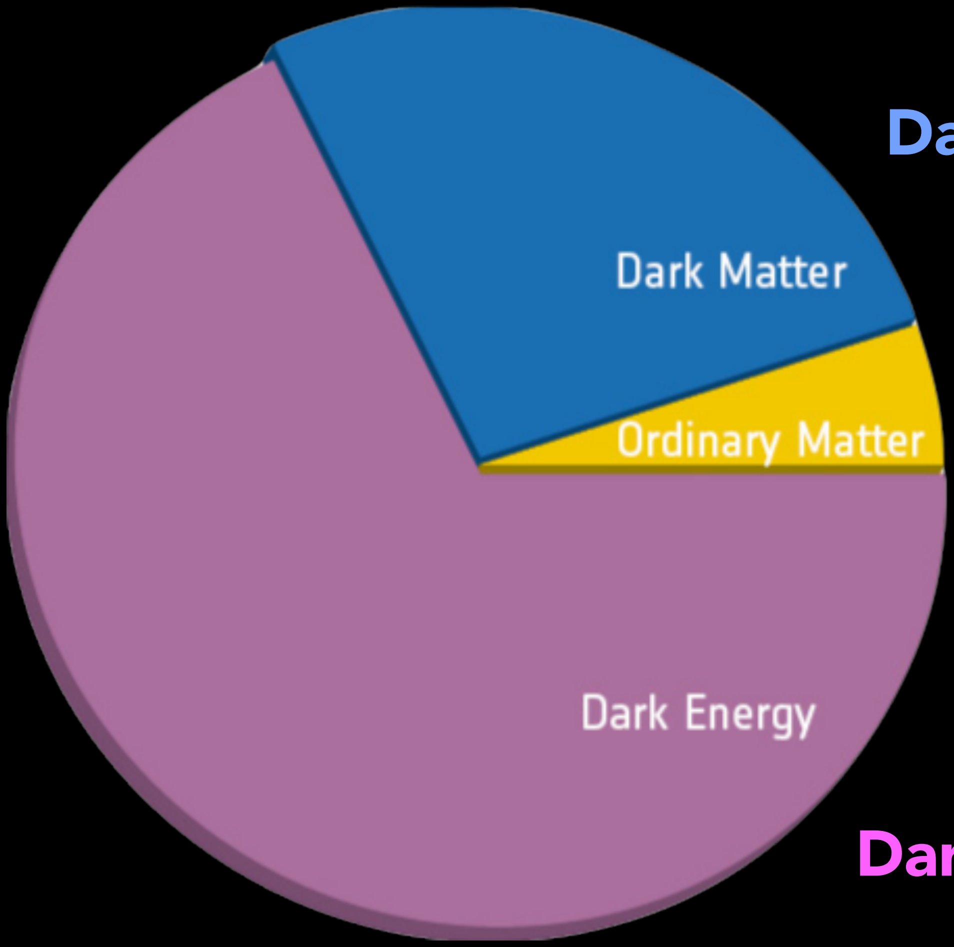
Testing Baryogenesis / Leptogenesis at Present & Future Colliders

Andrew J. Long
University of Michigan – LCTP

@ University of Cincinnati – IPA 2018
October 10, 2018

image credit: http://real.edu.my/of-earth-hour-and-a-thousand-cranes/

3 cornerstone problems in cosmology



Dark Matter: what is it?

Ordinary Matter:
where does it come from?

(interesting: uniquely connected with elementary particle physics)

Dark Energy: what is it?

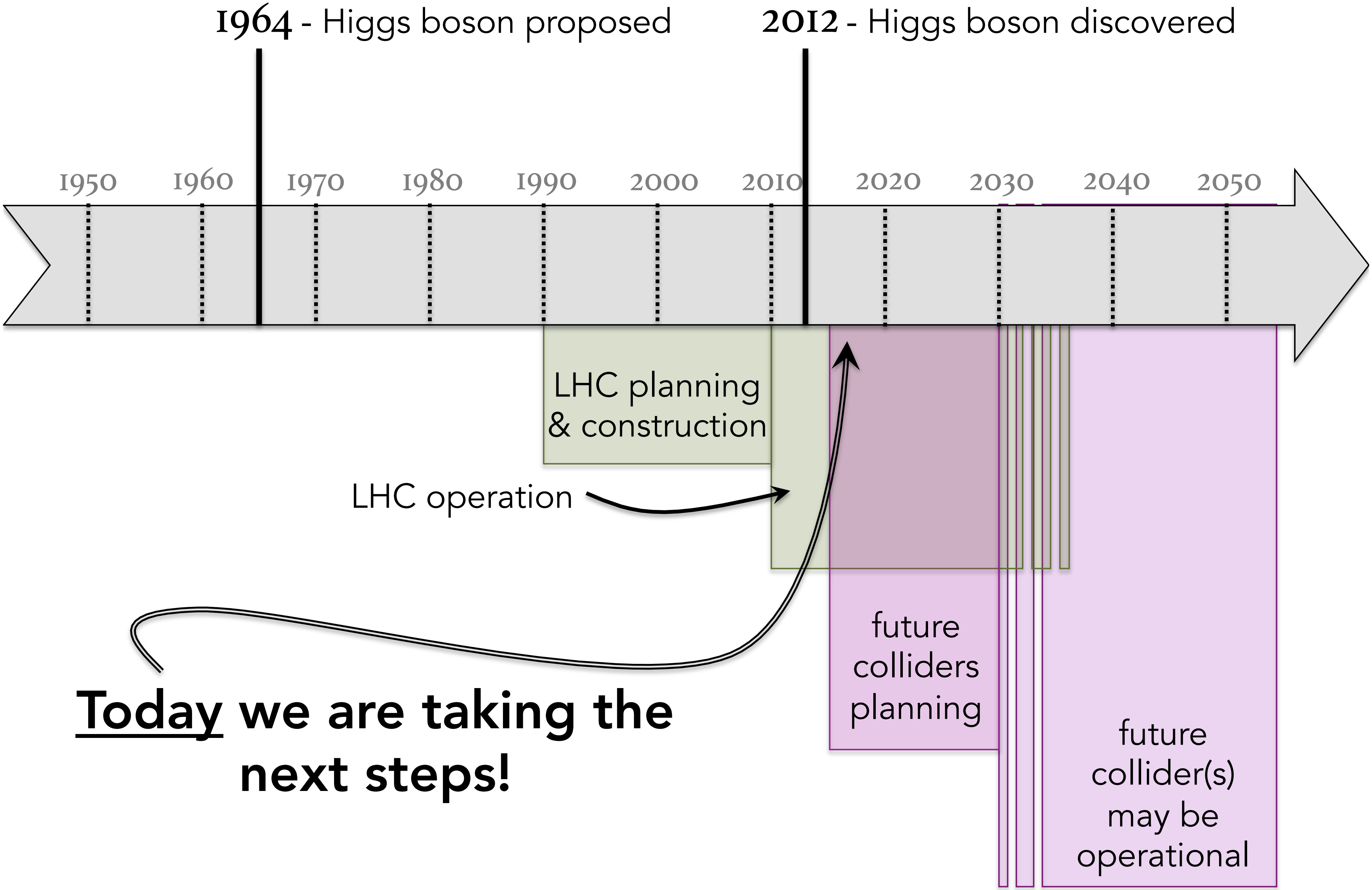
composition of our universe (by energy)

Baryogenesis. An event that took place in the early universe that created the excess of matter (baryons) over antimatter (antibaryons).

- electroweak baryogenesis
- local electroweak baryogenesis
- cold electroweak baryogenesis
- GUT baryogenesis
- Affleck-Dine baryogenesis
- spontaneous baryogenesis
- post-sphaleron baryogenesis
- magnetic-assisted baryogenesis
- dissipative baryogenesis
- warm baryogenesis
- cloistered baryogenesis
- Planck baryogenesis
- WIMPy baryogenesis
- cosmic string baryogenesis
- axion domain wall baryogenesis
- new GUT baryogenesis
- PBH baryogenesis
- supersonic baryogenesis
- …

Leptogenesis. A class of models in which the asymmetry is first generated in leptons & then transferred to baryons

- high-scale (thermal) leptogenesis
- low-scale (ARS) leptogenesis
- Dirac leptogenesis
- gravitational leptogenesis
- CPPT leptogenesis
- Higgs relaxation leptogenesis
- B-L string leptogenesis
- …



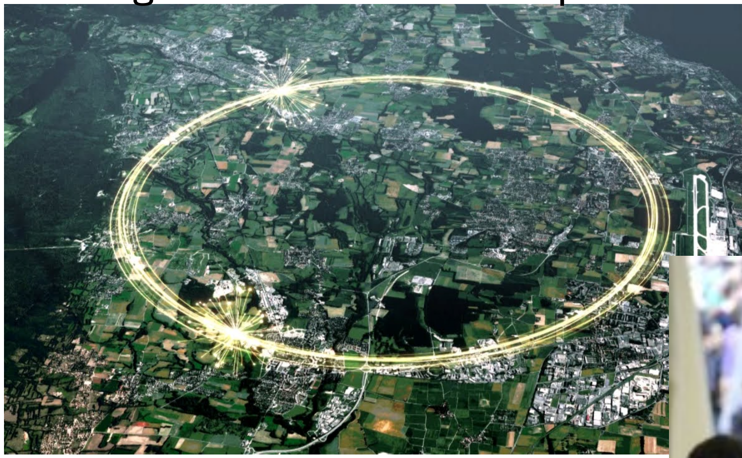
Today we are taking the next steps!

what does it collide?	**where is it located?**	**what is it called?**	**what is the energy?**
e^+e^-	China Europe Japan	CEPC FCC-ee ILC	E = 90 GeV → study Z E = 250 GeV → study Higgs E = 350 GeV → study top
pp	China Europe	SppC FCC-hh	E =100 TeV → discovery

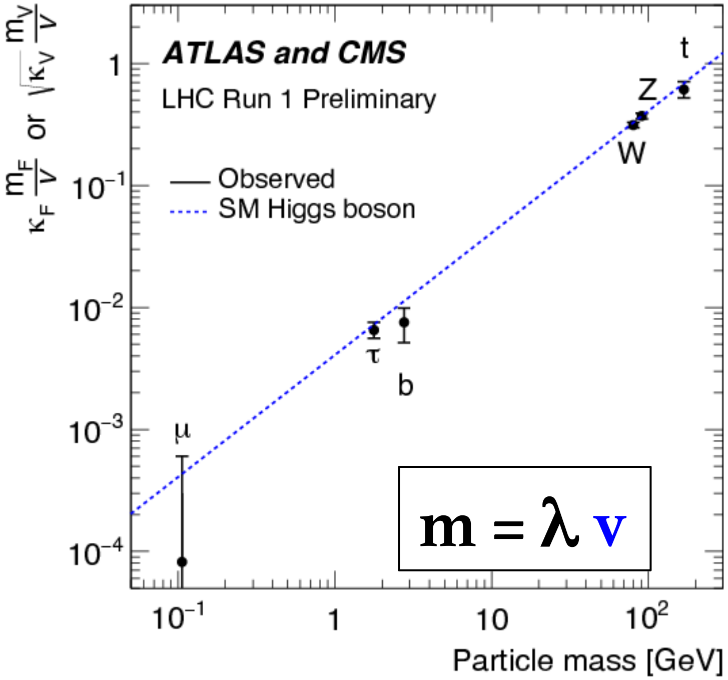
[see also Liantao Wang’s talk on Friday]

What we know
and what we don't know
about the Higgs

Large Hadron Collider experiment



$$\mathbf{m_h \simeq 125.09 \pm 0.24\,GeV/c^2}$$

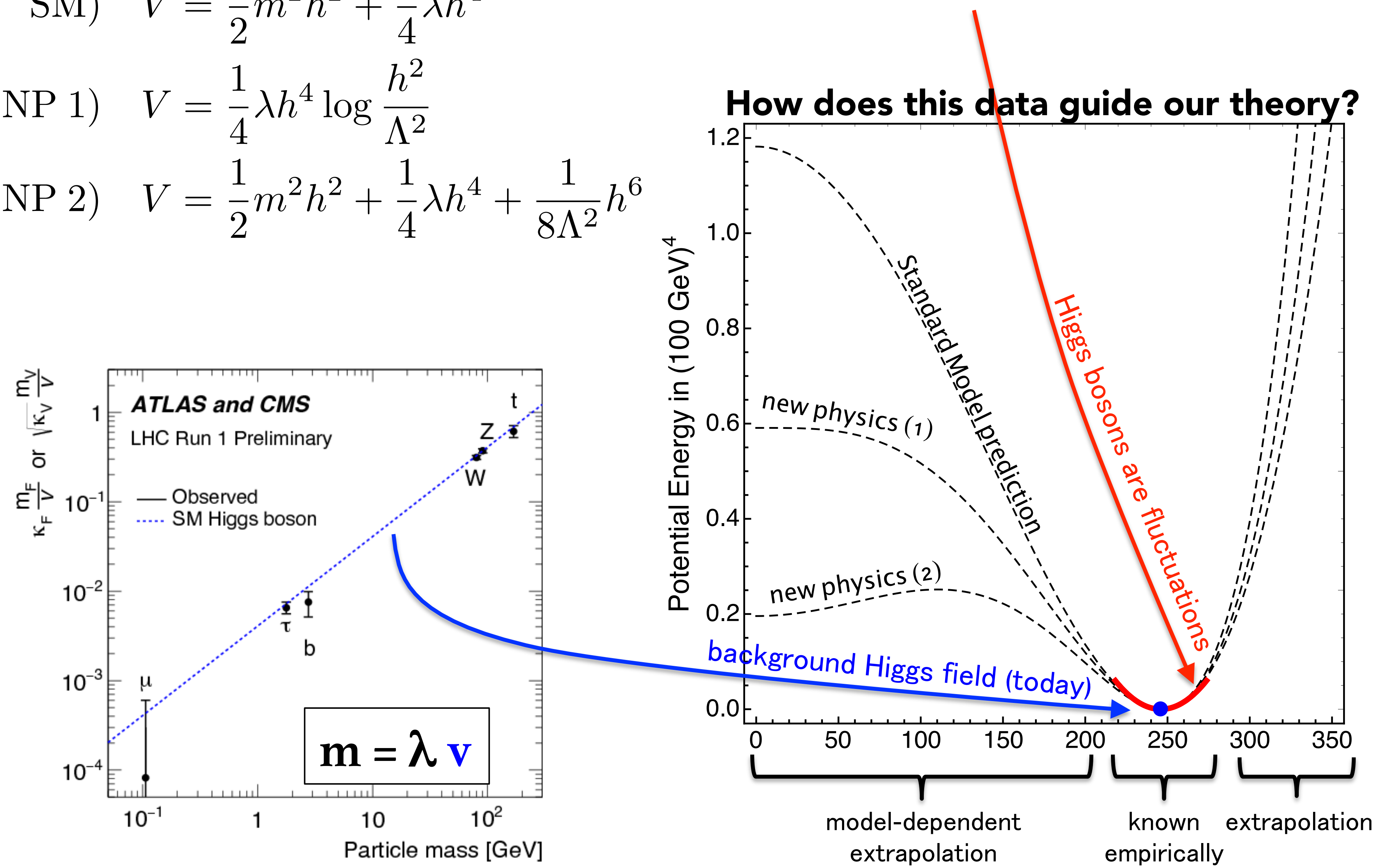


$$\mathbf{m_h \simeq 125.09 \pm 0.24\,GeV/c^2}$$

$$\text{SM)} \quad V = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4$$

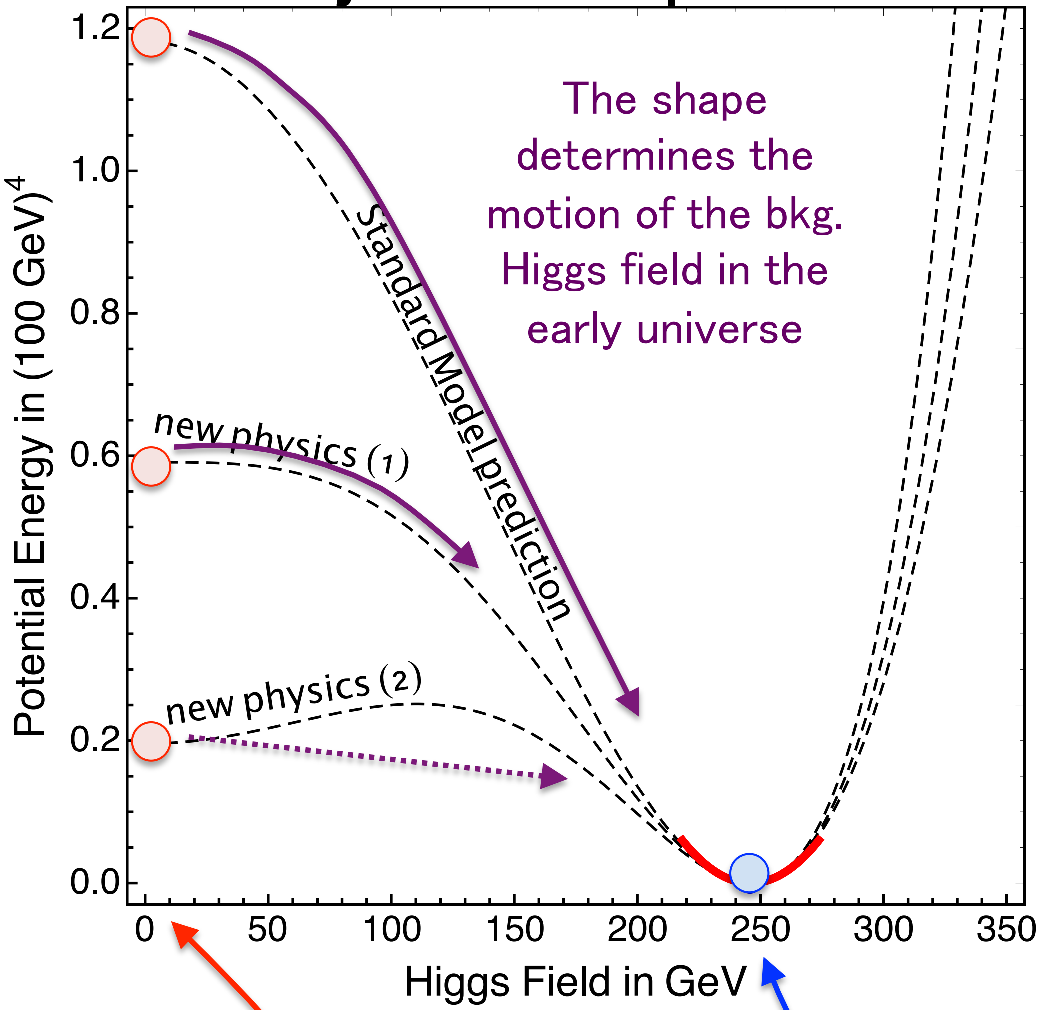
$$\text{NP 1)} \quad V = \frac{1}{4}\lambda h^4 \log\frac{h^2}{\Lambda^2}$$

$$\text{NP 2)} \quad V = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{8\Lambda^2}h^6$$



How does this data guide our theory?

Why does the shape matter?



The shape determines the motion of the bkg. Higgs field in the early universe

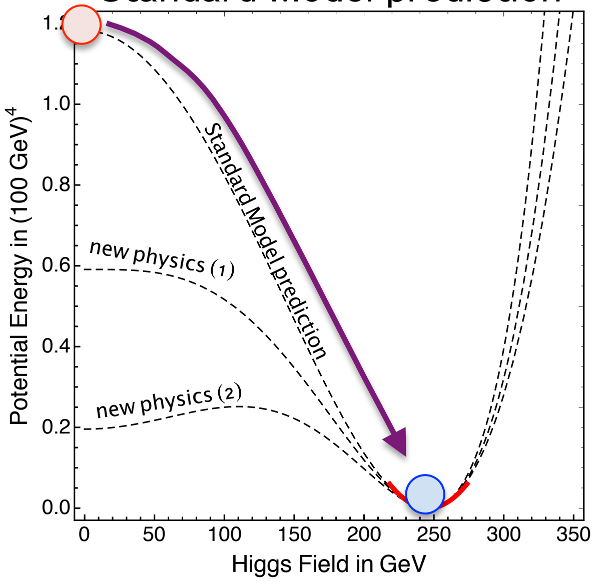
background Higgs field was here in the early universe (T > 100 GeV)

recall: F = E - TS ➔ min[F] = max[S]

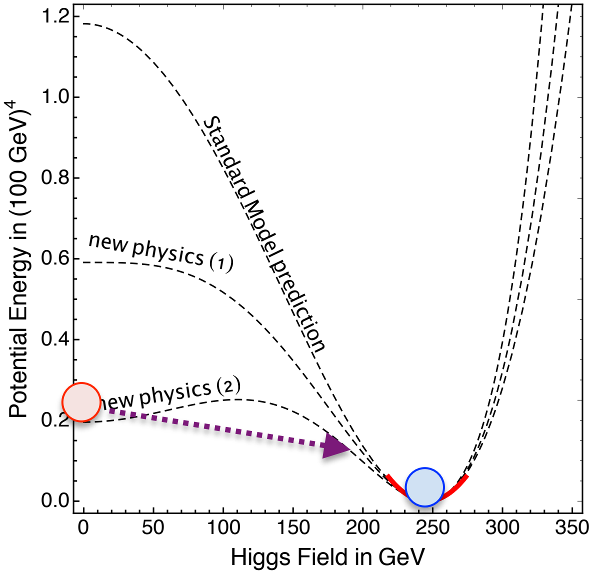
background Higgs field is here today … gives mass to SM particles

Electroweak Phase Transition. How does the background Higgs field move from zero in the early universe to its nonzero value today? (T ~ 100 GeV, t ~ 10 ps)

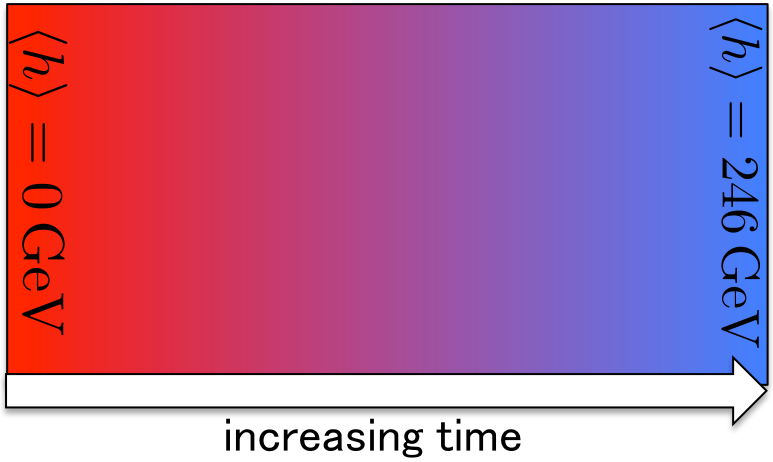
Standard Model prediction



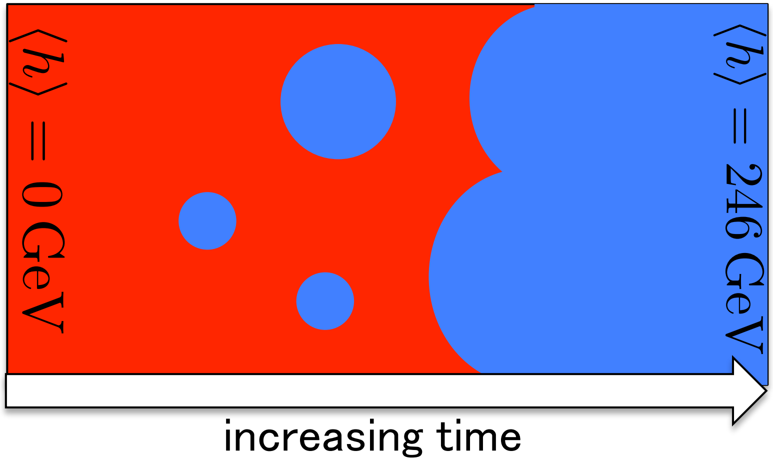
SM + new physics allows



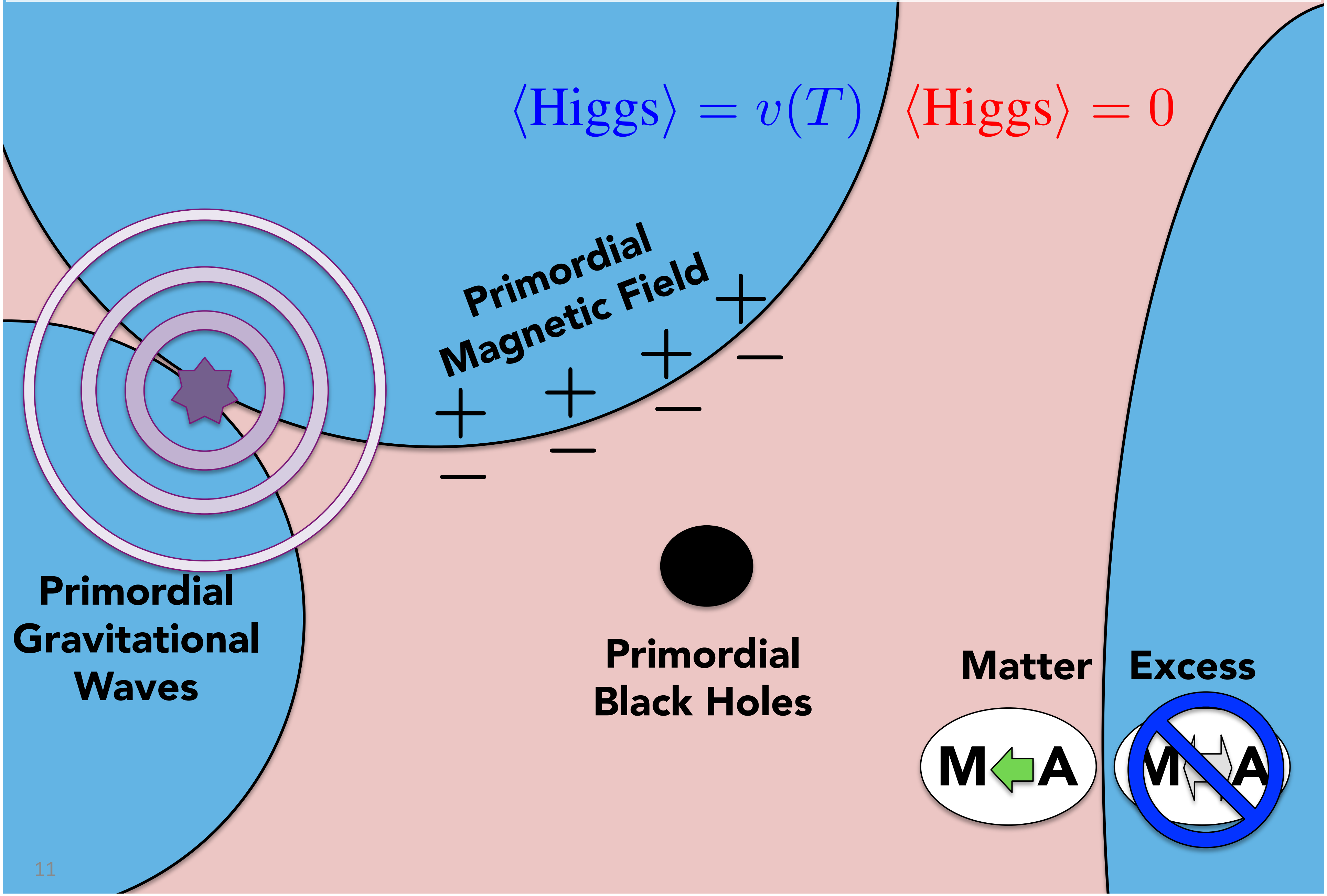
Continuous Crossover



First Order Phase Transition



1st Order EWPT has profound implications for cosmology



$\langle \mathrm{Higgs} \rangle = v(T)$

$\langle \mathrm{Higgs} \rangle = 0$

Primordial Magnetic Field

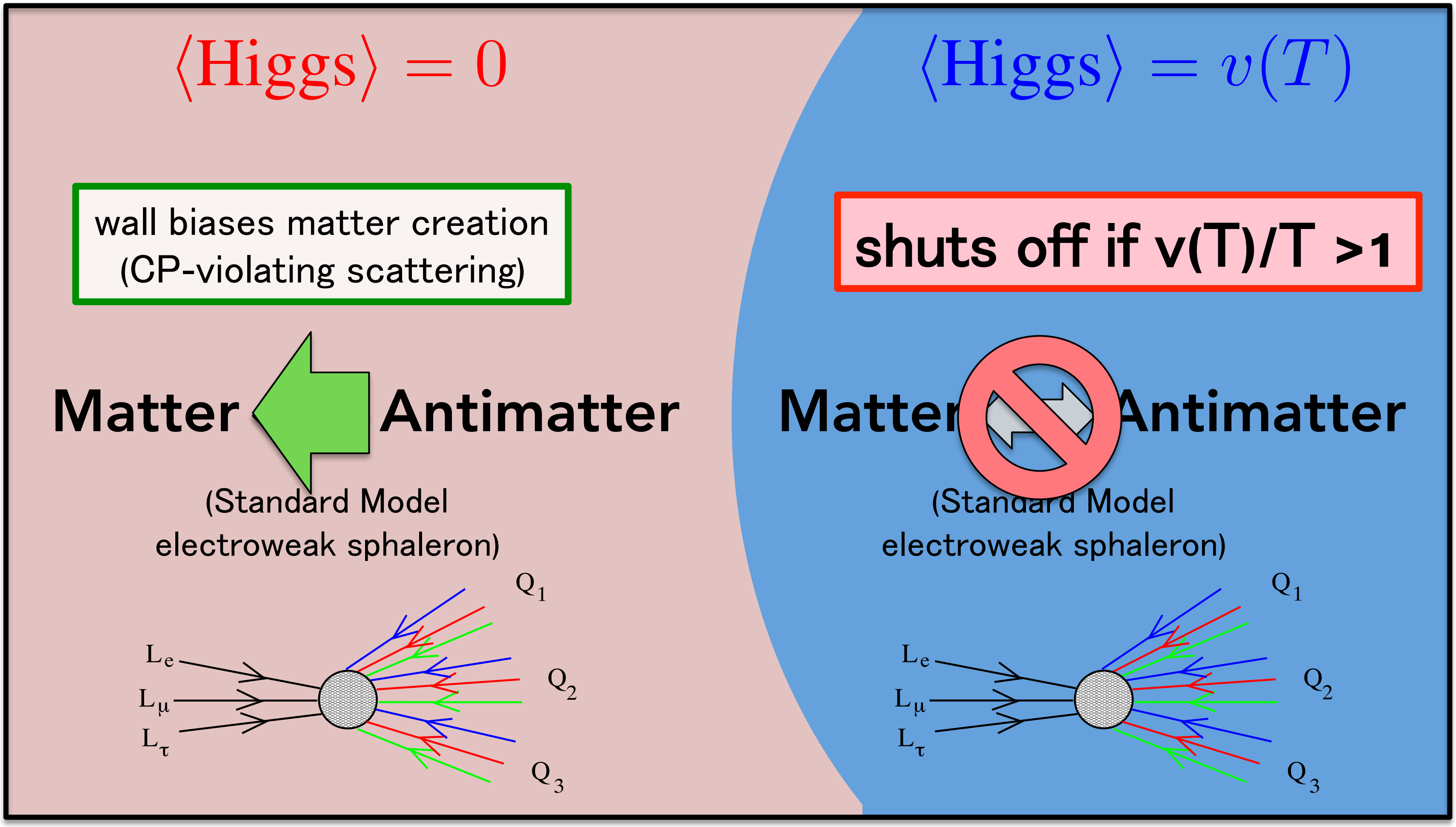
Primordial Gravitational Waves

Primordial Black Holes

Matter Excess

Klinkhamer & Manton (1984); Kuzmin, Rubakov, & Shaposhnikov (1985); Cohen, Kaplan, & Nelson (1990)

Electroweak baryogenesis. The creation of the matter-antimatter asymmetry of the universe at the electroweak phase transition.



$\langle \text{Higgs} \rangle = 0$

wall biases matter creation
(CP-violating scattering)

Matter ← **Antimatter**

(Standard Model
electroweak sphaleron)

$\langle \text{Higgs} \rangle = v(T)$

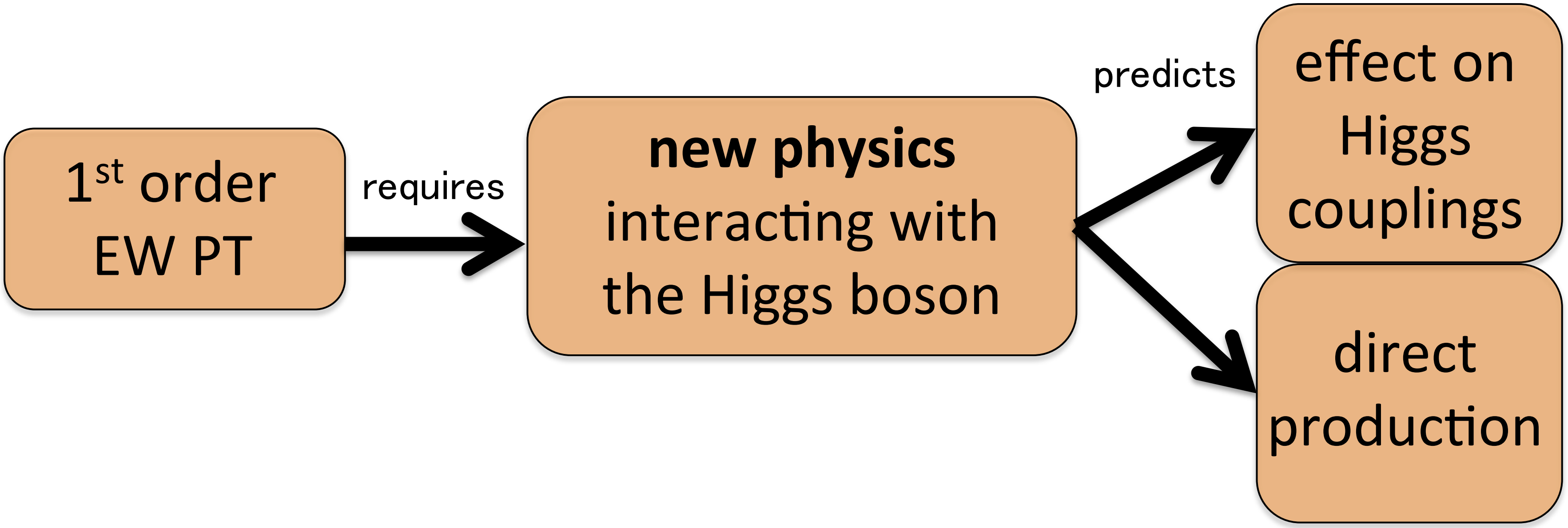
shuts off if v(T)/T >1

Matter ⇄ **Antimatter**

(Standard Model
electroweak sphaleron)

Studying the Higgs @ Future Colliders

How can we learn about the electroweak phase transition?



1st order EW PT

requires

new physics interacting with the Higgs boson

predicts

effect on Higgs couplings

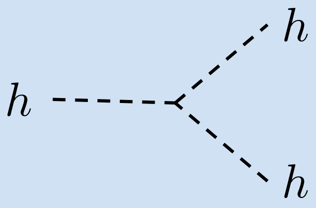
direct production

[Noble & Perelstein (2007)]
[Katz & Perelstein (2014)]

Effect on Higgs couplings

Higgs cubic self-coupling (hhh)

$$\lambda_3 =$$

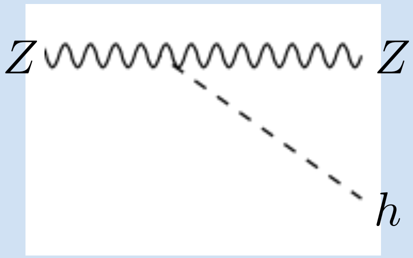


PRO:
Directly related to the shape of the Higgs potential (V‴).

CON:
Very challenging to measure. Target of FCC-hh & SppC.

Higgs coupling to Z-boson (hZZ)

$$g_{hZZ} =$$



CON:
An indirect probe of new physics & the EWPT.

PRO:
It can be measured very precisely. Target of Higgs factories: FCC-ee, CEPC, & ILC.

Higgs Factories – precision Higgs measurements

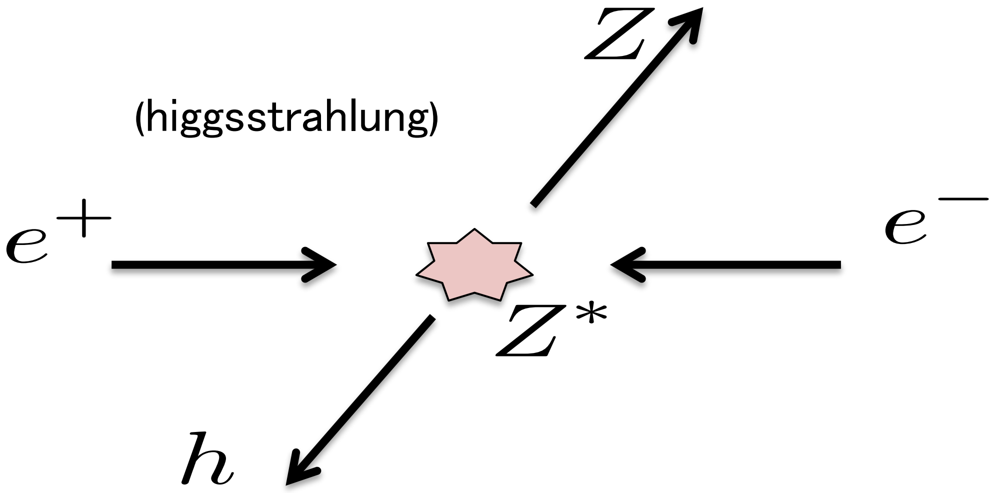
Lepton colliders provide “clean” environment to study Higgs physics.

At E = 250 GeV, the production of Higgs + Z-boson is optimized.

Precision measurements of Higgs-Z-Z coupling at the sub-percent level!

Proposed Higgs factories:

- ➔ FCC-ee (Europe / CERN)
- ➔ CEPC (China)
- ➔ ILC (Japan)



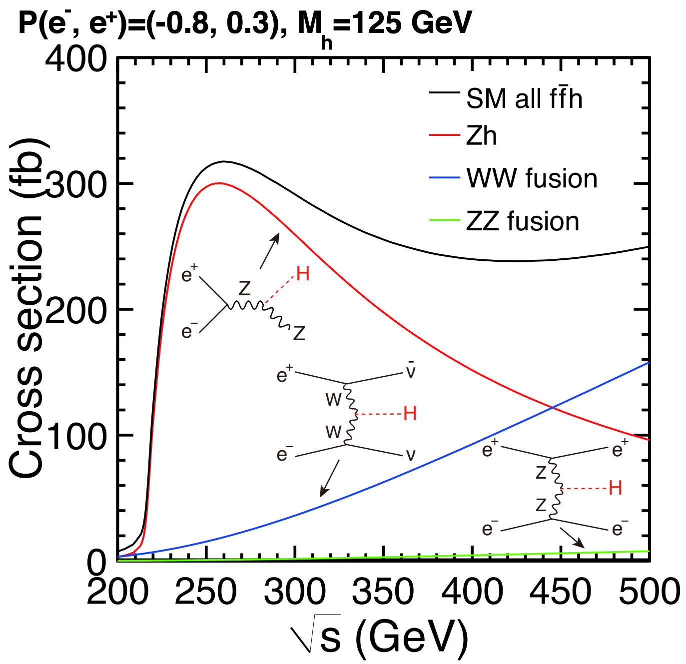


figure: ILC TDR, 1306.6352

Precision Higgs measurements

Projected sensitivities to various Higgs couplings at current & future colliders:

	current	HL-LHC	CEPC	ILC	FCC-ee	FCC-hh
hZZ	27%	7%	0.25%	0.25%	0.15%	-
$\Gamma(h\rightarrow\gamma\gamma)$	20%	8%	4%	-	1.5%	-
hhh	-	[-0.8 , 7.7] 95% CL	43%	27%	43%	10%

Assumptions & references:

hZZ current = 5 fb^{-1} at $\sqrt{s}$ = 7 TeV & 20 fb^{-1} at 8 TeV (1606.02266)
hZZ @ HL-LHC = 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV (1307.7135, CMS)
hZZ @ CEPC = 5000 fb^{-1} at $\sqrt{s}$ = 250 GeV (pre-CDR)
hZZ @ ILC = 2000 fb^{-1} at $\sqrt{s}$ = 250 GeV (1506.05992)
hZZ @ FCC-ee = 2600 fb^{-1} at $\sqrt{s}$ = 250 GeV (1601.0640)
hhh @ HL-LHC = 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV (ATL-PHYS-PUB-2017-001, hh->bb$\gamma\gamma$)
hhh @ ILC = 4000 fb^{-1} at $\sqrt{s}$ = 500 GeV (1506.05992, e^+e^->Zhh, hh->bbbb & bbWW)
hhh @ FCC-hh = 30000 fb^{-1} at $\sqrt{s}$ = 100 TeV (1606.09408)
hhh @ CEPC/FCC-ee = 5000 fb^{-1} at $\sqrt{s}$ = 240 GeV + 1700 fb^{-1} at $\sqrt{s}$ = 350 GeV (1711.03978

Time to reach design sensitivity depends on run plan (not yet determined).

Phase transitions studies are a big industry …

Model	References
SM + EW-singlet Scalar	Espinosa & Quiros, 1993; Benson, 1993; Choi & Volkas, 1993; McDonald, 1994; Vergara, 1996; Branco, Delepine, Emmanuel-Costa, & Gonzalez, 1998; Ham, Jeong, & Oh, 2004; Ahriche, 2007; Espinosa & Quiros, 2007; Profumo, Ramsey-Musolf, & Shaughnessy, 2007; Noble & Perelstein, 2007; Espinosa, Konstandin, No, & Quiros, 2008; Ashoorioon & Konstandin, 2009; Das, Fox, Kumar, & Weiner, 2009; Espinosa, Konstandin, & Riva, 2011; Chung & AL, 2011; Wainwright, Profumo, & Ramsey-Musolf, 2012; Barger, Chung, AL, & Wang, 2012; Huang, Shu, Zhang, 2012; Chung, AL, & Wang, 2012; Profumo, Ramsey-Musolf, Wainwright, & Winslow, 2014; Katz & Perelstein, 2014; Jiang, Bian, Huang, Shu, 2015; Huang & Li 2015; Huang, AL, & Wang, 2016; Cline, Kainulainen, Tucker-Smith, 2017; Kurup & Perelstein, 2017; Chen, Kozaczuk, & Lewis, 2017
SM + EW-doublet Scalar	Davies, Froggatt, Jenkins, & Moorhouse, 1994; Huber, 2006; Fromme, Huber, & Seniuch, 2006; Cline, Kainulainen, & Trott, 2011; Kozhushko & Skalozub, 2011;
SM + EW-triplet Scalar	Patel, Ramsey-Musolf, 2012; Patel, Ramsey-Musolf, Wise, 2013; Huang, Gu, Yin, Yu, Zhang 2016
SM + Chiral Fermions	Carena, Megevand, Quiros, Wagner, 2005; Huang, AL, & Wang, 2016
MSSM	Carena, Quiros, & Wagner, 1996; Delepine, Gerard, Gonzales Felipe, & Weyers, 1996; Cline & Kainulainen, 1996; Laine & Rummukainen, 1998; Cohen, Morrissey, & Pierce,; Carena, Nardini, Quiros, & Wagner, 2012;
NMSSM / nMSSM / μνSSM	Pietroni, 1993; Davies, Froggatt, & Moorhouse, 1995; Huber & Schmidt, 2001; Ham, Oh, Kim, Yoo, & Son, 2004; Menon, Morrissey, & Wagner, 2004; Funakubo, Tao, & Toyoda, 2005; Huber, Kontandin, Prokopec, & Schmidt, 2006; Chung, AL, 2010, Huang, Kang, Shu, Wu, Yang, 2014; Bian, Guo, Shu (2017)
EFT-like Approach (H^6 operator)	Grojean, Servant, Wells, 2005; Chung, AL, & Wang, 2012; Huang, Gu, Yin, Yu, Zhang 2015; Huang, Joglekar, Li, Wagner, 2015; Huang, Wan, Wang, Cai, Zhang 2016; Huang, Gu, Yin, Yu, Zhang 2016; Cao, F.P. Huang, Xie, Zhang (2017)

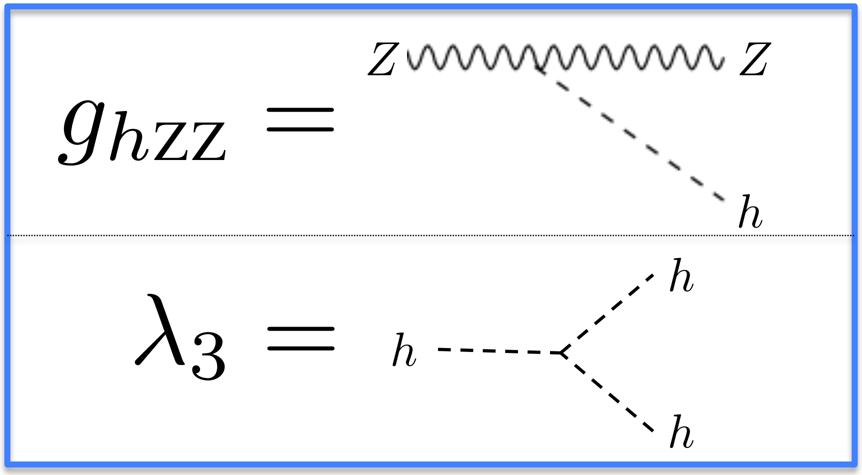
Example: an especially challenging scenario

Consider the theory:

SM + spin-0, colorless, uncharged particle **(aka., real scalar singlet)**

The new particle does not interact via the SM forces (strong, weak, EM)
- ➔ difficult to produce and detect at colliders
- ➔ (dark matter candidate if stable)

The new particle interacts with the Higgs boson
- ➔ induces 1st order phase transition
- ➔ affects Higgs couplings


$$g_{hZZ} =$$
$$\lambda_3 =$$

Interactions:

five model parameters

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\underset{\uparrow}{\partial\phi_s})^2 - \frac{m_s^2}{2}\phi_s^2 - \frac{a_s}{3}\phi_s^3 - \frac{\lambda_s}{4}\phi_s^4 - \underbrace{\lambda_{hs}H^\dagger H\phi_s^2 - 2a_{hs}H^\dagger H\phi_s}_{\text{Higgs portal}}$$

real scalar singlet

Higgs-singlet mixing:

$$\langle H\rangle = (0\,,\, v/\sqrt{2}) \qquad \text{and} \qquad \langle\phi_s\rangle = v_s$$

$$\sin 2\theta = \frac{4v(a_{hs} + \lambda_{hs}v_s)}{M_h^2 - M_s^2}$$

hhh coupling

(see e.g., Profumo, Ramsey-Musolf, Wainwright, & Winslow, 2014)

$$\lambda_3 \equiv g_{hhh} = \big(6\lambda_h v\big)\cos^3\theta + \big(6a_{hs} + 6\lambda_{hs}v_s\big)\sin\theta\cos^2\theta + \big(6\lambda_{hs}v\big)\sin^2\theta\cos\theta + \big(2a_s + 6\lambda_s v_s\big)\sin^3\theta$$

hZZ coupling

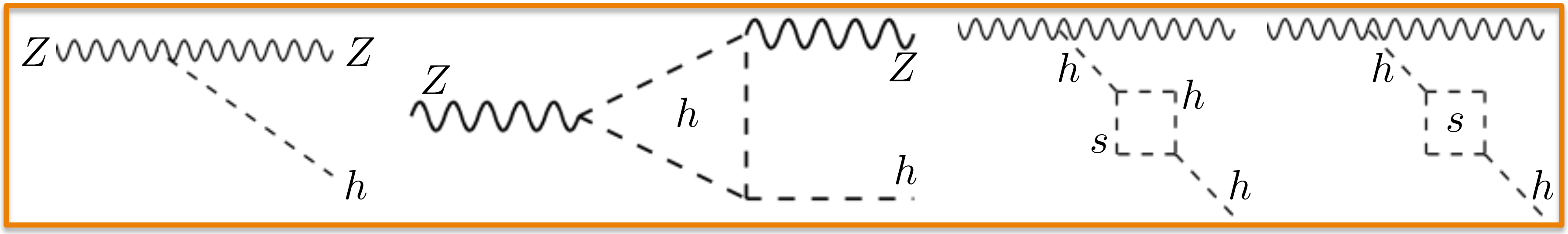
(adapted from: Craig, Englert, & McCullough 2013; McCullough, 2014; Curtin, Meade, & Yu, 2014)

(leading effect is from mixing)

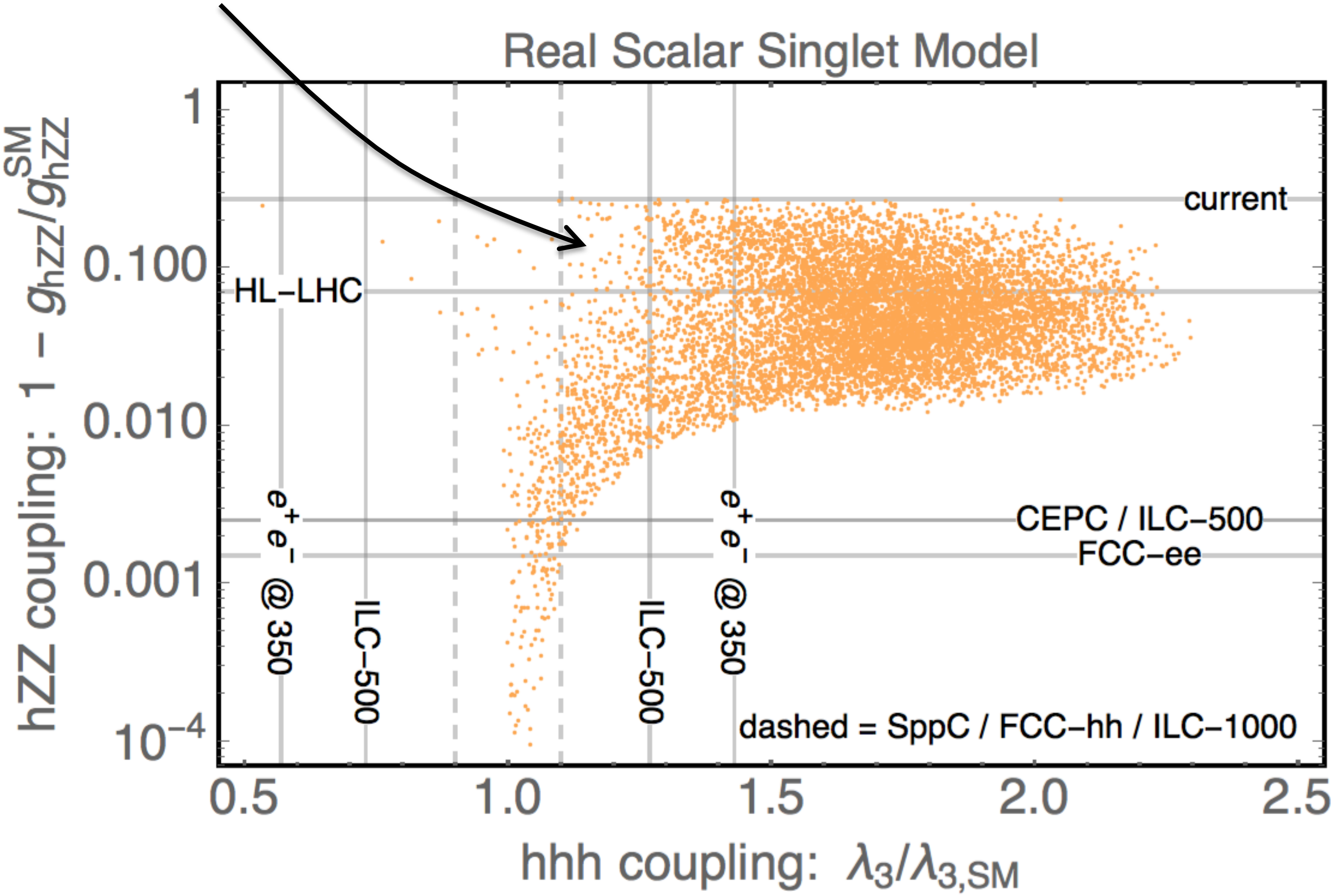
$$\frac{g_{hZZ}}{g_{hZZ,\mathrm{SM}}} \approx \cos\theta + 0.006\left(\frac{\lambda_3}{\lambda_{3,\mathrm{SM}}} - 1\right) - 2\frac{|a_{hs}+\lambda_{hs}v_s|^2}{16\pi^2} I_B(M_h^2; M_h^2, M_s^2) - \frac{|\lambda_{hs}|^2 v^2}{16\pi^2} I_B(M_h^2; M_s^2, M_s^2)\,.$$

(triangle probes self-coupling)

(Higgs wfcn. renorm.)



[Huang, AL, & Wang (2016)]



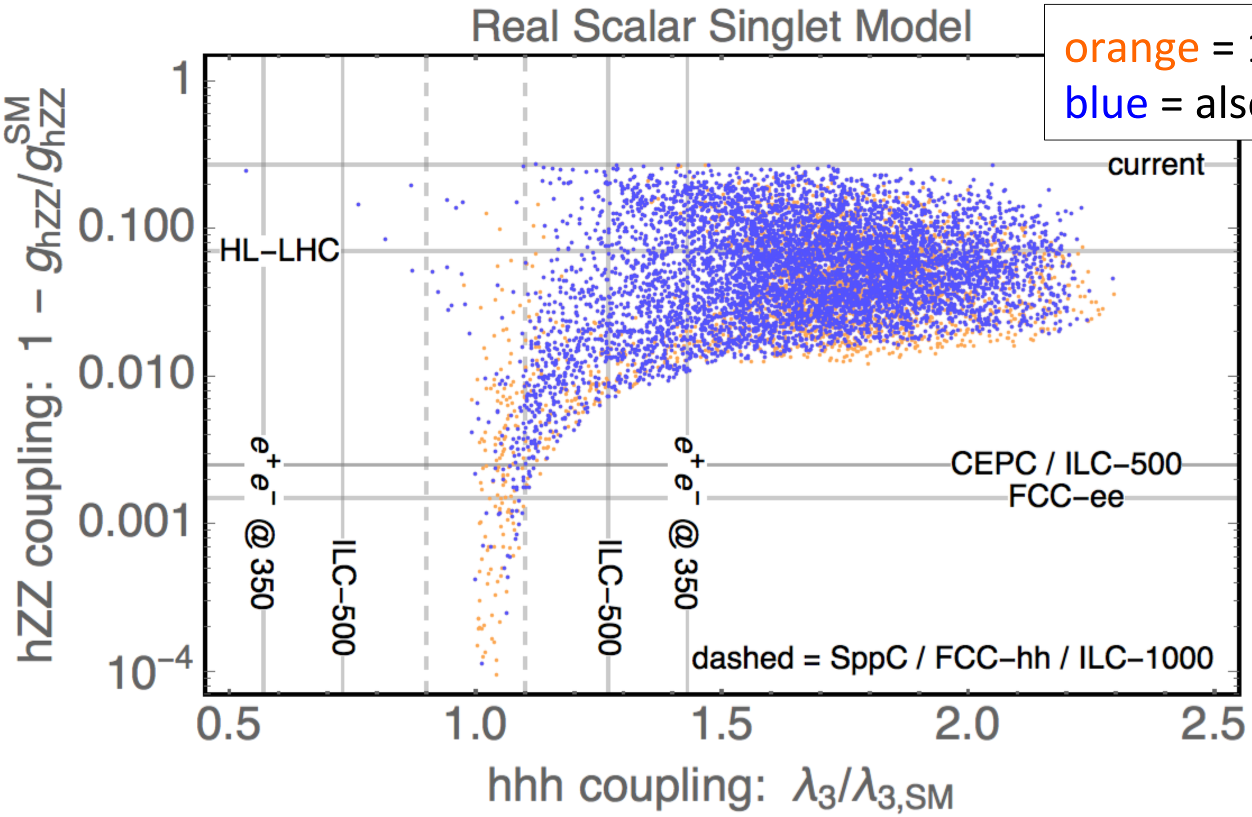
EWPT is 1st order

even hZZ measurements alone are a powerful test of PT!
(including also hhh is better)

[Huang, AL, & Wang (2016)]

Implications for the matter excess

Electroweak baryogenesis requires a *strongly* 1st order electroweak phase transition.



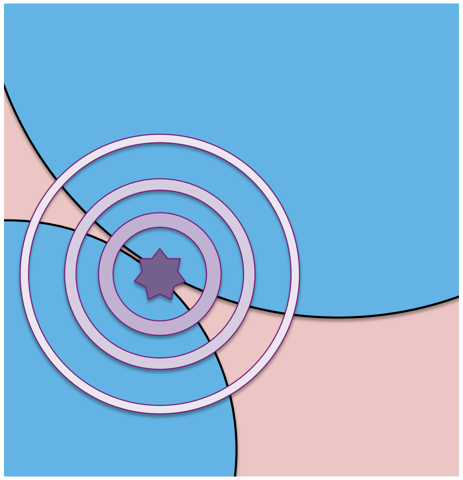
orange = 1st order EWPT
blue = also viable baryogenesis

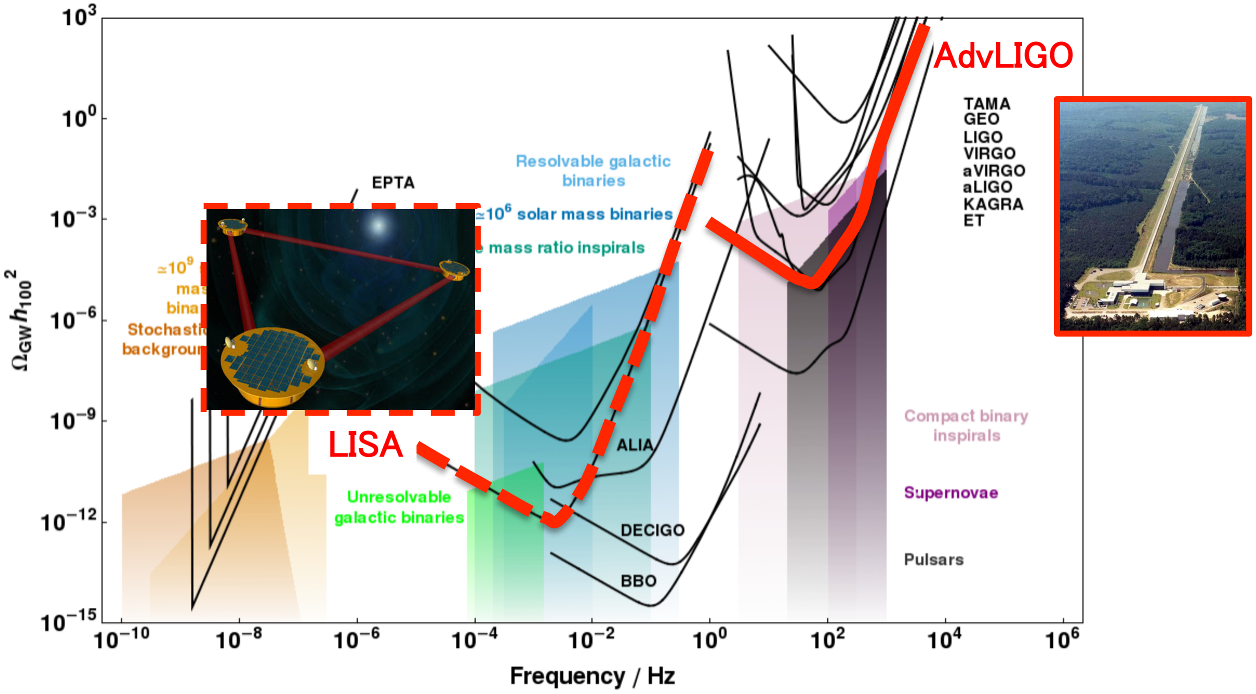
$$\frac{v(T)}{T} \gtrsim 1$$

Higgs precision may provide first clues to solve: what is the origin of matter-antimatter asymmetry?

Implications for gravitational waves

Bubble collisions & fluid motion create a gravitational wave “noise.”





GW spectrum set by bubble size at the time of collision.

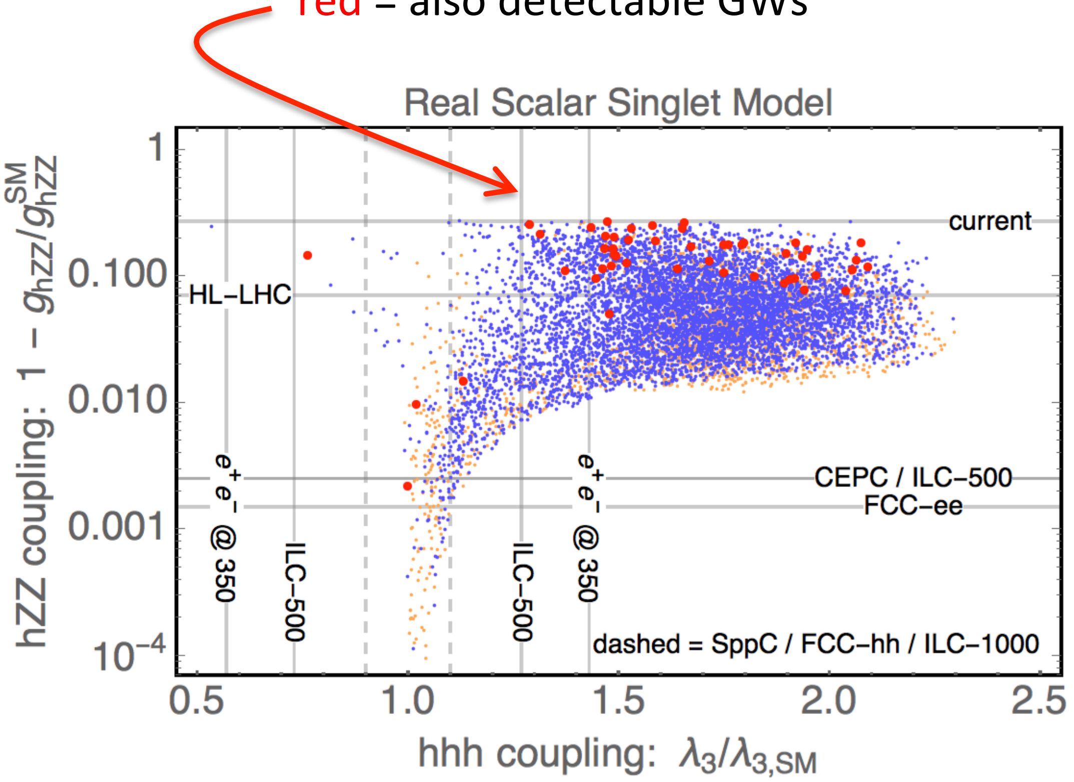
➔ Falls right into the sensitivity bands of proposed space-based interferometers!

figure: Moore, Cole, & Berry (2014)

[Huang, AL, & Wang (2016)]

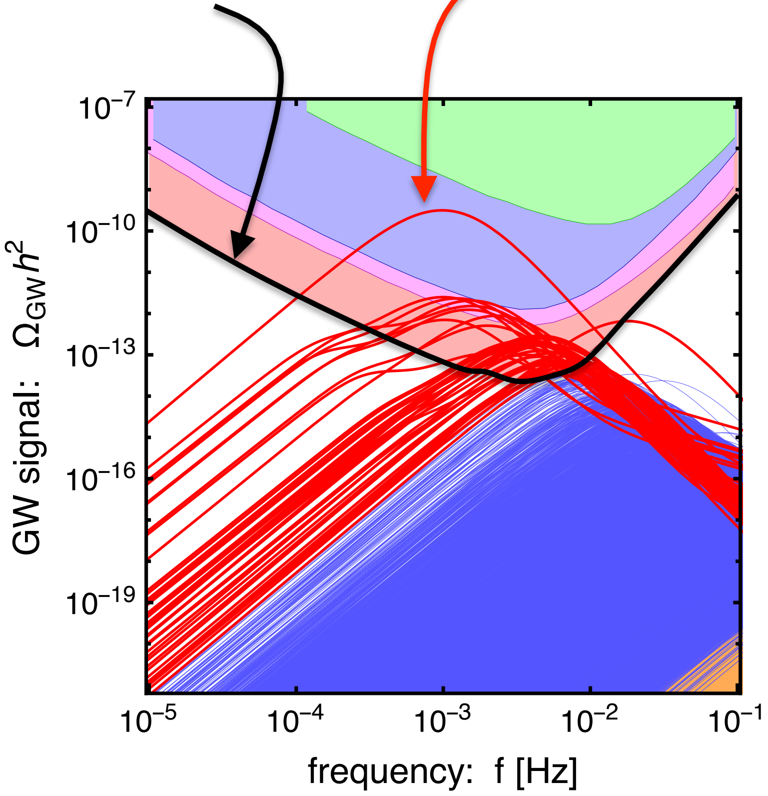
Implications for gravitational waves

orange = 1st order EWPT
blue = also viable baryogenesis
red = also detectable GWs



LISA projected sensitivity

predicted grav. wave spectra

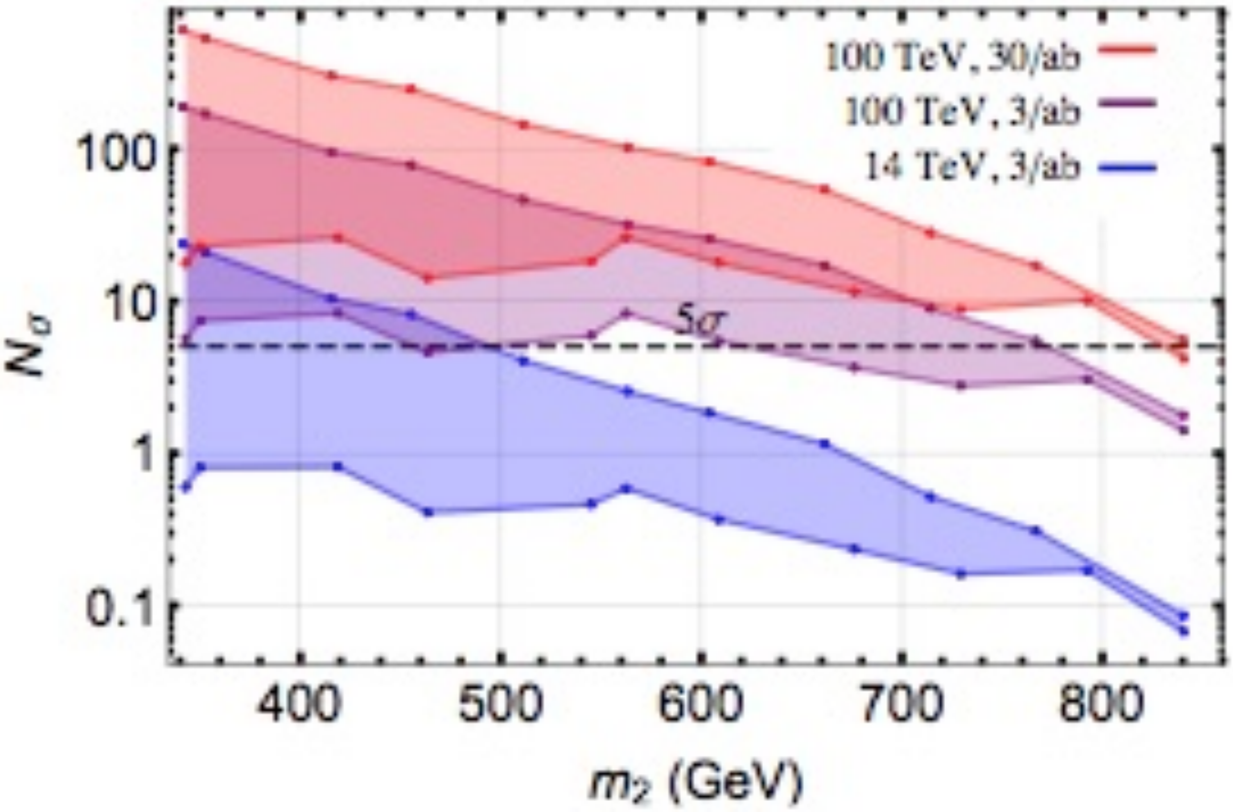


Models within reach of HL-LHC are also within reach of LISA!

[Kotwal, Ramsey-Musolf, No, & Winslow (2016)]

Resonant di-Higgs production

$$pp \to h_2 \to h_1 h_1 \to 4\tau \text{ or } b\bar{b}\gamma\gamma$$



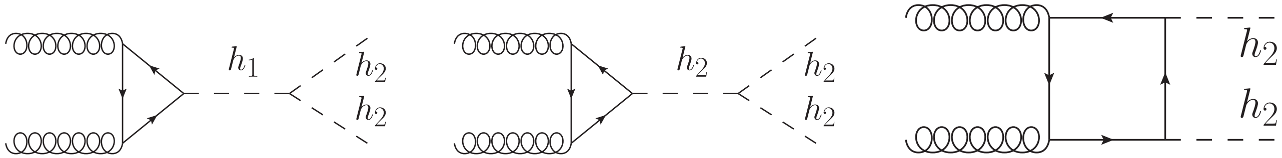
- A pp collider can test for the new singlet scalar (h_2) directly.
- Di-Higgs production is resonantly enhanced for $m_2 > 2m_h$.
- If the new scalar gives rise to a 1st order phase transition, then a 100 TeV pp collider (FCC-hh or SppC) should be able to discover it.

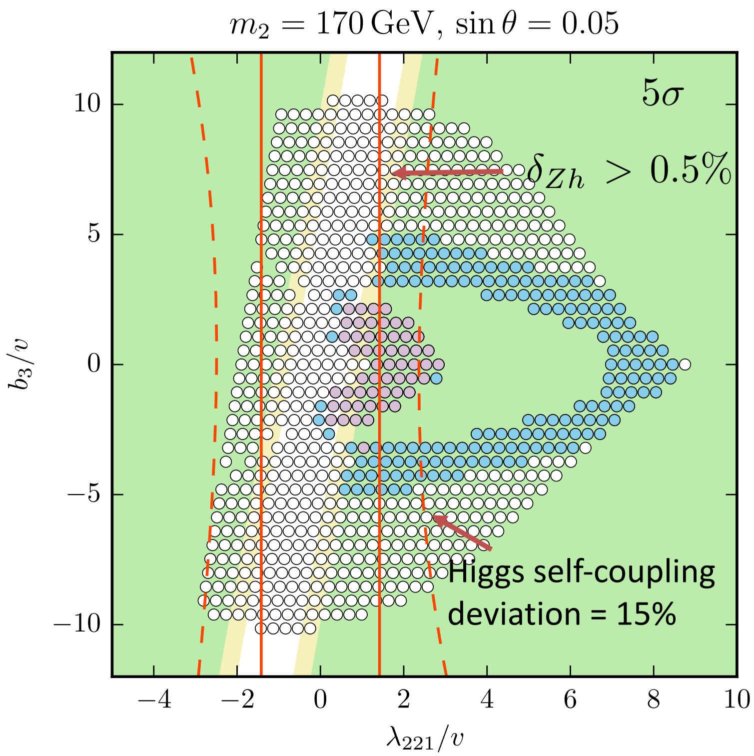
range = consistent w/ 1st order EWPT

[Chen, Kozaczuk, & Lewis (2017)]

Non-resonant di-singlet production

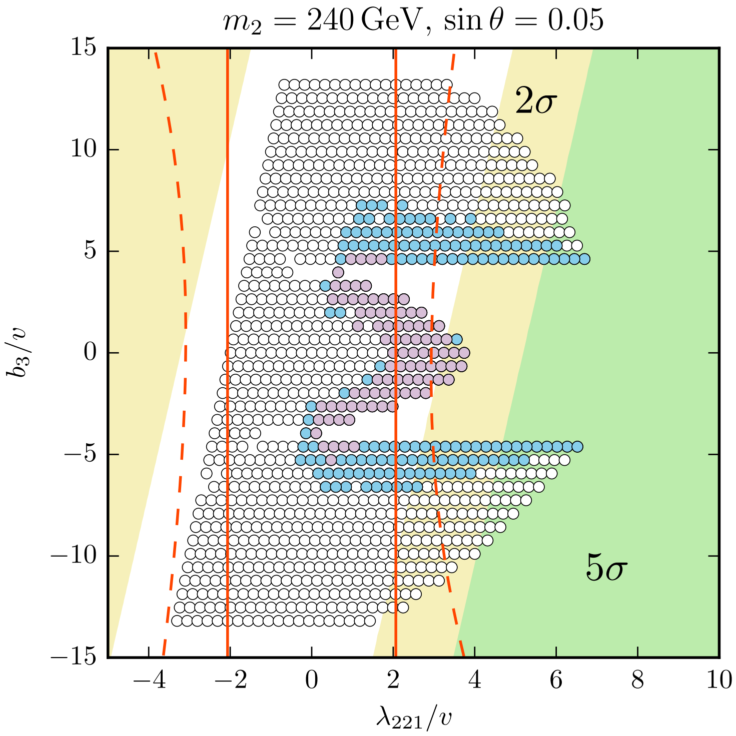
$$pp \to h_2 h_2 \to 4W \to 2j2l^{\pm}l'^{\mp}3\nu$$




$m_2 = 170\,\mathrm{GeV},\ \sin\theta = 0.05$

$\delta_{Zh} > 0.5\%$

Higgs self-coupling deviation = 15%


$m_2 = 240\,\mathrm{GeV},\ \sin\theta = 0.05$

all colored points = 1st order PT

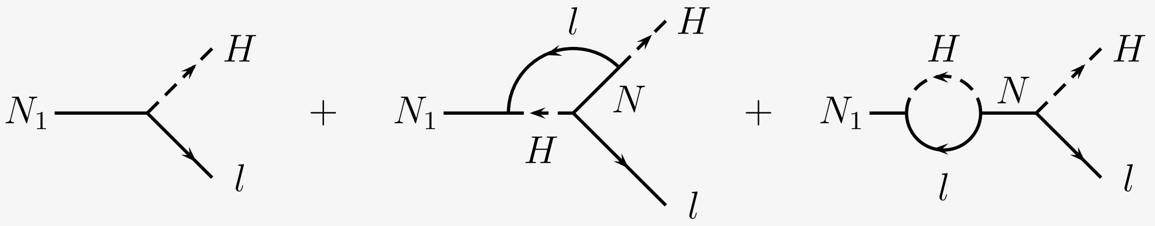
Falsifying High-Scale LG
and
Testing Low-Scale LG
at
Colliders

[Fukugita & Yanagida (1986)]

Leptogenesis. A class of models of baryogenesis in which the matter-antimatter asymmetry is first generated in leptons & then transferred to baryons (usually via the EW sphaleron).

E.g., high-scale (thermal) leptogenesis

$$\mathscr{L} = \frac{1}{2} M_N^{ij} N_i N_j - \lambda_N^{ij} L_i H N_j$$



$$\Gamma(N \to \bar{L}\bar{H}) > \Gamma(N \to LH)$$

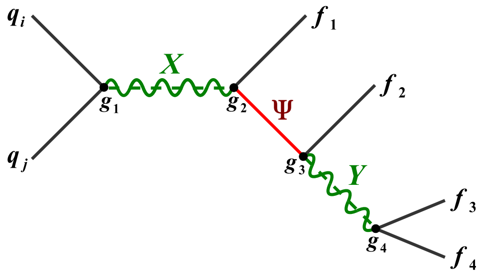
The lepton asymmetry is generated at T ~ M_N ~ 10^{12} GeV.

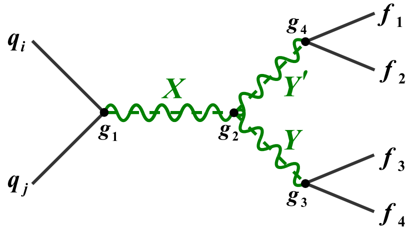
[Deppisch, Harz, & Hirsch (2013)]
[Deppisch, Harz, Huang, Hirsch, & Pas (2015)]

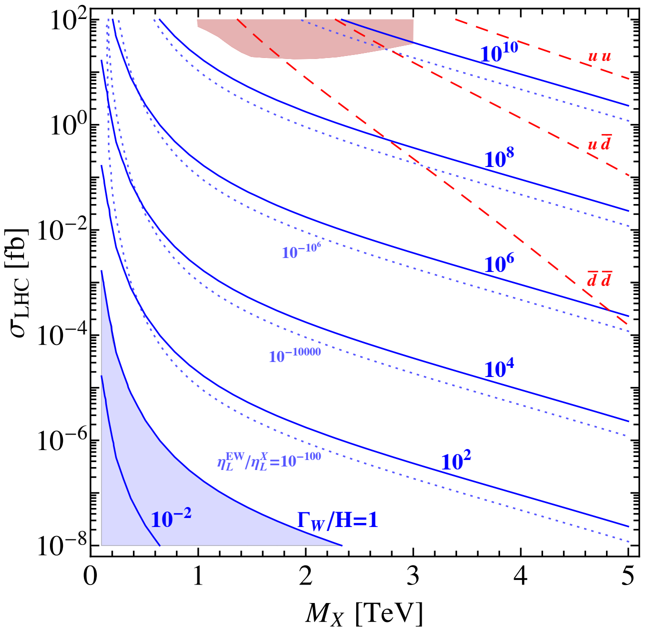
Falsifying high-scale (thermal) leptogenesis

If a collider experiment finds evidence for L-number violation at the TeV scale, then these L-violating interactions should have washed out the L asymmetry.

same sign dileptons: $pp \to l^{\pm} l^{\pm} qq$





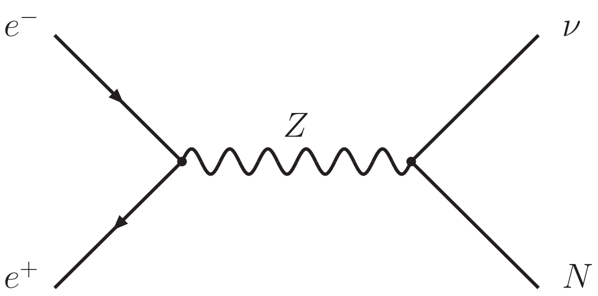


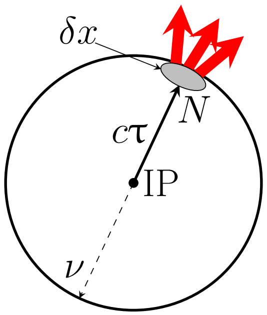
[Akhmedov, Rubakov, & Smirnov(1998)]
[Probing Leptogenesis, 1711.02865]
[Antusch, Cazzato, & Fischer (2016)]

Testing low-scale (ARS) leptogenesis

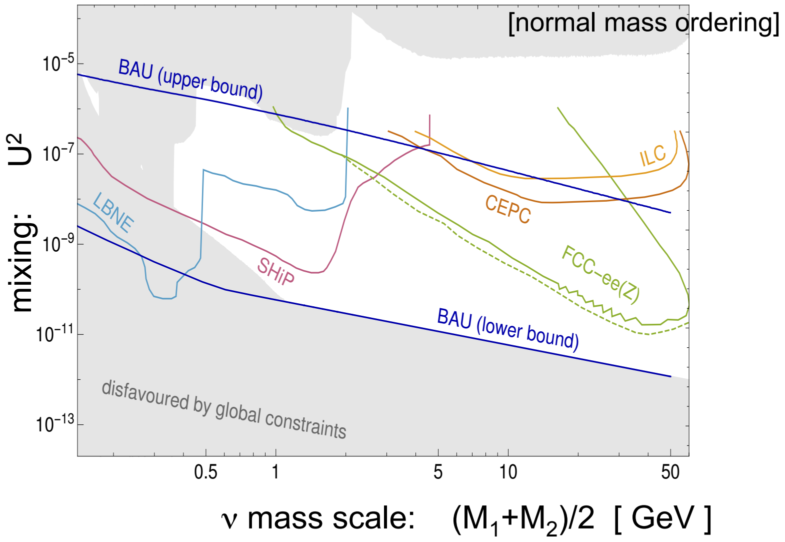
If M_N ~ GeV then the lepton asymmetry may arise at the weak scale from CP-violating neutrino flavor oscillations.

$$e^+e^- \to Z^* \to \nu N$$





signal



Conclusions

Some of the most compelling models of baryogenesis will be tested and falsified by next-generation collider experiments.