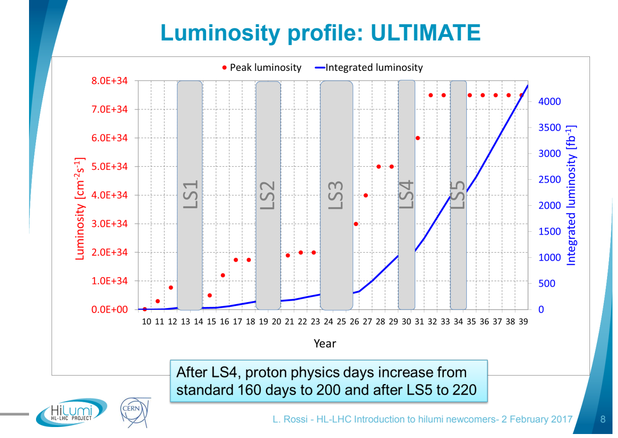
HH production at LHC and Future Colliders

Michihisa Takeuchi (Kavli IPMU, Univ. of Tokyo)

at IPMU 18th June 2018



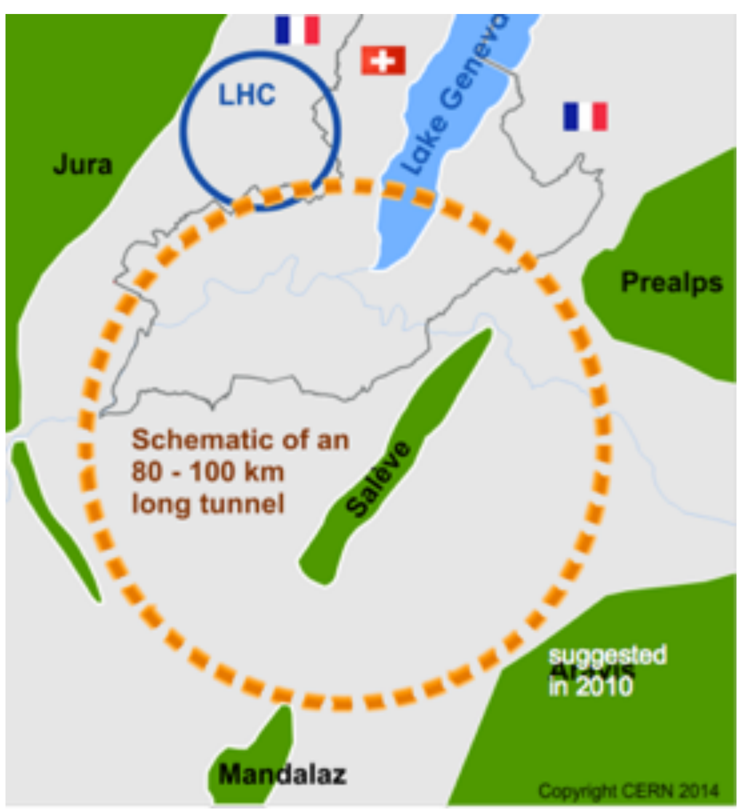
LHC & Future Colliders

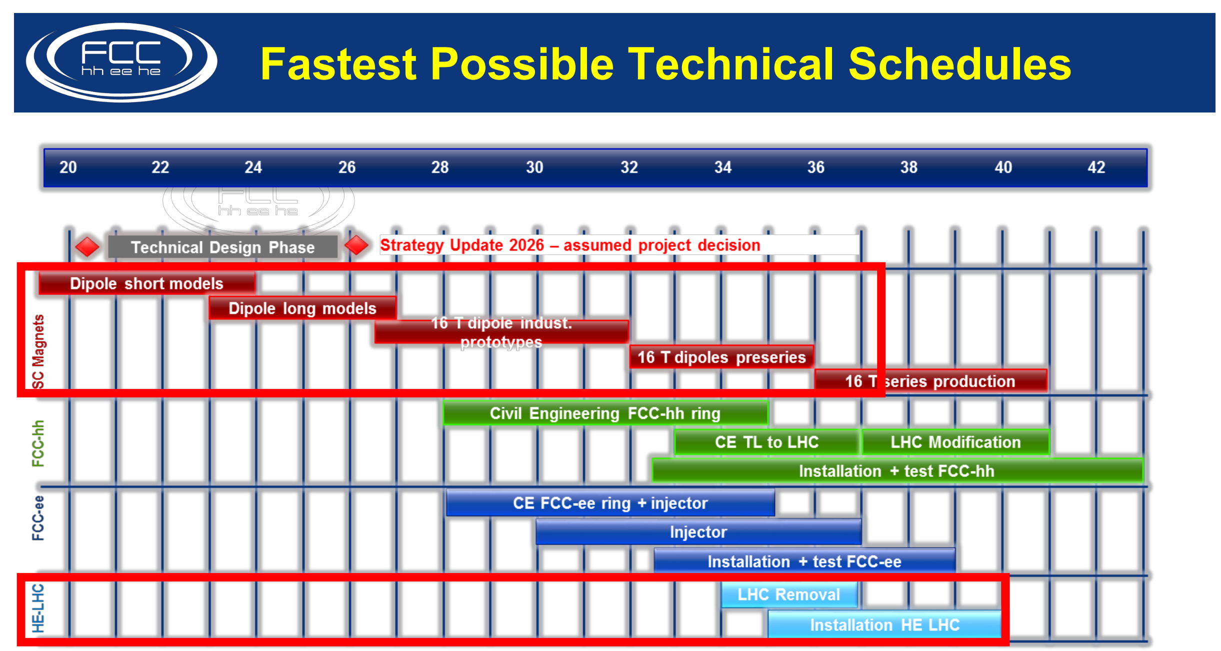
LHC: 14 TeV 3 ab^{-1} (or 4ab^{-1}) 8T dipole ~2039

HE-LHC: 27 TeV 15 ab^{-1} 16T dipole 2040~

100TeV collider: 100 TeV 30 ab^{-1} x3-4 long tunnel 16T dipole 2043~

CERN (earlier in China?)





technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

HE-LHC design & construction

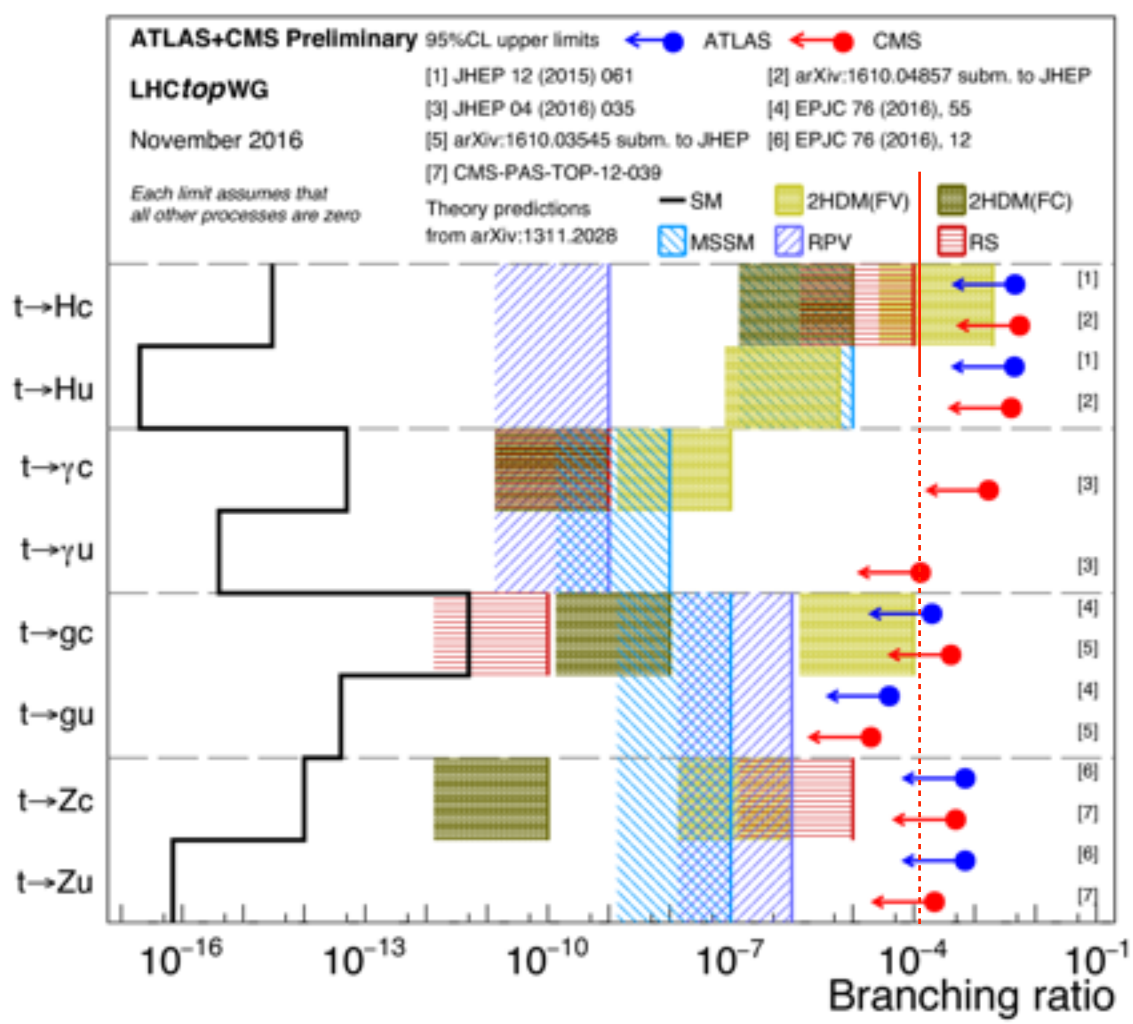
M. Benedikt

What do we search for with this machine ?
Can we answer qualitative question?

HL-LHC

top factory : 1nb x $3ab^{-1}$ = 3×10^9 pair of tops

good chance to discover top rare decays



little hope for MSSM, FC 2HDM

Top Variant Axion model

FV 2HDM motivated by solving strong CP, domain wall problem

Experimentalists can cite our model
as a well motivated model to predict t → ch

characteristic helicity structure in t → ch decay
important to measure the angular correlation in the rare decay

JHEP11(2015)057 [arXiv:1507.04354],
PhysRevD.97.035015 [arXiv:1711.02993], arxiv:1806.XXXX

HE-LHC (27TeV , 15 ab^{-1})

machine for the higgs self coupling measurement
at a meaningful level

Higgs Pair Production at Future Hadron Colliders:
From Kinematics to Dynamics [arXiv:1802.04319]

Michihisa Takeuchi
in collaboration with Dorival Goncalves, Tao Han, Felix Kling, Tilman Plehn

What is interesting to measure λ?

$\lambda_{SM} \approx 1/8.$ in the SM

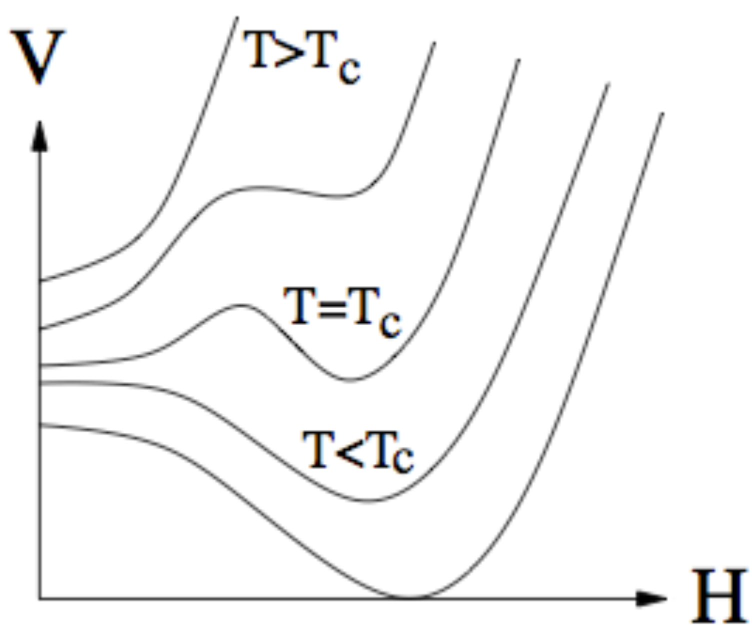
govern the shape of the Higgs potential

$$V(h) = \frac{\lambda}{4}h^4 + \lambda v h^3 + \cdots = \frac{\lambda_4}{4!}h^4 + \frac{\lambda_3}{3!}h^3 +$$

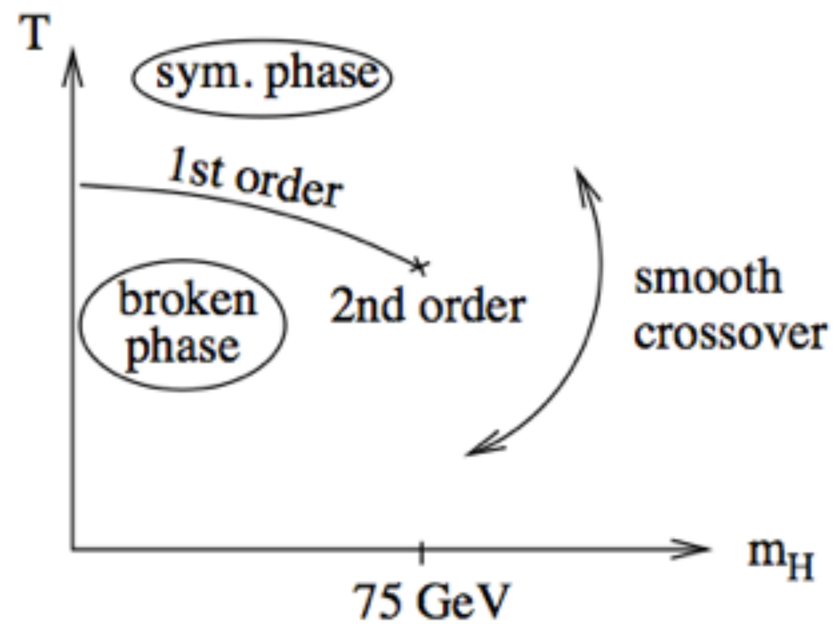
$$\lambda_4 = 6\lambda$$

$$\lambda_3 = 6\lambda v = \frac{3m_h^2}{v}$$

EWSB phase transition at early universe



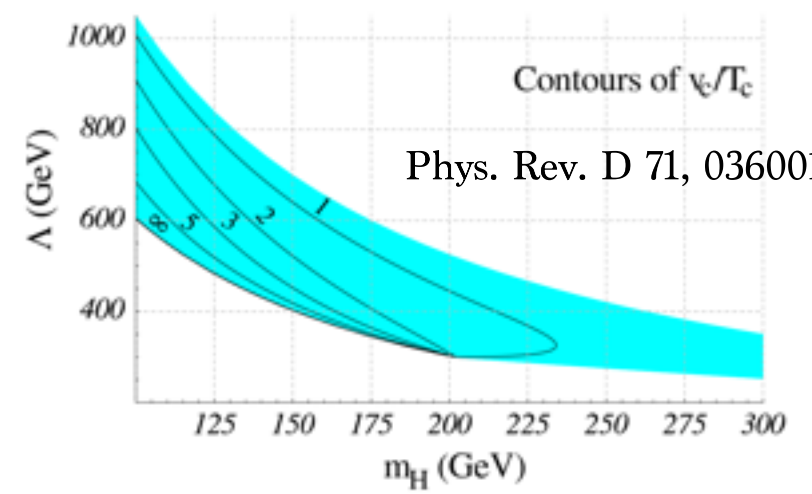
$$V_{tot} \cong m_H^2(T)H^2 - ETH^3 + \lambda H^4$$



For EW baryogenesis

strong 1st order PT required

(necessary condition)



strong 1st order PT → O(1) deviation in λ_3 required

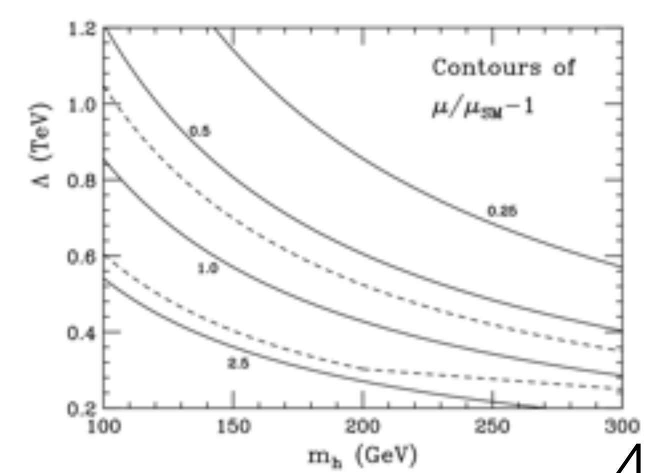
or

smooth 2nd order PT

[C. Grojean, G. Servant, J. Wells]

$$V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3$$

$$\lambda_3 = \frac{3m_h^2}{v} + \frac{6v^3}{\Lambda^2} \quad > 1.7$$



λ sensitivity at HL-LHC

Higgs pair production $pp \to hh$

40 fb = 120k events in full lifetime of LHC

$$\kappa_\lambda = \frac{\lambda}{\lambda_{\rm SM}} \,.$$

hh decays:

$b\bar{b}\gamma\gamma$ ← BR = 0.26% 0.1 fb with BR

Best sensitivity channel : bb: large BR
gamgam : clean channel

$b\bar{b}\tau\tau$

$b\bar{b}WW$

$b\bar{b}b\bar{b}$

$4W\,.$

$-0.8 < \kappa_\lambda < 7.7\,.$ at 95% confidence level

$-0.2 < \kappa_\lambda < 2.6$, at 95% CL ideal case, using full kinematics

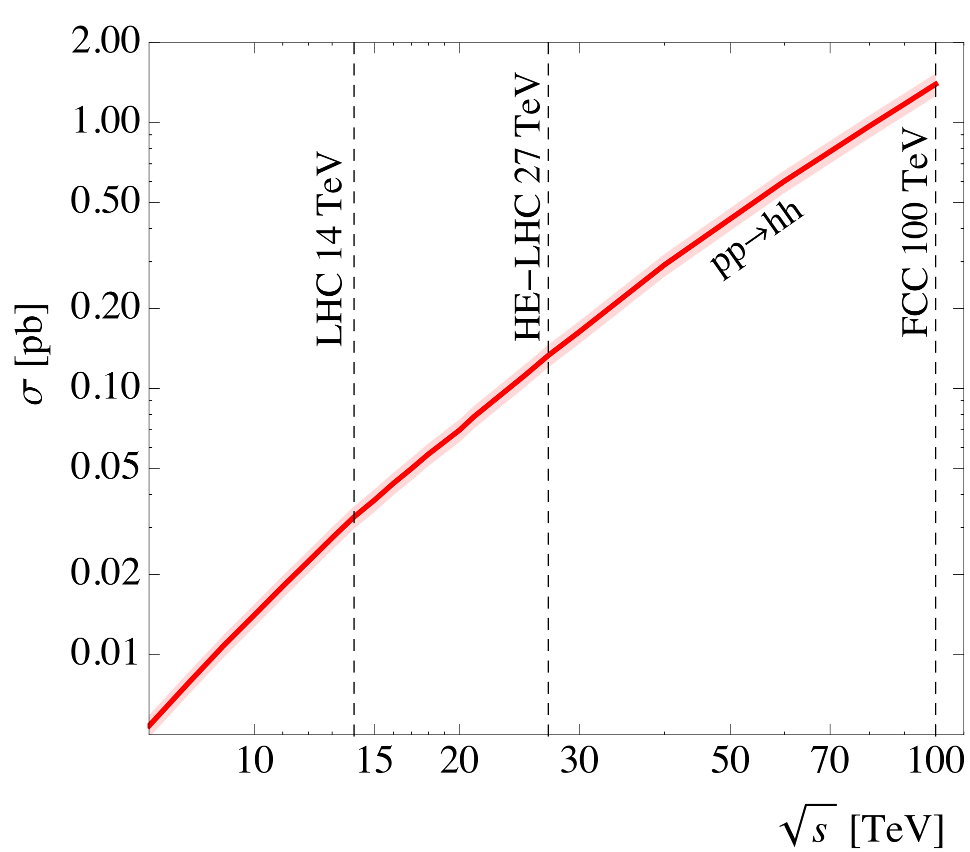
$0.4 < \kappa_\lambda < 1.75$ at 68% CL $\kappa_\lambda \approx 1^{+75\%}_{-60\%}$

not satisfactory at all.

after selection, based on O(10) events ~3% acceptance

HE-LHC and 100 TeV colliders

1. the 27 TeV high-energy LHC (HE-LHC) with an integrated luminosity of 15 ab^{-1},
2. a 100 TeV hadron collider with 30 ab^{-1}, under consideration at CERN (FCC-hh) [18] and in China (SppC) [19].



in cross section compared with 14TeV

factor 4 (27TeV)

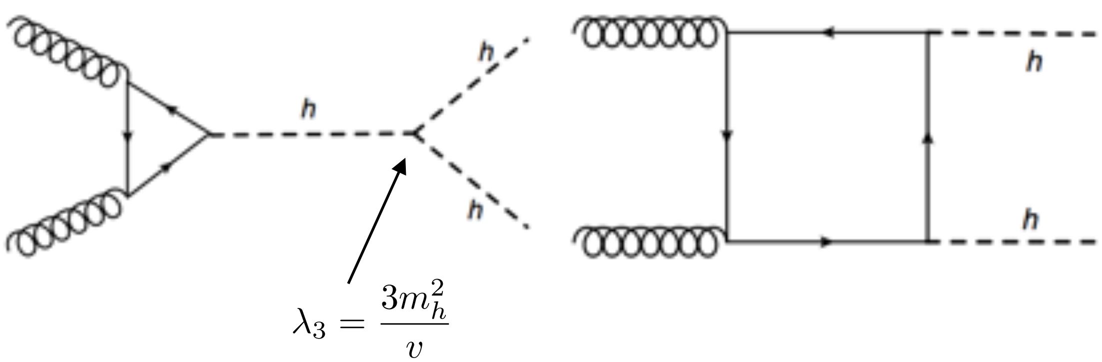
factor 40 (100TeV)

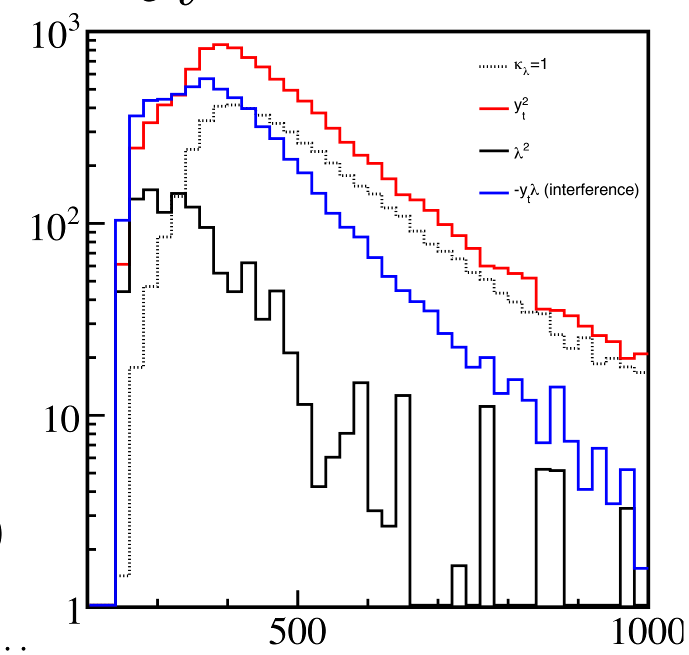
in event numbers

14 TeV → (x20) 27 TeV → (x20) 100 TeV

three phase space

strong destructive interference $\mathcal{M} = \kappa_\lambda \mathcal{M}_\triangle + y_t^2 \mathcal{M}_\Box$





$$m_{hh}^{(\mathrm{th})} \approx 2m_h$$

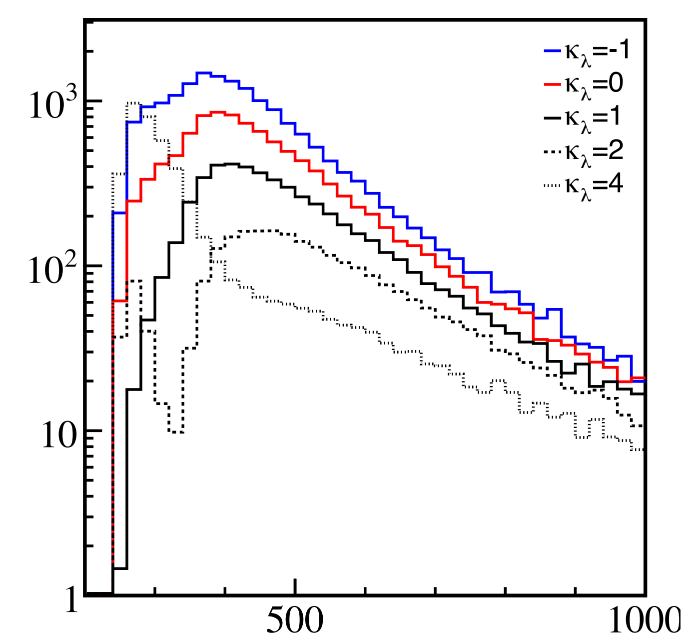
$$\frac{\alpha_s}{12\pi v}\left(\frac{\kappa_\lambda \lambda_{\mathrm{SM}}}{s-m_h^2} - \frac{1}{v}\right) \to \frac{\alpha_s}{12\pi v^2}(\kappa_\lambda - 1) \overset{\mathrm{SM}}{=} 0\ .$$

$$\frac{\alpha_S}{12\pi} G^{\mu\nu} G_{\mu\nu} \log(1+\frac{h}{v})$$

$$\log(1+\frac{h}{v}) = \frac{h}{v} - \frac{h^2}{2v^2} + \cdots$$

$$m_{hh}^{(\mathrm{abs})} \approx 2m_t\ .$$

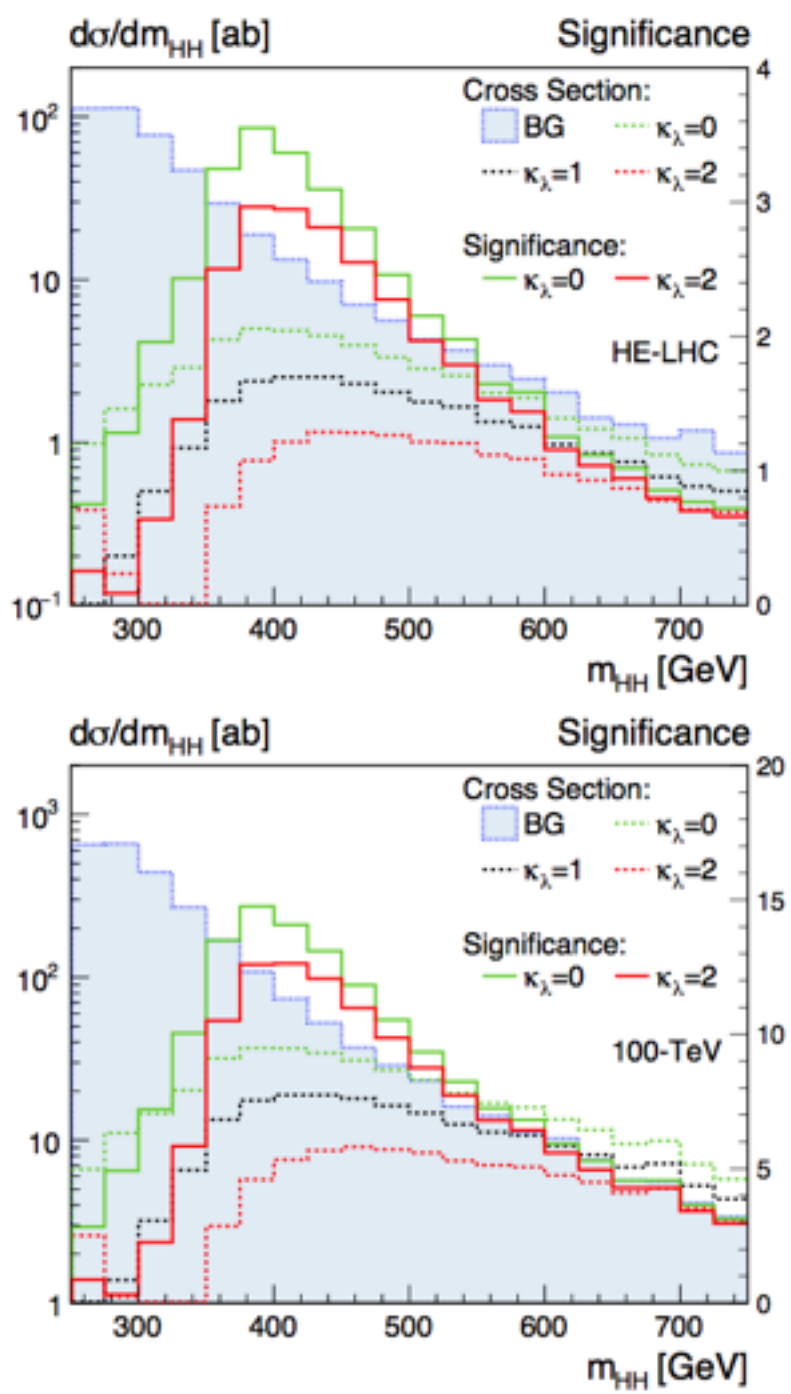
absorptive imaginary parts lead to a significant dip

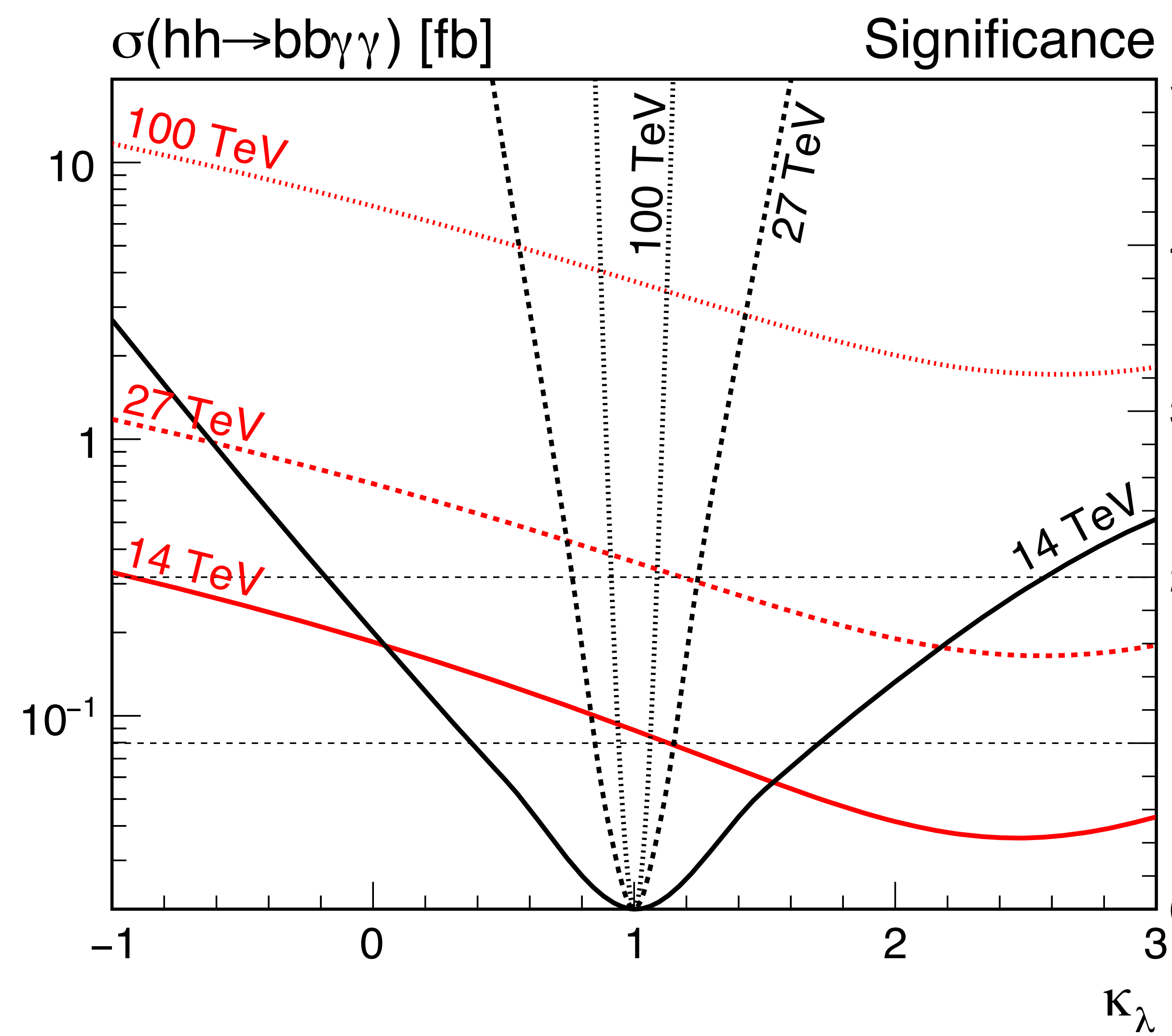


$$m_{hh}^{(\mathrm{high})} \gg m_h, m_t\ .$$

box contribution decay slower

maximum sensitivity



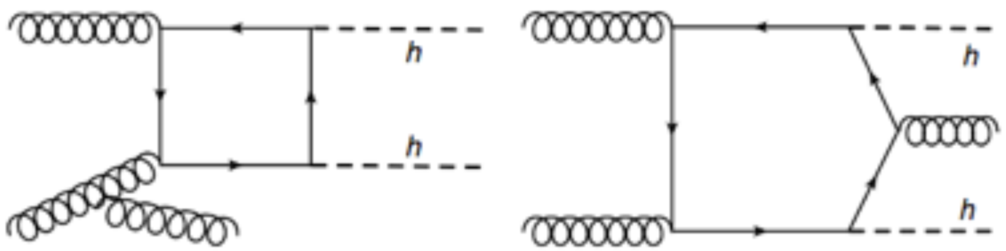


ideal case, using full kinematics

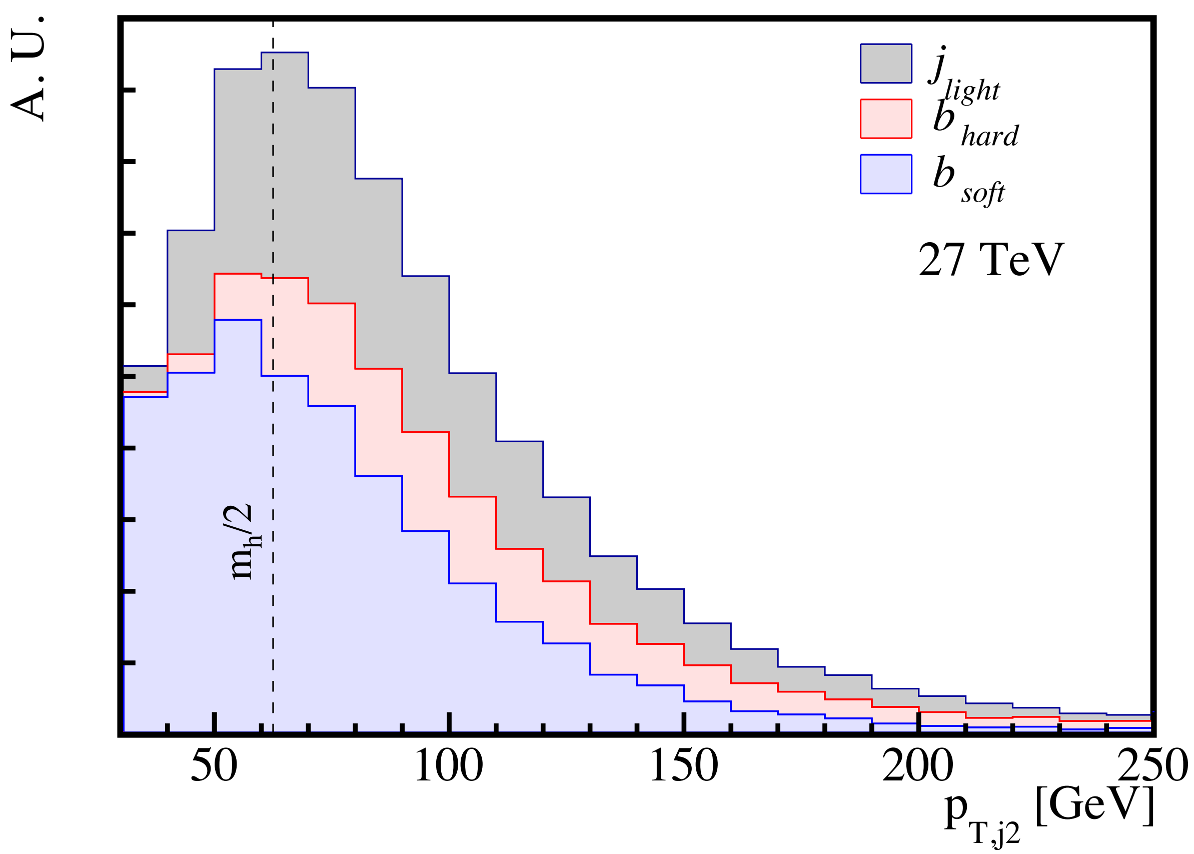
$$\sim \pm 15\% \text{ at } 68\% \text{ CL. at } 27 \text{ TeV}$$

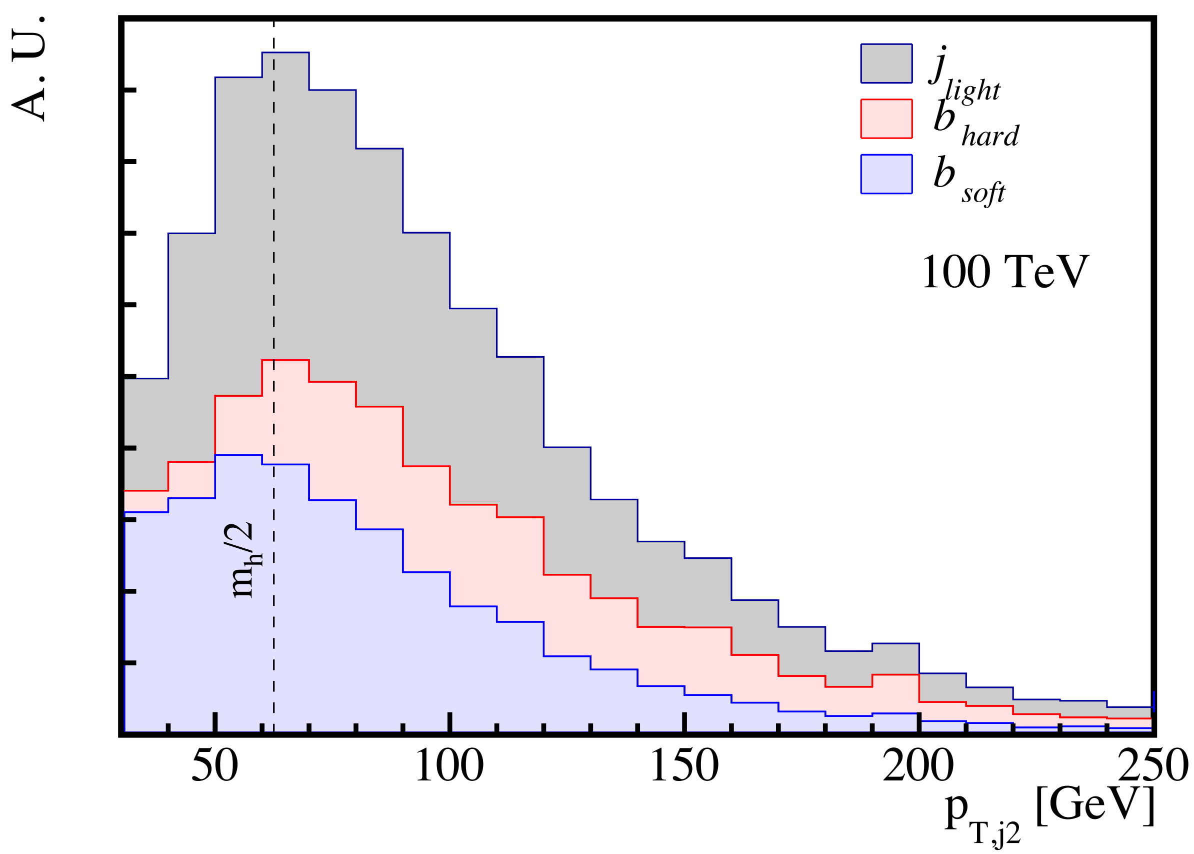
realistic analysis

$$pp \to hh \to b\bar{b}\,\gamma\gamma + X.$$



two H decay products not always found in the hardest two jets





All Signal/BG samples simulated with 1 additional jet in MLM matching

Requiring two b-tags in three hardest jets important! (50% acceptance higher)

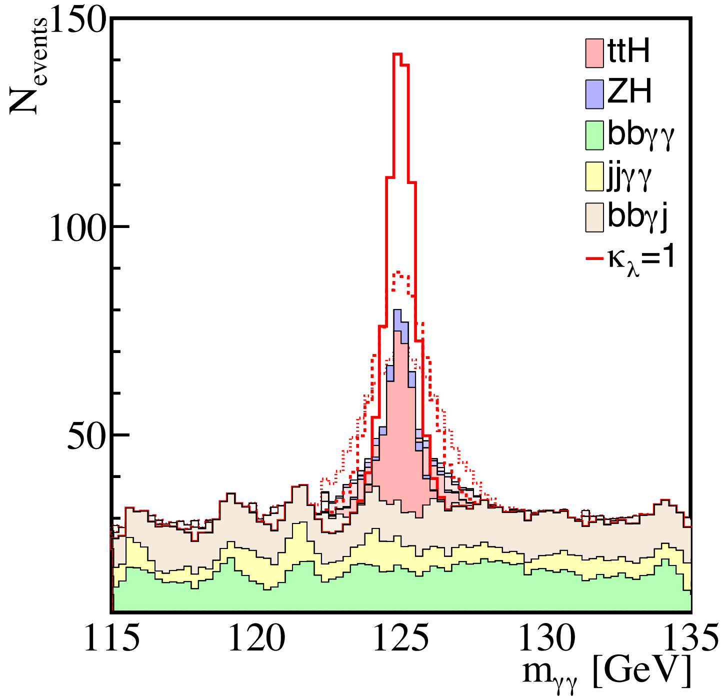
Collider	Process	κ_λ 0	1	2	$t\bar{t}h$	Zh	$b\bar{b}\gamma\gamma$	$jj\gamma\gamma$	$b\bar{b}\gamma j$	BG tot.	$S/\sqrt{S+B}_{1\mathrm{ab}^{-1}}$	S/B
HE-LHC (15 ab^{-1})	σ [fb]	0.69	0.36	0.18	6.43	0.77	1.24 pb	36.6 pb	506 pb			
	Baseline	2.87K	1.57K	838	21.8K	1.44K	1.19M	36M	1.13M	38.3M	0.07	$4 \cdot 10^{-5}$
	$n_j \leq 3$, $n_b = 2$	648	356	190	954	389	200K	67.4K	105K	374K	0.15	$1 \cdot 10^{-3}$
	$\Delta m_{bb} \leq 25$ GeV	470	260	140	195	66	43.7K	10.6K	25.8K	80.4K	0.24	0.003
	$\Delta m_{\gamma\gamma} \leq 3$ GeV	459	253	136	197	63	1.42K	505	758	2.94K	1.2	0.09
	$\Delta m_{\gamma\gamma} \leq 2$ GeV	459	253	136	197	63	957	342	504	2.06K	1.4	0.12
	$\Delta m_{\gamma\gamma} \leq 1$ GeV	459	253	136	197	63	485	182	245	1.17K	1.7	0.22
	$\Delta m_{\gamma\gamma} \leq 3$ GeV, $m_{hh} > 400$	320	206	120	56	21	324	97	178	676	1.8	0.30
	$\Delta m_{\gamma\gamma} \leq 2$ GeV, $m_{hh} > 400$	320	206	120	56	21	220	67	122	485	2.0	0.42
	$\Delta m_{\gamma\gamma} \leq 1$ GeV, $m_{hh} > 400$	320	206	120	56	21	115	41	61	293	2.4	0.70
100 TeV (30 ab^{-1})	σ [fb]	6.95	3.72	1.97	84.8	3.76	6.21 pb	126 pb	3.03 nb			
	Baseline	51.8K	29.8K	16.9K	535K	13.1K	13.6M	330M	18.6M	363M	0.29	$8 \cdot 10^{-5}$
	$n_j \leq 3$, $n_b = 2$	9.22K	5.28K	3.02K	18K	2.84K	1.79M	773K	1.42M	4.00M	0.48	0.001
	$\Delta m_{bb} \leq 25$ GeV	6.45K	3.80K	2.18K	3.3K	669	361K	218K	373K	956K	0.71	0.004
	$\Delta m_{\gamma\gamma} \leq 3$ GeV	6.30K	3.70K	2.13K	3.12K	653	8.34K	6.06K	8.99K	27.2K	3.9	0.14
	$\Delta m_{\gamma\gamma} \leq 2$ GeV	6.30K	3.70K	2.13K	3.12K	653	5.66K	4.13K	5.99K	19.5K	4.4	0.19
	$\Delta m_{\gamma\gamma} \leq 1$ GeV	6.30K	3.70K	2.13K	3.12K	653	2.82K	1.91K	2.99K	11.4K	5.5	0.32
	$\Delta m_{\gamma\gamma} \leq 3$ GeV, $m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	1.56K	1.10K	1.90K	5.86K	6.1	0.54
	$\Delta m_{\gamma\gamma} \leq 2$ GeV, $m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	1.04K	747	1.14K	4.23K	6.7	0.73
	$\Delta m_{\gamma\gamma} \leq 1$ GeV, $m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	523	359	617	2.79K	7.5	1.13

Baseline:

$$p_{T,j} > 30 \text{ GeV}, \quad |\eta_j| < 2.5 ,$$
$$p_{T,\gamma} > 30 \text{ GeV}, \quad |\eta_\gamma| < 2.5 ,$$
$$\Delta R_{\gamma\gamma,\gamma j,jj} > 0.4 .$$

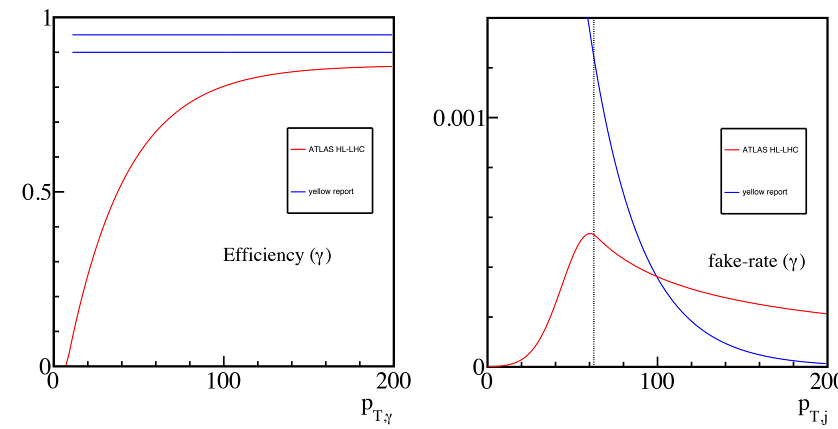
$$\epsilon_b = 70\%$$
$$\epsilon_c = 15\%$$
$$\epsilon_j = 0.3\%$$

including 3rd jets important



$$\epsilon_{\gamma\to\gamma} = 0.863 - 1.07 \cdot e^{-p_{T,\gamma}/34.8\ \mathrm{GeV}} ,$$

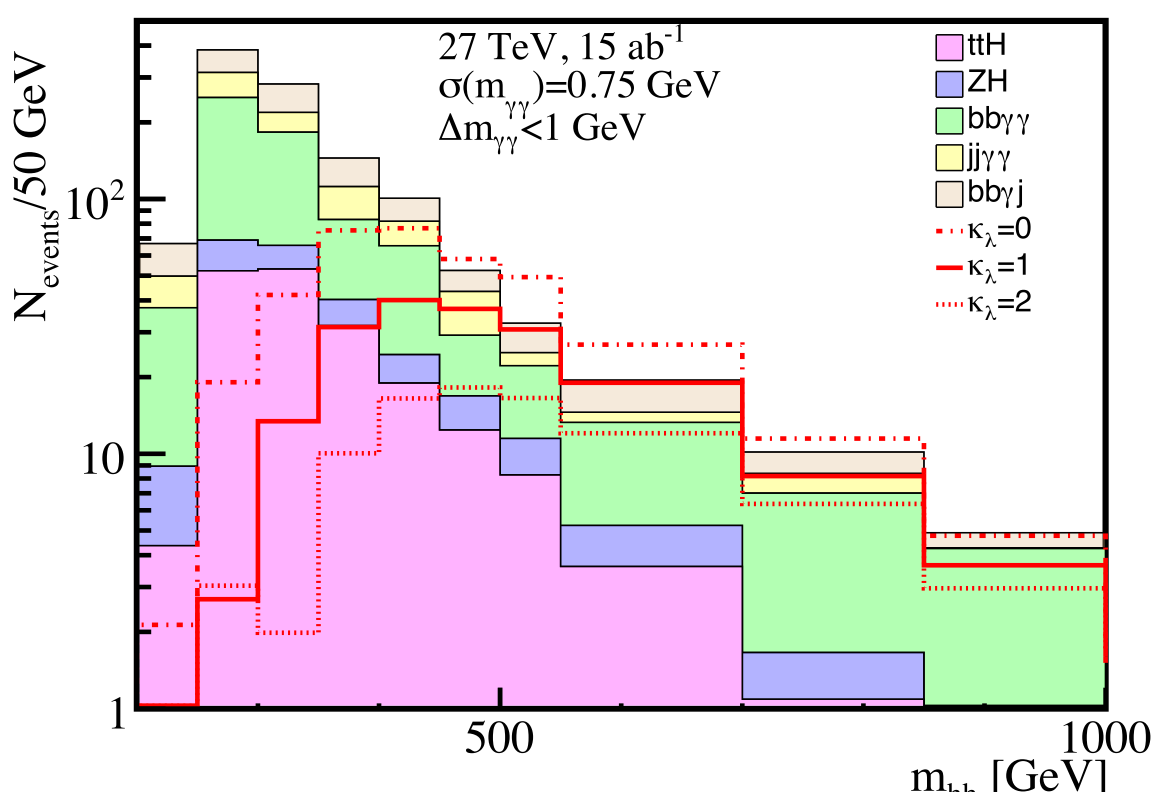
$$\epsilon_{j\to\gamma} = \begin{cases} 5.3\cdot 10^{-4} \exp\left(-6.5\left(\frac{p_{T,j}}{60.4\ \mathrm{GeV}} - 1\right)^2\right), & \text{pT<65GeV} \\ 0.88\cdot 10^{-4}\left[\exp\left(-\frac{p_{T,j}}{943\ \mathrm{GeV}}\right) + \frac{248\ \mathrm{GeV}}{p_{T,j}}\right], & \text{pT>65GeV} \end{cases}$$

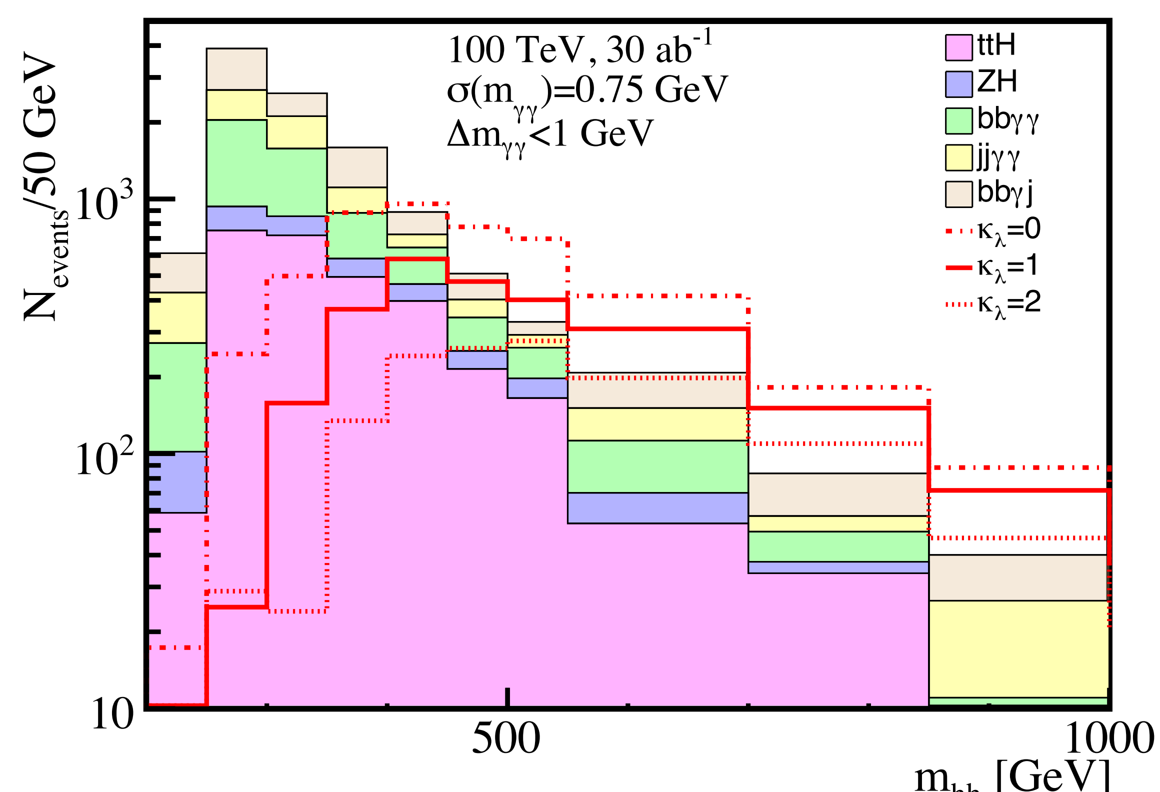


reducing fake photon important

Higgs BG: peaked

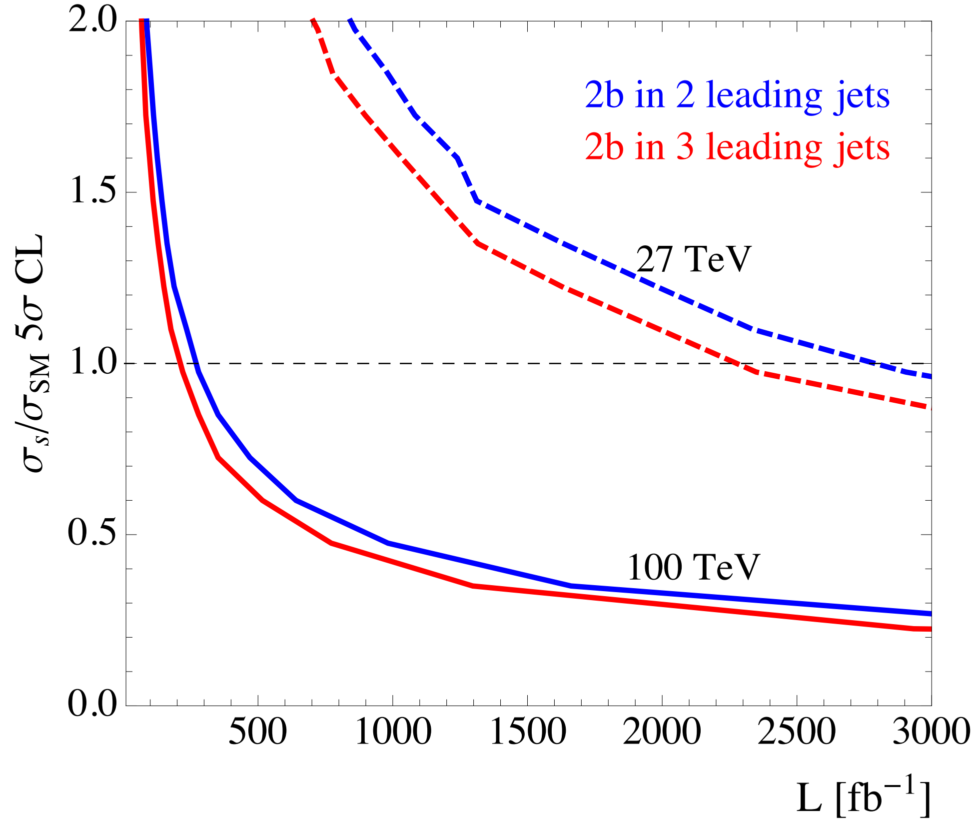
continuum BG: flat (controllable by side-bands)





characteristic structure should appear in low mhh region

but very difficult to access it due to too huge BG

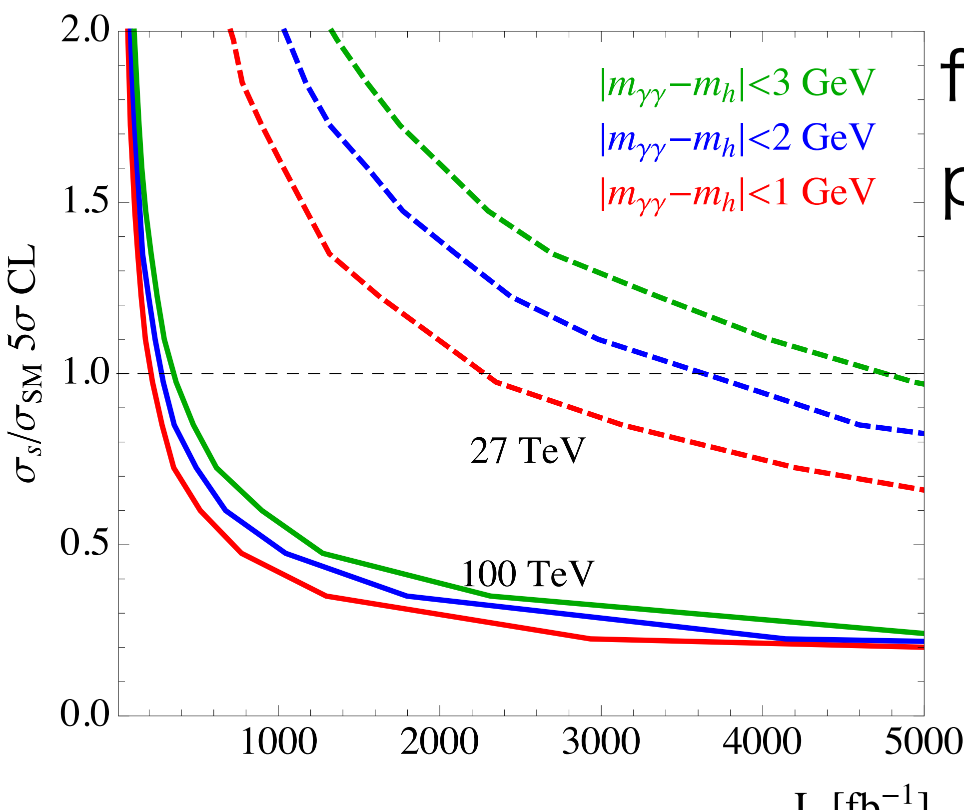


sub-samples $(b\bar{b}, b\bar{b}j)$ and $(jb\bar{b}, bjb)$

including b-tag in 3rd jet clearly improve the sensitivity

The 5σ measurement for HE-LHC is

2.8 ab^{-1} to below 2.3 ab^{-1}

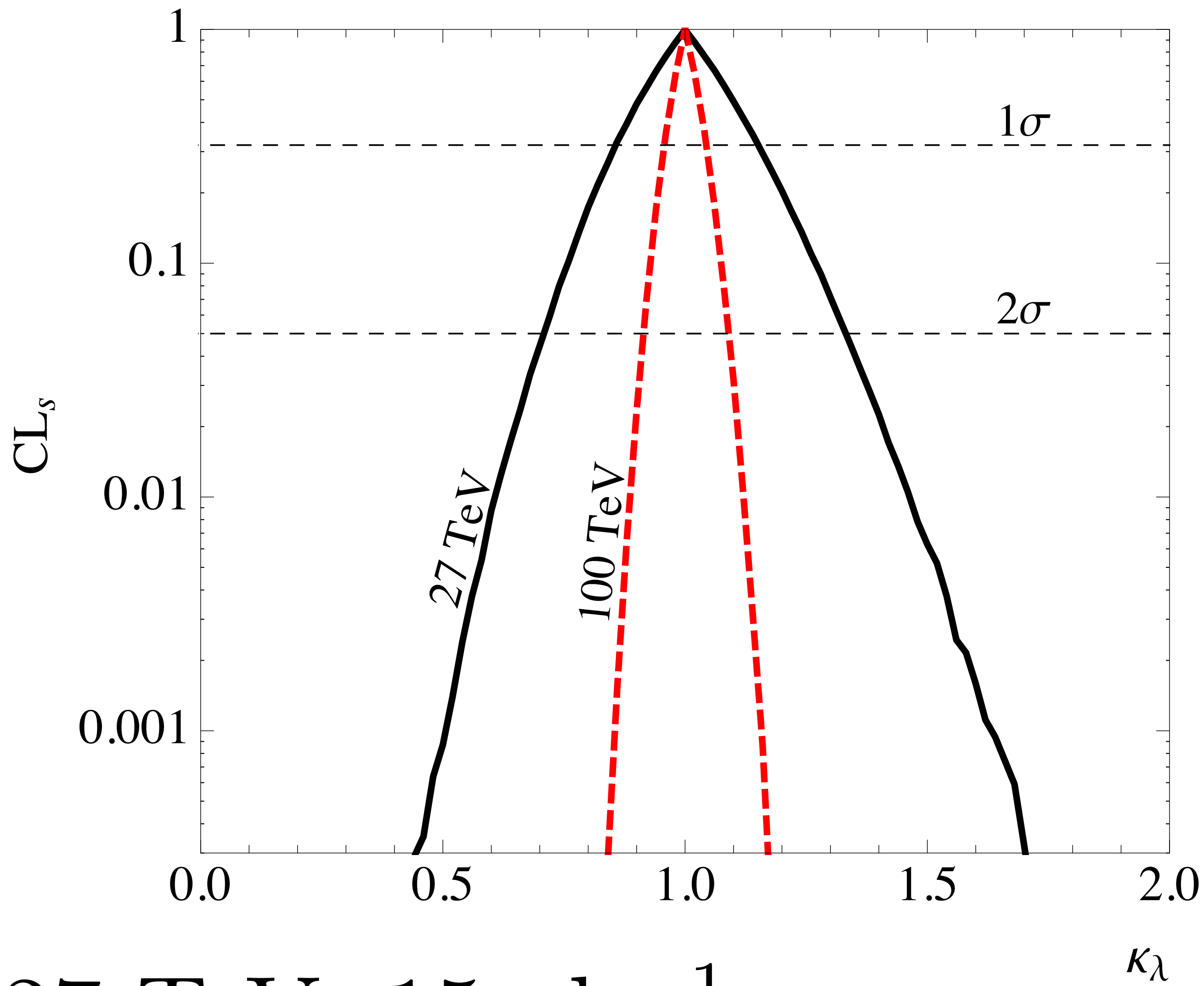


for Higgs self coupling sensitivity

photon invariant mass resolution most important

note that resolution of mgamgam=1.5 GeV is already achieved at LHC

important for detector design



arXiv:1802.04319

HE-LHC, 27 TeV, 15 ab^{-1}

$$\kappa_\lambda \approx 1 \pm 15\% \ (1\sigma) \qquad \kappa_\lambda \approx 1 \pm 30\% \ (2\sigma)$$

conclusive sensitivity to determine whether self-coupling deviation is O(1) or not

for 100 TeV, 30 ab^{-1} $\kappa_\lambda \approx 1 \pm 5\%(1\sigma), 10\%(2\sigma)$

EWkino as thermal relic

acceptable size of fine tuning subjective：10TeV SUSY still solve the big hierarchy prob.$\sim 10^{-30}$

attractive point of SUSY: neutralino thermal relic DM, suggests upper bound in the mass

pure Higgsino : 1.1TeV

pure Wino : 3 TeV with Sommerfeld Enhancement

cf) squark co-annihilation: 3 TeV [S-P. Liew, F.Luo, 1611.08133]

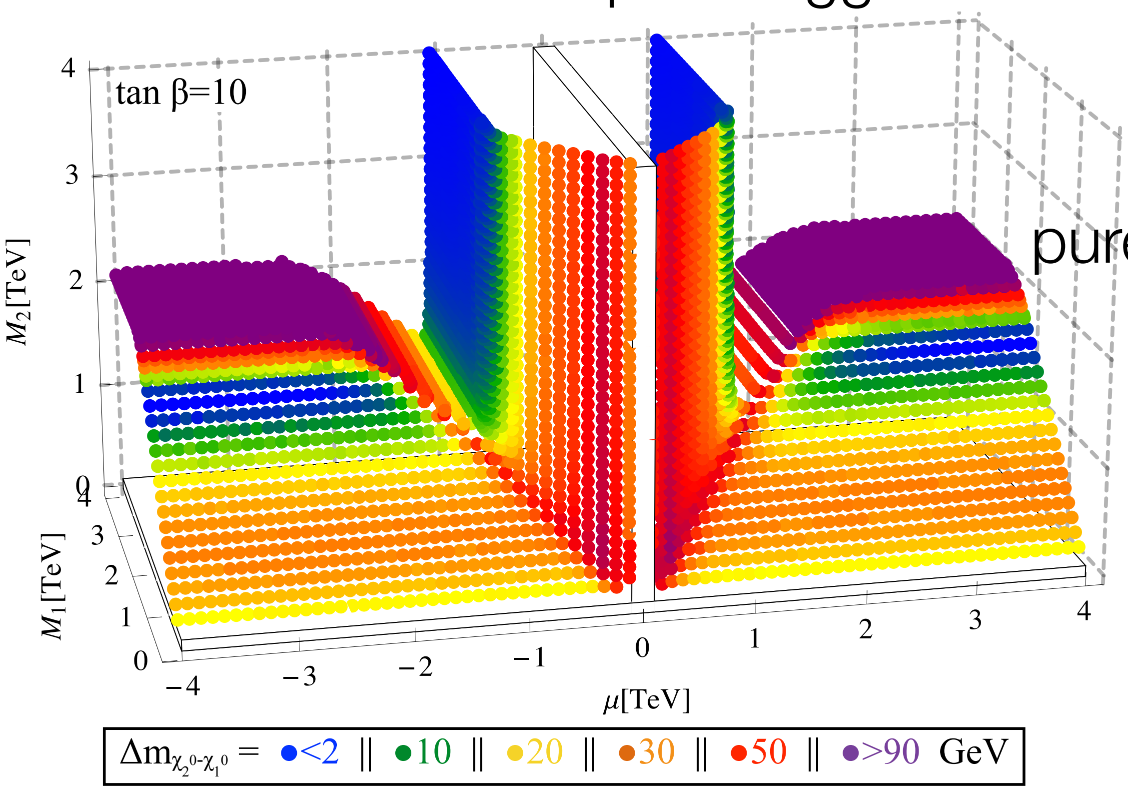
stop co-annihilation: 6 TeV [J. Ellis, K. Olive, J. Zheng, 1404.5571]

gluino co-annihilation: 8 TeV [J.Ellis, F. Luo, K. Olive, 1503.07142]

if all particles decoupled other than $\tilde{B}, \tilde{W}, \tilde{H}$, we can parametrize model with (M_1, M_2, μ) and obtain “Relic neutralino surface” to satisfy $\Omega_\chi h^2 = 0.12$

pure Higgsino DM

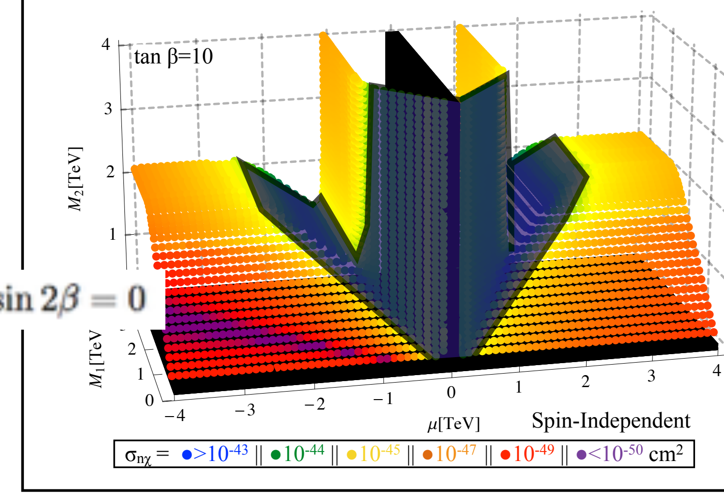
pure Wino DM



[J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, MT]

DMDD SI constraints

$m_{\chi_1} + \mu \sin 2\beta = 0$



pure wino, higgsino, wino-bino mixture remain

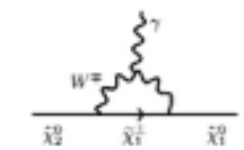
mass difference always small

$m_{\chi_2^0} - m_{\chi_1^0}, m_{\chi_1^\pm} - m_{\chi_1^0}$ $\Delta m \lesssim 30$ GeV

EWkino search strategies at LHC

$\Delta m = m_{NLSP} - m_{LSP}$

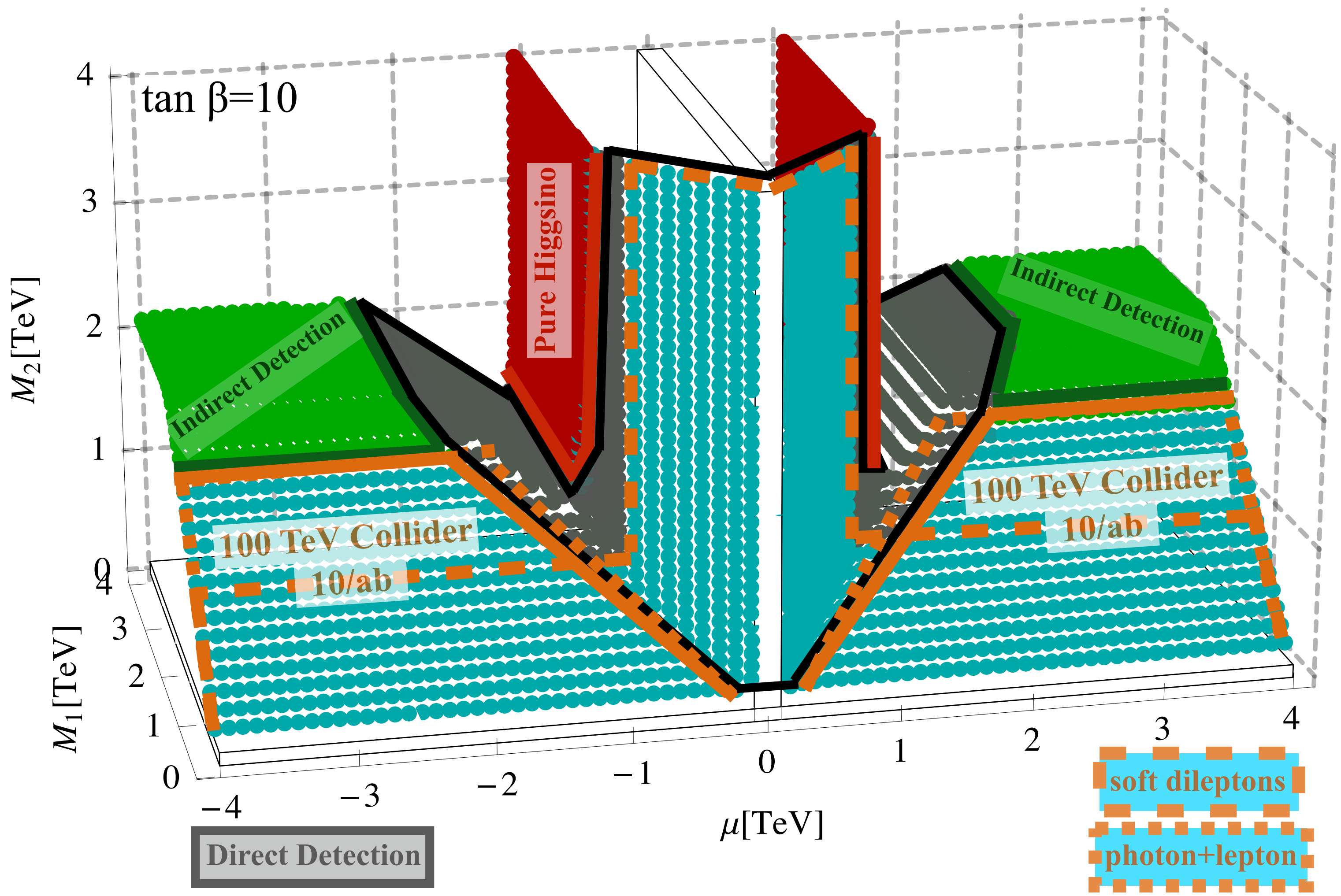
more compressed

$\Delta m > m_Z, m_W$	$\not{E}_T + 3\ell$	$\chi_2^0 \to \chi_1^0 Z, \chi_1^\pm \to \chi_1^0 W^\pm$
$0.2\text{GeV} < \Delta m < m_W$	$j^{\text{ISR}} + \not{E}_T + 2^+ \ell^{\text{soft}}$ For the same trigger ISR jet pT, BG is more boosted.	$\chi_2^0 \to \chi_1^0 \ell^+ \ell^-$ via Z^*  [Z. Han, G. Kribs, A. Martin, A. Menon]
	$\not{E}_T + 2^+ \ell^{\text{soft}} + \gamma$ $j^{\text{ISR}} + \not{E}_T + \ell^{\text{soft}} + \gamma$	$\chi_2^0 \to \chi_1^0 \gamma$ (1-loop)  [J. Bramante, A. Delgado, F. Elahi, A. Martin, B. Ostdiek] [C. Han, L. Wu, J-M. Yang, M. Zhang, Y. Zhang]
	$j^{\text{ISR}} + \not{E}_T$ (mono-jet)	too soft decay products
$\Delta m < 0.2\text{GeV}$	Disappearing tracks $+ j^{\text{ISR}} + \not{E}_T$	long-lived $\chi^\pm$

Main targets: 1.1TeV Higgsino, 3 TeV Wino, but even with 100TeV collider would be difficult
would be covered Bino-Wino mixed case [J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, MT]

Tracker upgrade and aggressive analysis at HE-LHC might reach 1.1 TeV pure Higgsino by DT
[H. Fukuda N. Nagata, H. Otono, S. Shirai, arXiv:1703.09675]

EWkino search strategies at LHC



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Summary

Naturalness : finally start to probe a natural parameter space

not surprising either if SUSY will be found or not

lots of opportunity still remain at LHC

HL−LHC

luminosity help to search for rare decays
new physics in top rare decay (Top-specific Variant Axion Model)

HE−LHC (27TeV)

machine for Higgs self-coupling measurement (EW Baryogenesis)

100TeV

almost full coverage of the EWkino thermal relic DM (200TeV would cover all?)

Back up

No signature of SUSY anywhere yet

no evidence of SUSY anywhere: Higgs measurement, Direct-Detection…

SUSY dead ? still attractive as a solution of the big hierarchy problem
(don't confuse with the "little" hierarchy)

why attractive: can solve DM and the fine tuning problem

Another fine tuning problem: strong CP problem $\text{Why } \theta_{\text{eff}} < 10^{-11} \text{ ?}$ $\mathcal{L}_\theta = \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$

attractive solution: PQ mechanism -> Axion : good DM candidate

similarly attractive and don't require new particles
-> naturally explain the current situation

Strong CP problem

QCD Lagrangian contains the total derivative term: θ-term

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \quad \longleftrightarrow \quad |\theta> = \sum_{n=-\infty}^{\infty} e^{in\theta} |n> \quad \theta\text{-vacuum}$$

$|n> \to |m>$ but $|\theta> \to |\theta>$

Note that θ is physical $0 \leq \theta < 2\pi$

Furthermore, chiral tr. $q \to e^{i\alpha\gamma_5} q$ induces $\theta \to \theta - 2\alpha$

massive fermion mass term is also changed.

$$\theta_{\rm eff} = \theta + \arg\det[M^u M^d] \quad \text{is invariant under the chiral tr.}$$

$$\propto \arg\det[v^6 Y^u Y^d]$$

$\theta_{\rm eff}$ can be measured from Neutron EDM $|d_n| = 4.5 \times 10^{-15} \theta_{\rm eff}\, e\text{cm}$

$$|d_n^{\rm obs}| < 2.9 \times 10^{-26} e\text{cm}$$

Why $\theta_{\rm eff} < 10^{-11}$?

while the origin of θ and arg M is completely different

Fine tuning problem

Peccei-Quinn mechanism

[R. D. Peccei, H. R. Quinn, PhysRevLett.38.1440]

1. introduce a field a, axion.
2. assuming axial U(1) sym. which is spontaneously broken at η above QCD scale
3. impose appropriate PQ charges into quarks so that there exists $\mathrm{U}(1)_{PQ}$-$\mathrm{SU}(3)$-$\mathrm{SU}(3)$ anomaly

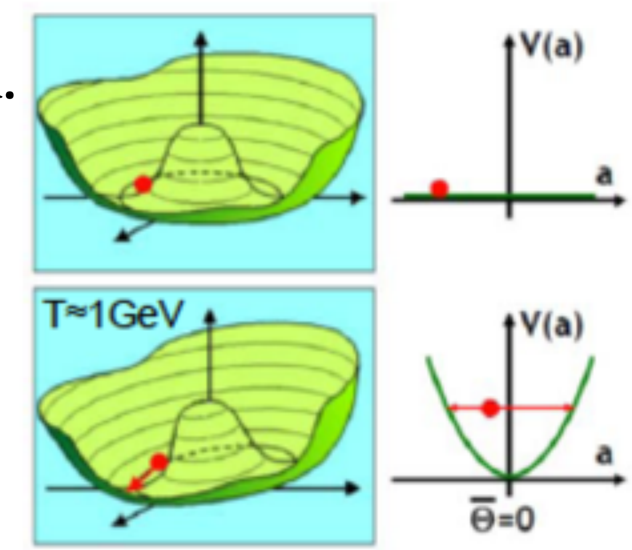
Due to the anomaly, $\mathrm{U}(1)_{PQ}$ current is not conserved, $\partial^\mu j_\mu^{\mathrm{PQ}} = -\frac{g^2}{32\pi^2} A G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$,

$\frac{a}{\eta} \to \frac{a}{\eta} + \epsilon$ induces $\delta\mathcal{L} = -\frac{g^2}{32\pi^2}\epsilon A G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$, induce the potential in the effective lagrangian

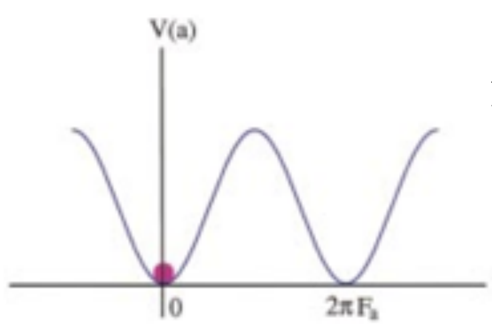
$$\mathcal{L}_{\text{eff}} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{g^2}{32\pi^2}\frac{a}{F_a}G^{a\mu\nu}\tilde{G}^a_{\mu\nu} - \frac{\bar{\theta} g^2}{32\pi^2}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$F_a = \eta / A$$

From the effective Lagrangian, effective potential to axion field can be computed.



QCD instanton effects give an axion a potential and minimizing it gives $< a > = -\bar{\theta} F_a$.

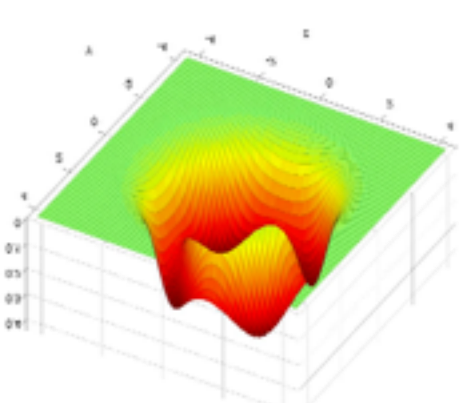


$1 - \cos(\frac{a}{F_a} - \bar{\theta})$

$a + (\theta_{\text{stong}} + \theta_{\text{EM}})F_a$

Domain wall problem

$U(1)_{PQ} \to Z_N, \quad N = |\sum_i^{N_g}(2q_i + u_i + d_i)|$ a : periodic in 2πη ⇔ θ periodic in 2πη/N



$N_{DW} = \left|\frac{N}{h_1 + h_2}\right| = N_g$ [C.Q. Geng, J. N. Ng, PhysRevD.41.3848] $N_g = 1$ is free from domain wall problem.

only 1 quark couples with PQ-charged Higgs solves the domain wall problem

Variant Axion model PQ charges: $u_3 = -1, h_2 = -1, \sigma = 1$

[R.D. Peccei, T.T. Wu and T. Yanagida, Phys. Lett. B172,
[C-R Chen, P. Frampton, F. Takahashi, T. T. Yanagida

Strong CP problem

↓

PQ solution with axion

very attractive

rapid progress in axion DM searches

↓

invisible axion models

KSVZ $N_{DM} = 1$

heavy Q introduced
no problem but no low energy phenomenology
(not interesting)

ZDFS $N_{DM} = 6$ $\Phi_1^\dagger \Phi_2 \sigma^2$

$N_{DM} = 3$ $m\Phi_1^\dagger \Phi_2 \sigma$

two Higgs doublet model,
no new fermion necessary introduced
can discuss low energy phenomenology

but suffer from Domain wall problem

↓

$N_{DM} = 1$

only 1 quark coupled to PQ-Higgs
domain wall problem absent

top-specific Variant Axion model

σ field integrated out, the effective theory is just a 2HDM

$$L^u = -\Phi_1 \overline{u}_{Ra}[Y_{u1}]_{ai}Q_i - \Phi_2 \overline{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.}$$

$$Y_{u1} = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}$$

Φ_2 only couple with u_{R3}

other quarks only couples with Φ_1

two Higgs easily results in FCNC. Usually people impose Z2 sym. to avoid FCNC.

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type-I	+	−	−	−	−	+
Type-II	+	−	−	+	+	+
Type-X	+	−	−	−	+	+
Type-Y	+	−	−	+	−	+

	Φ_1	Φ_2	t_R	c_R	u_R	d_R	ℓ_R	Q_L	L_L
top-specific VA Model	+	−	−	+	+	+	+	+	+

when we take top as the special one,

top FCNC is the prediction

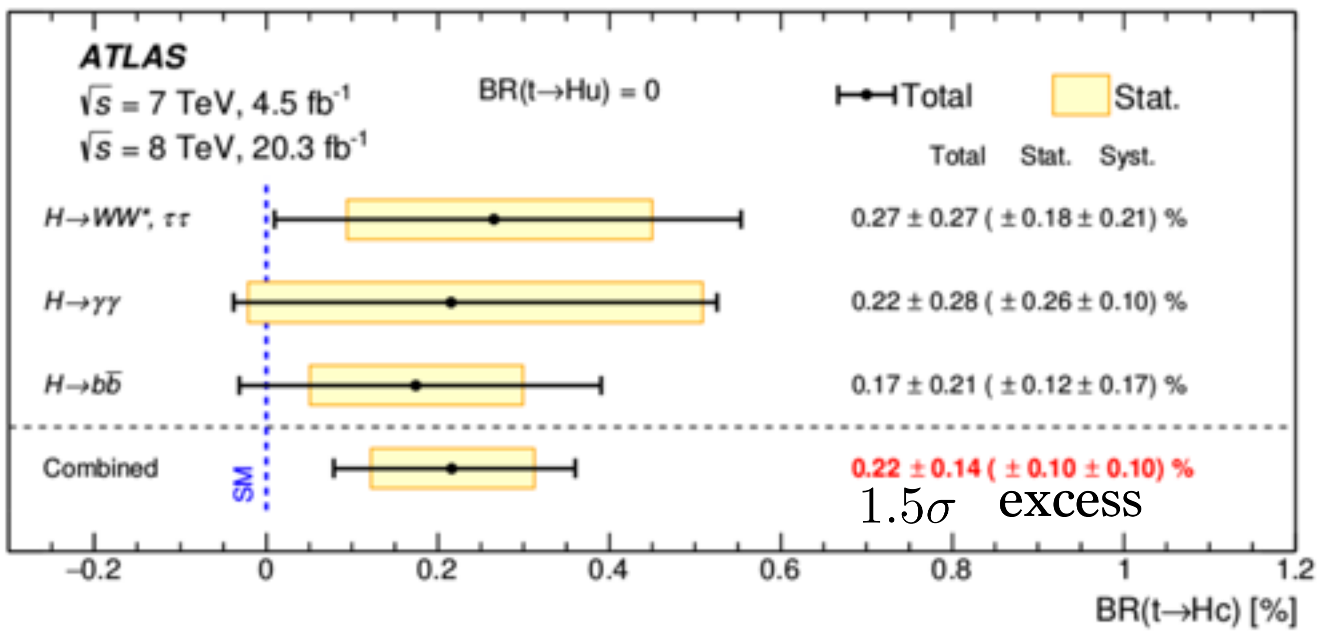
third gen. is identical to type II

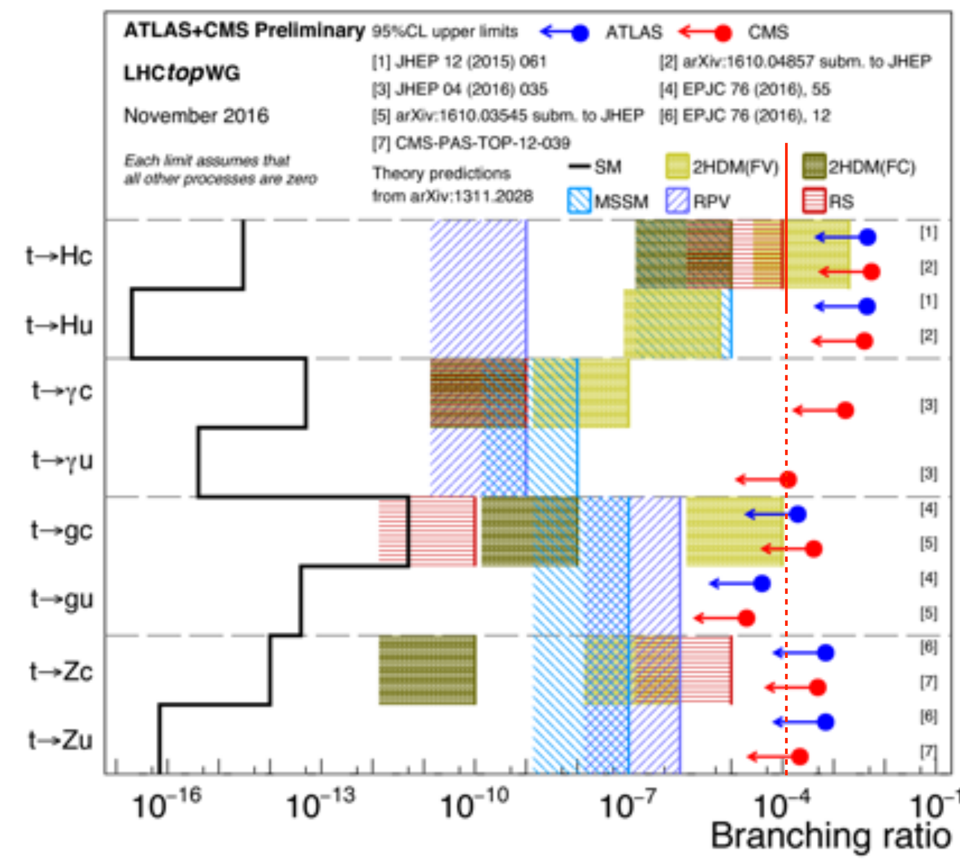
top-specific Variant Axion model

top FCNC is the prediction

$$BR(t \to ch) = 0.22 \pm 0.14\%$$

ATLAS 8TeV [JHEP 1512, 061 (2015)]





13 TeV ATLAS result set BR<0.22%

little hope for MSSM, FC 2HDM

Experimentalists can cite our model
as a well motivated model to predict t → ch

	Φ_1	Φ_2	t_R	c_R	u_R	d_R	ℓ_R	Q_L	L_L	top FCNC is the prediction
top-specific VA Model	+	−	−	+	+	+	+	+	+	third gen. is identical to type II

Y_u^{SM}, Y_u' in the Higgs basis

β

top-specific 2HDM

$$L^u = -\Phi_1 \overline{u}_{Ra}[Y_{u1}]_{ai} Q_i - \Phi_2 \overline{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.}$$

$$Y_{u1} = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}$$

$$Y_u^{\prime,\text{diag}} = \begin{pmatrix} -\tan\beta & & \\ & -\tan\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{\text{diag}} + (\tan\beta + \cot\beta) H_u Y_u^{\text{diag}},$$

$$H_u \equiv V \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} V^\dagger - \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} \to \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1-\cos\rho & \sin\rho \\ 0 & \sin\rho & \cos\rho - 1 \end{pmatrix}$$

using $\begin{pmatrix} H \\ h \end{pmatrix} = R_{\beta-\alpha} \begin{pmatrix} h^{\text{SM}} \\ h' \end{pmatrix}$

$$\xi_f \equiv \begin{cases} \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) & (\text{for } f = t) \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for } f \neq t) \end{cases}$$

as usual in 2HDM

$$\mathcal{L}_Y \equiv -\sum_{f=e,\cdots,u,\cdots,d,\cdots} \xi_f \frac{m_f}{v_{\text{SM}}} h\overline{f}f + \mathcal{L}_{\text{FCNC}}$$

with $\mathcal{L}_{\text{FCNC}} = -a \sum_{f,f'=u,c,t} (H_u)_{ff'} \frac{m_{f'}}{v_{\text{SM}}} h\overline{f}_R f'_L + \text{h.c.}$

$$a \equiv (\tan\beta + \cot\beta)\cos(\beta-\alpha) \,.$$

FC effect proportional to a and m_{f_L}

prediction in VA

Large

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\text{SM}}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t\sin\rho \\ m_c\sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

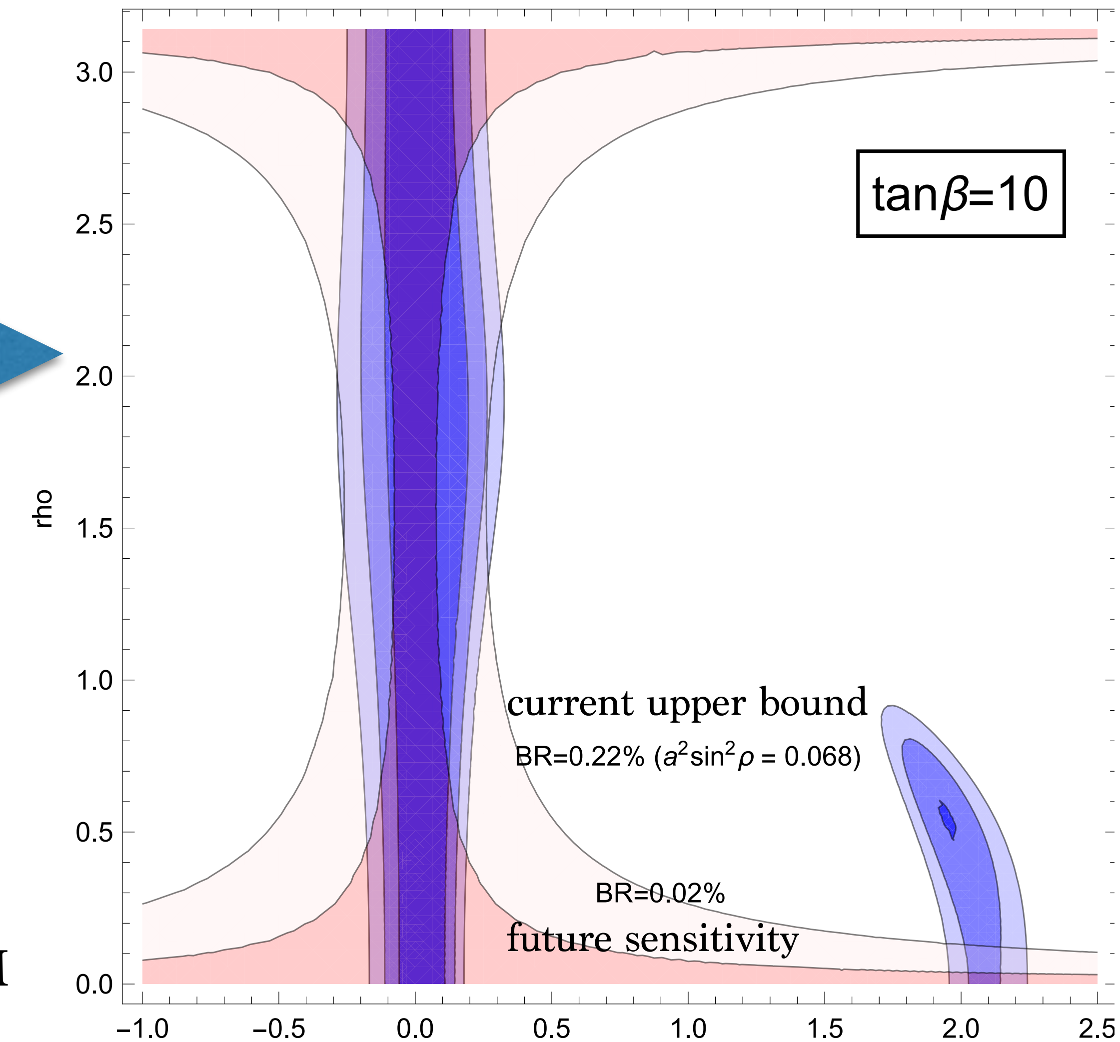
Small

Higgs global fit (with latest data)

model parameter: tanβ, cos(β-α), ρ

	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb
$ggF^{7,8\text{TeV}}$	$1.10^{+0.23}_{-0.22}$	$1.13^{+0.34}_{-0.31}$	0.84 ± 0.17	1.0 ± 0.6	–
$ggF^{13\text{TeV}}_{\text{ATLAS}}$	$0.8^{+0.19}_{-0.18}$ [54]	1.11 ± 0.245 [53]	–	–	–
$ggF^{13\text{TeV}}_{\text{CMS}}$	$1.11^{+0.19}_{-0.18}$ [51]	$1.20^{+0.22}_{-0.21}$ [49]	$0.9^{+0.4}_{-0.3}$ [65]	$1.17^{+0.47}_{-0.40}$ [66]	$2.3^{+1.8}_{-1.6}$ [68]
$VBF^{7,8\text{TeV}}$	1.3 ± 0.5	$0.1^{+1.1}_{-0.6}$	1.2 ± 0.4	1.3 ± 0.4	–
$VBF^{13\text{TeV}}_{\text{ATLAS}}$	2.1 ± 0.6 [54]	4.0 ± 1.77 [53]	$3.2^{+4.4}_{-4.2}$ [59]	–	$-3.9^{+2.8}_{-2.7}$ [61]
$VBF^{13\text{TeV}}_{\text{CMS}}$	$0.54^{+0.6}_{-0.5}$ [51]	$0.06^{+1.03}_{-0.06}$ [49]	1.4 ± 0.8 [65]	$1.11^{+0.34}_{-0.35}$ [66]	$-3.7^{+2.4}_{-2.5}$ [62]
$VH^{7,8\text{TeV}}$	0.5 ± 1.1	–	2.3 ± 1.0	-0.2 ± 1.1	0.63 ± 0.3
$VH^{13\text{TeV}}_{\text{ATLAS}}$	$0.7^{+0.9}_{-0.8}$ [54]	< 3.8 [53]	$1.7^{+1.1}_{-0.9}$ [59]	–	$1.20^{+0.42}_{-0.36}$ [55]
$VH^{13\text{TeV}}_{\text{CMS}}$	$2.29^{+1.1}_{-1.0}$ [51]	< 2.8 [49]	-0.3 ± 1.3 [65]	–	–
$ttH^{7,8\text{TeV}}$	$2.2^{+1.6}_{-1.3}$	–	$5.0^{+1.8}_{-1.7}$	$-1.9^{+3.7}_{-3.3}$	1.1 ± 1.0
$ttH^{13\text{TeV}}_{\text{ATLAS}}$	0.5 ± 0.6 [54]	(WW)	$2.5^{+1.3}_{-1.1}$ [56]	(WW)	$2.1^{+1.0}_{-0.9}$ [56]
$ttH^{13\text{TeV}}_{\text{CMS}}$	$2.22^{+0.9}_{-0.8}$ [51]	(WW)	1.5 ± 0.5 [67]	$0.72^{+0.62}_{-0.53}$ [64]	-0.19 ± 0.80 [63]

blue : Higgs data, red: t → ch



for ρ=0, 3rd gen is identical to type2 THDM

$$\xi_f = \begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=t)\ , \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=c)\ , \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others})\ . \end{cases}$$

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\text{SM}}} h \left(\bar{c}_R \quad \bar{t}_R\right) \begin{pmatrix} m_c(1-\cos\rho) & m_t\sin\rho \\ m_c\sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

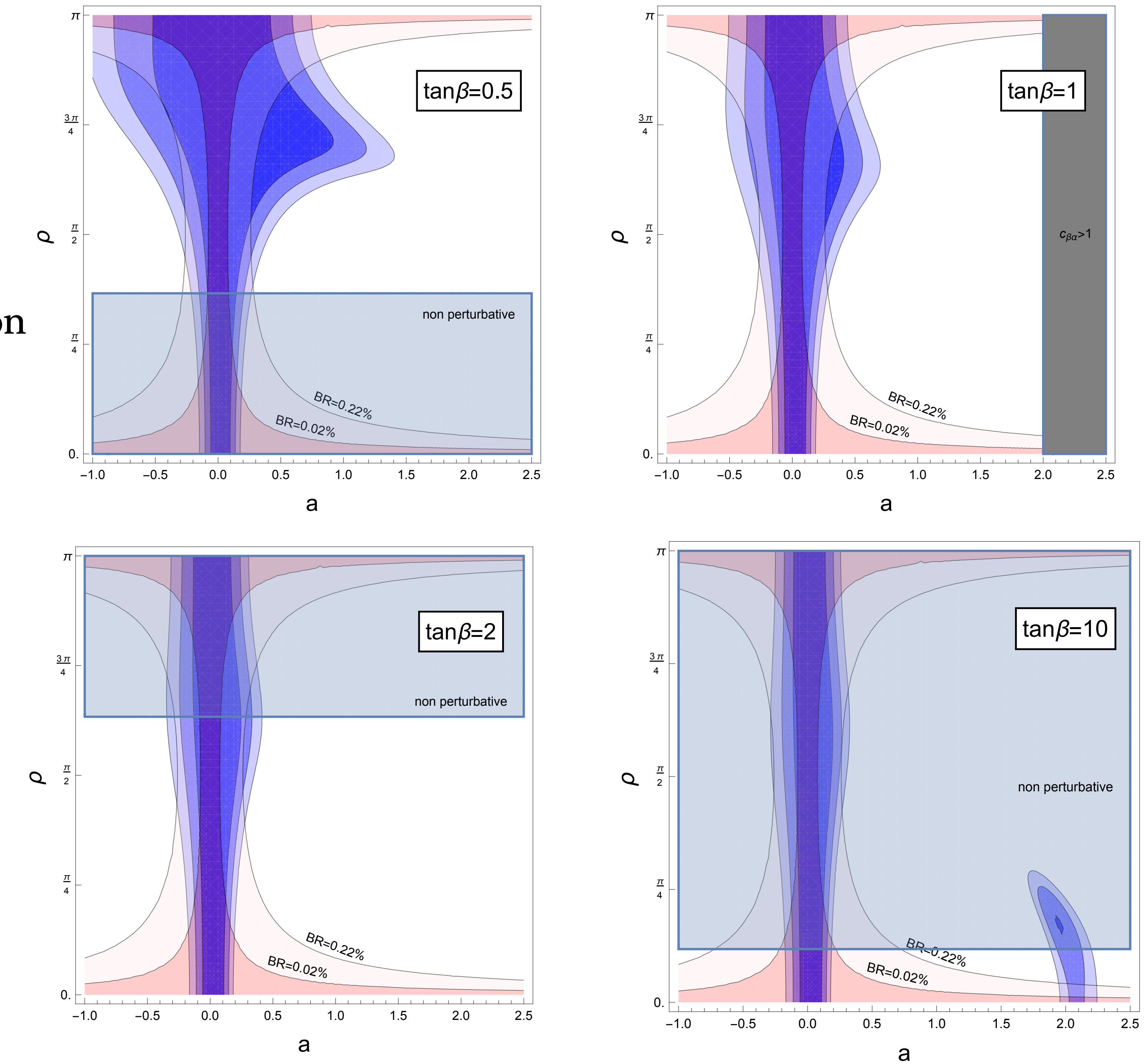
tan beta dependence

$$a \equiv (\tan\beta + \cot\beta)\cos(\beta - \alpha)\ .$$

low tan beta provide broader parameter region consistent with Higgs data

mainly by the condition $\xi_t/\xi_b = 1$

upper bound on tan beta
assuming BR=0.22%
and consistent with Higgs data



$$\xi_f = \begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f = t)\ , \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f = c)\ , \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others})\ . \end{cases}$$

helicity structure in top FC decay

$t \to ch$

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\rm SM}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t \sin\rho \\ m_c \sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

Large ($m_t \sin\rho$), Small ($m_c \sin\rho$)

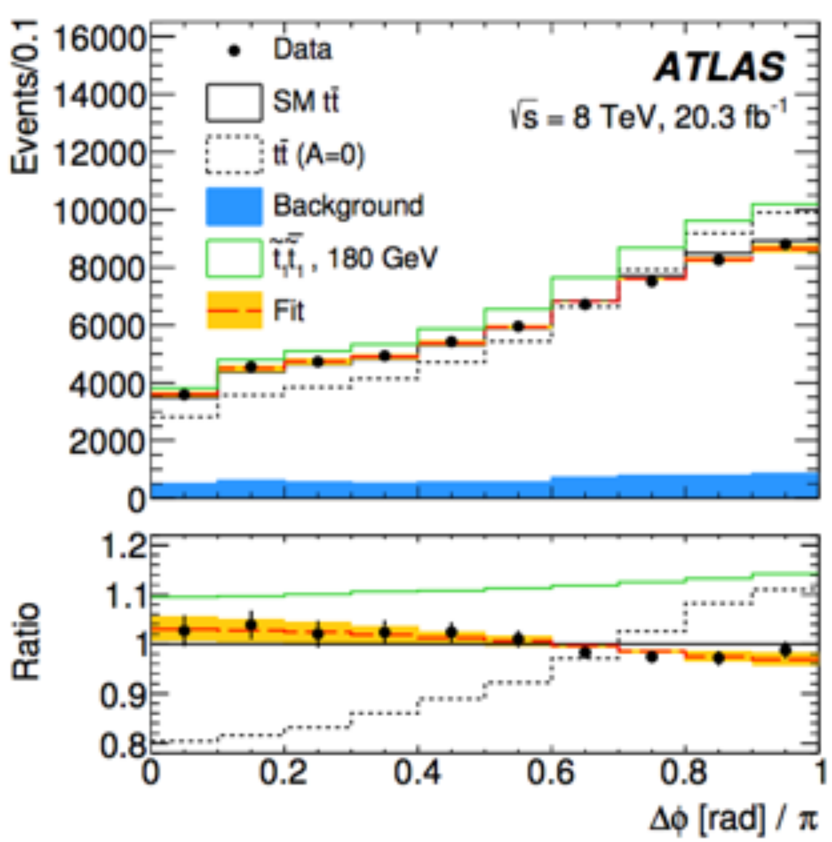
$h\bar{c}_R t_L$: always c_R observed $(m_c \ll m_t)$

from spin conservation, top helicity and direction of c_R is alined.

Spin analyzing power:

$$\frac{1}{\Gamma_i}\frac{d\Gamma_i}{d\cos\theta_i} = \frac{1}{2}(1 + \kappa_i P \cos\theta_i)$$

κ_{ℓ^+}	$\kappa_{\bar{d}}$	κ_u	κ_b	κ_c	κ_h
$+1$	$+1$	-0.32	-0.39	$+1$	-1



Already measured by ATLAS, CMS

arXiv:1412.4742 CMS-PAS-TOP-13-015

$$A_{\rm hel}^{{\rm SM},8TeV} = 0.318 \pm 0.005$$

$$A_{\rm hel}^{{\rm ATLAS},8TeV} = 0.38 \pm 0.04$$

Using spin correlation, we can check it.

$$A_{\rm hel} = \frac{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) - N(t_\uparrow \bar{t}_\downarrow) - N(t_\downarrow \bar{t}_\uparrow)}{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) + N(t_\uparrow \bar{t}_\downarrow) + N(t_\downarrow \bar{t}_\uparrow)} \sim 0.35 \quad (14\text{TeV})$$

helicity structure in top FC decay

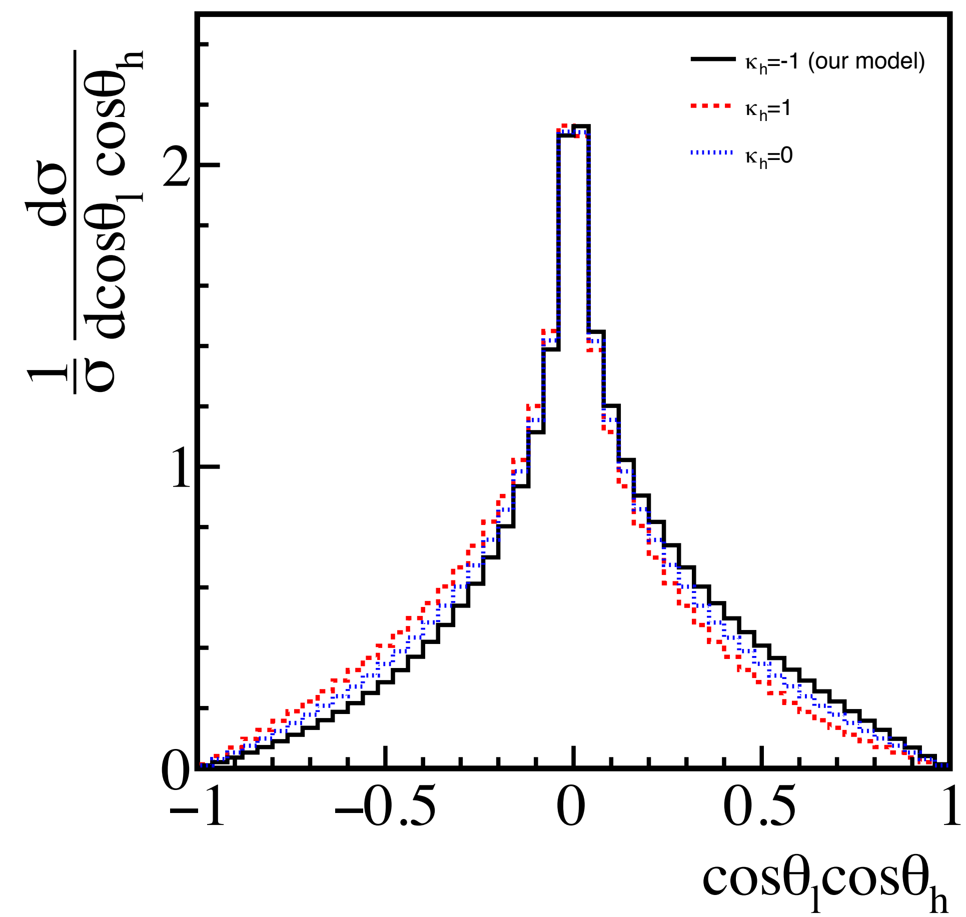
$t \to ch$

always c_R observed $(m_c \ll m_t)$

c is aligned to the top spin direction

$$A_{\rm hel} = \frac{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) - N(t_\uparrow \bar{t}_\downarrow) - N(t_\downarrow \bar{t}_\uparrow)}{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) + N(t_\uparrow \bar{t}_\downarrow) + N(t_\downarrow \bar{t}_\uparrow)} \sim 0.35$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i d\cos\theta_j} = \frac{1}{4}(1 + A_{\rm hel}\,\kappa_i \bar{\kappa}_j \cos\theta_i \cos\theta_j)$$



rough estimate of the sensitivity:

$$A_{\ell h} = \frac{N(\cos\theta_\ell \cos\theta_h > 0) - N(\cos\theta_\ell \cos\theta_h < 0)}{N(\cos\theta_\ell \cos\theta_h > 0) + N(\cos\theta_\ell \cos\theta_h < 0)} = \frac{A_{\rm hel}\kappa_{\ell+}\bar{\kappa}_h}{4} \sim 0.088\bar{\kappa}_h.$$

$\Delta A_{\ell h} \simeq \Delta N/N \simeq 1/\sqrt{N} > 0.088$ → at least 130 signal events needed.

with $\sigma(t\bar{t}) \sim 1$ nb for 3 ab^{-1}, 3×10^9 top pair expecetd

even for $BR(t \to ch) BR(h \to \gamma\gamma) = 2.2 \times 10^{-3} \times 2.3 \times 10^{-3}$,

~ 5000 of $t \to ch_{\to\gamma\gamma}$ events expected   not so difficult

using h→bb would improve the sensitivity

Summary

We consider top specific 2HDM, which predicts FCNC $t \to ch$

Strong CP problem

↓

PQ solution with axion — promising axion DM searches near future

↓

top-specific invisible axion model (ZDFS) $N_{DM} = 1$

a well motivated model for FV 2HDM

Central value of the current excess BR=0.22% and Higgs data is compatible to our model

We predict in general distinct helicity structure in FC higgs couplings.

As top pairs are produced copiously at LHC, we should be able to test it using the spin correlation for a reasonable $BR(t \to ch)$.

improving the analysis on this mode would be very important [LHC: top factory]

more detail: JHEP11(2015)057 [arXiv:1507.04354], PhysRevD.97.035015 [arXiv:1711.02993], arxiv:1806.XXXX