A New Paradigm

---Role of electron-positron and hadron colliders

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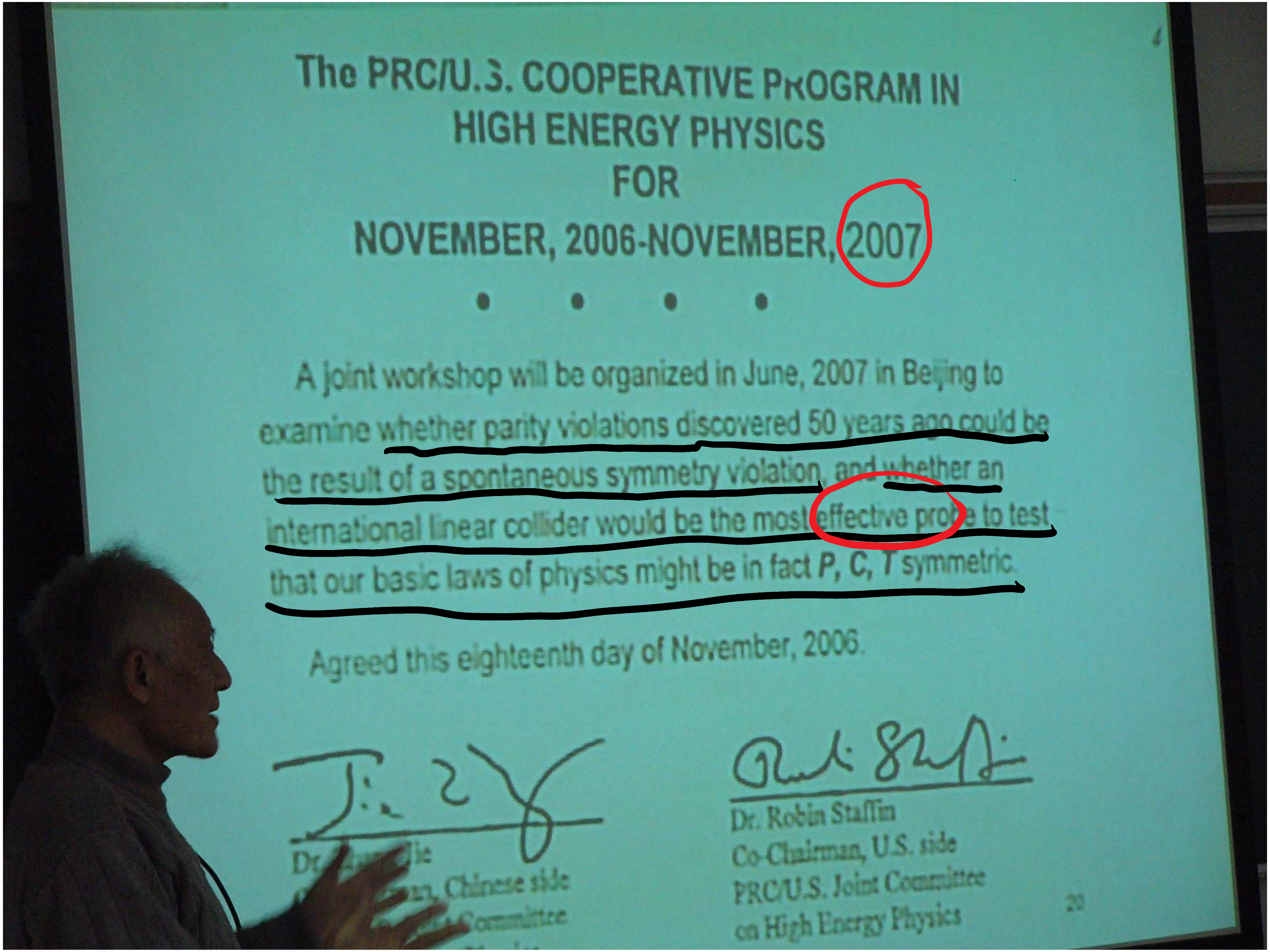
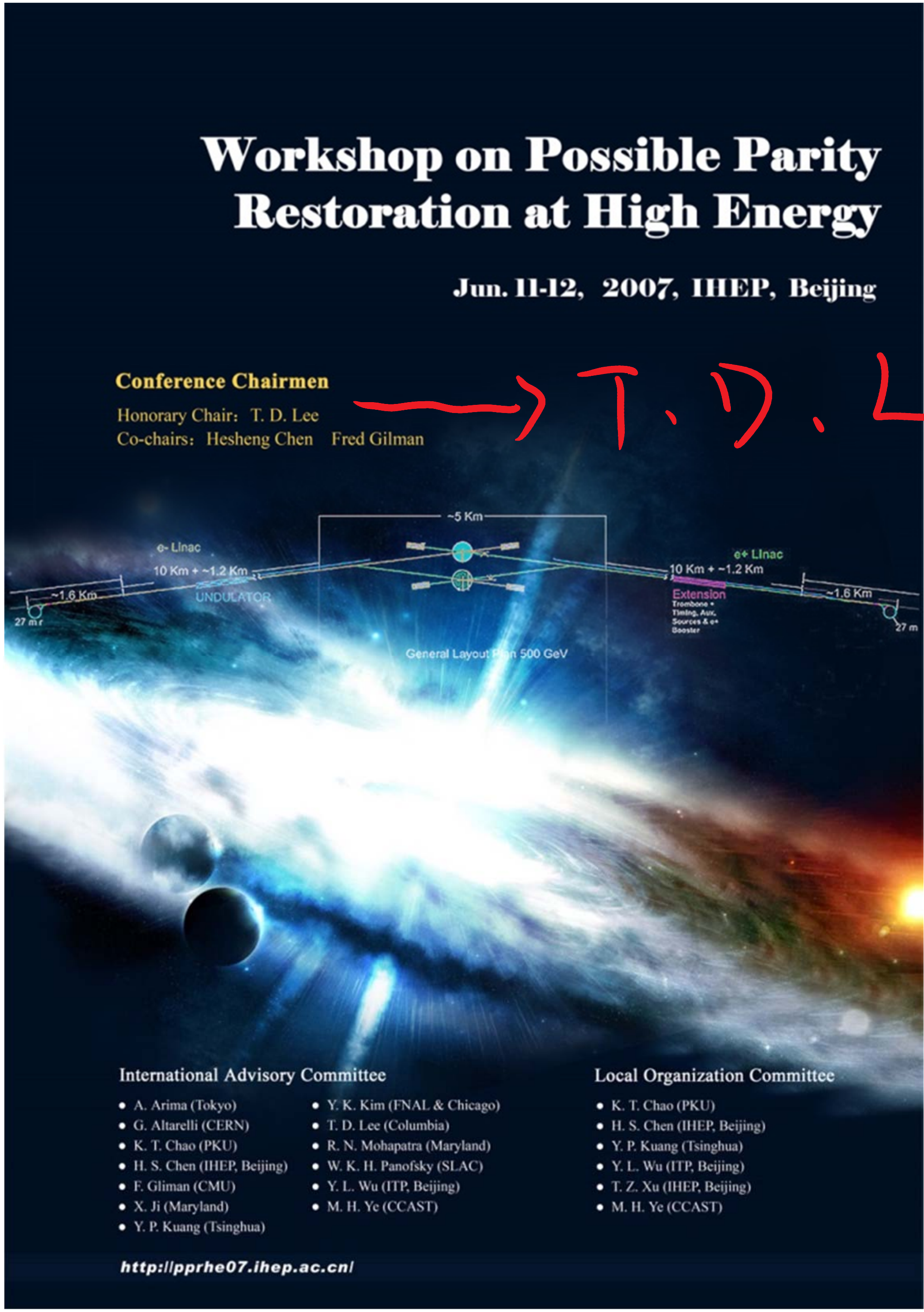
2014/10/9



The PRC/U.S. COOPERATIVE PROGRAM IN
HIGH ENERGY PHYSICS
FOR
NOVEMBER, 2006-NOVEMBER, 2007
A joint workshop will be organized in June, 2007 in Beijing to examine whether parity violations discovered 50 years ago could be the result of a spontaneous symmetry violation, and whether an international linear collider would be the most effective probe to test that our basic laws of physics might be in fact P, C, T symmetric.
Agreed this eighteenth day of November, 2006.
Chinese side
Committee
Dr. Robin Staffin
Co-Chairman, U.S. side
PRC/U.S. Joint Committee
on High Energy Physics
20

2007.1, Mini-workshop @ High Energy Center, Peking U.

"Experimental and theoretical Overview on Left-right models"



Workshop on Possible Parity Restoration at High Energy
Jun. 11-12, 2007, IHEP, Beijing
Conference Chairmen
Honorary Chair: T. D. Lee
Co-chairs: Hesheng Chen Fred Gilman
~5 Km
e- Linac
10 Km + ~1.2 Km
UNDULATOR
~1.6 Km
e+ Linac
10 Km + ~1.2 Km
Extension
~1.6 Km
International Advisory Committee
• A. Arima (Tokyo)
• G. Altarelli (CERN)
• K. T. Chao (PKU)
• H. S. Chen (IHEP, Beijing)
• F. Gliman (CMU)
• X. Ji (Maryland)
• Y. P. Kuang (Tsinghua)
• Y. K. Kim (FNAL & Chicago)
• T. D. Lee (Columbia)
• R. N. Mohapatra (Maryland)
• W. K. H. Panofsky (SLAC)
• Y. L. Wu (ITP, Beijing)
• M. H. Ye (CCAST)
Local Organization Committee
• K. T. Chao (PKU)
• H. S. Chen (IHEP, Beijing)
• Y. P. Kuang (Tsinghua)
• Y. L. Wu (ITP, Beijing)
• T. Z. Xu (IHEP, Beijing)
• M. H. Ye (CCAST)
http://pprhe07.ihep.ac.cn/

T. D. Lee

My personal impression

- Scale of parity restoration in L-R models is usually too high to electron-positron colliders (or even LHC). Need higher energy hadron colliders!
- Electron-positron colliders may reach alternative parity restoration approach, like mirror models etc., likely via the complicated scalar sector
- …

The story continues today

- P restoration is replaced by CP (or T) restoration
- While P is maximally broken in weak interaction, CP symmetry was approximately conserved. It was thought strictly conserved before 1964.

Take-home messages

- We found that the small observed CP violation is intimately correlated with lightness of observed H(125), if CP is spontaneously broken which was proposed by T.D. Lee in 1973
- If it is true, the corresponding whole picture (a new paradigm) can only be revealed by both electron-positron and hadron colliders.

Content

- Brief overview on motivations for BSM
- Lightness of H(125) and smallness of CP violation
- A new paradigm and scalar chemistry
- Questions to be answered by HF

Fact-1: Observed CPV is small

C. Jarlskog, Phys. Rev. Lett. 55, 1039 (1985)

$$J = A^2\lambda^6\eta = (2.96^{+0.20}_{-0.16}) \times 10^{-5}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Fact-2: Observed H(125) is light

- In the SM, 125 GeV Higgs just means the theory is simply weak-coupled.
- However, in the BSM, H(125) is quite light compared to the allowed BSM scale, because experiments are still consistent with the SM predictions.

How to understand these two facts?

?

Now that Higgs boson mass arises from spontaneous symmetry breaking (SSB), if CPV arises also from SSB, is there any connection between CPV and the Higgs boson mass?

Simplest Spontaneous CPV model

T. D. Lee, Phys. Rev. D 8, 1226 (1973)

$$\mathcal{L} = (D_\mu \phi_1)(D^\mu \phi_1) + (D_\mu \phi_2)(D^\mu \phi_2) - V(\phi_1, \phi_2)$$

$R(I)_{ij}$ as the real(imaginary) part of $\phi_i^\dagger \phi_j$

$$\begin{aligned} V &= V_2 + V_4 \\ &= \mu_1^2 R_{11} + \mu_2^2 R_{22} \\ &\quad + \lambda_1 R_{11}^2 + \lambda_2 R_{11} R_{12} + \lambda_3 R_{11} R_{22} \\ &\quad + \lambda_4 R_{12}^2 + \lambda_5 R_{12} R_{22} + \lambda_6 R_{22}^2 + \lambda_7 I_{12}^2; \end{aligned}$$

All parameters are real due to the CP symmetry!

Complex vacuum

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + R_1 + iI_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 e^{i\xi} + R_2 + iI_2}{\sqrt{2}} \end{pmatrix}$$

$$\tan\beta \equiv v_2/v_1 \qquad v = \sqrt{v_1^2 + v_2^2} = 246\text{GeV}$$

Neutral scalars

After rotating away Goldstone mode

We expand the matrix $\tilde{m}$ in series of $t_\beta(s_\xi)$ as

$$\tilde{m} = \tilde{m}_0 + (t_\beta s_\xi)\tilde{m}_1 + (t_\beta s_\xi)^2\tilde{m}_2 + \cdots$$

$$\lim_{t_\beta s_\xi \to 0} \det(\tilde{m}) = \det(\tilde{m}_0) = 0$$

Lightest neutral scalar

To the leading order of $t_\beta s_\xi$,

$$m_h^2 = \frac{v^2 t_\beta^2 s_\xi^2}{2}\left(\frac{(\tilde{m}_1)_{12}^2}{(\tilde{m}_0)_{22}} + \frac{(\tilde{m}_1)_{13}^2}{(\tilde{m}_0)_{33}} + (\tilde{m}_2)_{11}\right)$$
$$= \frac{v^2 t_\beta^2 s_\xi^2}{2}\Bigg[4(\lambda_3+\lambda_7)^2\left(\frac{c_\theta^2}{(\tilde{m}_0)_{22}} + \frac{s_\theta^2}{(\tilde{m}_0)_{33}}\right) + \lambda_5^2\left(\frac{s_\theta^2}{(\tilde{m}_0)_{22}} + \frac{c_\theta^2}{(\tilde{m}_0)_{33}}\right) - 2\lambda_5(\lambda_3+\lambda_7)s_{2\theta}\left(\frac{1}{(\tilde{m}_0)_{22}} - \frac{1}{(\tilde{m}_0)_{33}}\right) + 4\lambda_6\Bigg]$$

$$\theta = (1/2)\tan^{-1}(2\lambda_2/(4\lambda_1 - \lambda_4 + \lambda_7))$$

Yukawa interaction and Ys are real

$$(M_U)_{ij} = \frac{v}{\sqrt{2}}(Y_{1u}c_\beta + Y_{2u}s_\beta e^{-i\xi})_{ij},$$

$$(M_D)_{ij} = \frac{v}{\sqrt{2}}(Y_{1d}c_\beta + Y_{2d}s_\beta e^{i\xi})_{ij}.$$

$$U_L M_U U_R^\dagger = \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix}$$

$$V_{\mathrm{CKM}} = U_L D_L^\dagger \text{ i}$$

$$D_L M_D D_R^\dagger = \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix}$$

All CPV arise from complex vacuum!

Measures of CPV in CKM and Higgs sector

To the leading order of $t_\beta s_\xi$,

$$K = c_1 c_2 c_3 = -s_\theta c_\theta (1+\eta_1) t_\beta s_\xi \propto t_\beta s_\xi$$

$$J = \frac{\prod C_i \sum (C_i^*/Ci)}{\prod \left(m_{U_i}^2 - m_{U_j}^2\right) \prod \left(m_{D_i}^2 - m_{D_j}^2\right)} \propto t_\beta s_\xi$$

$$m_h^2 = \frac{v^2 t_\beta^2 s_\xi^2}{2} \left(\frac{(\tilde{m}_1)_{12}^2}{(\tilde{m}_0)_{22}} + \frac{(\tilde{m}_1)_{13}^2}{(\tilde{m}_0)_{33}} + (\tilde{m}_2)_{11} \right)$$

Phenomenology

- Consistent with ALL LHC data & low energy expt: FCNC, EDM, B- & K-meson …

Mao and Zhu, 1409.6844

Even though Higgs mass and CPV correlated, implications?

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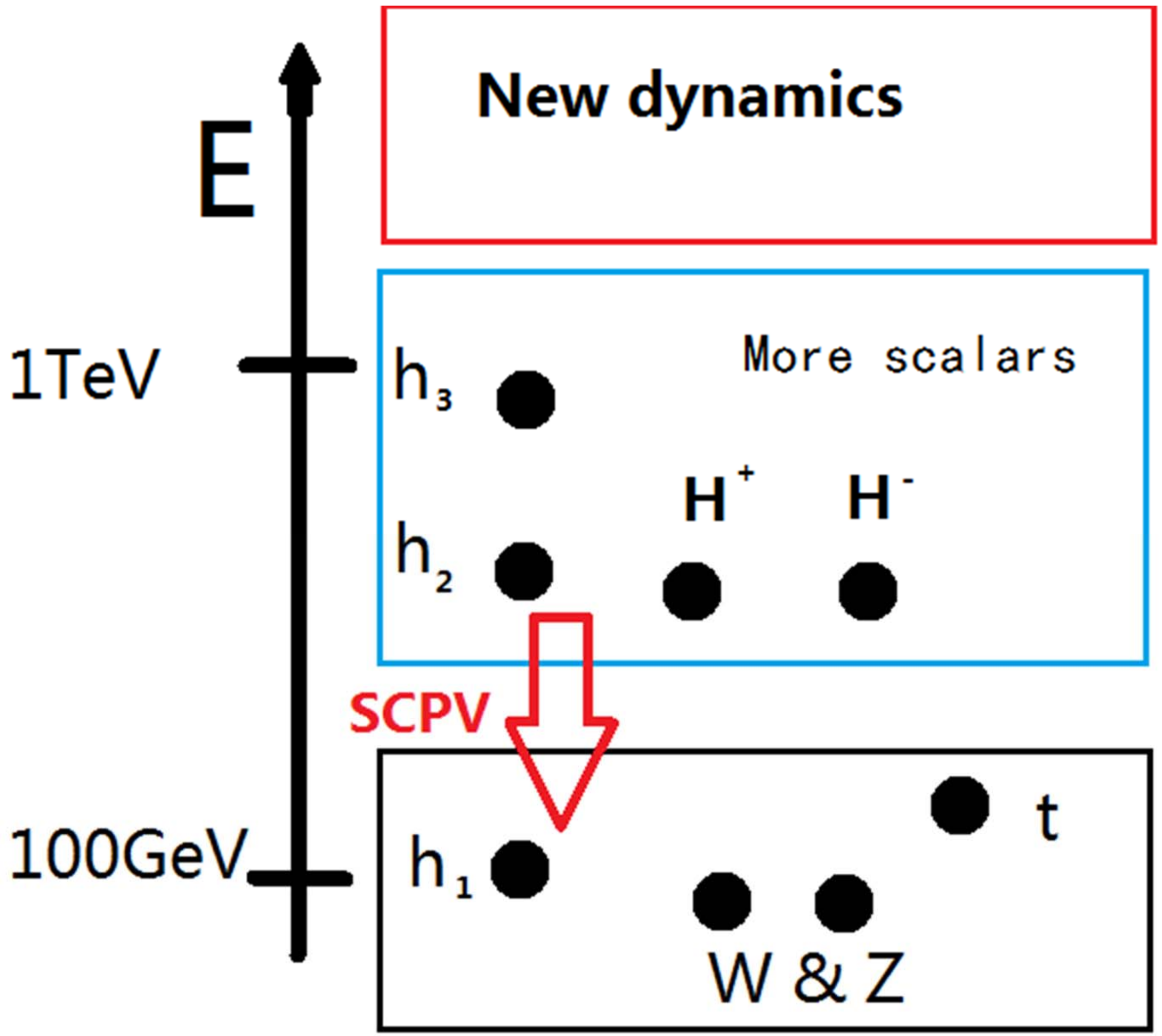
- A new paradigm and scalar chemistry
- Questions to be answered by HF

A new paradigm



- H(125) is due to approximate CP symmetry
- Heavier scalars need to be understood
- New paradigm to understand EWSB and CPV
- Scalar chemistry

Scalar Chemistry: General features

- H(125) is not SM-like, instead H(125) is the CP mixing state
- There are usually extra CP violation in scalar sector, besides CKM matrix, though they arise both from the complex vacuum
- There are other heavy neutral and charged Higgs bosons
- The scale of the new mechanism for the complicated scalar sectors is higher.

Scalar Chemistry: General Signals

- H(125): Deviations from SM. (1) Couplings with W&Z suppressed by $t_\beta s_\xi$,(2) H(125) to b-pair decay or VBF, VH associated production channel are suppressed
- H(125): CPV
- H(125): Possible large FCNC
- New neutral/charged scalars
- Other new states for new dynamics

Scalar chemistry @ LHC: Hardest Case

Table 1: Abilities to test the scenario at $\sqrt{s} = 14\text{TeV}$ LHC. Lower limit for the allowed c_V at 2σ and 3σ level are listed in the tables. For the up/down tables we assume all signal strengths are consistent with SM at $1\sigma/2\sigma$ level respectively.

Excluded level	2σ	3σ
300fb^{-1}	0.62	0.55
3000fb^{-1}	0.77	0.72

Excluded level	2σ	3σ
300fb^{-1}	0.53	0.45
3000fb^{-1}	0.7	0.65

Scalar chemistry @ Electron-Positron Colliders

- For the total cross section of H(125) production, a measurement with O(10%) accuracy is enough to distinguish from SM at 3 or even 5 sigma significance. Such accuracy can be easily achieved at future electron-positron colliders
- CPV measurement on h->tau pair for H(125) can reach higher precision than LHC
- FCNC Higgs coupling measurements
- ……

Scalar chemistry @ Higher Energy Hadron Colliders

- Discover heavy scalars for sure
- Reveal new dynamics behind scalar field: Origin of EWSB/CP/P violation?
- How high? Need the inputs from LHC/electron-positron collider

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8 theory working groups for CEPC/SPPC

1. SM tests (conveners: Qing-hong Cao/Li-lin Yang/Zhao Li/Chong Sheng Li)
2. Higgs Physics (Hong-jian He/Shou-hua Zhu/Tao Liu)
3. BSM: SUSY(Tianjun Li/Jin-min Yang)
4. BSM: Non-SUSY(Qi-shu Yan/Jing Shu/Wen-Gan Ma/Yi Liao/Wei Liao)
5. Flavor Physics(Cai-Dian Lu/Zong-Guo Si)
6. TeV Cosmology(Xiao-jun Bi/Yu-Feng Zhou)
7. Heavy Ion(Xin-nian Wang/Qun Wang)
8. MC tools(Qi-shu Yan/Jian-Xiong Wang)

Brief History (1)

- 2012/11/7, the theory working group formed
- 2012/12/20, first group meeting at Tsinghua U
- 2013/8/25, small scale meeting at Dalian (TeV working group workshop)
- 2013/9/14, Kick-off meeting, adding “flavor” and “TeV cosmology” working groups
- 2013/11, second group meeting at Peking U
- 2013/12/16, preliminary report
- 2014/1, adding “heavy ion” working group
- 2014/2/24-25, 1st CFHEP symposium

Brief history (2)

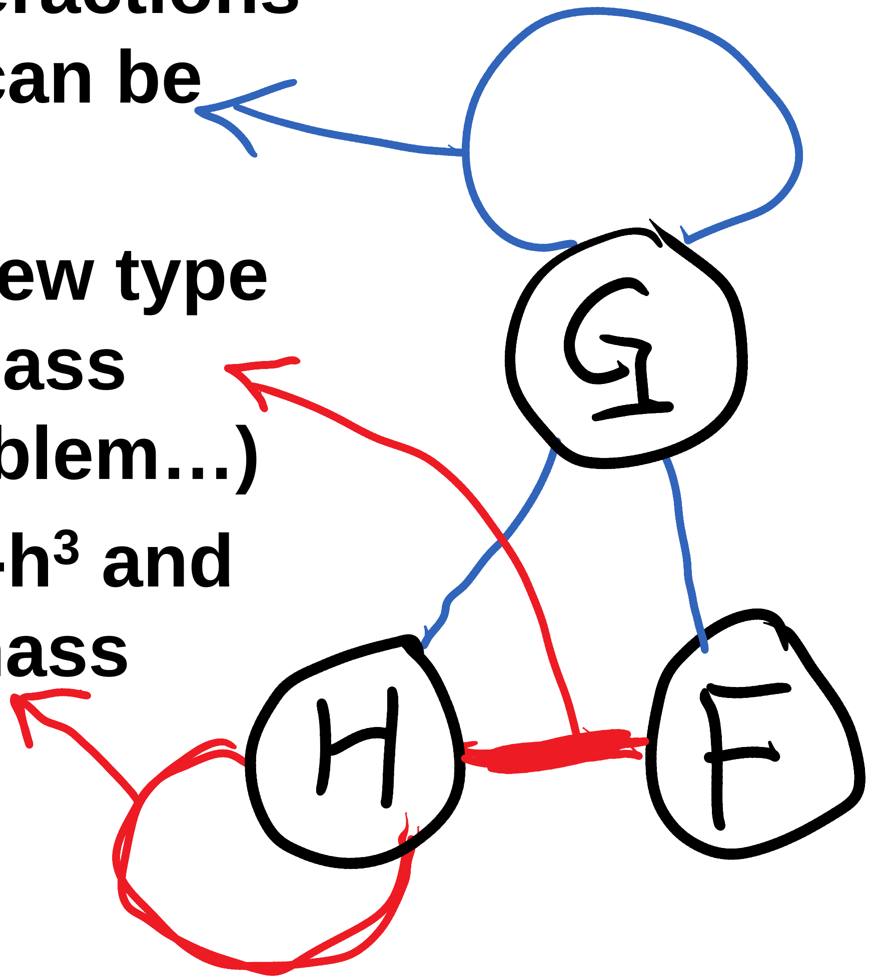
- 2014/5/19, TeV Working group Workshop, Guangzhou, open discussion on CEPC/SPPC, and round-table meeting for pre-cdr
- 2014/6/15, Mini-workshop on LHC physics, Xi-an, round-table meeting for pre-cdr
- 2014/8, 2st CFHEP symposium
- 2014/9, 4th CEPC workshop, Shanghai

Status report, please see:

- http://indico.ihep.ac.cn/materialDisplay.py?contribId=10&sessionId=6&materialId=slides&confId=4338
- Talk at “The Fourth International Workshop on Future High Energy Circular Colliders”

Motivation(I): Test new type interactions and discover possible deviations

1. Well-tested gauge interactions (strong, electroweak can be excellently descried)
2. Yukawa interaction (New type interaction, fermion mass generation, flavor problem…)
3. Higgs self-interaction-h^3 and h^4 couplings (Higgs mass generation, order of electroweak phase transition…)



Motivation(II):
Astrophysical observations

- Dark matter (DM candidate, new symmetry…, complete theory likely related to Higgs field)
- Baryon Asymmetry(Higgs self-interaction, CP-Violation…)
- Inflation (Higgs related?)
- …

Motivation(III): Theoretical

- **Too many parameters in SM (origin of electro-weak symmetry breaking, CPV, flavor…)**
- **Naturalness (new strong interaction, supersymmetry, extra-dimension…)**
- **+gravity (insight into space-time and quantum theory)**
- **…**

Motivation(IV): Common sense

1. New physics object --- scalar particle: Need to measure its properties as precisely as possible

2. Going to higher energy and smaller distance to discover the unexpected phenomena and explore the unknown regime is the pursue of fundamental science

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To be answered by HF

- A new paradigm=an example
- Couplings of H(125) SM-like?
- H(125) CP mixing state?
- More scalars?
- What behind scalar boson(s)?
- Tremendous measurements (scalar chemistry), especially the scalar-fermion couplings, need generation(s) to do!

Physics is the thing we need time to understand!

expt + th

Thanks for your attention!

Lightest neutral scalar

To the leading order of $t_\beta s_\xi$,

$$h = I_2 + t_\beta s_\xi \left(\frac{(\tilde{m}_1)_{12}}{(\tilde{m}_0)_{22}} (c_\theta R_1 + s_\theta R_2) + \frac{(\tilde{m}_1)_{13}}{(\tilde{m}_0)_{33}} (c_\theta R_2 - s_\theta R_1) - \frac{I_1}{t_\xi} \right)$$

$$= I_2 + t_\beta s_\xi \left[\left(2(\lambda_3 + \lambda_7) \left(\frac{c_\theta^2}{(\tilde{m}_0)_{22}} + \frac{s_\theta^2}{(\tilde{m}_0)_{33}} \right) + \frac{\lambda_5 s_{2\theta}}{2} \left(\frac{1}{(\tilde{m}_0)_{22}} - \frac{1}{(\tilde{m}_0)_{33}} \right) \right) R_1 + \left((\lambda_3 + \lambda_7) s_{2\theta} \left(\frac{1}{(\tilde{m}_0)_{22}} - \frac{1}{(\tilde{m}_0)_{33}} \right) + \lambda_5 \left(\frac{s_\theta^2}{(\tilde{m}_0)_{22}} + \frac{c_\theta^2}{(\tilde{m}_0)_{33}} \right) \right) R_2 - \frac{I_1}{t_\xi} \right].$$

Probing Higgs CPV Couplings at CEPC

Colliders	LHC	HL-LHC	CEPC(1ab^{-1})	CEPC(3ab^{-1})	CEPC(10ab^{-1})
Accuracy(1σ)	25°	8.0°	5.5°	3.2°	1.7°

Table 6. The accuracy in measuring Δ, the CPV phase in Higgs coupling with $\tau^+\tau^-$, at the 14 TeV LHC, HL-LHC and the CEPC. Here 70% τ_h efficiency is assumed for the LHC and the HL-LHC.

Colliders	LHC	HL-LHC	$e^+e^-(0.25ab^{-1})$	Target (theory)
VVh	4×10^{-4}	1.2×10^{-4}	7×10^{-4}	$< 10^{-5}$

SPPC

NLO rates $\mathbf{R(E)} = \sigma(E\ \text{TeV})/\sigma(14\ \text{TeV})$

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42