Collider and Gravitational Wave Complementarity in Probing the Electroweak Phase Transition

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UCAS (ICTP-AP)

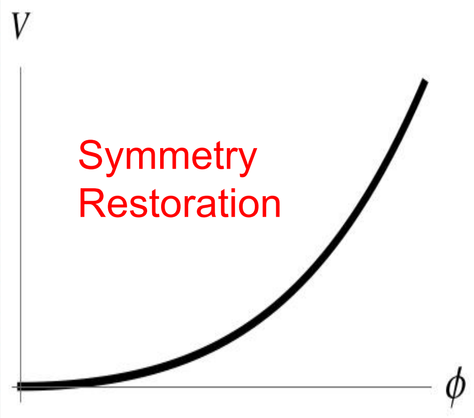
2023-8-16

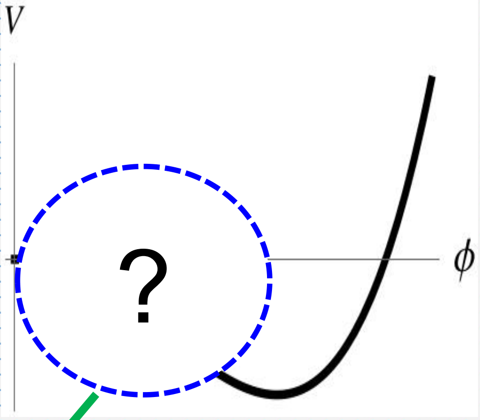
Ghosh, HG, Han, Liu, JHEP [2012.09758]
Alves, Goncalves, Ghosh, HG, Sinha, PLB [2007.15654]
Alves, Goncalves, Ghosh, HG, Sinha, JHEP [1909.05268]
Alves, Ghosh, HG, Sinha, Vagie, JHEP [1812.09333]
Alves, Ghosh, HG, Sinha, JHEP [1808.08974]
Zhou, Bian, HG, PRD [1910.00234]
HG, Li, Liu, Ramsey-Musolf, Shu, PRD [1609.09849]

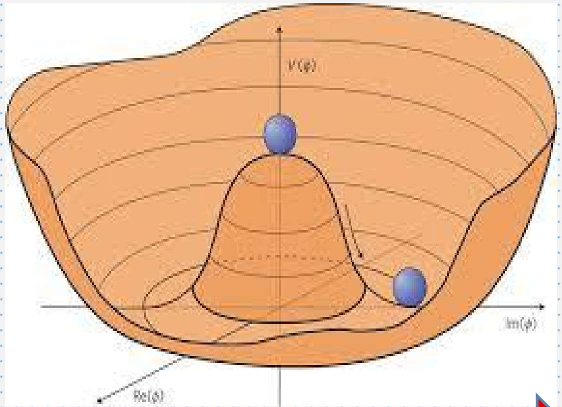
CEPC味物理-新物理和相关探测技术研讨会

Electroweak Phase Transition

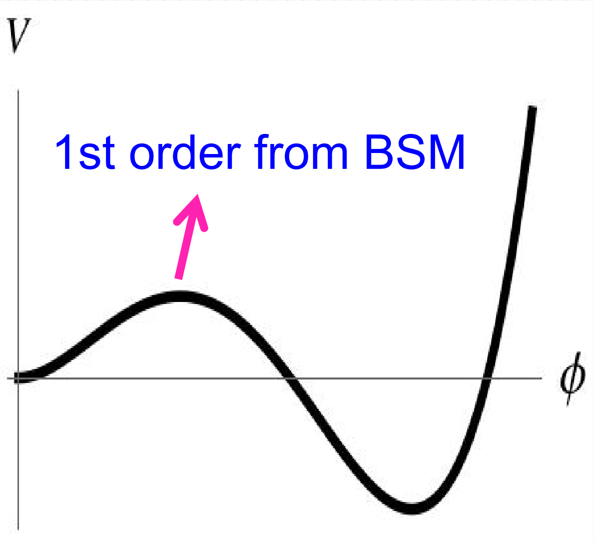
See also Ligong Bian's talk



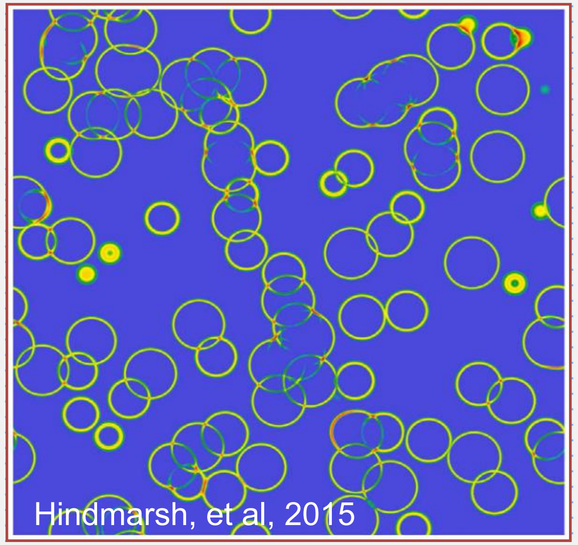




Temperature drops



bubbles, plasma, MHD



→ Gravitational Waves

→ Baryon Asymmetry (EWBG)

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

Morrissey,Ramsey-Musolf, NJP [1206.2942]

Collider and Gravitational Wave Complementarity

See also Yun Jiang, Wei Liu, Wei Su's talks

- Collider and GW work towards a common goal
- Correlation and complementarity in their roles

Detection of early-universe gravitational-wave signatures and fundamental physics

Robert Caldwell, Yanou Cui, Huai-Ke Guo, Vuk Mandic, Alberto Mariotti, Jose Miguel No, Michael J. Ramsey-Musolf, Mairi Sakellariadou, Kuver Sinha, Lian-Tao Wang, Graham White, Yue Zhao, Haipeng An, Ligong Bian, Chiara Caprini, Sebastien Clesse, James M. Cline, Giulia Cusin, Bartosz Fornal, Ryusuke Jinno, Benoit Laurent, Noam Levi, Kun-Feng Lyu, Mario Martinez, Andrew L. Miller, Diego Redigolo, Claudia Scarlata, Alexander Sevrin, Barmak Shams Es Haghi, Jing Shu, Xavier Siemens, Danièle A. Steer, Raman Sundrum, Carlos Tamarit, David J. Weir, Ke-Pan Xie, Feng-Wei Yang & Siyi Zhou — Show fewer authors

General Relativity and Gravitation **54**, Article number: 156 (2022) | Cite this article

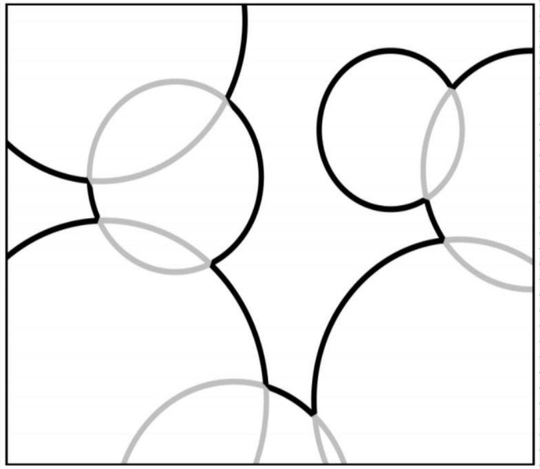
Contents

Snowmass 2021 Whitepaper, GRG [2203.07972]

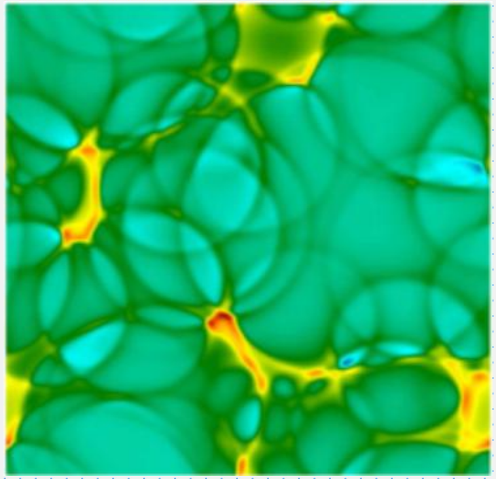
See also (Higgs exotic decay): Carena, Kozaczuk, Liu, Ou, Ramsey-Musolf, Shelton, Wang, Xie, LHEP [2203.08206]

Gravitational Wave Sources

Bubble Collisions

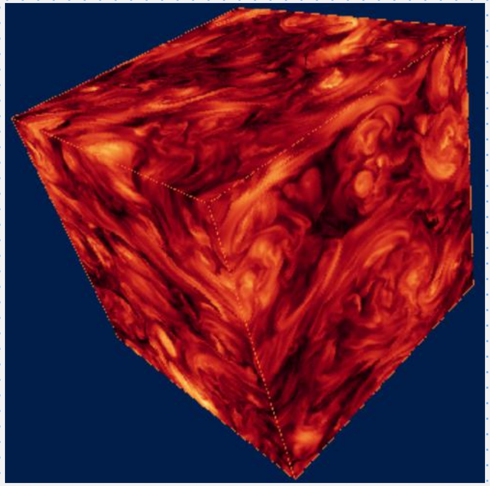


Sound Waves



Hindmarsh, et al,PRL112,041301(2013)

MagnetoHydrodynamic Turbulence



https://home.mpcdf.mpg.de/~wcm/projects/homog-mhd/mhd.html

energy concentrated at walls

acoustic production

turbulent motion

New observables: primordial magnetic field, scalar perturbations, anisotropy, primordial black hole...

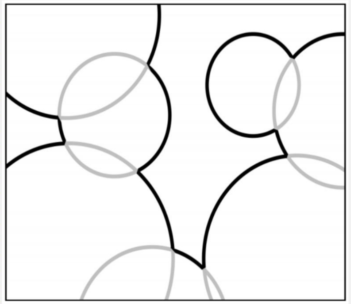
Di, Wang, Zhou, Bian, Cai, Liu, PRL 126 (2021) 25, 251102
Jing, Bian, Cai, Guo, Wang, PRL 130 (2023) 051001
Li, Huang, Wang, Zhang, PRD 105 (2022) 083527
Huang, Xie, PRD105 (2022) 11, 115033, JHEP 09 (2022) 052

The GW Observables

Energy density Spectrum

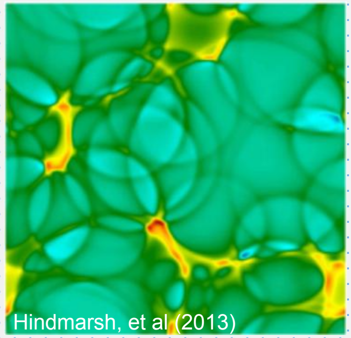
$$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

bubble collision



$$\Omega_{\rm coll}(f)h^2 = 1.67\times10^{-5}\Delta\left(\frac{H_{\rm pt}}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2 \times\left(\frac{100}{g_*}\right)^{1/3}S_{\rm env}(f),$$

sound waves



Hindmarsh, et al (2013)

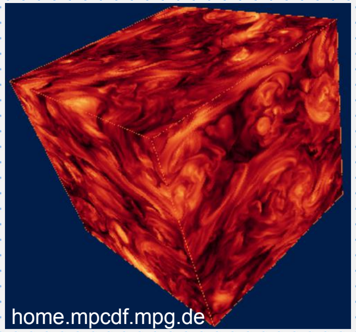
$$\Omega_{\rm sw}(f)h^2 = 2.65\times10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

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

HG,Sinha,Vagie,White, JCAP [2007.08537]

adopted by LIGO, NANOGrav, etc

MHD



home.mpcdf.mpg.de

$$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

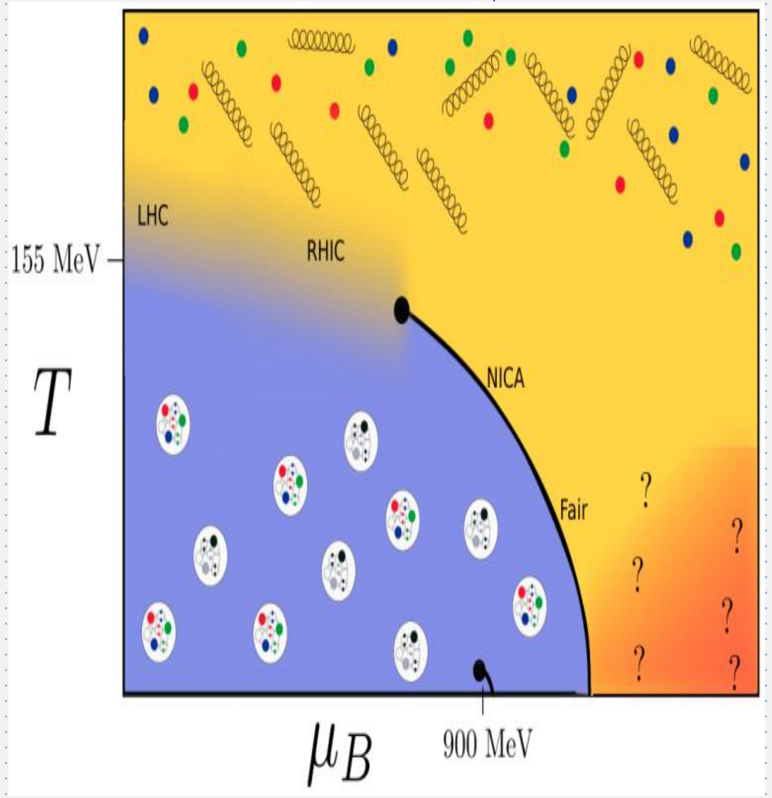
Chiara Caprini et al JCAP04(2016)001

Generic Features

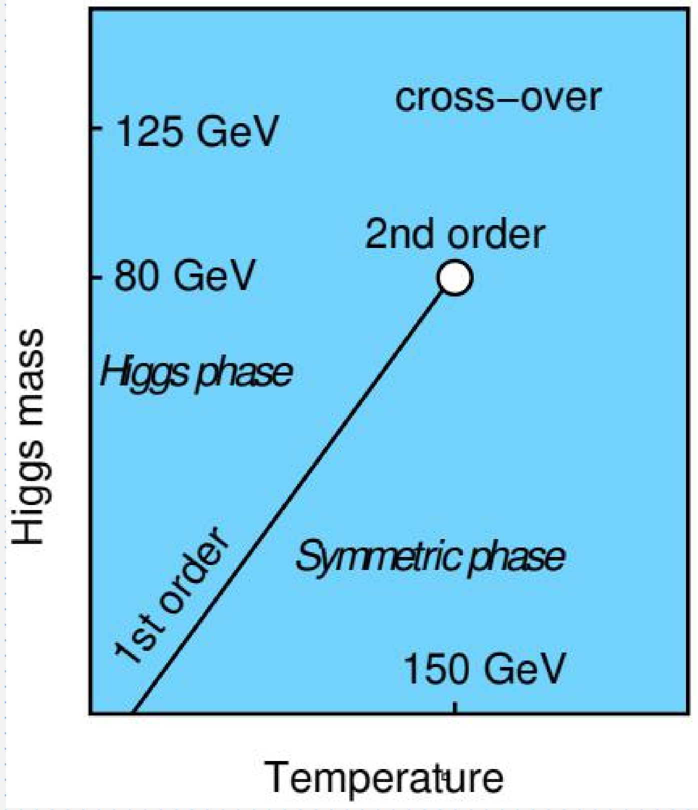
- LIGO (~100Hz) : (~PeV - EeV)
- LISA, Taiji, Tianqin: ~mHz : (~100GeV)
- PTA: nHz (~100MeV)

QCD PT

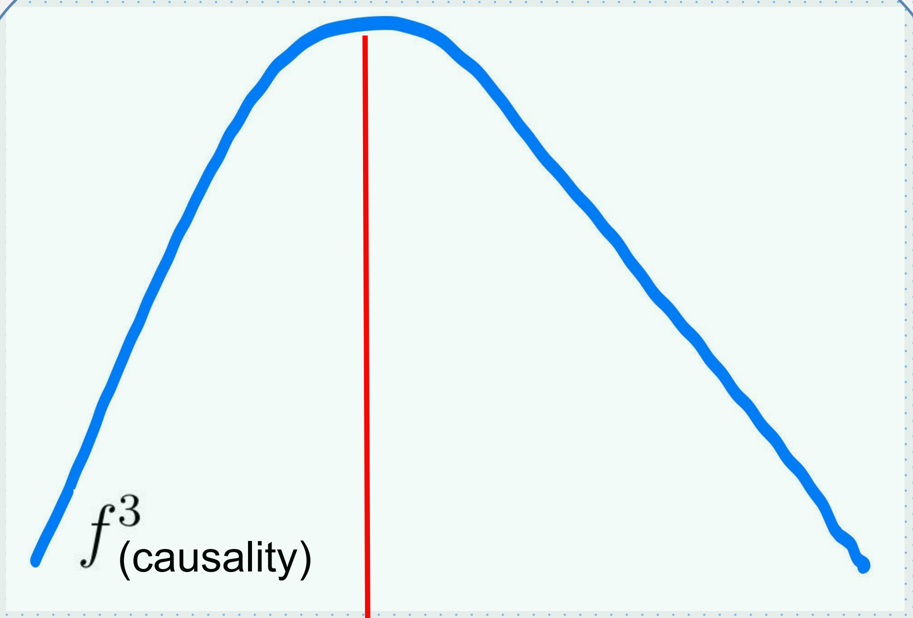
EWPT



Guenther [2010.15503]



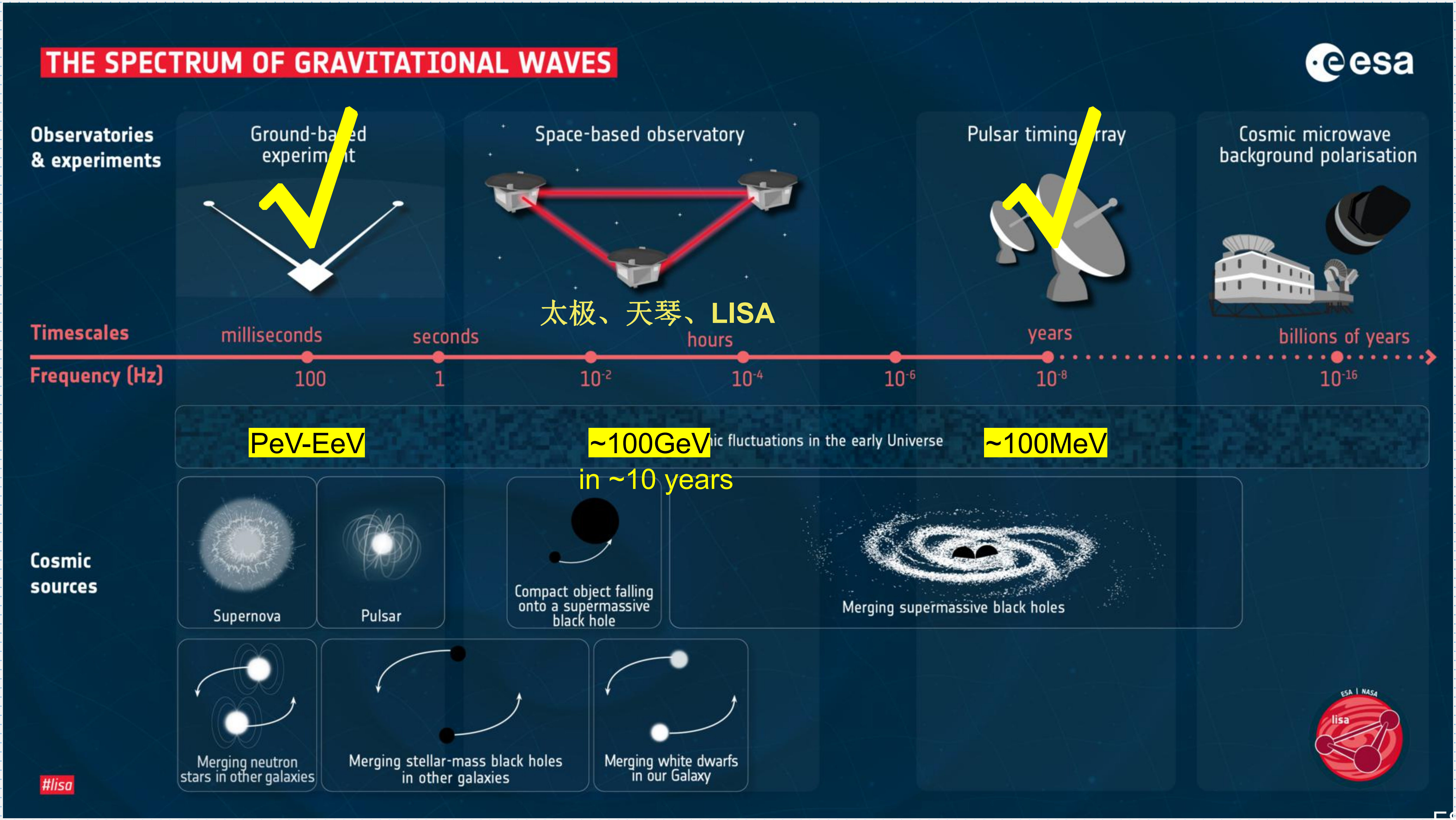
Hindmarsh et al SciPost Phys.Lect.Notes 24 (2021)



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

typical length scale

tells PT temperature
(symmetry breaking scale)



THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
太极、天琴、LISA
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-16}
PeV-EeV
~100GeV
in ~10 years
ic fluctuations in the early Universe
~100MeV
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
#lisa
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BSM studies

Chung,Long,Wang, PRD [1209.1819]

- Large cubic term from thermal correrctions (loop level)
- Add new scalars (tree level)
- Including non-renormalizable operators

EFT approach: Cai,Hashino,Wang,Yu [2202.08295]
Global fit: Du, NPPP [2303.16400]

Classification according to the symmetries

Classification according to the problems

Models	Strong 1st order phase transition	GW signal	Cold DM	Dark Radiation and small scale structure
SM charged				
Triplet [20–22]	✓	✓	✓	✗
complex and real Triplet [23] (Georgi-Machacek model)	✓	✓	✓	✗
Multiplet [24]	✓	✓	✓	
2HDM [25–30]	✓	✓		✗
MLRSM [31]	✓	✓	✗	✗
NMSSM [32–36]	✓	✓	✓	✗
SM uncharged				
S_r (xSM) [37–49]	✓	✓	✗	✗
2 S_r's [50]	✓	✓	✓	✗
S_c (cxSM) [49, 51–54]	✓	✓	✓	✗
$U(1)_D$ (no interaction with SM) [55]	✓	✓	✓	✗
$U(1)_D$ (Higgs Portal) [56]	✓	✓	✓	
$U(1)_D$ (Kinetic Mixing) [57]	✓	✓	✓	
Composite $SU(7)/SU(6)$ [58]	✓	✓	✓	
$U(1)_L$ [59]	✓	✓	✓	✗
$SU(2)_D \to$ global $SO(3)$ by a doublet [60–62]			✓	✗
$SU(2)_D \to U(1)_D$ by a triplet [63–65]			✓	✓
$SU(2)_D \to Z_2$ by two triplets [66]			✓	✗
$SU(2)_D \to Z_3$ by a quadruplet [67, 68]			✓	✗
$SU(2)_D \times U(1)_{B\text{-}L} \to Z_2 \times Z_2$ by a quintuplet and a S_c [69]			✓	✗
$SU(2)_D$ with two dark Higgs doublets [70]	✓	✓	✗	✗
$SU(3)_D \to Z_2 \times Z_2$ by two triplets [62, 71]			✓	✗
$SU(3)_D$ (dark QCD) (Higgs Portal) [72, 73]	✓	✓	✓	
$G_{SM} \times G_{D,SM} \times Z_2$ [74]	✓	✓	✓	
$G_{SM} \times G_{D,SM} \times G_{D,SM} \cdots$ [75]	✓	✓	✓	
Current work				
$SU(2)_D \to U(1)_D$ (see the text)	✓	✓	✓	✓

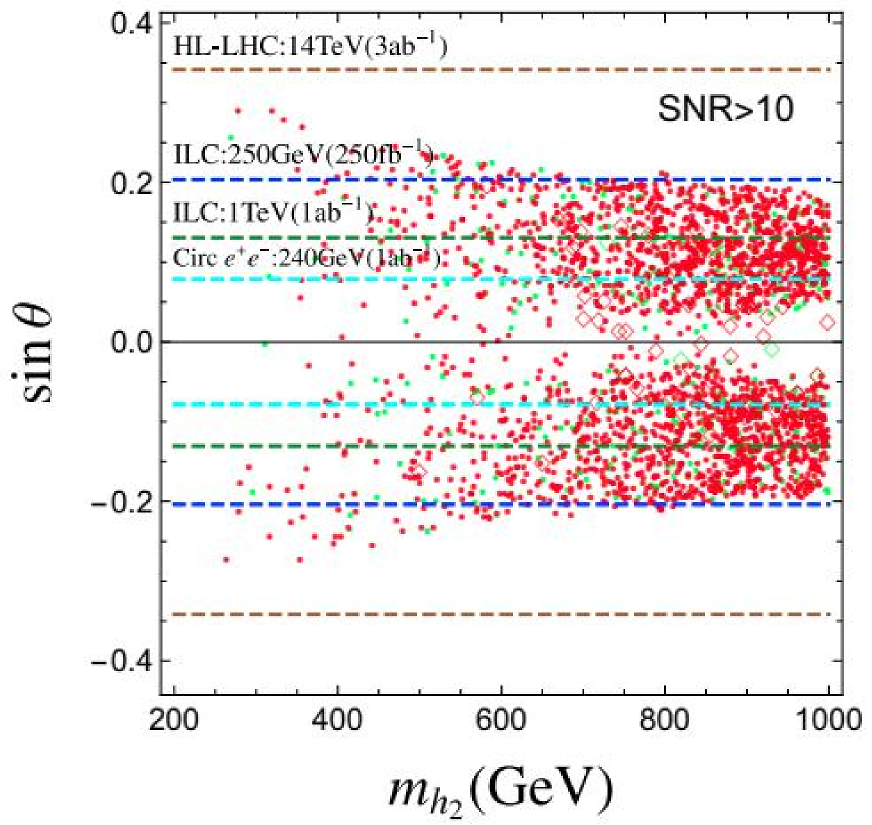
Ghosh,HG,Han,Liu, JHEP [2012.09758]

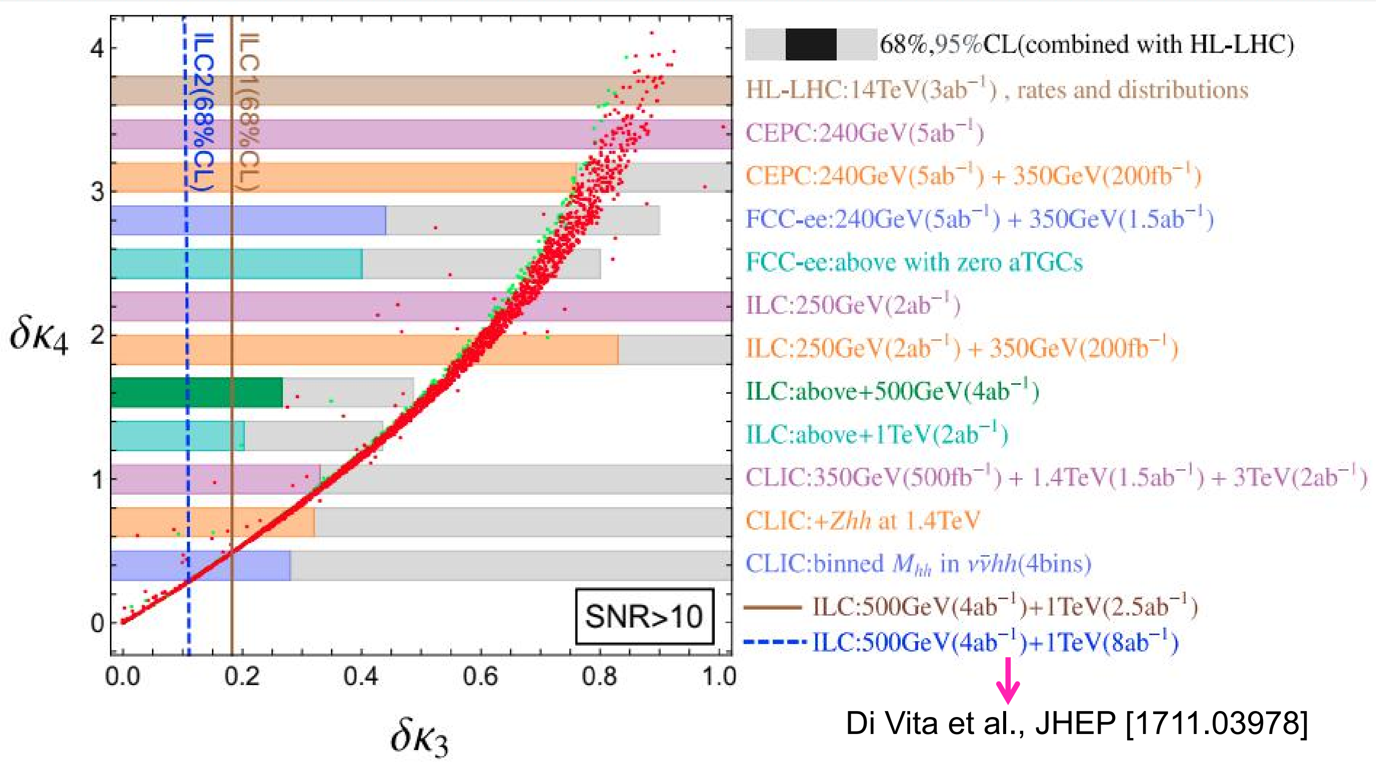
Higgs Precision Measurements

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

h1: the Higgs
h2: heavier scalar

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





Di Vita et al., JHEP [1711.03978]

Alves, Ghosh, HG, Sinha, Vagie, JHEP [1812.09333]

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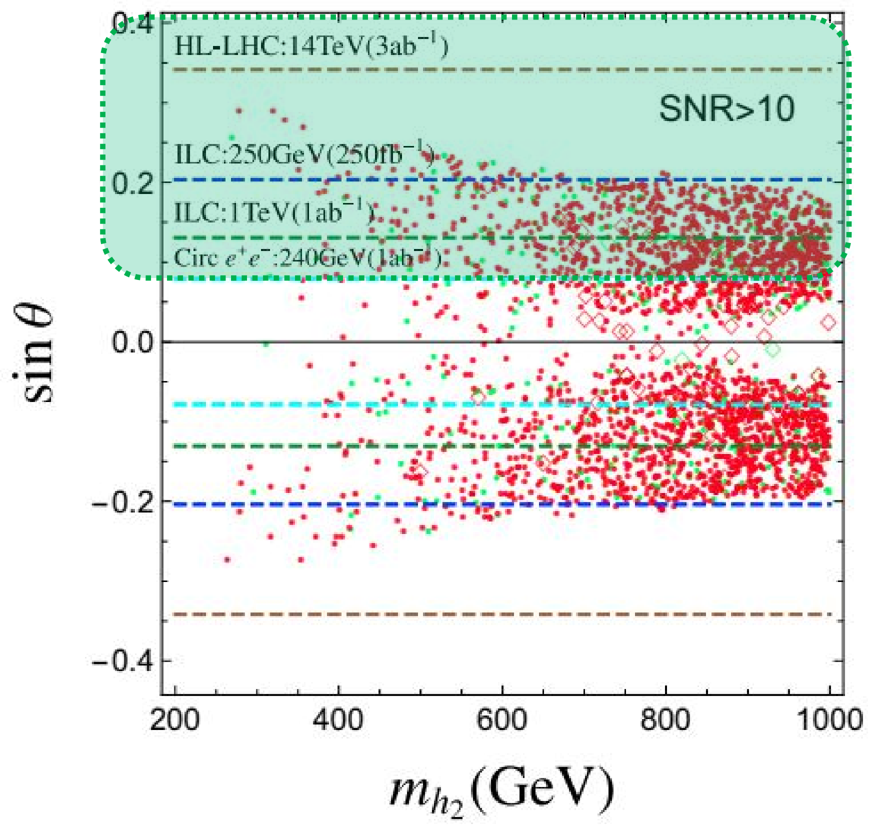
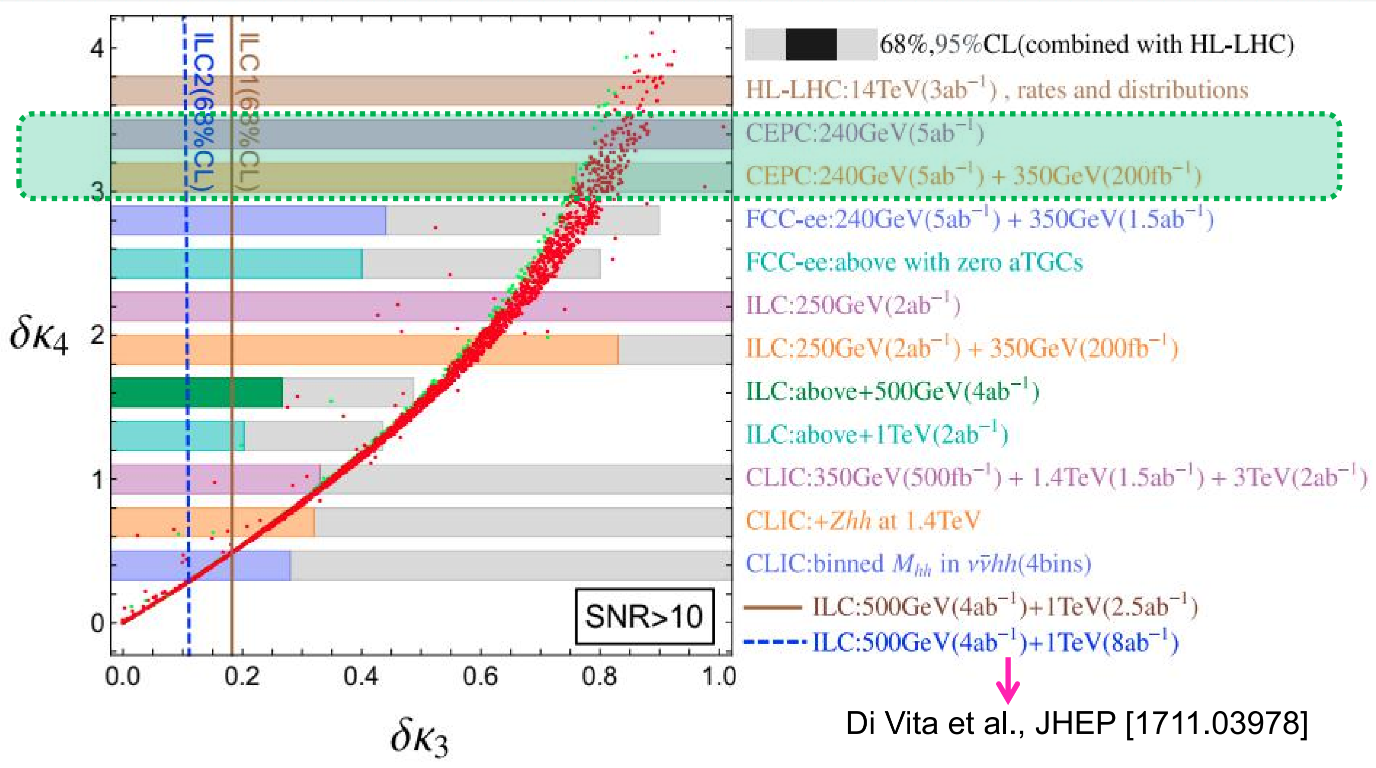




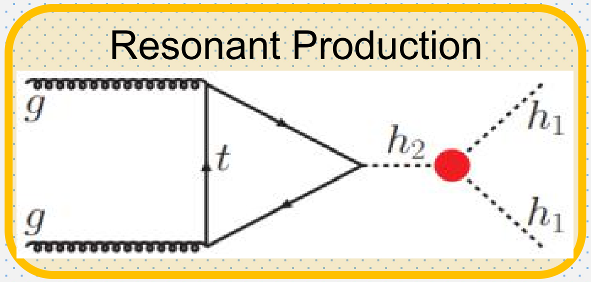
Di Vita et al., JHEP [1711.03978]

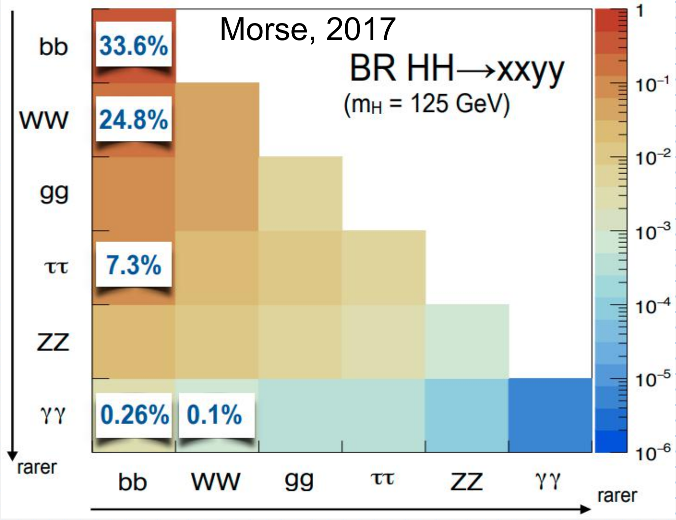
Alves, Ghosh, HG, Sinha, Vagie, JHEP [1812.09333]

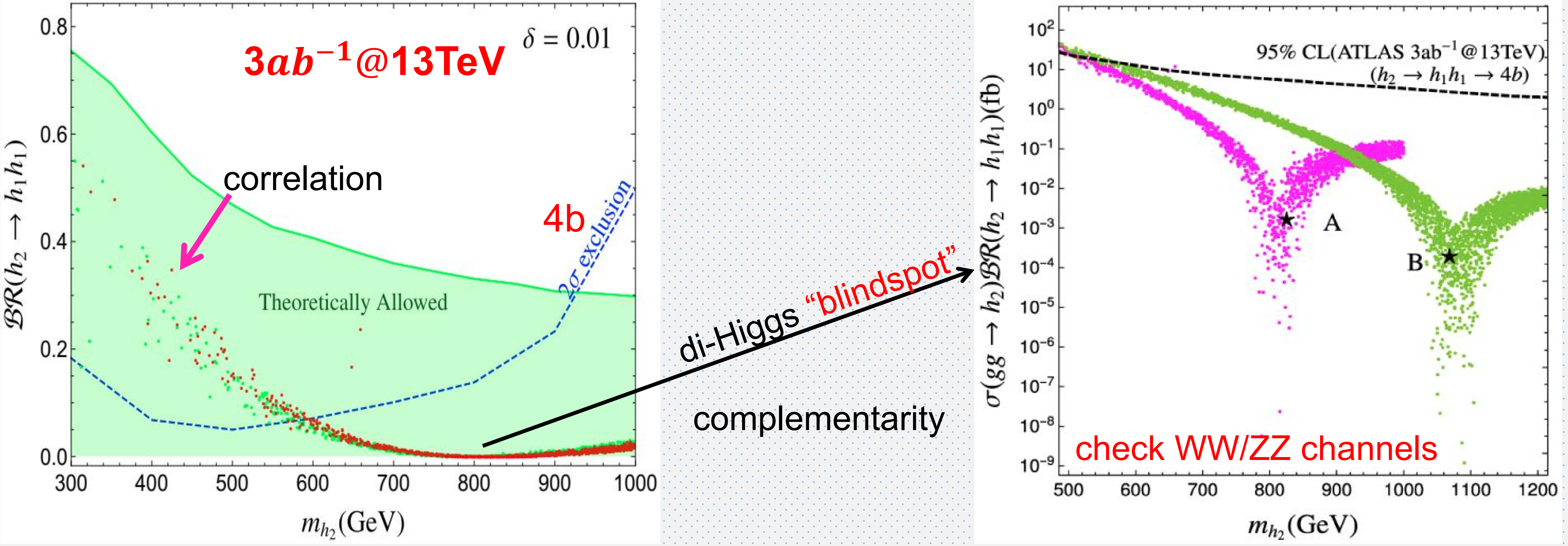
Di-Higgs Production

- Enhanced (resonant) di-Higgs production

See also:
No,Ramsey-Musolf, PRD [1310.6035]
Li,Ramsey-Musolf,Willocq, JHEP [1906.05289]
Huang,No,Pernie,Ramsey-Musolf,Safonov, PRD [1701.04442]
Zhang,Li,Liu,Ramsey-Musolf,Zeng,Arunasalam [2303.03612]
Liu,Xie,JHEP [2101.10469]
and more...







Alves,Gonçalves,Ghosh,HG,Sinha, JHEP [1909.05268]

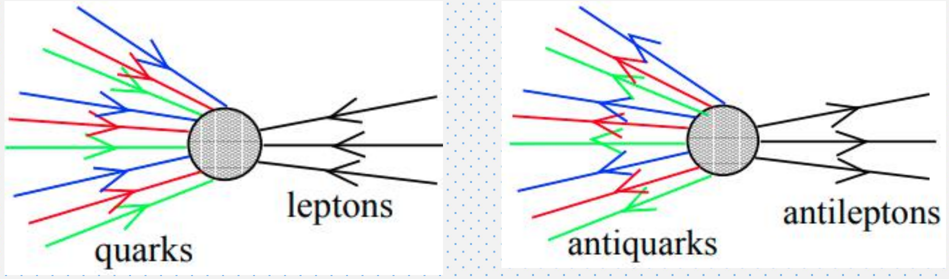
Alves,Gonçalves,Ghosh,HG,Sinha, PLB [2007.15654]

B-violation in the SM

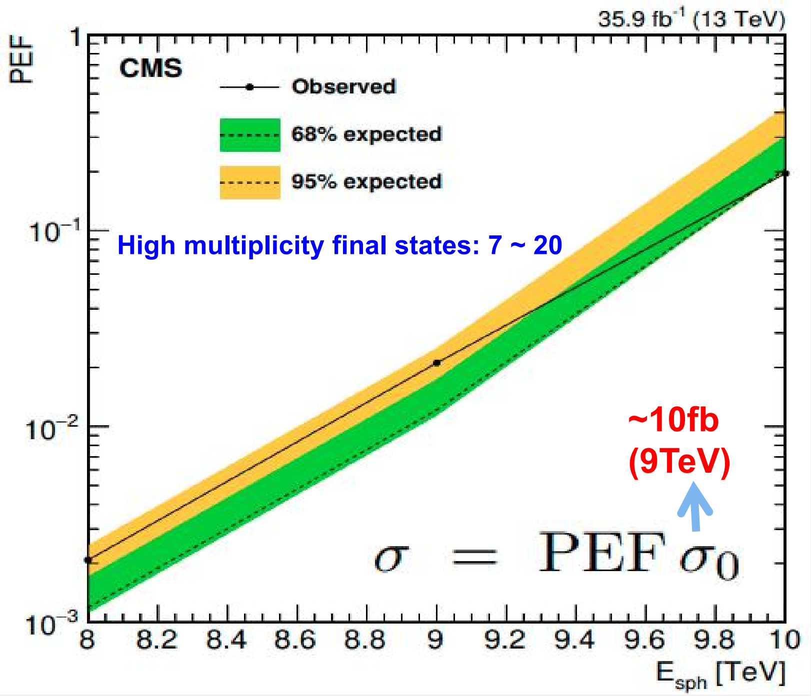
$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_l = n_f \left[\frac{g^2}{32\pi^2} W_{\mu\nu} \widetilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} F_{\mu\nu} \widetilde{F}^{\mu\nu} \right]$$

A SM process

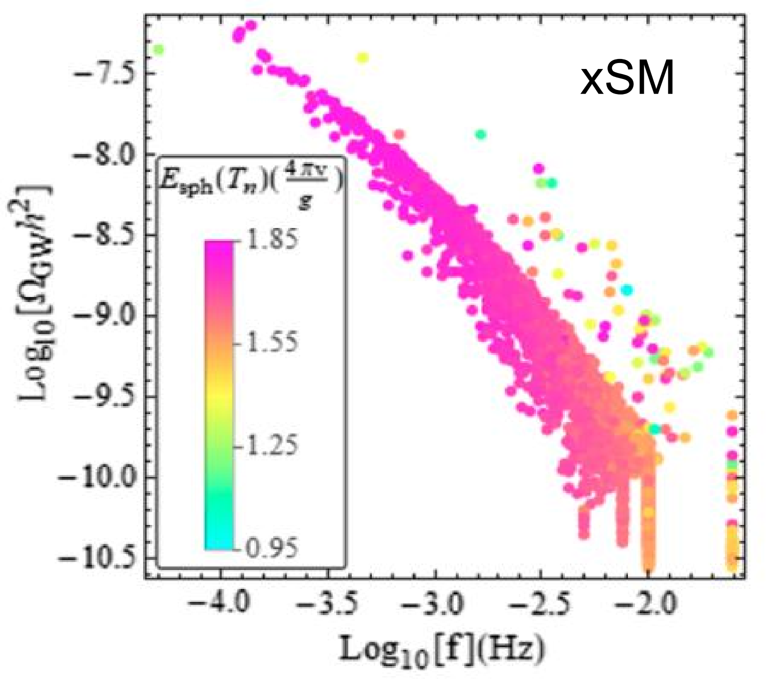
- Searchable at colliders but difficult
- B-violation at the EWPT: probable by GWs (Sphaleron)



Cline, arxiv:0609145



CMS, JHEP [1805.06013]



Zhou, Bian, HG, PRD (R) [1910.00234]

See also Xin Chen's talk

CP-Violation

Lepton-flavored EWBG

HG, Li, Liu, Ramsey-Musolf, Shu, PRD [1609.09849]

- Effective for baryon asymmetry generation
- GW less affected by the small CPV
- Definitive target for CEPC and others

With GWs: Xie, JHEP [2011.04821] and others

Type III 2HDM

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

Jarlskog invariant

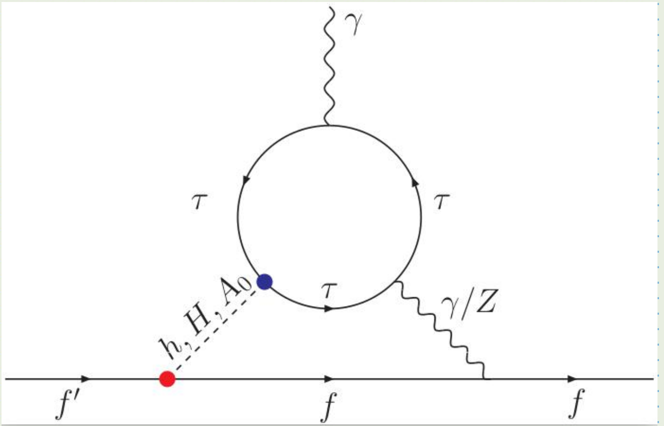
$$J_A = \frac{1}{v^2 \mu_{12}^{\text{HB}}} \sum_{a,b,c=1}^{2} v_a v_b^* \mu_{bc} \text{Tr}[Y_c Y_a^\dagger]$$

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

OK

discovery or exclusion

Unconstrained from EDM measurements



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

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

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 [2205.07715]

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HG, Li, Liu, Ramsey-Musolf, Shu, PRD [1609.09849]

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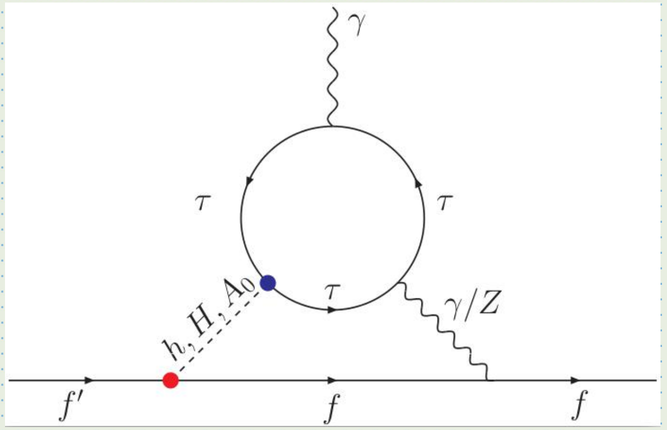
Unconstrained from EDM measurements



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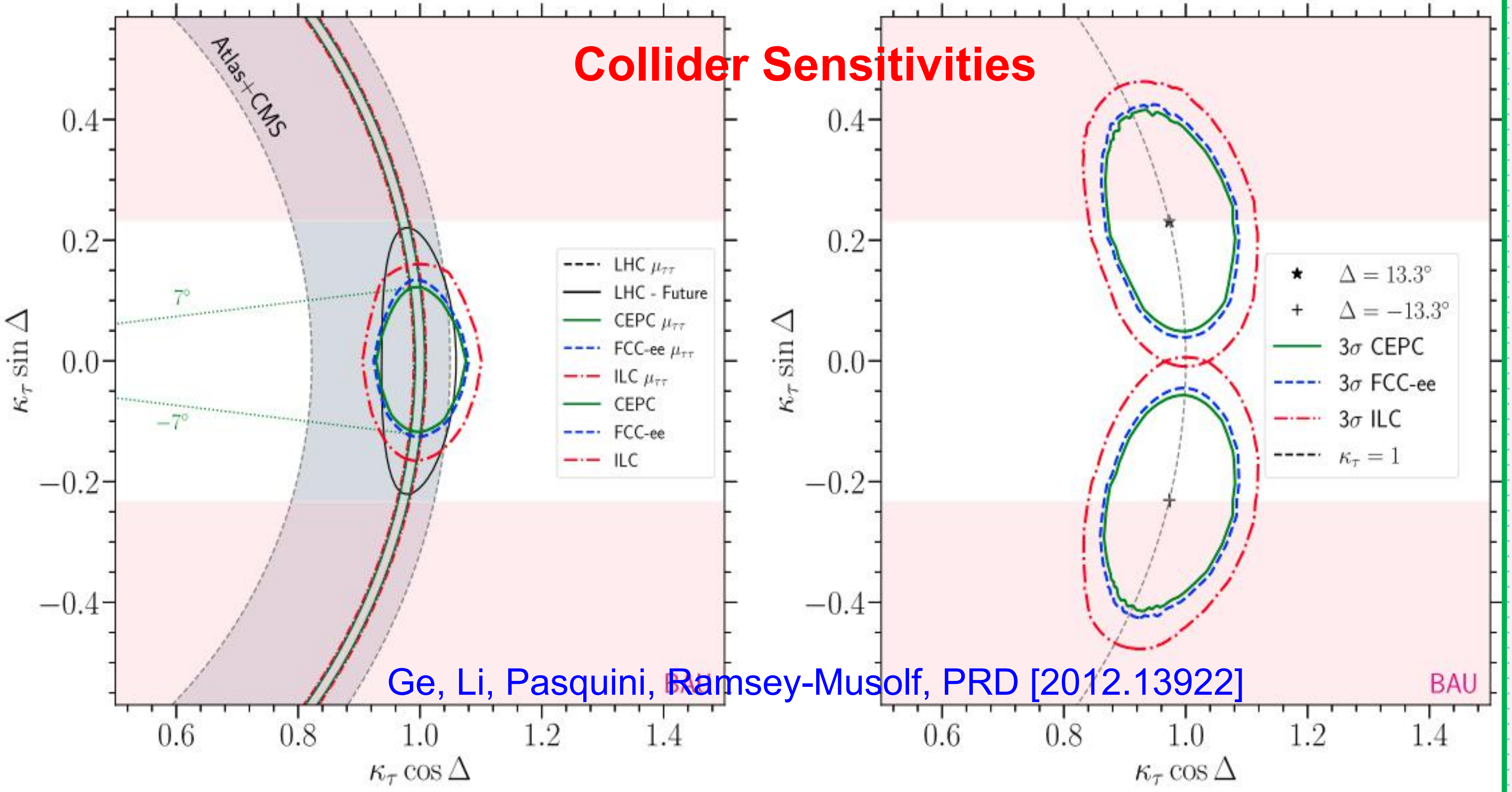
$$\text{ACME 2014: } \left|\frac{d_e}{e}\right| < 8.7\times 10^{-29} e\cdot\mathrm{cm}$$

Collider Sensitivities



Ge, Li, Pasquini, Ramsey-Musolf, PRD [2012.13922]

Summary

- GW serves as a new tool for probing the EWPT
- Correlation and complementarity exist between colliders and GW
- Studies at colliders can guide future detections at 太极、天琴、LISA

The 2023 Shanghai Symposium on Particle Physics and Cosmology: Phase Transitions, Gravitational Waves, and Colliders (SPCS 2023)

Organizing Committee

- Michael Ramsey-Musolf 任穆 (Shanghai Jiao Tong University, Tsung-Dao Lee Institute)
- Huaike Guo (University of Chinese Academy of Sciences, ICTP-AP)
- Fa Peng Huang (Sun Yat-Sen University)
- Shu Li (Shanghai Jiao Tong University, Tsung-Dao Lee Institute)
- Kun Liu (Shanghai Jiao Tong University, Tsung-Dao Lee Institute)
- Lei Zhang (Nanjing University)

Website: https://indico-tdli.sjtu.edu.cn/event/1741/