CP and Flavour beyond the Standard Model & Cosmology

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Three good reasons why we need New Physics beyond the Standard Model of particle physics

- The so-called "Hierarchy problem": how to stabilize the Higgs mass $m_H \sim 10^{-16} M_{\text{Planck}}$
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- Baryogenesis: how to generate a matter-antimatter asymmetry $\frac{n_B}{n_\gamma} \sim \frac{n_N - n_{\overline{N}}}{n_N} \sim 10^{-10}$
- (in the absence of an asymmetry, we would get : $\frac{n_N}{n_\gamma} = \frac{n_{\overline{N}}}{n_\gamma} \sim 10^{-19}$)
- What makes the "dark matter" $\Omega_{\text{DM}} \sim 83\% \; \Omega_{\text{M}}$

but also:

Dark energy, the flavor puzzle, neutrino masses, strong CP problem, gauge coupling unification

The 3 Sakharov criteria to generate a matter-antimatter asymmetry in the universe

Sakharov '1967

- Baryon number violation

  If B is conserved, the present baryon asymmetry can only reflect (highly fine-tuned) asymmetric initial conditions

- C and CP violation

  C: charge conjugation; CP: charge conjugation × parity

  There must be a preference for matter or antimatter, otherwise, baryon and antibaryon excesses are produced at the same rate

- Departure from thermal equilibrium

  At thermal equilibrium, the system relaxes to maximize its entropy, i.e. towards the state of vanishing chemical potential for baryon number

More on the "C and CP violation" condition

Start with an equal number of X and $\overline{X}$:

$$X \longrightarrow uu \qquad \Delta B = 2/3 \qquad \text{branching ratio} = r$$

$$X \longrightarrow e^+ \overline{d} \qquad \Delta B = -1/3 \qquad \text{branching ratio} = 1-r$$

$$\overline{X} \longrightarrow \overline{uu} \qquad \Delta B = -2/3 \qquad \text{branching ratio} = \overline{r}$$

$$\overline{X} \longrightarrow e^- d \qquad \Delta B = 1/3 \qquad \text{branching ratio} = 1-\overline{r}$$

The net baryon number produced in the decays of X and $\overline{X}$ is

r(2/3)+(1-r)(-1/3) + (-2/3)+(1-$\overline{r}$)(1/3)= r - $\overline{r}$

If C or CP is conserved : r = $\overline{r}$

C and CP act on Dirac spinors as: $\psi \xrightarrow{C} C\overline{\psi}^T$, $\psi \xrightarrow{P} \gamma^0 \psi$

$$B \sim \psi^\dagger \psi \xrightarrow{C} \overline{\psi}^{T\dagger} C^\dagger C \overline{\psi}^T = -\psi^\dagger \psi \qquad \psi^\dagger \psi \xrightarrow{CP} -\psi^\dagger \psi$$

If C and CP are conserved, B=0. If the universe is initially in an eigen state of C and CP, it remains in this state if [H,C]= [H,CP]=0 . To generate B≠0, it is necessary to violate both C and CP.

More on the "out-of-equilibrium "condition

If no further baryon-violating reactions (e.g. no back-reactions), a net baryon asymmetry persists after X and $\overline{X}$ decays

Absence of back reaction $\Longrightarrow$ Out of equilibrium condition

In other words, the thermal average of B vanishes: (assuming CPT)

$$\begin{aligned}\langle B\rangle_T &= \mathrm{Tr}\,(e^{-\beta H}B) = \mathrm{Tr}\,[(CPT)(CPT)^{-1}e^{-\beta H}B)] \\ &= \mathrm{Tr}\,(e^{-\beta H}(CPT)^{-1}B(CPT)] = -\mathrm{Tr}\,(e^{-\beta H}B)\end{aligned}$$

Electroweak baryogenesis

A beautiful mechanism to generate the matter-antimatter asymmetry of the universe involving electroweak (EW) physics only:

- *B is violated at high temperature in the SM*
- *C and CP are violated in the SM*
- *Out-of-equilibrium dynamics at the EW phase transition*

Cohen-Kaplan-Nelson '90

Electroweak baryogenesis :

A beautiful mechanism to generate the matter-antimatter asymmetry of the universe involving EW physics only.

CP violation at phase interface, responsible for mechanism of charge separation

(CP violation)

$$\Gamma \propto \alpha_W^5 T^4$$

Very active sphalerons
(C & B violation)

Convert chiral asymmetry into baryon asymmetry

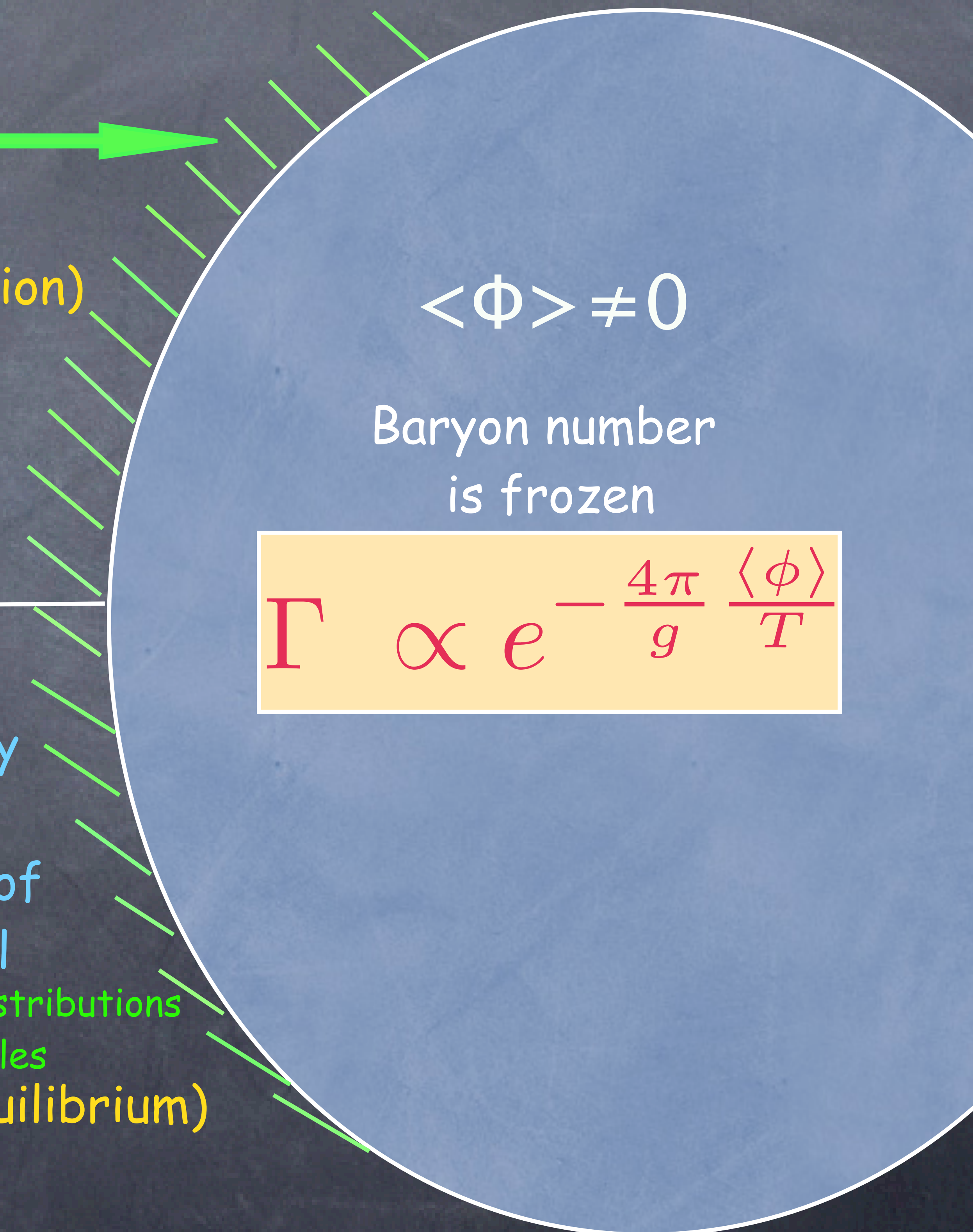
$$\frac{dn_B}{dt} \propto n_L$$

left-handed fermions

v

Chirality Flux in front of the wall

NON thermal distributions of particles
(Out-of-equilibrium)



Size of CP-violating effects

In the SM, the only source of CP violation is the Kobayashi-Maskawa phase

$$\epsilon_{\rm CP} \sim \frac{J_{\rm CP}}{T_c^2}(m_t^2-m_u^2)(m_t^2-m_c^2)(m_c^2-m_u^2)(m_b^2-m_s^2)(m_b^2-m_d^2)(m_s^2-m_d^2) \sim 10^{-19}$$

where $T_c \sim 100$ GeV

Had quark masses been heavier, the Kobayashi-Maskawa phase could be the only source of CP violation playing a role in baryogenesis

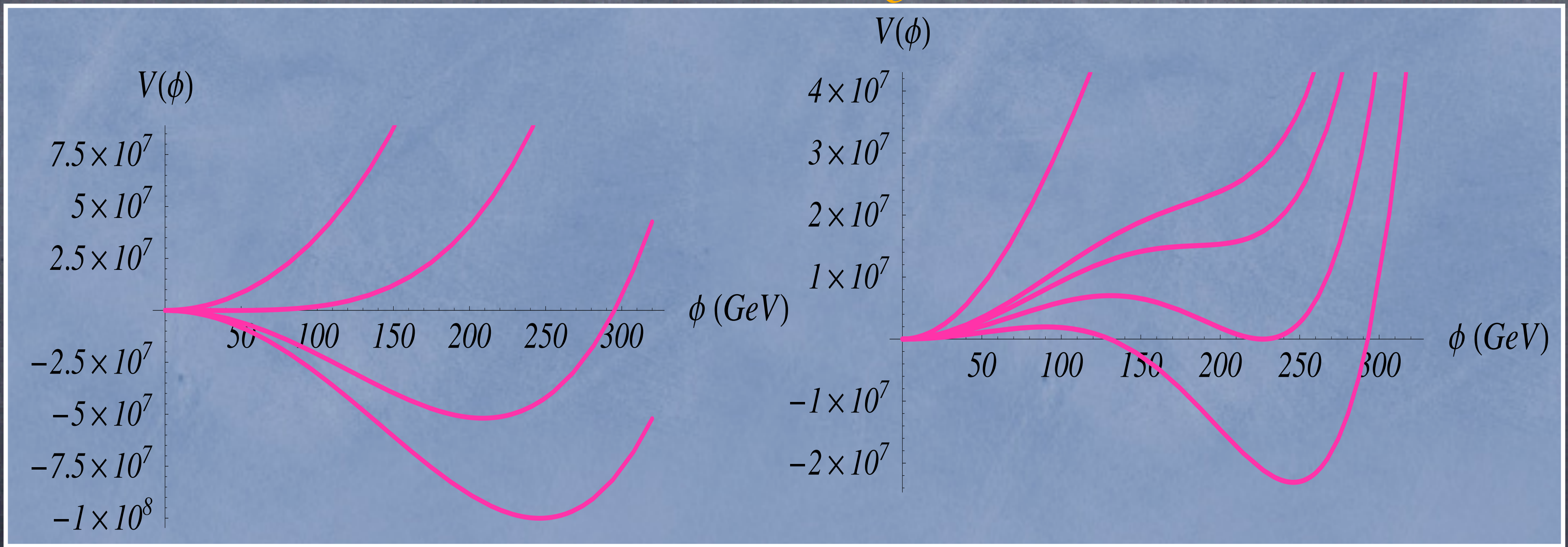
see recent proposal for time-variation of Yukawa couplings
Berkhooz-Nir-Volansky '04

Second reason why EW baryogenesis fails in the Standard Model:

The electroweak phase transition is not first order.
Using the standard mexican hat scalar potential for the Higgs,
the phase transition is 1rst order only if $M_H < 72$ GeV

However, it is easy to modify the Higgs sector in such a way that
the EW phase transition becomes first order.

Second order versus first order :

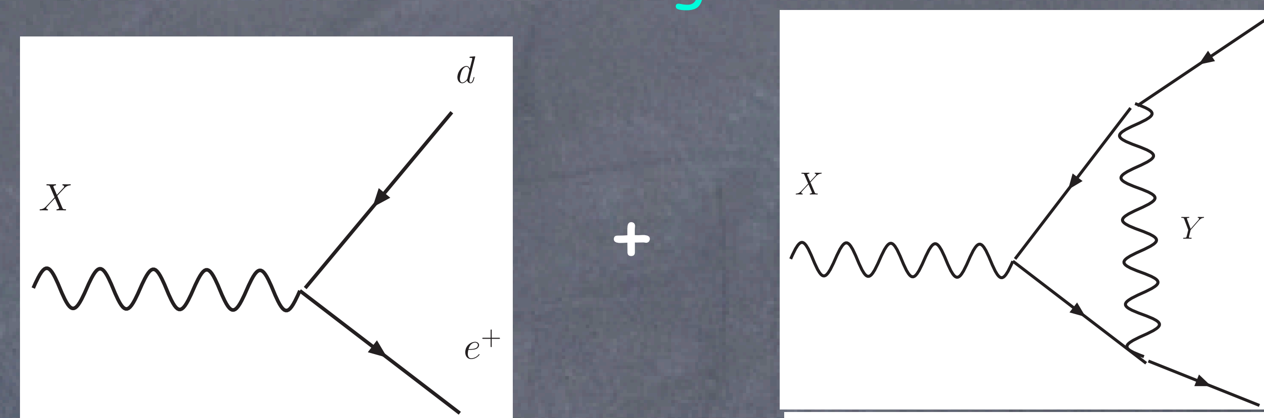


We presently have no clue on the nature of the Higgs potential.
LHC will help shedding light on the nature of the EW phase transition.

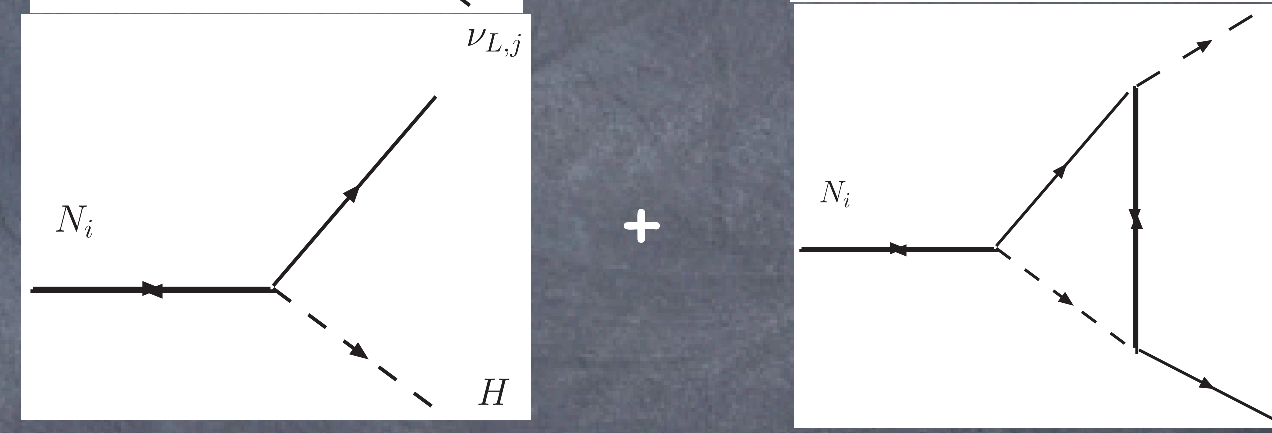
Other famous baryogenesis mechanisms:

via heavy particle decays which are ✔ out-of-equilibrium,
✔ B (or L)-violating,
✔ CP-violating

- GUT baryogenesis



- Leptogenesis



CP-violation comes from the interference between the tree level and 1-loop diagrams

In the last few years , a lot of experimental and theoretical activity in neutrino physics.
Leptogenesis has become a favourite scenario for bayogenesis.

$\Rightarrow$ *Revival of Leptogenesis*

A minimal extension of the Standard Model:

The simplest extension capable of generating non vanishing neutrino masses is to add one right-handed neutrino per generation

Dirac neutrino mass matrix

right-handed Majorana neutrino mass matrix

charged lepton mass matrix

$$\mathcal{L}_m = -\left[\overline{\nu}_L^0 m_D \nu_R^0 + \frac{1}{2}\nu_R^{0T} C M_R \nu_R^0 + \overline{\ell}_L^0 m_\ell \ell_R^0\right] + \text{H.c.}$$
$$= -\left[\frac{1}{2} n_L^T C \mathcal{M}^* n_L + \overline{\ell}_L^0 m_\ell \ell_R^0\right] + \text{H.c.},$$

$$n_L = (\nu_L^0, (\nu_R^0)^c)$$

Neutrino mass matrix

$$V = \begin{pmatrix} K & Q \\ S & T \end{pmatrix}, \quad \mathcal{D} = \begin{pmatrix} d_\nu & 0 \\ 0 & D_R \end{pmatrix}, \quad \mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

$$V^T \mathcal{M}^* V = \mathcal{D},$$

See-Saw formula:

$$d_\nu \simeq -K^\dagger m_D M_R^{-1} m_D^T K^* \equiv K^\dagger \mathcal{M}_\nu K^* \quad \longrightarrow m_\nu \sim \frac{M_W^2}{M_R}$$

In the lepton flavor parameters, there are now three phases

Leptogenesis from CP asymmetries in heavy Majorana Neutrino Decays

CP asymmetry $$\varepsilon_j = \frac{\Gamma(N_j \to \ell\,\phi) - \Gamma(N_j \to \bar{\ell}\,\phi^\dagger)}{\Gamma(N_j \to \ell\,\phi) + \Gamma(N_j \to \bar{\ell}\,\phi^\dagger)} \propto \sum_{k \neq j} Im[(m_D^\dagger m_D)^2_{jk}]$$

only sensitive to CP violating phases appearing in m_D

Unfortunately, it is difficult to test as one can hardly extract information on the phases relevant to leptogenesis from low energy CP violation (as measured in neutrino oscillations)

In any case, even if leptogenesis is the answer to the baryon asymmetry puzzle, there is still strong motivation to search for CP violation in experiments

Indeed, present and near future measurements have a strong impact on theoretical understanding of New Physics and model building at the TeV scale...

The "new physics flavor problem"

To prevent the Higgs mass from getting a large radiative correction, new degrees of freedom are needed at the scale $\Lambda \sim \mathrm{TeV}$

However, those tend to spoil the successful fit of the SM to EW precision measurements and various measurements related to flavour (CP not really a pb)

In particular, any generic new physics model will introduce effective flavor-changing Fermi operators of the form $\frac{q_1\overline{q}_2 q_3\overline{q_4}}{\Lambda^2}$

Measurements of meson mixing and CP violation put severe constraints on Λ

K physics gives strongest bound: $\frac{s\bar{d}s\bar{d}}{\Lambda^2} \Rightarrow \Lambda > 10^4\mathrm{TeV}$

There is a tension between the new physics scale required to solve the hierarchy problem and the one needed not to contradict the flavor bounds

While the Standard Model scalar sector is unnatural, its flavour sector is impressively successful. This success is linked to the fact that the SM flavor structure is special:

- Charged current interactions are universal
- Flavor Changing Neutral Currents are highly suppressed

Any extension of the SM must conserve these successful features.

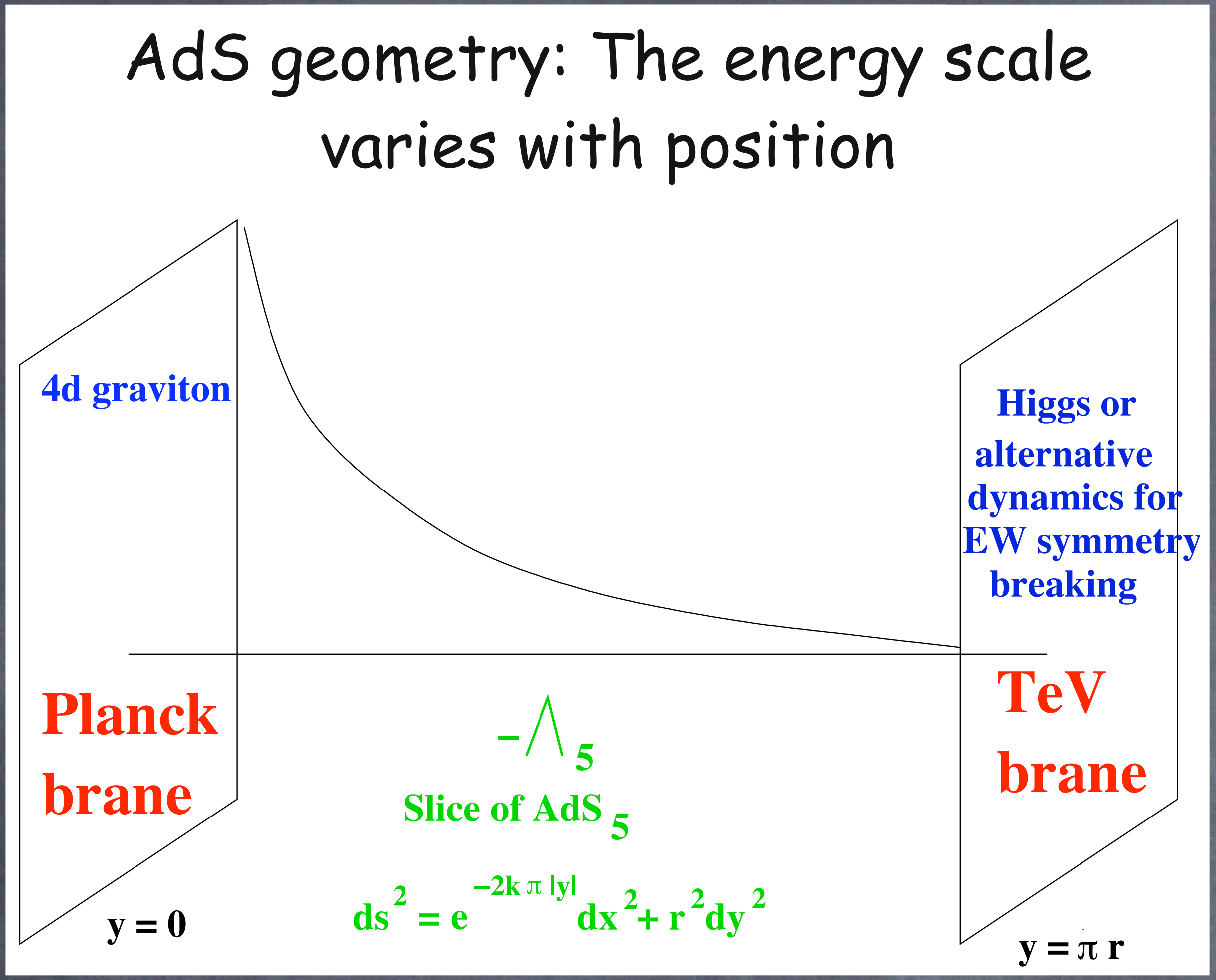
There are several solutions:

✔ Minimal flavor violation i.e. flavor violation related to Yukawa couplings only

✔ Flavor suppression mainly in first two generations

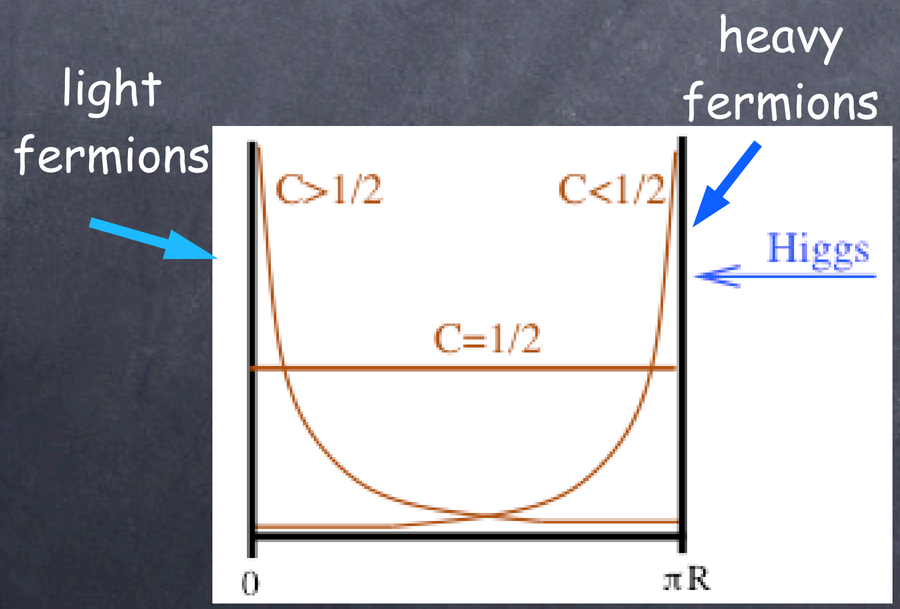
✔ New flavor physics mainly in the up sector

An extra-dimensional example: Bulk fermions in the Randall-Sundrum model



A solution to the hierarchy problem without supersymmetry

$$\Rightarrow \quad M_{\rm EW} \sim M_{\rm Pl} e^{-k\pi r}$$



Fermion masses depend on their location in the extra dimension.

The supersymmetric extension of the Standard Model contains 43 new phases!

$$W = \sum_{i,j} \left(Y^u_{ij} H_u Q_{Li} \overline{U}_{Lj} + Y^d_{ij} H_d Q_{Li} \overline{D}_{Lj} + Y^\ell_{ij} H_d L_{Li} \overline{E}_{Lj} \right) + \mu H_u H_d .$$

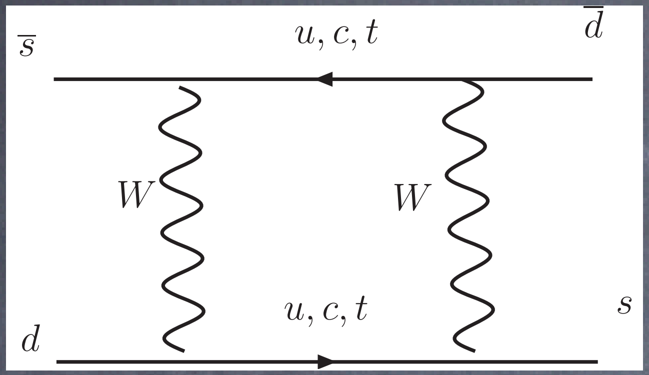
Soft supersymmetry breaking terms

$$\mathcal{L}_{\rm soft} = - \left(A^u_{ij} H_u \tilde{Q}_{Li} \tilde{\overline{U}}_{Lj} + A^d_{ij} H_d \tilde{Q}_{Li} \tilde{\overline{D}}_{Lj} + A^\ell_{ij} H_d \tilde{L}_{Li} \tilde{\overline{E}}_{Lj} + B H_u H_d + {\rm h.c.} \right)$$

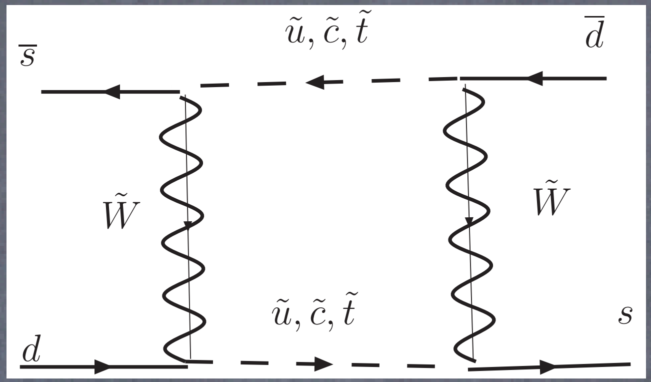
$$- \sum_{\rm all \;\; scalars} (m^2_S)_{ij} A_i \bar{A}_j - \frac{1}{2} \sum_{(a)=1}^{3} \left(\tilde{m}_{(a)} (\lambda\lambda)_{(a)} + {\rm h.c.} \right) .$$

Supersymmetric CP violation

Standard model diagram for K system



Supersymmetric diagram



measurements of flavor changing and CP violating processes lead to very constrained structure of the soft supersymmetry breaking terms and provide clues on how supersymmetry breaks

Conclusion

The main goal of high energy physics is to find the theory that extends the Standard Model into shorter distances.
Flavor and CP physics are very good tools for such a mission

CP violation plays a crucial role both in understanding New Particle Physics beyond the SM and in cosmology

More data is needed to look further for fundamental physics using low energy flavor-changing processes.