Flavor Violation and Electroweak Baryogenesis

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(arXiv:1609.09849)

ITP-CAS

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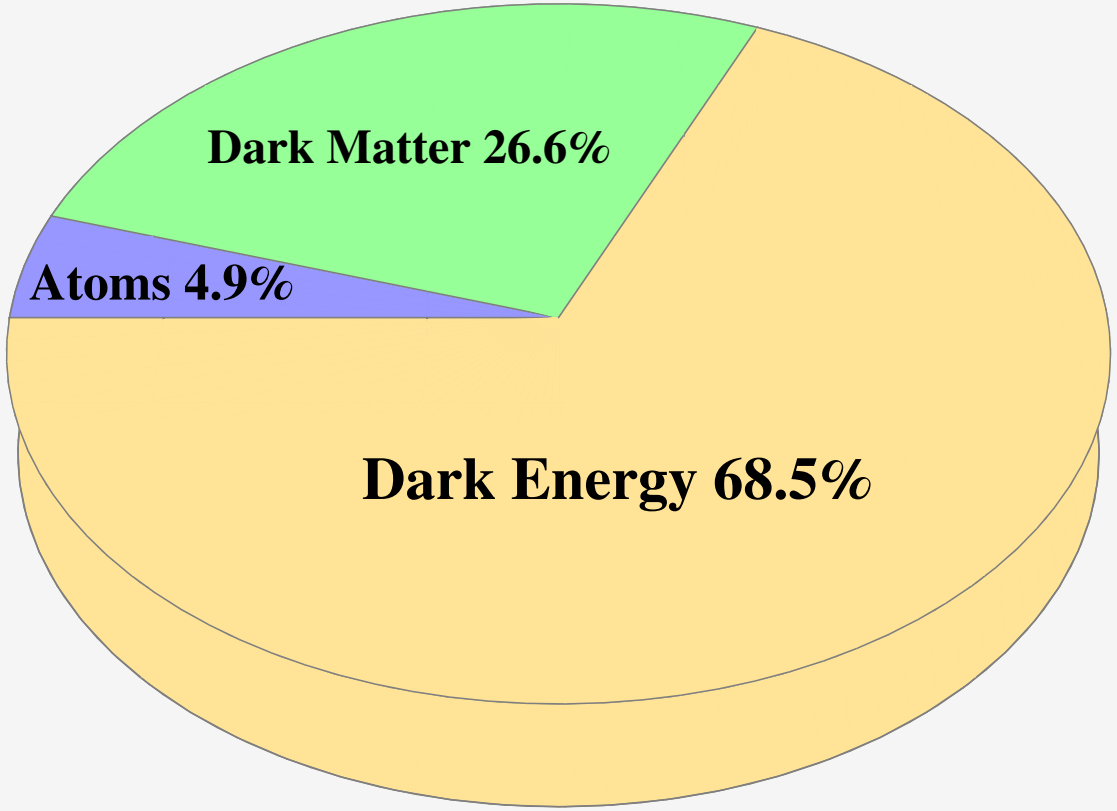
The Matter/Energy Budget of our Universe



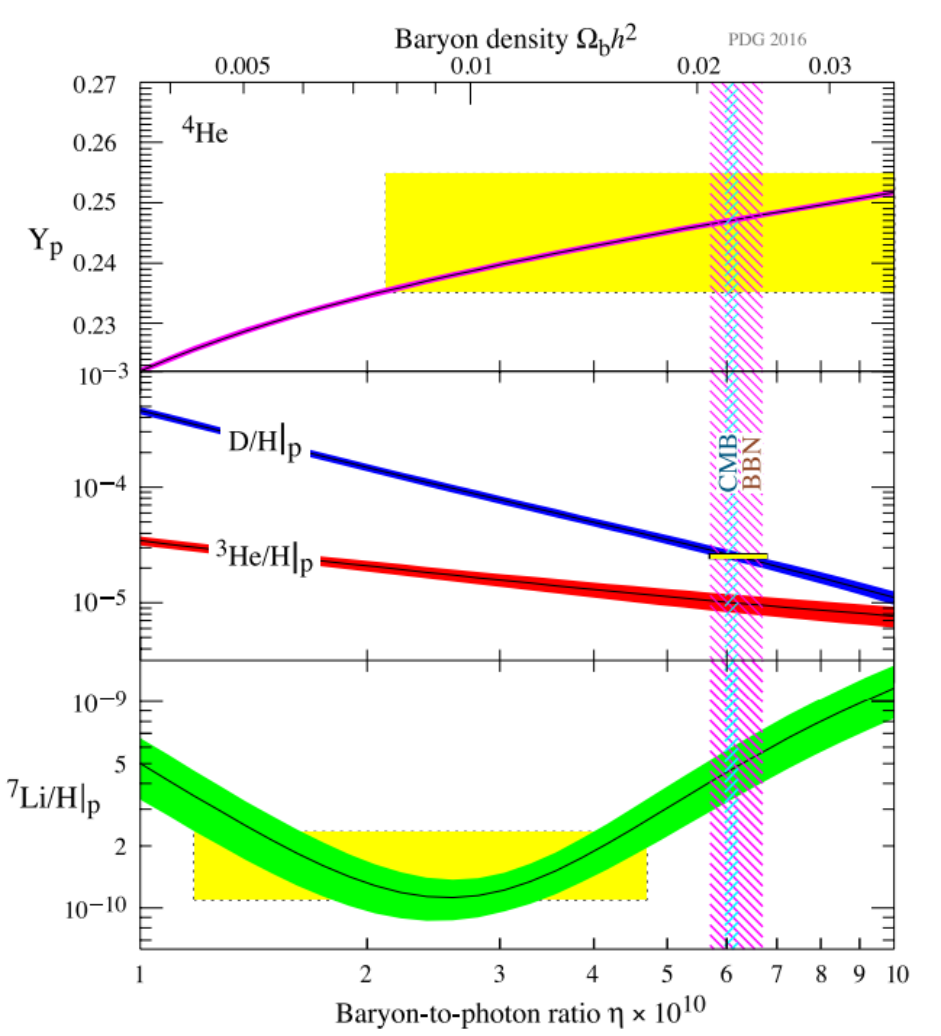
Planck, 2013. Astron.Astrophys. (2014)

Cosmological Parameters from Planck

Parameter	*Planck* TT+lowP+lensing
$\Omega_b h^2$	0.02226 ± 0.00023
$\Omega_c h^2$	0.1186 ± 0.0020
$100\theta_{MC}$	1.04103 ± 0.00046
τ	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.062 ± 0.029
n_s	0.9677 ± 0.0060
H_0	67.8 ± 0.9
Ω_m	0.308 ± 0.012
$\Omega_m h^2$	0.1415 ± 0.0019
$\Omega_m h^3$	0.09591 ± 0.00045
σ_8	0.815 ± 0.009
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088
Age/Gyr	13.799 ± 0.038
r_{drag}	147.60 ± 0.43
k_{eq}	0.01027 ± 0.00014

Planck 2015 Fit of the base ΛCDM at 68% CL, arxiv:1502.01582v2

Big Bang NucleoSynthesis



PDG 2015, Rev.Mod.Phys,88,015004

Baryon Asymmetry

A very tiny imbalance

$$\eta = \frac{n_B}{n_\gamma} \sim 10^{-10} \qquad \rightarrow \qquad \boxed{\text{Baryogenesis}}$$

Sakharov Conditions for Baryogenesis, 1967

- ◊ B Violation (Electroweak Sphalerons)
- ◊ C, CP Violation
- ◊ Out of equilibrium
  (Expansion of Universe, First-Order Phase Transition)

Mechanisms of Baryogenesis

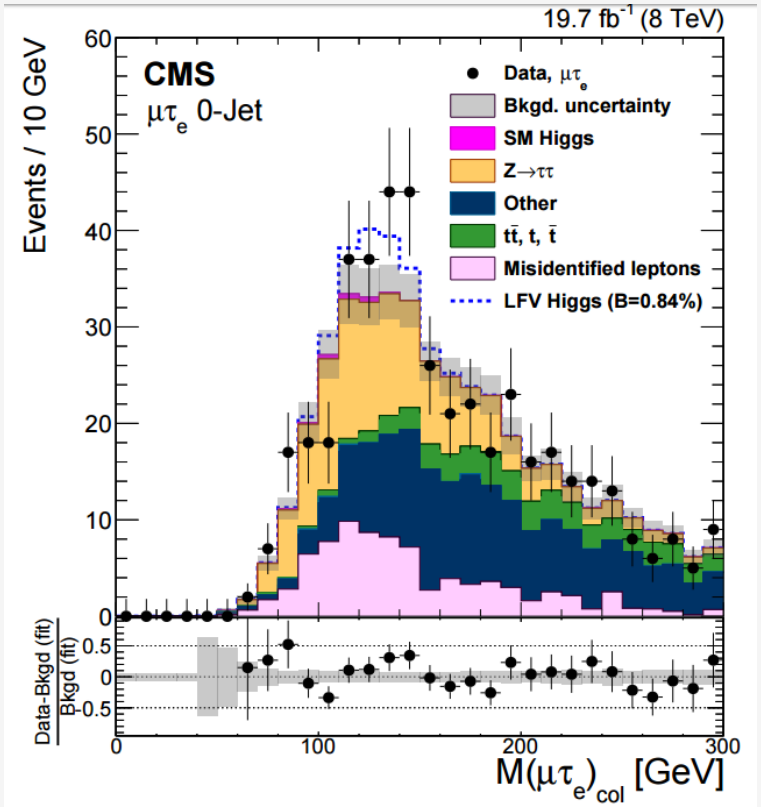
- ◊ GUT Baryogenesis ($\sim 10^{16}$GeV)
- ◊ Affleck-Dine mechanism
- ◊ Modified Cosmology Model
- ◊ Baryogenesis via Leptogenesis
- ◊ Spontaneous Baryogenesis
- ◊ Electroweak Baryogenesis ($\sim$ 100GeV)

Electroweak Baryogenesis: An Application

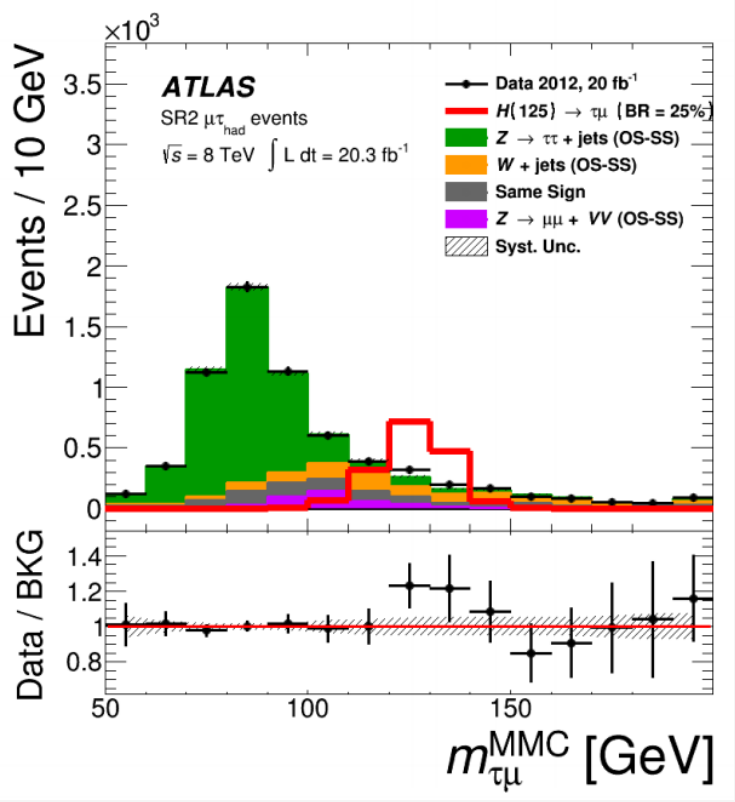
A lepton-flavored Electroweak Baryogenesis scenario (arxiv:1609.09849)

- CP nature of the Higgs boson
- Flavor nature of the Higgs boson
- EDM

$h \to \tau\mu$



Phys.Lett.B07,053



arXiv:1508.03372

$$\mathrm{Br}(h \to \tau\mu) = \begin{cases} < 1.85\% & \text{ATLAS 2015} \\ < 1.51\% & \text{CMS 2015, Best Fit } 0.84^{+0.39}_{-0.37} \end{cases}$$

LFV → New Physics → CPV ?

New physics from an extended Leptonic Yukawa sector ?

↓

Also need CP-violation for baryogenesis

↓

Two Higgs Doublet Model

↑

A SM Limit Exists

Potentials

Convential Form:

$$
\begin{aligned}
V_H = & \, m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) \\
& + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + h.c. \right]
\end{aligned}
$$

A different form:

$$
V_H = \sum_{a,b=1}^{2} \mu_{ab} \, \Phi_a^\dagger \Phi_b + \frac{1}{2} \sum_{a,b,c,d=1}^{2} \lambda_{ab,cd} \left(\Phi_a^\dagger \Phi_b \right) \left(\Phi_c^\dagger \Phi_d \right) ,
$$

Types of 2HDM

The Four types of 2HDM with no LFV.

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Phys.Rept.2012.02.002

To have LFV $\rightarrow$ Couple e_R^i to both doublets

CPV - Invariant

How to properly define a CPV source

↓

Jarlskog-like Invariant

CPV in SM: the CKM Matrix

$$V_{\text{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Rephasing Invariant Quantities:

- $|V_{ij}|^2$
- $V_{\alpha i}V_{\beta j}V^*_{\alpha j}V^*_{\beta i} \rightarrow$ Imaginary Part corresponds to CPV

Condition 2: CPV in SM: Jarlskog Invariant

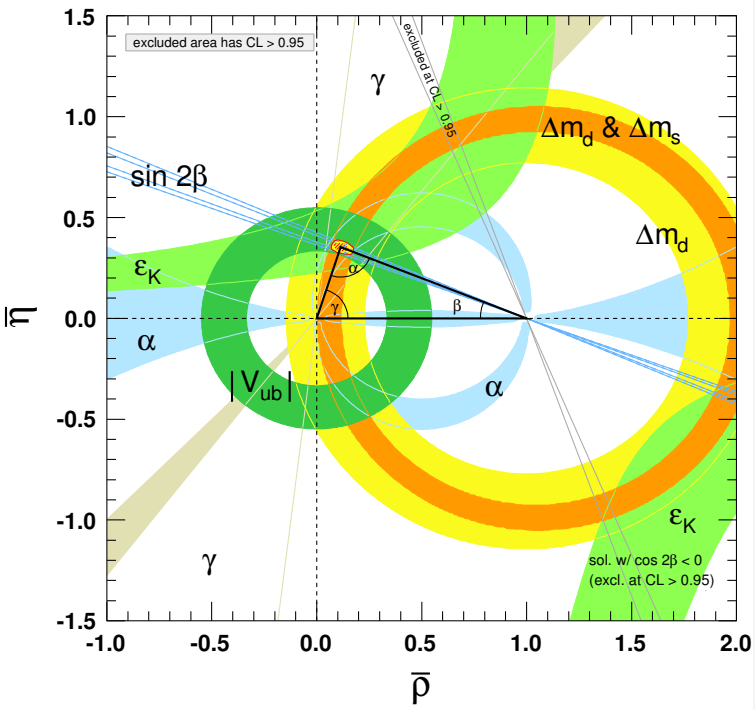


Fig. 12.2, PDG, 2014

$$J = c_1 s_1^2 c_2 s_2 c_3 s_3 \sin\delta = 3.06^{+0.21}_{-0.20} \times 10^{-5}$$

$$J' = \frac{\det[m_u^2, m_d^2]}{(100\text{GeV})^{12}} \sim 10^{-20}$$

Not large enough! $\Rightarrow$ New Physics

CPV Invariant in SM

Rephasing Invariants

$$Q_{\alpha i \beta j} = V_{\alpha i} V_{\beta j} V^*_{\alpha j} V^*_{\beta i}. \quad \alpha \neq \beta, \quad i \neq j, \quad \xrightarrow{\text{CKM Unitarity}} \quad \boxed{J \equiv \mathrm{Im} Q_{1122}}$$

$\downarrow$

Jarlskog, Dunietz, Greenberg, Wu 1985.

$$\det[M_U, M_D] = 2i \boxed{(m_t - m_u)(m_t - m_c)(m_c - m_u)(m_b - m_d)(m_b - m_s)(m_s - m_d) J}$$

$\downarrow$

Branco, Lavoura, Silva, 1999. $(H_f \equiv M_f M_f^\dagger)$

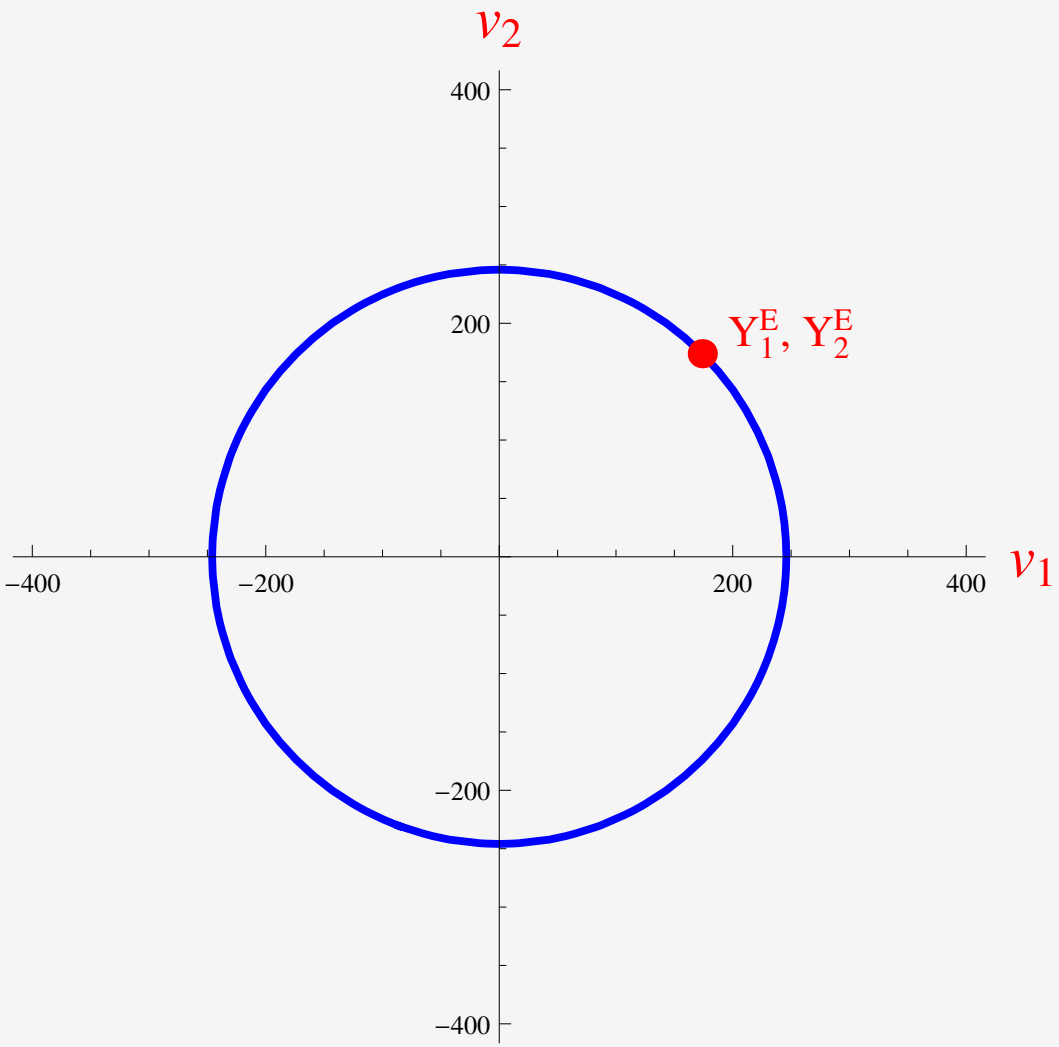
$$\mathrm{tr}([H_U, H_D]^3) = 6i \boxed{(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) J}$$

Symmetries in Type III 2HDM

$$e_R'^{\,i} = U(e_R)_{ij} e_R^j,$$

$$E_L'^{\,i} = U(E_L)_{ij} E_L^j,$$

$$\Phi_i' = U(\Phi)_{ij} \Phi_j$$



The CPV Flow

Botella, Silva, 1995

$$\boxed{J_E = \frac{1}{v^2 \mu_{12}^{\rm HB}} \sum_{a,b,c=1}^{2} v_a v_b^* \mu_{bc} \sum_{ij=\tau,\mu} (Y_c^E)_{ij} (Y_a^{E\dagger})_{ji}}$$

$$\mathrm{Im} J_E = \begin{cases} \text{Gauge Basis: } -Y^E_{2,\tau\mu} \mathrm{Im} Y^E_{2,\tau\mu} & \Rightarrow \quad \text{Baryon Asymmetry} \\ \\ \text{Mass Basis: } \quad 2 m_\tau \mathrm{Im} N^E_{\tau\tau}/v^2 & \Rightarrow \quad \text{CP-violating } h\bar{\tau}\tau \end{cases}$$

Transport Equations

$$
\begin{aligned}
\partial_\mu Q_3^\mu &= \Gamma_{mt}(\xi_T - \xi_{Q_3}) + \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) + 2\Gamma_{ss}\delta_{ss}, \\
\partial_\mu H &= \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) + \Gamma_\tau(\xi_{E_3} - \xi_{\tau_R} - \xi_H) - 2\Gamma_h H, \\
\partial_\mu E_3^\mu &= -\Gamma_{m\tau}(\xi_{E_3} - \xi_{\tau_R}) - \Gamma_\tau(\xi_{E_3} - \xi_{\tau_R} - \xi_H) + S_{\tau_L}^{C/P}, \\
\partial_\mu {\tau_R}^\mu &= -\Gamma_\tau(\xi_H + \xi_{\tau_R} - \xi_{E_3}) + \Gamma_{m\tau}(\xi_{E_3} - \xi_{\tau_R}) + S_{\tau_R}^{C/P}, \\
\partial_\mu T^\mu &= -\Gamma_{mt}(\xi_T - \xi_{Q_3}) - \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) - \Gamma_{ss}\delta_{ss}, \\
\partial_\mu \mu_R^\mu &= S_{\mu_R}^{C/P}, \qquad (10)
\end{aligned}
$$

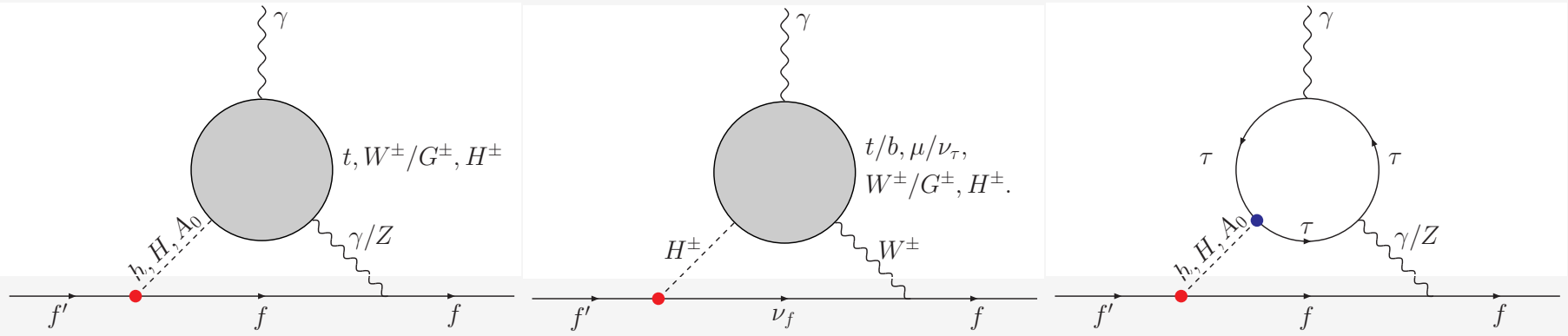
Phenomenological Implications

- $h \to \tau^{\pm}\mu^{\mp}$
- $\tau \to \mu\gamma$
- EDM
- Higgs signal strength $h \to \bar{\tau}\tau$

EDM, MDM and $\tau \to \mu\gamma$

$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \text{ 90C.L., BaBar, PhysRevLett.104.021802}$$

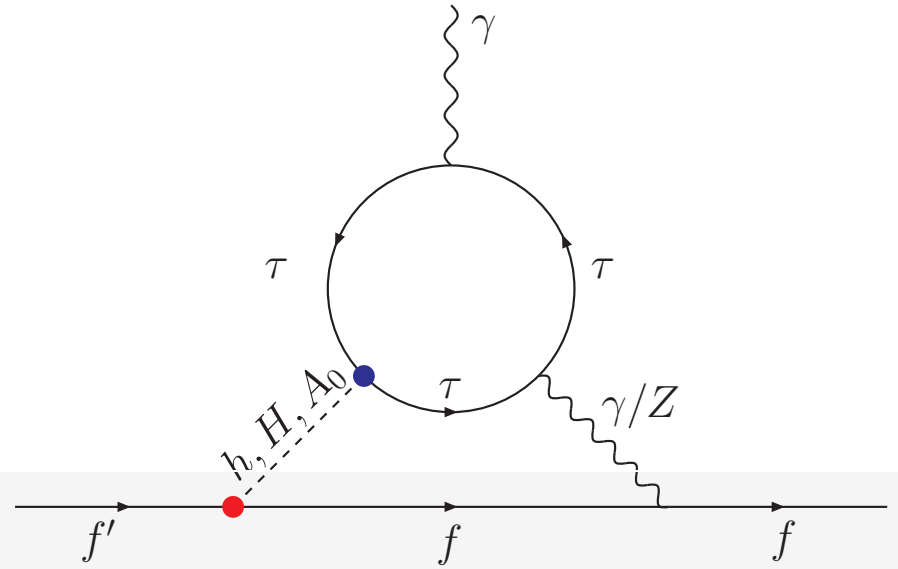
Two Loop:



One Loop:

$$\text{No CPV from } h\tau\mu: \; N^E_{\tau\mu} N^E_{\mu\tau} = 0$$

EDM

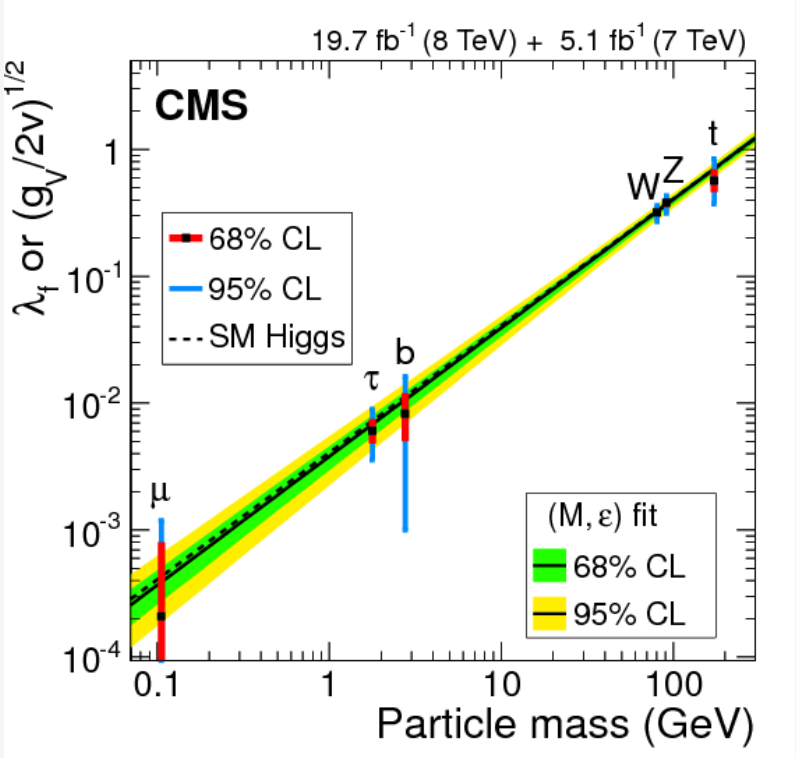


$$\left|\frac{d_e}{e}\right| \approx 1.87 \times 10^{-29} |\mathrm{Im} y_\tau|$$

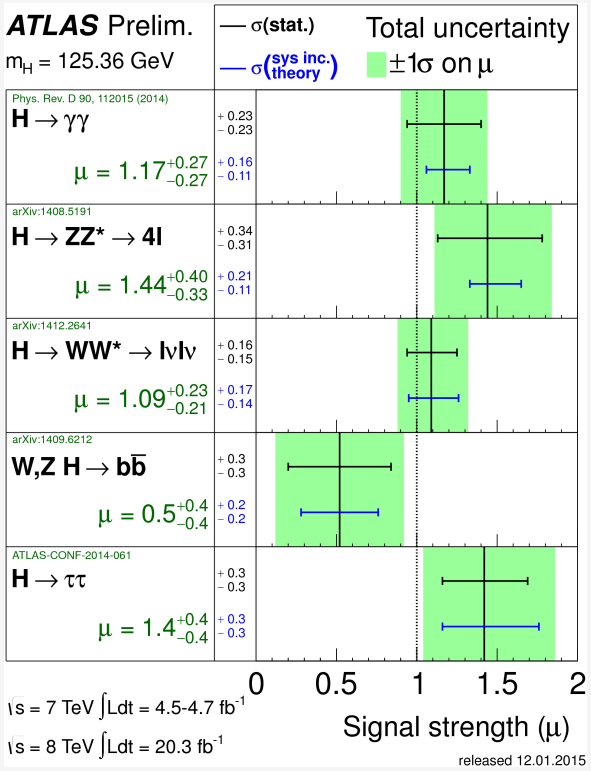
$$\boxed{\text{ACME 2014: } \left|\frac{d_e}{e}\right| < 8.7 \times 10^{-29} e \cdot \mathrm{cm}}$$

$$\boxed{|\mathrm{Im} y_\tau| < 4.66 \rightarrow \text{CPV is less constrained}}$$

$h \to \tau\tau$



JHEP1405,104



JHEP1504,117

$$\mu_{\tau\tau} = \begin{cases} 1.43^{+0.43}_{-0.37} & \text{ATLAS 2015} \\ 0.78 \pm 0.27 & \text{CMS 2014} \end{cases}$$

A CP-violating $h\bar{\tau}\tau$

$$-\frac{m_f}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau+\sin\phi_\tau\bar{\tau}i\gamma_5\tau)h$$

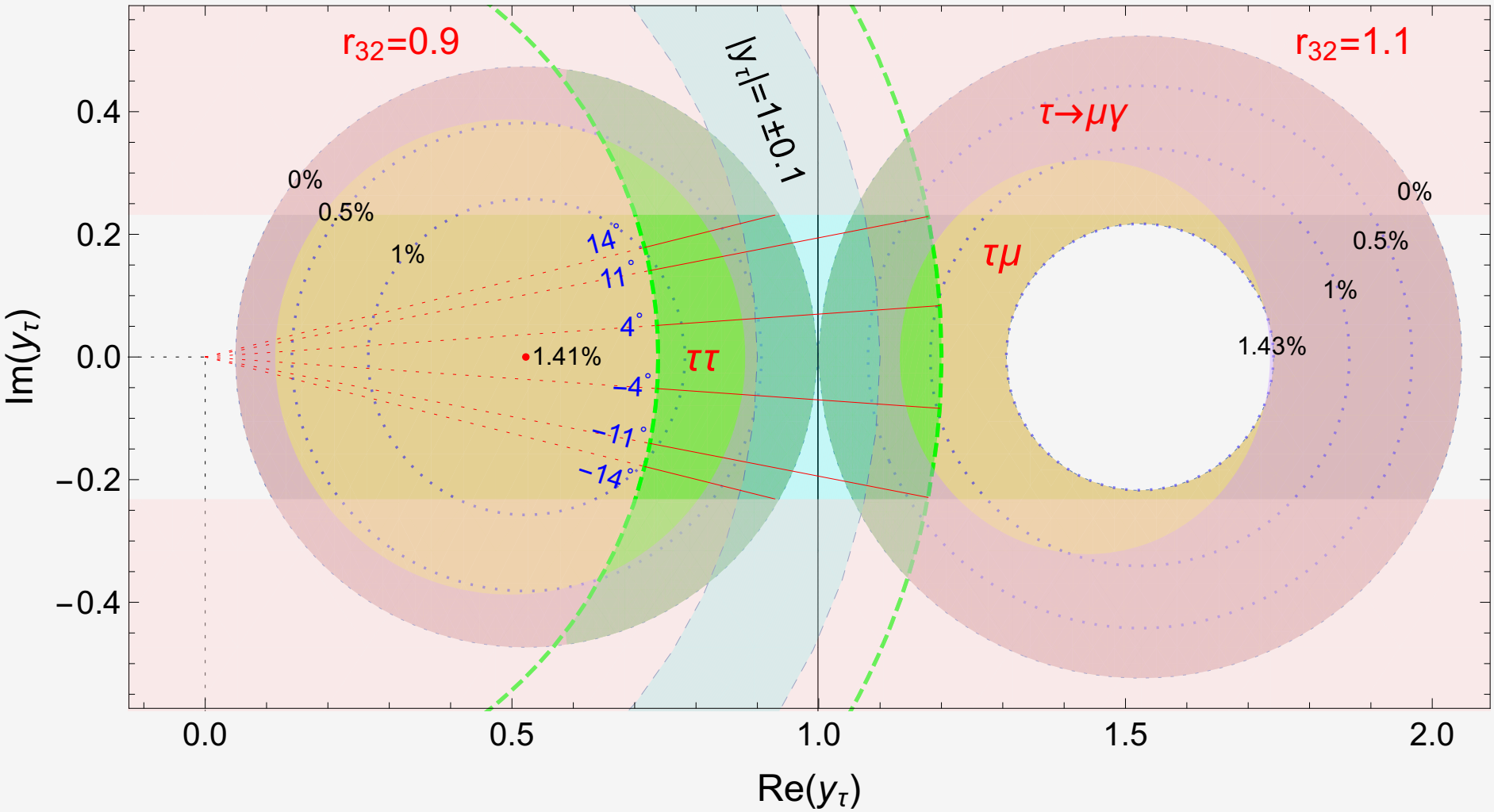
Sensitivities:

- LHC (PhysRevD.92.096012(2015))

150fb^{-1}	500fb^{-1}	3ab^{-1}
15°	9°	4°

- Higgs factories: $\approx 4.4^\circ$ at 250GeV with 1ab^{-1} PhysRevD.88.076009(2013).

Physical Implications of the Lepton-Flavored EWBG



Summary and Outlook

- ◊ Mechanisms of Electroweak Baryogenesis is discussed.
- ◊ A Lepton flavored scenario is studied.
  - CP-violating $h\bar{\tau}\tau$ is expected from EWBG and can be probed at colliders.
  - This is correlated with discovery of $h\tau^{\pm}\mu^{\mp}$.
- ◊ More dedicated work on this subject can be interesting and important.

Thanks

Parameters

Table 1. Primordial, baseline, and optional late-time cosmological parameters.

Parameter	Definition
A_s	Scalar power spectrum amplitude (at $k_* = 0.05\,\mathrm{Mpc}^{-1}$)
n_s	Scalar spectral index (at $k_* = 0.05\,\mathrm{Mpc}^{-1}$, unless otherwise stated)
$\mathrm{d}n_s/\mathrm{d}\ln k$	Running of scalar spectral index (at $k_* = 0.05\,\mathrm{Mpc}^{-1}$, unless otherwise stated)
$\mathrm{d}^2n_s/\mathrm{d}\ln k^2$	Running of running of scalar spectral index (at $k_* = 0.05\,\mathrm{Mpc}^{-1}$)
r	Tensor-to-scalar power ratio (at $k_* = 0.05\,\mathrm{Mpc}^{-1}$, unless otherwise stated)
n_t	Tensor spectrum spectral index (at $k_* = 0.05\,\mathrm{Mpc}^{-1}$)
ω_b	Baryon density today
ω_c	Cold dark matter density today
θ_{MC}	Approximation to the angular size of sound horizon at last scattering
τ	Thomson scattering optical depth of reionized intergalactic medium
N_{eff}	Effective number of massive and massless neutrinos
Σm_ν	Sum of neutrino masses
Y_P	Fraction of baryonic mass in primordial helium
Ω_K	Spatial curvature parameter
w_{de}	Dark energy equation of state parameter (i.e., p_{de}/ρ_{de}) (assumed constant)

Planck 2015, arxiv:1502.02114

Approximations

- Local chemical equilibrium.
- Neglect weak sphaleron interactions in transport equations.
- Local Baryon number conservation.
- Weak interactions are in thermal equilibrium.
- Chemical equilibrium for strong sphaleron interactions.

Outline

- Mechanisms of Electroweak Baryogenesis
  - Why going beyond the SM ?
- Example: Lepton-Flavored Electroweak Baryogenesis
- Gravitational Waves from Electroweak Phase Transition

Condition 1: The Anomalous Baryonic Current

Anomalies: ($\pi^0 \to \gamma\gamma \Rightarrow$ Adler, 1969; Bell and Jackiw 1969; Fujikawa 1979.)

$$\partial_\mu J^\mu_{B_L+L_L} = \frac{n_f g^2}{32\pi^2}\epsilon_{\alpha\beta\gamma\delta}W_a^{\alpha\beta}W_a^{\gamma\delta}$$

$$\downarrow$$

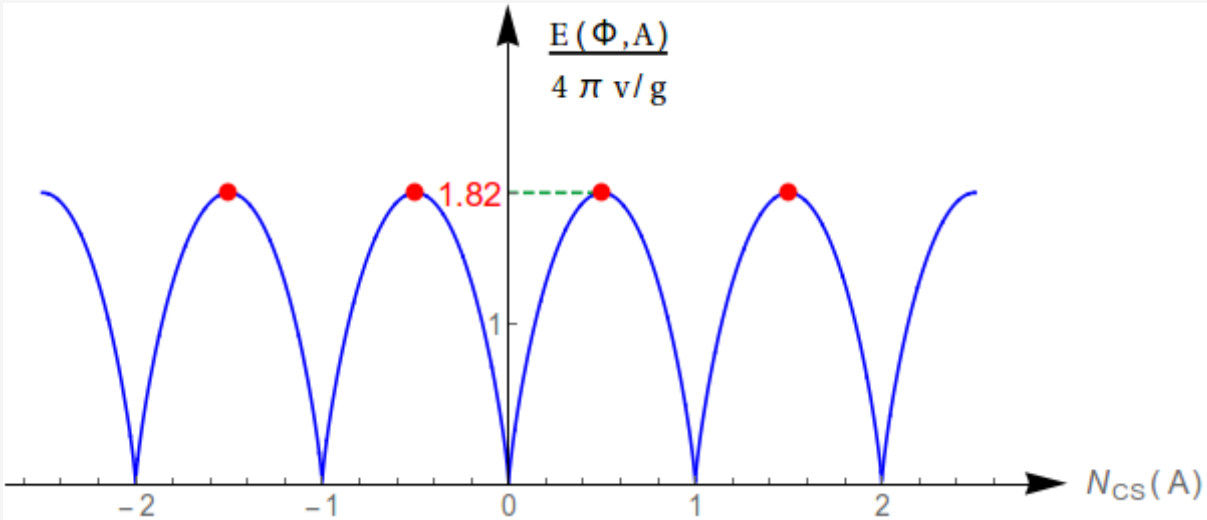
$$B(t_f) - B(t_i) = \int_{t_i}^{t_f}\int d^3x\left[n_f\frac{g^2}{32\pi^2}W_{\mu\nu}\widetilde{W}^{a\mu\nu}\right]$$

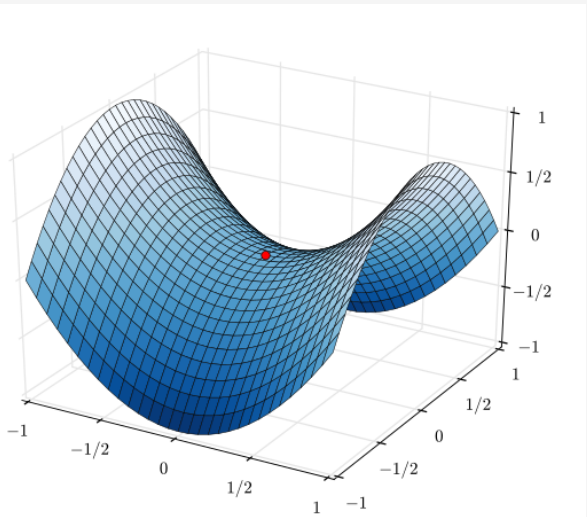
$$\downarrow$$

$$\Delta B = n_f[N_{CS}(t_f) - N_{CS}(t_i)]$$

Condition 1: The n-Vacua and Sphalerons

Instanton('t Hooft 1976) mediated tunnelling rate: $e^{-\frac{8\pi^2}{g^2}} \approx 10^{-173}$



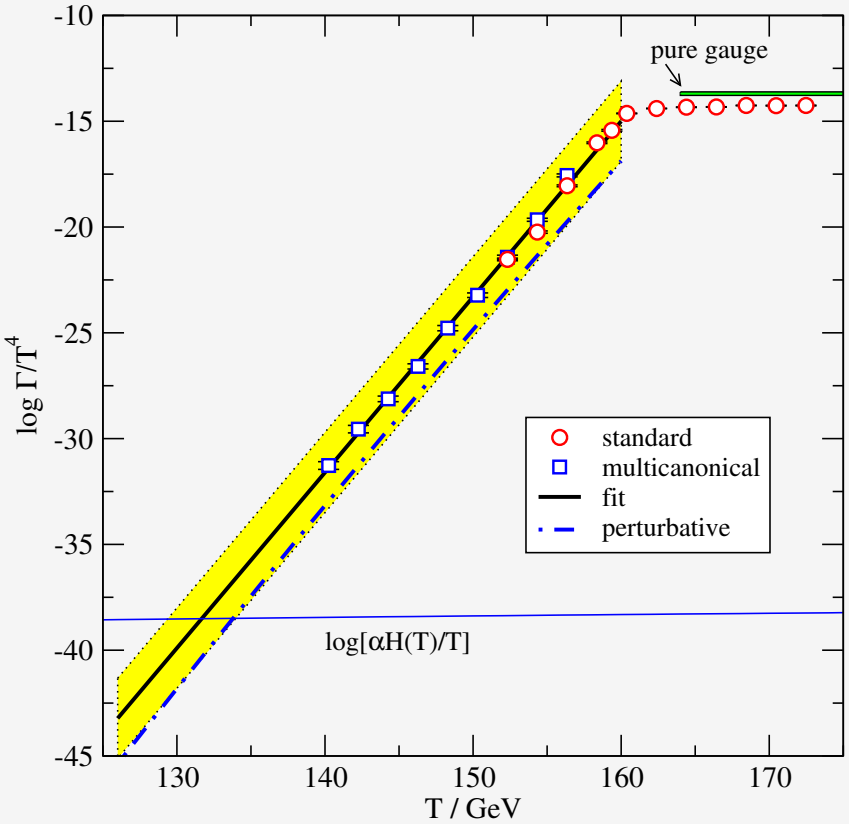


Saddle point solution, Sphalerons (Manton, 1983).

Sphaleron Energy: $E = (1.6 \sim 2.7) \times \dfrac{4\pi v}{g}$

Rate unsuppressed at high T

Condition 1: Sphaleron Rate in SM



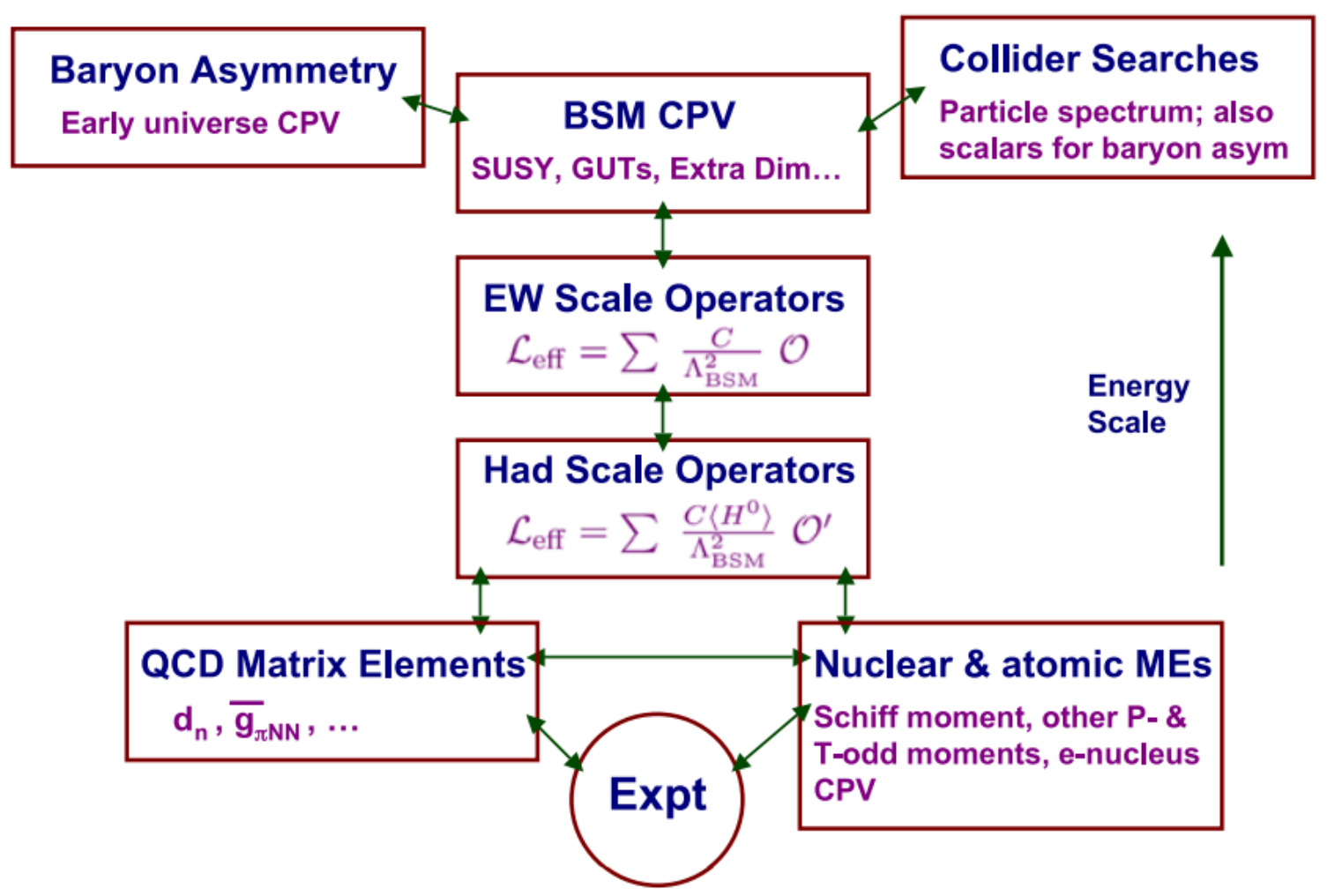
Lattice result, $\boxed{T_C = (159.5 \pm 1.5)\text{GeV}}$, Phys.Rev.Lett,113, 141602 (2014).

$$\boxed{\Gamma^{\text{sym}} \approx 6 \times (18 \pm 3)\alpha_W^5 T^4, \qquad \Gamma^{\text{brok}} \sim T^4 \exp(-\frac{E_{\text{sph}}}{T})}$$

Condition 2: CPV in SM: the CKM Matrix

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Condition 2: CPV: Electric Dipole Moments



J. Engel et al. Progress in Particle and Nuclear Physics 71 (2013) 2174

Condition 2: CPV: EDM Experimental Status

System	Present 90% C.L.	Sensitivity goal[b]	Group	SM CKM (e fm)[c]
	Limit (e fm)[a]			
Cs	1.2×10^{-10}		[169]	$\sim 10^{-23}$
Tl	9.5×10^{-12}		[170]	$\sim 10^{-22}$
YbF[d]	10.5×10^{-15}		[152]	$\sim 10^{-19}$
ThO[d]	–	$10^{-15} \rightarrow 10^{-17}$		
n	2.7×10^{-13}		[171]	$1.6 \times 10^{-18} \rightarrow 1.4 \times 10^{-20}$
n		$(1-3) \times 10^{-14}$	CryoEDM	
n		4×10^{-15}	nEDM/SNS	
n		5×10^{-14}	nEDM/PSI	
n		5×10^{-15}	n2EDM/PSI	
n		2×10^{-15}	nedm/FRM-II Munich	
n		$10^{-14} - 10^{-15}$	TRIUMF	
p		10^{-16}	srEDM	
^{199}Hg	2.6×10^{-16}	$(2.6-5) \times 10^{-17}$	[172]	–
^{225}Ra		$(10-100) \times 10^{-15}$	Argonne	–
$^{221/223}$Rn		1.3×10^{-14}	TRIUMF	–
$^{221/223}$Rn		2×10^{-15}	FRIB	–
^{129}Xe	5.5×10^{-14}		[173]	–

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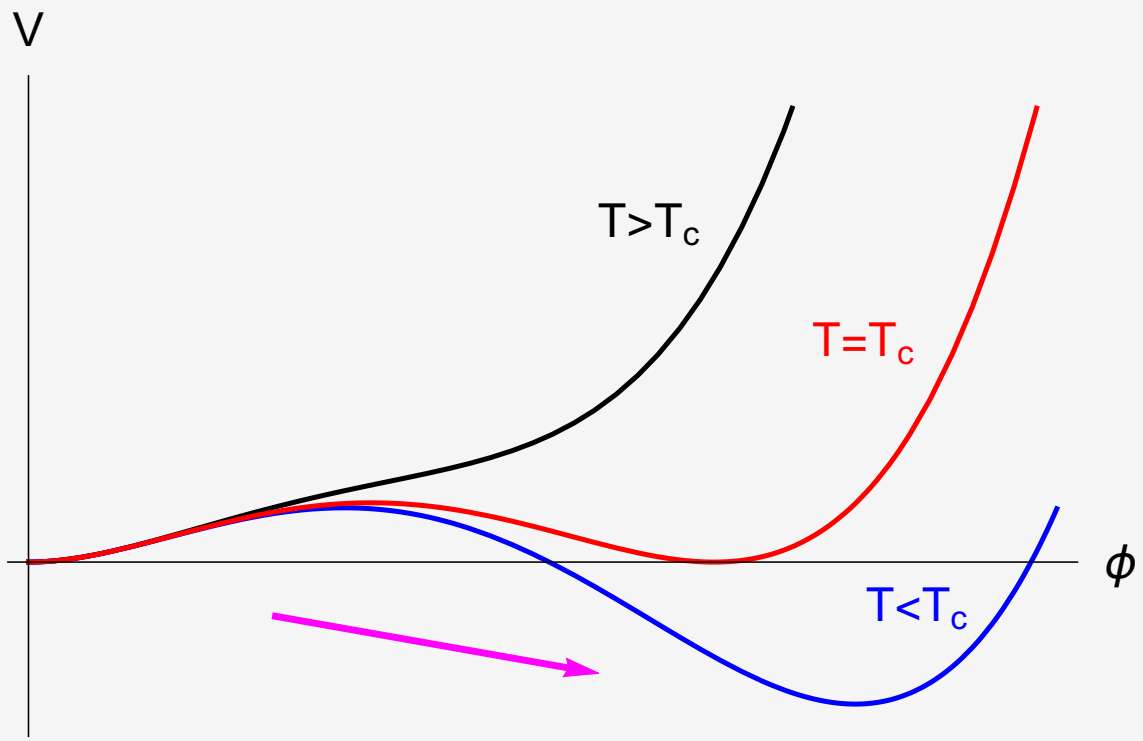
Condition 3: Electroweak Phase Transition



Strongly first order EWPT.

- Bubble Nucleation
- Bubble Expansion
- Bubble Percolation

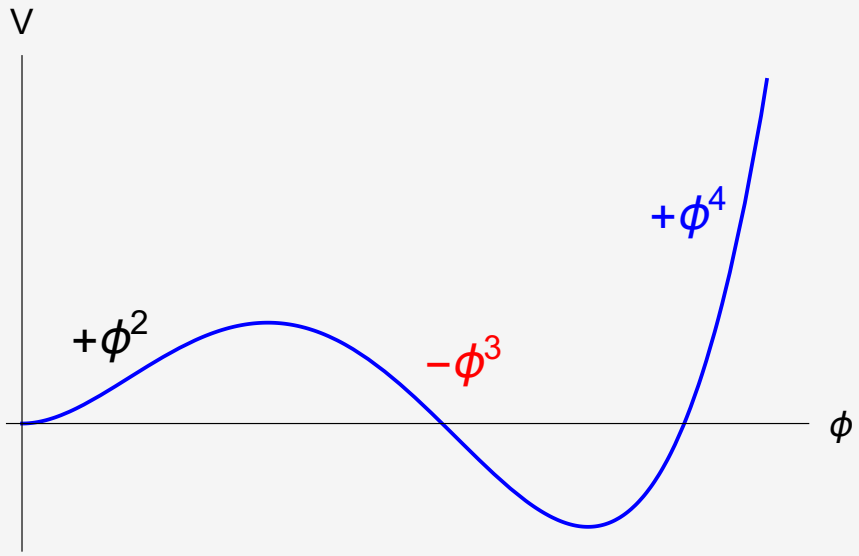
Condition 3: EWPT: Effective Potential

$$V_{\text{eff}}^{T}(\phi) = V_{\text{eff}}^{T=0}(\phi) \quad + \quad \frac{T^4}{2\pi^2}[\sum_{\text{scalars}} J_B(\frac{M^2}{T^2}) + 3\sum_{\text{gauge}} J_B(\frac{\mu^2}{T^2})$$
$$- \sum_{\text{gauge}} J_B(\frac{\xi\mu^2}{T^2}) - 4\sum_{\text{fermions}} n_C^f J_F(\frac{m_f^2}{T^2})].$$

? ξ: gauge-fixing parameter

Condition 3: EWPT: Analytical Treatment

$$V(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda(T)}{4}\phi^4,$$

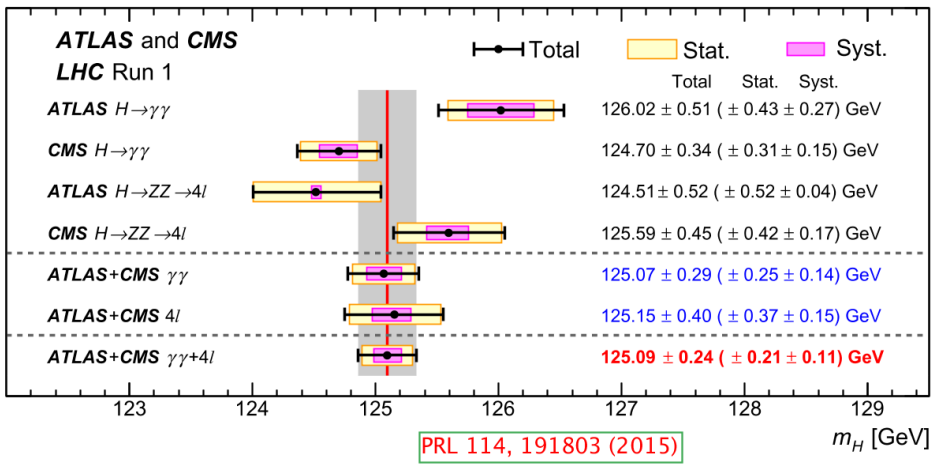


- ξ-independent

Condition 3: Incapability of first order EWPT in SM

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[71]	80 ± 7
4D Anisotropic	[69]	72.4 ± 1.7
3D Isotropic	[67]	72.3 ± 0.7
3D Isotropic	[65]	72.4 ± 0.9

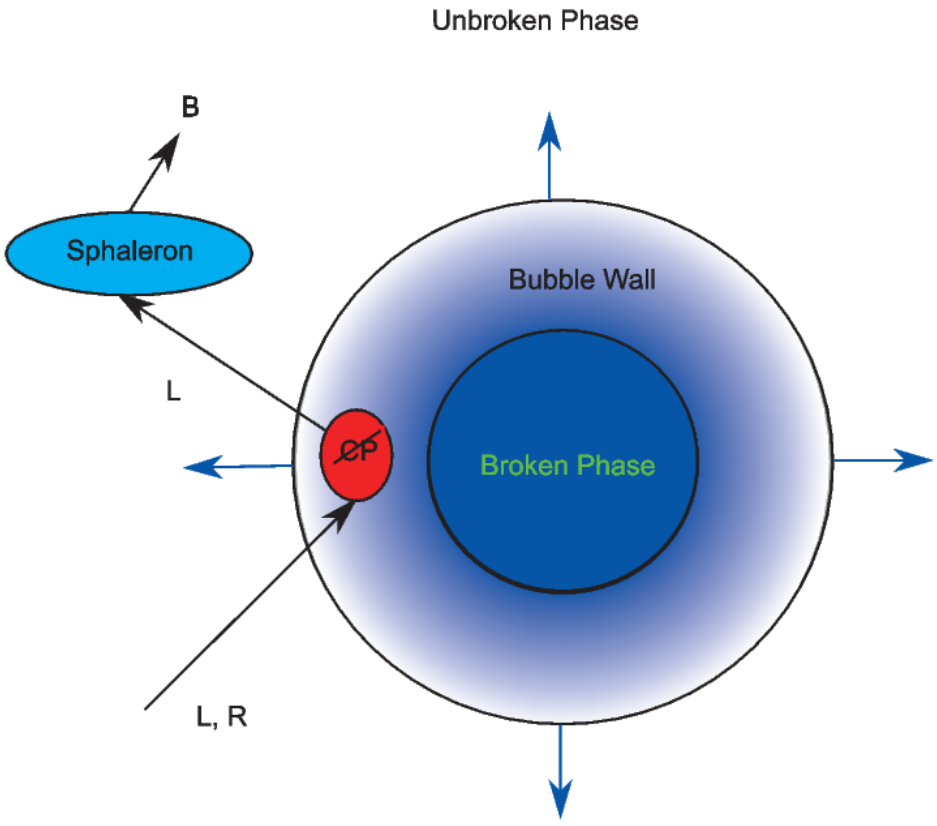
Morrissey, Ramsey-Musolf, New Journal of Physics, 14,125003(2012)



$$m_H = 125.09 \pm 0.21 \pm 0.11\text{GeV} \rightarrow \boxed{\text{New Physics}}$$

Electroweak Baryogenesis: The Picture

$T \approx 100\text{GeV} \approx 10^{15}\text{K}$



Gravitational Waves (mHz level), LISA, Taiji, TianQin, DECIGO

Diffusion

- Diffusion enhances baryon asymmetry generation. (Cohen, Kaplan, Nelson, Phys.Lett.B336(1994)41)
  Non-Local vs Local

- Closed-Time-Path(CTP) Formalism (Riotto, PRD58 (1998) 095009, Lee, Cirigliano, Ramsey-Musolf,PRD71,075010(2005))
  Resonant Enhancement

Transport Equations

$$\frac{\partial n}{\partial X_0} + \nabla \cdot \vec{j}(X) = -\int d^3z \int_{-\infty}^{X_0} dz_0 \mathrm{Tr}\Big[\Sigma^{>}(X,z)S^{<}(z,X) - S^{>}(X,z)\Sigma^{<}(z,X) + S^{<}(X,z)\Sigma^{>}(z,X) - \Sigma^{<}(X,z)S^{>}(z,X)\Big]$$

$$\partial_\mu j_i^\mu = -\frac{T^2}{6}\sum_X \Gamma_X(\mu_i + \mu_j + \cdots - \mu_k - \mu_l - \cdots) + S_i^{C/P}$$

$$\partial_\mu n_B{}^\mu = -\Theta(-\bar{z})\Gamma_{ws}(\frac{15}{4}n_B + 3\, n_L)$$

n_B is a constant in the broken phase