Electroweak Baryogenesis, ACME II and Dark Sector CP Violation

Yue Zhang

Carleton University

HEP Theory Seminar, Jozef Stefan Institute

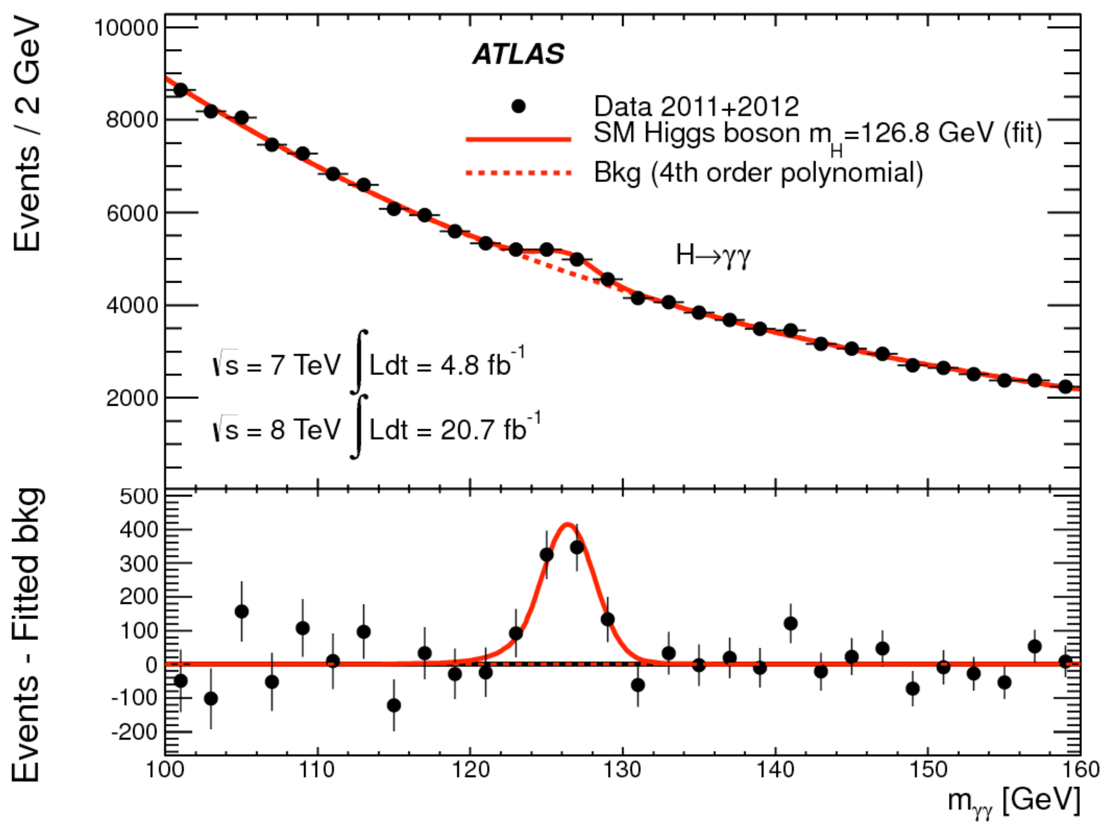
July 7, 2020

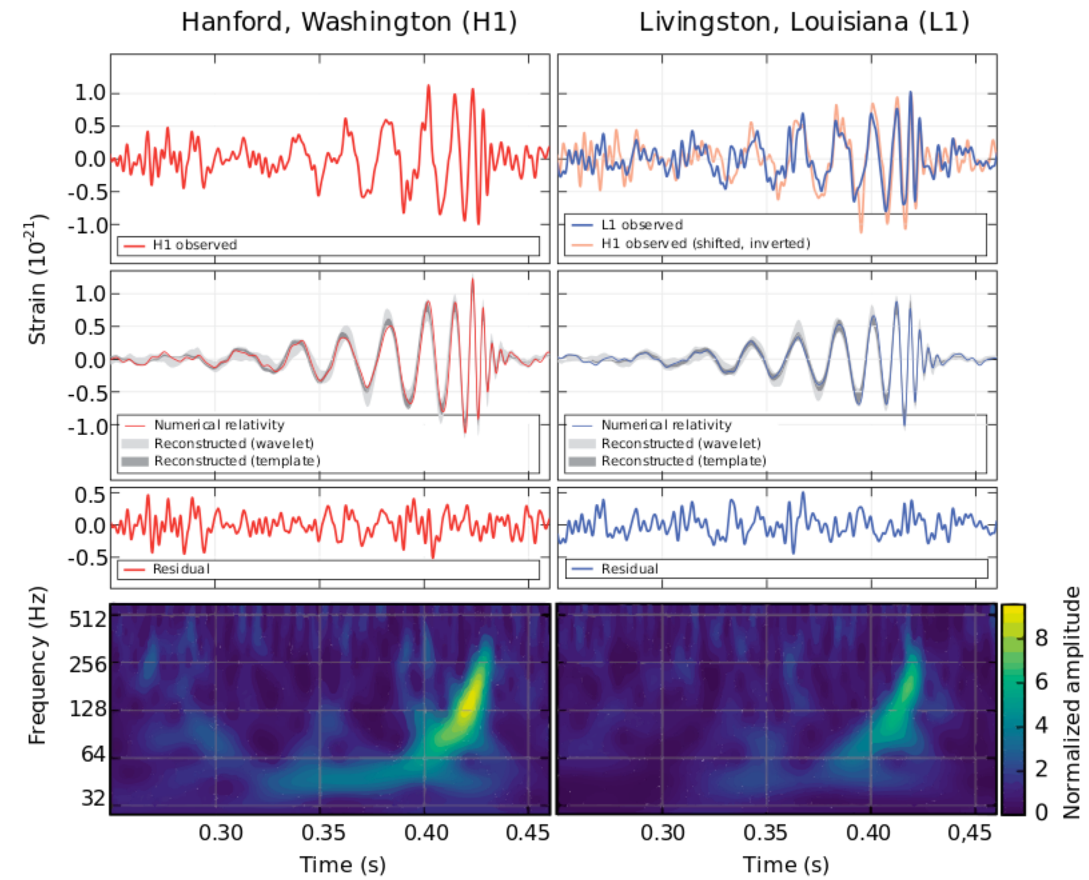
Carena, Quirós, YZ (1811.09719, PRL; 1908.04818, PRD)

Outline

- The cosmic baryon asymmetry Puzzle
- Overview: electroweak baryogenesis
- Challenge: ACME II
- New idea: CP violation from dark sector
- Phenomenology
- Conclusion

Recent Milestones





Discovery of the Higgs boson (2012)

Nobel Prize (2013)

Standard Model works!

Discovery of gravitational waves (2015)

Nobel Prize (2017)

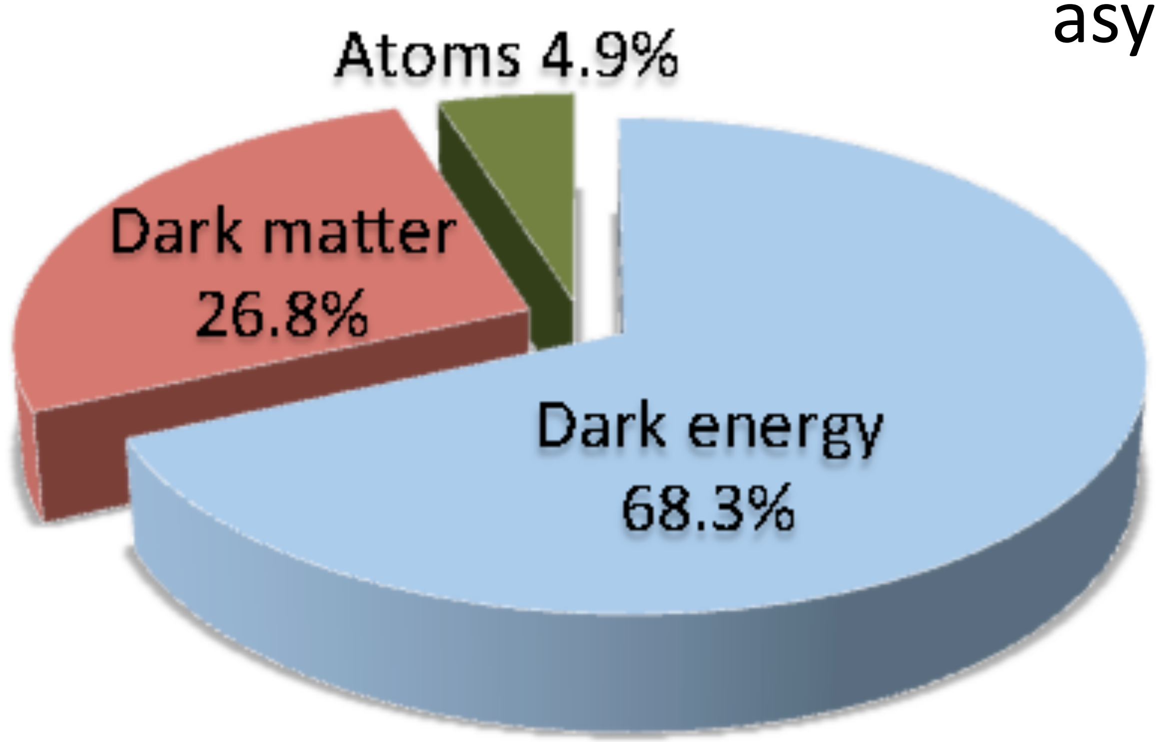
Einstein's gravity works!

Explore Our Universe

Recipe for Our Universe

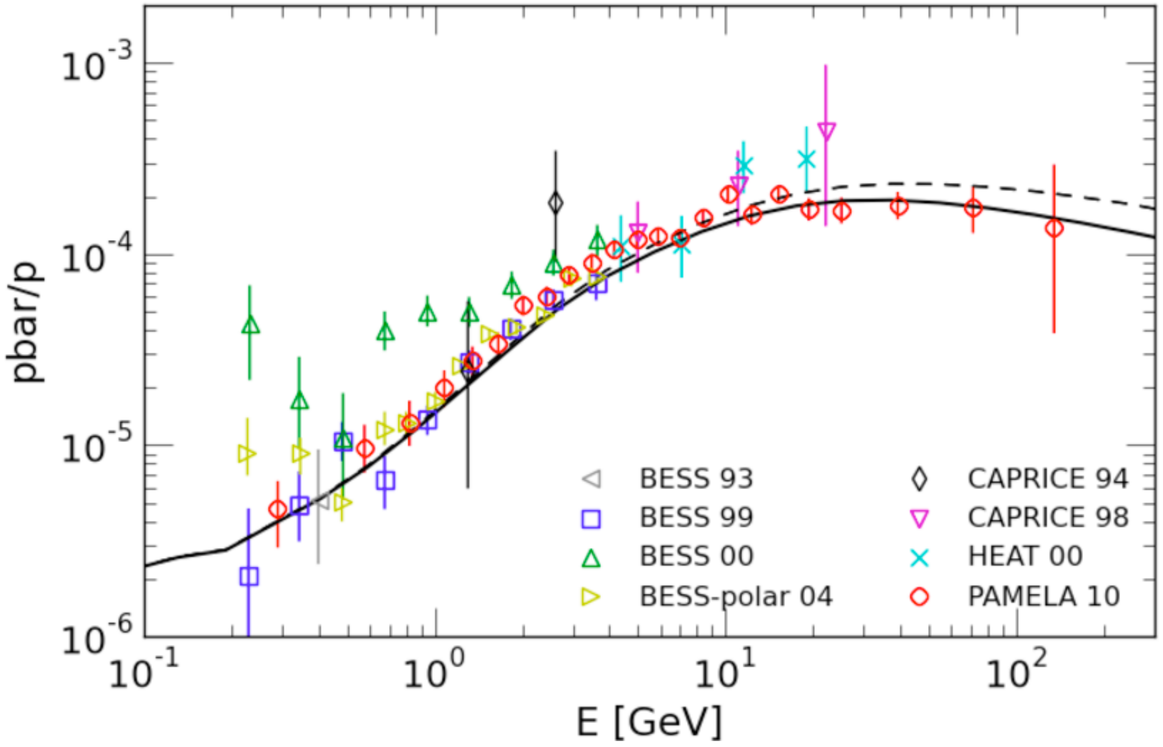
What is the nature of dark matter?

What is the origin of matter-anti-matter asymmetry?



Is dark energy a cosmological constant?

The Asymmetric Visible Universe

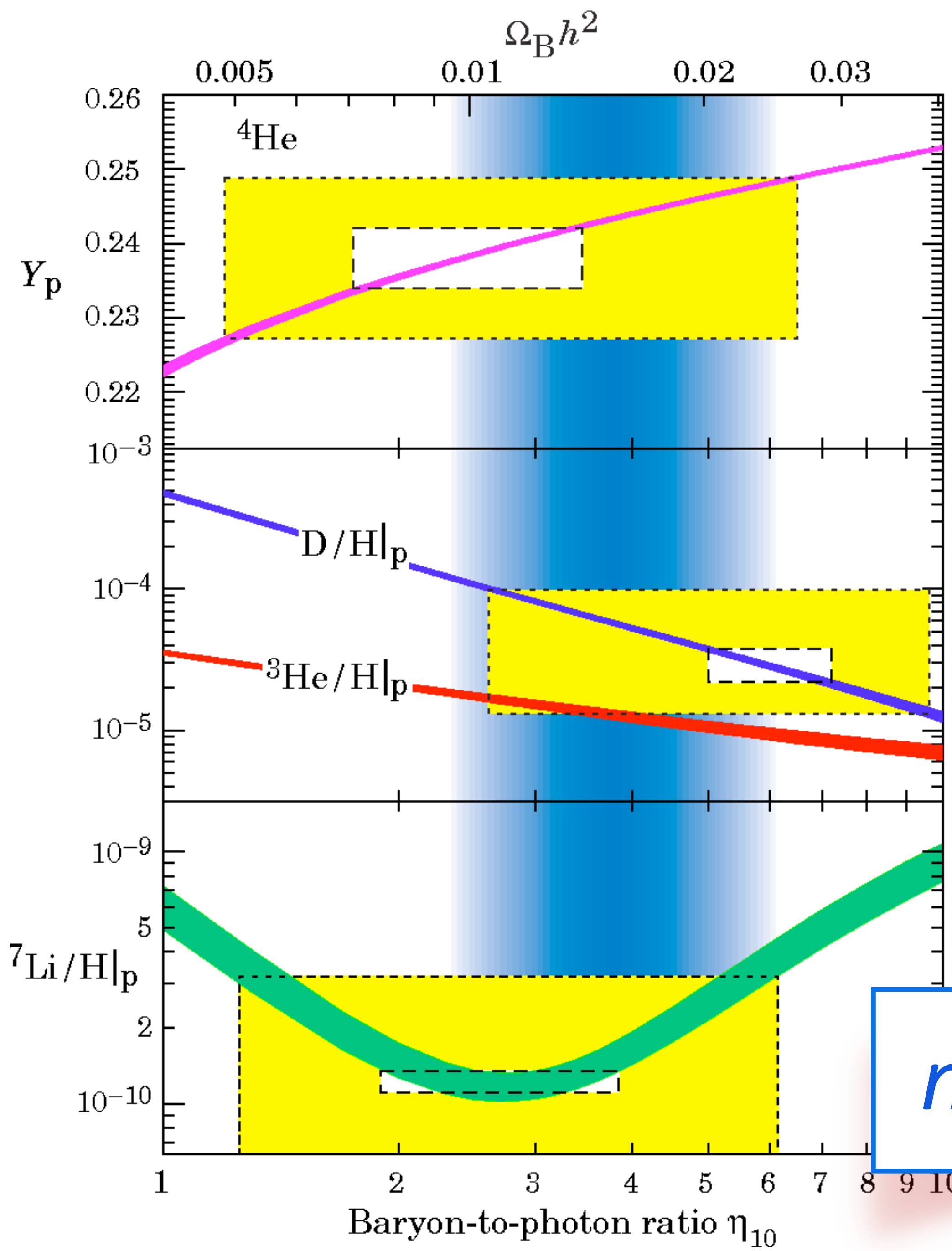


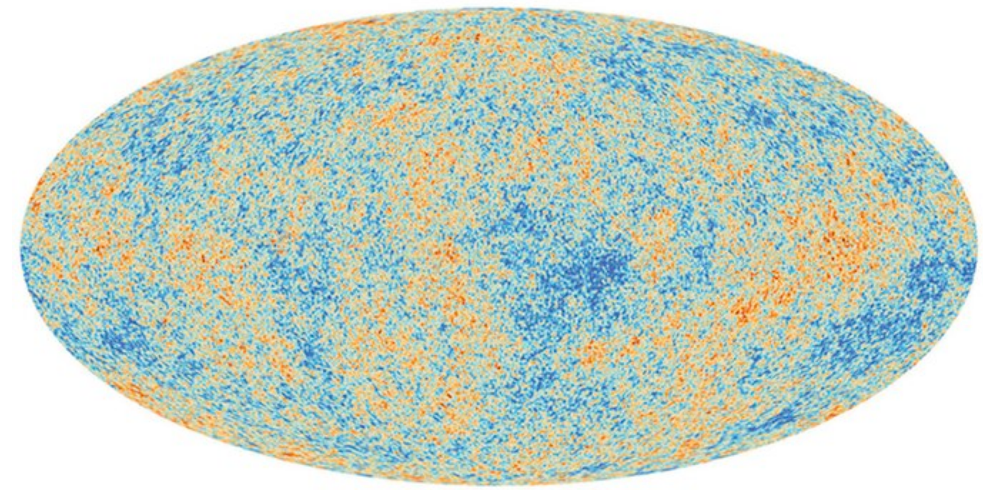
All the visible stuff (stars, gas) are made of baryons (matter).

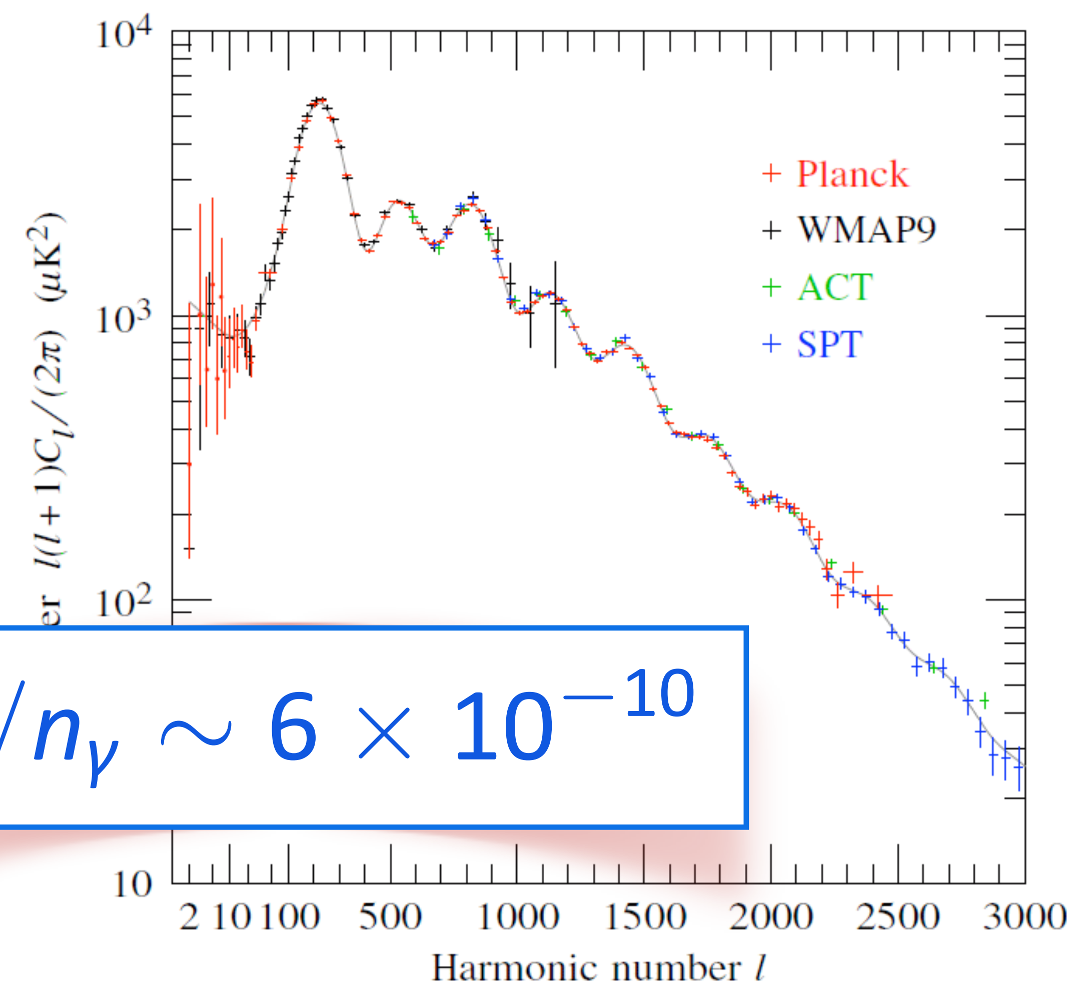
Anti-matter are only seen in cosmic rays, or produced in the laboratories.

Anti-proton to proton ratio in cosmic rays is consistent with secondary production, $n_{\bar{p}}/n_p \sim 10^{-4}$.

Precision Cosmology







$$n_B/n_\gamma \sim 6 \times 10^{-10}$$

Tantalizing Puzzle

What is the origin of such an asymmetry? Initial condition, or was it generated during the evolution of universe?

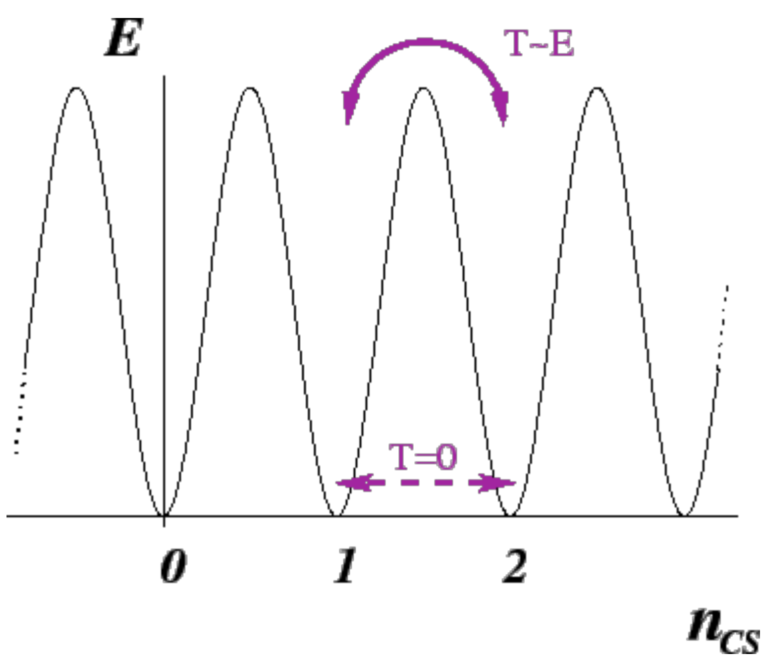
Baryon asymmetry of the universe is a CPT violating quantity.

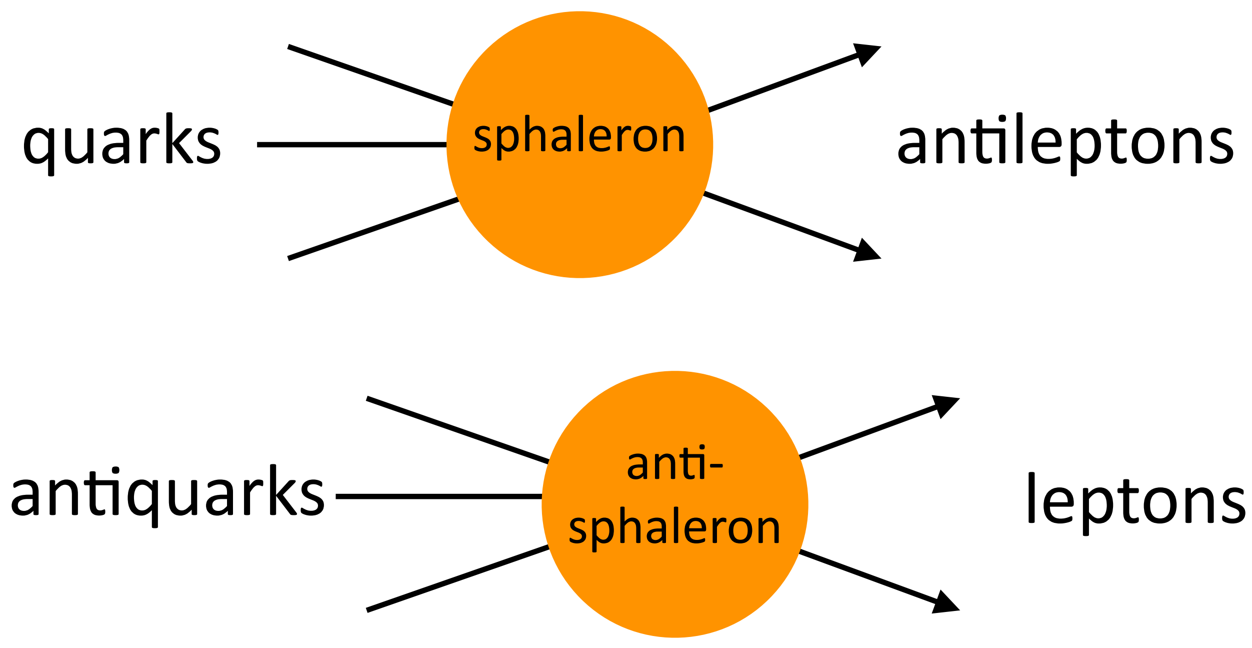
Starting from a CPT conserving theory, necessary conditions for generating nonzero baryon asymmetry are (Sakharov, 1962)

- Baryon number violation: if universe starts symmetric
- CP violation: treat baryon/anti-baryon differently
- Out-of-thermal equilibrium: suppress inverse processes

Baryon Number Violation

It is well known SM offers a baryon number violation process in early universe (Klinkhamer, Manton, 1984).





Different N_{CS} correspond to different $B+L$ quantum numbers, $B+L$ can be violated by transitions between vacua (but conserve B-L).

It would be simple and elegant to make use of this effect.

Electroweak Baryogenesis

For a short period, EW sphalerons work out of equilibrium in a preferred direction to generate the desired baryon asymmetry; It then shuts off quickly to prevent washout.

Among every 10^{10} quarks/antiquarks in the universe, only one participates in such a process (highly out-of-equilibrium).

(Kuzmin, Rubakov, Shaposhniov, 1985; Cohen, Kaplan, Nelson, 1990, 1991; Farrar, Shaposhnikov, 1993; Huet, Nelson, 1995, 1996; Riotto, 1995; Carena, Quiros, Riotto, Seco, Vilja, Wagner, 1997, 2001, 2003; Cline, Joyce, Kainulainen, 2000; Lee, Cirigliano, Ramsey-Musolf, 2004 …)

How Short Period Is Short?

EW sphaleron reaction rate (Shaposhnikov, 1985)

$$\Gamma_{\rm sph} \sim 120\alpha_2^5 T \exp\left(-\frac{8\pi v(T)}{g_2 T}\right)$$

EW phase transition switches it off: above critical temperature T_c (early on), v=0, sphalerons are fast; below T_c (later), EW symmetry broken; If v~T_c, sphalerons exponentially suppressed.

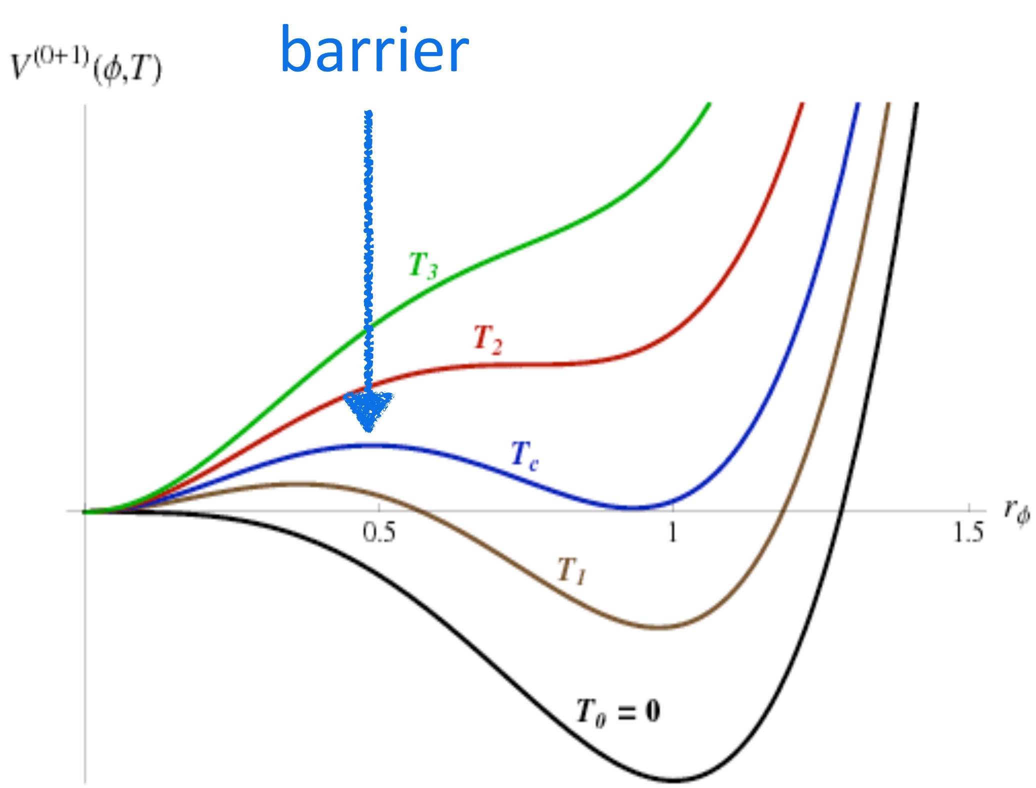
Problem: around critical temperature T_c, the universe expands too slowly, $H \sim T^2/M_{\rm M_P} \ll \Gamma_{\rm sph}$, no out-of-equilibrium.

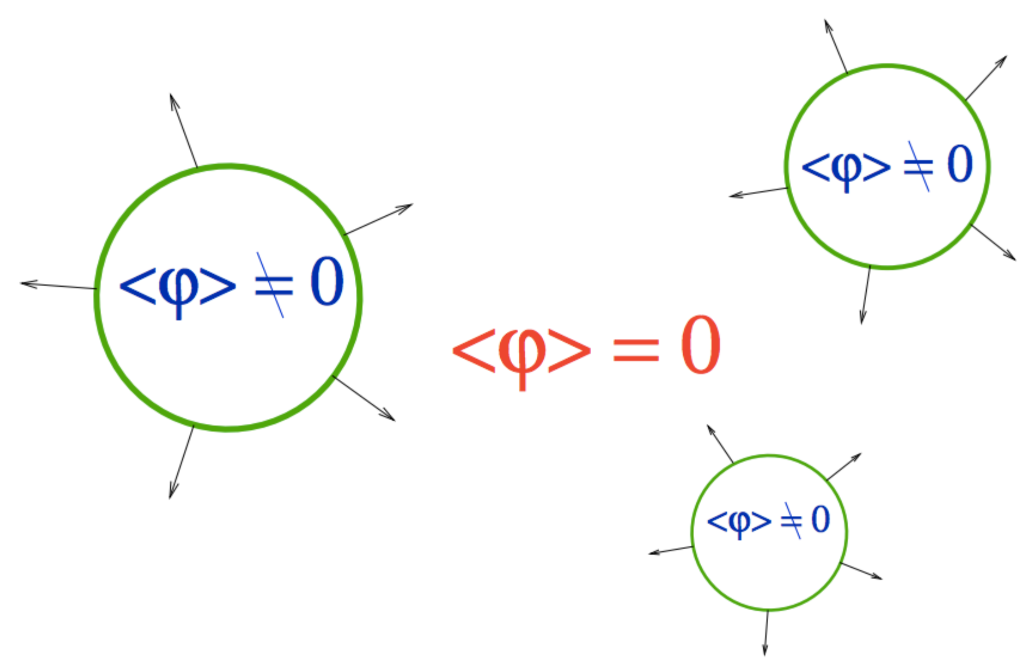
Cosmological time scale is too long, a new time scale needed.

First Order Phase Transition

In a first order EW phase transition, universe tunnels from h=0 to h≠0 vacuum via bubble nucleation.

Bubbles expansion velocity close to *c*. Processes nearby highly out-of-equilibrium, no time for inverse sphalerons to occur.



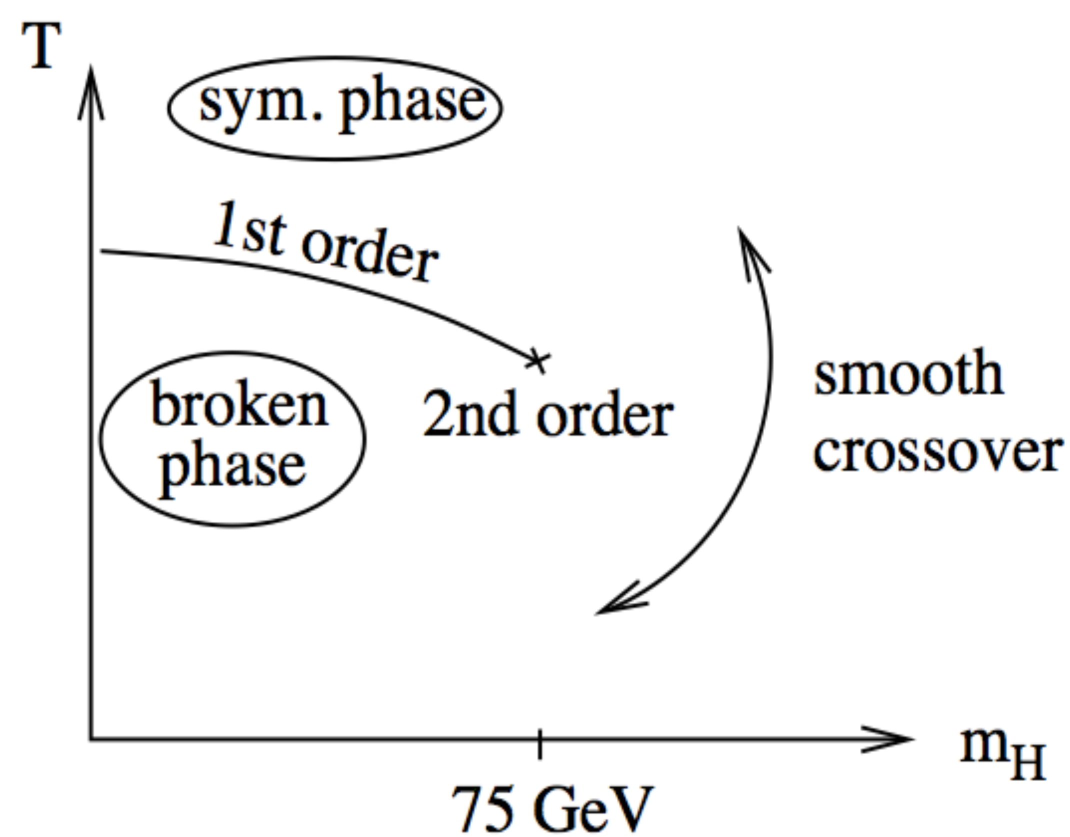


Nature of EW Phase Transition

Within SM, with the measured Higgs mass (125 GeV), lattice simulations tell that EW phase transition is smooth cross over.
(Kajantie, Laine, Rummukainen, Shaposhnikov, hep-ph/9605288)

First order phase transition widely occurs in extended Higgs sector models.

There are consequences in the form of effective Higgs potential and Higgs physics, as well as gravity waves.

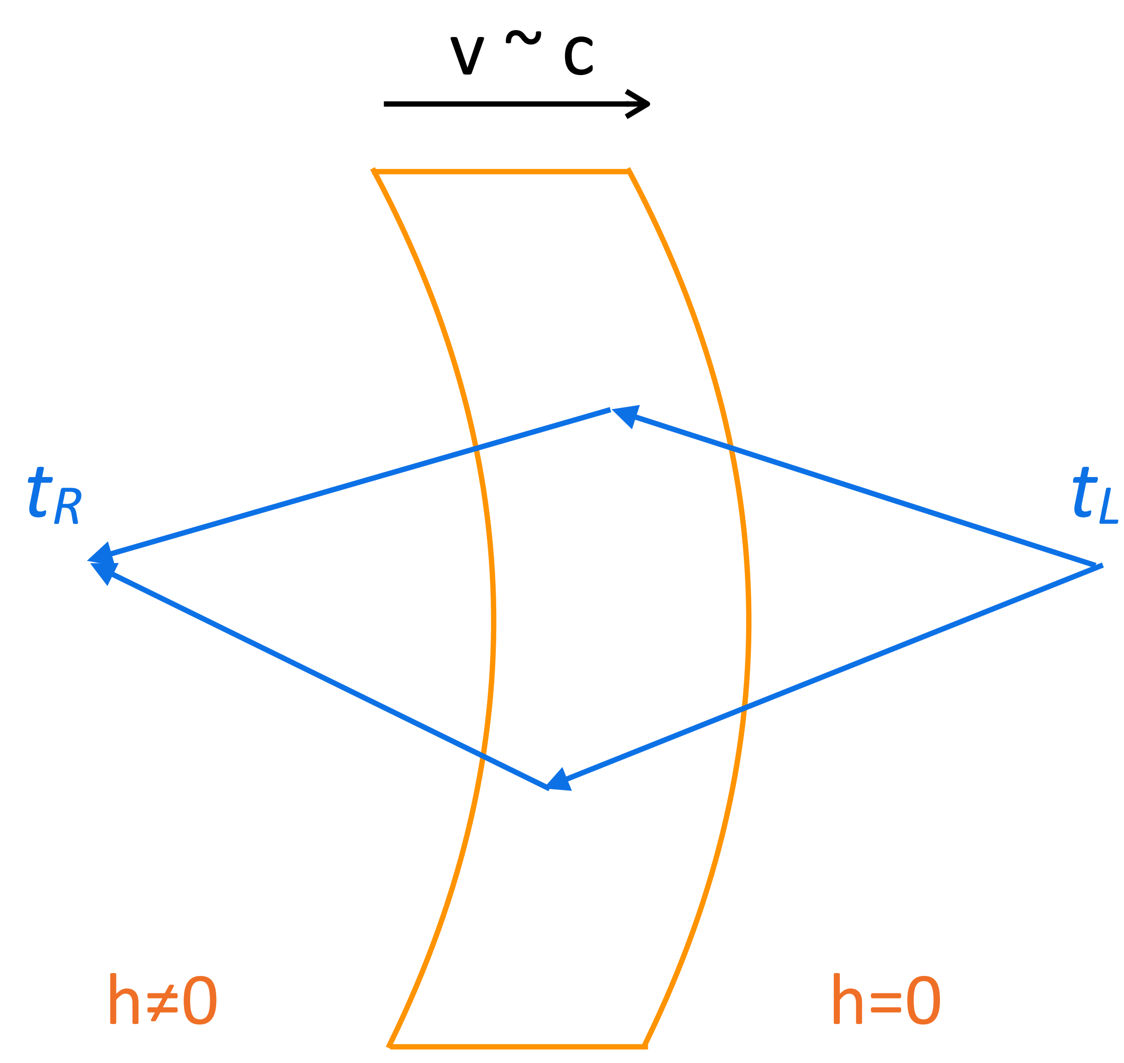


Higgs Physics Near Bubble Wall

Expanding bubble wall serves as the border where the Higgs field quickly changes from 0 to v. Particles flow into it.

- Assume CP violation exists, particles interact with wall at different x (interference).
- Yukawa interaction with Higgs field flips chirality.
- $\sigma_{t_L \to t_R} \neq \sigma_{t_L^c \to t_R^c}$
- First generates a chiral charge asymmetry

$$\Delta \equiv n_{t_L} - n_{t_L^c} = -(n_{t_R} - n_{t_R^c}) \neq 0$$



From Chiral to Baryon Asymmetry

The generated chiral charge asymmetry, in particular, $n_{t_L} - n_{t_L^c}$, has a distribution around the bubble wall.

Outside the bubble (v=0), EW sphalerons allow a fraction (*f*) of asymmetry in left-handed top quarks to be shared with leptons.

Asymmetry in right-handed fields is not touched by sphalerons.

A net baryon asymmetry will be generated this way

$$n_B - n_{\bar{B}} \propto \left[n_{t_R} - n_{t_R^c}\right] + (1-f)\left[n_{t_L} - n_{t_L^c}\right] = f\Delta$$

Worth mentioning that equal amount of asymmetry is stored in the lepton number (sphalerons breaks *B*+*L*).

The Role of CP Violation

Semiclassical picture of how CP violation works in baryogenesis.

Space-time dependent mass near bubble wall $m_t(x) = y_t h(x)$

For a fixed energy fermion state, the Dirac equation reads

$$\left[E\gamma^0 - i\gamma^i\partial_i - m_t(x)P_L - m_t^*(x)P_R\right] t = 0$$

Dispersion relation modified by when derivative hits on mass

$$E = \sqrt{[p \pm \arg(m_t)']^2 + |m_t|^2} \mp \arg(m_t)'$$

The wall exerts different "forces" on particle and antiparticle

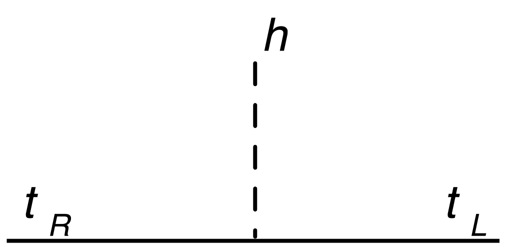
$$\dot{p} = \frac{\partial E}{\partial z} \sim \pm \frac{(|m_t|^2 \arg(m_t)')'}{E^2}$$

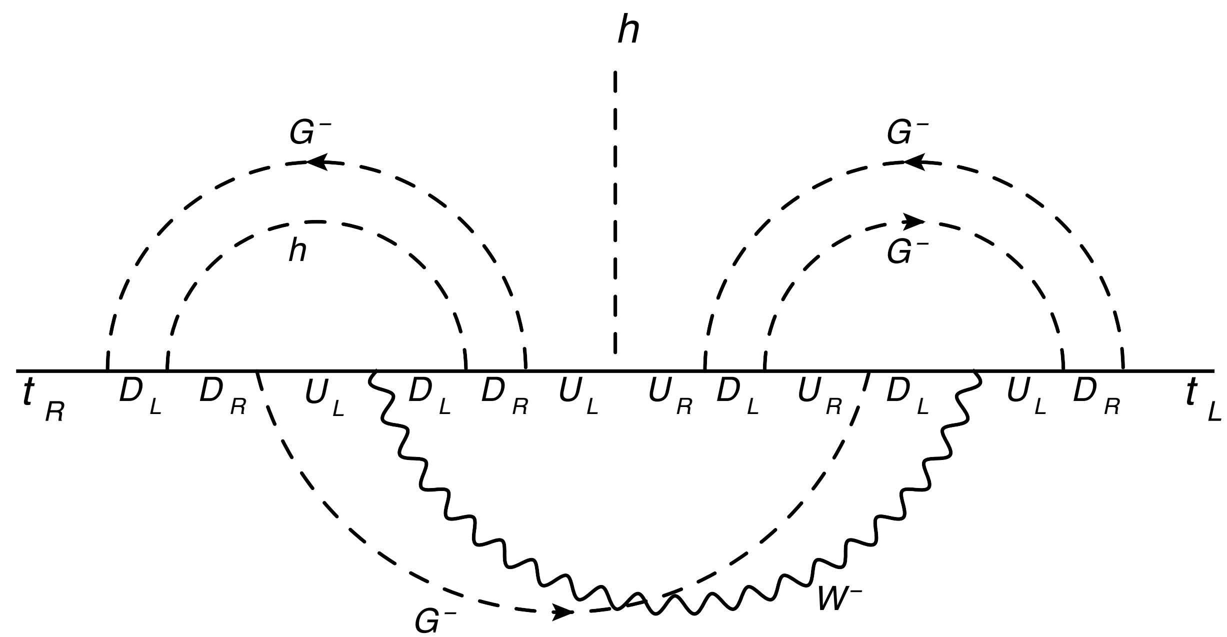
Cline, hep-ph/0609145

Source of CP Violation in SM

Contribution from SM CP violation (CKM) is highly suppressed.

How to generate complex top quark mass with a physical phase?





Maximal CP phase is (another reason where SM fails)

$$\delta_{\rm CPV} \sim {\rm Im\,Tr}(\mathcal{M}_u^2 \mathcal{M}_d^2 \mathcal{M}_u \mathcal{M}_d) \sim \left(\frac{\alpha_2}{M_W^2}\right)^6 s_1^2 s_2 s_3 \sin\delta\, m_t^4 m_b^4 m_c^2 c_s^2 < 10^{-20}$$

$$\mathcal{M}_q = Y_q Y_q^\dagger$$

Shaposhnikov, 1986

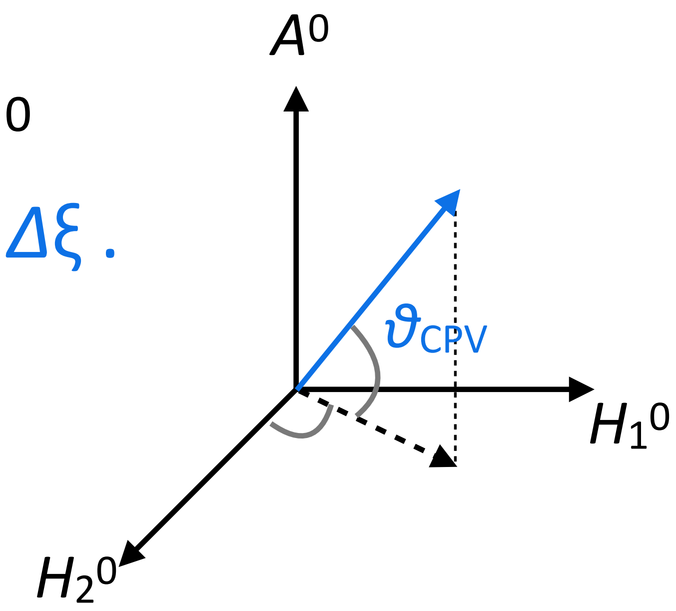
CP Violation from New Physics

Two Higgs doublet models: two Higgs VEVs during EWPT

$$\langle H_1 \rangle = \left[0,\ v_1(t) e^{i\xi_1(t)}\right]^T, \quad \langle H_2 \rangle = \left[0,\ v_2(t) e^{i\xi_2(t)}\right]^T$$

Top quark mass $m_t = y_1 v_1 \exp(i\xi_1) + y_2 v_2 \exp(i\xi_2)$. Relative phase $\Delta\xi$ has a potential, $V \supset m_{12}^2 (H_1^\dagger H_2) + \lambda_{12} (H_1^\dagger H_2)^2 + \text{h.c.}$

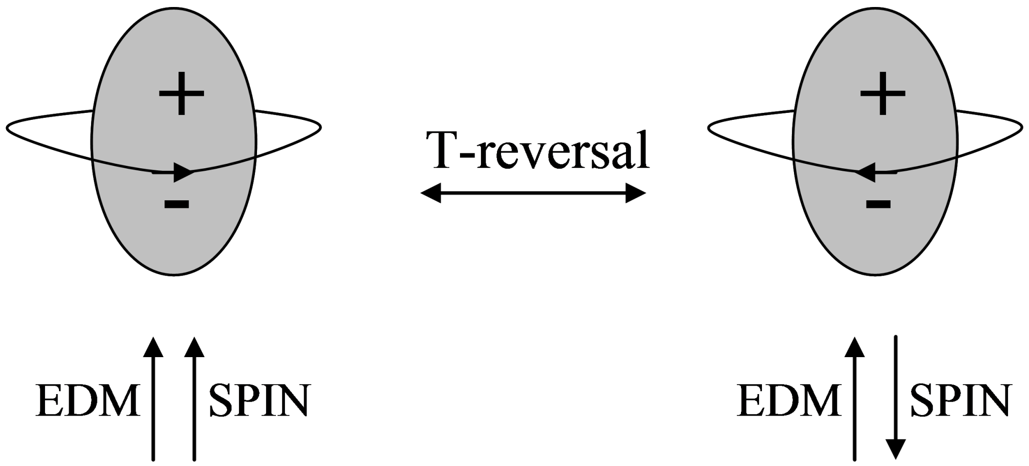
The 125 GeV Higgs boson could contain a CP odd A^0 component (mixing angle ϑ_{CPV}). Generically, $\vartheta_{CPV} \sim \Delta\xi$.



$$\mathcal{L} \sim \frac{m_t}{v} \bar{t} \left(\cos\vartheta_{CPV} + i\gamma_5 \sin\vartheta_{CPV}\right) th$$

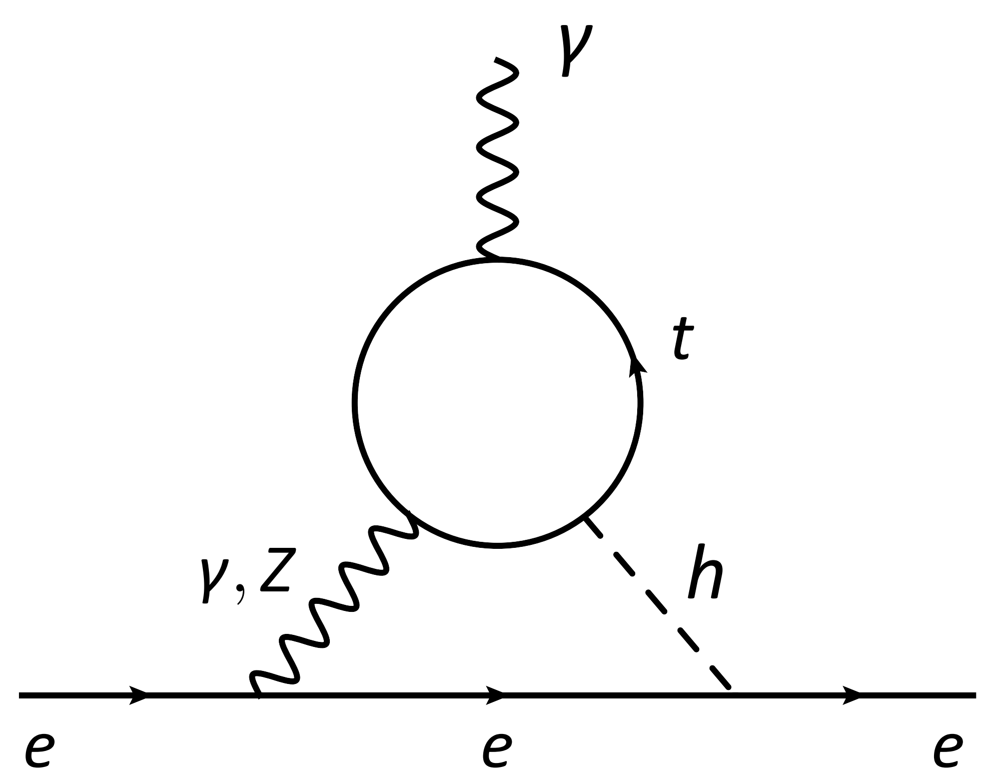
SUSY: similar role of top could be played by charginos/ neutralinos.

Electric Dipole Moments

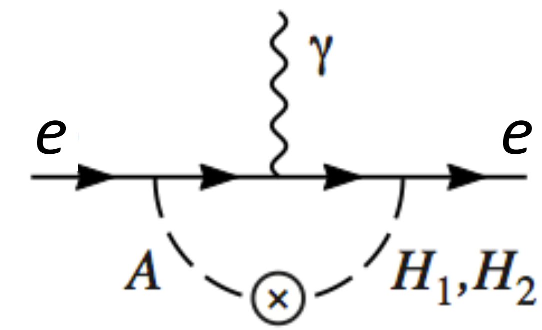


$$H = d_e \vec{s} \cdot \vec{E}$$

Electron EDM and ACME II



>>



Barr, Zee, 1990

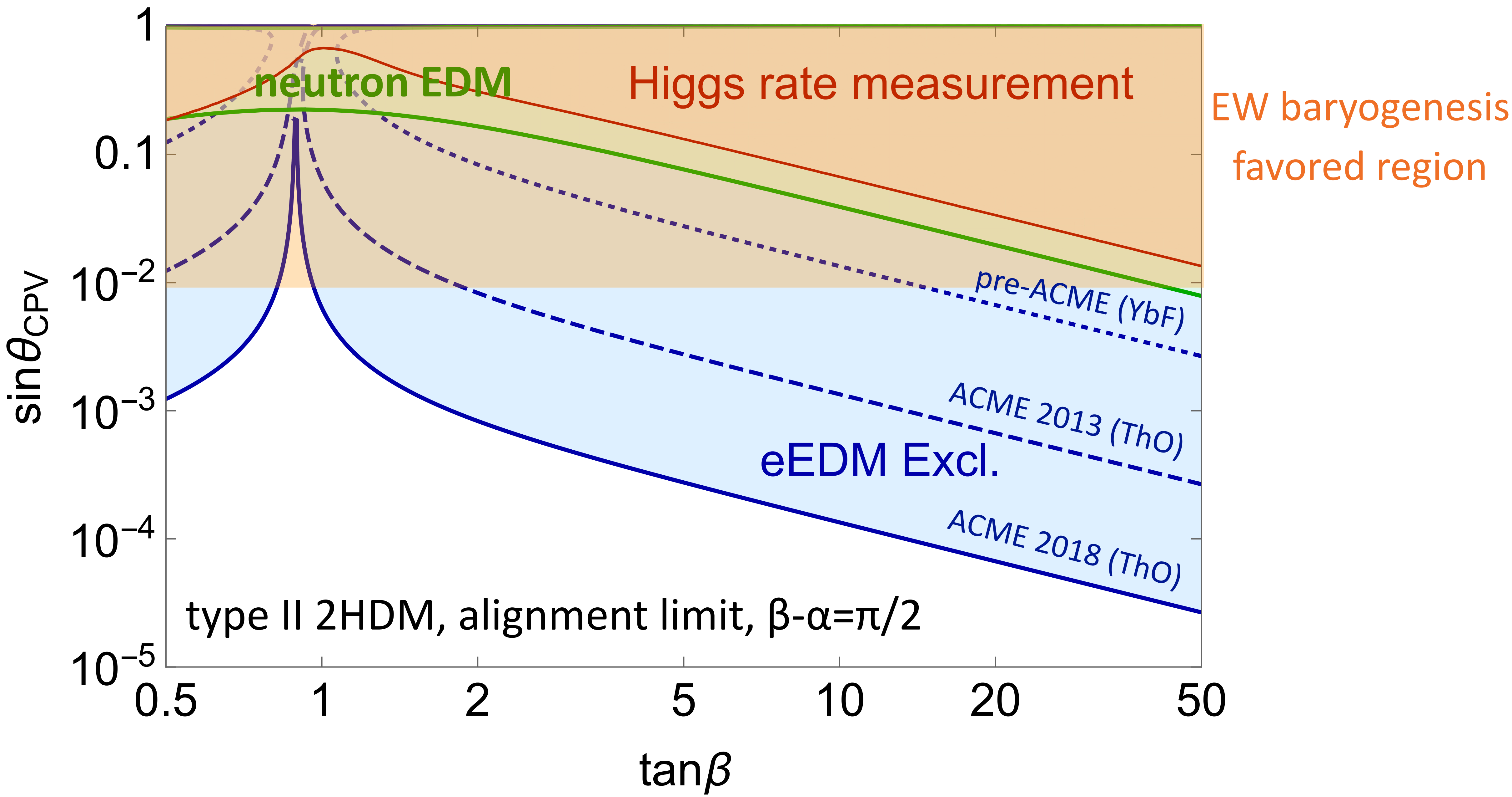
Weak scale CP violation, a back-of-envelop estimate

$$d_e \sim \frac{e\, G_F\, m_e}{(16\pi^2)^2}\, \vartheta_{\rm CPV} \sim 10^{-26}\, \vartheta_{\rm CPV}\, e\,{\rm cm}$$

Latest electron EDM measurement $d_e < 1.1 \times 10^{-29}\, e\,{\rm cm}$

ACME collaboration 2018

Severe Challenge Now



Shu, **YZ**, 1304.0773, PRL

Inoue, Ramsey-Musolf, **YZ**, 1403.4257, PRD

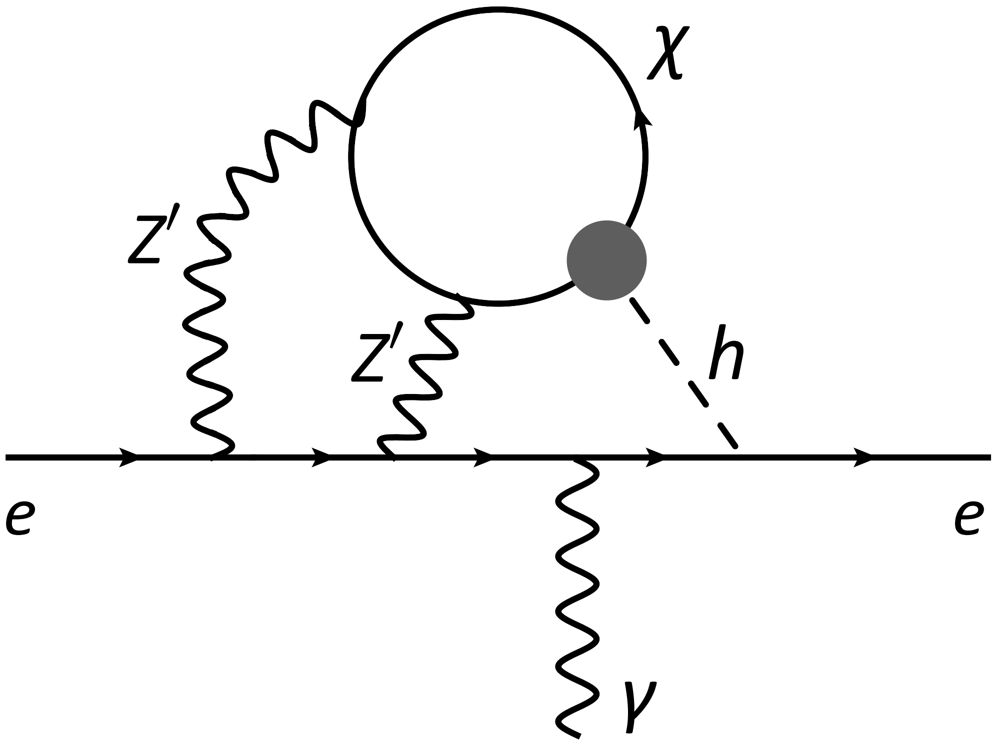
A Simple Way to Suppress EDM

Electron EDM can be suppressed if the CP violating fermion is a SM gauge singlet (does not couple to photon).

How to transfer CP violation in the early universe? I will discuss a new mechanism with two ingredients:

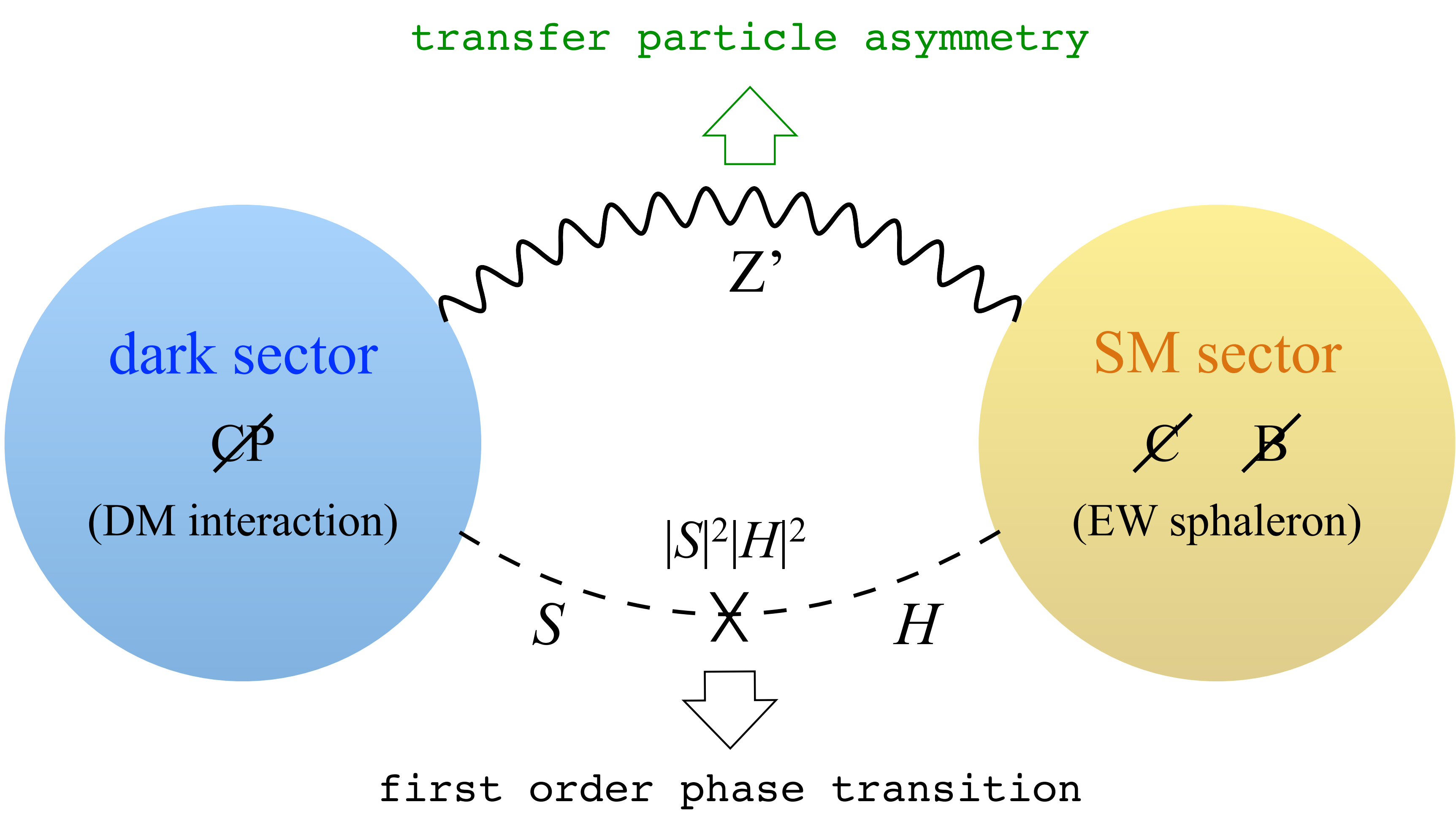
- Higgs portal (sourcing CP violation & phase transition)
- Z' portal (for transfer CP violation)

In this case, the leading EDM contribution has to arise with extra loop factors.



Carena, Quirós, **YZ**, 1811.09719, PRL

Ingredient of Dark Sector Model



Carena, Quirós, **YZ**, 1811.09719, PRL

The Role of Higgs Portal

The direct coupling between a SM gauge singlet fermion χ and the Higgs boson would be higher dimensional.

To write down a renormalizable theory, introduce a new scalar, S, also SM gauge singlet, with Yukawa coupling to χ

$$\mathcal{L} \sim \bar{\chi}_L (m_0 + yS)\chi_R + \text{h.c.}$$

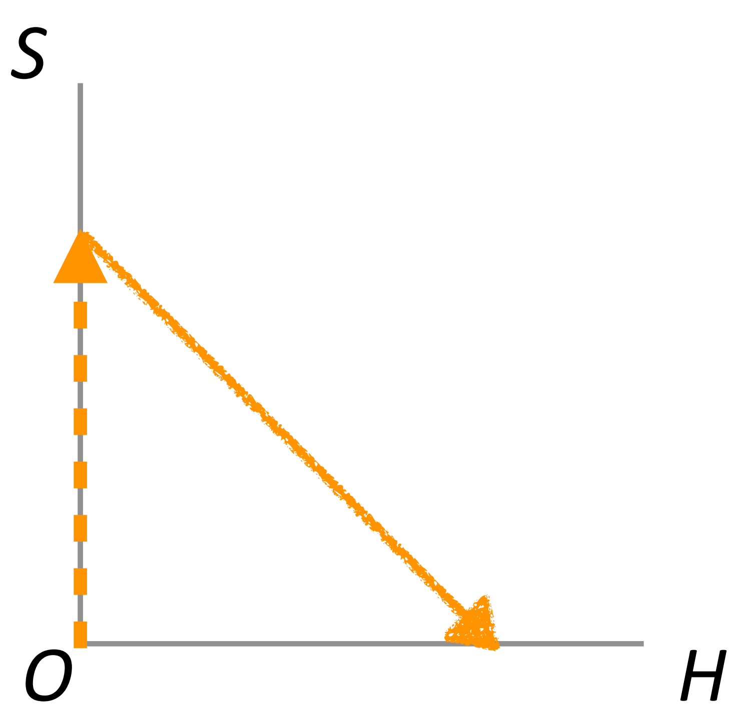
A first order phase transition involving S field, in presence of a relative phase between m_0 and y, can generate chiral charge asymmetry in χ particles (analogue of top-Higgs interaction)

$$\Delta \equiv n_{\chi_L} - n_{\chi_L^c} = -(n_{\chi_R} - n_{\chi_R^c}) \neq 0$$

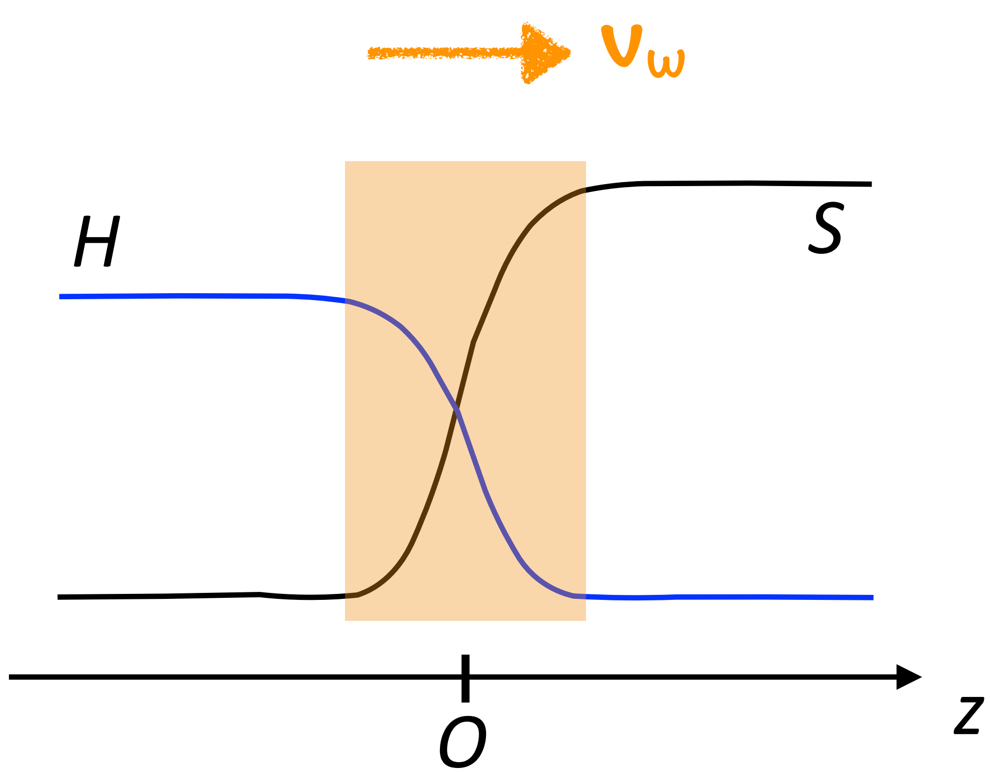
Carena, Quirós, **YZ**, 1811.09719, PRL

New EW Phase Transition

A scalar-Higgs interaction, $\lambda|S|^2|H|^2$, with $\lambda>0$, can trigger strong first order EW phase transition of the following form (with $m_S \sim S \sim$ hundreds of GeV, and $\lambda \sim$ 1-3).



field space



bubble wall profile

Espinosa, Konstandin, Riva, 1107.5441

The Role of Z' Portal

EW sphalerons cannot touch the chiral charge asymmetries in χ because it is an SU(2) singlet — must transfer such a CPV effect in other ways to the SM sector.

Introduce a Z' vector boson (will be gauge boson of a new U(1)) with the following interactions. First, coupling with χ

$$g' Z'_\alpha \left[q_{\chi_L} \bar{\chi}_L \gamma^\alpha \chi_L + q_{\chi_R} \bar{\chi}_R \gamma^\alpha \chi_R \right]$$

$\uparrow$ Δ $\qquad$ $\uparrow$ $-\Delta$ $\qquad$ (α=0 component)

If $q_{\chi_L} \neq q_{\chi_R}$, there is a net charge density, generates a background for the Z'^0 component (analogue of static electric potential).

Carena, Quirós, **YZ**, 1811.09719, PRL

Chemical Potentials from Z'^0

In addition, Z' also couples to SM fermions, with the following generic charge assignment

$$g' Z'_\alpha \sum_{i=1}^{3} \left[q_{L_{L_i}} \bar{L}_{L_i} \gamma^\alpha L_{L_i} + q_{e_{R_i}} \bar{e}_{R_i} \gamma^\alpha e_{R_i} + q_{\nu_{R_i}} \bar{\nu}_{R_i} \gamma^\alpha \nu_{R_i} \right.$$
$$\left. + \, q_{Q_{L_i}} \bar{Q}_{L_i} \gamma^\alpha Q_{L_i} + q_{u_{R_i}} \bar{u}_{R_i} \gamma^\alpha u_{R_i} + q_{d_{R_i}} \bar{d}_{R_i} \gamma^\alpha d_{R_i} \right]$$

If Z'^0 background is nonzero, the above interactions generate a chemical potential $\mu = qZ'^0$ for each fermion ($H \sim \mu N$).

With a chemical potential, the thermal equilibrium asymmetry between the f and f^c number densities will dictated by μ.
(Out of thermal equilibrium? Solve Boltzmann equations…)

Carena, Quirós, **YZ**, 1811.09719, PRL

Driving the EW Sphalerons

Important constraint: All SM fermions share the same number changing process — EW sphalerons (outside bubbles). Must add up all the fermions to the total *B+L* number.

There is only one Boltzmann equation

$$\frac{\partial \Delta n_{(B+L)_L}}{\partial t} = \Gamma_{\rm sph}\left[\sum_{i=1}^{3}\left(\Delta n^{\rm EQ}_{L_{L_i}} + \Delta n^{\rm EQ}_{Q_{L_i}}\right) - \Delta n_{(B+L)_L}\right]$$

$$= \Gamma_{\rm sph}\left[\frac{2}{3}T^2 g' \sum_{i=1}^{3}\left(q_{L_{L_i}} + 3q_{Q_{L_i}}\right) Z'_0 - \Delta n_{(B+L)_L}\right]$$

massless fermions

A coincidence with the non-conservation of the Z' current

$$\partial_\mu J^\mu \propto \sum_{i=1}^{3}\left(q_{L_{L_i}} + 3q_{Q_{L_i}}\right) {\rm tr}(W\widetilde{W})$$

Carena, Quirós, **YZ**, 1811.09719, PRL

Requirement on *Z′* Charges

There are special cases for the charge assignment where the source term in the *B+L* Boltzmann equation vanishes — that is, when the current is anomaly free with respect to $SU(2)_L^2$.

The current *Z′* couples to must be anomalous!

Key ingredient for the success of new electroweak baryogenesis mechanism proposed here. Guiding principle for constructing UV complete theories.

- Non-working U(1)s: hypercharge, *B-L*, L_μ-L_τ.
- Working U(1) theories: baryon number, lepton number, L_μ+L_τ.

Carena, Quirós, **YZ**, 1811.09719, PRL

A UV Completion

Extending the SM with gauged lepton number symmetry $U(1)_\ell$.

Particle	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
Q_{L_i}	3	2	1/6	0
u_{R_i}	3	1	2/3	0
d_{R_i}	3	1	-1/3	0
L_{L_i}	1	2	-1/2	1
e_{R_i}	1	1	-1	1

⇨ not anomaly free

⇨

⇨

Fileviez, Wise, 1002.1754; Schwaller, Tait, Vega-Morales, 1305.1108

A UV Completion

Extending the SM with gauged lepton number symmetry $U(1)_\ell$.

Particle	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
Q_{L_i}	3	2	1/6	0
u_{R_i}	3	1	2/3	0
d_{R_i}	3	1	-1/3	0
L_{L_i}	1	2	-1/2	1
e_{R_i}	1	1	-1	1
ν_{R_i}	1	1	0	1

Fileviez, Wise, 1002.1754; Schwaller, Tait, Vega-Morales, 1305.1108

A UV Completion

Extending the SM with gauged lepton number symmetry U(1)$_\ell$.

Particle	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
Q_{L_i}	3	2	1/6	0
u_{R_i}	3	1	2/3	0
d_{R_i}	3	1	-1/3	0
L_{L_i}	1	2	-1/2	1
e_{R_i}	1	1	-1	1
ν_{R_i}	1	1	0	1
$L' = (\nu'_L, e'_L)^T$	1	2	-1/2	q
e'_R	1	1	-1	q
χ_R	1	1	0	q
$R' = (\nu''_R, e''_R)^T$	1	2	-1/2	q + 3
e''_L	1	1	-1	q + 3
χ_L	1	1	0	q + 3

Fileviez, Wise, 1002.1754; Schwaller, Tait, Vega-Morales, 1305.1108

A UV Completion

Extending the SM with gauged lepton number symmetry $U(1)_\ell$.

Particle	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
Q_{L_i}	3	2	1/6	0
u_{R_i}	3	1	2/3	0
d_{R_i}	3	1	-1/3	0
L_{L_i}	1	2	-1/2	1
e_{R_i}	1	1	-1	1
ν_{R_i}	1	1	0	1
$L' = (\nu'_L, e'_L)^T$	1	2	-1/2	q
e'_R	1	1	-1	q
χ_R	1	1	0	q
$R' = (\nu''_R, e''_R)^T$	1	2	-1/2	$q+3$
e''_L	1	1	-1	$q+3$
χ_L	1	1	0	$q+3$
Φ, S	1	1	0	3

Fileviez, Wise, 1002.1754; Schwaller, Tait, Vega-Morales, 1305.1108

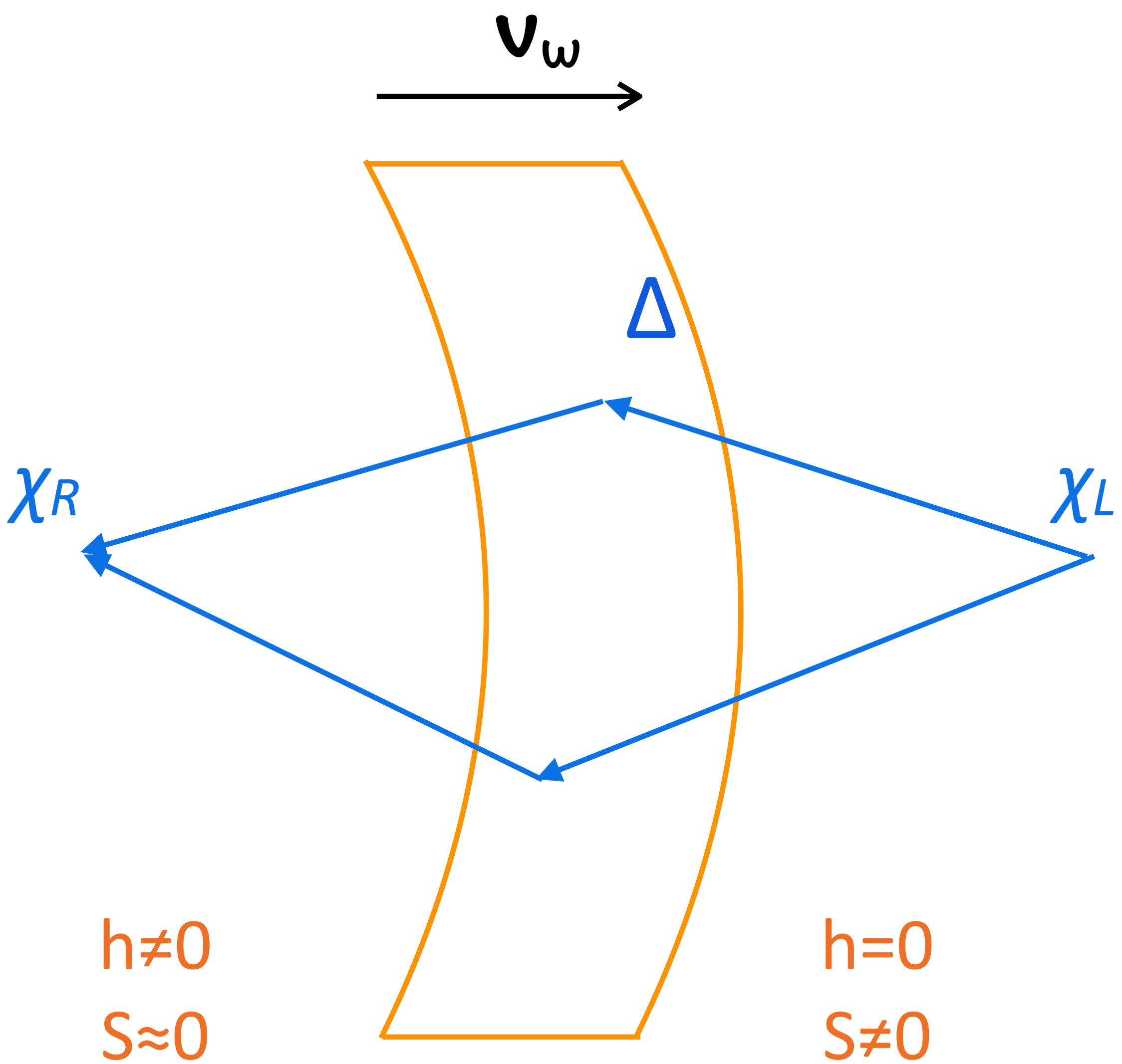
Symmetry Breaking History

$U(1)_\ell$ is first spontaneously broken above the EW scale by Φ.

- Condensate of Φ makes L', R', e_R', e_L'' heavy, integrated out, but leaves χ_L, χ_R light due to smaller Yukawa coupling.
- Also leaves Z' light with a small gauge coupling g'.
- $U(1)_\ell$ is anomalous w.r.t. $SU(2)_L$ for the remaining fermions.
- Remarkably, χ_L, χ_R carry different $U(1)_\ell$ changes by construction.

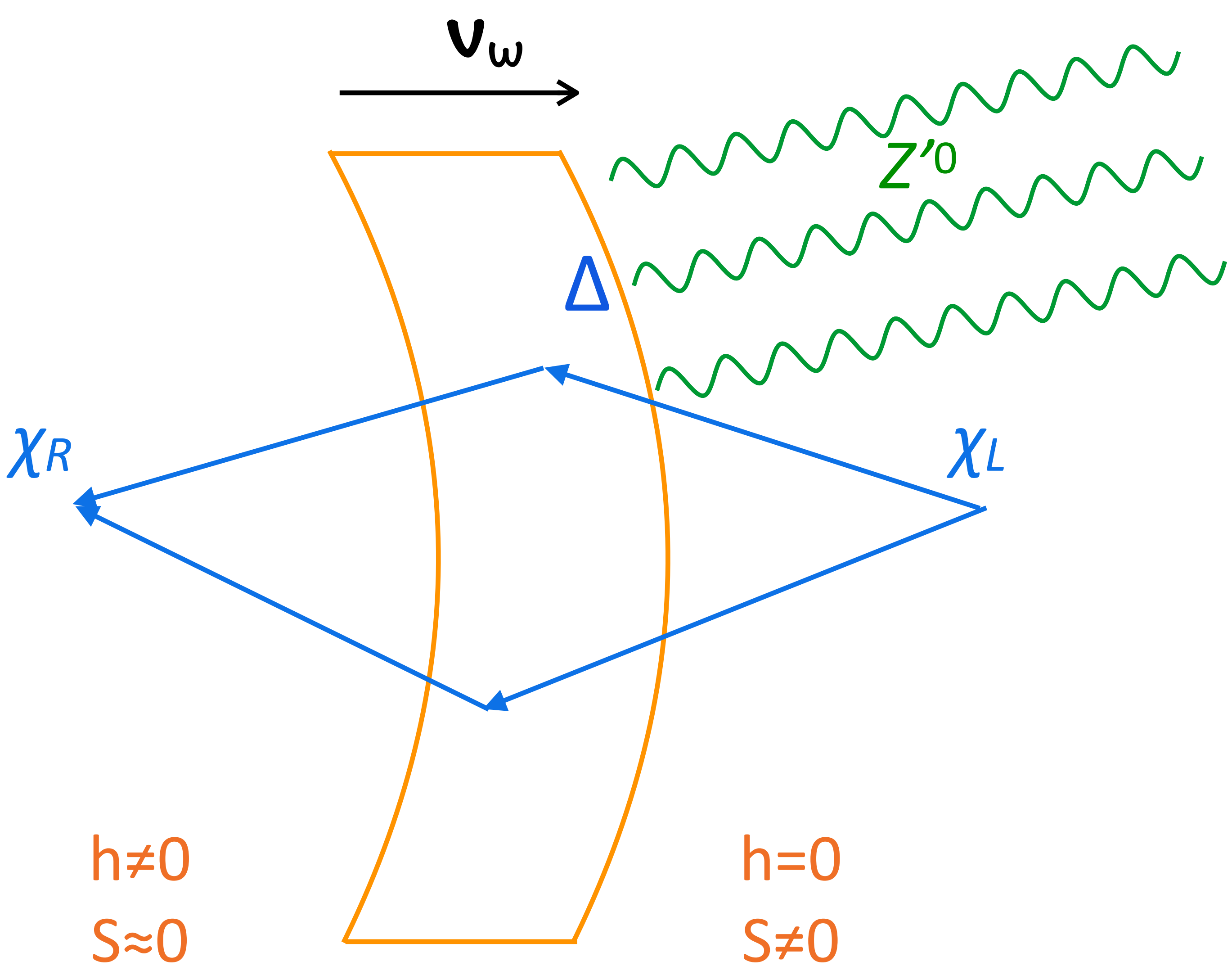
Around EW scale, interaction between the extra scalar S and Higgs field triggers a strong first order EW phase transition.

The New Baryogenesis Picture



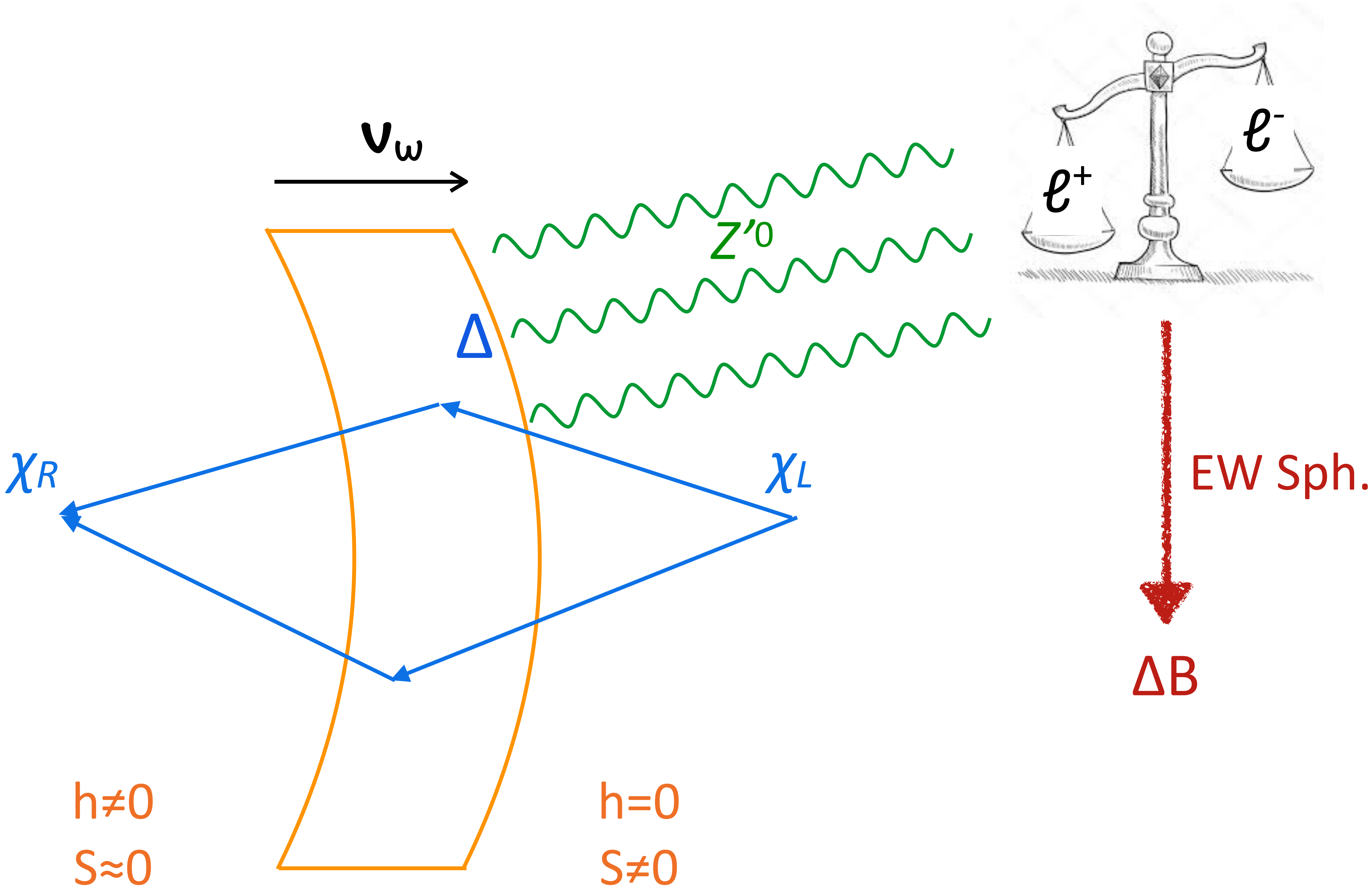
Carena, Quirós, **YZ**, 1811.09719, PRL

The New Baryogenesis Picture



Carena, Quirós, **YZ**, 1811.09719, PRL

The New Baryogenesis Picture



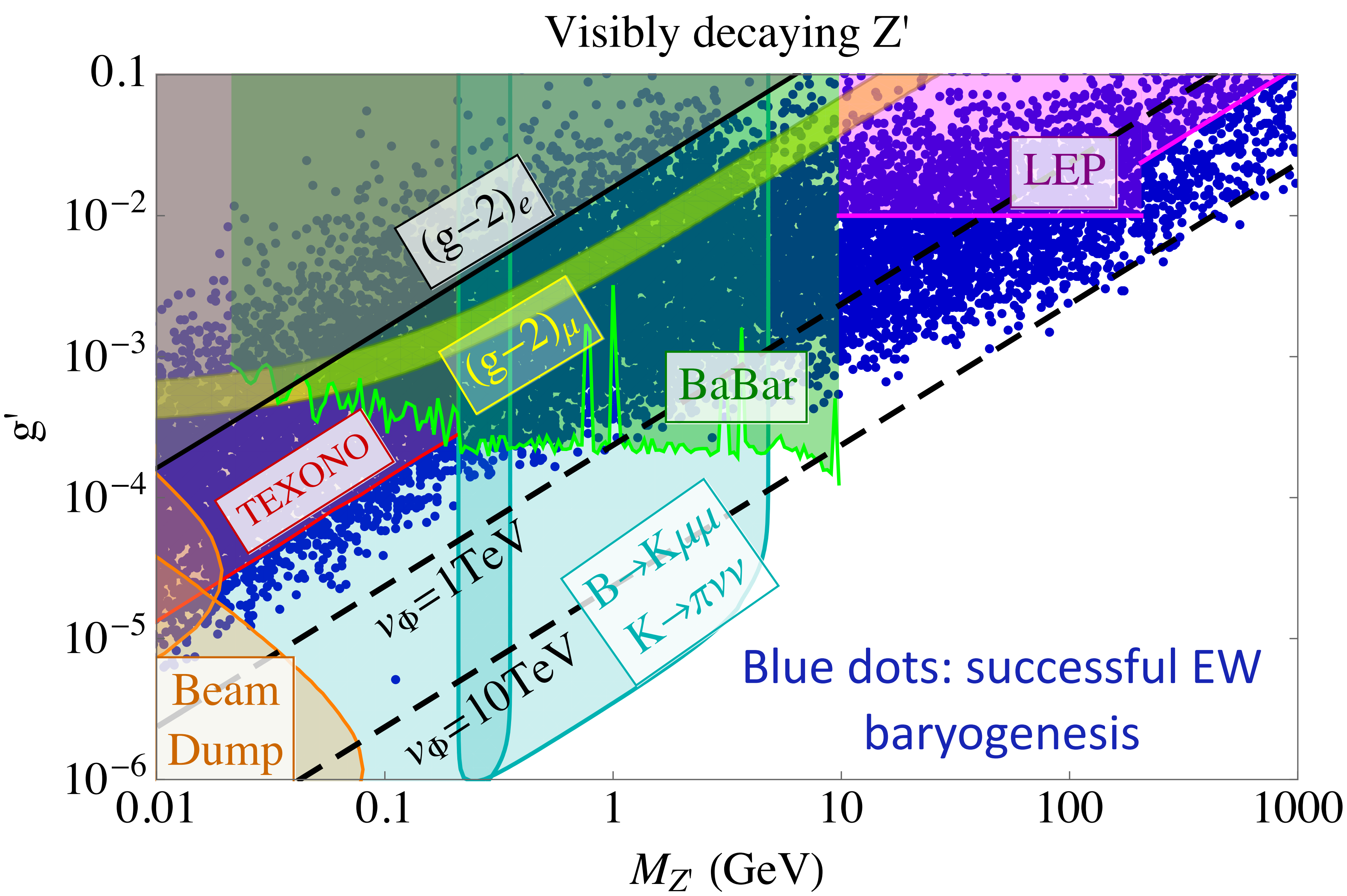
Carena, Quirós, **YZ**, 1811.09719, PRL

Phenomenological Implications

This model has a number of attractive predictions.

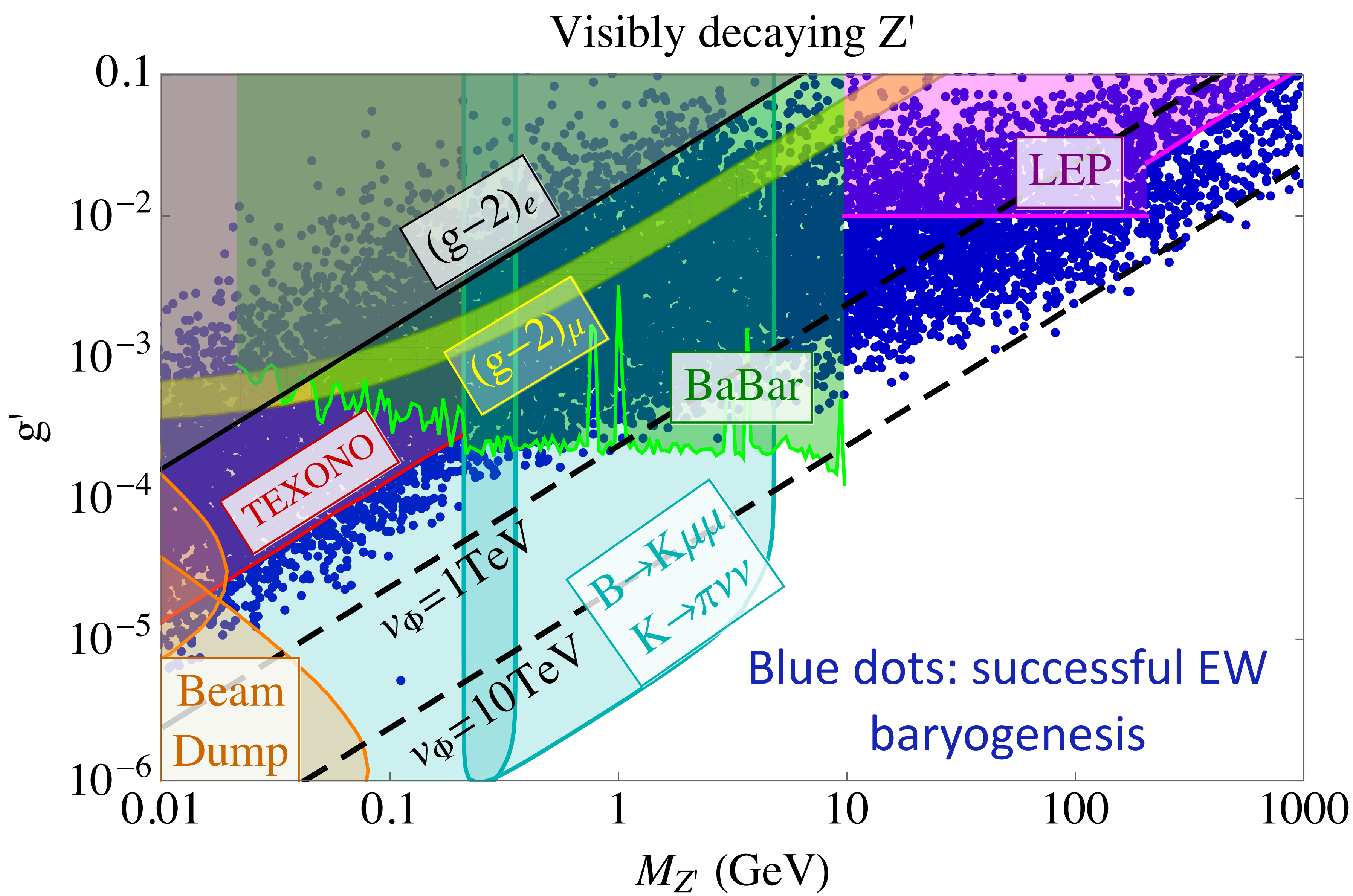
- Predicts the existence of a new force carrier Z', leptophilic. Offers a great motivations for new Z' (dark photon) searches.
- Predicts very small electric dipole moments.
- The χ particle in this model qualifies to be a thermal dark matter candidate.
- Predicts a new Higgs portal scalar S, which could mainly decay into Z's.

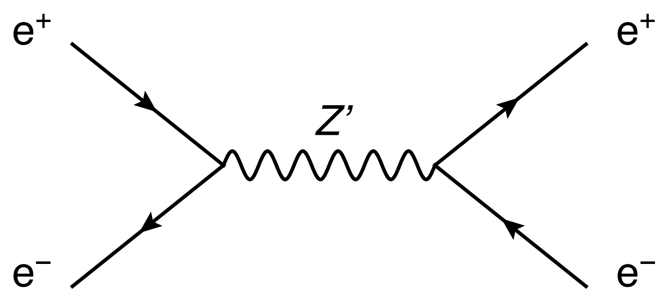
Leptophilic Z’: Target and Searches



Carena, Quirós, **YZ**, 1811.09719, PRL, 1908.04818, PRD

Leptophilic *Z'*: Target and Searches

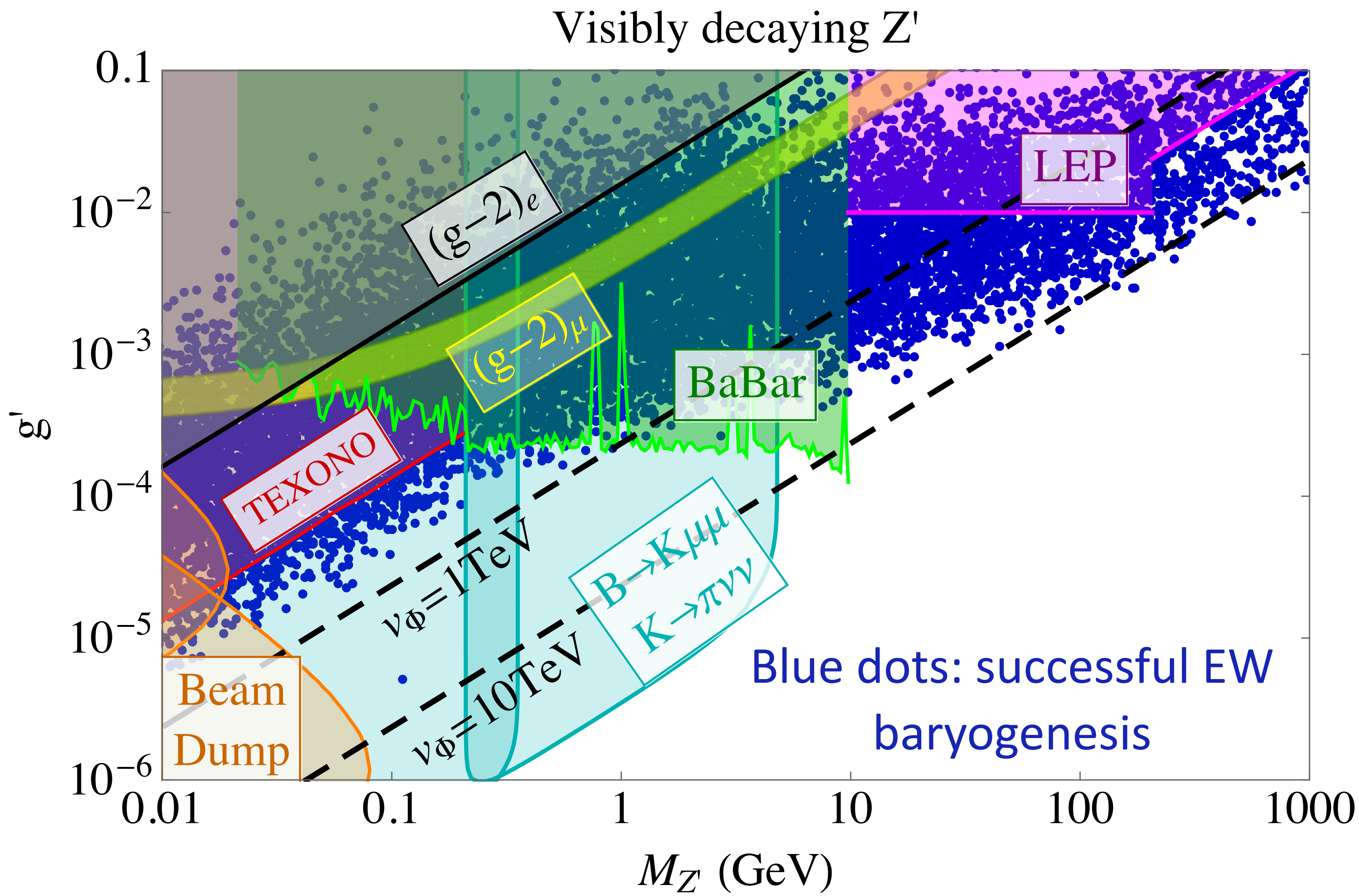


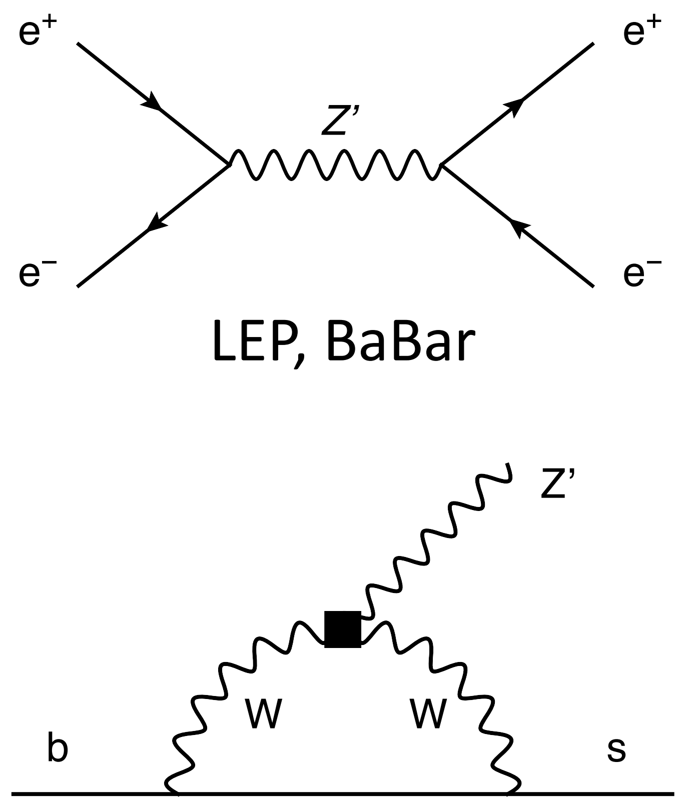


LEP, BaBar

Carena, Quirós, **YZ**, 1811.09719, PRL, 1908.04818, PRD

Leptophilic Z': Target and Searches



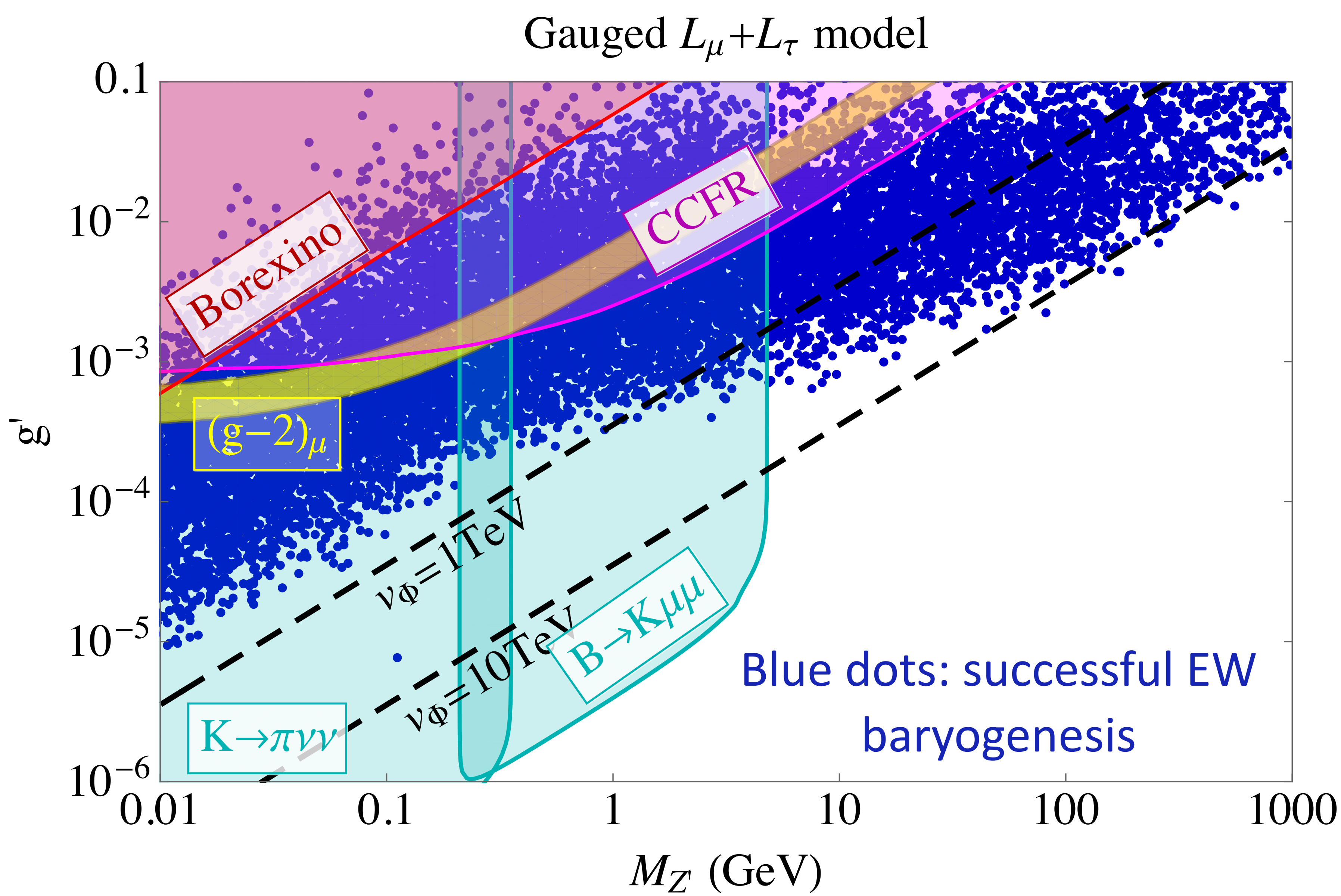


LEP, BaBar

Dror, Lasenby, Pospelov (1705.06726, 1707.01503)

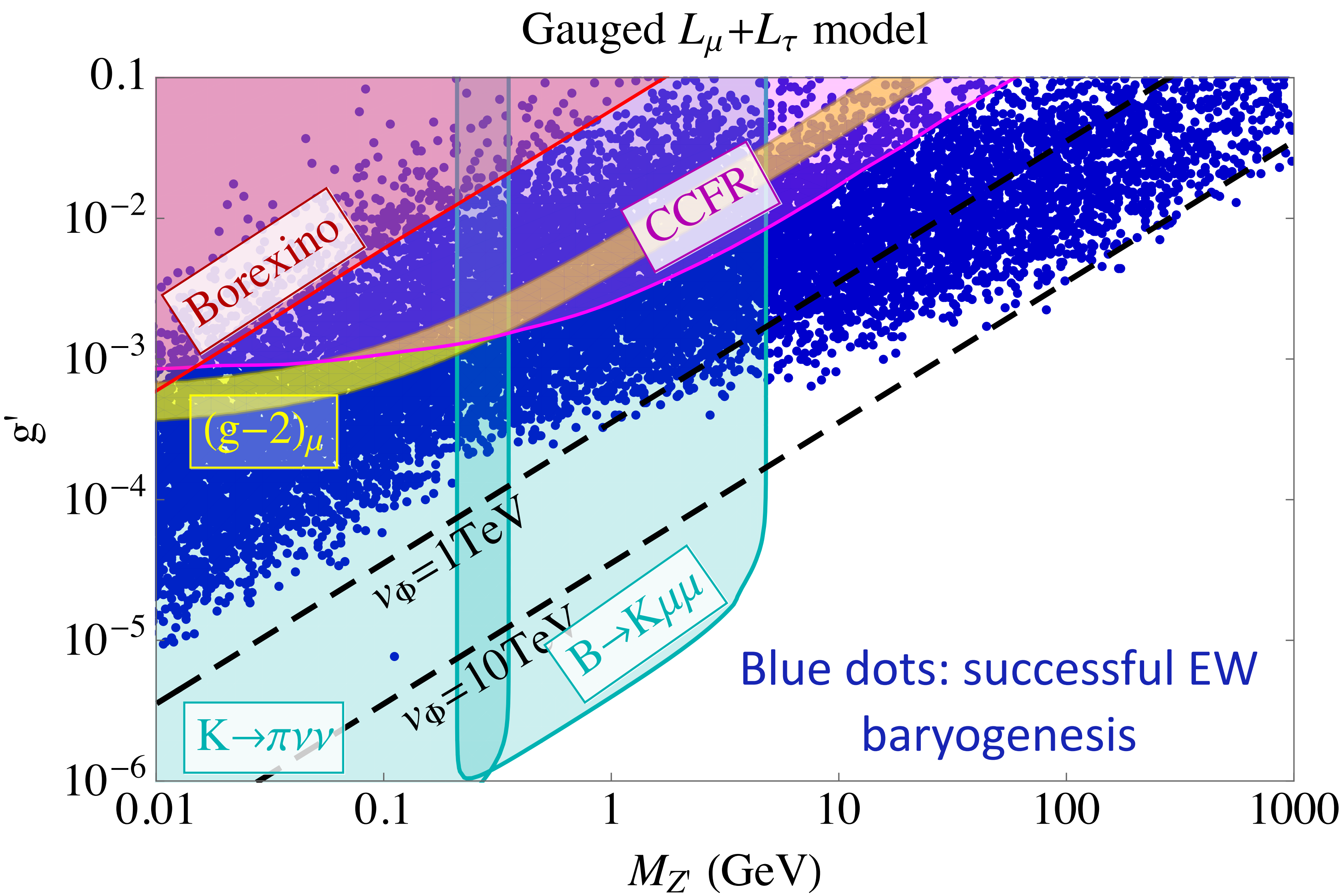
Carena, Quirós, **YZ**, 1811.09719, PRL, 1908.04818, PRD

Gauge Two Lepton Generations

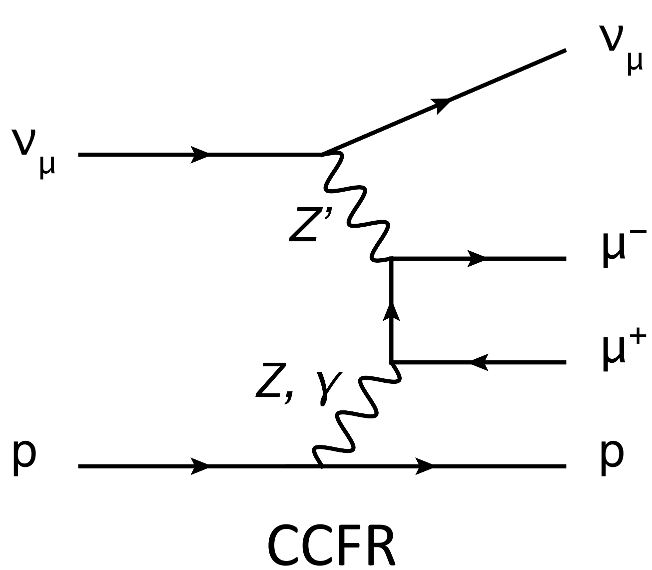


Carena, Quirós, **YZ**, 1811.09719, PRL, 1908.04818, PRD

Gauge Two Lepton Generations

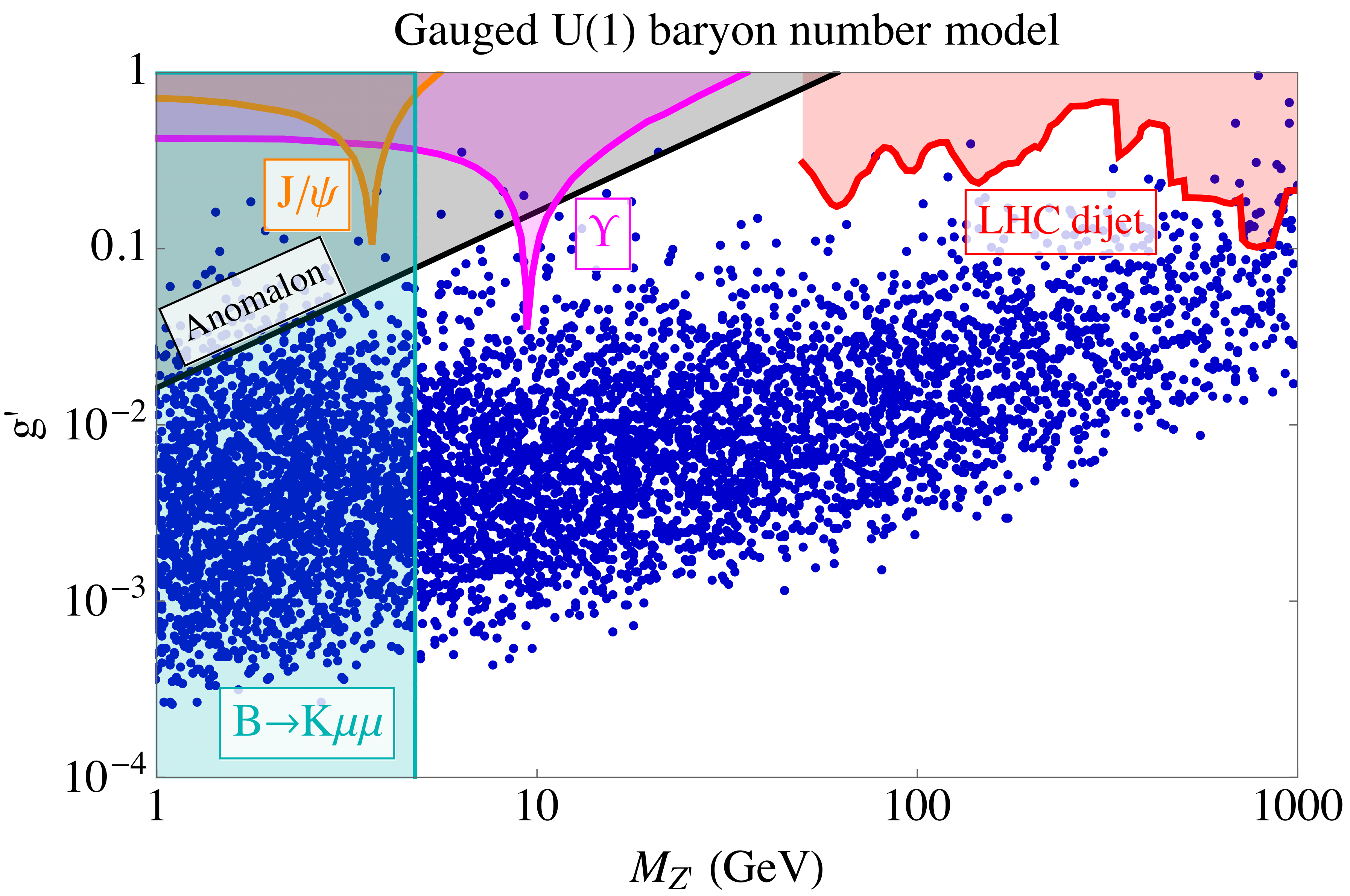


Blue dots: successful EW baryogenesis



Carena, Quirós, **YZ**, 1811.09719, PRL, 1908.04818, PRD

Gauge Baryon Number



Carena, Quirós, **YZ**, 1811.09719, PRL, 1908.04818, PRD

Conclusion

The new physics we will discover next may be connected to the origin of baryon asymmetry in the universe.

Electroweak baryogenesis requires new CP violation near the weak scale. New ACME II result challenges many models.

I present a new idea that makes EW baryogenesis viable where CP violation first occurs in the dark sector, and is transferred to the visible sector in early universe through a new *Z′* force.

Motivate *Z′* searches with anomalous low-energy couplings; predict highly suppressed EDMs.

Thanks!

Stay safe!