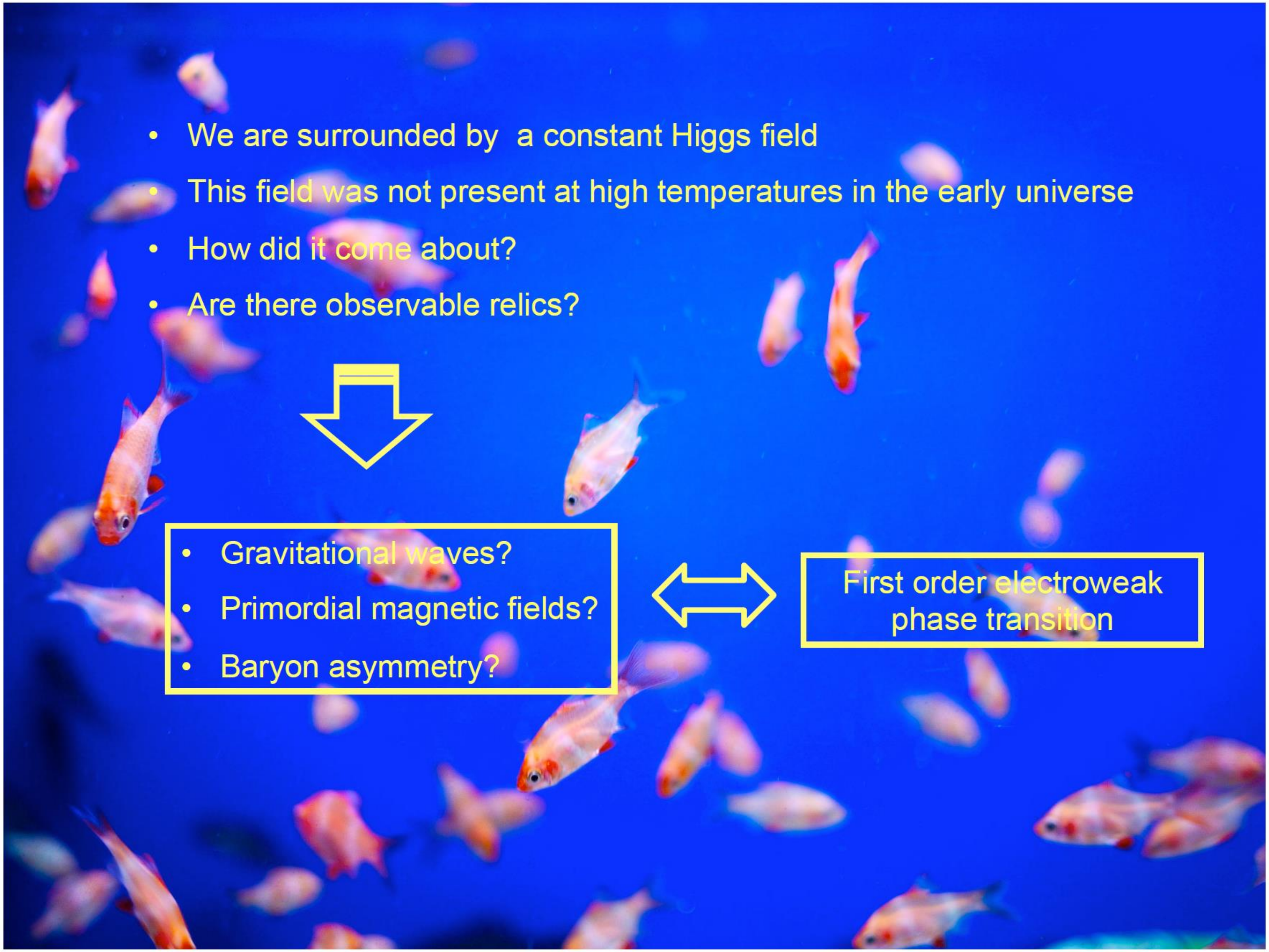
FirstOrderElectroWeakPhaseTransition & CEPC Astro Summary

[Contain Slides adapted from Huber,
CEPC workshop talks, CEPC white paper, etc.]



- We are surrounded by a constant Higgs field
- This field was not present at high temperatures in the early universe
- How did it come about?
- Are there observable relics?

- Gravitational waves?
- Primordial magnetic fields?
- Baryon asymmetry?

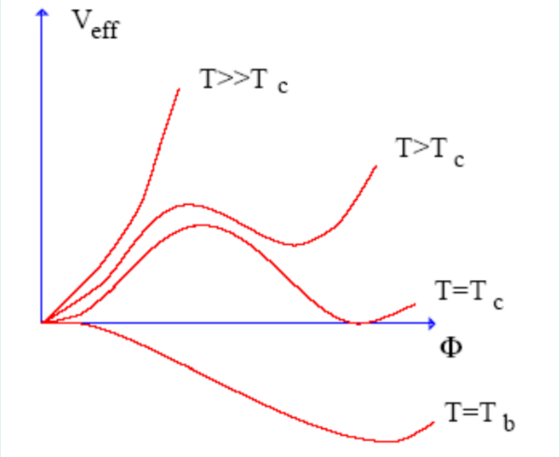
⇔

First order electroweak phase transition

The strength of the PT

Thermal potential:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$



- Boson loops:

SM: gauge bosons

strong PT: m_h<40 GeV (no top)

never (with realistic top mass)

Lattice: crossover for m_h>80 GeV → no phase transition in the SM

Kajantie, Laine, Rummukainen, Shaposhnikov 1996

Csikor, Fodor, Heitger 1998

The strength of the PT

Thermal potential:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

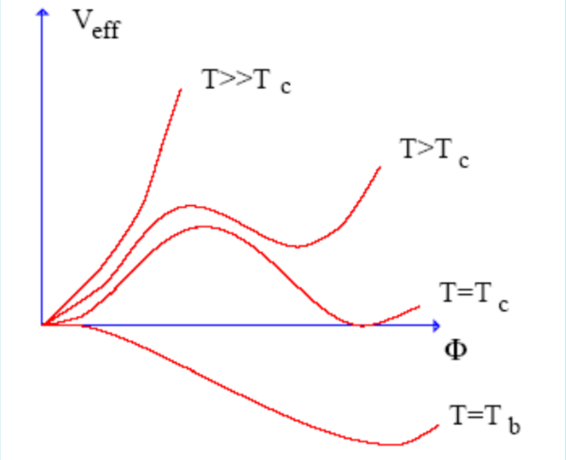
- Boson loops:

  SM: gauge bosons

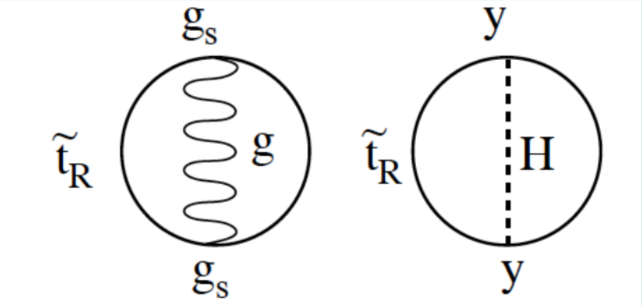
  SUSY: light stops

  2HDM: extra Higgses

- tree-level: extra singlets: λSH^2, NMSSM, etc.
- replace H^4 by H^6, etc.



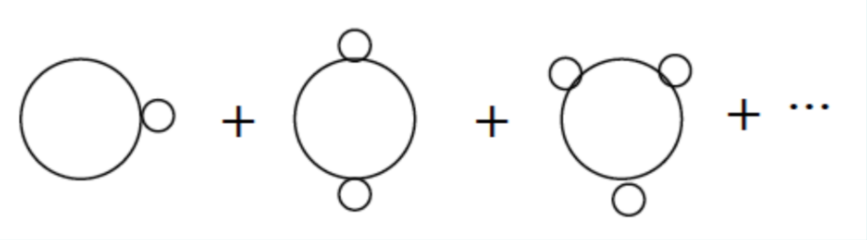
2-loop contributions can be important:



$$
\begin{aligned}
V_{SM}^{(2)} &= \frac{g^2}{16\pi^2} T^2 \left[M^2 \left(\frac{3}{4} \log \frac{M_L}{T} - \frac{51}{8} \log \frac{M}{T} \right) + \frac{3}{2} \left(M^2 - 4M_L^2 \right) \log \frac{M + 2M_L}{3T} + 3MM_L \right] \\
&\quad + \frac{m_t^2(\varphi) T^2}{64\pi^2} \left[16 g_s^2 \left(\frac{8}{3} \log 2 - \frac{1}{2} - c_B \right) + 9 h_t^2 \sin^2 \beta \left(\frac{4}{3} \log 2 - c_B \right) \right] \qquad (22)
\end{aligned}
$$

Daisy resummation:

➔ thermal masses



FOEWPT can create vacuum bubbles and mediate baryogenesis.

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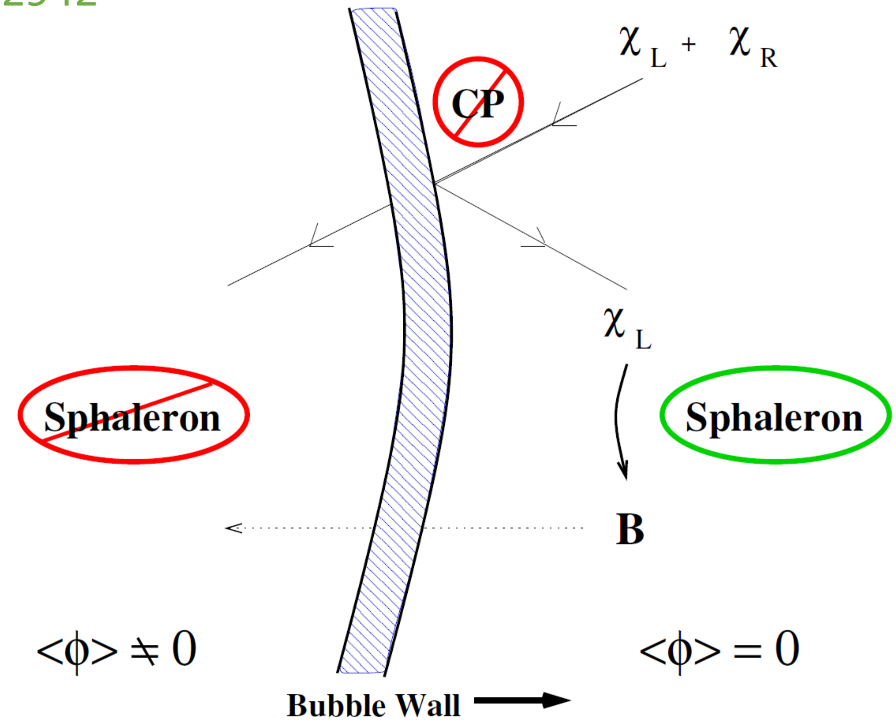
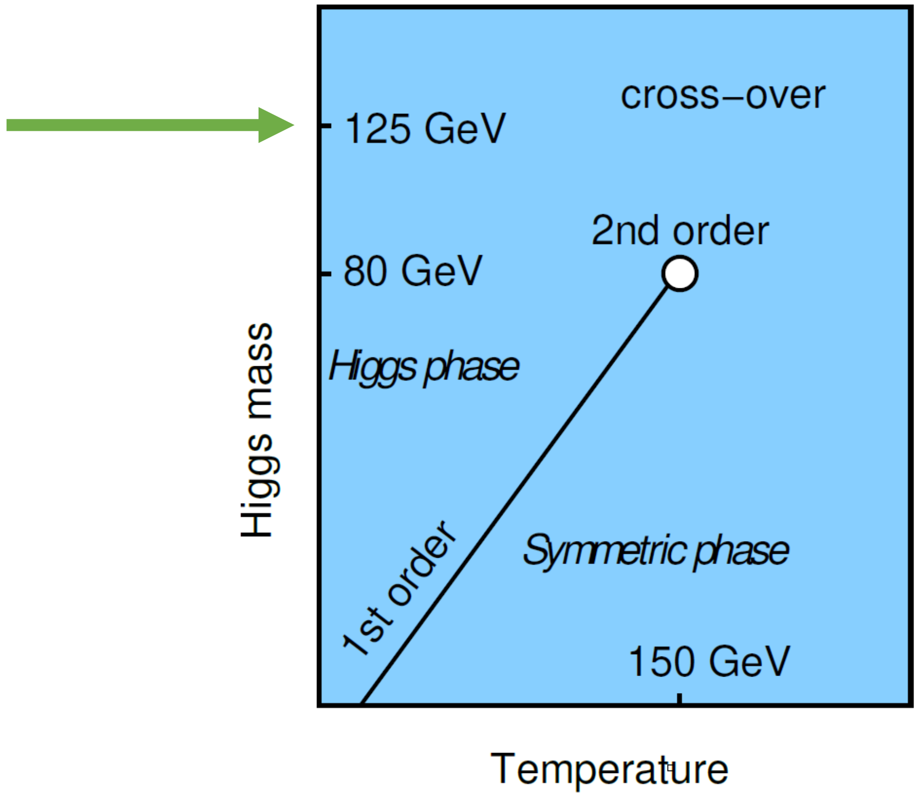


Figure 2. Baryon production in front of the bubble walls.

$$\partial_\mu J^\mu_B = -\frac{g_2^2}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}W^a_{\mu\nu}W^a_{\rho\sigma}$$

BNV by anomaly, in presence of $SU(2)_L$ field

t'Hooft, 1976



The phase diagram of the Standard model. Higgs masses of $m_H < 75$ GeV (excluded) the Standard Model undergoes a FOEWPT (figure from 2008.09136)

SM:

SM Higgs mass too low
for FOPT. (<70 GeV)
Bochkarev and M. E. Shaposhnikov, 1987

Even w FOPT, SM's CKM
insufficient for baryogenesis
see hep-ph/9312215, /9404302,/9406289

BSM:

Must exist in abundance
around transition Tc
(-> close to EW scale)

Moderately (at least) coupled
to the SM
(-> coupled sectors)

- 2HDM: m_H>~300 (transport by tops)
- SM with a dim-6 Higgs potential for M<800 GeV
(EDMs similar to 2HDM)
- MSSM: light stop for the phase transition
(very constrained now!)
transport by the charginos (instead of tops)
severe constraints from EDMs
- Singlet models (NMSSM): many possiblities
cubic terms in the tree-level potential
induce a strong phase transition
EDM constraints somewhat relaxed (or
totally absent for transitional CP)

bonus -> GW from FOEWPT

A Very Inert (Z_2) Example:

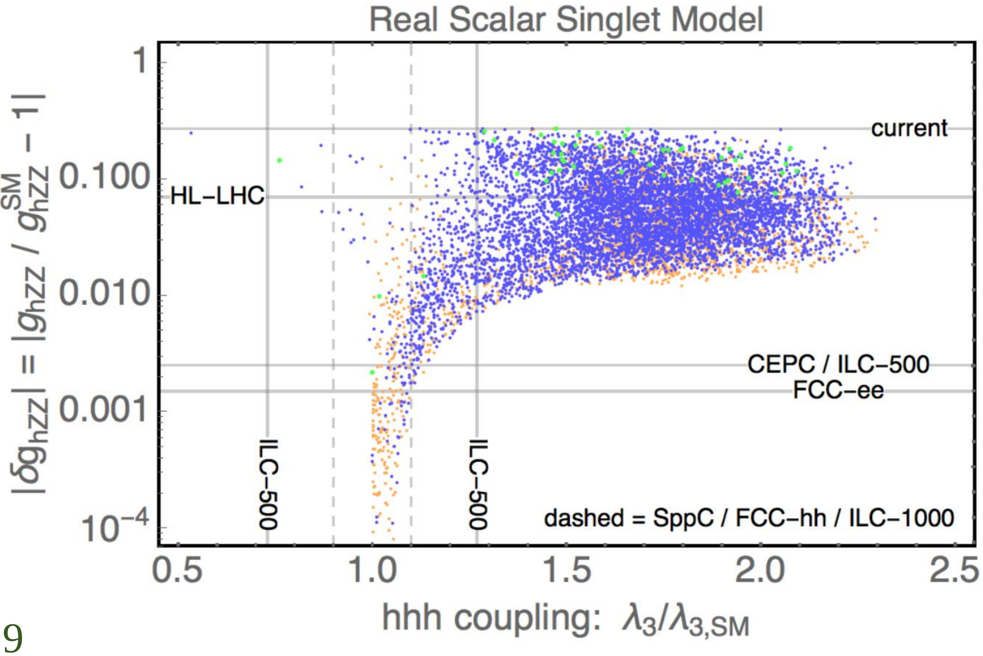
SM + real singlet scalar

BSM singlet carries odd parity

$$\lambda_{hs}\Phi^\dagger\Phi S^2$$

-> h-s mixing forbidden by Z_2

-> modified Higgs (125GeV) branching & couplings at loop level



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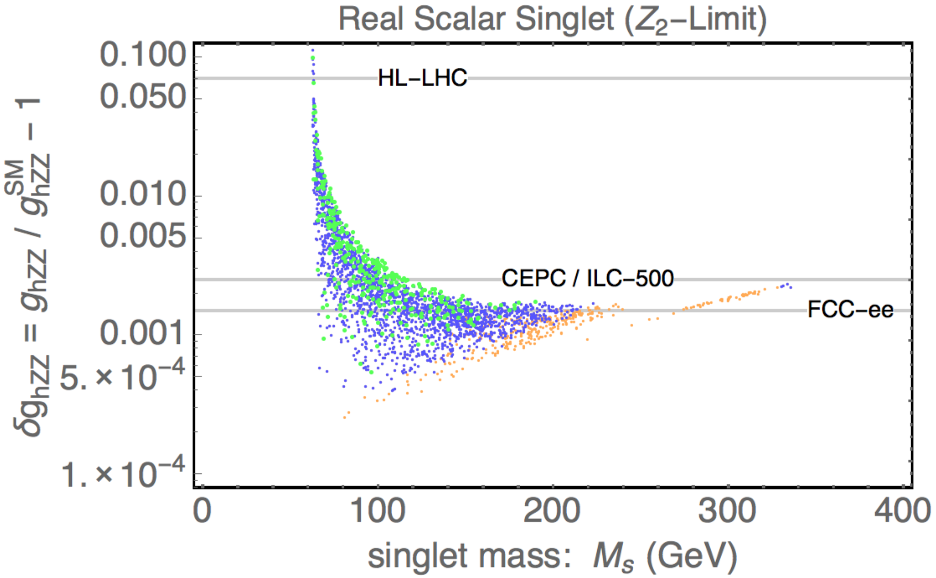
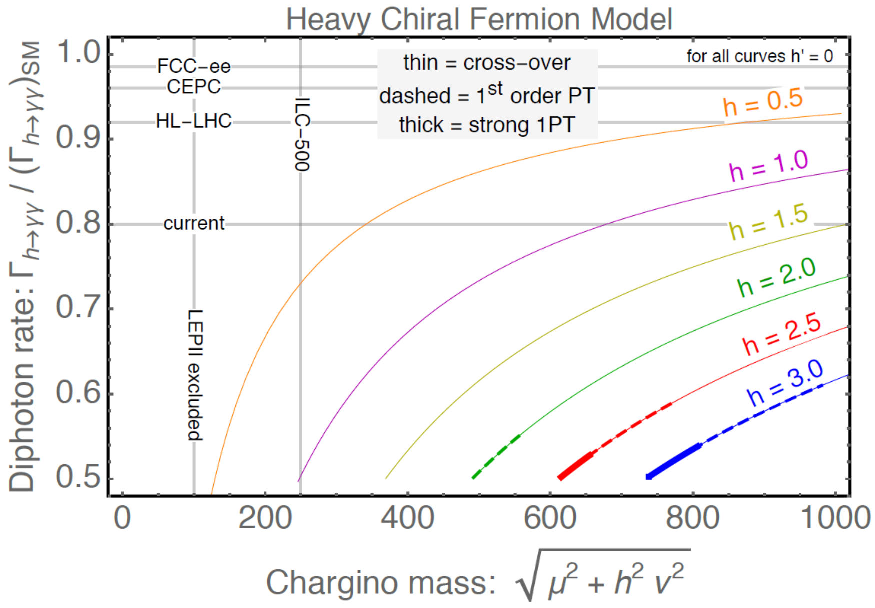


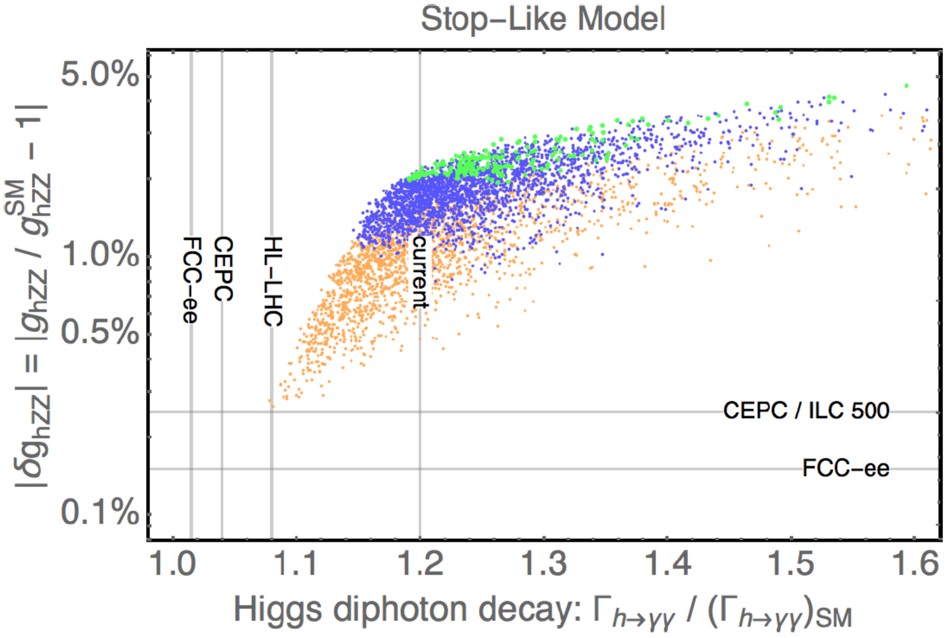
Yield hzz correction up to 30% (of SM)

Large range of hhh cubic coupling (compared to SM) gives FOEWPT

New charged doublet/fermions

Loop correction to Higgs branching into diphotons.





Summary from workshop:

Astro/GW connection

The total Gravitational Wave: $h^2\Omega_{\rm GW} \simeq h^2\Omega_\phi + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$

Three sources of energy

① Bubble collision
② Sound wave in plasma
③ Magetic Turbulence

BSM Phenomena cross-check need model interpretation.

SFOEWPT & Gravitational Wave Signal

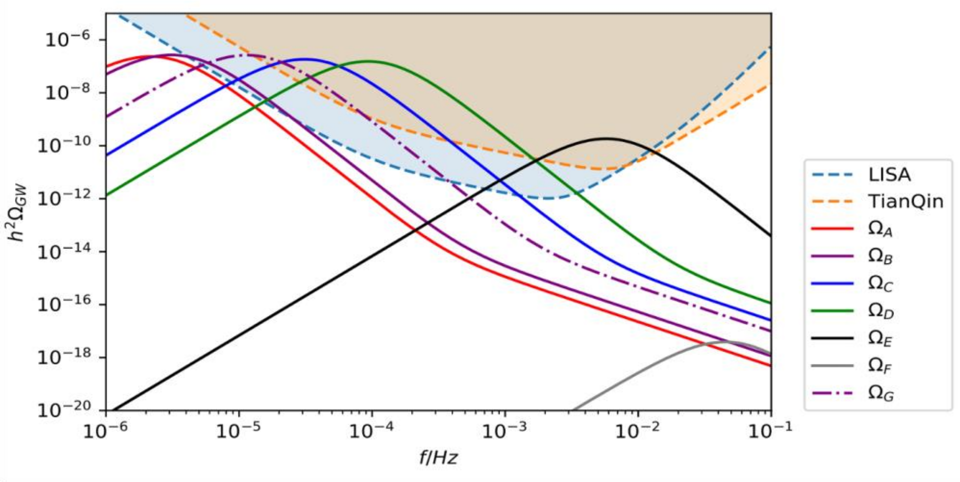
See talks from
Ligong Bian
& Jiang Zhu

Radiative Classical Scale Invariance Breaking by Dark Matter:

Lagrangian: $\mathcal{L} = \mathcal{L}_{\mathcal{SM}}|_{\lambda=0,\mu=0} + K_{scalar} - V_{scalar}$

$$V_{scalar} = \lambda_1 (H^\dagger H)^2 + \frac{1}{4}\lambda_2 S^4 + \frac{1}{4}\lambda_3 X^4 + \frac{1}{2}\lambda_{12} S^2 H^\dagger H + \frac{1}{2}\lambda_{13} X^2 H^\dagger H + \frac{1}{4}\lambda_{23} S^2 X^2$$

$$H = \begin{pmatrix} \phi_1 + i\phi_2 \\ \frac{H_0 + i\phi_3}{\sqrt{2}} \end{pmatrix} \qquad H_0 = (v + h) \text{ and } S = (v_s + s)$$



$$\boxed{\lambda_{hhhh} = A_4 \lambda_{hh}}$$

$$\boxed{\lambda_{hhh} = A_3 \lambda_{hh}}$$

$e^+e^- \to Zhh$ **Channel:**

Modified Higgs cubic and quartic couplings.

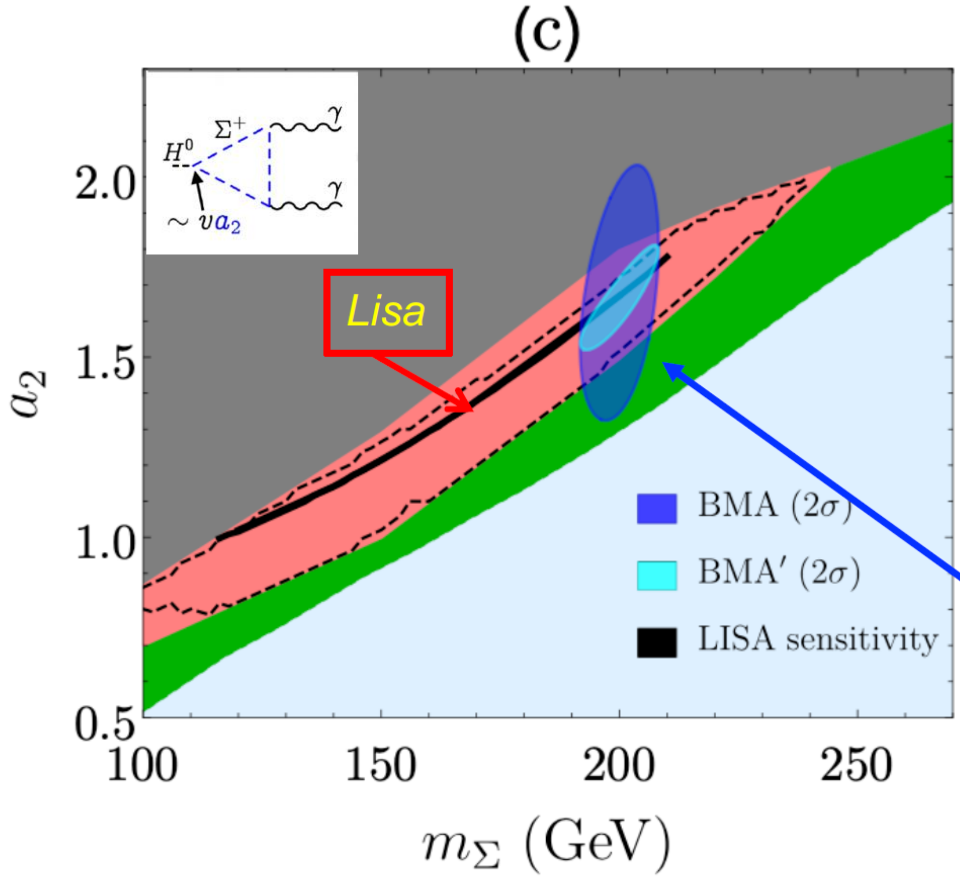
GW - CEPC

CEPC can probe BSM potentials that yield SFOEWPT, w precision *Higgs* measurements. Can cross-test with GW experiments.

Doublet + Triplet Higgs Model (w/o Z_2)

See Tran's talk at CEPC workshop

Friedrich, MJRM, Tenkanen, Tran 2203.05889



Hypothetical set of measurements:

$$\delta_{\gamma\gamma} = -0.132 \pm 0.015,$$
$$m_\Sigma = (200 \pm 5)\ \mathrm{GeV}$$
$$\mathrm{BR}(\Sigma^0 \to ZZ) = 0.01 \pm 0.002\ ,$$

FCC-ee

BMA: $m_\Sigma + \delta_{\gamma\gamma}$

BMA' : BMA + $BR(\Sigma^0 \to ZZ)$

- GW-collider overlapped → model is responsible to both GW and collider signals
- If collider observed triplet scalar but the collider regions don't overlap with LISA region → model is not responsible to GW signal → need another BSM

A neutrino connection: CEPC's complementary measurement of

Modification of matter potential

Jiajun Liao's talk

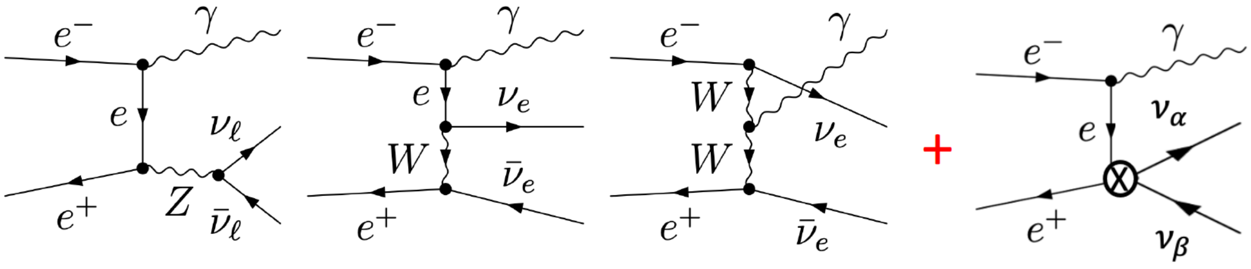
SM

$$i\frac{\mathrm{d}}{\mathrm{dt}}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Effective coefficient $\varepsilon_{\alpha\beta} \equiv \sum_{f,C}\varepsilon^{fC}_{\alpha\beta}\frac{N_f}{N_e}$

$A \equiv 2\sqrt{2}G_F N_e E$

On earth $N_u = N_d = 3N_e$



$e^+e^- \to \nu\bar{\nu}\gamma$ $\qquad \frac{d^2\sigma}{dx_\gamma dz_\gamma} = H\left(x_\gamma, z_\gamma; s\right)\sigma_0(s_\gamma)$

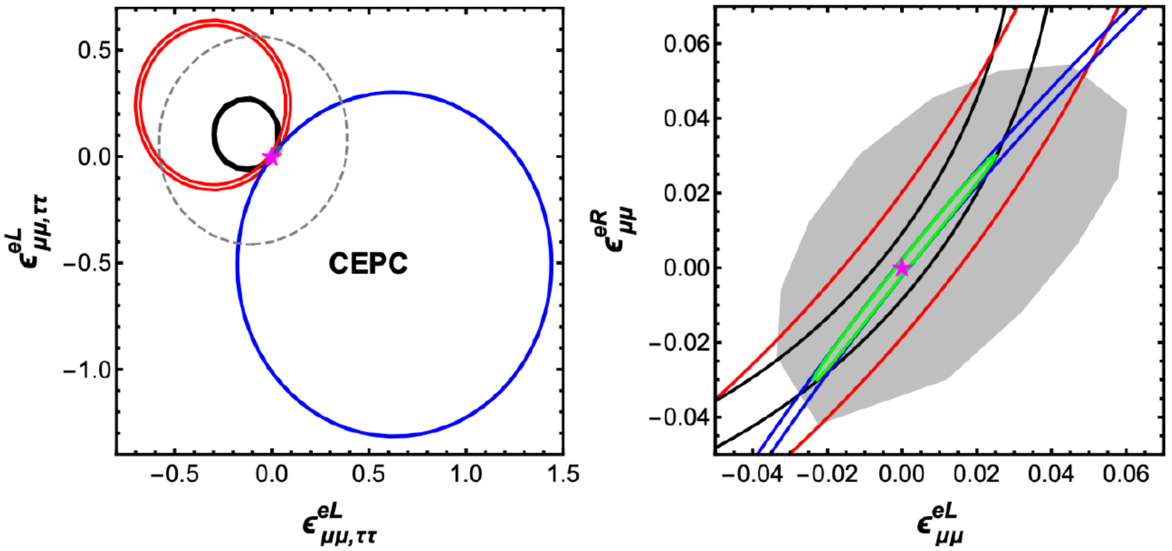
Berezhiania , Rossi, Phys.Lett.B 535 (2002)

$$\sigma_0^{\mathrm{NSI}}(s) = \sum_{\alpha,\beta=e,\mu,\tau}\frac{G_F^2}{6\pi}s\left[\left((\epsilon^{eL}_{\alpha\beta})^2 + (\epsilon^{eR}_{\alpha\beta})^2\right) - 2\left(g_L\epsilon^{eL}_{\alpha\beta} + g_R\epsilon^{eR}_{\alpha\beta}\right)\frac{M_Z^2\left(s-M_Z^2\right)}{\left(s-M_Z^2\right)^2 + \left(M_Z\Gamma_Z\right)^2}\right]$$

$$+\frac{G_F^2}{\pi}\epsilon^{eL}_{ee}M_W^2\left[\frac{\left(s+M_W^2\right)^2}{s^2}\log\left(\frac{s+M_W^2}{M_W^2}\right) - \frac{M_W^2}{s} - \frac{3}{2}\right]. \qquad \alpha,\beta = e,\mu,\tau$$

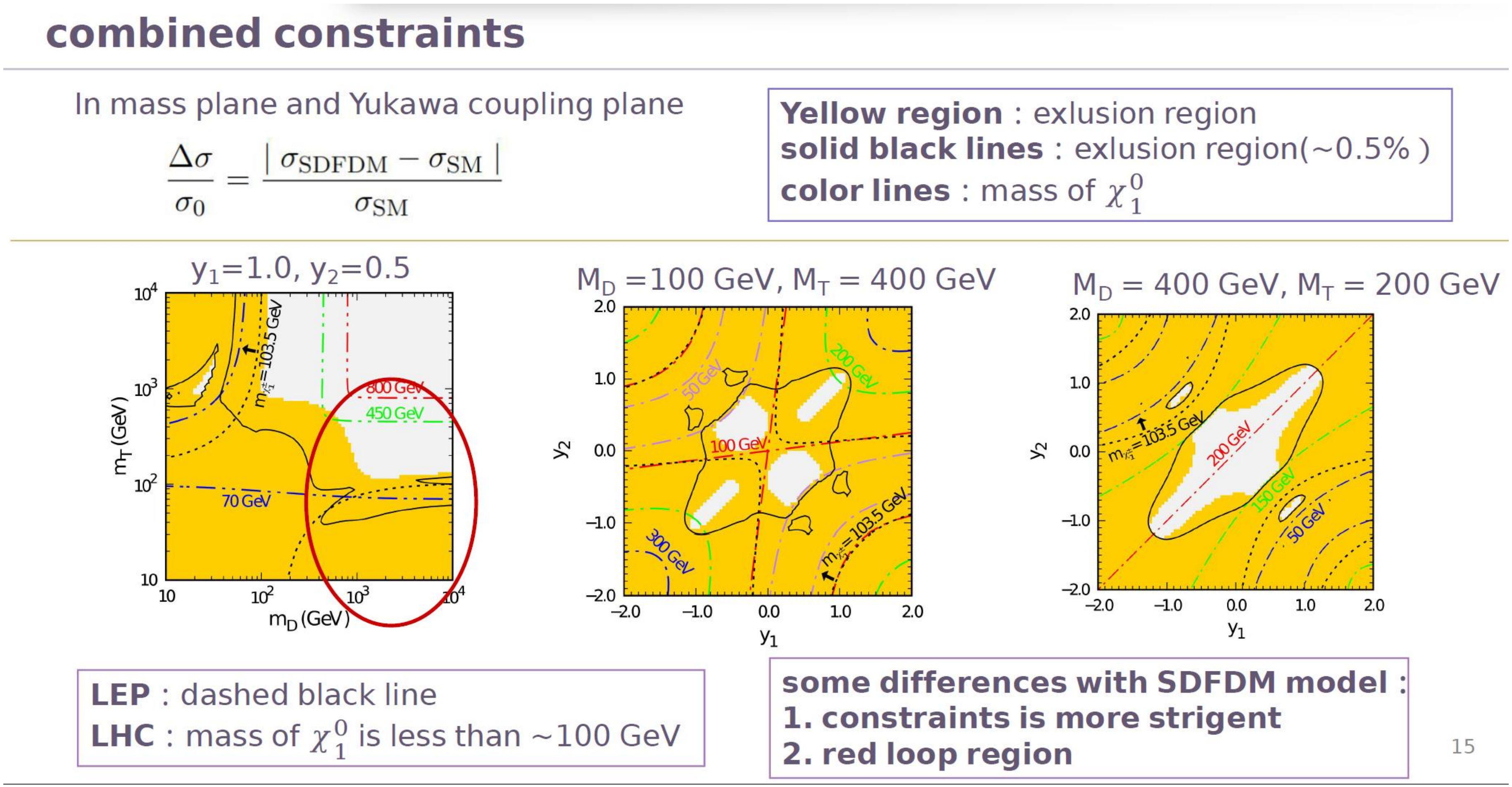
12 independent NSI parameters

NSI@CEPC



	CEPC-91.2 $L = 16$ ab^{-1}	CEPC-160 $L = 2.6$ ab^{-1}	CEPC-240 $L = 5.6$ ab^{-1}	CEPC-combined $L = 24.2$ ab^{-1}	Previous Limit 90% Allowed [45]
ϵ^{eL}_{ee}	[-0.0037,0.0037]	[-0.0036,0.0035]	[-0.0010,0.0010]	[-0.00095,0.00095]	[-0.03,0.08]
ϵ^{eR}_{ee}	[-0.0017,0.0017]	[-0.014,0.015]	[-0.0065,0.0070]	[-0.0017,0.0017]	[0.004,0.15]
$\epsilon^{eL}_{\mu\mu/\tau\tau}$	[-0.0014,0.0014]	[-0.012,0.012]	[-0.0055,0.0053]	[-0.0013,0.0013]	[-0.03,0.03]/[-0.5,0.3]
$\epsilon^{eR}_{\mu\mu/\tau\tau}$	[-0.0017,0.0017]	[-0.014,0.015]	[-0.0065,0.0070]	[-0.0017,0.0017]	[-0.03,0.03]/[-0.3,0.4]

Jiajun Liao： CEPC can probe NSI to 10^{-3}



combined constraints

In mass plane and Yukawa coupling plane

$$\frac{\Delta\sigma}{\sigma_0} = \frac{|\,\sigma_{\rm SDFDM} - \sigma_{\rm SM}\,|}{\sigma_{\rm SM}}$$

Yellow region : exlusion region
solid black lines : exlusion region(~0.5%)
color lines : mass of χ_1^0

LEP : dashed black line
LHC : mass of χ_1^0 is less than ~100 GeV

some differences with SDFDM model :
1. constraints is more strigent
2. red loop region

Linqing Gao’s talk: CEPC sensitive to 10^2 GeV Weak multiplet DM

via combined fit to ee->WW,Zh,ZZ,Zγ, μ μ
cross-sections @ one-(DM)-loop level

CEPC can probe asymmetric composite dark matter via displaced lepton jet

See Mengchao Zhang’s talk

Scalar mediator Φ helps to generate DM (dark baryon) and Baryon simultaneously:

$\mathcal{L} \supset \kappa\Phi\boxed{\bar{q}}\boxed{q}$ quark

dark quark

arXiv:1306.4676

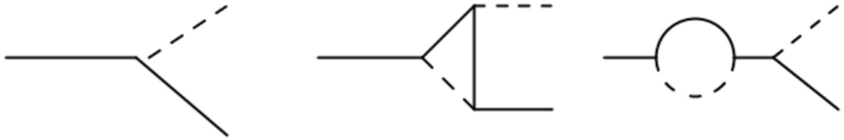
$\mathcal{L} \supset \kappa\Phi\boxed{\bar{q}}\boxed{l}$ lepton

dark quark

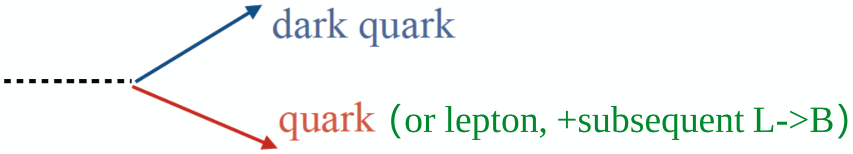
arXiv:2104.06988

Step 1: generate the asymmetry of mediator Φ. For example, CPV& out of equilibrium decay of heavy neutral particle:

$$\mathcal{L} \supset k_i \bar{Y}_1 \Phi N_i + \text{h.c.}$$



Step 2: mediator Φ decay to “dark quark” and SM quark, and thus generate “dark baryon” and baryon asymmetry simultaneously:



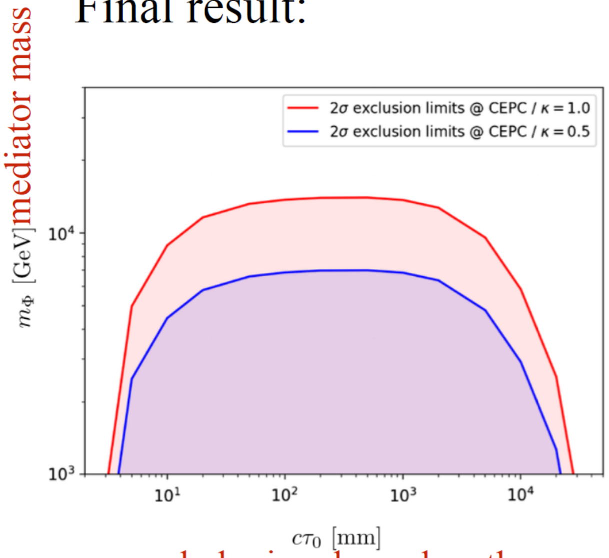
dark quark

quark (or lepton, +subsequent L->B)

Pheno @ CEPC
production via colored scalar

-> dark jets & dark pions
->invisibles
-> displayed dark pion decays

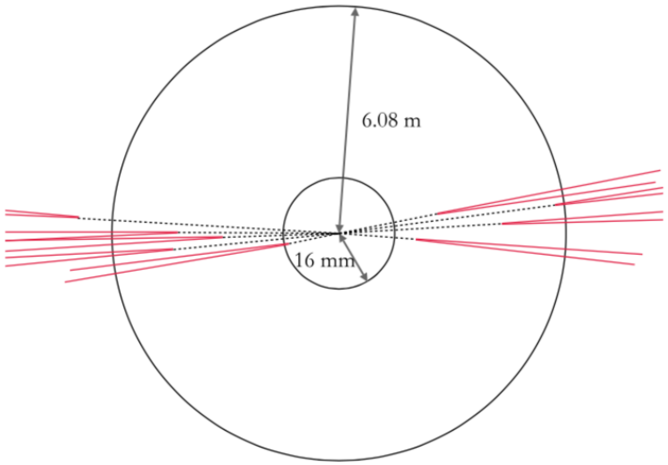
Final result:



mediator mass

dark pion decay length

BKG estimation: BKG free! (thanks to Manqi)



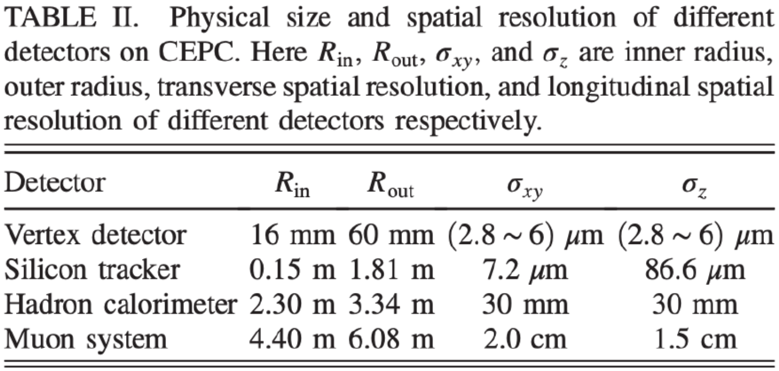


TABLE II. Physical size and spatial resolution of different detectors on CEPC. Here R_{in}, R_{out}, σ_{xy}, and σ_z are inner radius, outer radius, transverse spatial resolution, and longitudinal spatial resolution of different detectors respectively.

Detector	R_{in}	R_{out}	σ_{xy}	σ_z
Vertex detector	16 mm	60 mm	$(2.8 \sim 6)\ \mu$m	$(2.8 \sim 6)\ \mu$m
Silicon tracker	0.15 m	1.81 m	7.2 μm	86.6 μm
Hadron calorimeter	2.30 m	3.34 m	30 mm	30 mm
Muon system	4.40 m	6.08 m	2.0 cm	1.5 cm

displaced lepton jet tagging efficiency estimation