Top and Higgs save the world

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IIHE Internal Seminar

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Introduction

- The **heaviest elementary particle** ever discovered (1995)
- Almost exclusively decays to W boson and b quark
- **Short lifetime** makes it decay before hadronization (**τ** ≈ $4\text{x}10^{-25}$ s)
- Represents relatively clean experimental signature to study

- The **most Godly particle** ever discovered (2012)
- The last predicted missing particle in SM now observed
- Gives mass to all particles via Higgs field
- Its properties and implications for SM are currently being studied in details

In SM top is expected to strongly couple to Higgs ($y_t \approx 1$)

Why top Yukawa coupling is so strong ?

Yukawa interaction with quarks:

$$\mathcal{L} = \frac{1}{\sqrt{2}}\overline{Q}_{2/3}\lambda_{2/3}Q_{2/3}(H+v) + \frac{1}{\sqrt{2}}\overline{Q}_{-1/3}\lambda_{-1/3}Q_{-1/3}(\overset{\text{Higgs field}}{H}+\overset{\text{Vacuum expectation}}{v})$$

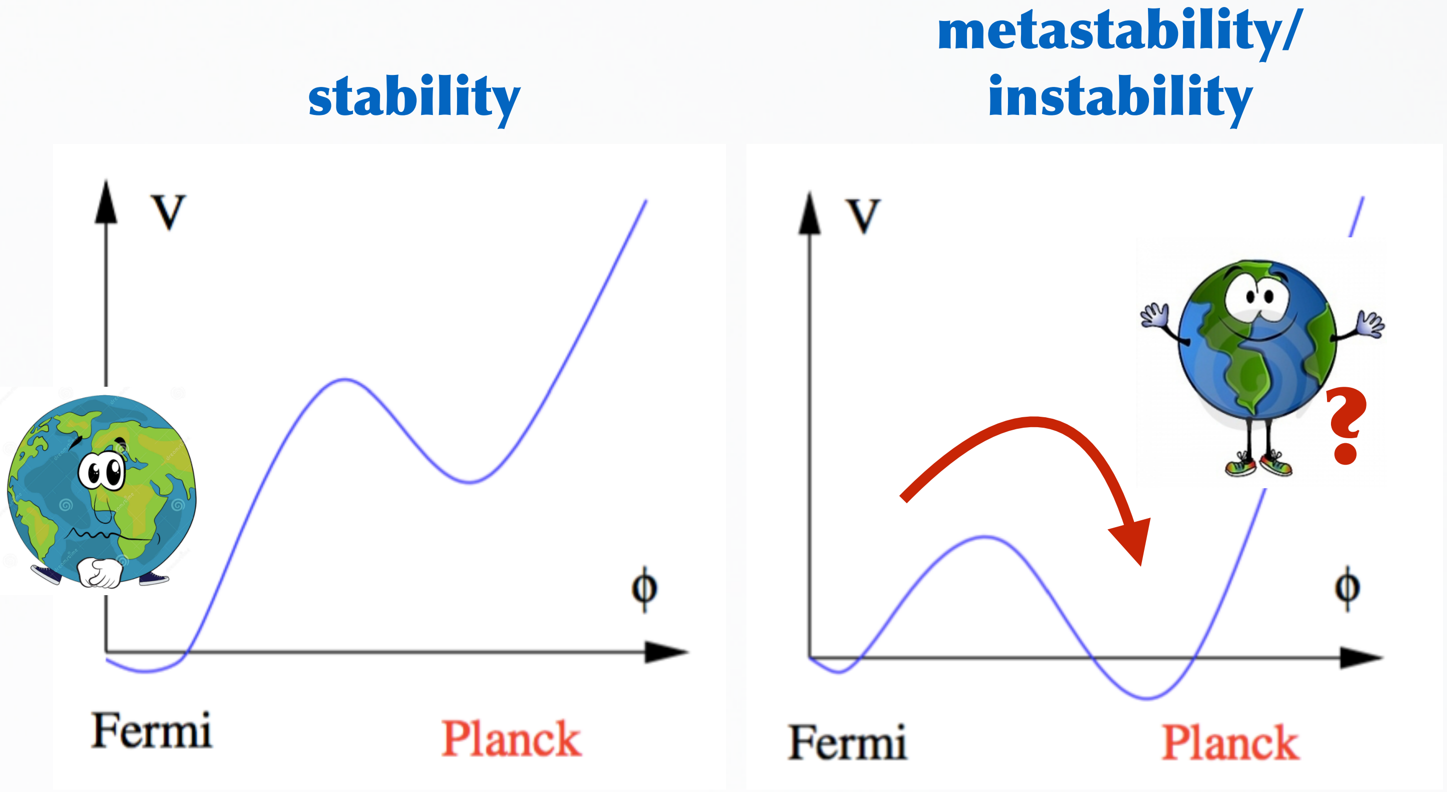
↓ **diagonalisation**

$$\mathcal{L} = \overline{Q}_{2/3}(\boxed{\frac{m_{2/3}}{v}}H + m_{2/3})Q_{2/3} + \overline{Q}_{-1/3}(\boxed{\frac{m_{-1/3}}{v}}H + m_{-1/3})Q_{-1/3}$$

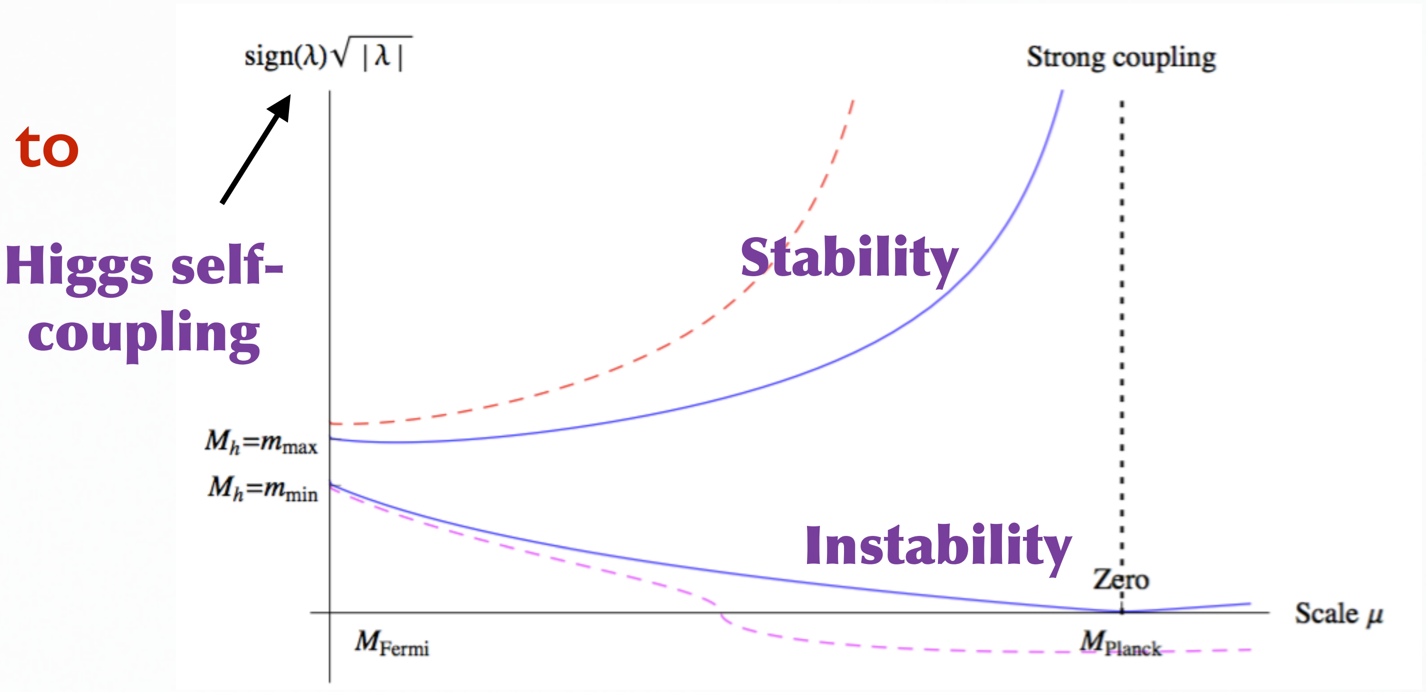
Yukawa coupling $\boxed{= \sqrt{2}\frac{m_Q}{v}}$

Top quark Yukawa coupling (y_t) = 1.4*(173 GeV)/(246 GeV) ≈ 0.98
precise calculations give 0.990 +/- 0.003
→ presumably enhanced sensitivity to BSM particles

Is our world stable ?

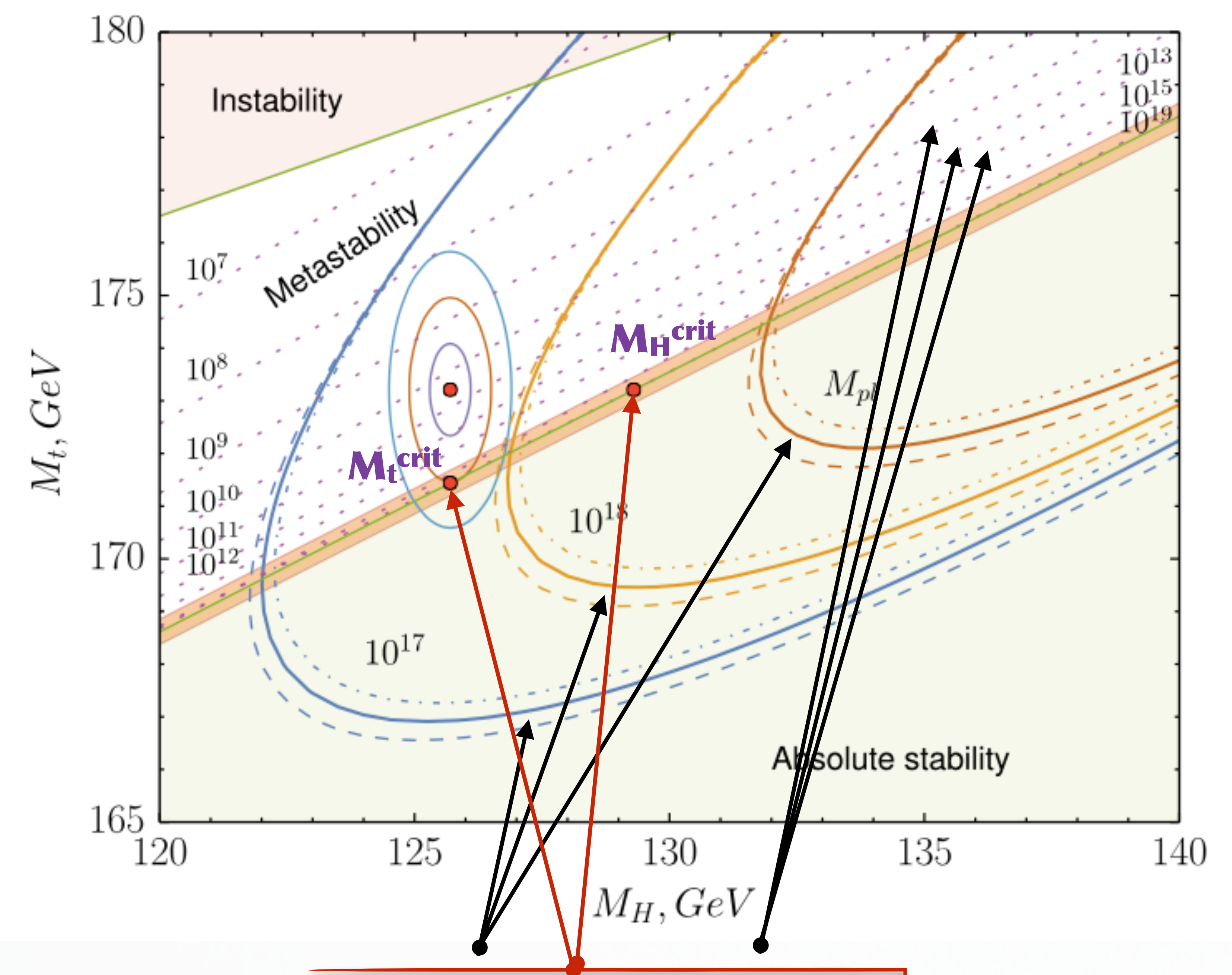


- Our world is **stable** if there are no other potential minima $V < V_{Fermi}$
- Our world is **metastable** if there is another potential minimum with a tunneling time greater than the age of our universe ($P^{-1}_{tunnel} > \tau_{universe}$)
- Our world is **unstable** if $P^{-1}_{tunnel} < \tau_{universe}$
- **The answer is strongly connected to top and Higgs properties !**
- $\mu^{thr} = O(v = 246\ \text{GeV})$
- $\mu^{cri} = O(M_{Planck} = 1.22\text{x}10^{19}\ \text{GeV})$



JHEP10 (2012) 140

When the world (almost) crashes down



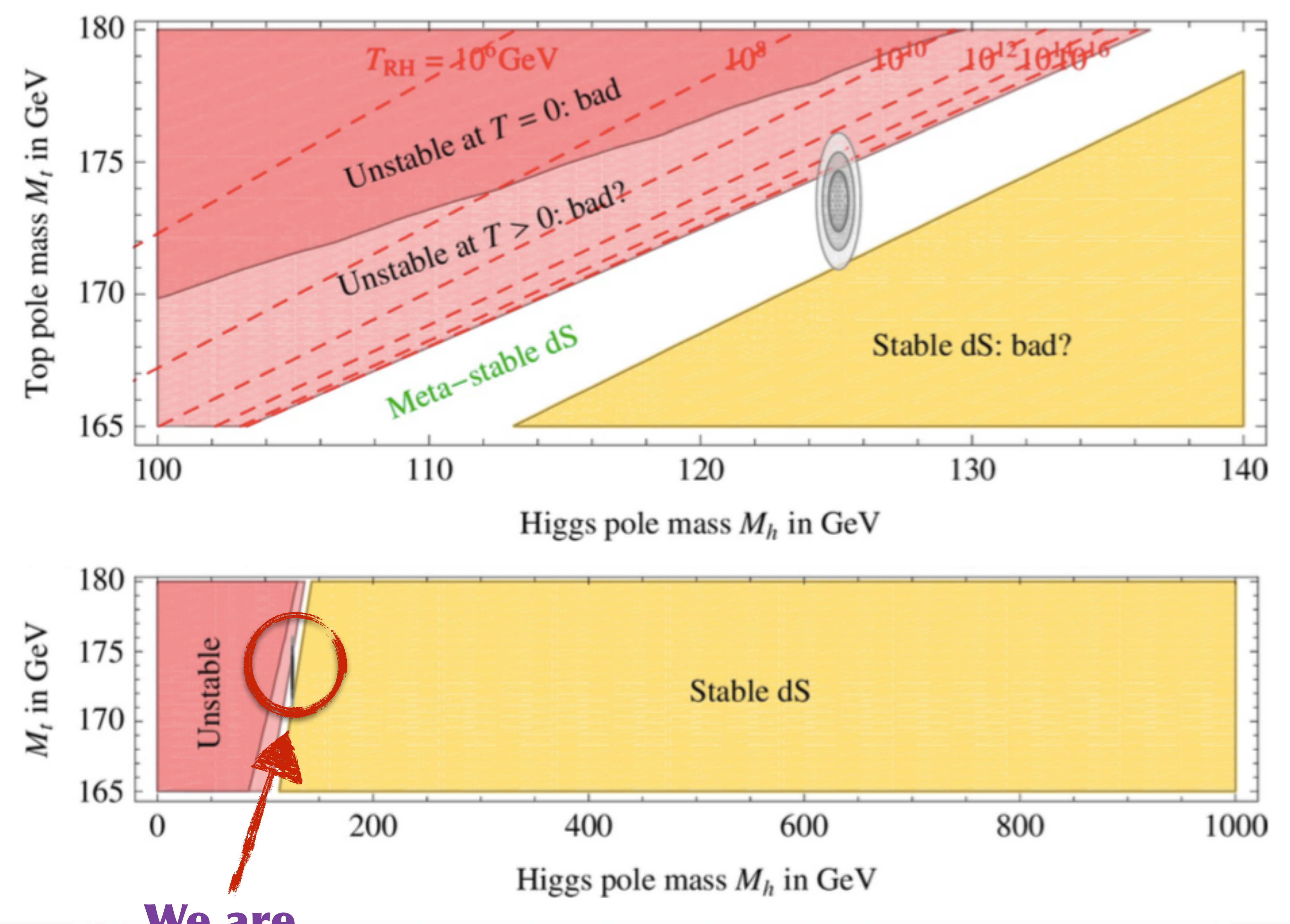
$$\lambda(\mu^0) = 0 \qquad \beta_\lambda(\mu^0) = 0$$

vacuum stability condition

- Our world is **unstable** at **1.3σ**
- We seem to live in a **metastable** world → **transition time between two minima > lifetime of the universe**
- Main uncertainties on our fate come from **m_t, m_H** and **y_t determination**

Phys. Rev. Lett. 115, 201802 (2015)

Lucky (?)



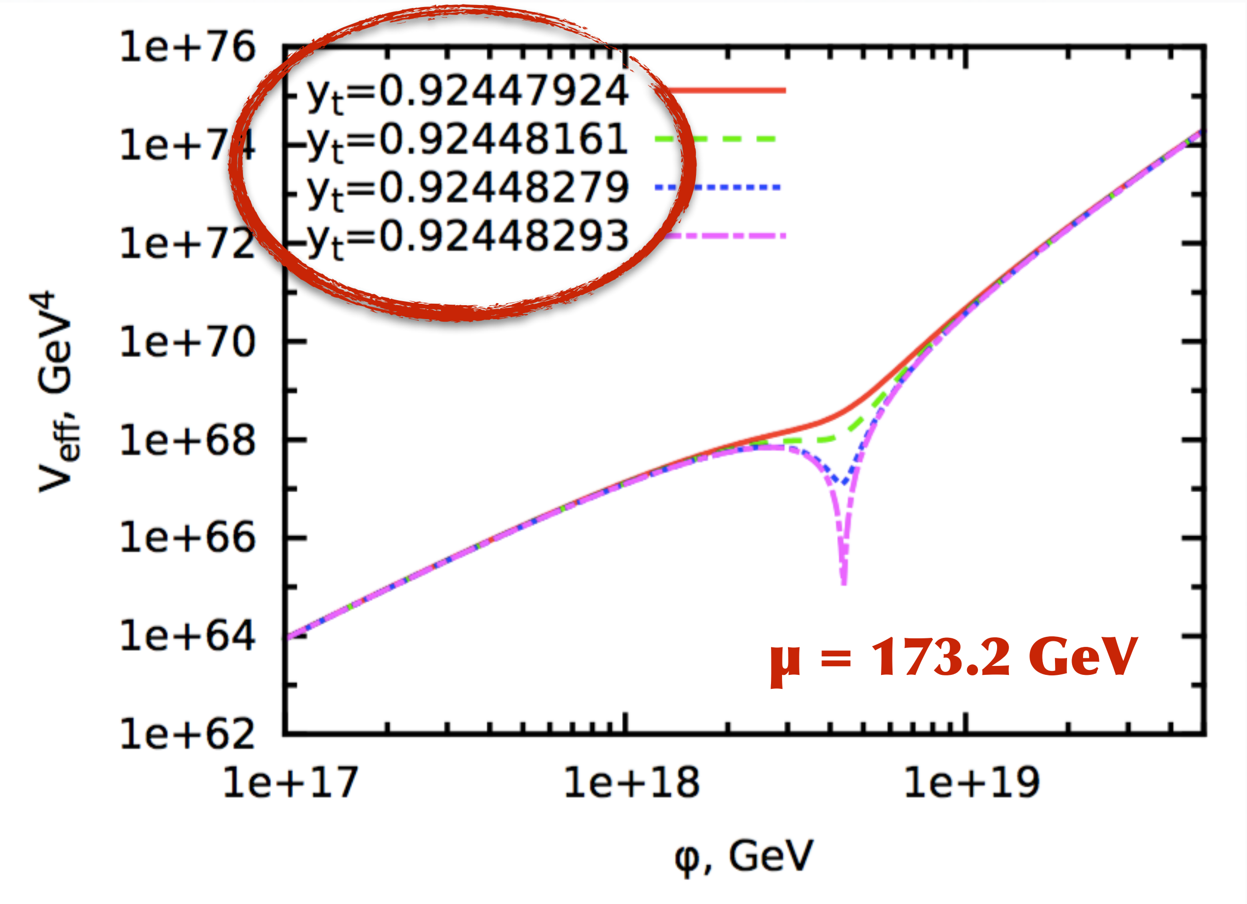
We are here

JHEP09 (2015) 174

The importance of being y_t

- **Critical y_t**: Higgs field has two degenerate minima
- **$y_t \in [y_t^{crit}, y_t^{crit} + 0.04]$**: the new minimum is deeper than ours, the age of the universe is smaller than the life-time of our vacuum (**metastability**)
- **$y_t > y_t^{crit} + 0.04$ (m_t > 178 GeV)**: the life-time of our vacuum is smaller than the age of the universe
- **$y_t < y_t^{crit}$ - $1.2\text{x}10^{-6}$**: our vacuum is unique
- **$y_t \in [y_t^{crit}$ - $1.2\text{x}10^{-6}$, $y_t^{crit}]$**: our vacuum is deeper than the other one

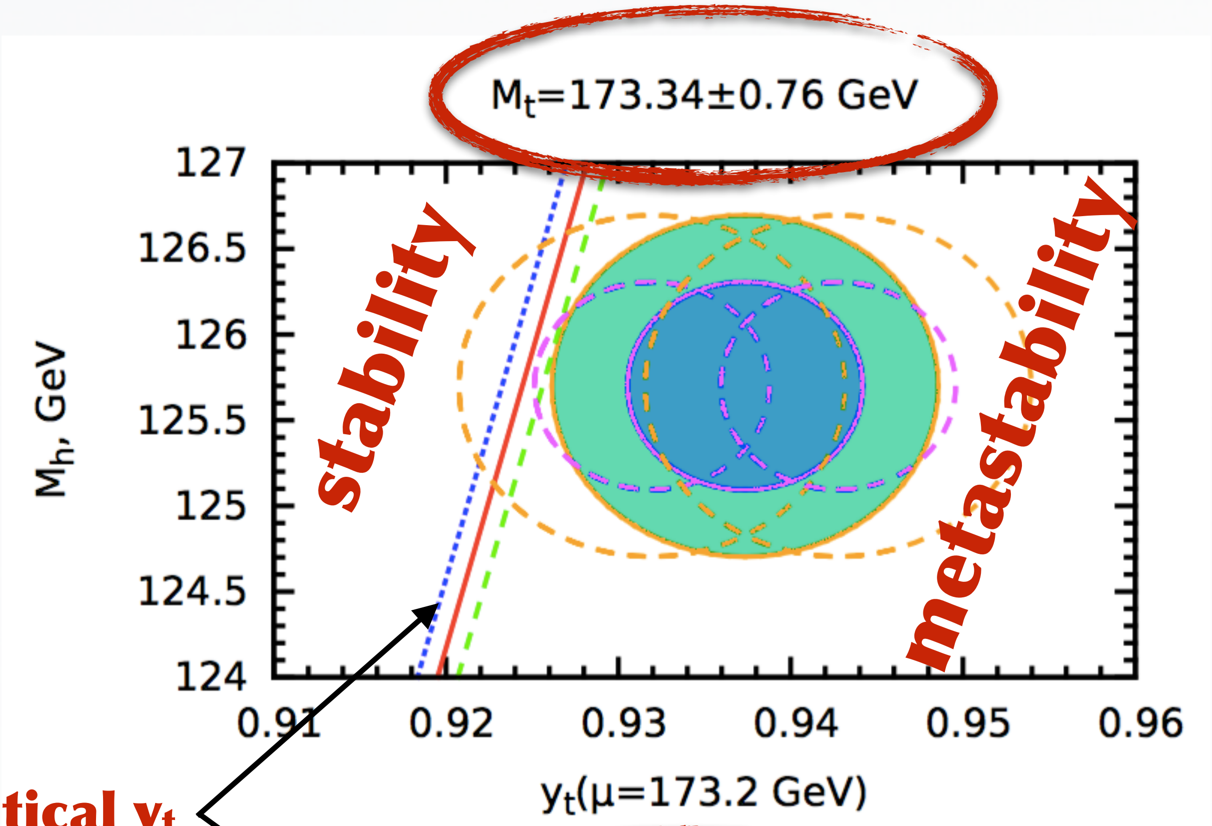
$$y_t^{\rm crit} = 0.9244 + 0.0012 \times \frac{M_h/{\rm GeV} - 125.7}{0.4} + 0.0012 \times \frac{\alpha_s(M_Z) - 0.1184}{0.0007}$$



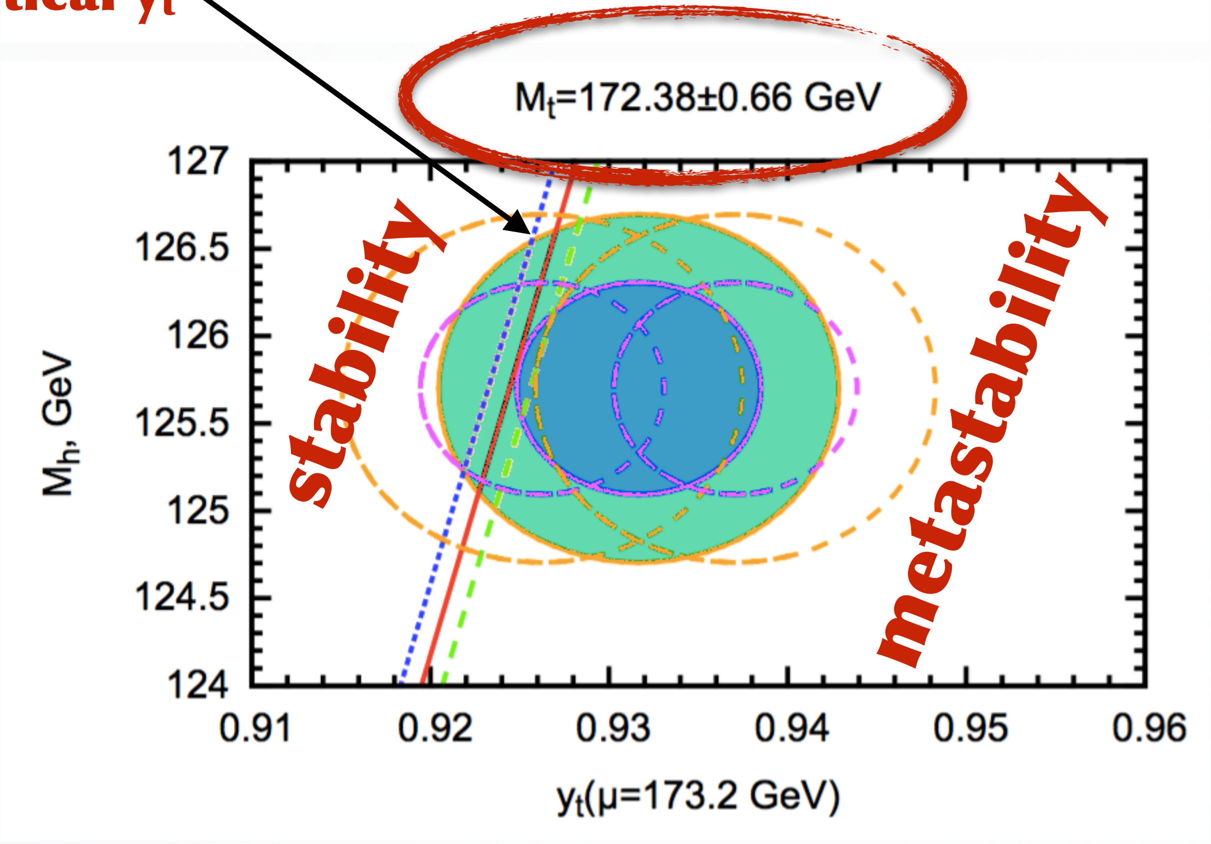
J. Exp. Theor. Phys. 120 (2015) 3

Mass, Yukawa and stability

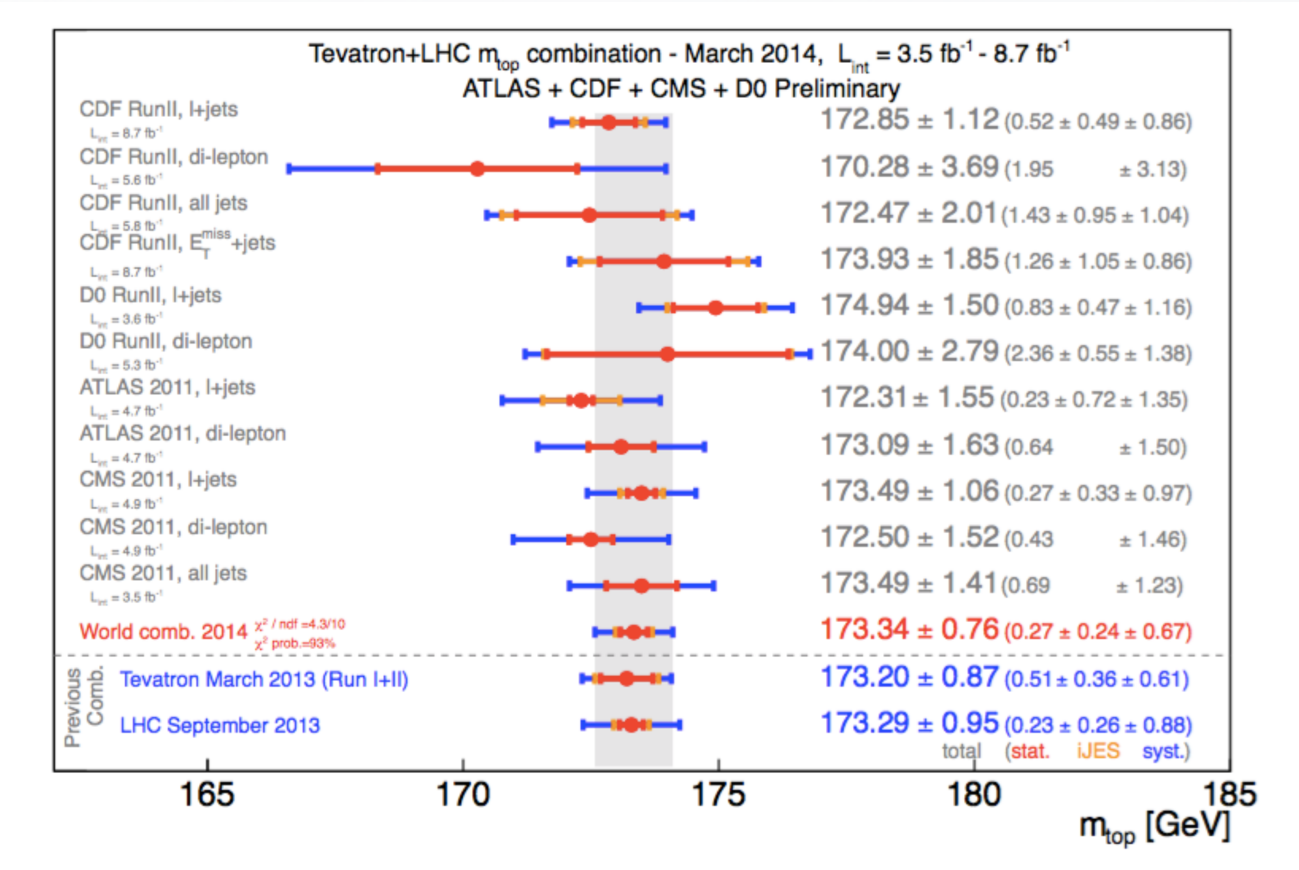
Latest results

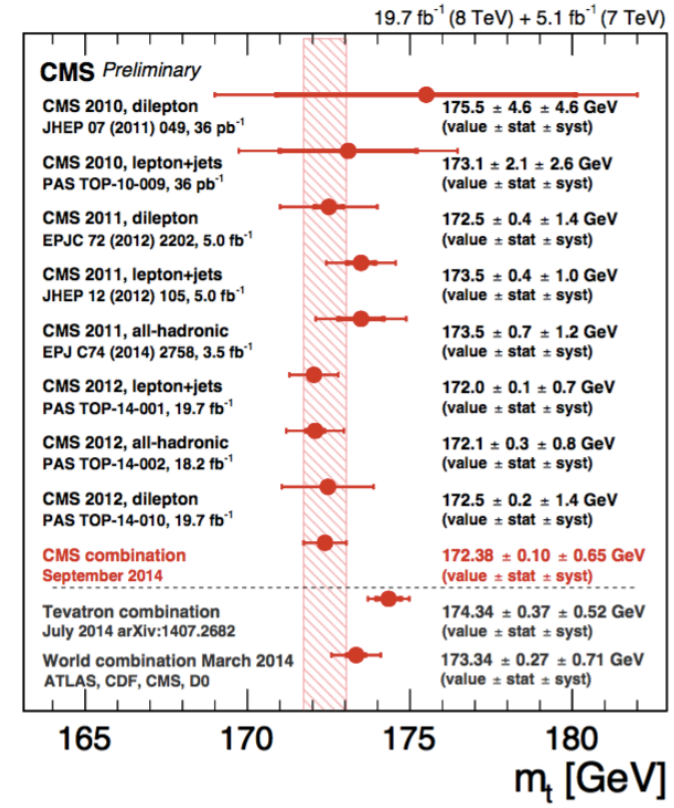


Critical y_t



Run I CMS results

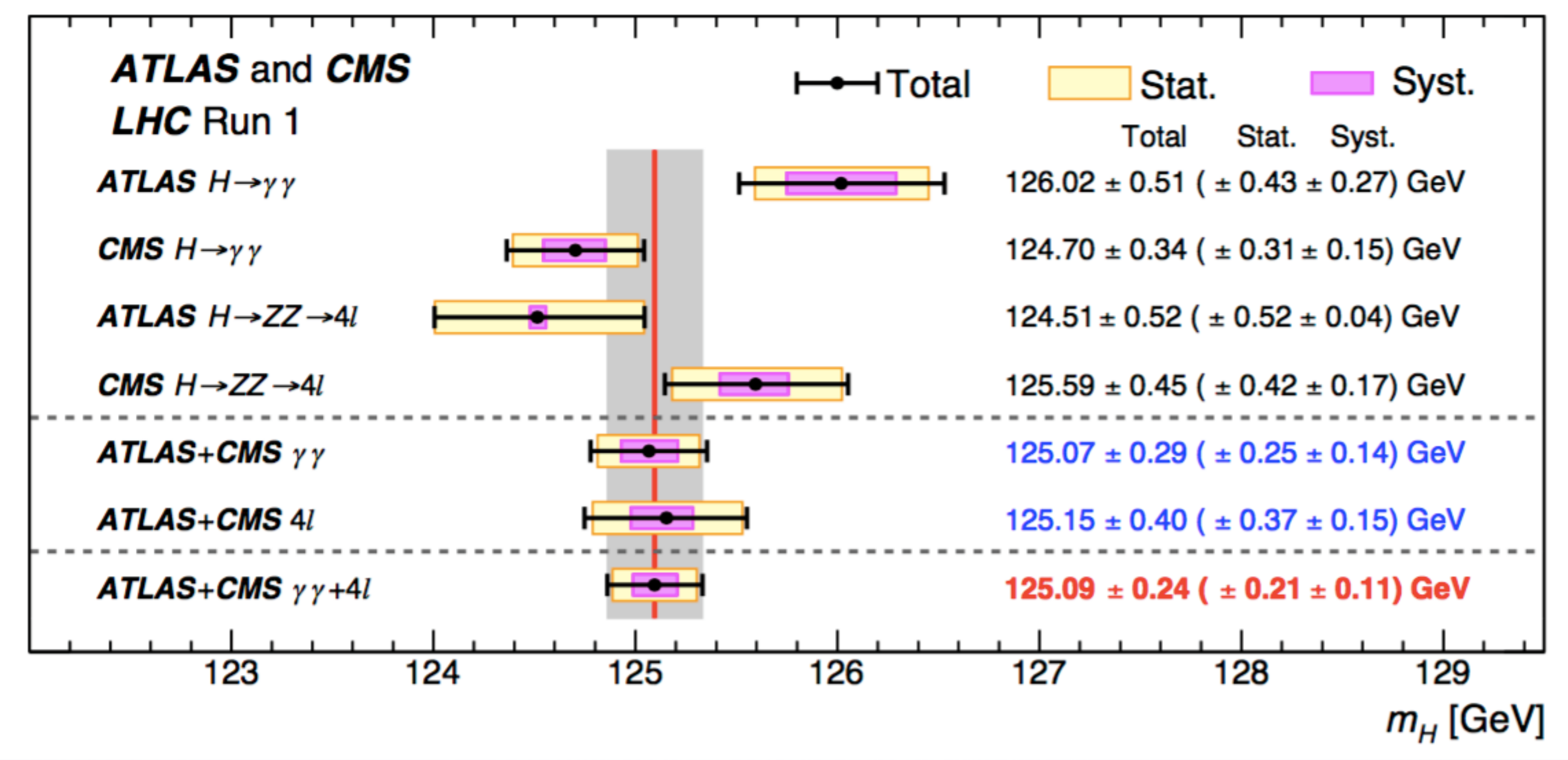




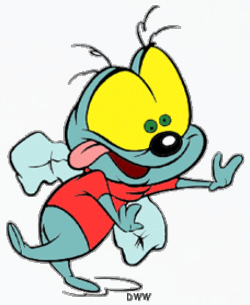
Precision mass measurements for top and Higgs, and y_t determination are crucial to understand where we live !

J. Exp. Theor. Phys. 120 (2015) 3

Higgs mass measurements

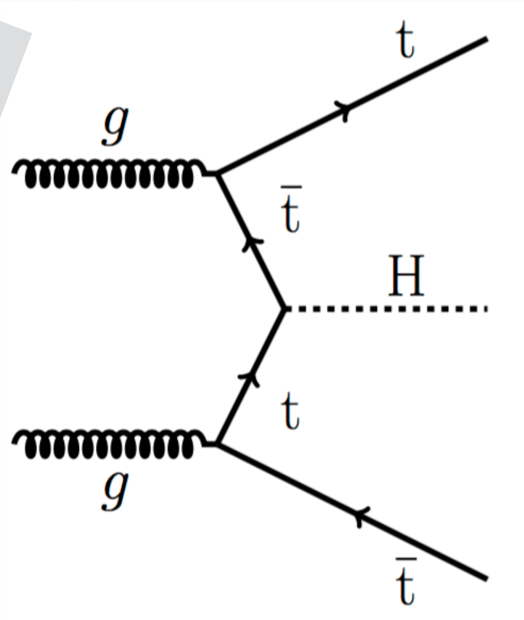


How to catch Yukawa ?

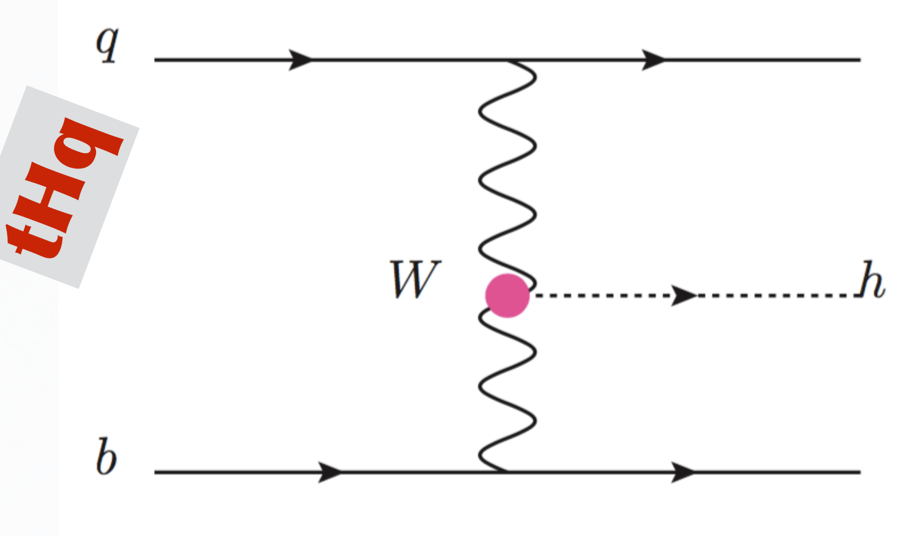


Directly

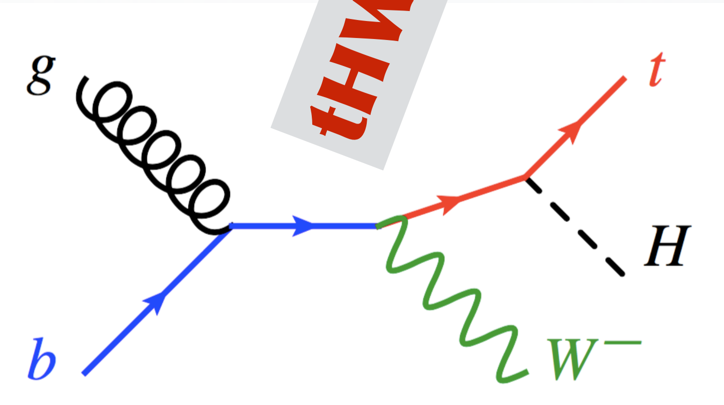
ttH



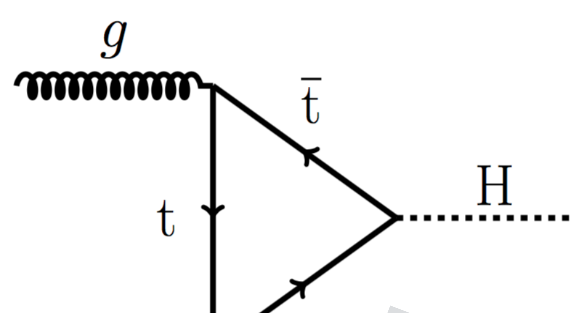
tHq



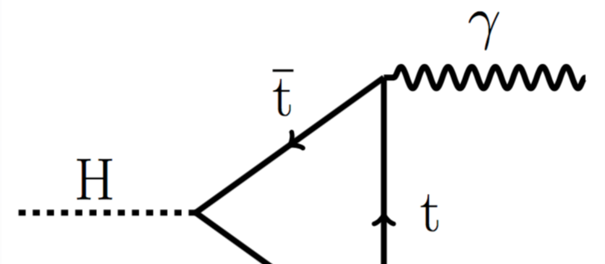
tHW



Indirectly

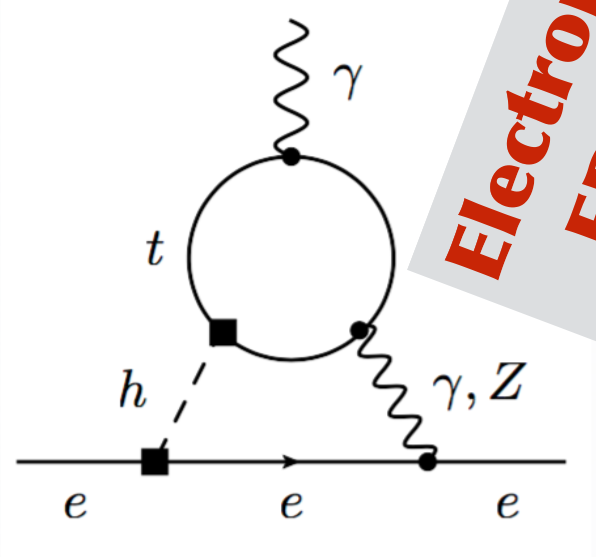


ggH



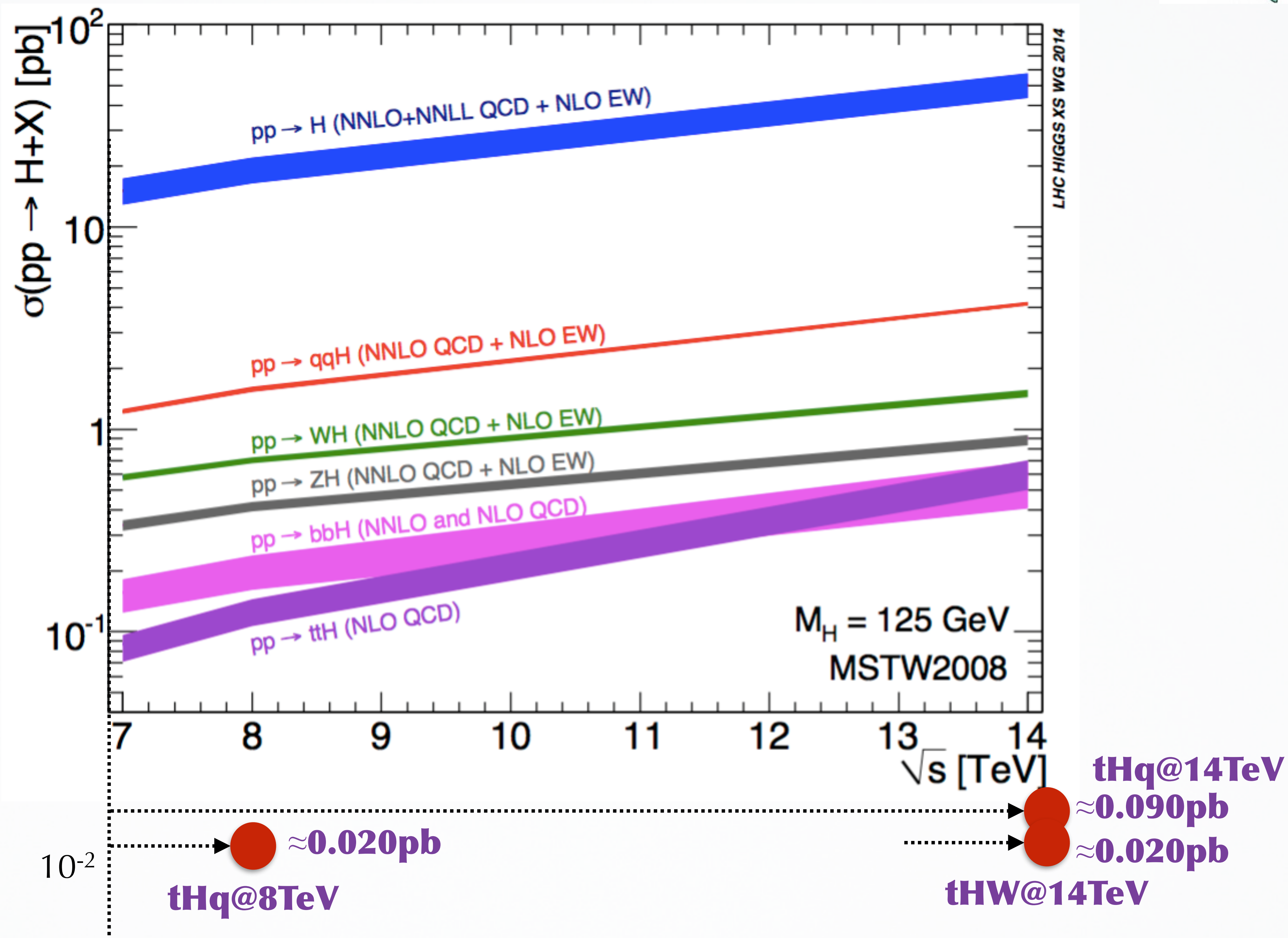
H→γγ

Electron EDM



Caveat: new particles could contribute to the loops !

Catch me directly, if you can



≈0.020pb

tHq@8TeV

tHq@14TeV

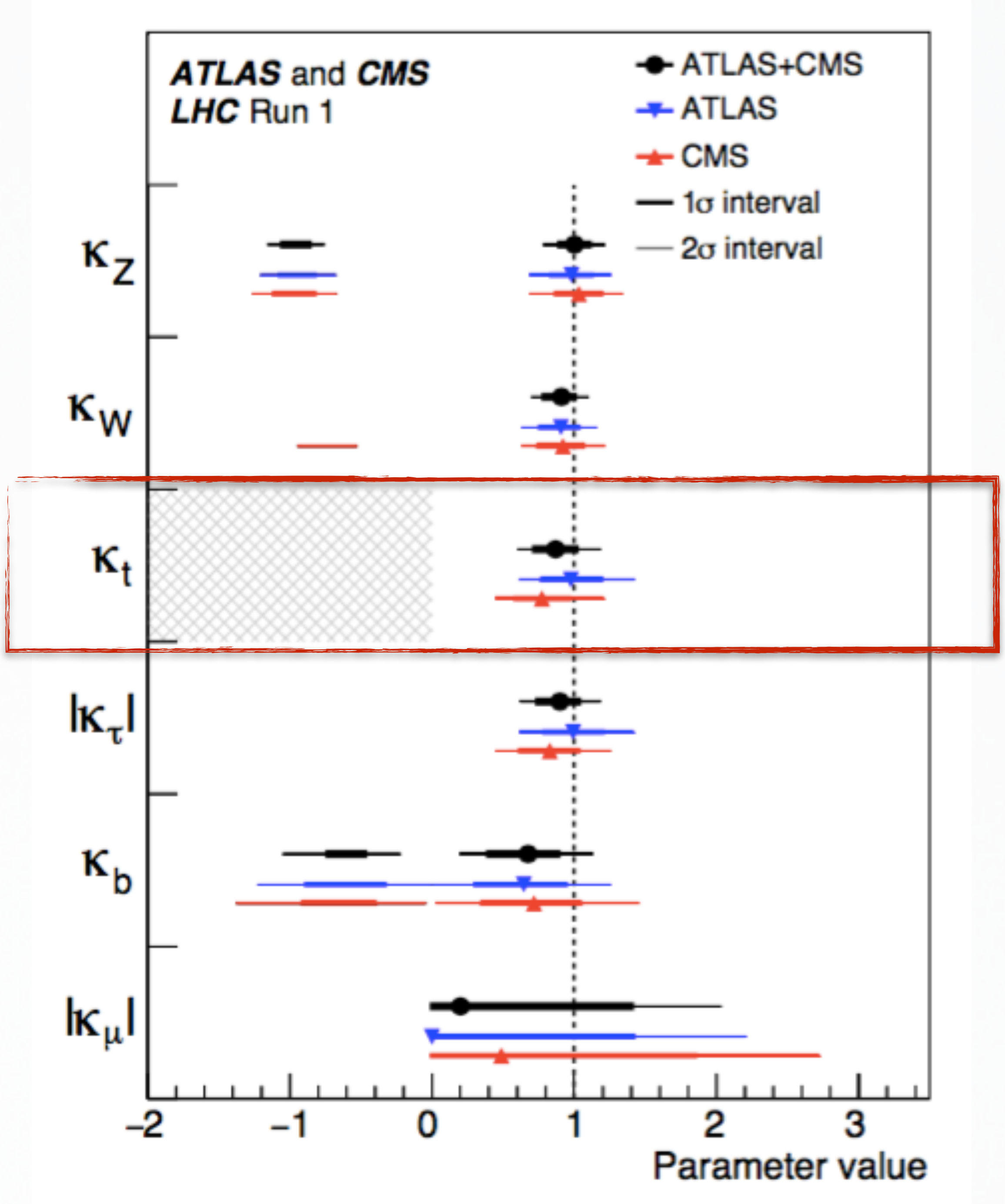
≈0.090pb

≈0.020pb

tHW@14TeV

How well do we know y_t ?

$$\kappa = \frac{\sigma}{\sigma_{SM}}$$



But mostly comes from indirect search analyses !

JHEP08 (2016) 045

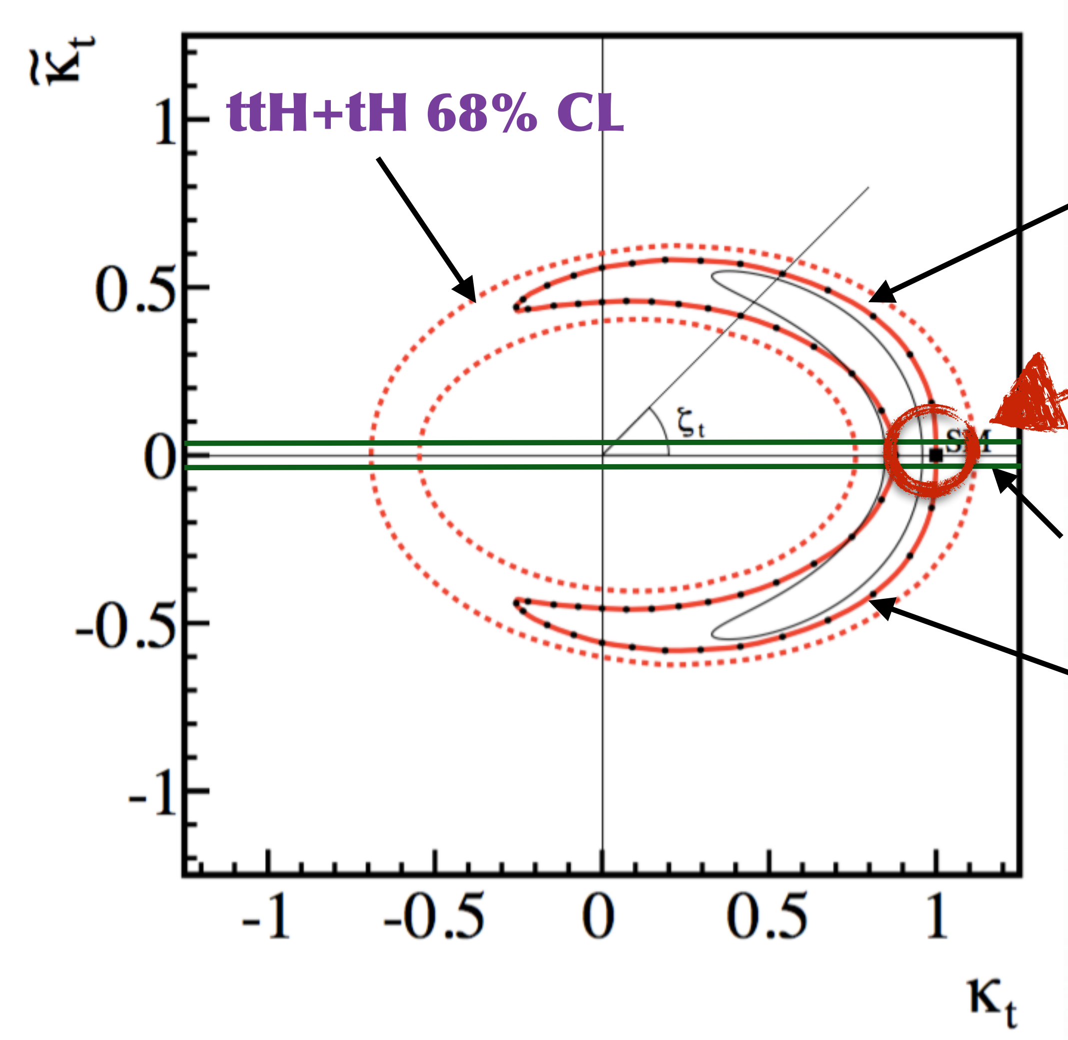
y_t and CP violation

Top-Higgs interaction

scalar **pseudoscalar**

$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

CP violation phase: $\zeta_t = arctan(\tilde{\kappa}_t/\kappa_t)$



ttH+tH 68% CL

ttH+tH 95% CL

SM: κ_t = 1, $\tilde{\kappa}_t$ = 0

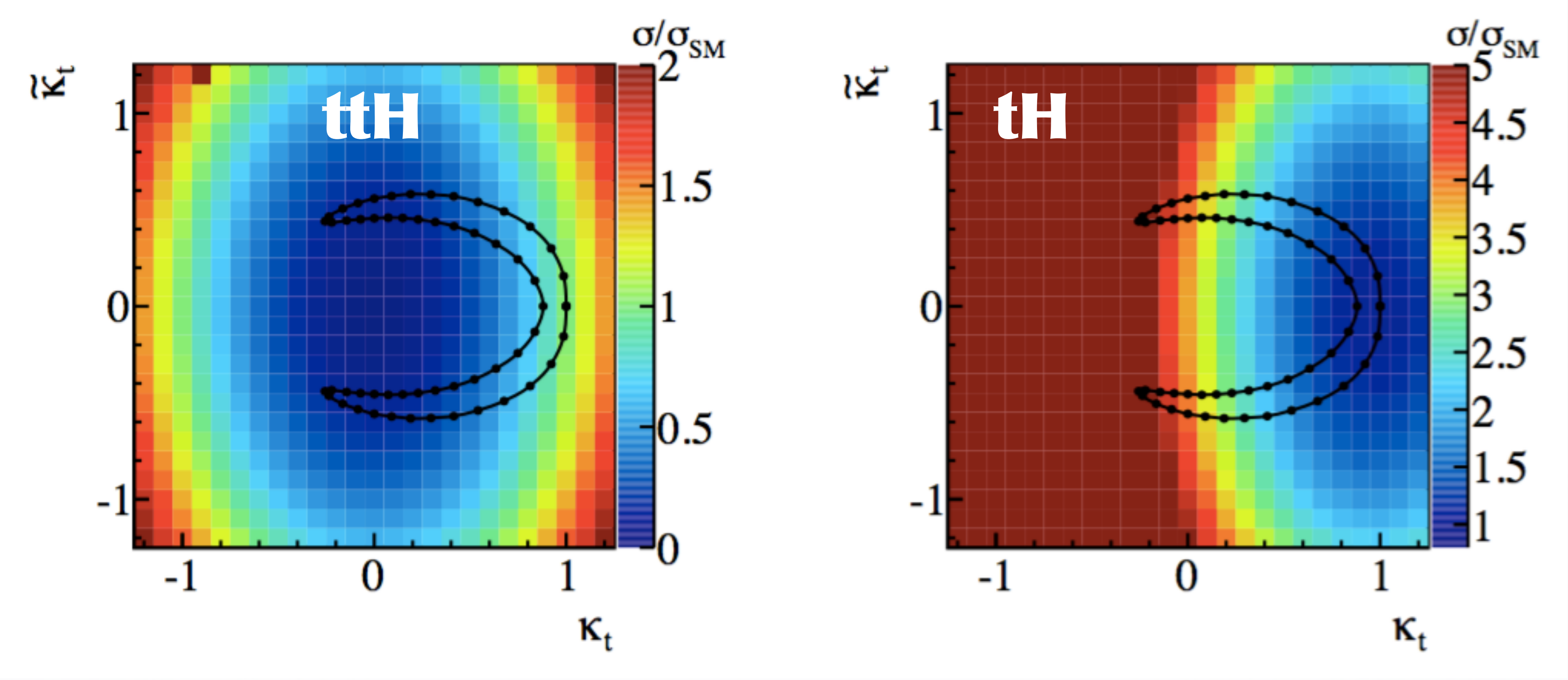
Electron EDM (indirect): $|\tilde{\kappa}_t| < 0.01$

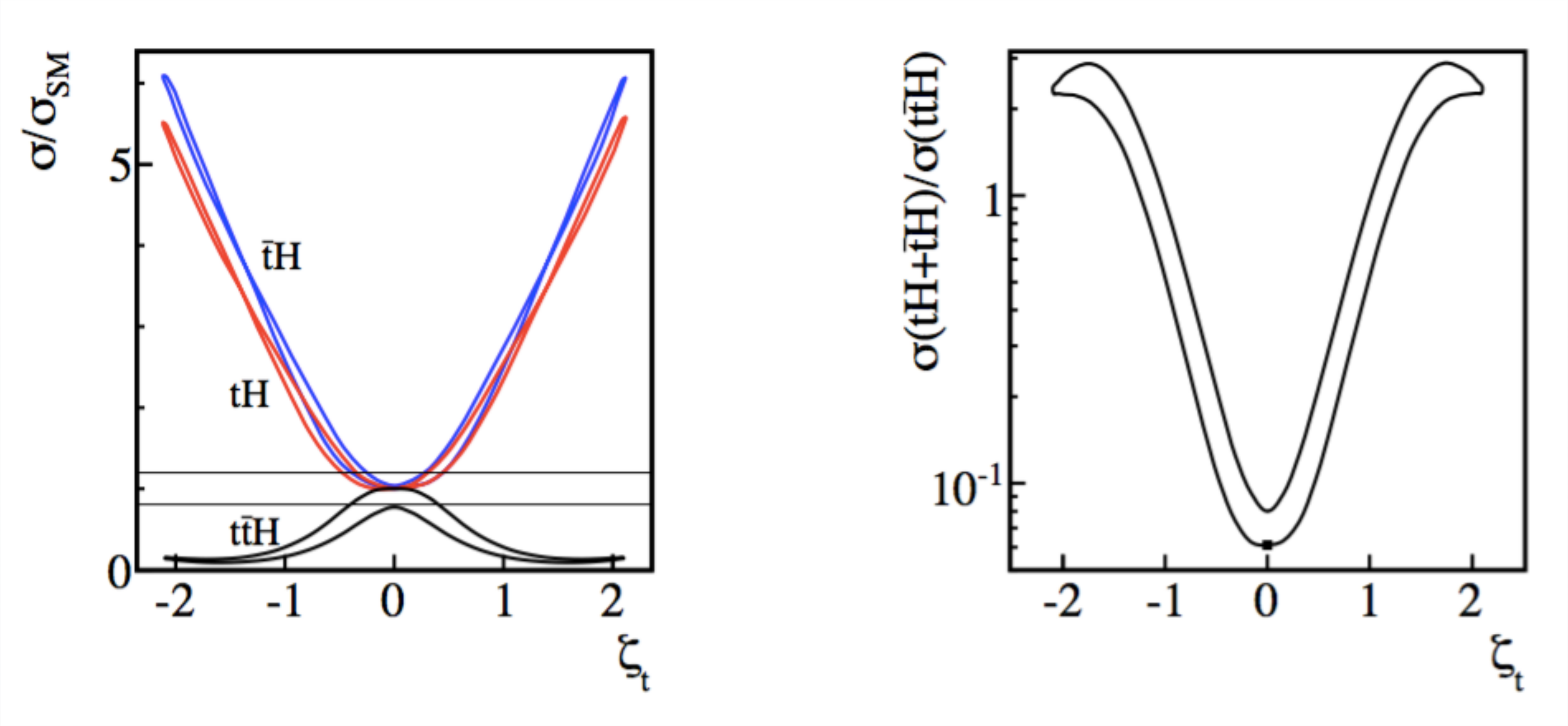
All Higgs results

JHEP04 (2014) 004

JHEP 1311 (2013) 180

y_t and CP violation





JHEP04 (2014) 004

Direct CP measurement of y_t

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$

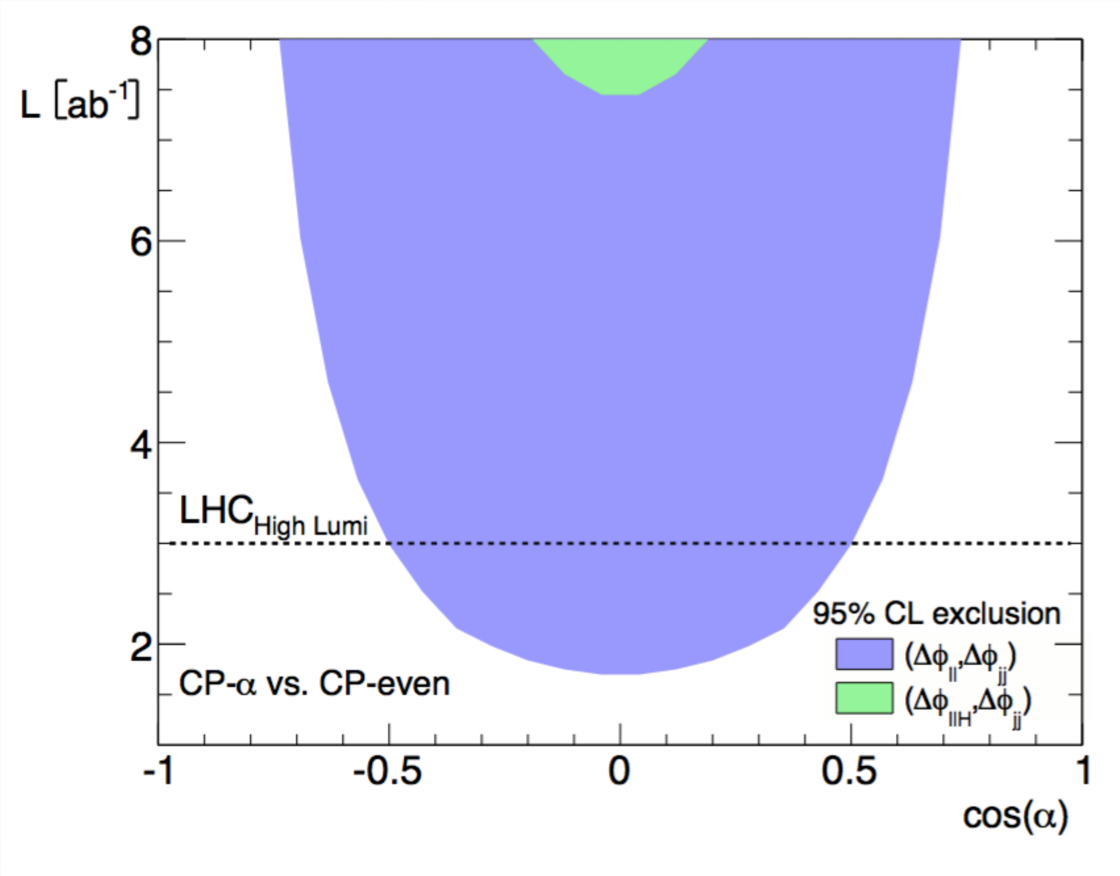
Real number

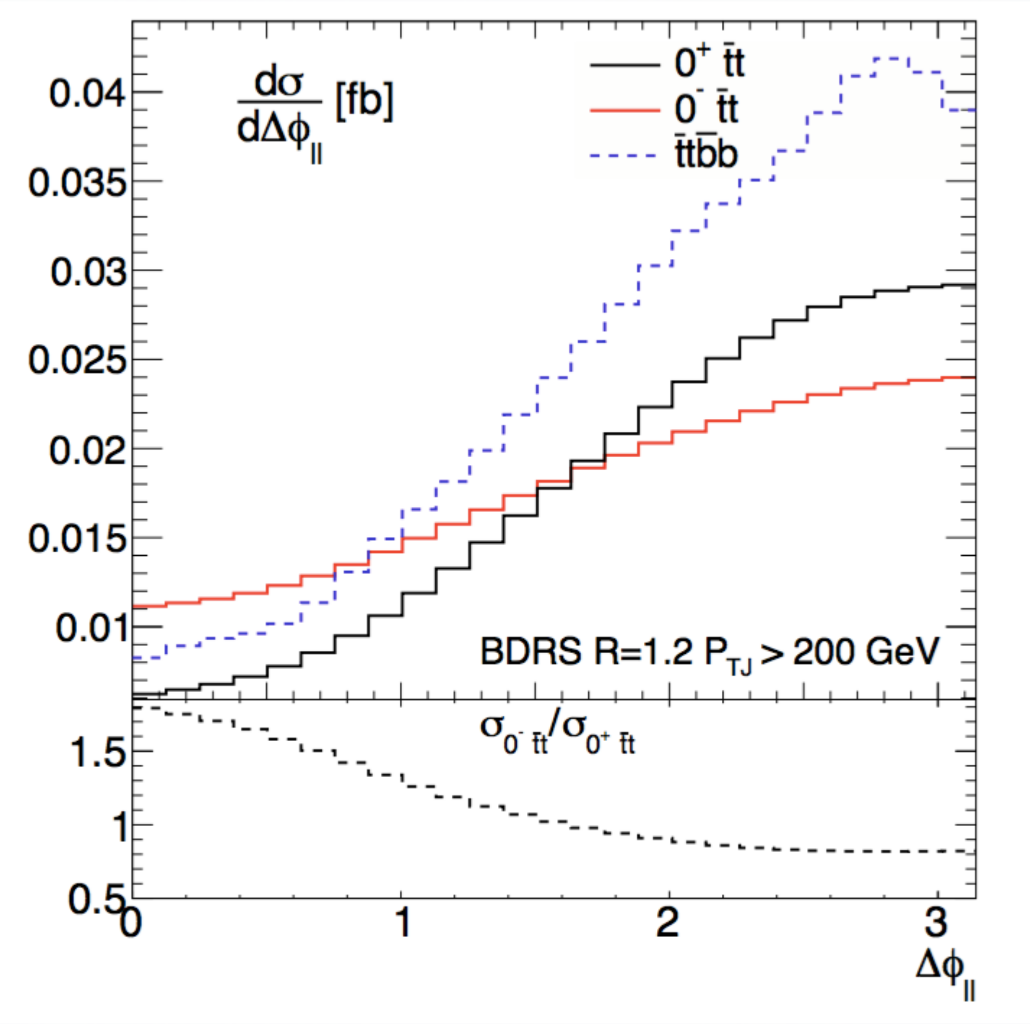
CP-phase

CP-even SM Higgs 0^+ ($K=1, \alpha=0$)

CP-odd SM Higgs 0^- ($K=1, \alpha=\pi/2$)

- Probe CP of y_t in ttH dilepton events
- Sensitive to $\Delta\phi_{\ell\ell}$
- Even more pronounced in **boosted regime**



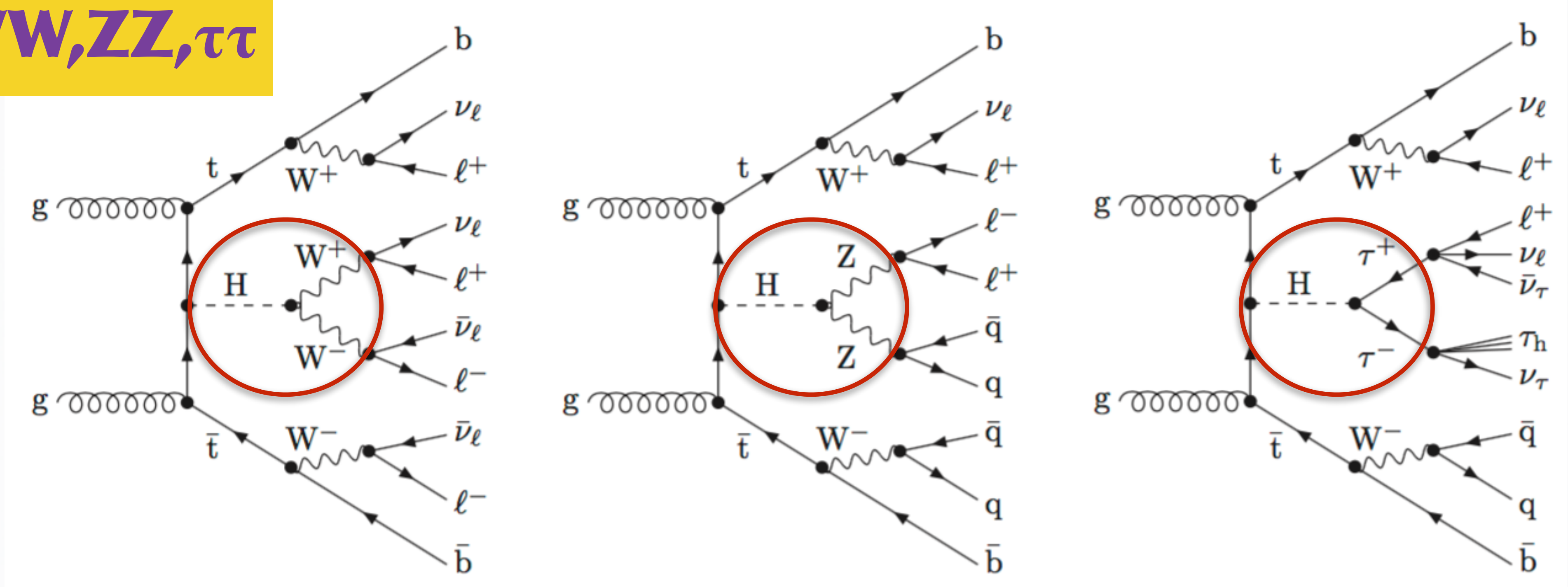


Phys. Rev. Lett. 116, 091801 (2016)

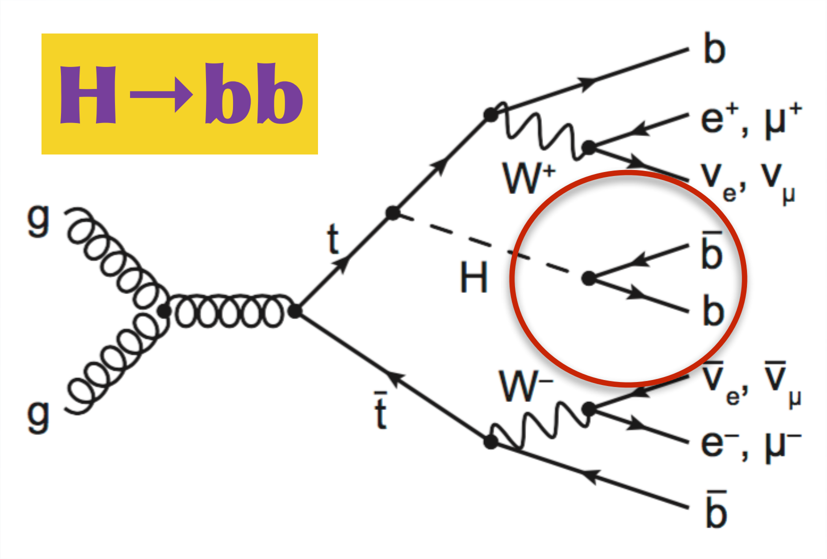
ttH

Golden process to directly probe y_t but a very complex final state !

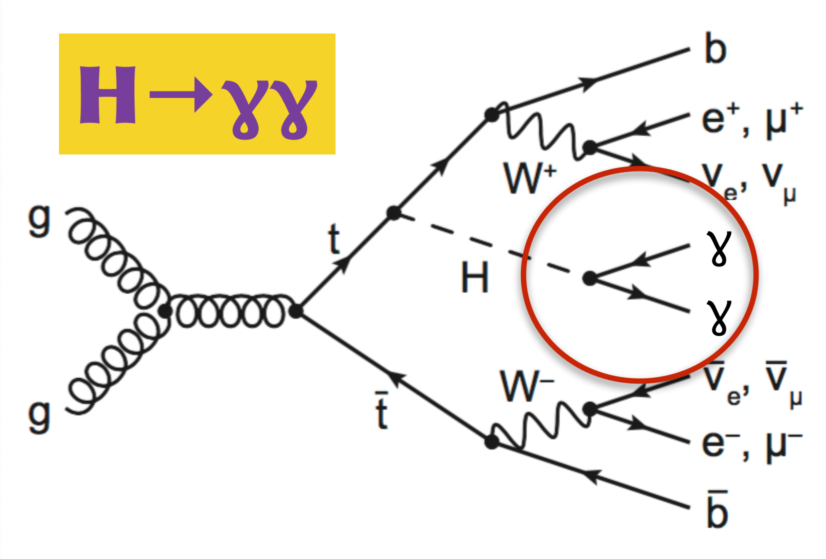
H→WW,ZZ,ττ



H→bb

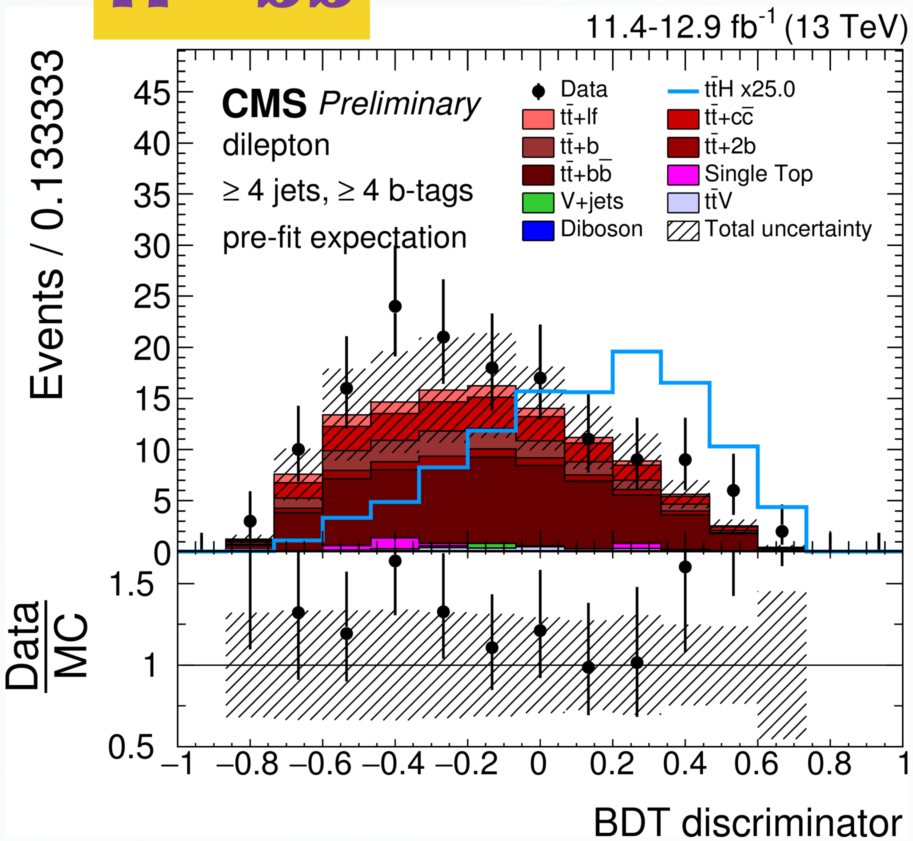


H→γγ



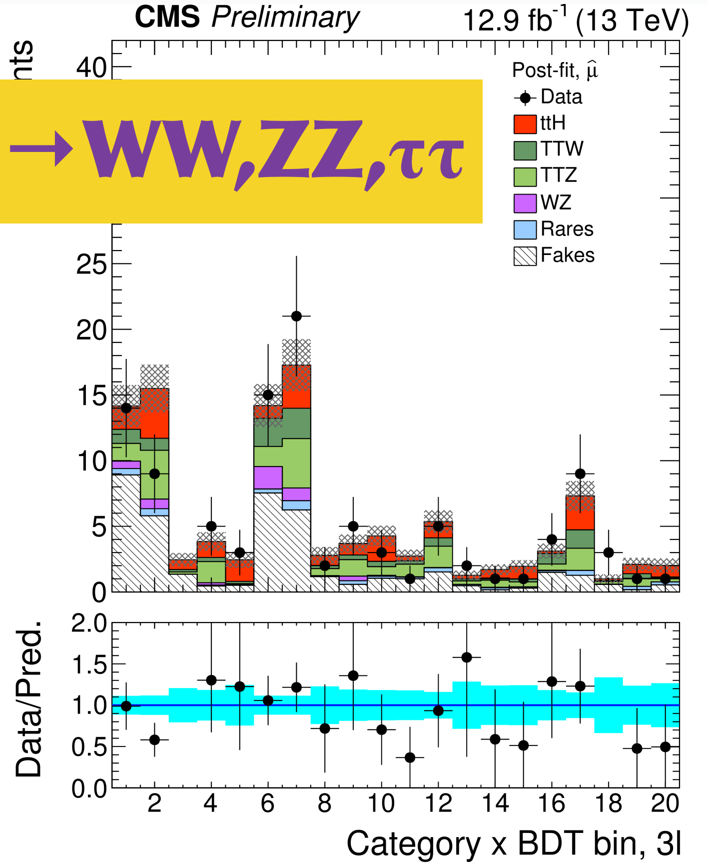
ttH search results

H→bb



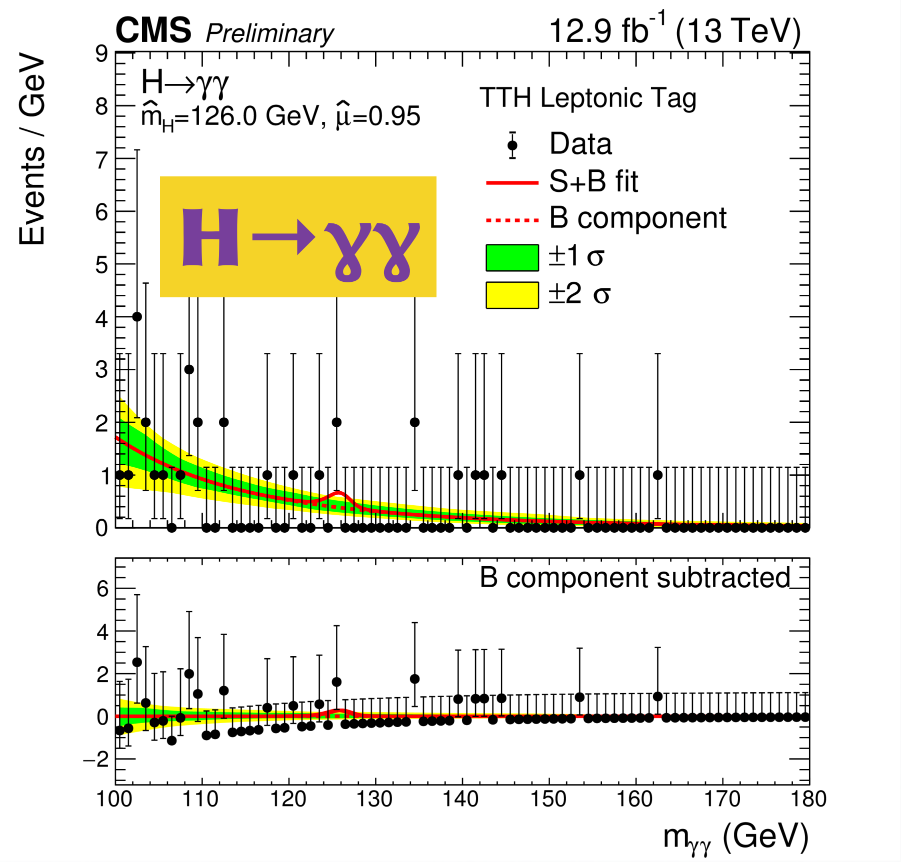
CMS-PAS-HIG-16-038

H→WW,ZZ,ττ



CMS-PAS-HIG-16-022

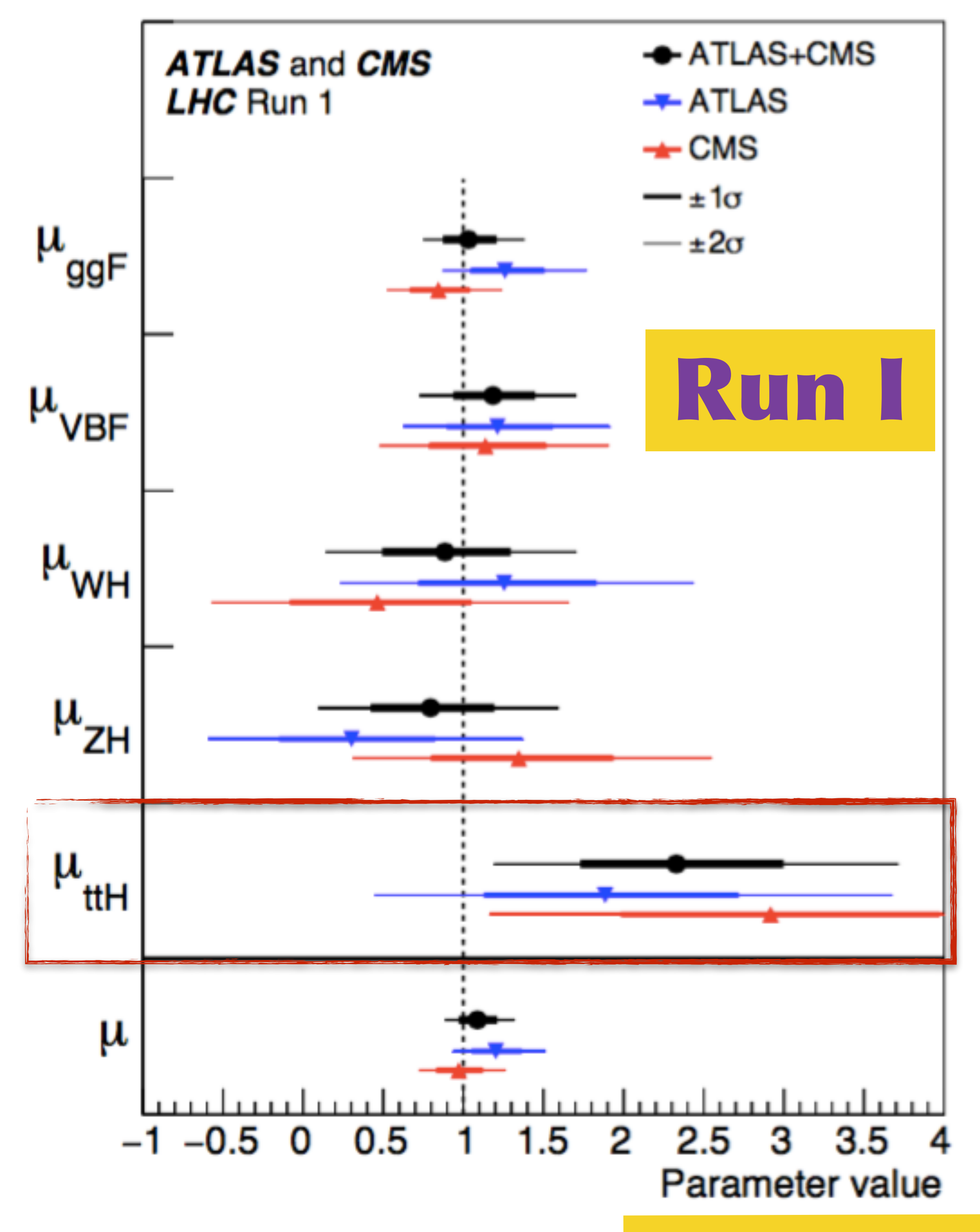
H→γγ



CMS-PAS-HIG-16-020

ttH search results

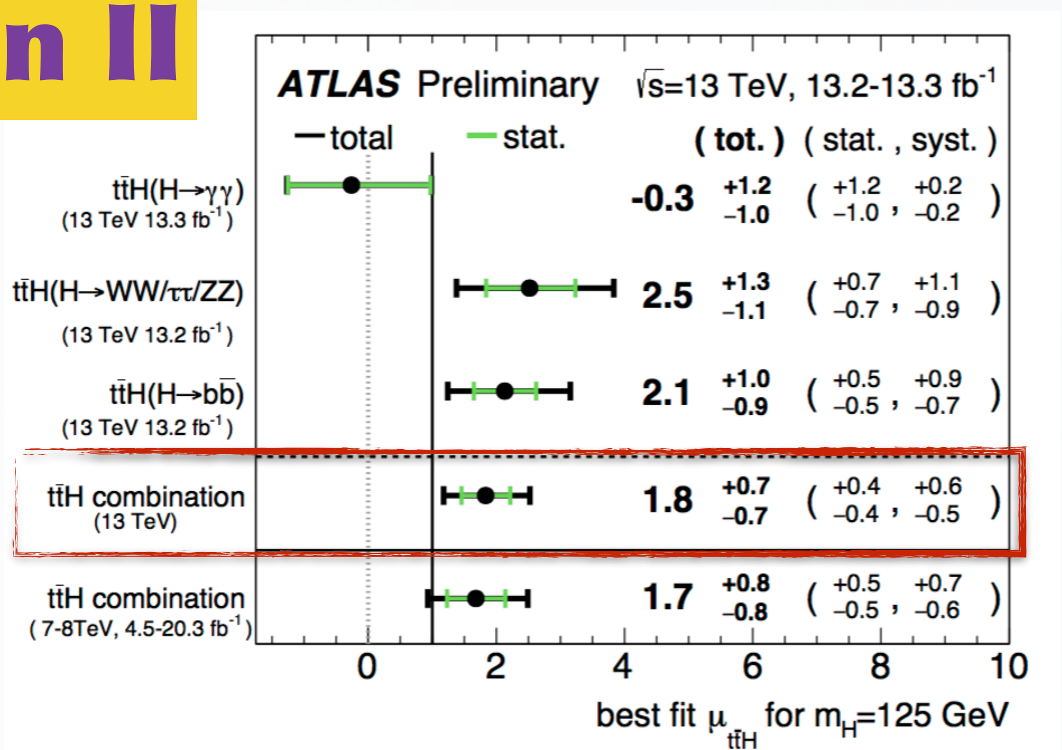
JHEP08 (2016) 045



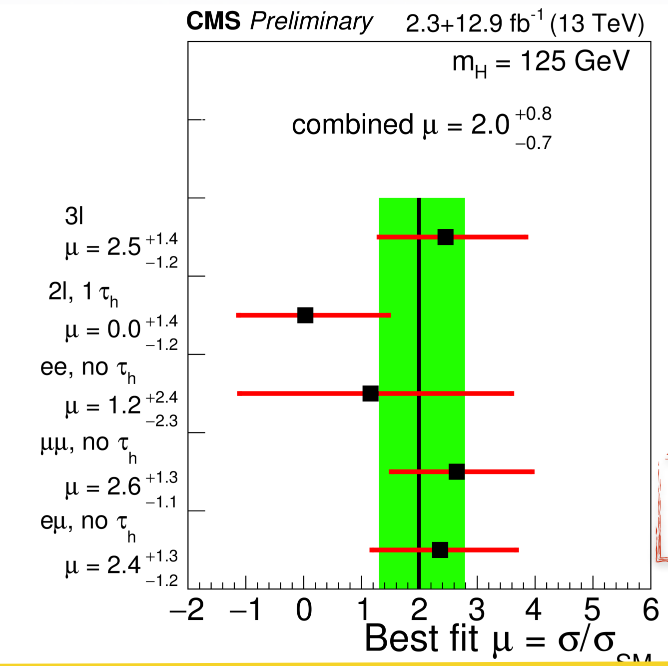
Run I

ATLAS-CONF-2016-068

Run II



CMS-PAS-HIG-16-022



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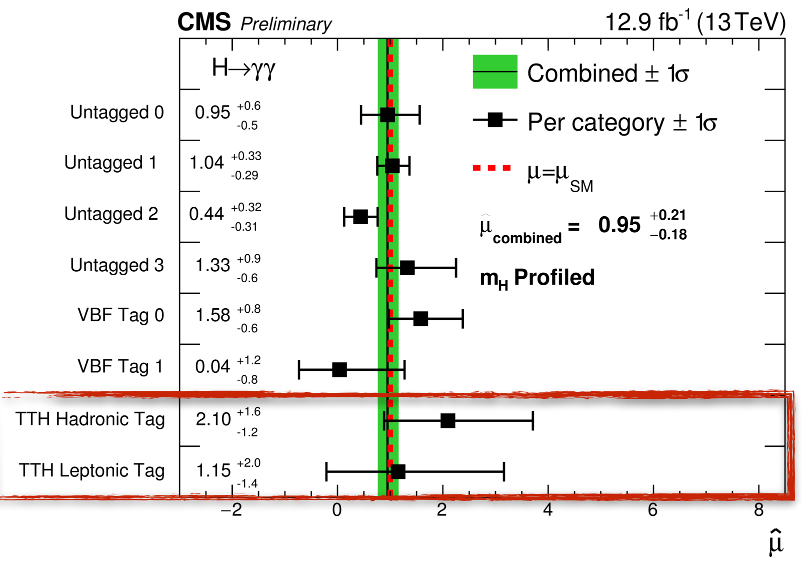
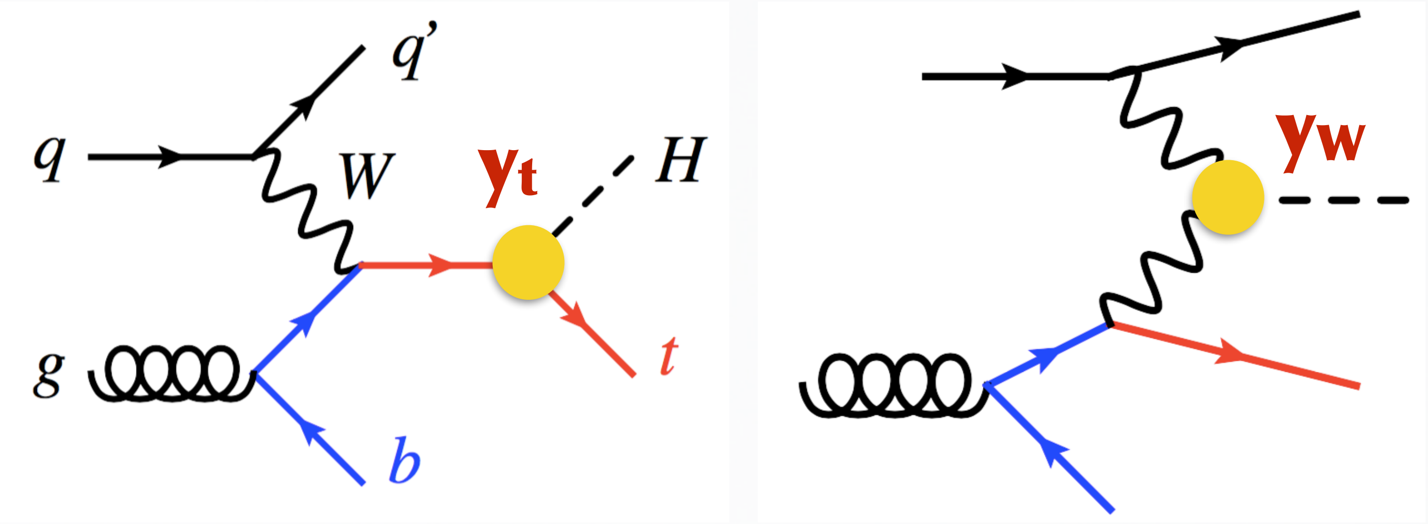


Evidence for ttH reported yesterday at Moriond !

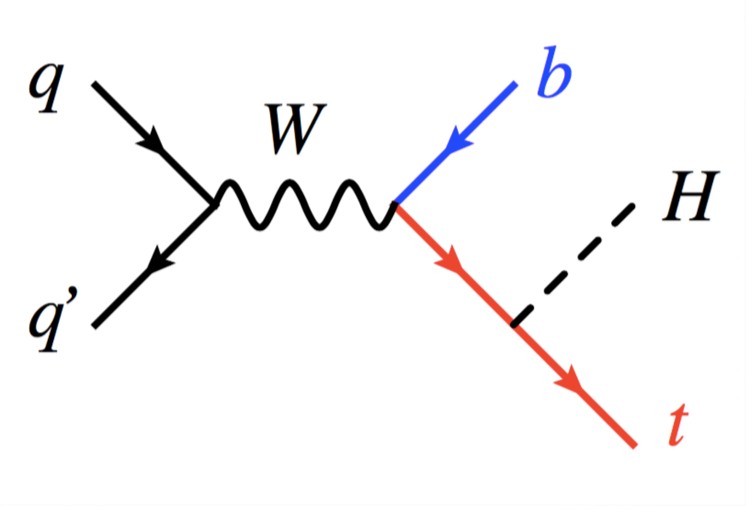
tHq

- Suppressed in SM by destructive interference: $y_t \cdot y_W < 0$
- **tHq is sensitive to both magnitude and sign of y_t**
- BSM can be looked for by probing **negative y_t** still allowed from global fits
- 15x increase in tHq cross section assuming inverted coupling scenario, $y_t = -1$

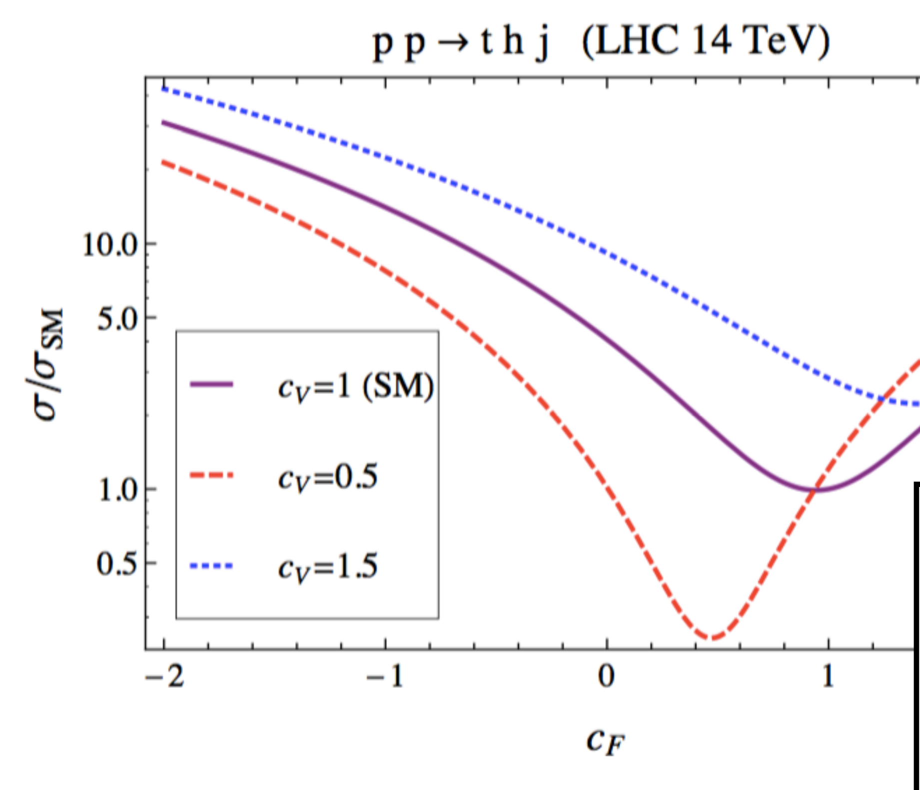
t channel

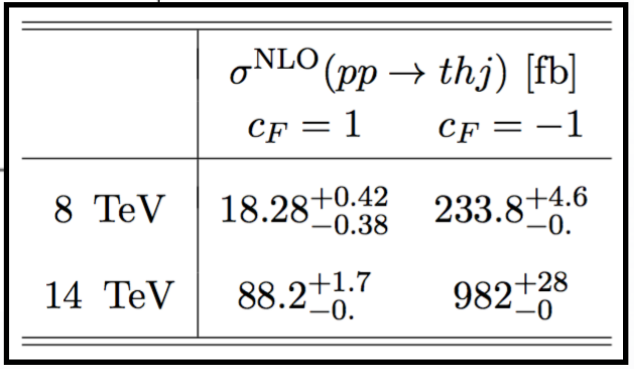


s channel



Eur. Phys. J. C (2015) 75: 267

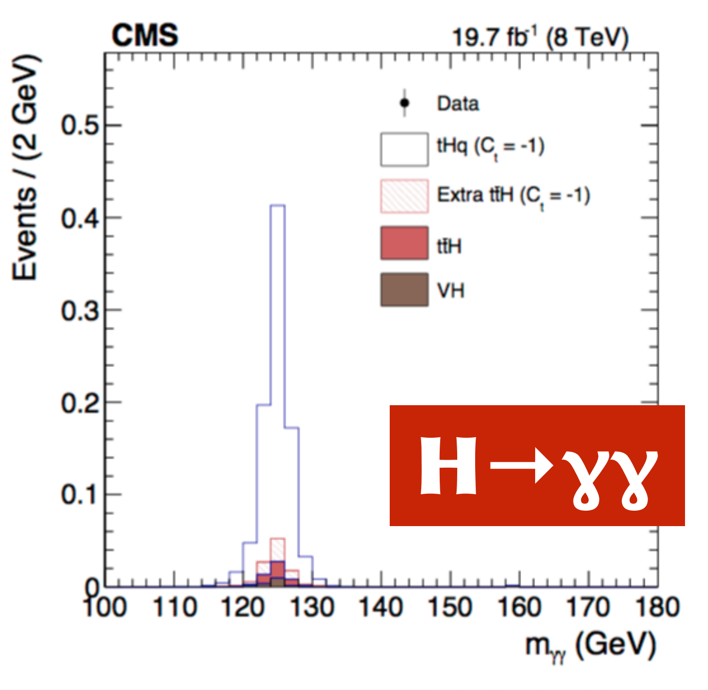




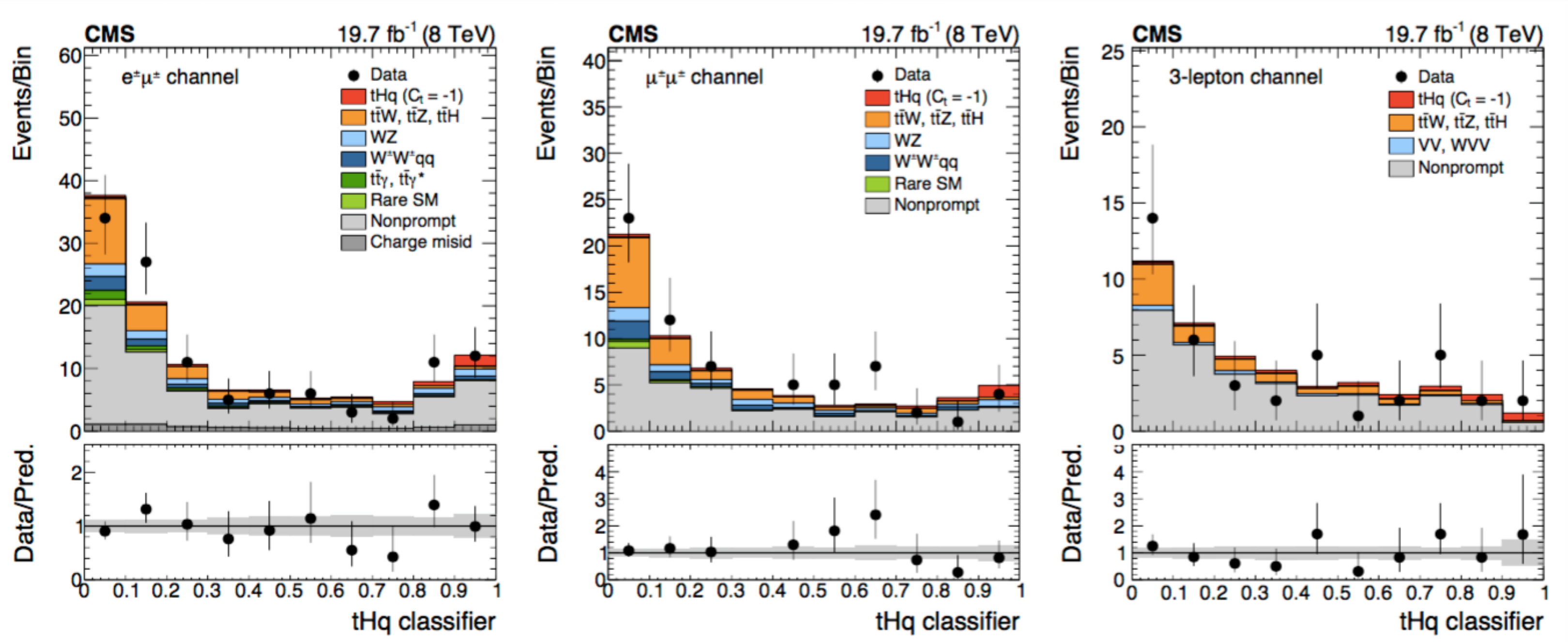
	$\sigma^{\mathrm{NLO}}(pp \to thj)$ [fb]	
	$c_F = 1$	$c_F = -1$
8 TeV	$18.28^{+0.42}_{-0.38}$	$233.8^{+4.6}_{-0.}$
14 TeV	$88.2^{+1.7}_{-0.}$	982^{+28}_{-0}

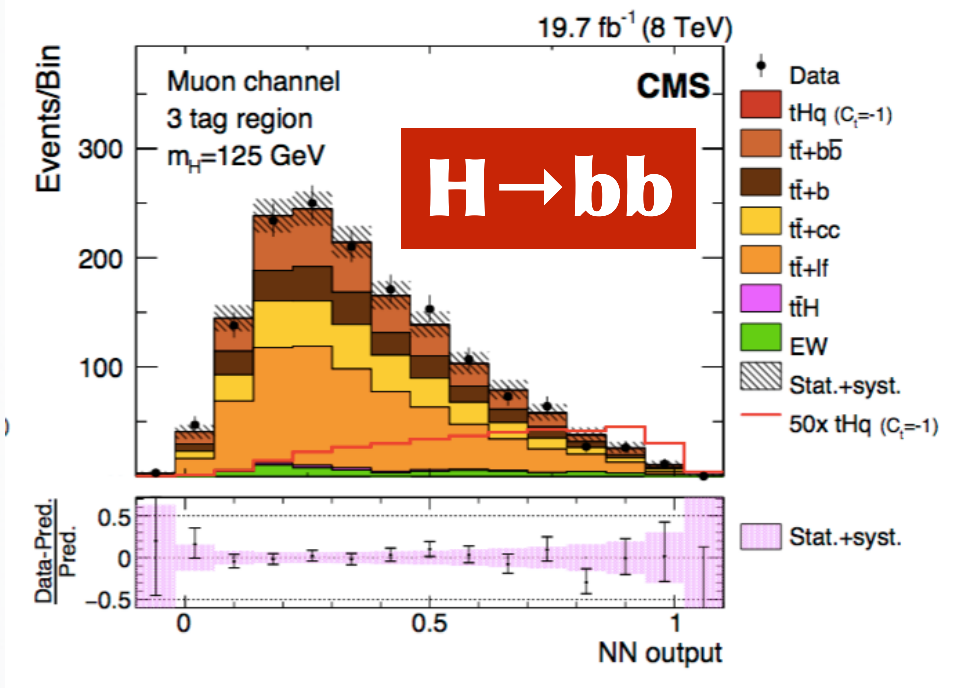
J. High Energ. Phys. (2013) 2013: 22

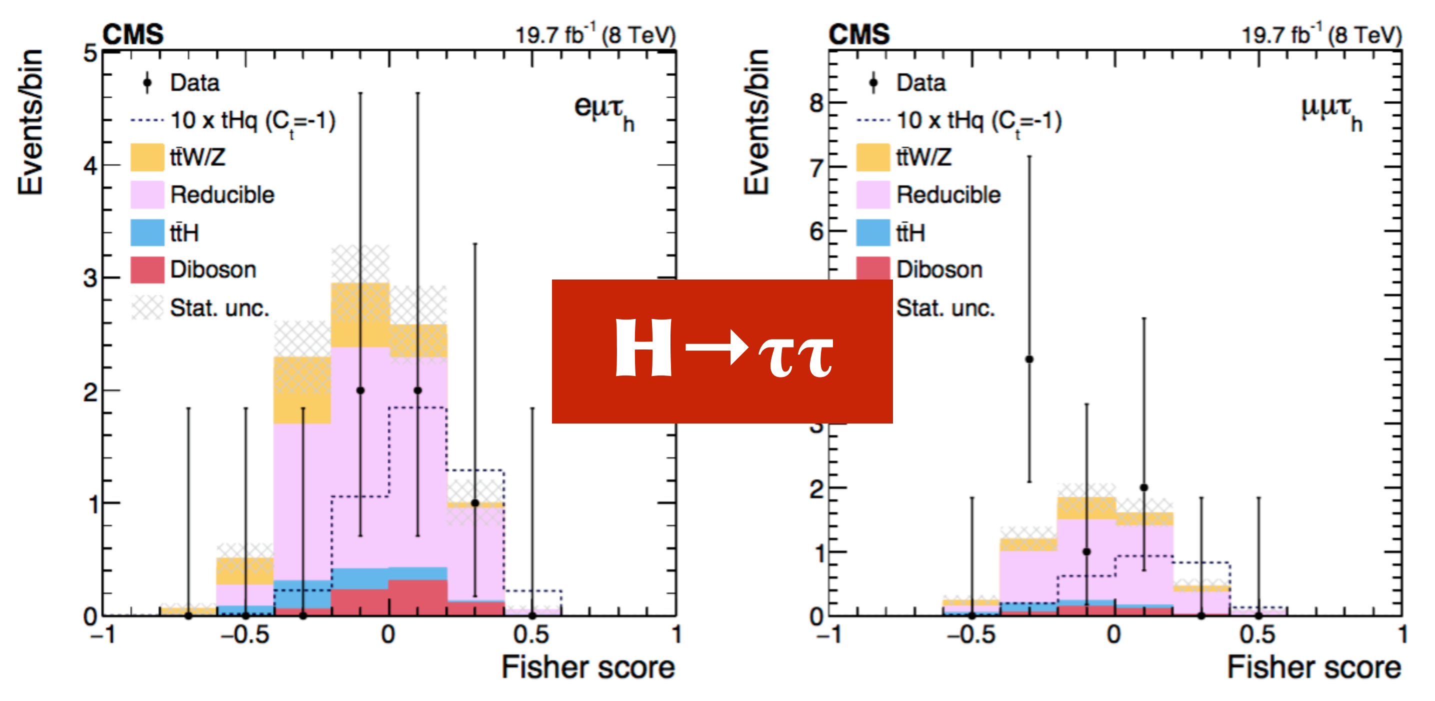
tHq search results


H→γγ

H→WW

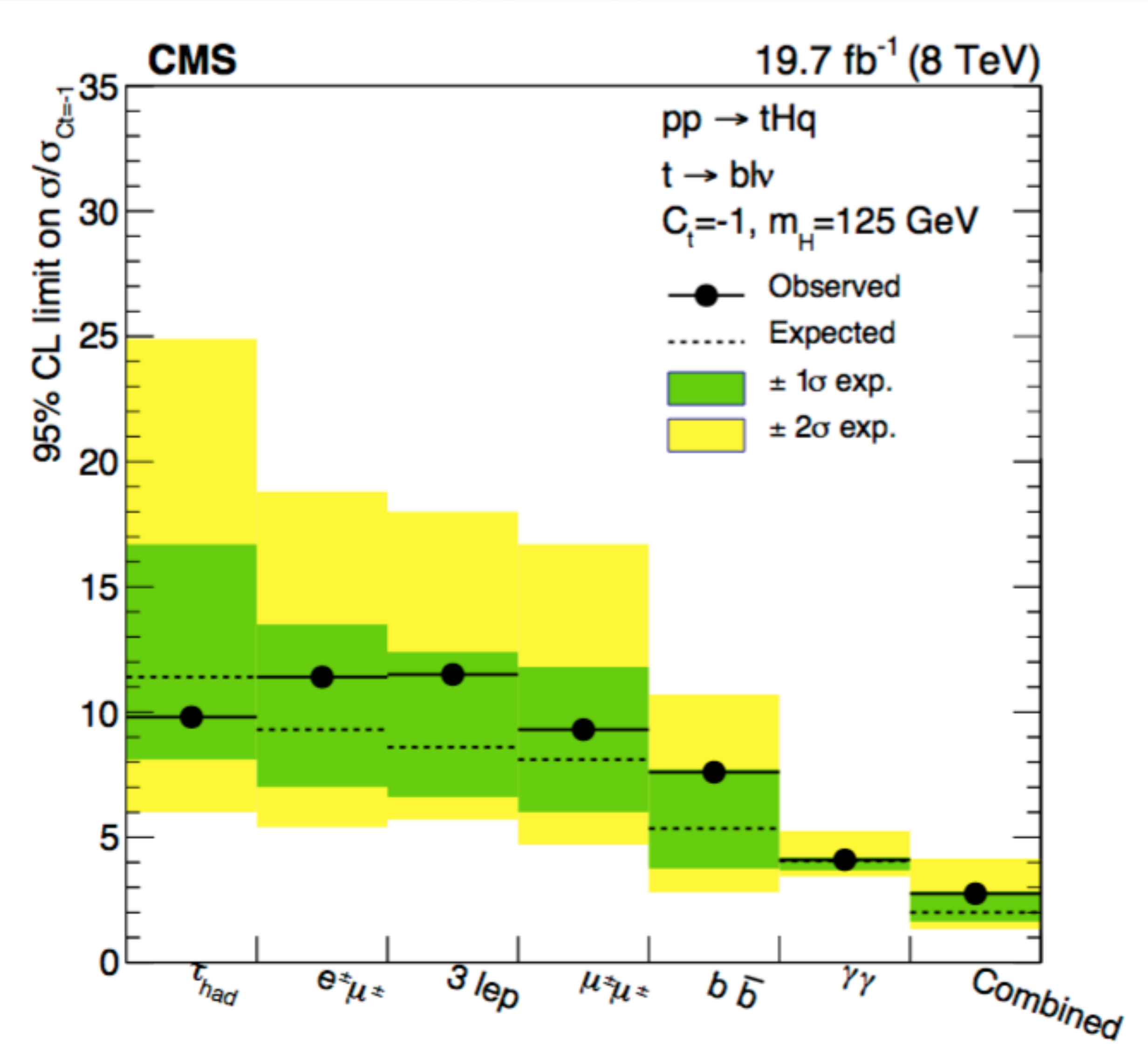


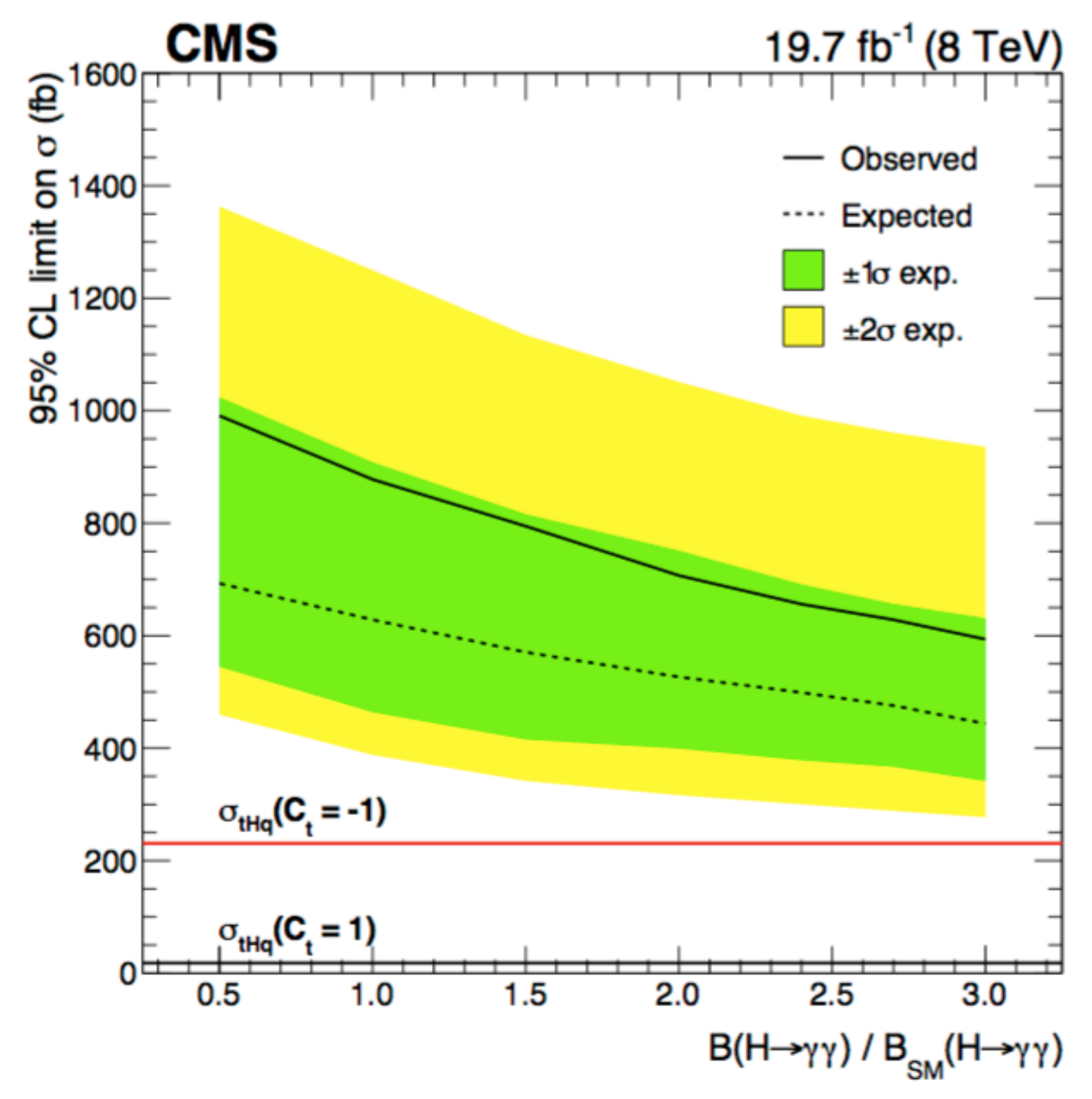

H→bb


H→ττ

JHEP06 (2016) 177

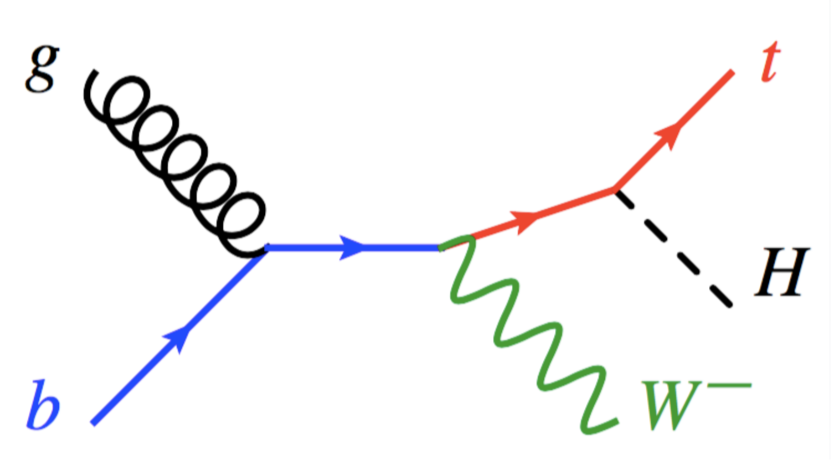
tHq search results

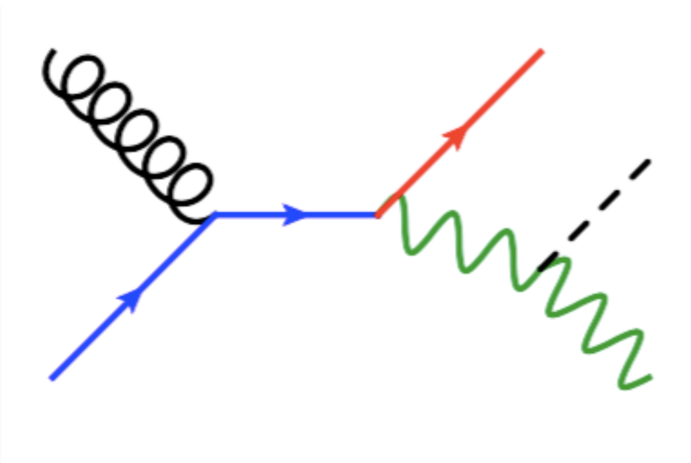




JHEP06 (2016) 177

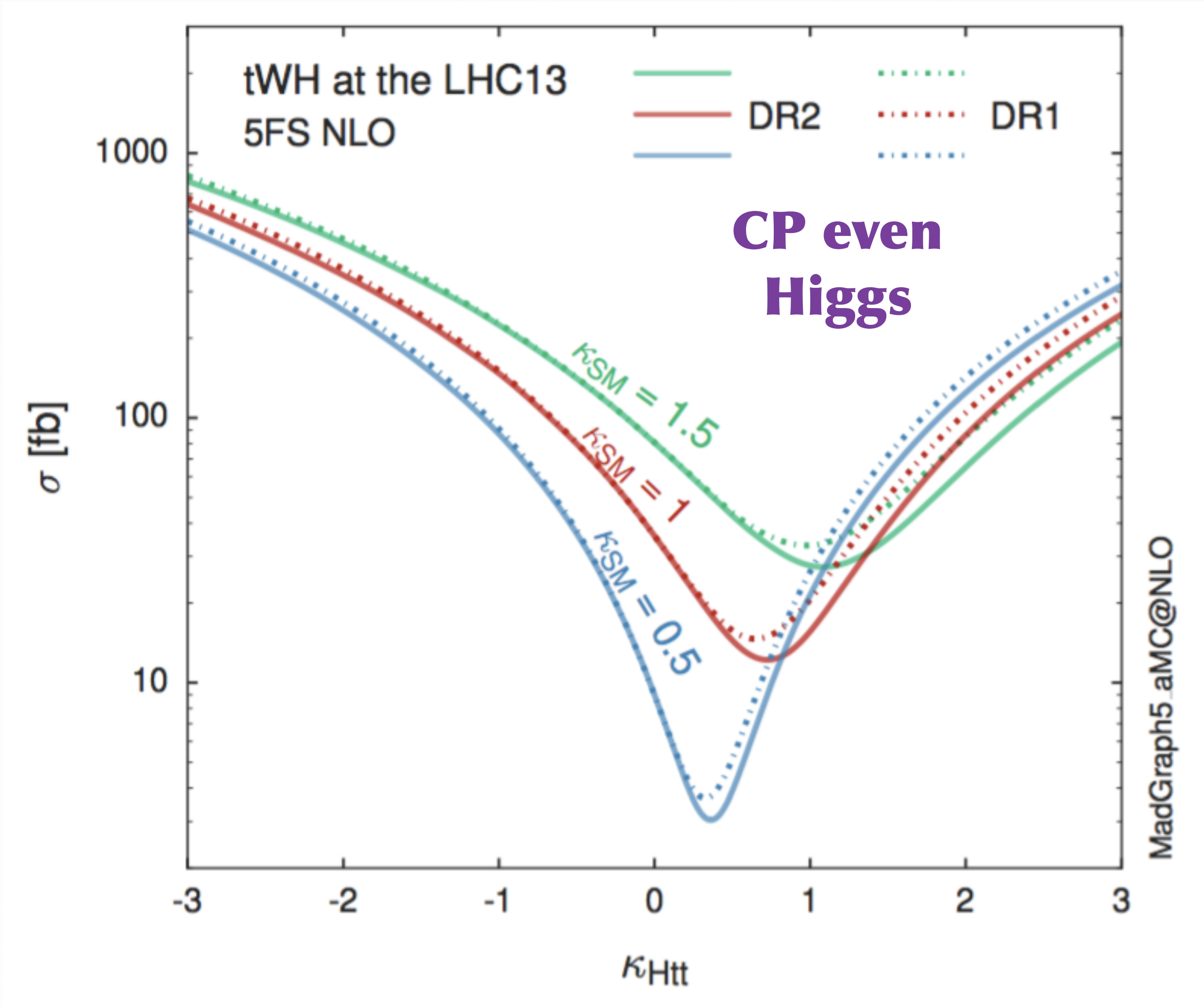
tHW





- As tHq, suppressed in SM by destructive interference: $\mathbf{y_t \cdot y_W < 0}$
- **Sensitive to both magnitude and sign of y_t**
- Significant increase in tHW cross section (up to 50x) in some phase space of (y_t, y_W)

No experimental results yet



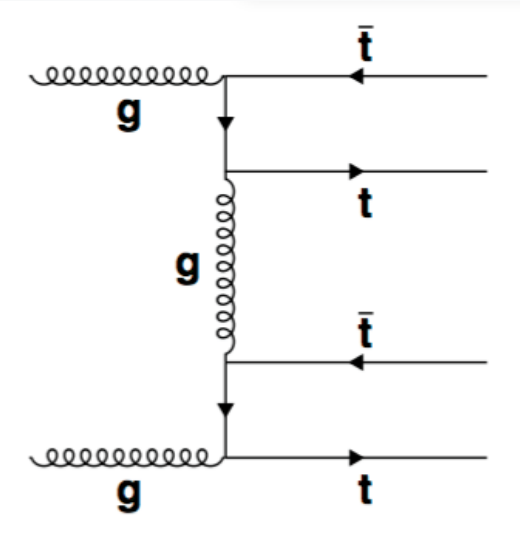
CP even **CP odd**

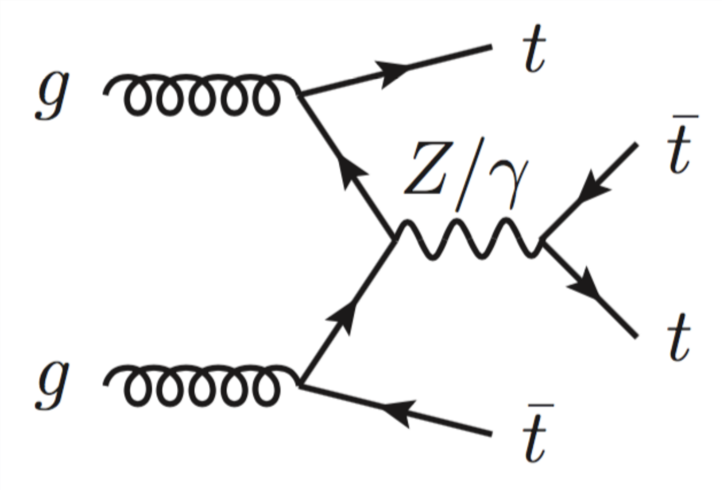
$$\mathcal{L}_0^t = -\bar{\psi}_t \left(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\, \gamma_5\right) \psi_t\, X_0$$

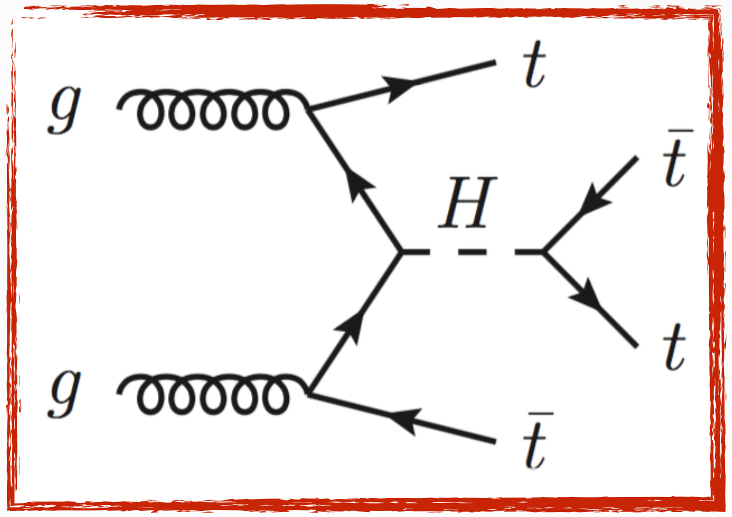
$$\mathcal{L}_0^V = \kappa_{\rm SM}\left(\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\right) X_0$$

Eur. Phys. J. C (2017) 77: 34

Indirect probe of y_t in four tops

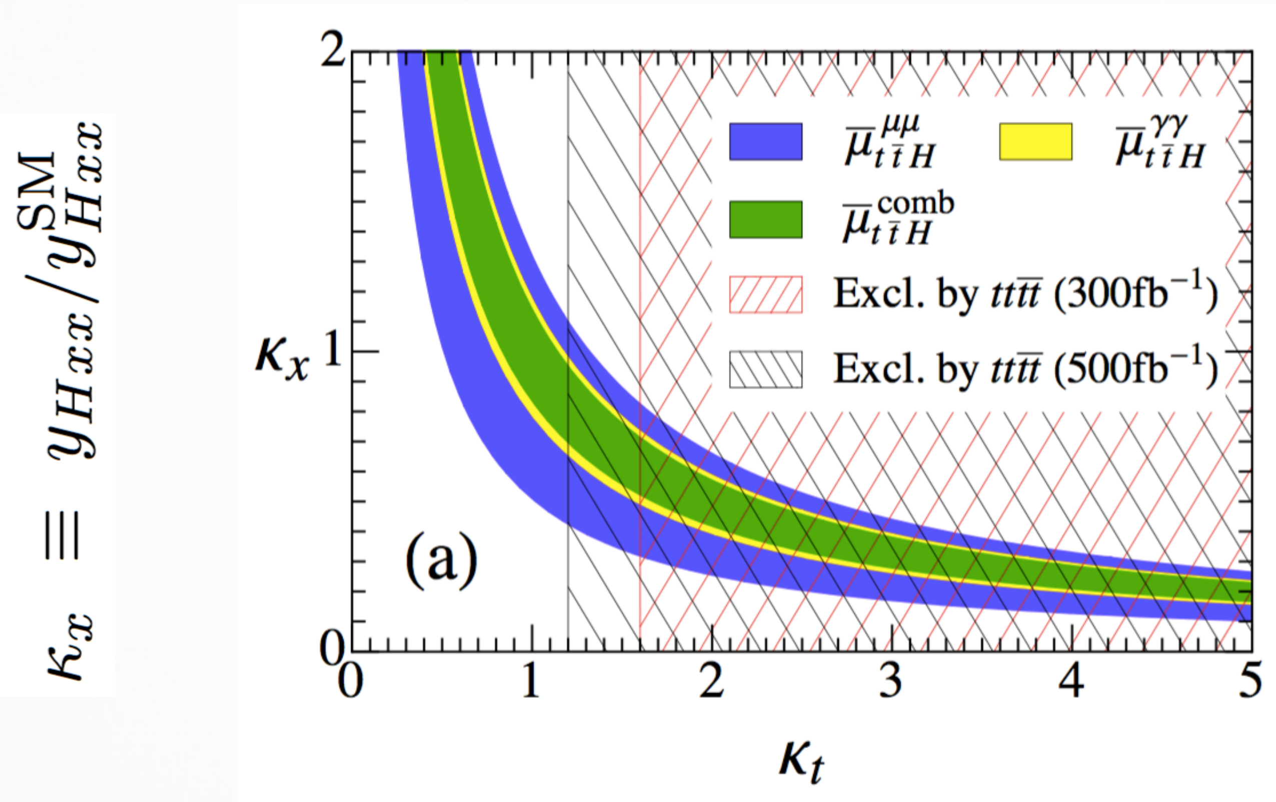






$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2\sigma^{\mathrm{SM}}_{\mathrm{int}} + \kappa_t^4\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$$

arXiv:1602.01934



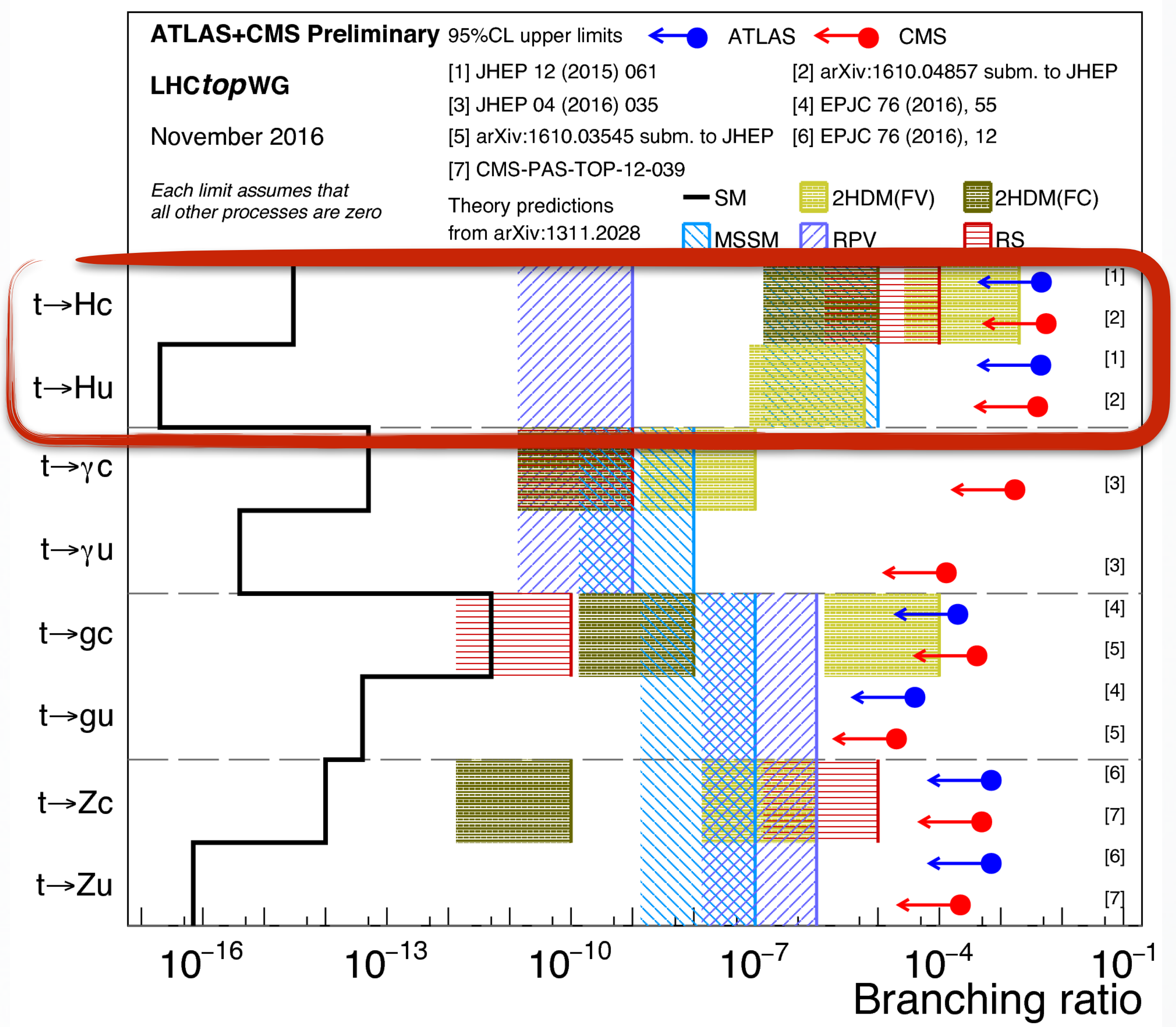
	8 TeV	14 TeV
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.193 fb,	12.390 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$:	0.166 fb,	1.477 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{\mathrm{int}}$:	−0.229 fb,	−2.060 fb.

LHC data results @8TeV:

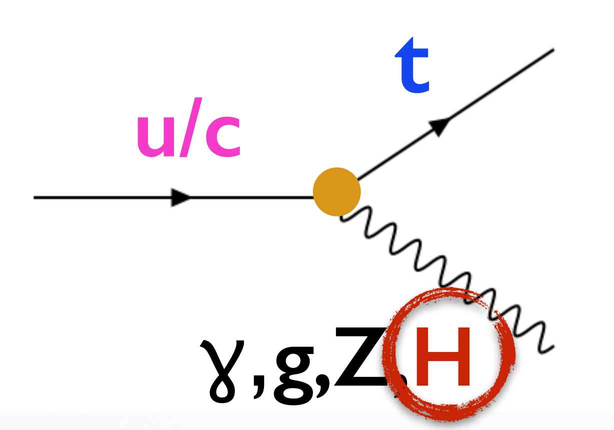
$\sigma(t\bar{t}t\bar{t}) \leq 23\ \mathrm{fb} \longrightarrow \kappa_t \leq 3.49$

When flavours change but charge remains the same

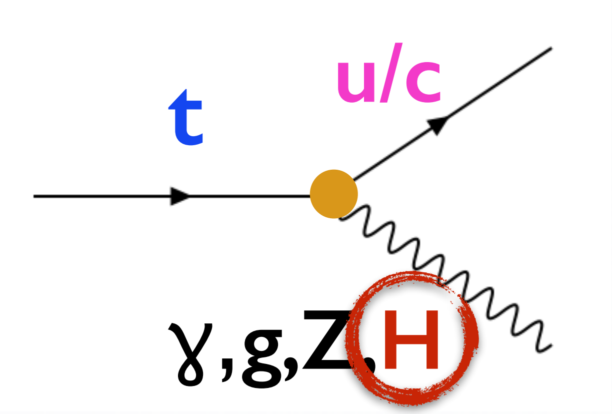
- Flavour-changing neutral currents (FCNC) suppressed at tree level in SM by GIM mechanism
- Could be significantly enhanced in BSM
- Direct probe of anomalous y_t



FCNC in production

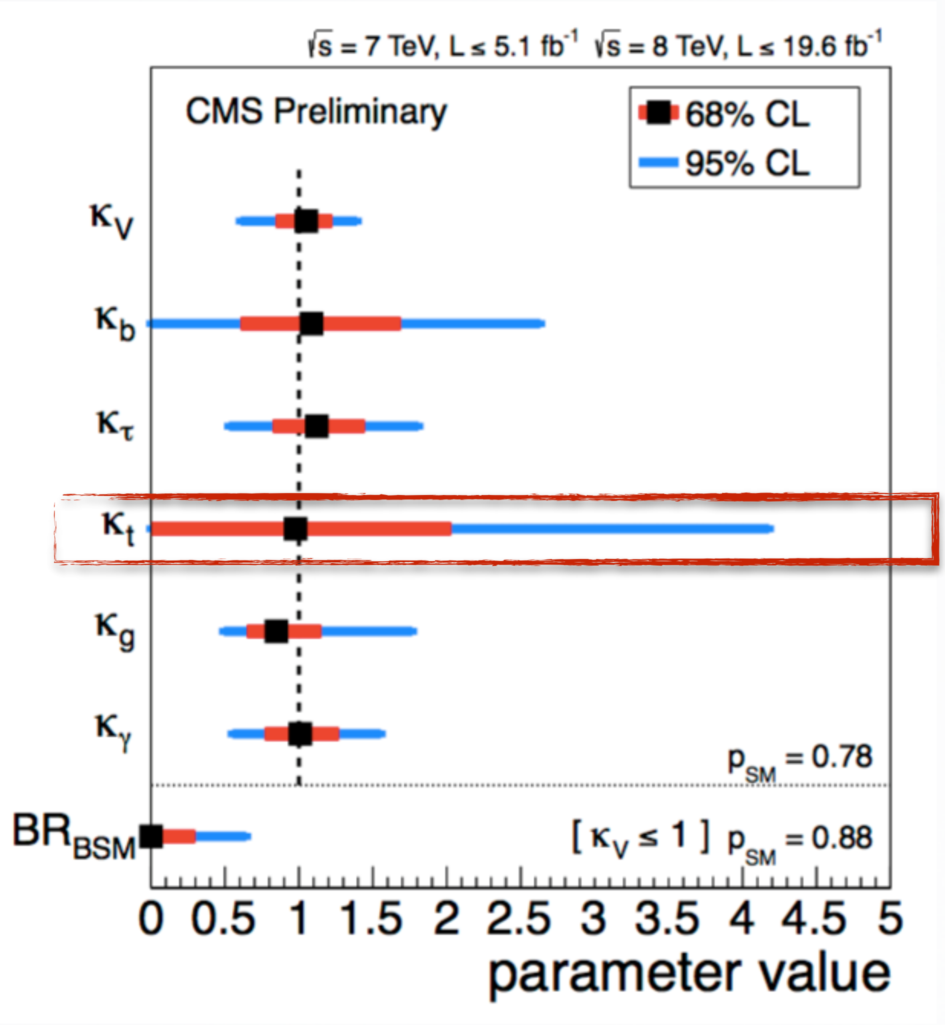


FCNC in decay



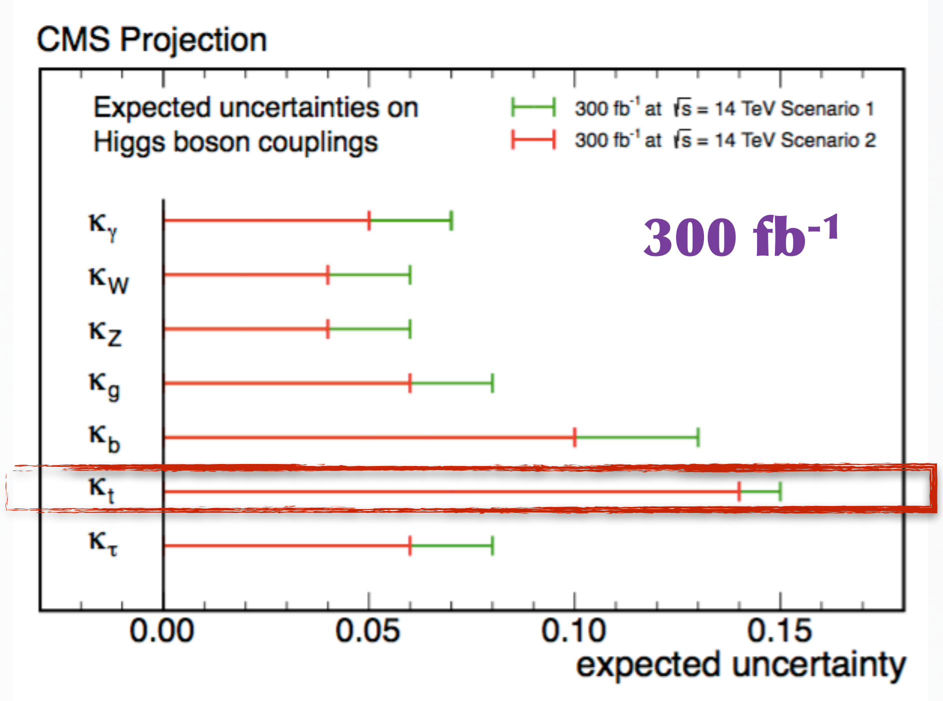
From LHC to HL-LHC

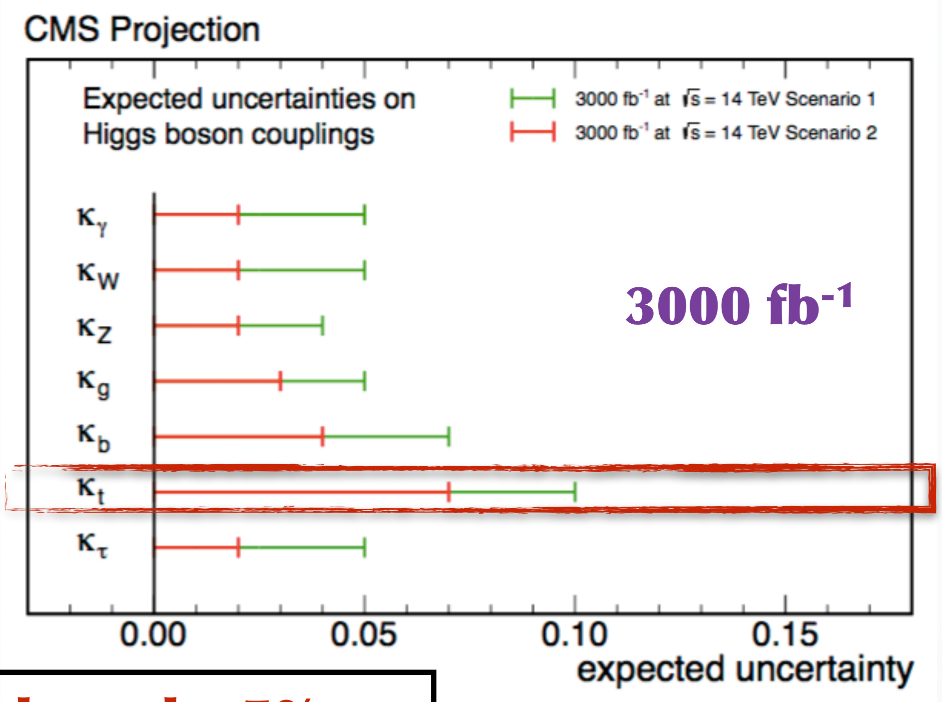
LHC **Global data fit results**



arXiv:1307.7135

HL-LHC **Projection**





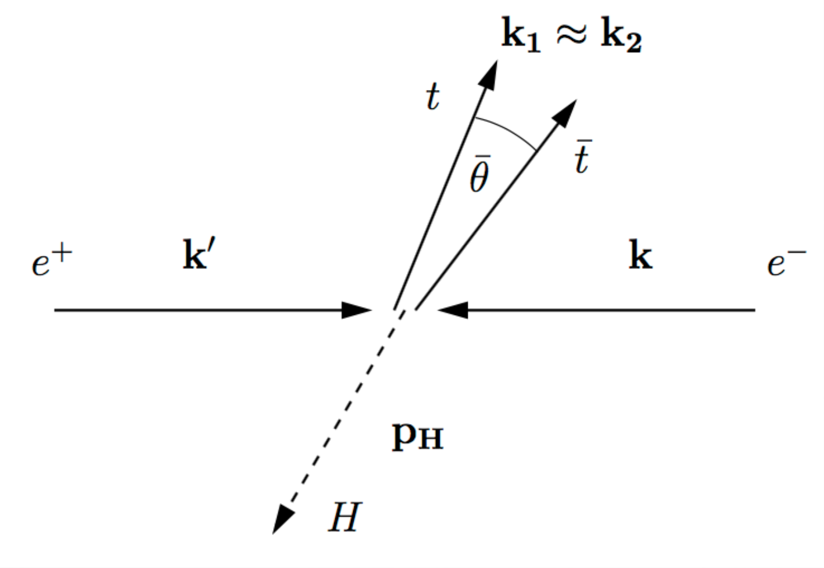
- ***Scenario 1***: systematics unchanged
- ***Scenario 2***: scale theoretical uncertainties by 1/2, others are scaled by IL

Could reach ≈5% uncertainty in y_t !

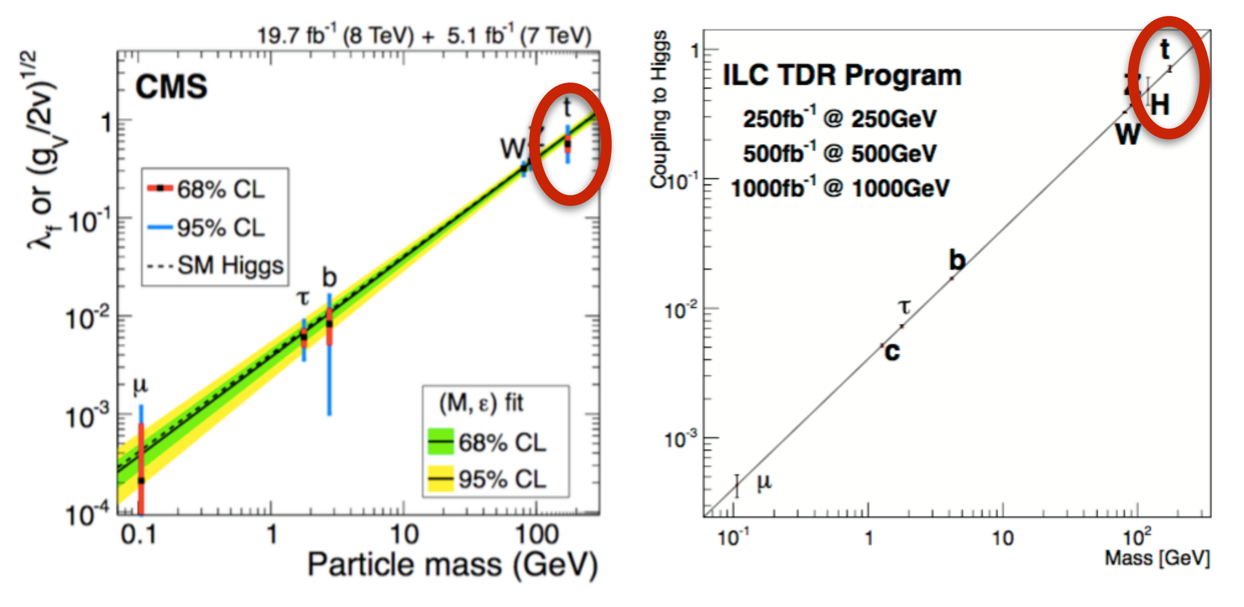
Study of y_t at future colliders

@ILC/CLIC

$e^+e^- \to Z/\gamma^* \to ttH$ arXiv:0604166



arXiv:1506.05992



@100TeV

		$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$m_t = 174.1$ GeV	0.3640	0.5307	0.6860
	$m_t = 172.5$ GeV	0.3707	0.5454	0.6800
100 TeV	$m_t = 174.1$ GeV	23.88	37.99	0.629
	$m_t = 172.5$ GeV	24.21	38.73	0.625

arXiv:1507.08169

Collider	HL-LHC	ILC	LC 1-3 TeV	FCC-ee+hh
λ_t	4%	14%	2 – 4%	1 – 2%
λ_H	50%	83%	10 – 15%	5 – 10%

arXiv:1510.09056

Expected precision in y_t determination

Conclusion

- We live in a beautiful metastable world
- Top quark Yukawa coupling might be a portal to other worlds with new physics
- Experimental studies of this vital fundamental parameter in SM have just begun
- A broad range of analyses in the top-Higgs sector is being performed by the LHC experiments
- Very good prospects for y_t determination at future colliders !