Probing Higgs Boson CP Properties with ttH at the LHC and the future pp collider

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New particle searches confronting the first LHC run-2 data

September 7, 2015

In collaboration with Xiao-Gang He and Guan-Nan Li, IJMPA 30(2015)0550156

Outline

- Motivation
- The status of Higgs measurements, Higgs CP properties
- Effective couplings for the CP-mixed Higgs state, ttH
- Production of ttH at pp colliders with arbitrary CP-mixing angle
- Discrimination power from different operators for ttrr and ttbb process and its behaviours at pp colliders
- Summary

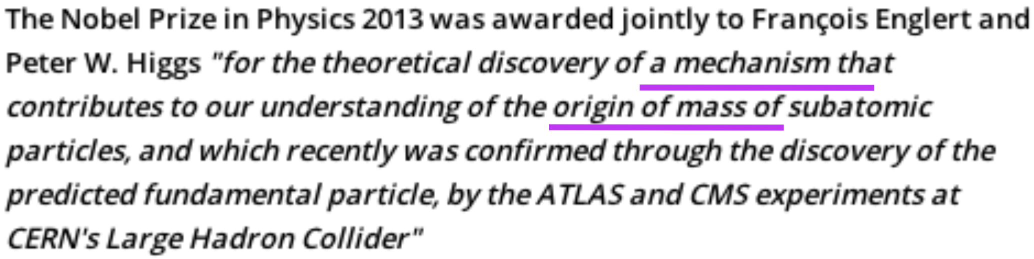
Motivation

Photo: A. Mahmoud

François Englert

Photo: A. Mahmoud

Peter W. Higgs

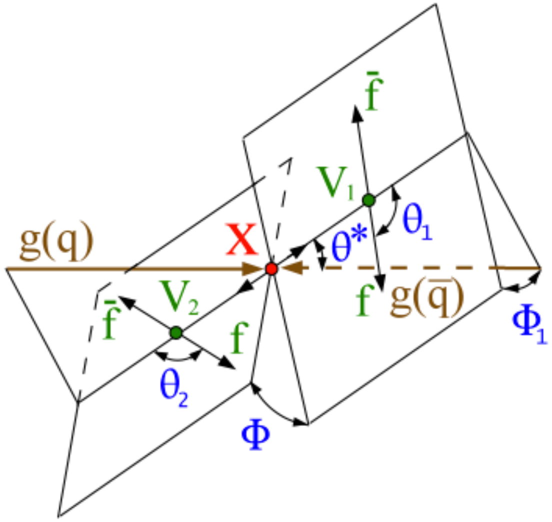


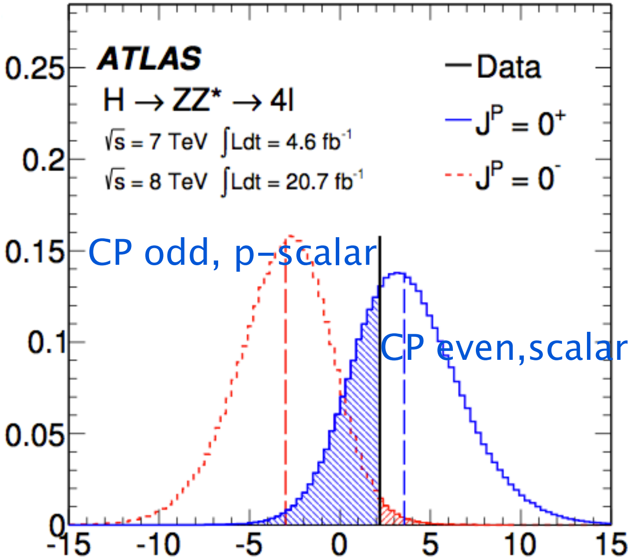
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Higgs boson

- Just the discovery of the Higgs boson is not sufficient to validate the minimal SM
- In the SM, the only fundamental neutral scalar is a $J^{PC} = 0^{++}$ state
- Various extensions of the SM can have several Higgs with different CP properties: e.g. MSSM has two CP-even and one CP-odd states
- Therefore, should a neutral spin-0 particle be detected, a study of its CP-properties would be essential to establish it as the SM Higgs boson
- Higgs has the largest coupling to the top quark and top-Higgs interaction can be sensitive to determining Higgs properties and probing BSM physics

Higgs spin and CP properties





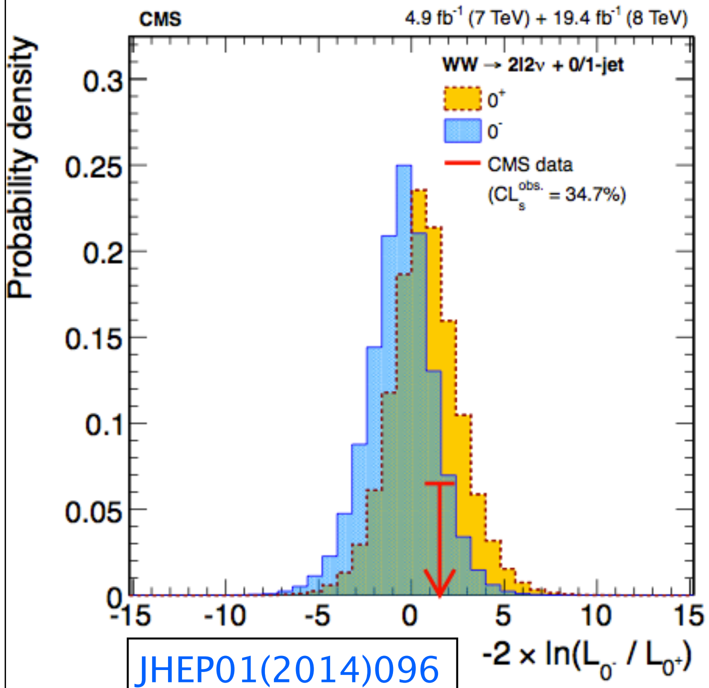
CP odd, p-scalar

CP even,scalar

Discovery of Higgs boson in rr, ZZ, WW final state is established. The new discovered boson is “SM-like”, signal strength compatible with mu=1.

spin=0

PRD 89 (2014) 092007



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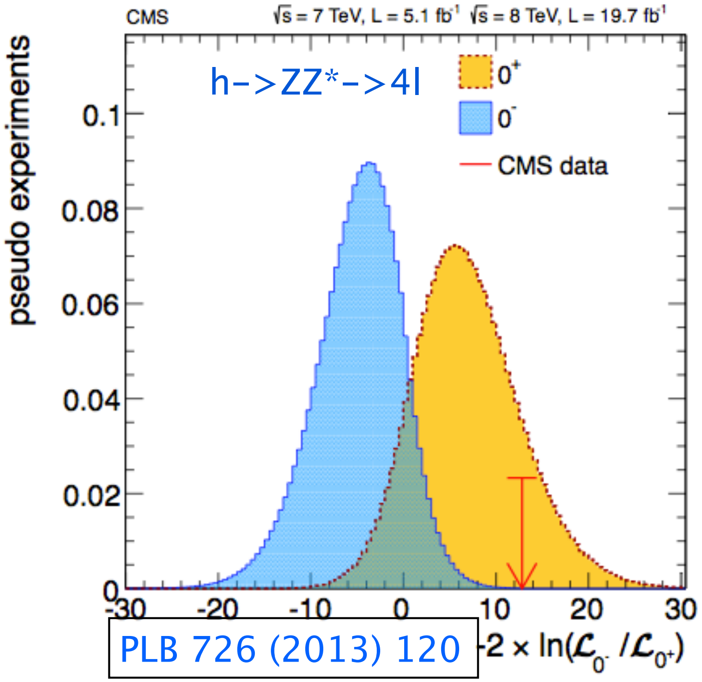


h->ZZ*->4l

PLB 726 (2013) 120

$J^P = 0^+$ is favored

but Higgs can still have a pesudoscalar component

Global Fit

general CP mixture state:

$$\phi = \cos\alpha \; \underset{\substack{\downarrow \\ \text{even}}}{H} + \sin\alpha \; \underset{\substack{\downarrow \\ \text{odd}}}{A}$$

Production rate: $\underset{\text{exp}}{R(H\to ff)} = \int \underset{\text{exp}}{Ldt} \cdot \underset{\text{th}}{\sigma(pp\to H)} \cdot \frac{\Gamma_f}{\Gamma}$ th

$\rightarrow$ get partial decay width then $\Gamma_f \sim g_f^2 \longrightarrow$ coupling

$$\frac{\Gamma[\phi\to WW^*]}{\Gamma_{\rm SM}[H\to WW^*]} = \frac{\Gamma[\phi\to ZZ^*]}{\Gamma_{\rm SM}[H\to ZZ^*]} = \underline{\cos^2\alpha} \qquad \frac{\Gamma[\phi\to \tau^+\tau^-]}{\Gamma_{\rm SM}[H\to \tau^+\tau^-]} = (y_{\rm d}\,\underline{\cos\alpha})^2 + (x_{\rm d}\,\underline{\sin\alpha})^2$$

H> VV, qq, rr, gg : ($\cos\alpha$, $\sin\alpha$)

ATLAS, CMS, CDF/D0 → α< 1.1 (0.7) at 8 (14) TeV LHC Freitas,Schwaller,PRD(2013)

ATLAS, CMS 7+8 (gg>H>VV,rr, tata, bb) → α < 0.75 pi Djouadi,Moreau, EPJC (2013)

gg>H> rr → α < 0.64 pi Kobakhidze,Wu,Yue, JHEP (2014)

if XS(ttH) error±20% → α < 0.17 pi Ellis, Hwang, Sakurai, Takeuchi JHEP (2014)

Cheung,Lee, Tseng PRD(2014), Bhattacharyya, Das,Pal PRD87(2013), Shu,Zhang PRL (2013), Inoue, Ramsey-Musolf, Zhang PRD89(2014), Bolognesi, Gao, Gritsan, Melnikov, Schulze, Tran, Whitbeck, PRD(2012), Englert, Goncalves-Netto, Mawatari,Plehn,JHEP(2013),

Higgs Yukawa couplings

SM Higgs fermion coupling: g=m/v v = 246 GeV

General CP mixed quark-antiquark-Higgs coupling: $\overline{Q}(c+id\gamma_5)Qh$

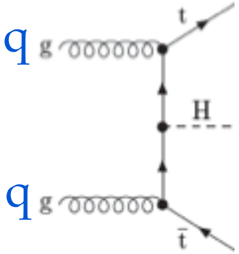
For this two processes, production from pp collider: $gg \to Q\overline{Q}h$ and $q\bar{q} \to Q\overline{Q}h$

cross section proportional to $\underline{(c^2+d^2)}$ and $\underline{(c^2-d^2) \times m_q^2}$

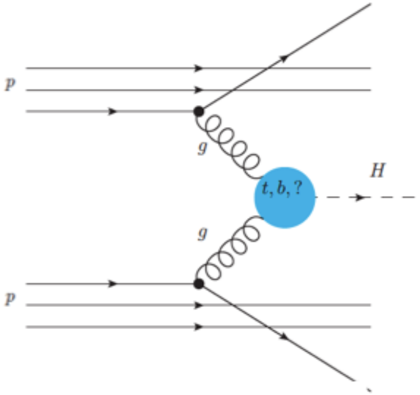
↓ Normalized to 1

↓ enhanced by top mass

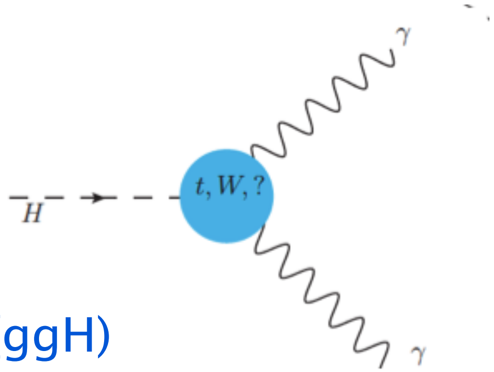
Gunion, He PRL (1996)

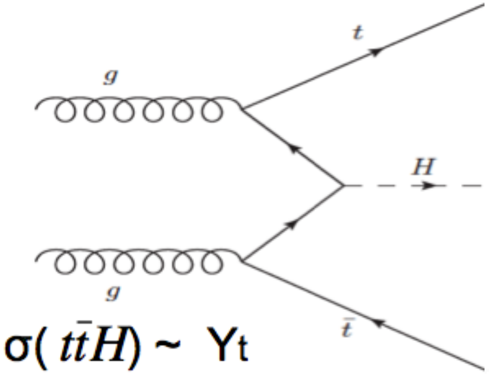


The Higgs boson has the largest coupling to the top quark. ttH ★



indirect (ggH)





direct: $\sigma(t\bar{t}H) \sim Y_t$

Effective couplings for the CP-mixed Higgs state

Fermion:

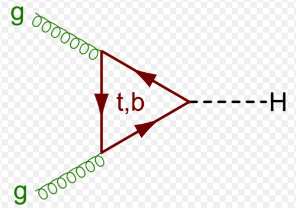
$$\mathcal{L}_{Ht\bar{t}} = -a\frac{m_t}{v}\bar{t}(\underbrace{\cos\xi}_{\text{even}} + i\gamma_5 \underbrace{\sin\xi}_{\text{odd}})tH,$$

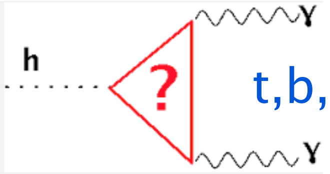
$$\left.\begin{array}{r} a = 1 \\ \cos\xi = 1 \end{array}\right. \longrightarrow \text{SM Higgs}$$

gauge bosons

$$\mathcal{L}_{HVV} = a\cos\xi\left(\frac{2m_W^2}{v}HW^\mu W_\mu + \frac{2m_Z^2}{v}HZ^\mu Z_\mu\right)$$

CP even component





t,b,W

$$\mathcal{L}_{Hgg} = \left[I_a^g G_{\mu\nu}G^{\mu\nu} + I_b^g \tilde{G}_{\mu\nu}G^{\mu\nu}\right]H$$

$$\mathcal{L}_{H\gamma\gamma} = \left[I_a^\gamma F_{\mu\nu}F^{\mu\nu} + I_b^\gamma \tilde{F}_{\mu\nu}F^{\mu\nu}\right]H$$

from factors:

$$I_a^g = a\cos\xi\sum_{i=b,t}F_a(\tau_i)$$

$$I_b^g = a\sin\xi\sum_{i=b.t}F_b(\tau_i)$$

$$F_a(\tau) = \tau^{-1}\left[1 + (1-\tau^{-1})f(\tau)\right]$$

$$F_b(\tau) = \tau^{-1}f(\tau)$$

scalar $\quad I_a^\gamma = a\cos\xi[2\sum_{i=b,t}N_C Q_i^2 F_a(\tau_i) - F_1(\tau_W)]$

p-scalar $\quad I_b^\gamma = 2a\sin\xi\sum_{i=b,t}N_C Q_i^2 F_b(\tau_i)$

$$F_1(\tau) = 2 + 3\tau^{-1} + 3\tau^{-1}(2-\tau^{-1})f(\tau)$$

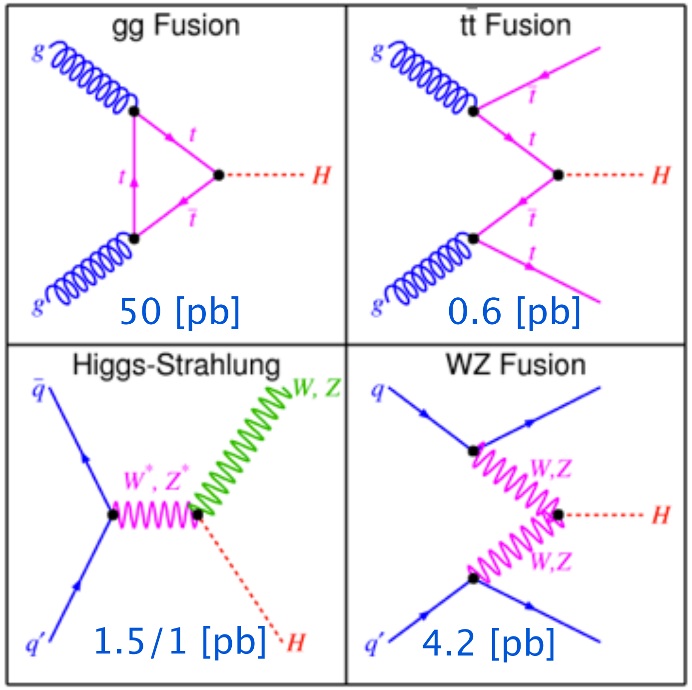
$\tilde{G}_{\mu\nu}$: $(i/2)\epsilon_{\mu\nu\alpha\beta}G^{\alpha\beta}$ The dual of $G_{\mu\nu}$

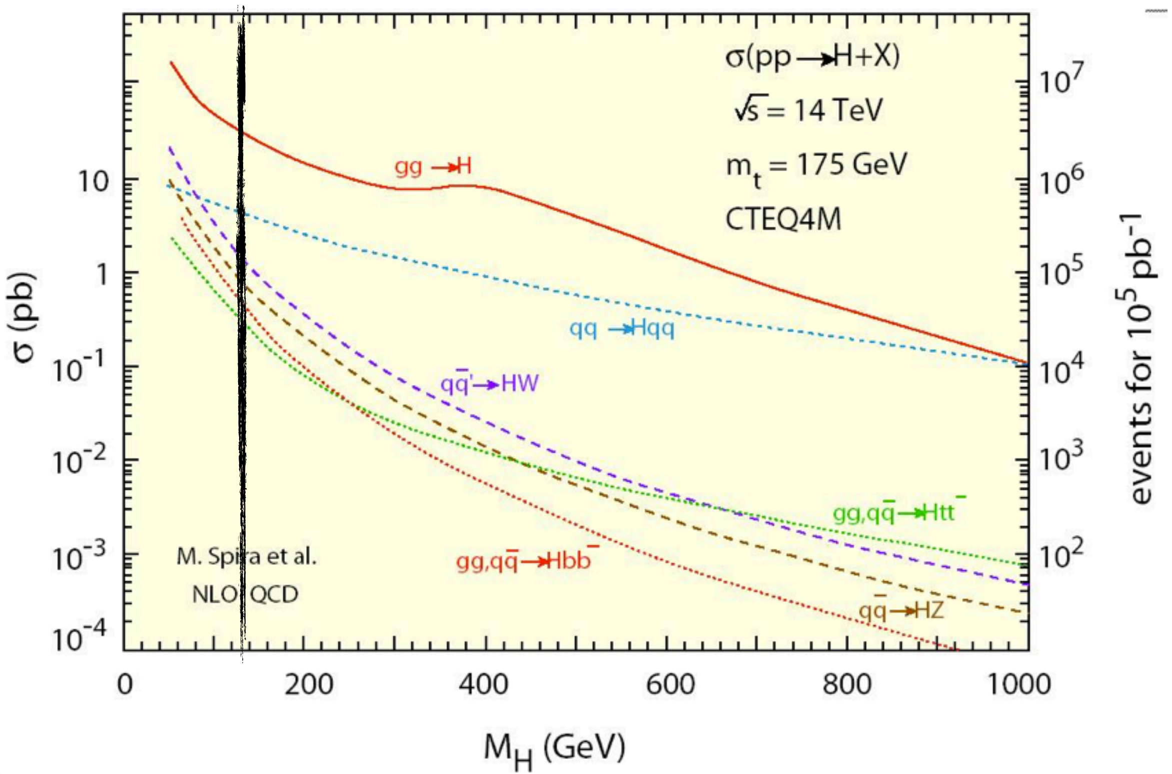
$$f(\tau) = \begin{cases} \left[\sin^{-1}(\sqrt{\tau})\right]^2, & \text{if } \tau \leq 1, \\ -\frac{1}{4}\left[\ln(\frac{\sqrt{\tau}+\sqrt{\tau-1}}{\sqrt{\tau}-\sqrt{\tau-1}}) - i\pi\right]^2, & \text{if } \tau > 1. \end{cases}$$

$$\tau_i = m_H^2/4m_i^2$$

$$N_C = 3$$

Higgs production cross section-> ttH





The ttH represents the smallest XS of the Higgs production mechanisms ~ 1/200

	LHC run I		LHC run II		HE-LHC/SppC/...	
/s(TeV)	7	8	13	14	33	100
XS(ttH) [pb]	0.086	0.13	0.51	0.61	4.6	37

×60

Production of ttbb/ttrr at pp colliders

Deviations of Higgs coupling to top quark from SM one can show up in different ways.

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

$H \to b\bar{b}$

$H \to \gamma\gamma$

Observed upper bound:

ttbb (LHC8) ⟶ $\sigma < 4.1\sigma_{\rm SM}, 3.3\sigma_{\rm SM}$ ATLAS-CONF-2014-011, CMS PAS HIG-14-010

ttrr (LHC8) ⟶ $\sigma < 6.7\sigma_{\rm SM}$ ATLAS-CONF-2014-061

$$\mathcal{L}_{Ht\bar{t}} = -a\frac{m_t}{v}\bar{t}(\cos\xi + i\gamma_5 \sin\xi)tH,$$

affects both production and decay

Using MadGraph5_aMC – heft model ⟶ Tree level cross section

↓

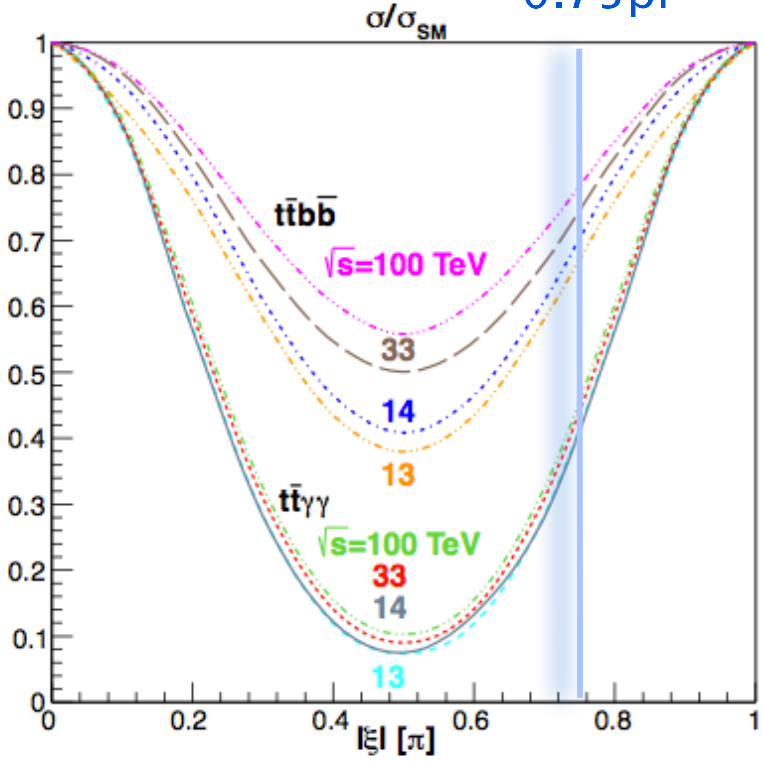
K-factor: 1.19 - 1.40

Parameter set: $a = 1$ $m_H = 125$ GeV

mild cut: $|\eta_{t,\bar{t}}| < 4$

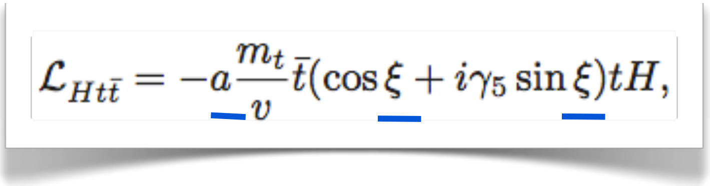
/s=13,14,33,100 TeV, xi=0~pi

0.75pi



Discussions

- a=1, xi=0 -> SM
- xi increases, XS become considerably smaller than SM predictions → distinguish
- if observation unequal to the prediction of SM a=1, xi=0 → BSM
- if observation ~ SM value, one cannot rule out the possibility of BSM ttH coupling



$$\mathcal{L}_{Ht\bar{t}} = -\underline{a}\frac{m_t}{v}\bar{t}(\cos\underline{\xi} + i\gamma_5\sin\underline{\xi})tH,$$

reason: a can be adjusted

xi ≠0, a=1 → XS (ttH) <SM (ttH)

xi ≠0, 1/a^2~ $\sigma/\sigma_{\rm SM}$ → XS (ttH) ~SM (ttH)

- just measuring cross section gives no information about Higgs CP proterties, it is disirable to find ways to distinguish SM from BSM ttH coupling independent of the overall scaling parameter a

Operators in ttH process

operators from ttH final state, sensitive to Higgs CP magnitudes $\cos^2\xi - \sin^2\xi$

O1, O2, O3, O5:
transverse
momentum of t,tbar

$$\mathcal{O}_1 \equiv \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{|(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})|}, \quad \mathcal{O}_2 \equiv \frac{p_t^x p_{\bar{t}}^x}{|p_t^x p_{\bar{t}}^x|}$$

$$\mathcal{O}_3 \equiv \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{p_t^T p_{\bar{t}}^T}, \quad \mathcal{O}_4 \equiv \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{|\vec{p}_t||\vec{p}_{\bar{t}}|},$$

$$\mathcal{O}_5 \equiv \frac{p_t^x p_{\bar{t}}^x}{p_t^T p_{\bar{t}}^T}, \quad \mathcal{O}_6 \equiv \frac{p_t^z p_{\bar{t}}^z}{|\vec{p}_t||\vec{p}_{\bar{t}}|},$$

O4, O6 needs full
momentum of t and tbar

- $p^T_{t,\bar{t}}$ denote the magnitudes of the t and anti-t transverse momenta
- $\hat{n}$ is a unit vector in the direction of the beam line and defines the z axis
- x axis is chosen to be any fixed direction perpendicular to the beam
- There maybe other opeartors but we take the six operators as examples

to be independent
of scaling factor a

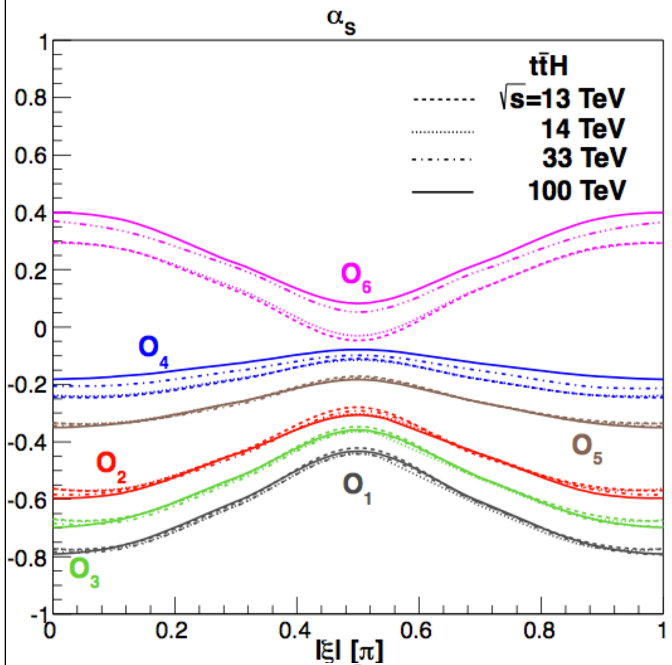
$$\alpha[\mathcal{O}_i] \equiv \frac{\int [\mathcal{O}_i] \{d\sigma(pp \to t\bar{t}XX)/dR\} dR}{\int \{d\sigma(pp \to t\bar{t}XX)/dR\} dR}$$

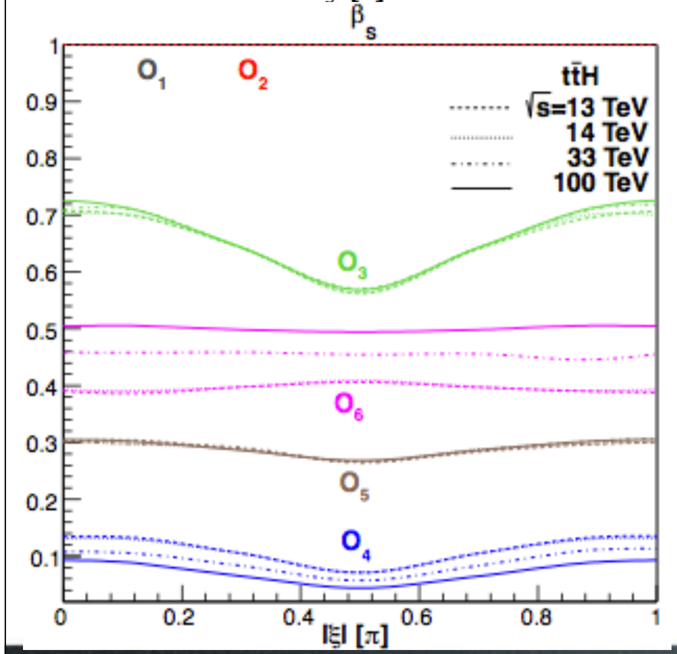
XX is the Higgs
decay products, R
is the phase space

weighted moments

Gunion, He PRL (1996)

Weighted moments





- The changes of alphaS against xi is significant providing hope to distinguish Higgs boson coupling with top quark with mixed CP component
- To what accuracy for a given alphaS it can be measured?

experimental errors of alphaS:

$$\delta\alpha_S = \frac{1}{\sqrt{S}}\left[\beta_S - \alpha_S^2 + \frac{B}{S}(\beta_B - 2\alpha_B\alpha_S + \alpha_S^2)\right]^{1/2}$$

S, B the total # of events for signal and bkg process

$$\beta[\mathcal{O}_i] \equiv \frac{\int [\mathcal{O}_i]^2\{d\sigma(pp \to t\bar{t}XX)/dR\}dR}{\int\{d\sigma(pp \to t\bar{t}XX)/dR\}dR}$$

Note that $\beta_S(\mathcal{O}_{1,2})$ are equal to 1

$$\mathcal{O}_1 \equiv \frac{(\vec{p}_t \times \hat{n})\cdot(\vec{p}_{\bar{t}} \times \hat{n})}{|(\vec{p}_t \times \hat{n})\cdot(\vec{p}_{\bar{t}} \times \hat{n})|}, \quad \mathcal{O}_2 \equiv \frac{p_t^x p_{\bar{t}}^x}{|p_t^x p_{\bar{t}}^x|}$$

Discrimination power for ttbb and ttrr processes

To quantify the ability to distinguish the SM pure scalar case from any CP-mixed Higgs state of each operator

discrimination power:

$$D \equiv \frac{|\alpha_S^{\mathrm{SM}}(\xi = 0) - \alpha_S^{\xi}(\xi)|}{\delta\alpha_S^{\mathrm{SM}}(\xi = 0)}$$

xi= 0 ~ pi

for full consideration → top and Higgs decay

Using MadGraph5_aMC - heft model

H-> bb, H -> rr

for ttrr, adopt cuts: $|\eta_{t,\bar{t},\gamma}| < 4 \quad p_\gamma^T > 25\ \mathrm{GeV} \quad |M_{\gamma\gamma} - m_H| < 5\ \mathrm{GeV}$

for ttbb, adopt cuts: $|\eta_{t,\bar{t},b,\bar{b}}| < 4 \quad p_{b,\bar{b}}^T > 25\ \mathrm{GeV}$

top-> semileptonically, antitop->hadronically

tt -> $2b\text{-jet} + 2j + \ell + \not{E}_T$ → $n \equiv \mathcal{B}(t \to bW)^2 \mathcal{B}(W \to l\nu)\mathcal{B}(W \to jj) \simeq \left(\frac{9}{10}\right)^2 \times \frac{1}{3} \times \frac{2}{3}$

signal cross section reduced by n due to top pair decay

for ttrr, n=0.18 → D ->0.42 D

for ttbb, +b-tagging efficiency (60%), n=0.065 → D ->0.25 D

Prediction from discrimination power

- Given $\alpha_S, \beta_S, \alpha_B, \beta_B$ and bkg event number B → S for certain D
- e.g. to discriminate ttH coupling of xi=0 from xi=0.3pi at 3sigma level, predictions from ttrr and ttbb are different
  - for ttrr, B~50 (2300) for /s=13 (100) TeV, D=3 requires S=750 (1950) from O3

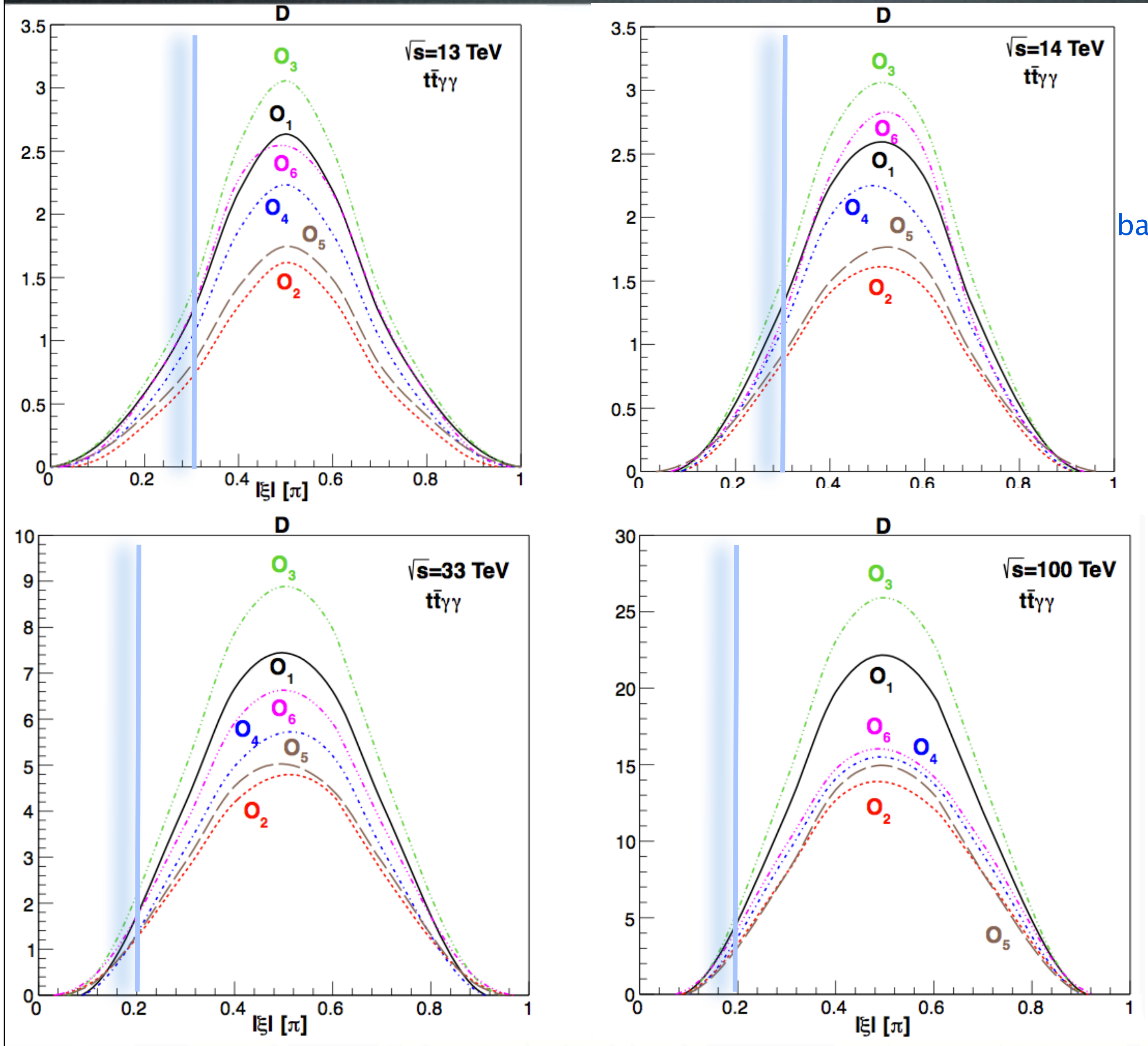
    Simulated: S =160 (9900)   13 TeV × , 100 TeV √

    for ttbb, B~8*10^5 (8*10^7) for /s=13 (100) TeV, D=3 requires S = 4*10^4 (4*10^5) from O6

    Simulated: S =7*10^4 (4*10^6)   13 TeV √ , 100 TeV √

- Using ttrr channel, it is difficult to discriminate the ttH SM coupling from a 0.3pi mixed coupling at 3sigma level at 13 TeV, 100 TeV can achieve the discrimination larger than 3sigma level
- From ttbb channel, one is able to discriminate the ttH SM coupling from a 0.3pi mixed state at more than 3sgima, at any collision energy with /s >13 TeV.

Discrimination power for ttrr



assume: $\mathcal{L} = 300\ \mathrm{fb}^{-1}$

$\mathcal{L}$ =3 ab^{-1} D->3.2D

O1,O3,O4,O6 are most useful balancing the sensitivity and errors

$$\mathcal{O}_3 \equiv \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{p_t^T p_{\bar{t}}^T}$$

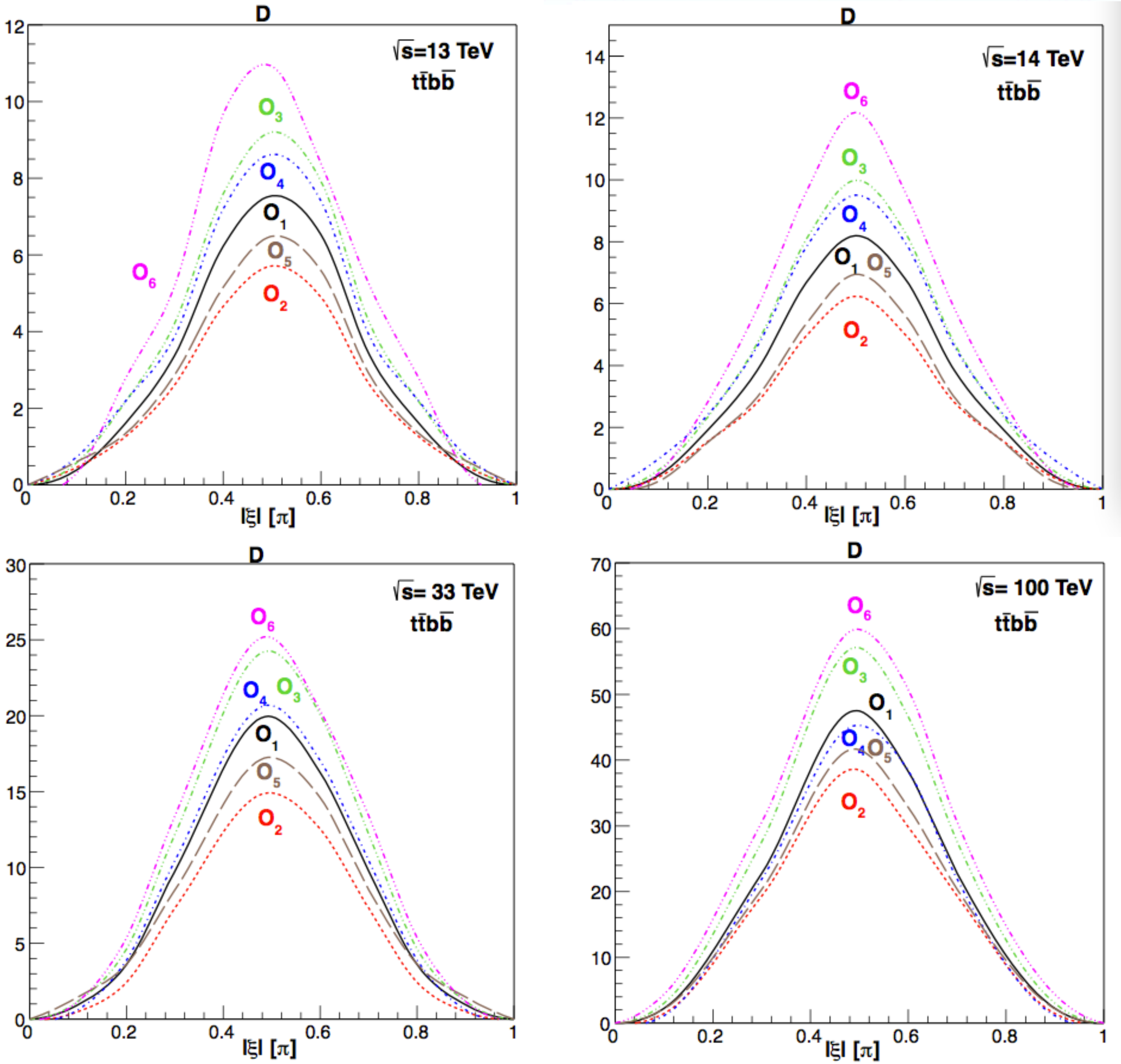
at 13,14 TeV, D<3;
HL-LHC, xi>0.3pi, D>3

at 33, 100 TeV, D>3
with xi >0.2pi

O3 performs the best
for all operators

at xi=0.5pi, all the
operators reach maximal D

Discrimination power for ttbb



H > bb decay modes show better discrimination powers due to the large event rate of the Higgs to bb decay branching ratio

O3 and O6 give the best discrimination powers

$$\mathcal{O}_3 \equiv \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{p_t^T p_{\bar{t}}^T}$$

$$\mathcal{O}_6 \equiv \frac{p_t^z p_{\bar{t}}^z}{|\vec{p}_t||\vec{p}_{\bar{t}}|}$$

imposing further cuts on ttbb final state (jet multiplicities) will obtain even better discrimination power

Summary

- The Higgs boson H has the largest coupling to the top quark t. The ttH interaction can be sensitive to the investigation of BSM.
- We studied the potential of determining Higgs boson CP properties at the LHC and future 33 TeV and 100 TeV pp colliders by analysing various operators from ttH final state.
- When the CP mixing angle increases, the cross section becomes smaller than SM one.-> distinguish the SM ttH coupling with BSM
- Weighted moments and discrimination power are defined for ttbb and ttrr process, at L=300/fb, we find that for ttrr the discrimination power is below 3sigma at the LHC, at 33 TeV and 100 TeV, more than 3sigma sensitivity can be reached. ttbb process can provide more than 3sgima discrimination power in a wide range at the LHC and 33, 100 TeV pp colliders.
- Detector simulations and more interesting phenomenologies...

Thanks for your attention!