Testing Electroweak Baryogenesis
LHC Observables and Gravitational Wave Signals

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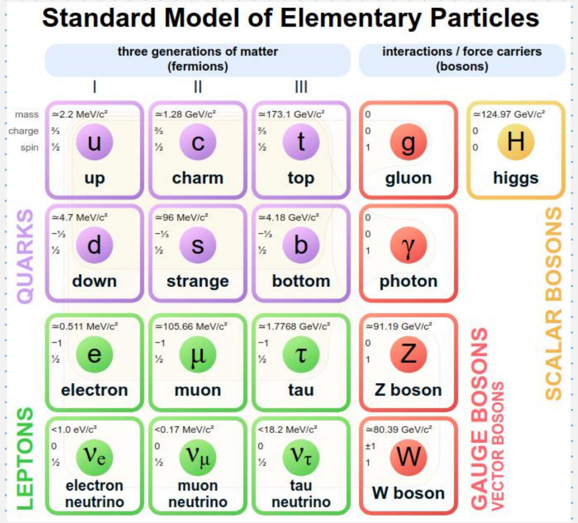
2022年10月29日

26th Mini-workshop on the frontier of LHC

The Problem of Baryon Asymmetry

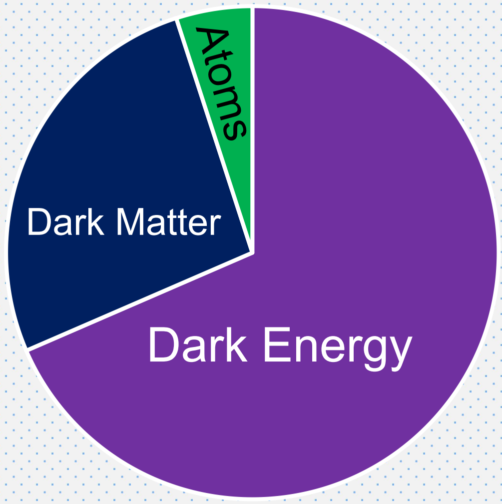
How can we reconcile the Standard Models of particle physics and cosmology?

Particle Physics



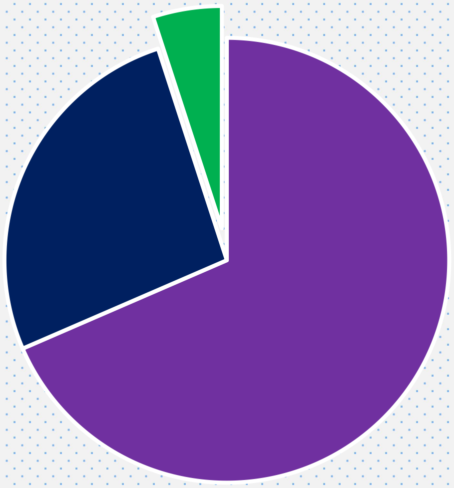
Physics Beyond the SM?

Cosmology

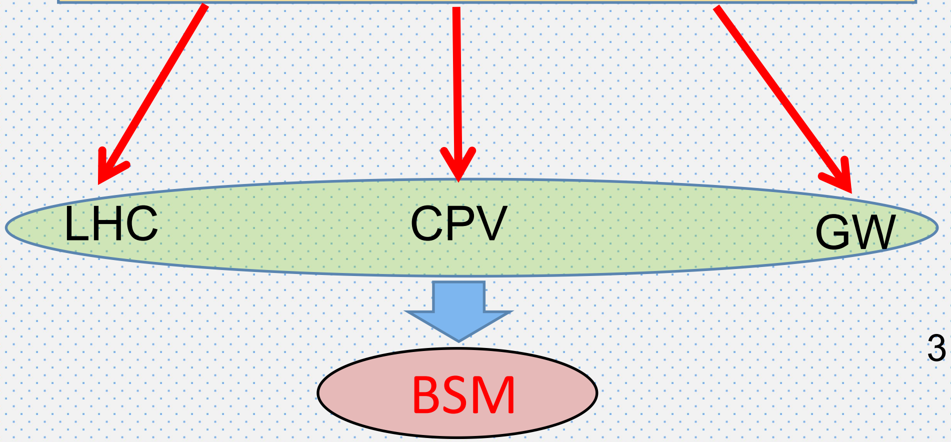


What is dark matter?
Why more matter than anti-matter?
What is dark energy?

Mechanisms



- GUT Baryogenesis
- Affleck-Dine Mechanism
- Leptogenesis
- Spontaneous Baryogenesis
- Electroweak Baryogenesis

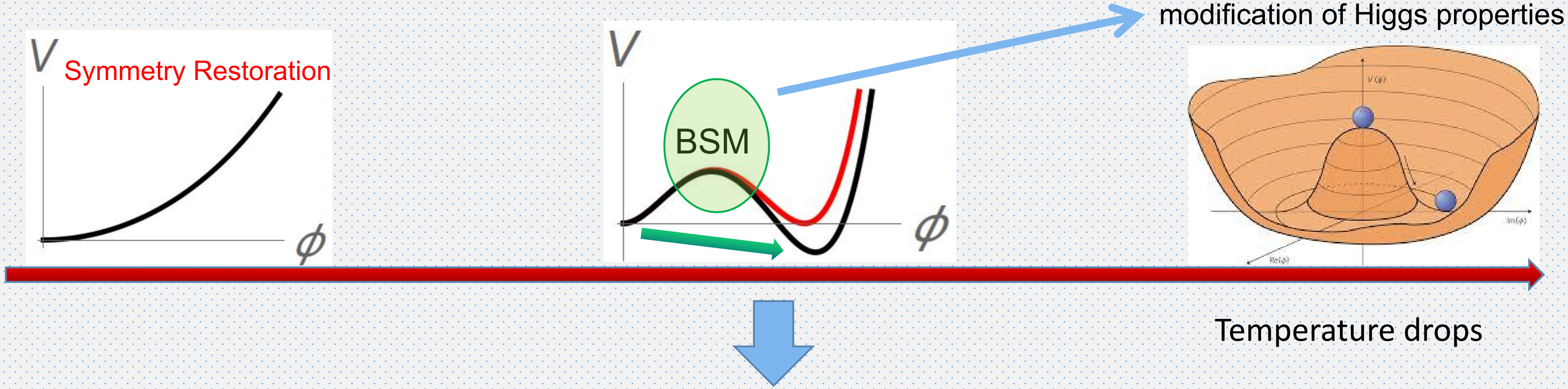


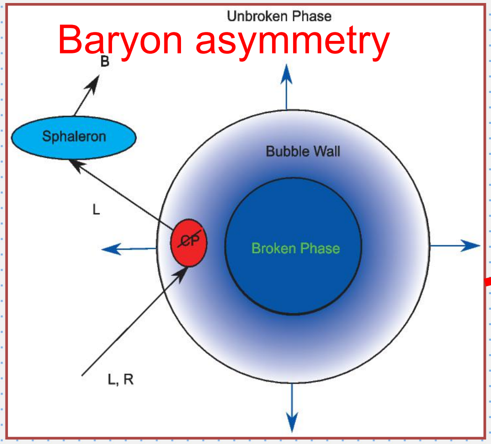
Sakharov conditions(1967)

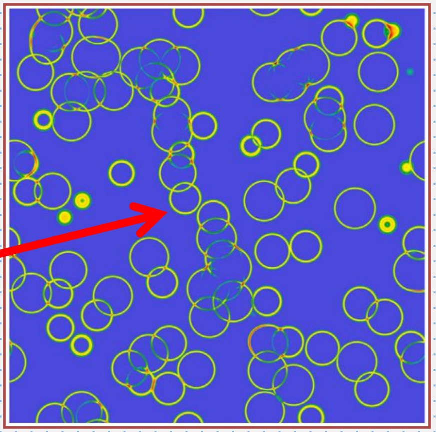
- ✓ B-violation
- ✓ C, CP violation
- ✓ Out-of-Equilibrium

Electroweak Baryogenesis

Symmetry-breaking in the early universe

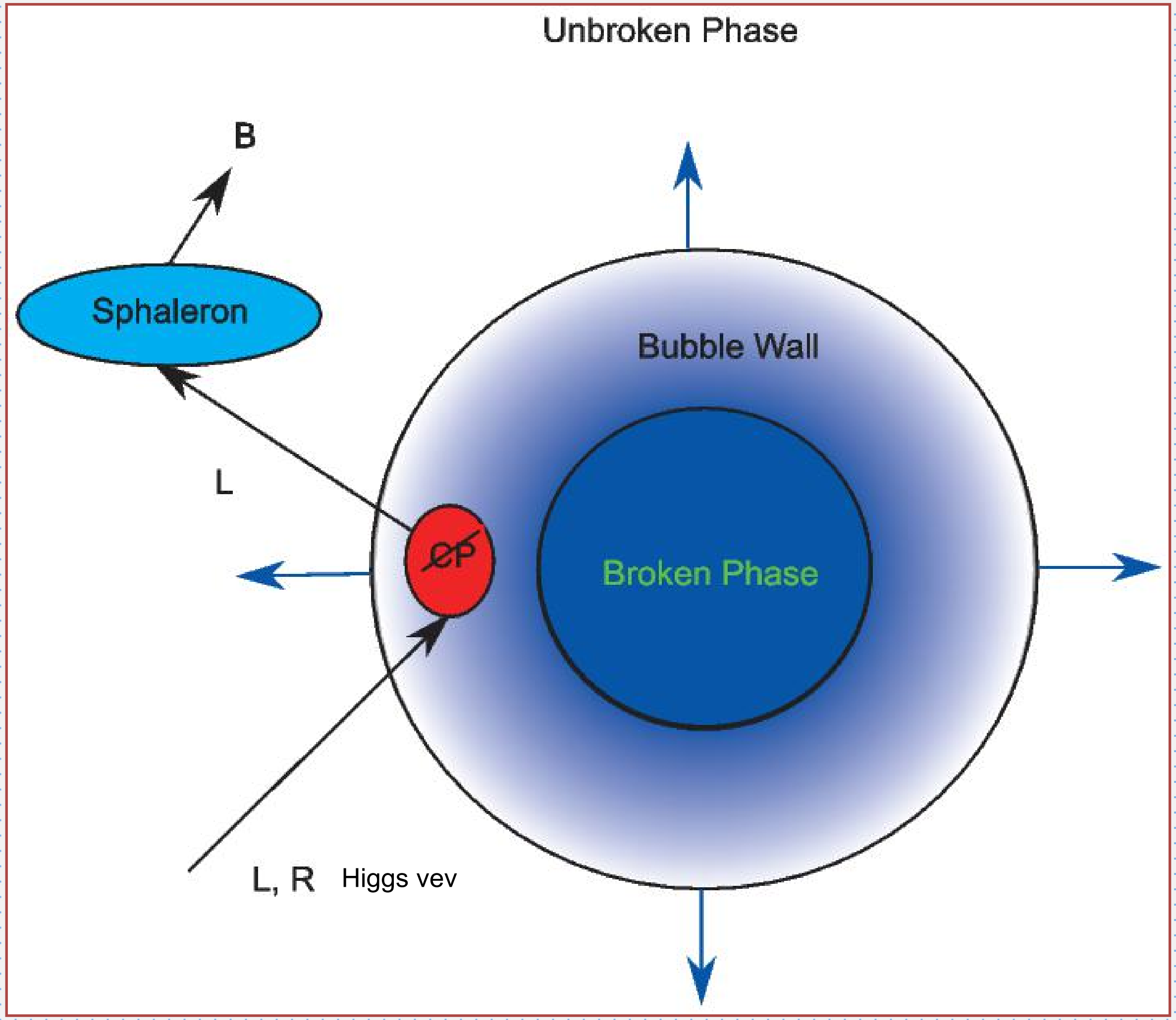




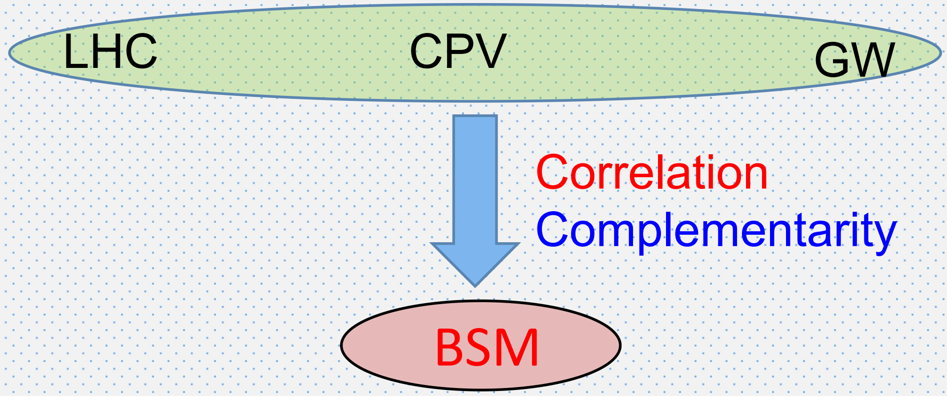


Hindmarsh, et al, 2015

Experimental Observables

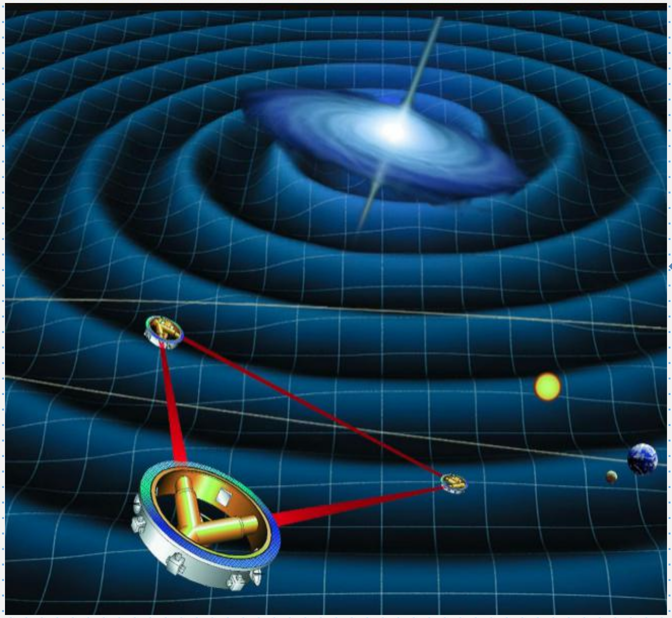


- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- B-violation: Sphaleron process (LHC, GW)

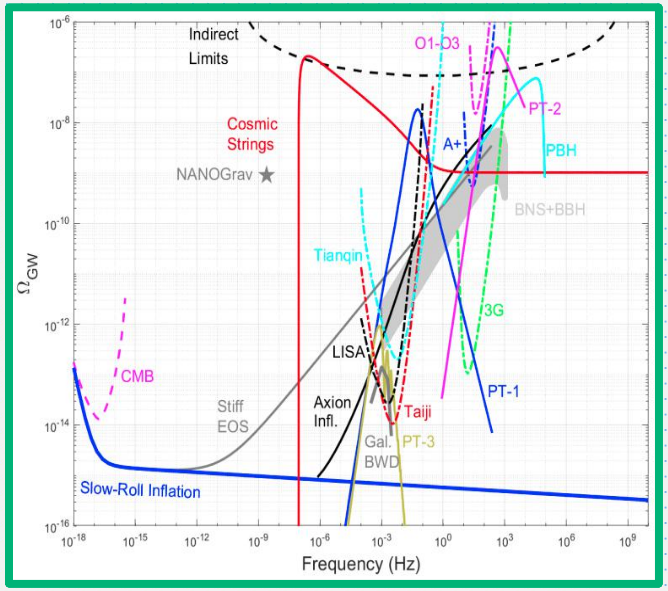


Flow of Studies with GWs

theoretical calculation of gravitational wave spectrum and detector simulation



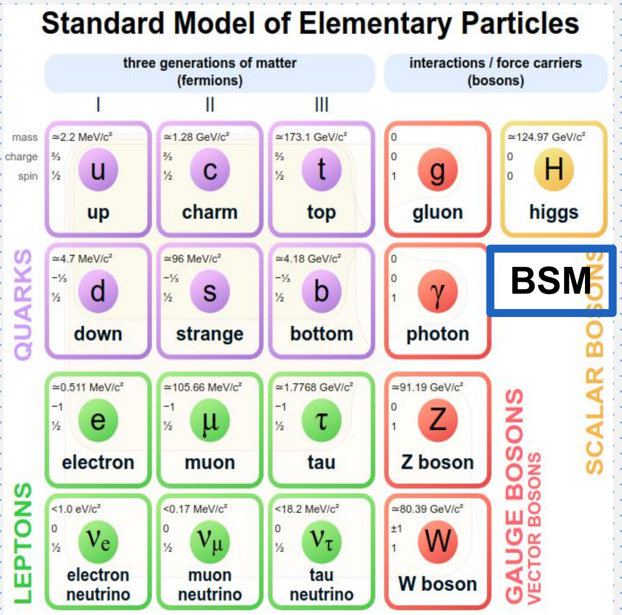
LIGO, LISA, Taiji, Tianqin...



Gravitational Wave Spectrum

α
β
v_w
T_*
g_s
...

Phase Transition Parameters



Particle Physics Model

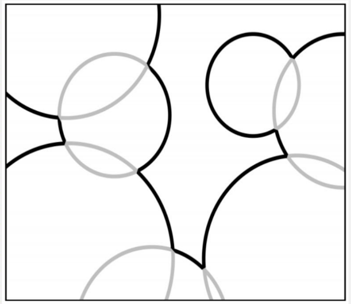
data analysis, constraints or discovery(parameter estimation)

The GW Observable

Energy density Spectrum

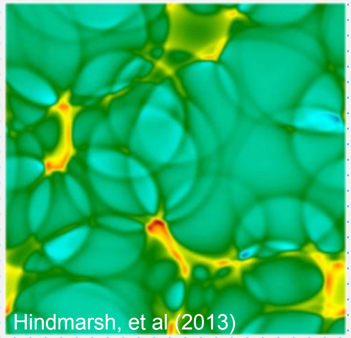
$$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

bubble collision



$$\Omega_{\rm coll}(f)h^2 = 1.67\times 10^{-5}\Delta\left(\frac{H_{\rm pt}}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2 \times\left(\frac{100}{g_*}\right)^{1/3} S_{\rm env}(f),$$

sound waves

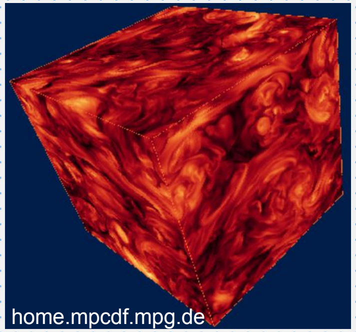


$$\Omega_{\rm sw}(f)h^2 = 2.65\times 10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

$$\Upsilon = 1-(1+2\tau_{\rm sw}H_{\rm pt})^{-1/2}$$ (RD)

HG, Sinha, Vagie, White, JCAP 01 (2021) 001

MHD



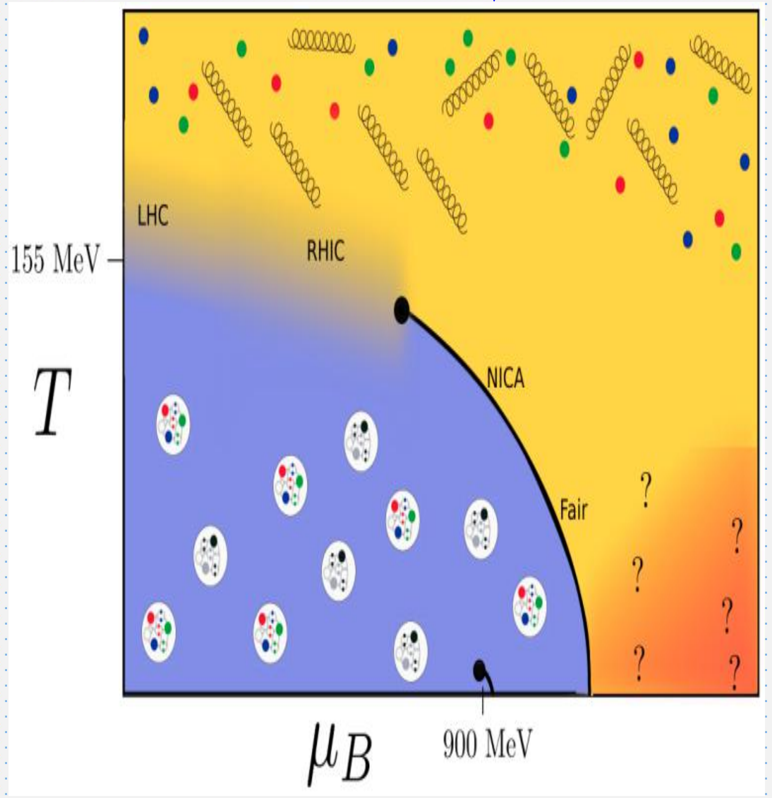
$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

Features of GWs

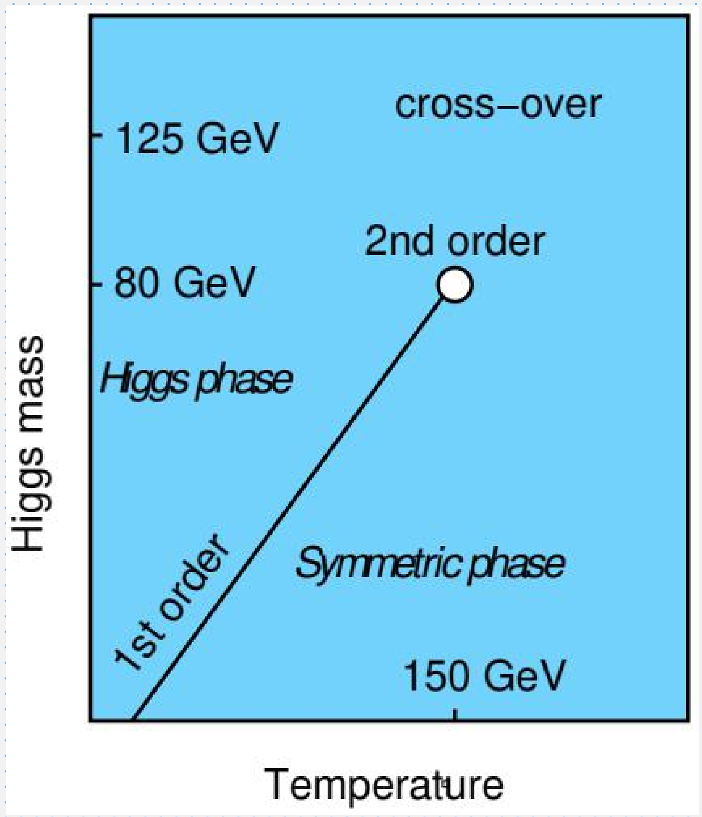
- LIGO (~100Hz) : (~PeV - EeV)
- LISA, Taiji, Tianqin: ~mHz : (~100GeV)
- PTA: nHz (~100MeV)

EWPT

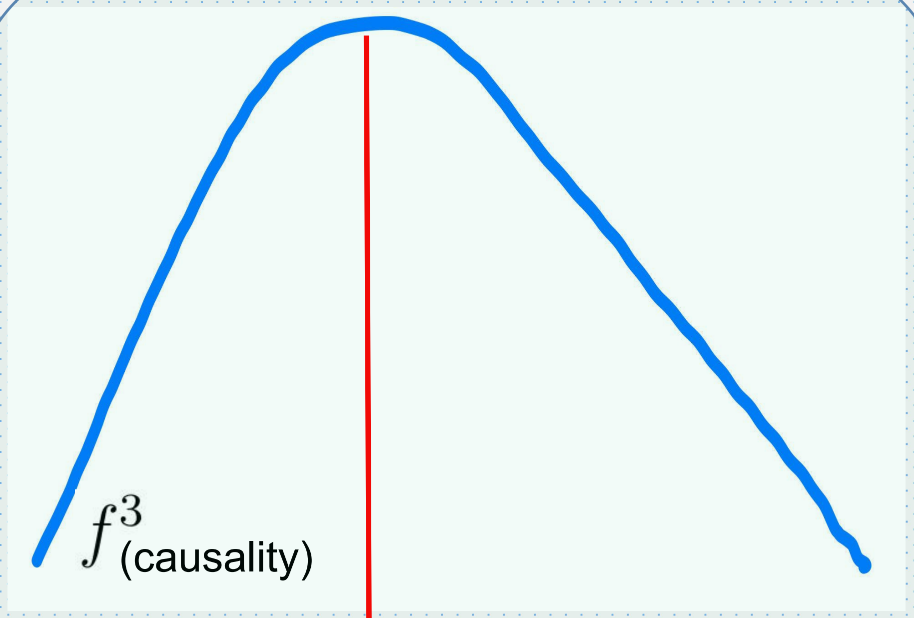
QCD PT



Guenther, arxiv: 2010.15503



Hindmarsh et al SciPost Phys.Lect.Notes 24 (2021)



$$f_{\rm peak} \sim 10^{-3}{\rm Hz}\left(\frac{g_s(T_*)}{100}\right)^{1/6}\left(\frac{T}{100{\rm GeV}}\right)$$

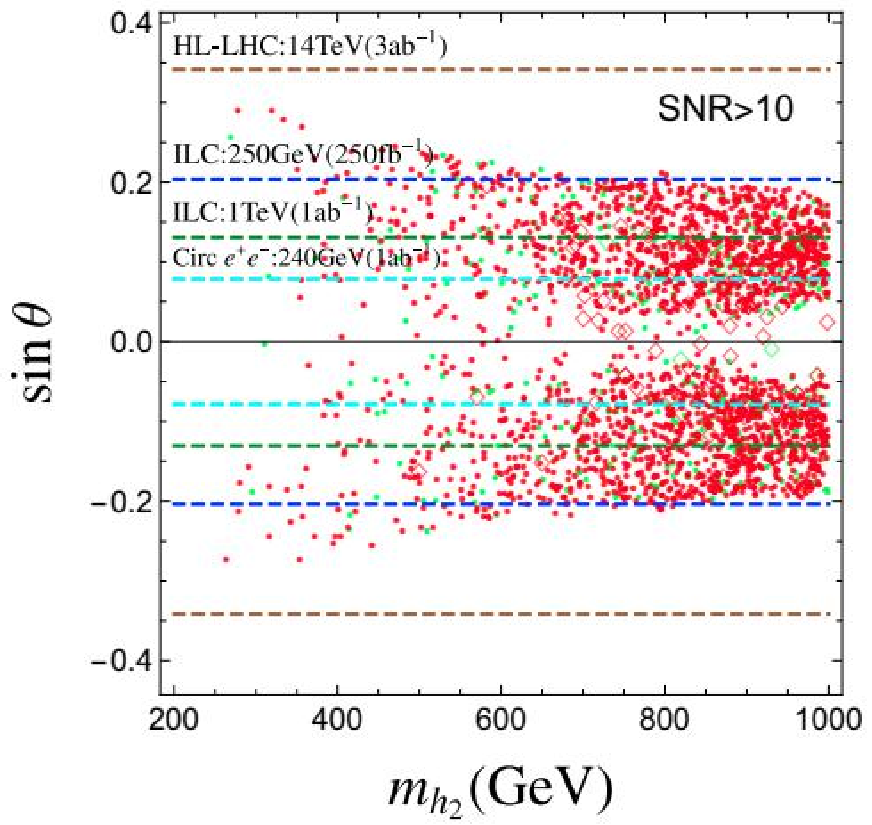
typical length scale

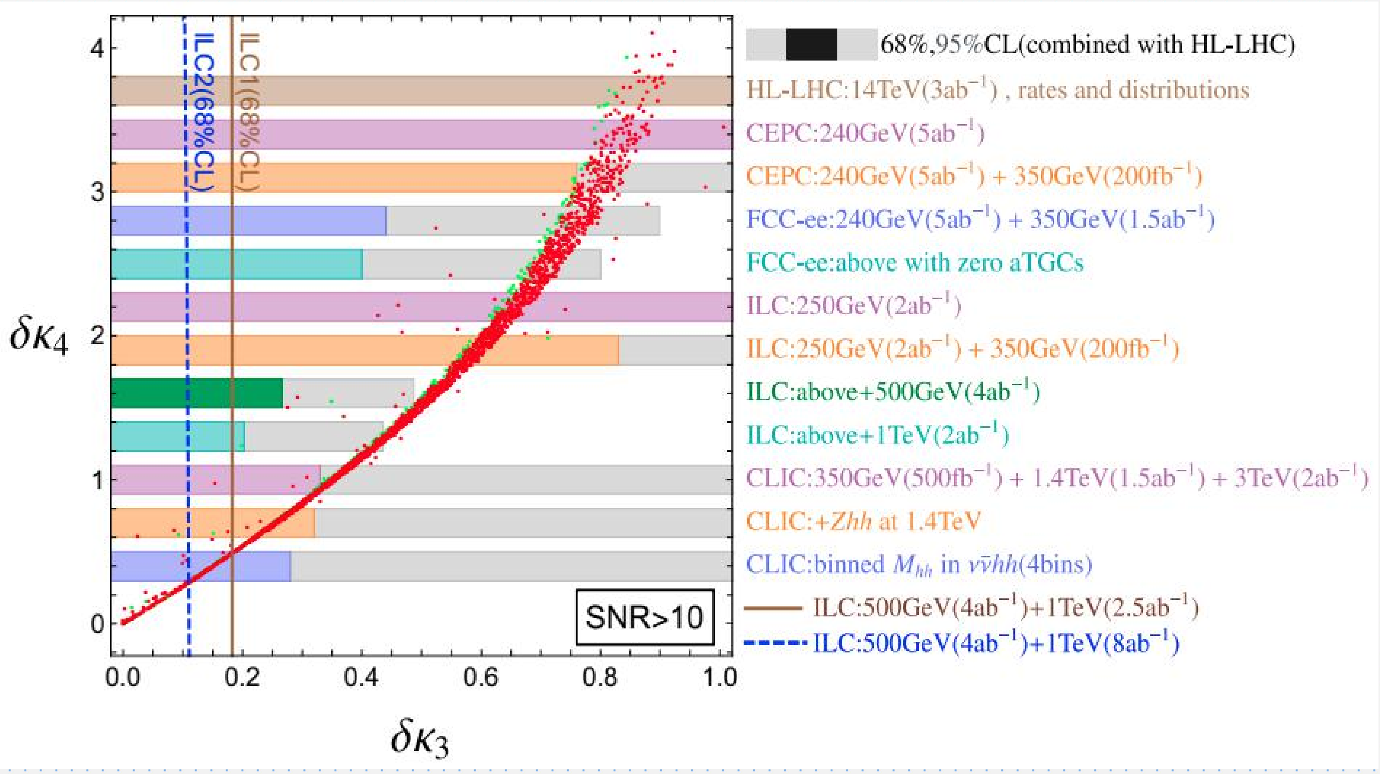
Higgs Precision Measurements

- First order EWPT achievable in simplest SM+Singlet model
- Correlation and complementarity between collider and GW probes

h1: the Higgs
h2: heavier scalar

$$\Delta\mathcal{L} = -\frac{1}{2}\frac{m_{h_1}^2}{v}(1+\delta\kappa_3)h_1^3 - \frac{1}{8}\frac{m_{h_1}^2}{v^2}(1+\delta\kappa_4)h_1^4$$

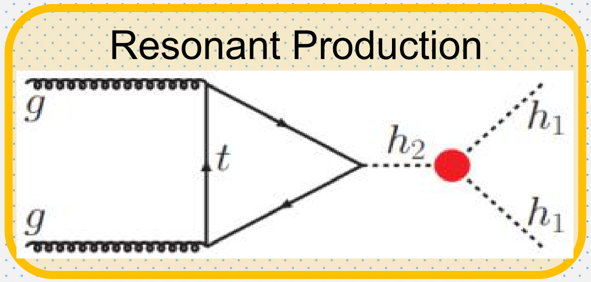


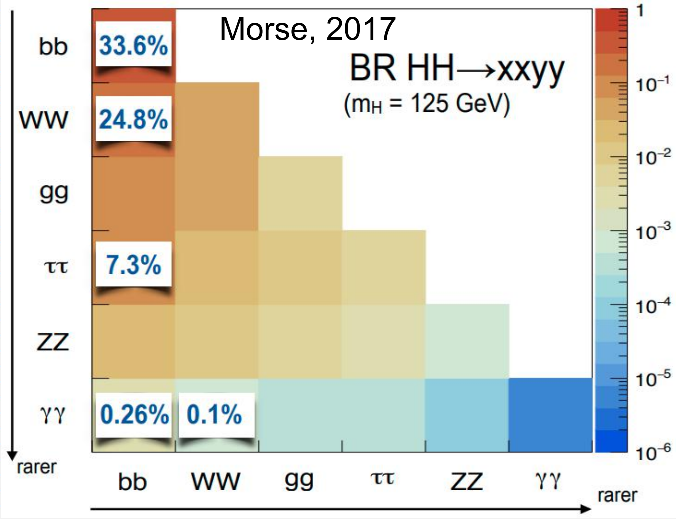


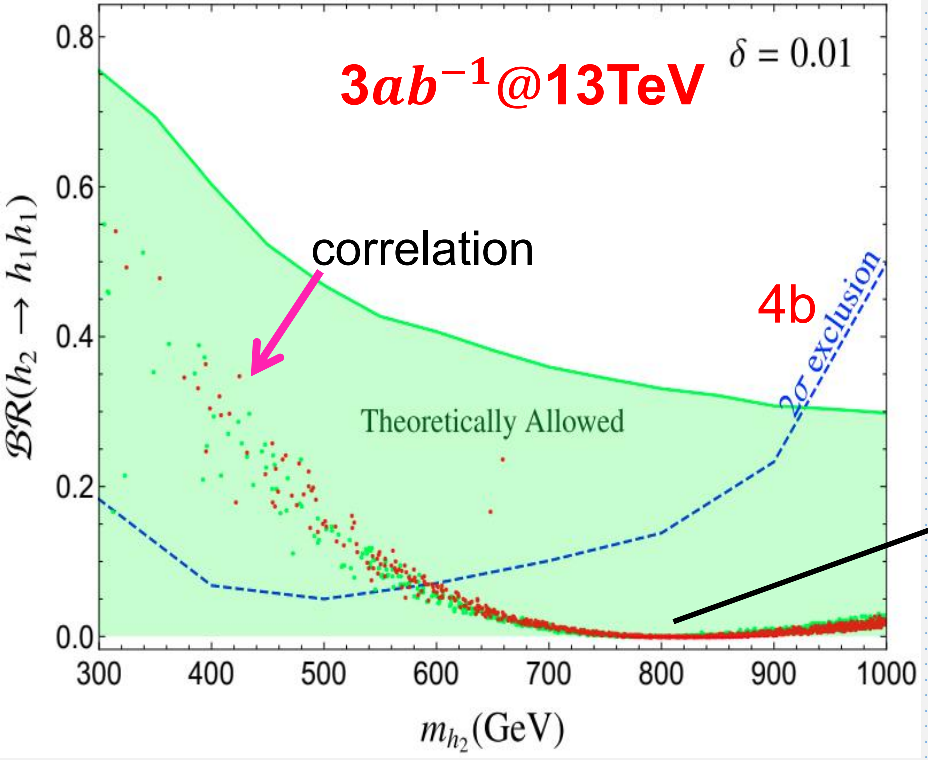
Alves, Ghosh, HG, Sinha, Vagie, JHEP04(2019)052

Di-Higgs Production

- Enhanced (resonant) di-Higgs production

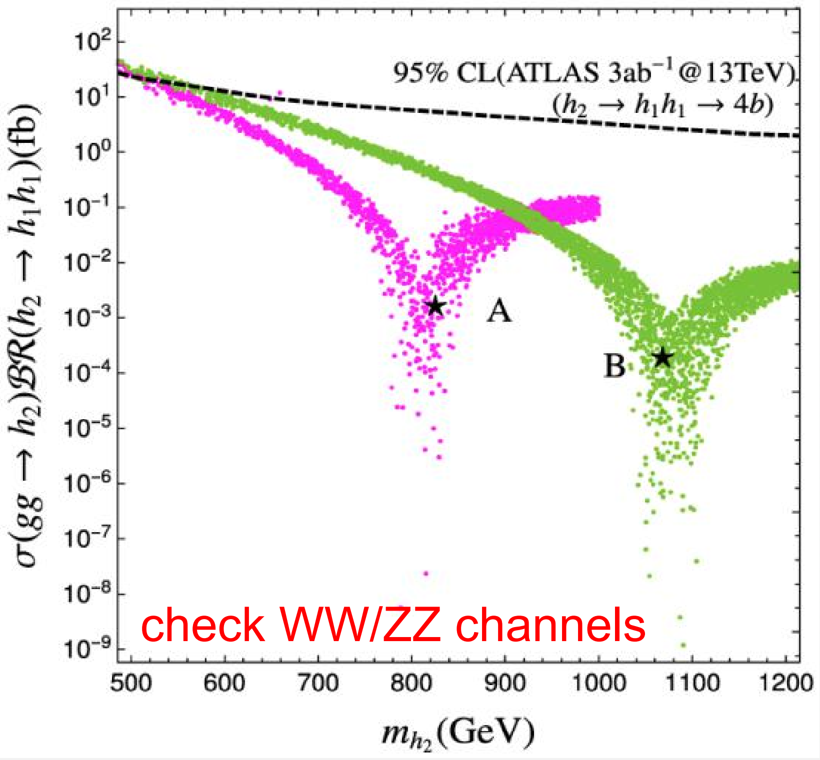






di-Higgs blindspot

complementarity



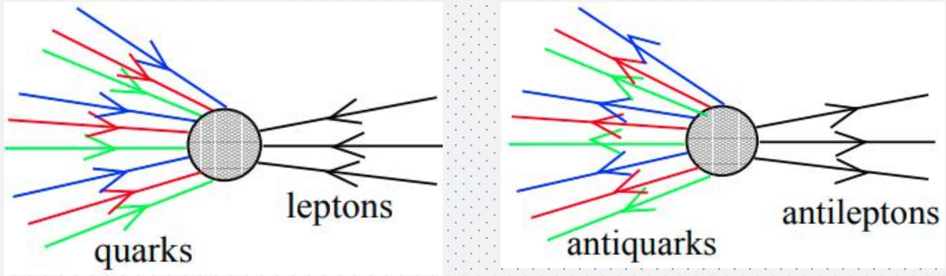
Alves, Gonçalves, Ghosh, HG, Sinha, JHEP 03,053(2020)

Alves, Gonçalves, Ghosh, HG, Sinha, PLB818,136377(2021)

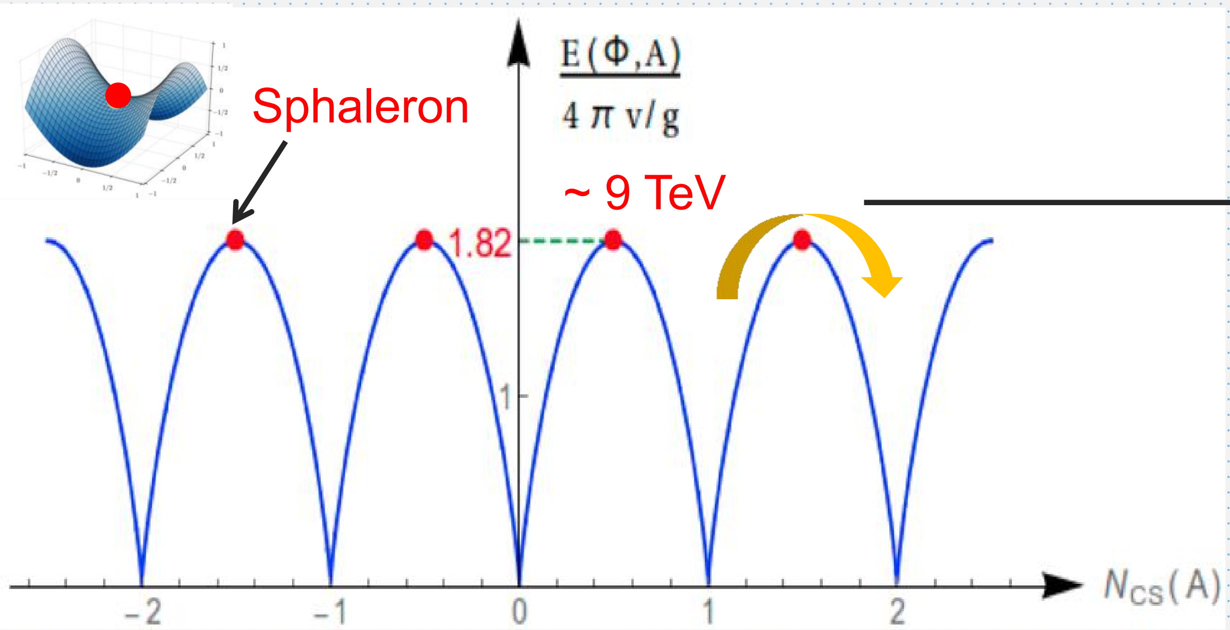
B-violation in the SM

Sphaleron (Manton, 1983)

- Transitions between vacua violates B
- Provides B-violation for Baryon asymmetry generation
- Can also be searched for at colliders



Cline, arxiv:0609145



$$\partial_\mu j_B^\mu = \partial_\mu j_l^\mu = n_f \left[\frac{g^2}{32\pi^2} W_{\mu\nu} \widetilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} F_{\mu\nu} \widetilde{F}^{\mu\nu} \right]$$

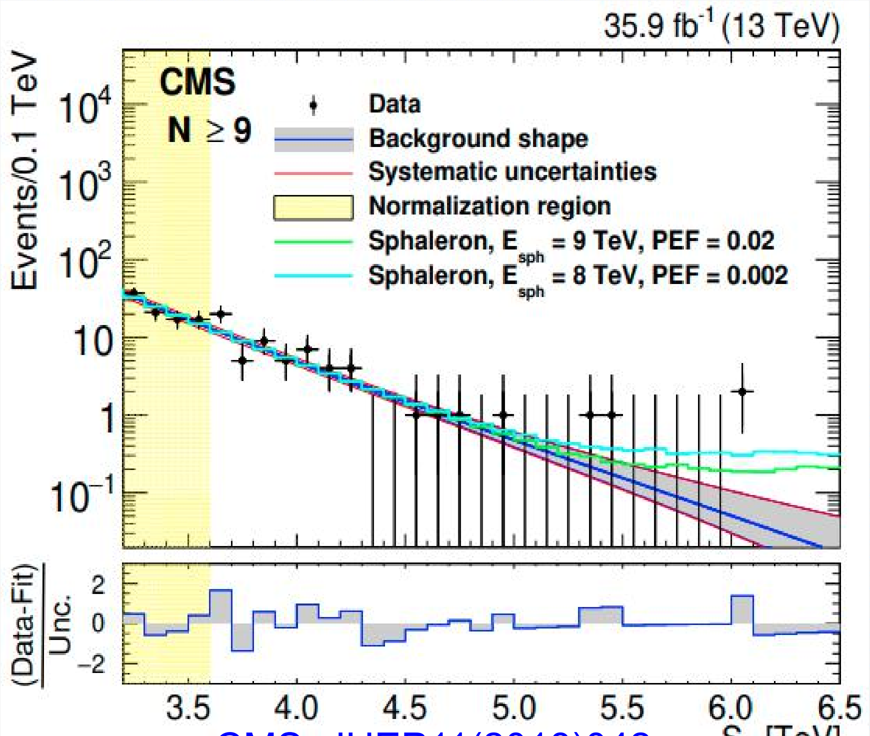
$$B(t_f) - B(t_i) = \int_{t_i}^{t_f} \int d^3x \left[n_f \frac{g^2}{32\pi^2} W_{\mu\nu} \widetilde{W}^{a\mu\nu} \right]$$

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

Sphaleron Searches@LHC

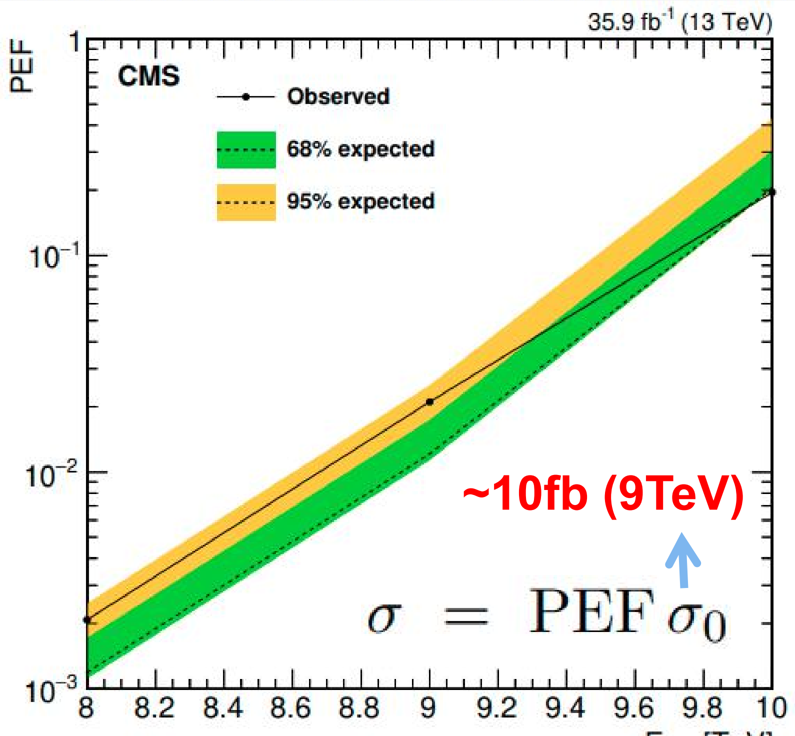
First search already done

- High multiplicity final states: 7 ~ 20
- Null detection yet



CMS, JHEP11(2018)042

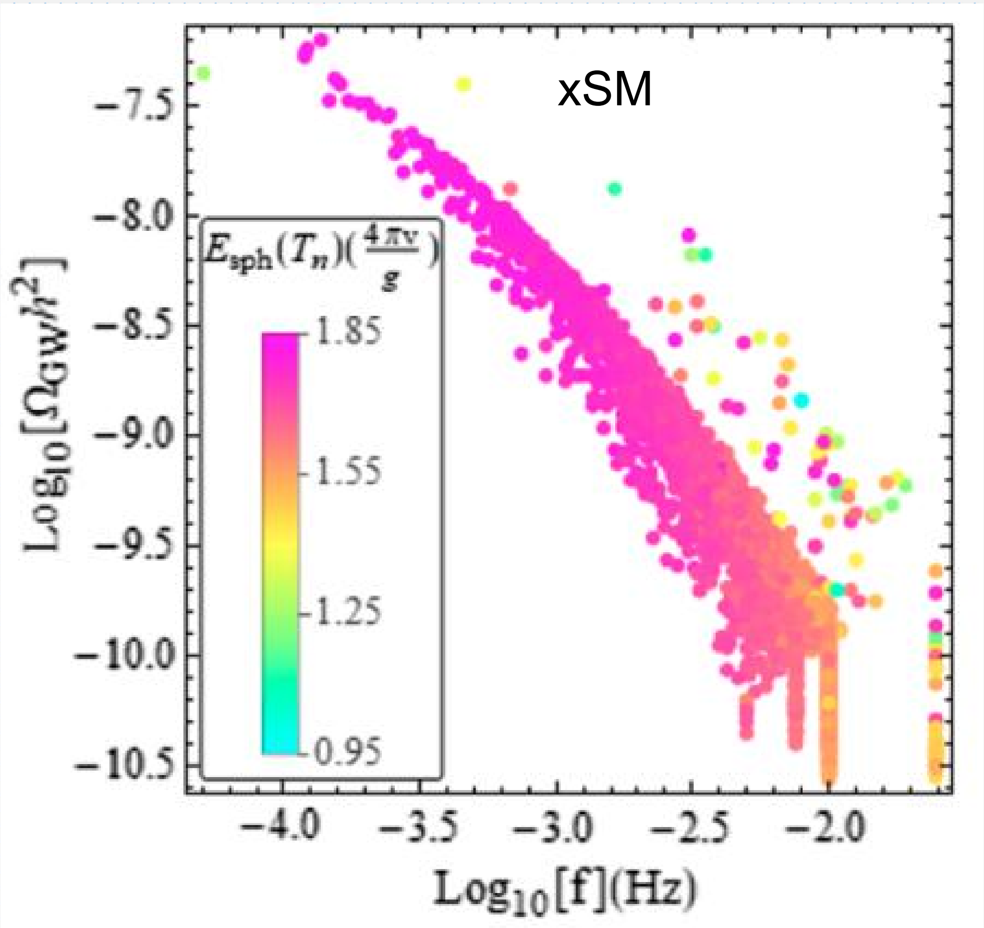
Bloch wave interpretation (valid **?**)
Ellis&Sakurai, JHEP04(2016),086

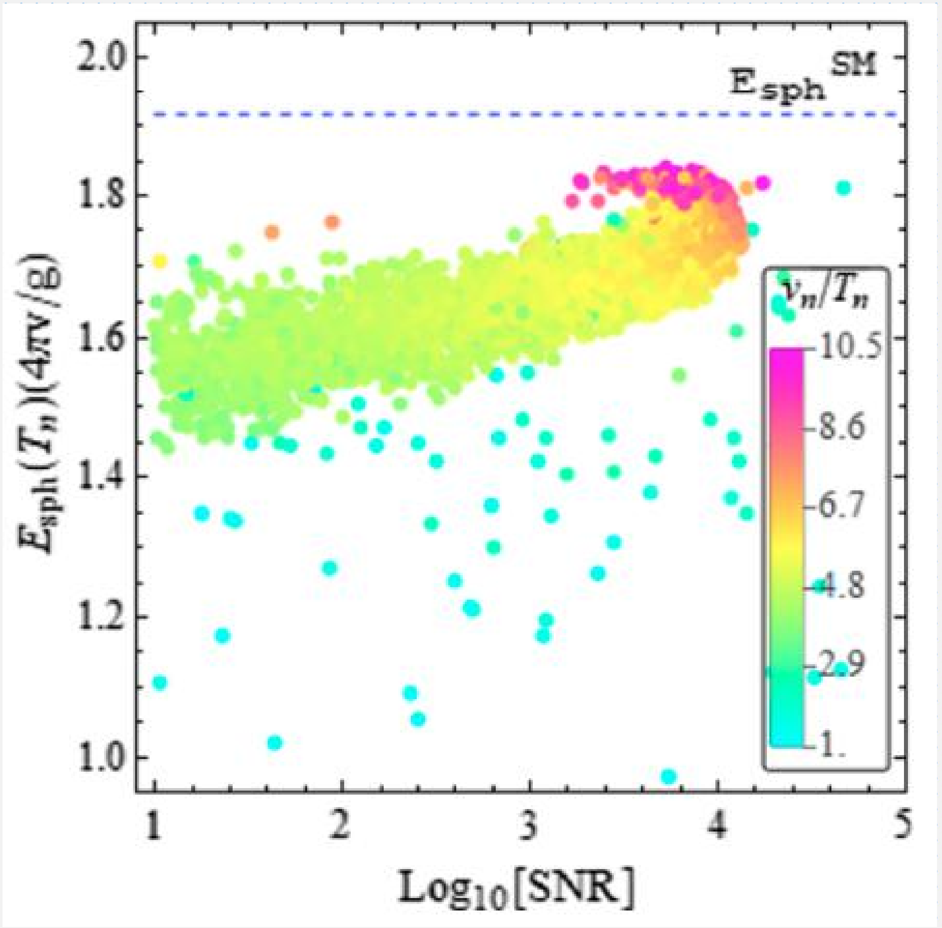


CMS, JHEP11(2018)042

Relating Sphaleron to GWs

- The Sphaleron can be probed with GWs



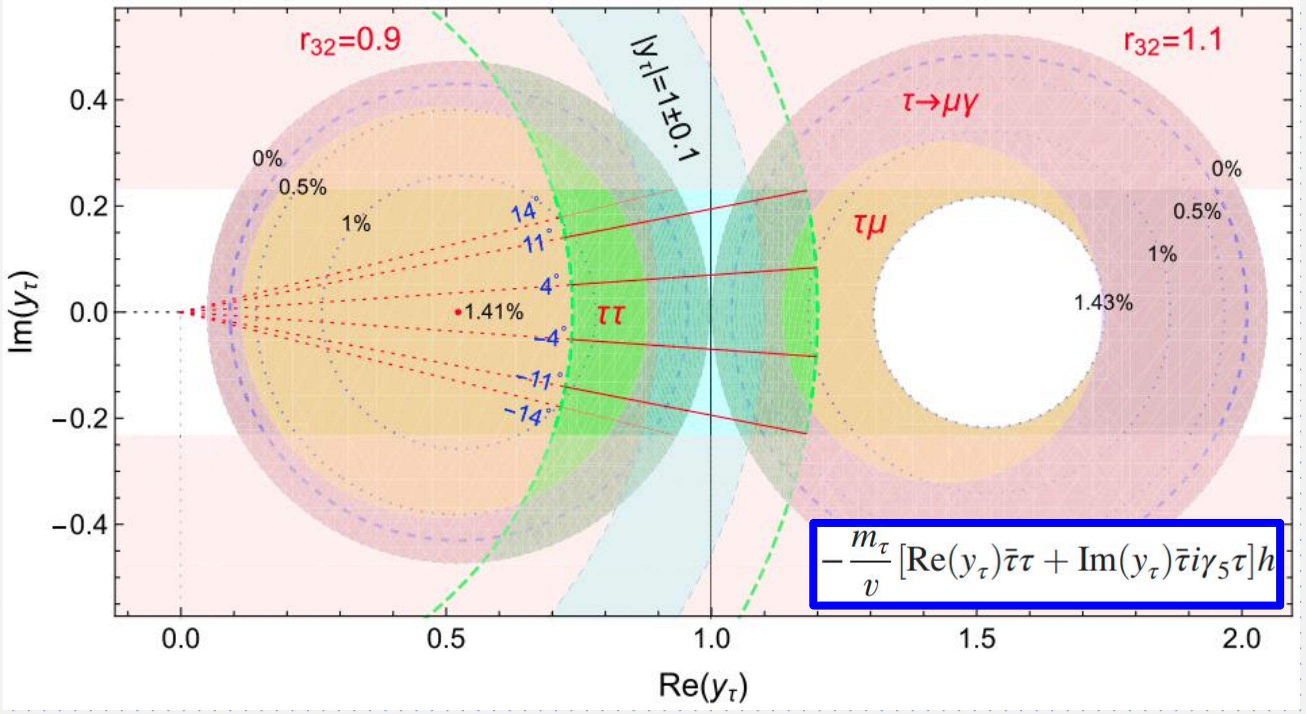


Ruiyu Zhou, Ligong Bian, HG, Phys.Rev.D (R) 101 (2020) 9, 091903

CP-Violation: Lepton-flavored Electroweak Baryogenesis

- CP-violation is generally small, decoupled from GW analysis
- Lepton-flavored EWBG is effective for baryon asymmetry generation

HG, Li, Liu, Ramsey-Musolf, Shu, PRD96,115034 (2017)



Type III 2HDM

$$\mathcal{L}^{\mathrm{Lepton}}_{\mathrm{Yukawa}} = -\overline{L^i}[Y_{1,ij}\Phi_1 + Y_{2,ij}\Phi_2]e^j_R + \mathrm{H.c.}$$

Jarlskog-like invariant

$$J_A = \frac{1}{v^2\mu^{\mathrm{HB}}_{12}}\sum_{a,b,c=1}^{2} v_a v_b^* \mu_{bc}\mathrm{Tr}[Y_c Y_a^\dagger]$$

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

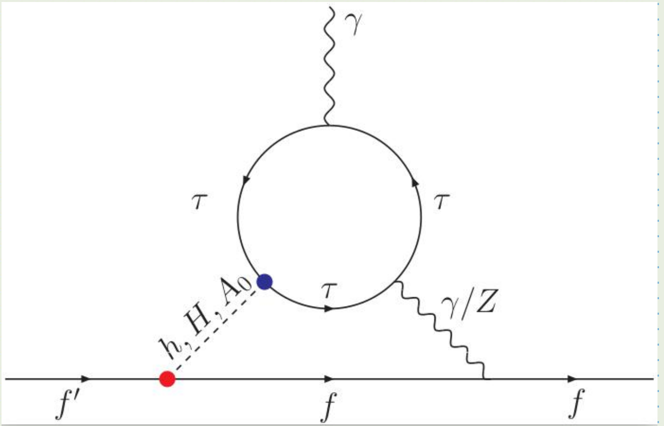
Prediction: CP-violating $h\tau\tau$

$$-\frac{m_\tau}{v}\left[\mathrm{Re}(y_\tau)\bar{\tau}\tau + \mathrm{Im}(y_\tau)\bar{\tau}i\gamma_5\tau\right]h$$

OK

discovery or exclusion?

Unconstrained from EDM measurements



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

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

Collider Sensitivities

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000		125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000		250			
HZZ/HWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.4\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~1	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Snowmass White Paper: Gritsan et al arXiv:2205.07715

Prediction: CP-violating $h\tau\tau$

$$-\frac{m_\tau}{v}\left[\mathrm{Re}(y_\tau)\bar{\tau}\tau + \mathrm{Im}(y_\tau)\bar{\tau}i\gamma_5\tau\right]h$$

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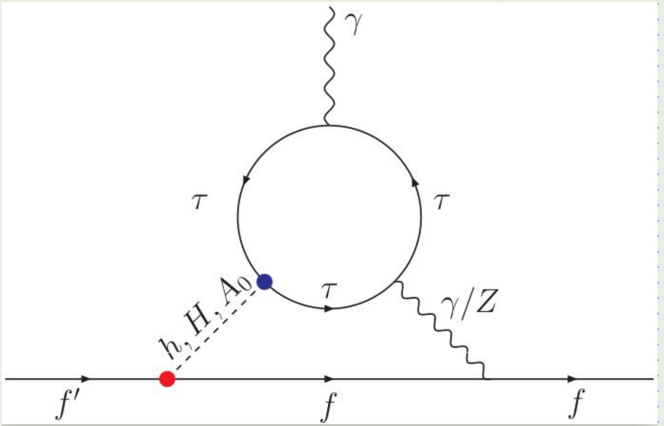

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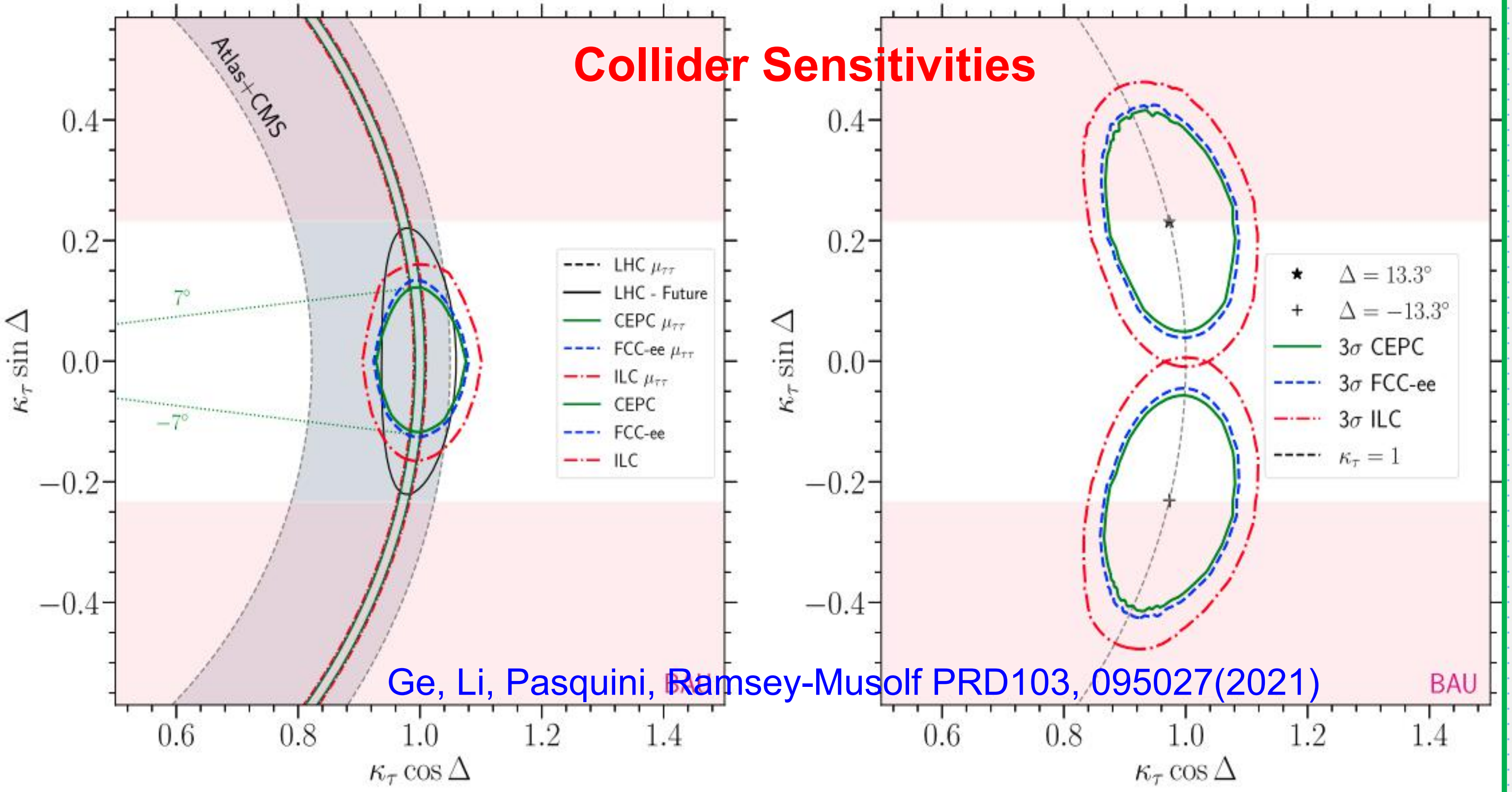
Collider Sensitivities



Ge, Li, Pasquini, Ramsey-Musolf PRD103, 095027(2021)

Summary

- EWBG remains a viable and highly testable mechanism
- GW becomes now an increasingly important new observable
- Correlation and complementarity exist between collider and GW probes