

# Standard Model Baryon Number Violation at Zero Temperature from Higgs Bubble Collisions

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**Based on hep-ph/2508.21825**

Bhusal, Blasi, MC, Chatrchyan, Gorghetto, Servant

Very first computation of Chern-Simons (CS) variations at  $T=0$  from Higgs Bubble Collisions in a strongly First Order ElectroWeak Phase Transition (FOEWPT)

# Cold baryogenesis from Higgs Bubble Collisions:

(original Cold Baryogenesis by tachyonic instability in a quenched EW crossover)

Krauss, Trodden, Phys. Rev. Lett. 83 (1999) 1502  
 Garcia-Bellido, et al. Phys. Rev. D 60 (1999) 123504  
 E. J. Copeland, et al. Phys. Rev. D 64 (2001) 043506  
 Tranberg, Smit, JHEP 0311 (2003) 016

first idea of Cold Baryogenesis in a FOPT in

Konstandin, Servant, JCAP07(2011)024  
 Servant, Phys. Rev. Lett. 113, 171803 (2014)

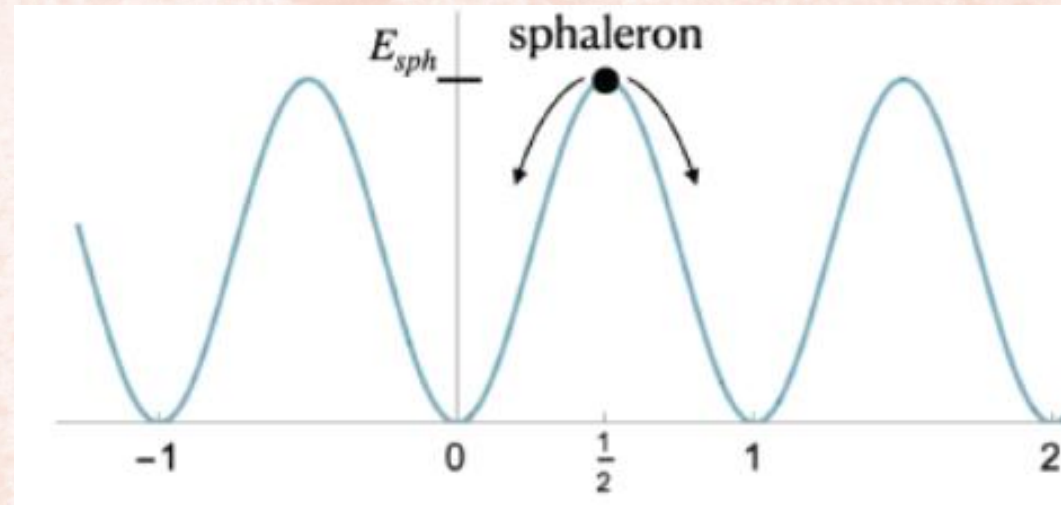
1) low temperature

thermal sphalerons suppressed  
 $T_{reh} < T_{f.o.} = 130 \text{ GeV}$



2) large bubble wall velocity

$$v_w > v_s$$



Chern-Simons number of the  $SU(2)$ -gauge fields:

$$N_{CS}(t) - N_{CS}(0) \equiv \frac{g^2}{16\pi^2} \int_0^t dt' \int d^3x \text{Tr}[W^{\mu\nu} \tilde{W}_{\mu\nu}]$$

$$\Delta B = 3 \Delta N_{CS}$$

→ It opens up a new parameter space where Standard ElectroWeak Baryogenesis via charge transport mechanism is *not* efficient



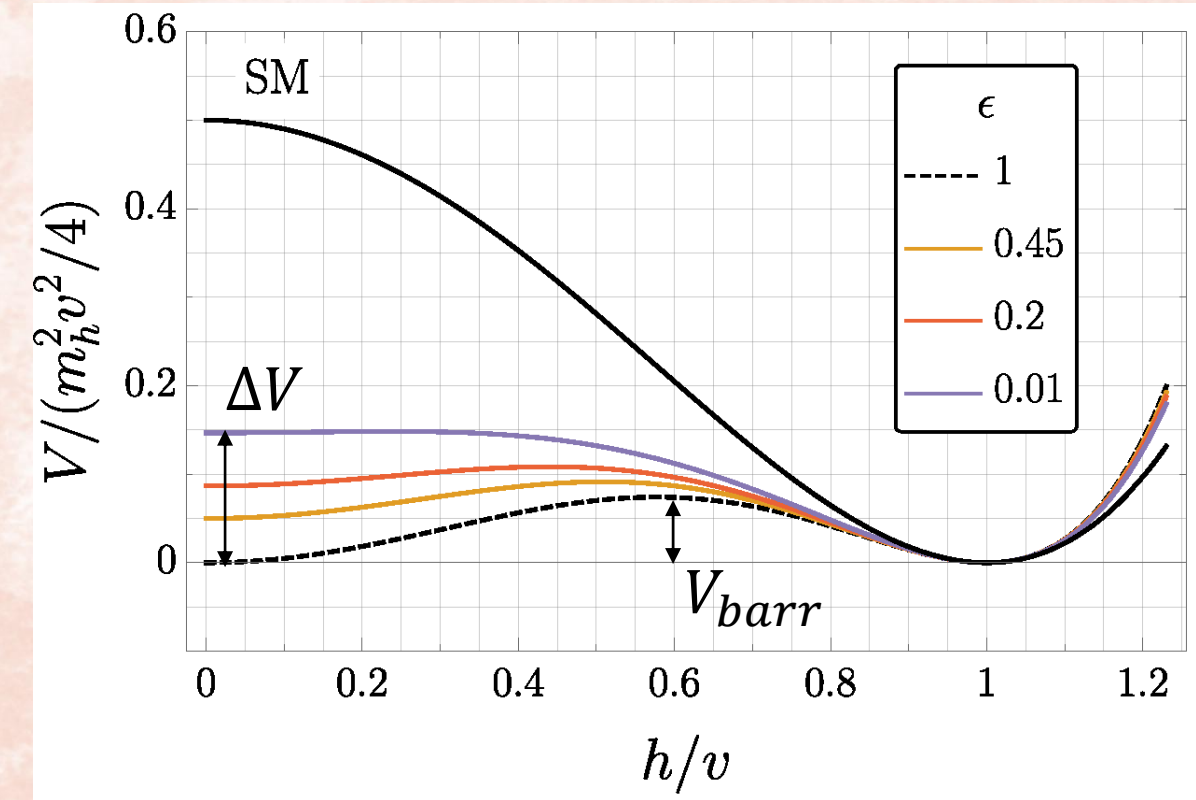
Study of dependence CS number transitions on:

1) Lorentz-boost factor of bubble walls at collision

$$\gamma_{\star} = \frac{R_{\star}}{R_c}$$

2) Higgs potential's shape, i.e. degeneracy parameter

$$\epsilon = \frac{V_{barr}}{V_{barr} + |\Delta V|} \in (0,1)$$





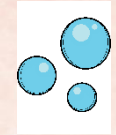
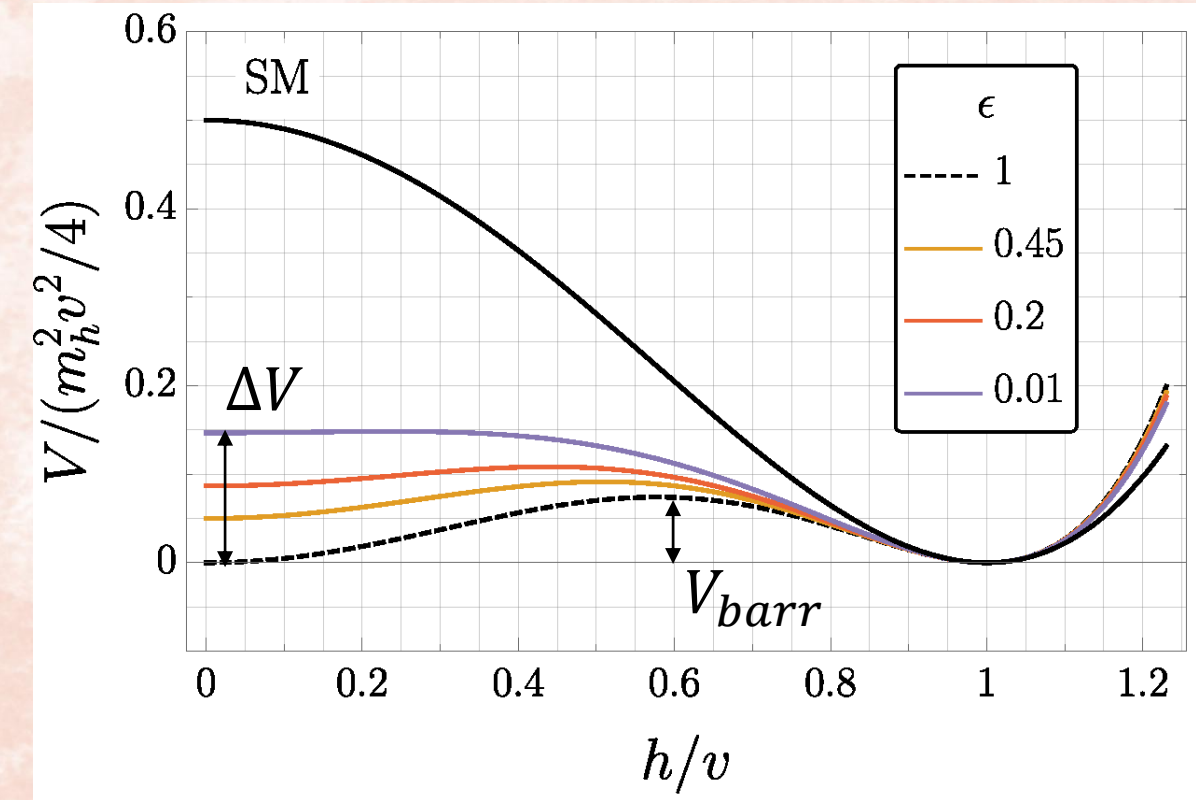
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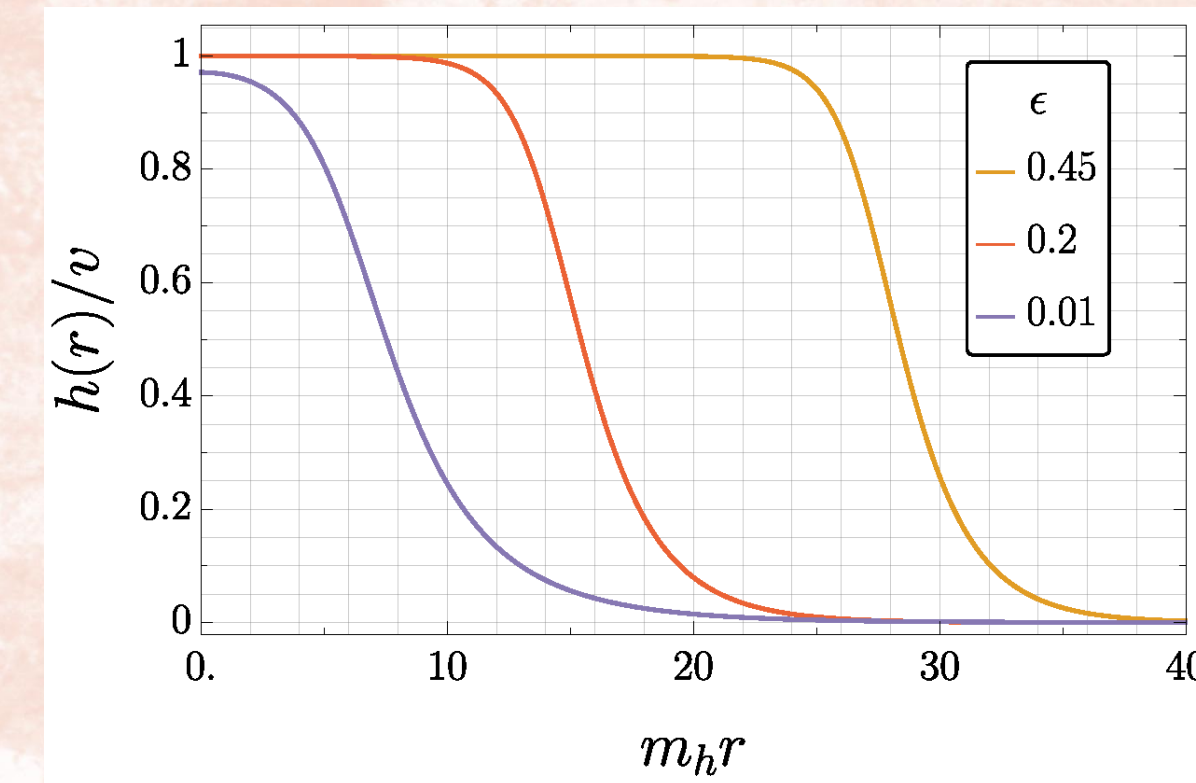
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Via large-scale (3+1)D lattice simulations of Higgs doublet and  $SU(2)$ -gauge fields

Runaway critical Higgs bubbles nucleated simultaneously with random positions and  $SU(2)$ -phase orientations

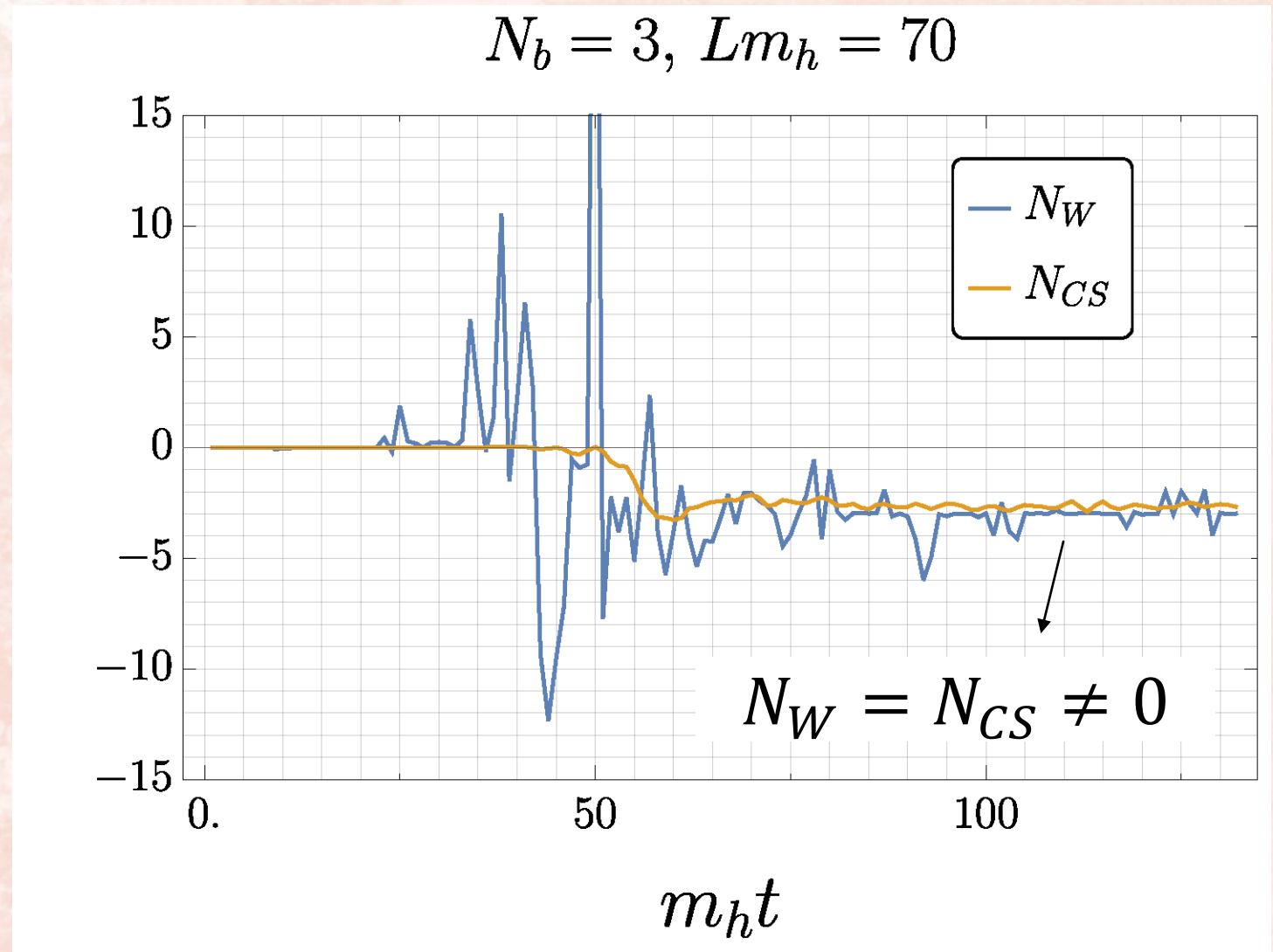


Higgs bubble collisions induce Higgs field inhomogeneities due to different  $SU(2)$  orientations

Production and decay of  $SU(2)$ -gauge textures, non-trivial Higgs configurations labeled by the winding number

$$N_W = \frac{1}{24 \pi^2} \int d^3x \epsilon_{ijk} \text{Tr}[(\partial_i U)U^\dagger(\partial_j U)U^\dagger(\partial_k U)U^\dagger]$$

$$U = \frac{(i \sigma^2 \phi^*, \phi)}{\phi^\dagger \phi} \in SU(2)$$



Non-zero Chern-Simons rate

$$\Gamma_{CS} = \frac{1}{L^3} \frac{d\Delta N_{CS}^2(t)}{dt}$$

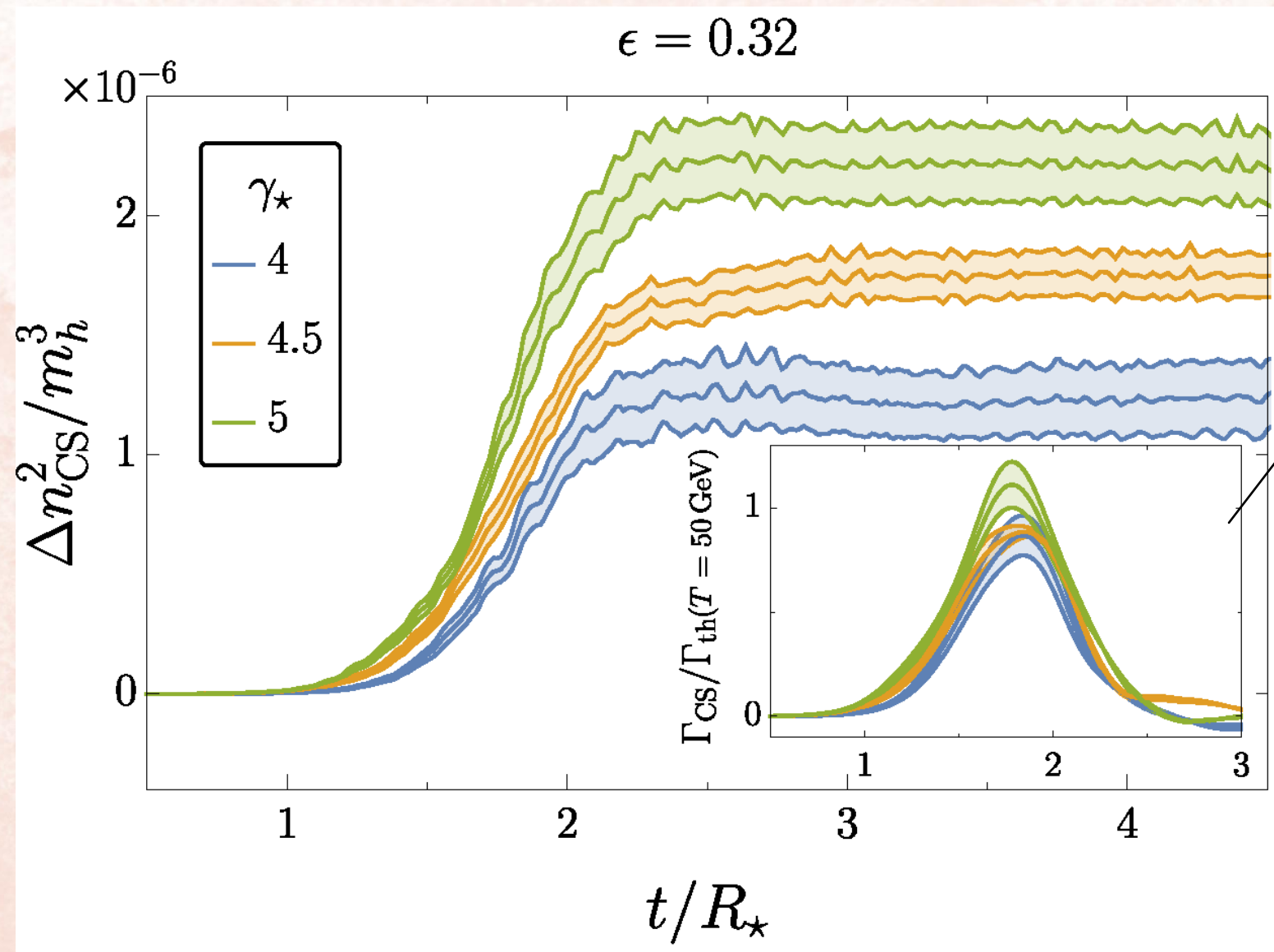
with Chern-Simons variance (averaged over many realizations)

$$\Delta N_{CS}^2(t) \equiv \langle N_{CS}(t)^2 \rangle - \langle N_{CS}(t) \rangle^2$$

Note:  $CP$ -violation is not included in our simulations

$$\langle N_{CS} \rangle = 0$$

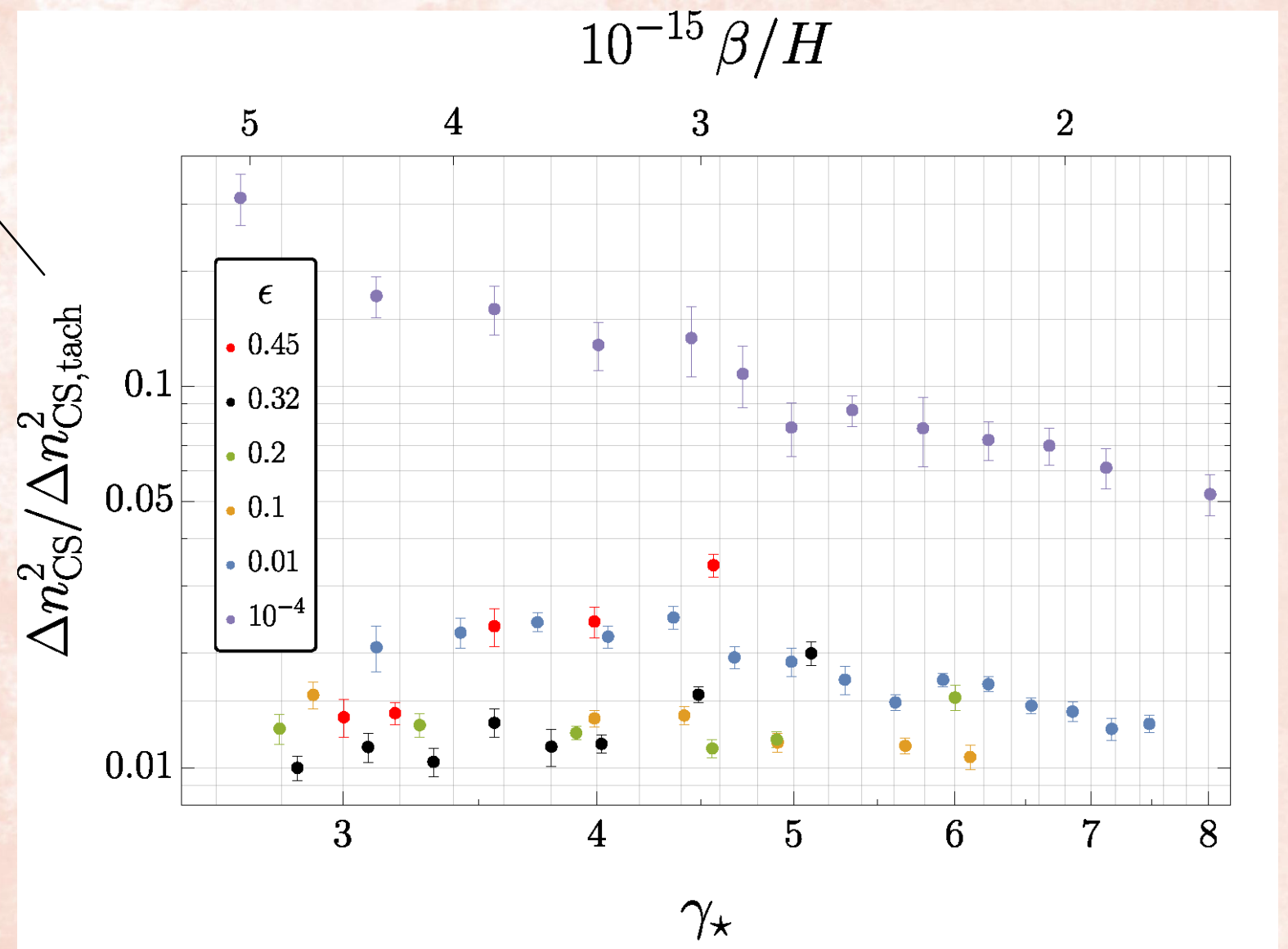
See <https://www.youtube.com/watch?v=LhZFCxJ5-4g> for an animation!



$$\Delta n_{CS,tach}^2 = 10^{-4} m_h^3$$

$$\Gamma_{th} \sim 25 \alpha_w^5 T^4$$

D'Onofrio, et al., Phys. Rev. Lett. 113, 141602 (2014)



Given the parametrization  $\Delta n_{CS}^2 \propto \gamma_*^a$  (thus  $\Gamma_{CS} \propto \gamma_*^{a-1}$ ),

for large  $\epsilon > 0.2$  constant or increasing CS variance in the physical limit  $\gamma_* \rightarrow \infty$

$$a > 0$$

Note: clearer hint for linear dependence, i.e.  $a = 1$ , in the (1+1)D case with  $U(1)$ -gauge field!

- Sizable baryon number production at large  $\epsilon$
- Same order of magnitude as thermal sphaleron rate in the symmetric phase at electroweak temperatures

# Summary

 Very first computation of SM Baryon Number Violation at Zero Temperature from Higgs Bubble Collisions in a strongly First Order ElectroWeak Phase Transition

 New ElectroWeak Baryogenesis mechanism for FOEWPT with:      1) low reheat temperature  
2) large bubble wall velocity

 CS production strongly depends on Higgs potential's shape, controlled by degeneracy parameter  $\epsilon$

 For large  $\epsilon > 0.2$ , *non-decreasing* CS variance with bubble wall Lorentz-factor at collision  $\gamma_*$

Sizable baryon number production, potentially leading to correct baryon asymmetry e.g with *CP*-violating source

$\mathcal{O} = \frac{g^2}{32\pi^2\Lambda^2} \phi^\dagger \phi W_{\mu\nu}^a W^{\mu\nu a}$  Next: include numerically *CP*-violation.

And more details in [2508.21825](#)

Check out  
the paper!

# Backup – (3+1)D simulations

→ Extensive lattice implementation of Higgs doublet and  $SU(2)$ -gauge fields and critical bubble profile

$$\mathcal{L} \sim \text{Tr}[F_{\mu\nu}F^{\mu\nu}] + |D_\mu \mathcal{H}|^2 - V(h)$$

w/ toy potential

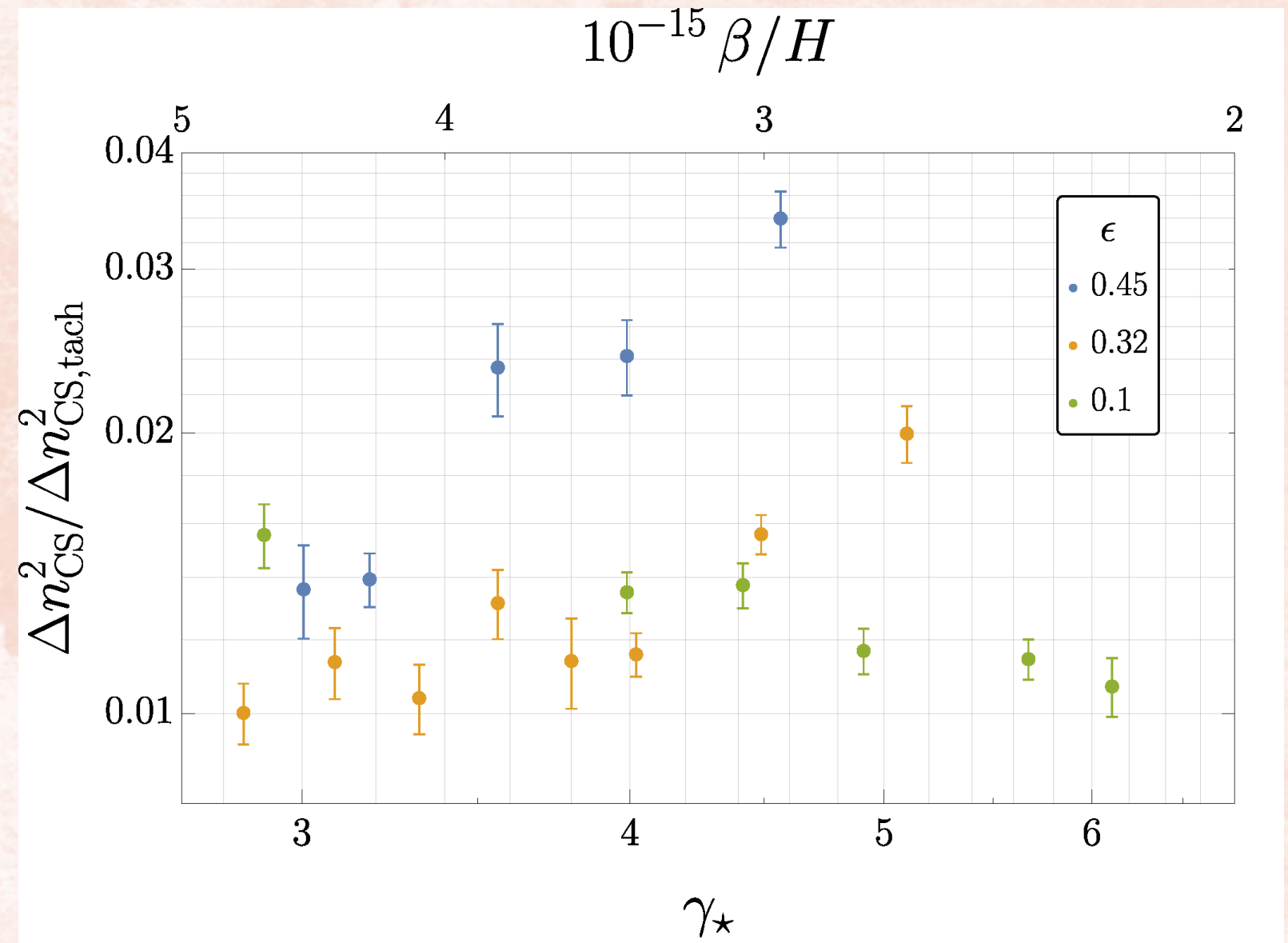
$$V = \frac{1}{2}\mu^2 h^2 - \frac{1}{4}\lambda h^4 + \frac{1}{8\Lambda^2}h^6$$

→ 
$$\gamma_w^* \sim \frac{R_*}{R_c} \sim \frac{Lm_H}{R_c m_H} \frac{\sqrt{3}}{2} \left( \frac{3}{4\pi n_b} \right)^{1/3}$$

→ Sphaleron rate in the symmetric phase:  $\Gamma_{th} \sim 25 \alpha_w^5 T^4$

→ Effective sphaleron rate in a quenched EW crossover (tachyonic instability):  $\Gamma_{tach} = \alpha_w^4 T_{eff}^4$

with CS variance for instantaneous quench  $\Delta n_{CS,tach}^2 = 10^{-4} m_h^3$



## Backup - Dependence of CS variance on $\epsilon$ : (1+1)D case with $U(1)$ -gauge field

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_{\mu}\psi|^2 - V(\psi), \quad D_{\mu}\psi = \partial_{\mu}\psi - igA_{\mu}\psi,$$

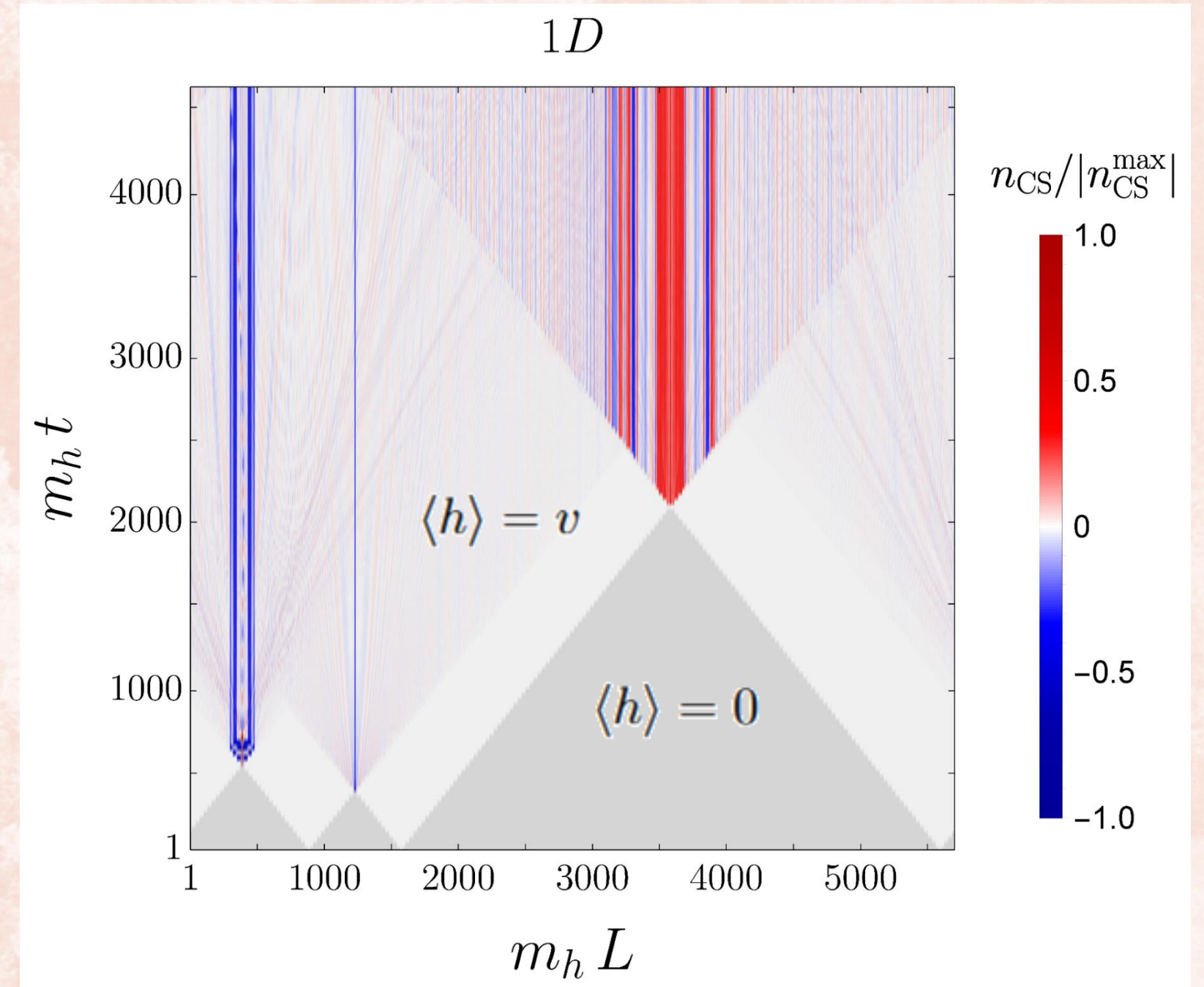
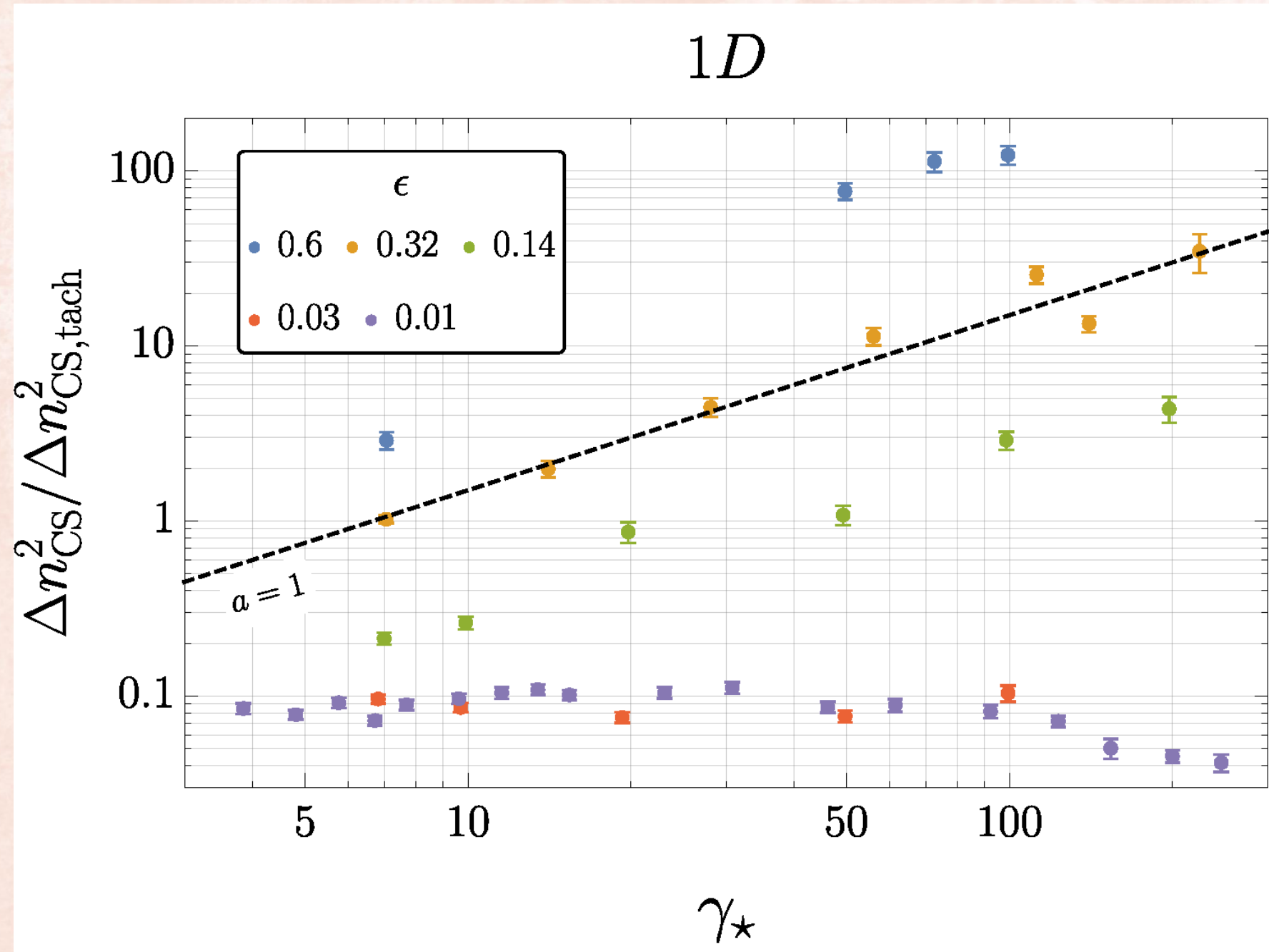
$$N_W = 1/(2\pi) \int dx \partial_x \text{Arg}[\psi]$$

$$N_{CS} = g/(2\pi) \int dx A_1$$

# Backup - Dependence of CS variance on $\epsilon$ : (1+1)D case with $U(1)$ -gauge field

Probe larger  $\epsilon$  and  $\gamma_*$

$\epsilon = 0.32$



→ CS production changes behavior

For  $\epsilon \sim 0.1$

# Backup – CS Spectra

