



# Higgs Theory Overview

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# 简介

- 简介
- Higgs基本性质要素和Higgs物理核心问题
- 当前Higgs理论模型实验现状
- Higgs粒子宇宙学?
- 结论

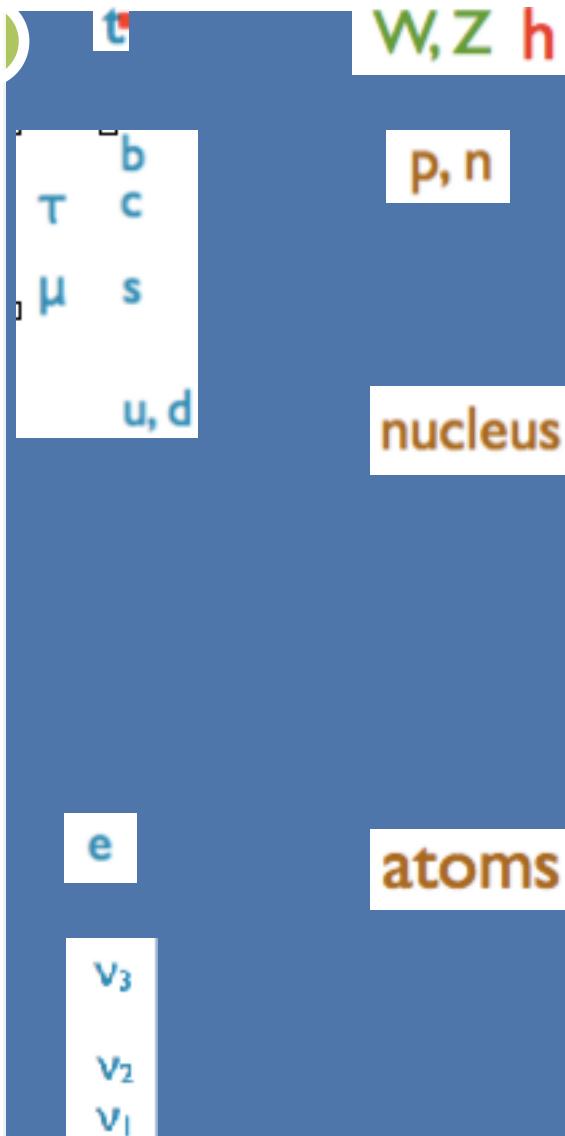
# 我们的高能物理

TeV

GeV

MeV

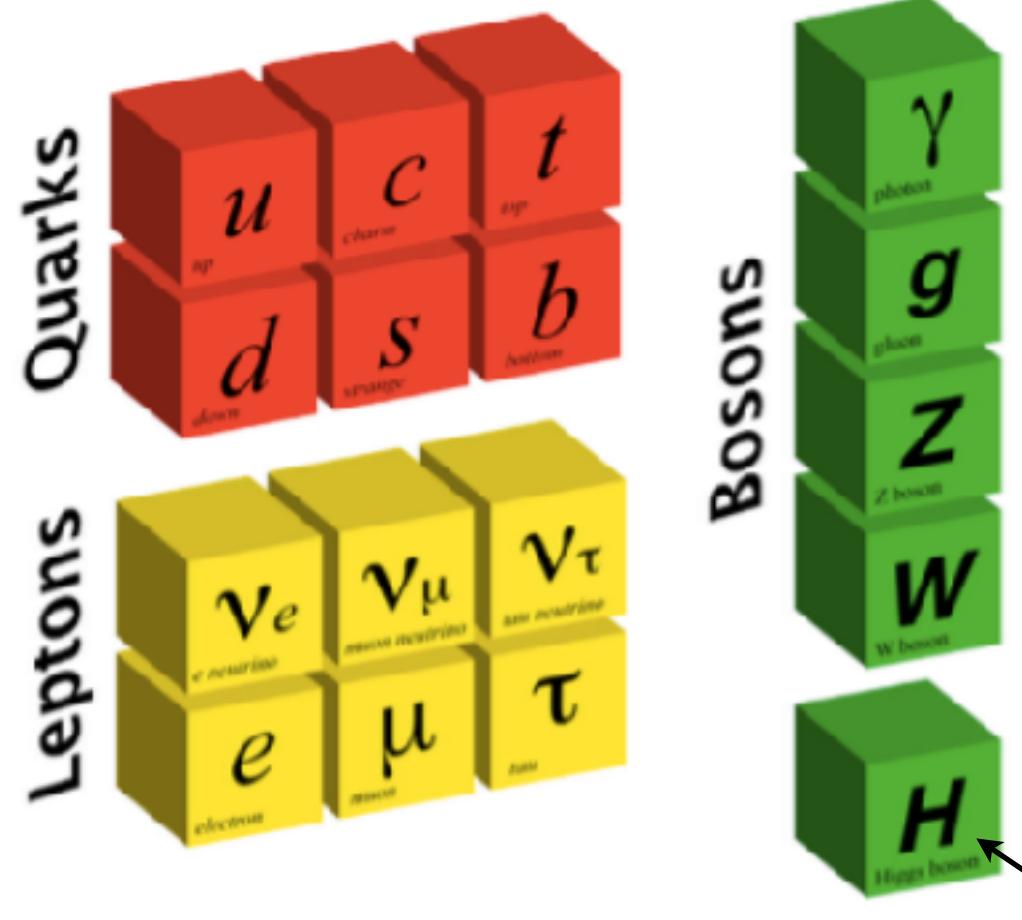
eV



未来高能量前沿  
继续探索未知

过去一个世纪  
的高能物理学

# 我们已知的“旧”物理



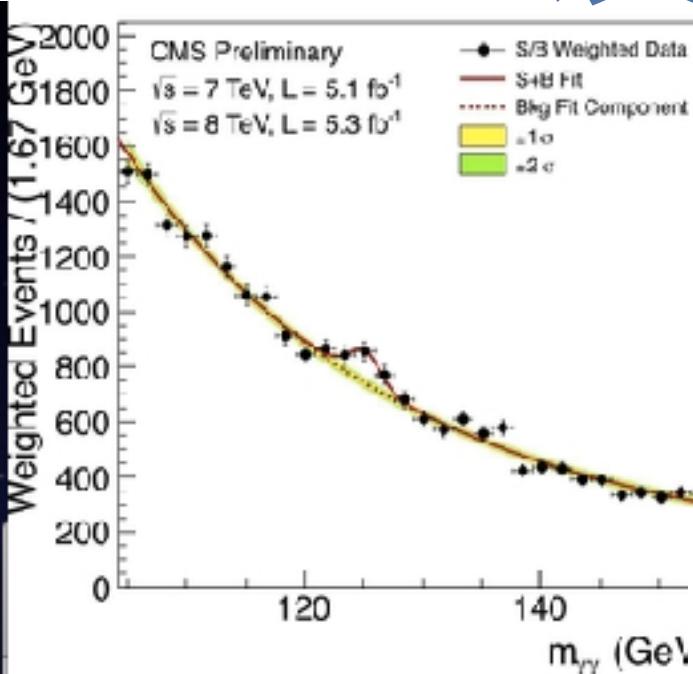
基本粒子图谱

## The Weinberg-Salam Model

$$\begin{aligned}\mathcal{L} = & \bar{E}_L(i\partial)E_L + \bar{e}_R(i\partial)e_R + \bar{Q}_L(i\partial)Q_L + \bar{u}_R(i\partial)u_R + \bar{d}_R(i\partial)d_R \\ & + g(W_\mu^+ J_W^{\mu+} + W_\mu^- J_W^{\mu-} + Z_\mu^0 J_Z^\mu) + e A_\mu J_{EM}^\mu,\end{aligned}$$
$$J_W^{\mu+} = \frac{1}{\sqrt{2}}(\bar{\nu}_L \gamma^\mu e_L + \bar{u}_L \gamma^\mu d_L);$$
$$J_W^{\mu-} = \frac{1}{\sqrt{2}}(\bar{e}_L \gamma^\mu \nu_L + \bar{d}_L \gamma^\mu u_L); \quad e = \frac{gg'}{\sqrt{g^2 + g'^2}},$$
$$J_Z^\mu = \frac{1}{\cos \theta_w} \left[ \bar{\nu}_L \gamma^\mu \left( \frac{1}{2} \right) \nu_L + \bar{e}_L \gamma^\mu \left( -\frac{1}{2} + \sin^2 \theta_w \right) e_L + \bar{e}_R \gamma^\mu \left( +\frac{2}{3} \sin^2 \theta_w \right) e_R \right. \\ \left. + \bar{u}_L \gamma^\mu \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_w \right) u_L + \bar{u}_R \gamma^\mu \left( -\frac{2}{3} \sin^2 \theta_w \right) u_R \right. \\ \left. + \bar{d}_L \gamma^\mu \left( -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_w \right) d_L + \bar{d}_R \gamma^\mu \left( \frac{1}{3} \sin^2 \theta_w \right) d_R \right],$$
$$J_{EM}^\mu = \bar{e} \gamma^\mu (-1) e + \bar{u} \gamma^\mu (+\frac{2}{3}) u + \bar{d} \gamma^\mu (-\frac{1}{3}) d.$$

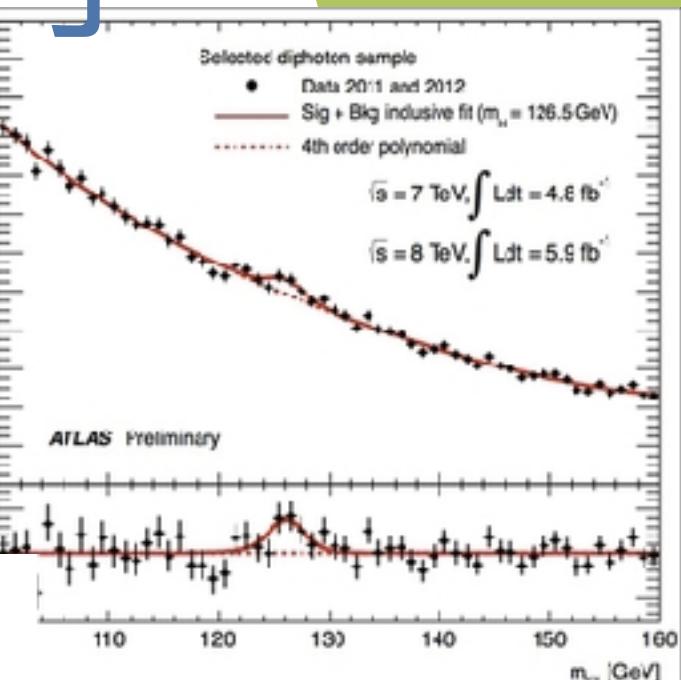
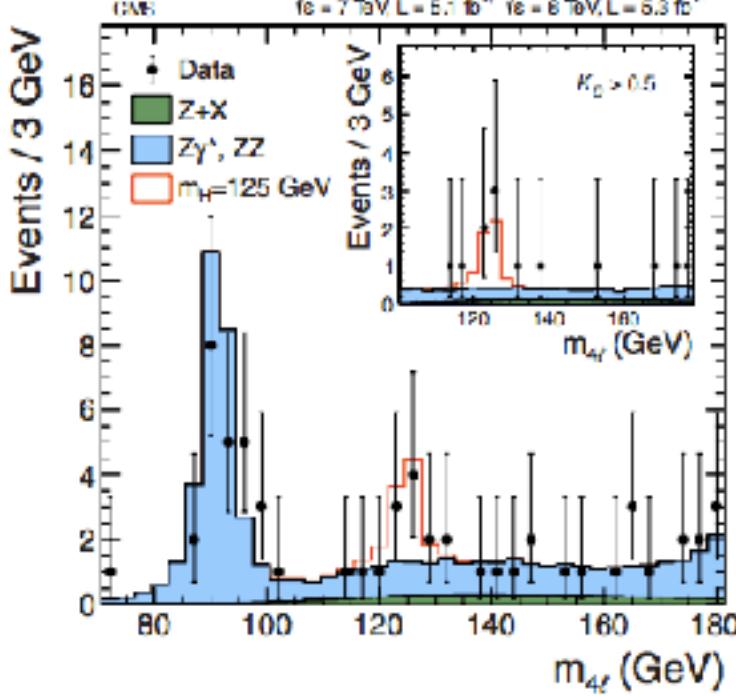
The chosen one!

# 发现Higgs粒子



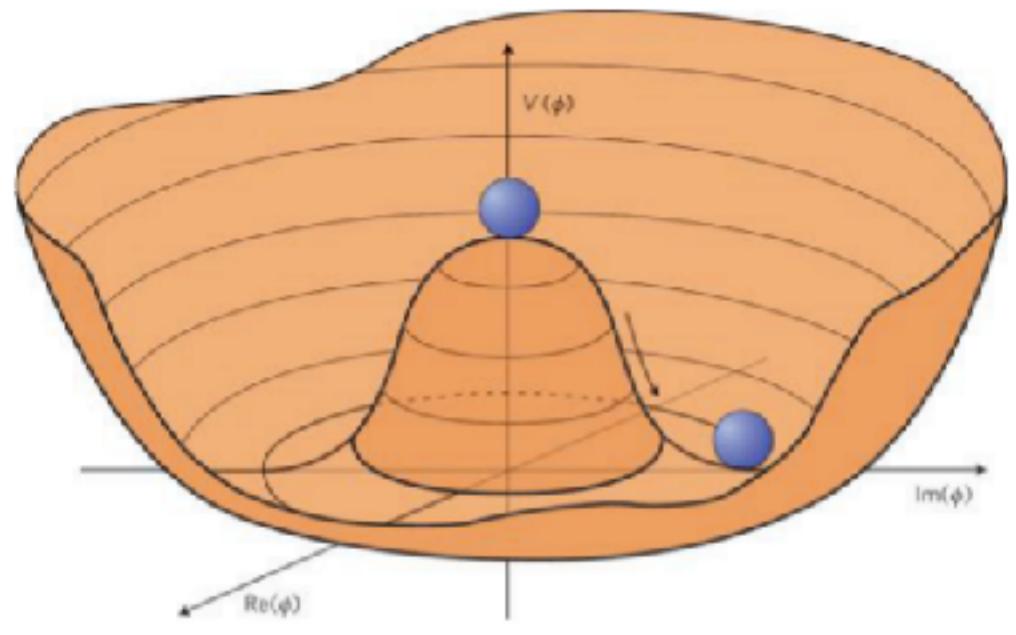
CMS diphoton

July 4th 2012  
CMS ZZ



ATLAS diphoton

# 为什么Higgs是上帝粒子



Higgs 粒子的势能项

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4$$

自发性电弱对称性破缺  
(Higgs机制)

$$\langle h \rangle \equiv v \neq 0 \rightarrow m_W = g_W \frac{v}{2}$$

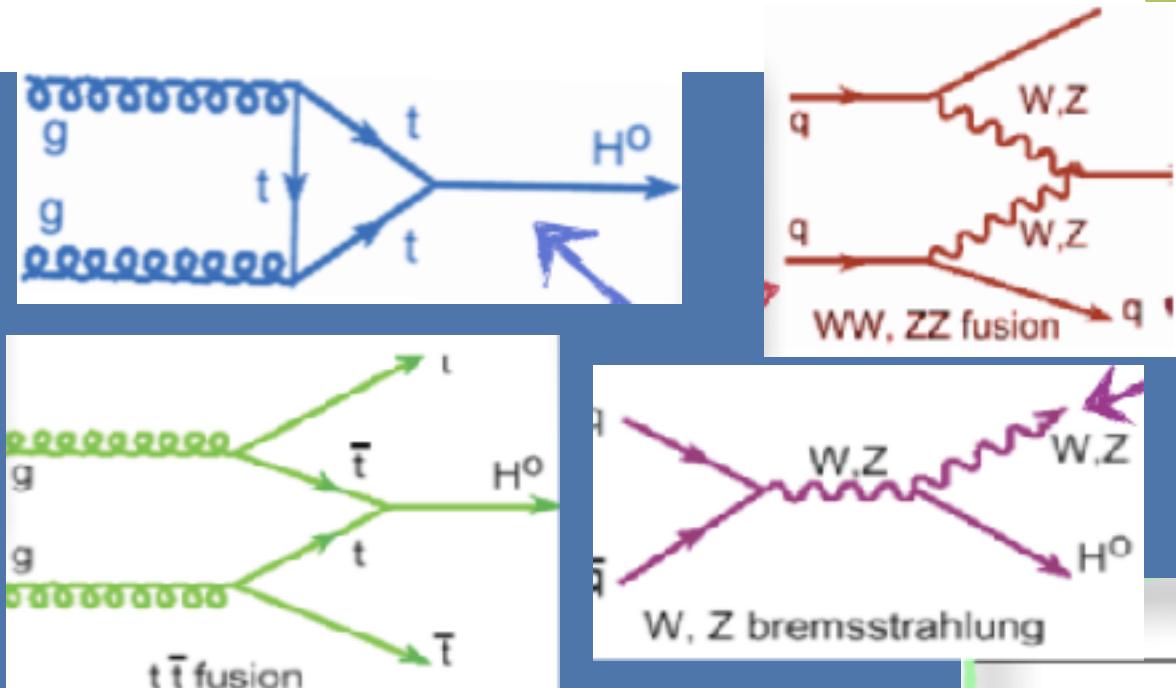
Higgs机制给予所有基本粒子质量

Higgs机制 NOT Higgs粒子

发现Higgs让我们对  
质量起源了解更多

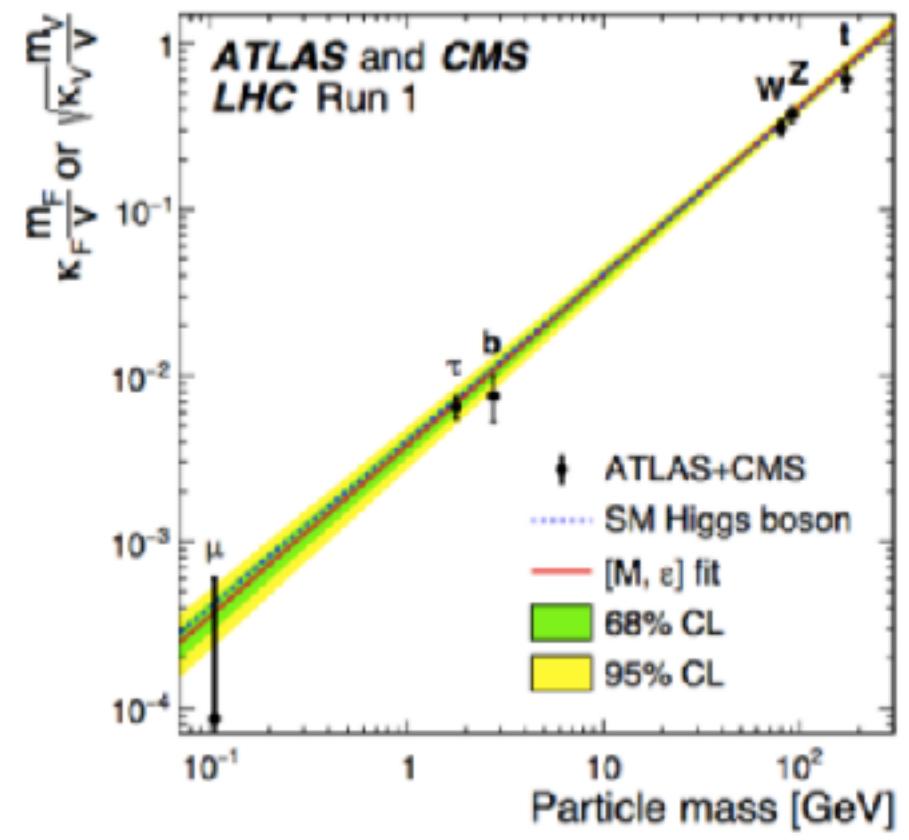
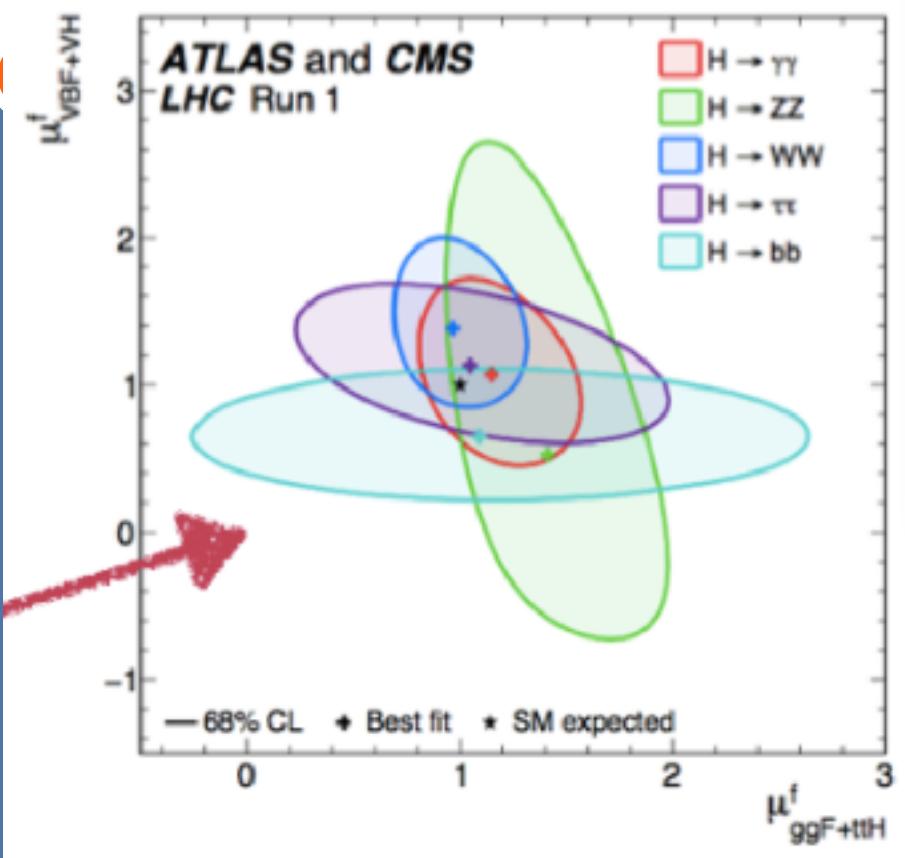
# Higgs 产生 衰变

	$m_H = 125.09$ GeV	$\sigma(\text{pb}) 13 \text{ TeV}$
ggF	49	
VBF	3.8	
Z(W)H	0.9(1.4)	
tH	0.5	



	ggF	VBF	VH	t <bar>t</bar> H	BR(%)
$H \rightarrow \gamma\gamma$	✓	✓	✓	✓	57
$H \rightarrow ZZ^* \rightarrow 4l$	✓	✓	✓	✓	22
$H \rightarrow WW^* \rightarrow 2l2\nu$	✓	✓	✓	✓	6.2
$H \rightarrow \tau\tau$	✓	✓	✓	✓	2.8
$H \rightarrow b\bar{b}$	✗	✗	✓	✓	0.23
$H \rightarrow \mu\mu$	✓	✓	✗	✗	0.15

# Higgs的性质



Higgs 质量

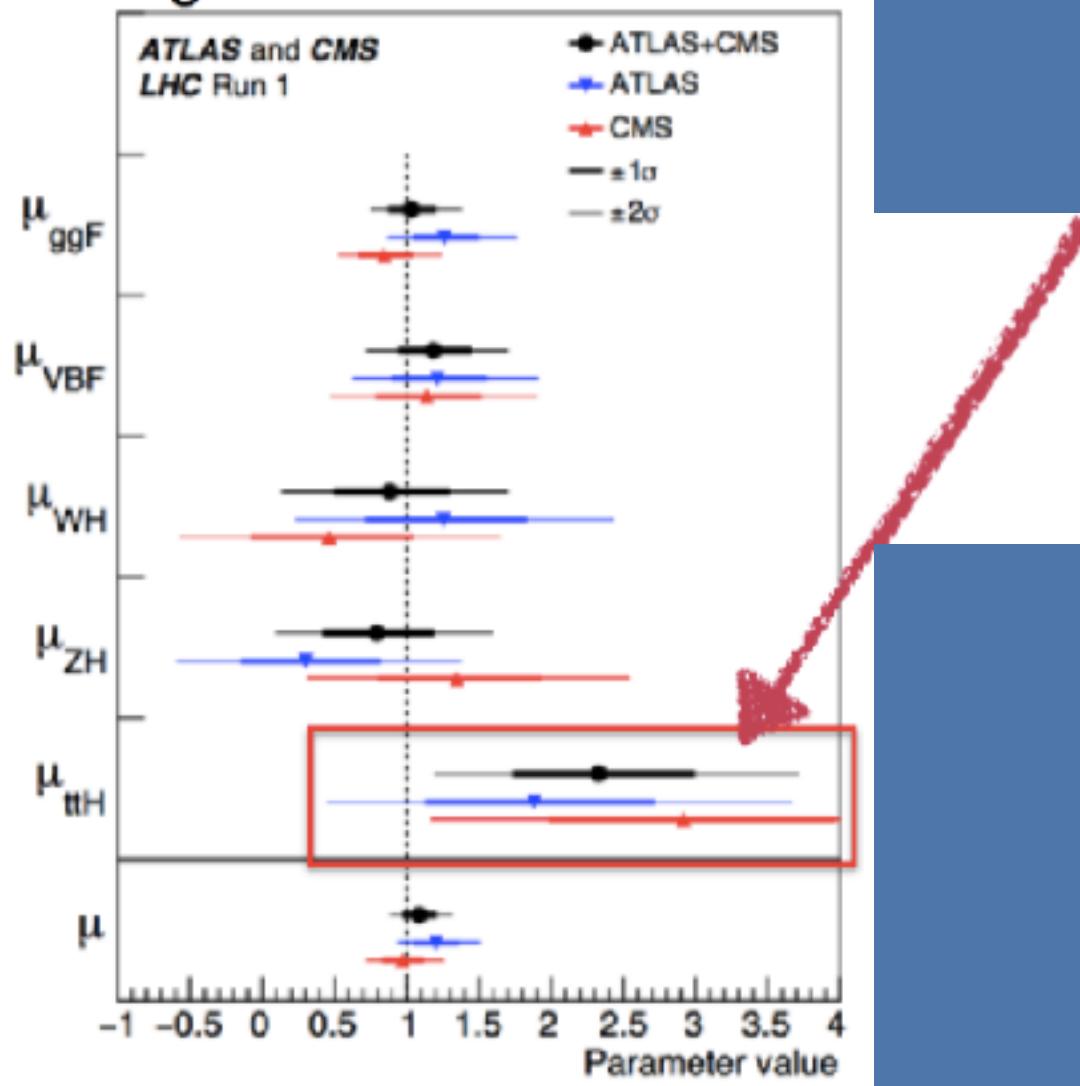
$$m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst}) \text{ GeV}$$

Run 2 结果类似

相互作用正比  
于质量

# Higgs的性质

Assuming SM BR



基本上都在2个  
sigma以内，除  
了 $t\bar{t}H$ 有点点接  
近3sigma涨落

# Higgs物理中的未知?



Higgs的势能

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4$$

Laudau-Ginzberg 势能 (超导)

$$m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!}\Lambda^2(h^\dagger h)^3.$$

必须是一个负数  
有原因么

$$\frac{1}{2}\lambda(h^\dagger h)^2 \log \left[ \frac{(h^\dagger h)}{m^2} \right]$$

$$V(h) \simeq -\gamma s_h^2 + \beta s_h^4.$$

我们其实从来也不知道，更不知道  
为什么会有电弱对称性破缺

# 电弱对称性破缺的起源



对于Higgs势能的量子  
涨落，泰勒展开式

$$h^3 \quad h^4 \quad h^5 \dots \dots \dots h^9$$

非常困难      暂时实验上看不到希望

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4$$

$$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4}h^4 + \frac{1}{\Lambda^2}h^6$$

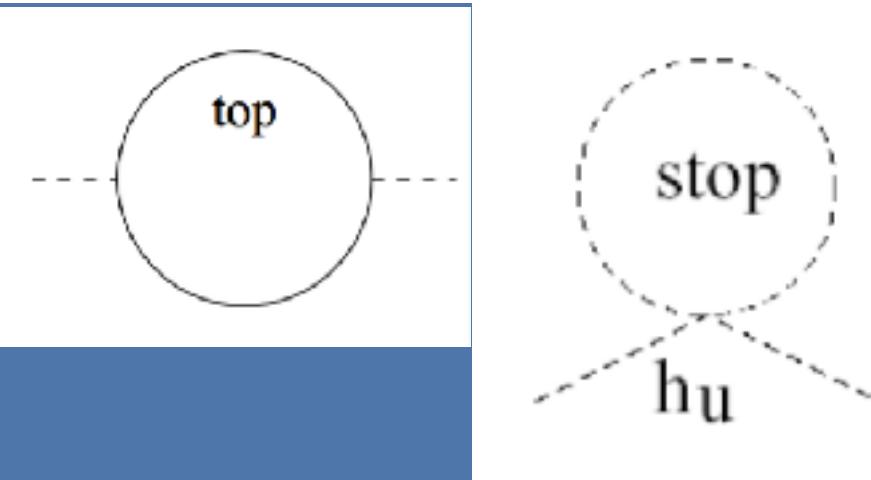
相同的对撞  
机信息，不  
同的势能

强一阶相变，引力波实验

# 超对称性

$$m_h^2 \simeq m_{\text{SUSY}}^2 \left( 1 - \frac{y_{\text{top}}^2}{16\pi^2} \log \left[ \frac{\Lambda^2}{m_{W,Z}^2} \right] + \dots \right)$$

微小的量子辐射修正



$$\begin{aligned} 16\pi^2 \mu \frac{d}{d\mu} m_{H_u}^2 &= 3X_t - 6g_2^2 M_2^2 - \frac{6}{5}g_1^2 M_1^2, \\ 16\pi^2 \mu \frac{d}{d\mu} m_{H_d}^2 &= -6g_2^2 M_2^2 - \frac{6}{5}g_1^2 M_1^2, \\ 16\pi^2 \mu \frac{d}{d\mu} m_{Q_3}^2 &= X_t - \frac{32}{3}g_3^2 M_3^2 - 6g_2^2 M_2^2 - \frac{2}{15}g_1^2 M_1^2, \\ 16\pi^2 \mu \frac{d}{d\mu} m_{U_3}^2 &= 2X_t - \frac{32}{3}g_3^2 M_3^2 - \frac{32}{15}g_1^2 M_1^2. \end{aligned}$$

$$X_t = 2h_t^2(m_{H_u}^2 + m_{Q_3}^2 + m_{U_3}^2)$$

完整的SUSY RGE

负数

SUSY中的质量起源

GUT能标下的初条件?

# Higgs粒子的复合性?

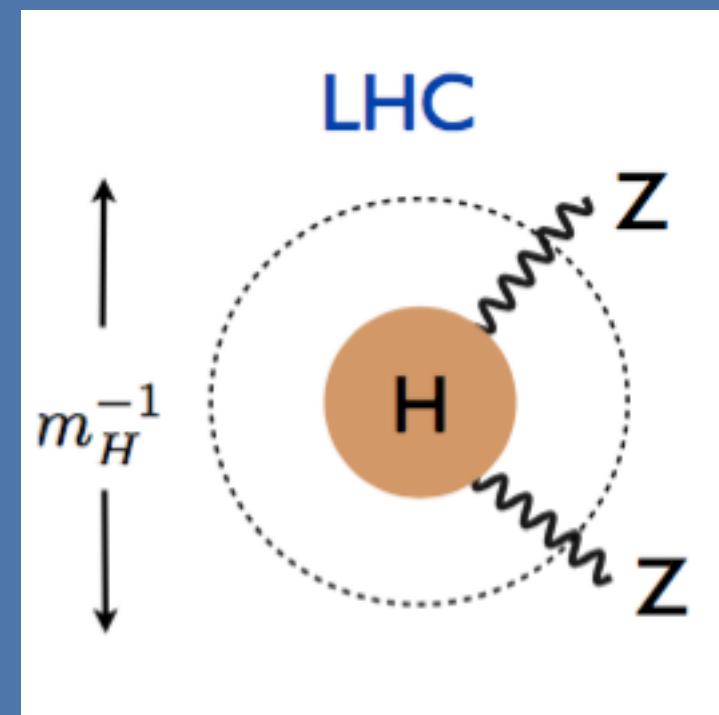


直到QCD能标下，我们才能看见Pi介子的结构（形状因子和I的偏移）

可能的新物理偏移

$$\delta = c \frac{m_W^2}{M_{\text{NP}}^2}, \quad c = \mathcal{O}(1)$$

现在复合能标在TeV左右



# 复合Higgs模型

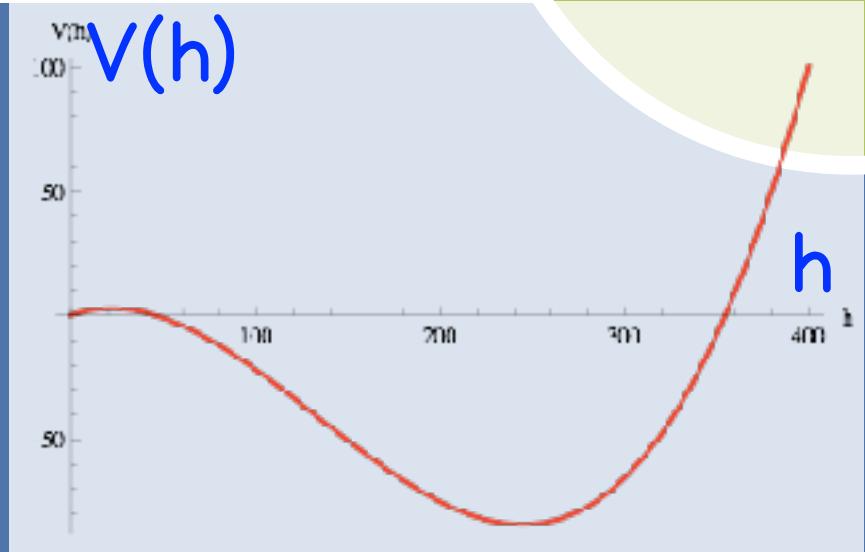
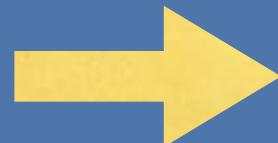


Pi介子没有真空期望值

只有正的质量项

Higgs势能可能的源：

- 复合Higgs中基本部分子的质量
- SM粒子的（主要是Top夸克的）量子辐射修正（卷图效应）？



# 复合Higgs粒子

Higgs作为一个pNGB粒子

Kaplan, H. Georgi, Phys.Lett.B 136 (1984) 183

Kaplan, H. Georgi, Phys.Lett.B 145 (1984) 216

● AdS/CFT框架下的对偶，最小复合Higgs粒子模型

K. Agashe, R. Contino, A. Pomarol, NPB 719 (2005) 165

● 大型强子对撞机时代，关心最普适的模型有效理论和对撞机实验信号。

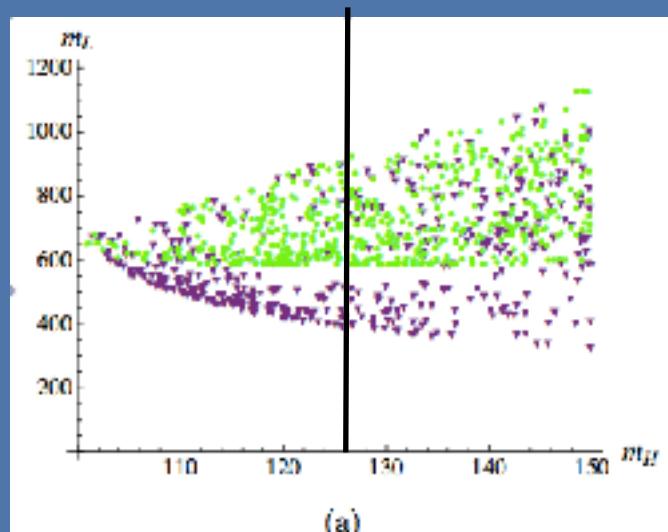
D. Marzocca, M. Serone, J. Shu., JHEP 1208, 013 (2012)

最新复合Higgs模型的突破

C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 119  
(2017) no13, 131803

如果伴随子不带QCD色荷的情况

C. Csaki, T. Ma, J. Shu., 1709.08636



# 如果Higgs是基本的

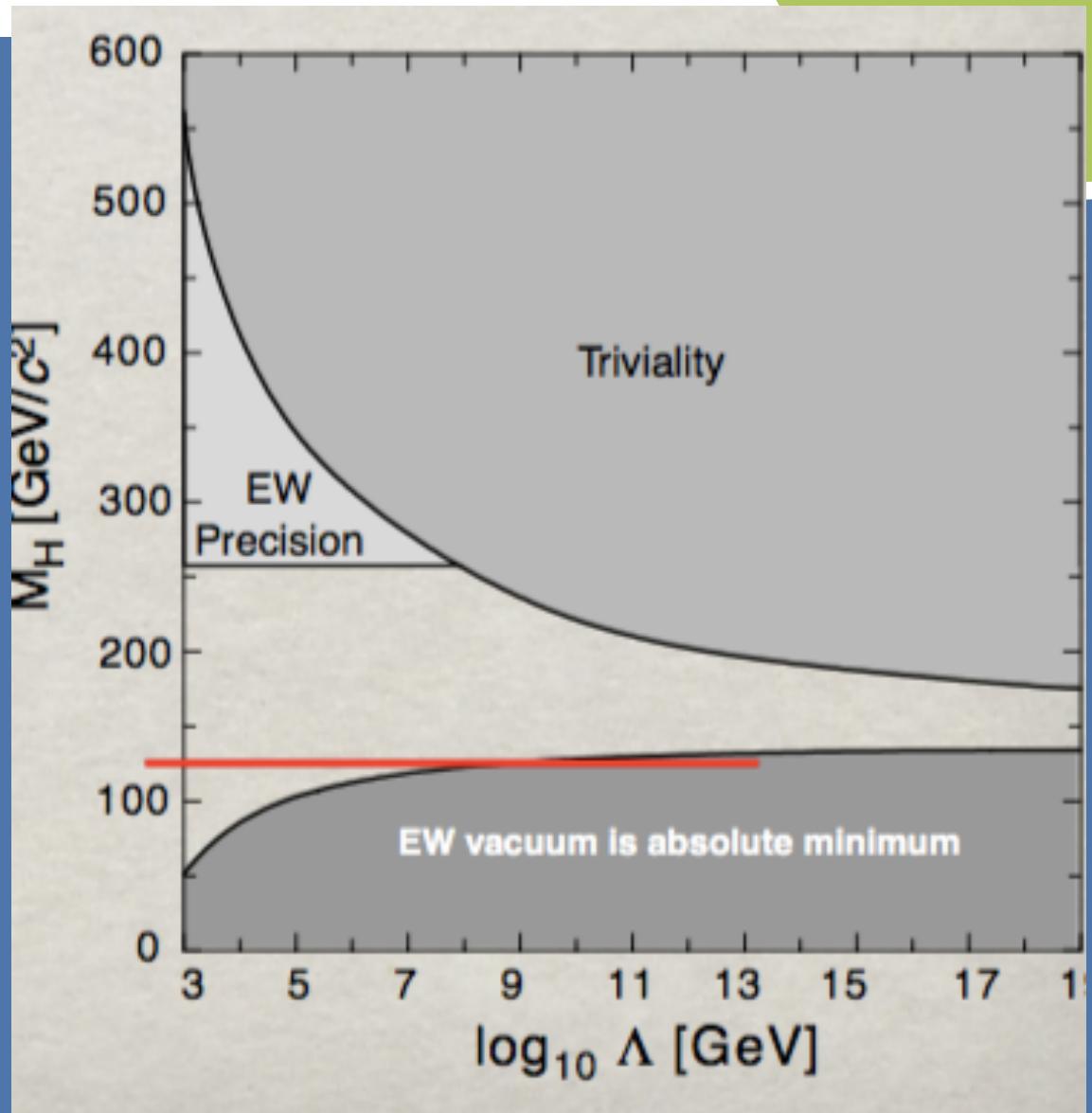


EW Vacuum stability

标准模型能够外推  
到非常高的能标

标度不变的模型

A. Farzinnia, Hong-jian He, Ren Jing,  
Phys.Lett.B, 727, (2013) 141



# 规范等级度的问题

.....



质量起源的能标

$$m_{phys}^2 = m_0^2 + c\Lambda^2 + \dots$$



- 如果Lambda是我们的某些基本高能标 (Plank? GUT? etc), 可怕的相消. 规范等级度的问题  
(Gauge Hierarchy Problem)

电弱能标

Top, Higgs, W, Z, etc

# Higgs自然性和Higgs'性质



Low energy Higgs theorem

$$\mathcal{L}_{\gamma\gamma} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \sum_i \frac{b_i e^2}{16\pi^2} \log \frac{\Lambda^2}{m_i^2} + \dots ,$$

QED effective action  
when integrating out  
a charged field  
Similar for QCD

Leading linear expansion in the Higgs background fields

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi} \frac{h}{v} \left[ \sum_i b_i \frac{\partial}{\partial \log v} \log (\det \mathcal{M}_{F,i}^\dagger \mathcal{M}_{F,i}) + \sum_i b_i \frac{\partial}{\partial \log v} \log (\det \mathcal{M}_{B,i}^2) \right] F_{\mu\nu} F^{\mu\nu} ,$$

Non-SUSY理论越自然, Higgs产生越小(伴随子带QCD色)

I. Low, R. Rattazzi, A. Vichi, JHEP, 1004, (2010) 126

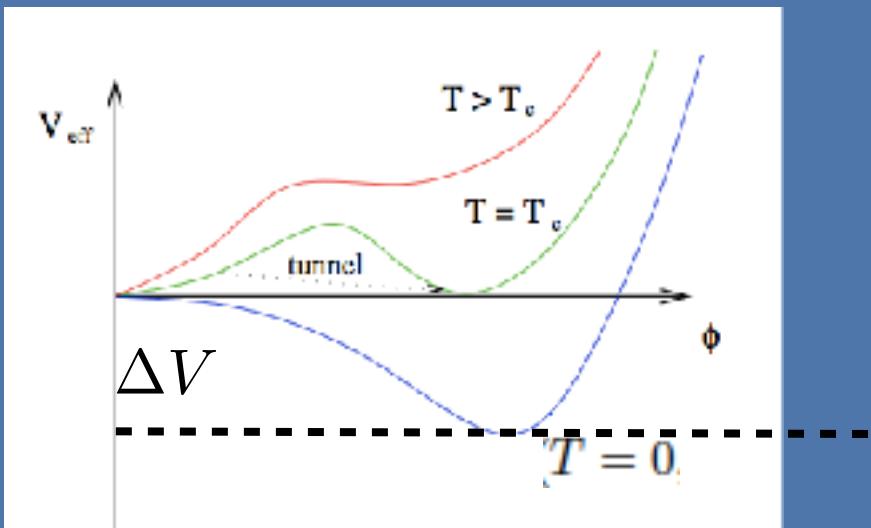
SUSY理论越自然, Higgs产生越大  
(伴随子带QCD色)

R. Dermisek, I. Low, Phys.Rev.D, 77, (2008) 035012

$$\frac{1}{16\pi^2} \Lambda^2 \text{Str } \mathcal{M}^\dagger \mathcal{M} ,$$

# 一阶相变基本条件

标量场产生的 1st order EWPT:



$$\frac{v_c}{T_c} \simeq \frac{v^4 E}{2\Delta V}$$

J. S, private derivations.

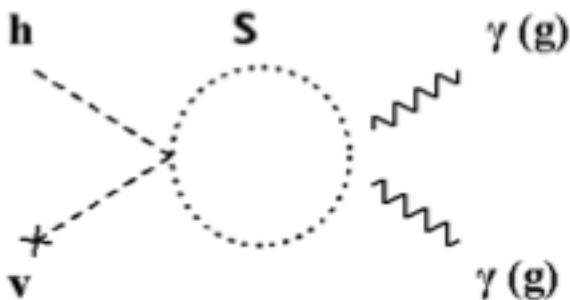
假设  $v_c \approx v,$

Better in stronger  
EWPT

- 增大  $E\phi^3 T$  项
- 减小  $T=0$  能量差  $\Delta V$  (微调势能)

# Higgs性质和电弱相变

如果粒子S带SU(3)色或者电荷的话



$$\frac{\sigma(gg \rightarrow h)}{\sigma(gg \rightarrow h)_{\text{SM}}} = \frac{\Gamma(h \rightarrow gg)}{\Gamma(h \rightarrow gg)_{\text{SM}}} = \frac{\hat{c}_{g,\text{SM}} + \delta c_g}{\hat{c}_{g,\text{SM}}}$$

$$\frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}}} = \frac{\hat{c}_{\gamma,\text{SM}} + \delta c_\gamma}{\hat{c}_{\gamma,\text{SM}}}$$

$$\delta c_g = \frac{C(r_s)}{2} \frac{\alpha v^2}{m_s^2} A_s(\tau_s)$$

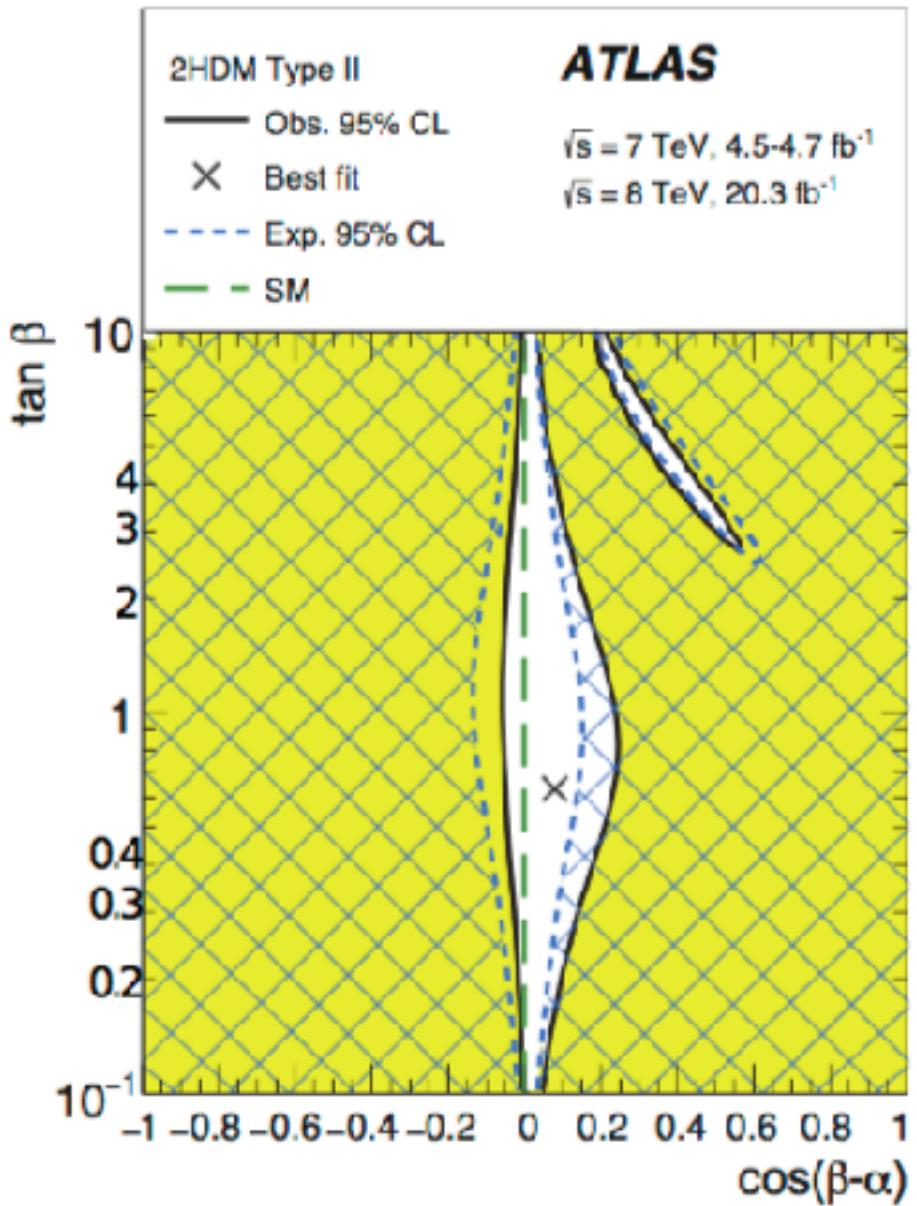
$$\delta c_\gamma = \frac{N(r_s) Q_s^2}{24} \frac{\alpha v^2}{m_s^2} A_s(\tau_s)$$

强一阶电弱相变  
增大的 Higgs 产率  
压低的 Higgs 双光子 BR

MSSM Stop 已经被排除了

W. Huang, J. S, Y. Zhang, JHEP 1303 (2013) 164  
D. Chung, A. Long, L. T. Wang, PRD 87 (2013) 023509

# Higgs物理



SUSY Type II 2HDM

只在Alignment  
limit附近满足

Alignment limit附近重的Higgs  
仅仅和费米子相互作用  
H to tau tau

Jun-jie. Cao, Zhao-xia Han, Jinmin Yang, Yan-Ming  
Zhang, Jing-ya Zhu, JHEP, 1203, (2012) 086

Jun-jie. Cao, Zhao-xia Han, Dong-wei Li, Jinmin Yang,  
Phys. Lett.B, 710, (2012) 665

# Higgs有效场论



$$SU(2)_L \times SU(2)_R$$

$\Sigma(x) = \exp(i\sigma^a \chi^a(x)/v)$  Goldstone 相互作用

Higgs是custodial symmetry下的singlet

$$\begin{aligned} \mathcal{L}_H = & \frac{1}{2}(\partial_\mu h)^2 + V(h) + \frac{v^2}{4} Tr[(D_\mu \Sigma)^\dagger (D_\mu \Sigma)] (1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \dots) \\ & - \frac{v}{\sqrt{2}} \Sigma [1 + c_j \frac{h}{v} + \dots] \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c. \end{aligned}$$

$$\begin{aligned} f^2 \sin^2 \frac{h}{f} = & f^2 \left[ \sin^2 \frac{\langle h \rangle}{f} + 2 \sin \frac{\langle h \rangle}{f} \cos \frac{\langle h \rangle}{f} \left( \frac{h}{f} \right) \right. \\ & \left. + \left( 1 - 2 \sin^2 \frac{\langle h \rangle}{f} \right) \left( \frac{h}{f} \right)^2 + \dots \right] \end{aligned}$$

$$= v^2 + 2v \sqrt{1-\xi} h + (1-2\xi) h^2 + \dots$$

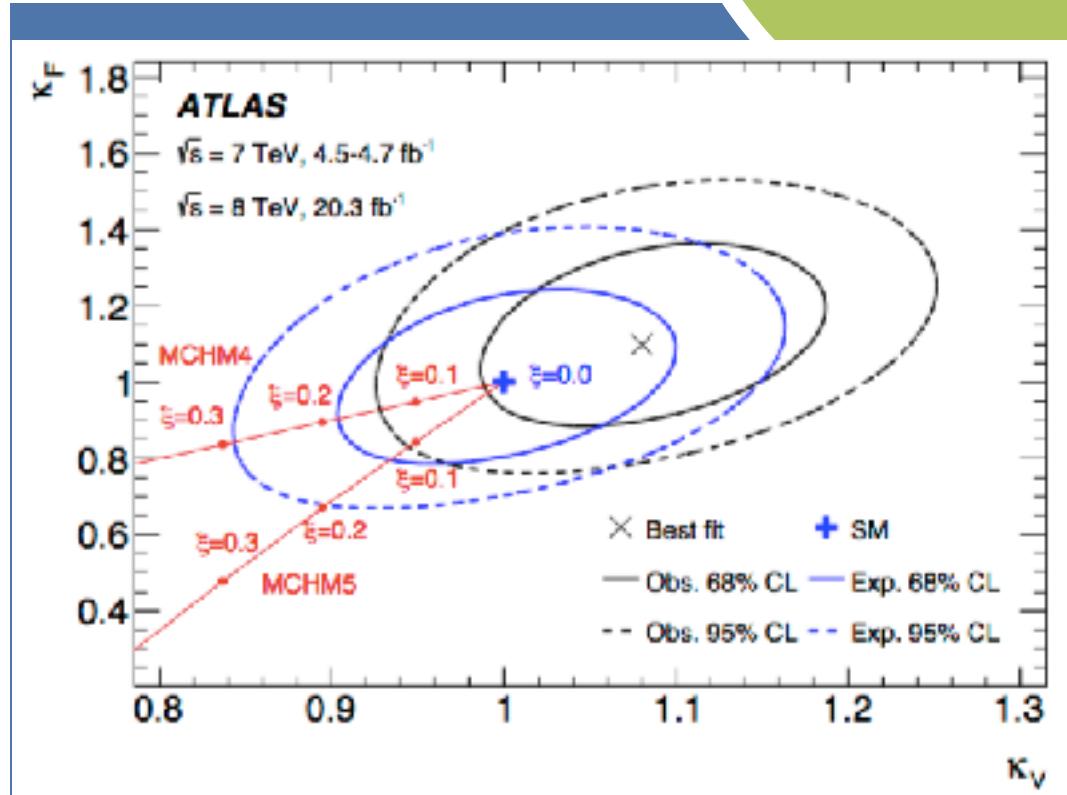
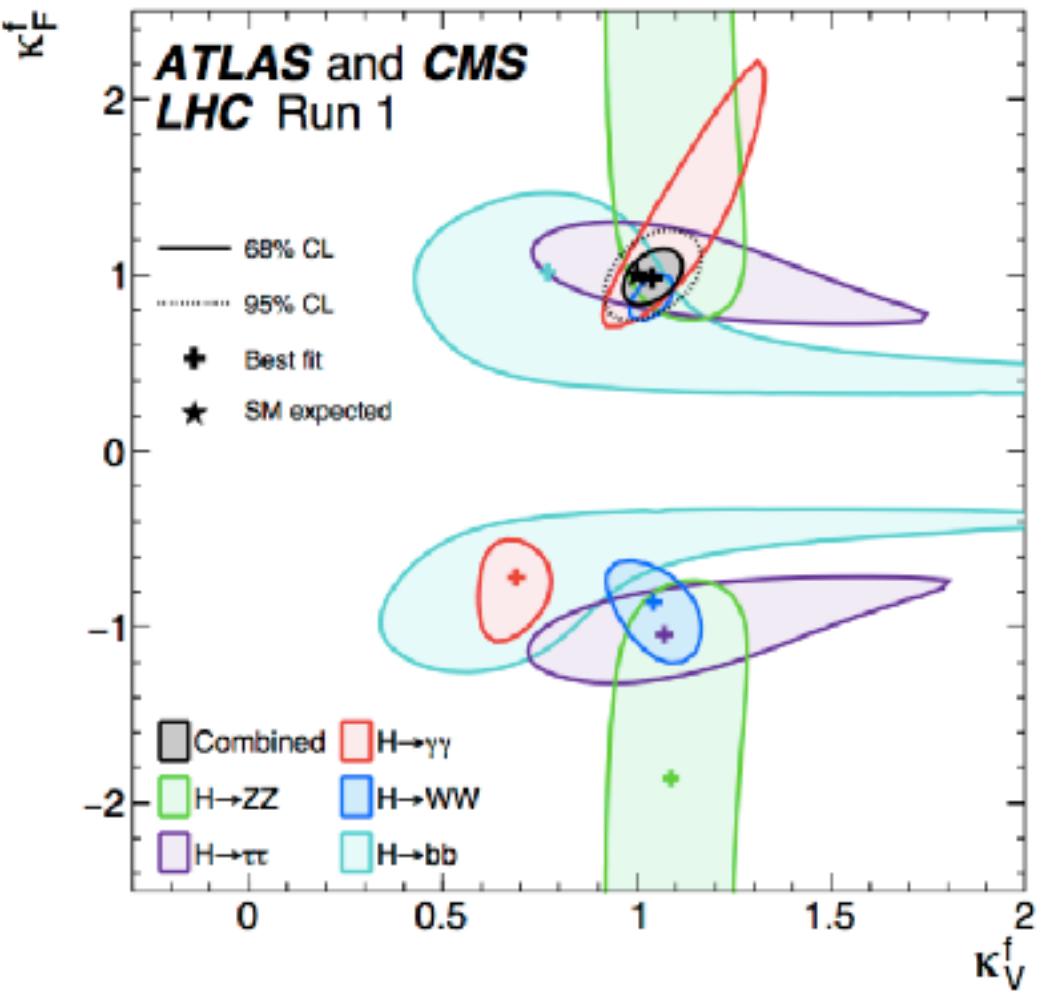
W波色子

$$a = \sqrt{1-\xi} \quad b = 1-2\xi$$

费米子

$$m_f(h) \propto \sin \left( \frac{2h}{f} \right) \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

# Higgs物理

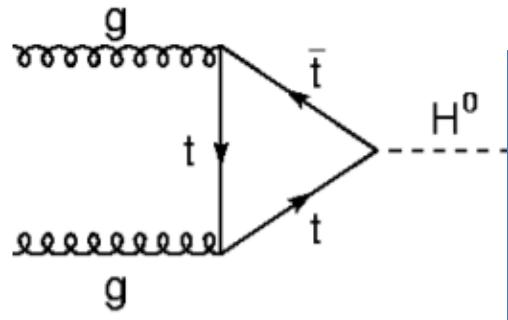


复合Higgs模型

Top耦合为负的情况不再存在

Higgs 拟合  $\xi < 0.1$

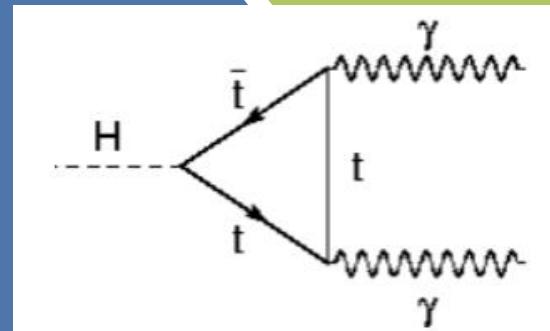
# LHC Higgs物理和 CP破坏



if colored

$$m_\chi(v)e^{i\theta(v)}$$

复的质量项



if electric charged

2HDM

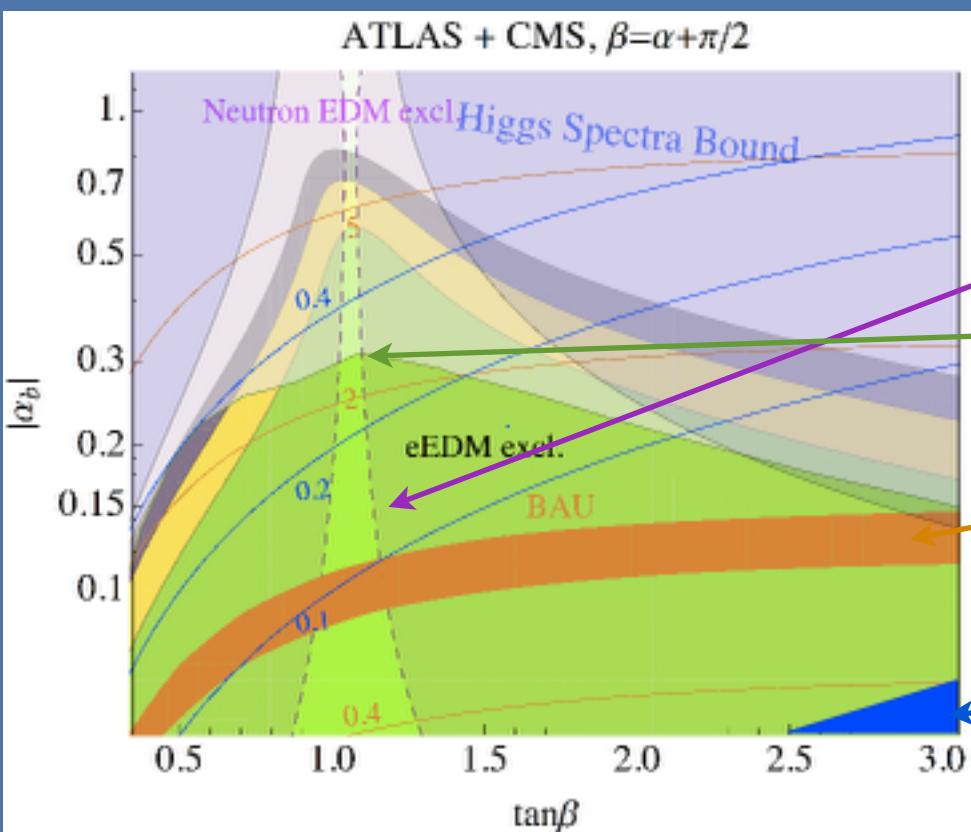
ACME bound

当前中子  
EDM 实验

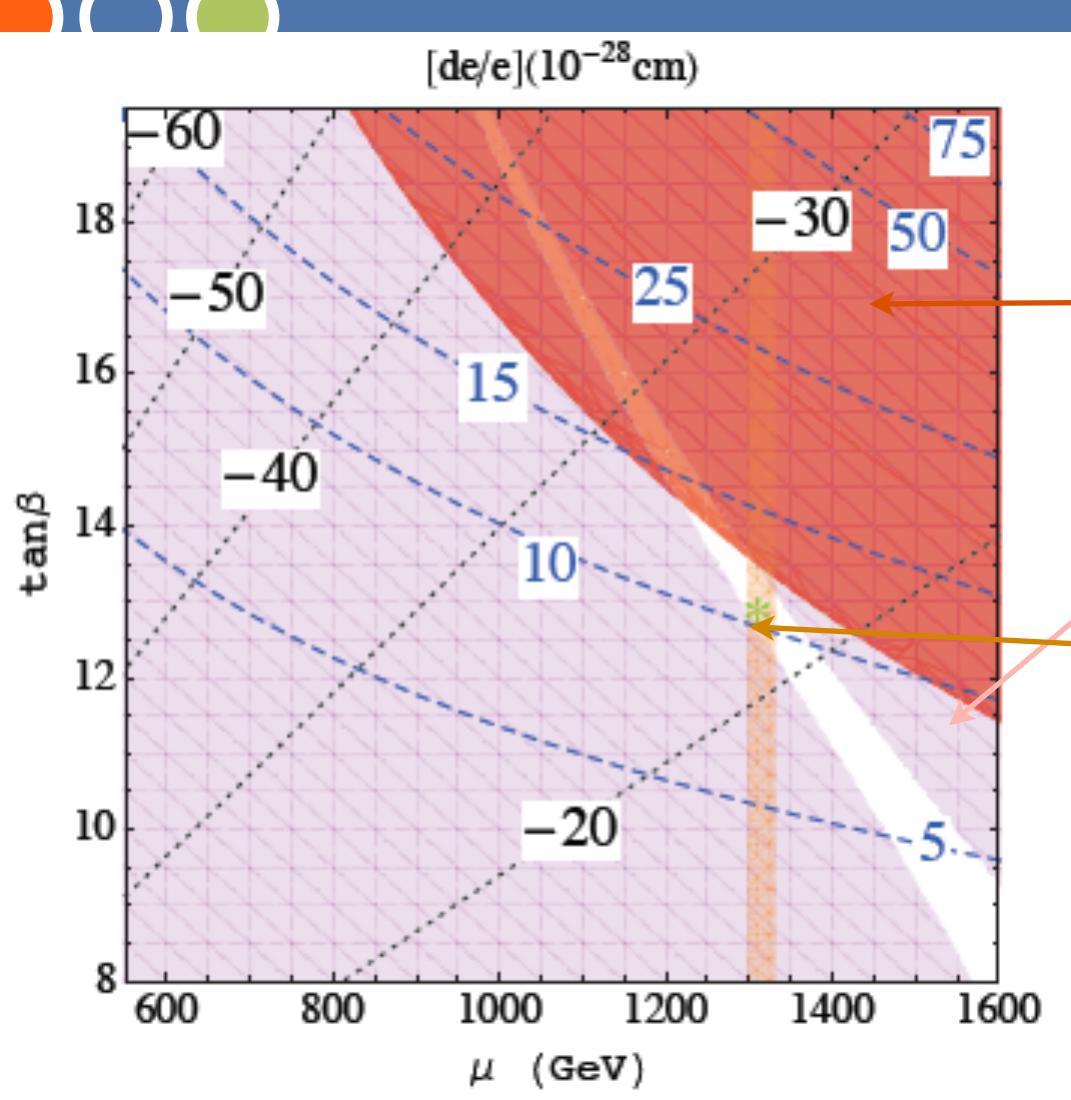
EWBG的区域

Higgs全局拟合有限制

$$\tilde{c}_t \sim \mathcal{O}(10^{-2})$$



# MSSM中Higgs CP破坏区域



重的 Higgs CP破  
坏的寻找  
**Mercury exclusion**

ACME 排除  
EWBG

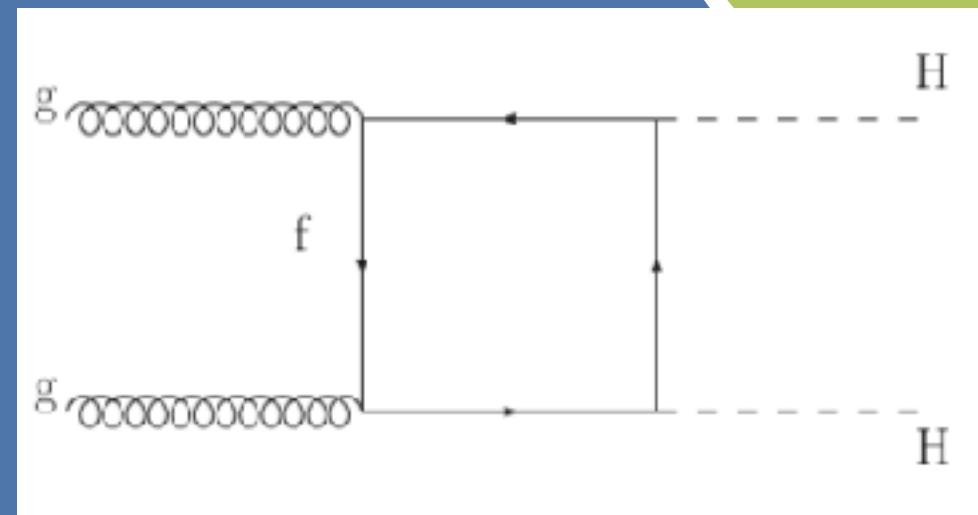
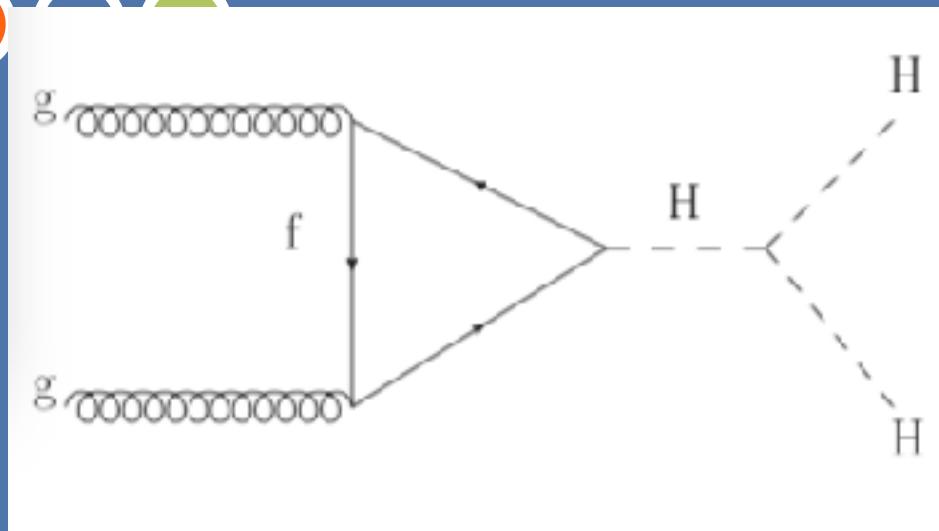
L-g, Bian, T. Liu, J. S, Phys.  
Rev. Lett. 115 (2015) 021801

tth Higgs CP

John F.Gunion, Xiao-gang He,  
Phys.Rev.Lett. 77 (1996) 5172

Jinmian, Li, Zhong-guo Si, Lei Wu,  
Jason Yue, arxiv: 1701.00224

# 双Higgs产生衰变



Andreas Papaefstathiou, Li Lin. Yang, Jose Zurita, PRD, 87, (2012) 011301

Florian Goertz, Andreas Papaefstathiou, Li Lin. Yang, Jose Zurita, JHEP, 06, (2013) 016

Qiang Li, Zhao Li, Qishu Yan, Xiaoran Zhao, PRD, 92, (2015) 01 014015

Jun-jie. Cao, Zhao-xia Han, Liangliang Shang, Peiwen Wu, Jinmin Yang, JHEP, 1304, (2013) 134

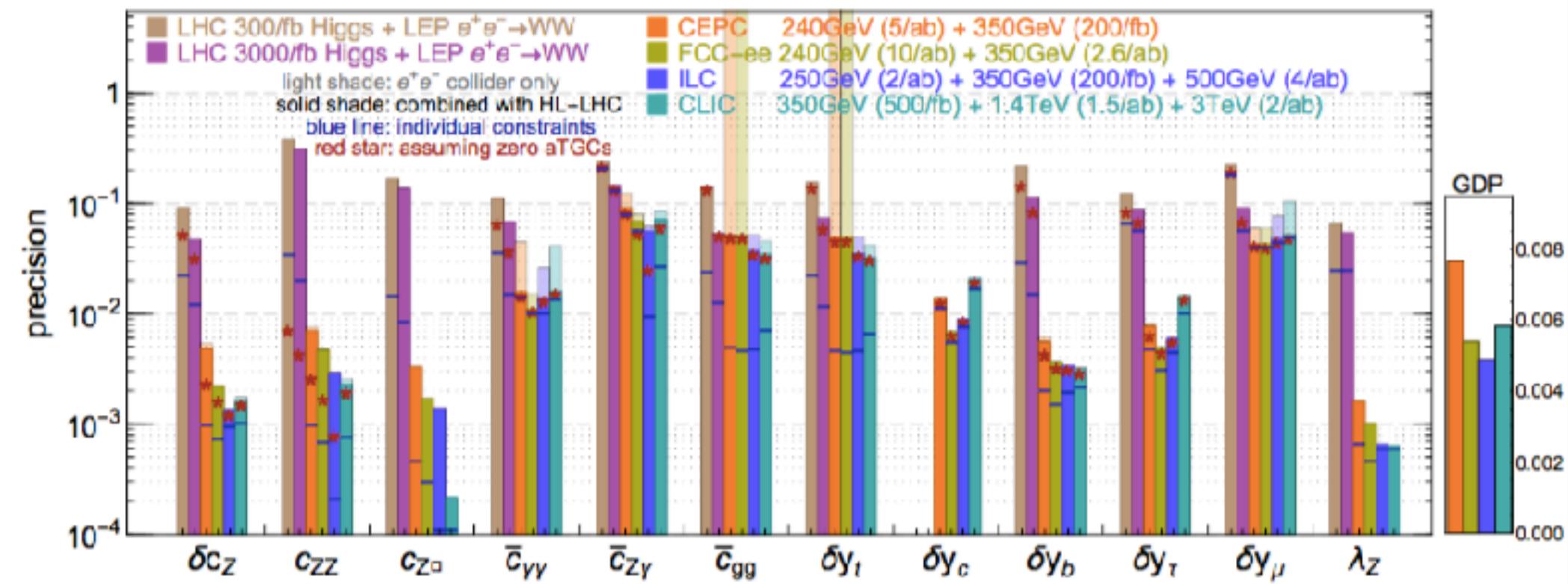
Q-h. Cao, Gang Li, Bin Yan, Hao Zhang, PRD, 96, (2017) 09 095031

个人认为是最核心的channel

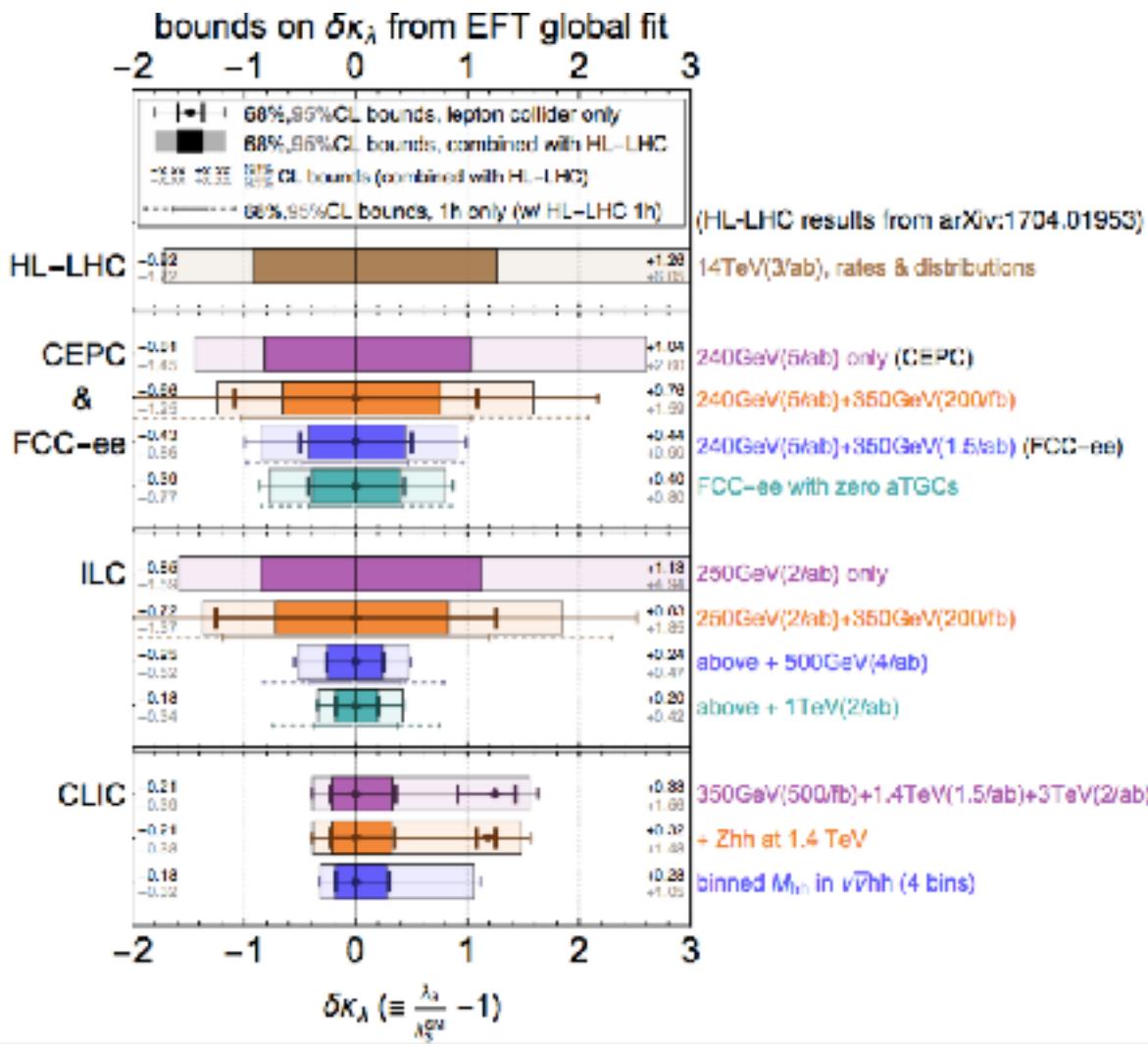
新物理模型Higgs势能，电弱相变相关

# 未来Higgs精确测量

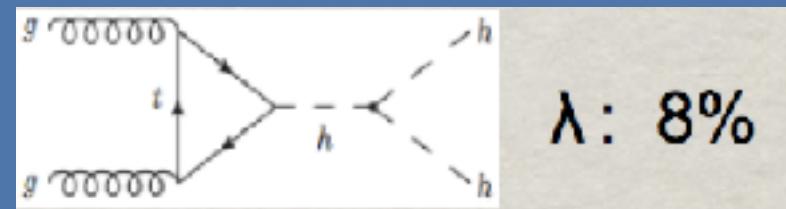
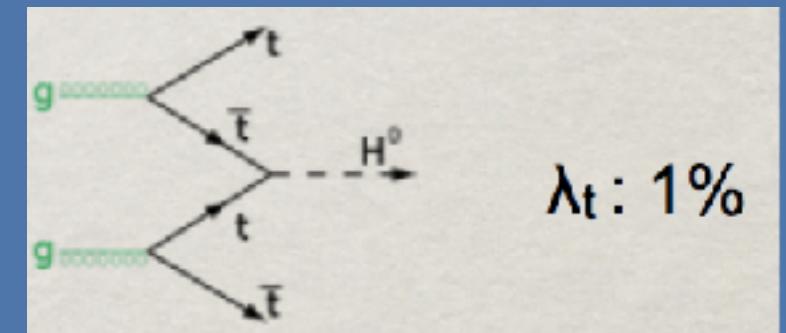
precision reach of the 12-parameter fit in Higgs basis



# 未来Higgs自相互作用测量



## 100 TeV 对撞机



N. Arkani-Hamed, Tao Han, M. Mangano, Lian-tao Wang, Phys.Rept. 652 (2016) 1

# UV & IR 理论互动

最近量子场论散射振幅的一个很有趣的发展就是某些类型的理论完全能够被他IR极限下的理论重建.

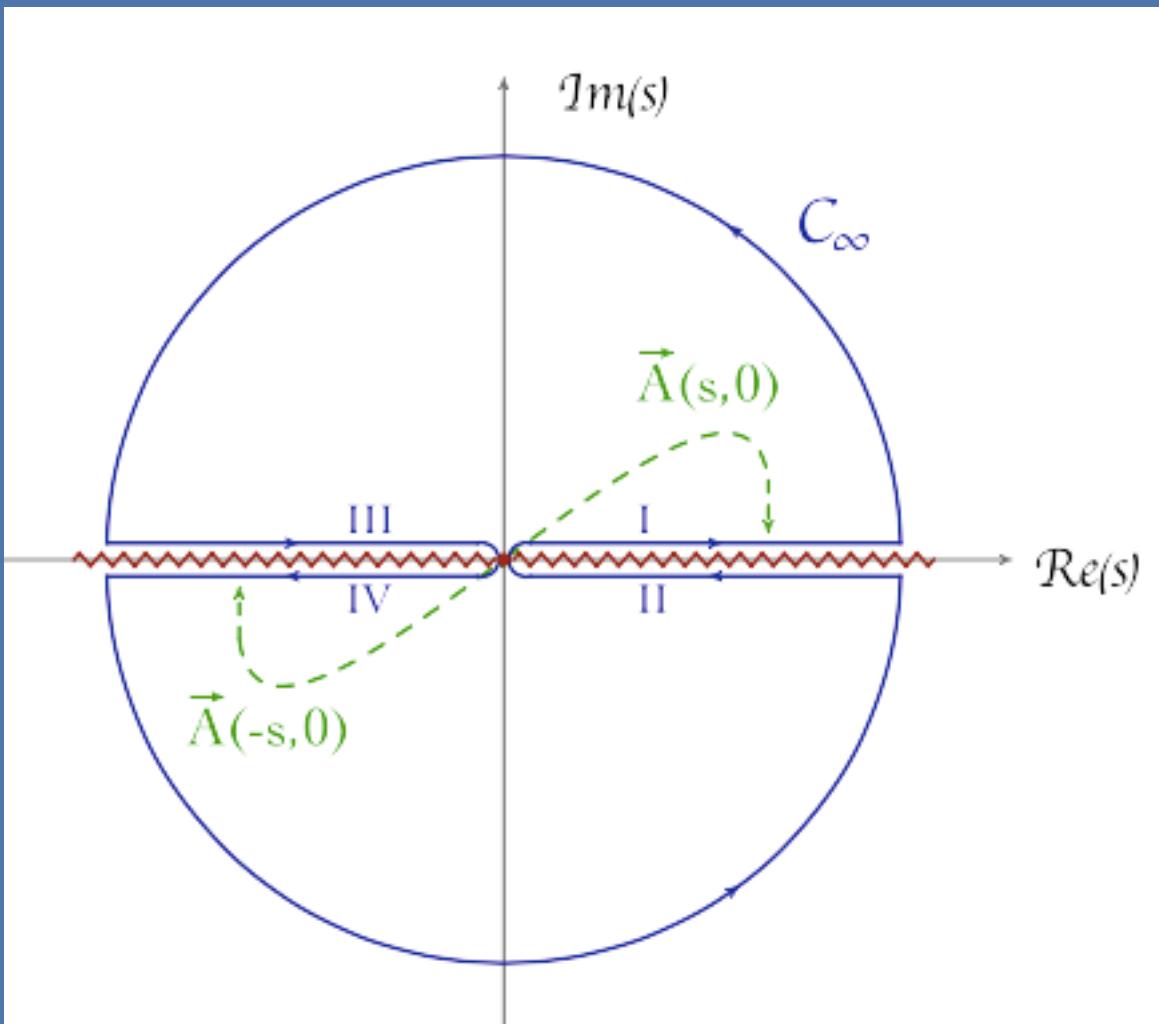
Nonlinear sigma model, DBI, Galilean, etc.

第一类就是QCD里面的pion soft theorem

In QCD, 我们有Adler-Weinberg sum rule!

$$\frac{2}{v^2} = \frac{2}{\pi} \int_0^\infty \frac{ds}{s} \left[ \frac{1}{3}\sigma^{I=0}(s) + \frac{1}{2}\sigma^{I=1}(s) - \frac{5}{6}\sigma^{I=2}(s) \right]$$

# Matching amplitudes



Matching  
amplitudes in  
the residue of  
the IR and UV

# Constraining SM Amplitudes

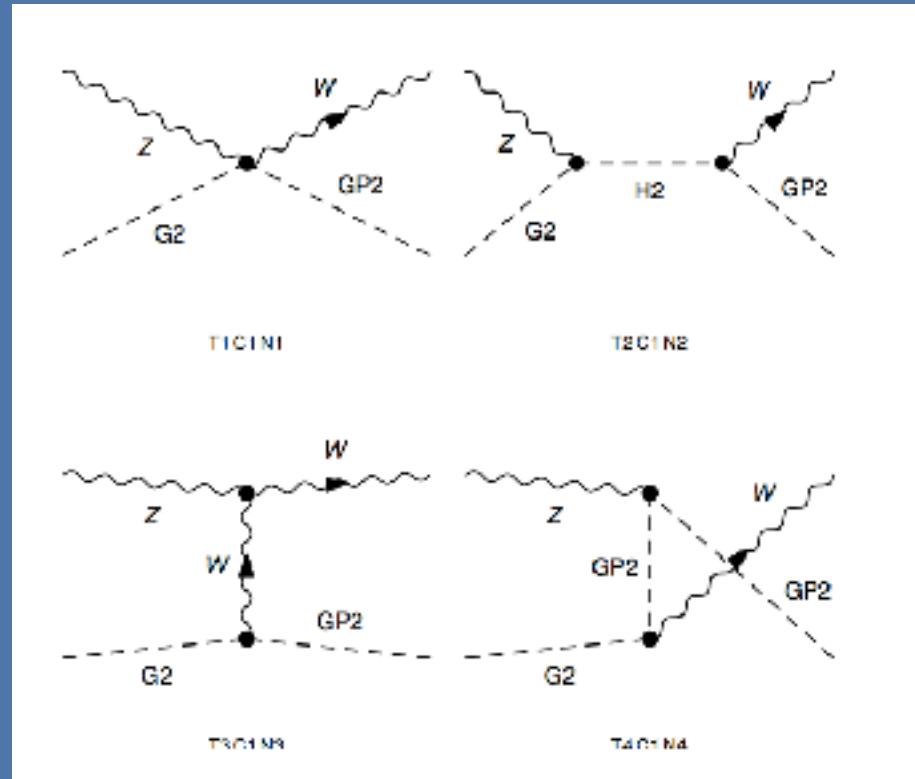


看最一般的W/Z higgs的2到2过程的散射振幅

T. Ma, H. Murayama, J. Shu., in progress

$\mathcal{O}_{SM}^H \equiv (D_\mu H)^\dagger D_\mu H$	$W_\mu \pi \rightarrow W_\mu \pi$
$\mathcal{O}_{SM}^\lambda \equiv \frac{1}{2}(H^\dagger H)^2$	$\pi\pi \rightarrow \pi\pi$
$\mathcal{O}_{SM}^G \equiv -\frac{1}{4}W_{\mu\nu}^a W_{\mu\nu}^a$	$W_\mu W_\nu \rightarrow W_\mu W_\nu$
$\mathcal{O}_H \equiv \frac{1}{2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H)$	$\pi\pi \rightarrow \pi\pi$
$\mathcal{O}_T \equiv \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}_\mu H)$	$\pi\pi \rightarrow \pi\pi$
$\mathcal{O}_W \equiv i\frac{g}{2}(H\sigma^i \overleftrightarrow{D}_\mu H)(D^\nu W_{\mu\nu})^i$	$W\pi \rightarrow W\pi$
$\mathcal{O}_{HW} \equiv ig(D_\mu H)^\dagger \sigma^i (D_\nu H) W_{\mu\nu}^i$	$W\pi \rightarrow W\pi$
$\mathcal{O}_{2W} \equiv -\frac{g^2}{2}(D_\mu W_{\mu\nu})^i (D_\rho W^{\rho\nu})^i$	$W_\mu W_\nu \rightarrow W_\mu W_\nu$
$\mathcal{O}_{3W} \equiv g^3 \epsilon_{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W^{k\rho\mu}$	$W_\mu W_\nu \rightarrow W_\mu W_\nu$

Consider BSM with  
D=6 operators



# 类似的结论



LL scattering

$$c_H = \frac{f^2}{4} \int_0^\infty \frac{ds}{s^2} \left[ \frac{1}{3} \text{Im } \mathcal{T}_0(s) + \frac{1}{2} \text{Im } \mathcal{T}_1(s) - \frac{5}{6} \text{Im } \mathcal{T}_2(s) \right]_{\infty}$$

LT scattering

$$\begin{aligned} C_W + C_{HW} &= c'_\infty \\ &+ \frac{1}{2\pi g^2} \int_0^\infty \frac{ds}{s} [\frac{1}{3} \sigma_0^{W\pi}(s) + \frac{1}{2} \sigma_1^{W\pi}(s) - \frac{5}{6} \sigma_2^{W\pi}(s)]. \end{aligned}$$

TT scattering

$$\beta = \frac{1}{8\pi g^4} \int_0^\infty \frac{ds}{s} [\frac{1}{3} \sigma_0^{WW}(s) + \frac{1}{2} \sigma_1^{WW}(s) - \frac{5}{6} \sigma_2^{WW}(s)],$$

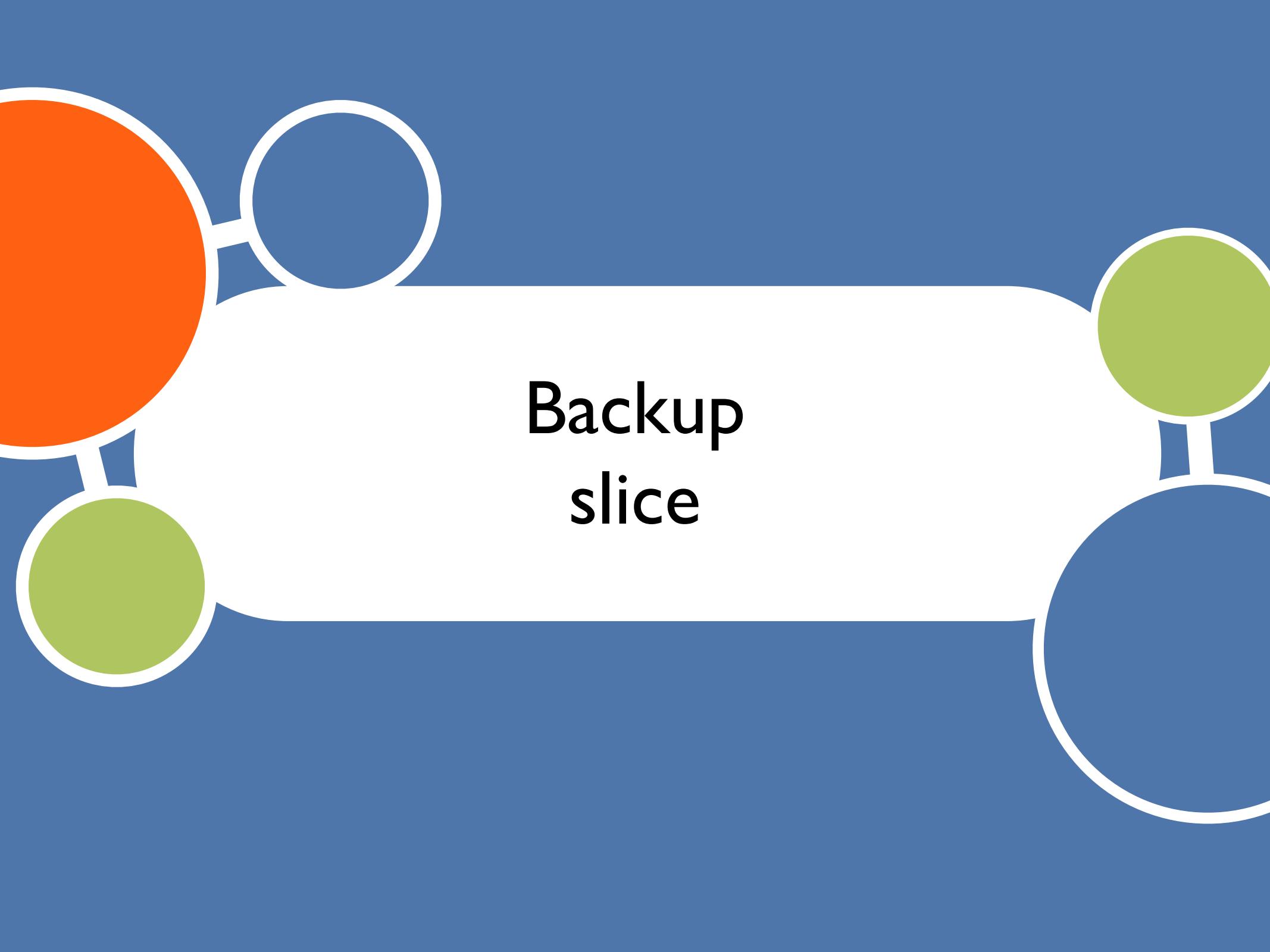
WZ 或者 Higgs 和 top quark 的散射也可以这么做，和电弱对称破缺相关

解释  $t\bar{t}h > 1$

# 总结



- TeV物理核心问题, 电弱自发性对称破缺机制和Higgs物理相关。
- 当前我们的Higgs精确测量没有新物理迹象, Higgs相关新物理限制在TeV能标左右。
- 未来Higgs新物理测量最重要的是自相互作用。
- Higgs和宇宙学方面. 强一阶电弱相变, Higgs CP破坏都和我们Higgs的精确测量相关。



Backup  
slice

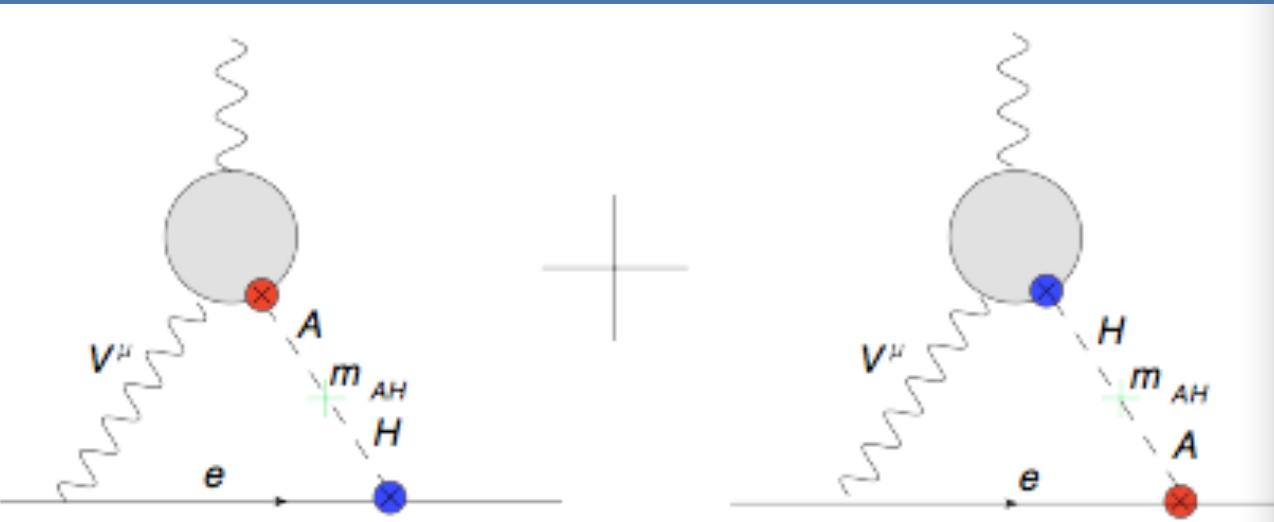
# 2HDM 的例子

$$\begin{aligned}\mathcal{L}_{\text{eff}} = & \frac{m_f}{v} h \bar{f} (c_f + i \tilde{c}_f \gamma^5) f \\ & + \frac{\alpha}{\pi v} h \left( c_\gamma F^{\mu\nu} V_{\mu\nu} + \tilde{c}_\gamma F^{\mu\nu} \tilde{V}_{\mu\nu} \right),\end{aligned}$$

$$\mathcal{L}_{\text{eff}} = -i d_e \bar{e} \sigma^{\mu\nu} \gamma_5 e \partial_\mu A_\nu$$

$$\frac{d_e}{e} = \frac{\alpha m_e}{4\pi^3 v^2} \left[ -c_e \tilde{c}_\gamma \log \left( \frac{\tilde{\Lambda}_{\text{UV},i}^2}{m_{h_i}^2} \right) + \tilde{c}_e c_\gamma \log \left( \frac{\Lambda_{\text{UV},i}^2}{m_{h_i}^2} \right) \right]$$

EFT only for illustration



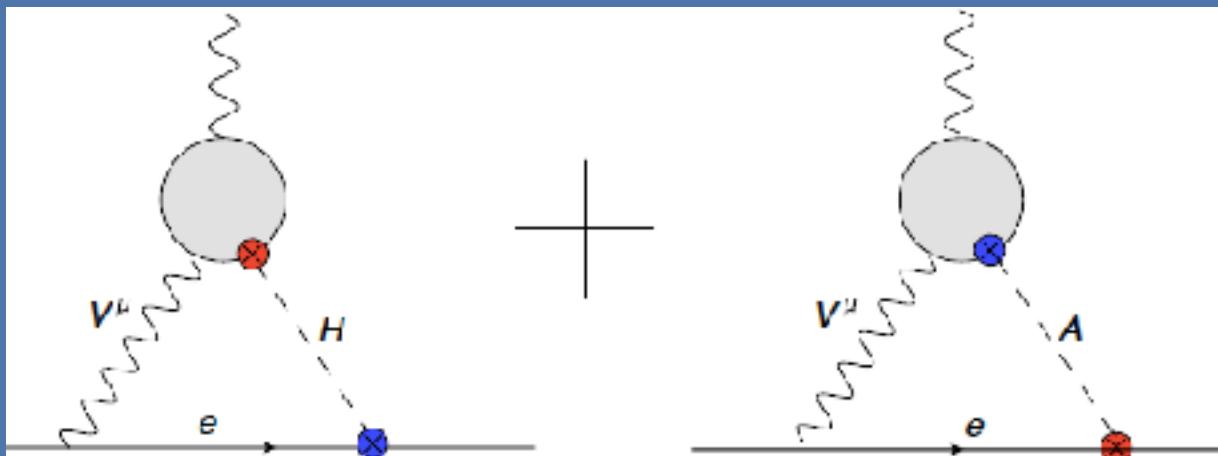
The 125 GeV  
Higgs 是一个  
CP 混合态!

# MSSM 的情况



$$\left[ \frac{de}{e} \right] \approx C \tilde{c}_e^A \sum_{j=1,2} \left( c_{\gamma}^{\tilde{\chi}_j^\pm} \ln \frac{1}{z_{\tilde{\chi}_j^\pm}^A} + c_{\gamma}^{\tilde{\tau}_j^\pm} \ln \frac{1}{z_{\tilde{\tau}_j^\pm}^A} \right) - C \tilde{c}_e^H \sum_{j=1,2} \tilde{c}_{\gamma}^{\tilde{\chi}_j^\pm} \ln \frac{1}{z_{\tilde{\chi}_j^\pm}^H}$$

EFT only for illustration



MSSM 里面的  
chargino & staus

Higgs 里面的 CPV 可  
以忽略 (圈图)

重的 Higgs 耦合被  
tan beta 增强

重的 Higgs 产生  
相消机制