2018年TeV工作组学术研讨会，南开大学

Probing CP-violating Higgs-top Coupling

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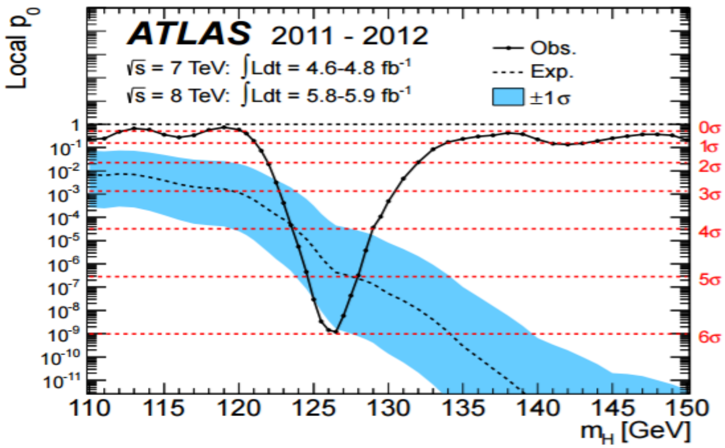
JHEP 1604 (2016) 011 ;
JHEP 1410 (2014) 100.

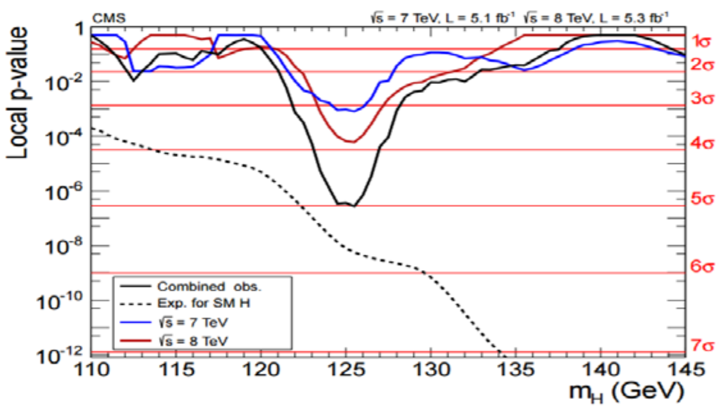
Outline

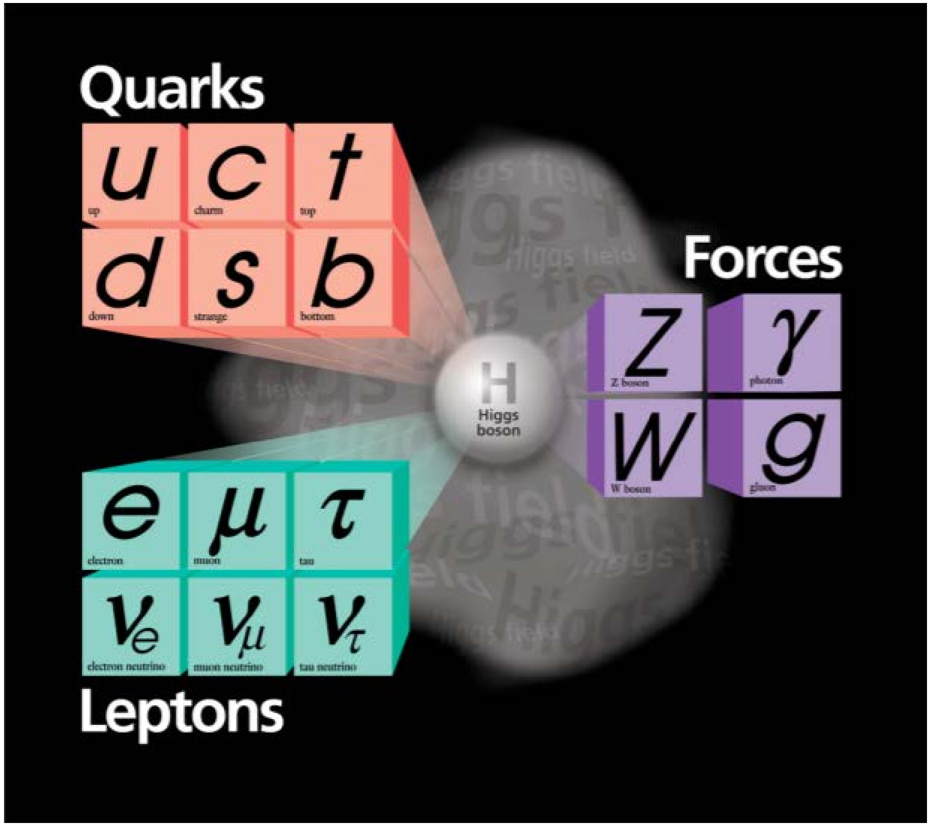
- Brief review of Higgs measurements
- Constraining CPV Higgs-top coupling
- Probing CPV Higgs-top coupling at the LHC and CEPC

1. Brief review of Higgs measurements

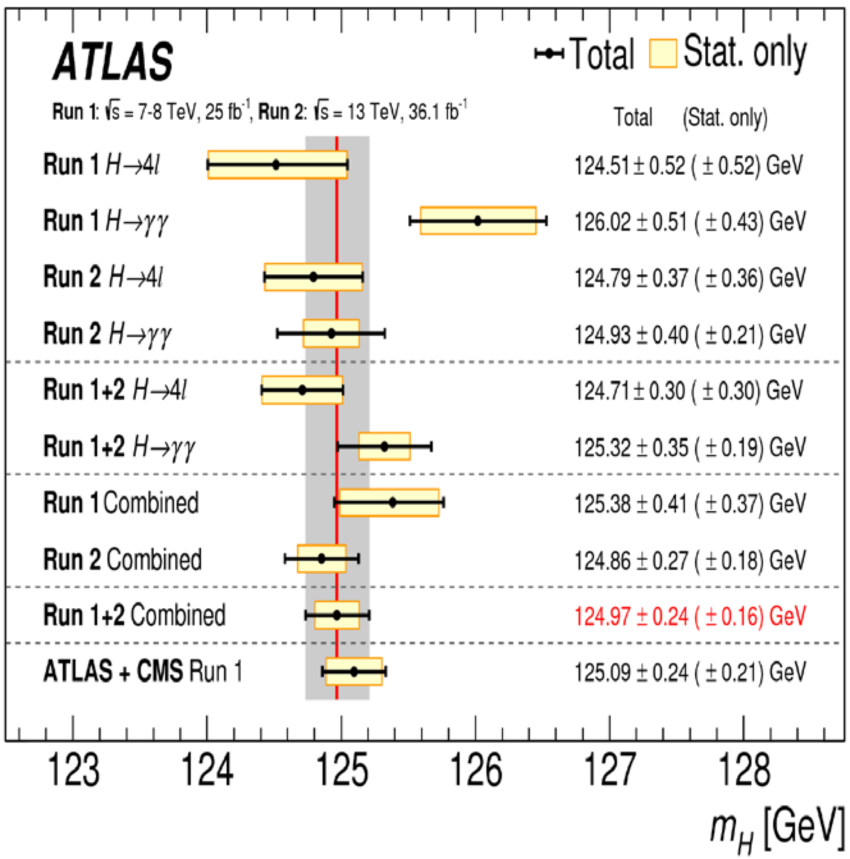
- **In 2012, ATLAS and CMS Collaborations discovered the Higgs boson. Completion of the SM!**

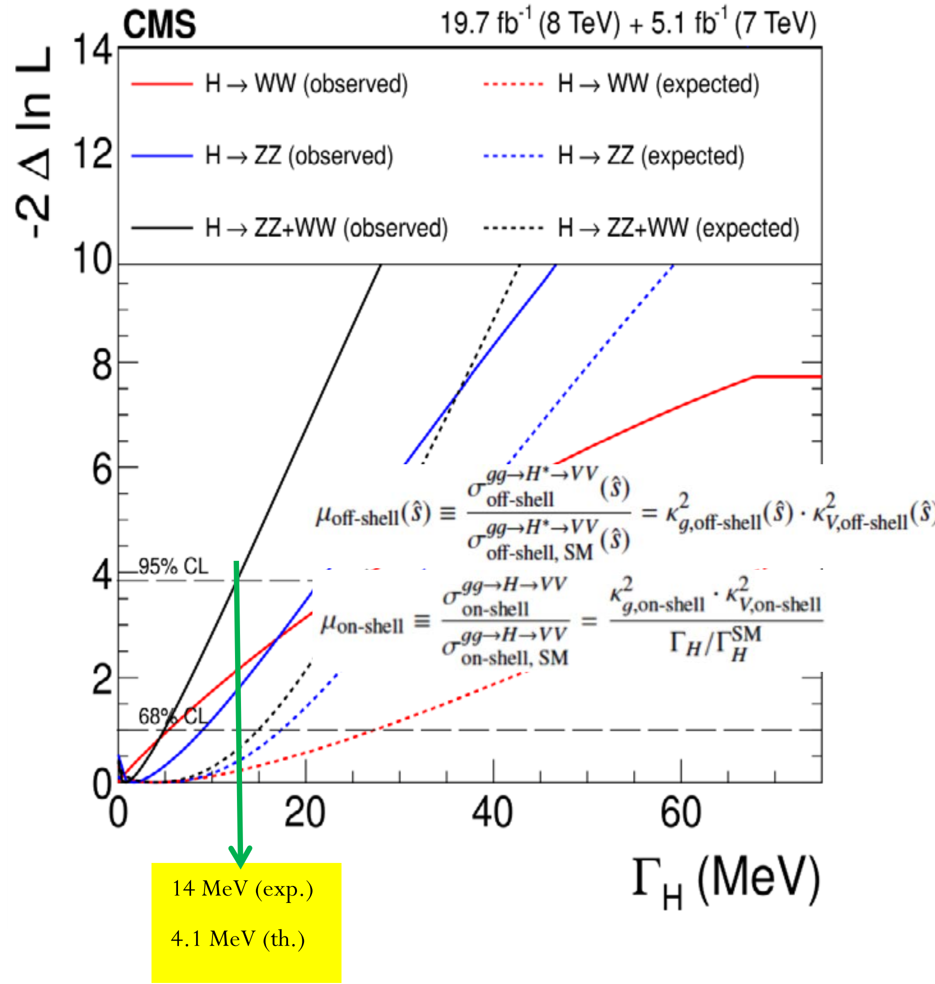


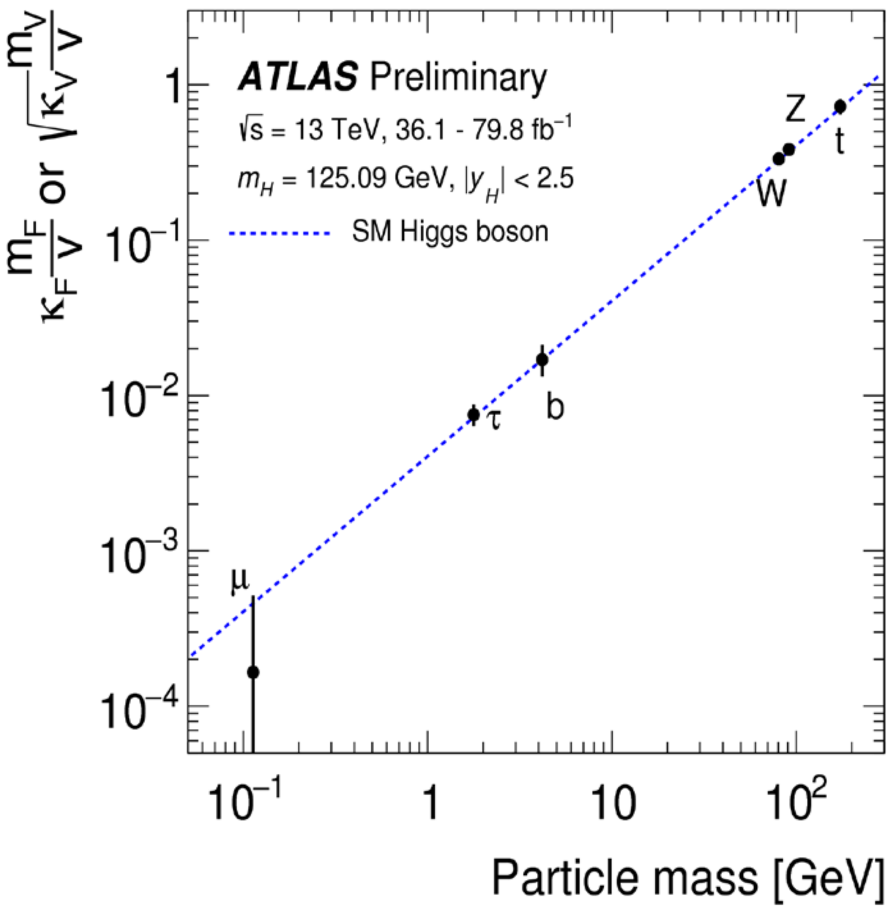


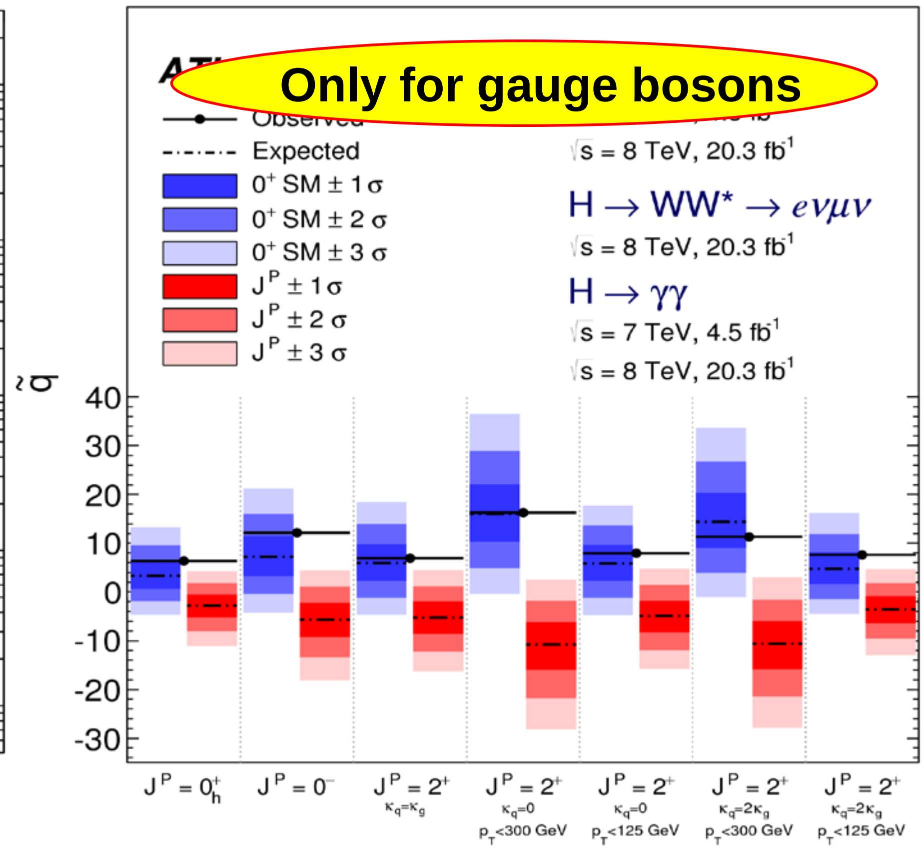


- **Higgs mass, width, CP, spin and couplings have been widely studied.**

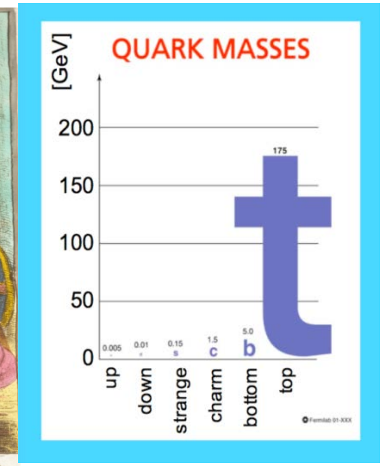




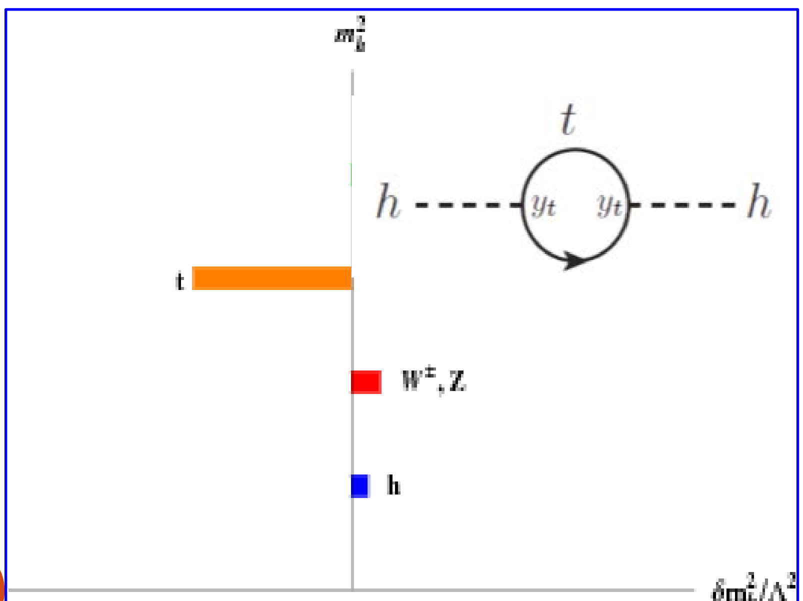


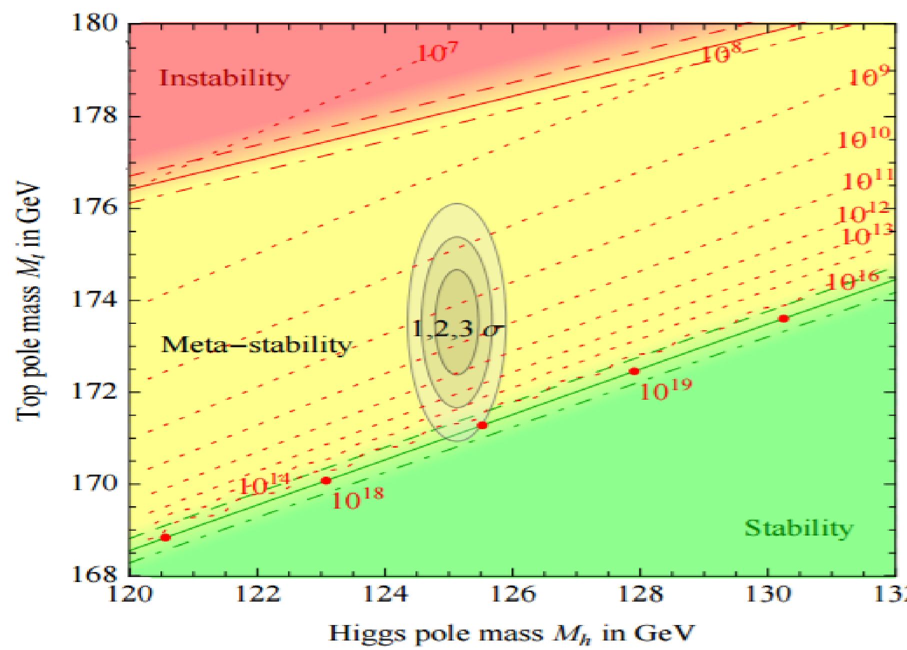


- **Higgs bosonic couplings seems consistent with the SM predictions.**
- **Higgs fermionic couplings are still unclear, e.g. CP nature.**

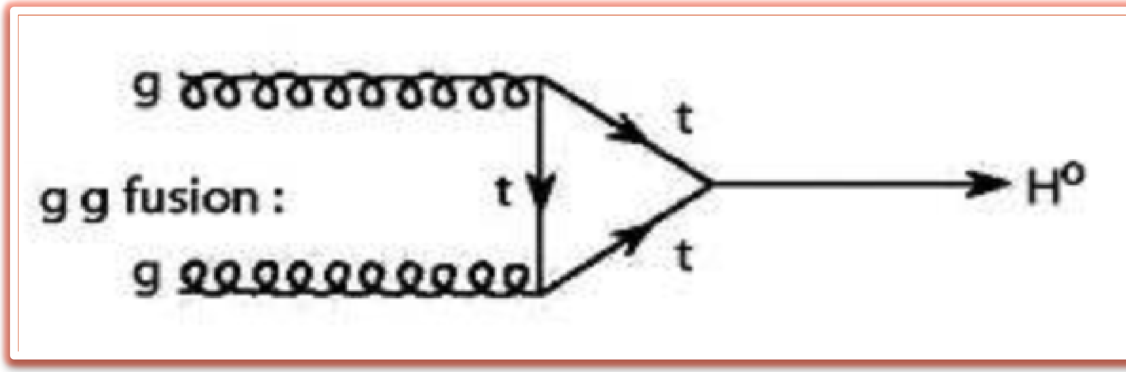


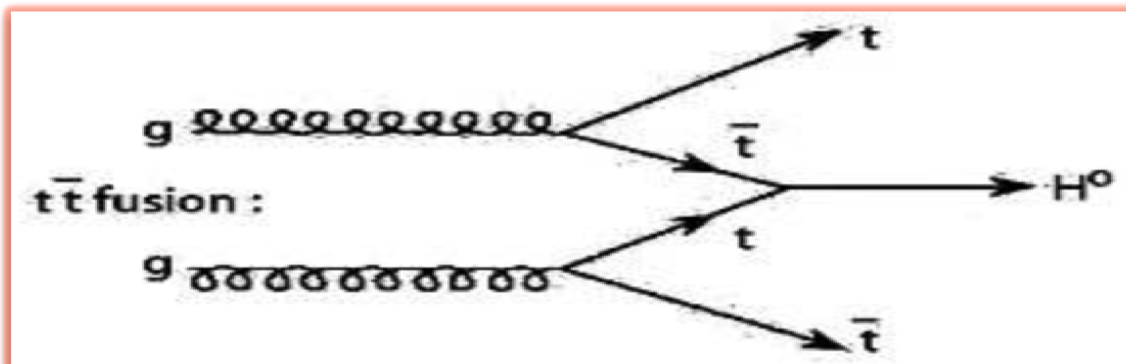
For $m_t = 173.34 \pm 0.76$ GeV → $\lambda_t = \frac{\sqrt{2} m_t}{v} = 0.996 \pm 0.004$

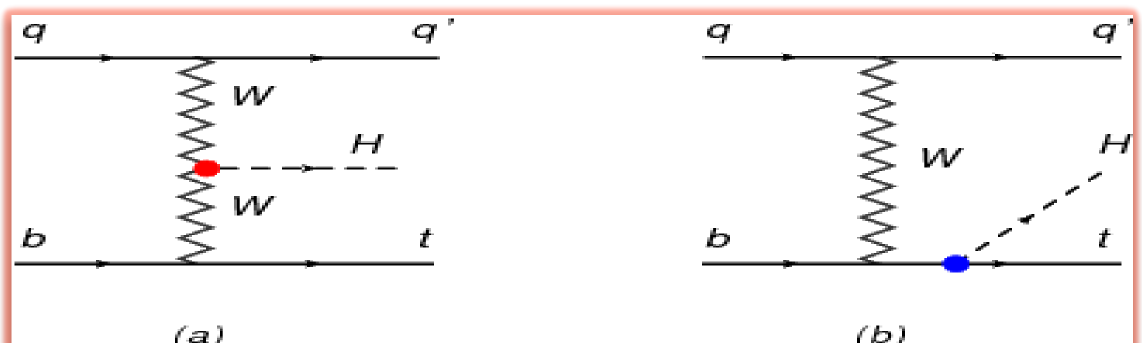


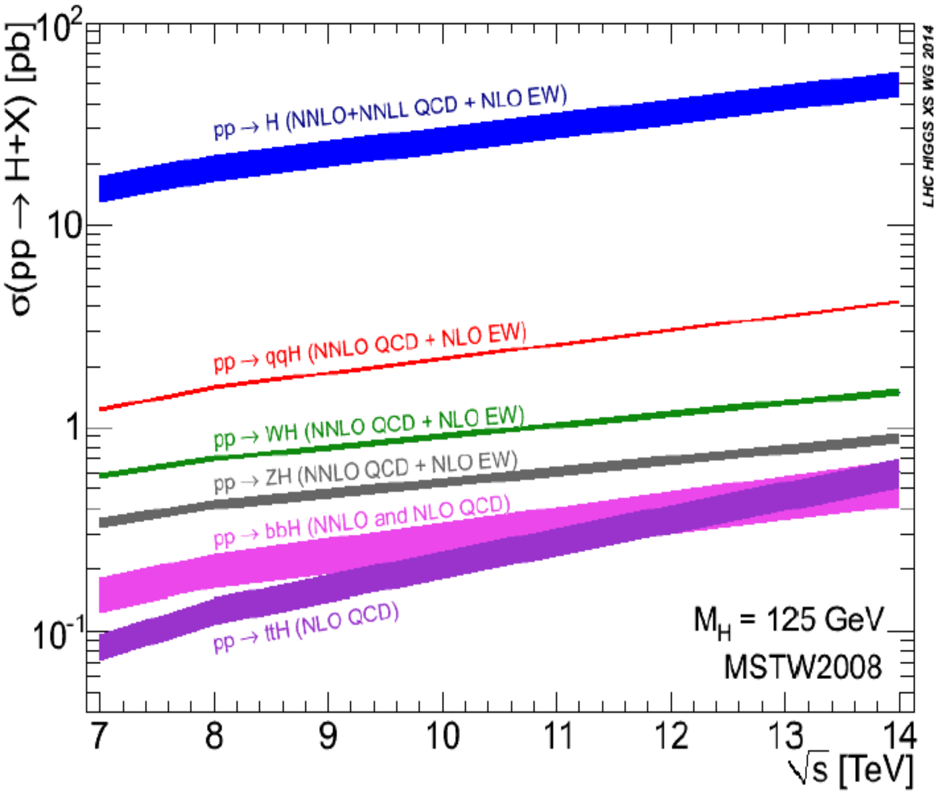


Measurements of Higgs-top coupling at the LHC









Hadronic

$H \to bb$, $H \to \tau_h \tau_h$

Leptonic

$H \to WW$, $H \to \tau_\ell \tau_{any}$

Bosonic:

$H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$

Cross section [pb] @125.09 GeV	ggF	VBF	WH	ZH	ttH	bbH
8 TeV	21.39	1.600	0.701	0.4199	0.1326	0.2015
13 TeV	48.52	3.779	1.369	0.8824	0.5065	0.4863
Ratio	2.27	2.36	1.95	2.10	3.82	2.41

BR:	21.5%	6.3%	58.1%	0.23%	2.6%
H decay	WW	ττ	bb	γγ	ZZ

		μ (Meas./SM)	Stat.	Syst.	Obv.	Data sets
ttH Multilepton	ATLAS	1.56	0.30	0.29	4.1σ	36.1 fb^{-1}
	CMS	1.23	0.26	0.36	3.2σ	35.9 fb^{-1}
ttH,H→bb (with lepton)	ATLAS	0.79	0.29	0.53	1.6σ	36.1 fb^{-1}
	CMS	0.72	0.24	0.38	1.6σ	35.9 fb^{-1}
ttH,H→$\gamma\gamma$	ATLAS	1.39	0.40	0.20	4.1σ	79.8 fb^{-1}
	CMS	2.3	0.76	0.24	~3σ?	35.9 fb^{-1}
ttH,H→ZZ	ATLAS	-	-	-	0σ	79.8 fb^{-1}
	CMS	-	-	-	-	35.9 fb^{-1}
Combined	ATLAS	1.32	0.18	0.20	6.3σ	7+8+13TeV
	CMS	1.26	0.16	0.24	5.2σ	7+8+13TeV

from Huaqiao Zhang

2. Constraining CPV Higgs-Top Coupling from Higgs data, EDM, Flavor Physics

- **New physics effects on Higgs-Top coupling can be parameterized by a gauge invariant dimension-six operator**

Aguailar-Saavedra, arXiv:0904.2387

$$\mathcal{L}^{6}_{t\bar{t}h} = -\frac{C^{33}_{u\phi}}{\Lambda^2}(\phi^\dagger\phi)(\overline{Q}_{3L}t_R\tilde{\phi}) + \text{ h.c.}$$

after EWSB,

$$\mathcal{L}_{t\bar{t}h} = -\frac{y_t}{\sqrt{2}}\bar{t}(\cos\theta + i\sin\theta\gamma^5)th,$$

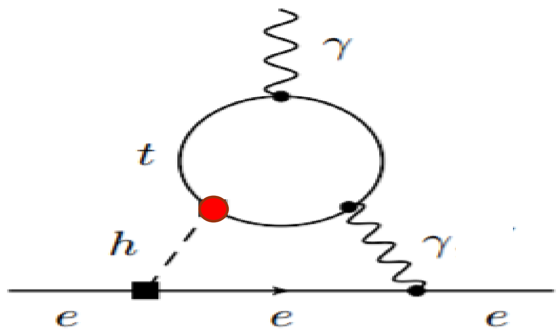
with

$$y_t\cos\theta = y_{t_{SM}} + \frac{v^2}{\Lambda^2}\text{Re } C^{33}_{u\phi}, \quad y_t\sin\theta = \frac{v^2}{\Lambda^2}\text{Im } C^{33}_{u\phi}.$$

For convenient,

$$C_t^s = y_t\cos\theta / y_{t_{SM}} \qquad C_t^p = y_t\sin\theta / y_{t_{SM}}$$

Electron EDM and B physics

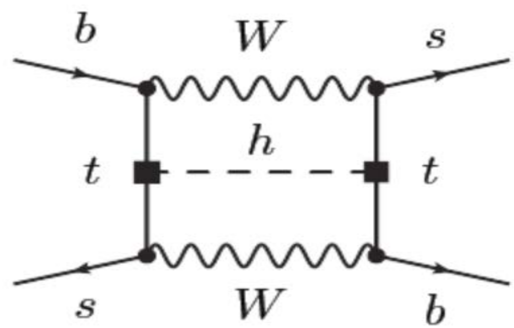


$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_e \left[C_e^s C_t^p f_1(x_{t/h}) + C_e^p C_t^s f_2(x_{t/h})\right]$$

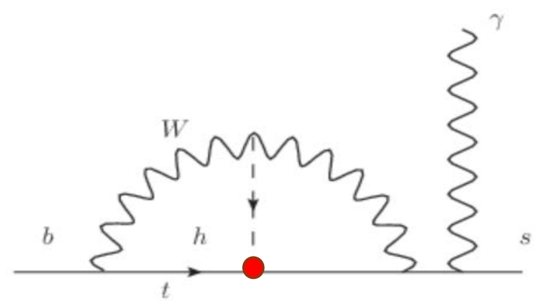
The ACME limit reads $\left|\frac{d_e}{e}\right| < 8.7 \cdot 10^{-29}$ cm

$C_e^s = 1, C_e^p = 0$ → $C_t^p < 0.01$

Top EDM measurement through top pair production at e+e- collider may provide a robust test!



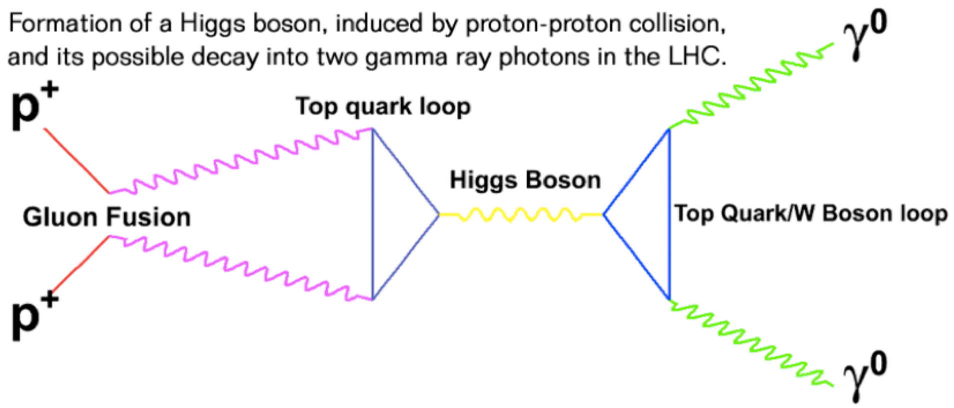
suppressed by light quark masses

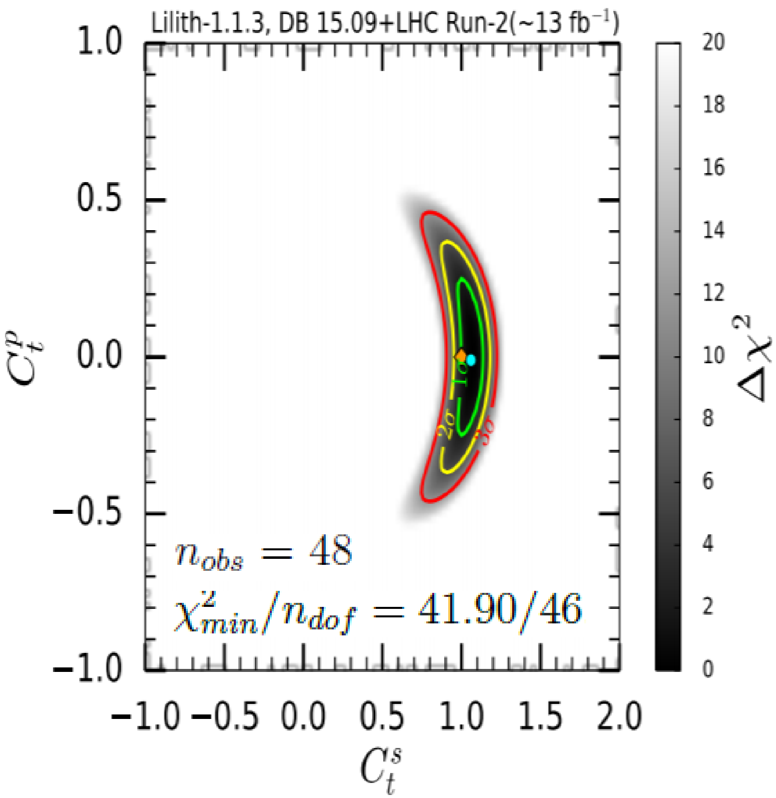


uncertainty still large

Higgs data fit

Kobakhidze, Liu, Wu, Yue, 1610.06676 (PRD)





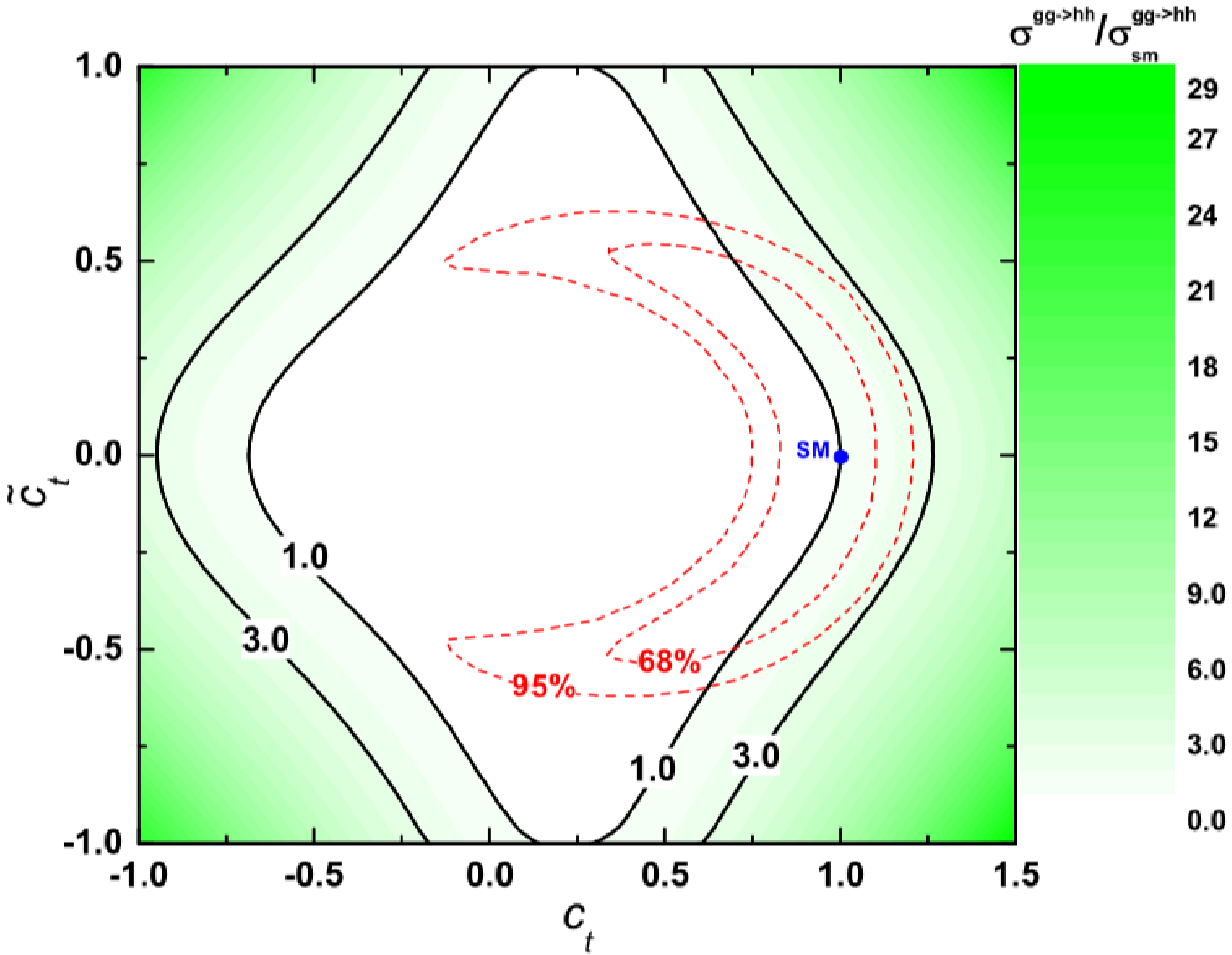
$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)|_{\rm SM}} \simeq \frac{\left|\frac{1}{4}A_1[m_W]+(\frac{2}{3})^2 C_t^s\right|^2+|(\frac{2}{3})^2\frac{3}{2}C_t^p)|^2}{\left|\frac{1}{4}A_1[m_W]+(\frac{2}{3})^2\right|^2}$$

$$\frac{\sigma(gg\to h)}{\sigma(gg\to h)|_{\rm SM}} = \frac{\Gamma(h\to gg)}{\Gamma(h\to gg)|_{\rm SM}} \simeq |C_t^s|^2+|\frac{3}{2}C_t^p|^2$$

$$|C_t^p| < 0.37 \text{ and } 0.68 < C_t^s < 1.2$$

Higgs Pair

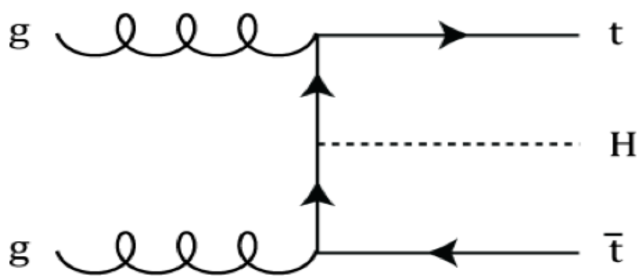
Liu, Hu, Yang, Han arXiv:1408.4191(JHEP)

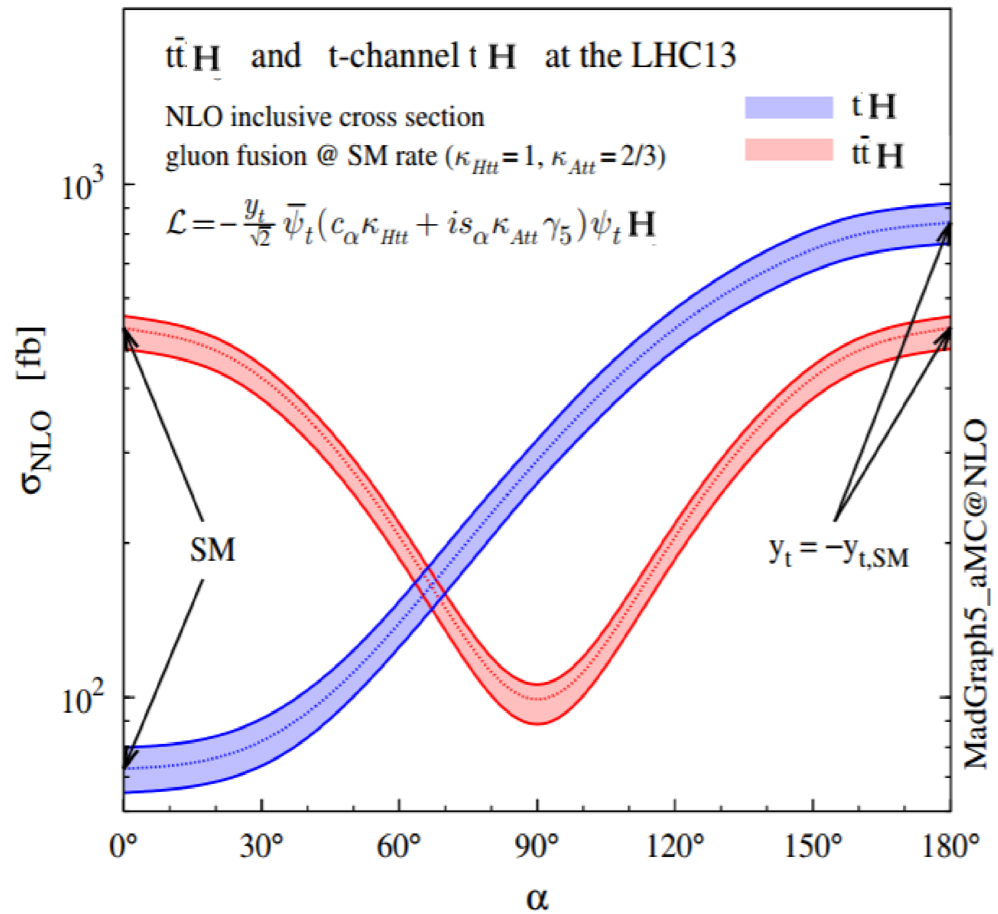


< 3 times !

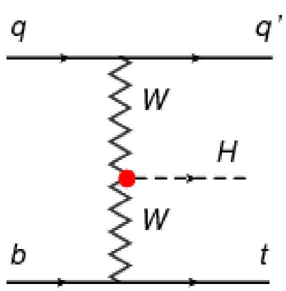
3. Probing CPV Higgs-Top Coupling at LHC and CEPC

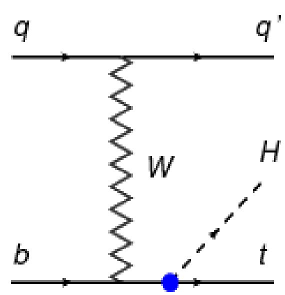
- **Two direct ways to probe top-Higgs couplings at the LHC.**





- In SM, large cross section.



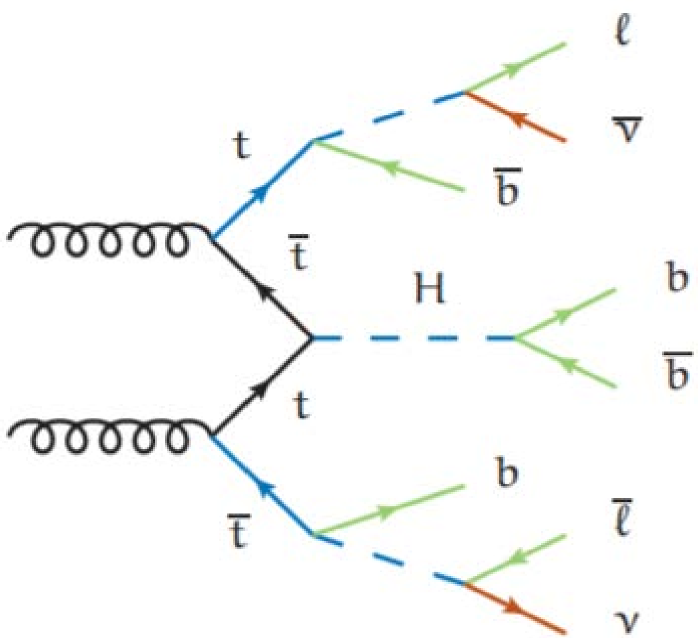


- In SM diagrams interfere destructively.

Li, Si, Wu, Yue, arXiv:1701.00224 (PLB)

- **Top pair and Higgs associated production at the LHC.**

Dileptonic tth(->bb)

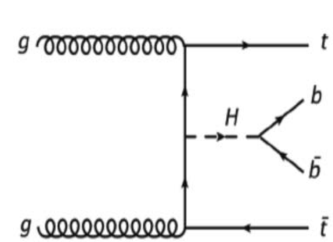


Advantages:

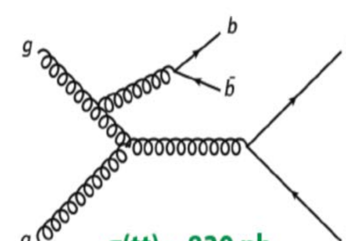
1. Dominant Higgs decay mode
2. Two leptons in the final states

Disadvantages:

1. Large backgrounds from tt+jets, especially tt+bb
2. Large uncertainty of modeling



$\sigma(ttH) \times BR(bb) = 0.3$ pb



$\sigma(tt) = 830$ pb
$\sigma(tt + b\text{-jets}) \sim O(10)$ pb

		μ (Meas./SM)	Stat.	Syst.	Obv.	Data sets
ttH Multilepton	ATLAS	1.56	0.30	0.29	4.1σ	36.1 fb^{-1}
	CMS	1.23	0.26	0.36	3.2σ	35.9 fb^{-1}
ttH,H→bb (with lepton)	ATLAS	0.79	0.29	0.53	1.6σ	36.1 fb^{-1}
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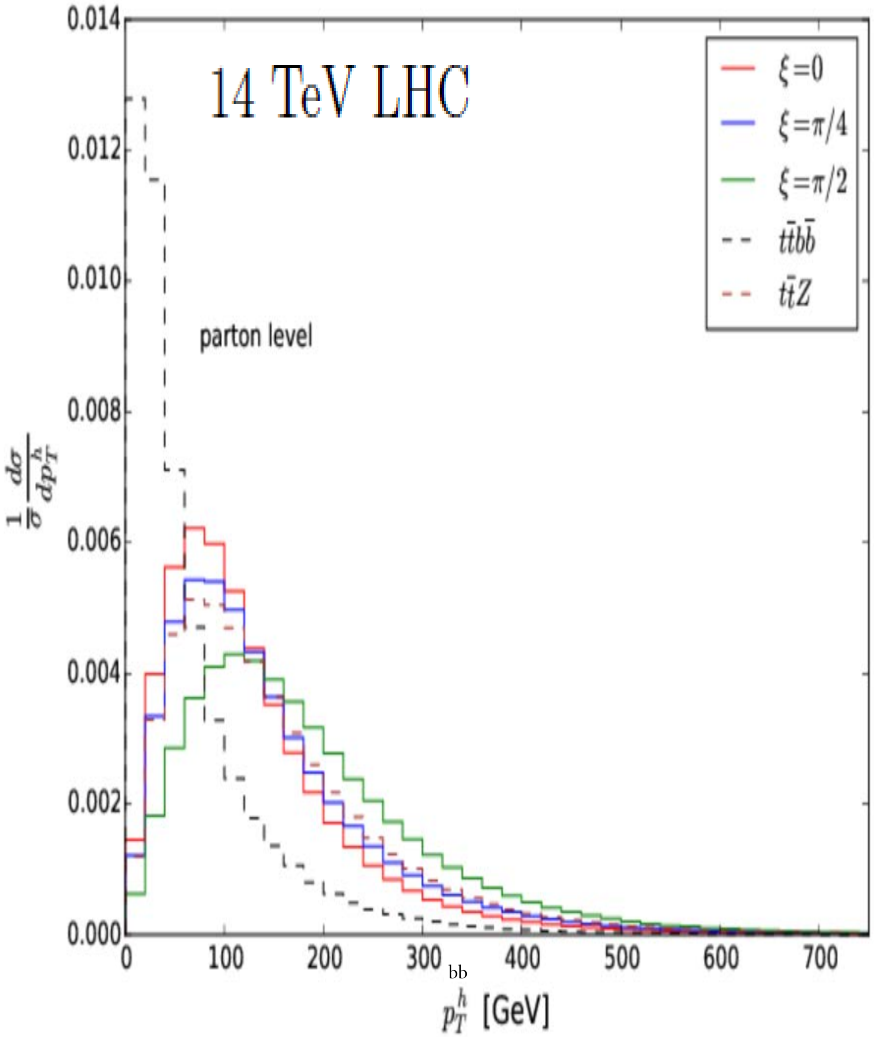
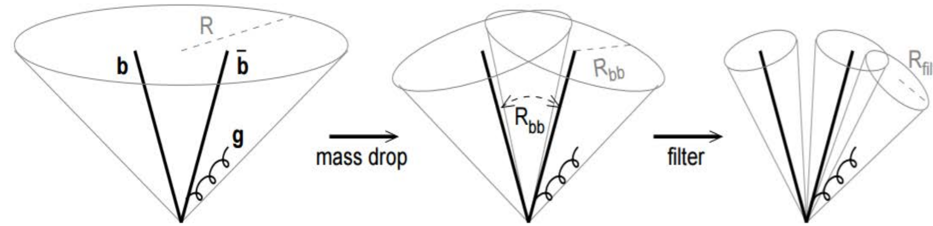
Combined	ATLAS	1.32	0.18	0.20	6.3σ	7+8+13TeV
	CMS	1.26	0.16	0.24	5.2σ	7+8+13TeV

from Huaqiao Zhang



BDRS method



- reconstructing the fat jets using C/A algorithm with radius $R = 1.5$ and $p_T^h > 150$ GeV;
- breaking each fat jet by undoing the clustering procedure, j_1 and j_2. Higgs jet candidate is taken as the leading fat jet that has large mass drop $m_{j_1} < \mu m_j$ ($\mu < 0.67$) and not too asymmetric mass splitting $y = min(p_{Tj_1}^2, p_{Tj_2}^2)/m_j^2 * \Delta R_{j_1,j_2}^2$ ($y_{cut} > 0.09$) at certain step during the de-clustering;
- filtering the Higgs neighbourhood by re-running the C/A algorithm with a finer angle $R_{filt} = \min(0.3, R_{j_1,j_2}/2)$ and taking the three hardest subjects;
- applying b-tag on the two leading subjects. The Higgs jet candidate is required to have both subjects being b-tagged.
- The constituents of the Higgs jet candidate are removed from those particle-flow objects. The remnants are clustered with the anti-k_T jet clustering algorithm with the cone radius of $R = 0.4$

cut	$t\bar{t}h(\xi=0)$	$t\bar{t}h(\xi=\pi/4)$	$t\bar{t}h(\xi=\pi/2)$	$t\bar{t}b\bar{b}$	$t\bar{t}Z(\to b\bar{b})$
2ℓ, $p_T^\ell > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$	13.31	9.14	5.31	2424.73	1.56
$p_T^{\rm BDRS}(b\bar{b}) > 150$ GeV	2.02	1.47	0.97	19.24	0.25
2 non-Higgs b's	0.28	0.21	0.15	1.41	0.04
$p_T^b(\text{non-}h) > 30$ GeV, $\lvert\eta_b(\text{non-}h)\rvert < 2.5$	0.22	0.17	0.13	1.13	0.03
$\lvert m_{b\bar{b}}^{\rm BDRS} - 125\rvert < 10$ GeV	0.053	0.048	0.042	0.09	0.0013

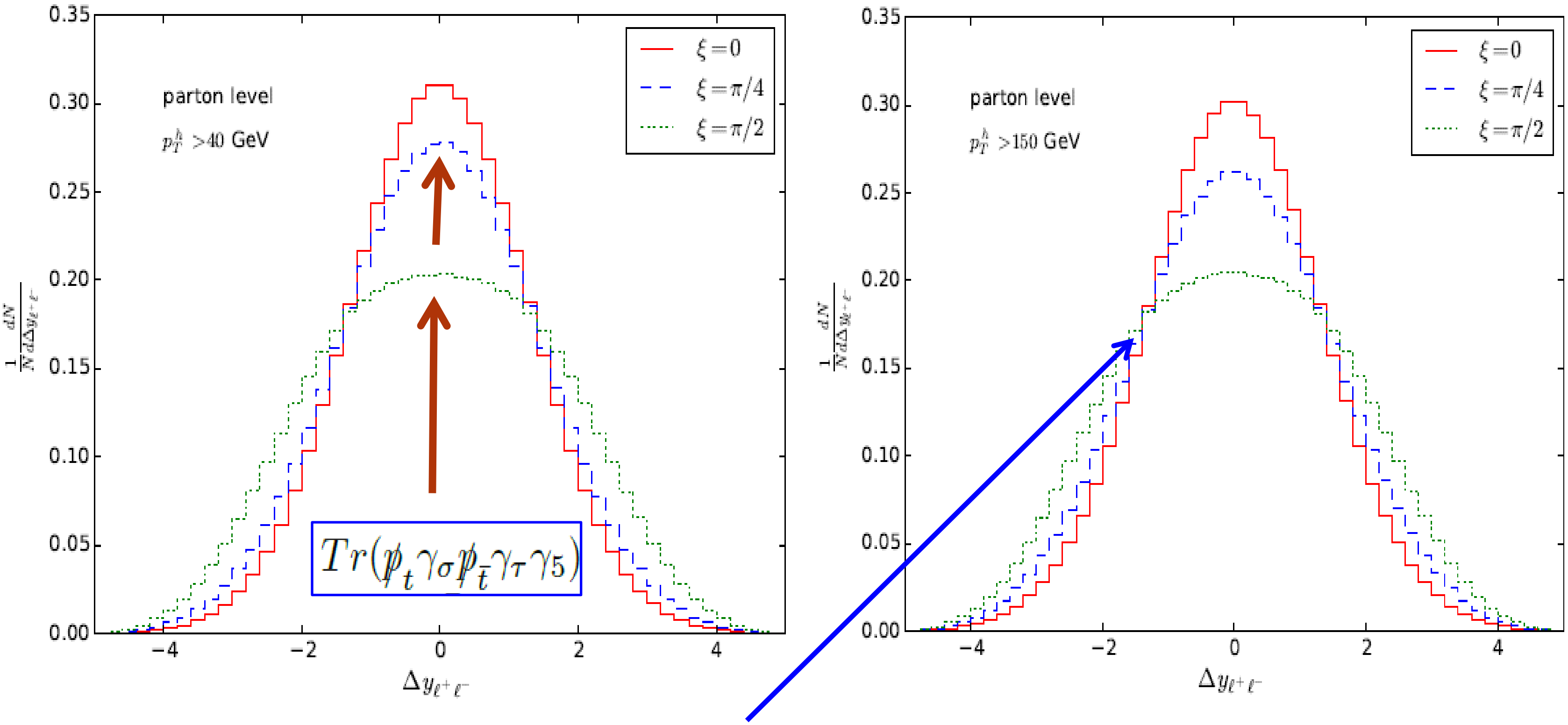
TABLE II. Cut flow of the cross sections of the signal $t\bar{t}h$ for $\xi = 0, \pi/4, \pi/2$ and backgrounds $t\bar{t}b\bar{b}$ and $t\bar{t}Z$ at 14 TeV LHC. The cross section is in unit fb.

- Cut $p_T^{BDRS}(b\bar{b}) > 150$ GeV, the $t\bar{t}b\bar{b}$ background is reduced by almost $\mathcal{O}(10^{-2})$, while the signals only by $\mathcal{O}(10^{-1})$.
- Cut $|m_{b\bar{b}}^{BDRS} - 125| < 10$ GeV will further suppress $t\bar{t}b\bar{b}$ and $t\bar{t}Z$ backgrounds by one order.

$S/\sqrt{B} = 5\sigma$ → $\xi = 0, \quad \pi/4, \quad \pi/2$

$\mathcal{L} = 795, \ 993, \ 1276 \ fb^{-1}$

- **Spin-analyzers of CP phase are usually frame dependent.**
- **Boost technique or experimental selections often affect the sensitivity of spin-discriminators.**



$$A_{CE} \equiv \frac{\sigma_{|\Delta y_{\ell^+\ell^-}|>|\Delta y^0_{\ell^+\ell^-}|} - \sigma_{|\Delta y_{\ell^+\ell^-}|<|\Delta y^0_{\ell^+\ell^-}|}}{\sigma_{|\Delta y_{\ell^+\ell^-}|>|\Delta y^0_{\ell^+\ell^-}|} + \sigma_{|\Delta y_{\ell^+\ell^-}|<|\Delta y^0_{\ell^+\ell^-}|}}$$

ξ	$A_{CE}(\ell^+\ell^-)(\%)$	
	$p_T^h > 40$ GeV	$p_T^h > 150$ GeV
0	-52.00	-48.92
$\pi/4$	-41.13	-35.58
$\pi/2$	-16.53	-16.73

TABLE I. Parton-level values of $A_{CE}(\ell^+\ell^-)$ with $p_T^h > 40, 150$ GeV for $\xi = 0, \pi/4, \pi/2$ at 14 TeV LHC.

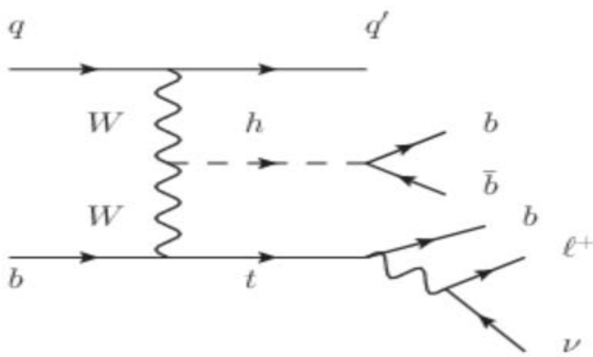
ξ	N_{events}		$A_{CE}(\ell^+\ell^-)(\%)$
	$\Delta\eta > 1.5$	$\Delta\eta < 1.5$	
0	2653	6230	-40.26
$\pi/4$	4239	7312	-26.60
$\pi/2$	7774	9400	-9.47

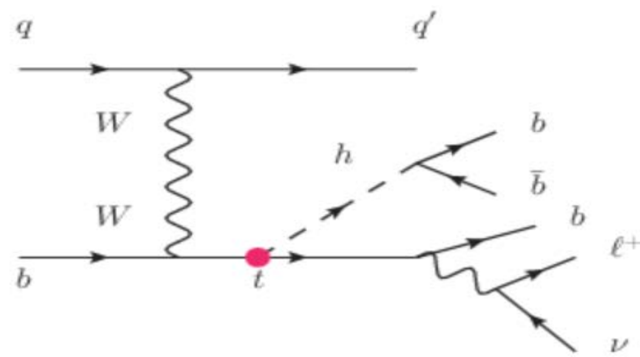
TABLE III. Reconstructed level values of $A_{CE}(\ell^+\ell^-)$ at 14 TeV LHC.

• Single top and Higgs associated production

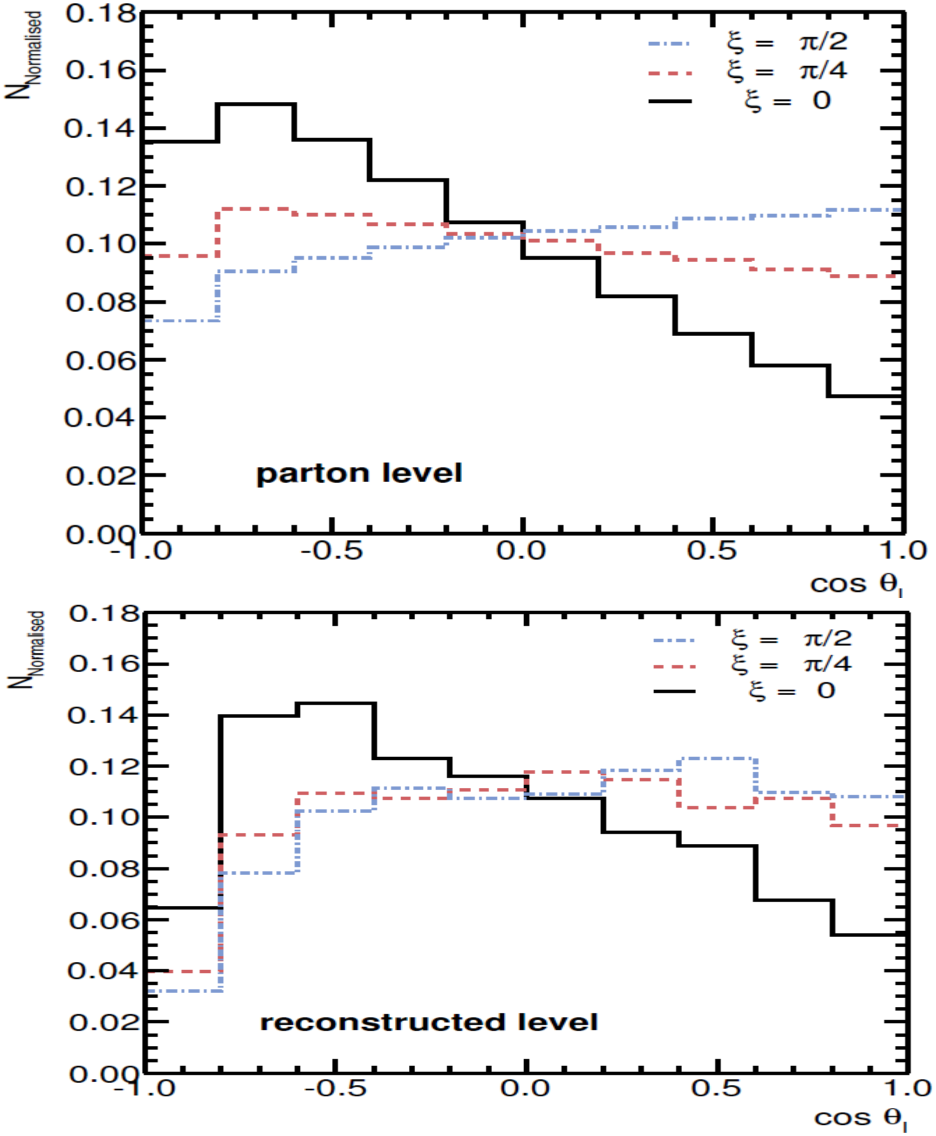
leptonic tjh(->bb)

Kobakhidze, Wu, Yue, 1406.1961 (JHEP)





Cuts		σ [fb]			
		thj			$t\bar{t}_{\text{matched}}$
		$\xi = 0$	$\xi = \pi/4$	$\xi = \pi/2$	
(C1)	$\Delta R_{ij} > 0.4$, $i,j = b, j$ or ℓ $p_T^b > 25$ GeV, $\lvert\eta_b\rvert < 2.5$ $p_T^\ell > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$ $p_T^j > 25$ GeV, $\lvert\eta_j\rvert < 4.7$	0.3169	0.6700	2.1860	712.4
(C2)	$M_{b\ell} < 200$ GeV	0.3152	0.6582	2.1446	708.7
(C3)	$\lvert\eta_j\rvert > 2.5$	0.1492	0.3314	1.1002	80.33
(C4)	$\lvert M_{b_1\bar{b}_2} - m_h\rvert < 15$ GeV	0.0443	0.1102	0.3762	15.82
	$S/\sqrt{B}$ with 3000 fb^{-1}	0.610	1.517	5.180	



$$\mathcal{A}_{FB}^{\ell} = \frac{\sigma(\cos\theta_\ell > 0) - \sigma(\cos\theta_\ell < 0)}{\sigma(\cos\theta_\ell > 0) + \sigma(\cos\theta_\ell < 0)}$$

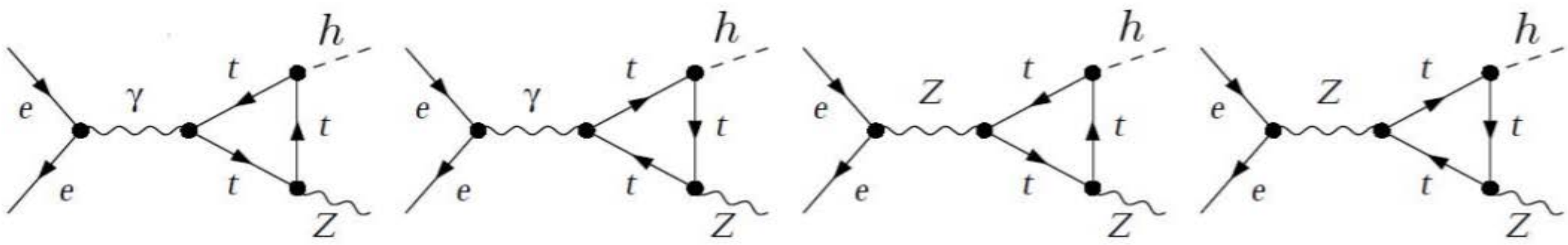
ξ	$\sigma(\cos\theta > 0)$ [fb]	$\sigma(\cos\theta < 0)$ [fb]	$\mathcal{A}_{FB}^{\ell}$ (%)
0	0.01458	0.0208	-17.6
$\pi/4$	0.04687	0.03991	8.0
$\pi/2$	0.1681	0.1276	13.7

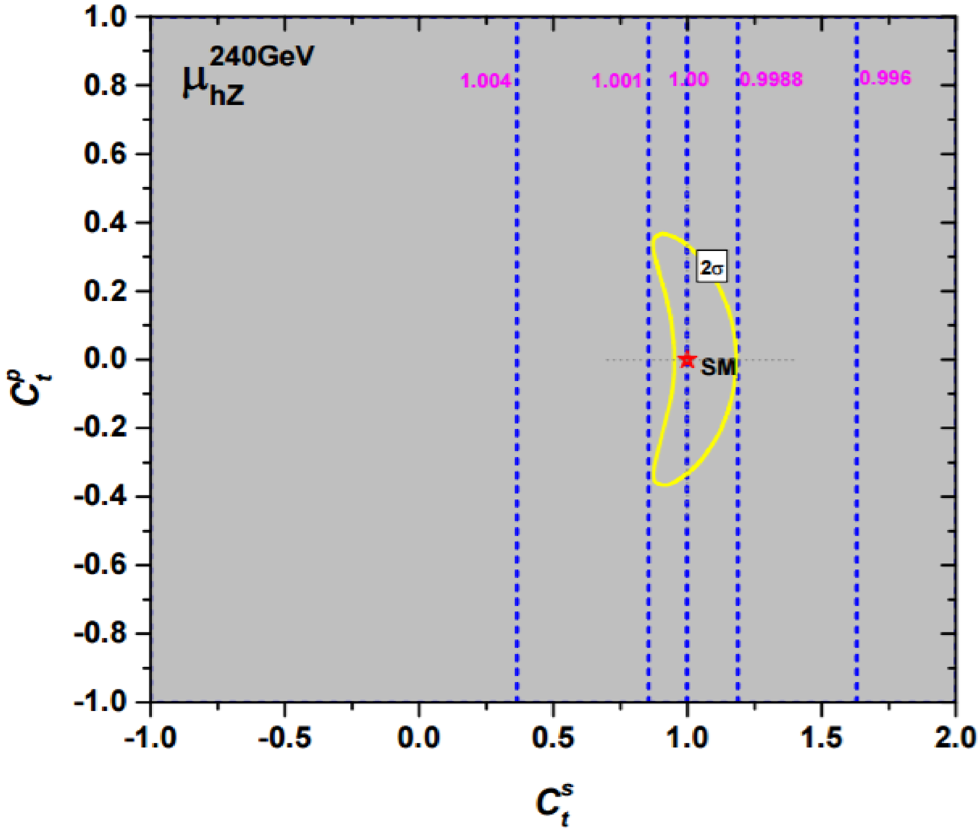
Table. 1.

List of the main observables and expected accuracy at FCC-ee and CEPC with 2 Million/1 Million Higgs boson respectively

	FCC-ee 240GeV	CEPC 250GeV
Higgs mass	-	5.4 MeV
$\sigma(ZH)$	0.4%	0.7%
$\sigma(ZH)\times Br(H\to bb)$	0.2%	0.4%
$\sigma(ZH)\times Br(H\to cc)$	1.2%	2.1%
$\sigma(ZH)\times Br(H\to gg)$	1.4%	1.8%
$\sigma(ZH)\times Br(H\to WW)$	0.9%	1.3%
$\sigma(ZH)\times Br(H\to ZZ)$	3.1%	5.1%
$\sigma(ZH)\times Br(H\to \tau\tau)$	0.7%	1.2%
$\sigma(ZH)\times Br(H\to \gamma\gamma)$	3.0%	8.0%
$\sigma(ZH)\times Br(H\to \mu\mu)$	13%	18%
$\sigma(\nu\nu H)\times Br(H\to bb)$	2.2%	3.8%

One-loop correction to $e^+e^- \to Zh$ production



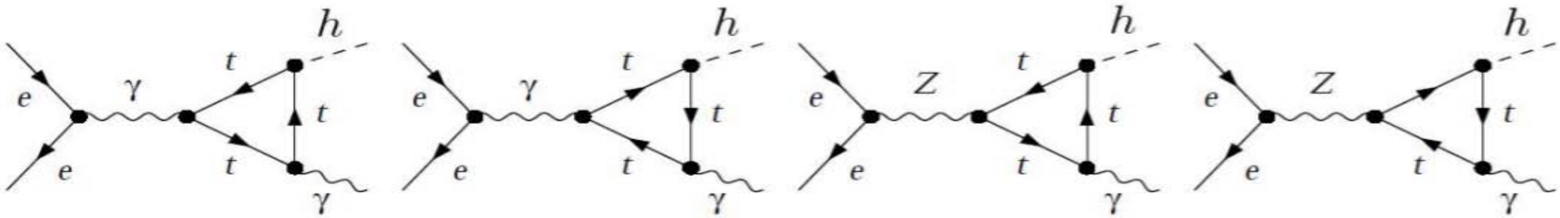


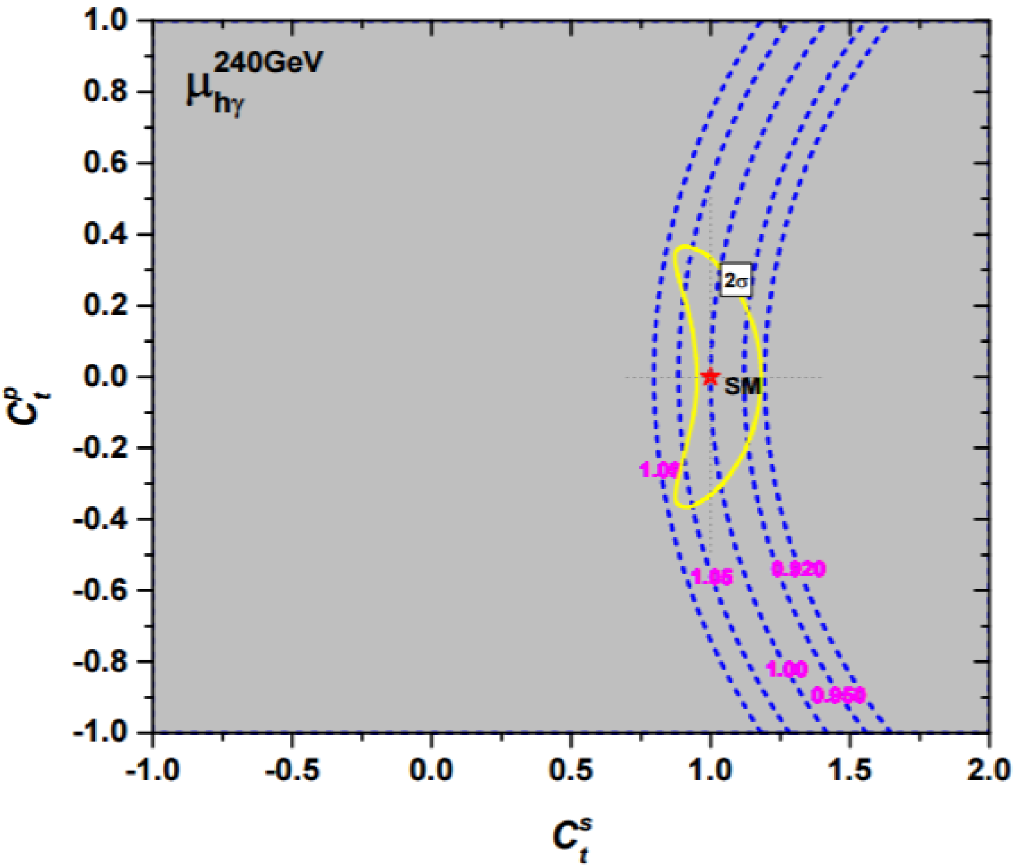
$$\mu_i = \frac{\sigma_i^{CPV}}{\sigma_i^{SM}}$$

- **Insensitive to pseudo-scalar part;**
- **Small effect in Zh production;**
- **Exclude flipped sign of tth.**
- **Forward-backward asymmetry ~1%**

Kobakhidze, Liu, Wu, Yue, 1610.06676 (PRD)

Higgs rare production process $e^+e^- \to h\gamma$





- **Same order as SM, sensitive to pseudo-scalar part;**
- **SM: 0.103 fb, ~500 events for 5k fb^-1;**
- **5% accuracy can constrain**

$$|C_t^p| < 0.19$$

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Conclusions

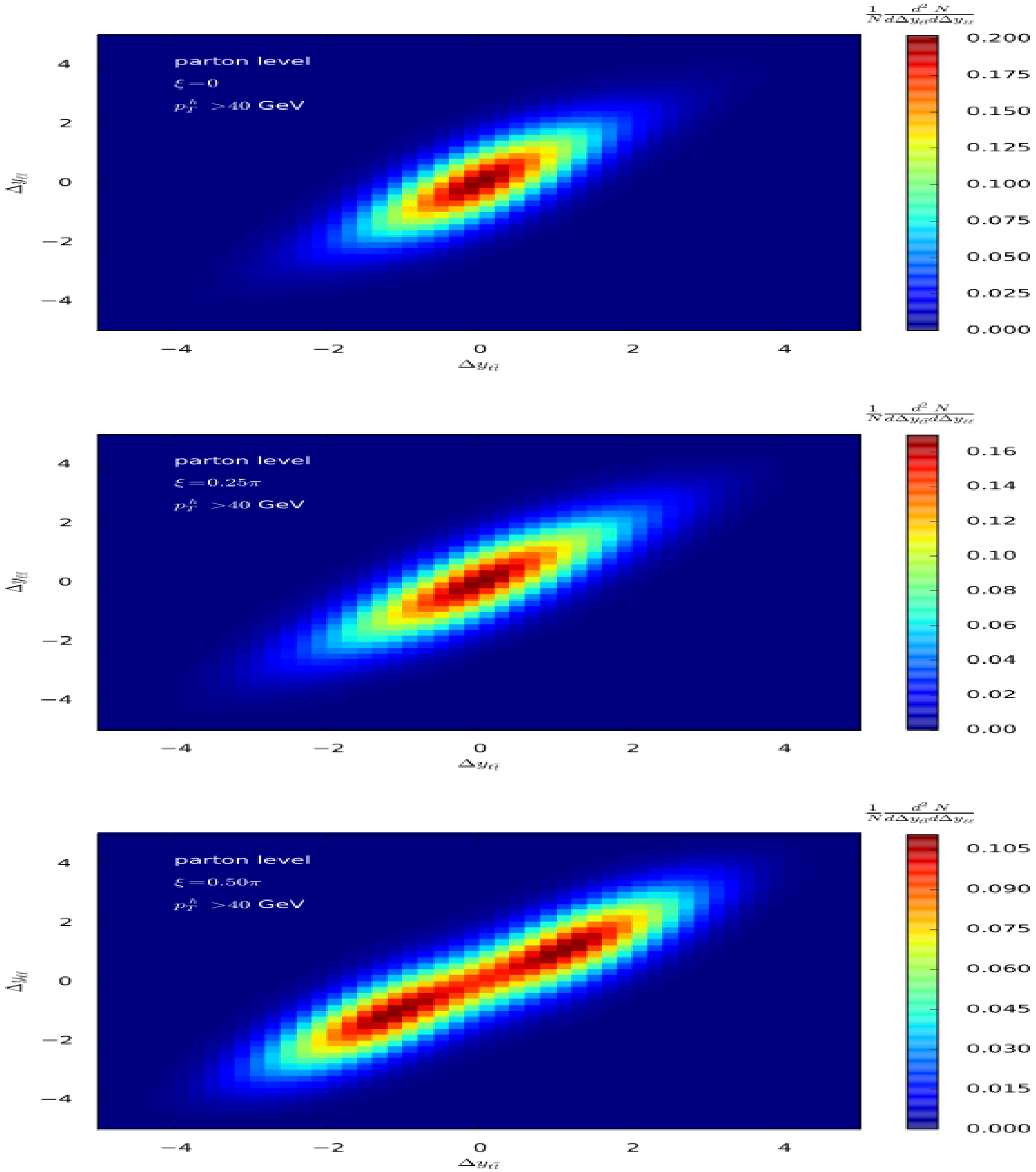
- **Top-Higgs coupling has been observed at the LHC.**
- **CP nature of Top-Higgs coupling may be determined at the LHC.**
- **CEPC can indirectly tell the CP nature of Top-Higgs coupling from precision measurements.**

Thank you!

Indirect tests at the CEPC

HiLumi HL-LHC PROJECT

		K_γ	K_W	K_Z	K_g	K_b	K_t	K_τ	$K_{Z\gamma}$	K_μ
$300fb^{-1}$	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
$300fb^{-1}$	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
$3000fb^{-1}$	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
$3000fb^{-1}$	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]


parton level
$\xi=0$
$p_T^{l\pm}$ >40 GeV
parton level
$\xi=0.25\pi$
$p_T^{l\pm}$ >40 GeV
parton level
$\xi=0.50\pi$
$p_T^{l\pm}$ >40 GeV
Δy_{ll}
$\Delta y_{t\bar{t}}$
$\frac{1}{N}\frac{d^2N}{d\Delta y_{t\bar{t}}d\Delta y_{ll}}$