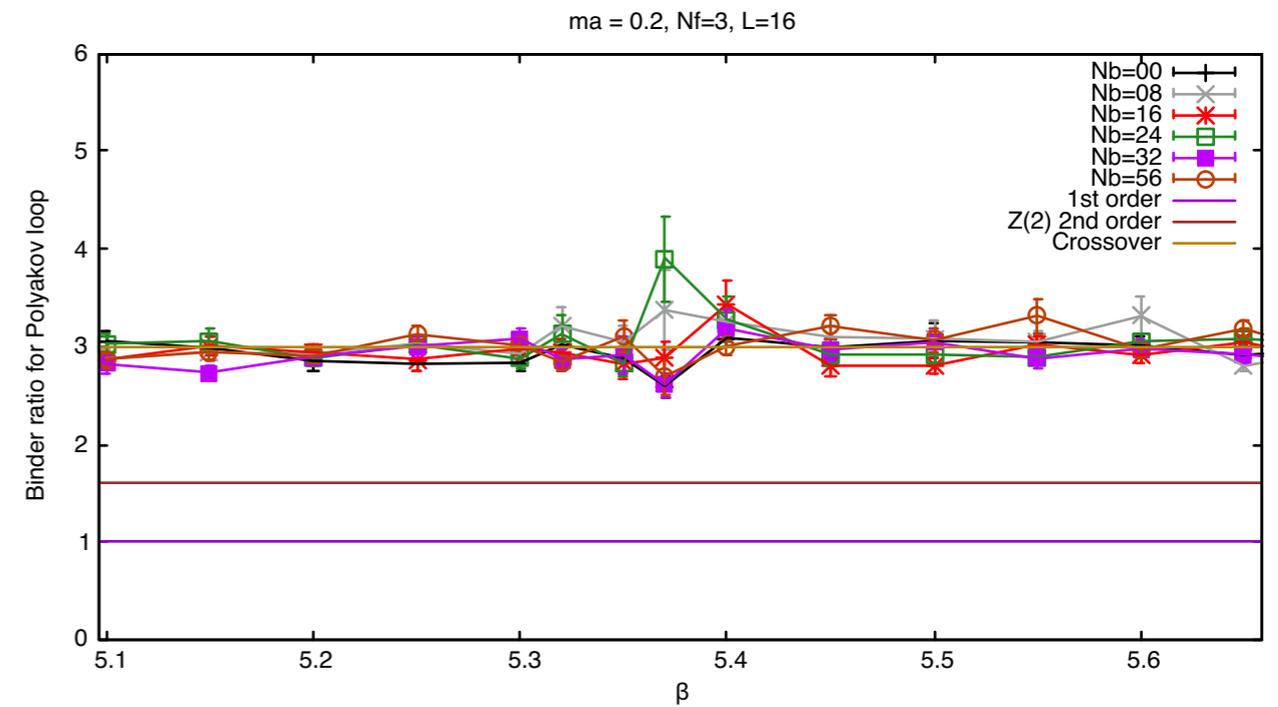
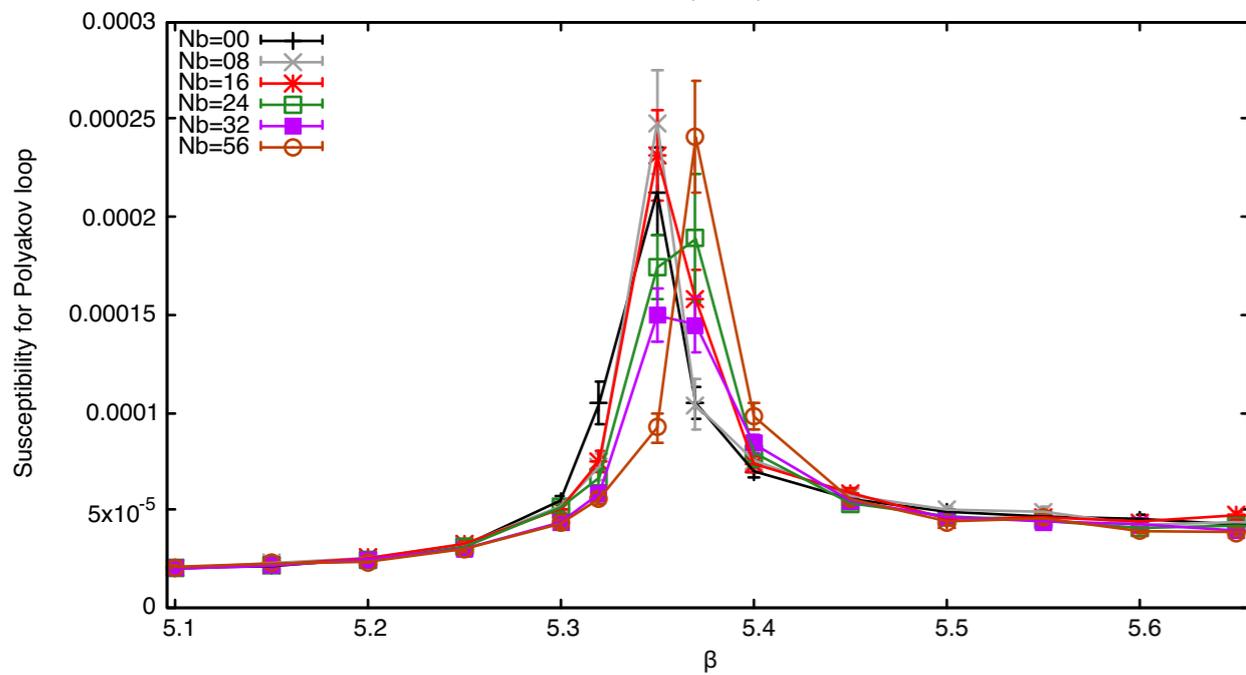
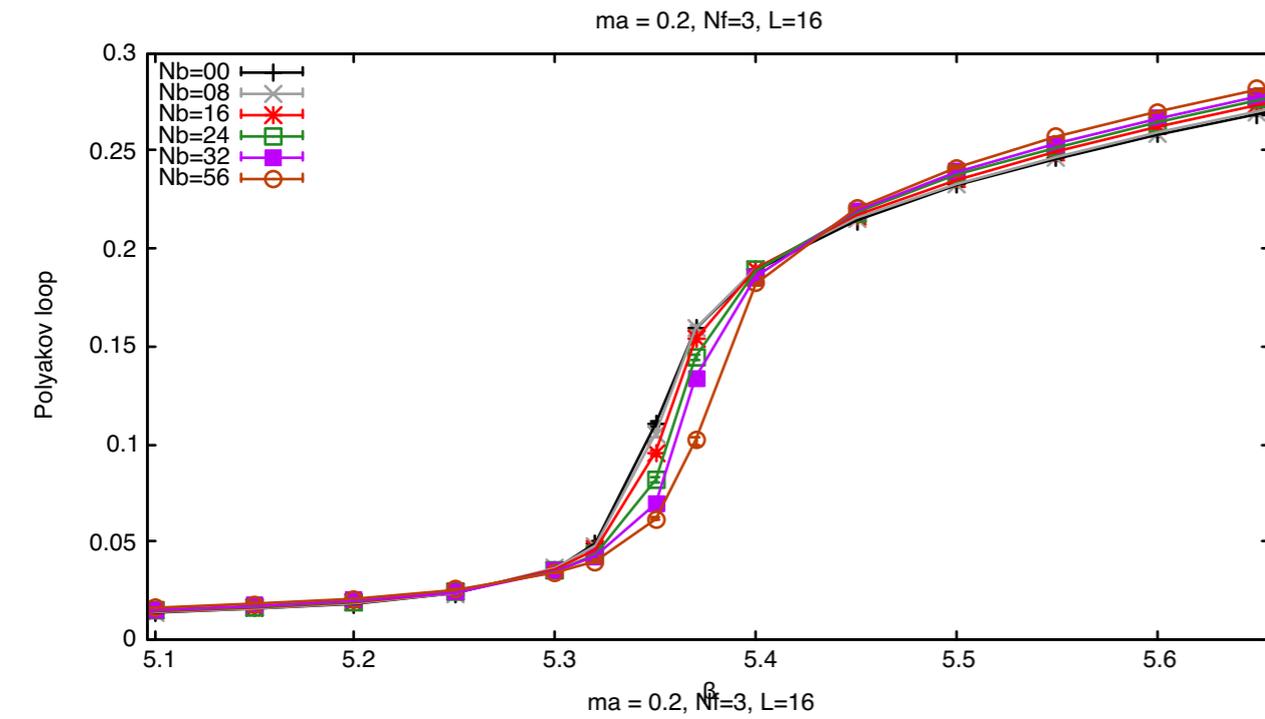
# ma = 0.2(crossover for Nb=0) Up quark condensate



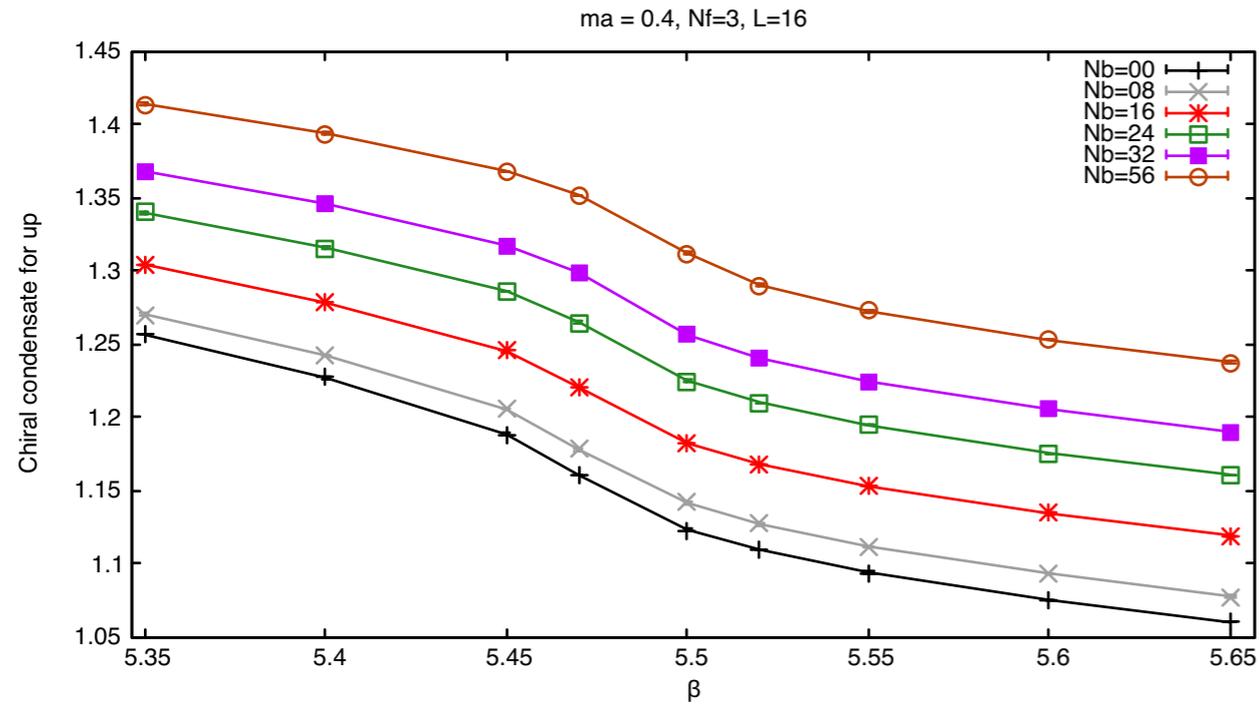
No criticality



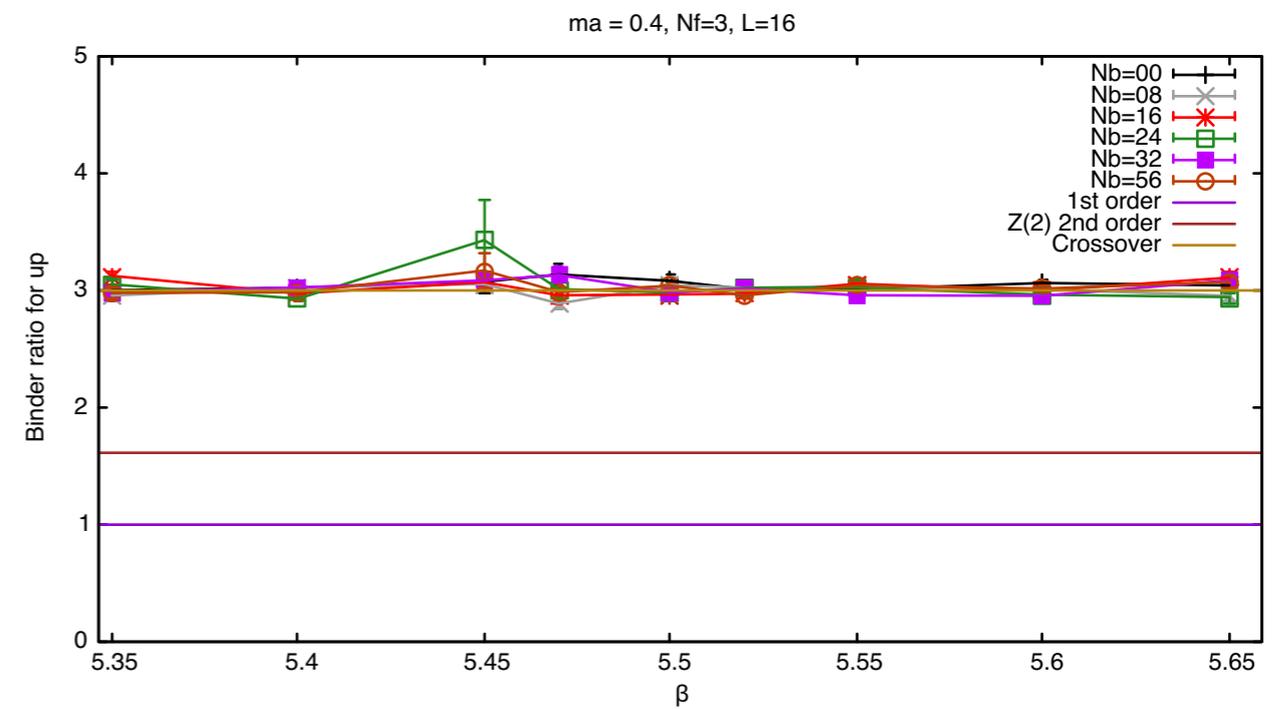
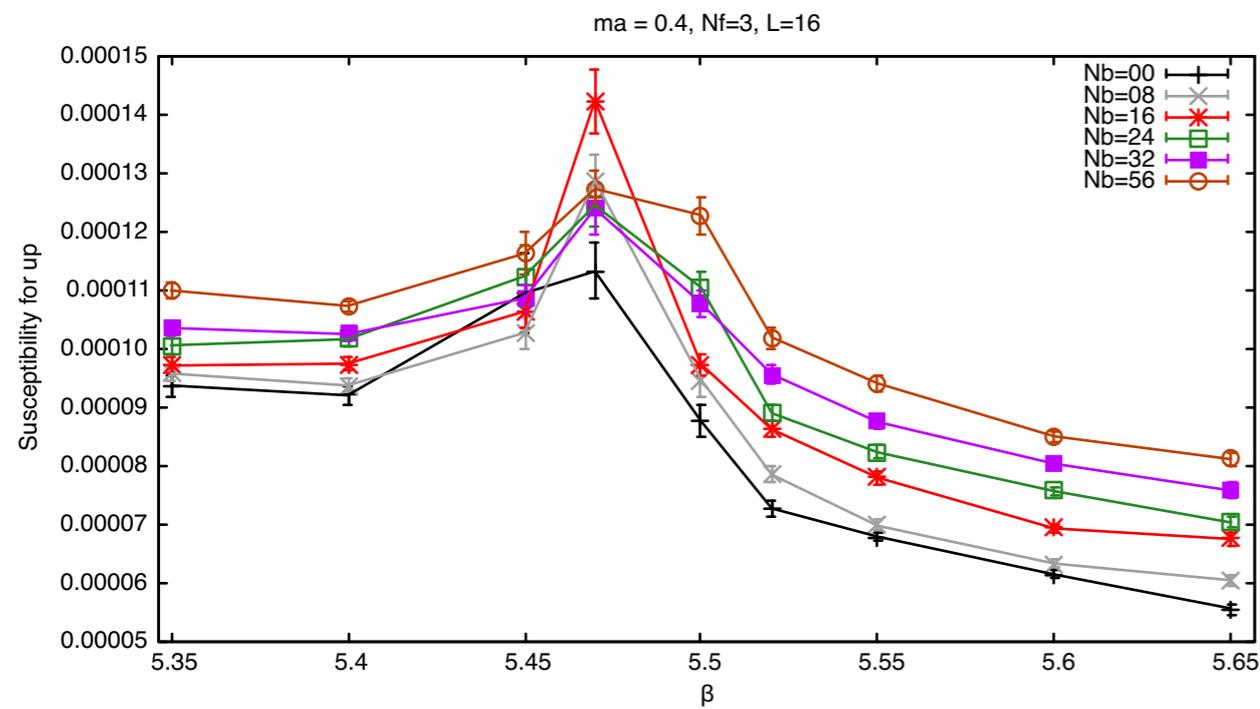
# ma = 0.2(crossover for Nb=0) Polyakov loop



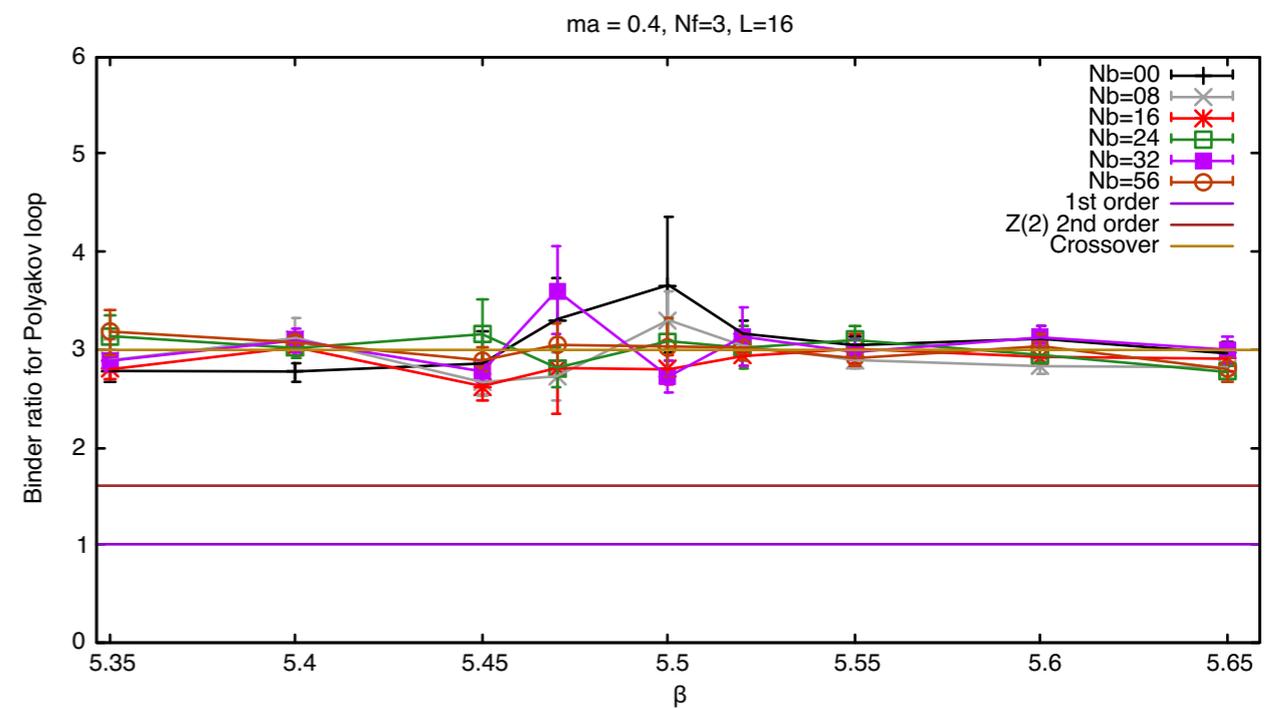
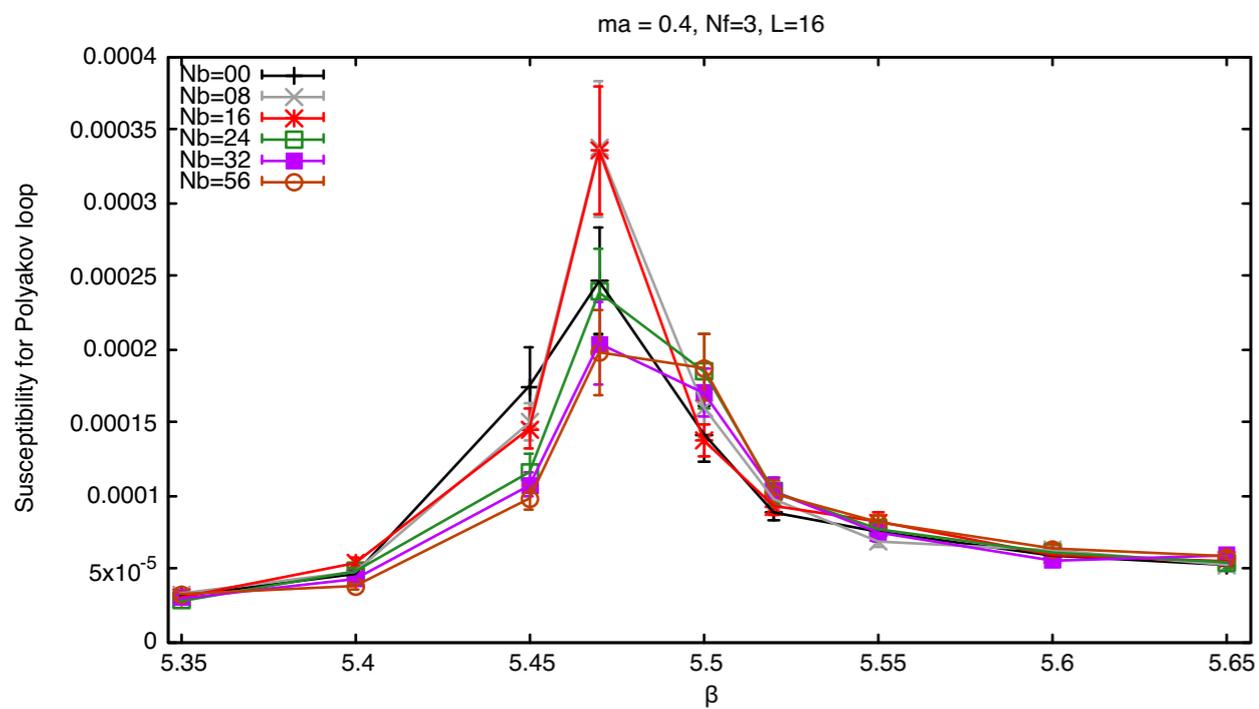
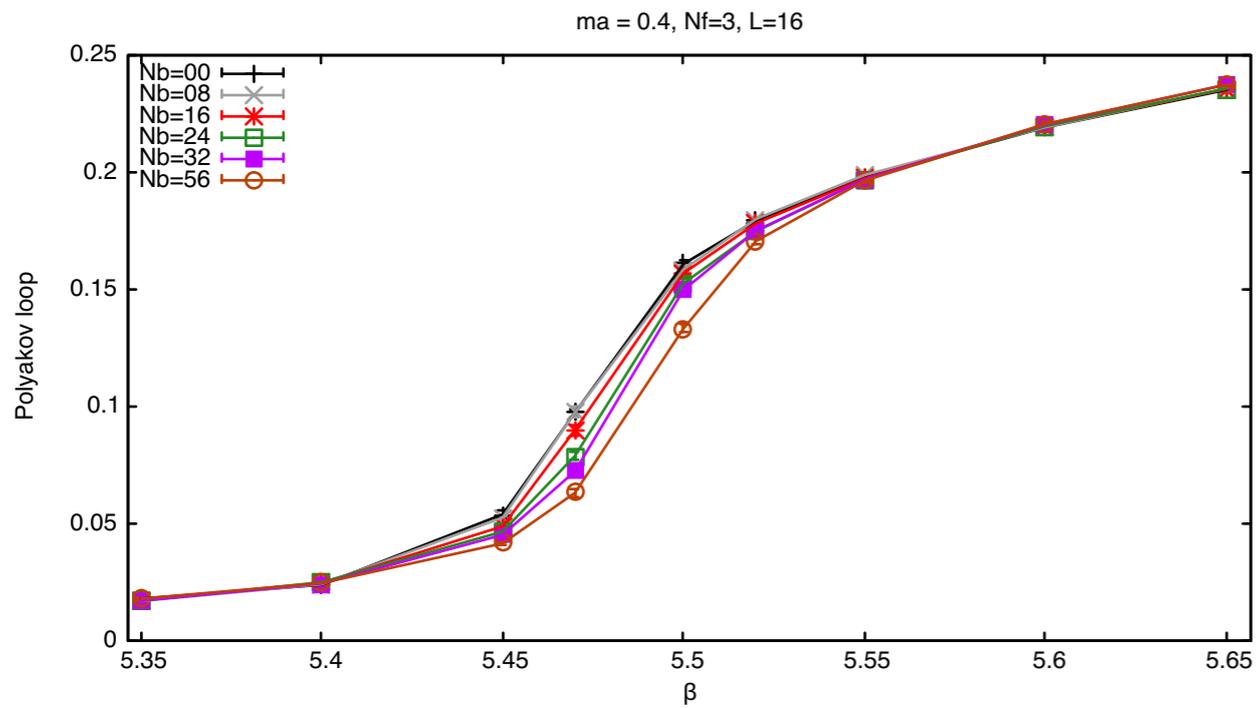
# ma = 0.4(crossover for Nb=0) Up quark condensate



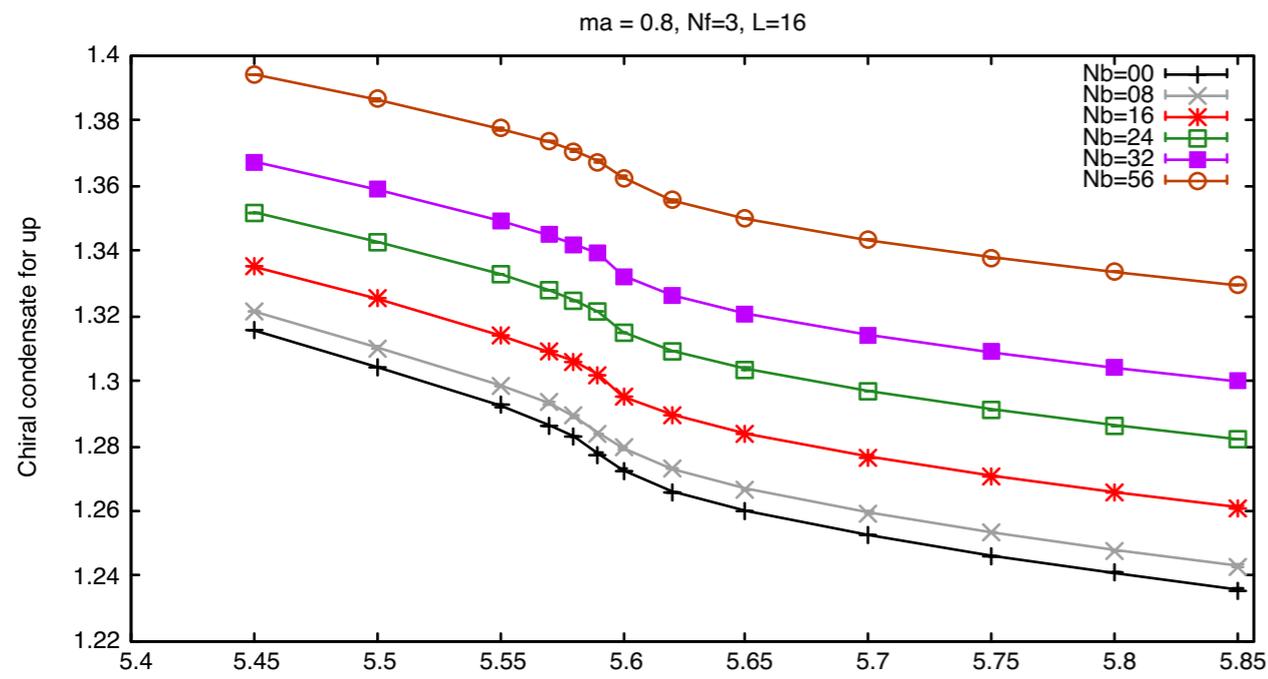
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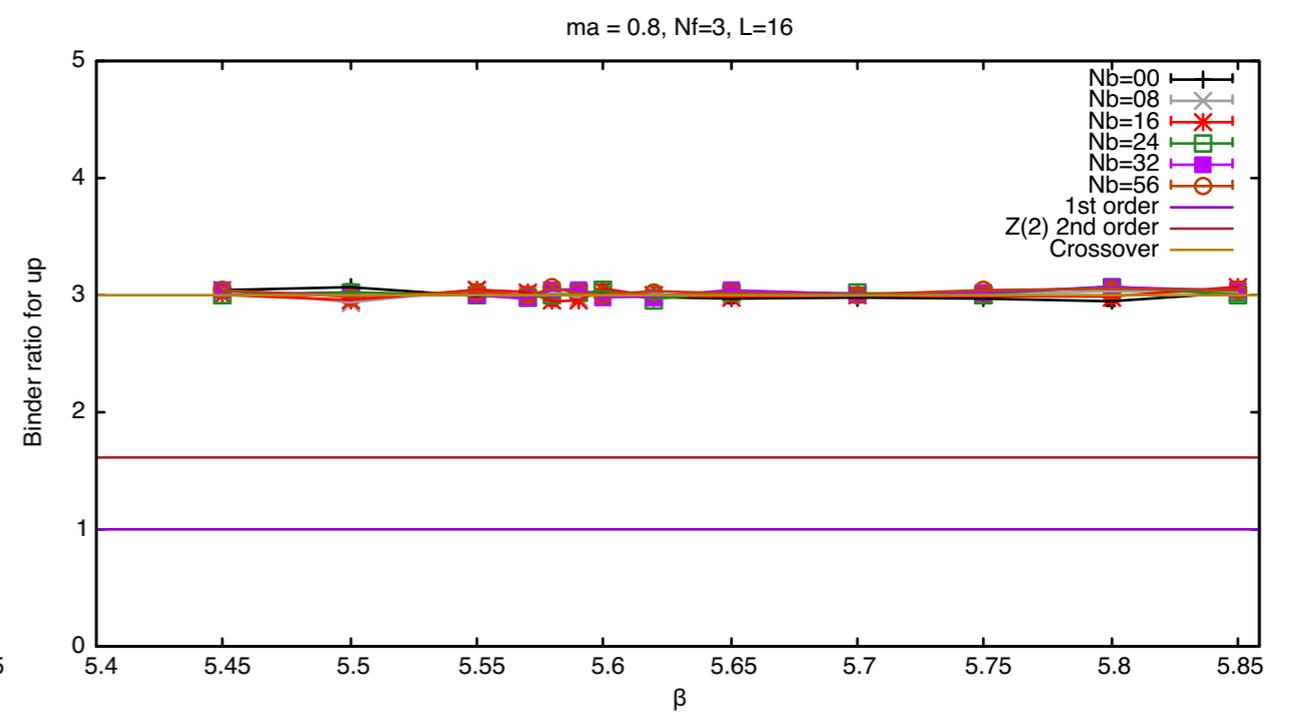
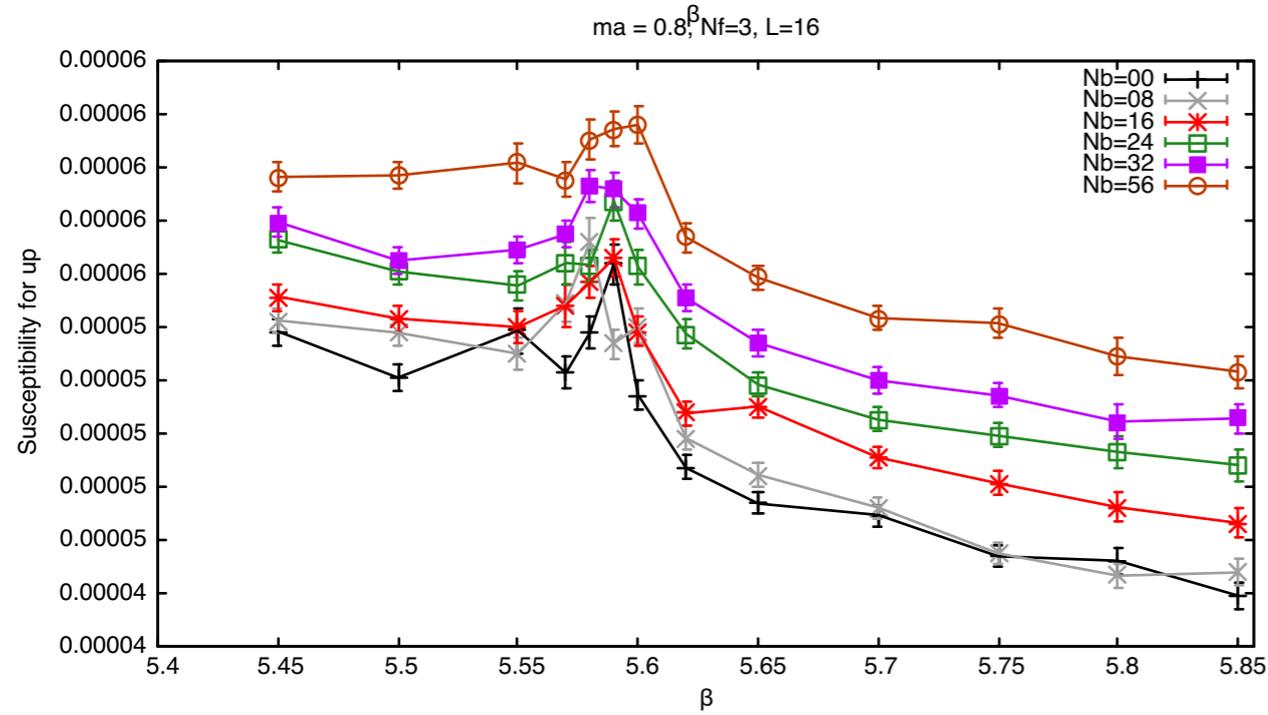
# ma = 0.4(crossover for Nb=0) Polyakov loop



# ma = 0.8 Up quark condensate



No criticality



# ma = 0.8 Polyakov loop

