Electroweak Baryogenesis and Sphaleron at LHC

Eibun Senaha (National Taiwan U)
Jan. 11, 2017@U of Tokyo

based on

[1] C.-W. Chiang (Natl Taiwan U), K. Fuyuto (UMass-Amherst), E.S., 1607.07316 [PLB]

[2] K. Funakubo (Saga U), K. Fuyuto, E.S., 1612.05431

Outline

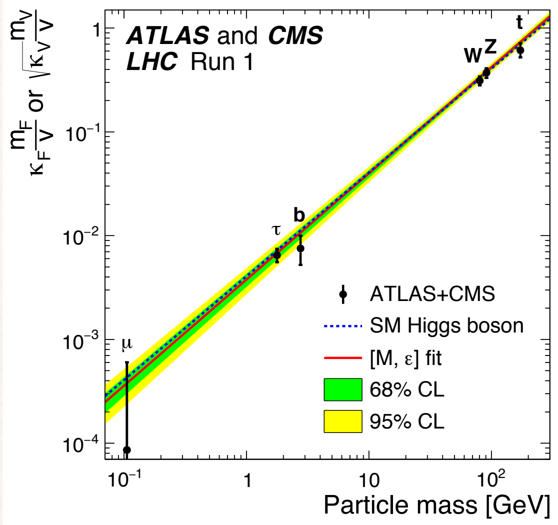
- Motivation
- Electroweak baryogenesis (EWBG) in a nutshell
- EWBG with lepton flavor violation
- Does a band structure affect (B+L)-changing processes?
  - (B+L)-changing process in high-E collisions
  - (B+L)-changing process at high-T
- Summary

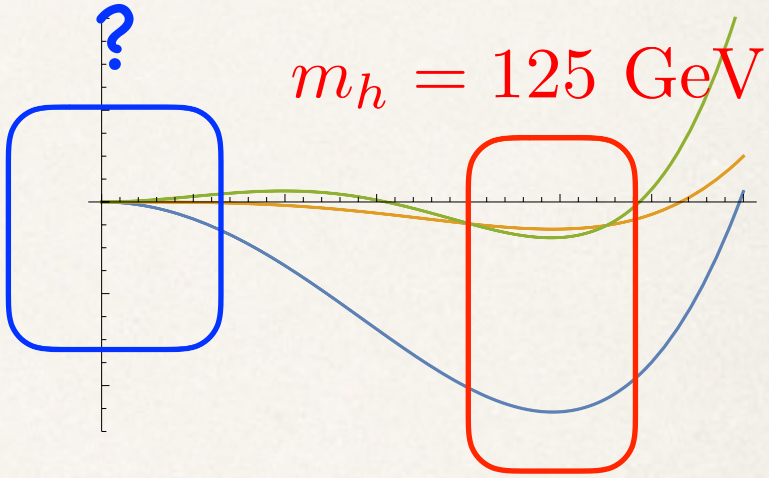
Introduction

problems after the Higgs discovery

Does the 125 GeV boson alone do the following jobs?

- mass generation
- EW symmetry breaking





Experiments will answer those grand questions in the near future.

Most importantly, those experiments may also shed light on unsolved problems.

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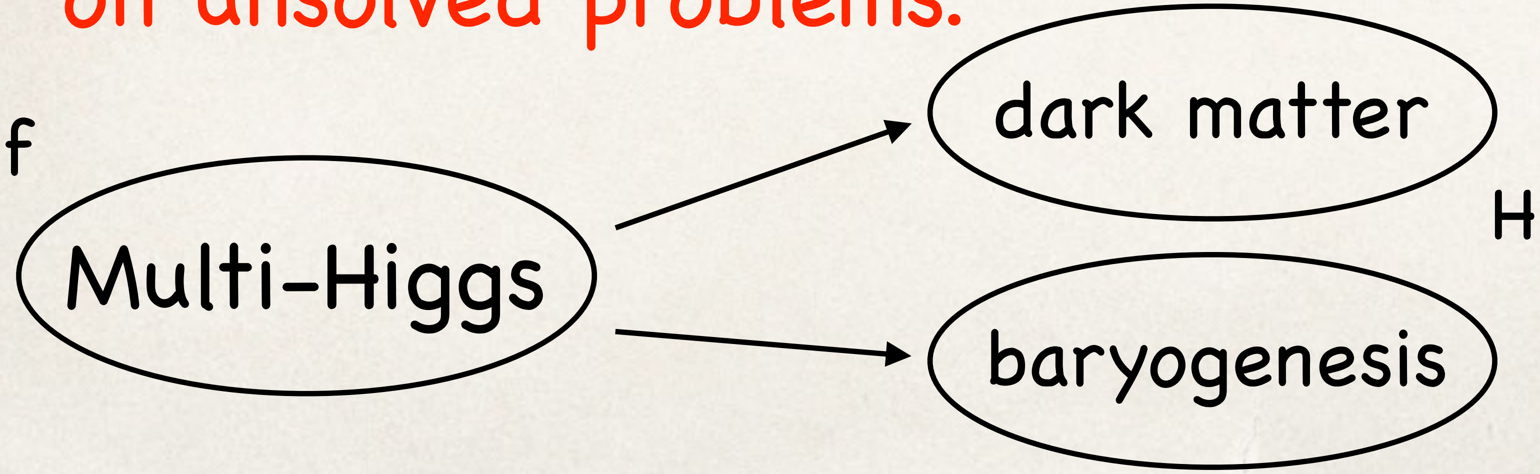

Higgs is a window to new physics.

Let us open the window!!

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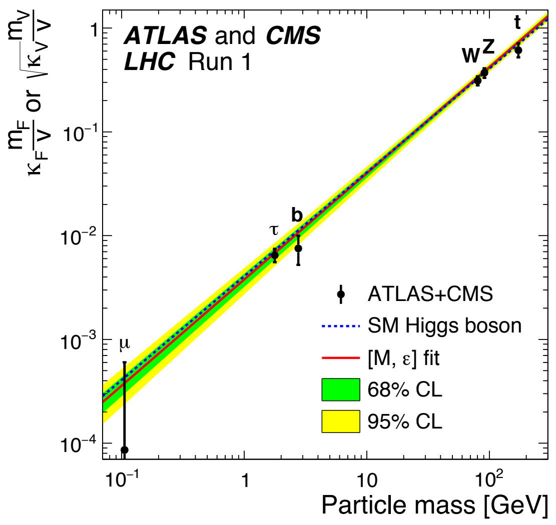

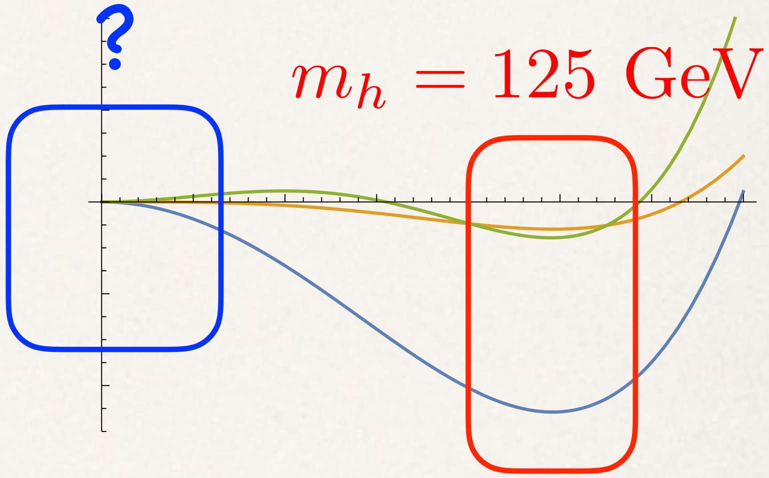

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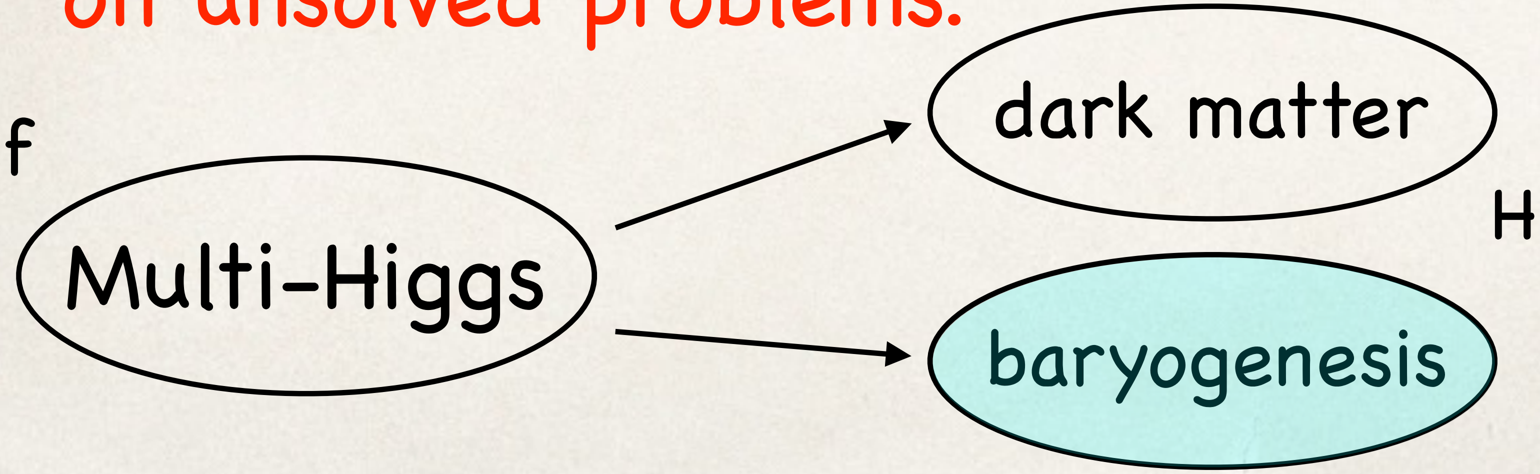

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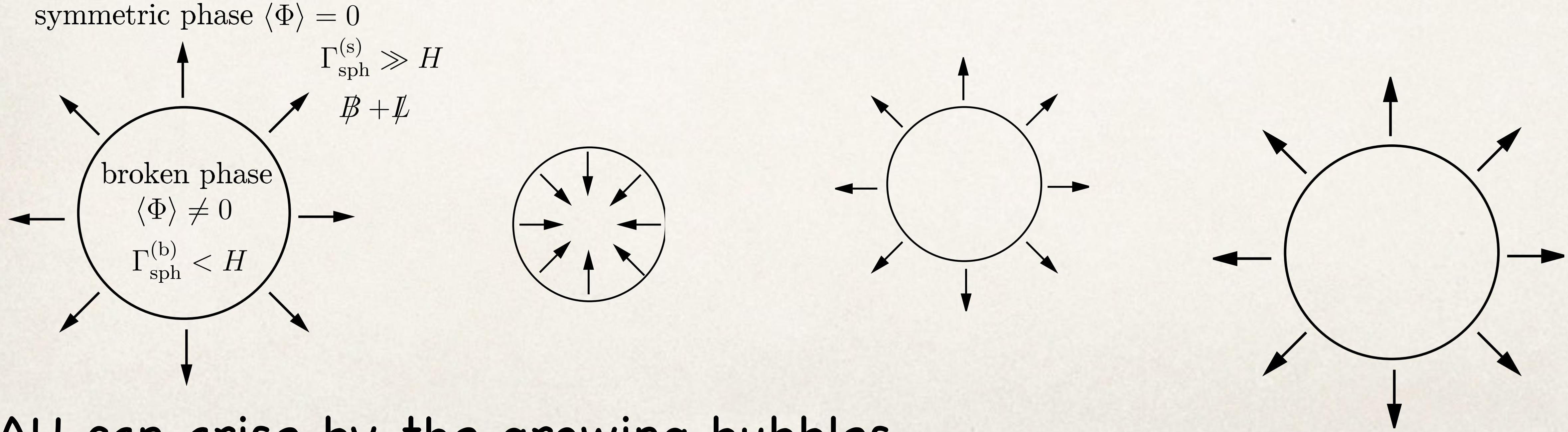
Electroweak baryogenesis

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 (‘85)]

Sakharov’s conditions

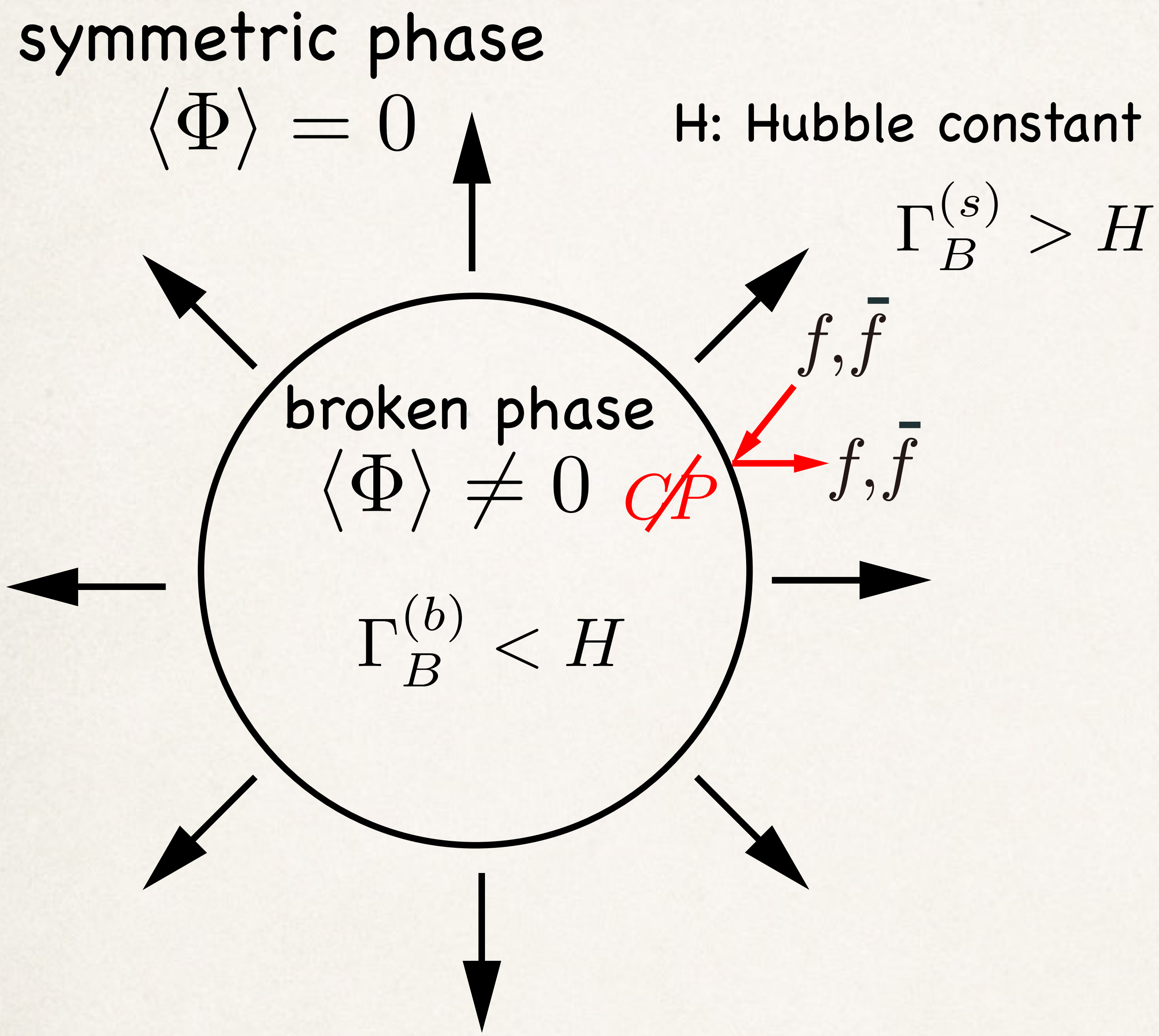
- B violation: anomalous (sphaleron) process $0 \leftrightarrow \sum_{i=1,2,3} (3q_L^i + l_L^i)$ (LH fermions)
- C violation: chiral gauge interaction
- CP violation: KM phase and/or other sources in beyond the SM
- Out of equilibrium: 1st order EW phase transition (EWPT) with expanding bubble walls



BAU can arise by the growing bubbles.

EWBG in a nutshell

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]



symmetric phase

$\langle\Phi\rangle = 0$

H: Hubble constant

$\Gamma_B^{(s)} > H$

$f, \bar{f}$

$f, \bar{f}$

broken phase

$\langle\Phi\rangle \neq 0$ $\not{C}\not{P}$

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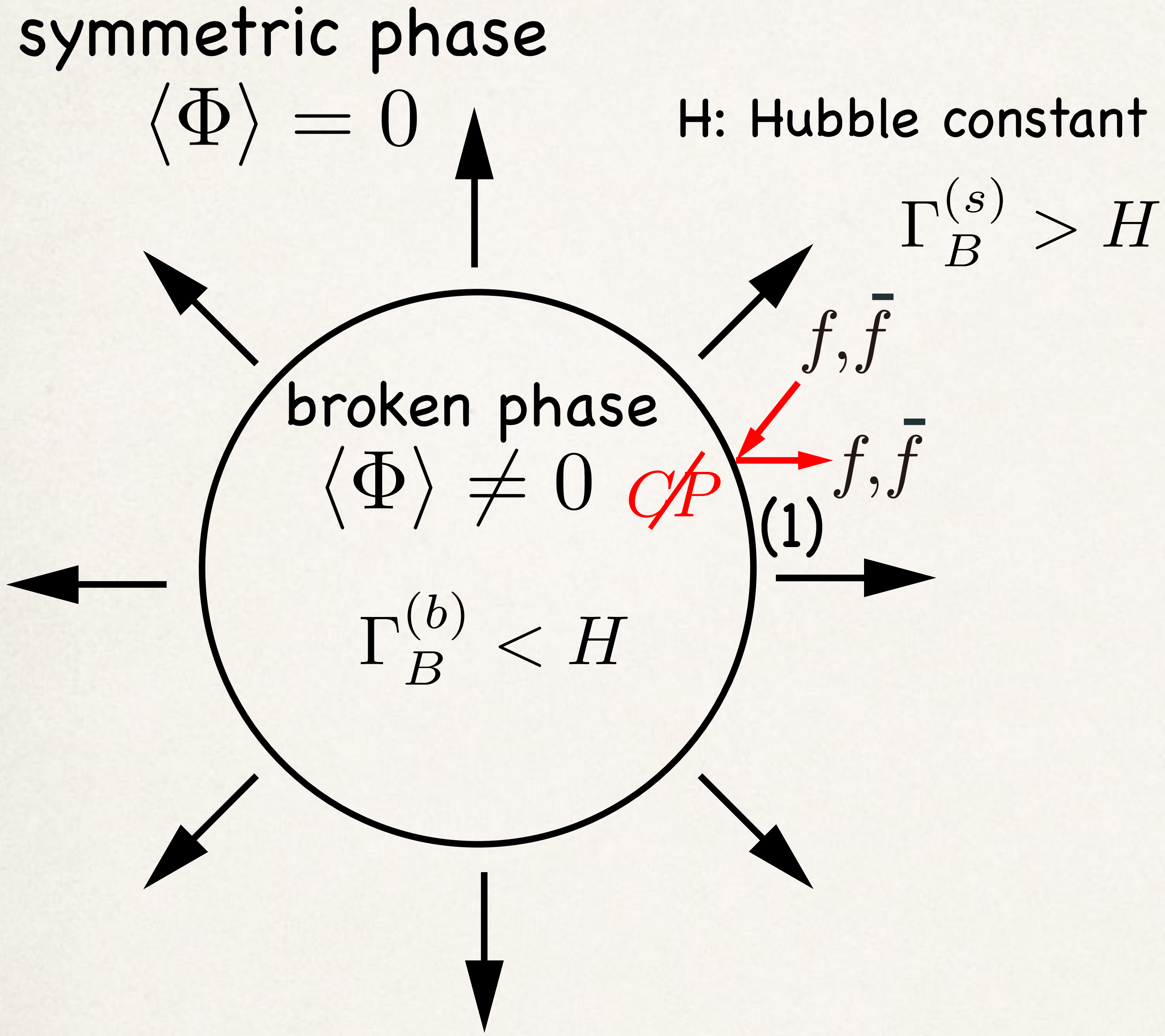

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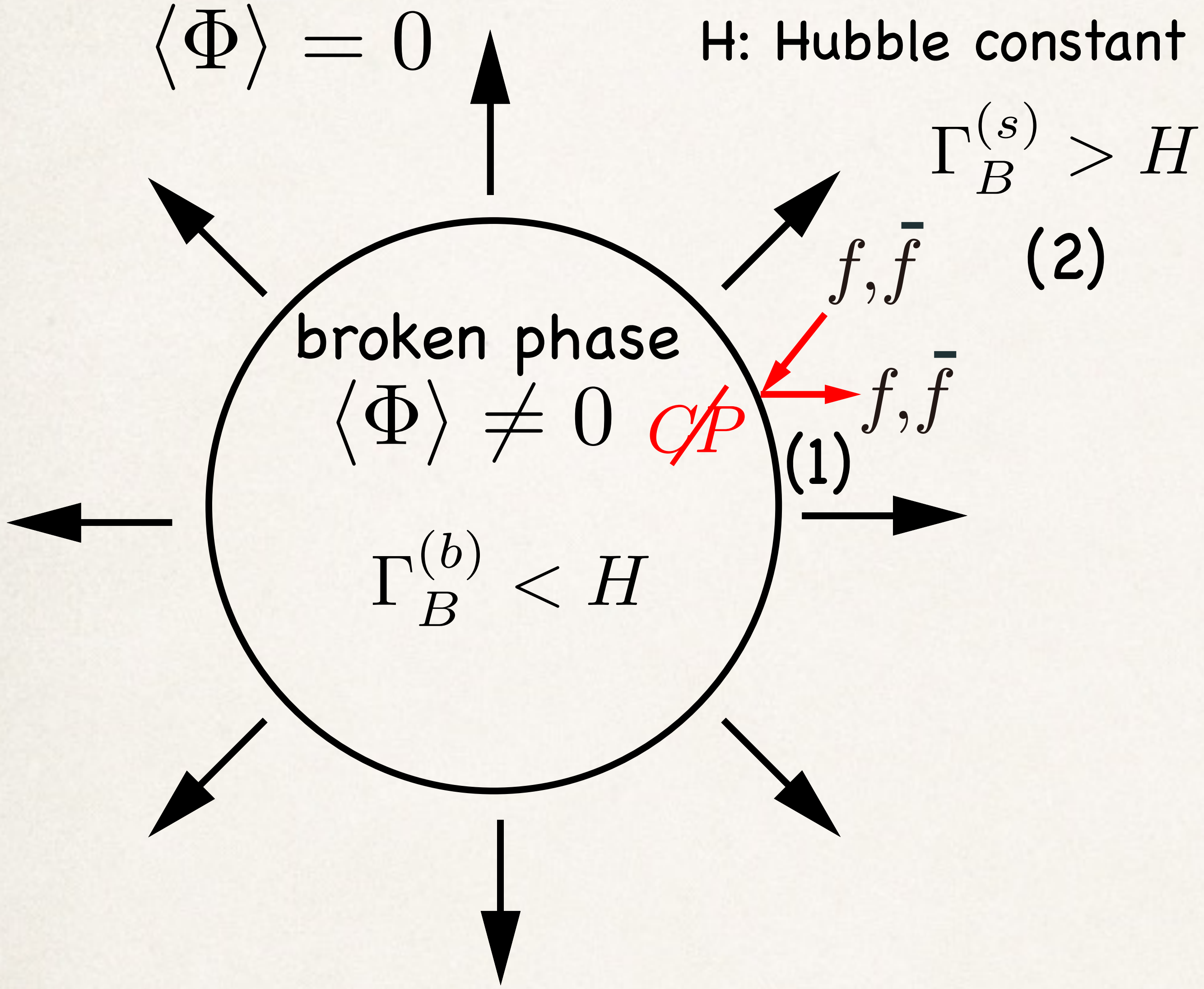

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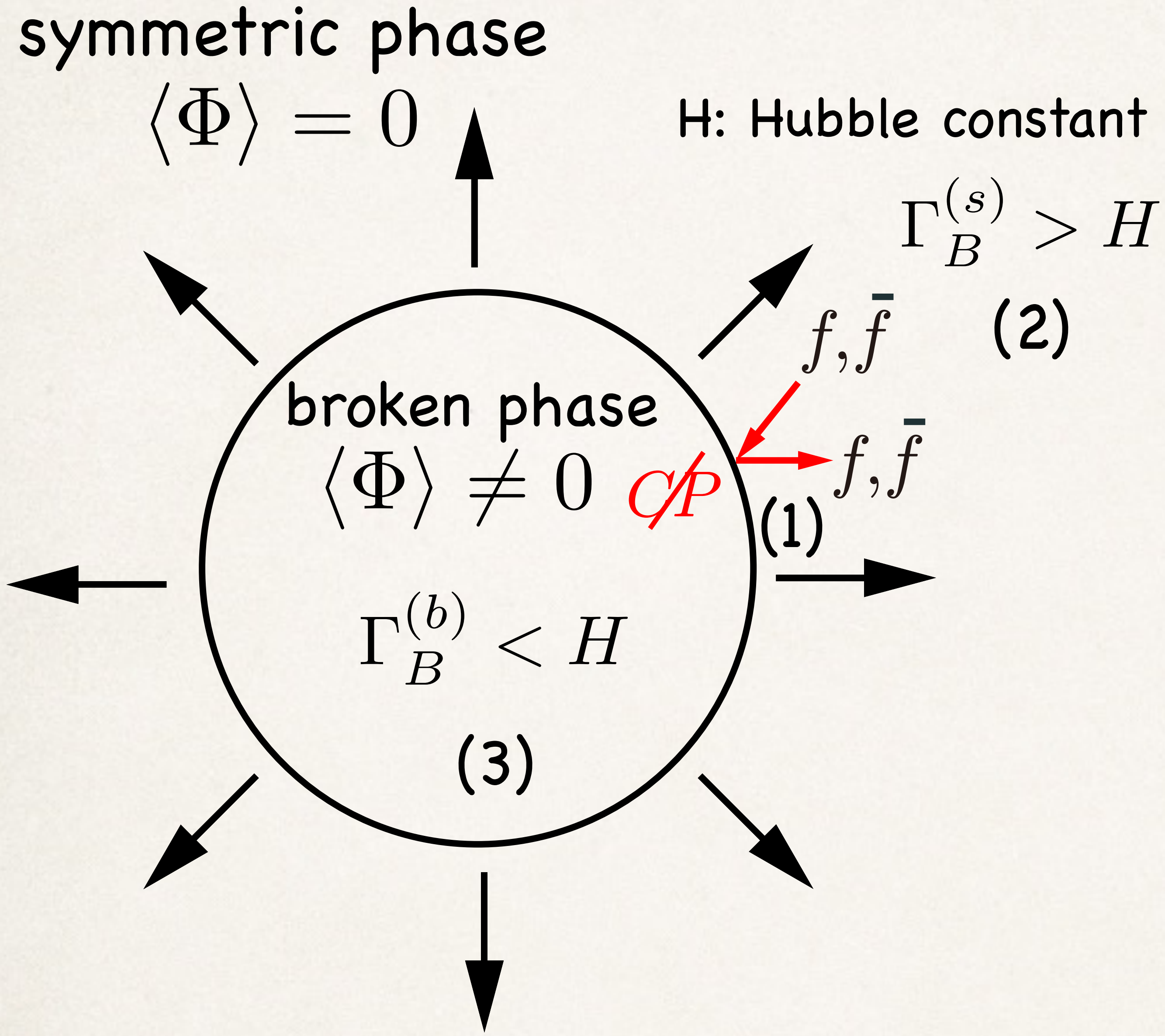

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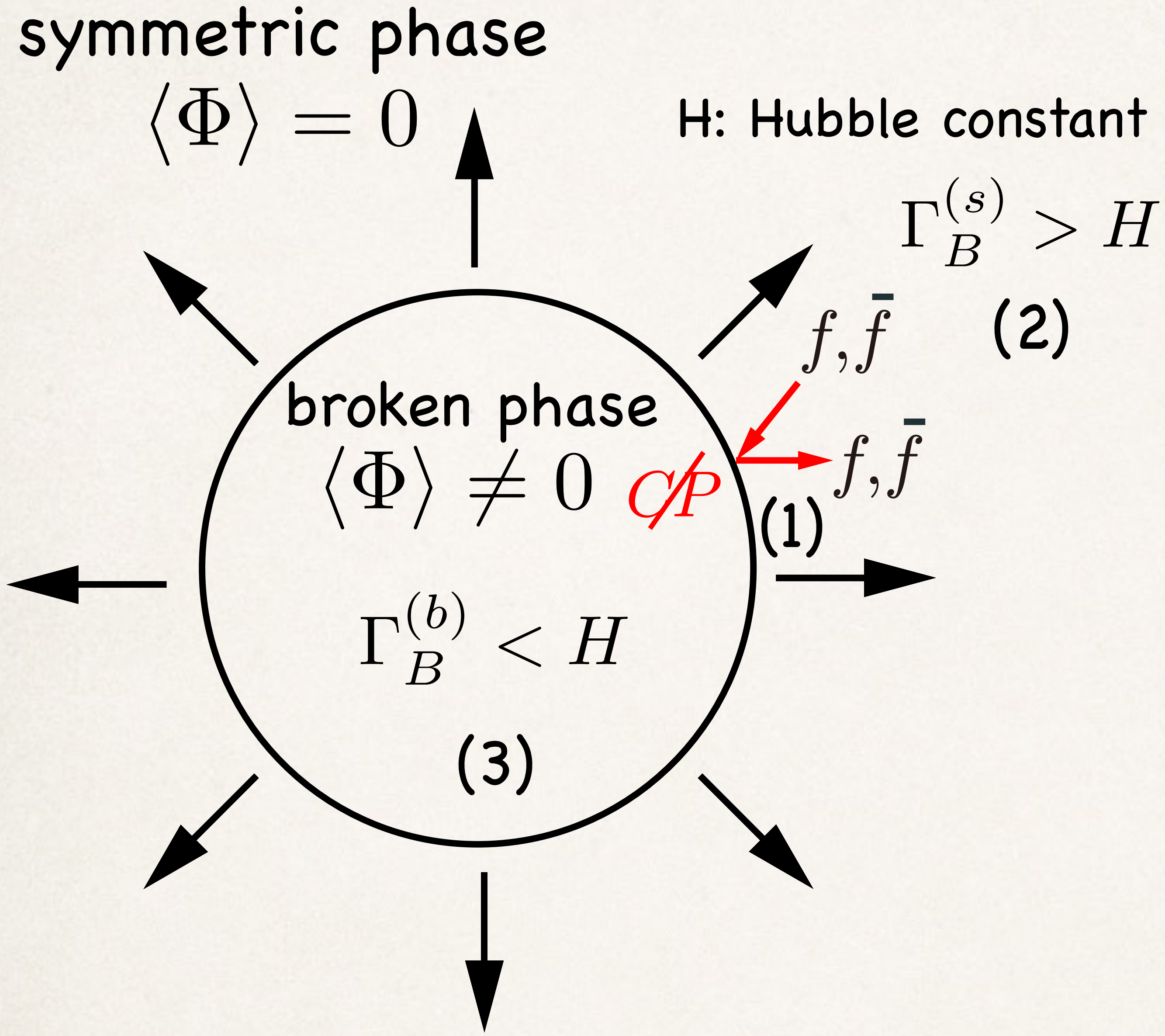

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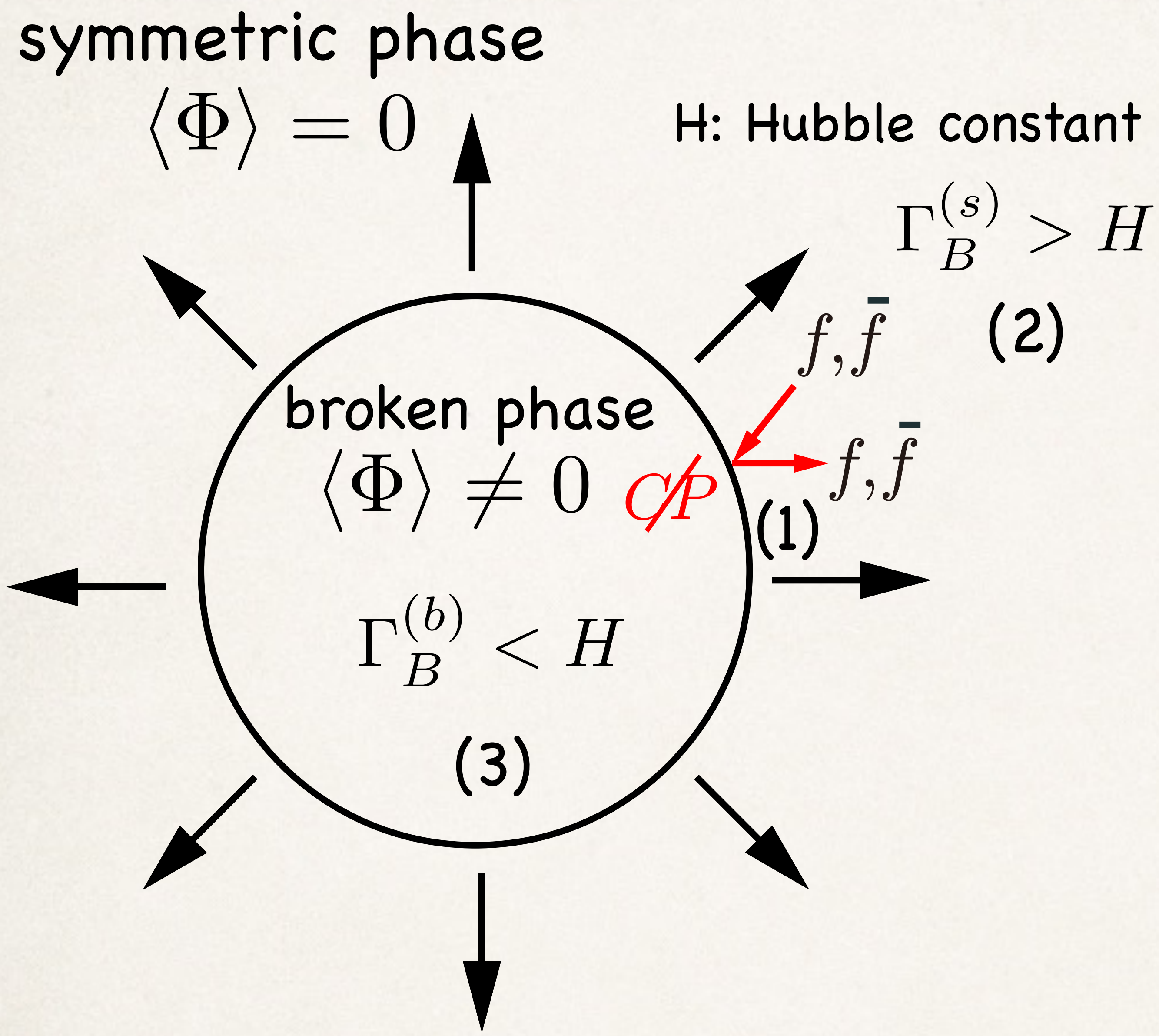

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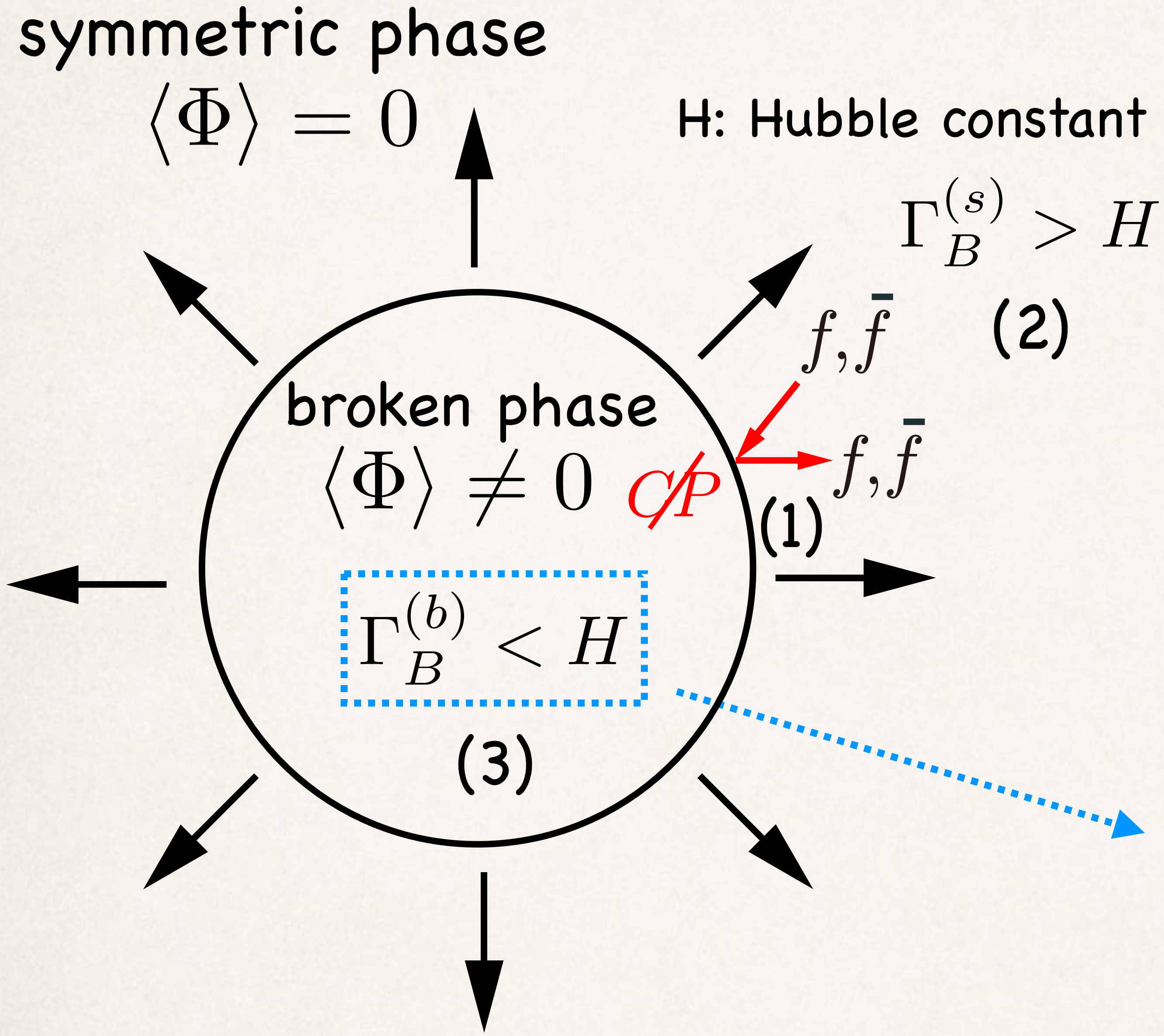

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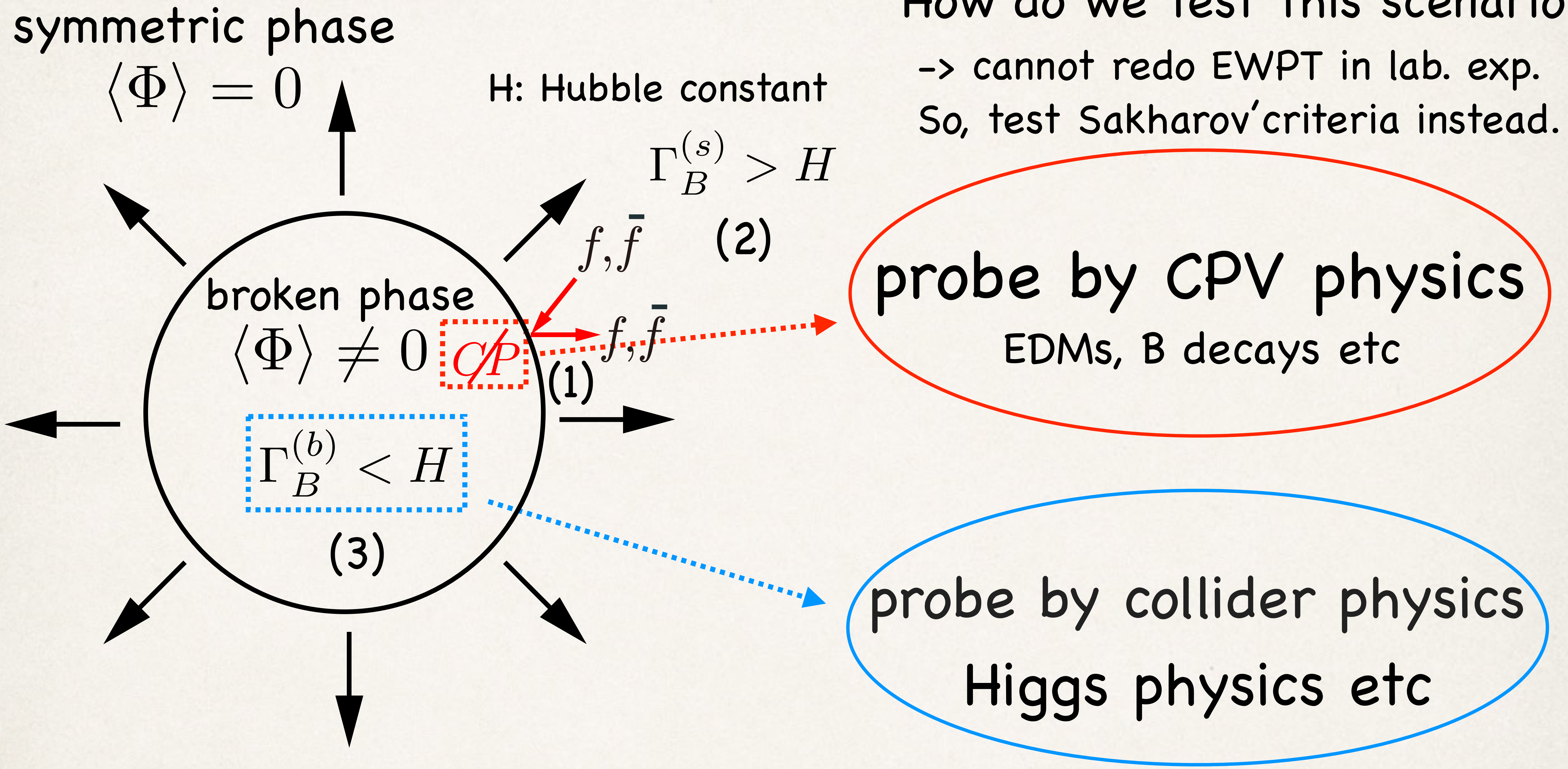

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EDMs, B decays etc

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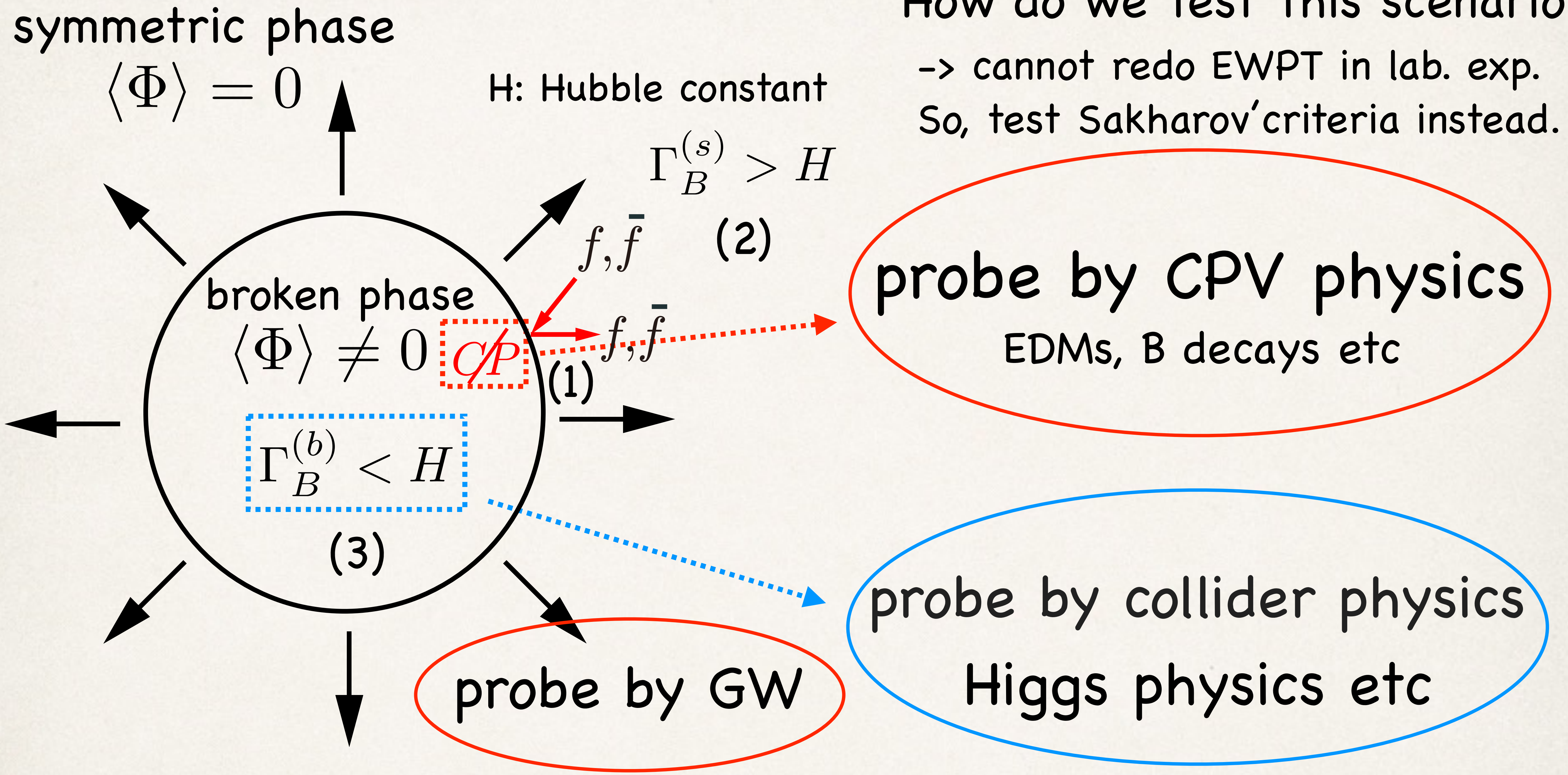

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probe by GW

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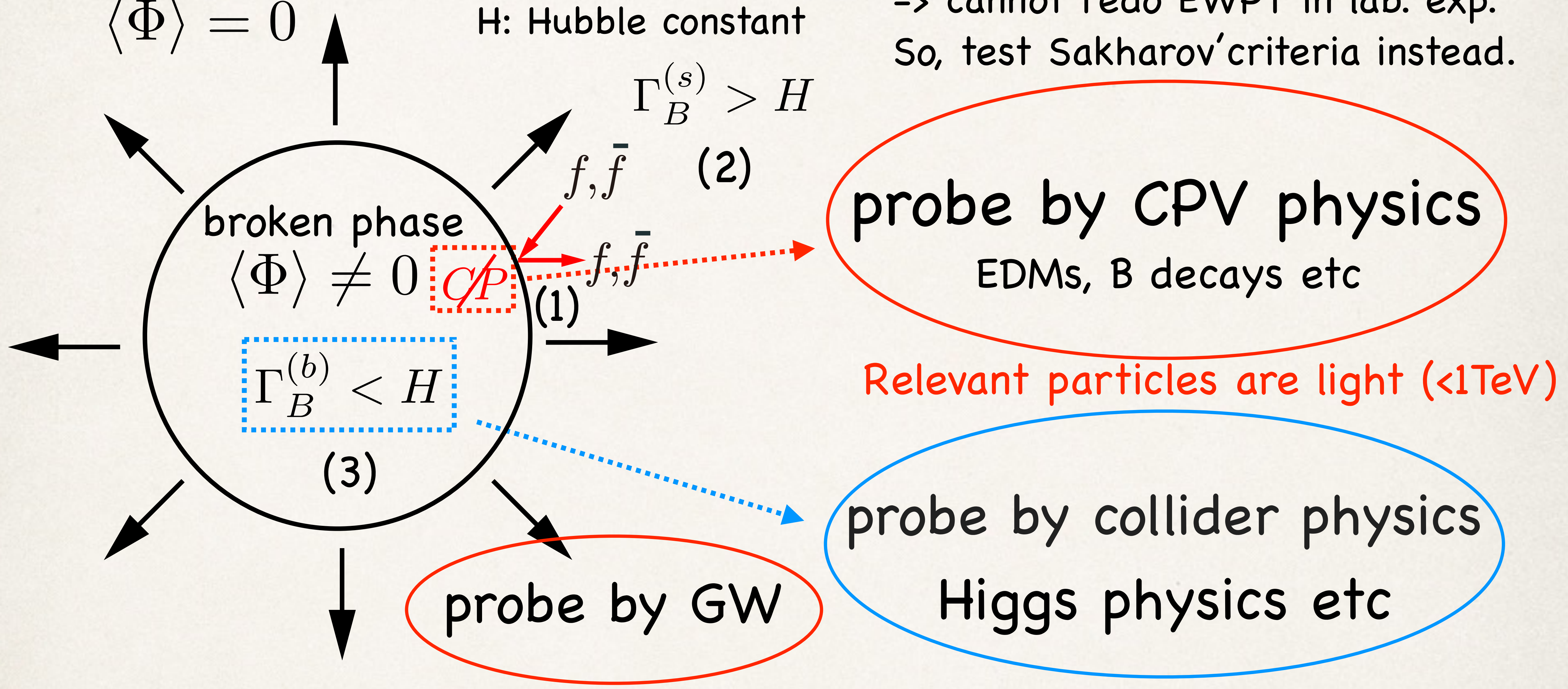

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Relevant particles are light (<1TeV)

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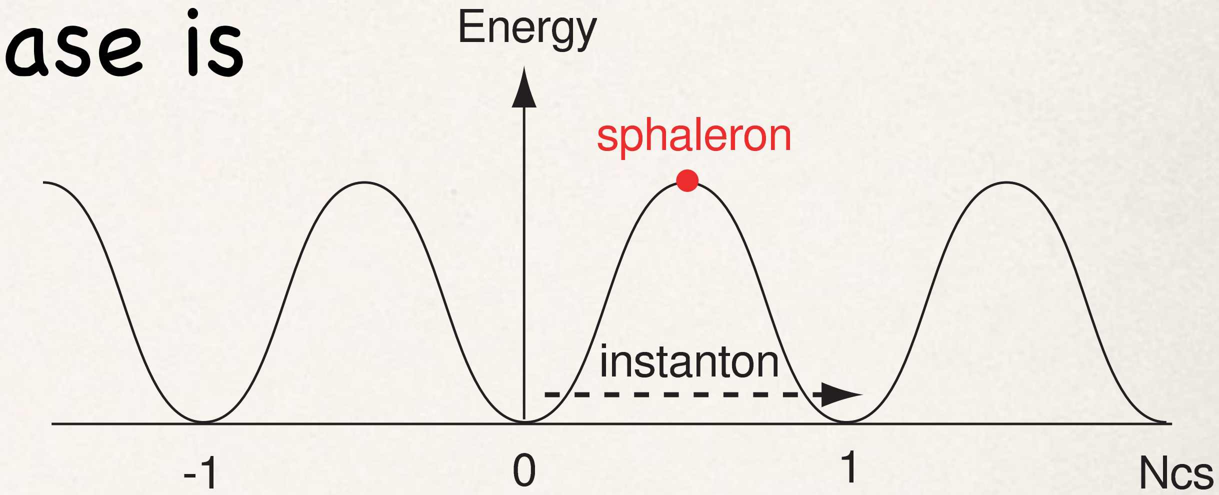
$$\boxed{\Gamma_B^{(b)} \simeq (\text{prefactor})e^{-E_{\text{sph}}/T}}$$



$\Delta B = 3\Delta n_{\text{CS}}$

E_{sph} is proportional to the Higgs VEV

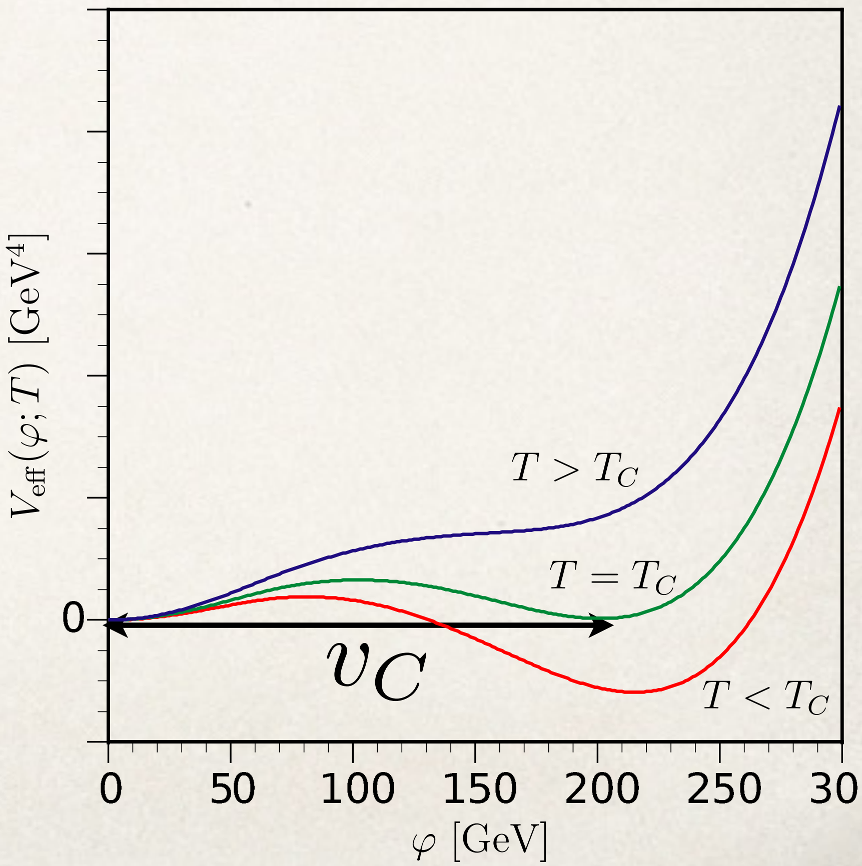
$$\boxed{E_{\text{sph}} \propto v(T)}$$

what we need is

large Higgs VEV after the EWPT

⇒ EWPT has to be “**strong**” 1st order!!

$$\Gamma_B^{(b)}(T_C) < H(T_C) \quad \rightarrow \quad \boxed{\frac{v_C}{T_C} \gtrsim 1}$$



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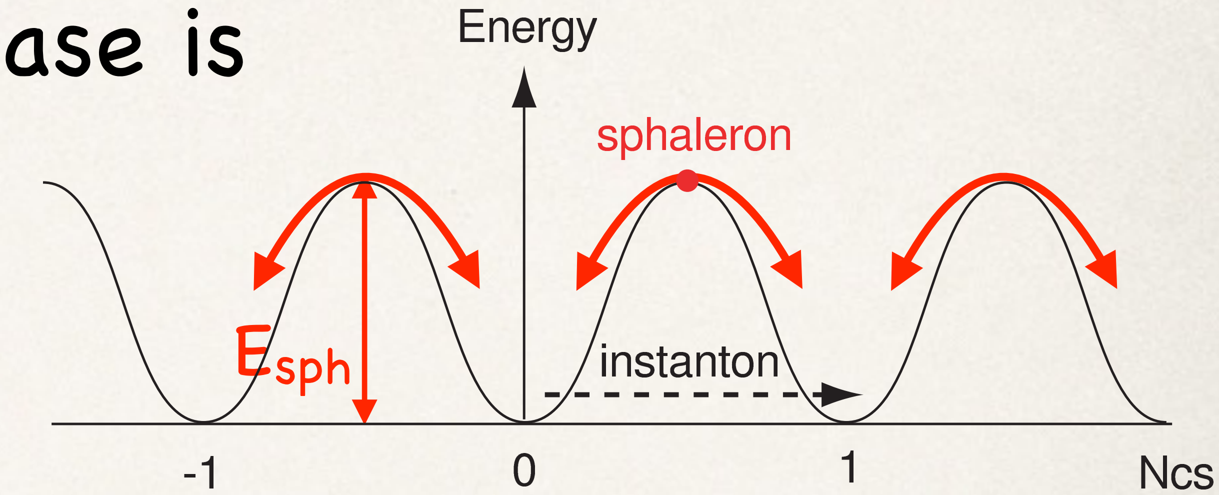

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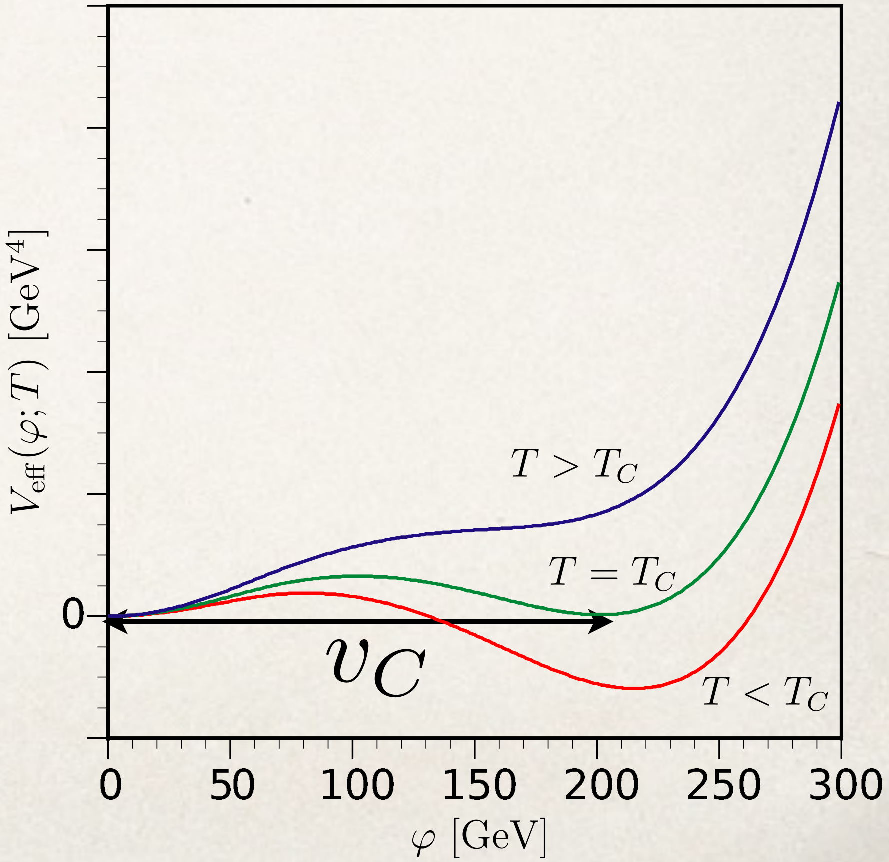

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$\because$ No 1^{st}-order PT for m_h=125 GeV.

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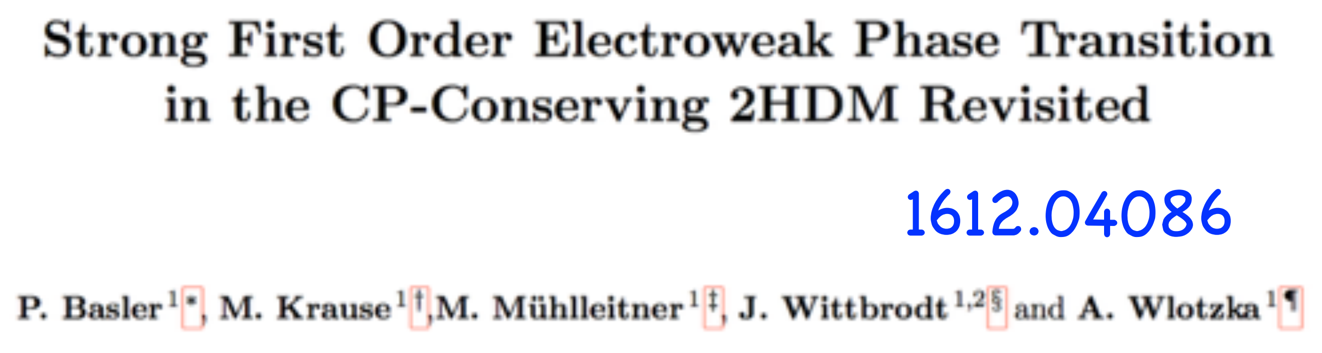
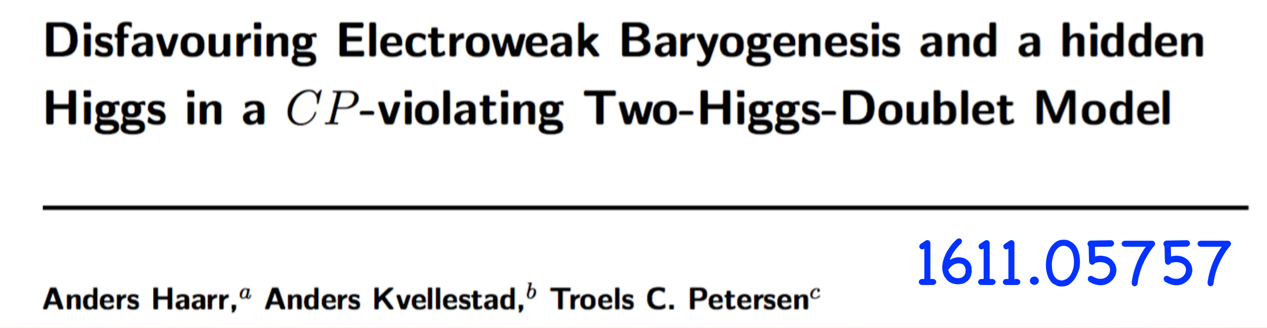
Recent papers on EWBG



Strong First Order Electroweak Phase Transition in the CP-Conserving 2HDM Revisited

1612.04086

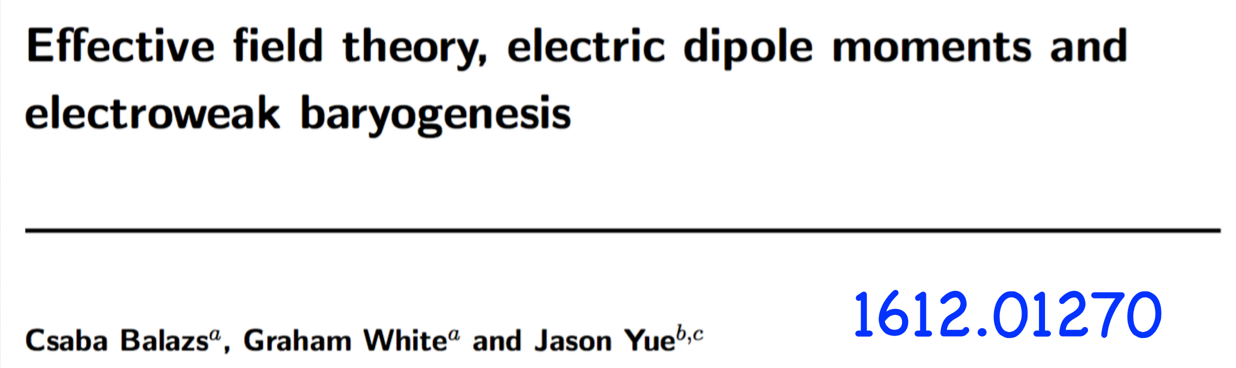
P. Basler[1][*], M. Krause[1][†], M. Mühlleitner[1][‡], J. Wittbrodt[1,2][§] and A. Wlotzka[1][¶]



Disfavouring Electroweak Baryogenesis and a hidden Higgs in a CP-violating Two-Higgs-Doublet Model

1611.05757

Anders Haarr,[a] Anders Kvellestad,[b] Troels C. Petersen[c]



Effective field theory, electric dipole moments and electroweak baryogenesis

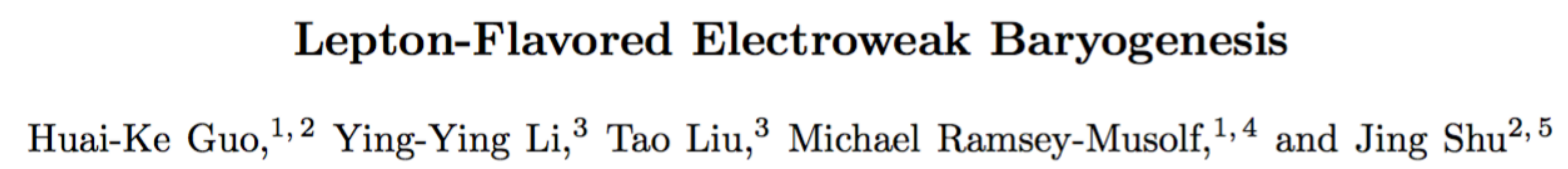
1612.01270

Csaba Balazs[a], Graham White[a] and Jason Yue[b,c]

Thermal Resummation and Phase Transitions

1612.00466

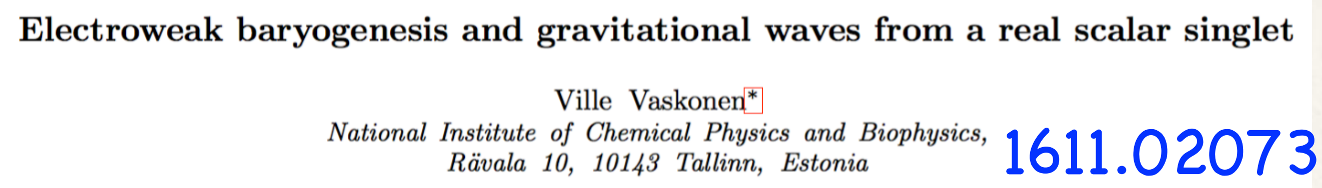
David Curtin[a] Patrick Meade[b] Harikrishnan Ramani[b]



Lepton-Flavored Electroweak Baryogenesis

Huai-Ke Guo,[1,2] Ying-Ying Li,[3] Tao Liu,[3] Michael Ramsey-Musolf,[1,4] and Jing Shu[2,5]

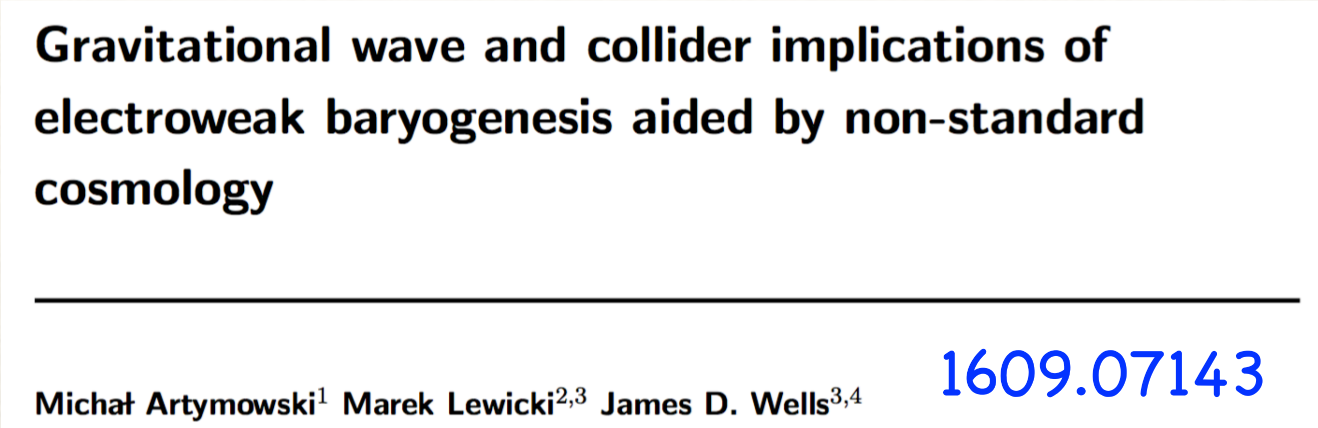
1609.09849



Electroweak baryogenesis and gravitational waves from a real scalar singlet

Ville Vaskonen[*]
National Institute of Chemical Physics and Biophysics, Rävala 10, 10143 Tallinn, Estonia

1611.02073



Gravitational wave and collider implications of electroweak baryogenesis aided by non-standard cosmology

1609.07143

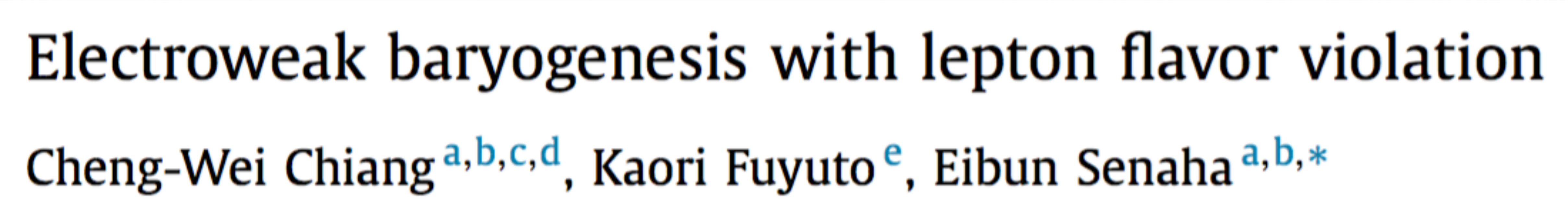
Michał Artymowski[1] Marek Lewicki[2,3] James D. Wells[3,4]

Enabling Electroweak Baryogenesis through Dark Matter

1601.01681

Marek Lewicki[1,2] Tanja Rindler-Daller[2,3] James D. Wells[2]

Sorry, this is incomplete list.



Electroweak baryogenesis with lepton flavor violation

Cheng-Wei Chiang [a,b,c,d], Kaori Fuyuto [e], Eibun Senaha [a,b,*]

C.-W. Chiang (Natl Taiwan U), K. Fuyuto (UMass-Amherst), E.S., 1607.07316 [PLB]

Higgs decay with LFV

CMS: $\mathrm{Br}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$ 1502.07400 [PLB] 2.4 σ excess

Atlas: $\mathrm{Br}(h \to \mu\tau) = (0.53 \pm 0.51)\%$ 1604.07730

What does lepton flavor-violating (LFV) Higgs tell us?

2 Higgs doublets model (2HDM) is one of the simplest solutions.

$$
\begin{aligned}
-\mathcal{L}_Y \ni\ & \bar{e}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho_{ij}c_{\beta-\alpha}\right]e_{jR}h \\
& + \bar{e}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}c_{\beta-\alpha} - \frac{1}{\sqrt{2}}\rho_{ij}s_{\beta-\alpha}\right]e_{jR}H + \frac{i}{\sqrt{2}}\bar{e}_{iL}\rho_{ij}e_{jR}A + \text{h.c.}\ ,
\end{aligned}
$$

- LFV comes from the off-diagonal entries of ρ_{ij}. $\rho_{ij} \in \mathbb{C} \Rightarrow$ CPV
- μ-τ flavor violation can explain h->μτ and g-2.

[Y. Omura, E.S., K.Tobe, JHEP052015028, PRD94,055019(2016)]

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EWBG with LFV

[C-W. Chiang, K.Fuyuto, E.S., arXiv:1607.07316 (PLB)]

benchmark point:

$m_A = m_{H^\pm}$, $M = 100$ GeV, $\tan\beta = 1$, $c_{\beta-\alpha} = 0.006$
$|\rho_{\tau\mu}| = |\rho_{\mu\tau}|$, $\phi_{\tau\mu} + \phi_{\mu\tau} = \pi/4$, $\lambda_{6,7} = 0$ $\mathrm{Br}(h \to \mu\tau) = 0.84$ %

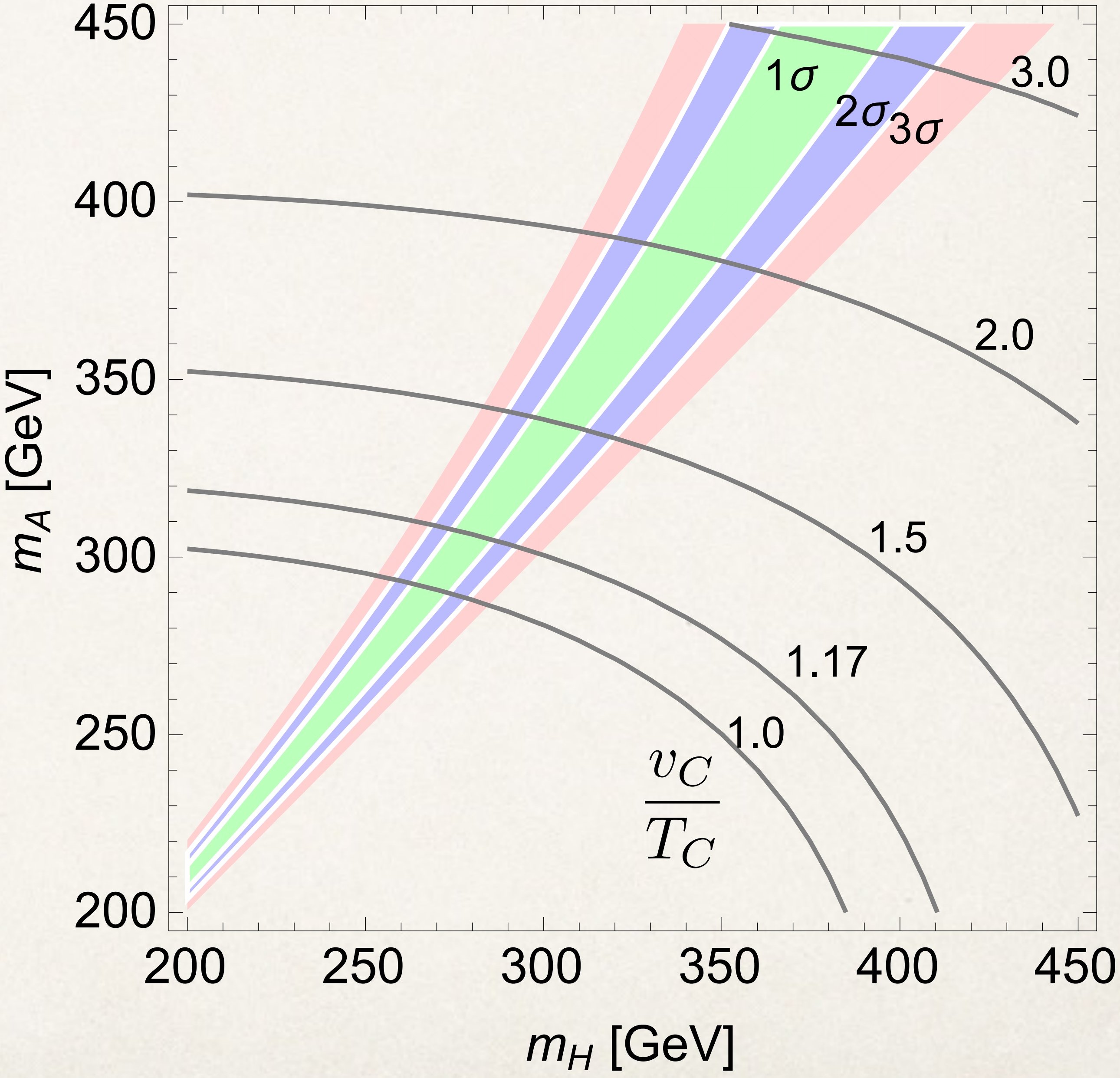
- Br(h->μτ)=0.84%
- g-2 favored region

$m_A \gtrsim m_H$

for $\mathrm{Re}(\rho_{\tau\mu}\rho_{\mu\tau})>0$.

- EWBG-viable region

$v_C/T_C > 1.17$



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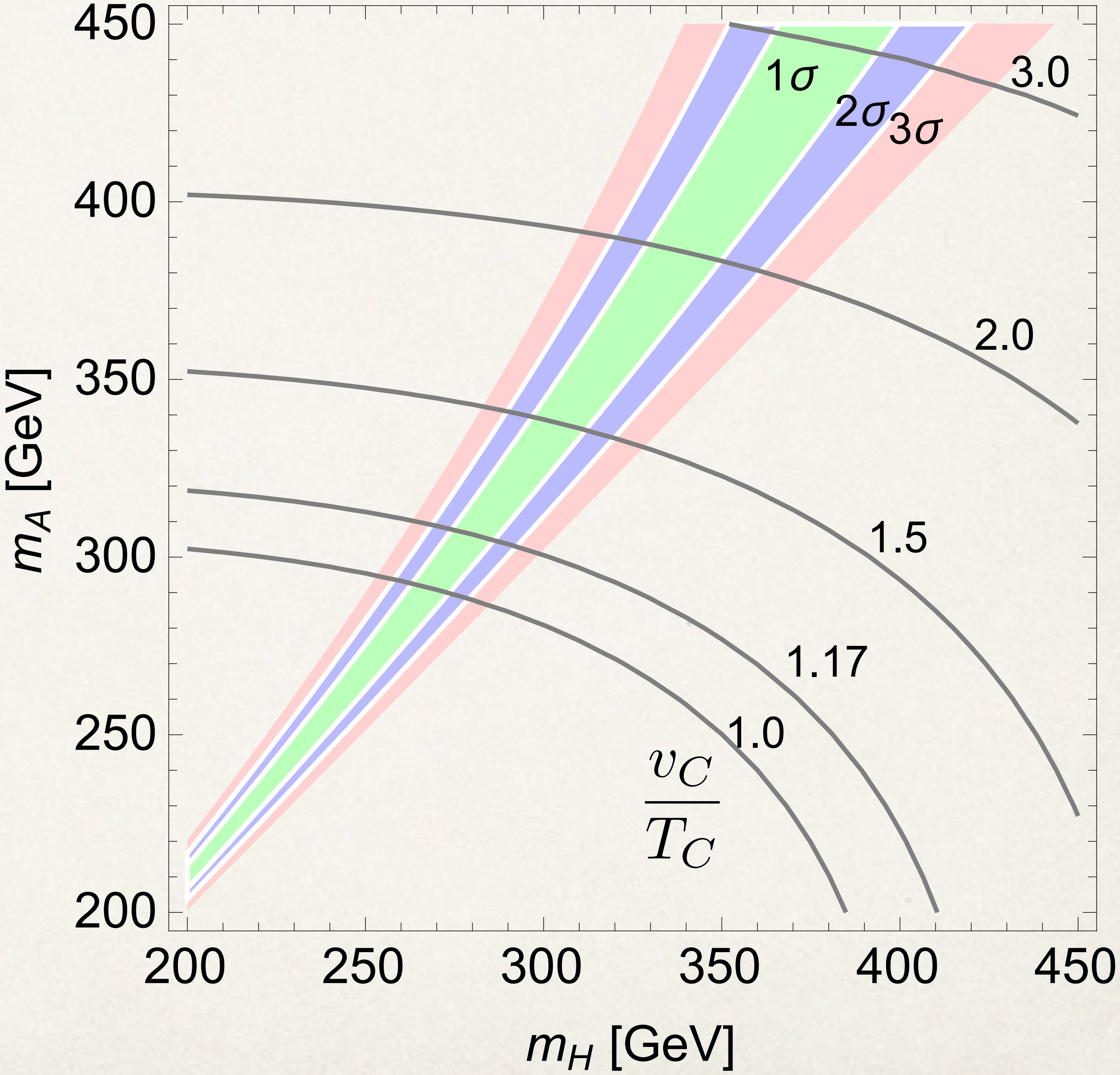

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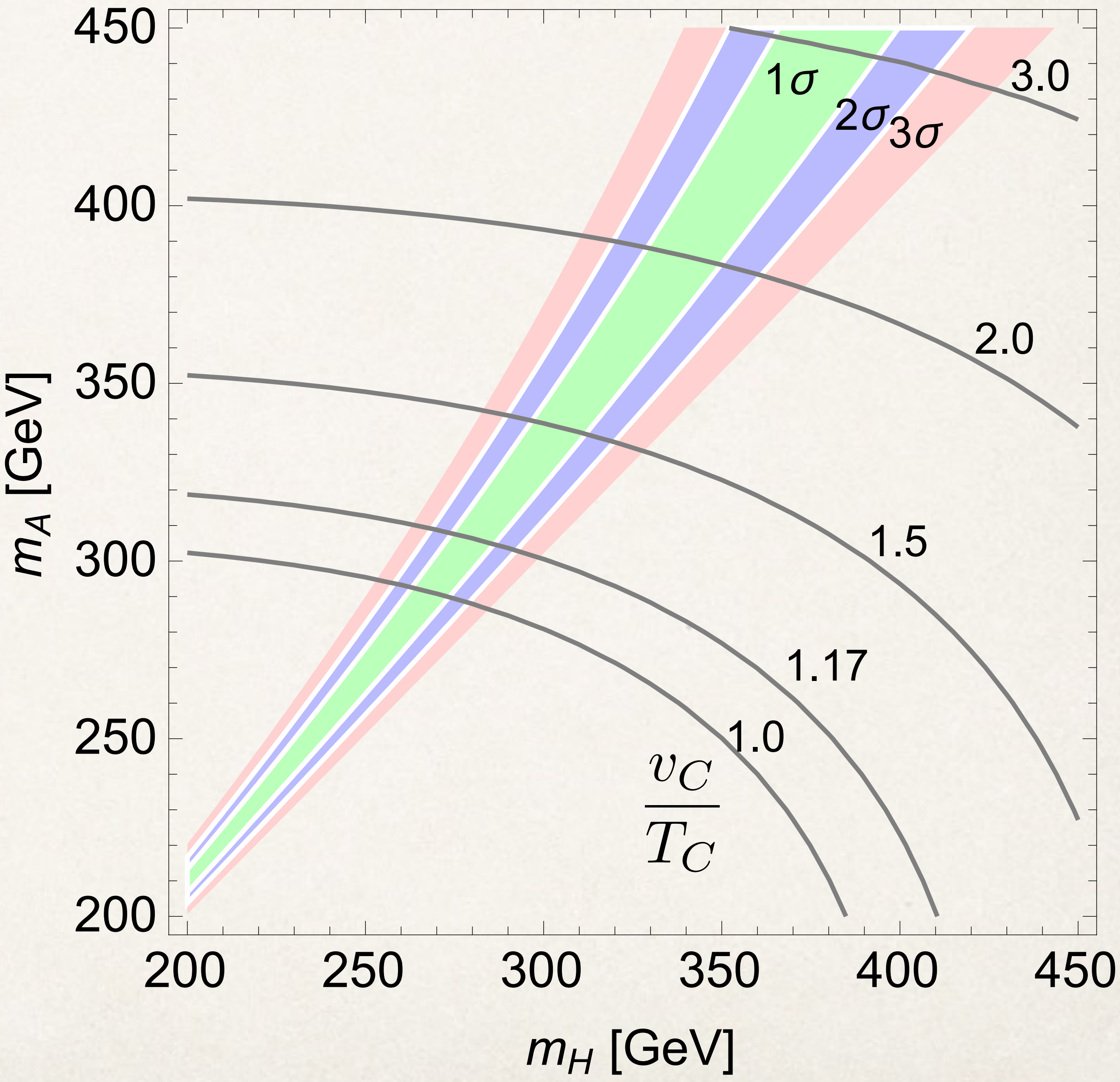

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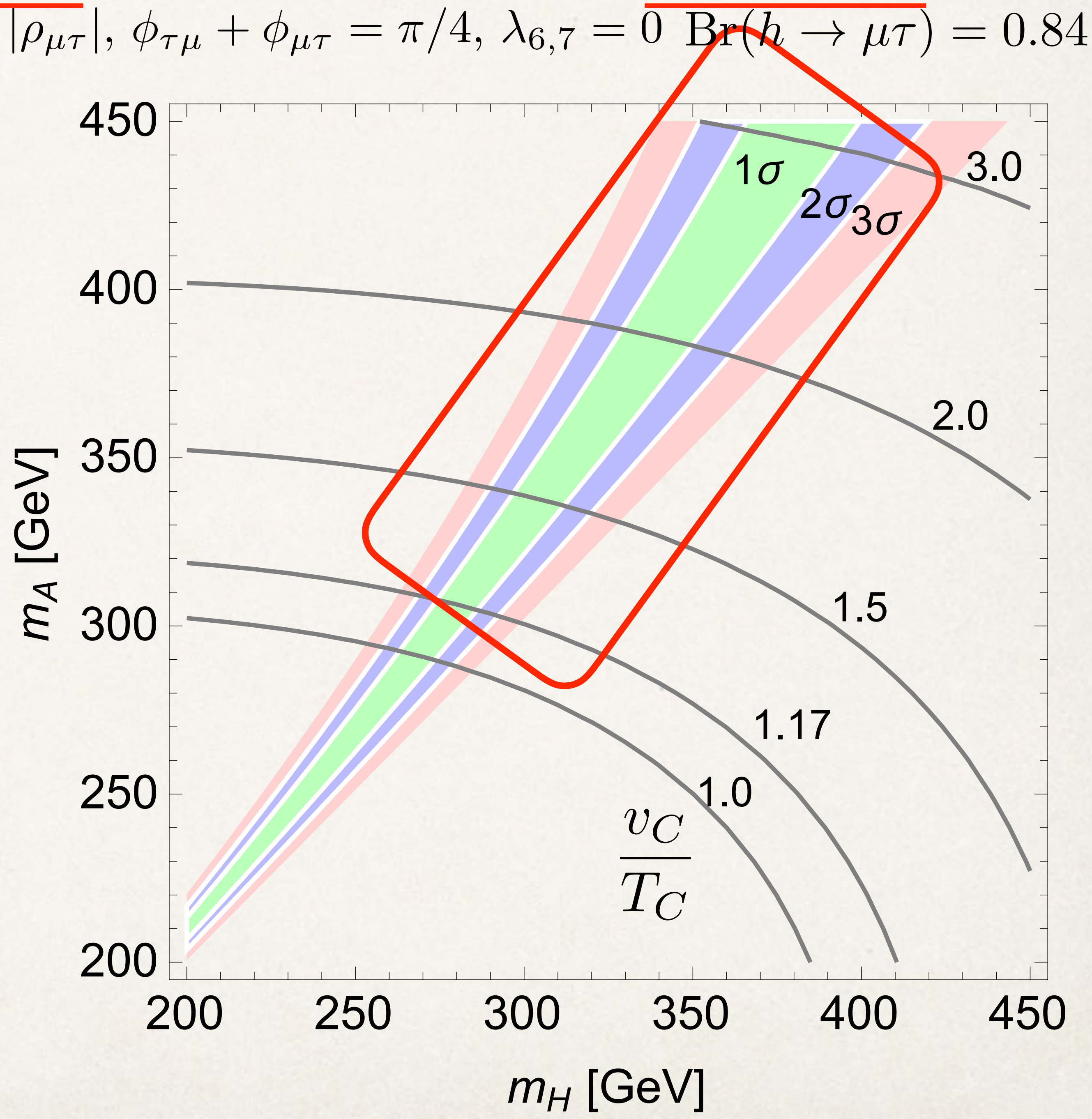


Combined: 300 GeV ≲ m_H ≲ m_A ≲ 450 GeV

$A \to \tau\tau$

ATLAS-CONF-2016-085

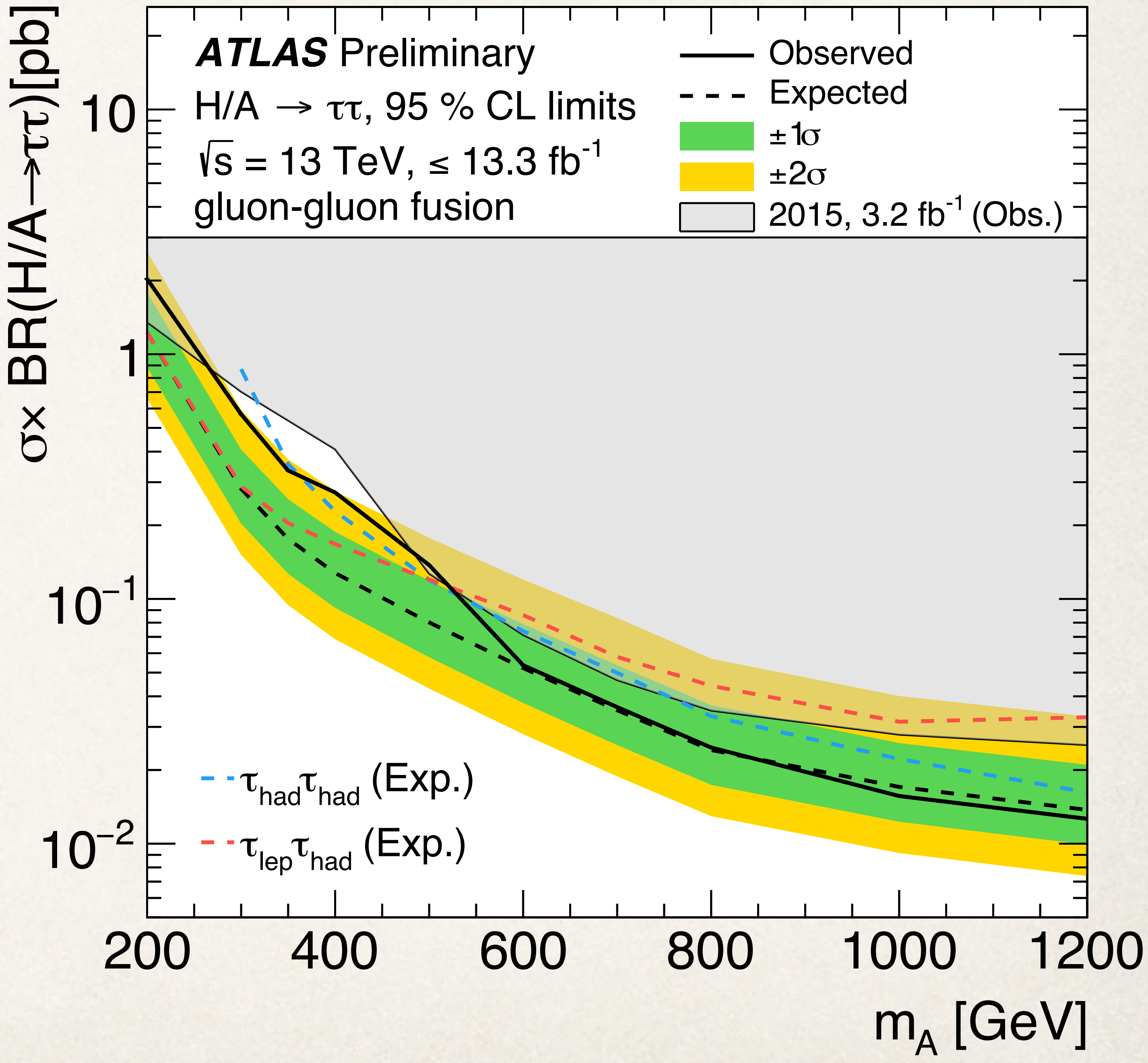
In our scenario:

For BAU

- $|\varrho_{\tau\mu}|=|\varrho_{\mu\tau}|=0.1-0.6$,
- $|\varrho_{\tau\tau}|=0.8-0.9$.

-> probed by $A \to \tau\tau$.

- $Br(A \to \tau\tau)$ also depends on other ϱ couplings. (model dependent)



A -> ττ

ATLAS-CONF-2016-085

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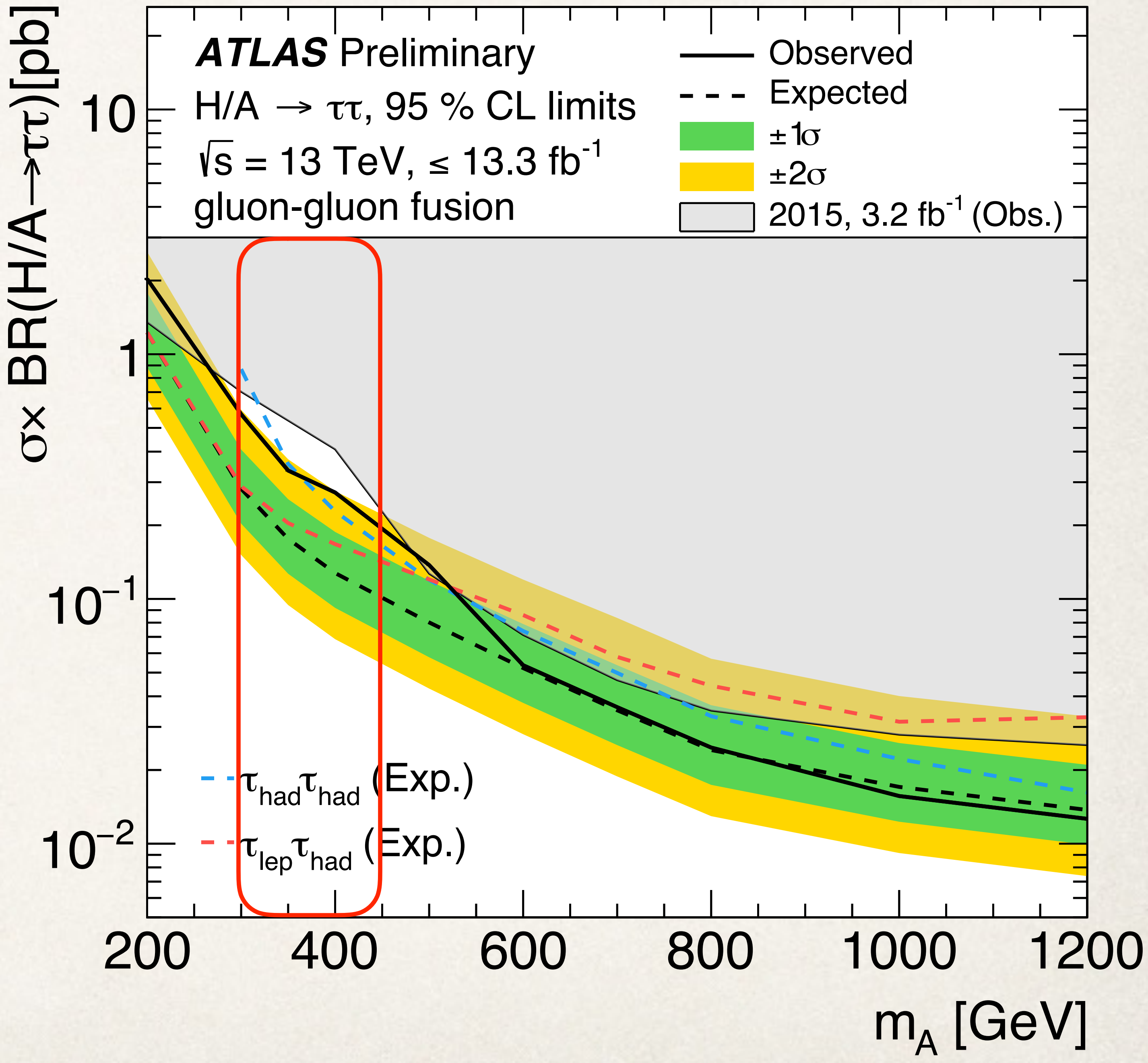


(B+L)-changing process and a band structure

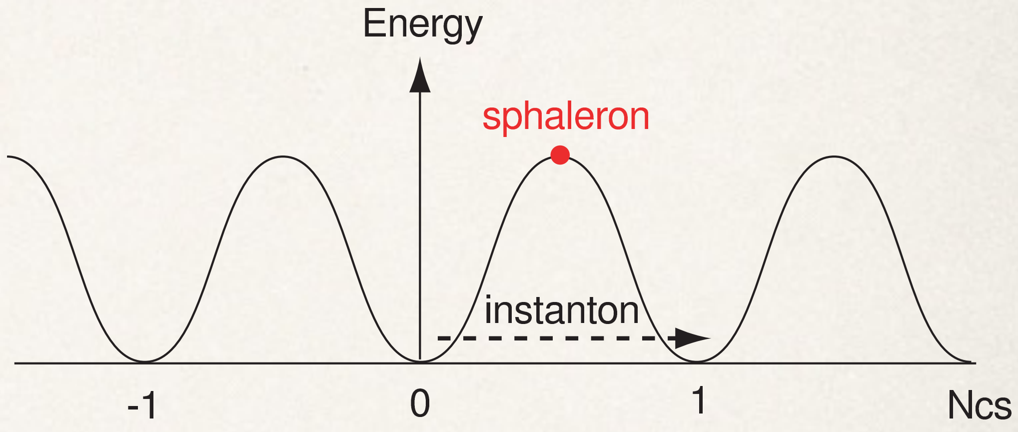
B+L violation

- (B+L) is violated by a chiral anomaly in EW theories.

Vacuum transition (instanton)

['t Hooft, PRL37,8 (1976), PRD14,3432 (1976)]

$$\sigma_{\text{instanton}} \simeq e^{-2S_{\text{instanton}}} = e^{-4\pi/\alpha_W} \simeq 10^{-162}$$



Transition rate at finite-E

instanton-based [Ringwald, NPB330,(1990)1, Espinosa, NPB343 (1990)310]

$$\sigma(E) \sim \exp\left(\frac{4\pi}{\alpha_W} F(E)\right)$$

E⤴ ⟹ σ(E)⤴

- But, instanton-based calculation is not valid at E>E_{sph}

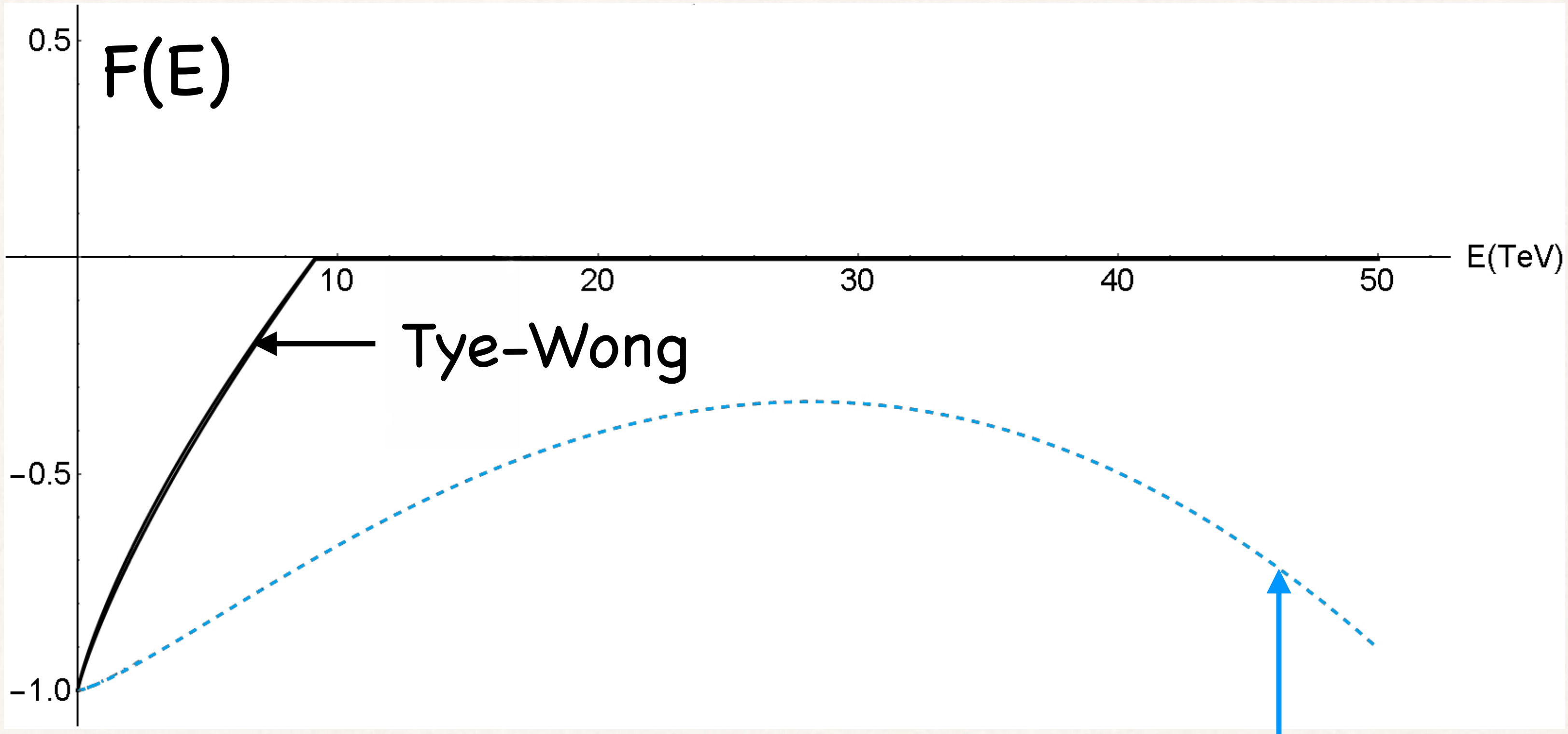
Bounce is more appropriate (transition between the finite-E states)

-> Reduced model.

[Aoyama, Goldberg, Ryzak, PRL60, 1902 ('88)]
[Funakubo, Otsuki, Takenaga, Toyoda, PTP87,663('92), PTP89,881('93)]
[H. Tye, S. Wong, PRD92,045005 ('15)]

Tye-Wong's work

[H. Tye, S. Wong, PRD92,045005 (2015)]



$$F(E) = -1 + \frac{9}{8}\left(\frac{E}{E_0}\right)^{4/3} - \frac{9}{16}\left(\frac{E}{E_0}\right)^{2} + \cdots$$ (instanton calculus) $E_0 \simeq 15$ TeV

F(E) = 0 for $E > E_{sph}$ (Tye-Wong) ∵ a band structure

Q1: Can we observe the sphaleron process at LHC?

Q2: Does the band affect sphaleron process at finite-T?

Reduced model

[Aoyama, Goldberg, Ryzak, PRL60, 1902 (1988)]
[Funakubo, Otsuki, Takenaga, Toyoda, PTP87, 663 (1992), PTP89, 881 (1993)]
[H. Tye, S. Wong, PRD92,045005 (2015)]

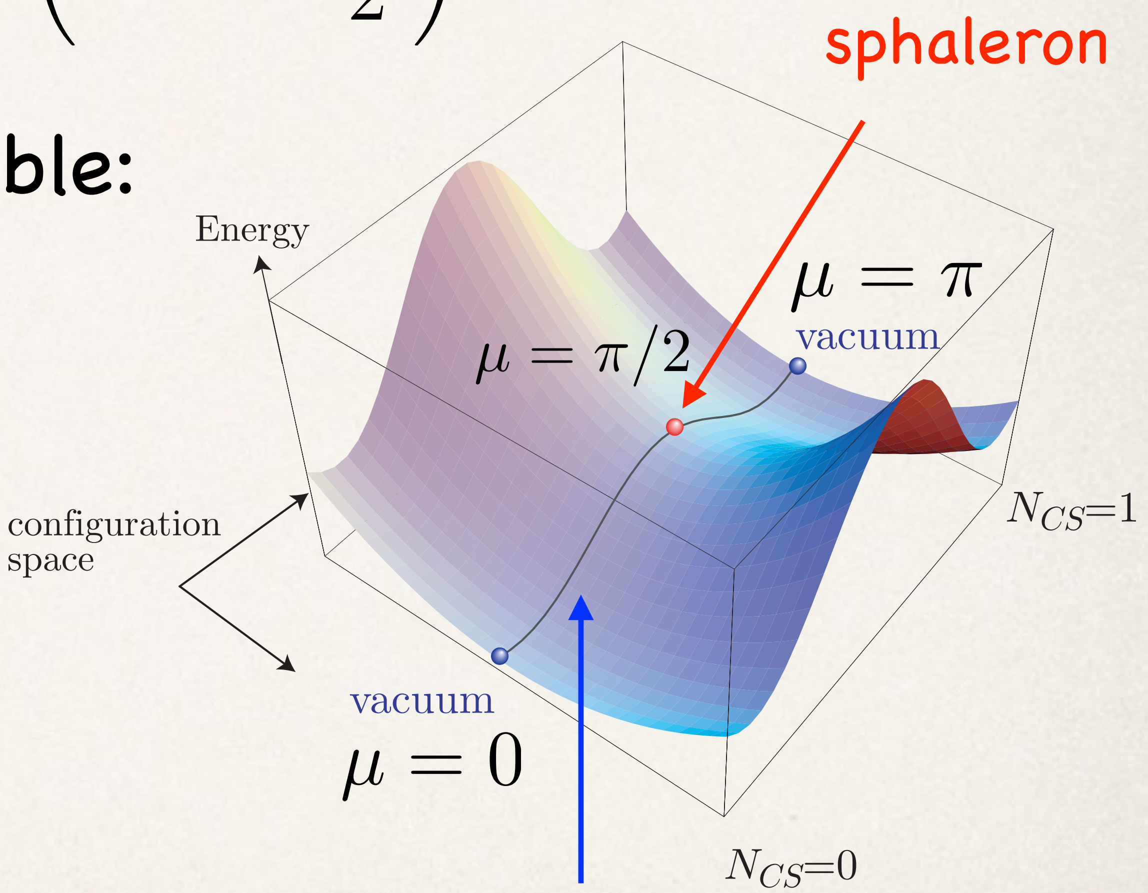
SU(2)-gauge Higgs system ($U(1)_Y$ can be neglected)

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + (D_\mu \Phi)^\dagger D^\mu \Phi - \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2 \qquad D_\mu = \partial_\mu + i g A_\mu$$

Let us promote μ to a dynamical variable:

$$\mu \Rightarrow \mu(t)$$

$\mu(-\infty)=0$, $\mu(+\infty)=\pi$: vacuum,
$\mu(t_{sph})=\pi/2$: sphaleron



- We construct a reduced model by adopting a Manton's ansatz.

Non-contractible loop
(least energy path)

Comparison with Tye-Wong's work

Some differences between our work and Tye-Wong's (TW's).

	A_0	Sphaleron mass	Method for band structure
this work	$A_0 \neq 0$	μ-dependent	WKB w/ 3 connection formulas
Tye-Wong	$A_0 = 0$	μ-independent	Schroedinger eq. numerically

We use a Manton's ansatz with $A_0 = \frac{i}{g_2} f(r) \partial_0 U U^{-1}$.

fully gauge inv.
-> no div. issue

Classical action:

$$S[\mu] = g_2 v \int dt \left[\frac{M(\mu)}{2} \left(\frac{d}{dt} \frac{\mu(t)}{g_2 v} \right)^2 - V(\mu) \right],$$

$$M(\mu) = \frac{4\pi}{g_2^2} \left(\alpha_0 + \alpha_1 \cos^2 \mu + \alpha_2 \cos^4 \mu \right), \quad V(\mu) = \frac{4\pi}{g_2^2} \sin^2 \mu \left(\beta_1 + \beta_2 \sin^2 \mu \right).$$

$$M_{\mathrm{sph}} = g_2 v M\left(\frac{\pi}{2}\right) \simeq 92.01 \text{ TeV}, \quad E_{\mathrm{sph}} = g_2 v V\left(\frac{\pi}{2}\right) \simeq 9.08 \text{ TeV}.$$

c.f., TW's: M_{sph} = 17.1 TeV. With same normalization, M_{sph}(ours) -> 23.0 TeV.

Band structure

E_{sph}=9.08 TeV

E_{sph}=9.11 TeV

Units: TeV

this work		Tye-Wong	
Band Centre E	Band Width	Band Centre E	Band Width
14.054	0.0744	?	?
13.980	0.0741	?	?
⋮	⋮	⋮	⋮
9.072	0.0104	9.113	0.0156
9.044	4.85×10^{-3}	9.081	7.19×10^{-3}
9.012	1.61×10^{-3}	9.047	2.62×10^{-3}
⋮	⋮	⋮	⋮
0.1015	1.88×10^{-199}	0.1027	$\sim10^{-177}$
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Band gaps still exist $E>E_{sph}$ due to nonzero reflection rate.

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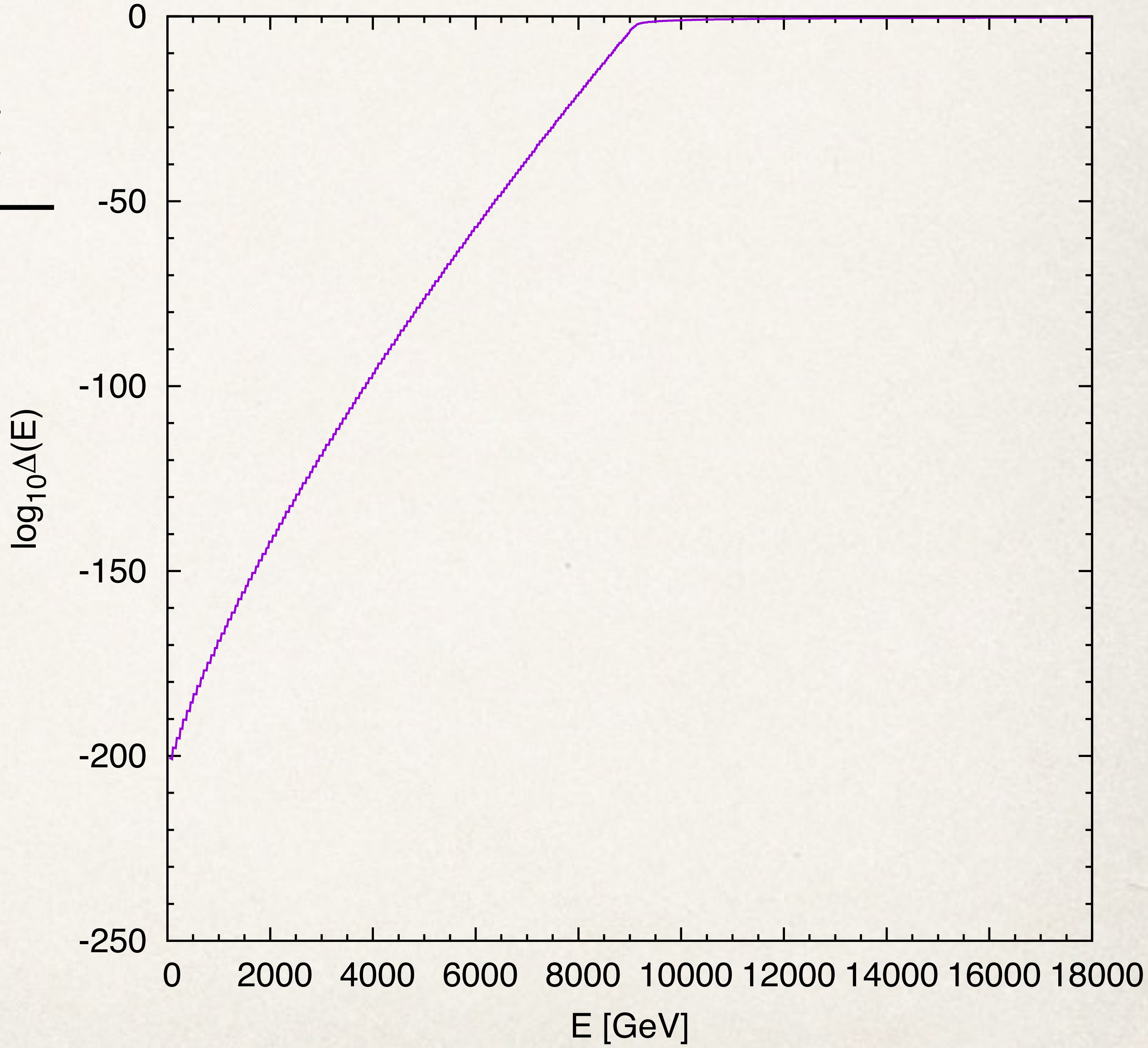
Transition factor

tunneling factor

$$\sigma_{\Delta(B+L)=\pm 1} \propto \begin{cases} 1 \times \exp\left(\frac{4\pi}{\alpha_W} F(E)\right) & \text{instanton calculus} \\ \Delta(E) \times 1 & \text{band picture} \end{cases}$$

$$\Delta(E) \simeq \frac{\text{sum of band widths up to E}}{\text{energy (E)}}$$



Band picture:

- State of density is restricted.

- Exponential suppression at $E \ll E_{sph}$ is due to the tiny band width.

N.B. $\Delta(E)$ is not exactly 1 at slightly above E_{sph}.

Q. Does the band structure affect the (B+L)-changing process in high-E collisions?

LHC analysis

[J.Ellis and K.Sakurai, JHEP04(2016)086]

Δ(B+L)≠0 process in the band picture:

$$\sigma(\Delta n=\pm 1)=\frac{1}{m_W^2}\sum_{ab}\int dE\,\frac{d\mathcal{L}_{ab}}{dE}\,\boxed{p}\,\exp\left(c\frac{4\pi}{\alpha_W}S(E)\right)$$

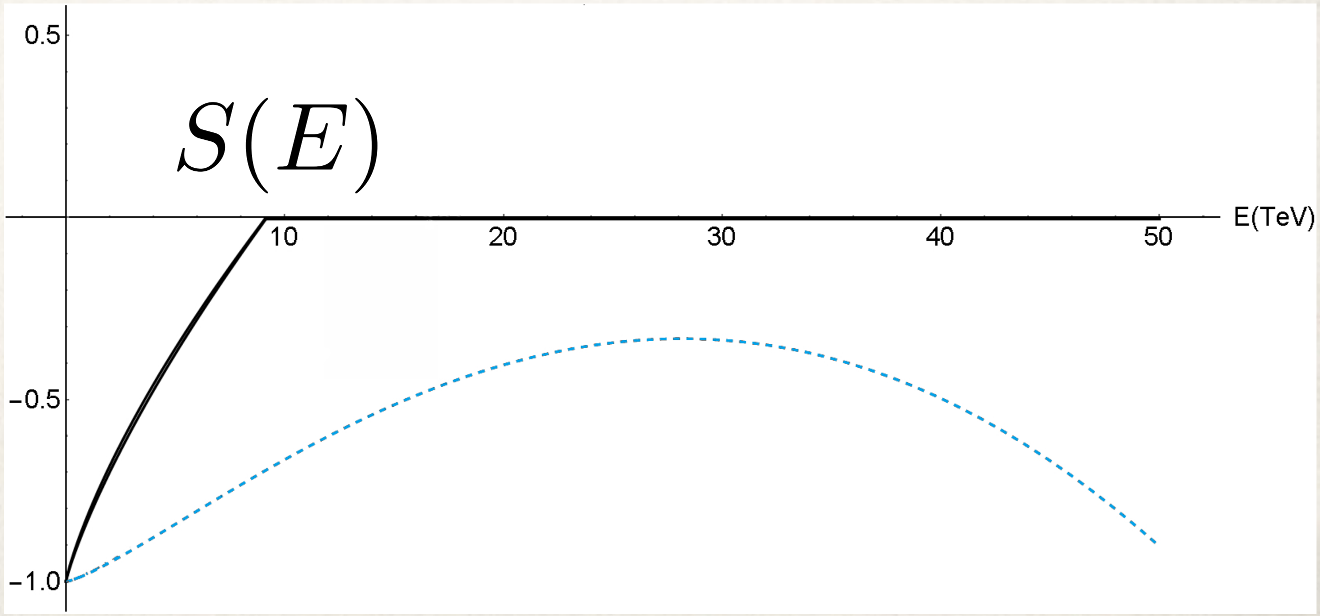
c≃2, p: unknown parameter

Here, S(E) is approximated by a fitting function.

$$S(E)=(1-a)\hat{E}+a\hat{E}^2-1$$

$$\text{for } 0\le\hat{E}\le 1$$

$$\hat{E}\equiv E/E_{\mathrm{Sph}},\ a=-0.005.$$

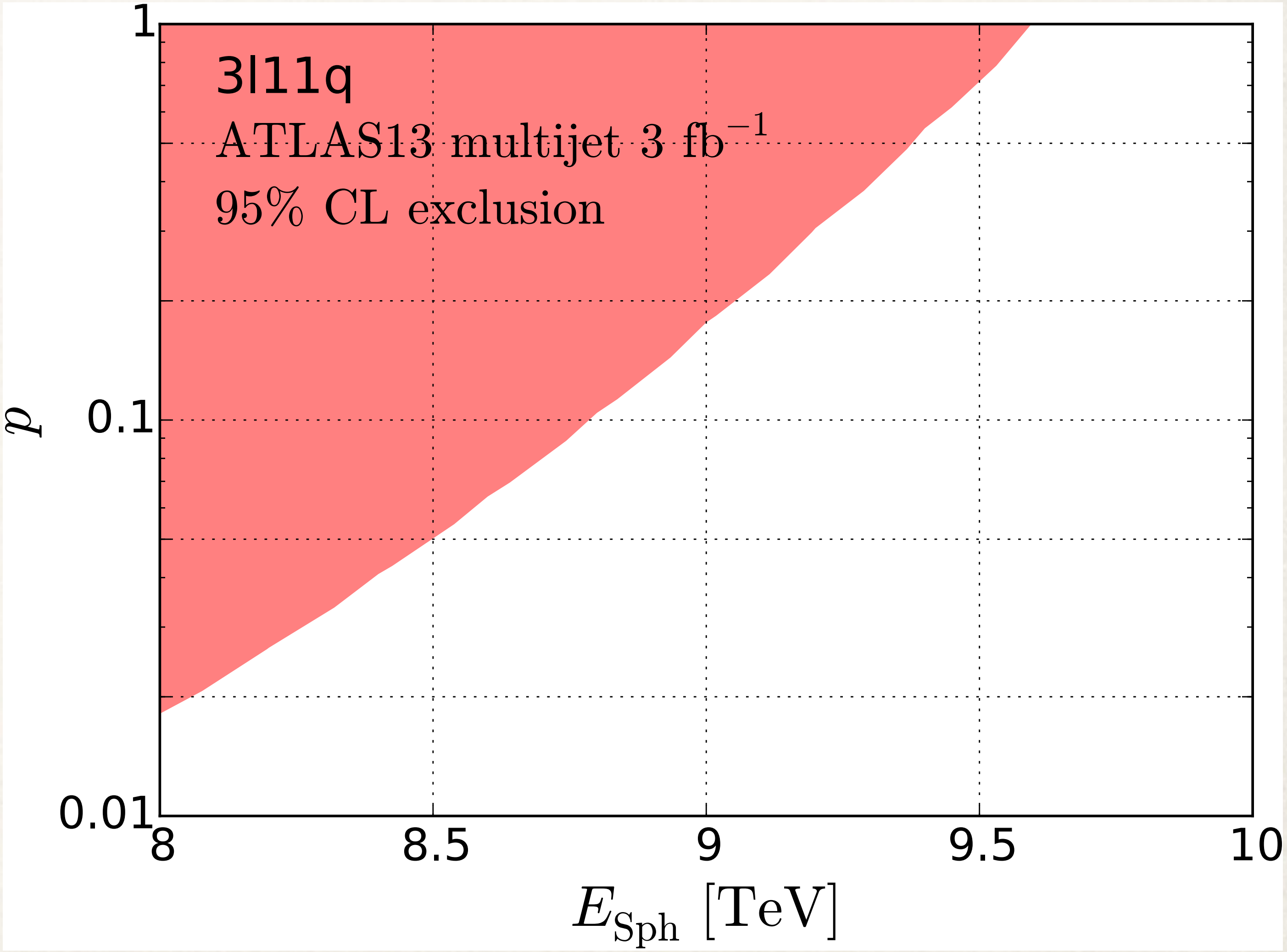


LHC analysis

Δn=-1 process: $qq \rightarrow \bar{\ell}\,\bar{\ell}\,\bar{\ell}\,\bar{q}\,\bar{q}\,\bar{q}\,\bar{q}\,\bar{q}\,\bar{q}\,\bar{q}$

Δn=+1 process: $q\,q \rightarrow \ell\,\ell\,\ell\,q\,q\,q\,q\,q\,q\,q\,q\,q\,q\,q$

Δn=+1 process



@E=E_{sph}=9TeV:

- current LHC data

  $p<0.2$

- LHC Run2 w/ 100fb^{-1}

  $p<0.01$

Q. Can $p \simeq 0.1-0.01$ be realized?

$\Delta(B+L)\neq 0$ process

[Funakubo, Otsuki, Takenaga, Toyoda, PTP87, 663 (1992), PTP89, 881 (1993)]

transition amplitude:

$$S_{fi}=\langle f|\hat{S}|i\rangle \sim \int\int \langle f|\phi(y),\pi(y)\rangle\langle\phi(y),\pi(y)|\hat{S}|\phi(x),\pi(x)\rangle\langle\phi(x),\pi(x)|i\rangle$$

path integral using coherent state $|\phi,\pi\rangle$

$\because$ appropriate for describing classical configuration

- tunneling suppression appears in the intermediate process.
- overlap issue: suppressions from $\langle f|\phi,\pi\rangle$ and $\langle\phi,\pi|i\rangle$.

This point is not properly discussed in the work of Tye and Wong.

Δ(B+L)≠0 process

[Funakubo, Otsuki, Takenaga, Toyoda, PTP87, 663 (1992), PTP89, 881 (1993)]

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path integral using coherent state |ϕ,π>

∵ appropriate for describing classical configuration

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overlap factor

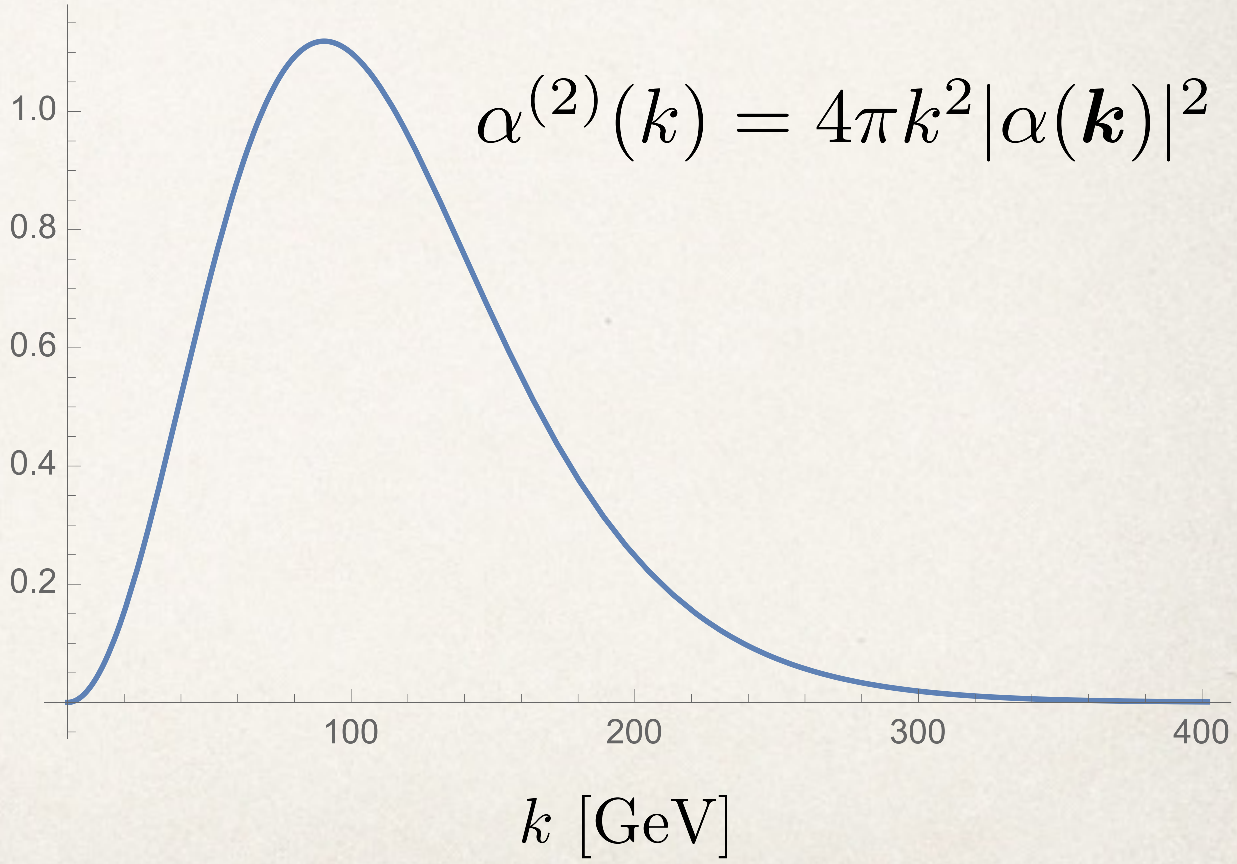
inner product between n particle state and coherent state:

$$\langle 0|\hat{a}(\boldsymbol{k}_1)\hat{a}(\boldsymbol{k}_2)\cdots\hat{a}(\boldsymbol{k}_n)|\phi(x),\pi(x)\rangle = \exp\left[-\frac{1}{2}\int d\boldsymbol{k}|\alpha(\boldsymbol{k})|^2\right]\alpha(\boldsymbol{k}_1)\alpha(\boldsymbol{k}_2)\cdots\alpha(\boldsymbol{k}_n)$$

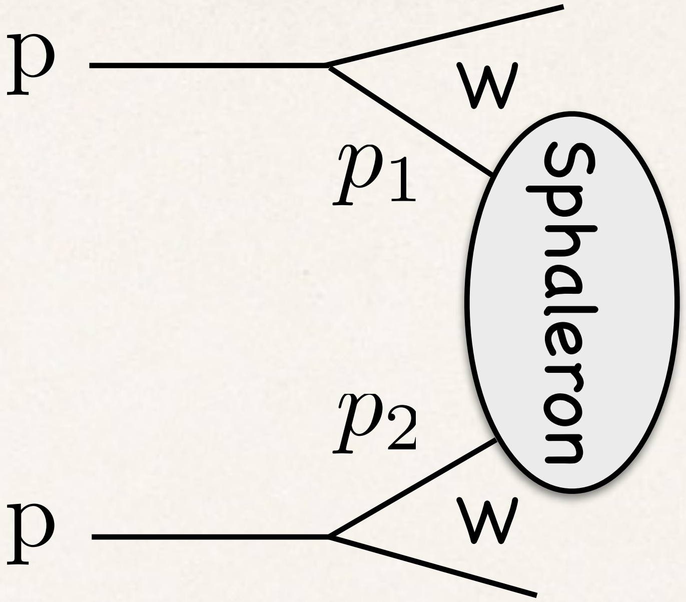
$$\alpha(k) = \int \frac{d^{d-1}\boldsymbol{x}}{(2\pi)^{d-1}}\frac{1}{\sqrt{2\omega_{\boldsymbol{k}}}}\left[\omega_{\boldsymbol{k}}\phi(x) + i\pi(x)\right]e^{-i\boldsymbol{k}\cdot\boldsymbol{x}}$$

- cross section ∝ $|\alpha_1|^2 \ldots |\alpha_n|^2$

- $|\alpha|^2$ has a peat at k=m_W.



Sphaleron at LHC



Case1: 2 -> sphaleron

For $|p_1|=|p_2|\simeq E_{sph}/2$

$$|\langle \phi(x), \pi(x) | \boldsymbol{p}_1 \boldsymbol{p}_2 \rangle|^2 \ni |\alpha(\boldsymbol{p}_1)|^2 |\alpha(\boldsymbol{p}_2)|^2$$

$$\sim e^{-\pi E_{\rm sph}/m_W} \sim \boxed{10^{-155}}$$

Creation of sphaleron from the 2 energetic particles is difficult.

Sphaleron at LHC

Case1: 2 -> sphaleron

For $|p_1|=|p_2|\simeq E_{sph}/2$

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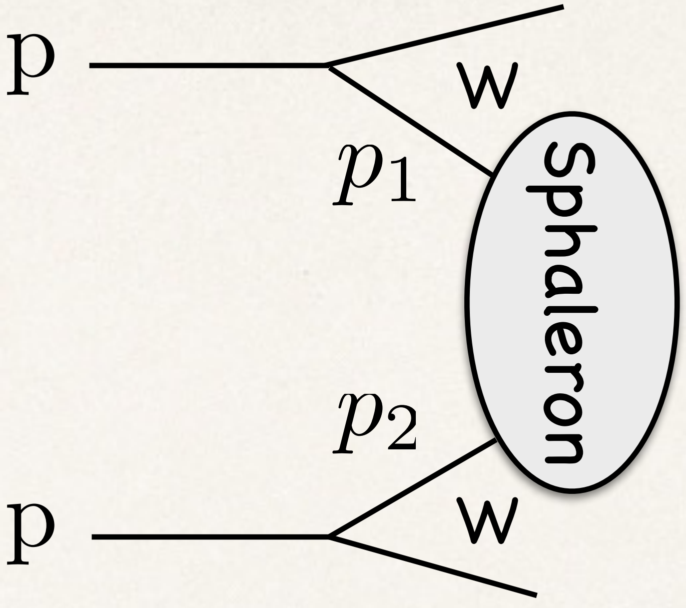
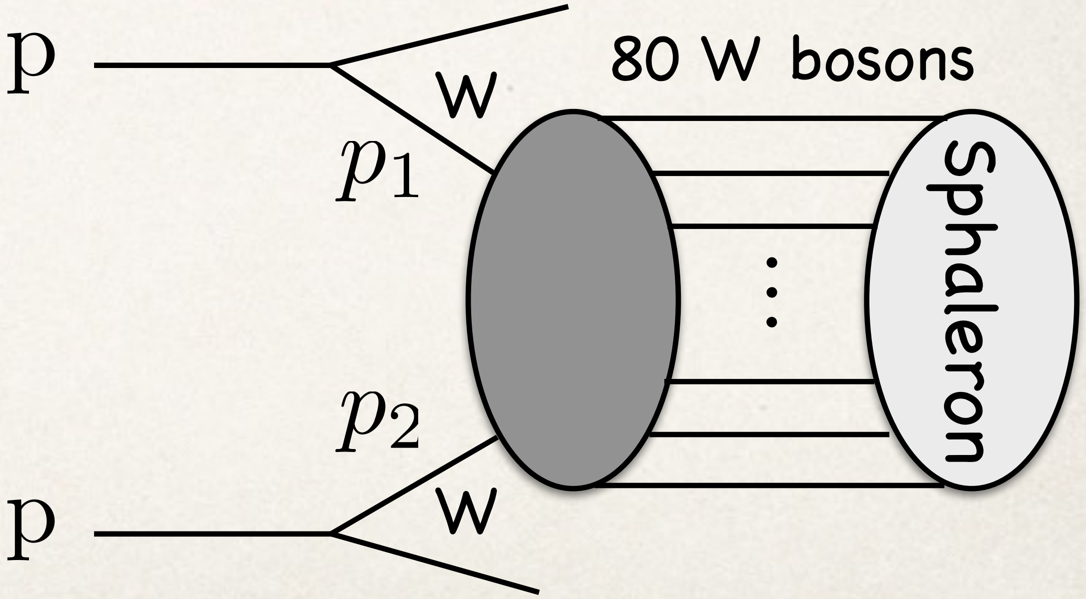


Creation of sphaleron from the 2 energetic particles is difficult.

Case2: 2 -> n W -> sphaleron

$n\simeq 80$ since $E_{sph}/\sqrt{2}m_W$

phase space factor: $\sim \left(\frac{1}{(4\pi)^2}\right)^{80} \sim \boxed{10^{-176}}$



difficult to produce about 80 W bosons.

How about high-T?

At high temperatures, the overlap suppressions do not exist.

∵

Particles with momenta $O(m_W)$ are abundant in thermal bath.

↓

sizable overlap with the classical configuration

Q. Does the band structure affect electroweak baryogengesis?

B preservation criteria

$$\underset{\substack{\uparrow \\ \text{modified?}}}{\Gamma_B^{(b)}}(T_C) < H(T_C)$$

B preservation criteria

$$\Gamma_B^{(b)}(T_C) < H(T_C)$$

↑

modified?

If yes, $\dfrac{v_C}{T_C} \gtrsim 1$ modified!

B preservation criteria

$$\Gamma_B^{(b)}(T_C) < H(T_C)$$

↑

modified?

If yes, $\frac{v_C}{T_C} \gtrsim 1$ modified!

→ EWBG-viable region must be re-analyzed!!

Vacuum decay rate at finite-T

Ordinary case: [Affleck, PRL46,388 (1981)]

$$\boxed{\begin{aligned}\Gamma_A(T) &= \frac{1}{Z_0(T)}\int_0^\infty dE\ J(E)e^{-E/T}\\ &\simeq \frac{1}{Z_0}\frac{\omega_-}{4\pi\sin\left(\frac{\omega_-}{2T}\right)}e^{-E_{\rm sph}/T} \quad \text{for } T > \underbrace{\frac{\omega_-}{2\pi}}_{\simeq 14\ \text{GeV}},\end{aligned}}$$

$$J(E) = \frac{T(E)}{2\pi},\ \ Z_0(T) = \left[2\sinh\left(\frac{\omega_0}{2T}\right)\right]^{-1},\ \ \frac{\omega_0}{g_2 v} = \underbrace{\sqrt{\frac{V''(0)}{M(0)}}}_{\simeq 0.42},\ \ \frac{\omega_-}{g_2 v} = \underbrace{\sqrt{\frac{V''(\pi/2)}{M(\pi/2)}}}_{\simeq 0.51}$$

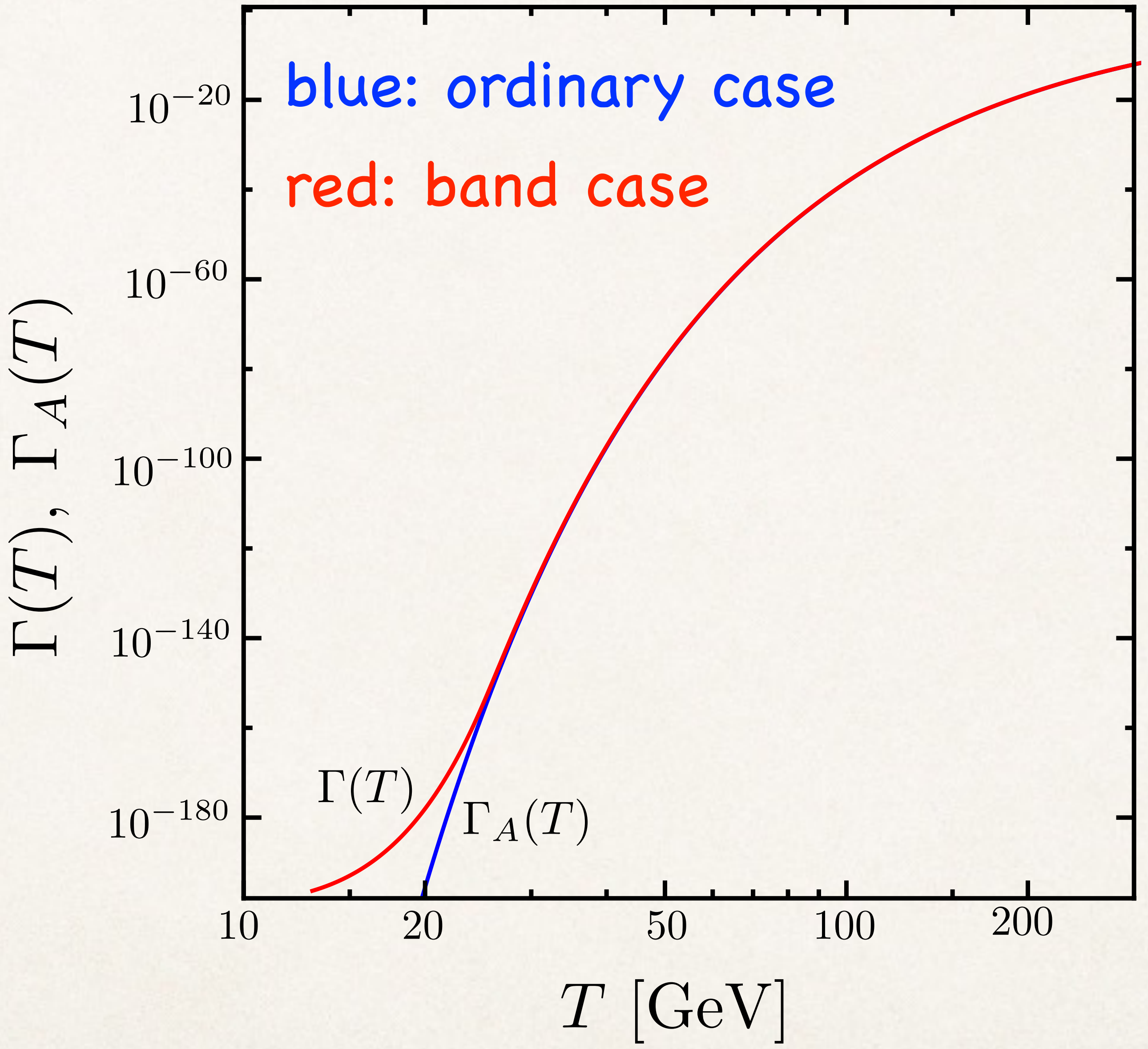
Band case: $J(E) \to \eta(E)/2\pi$

$$\boxed{\Gamma(T) = \frac{1}{Z_0(T)}\int_0^\infty dE\ \frac{\eta(E)}{2\pi}e^{-E/T}}$$

$\eta(E) = 1$ for the conducting band, $\eta(E) = 0$ for the band gap

Impact of band

For simplicity, we use the band structure obtained before.

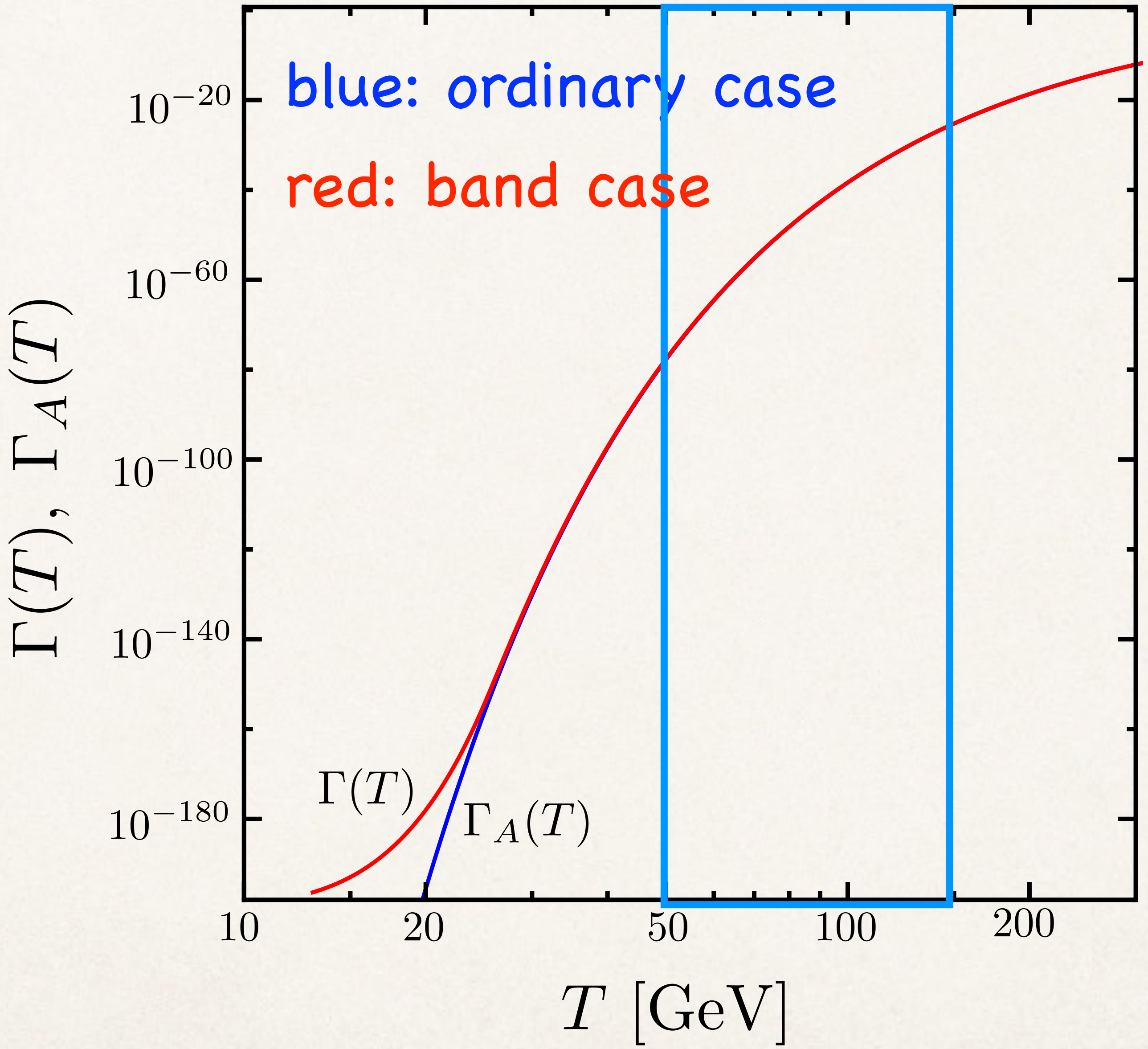


For T=100 GeV, $\Gamma / \Gamma_A = 1.06$.

How about B-number preservation criteria?

Impact of band

For simplicity, we use the band structure obtained before.



typical EWBG region

blue: ordinary case

red: band case

For T=100 GeV, $\Gamma / \Gamma_A = 1.06$.

How about B-number preservation criteria?

B preservation criteria

Γ with the band effect is

$$\Gamma(T) < H(T)$$

$$\Gamma(T) = R(T)\Gamma_A(A)$$

$$\Downarrow$$

$$E_{\rm sph} = \frac{4\pi v \mathcal{E}_{\rm sph}}{g_2}$$

$$\boxed{\frac{v(T)}{T} > \frac{g_2}{4\pi\mathcal{E}_{\rm sph}}\left[42.97 + \log\mathcal{N} + \log R(T) + \cdots\right]}$$

B preservation criteria

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zero mode factor

≃ 4.4 (MSSM)

B preservation criteria

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$\simeq$ 4.4 (MSSM)

$$\uparrow$$

$$\log R(T = 100\ \mathrm{GeV}) \simeq 0.05$$

B preservation criteria

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$\simeq$ 4.4 (MSSM)

$$\log R(T = 100\ \text{GeV}) \simeq 0.05$$

Band effect has little effect on the B preservation criteria.

Summary

- We have discussed EWBG with LFV in 2HDM.
  - some parameter space can explain h->$\mu\tau$, muon g-2, and BAU.

    300 GeV $\lesssim m_H \lesssim m_A$ for $\mathrm{Re}(\rho_{\tau\mu}\rho_{\mu\tau})>0$.
- We also discussed the band effect on the sphaleron processes at $T=0$ and $T\neq0$.
  - Even though the tunneling suppression disappears at $E \gtrsim E_{sph}$, sphaleron process in high-E collisions suffers from the overlap suppression. -> the process is unlikely to occur.
  - $T \simeq 100$ GeV, sphaleron process is virtually unaffected.

    -> no impact on EWBG.

Backup

Baryon Asymmetry of the Universe (BAU)

❒ Our Universe is baryon-asymmetric.

$$\eta_{\mathrm{BBN}} = \frac{n_B}{n_\gamma} = (5.8 - 6.6) \times 10^{-10} \ (95\% \ \mathrm{CL})$$ [PDG2016]

❒ Sakharov criteria ('67)

(1) Baryon number (B) violation
(2) C and CP violation
(3) Out of equilibrium

BAU must arise

- After inflation
- Before Big-Bang Nucleosynthesis (T≃O(1) MeV).

h->μτ and muon g-2

In 2HDM, it is easy to accommodate not only h->μτ but muon g-2. [Y. Omura, E.S., K.Tobe, JHEP05 2015028, PRD94,055019(2016)]

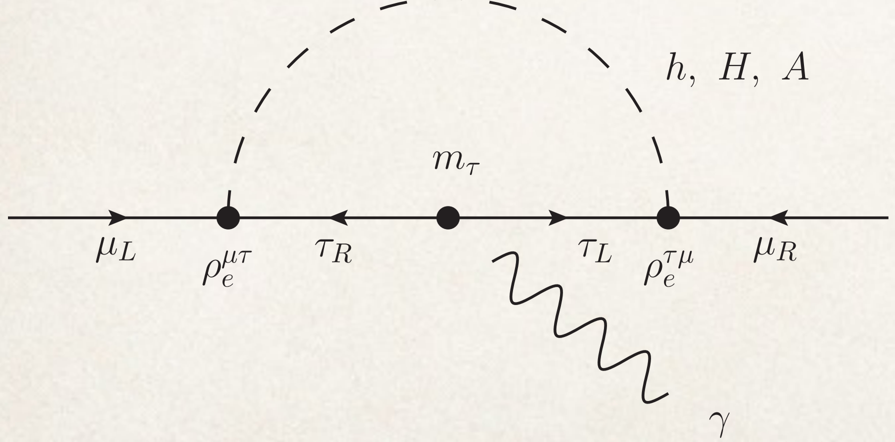
h-> μτ

$$\mathrm{Br}(h \to \mu\tau) = \frac{m_h(|\rho_{\mu\tau}|^2 + |\rho_{\tau\mu}|^2) c^2_{\beta-\alpha}}{16\pi\Gamma_h}, \quad \Gamma_h = 4.1 \text{ MeV}$$

$$\sqrt{\frac{|\rho_{\mu\tau}|^2 + |\rho_{\tau\mu}|^2}{2}} \simeq 0.26 \left(\frac{0.01}{|c_{\beta-\alpha}|}\right) \sqrt{\frac{\mathrm{Br}(h \to \mu\tau)}{0.84 \times 10^{-2}}}$$

muon g-2

$$\delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \times 10^{-10}$$



$$\delta a_\mu = \frac{m_\mu m_\tau \mathrm{Re}(\rho_{\mu\tau}\rho_{\tau\mu})}{16\pi^2} \times \left[\frac{c^2_{\beta-\alpha} f(r_h)}{m_h^2} + \frac{s^2_{\beta-\alpha} f(r_H)}{m_H^2} - \frac{f(r_A)}{m_A^2}\right]$$

$$f(r) \simeq \ln\frac{1}{r} - \frac{3}{2}$$

Appropriate mass differences among (m_h, m_H, m_A) are needed.

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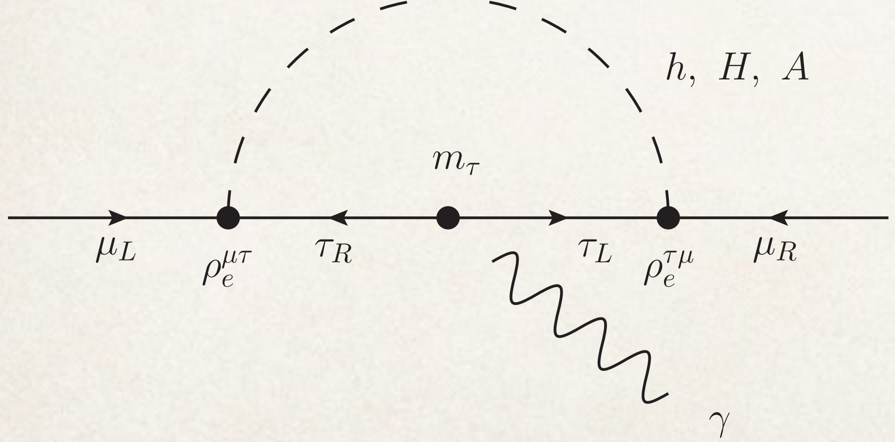

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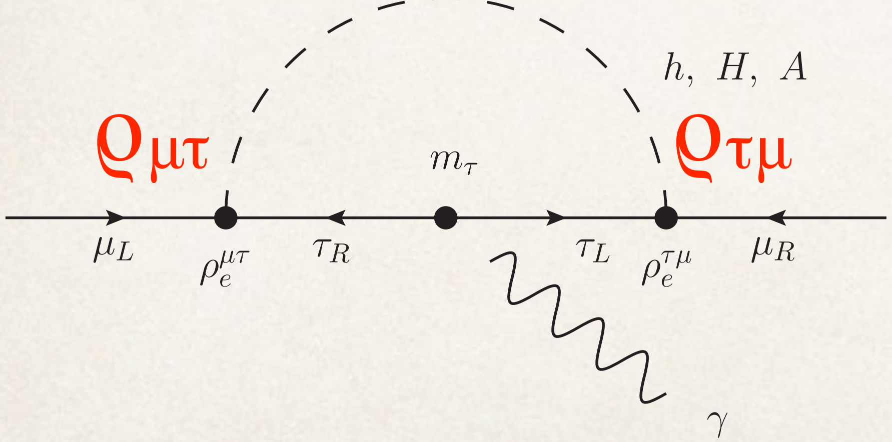

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$$f(r) \simeq \ln\frac{1}{r} - \frac{3}{2}$$

Appropriate mass differences among (m_h, m_H, m_A) are needed.

Baryon number density

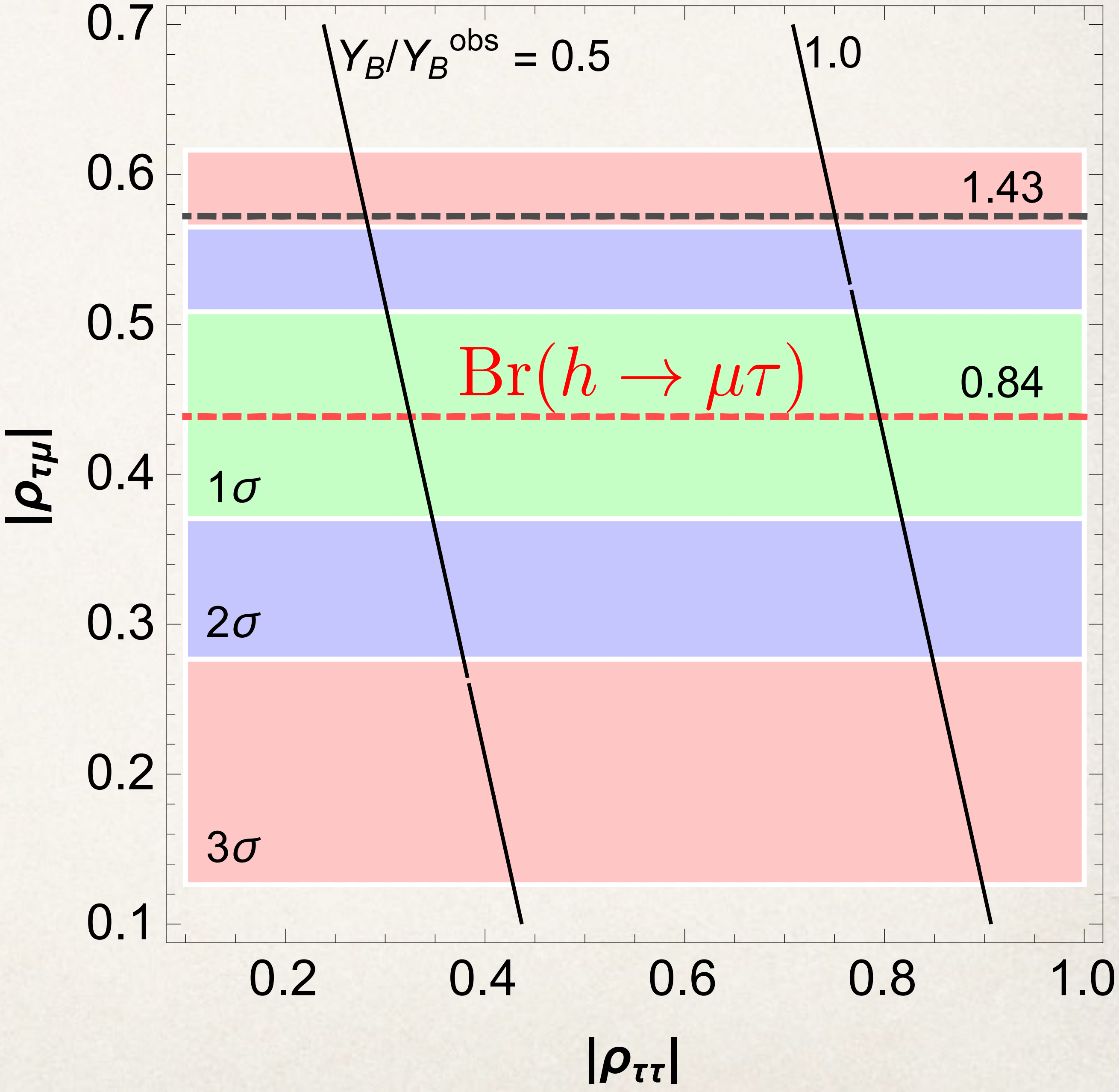
$m_H = 350$ GeV, $m_A = m_{H^\pm} = 400$ GeV, $c_{\beta-\alpha} = 0.006$, $|\rho_{\mu\tau}| = |\rho_{\tau\mu}|$
$\phi_{\tau\mu} + \phi_{\mu\tau} = \pi/4$, $\phi_{\tau\tau} = \pi/2$

$$Y_B \propto \mathrm{Im}\Big[(Y_1)_{32}(Y_2)^*_{32}\Big]$$

is a function of $\rho_{\tau\tau}$, $\rho_{\tau\mu}$ and $\rho_{\mu\tau}$

- Leading effect: $\rho_{\tau\tau}$

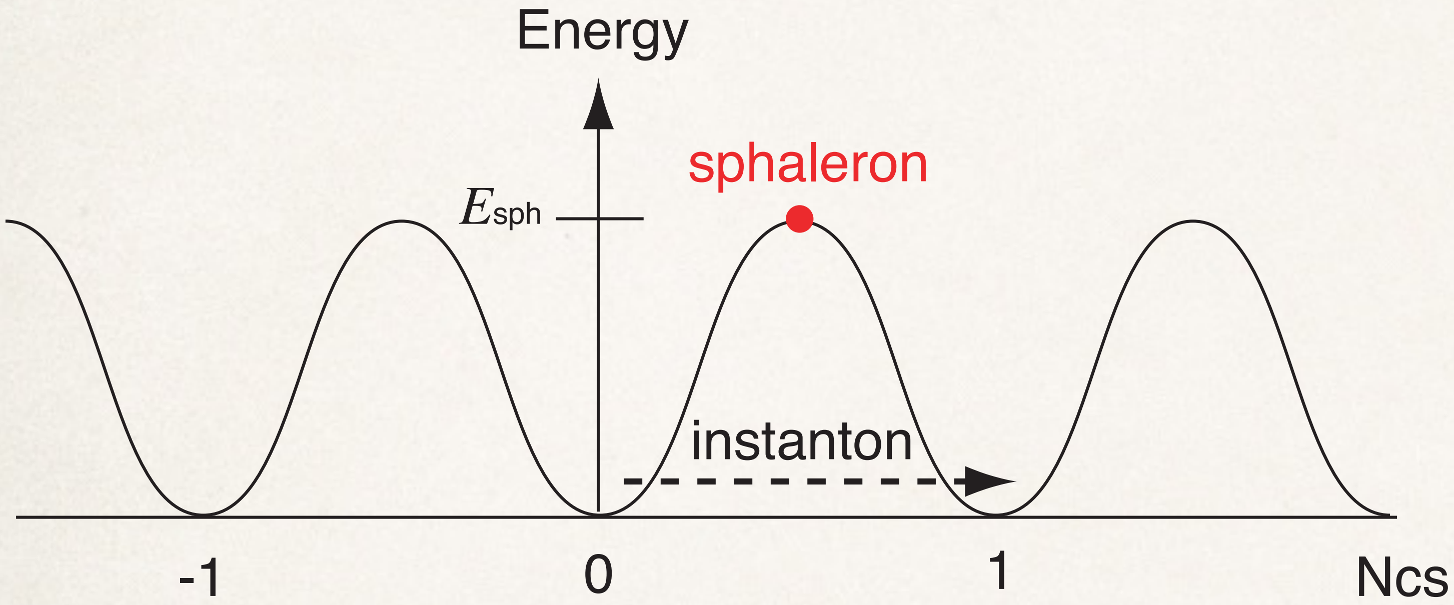
- Subheading effect: $\rho_{\tau\mu}$ and $\rho_{\mu\tau}$.



2HDM with LFV explains h->μτ, muon g-2, and BAU.

Sphaleron

- A static saddle point solution w/ finite energy of the gauge-Higgs system. [N.S. Manton, PRD28 ('83) 2019]



$\underline{\Delta B \neq 0}$

Instanton: quantum tunneling

Sphaleron: thermal fluctuation

B+L anomaly

$$\partial_\mu j^\mu_{B+L} = \frac{3}{16\pi^2}\left[g_2^2 \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right],$$

$$\partial_\mu j^\mu_{B-L} = 0,$$

$$\Delta B = 3\Delta N_{CS} \qquad N_{CS} = \frac{g_2^2}{32\pi^2}\int d^3x\ \epsilon_{ijk}\mathrm{Tr}\left[F_{ij}A_k - \frac{2}{3}g_2 A_i A_j A_k\right]$$

Eigenvalue problem

Hamiltonian:

$$\hat{H}(\mu,p)=g_2 v\left[\hat{p}\frac{1}{2M(\hat{\mu})}\hat{p}+V(\hat{\mu})\right], \qquad [\hat{\mu},\hat{p}]=i$$

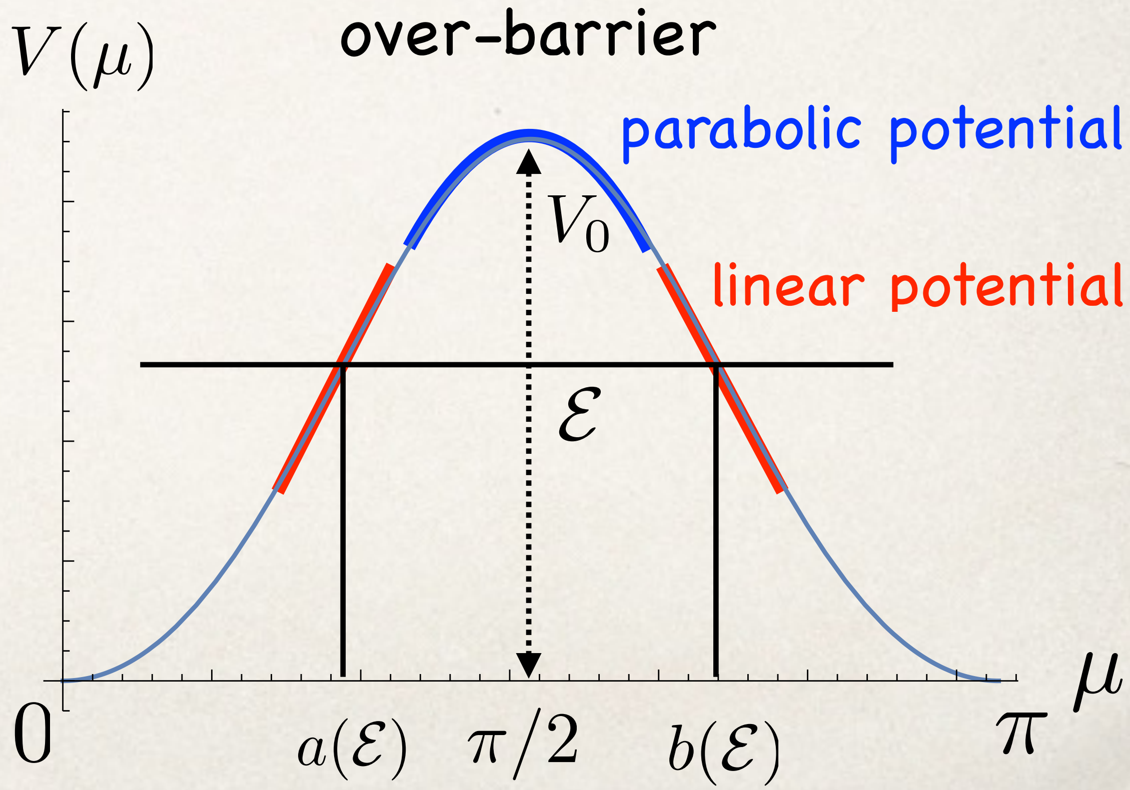
Band energy is determined by solving [N.L.Balazs, Ann.Phys.53,421 (1969)]

$$\boxed{\cos(\Phi(\mathcal{E}))=\pm\sqrt{T(\mathcal{E})}}$$

with 3 connection formulas depending on energy.

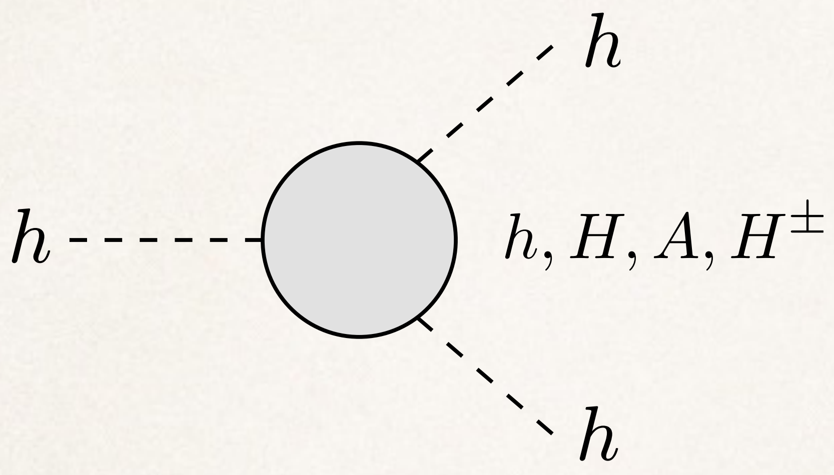
$$\Phi(\mathcal{E})=\begin{cases}\dfrac{1}{\hbar}\displaystyle\int_{b(\mathcal{E})}^{a(\mathcal{E})}d\mu\ p(\mu) & \text{for } \mathcal{E}<V_0,\\ \dfrac{1}{\hbar}\displaystyle\int_{-\pi/2}^{\pi/2}d\mu\ p(\mu) & \text{for } \mathcal{E}\geq V_0,\end{cases}$$

$$p(\mu)=\sqrt{M(\mu)(\mathcal{E}-V(\mu))}$$



hhh coupling in the 2HDM

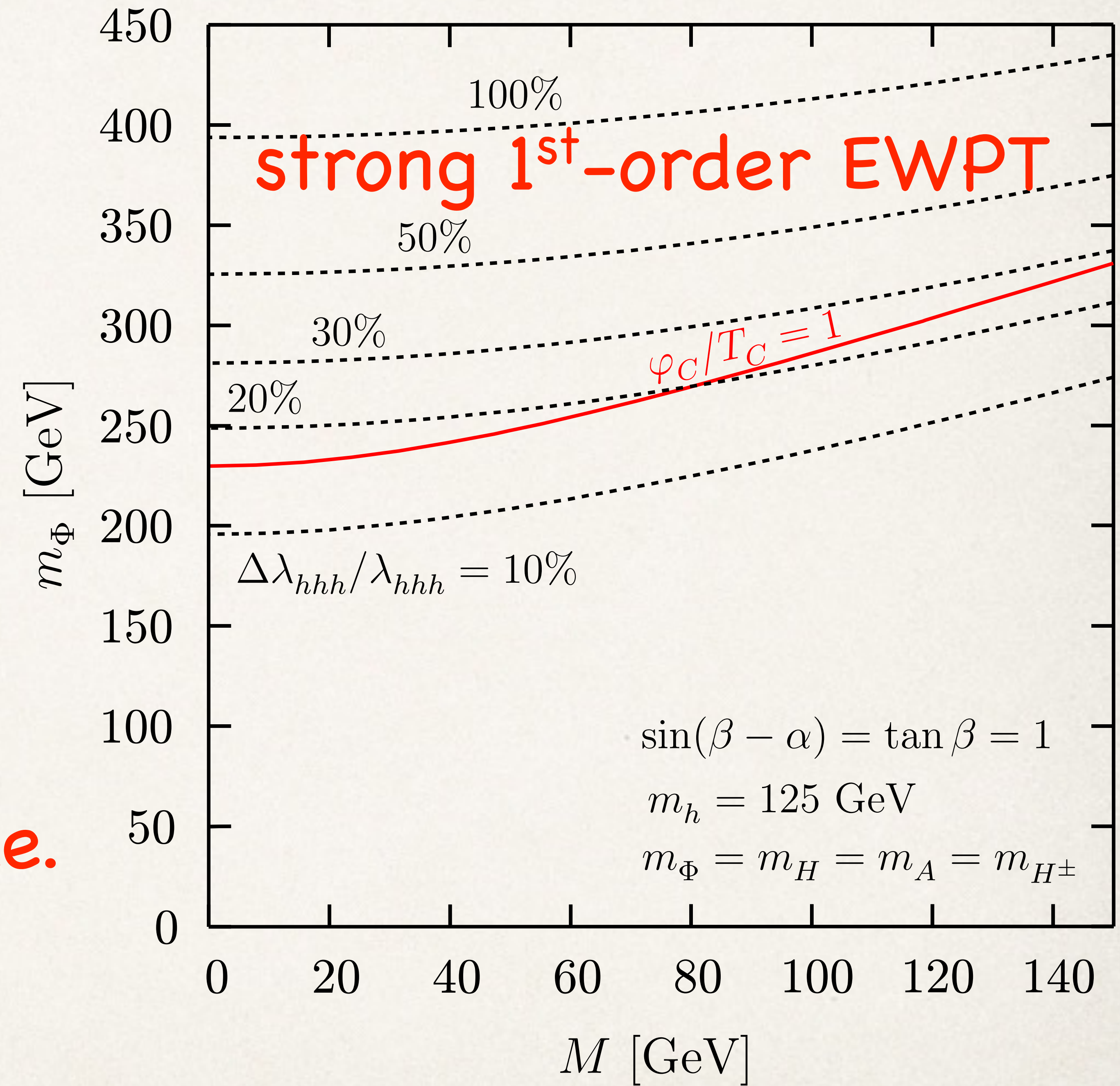
[update of Kanemura, Okada, E.S., PLB606,(2005)361]



- 1^{st}-order EWPT is induced by heavy Higgs bosons.

- hVV and hff can be SM-like.

- $\Delta\lambda_{hhh}>(15\text{-}20)\%$

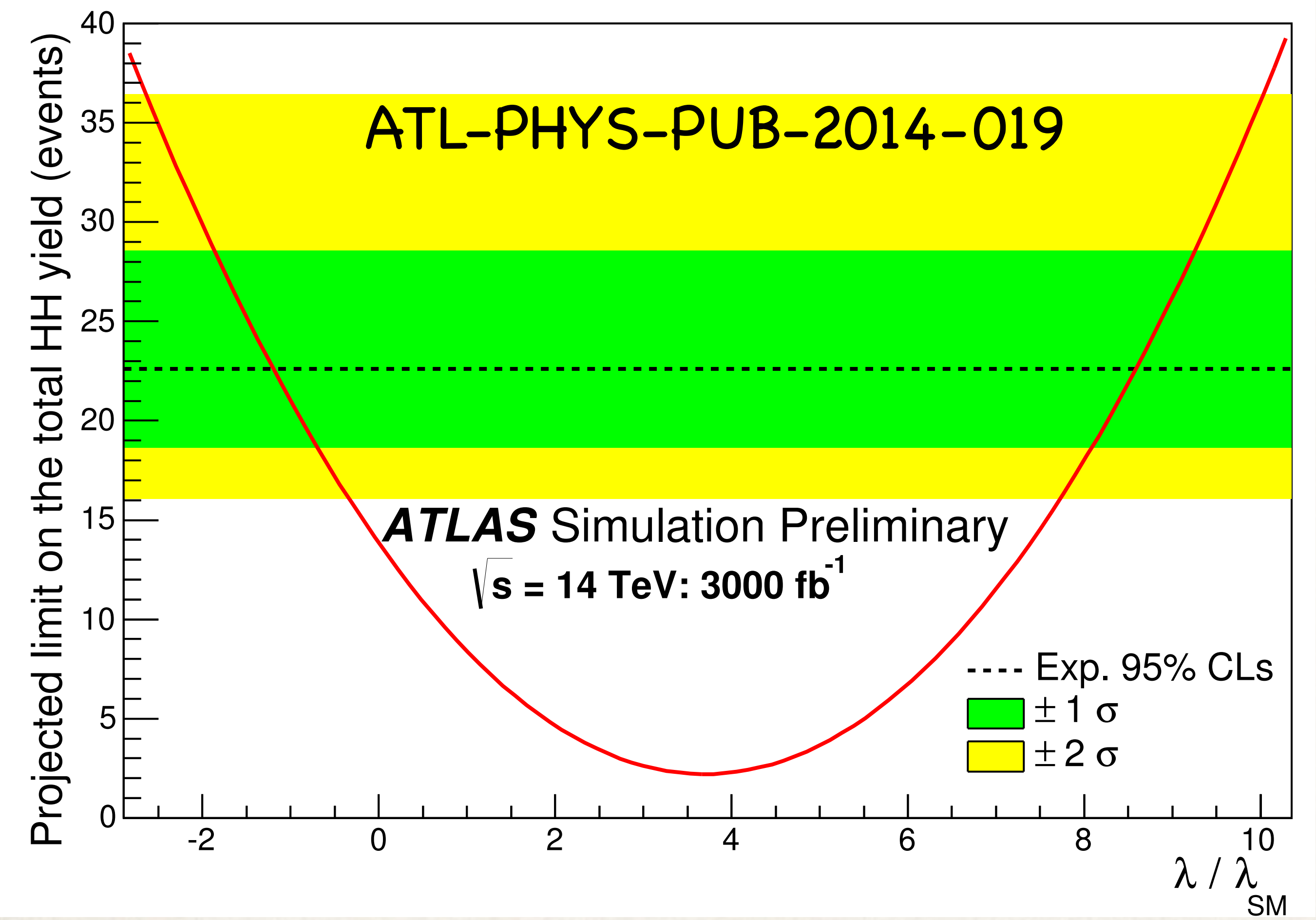


strong 1^{st}-order EWPT

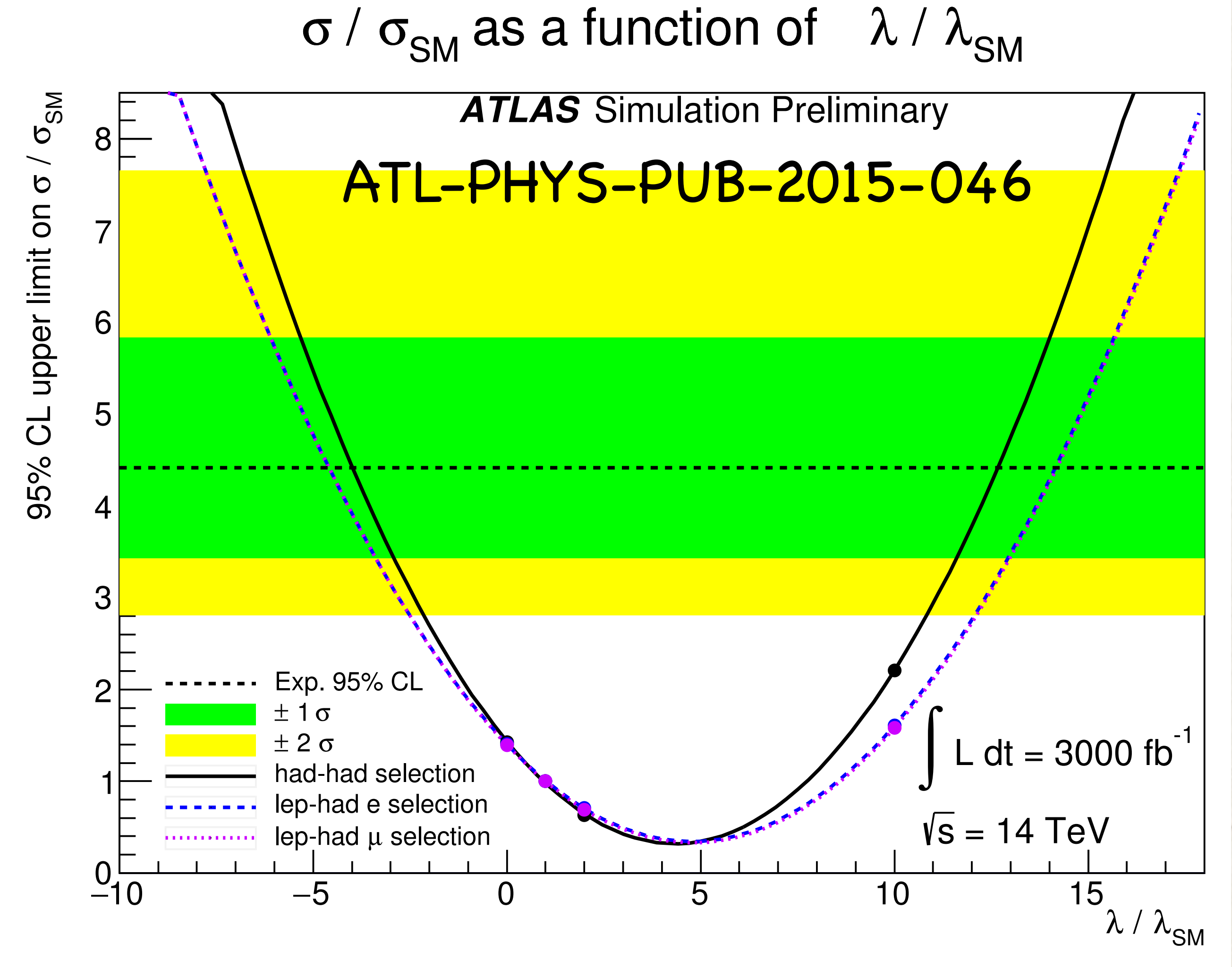
$$M = \sqrt{\frac{m_3^2}{\sin\beta\cos\beta}}$$

hhh coupling at LHC

$HH \to bb\gamma\gamma$

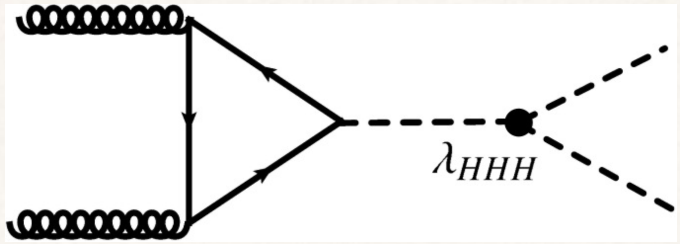


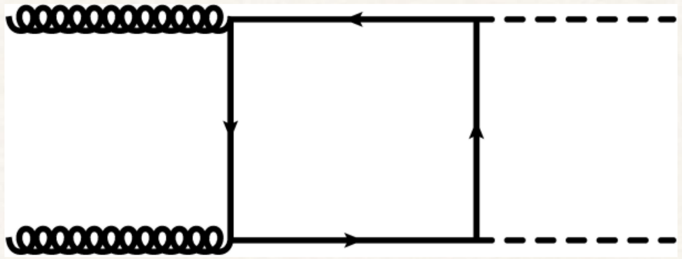
$HH \to bb\tau\tau$


σ / σSM as a function of λ / λSM

Access to λ_{hhh} of 2HDM at the LHC is challenging.

hhh coupling at LHC





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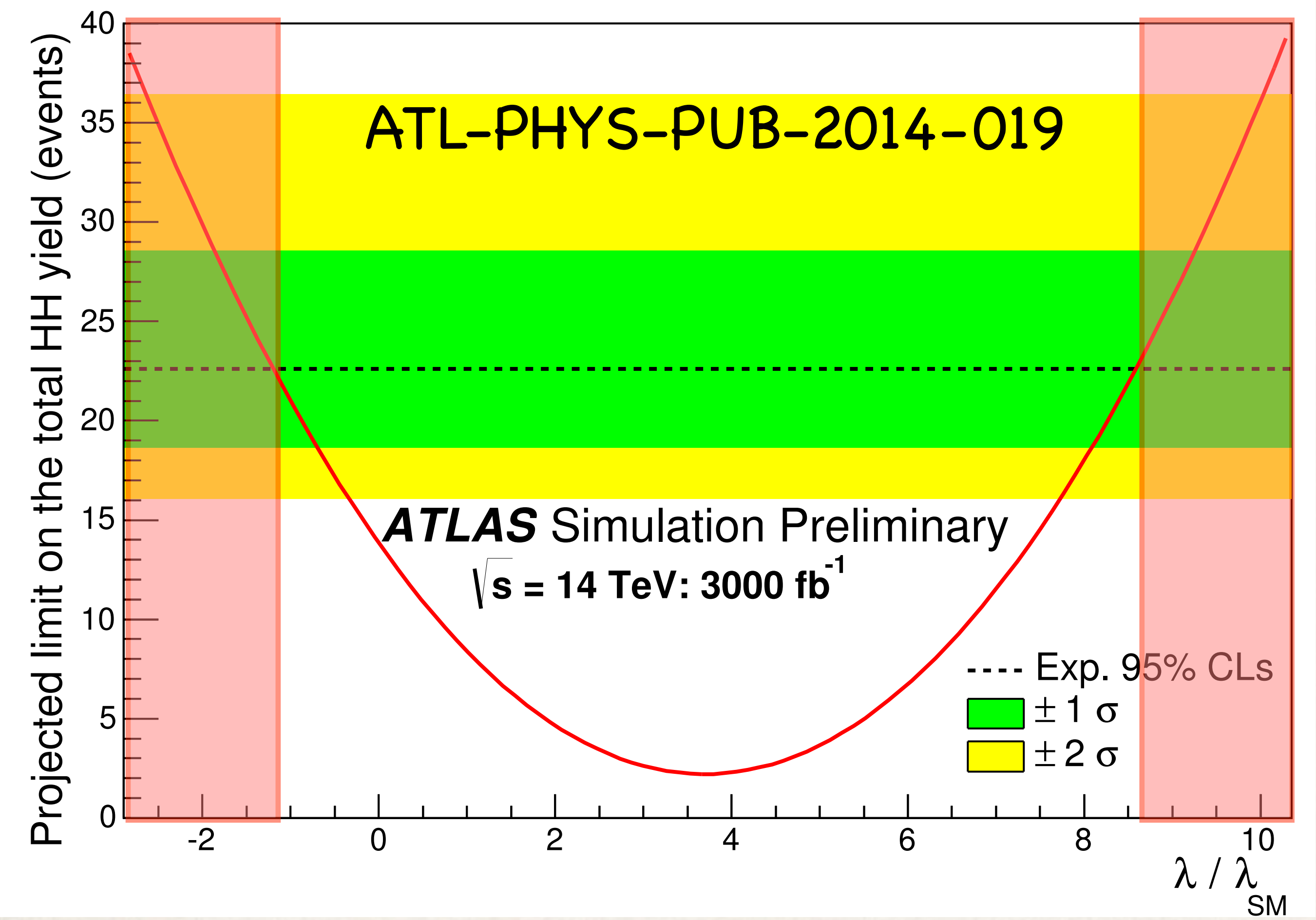

ATL-PHYS-PUB-2014-019

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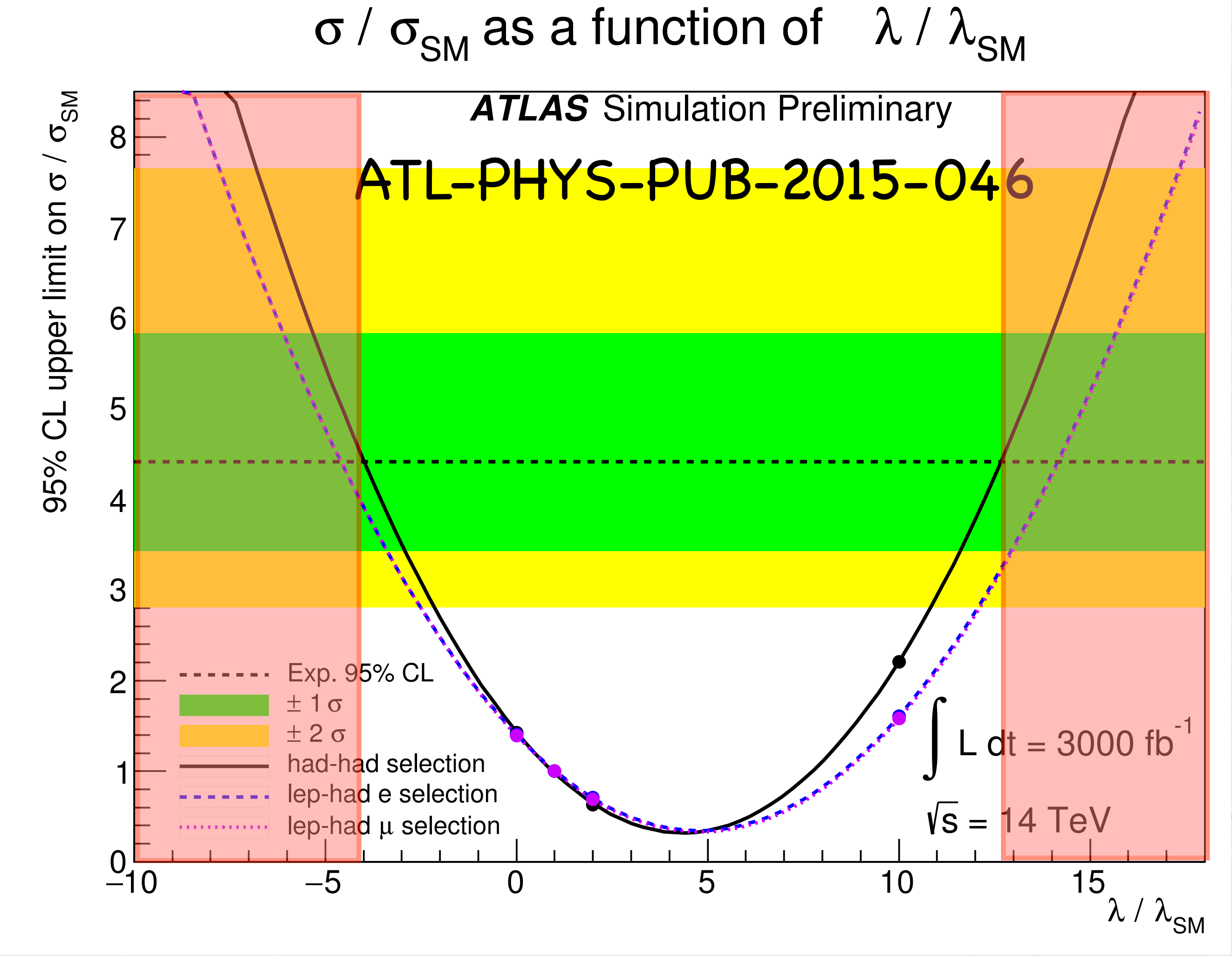

ATL-PHYS-PUB-2015-046

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Higgs couplings measurements@ILC

ILC white paper, 1310.0763

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.8 %	1.1 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.1 %	1.9 %
$b\bar{b}$	5.3 %	1.6 %	1.3 %	0.7 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.6 %	0.9 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.0 %
$\mu^+\mu^-$	91%	91%	16 %	10 %
$\Gamma_T(h)$	12 %	4.9 %	4.5 %	2.3 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %

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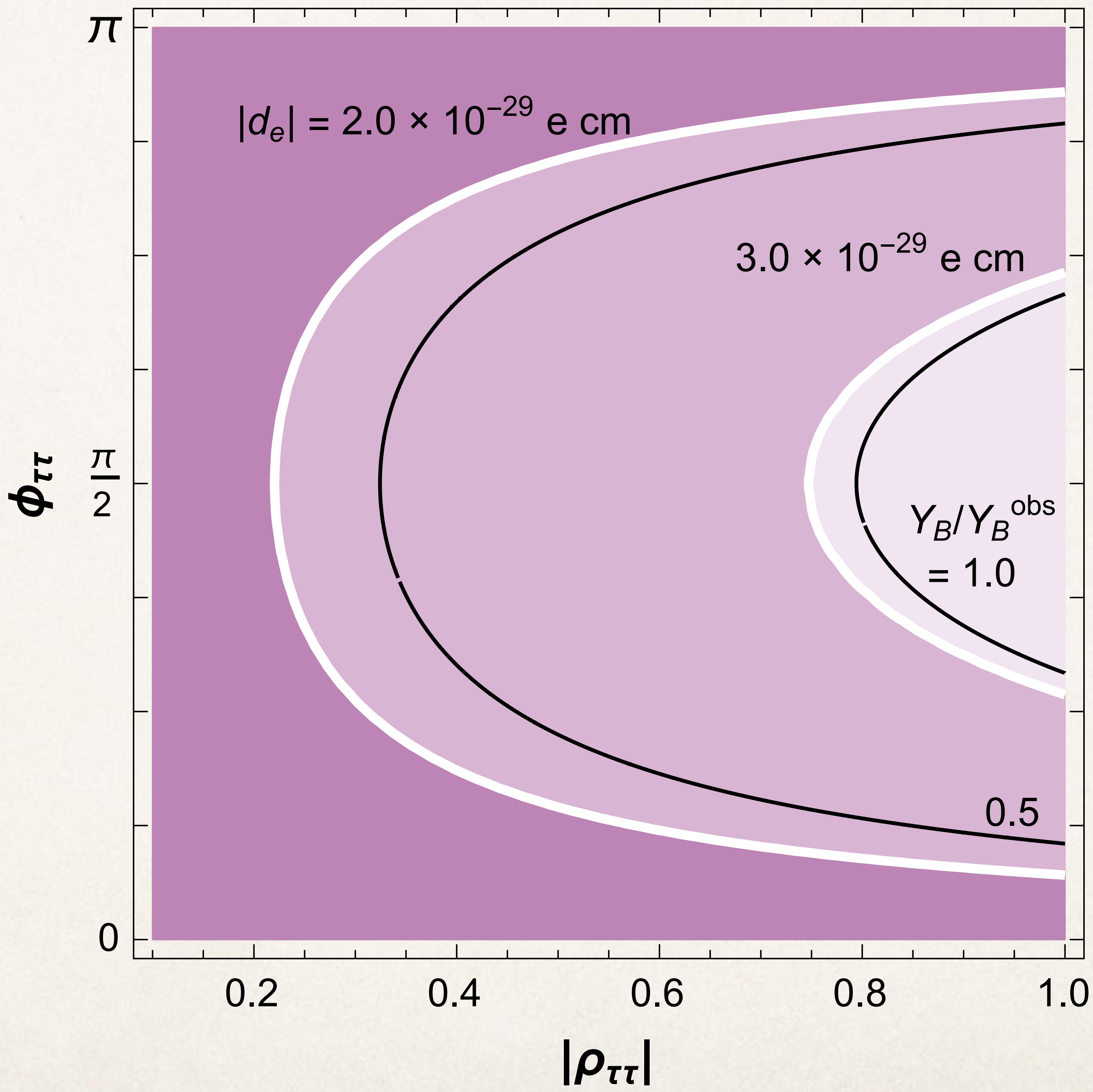
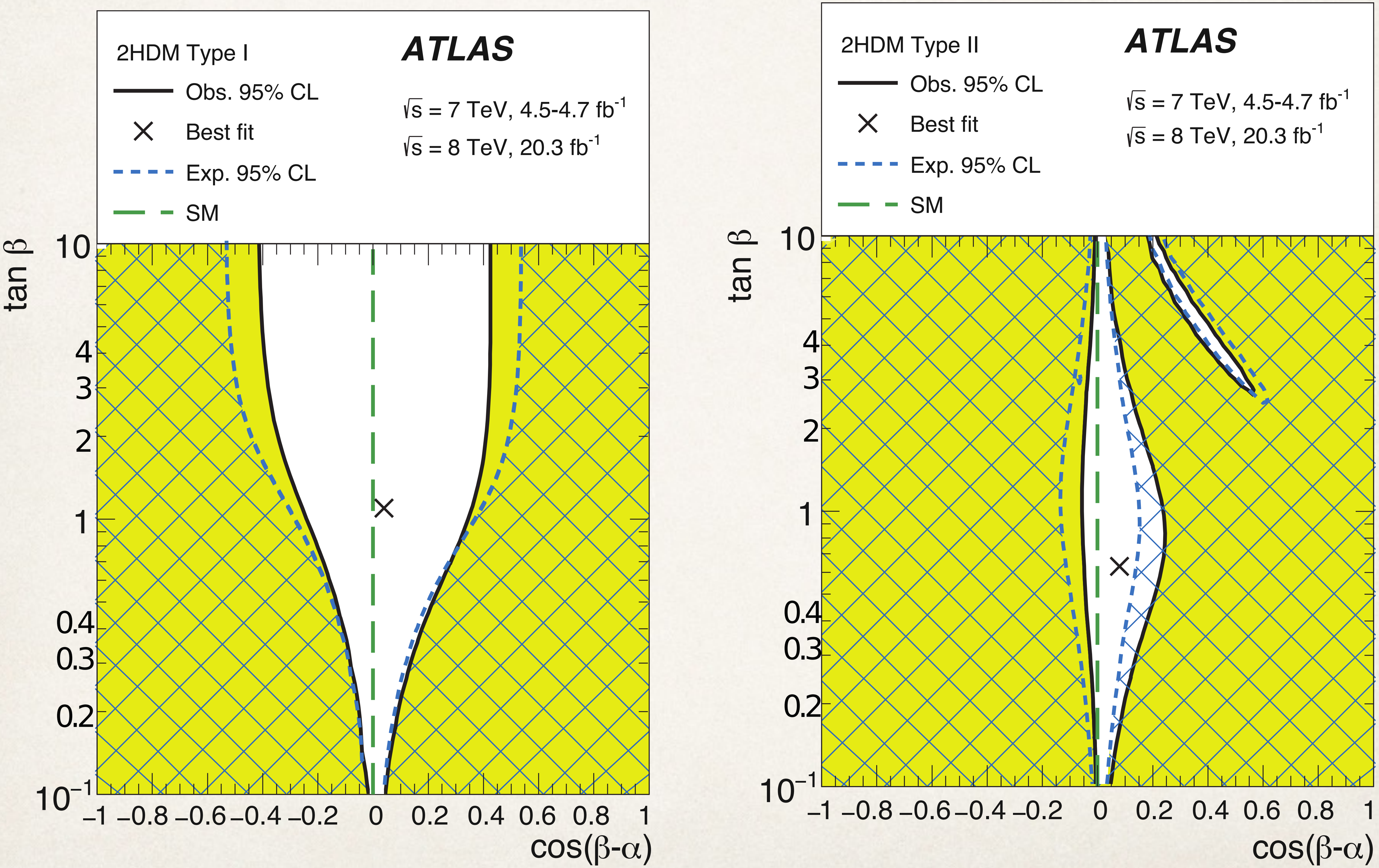
BAU vs. electron EDM



Constraints in (cos($\beta-\alpha$), tanβ) plane

arXiv:1509.00672



(a) Type I

(b) Type II

Constraint on μ-τ coupling

1502.07400