An adventure from Darwin's two-page note —- a reminiscence of Prof. Darwin Chang

19th Spring School, CYCU

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- Many thanks to Prof. Chien-Er Lee who initiated the Taiwan Spring School on Particles and Fields in 1986.
- This series of annual school has been providing the Taiwanese HEP community a great chance to meet and learn form experts all over the world and an important ground for the local people to meet each other.
- When I was a student, I benefited a lot from attending the school. And I believe which is also true for many other present or former students.

- Today, I am very glad to have the honor to contribute a presentation to this great tradition. On the other hand, I am also very sad. The main reason I am here because the school organizer wants me to say something about the works I have done with Prof. Darwin Chang. Darwin, our dear friend, passed away because of cancer in last Dec.

14th spring school Mar. 20, 2000 Tsing-Hua

- **The Darwin's way**
  Many of you know that Darwin was my former thesis advisor. Maybe some of you would be curious how Darwin interacted with his students.
- **An Introduction to CP violation and EDM**
  CP violation is one of Darwin's favorite research topics. And since this is a school, I am supposed to provide some materials (and homework?) for the students.
- **The Adventure**
  I will briefly mention some works I have done with Darwin which can be traced back to a 2-page note.
- **Final Words**

Begin of the story:

- On Sep. 23, 1998, I received an e-mail from Darwin asking me to Xerox some papers for him and come to his office to discuss. It was very typical, he liked to communicate and to give order by e-mails.
- The e-mail reads:

Can you copy the published version of
Abel and Frere: hep-ph/9608251 Phys.Rev. D55 (1997) 1623-1629
Falk and Olive hep-ph/9602299 Phys.Lett. B375 (1996) 196-202
I have Ellis and Flore..
Talk to me in the morning. I have to go to NCHU after 12noon.
Darwin

---------- Forwarded message ----------
Date: Wed, 23 Sep 1998 07:59:29 +0800 (CST)
From: "[amadeus on the run]" <chang@phys.nthu.edu.tw>
To: wai-yee <keung@tigger.cc.uic.edu>,
hsin-chia cheng <hcheng@fnal.gov>
Cc: "[amadeus on the run]" <chang@phys.nthu.edu.tw>,
"Chang: We-Fu" <d847305@phys.nthu.edu.tw>
Subject: susy CPX

Dear Yee, and Hsin-Chia,
On the flight back to Taiwan, I happens to read a paper that I collect
but never read by
Abel and Frere: hep-ph/9608251 Phys.Rev. D55 (1997) 1623-1629
they asked exactly the question I proposed to ask: <u>What if CKM pha</u>
<u>very small in SUSY model...</u>
Surprisingly, their answer differs ours.
(1)First of all, they argues that the edm constraint on phase \phi_A i
weaker than \phi_B quoting
Falk and Olive hep-ph/9602299 Phys.Lett. B375 (1996) 196-202

(2)Then they argue that \phi_A contribution in the box diagram is the
minimal model.
(3)Then they go ahead and investigate some non-minimal model.

Earlier, in our discussion, we were actually concentrating on the \phi_B
contribution because we were thinking of imposing the symmmetry on dim=3
terms such that A will be automatically zero.

I think what we need to do is
(1)Investigate how solid is the limit on \phi_B from edm. It seems to be
that
Ellis and Flore Phys.Lett. B377 (1996) 83
argued previous constraint on edm should be relaxed because
(i)Our current understanding of neutron spin implies that quark model
maynot be reliable estimate for spin related quantities.
(ii)There may be large strange quark content in neutron.
(iii)there may be cancellation between u, d and s contribution to neutron
edm.

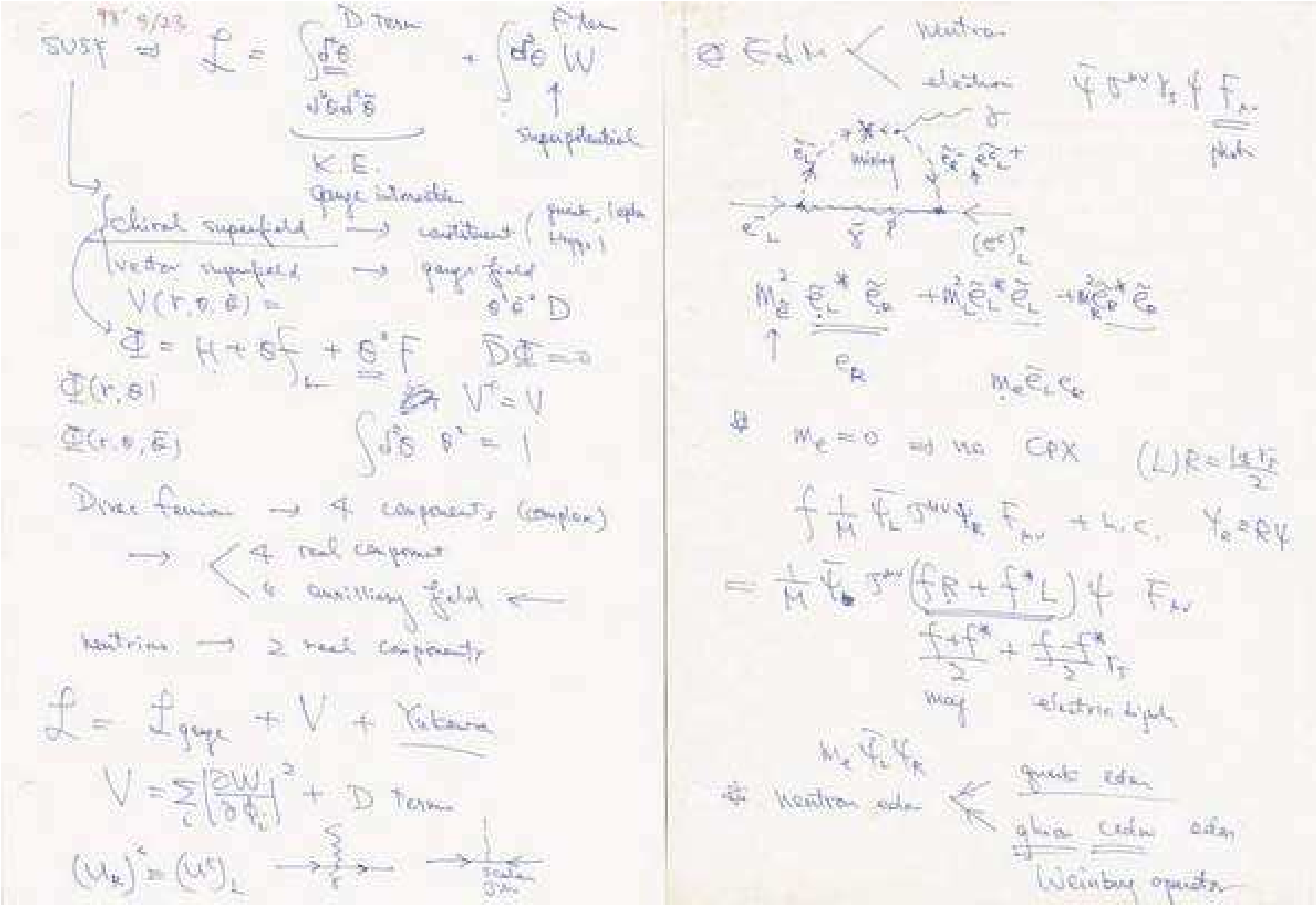
(2)Sit down and seriously work out the graph using \phi_B. There may be
cancellation in \phi_B contruibution similar to that involving \phi_A
pointed out by Abel/Frere too.... Abel/Frere didnot realized the top
enhencement effect that we talked about.

We may have a point to write if \phi_B can give large enough \epsilon.

Darwin

- At that time, the only supersymmetry I knew was at the popular science level.
  I had no idea what ϕ_A and ϕ_B are in Darwin's e-mail.
  And the electric dipole moment calculation was a totally new subject to me.
- After receiving that e-mail, I tried very hard to get myself familiar to the subjects without much progress.
  Apparently, the references he mentioned were too advanced for a beginner.
- So one night I came to talk with Darwin in his office at around 10 or 11 pm.
  (“Why is it so late?" you may ask.
  Well, because that's the normal time he was available to students.)
  And I complained to him that my knowledge on the proposed project is next to zero.
- He told me that's OK and started writing some things quickly (in a Huge font size!) on the paper to explain the things he thought is essential to me.
- It went on for about 30 mins or less. And he told me to start doing it, gave me tow pieces of paper, and waved me out of his office.

Here is the two-page note I refer to:



98' 5/23

SUSY ⇒ $\mathcal{L} = \int d^4\theta \; + \int d^2\theta\, W$

D term, F term

$d^2\theta d^2\bar\theta$, superpotential

K.E.

gauge interaction

chiral superfield → constituent (quark, lepton, Higgs)

vector superfield → gauge field

$V(x,\theta,\bar\theta) = \quad \theta^2\bar\theta^2 D$

$\Phi = H + \theta f_L + \theta^2 F \qquad \bar D \Phi = 0$

$\Phi(x,\theta) \qquad V^\dagger = V$

$\bar\Phi(x,\theta,\bar\theta) \qquad \int d^2\theta\, \theta^2 = 1$

Dirac fermion → 4 components (complex)

→ < 4 real component, 4 auxiliary field ←

neutrino → 2 real components

$\mathcal{L} = \mathcal{L}_{gauge} + V +$ Yukawa

$V = \sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2 +$ D term

$(M_R)^2 = (M^2)_L$ scale 3 TeV

e EDM < neutron, electron $\quad \bar\psi\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$ photon

$\tilde e_L$, mixing, $\tilde e_R$, $\tilde e_L^{c+}$, γ

$e_L \quad \tilde\gamma \quad (e^c)^\dagger_L$

$M_{\tilde e}^2\, \tilde e_L^*\, \tilde e_R + m_L^2\, \tilde e_L^*\tilde e_L + m_R^2\, \tilde e_R^*\tilde e_R$

$e_R \qquad m_e \bar e_L e_R$

$m_e = 0 \Rightarrow$ no CPX $\qquad (L)R = \frac{1\pm\gamma_5}{2}$

$f\frac{1}{M}\bar\psi_L\sigma^{\mu\nu}\psi_R F_{\mu\nu} + h.c. \qquad \psi_R = R\psi$

$= \frac{1}{M}\bar\psi\sigma^{\mu\nu}(fR + f^*L)\psi F_{\mu\nu}$

$\frac{f+f^*}{2} + \frac{f-f^*}{2}\gamma_5$

mag, electric dipole

$m_e\bar\psi_L\psi_R$

neutron edm < quark edm, gluon color edm

Weinberg operator

And here is its back :


cond-mat/9511085 16 Nov 1995

Submitted to Int. J. of Mod. Phys.

Spectral Anomaly and High Temperature Superconductors

Contents

Few comments:

- The project he proposed turned out to be abandoned because of this and that reasons.
  (In fact, almost every month he would think of a new idea for us students to try.
  And he usually completely forgot we were still struggling with the previous project.
  So it's also possible that Darwin simply forgot its existence.)
- From today's view, his note is too sketchy.
  Also, I think it's fair to say that it's not useful at all for doing that project.
- Anyway, I learnt SUSY by studying some books and review articles by myself later.
  The note became an existing proof of that night's meeting.
- In 1999, only when Wai-Yee, Darwin's long time friend and collaborator, came to visit Tsing-Hua, then I learnt the practical technics from him to carry out the two-loop EDM calculation.
- Darwin wanted me to extend their previous work on 2-loop EDM in MSSM calculation to include the charged Higgs contribution.

A side remark:

- About one year earlier, Darwin, Wai-Yee, and A. Pilaftsis published a Phys.Rev.Lett. on the 2-loop Barr-Zee EDM in MSSM.

NEW TWO LOOP CONTRIBUTION TO ELECTRIC DIPOLE MOMENT IN SUPERSYMMETRIC THEORIES.
By Darwin Chang (Taiwan, Natl. Tsing Hua U. & Fermilab), Wai-Yee Keung (Illinois U., Chicago & Fermilab), Apostolos Pilaftsis (CERN & Fermilab),. CERN-TH-98-343, FERMILAB-PUB-98-347-T, UICHEP-TH-98-12, Oct 1998. 11pp.
Published in **Phys.Rev.Lett.82:900-903,1999, Erratum-ibid.83:3972,1999**
e-Print Archive: **hep-ph/9811202**

TOPCITE = 100+
References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 182 times
Abstract and Postscript and PDF from arXiv.org (mirrors: au br cn de es fr il in it jp kr ru tw uk za aps lanl)
ADS Abstract Service
CERN Library Record
Fermilab Library Server (fulltext available)
Phys. Rev. Lett. Server

Among Darwin's scientific publication, this happens to be the highest cited one.

- Although I have got used to head for a new research field and to pick up everything from zero. Seven years ago, Darwin's suggestion on doing this project to me was as going for an adventure. Because it's all dark at the beginning. Now I can better appreciate Darwin's training.
- He knew there is a week point of the traditional education system in Asia, namely, the student has been trained to be obedient, told to carefully study textbooks line by line, used to memorize every details. Which is excellent in making high examination scores, however it's toxic for creativeness.
- During my student years under Darwin, he kept stressing that when encounter a problem, instead of going to fully study a whole book, we shall quickly pick up the minimum needed background and come back to solve the problem. We students shall learn things by getting our hands dirty.
- That's quite true. After finishing this project in few months, I knew SUSY much better and even became a small expert on the 2-loop EDM calculation.

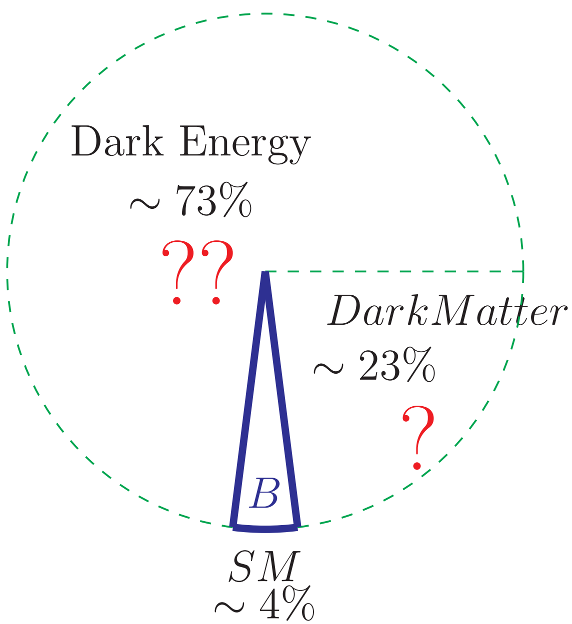
- Today, I will try to give you a rough idea what we have done.
  Also I will try to do a better job than what Darwin did at that night.
- However, I don't think it's possible for me to cover both SUSY and EDM in the rest of the talk.
- So I will try to focus only on the essential things I think you should know about the EDM. And hope after the introduction you can appreciate our works.

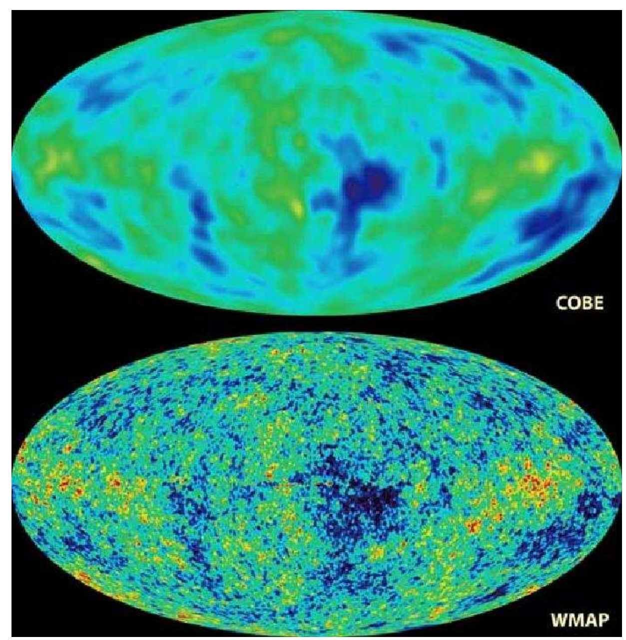
Part II —An Introduction to CPX and EDM

Beyond Standard Model

Standard Model is an extremely successful and profound theory which describes our world. But we strongly believe there must be something beyond it.

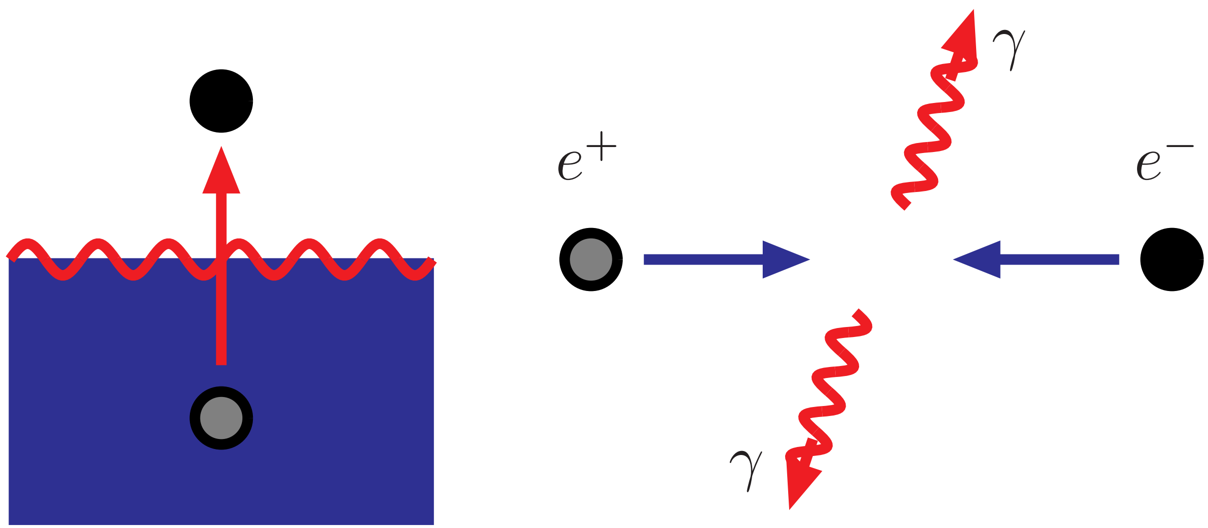
- Neutrino Physics
- Stability of the Higgs sector
- Flavor Physics
- SM is even more embarrassing after WMAP



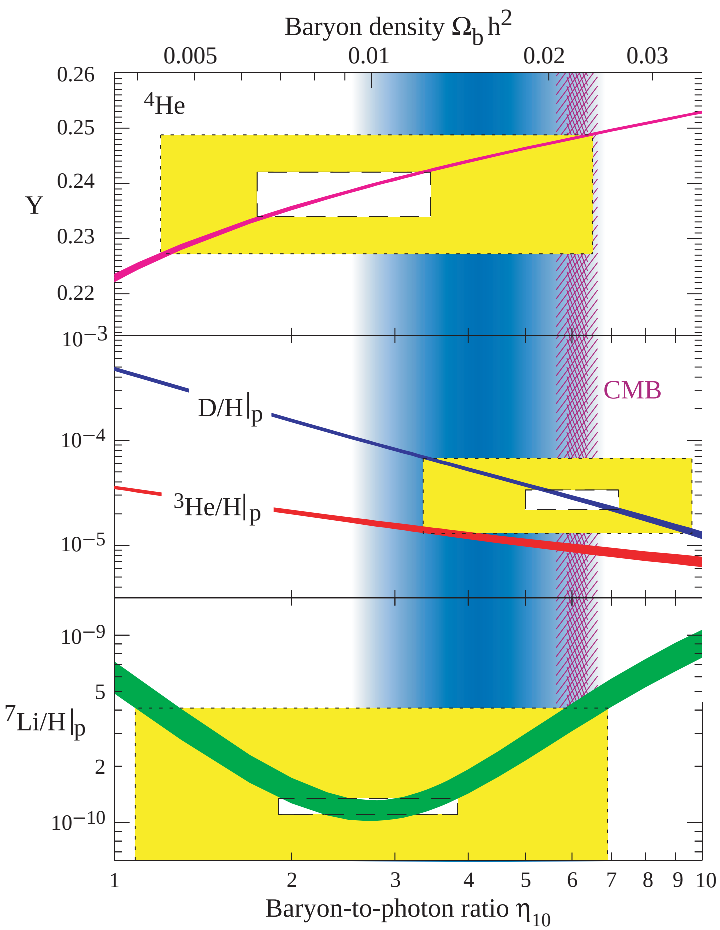


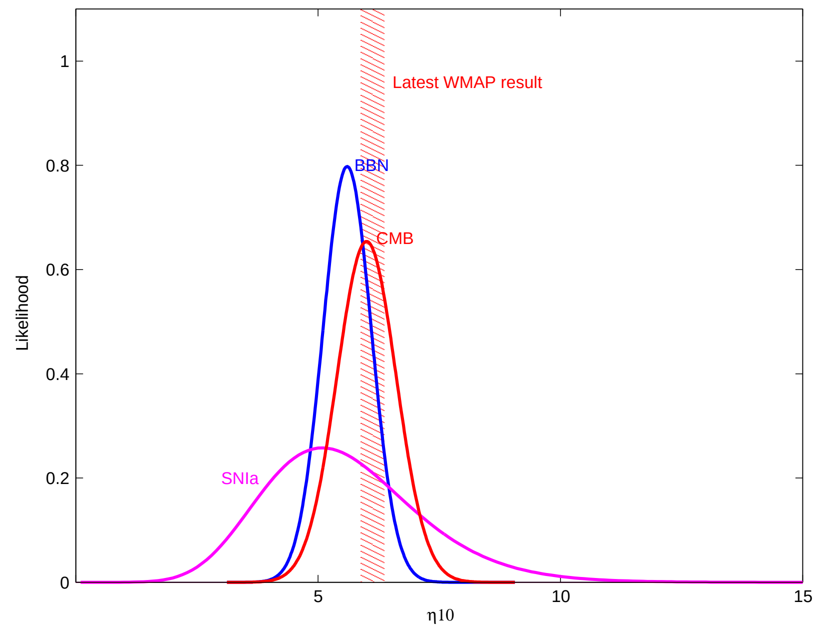
An everyday mystery

- Every single second, we witness one of Nature’s great mysteries.
- How can we be here sound (and sleeping?)
  Where goes the antimatter?



Baryon Asymmetry of the Universe



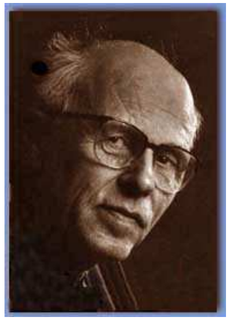


It's now well established that:

$$\eta_B \sim 5.6 \times 10^{-10}$$

$$\left(Y_B \sim \frac{\eta}{7}\right)$$

Sakharov's 3 conditions



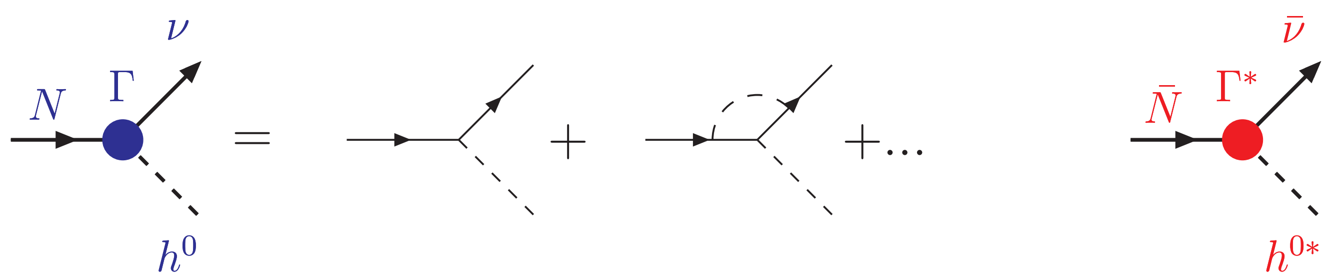
It was first realized by A. Sakharov in 1967 that to generate the matter anti-matter asymmetry from the initially symmetrical phase, the following three necessary conditions must be satisfied.

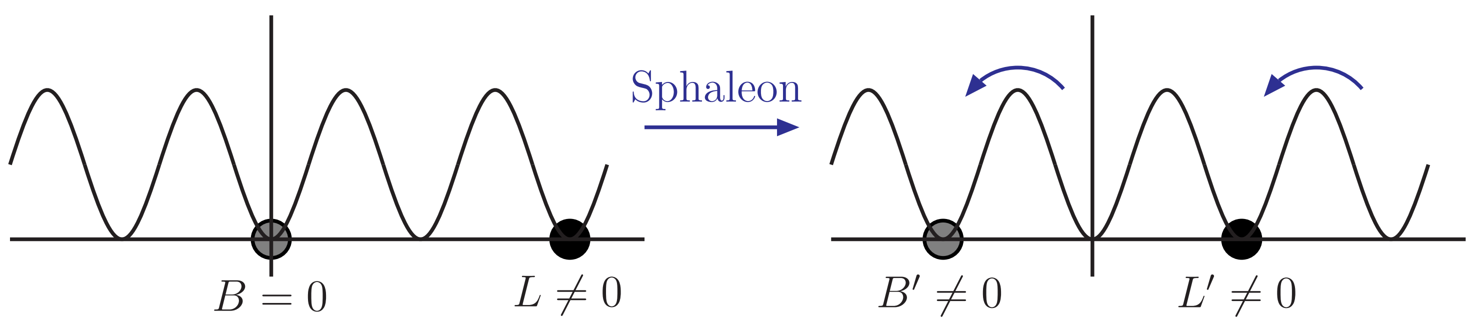
- Baryon (or Lepton) number violation
  - Because at the very beginning, $n_B - n_{\bar{B}} = 0$.
- C and CP violation
  - C violation is for distinguishing baryon from anti baryon.
  - CP violation is to mark a special reaction rate direction in the thermal soup.
- Out of equilibrium
  - Since CPT predicts $m_P = m_{\bar{P}}$, if it is in thermal equilibrium,

$$n_P = \int \frac{d^3k}{e^{-\beta\sqrt{k^2+m_P^2}} + 1} = n_{\bar{P}}$$

Leptogenesis ?

- However, SM, MSSM, and the GUT Baryogenesis have their problems.
- Leptogenesis is an attractive alternative:
  $\Rightarrow$ Net baryon number is arisen from the net lepton number.
- The CP violating decay of RH singlet (ν_R) generates Lepton number asymmetry:





$$(B - L) \; = \; (B' - L')$$

What is EDM and how to measure it?

- The classic EM definition

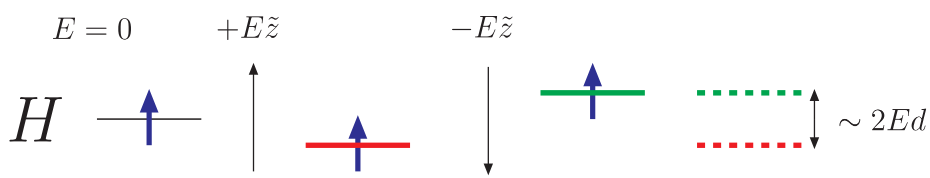
$$\overrightarrow{d} = \int d^3\vec{x}\rho(\vec{x})\vec{x}$$

  Note it is a vector.

- From the basic EM, we also know the energy of a dipole in the electric field is

$$\triangle H = -\vec{d} \cdot \vec{E}$$

- So, from measuring the energy dependence of electric field, we know the size of EDM.

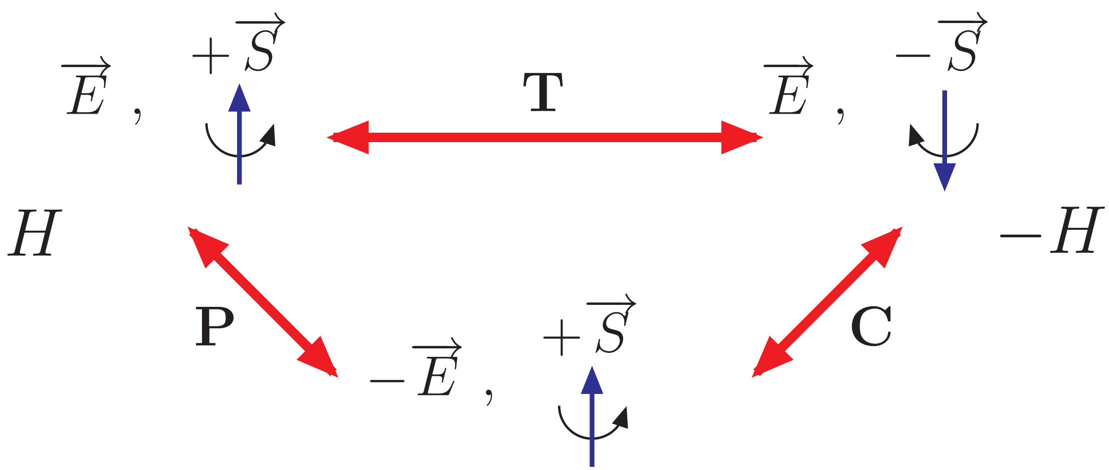


- State of art experimental methods and theoretical subtleties are needed to manifest this simple physics: there are designs using methods of optical spectroscopy, solid state physics, and storage ring..

$$d_e < 1.7 \times 10^{-27} e\,cm\,,\ d_n < 6.3 \times 10^{-26} e\,cm$$

EDM of a fumdamental particle

- The classic picture can't apply to fundamental particles; They are POINT like, so the volume integral doesn't exist!
- However, if the particle has nonzero spin, the intrinsic direction can be associated with a possible permanent EDM.
- If a fundamental spinning particle carries a nonzero EDM, CP is violated.



- in QFT,

$$CP violation \Leftrightarrow Physical\ complex\ couplings$$

Just like how Darwin did to his students. I'd like to ask the student who doesn't know this to go figure it out by yourself.

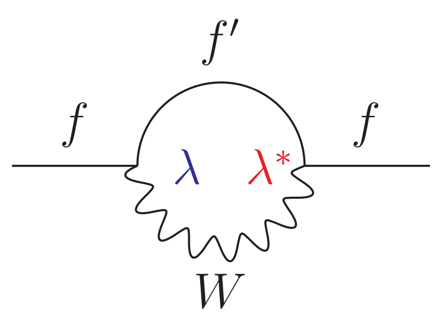
EDM in QFT?

- In QFT, EDM is a dim-5 operator

$$\mathcal{L} = -i\frac{d_f}{2}\bar{f}\sigma^{\mu\nu}\gamma_5 f F_{\mu\nu} \to d_f \overrightarrow{s} \cdot \overrightarrow{E} \; (\,NR\; limit\,)$$

  So EDM does not appear at the tree-level.
  Homework 1: Verify this NR limit.
  Homework 2: Show that to preserve the $SU(3)_c \times SU(2)_L \times U(1)_Y$ symmetry, the EDM operator starts at dim-6.

- In a renormalizable QFT, EDM comes from quantum corrections. Since there is no counter term to cancel the div. EDM must be finite.
- In SM the sole CP violation resides in the quark charged current CKM coupling. Because the complex coupling easily appear in conjugated pair, it is very hard to make the final result complex. Actually, there is no CP violation can be generated at 1-loop level which is clear from the following diagram.

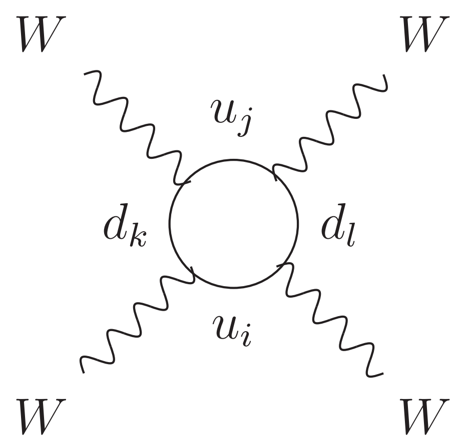


EDM in SM-1

- I'd like to mention one more thing about the CP violation in SM: There is a basis invariant measure call Jarlskog invariance to quantify how large the CP violation is. It is defined as:

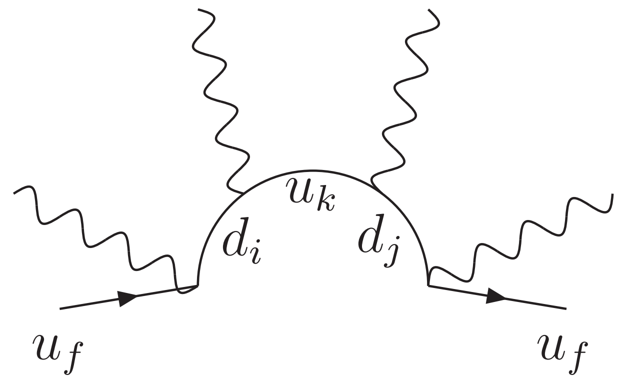
$$\sum \epsilon_{ijk}\epsilon_{\alpha\beta\gamma}J = Im[V^*_{\beta i}V_{\beta j}V^*_{\alpha j}V_{\alpha i}]$$

  and Nature picks a small value for $J \sim 10^{-5}$.
- Therefore, it's easy to see that the minimum possible EDM diagram must involve FOUR W bosons vertices as shown

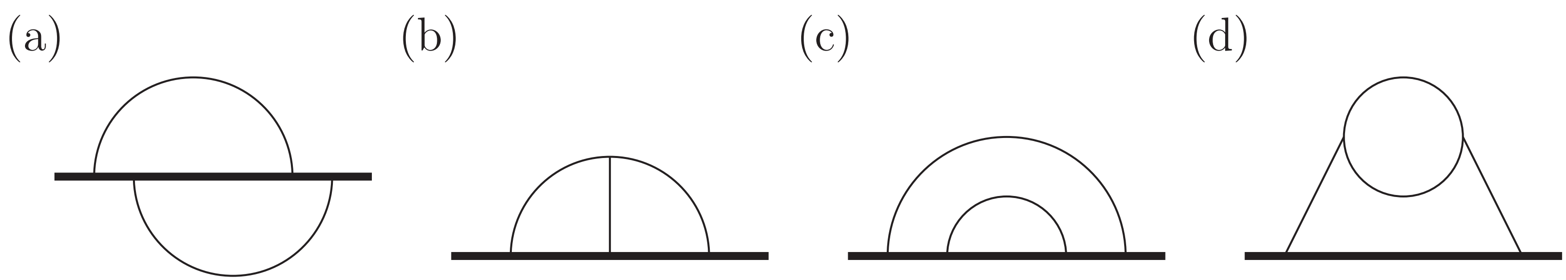


EDM in SM-2

- So, let's try to make a 2-loop quark EDM from the previous diagram.
- The most economic way is cutting one of the quark lines and make the 2 ends external as shown (external up quark as example)



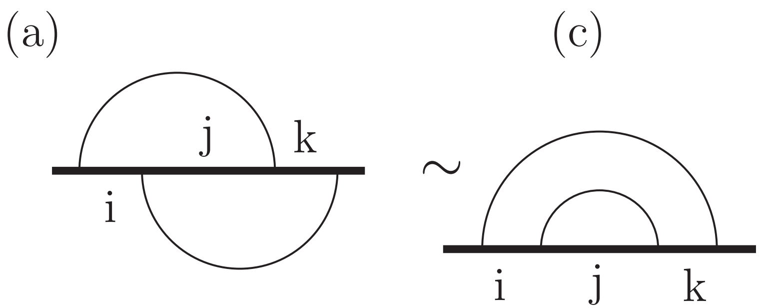
- and then try to hide the open W lines to form any one of the four 2-loop topology: Homework 3: Try and convince yourself that this is it at 2-loop level.



It's clear only type -(a) and (c) are possible.

EDM in SM-3

- First, if all quark masses are degenerated, the unitarity of CKM matrix guarantees that CP violation vanishes.



$\sim \sum_{ijk} V_{iu}(V^\dagger)_{ji} V_{kj} (V^\dagger)_{uk} = 1$

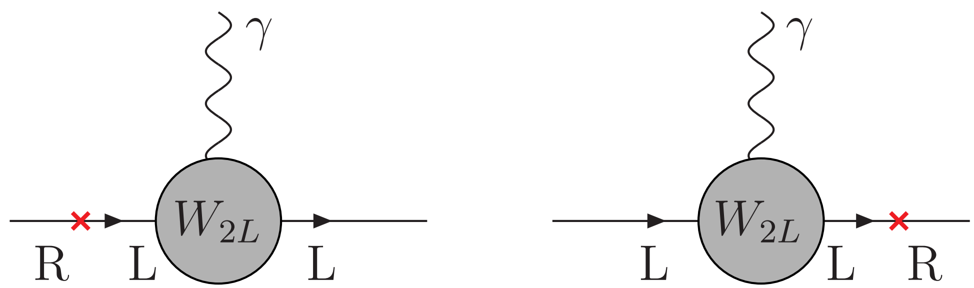
- How about putting in the quark masses?
  By dimensional analysis, we can guess the masses splitting effects must be proportional to the following factor

$$(m_d^2 - m_s^2)(m_s^2 - m_b^2)(m_b^2 - m_s^2)(m_u^2 - m_c^2)(m_c^2 - m_t^2)(m_t^2 - m_u^2) M_W^{-12} \sim 10^{-20}$$

- It's amazingly small. But is it in principle non-zero?

EDM in SM-4

- To answer it, I want to remind you that the SM Charged Current interaction is purely left-handed!
- Also we know the EDM operator must flips chirality of the external fermion!
- Which means, no matter how you play with the mass insertion game on the internal quark lines, eventually we need a mass insertion at one of the external fermions to make the chirality right. And we have tow ways to do it:



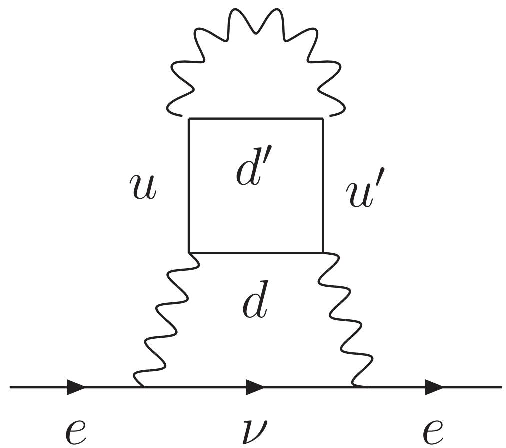
- Therefore, although each one is complex, their EDM parts just cancel!

$$c\bar{f}\sigma^{\mu\nu}(1+\gamma_5)fF_{\mu\nu} + c\bar{f}\sigma^{\mu\nu}(1-\gamma_5)fF_{\mu\nu}$$

- This shows you another tricky part of doing EDM calculation. You always need to worry about the conjugated diagram!

EDM in SM-5

- In the last 4 pages, I have shown you that in SM the quark EDM don't have any 2-loop contribution!!
- Same method can be applied to the charged lepton EDM. The minimal possible diagram is 3-loop. Because two of the W boson lines must end at the charged lepton. It looks like:



- Again, the pure left-handed CC interaction and the conjugated diagrams make this 3-loop EDM vanish!
- Assume that the electron(quark) EDM starts at 4-loop(3-loop), in SM the values are extremely tiny:

$$|d_n| < 10^{-30}\text{e-cm}\ ,\ |d_e| < 10^{-38}\text{e-cm}$$

Homework 4: Use simple power counting to obtain the above estimation.

Small Recap

Ok, let me summarize a little bit here:

- Even from the daily experience, we know there must be new CP violating source(s) beyond SM.
- EDM will be a very clean probe and constraint for CP violation beyond SM.

Part -III, The adventure

In this part, I would like to give you a brief overview about the "adventure" derived from that night's meeting.

- In short, all of them are related to 2-loop either EDM or $(g-2)$ constraint on new physics beyond Standard Model.
- Why do we care about 2-loop contribution rather than 1-loop ones?
- The main reason is the current limits on EDM and $g-2$ are already very stringent.

$$d_e < 1.7 \times 10^{-27} e\,cm\,,\ d_n < 6.3 \times 10^{-26} e\,cm$$

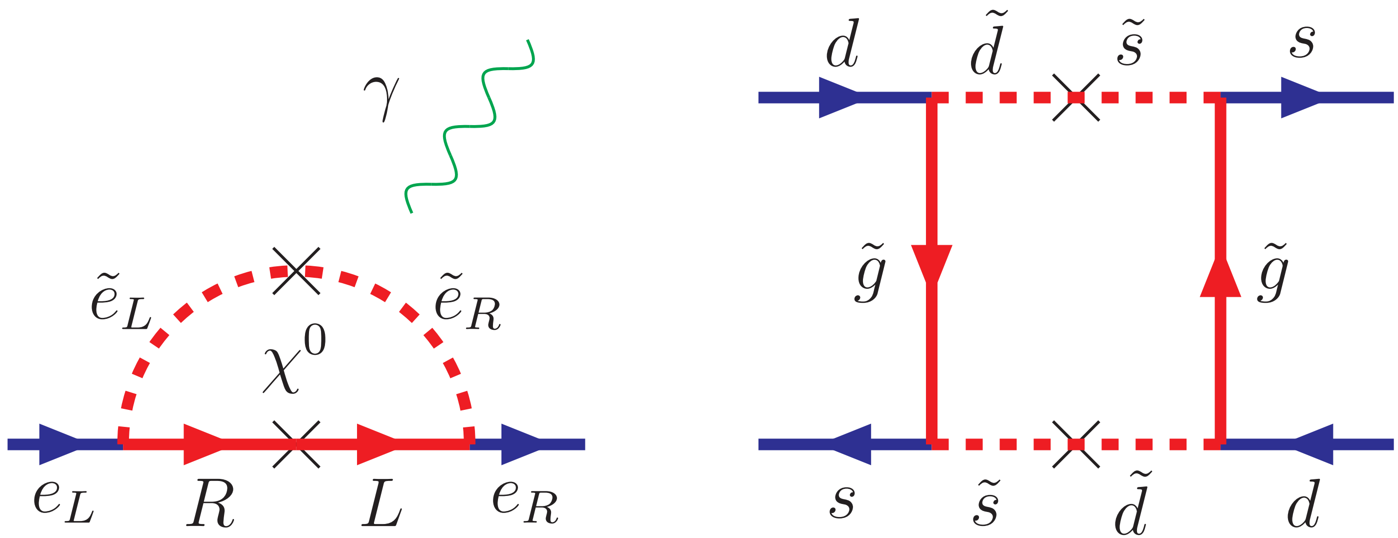
- Anyone who wants to build a realistic model beyond SM must find a way (natural or not) to suppress the EDM generated at 1-loop level.
  From a simple estimation, the 1-loop induced electron EDM has a typical value:

$$\sim \frac{m_e g^2}{16\pi^2} \frac{e \sin\phi_{CP}}{M^2} \ln\frac{M}{M_e} \sim 10^{-23} g^2 \sin\phi_{CP} \left(\frac{100\text{GeV}}{M}\right)^2 \text{e-cm}$$

  Assume $g \sim \sin\phi_{CP} \sim \mathcal{O}(1)$, this 1-loop EDM is way too large.

FCNC and CP violation in MSSM

- The typical 1-loop diagrams lead to FCNC and EDM and K- mixing.



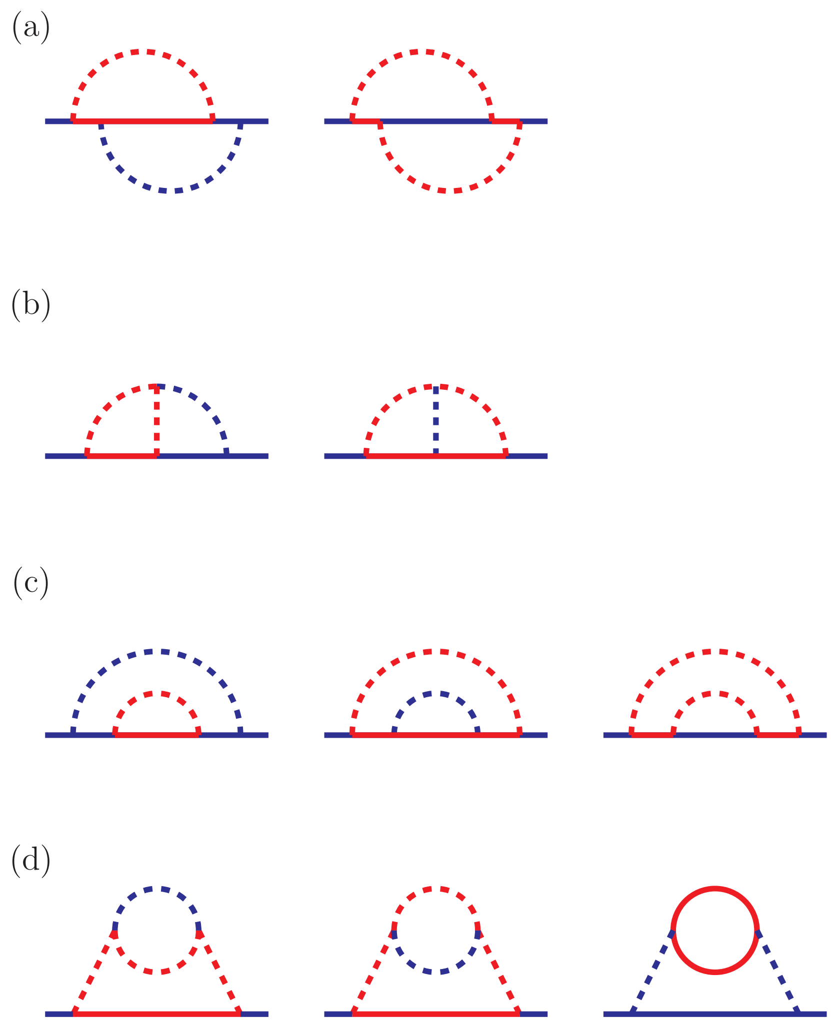
Split Supersymmetry as an example

Arkani-Hamed, Dimopoulos 2004

- No principal for the small Cosmological constant, just fine tune to make it small. Same for the gauge hierarchy problem, the EW Higgs mass is no longer protected by SUSY but just fine tuning.
- All scalars, except the CP-even SM like Higgs, are super heavy $\sim 10^9$ GeV - M_{GUT}
- Gaugino and Higgsino masses are around the EW scale to TeV protected by R-symmetry or PQ symmetry.
- μ parameter is around the EW scale such that the lightest neutralino can annihilate effectively to give the dark matter density.
- Unification still works, mainly due to the gauginos contributions.
- Now it's free of 1-loop problems.
- But does 2-loop EDM also go away?
  Note: even for SM, there are around 2000 2-loop diagrams.

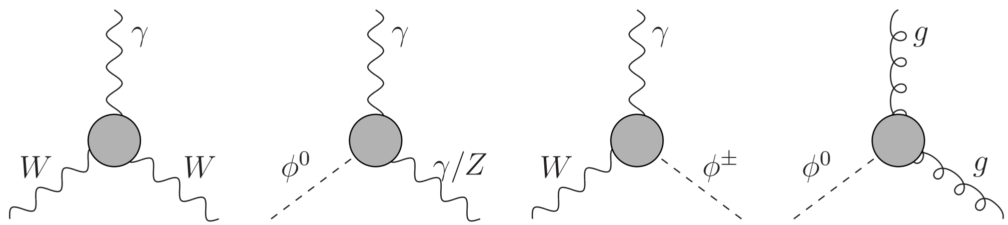
Digramatic proof of the Survival of BZ

- Blue(Red) stands for SM (SUSY) particles. Solid (dash) line stands for fermion(bosons).



Recipe for doing BZ

- If we were lucky, well, in most of the cases we are, the Barr-Zee type diagram is the most important EDM contribution.
- There are only few possible upper parts of Barr-Zee diagrams can generate sizable EDM. They are:



- You should first get the form factors for the upper loop. For example, for the $\gamma(k,\mu) \to \gamma(q,\nu)\phi(p)$ vertex, the most general gauge invariant form factor is:

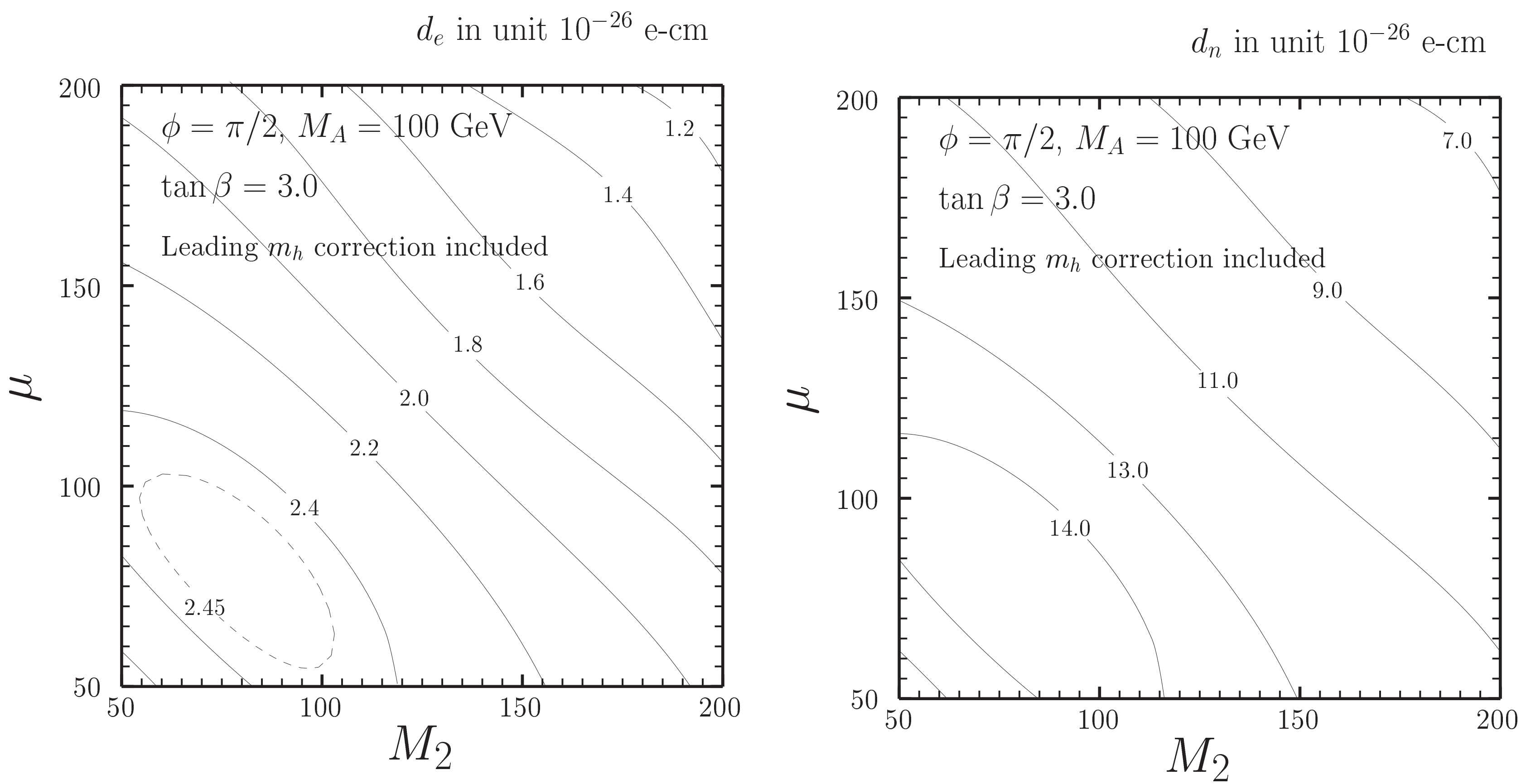
$$\Gamma^{\mu\nu} = S[k^\nu q^\mu - k\cdot q g^{\mu\nu}] + P[i\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta]$$

- Then it's easy, you just attach it to the electron or quark line to get the EDM. Be careful of the conjugated diagrams.
- I must warm you, the gauge independence is very important and usually the most tricky part. You should include every possible diagram to make them a gauge invariant set.

..and the notes have led to

- **"Electric dipole moment in the split supersymmetry models"**
  D. Chang, W. F. Chang and W. Y. Keung
  Phys. Rev. D **71**, 076006 (2005) [arXiv:hep-ph/0503055]
- **"New constraint from electric dipole moments on chargino baryogenesis in MSSM"**
  D. Chang, W. F. Chang and W. Y. Keung
  Phys. Rev. D **66**, 116008 (2002) [arXiv:hep-ph/0205084]
- **"Large two-loop contributions to g-2 from a generic pseudoscalar boson"**
  D. Chang, W. F. Chang, C. H. Chou and W. Y. Keung
  Phys. Rev. D **63**, 091301 (2001) [arXiv:hep-ph/0009292]
- **"The neutron electric dipole moment and CP violating couplings in the supersymmetric standard model without R-parity"**
  D. Chang, W. F. Chang, M. Frank and W. Y. Keung
  Phys. Rev. D **62**, 095002 (2000) [arXiv:hep-ph/0004170]
- **"Additional two-loop contributions to electric dipole moments in supersymmetric theories"**
  D. Chang, W. F. Chang and W. Y. Keung
  Phys. Lett. B **478**, 239 (2000) [arXiv:hep-ph/9910465]

EW Baryogenesis in MSSM



Some paragraphs from my article

...... 極為鼓勵學生在課堂中發問. 若有人指出他的錯誤或他答不出來的問題, 一般中國老師大多會覺得尷尬沒面子, 他不但不會生氣, 反而會非常高興的稱讚學生. 正因為如此, 所以我們這一群學生特別喜歡上他的課, 而且課堂上吵得不得了,大家都絞盡腦汁問出可以被他稱讚的問題......

...另外, 他常告訴我們不要K教科書, 一定要邊做題目,一邊學需要的知識.他總是說, 當初發現或發明一個定理的人, 可以拿到 Nobel prize or Fields medel. 但若我們花了許多精力及時間搞懂了一切,K完整本書, 什麼狗屁小獎也拿不到又常舉他自己念台大的例子: 說後悔當初花一大堆時間精力 K一本看起來最厚的場論教科書, 卻不懂什麼物理. 倒寧願把那些時間拿來好好玩....

...他曾對我們說, 他在 Maryland 作博士後時, 時常和 Mahapatra 聊物理.常常過一個禮拜,Mahapatra 就莫名其妙據此寫出了一篇論文草稿, 問他還有什麼建議.(聽起來,博士後和老闆的角色好像錯置了?).不過, 大家可以由這點看出來, Darwin 的點子真的很多.他對自己這個長處多少是有些自豪的, 又覺得中國的學生太保守, 死讀書.所以, 他訓練學生的目標, 是要我們能問出好問題.他常要求我們每天提一個新的研究 idea 讓他否決. 當他不能否決時, 那就是好的 idea.

Re: you must had heard the good news	We-Fu Chang	2005/12/3 下午 03:36
Re: you must had heard the good news	Darwin	2005/12/4 上午 11:05
check in...	Darwin	2005/12/10 下午 08:46
Fwd: Darwin Passed Away	geng@phys.nthu.edu.tw	2005/12/29 上午 11:27

Subject: **Re: you must had heard the good news**
From: Darwin <chang@phys.nthu.edu.tw>
Date: 2005/12/4 上午 11:05
To: We-Fu Chang <wfchang@phys.sinica.edu.tw>

yes,
possibly....
call me.
darwin

On 3 Dec 05, at 3:36 PM, We-Fu Chang wrote:

> Darwin, of course we will.
> I will go to Hsinchu next Tue. evening,
> are you able to see me after dinner?
>
> We-Fu
>
> Darwin wrote:
>
>> Hope we still have great days of doing physics before!!!!!
>> Darwin
>>
>> On 2 Dec 05, at 9:41 PM, Chang We-Fu wrote:

Call for contribution

- We are now trying to put up a web page for articles collection. It is still under construction but you are invited to take a look. The link is

$$http://www.phys.nthu.edu.tw/\sim wfchang/Darwin.html$$

- Also, if you would like to contribute your memory of Darwin, please send us your article in any potable format to:

$$WFCHANG@PHYS.SINICA.EDU.TW$$