Higgs CP violation

some remarks

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Workshop on the CP nature of the Higgs boson
ACFI, 2015

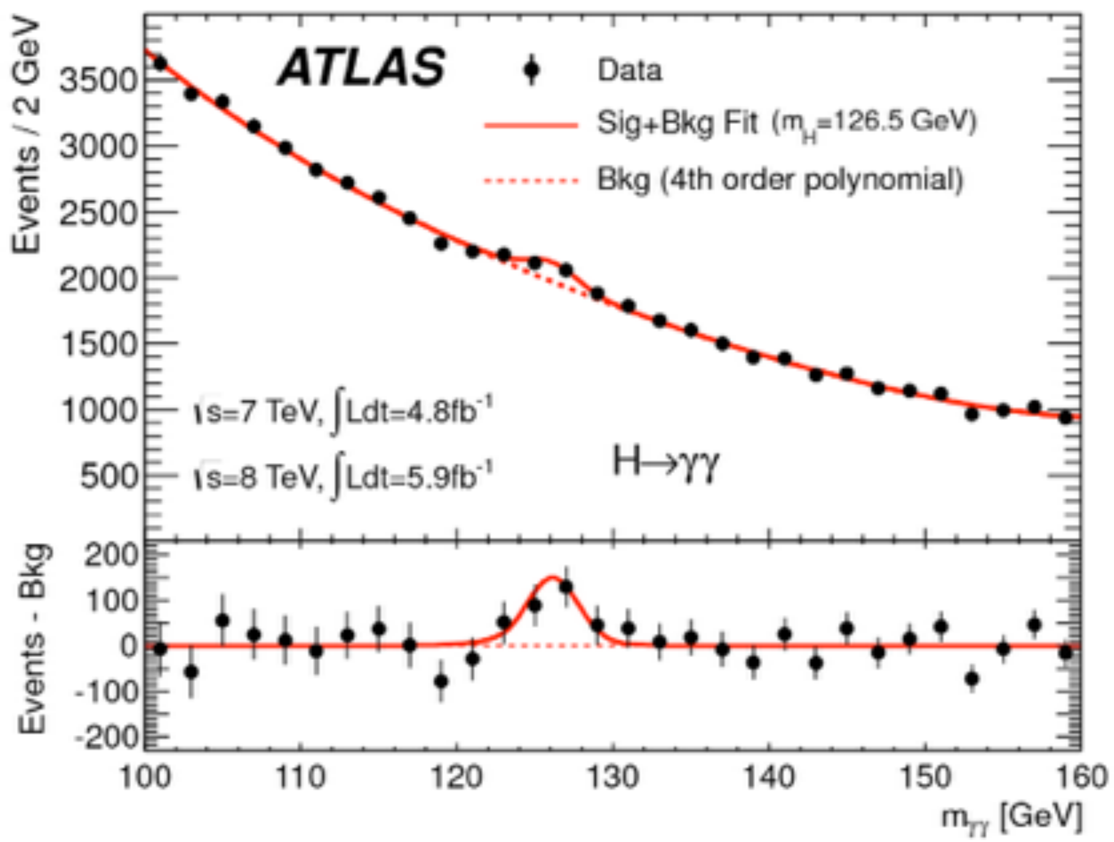
14 talks + 3 discussions

Topics from theory to experiment frontiers

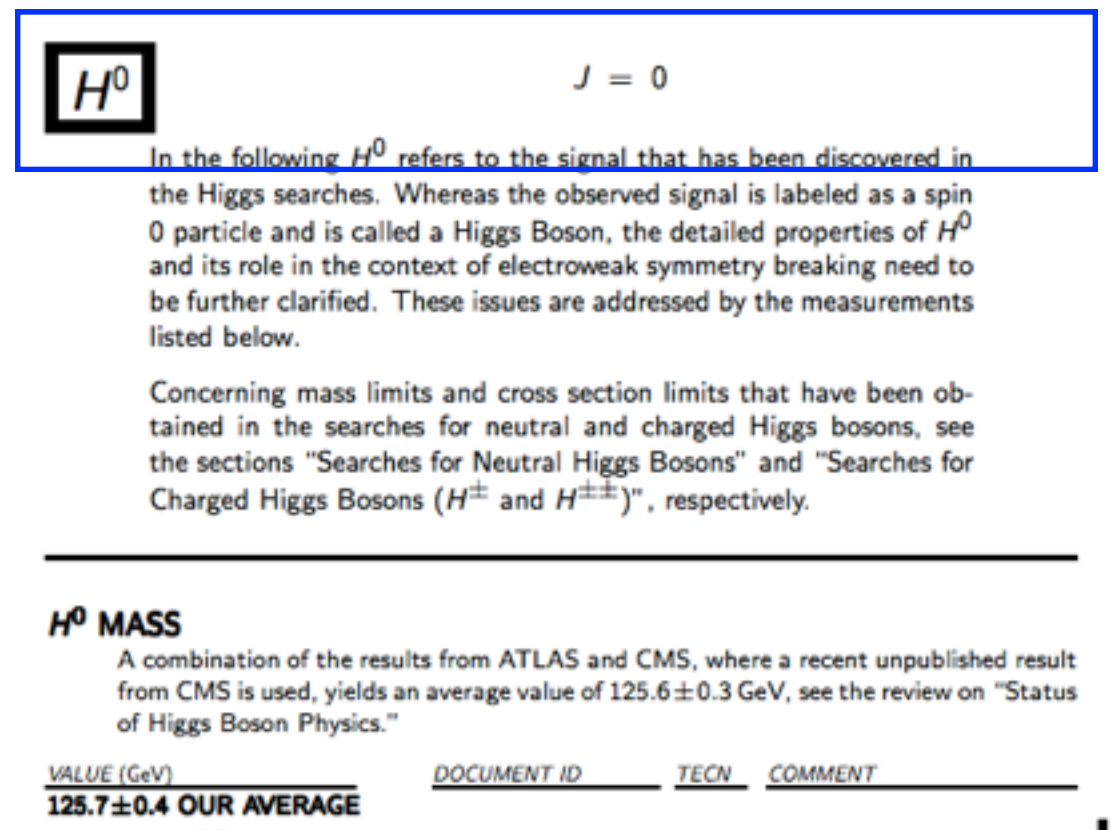
- theories — 2HDM, MSSM, etc
- colliders — Higgs production & decays, new particles
- low energy — electric dipole moments
- cosmology — electroweak baryogenesis

The CP nature of h_{125}

Higgs boson from Gevena to Particle data group



June 4, 2012



H^0 $J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^\pm$ and $H^{\pm\pm}$)", respectively.

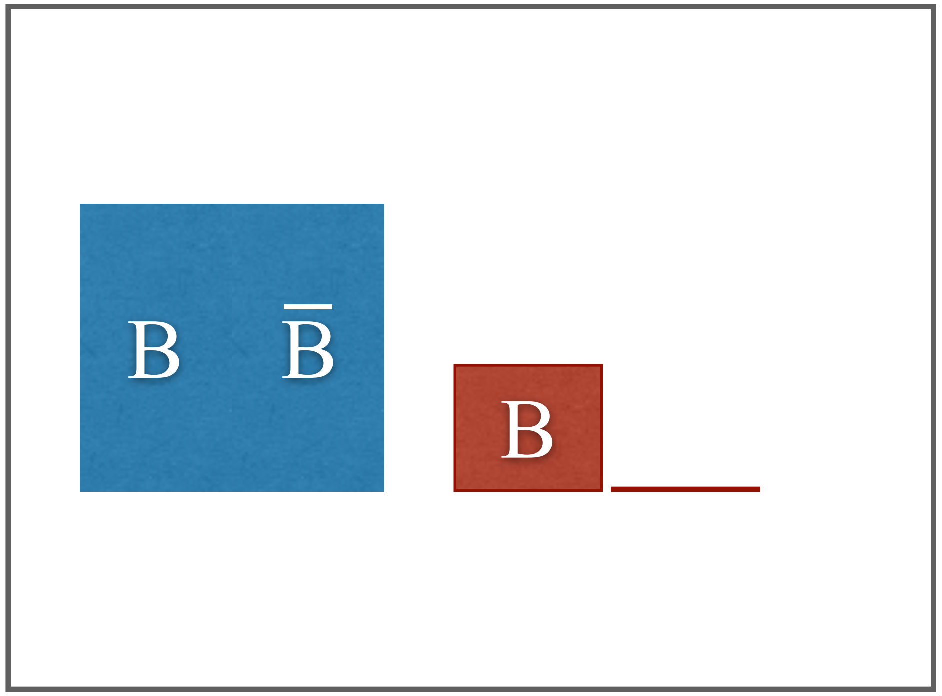
H^0 MASS

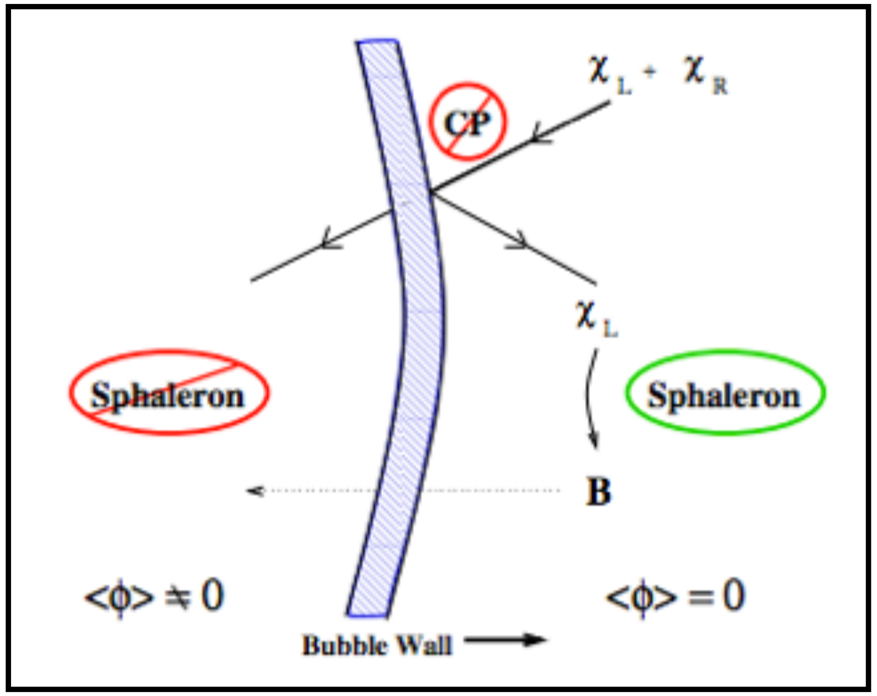
A combination of the results from ATLAS and CMS, where a recent unpublished result from CMS is used, yields an average value of 125.6±0.3 GeV, see the review on "Status of Higgs Boson Physics."

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
125.7±0.4 OUR AVERAGE			

no description about CP yet

motivation from cosmology





Necessary conditions

1) CP violation
2) B violation
3) Non equilibrium

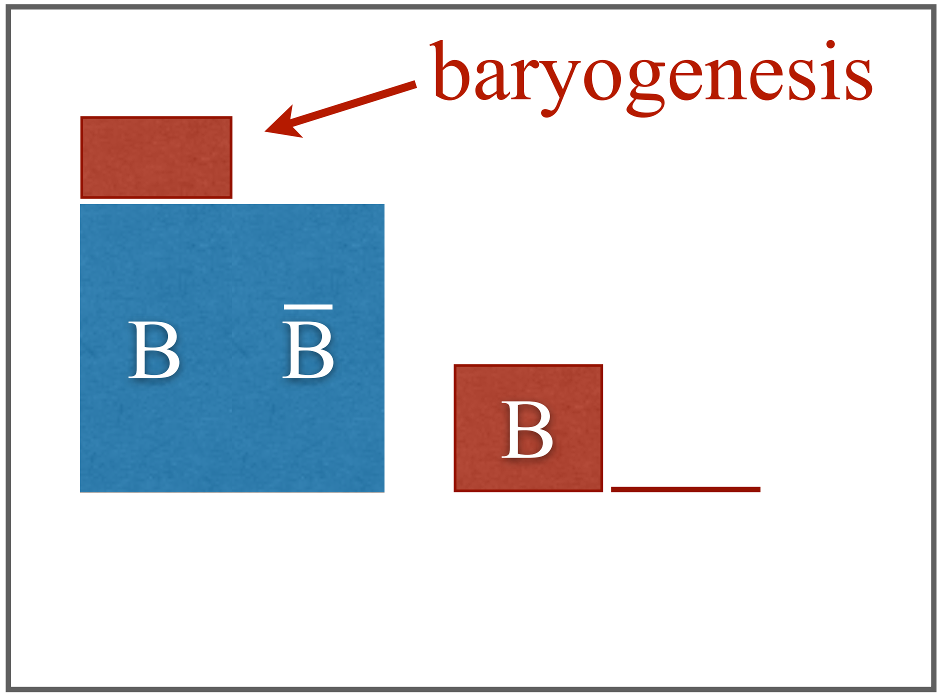
Sakharov, 1967

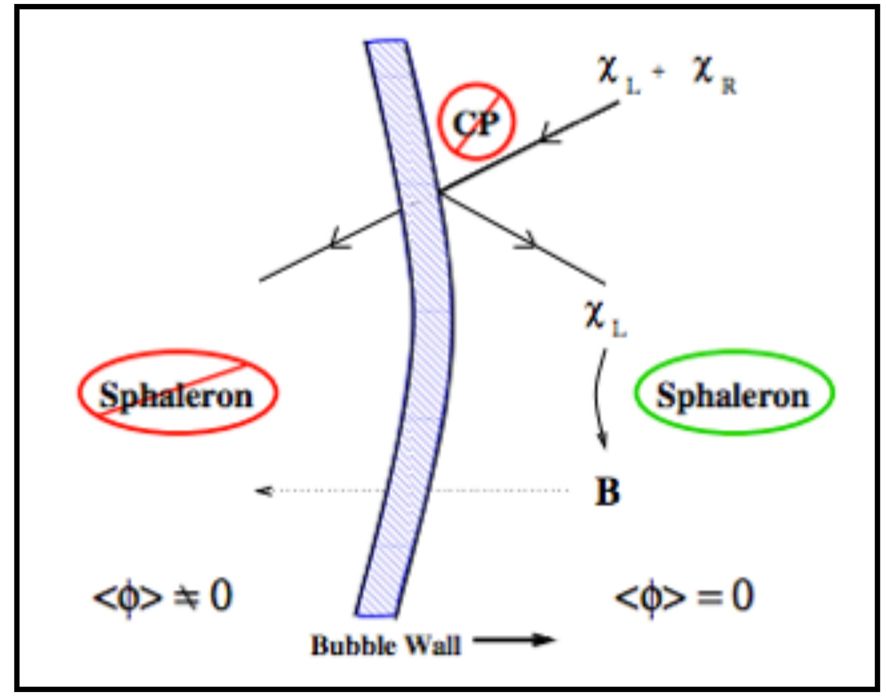
Electroweak baryogenesis

Kuzmin, Rubakov, Shaposhnikov, 1985;
Morrissey, Ramsey-Musolf, arxiv:1206.2942

talks by Liu, Ovanesyan and Shu

motivation from cosmology





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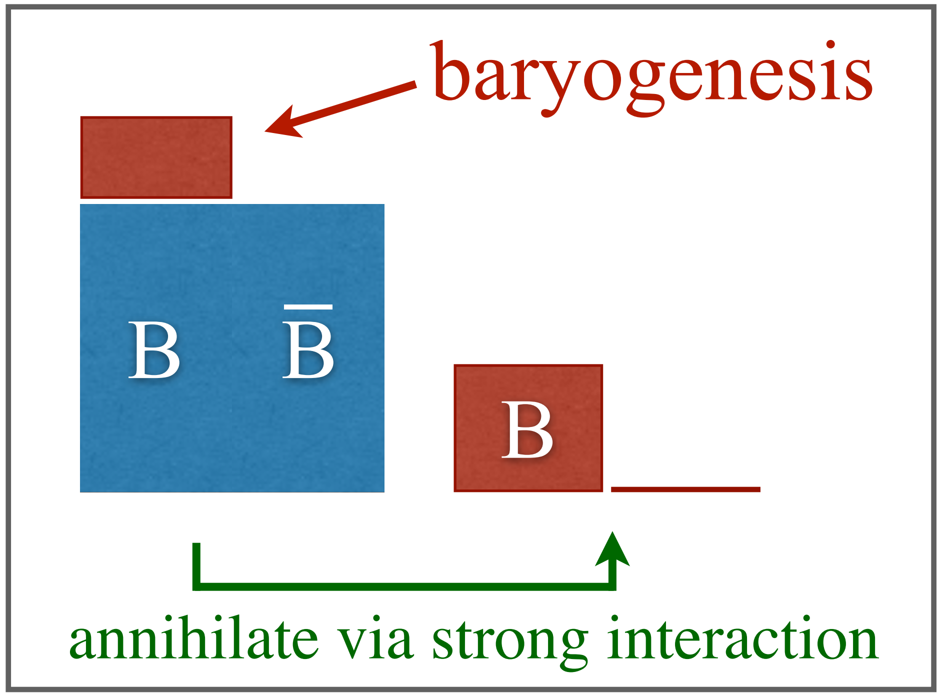

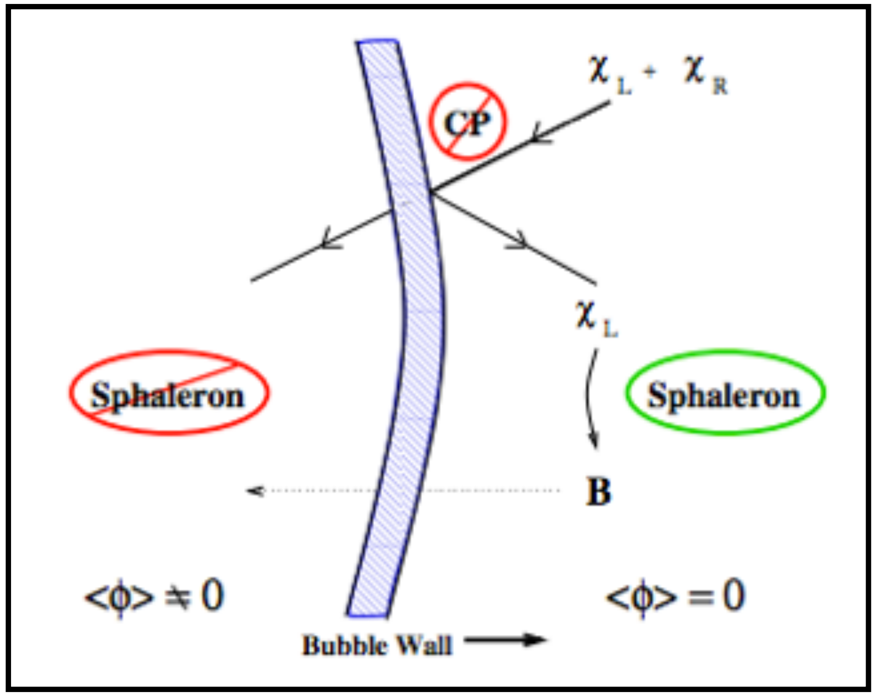

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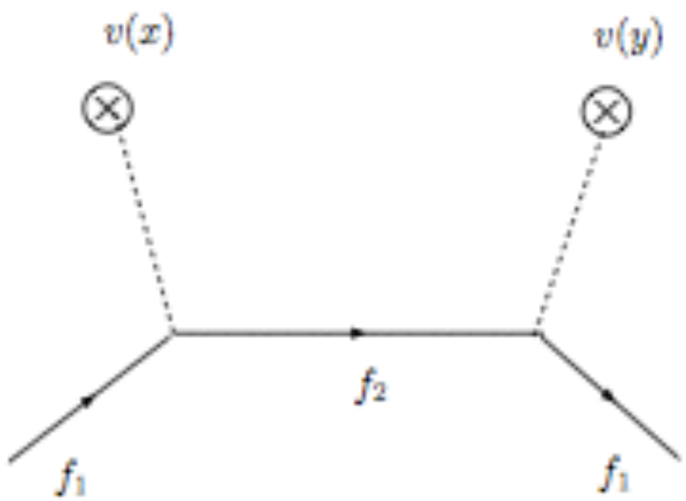
motivation from cosmology

Interact w. Higgs background in a CP violating way



can work with fermion or scalar

Final baryon asymmetry: $$\frac{n_b}{n_\gamma} \sim \frac{\alpha_w^4}{g_*} \Delta\theta(T_c) \sim 10^{-8} \Delta\theta(T_c)$$

$$\Delta\theta(T_c) \gtrsim 0.01$$

How $\Delta\theta(T_c)$ in early universe implies Higgs CP mixture today

talks by Liu, Ovanesyan and Shu

motivation from theory

We know theories that can violate CP

2HDM $$V(\phi_1, \phi_2) = \cdots + m_{12}^2(\phi_1^\dagger \phi_2) + \lambda_5(\phi_1^\dagger \phi_2)^2 + \text{h.c.}$$

Glashow, Weinberg, 1977

$$\mathcal{L}_Y = Y_u \bar{Q} \tilde{\phi}_1 u_R$$

Type II

$$+ Y_d \bar{Q} \phi_2 d_R$$

talk by Chen, Inoue and Liu

motivation from theory

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2HDM

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Type I

talk by Chen, Inoue and Liu

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Glashow, Weinberg, 1977

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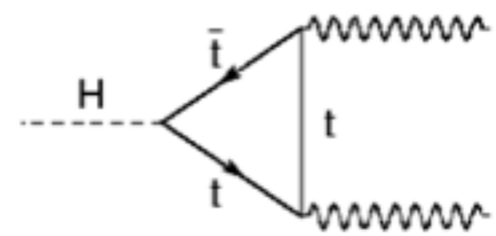
$$+ Y_d \bar{Q} \phi_1 d_R$$

Type I

If explicit break CP

All CP observables depend on $\text{Im}[\lambda_5^*(m_{12}^2)^2]$

$\Rightarrow h(c_f \bar{f} f + \tilde{c}_f \bar{f} i\gamma_5 f)$



$\Rightarrow hZ\tilde{Z} + \cdots$

talk by Chen, Inoue and Liu

motivation from theory

A theoretical motivation:

2HDM

$$V(\phi_1, \phi_2) = \cdots + m_{12}^2(\phi_1^\dagger \phi_2) + \lambda_5(\phi_1^\dagger \phi_2)^2 + \text{h.c.}$$

$$+ \left[\lambda_6(\phi_1^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \lambda_7(\phi_2^\dagger \phi_2)(\phi_1^\dagger \phi_2) + \text{h.c.}\right]$$

$$\mathcal{L}_Y = Y_u \bar{Q} \tilde{\phi}_1 u_R + Y_u' \bar{Q} \tilde{\phi}_2 u_R$$

$$+ Y_d \bar{Q} \phi_1 d_R + Y_d' \bar{Q} \phi_2 d_R$$

General

alignment, MFV …

motivation from theory

A theoretical motivation:

2HDM

$$V(\phi_1, \phi_2) = \cdots + m_{12}^2(\phi_1^\dagger \phi_2) + \lambda_5(\phi_1^\dagger \phi_2)^2 + \text{h.c.}$$

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$$+ Y_d \bar{Q} \phi_1 d_R + Y_d' \bar{Q} \phi_2 d_R$$

General

alignment, MFV …

Spontaneous CP violation

T.D.Lee, 1973

Start from real Lagrangian, reach complex vevs

$\Rightarrow$ CP phase in CKM matrix — *O(1)* CP mixture?

Must have : Y_u, Y_u', Y_d, Y_d' all nonzero — tree level FCNC?

Open questions

motivation from theory

If you believe in Supersymmetry

MSSM no CP violation at tree level

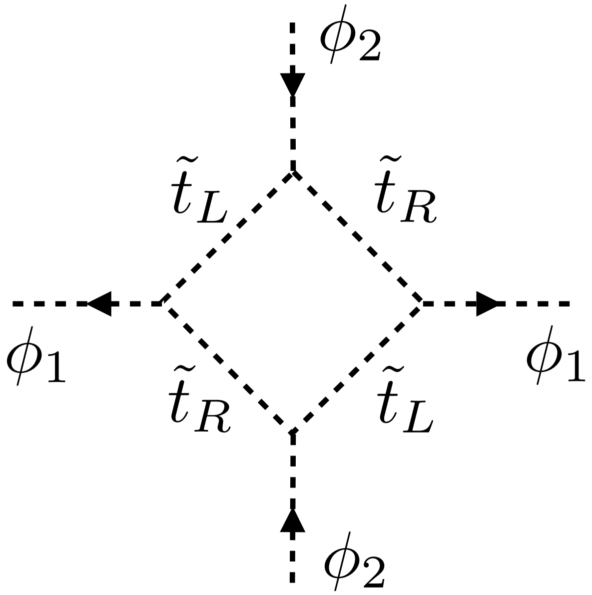
$$V(\phi_1, \phi_2) = \cdots + m_{12}^2(\phi_1^\dagger \phi_2) + \lambda_5(\phi_1^\dagger \phi_2)^2 + \text{h.c.}$$

B_μ 0

CPV from radiative corrections:

$$\mathcal{L} \ni \tilde{t}_L^*(A_t \phi_1 - \mu y_t \phi_2^*)\tilde{t}_R$$

$$\lambda_5, \lambda_6, \lambda_7 \sim \frac{1}{16\pi^2}$$



recent work by Wagner, 1502.02210

motivation from theory

Effective operators

Operator	Mass term	Higgs-fermion coupling
$y_t(\bar{Q}_L t_R H^c) + \text{h.c.}$	$m_t = \frac{y_t v}{\sqrt{2}}$	$\frac{y_t}{\sqrt{2}}$
$\frac{H^\dagger H}{\Lambda^2}(\bar{Q}_L t_R H^c) + \text{h.c.}$	$\delta m_t \propto \frac{(v/\sqrt{2})^3}{\Lambda^2}$	$\delta y_t \propto 3\frac{(v/\sqrt{2})^2}{\Lambda^2}$

talk by Brod and Yu

$$\Rightarrow h(c_f \bar{f} f + \tilde{c}_f \bar{f} i\gamma_5 f)$$

More possibilities:

scalar singlet, vector-like fermions, models for neutrino mass

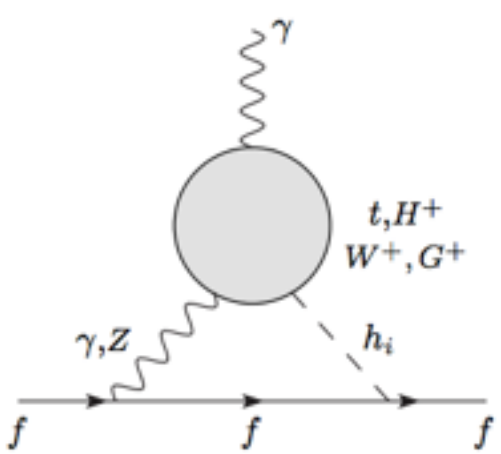
Experimental tests

Instead of telling Nature what to do, listen what Nature really does

Experimentally, how large can CPV be?
where to look for?

But, break CP at weak scale,

Severe constraints from EDM?



Barr, Zee, 1990

For example $d_e \sim e\frac{m_e\,\theta_{\rm CPV}}{(16\pi^2)^2\Lambda_{EW}^2} \sim 10^{-26}\,\theta_{\rm CPV}\,e\,{\rm cm}$

$\lesssim 10^{-28}\,e\,{\rm cm}$ (ACME)

(for two-loop diagram)

c.f. $\Delta\theta(T_c) \gtrsim 0.01$ from genesis

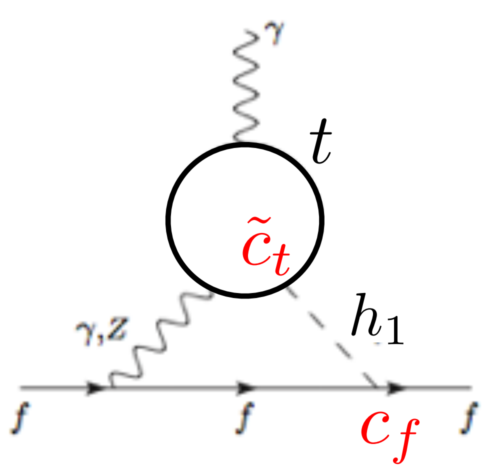
EDM

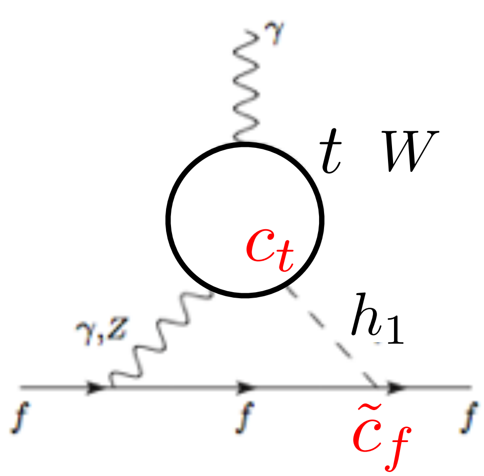
Can be powerful, but interpretation need great care.

indirect

Other sources: SUSY, Left-right models, etc.

Even for CPV involving Higgs itself: an example: eEDM





1) cancelation occurs if

$$c_t \tilde{c}_e \approx c_e \tilde{c}_t \approx a \tilde{c}_e$$

J. Shu, Y.Z., arxiv:1304.0773
Inoue, Ramsey-Musolf, Y.Z., 1403.4257

2) strong constraints on $\tilde{c}_t$ if

$\tilde{c}_e = 0$ *talk by Brod*

Brod, Haisch, Zupan, 1310.1385

Distinguish scenarios?

Directly measure CPV in Higgs and electron coupling

seems hard..

Measure Higgs CPV at colliders

if we see them, possibly from heavy flavor

$$\Rightarrow h(c_t \bar{t}t + \tilde{c}_t \bar{t} i\gamma_5 t)$$

The inverse problem

what if we see CPV at colliders but not in EDM

Wait and see what Nature dictates

Many EDMs

Complementary bounds

Quite a few observables

System	Year/ref	Result	
Paramagnetic systemss			
Cs	1989 [37]	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	e cm
		$d_e = (-1.5 \pm 5.6) \times 10^{-26}$	e cm
Tl	2002 [9]	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	e cm
		$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	e cm
YbF	2011 [8]	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	e cm
ThO	2014 [7]	$\omega^{NE} = 2.6 \pm 5.8$	mrad/s
		$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	e cm
		$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	
Diamagnetic systems			
^{199}Hg	2009 [5]	$d_A = (0.49 \pm 1.5) \times 10^{-29}$	e cm
^{129}Xe	2001 [38]	$d_A = (0.7 \pm 3) \times 10^{-27}$	e cm
TlF	2000 [39]	$d \ = (-1.7 \pm 2.9) \times 10^{-23}$	e cm
neutron	2006 [4]	$d_n = (0.2 \pm 1.7) \times 10^{-26}$	e cm

Beware of hadronic uncertainties

Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
Im C_{qG}	β_n^{uG}	4×10^{-4}	$(1-10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2-18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09-0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2-1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2-20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4-40) \times 10^{-9}$
Im $C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2-0.6) \times 10^{-3}$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8-2.4) \times 10^{-3}$
d_q	ρ_n^u	-0.35	(-0.17)–0.52
	ρ_n^d	1.4	0.7–2.1
δ_q	ζ_n^u	8.2×10^{-9}	$(4-12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16-50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2-40) \times 10^{-7}$
Im $C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1-10) \times 10^{-8}$
Im $C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10-80) \times 10^{-7}$
Im $C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
Im $C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

talk by Ramsey-Musolf

new EDM experiments

- ThO, current limit on eEDM: 10^{-28} e-cm, next ×10 improvement.

- ^{199}Hg EDM <10^{-29} e-cm sensitivity, imminent
- nEDM at PSI 10^{-26} e-cm sensitivity, 2015 - 2017
- nEDM at PSI 10^{-27} e-cm sensitivity, 2018 - ...
- nEDM at SNS ~2×10^{-28} e-cm starting data taking 2021

- TUM nEDM effort, making progress in B-field shielding, met B-field specs. It moves to ILL in 2015, goal: 10^{-28} e-cm, staged approach, starting in 2016.
- ^{225}Ra EDM, ~5×10^{-22} e-cm now, ~3×10^{-28} e-cm w/ FRIB

- Storage ring EDM: pEDM first goal 10^{-29} e-cm, start taking data early 2020's. Strength: statistics

talk by Semertzidis

Direct tests

Make the Higgs boson, and watch

1) the shape of its decay products

2) shape of particles produced in association with Higgs

Direct tests

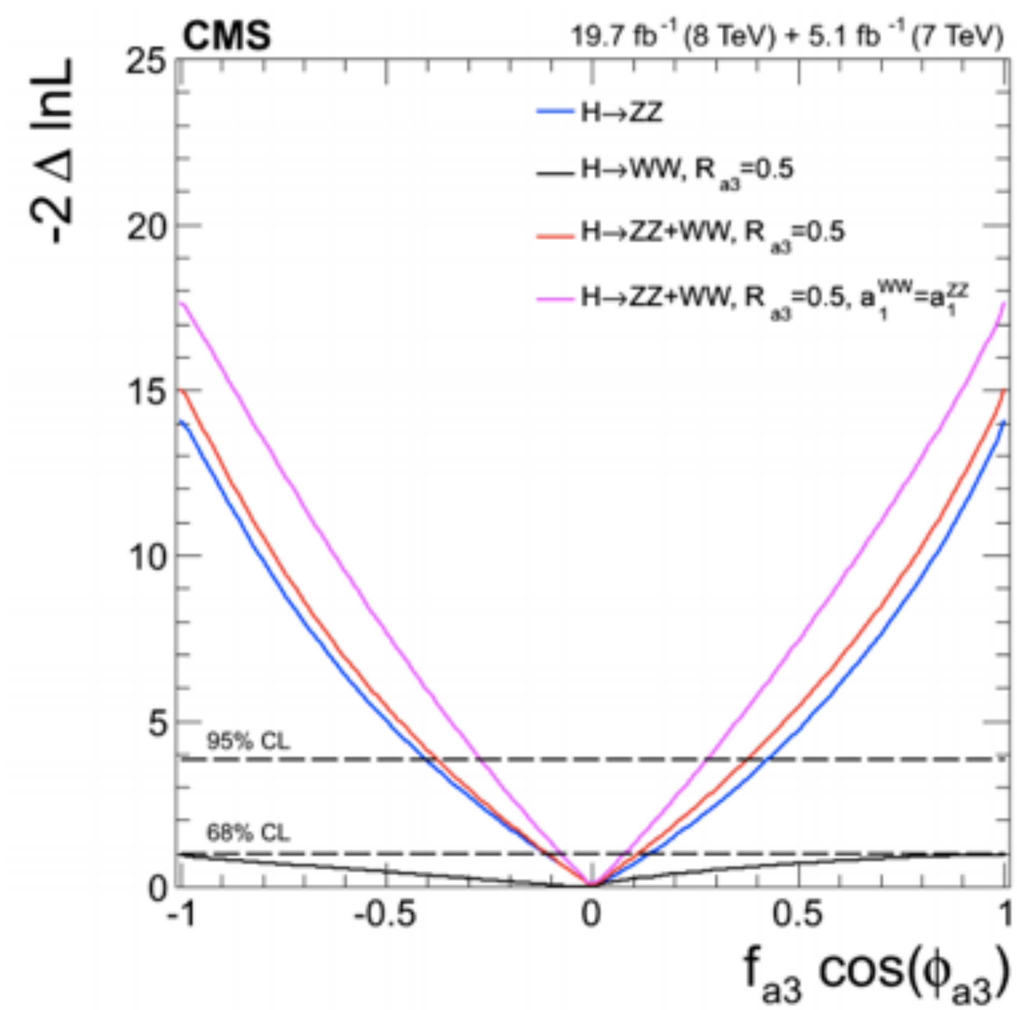
$$H \to ZZ \to 4\ell$$

Probes the presence of

$$a_3 \frac{h}{v} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

Future LHC reach

$$f_{a3} \sim \frac{|a_3|^2}{|a_1|^2} < 0.13(0.04) \qquad 300\ (3000)\ /\text{fb}$$



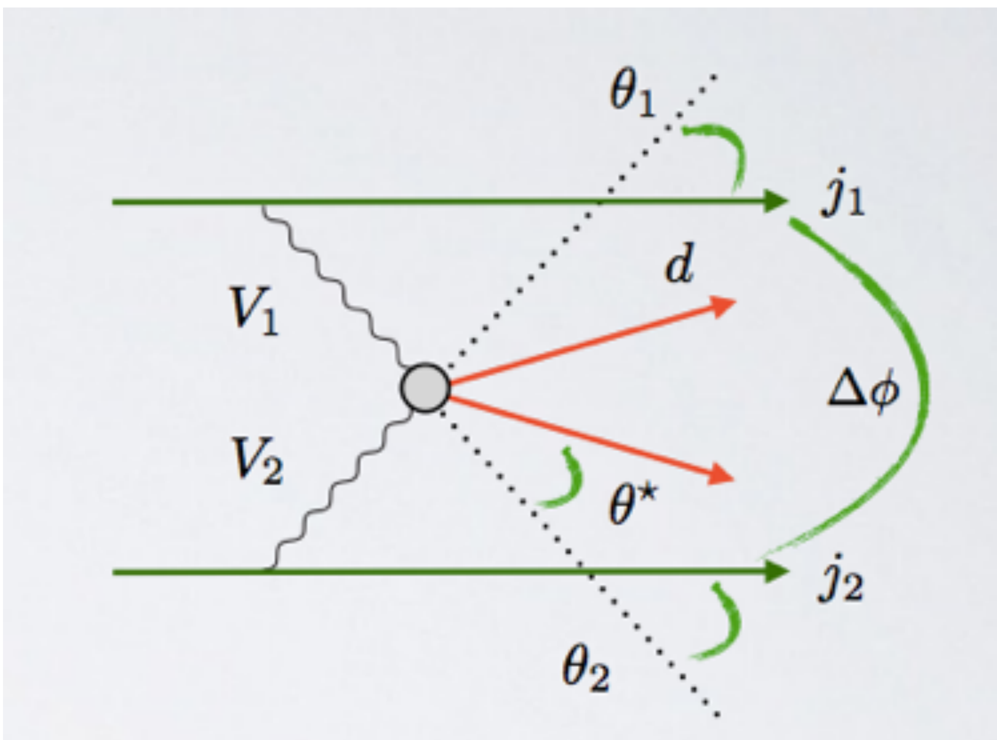
Models: competing loop with tree

$$a_3 \sim \frac{1}{16\pi^2} \qquad (a_1 \sim 1)$$

talk by Whitbeck

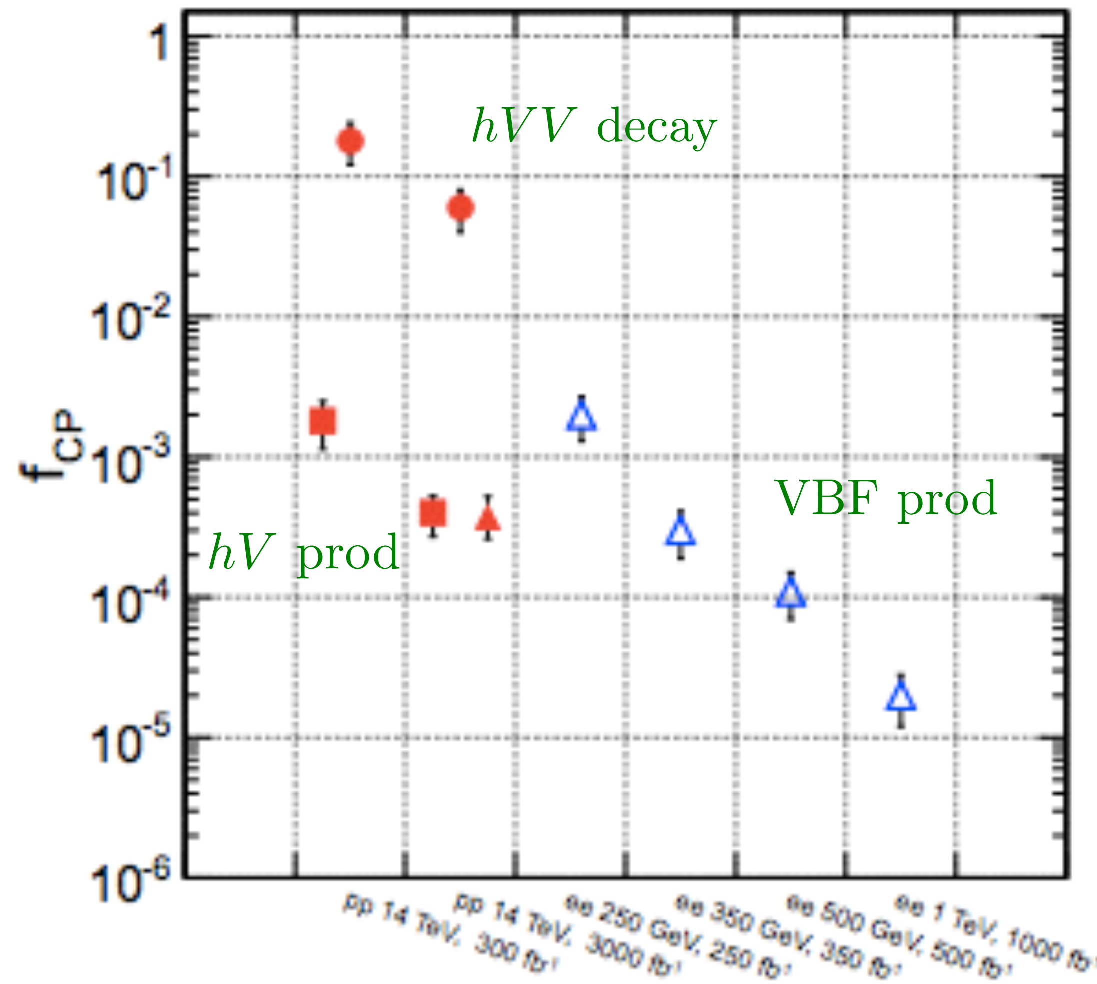
Direct tests

VFB and VF production



Snowmass Higgs, 1310.8361

$\theta_{\rm CPV}$



1

0.1

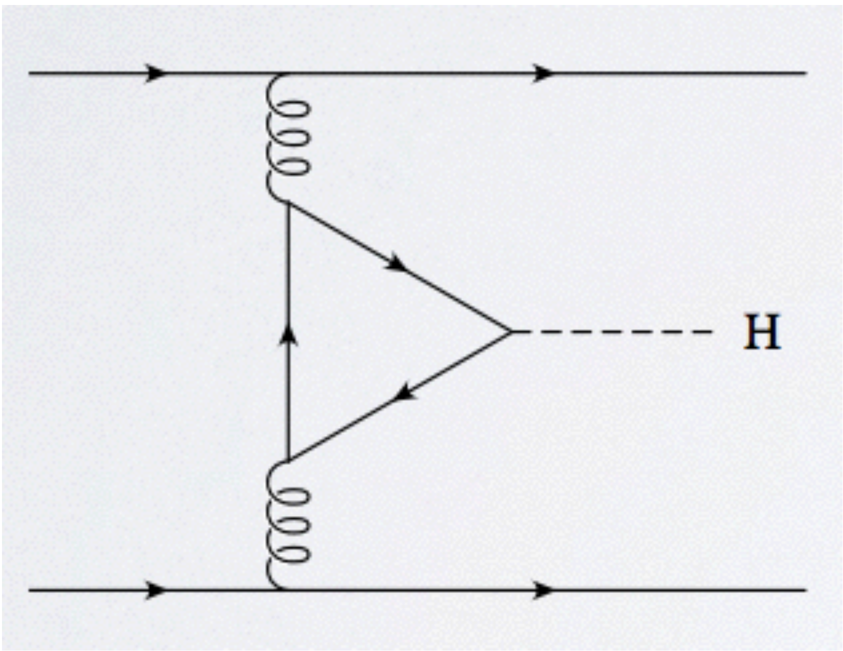
talks by Dolan and Yu

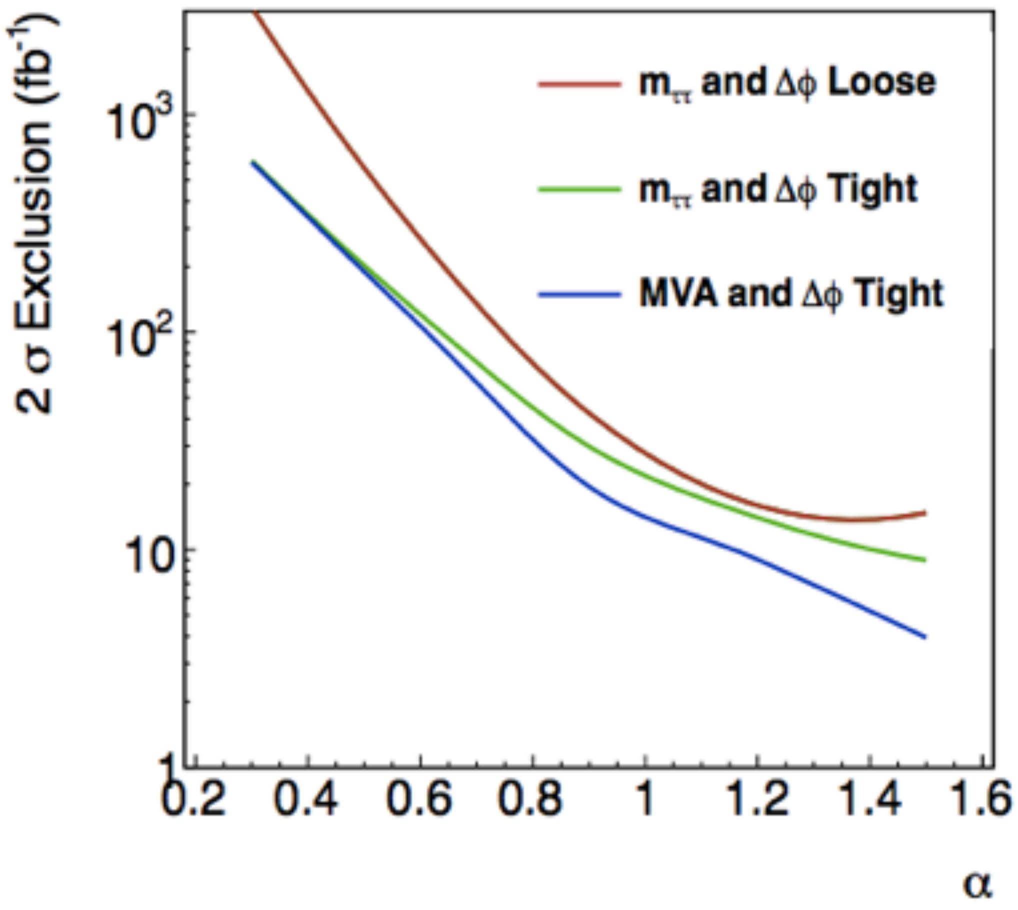
$$h(\cos\theta_{\rm CPV}\bar{t}t + \sin\theta_{\rm CPV}\bar{t}\gamma_5 t)$$

Direct tests

talk by Dolan

ggh with forward jets





both CP even and odd processes go via loop

better understanding QCD multi jet events

Direct tests

$$\begin{aligned} h &\longrightarrow \tau^- \tau^+ \\ &\longrightarrow \rho^- \nu_\tau \, \rho^+ \bar{\nu}_\tau \\ &\longrightarrow \pi^- \pi^0 \, \nu_\tau \, \pi^+ \pi^0 \, \bar{\nu}_\tau \, . \end{aligned}$$

talk by Yu

not loop suppressed

could be probed at both e+e- and hadron colliders

$$\frac{m_\tau}{v} h(\cos\theta_{\rm CPV}\bar{\tau}\tau + \sin\theta_{\rm CPV}\bar{\tau} i\gamma_5\tau)$$

Colliders	LHC	HL-LHC	ILC (1 ab^{-1})	FCCee/CEPC (1 ab^{-1})	FCCee/CEPC (5 ab^{-1})	FCCee/CEPC (10 ab^{-1})
Accuracy(1σ)	25°	8.0°	4.4°	5.5°	2.5°	1.7°
$\theta_{\rm CPV}$	0.4	0.14	0.08	0.1	0.04	0.03

Direct tests

$pp \to t\bar{t}h$

Still need a roadmap

talk by Liu and Yu

$h \to \gamma\gamma \qquad h \to Z\gamma$

measure photon polarization

interference with background, on the Higgs pole

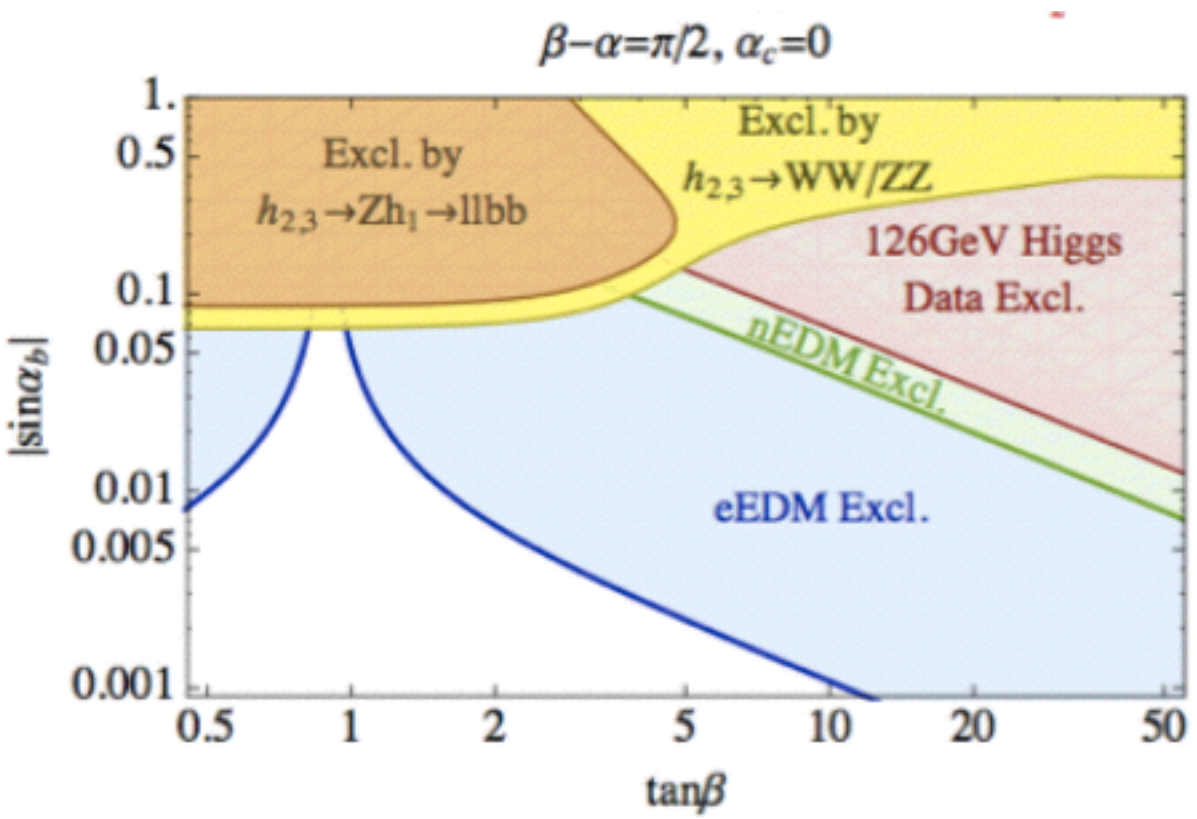
talk by Marco and Yu

More tests

Higgs CPV means something not decoupled

(in 2HDM, heavy scalars)

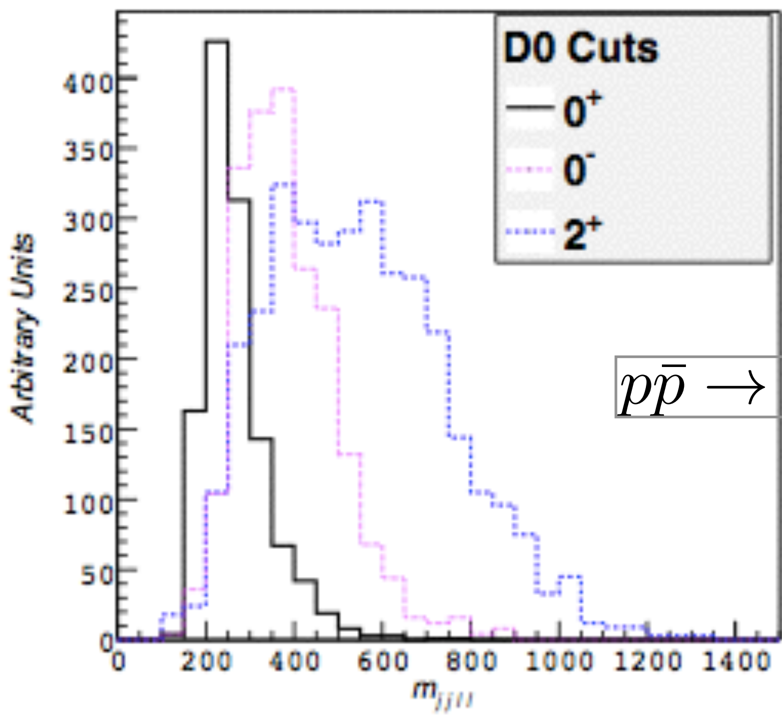
Some decay channels more sensitive to CPV



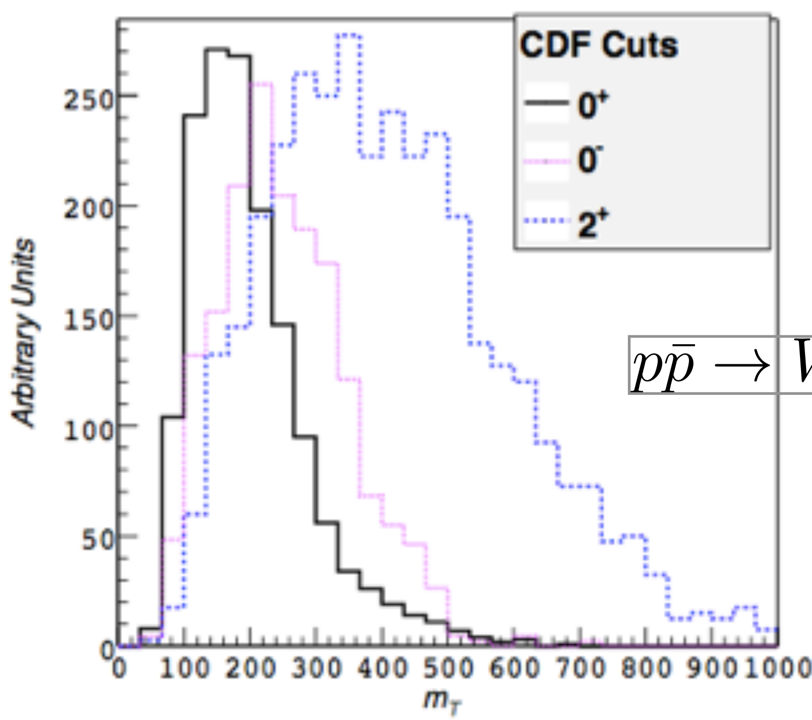
apply the LHC heavy Higgs search data

talk by Chen

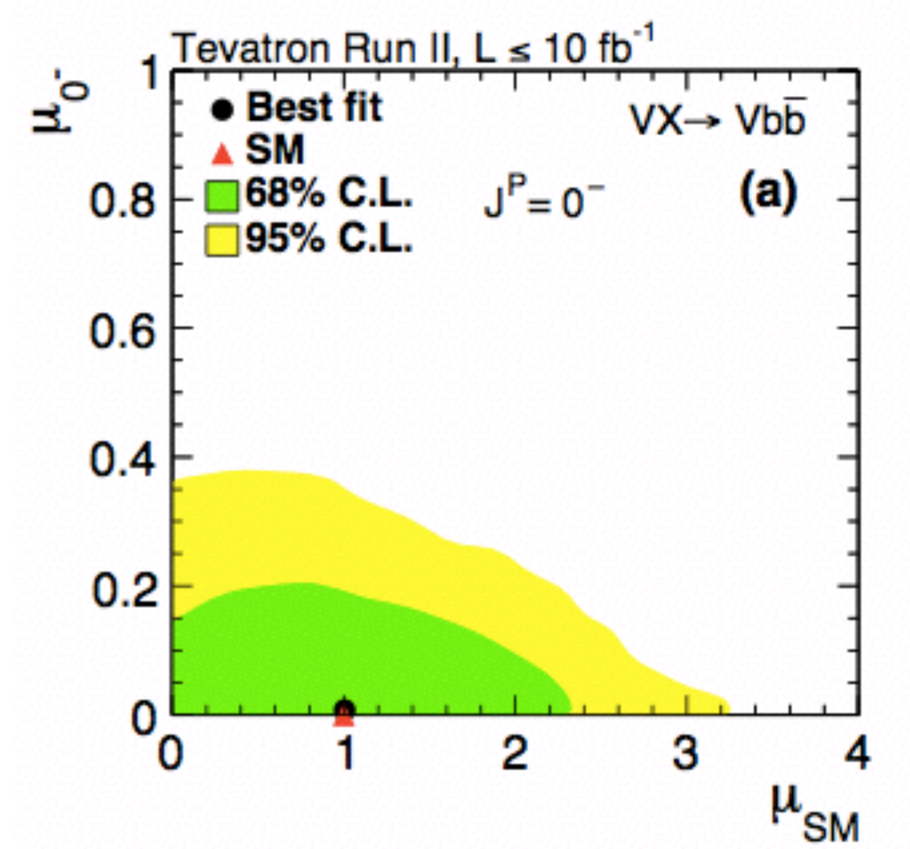
More tests



$p\bar{p} \to Zh \to \ell\ell bb$



$p\bar{p} \to Wh \to \ell\nu bb$



Again, μ_{0^-} typically loop suppressed

Ellis, Hwang, Sanz, You, 1208.6002
CDF+D0, 1502.00967

Summary

Higgs boson has been discovered

One next task is to reveal its CP nature

Well motivated: theoretically and experimentally

already have several handles to this question

Develop new observables; further explore their interplays

Exciting discovery awaits us!

talk by Dolan

Maybe cooler if

talk by Dolan

Maybe cooler if

$h^0(125)$

$h^0(400)$

$h^0(425)$

$h^{\pm}(450)$

talk by Dolan

Maybe cooler if

$h^0(125)$

$h^0(400)$

$h^0(425)$

$h^\pm(450)$