Disentangling degeneracy in modified Higgs couplings at LHC

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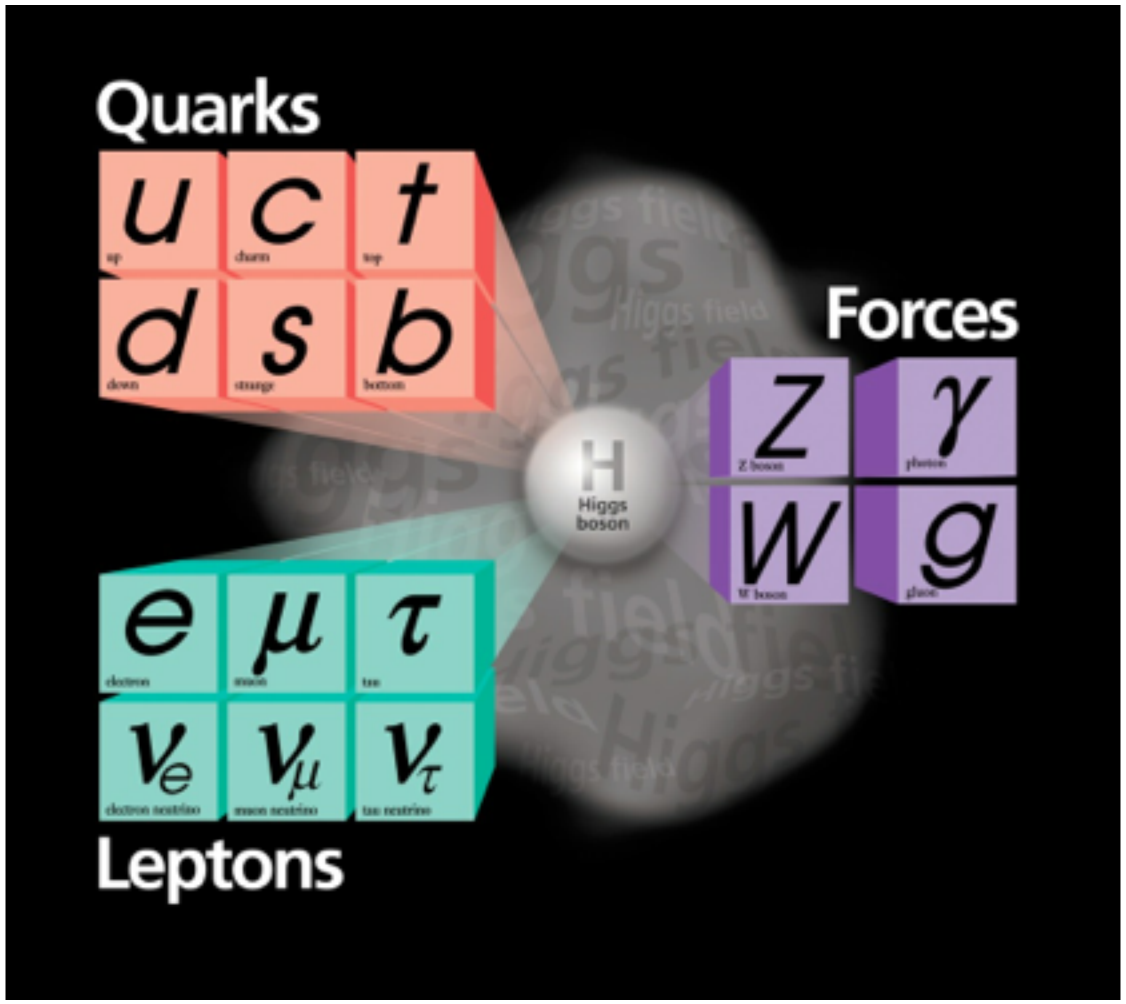
2015. 6. 24 Kyoto U.

What is the Universe made of?



Standard Model: 12 + 4 + 1 particles

matter (12)

electromagnetism
strong force
weak force (4)

origin of mass (1)

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.$$
$$+ \bar{\psi}_i y_{ij}\psi_j\phi + h.c.$$
$$+ |D_\mu\phi|^2 - V(\phi)$$

$\alpha_1, \alpha_2, \alpha_3,\ m_i,$ mixings, $v,\ \lambda$

only 23 parameters

Higgs VEV provides all masses

Many consistent observations, no significant deviations

$m_t \sim 173$ GeV (1995) $\quad m_H \sim 125$ GeV (2012)

SM has completed! Great success.

Dark matter

However, SM explains only 4%

Rotation curve

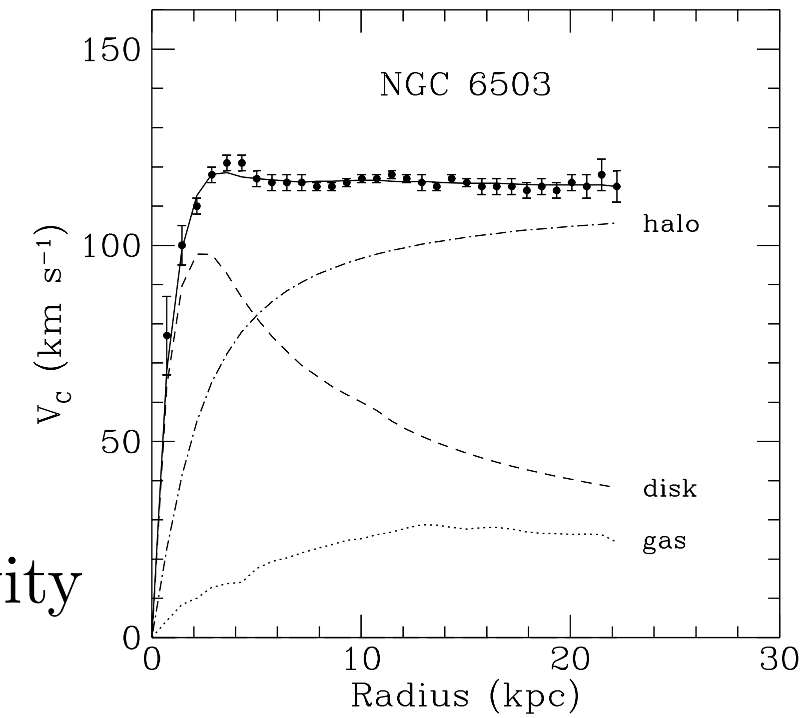
Cluster merger

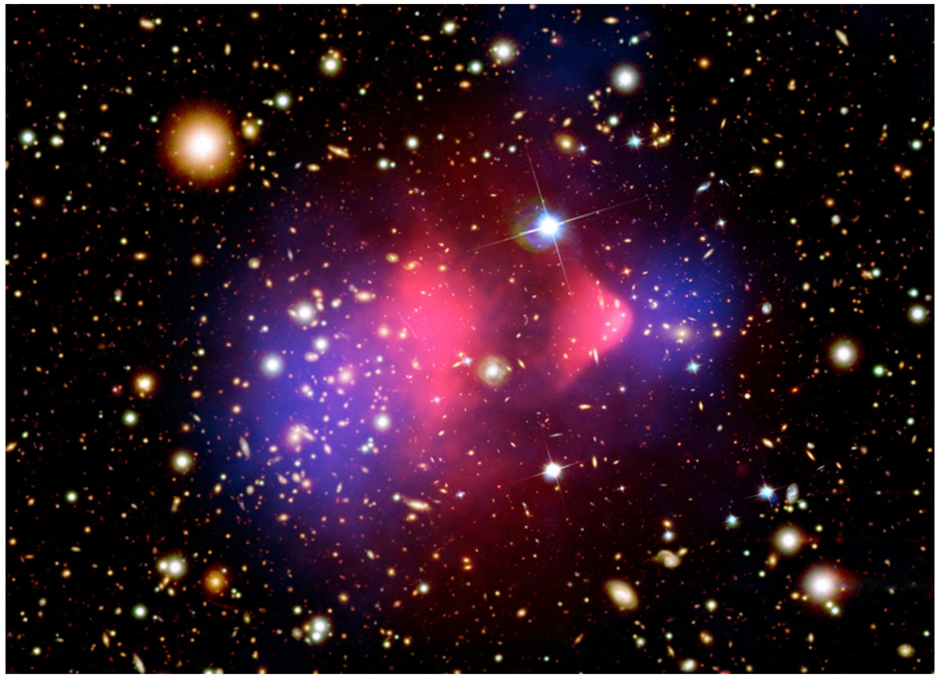
N-body simulation

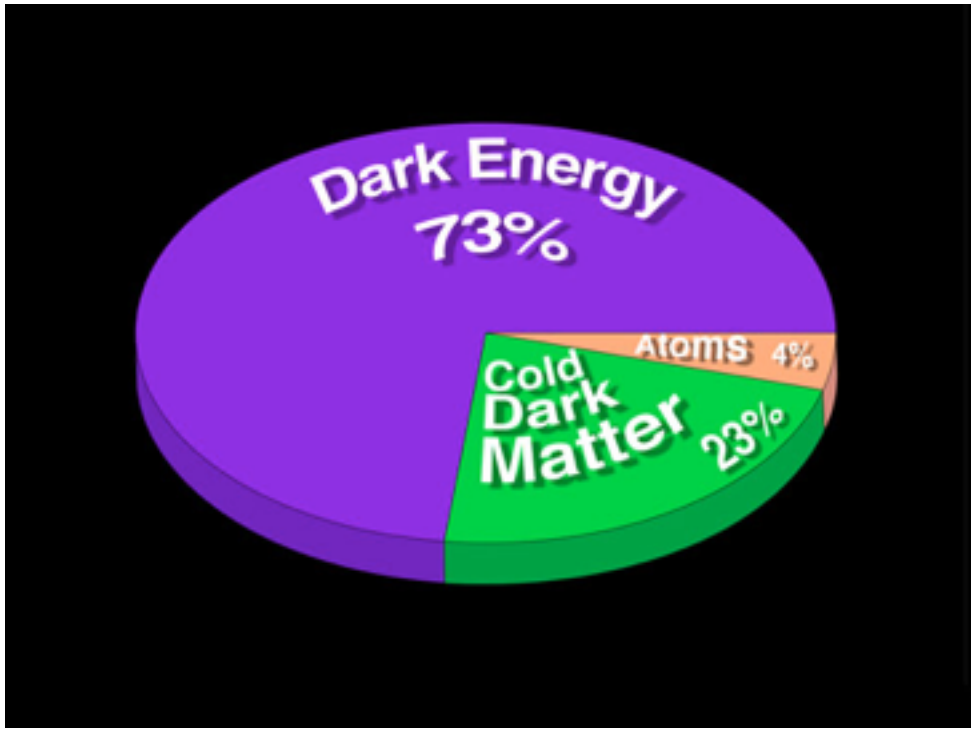
WMAP, BAO etc.

$\Omega_{\rm cdm} h^2 = 0.113$

All evidences from gravity







Obviously, SM not enough to describe Universe

– What is dark matter?

WIMP (Weakly interacting massive particle)?

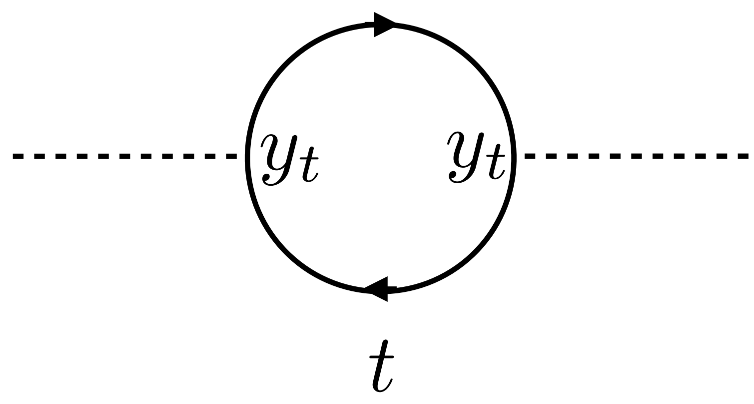
$$\Omega_\chi \sim \frac{0.1\text{pb}}{<\sigma_A v>}, \quad <\sigma_A v> \sim \frac{\alpha^2}{m_\chi^2} \sim 10^{-9}\text{GeV}^{-2},$$

$\alpha_2 \sim 1/30 \rightarrow m_\chi \sim 1$ TeV $\Rightarrow$ new particle in TeV?

Fine tuning problem

Higgs: only scalar elementary particle in the SM

$\delta m_h^2 \sim$



$$\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\rm SM}^2 \sim 10^{38}\,{\rm GeV}^2 (\Lambda_{\rm SM} = m_{\rm Pl})$$

$$\sim 10^{6}\,{\rm GeV}^2 (\Lambda_{\rm SM} = 1{\rm TeV})$$

$$m_{h,\rm phys}^2 = m_{h,\rm tree}^2 + \delta m_h^2 \qquad \sim 125^2\,{\rm GeV}^2 \sim 10^4\,{\rm GeV}^2$$

Higgs mass receives quantum corrections of the order of highest mass scale

⇨ New physics should appear around TeV scale to avoid fine tuning

Fine tuning problem

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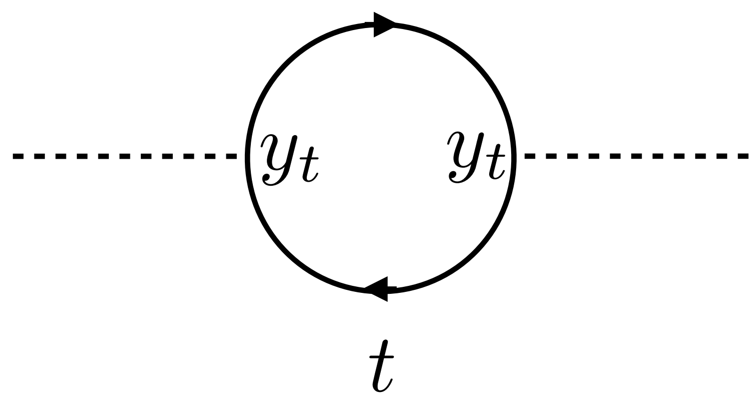

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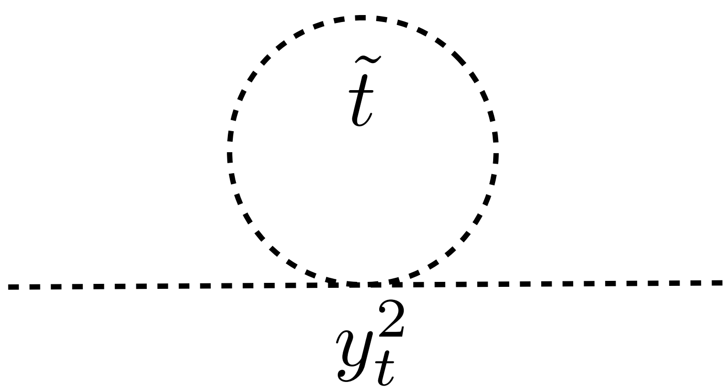


$$\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$$

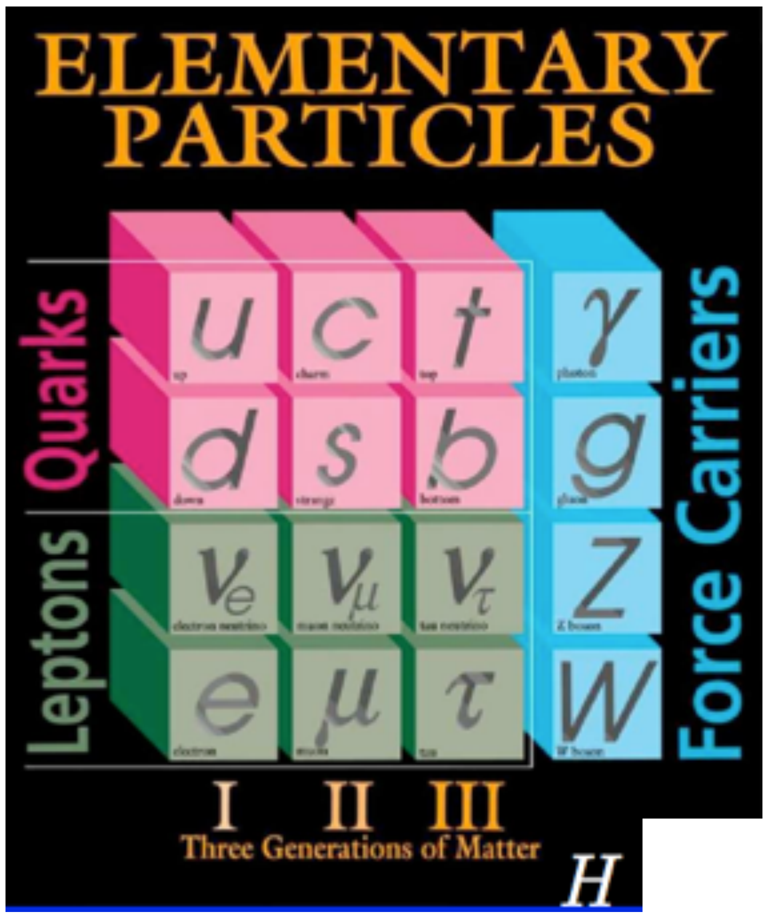
new particle, same coupling by symmetry SUSY: popular candidate

or Higgs as pNGB: Composite Higgs, strong int. at f, Top partner

Supersymmetry (SUSY)

- symmetry : fermion ⇔ boson

predicts partners for SM particles



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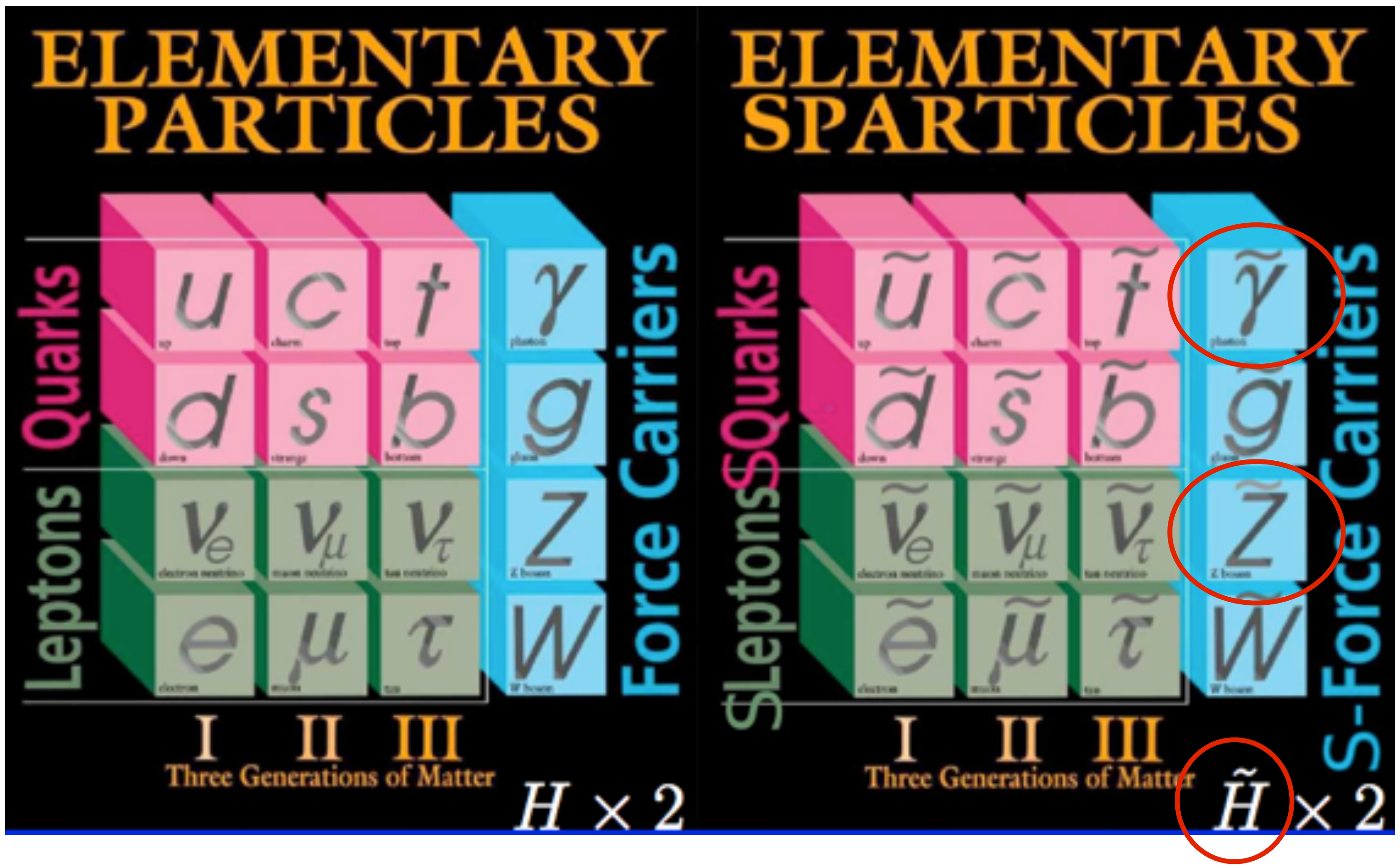

- R-parity : natural DM candidate

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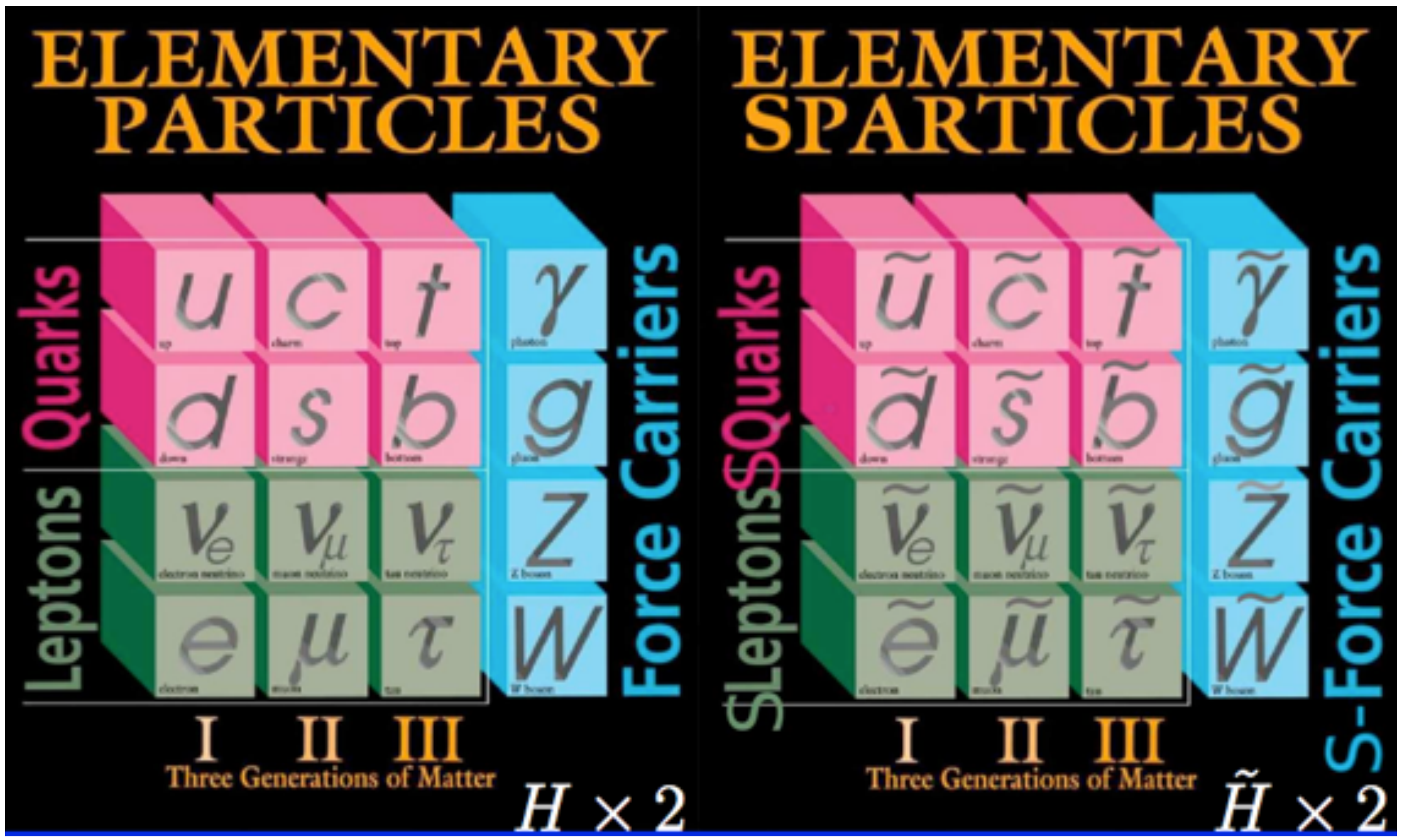
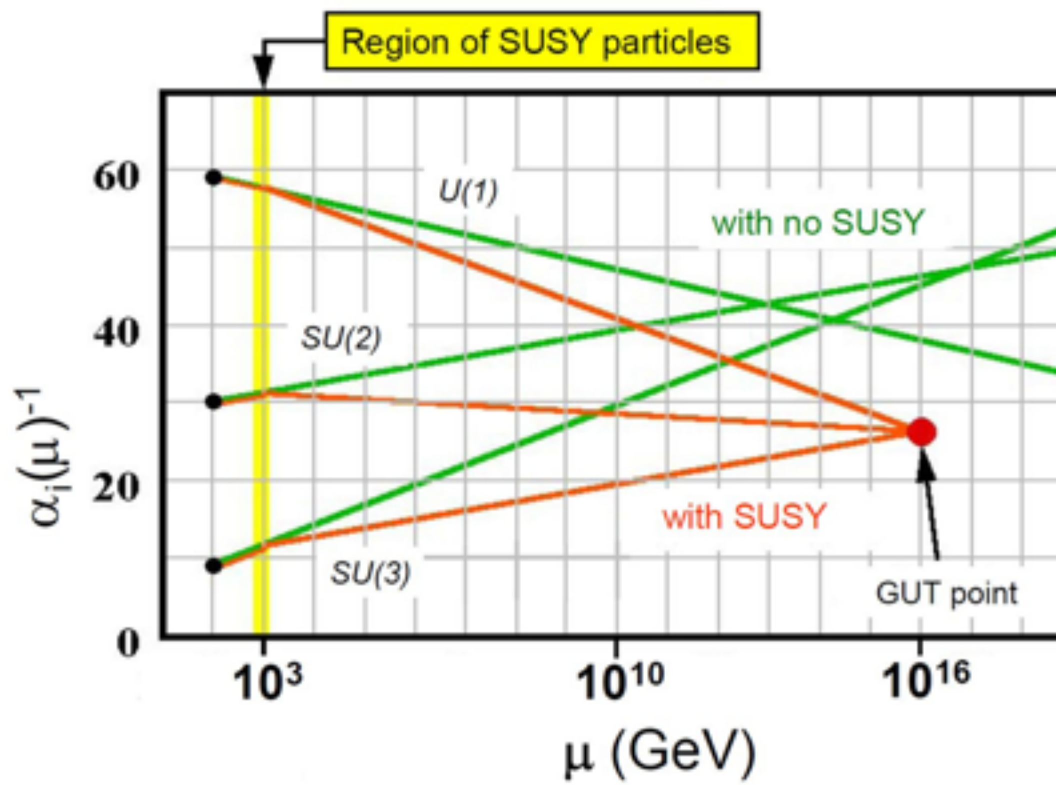




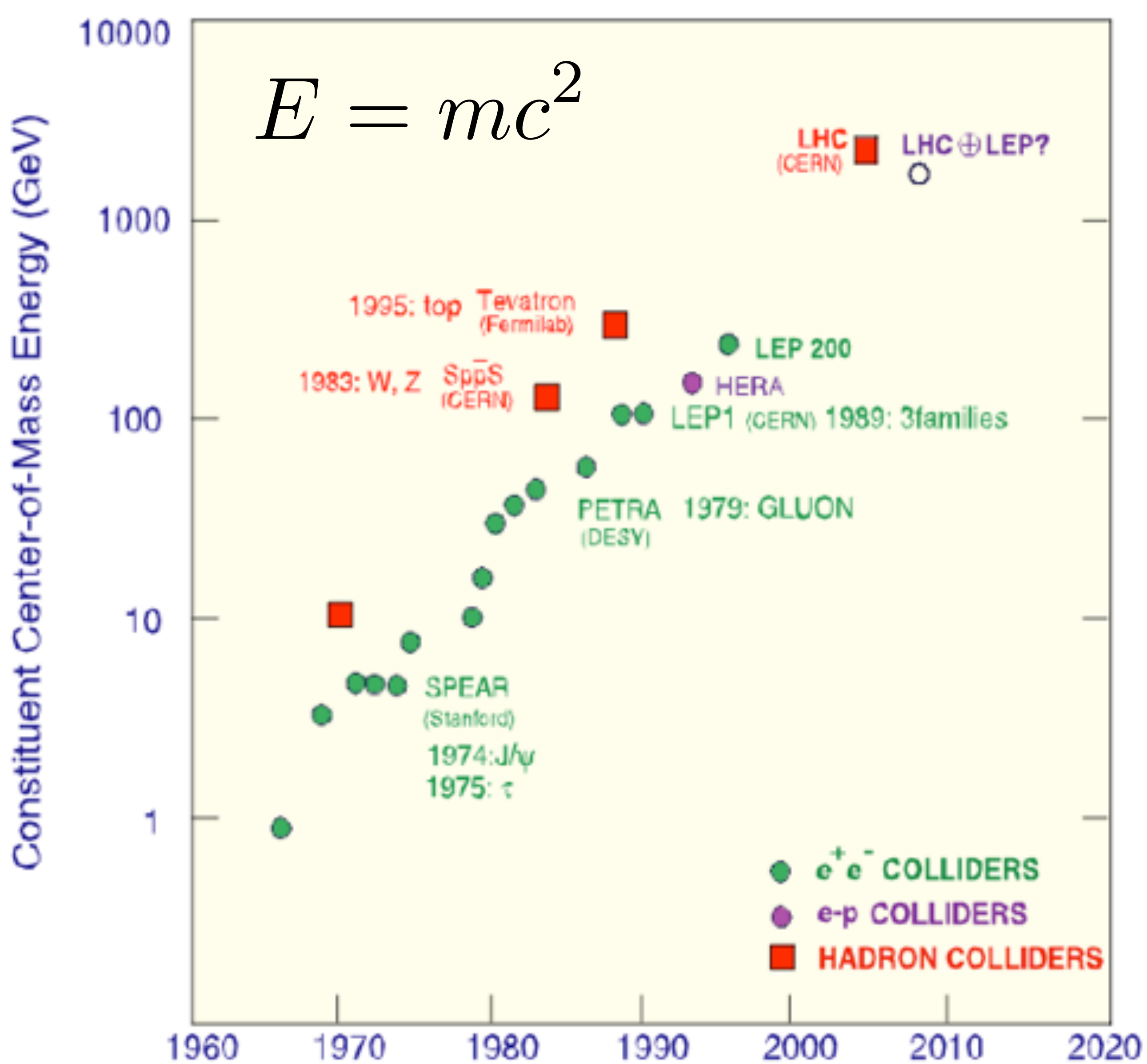
- R-parity : natural DM candidate

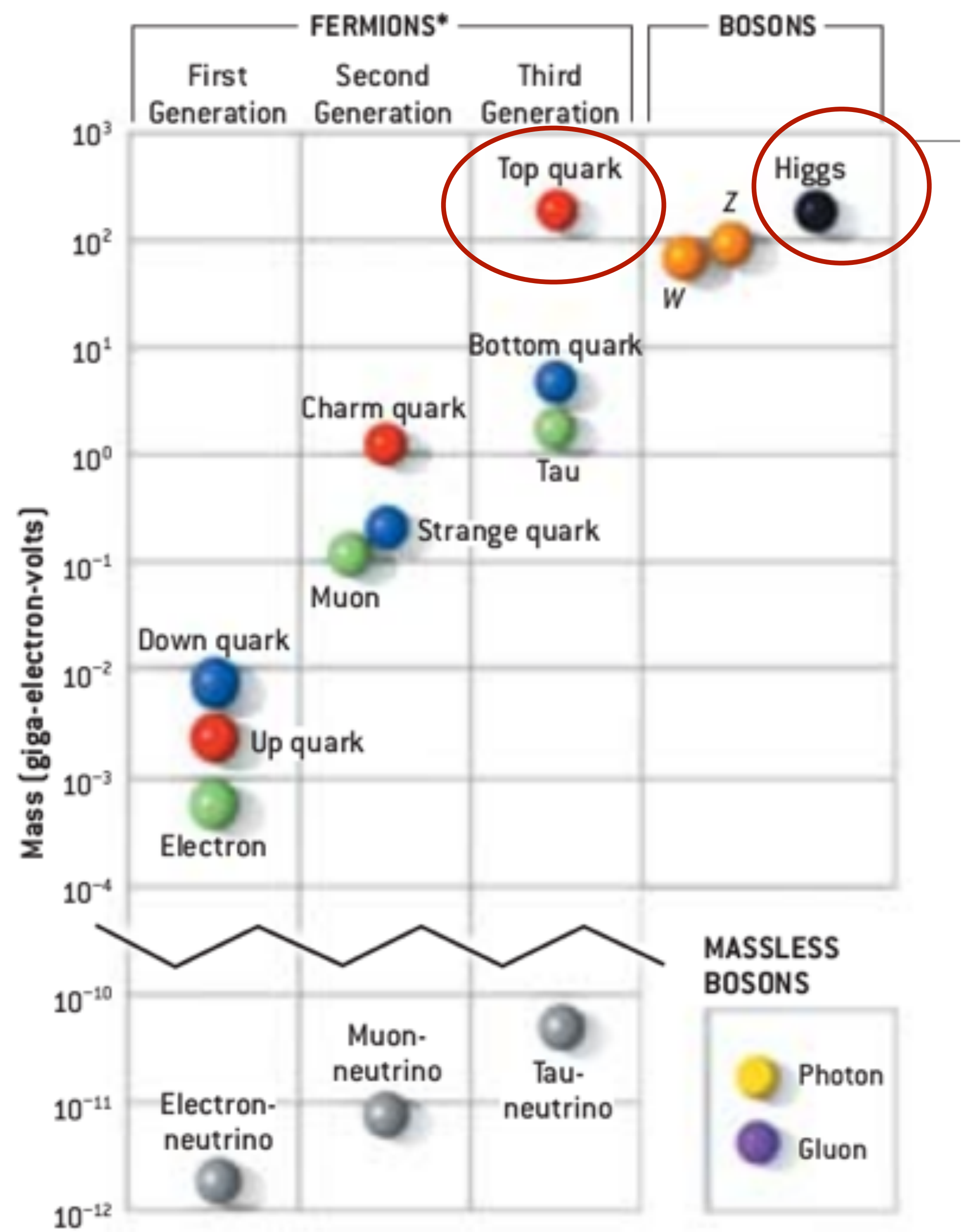
- coupling unification → TeV

- We expect they are produced at LHC

Collider experiments

$$E = mc^2$$





In a circular machine:

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

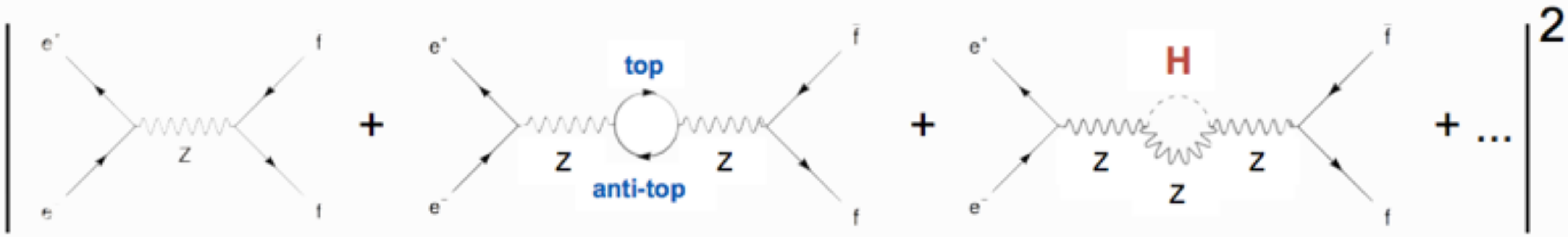
Energy loss/turn (ΔE); Particle energy (E); Particle mass (m); Bending radius (R)

$$m_p \sim 2000 m_e$$

Hadron collider for heavy particles

Indirect information from LEP

$$\sigma(e^+e^- \rightarrow f\bar{f}) =$$

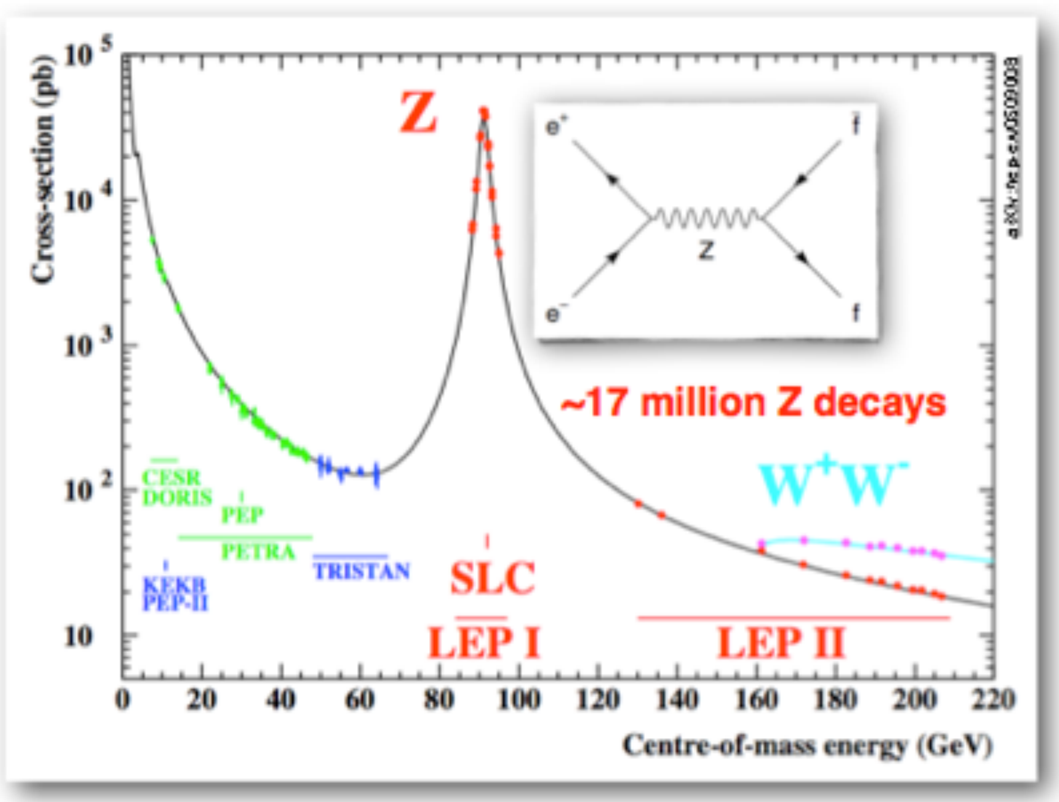


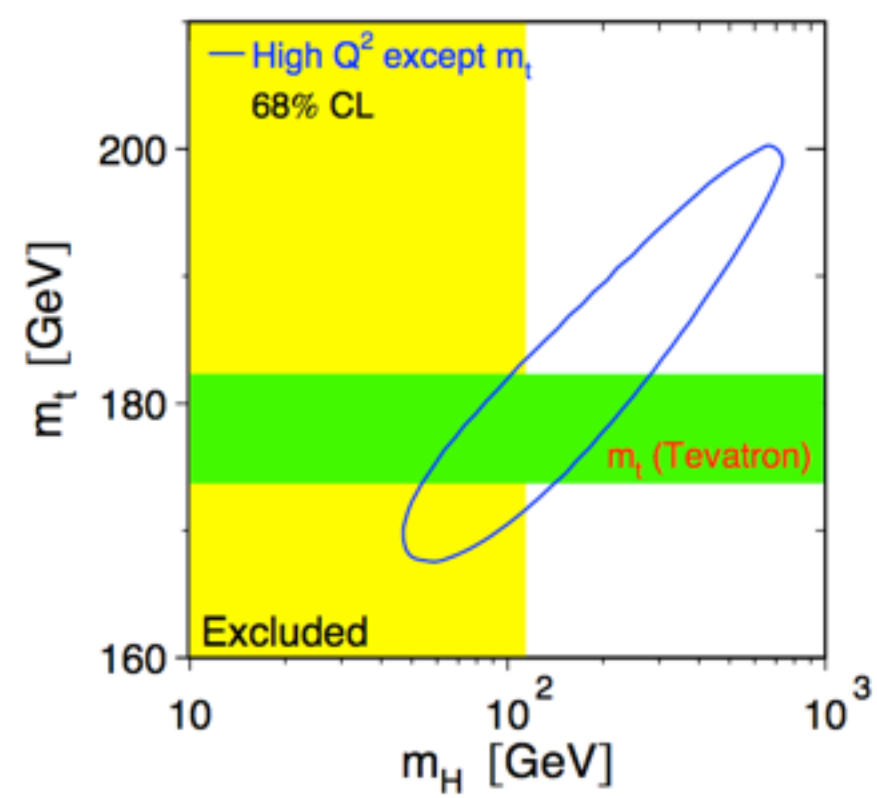
$\propto \; M_t^2$

% level correction

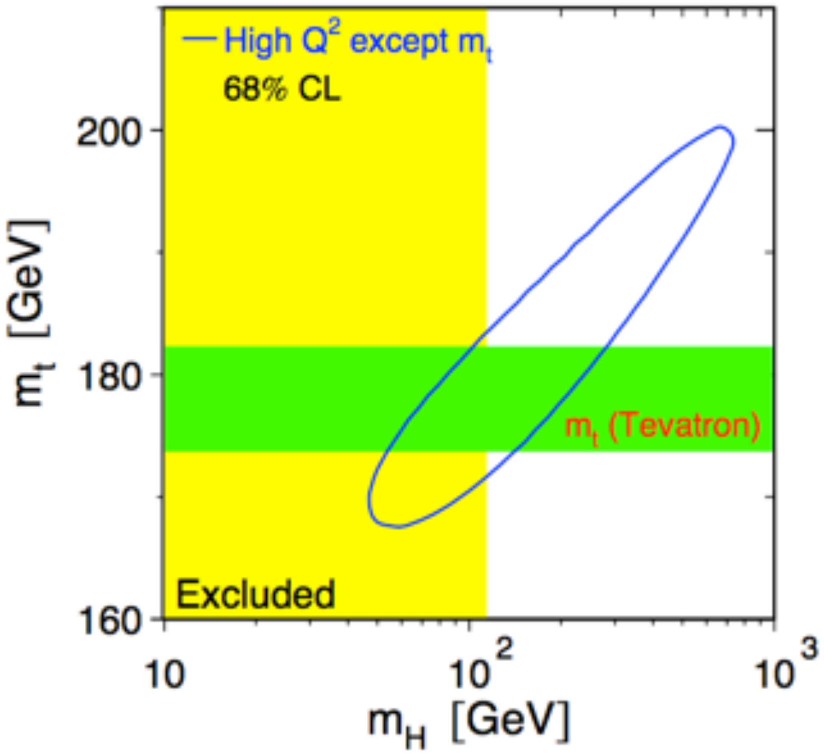
$\propto \; \log M_H^2$

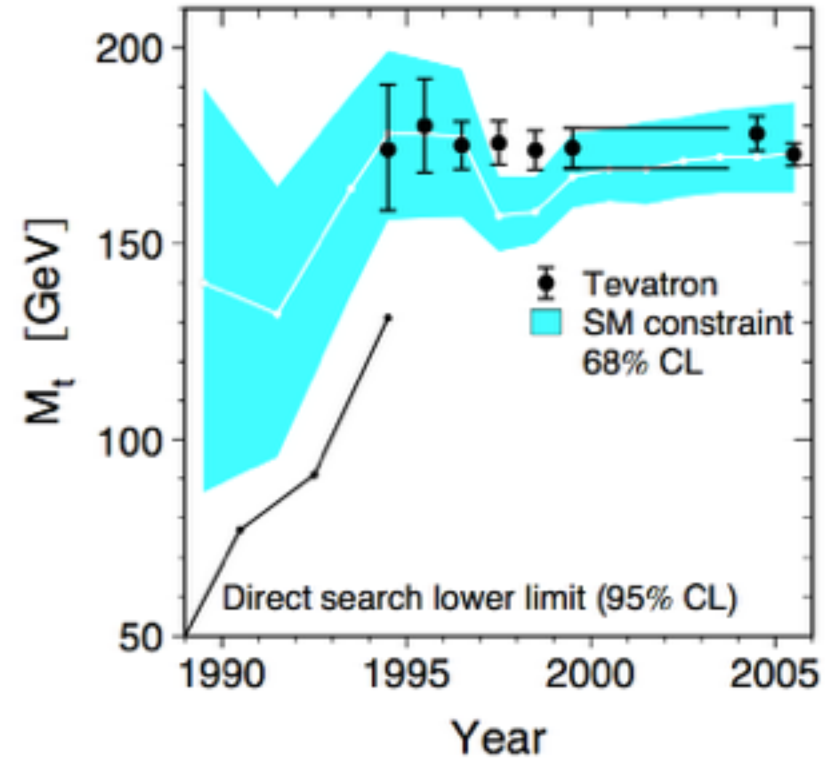
sub-% level correction





direct new particle production is better





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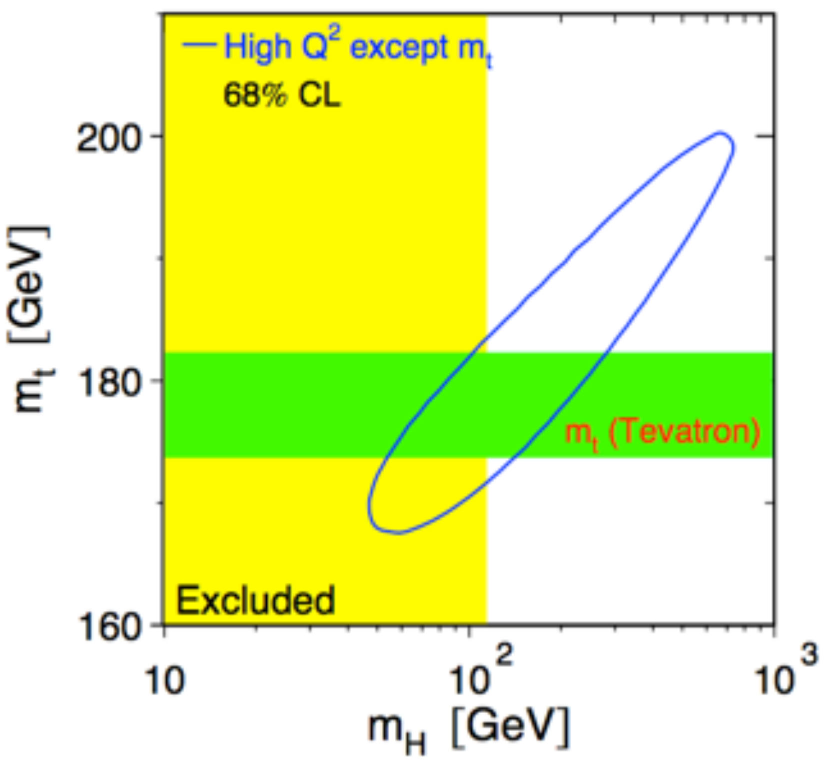
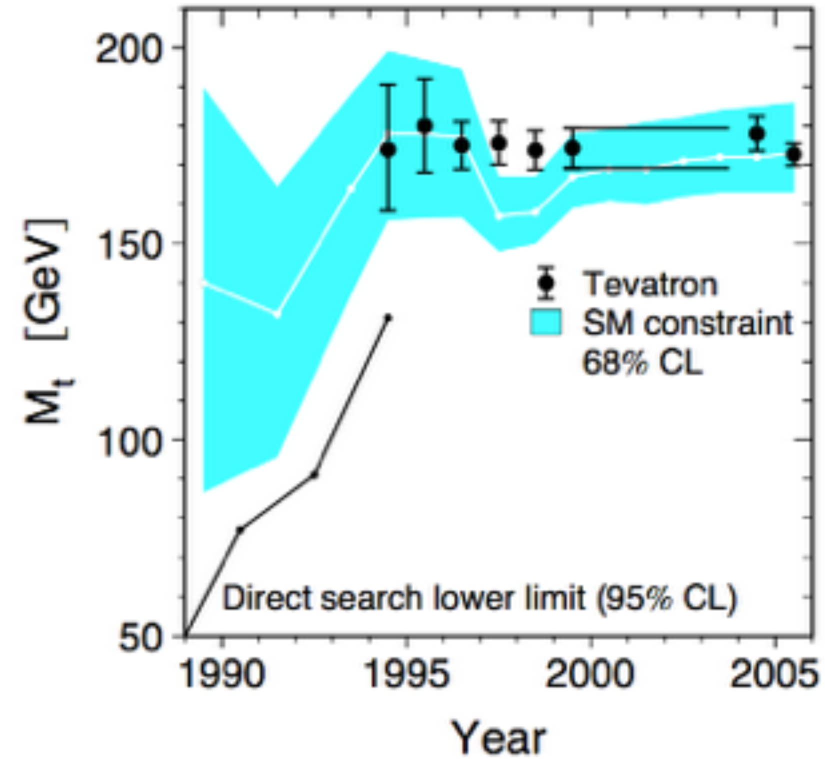
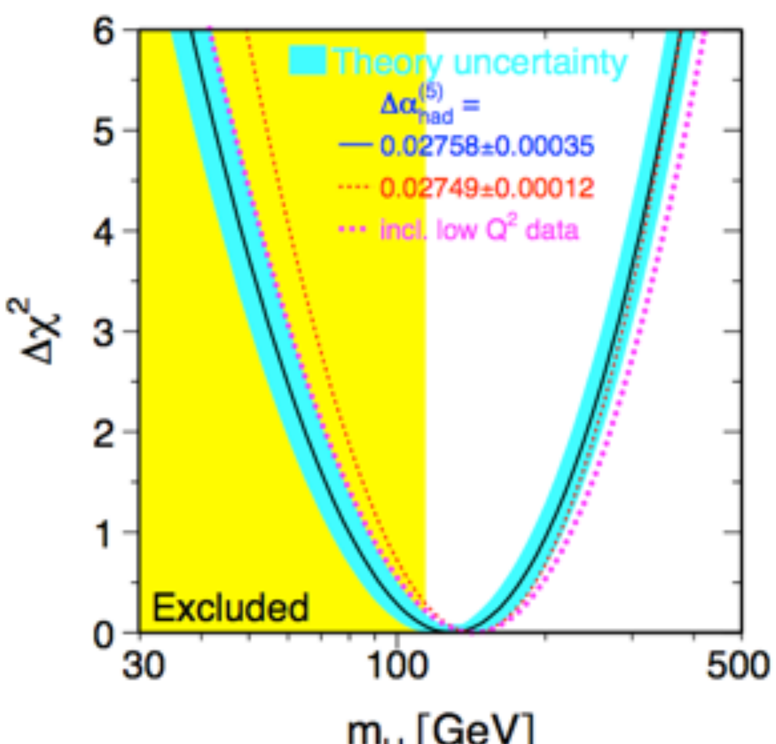
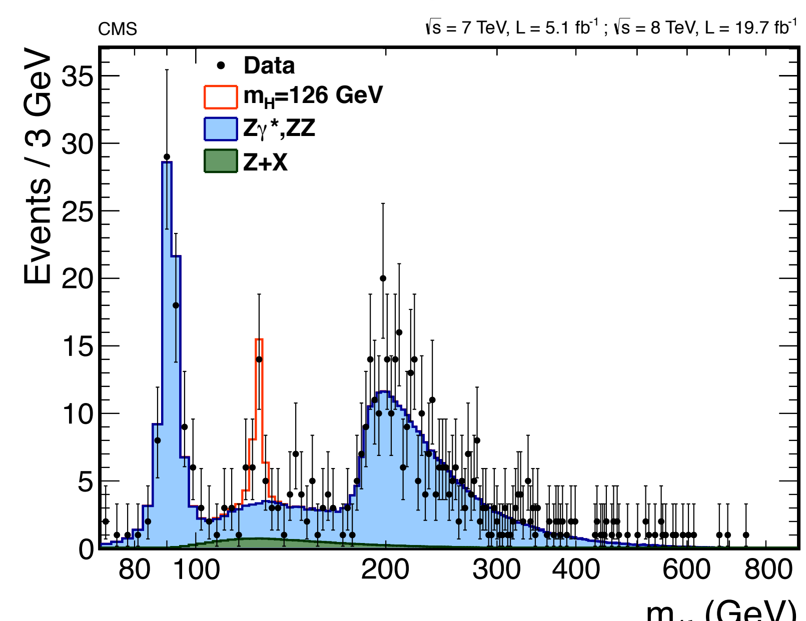






$129^{+74}_{-49}\mathrm{GeV}$



$125.6 \pm 0.4(\mathrm{stat.}) \pm 0.2(\mathrm{syst.})\mathrm{GeV}$

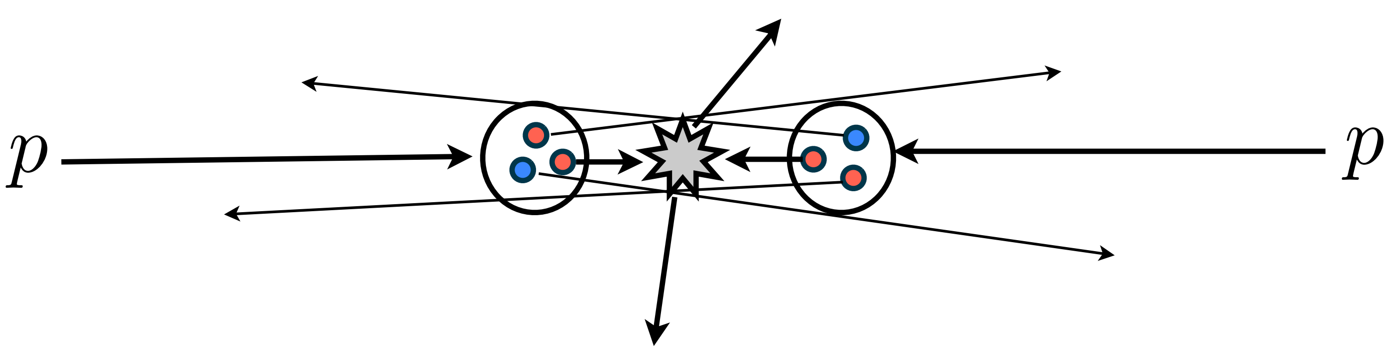
exploiting full potential of LHC desired

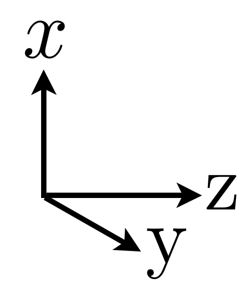
Hadron Collider

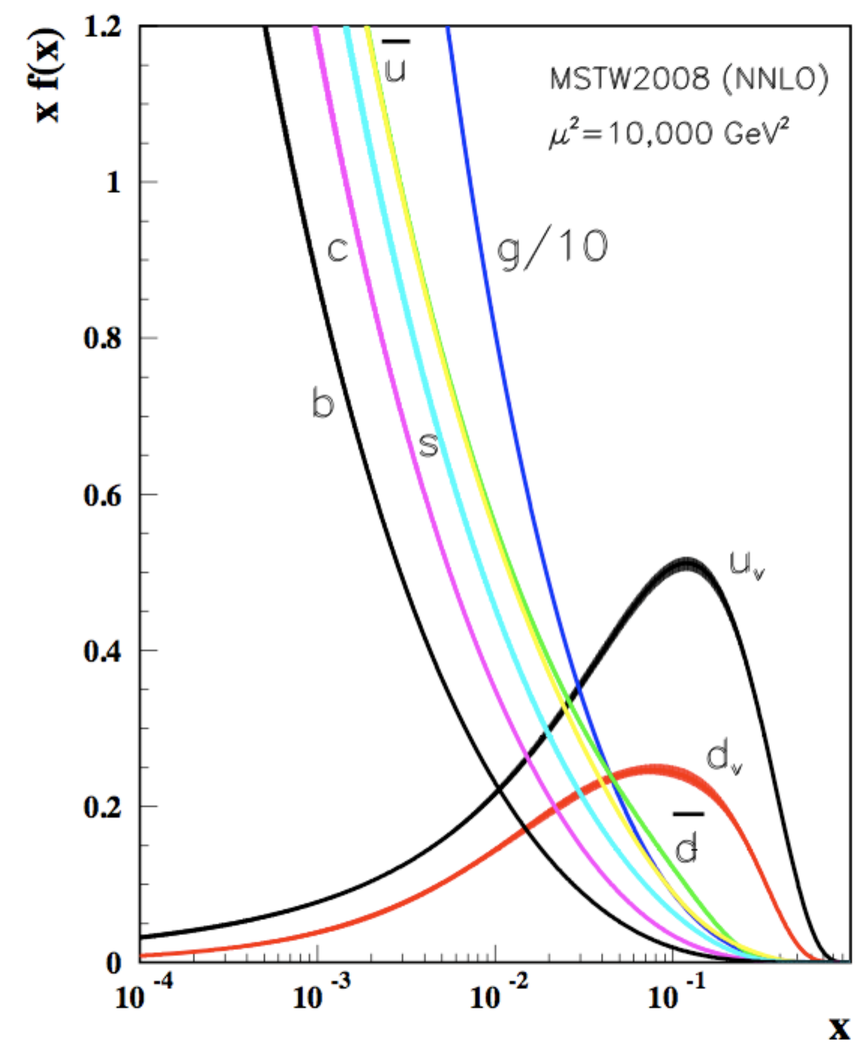
much complex compared with lepton collider

proton: not elementary particle

mixed beam with u, d, gluon, ...







we don’t know what collide

we don’t know collision energy

only transverse momentum conservation

$p_x = 0$

$p_y = 0$

p_z moving

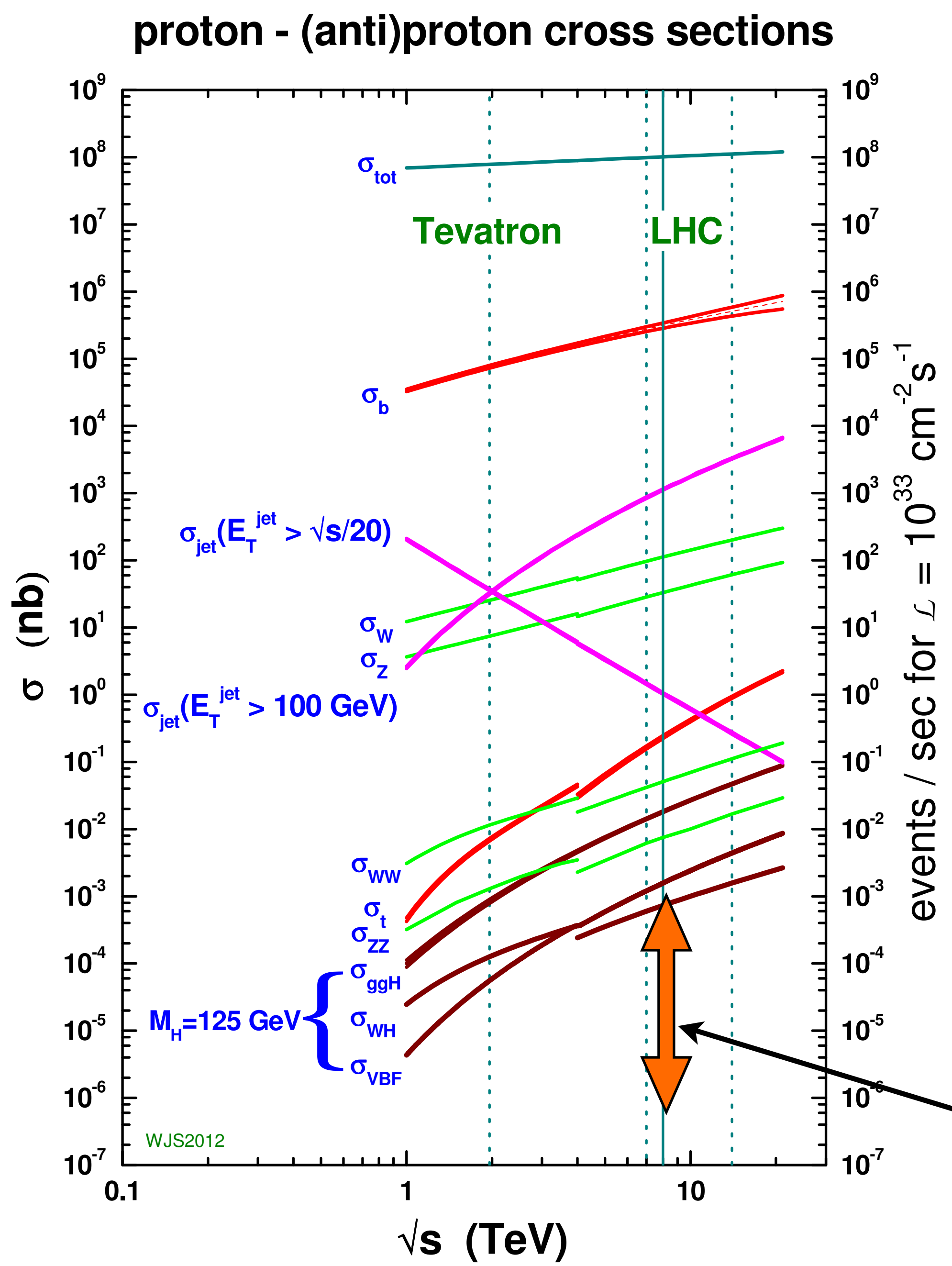
full reconstruction not possible event by event

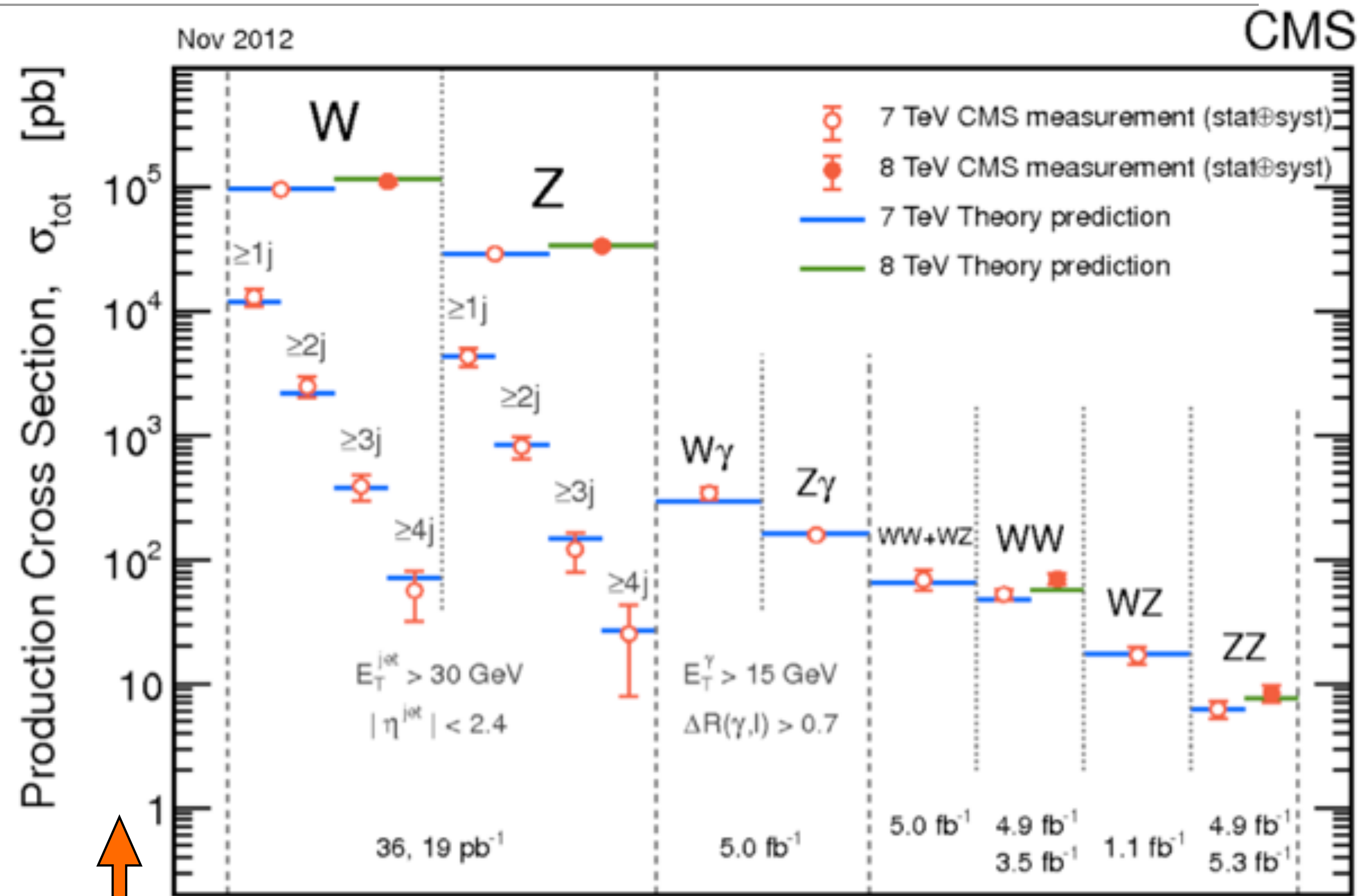
precision physics possible by statistics

strong interaction : PDF, jets, understanding QCD important

Hadron Collider

Huge difference in cross sections (every event is essentially BG)





new physics: typically 1fb~1pb (SUSY)

capturing any tiny signature important

Higgs: 1 in 1,000,000,000 BG

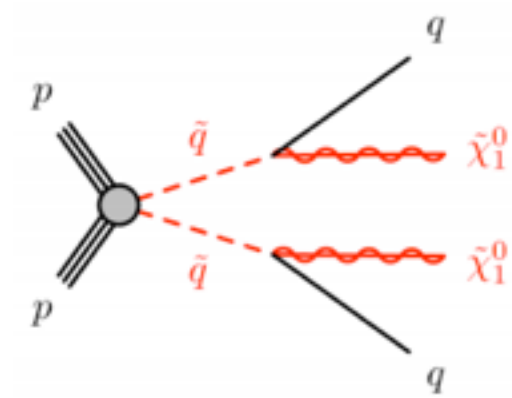
BG has to be subtracted: handles - high pT lepton, jets, b-tag, photon, missing momentum

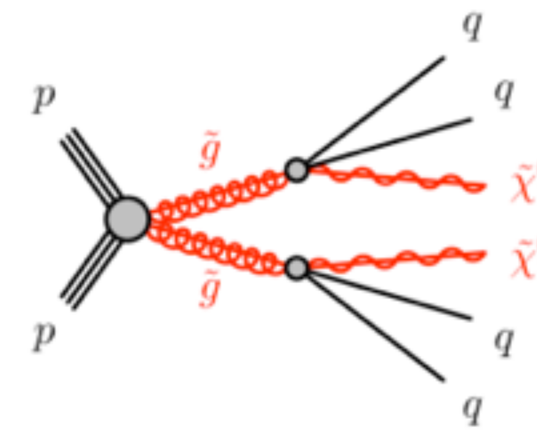
(heavy particles immediately decays: t, H, W, Z)

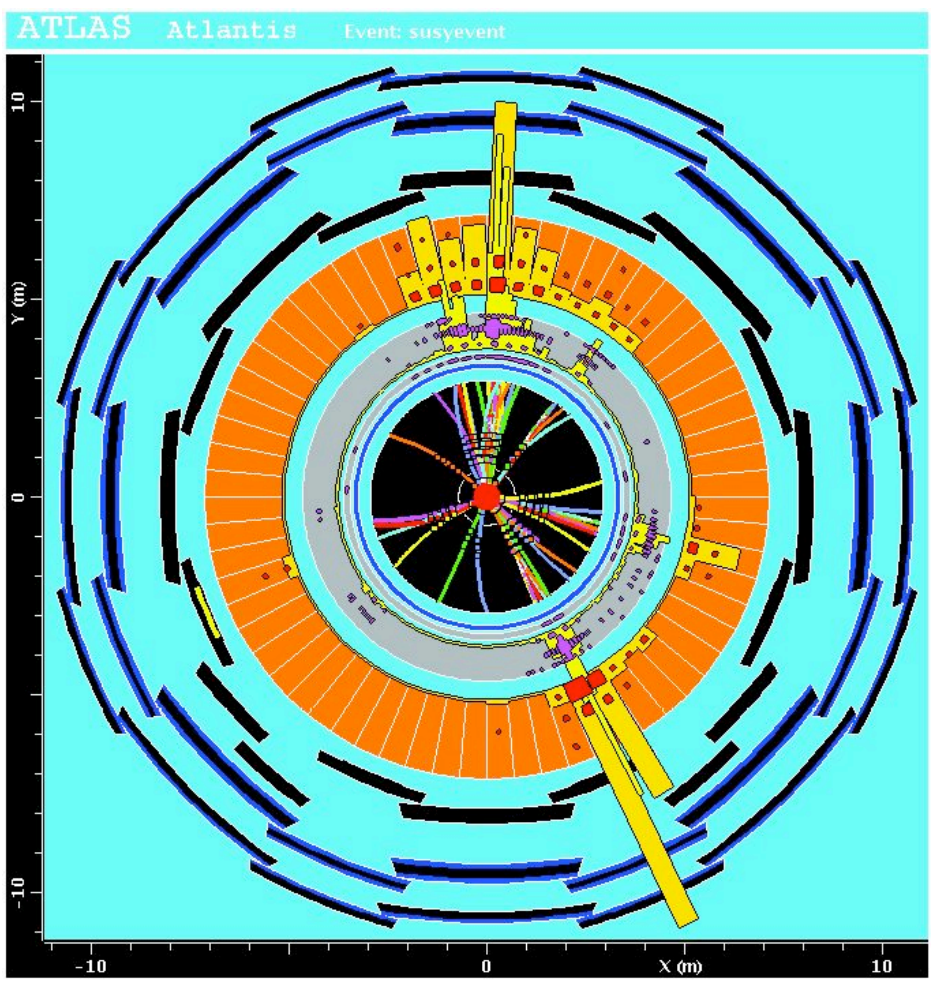
typical SUSY searches

colored susy particles produced in pair

$$\tilde{g}, \tilde{q} \sim \text{TeV}$$







– cascade decay $\tilde{g} \to \tilde{q} q$

$$\tilde{q} \to q\tilde{\chi}^0(\text{DM})$$

– signal:

multiple jets, missing transverse momentum $\not{E}_T$

– BG:

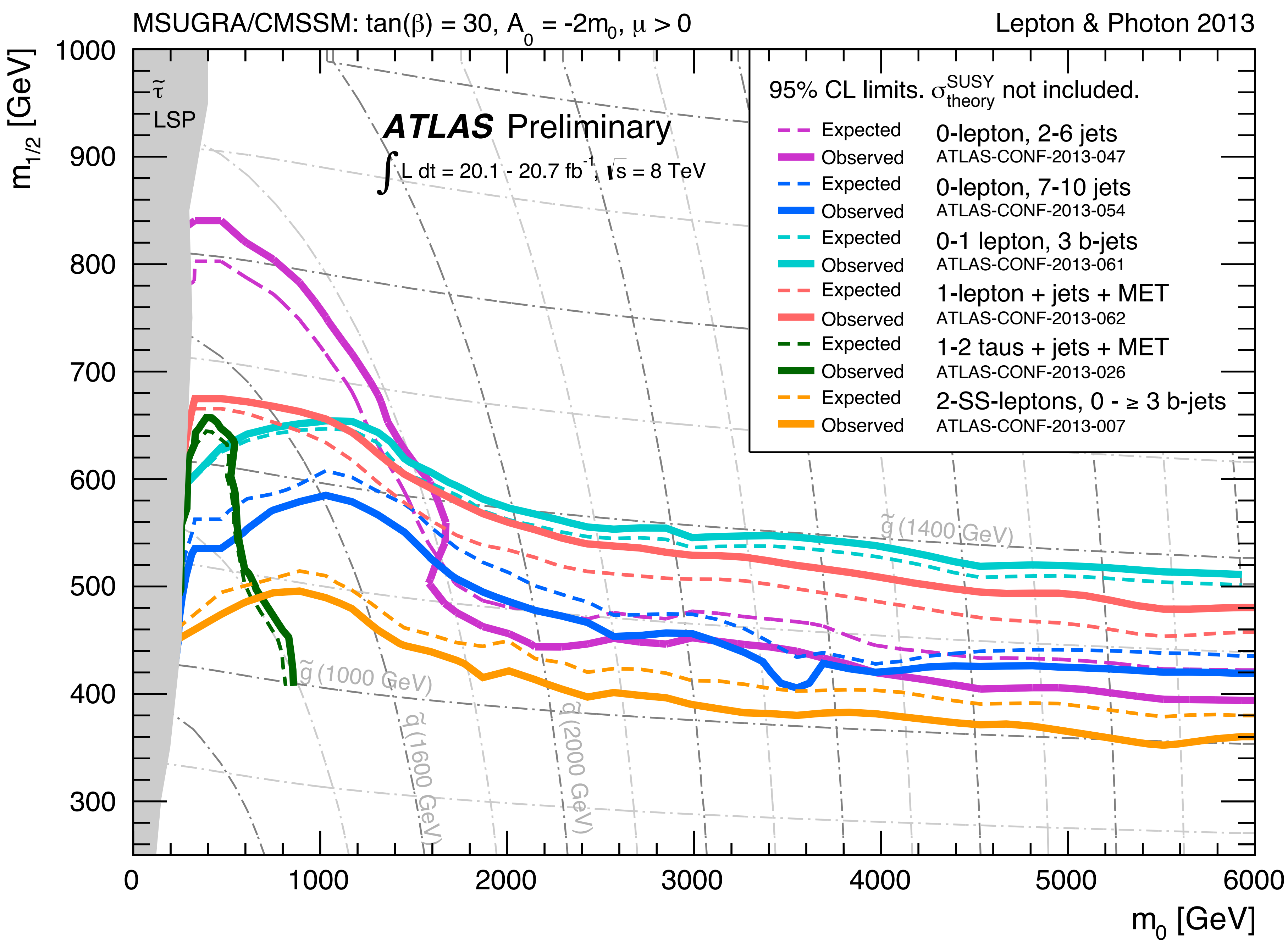
$W \to l\nu$

$Z \to \nu\bar{\nu}$

$t \to bW \to bl\nu$

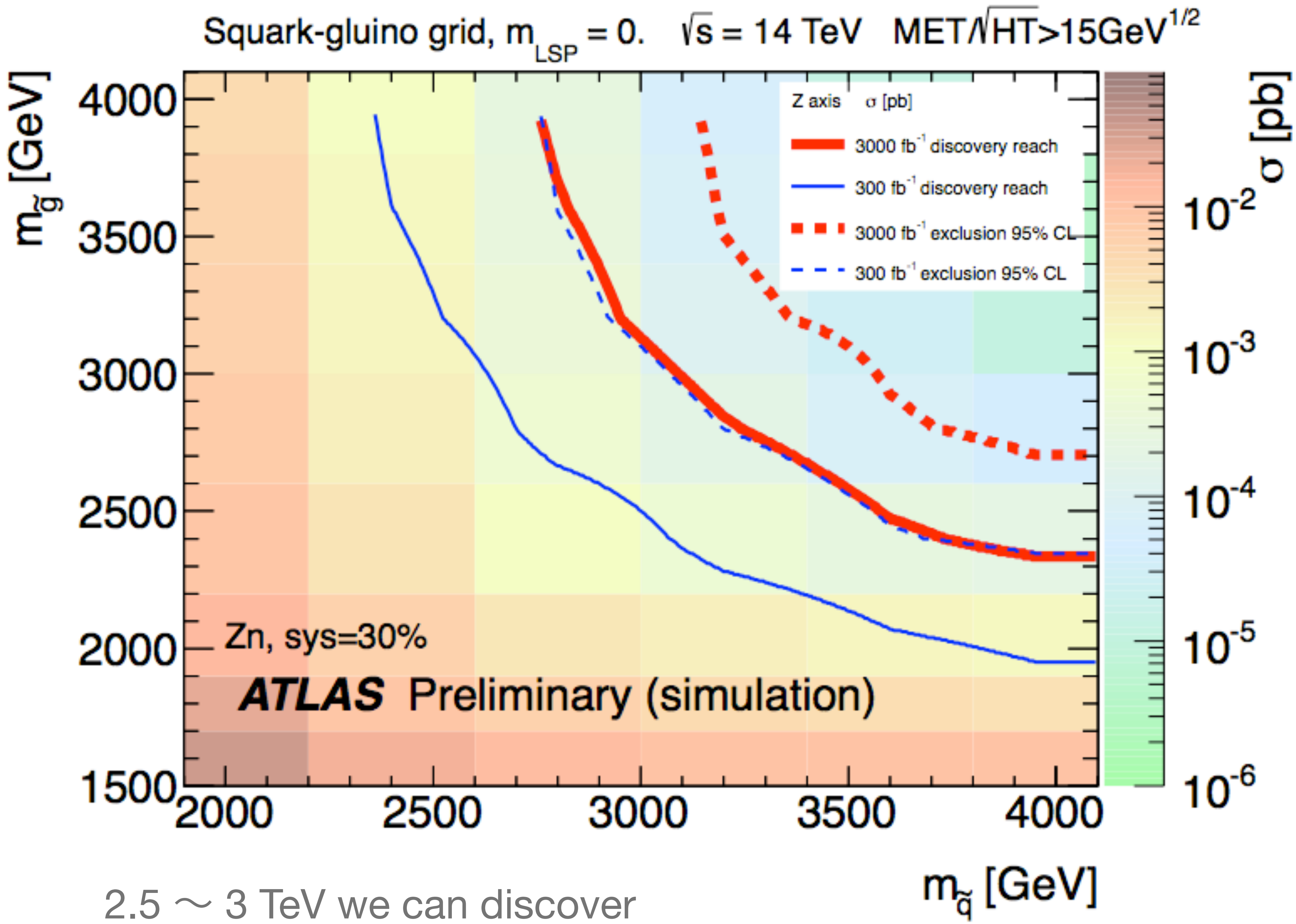
SUSY should have been found easily

- if ~ 1 TeV scale sparticles exist ...



gluino > 1400 GeV, squark > 1700 GeV,   but not yet 8 TeV ...

How heavy can we explore?

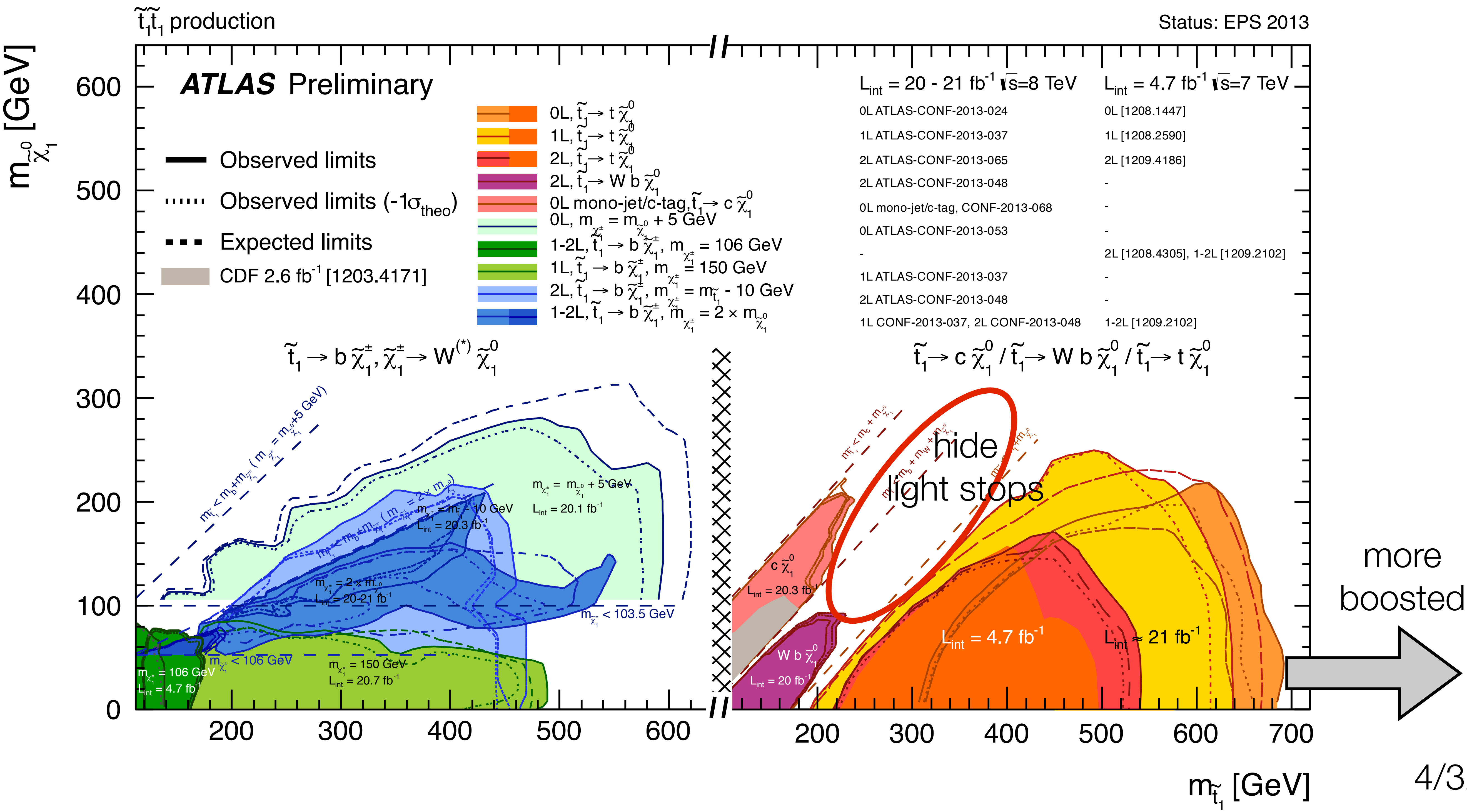


2.5 〜 3 TeV we can discover

stop search at 8TeV

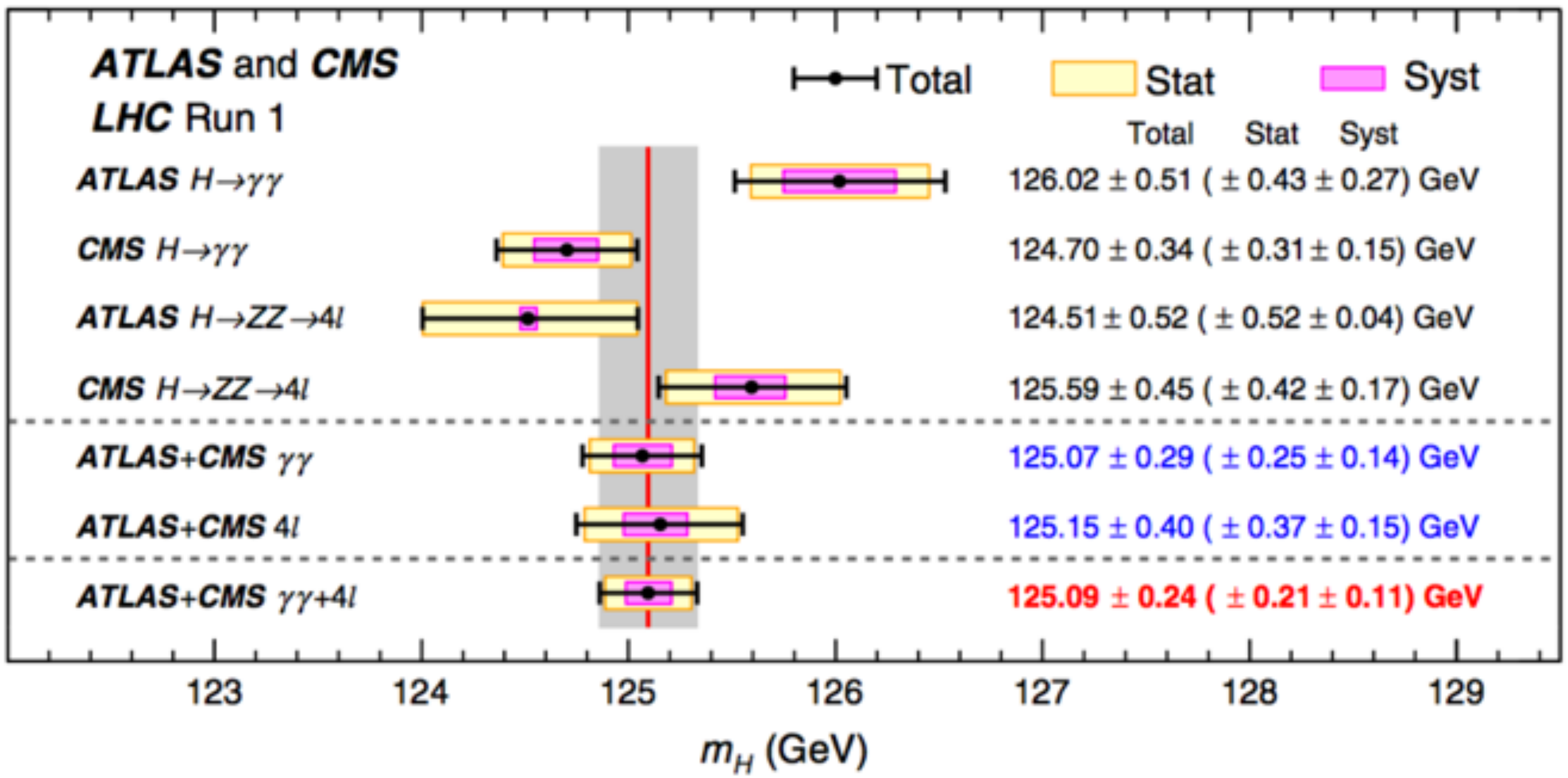
upto 660 GeV excluded 95% C.L.

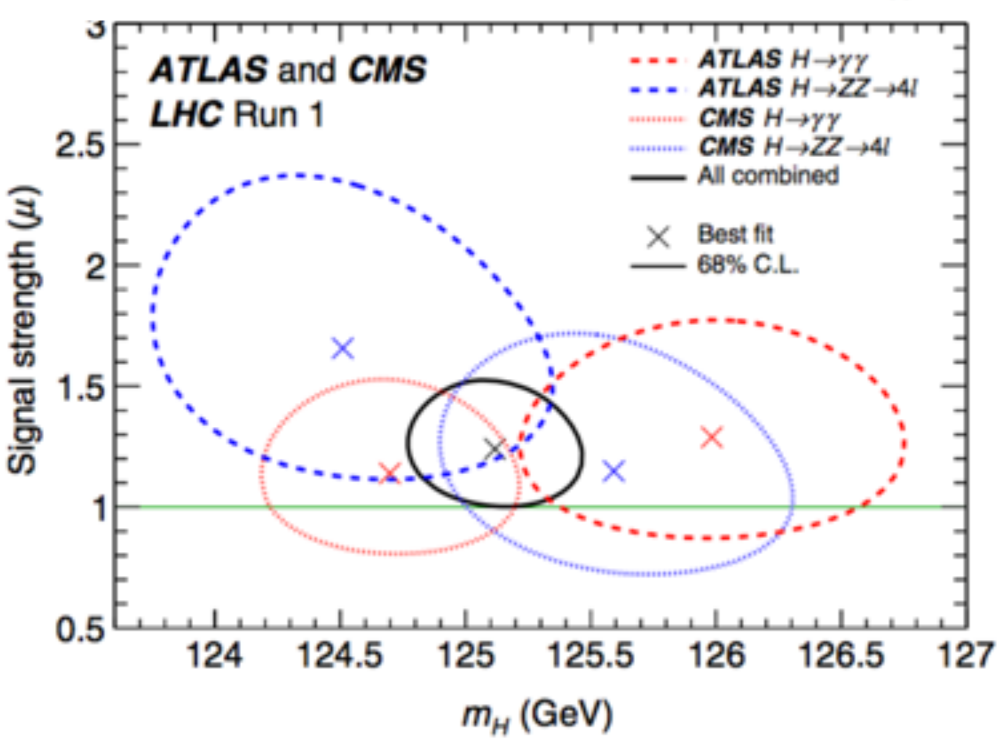
top partner also excluded ~700 GeV



Higgs combined results from LHC run 1

PhysRevLett.114.191803





125 GeV with 0.2% error

coupling fit

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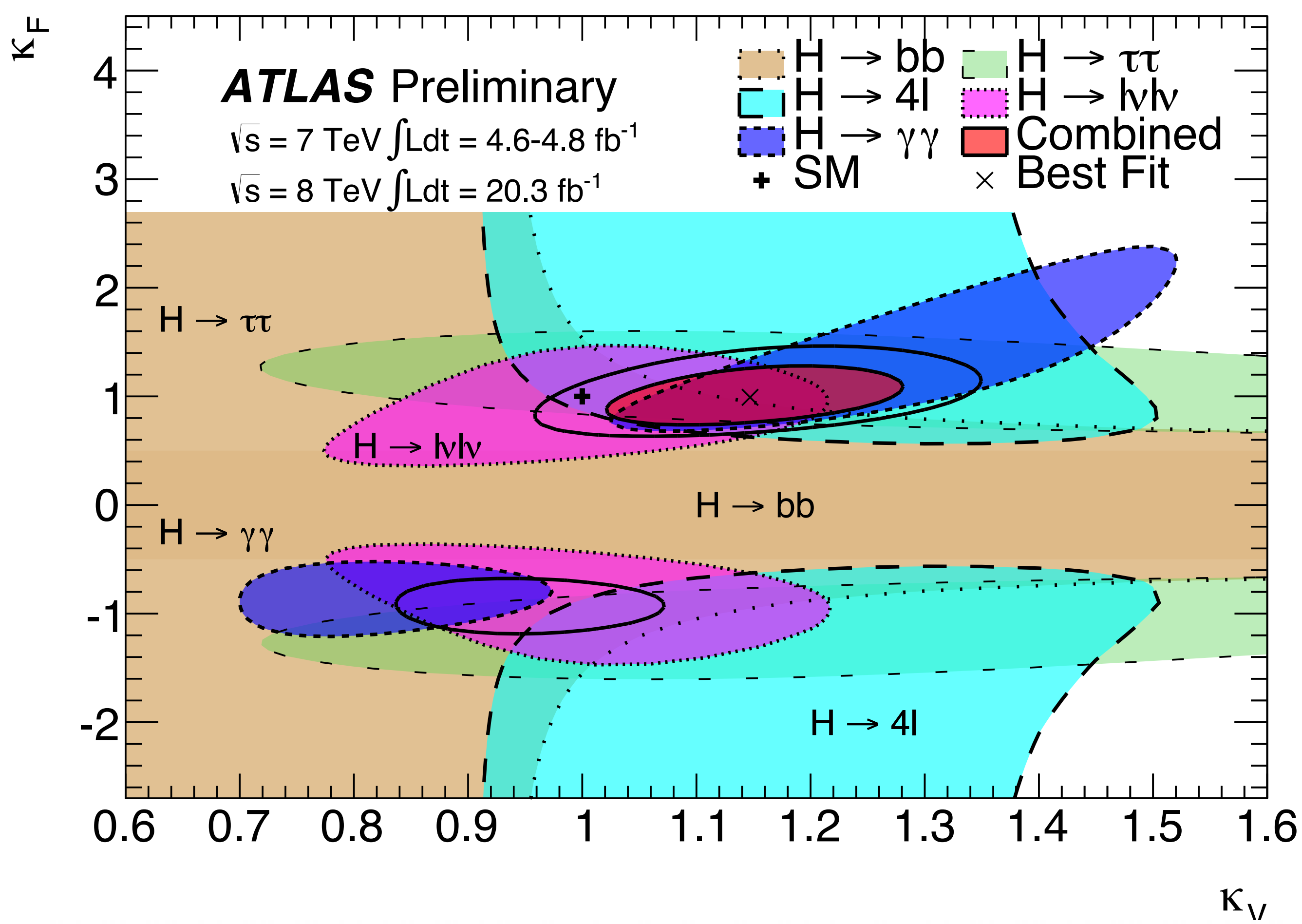
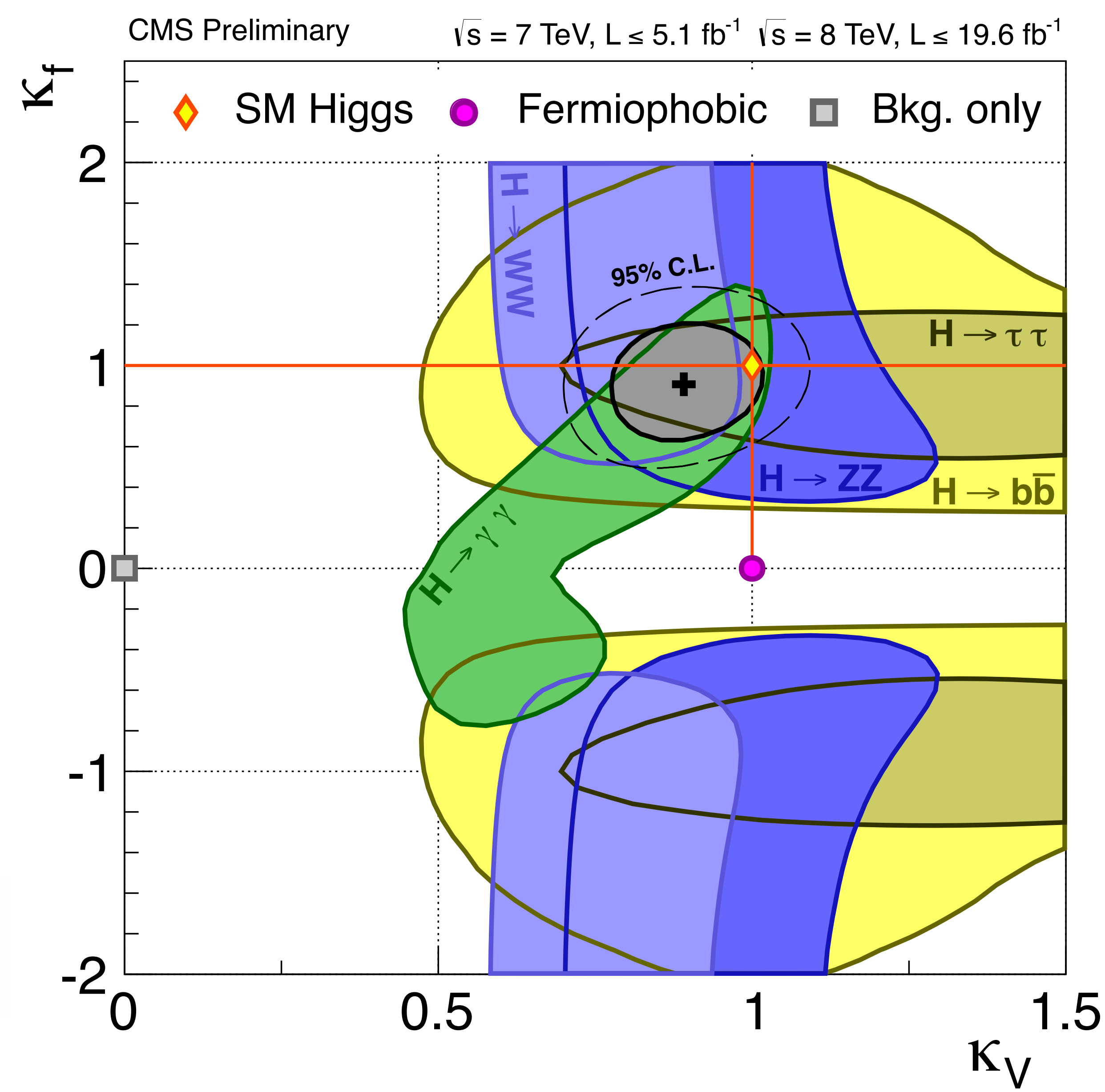


CMS-Hig-13-005



ATLAS: κ_V **[1.05,1.22] at 68% CL** - κ_F **[0.76,1.18] at 68% CL**

CMS: κ_V **[0.74,1.06] at 95% CL** - κ_F **[0.61,1.33] at 95% CL**

$$\text{production}: ggF, VBF, VH$$

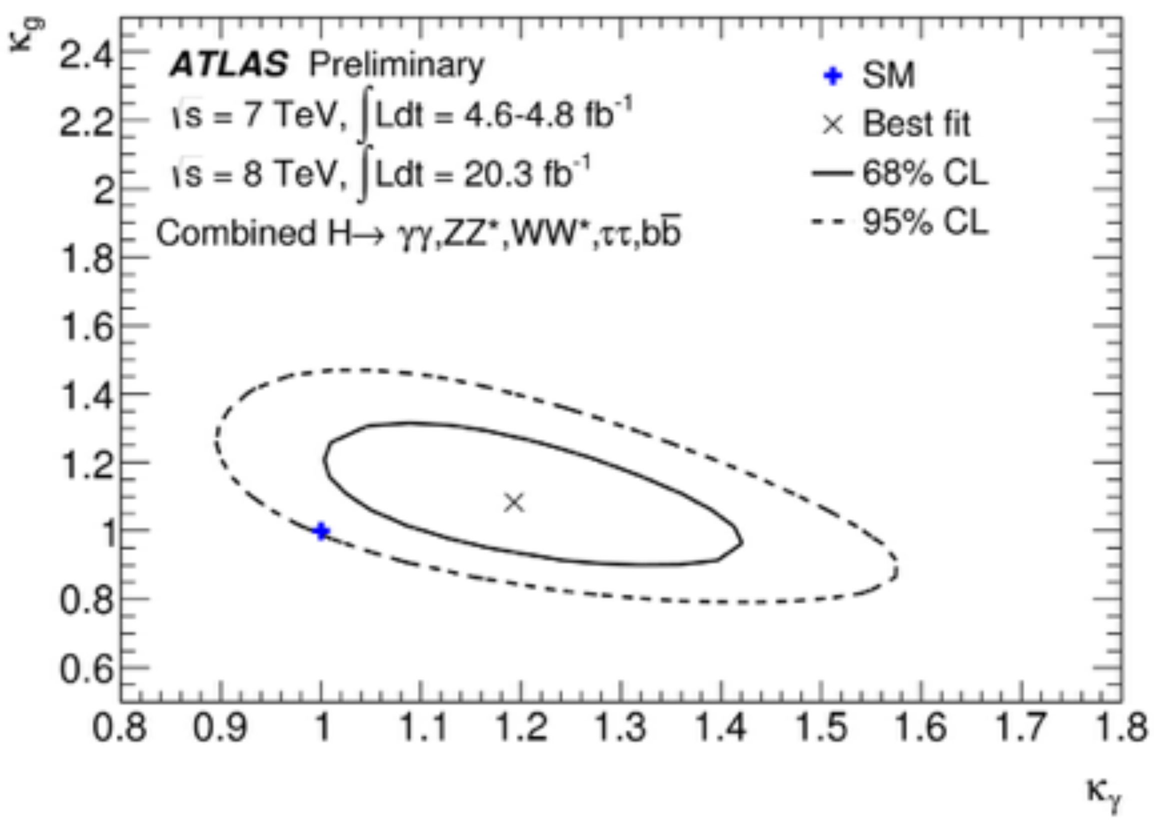
$$\text{decay}: \gamma\gamma, ZZ, WW, bb, \tau\tau$$

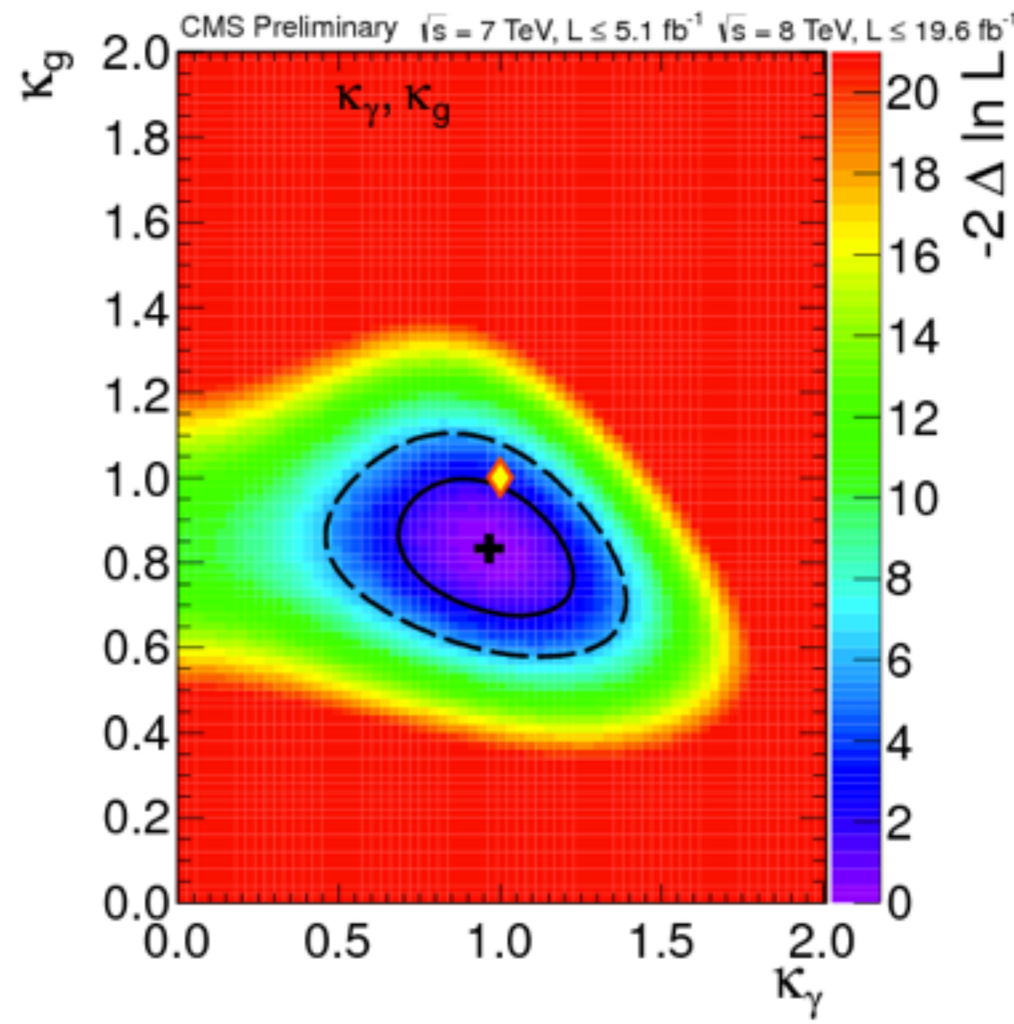
compatible in 10-20%

$$\kappa_g, \kappa_\gamma, \kappa_Z, \kappa_W, \kappa_b, \kappa_\tau$$

coupling fit (gg, gammagamma)

ATLAS-CONF-2014-009 | CMS-Hig-13-005

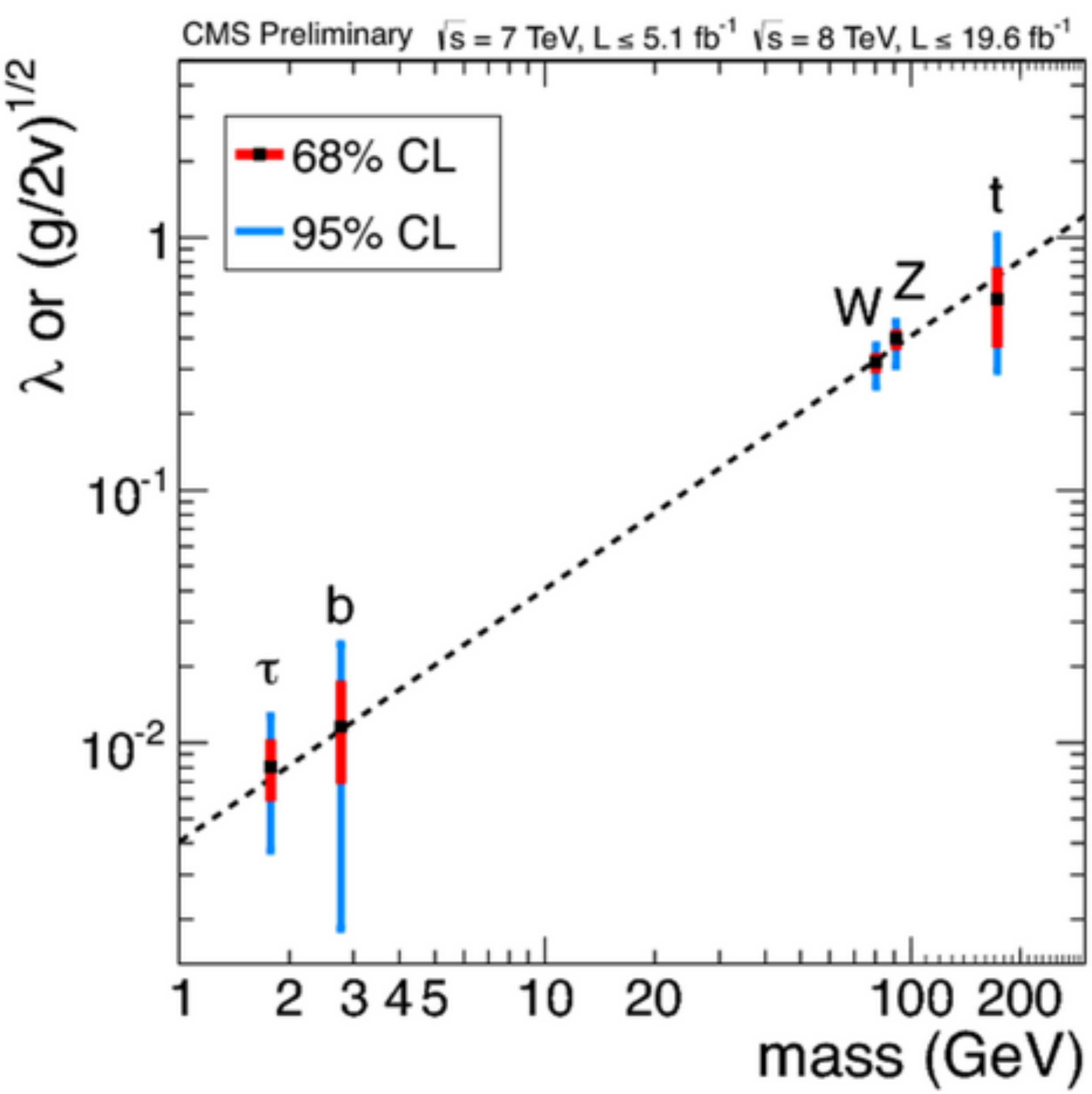




$\kappa_Z = \kappa_W = \kappa_b = \kappa_\tau = 1$

No new physics evidence here yet, but still large room

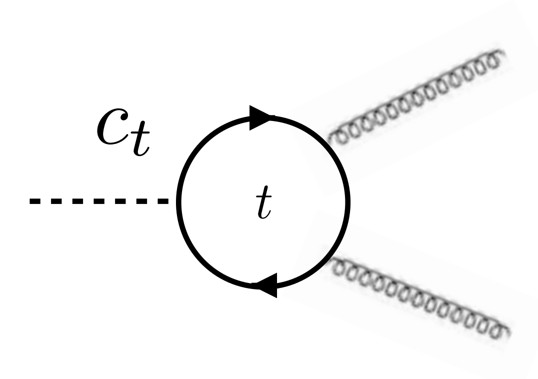
ttH coupling and ggH coupling



$\text{production}: ggF, VBF, VH$

$\text{decay}: \gamma\gamma, ZZ, WW, bb, \tau\tau$

$\kappa_g, \kappa_\gamma, \kappa_Z, \kappa_W, \kappa_b, \kappa_\tau$



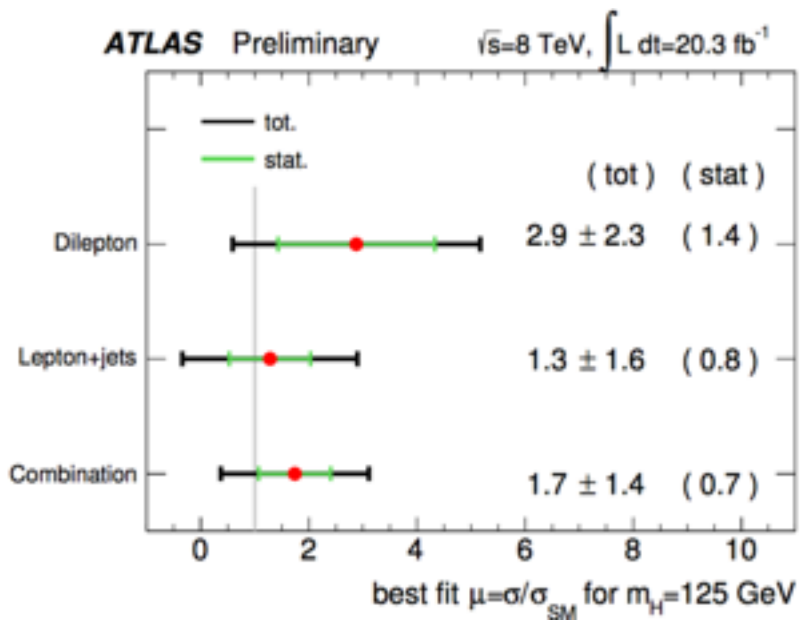
$\kappa_g = \kappa_t$ is sometimes assumed

ttH is indirectly measured by ggH coupling

However, κ_g can include new particle effects $\kappa_g = \kappa_t + \kappa_g^{NP}$

We want to measure κ_g and κ_t independently

ttH coupling direct measurement



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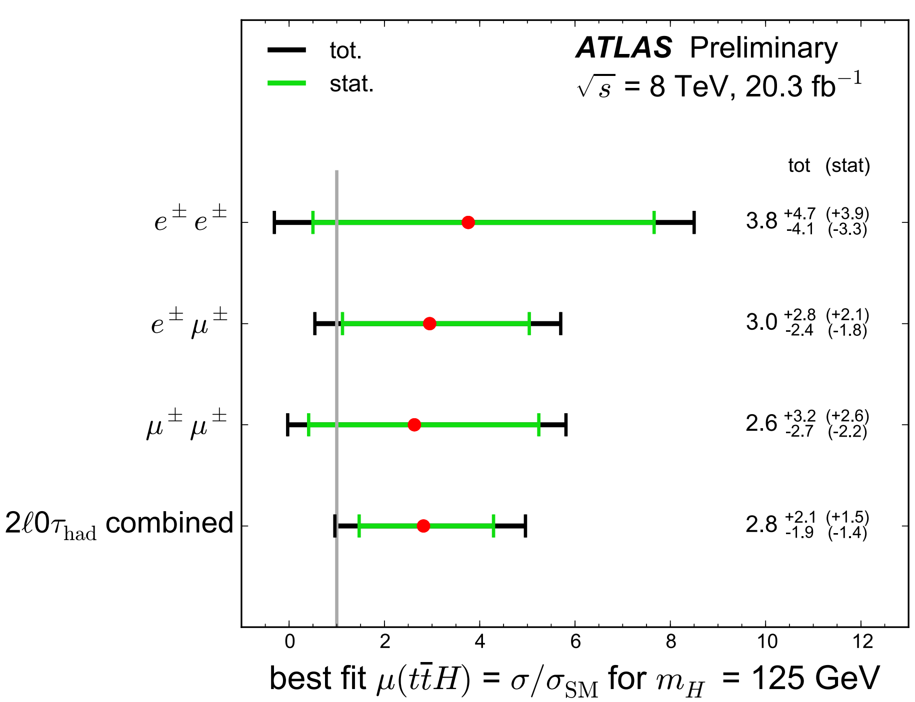
ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$



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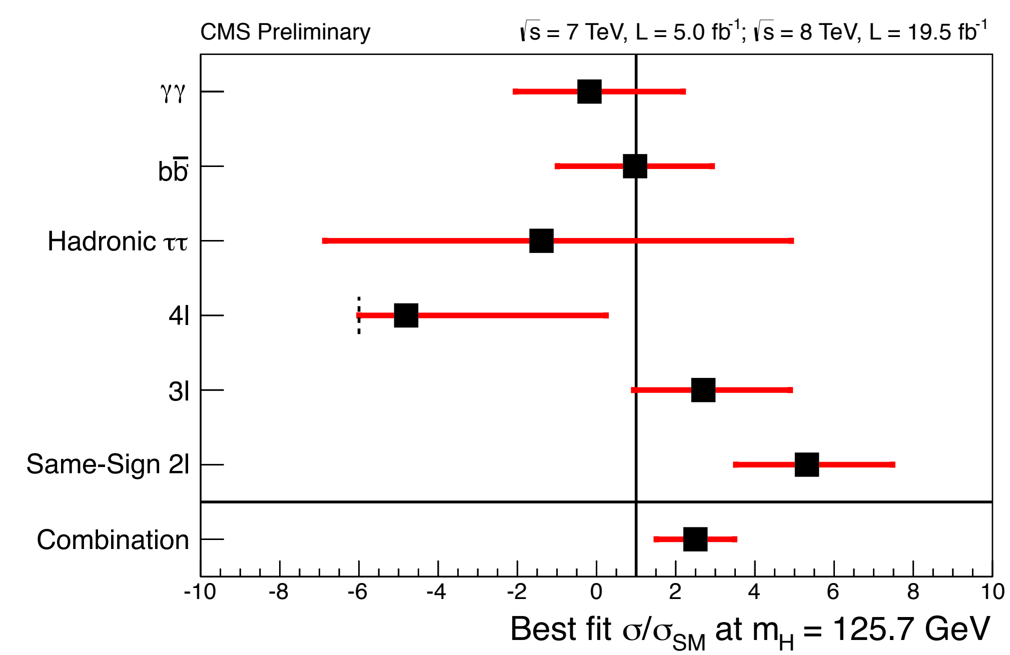


ttH coupling directly starts to be constrained but weakly non 0 at 1-2 sigma

higgs coupling measurement perspective

$$g = g_{SM}[1 \pm \Delta]$$

coupling	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.09	0.08	0.011	0.006	0.005
hZZ	0.11	0.08	0.008	0.005	0.004
htt	0.15	0.12	0.040	0.017	0.015
hbb	0.20	0.16	0.023	0.012	0.011
$h\tau\tau$	0.11	0.09	0.033	0.017	0.015
$h\gamma\gamma$	0.20	0.15	0.083	0.035	0.024
hgg	0.30	0.08	0.054	0.028	0.024
h_{invis}	—	—	0.008	0.004	0.004

$$\begin{aligned} LHC &\quad 300 fb^{-1} \\ HL-LHC &\quad 3000 fb^{-1} \\ LC &\quad 250+500\text{GeV}\ with\ 250+500 fb^{-1} \\ HL-LC &\quad 250+500+1000\text{GeV}\ with\ 1150+1600+2500 fb^{-1} \end{aligned}$$

table from C. Englert, A. Freitas, M. Muhlleitner, T. Plehn, M. Rauch, M. Spira, K. Walz arXiv:1403.7191 [hep-ph]

$\sim 10\%$ for all couplings at HL-LHC

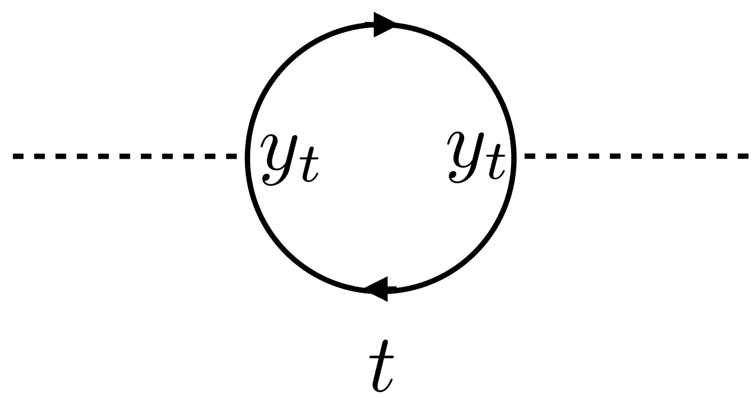
We want to measure κ_g and κ_t independently

one option: ttH measurement

new option: Boosted Higgs shapes

Fine tuning problem

Higgs: only scalar elementary particle in the SM

$\delta m_h^2 \sim$ 

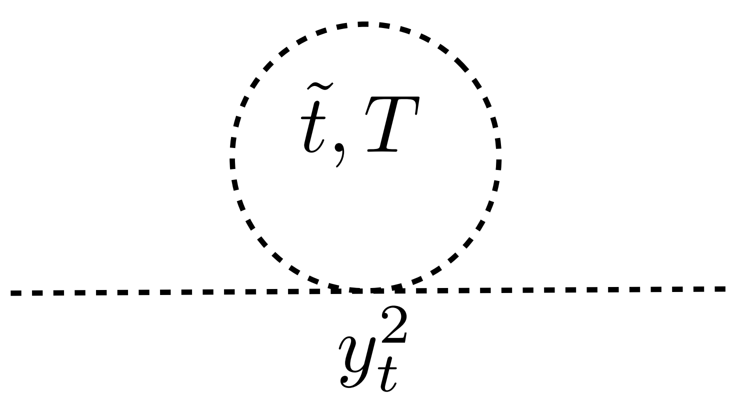
$\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\mathrm{SM}}^2 \sim 10^{38}\mathrm{GeV}^2 (\Lambda_{\mathrm{SM}} = m_{\mathrm{Pl}})$

$\sim 10^6 \mathrm{GeV}^2 (\Lambda_{\mathrm{SM}} = 1\mathrm{TeV})$

$m_{h,\mathrm{phys}}^2 = m_{h,\mathrm{tree}}^2 + \delta m_h^2 \qquad \sim 125^2 \mathrm{GeV}^2 \sim 10^4 \mathrm{GeV}^2$

Higgs mass receives quantum corrections of the order of highest mass scale

⇒ New physics should appear around TeV scale to avoid fine tuning

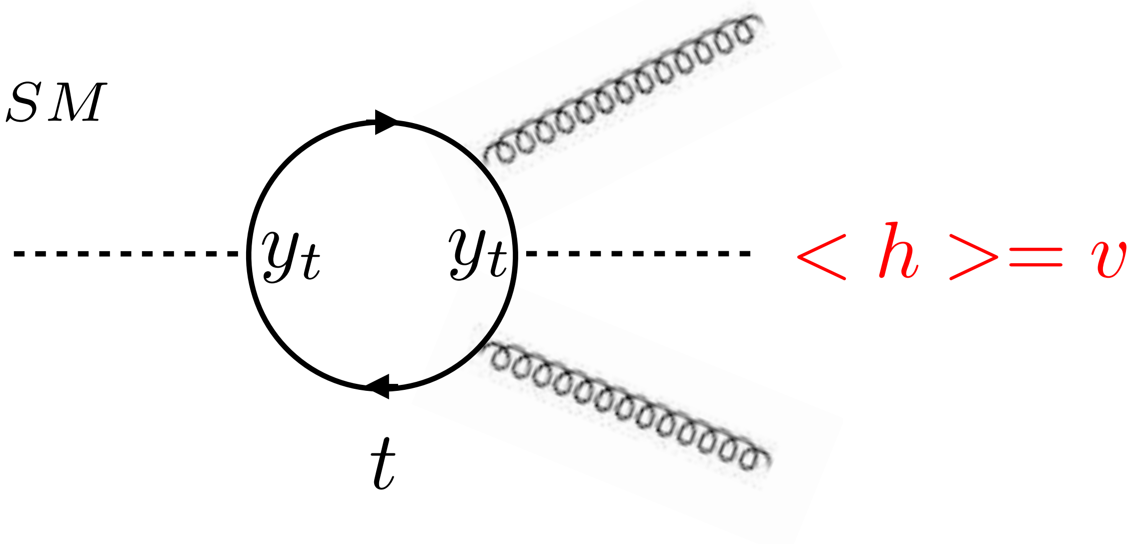
$\delta m_h^2 \sim$ 

$\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$

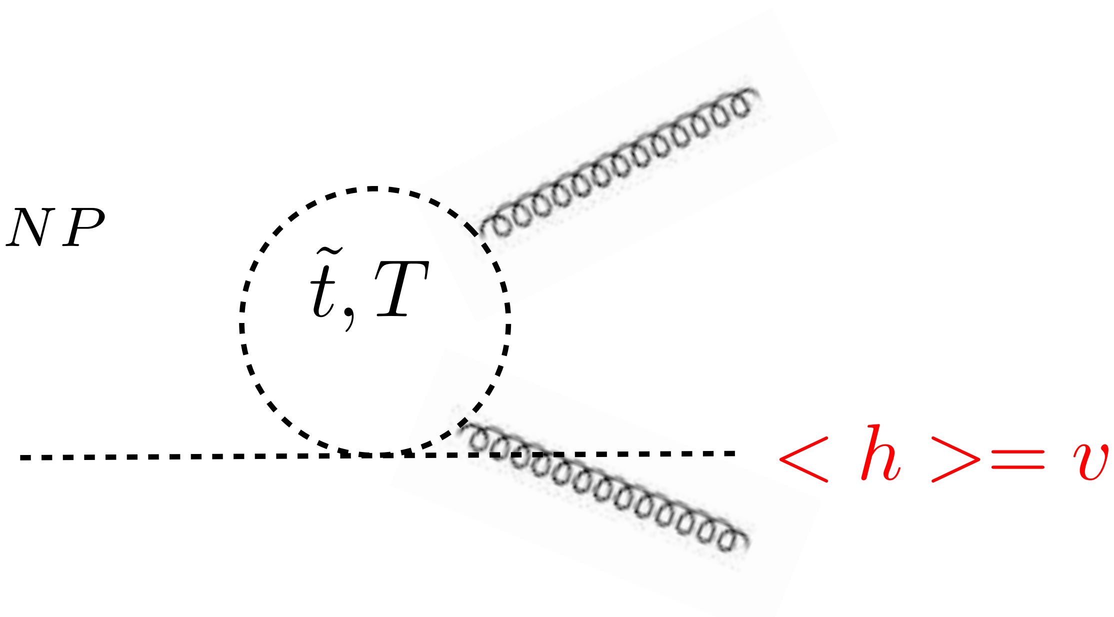
new particle, same coupling by symmetry SUSY: popular candidate
or Higgs as pNGB: Composite Higgs, strong int. at f, Top partner

Top partners affect higgs couplings?

$\mathcal{M}(h \to gg)_{SM}$

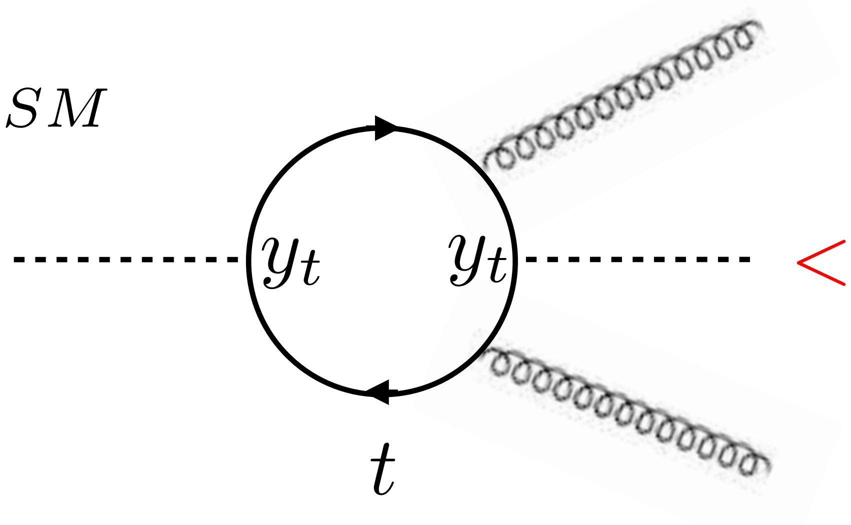


$\mathcal{M}(h \to gg)_{NP}$



Top partners affect higgs couplings?

$\mathcal{M}(h \to gg)_{SM}$



$< h >= v$

$$\Gamma(h \to gg) = \frac{\alpha_s m_h^3}{128\pi^2} |\mathcal{A}_{gg}|^2$$

$$\mathcal{A}_{gg} = \frac{1}{v} \sum_q A_{1/2}(\tau_q)$$

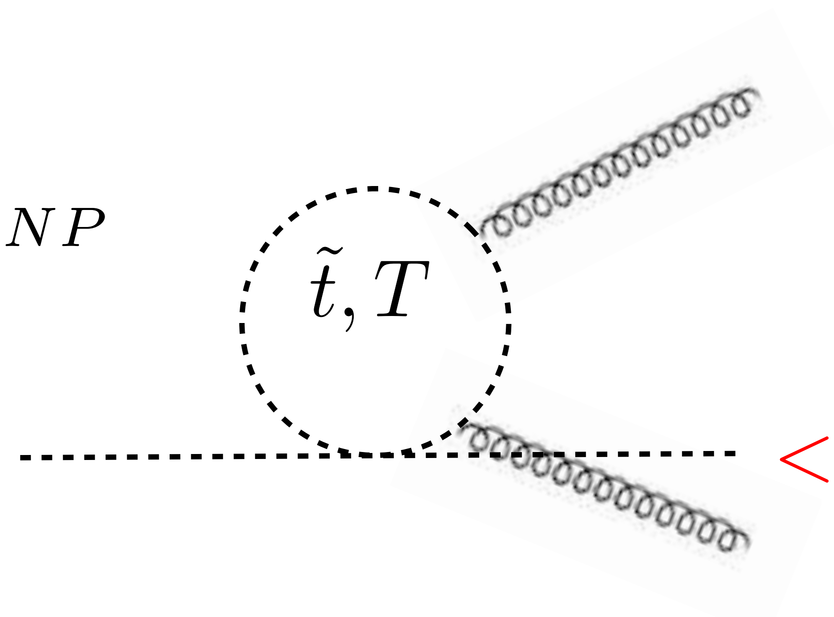
$$\tau = 4m_q^2/m_H^2$$

$$A_{1/2}(\tau) = 2\tau[1 + (1-\tau)f(\tau)] \quad \to \frac{4}{3}$$

$$f(\tau) = \arcsin^2 \sqrt{1/\tau} \quad (\tau \geq 1)$$

$$f(\tau) = -\frac{1}{4} \log \left[\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right]^2 \quad (\tau < 1)$$

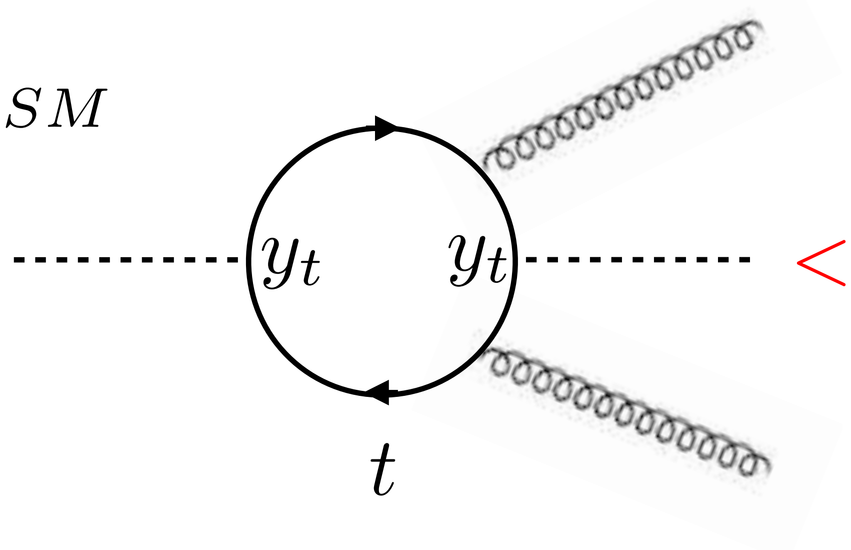
$\mathcal{M}(h \to gg)_{NP}$



$< h >= v$

Top partners affect higgs couplings?

$\mathcal{M}(h \to gg)_{SM}$



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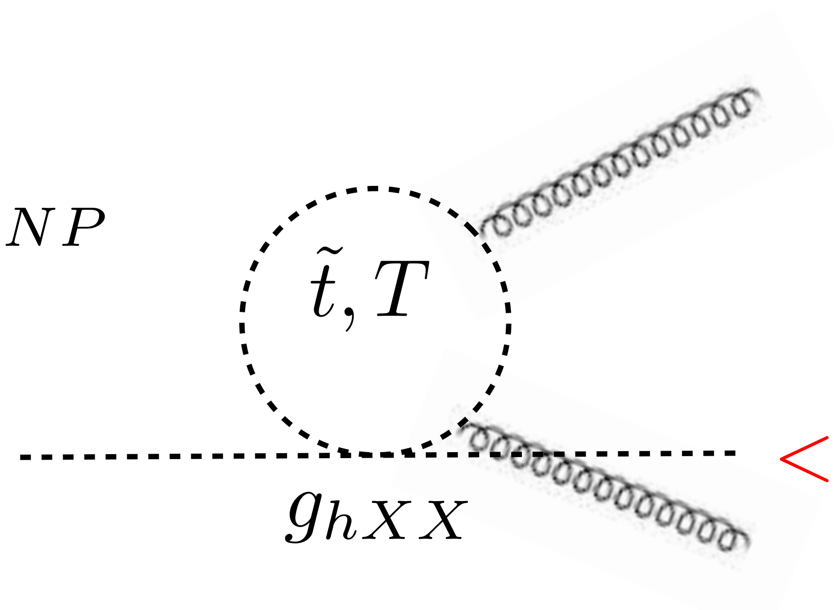
$\mathcal{M}(h \to gg)_{NP}$



$< h >= v$

$$\Delta\mathcal{A}_{gg} = \frac{g_{hXX}}{m_X}A_{1/2}(\tau_X)$$

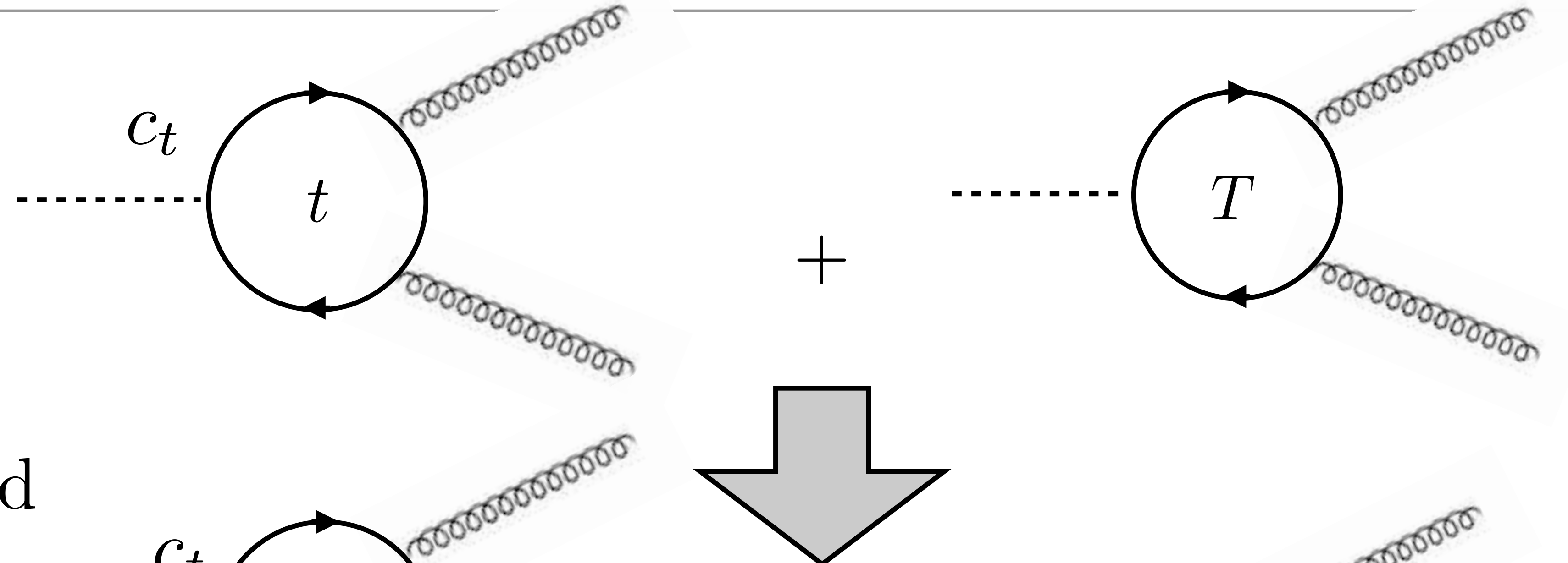
$$\Delta\mathcal{A}_{gg} = \frac{g_{hXX}}{2m_X^2}A_{0,1}(\tau_X)$$

$$A_1(\tau) = -[2 + 3\tau + 3\tau(2-\tau)f(\tau)] \to -7$$

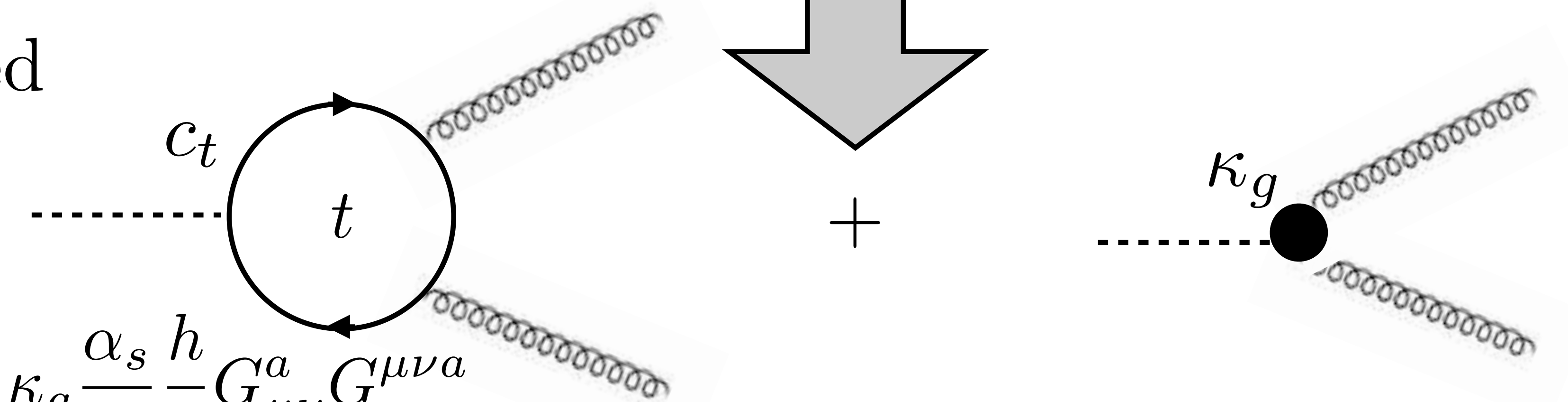
$$A_0(\tau) = -\tau[1 - \tau f(\tau)] \quad \to \frac{1}{3}$$

Effective Lagrangian for higgs physics

UV theory

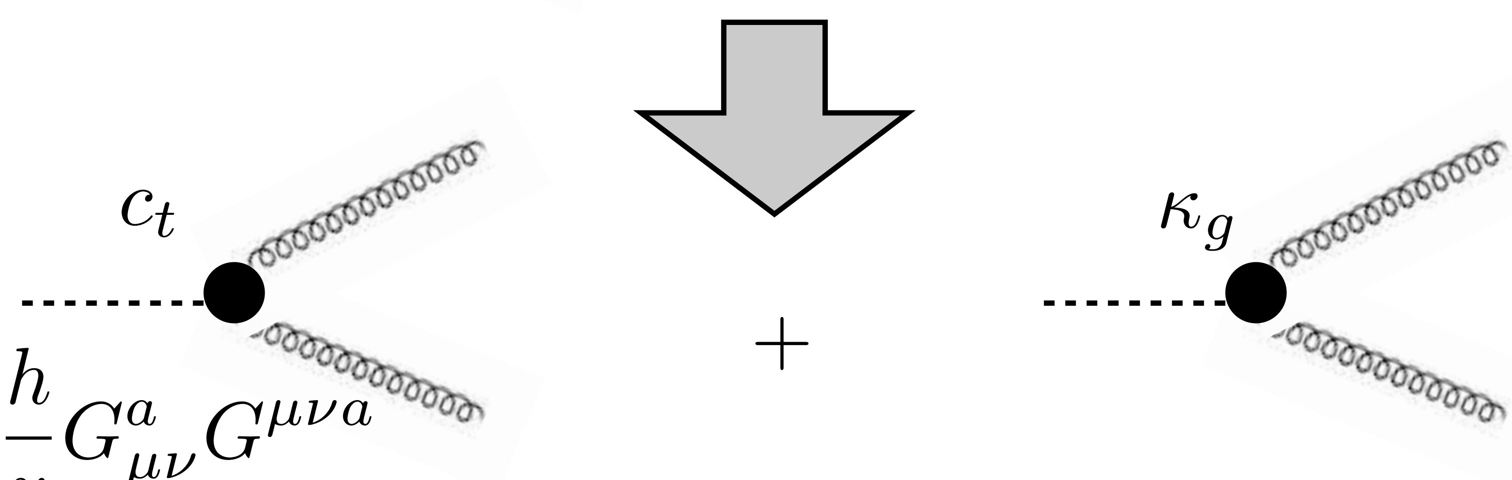


top partner decoupled



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - c_t \frac{m_t}{v} \bar{t} t h + \kappa_g \frac{\alpha_s}{12} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu a}$$

top decoupled (at m_H)



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + (c_t + \kappa_g) \frac{\alpha_s}{12} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu a}$$

what we measure in inclusive $H \to gg$ is $\kappa_g^{\text{eff}} = c_t + \kappa_g$

Composite Higgs model example

Interestingly, we have $c_t + \kappa_g = 1 - \mathcal{O}(\xi)$ in many CH models ($\xi = v^2/f^2$)

independent of top partner mass m_T

$SO(5)/SO(4)$ minimal composite Higgs model

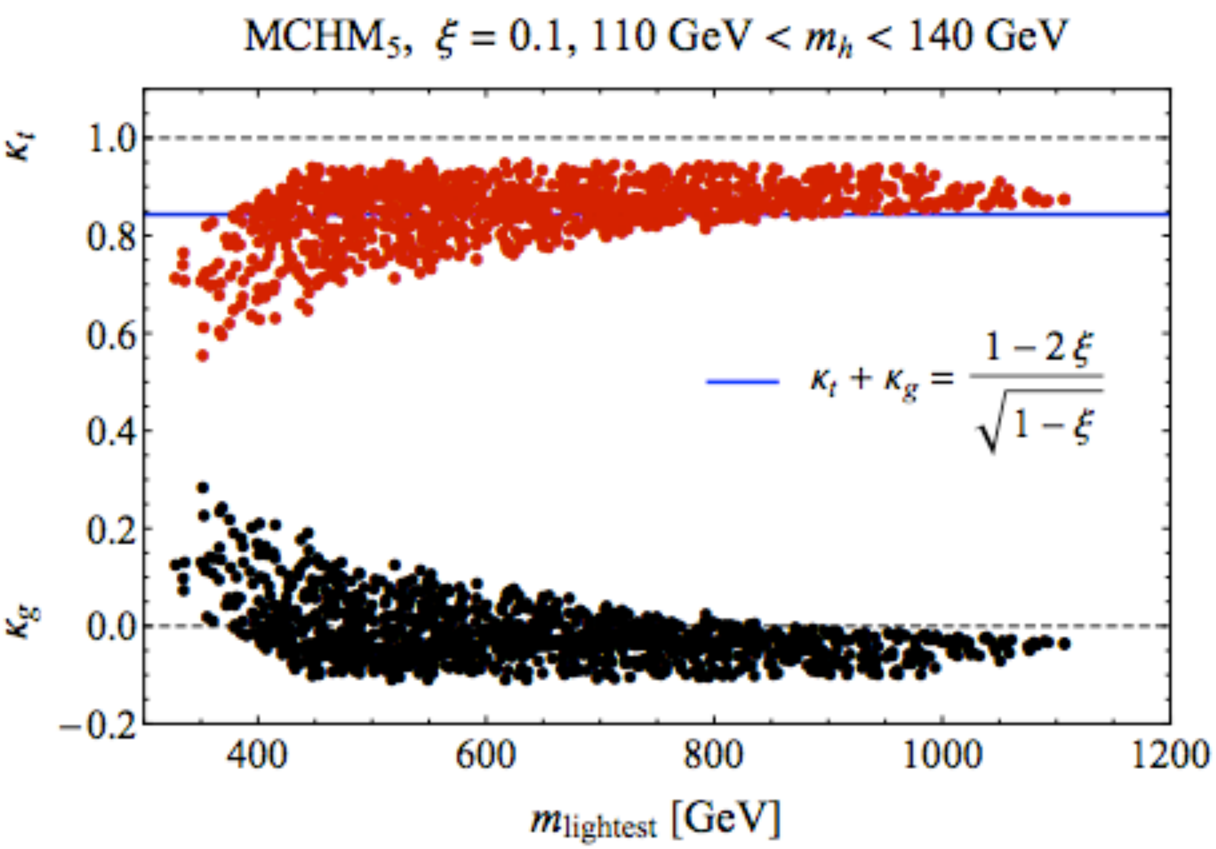
$$\Sigma = \Sigma_0 e^{i\Pi/f}\ , \quad \Sigma_0 = (0,0,0,0,1)\ , \quad \Pi = i\begin{pmatrix} 0_4 & -\vec{h} \\ \vec{h}^T & 0 \end{pmatrix}$$

Top sector

$$(\bar{t}_L\, \bar{T}_L)\begin{pmatrix} \frac{y_t h}{\sqrt{2}} & \Delta \\ 0 & M \end{pmatrix}_{h=v}\begin{pmatrix} t_R \\ T_R \end{pmatrix}$$

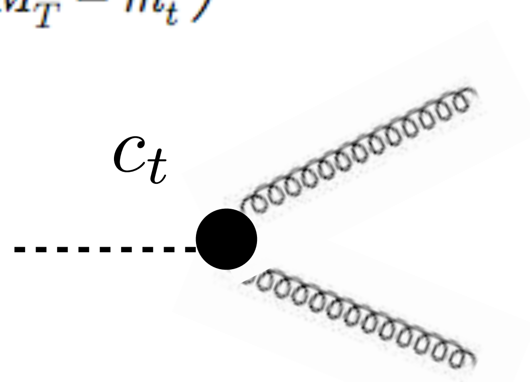
$$\xrightarrow{\text{diagonalize}} \quad h\bar{t}t : \frac{m_t}{v}\cos^2(\theta_R), \quad h\overline{T}T : \frac{M_T}{v}\sin^2(\theta_R)$$

$$\theta_R = \frac{1}{2}\arcsin\left(\frac{2m_t M_T \eta}{M_T^2 - m_t^2}\right)$$

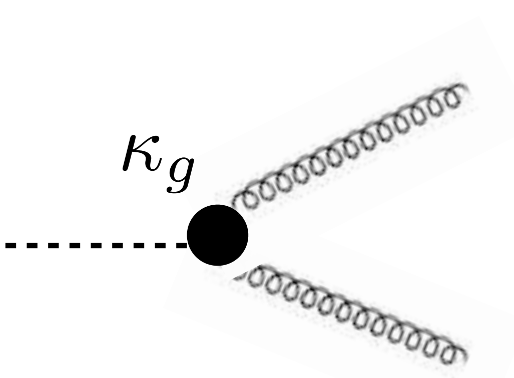


$$\Delta\mathcal{A}_{gg} = \frac{g_{hXX}}{m_X}A_{1/2}(\tau_X)$$

$$\kappa_g^{\text{eff}} = c_t + \kappa_g = 1 - \tfrac{3}{2}\xi$$



$+$



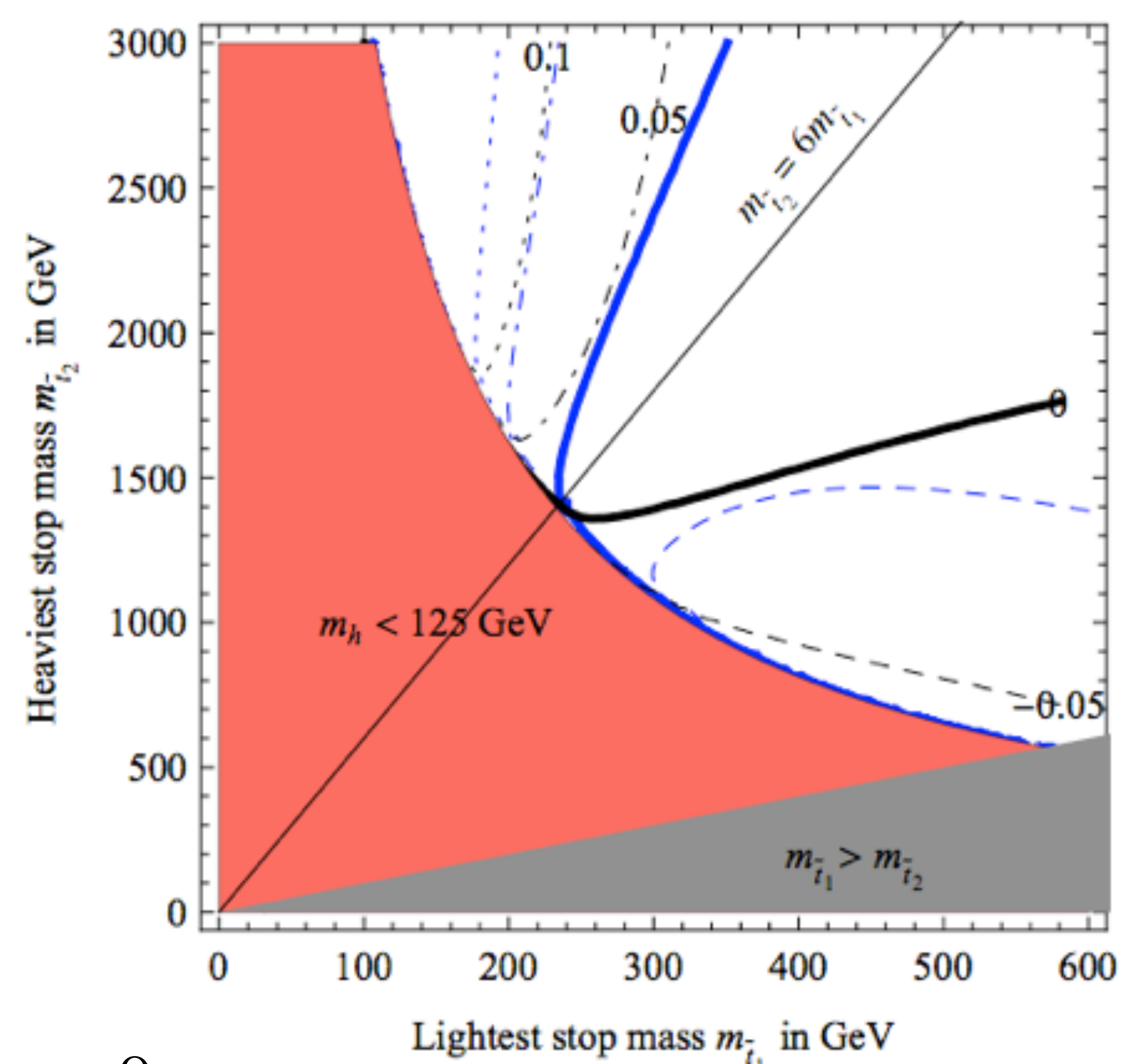
Natural SUSY

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3y_t m_t^2}{4\pi^2}\left[\log\frac{m_S^2}{m_t^2} + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$

$$X_t = \frac{A_t + \mu\cot\beta}{m_S}, m_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$m_S \sim 500 \text{ GeV and } X_t \sim \sqrt{6}$$

Antonio Delgado, Gian F. Giudice, Gino Isidori, Maurizio Pierini, Alessandro Strumia

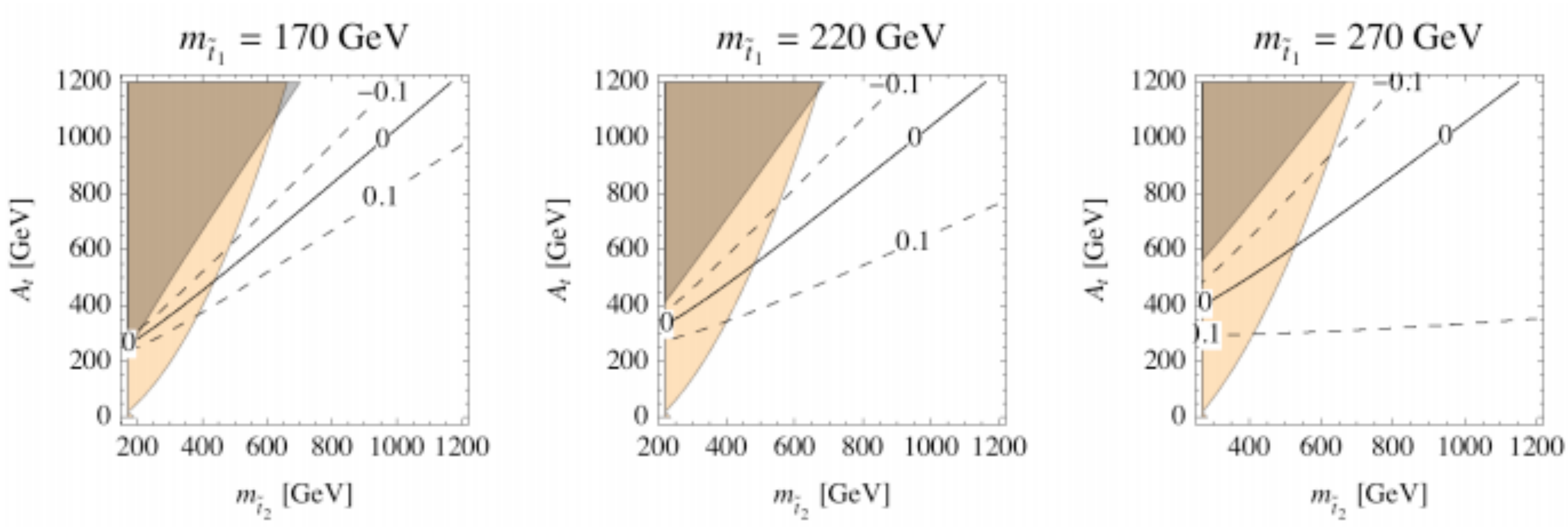


$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{SM}} = (1 + \Delta_t)^2$$

$$\Delta_t \sim \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_S^2}\right)$$

With $X_t^2 \sim 6$, $m_{\tilde{t}_2} = 6m_{\tilde{t}_1}$ gives $\Delta_t \sim 0$

Natural SUSY



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$$\Delta_t \sim \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_S^2}\right)$$

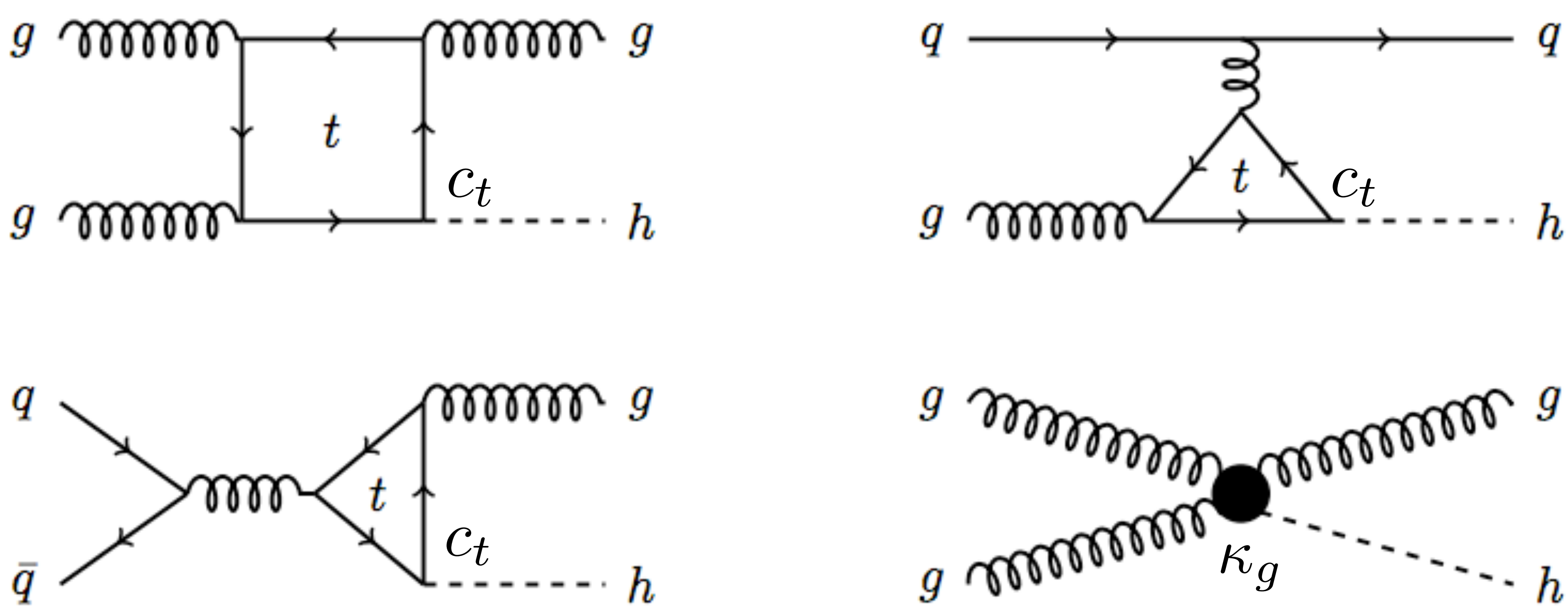
There are many models with relatively light top partner but essentially no effect in $\Gamma(h \to gg)$

Off-shell gluon breaks top loops

arXiv:1405.4295 M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - c_t \frac{m_t}{v} \bar{t}th + \kappa_g \frac{\alpha_s}{12} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu a}$$

$$\mathcal{M}(c_t, \kappa_g) = c_t \mathcal{M}(m_t) + \kappa_g \mathcal{M}(\infty)$$



on-shell gluon amplitude has only scale m_H
(only τ_X is sensitive to the mass but very weak)

gluon off-shellness can probe the mass scale in the loop.

H + j : $p_{T,H}$ distribution is the observable

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$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [fb]	δ	ϵ	gg, qg [%]
14	100	2180	0.0031	0.031	67, 31
	150	837	0.070	0.13	66, 32
	200	351	0.20	0.30	65, 34
	250	157	0.39	0.56	63, 36
	300	74.9	0.61	0.89	61, 38
	350	37.7	0.85	1.3	58, 41
	400	19.9	1.1	1.7	56, 43
	450	10.9	1.4	2.3	54, 45
	500	6.24	1.7	2.9	52, 47
	550	3.68	2.0	3.6	50, 49
	600	2.22	2.3	4.4	48, 51
	650	1.38	2.6	5.2	46, 53
	700	0.871	3.0	6.2	45, 54
	750	0.562	3.3	7.2	43, 56
	800	0.368	3.7	8.4	42, 57

$$\mathcal{M}(c_t, \kappa_g) = c_t \mathcal{M}(m_t) + \kappa_g \mathcal{M}(\infty)$$

$$\frac{\sigma(p_T^{\rm cut})}{\sigma^{SM}(p_T^{\rm cut})} = \frac{\int_{p_T^{\rm cut}}^{\infty} dp_T d\Omega |c_t \mathcal{M}_{IR}(m_t) + \kappa_g \mathcal{M}_{UV}|^2}{\int_{p_T^{\rm cut}}^{\infty} dp_T d\Omega |\mathcal{M}_{IR}(m_t)|^2}$$
$$= (c_t + \kappa_g)^2 + \delta(p_T^{\rm cut}) c_t \kappa_g + \epsilon(p_T^{\rm cut}) \kappa_g^2,$$

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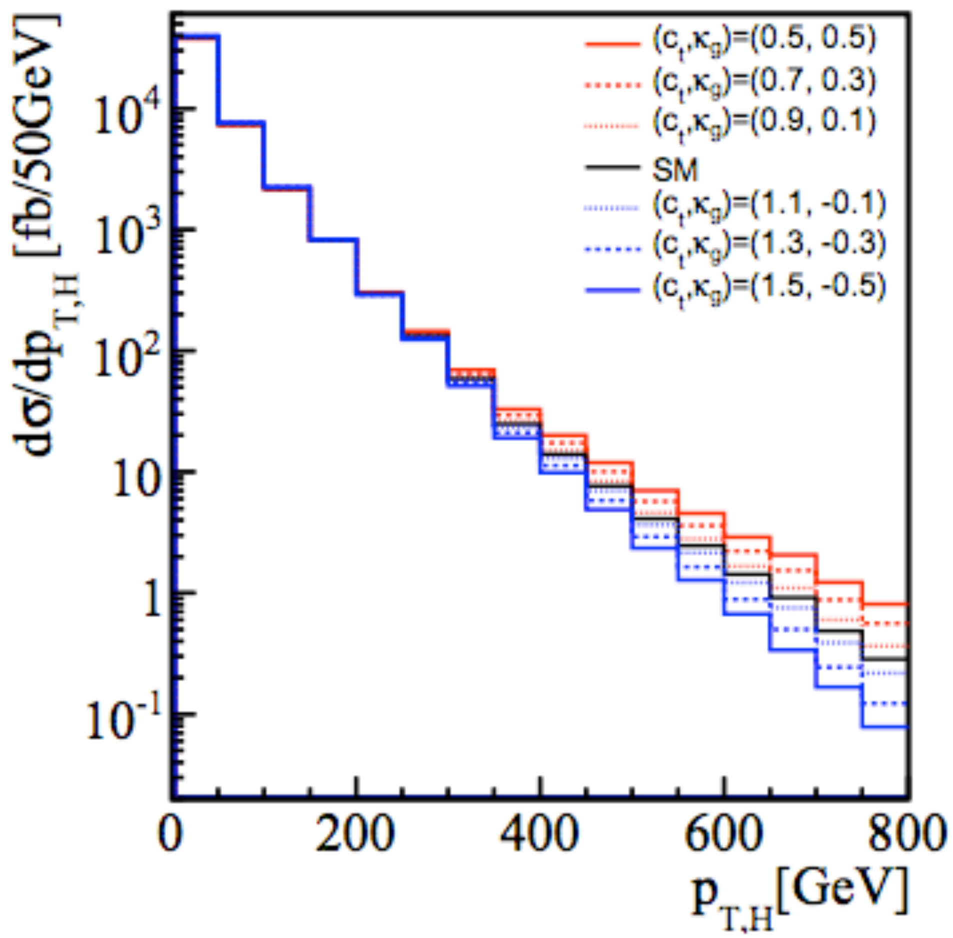

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$$= (c_t+\kappa_g)^2 + \delta(p_T^{\rm cut})c_t\kappa_g + \epsilon(p_T^{\rm cut})\kappa_g^2,$$

$SM : \mathcal{M}(1,0)$ $\qquad$ $LOMC : \mathcal{M}(0,1)$

reweight with $\frac{|\mathcal{M}(c_t,\kappa_g)|^2}{|\mathcal{M}(0,1)|^2}$

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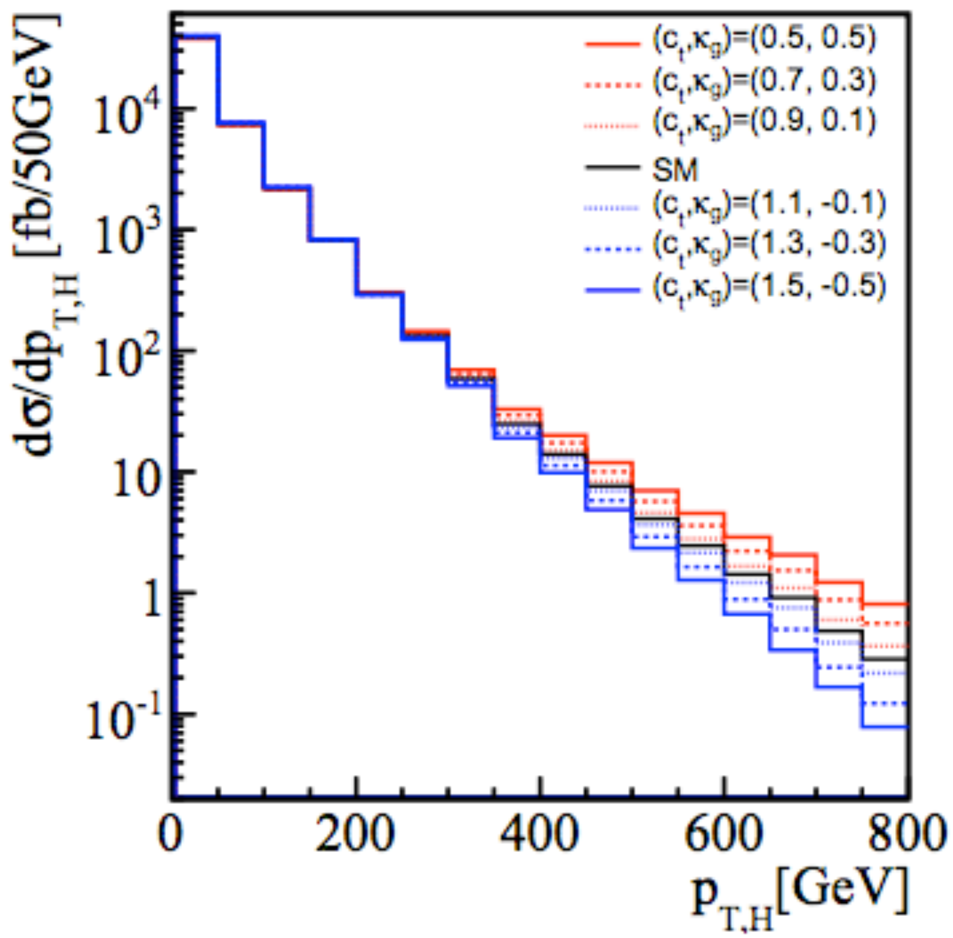

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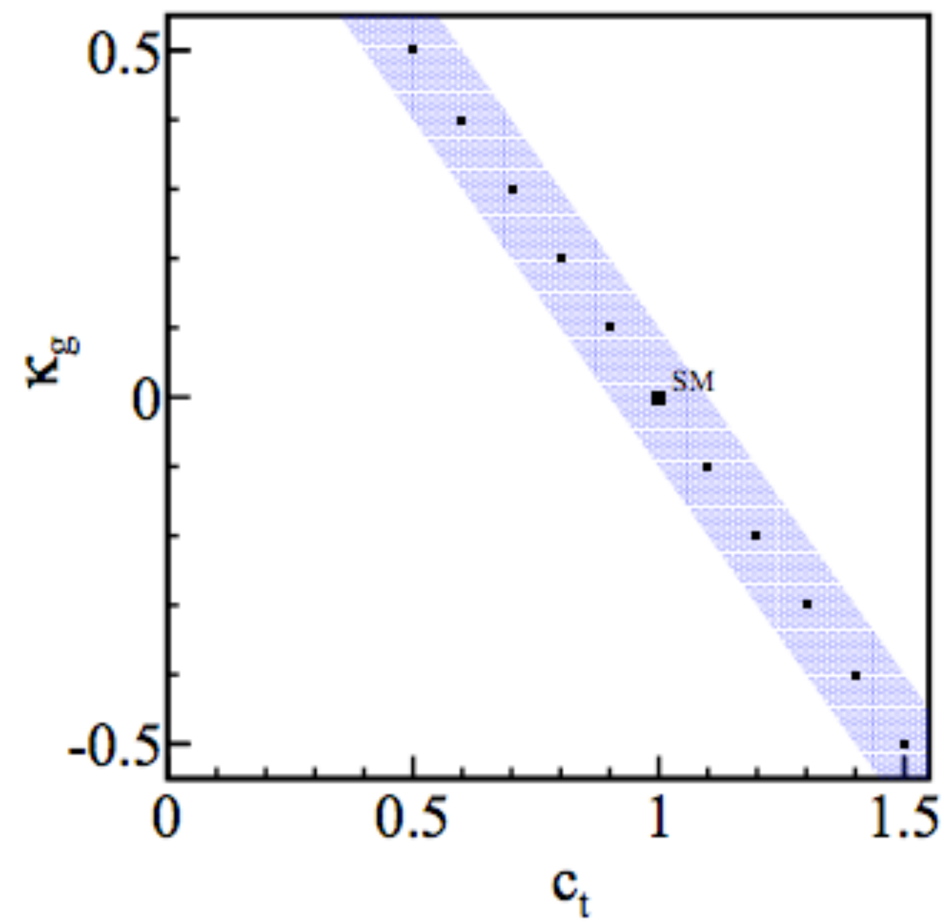

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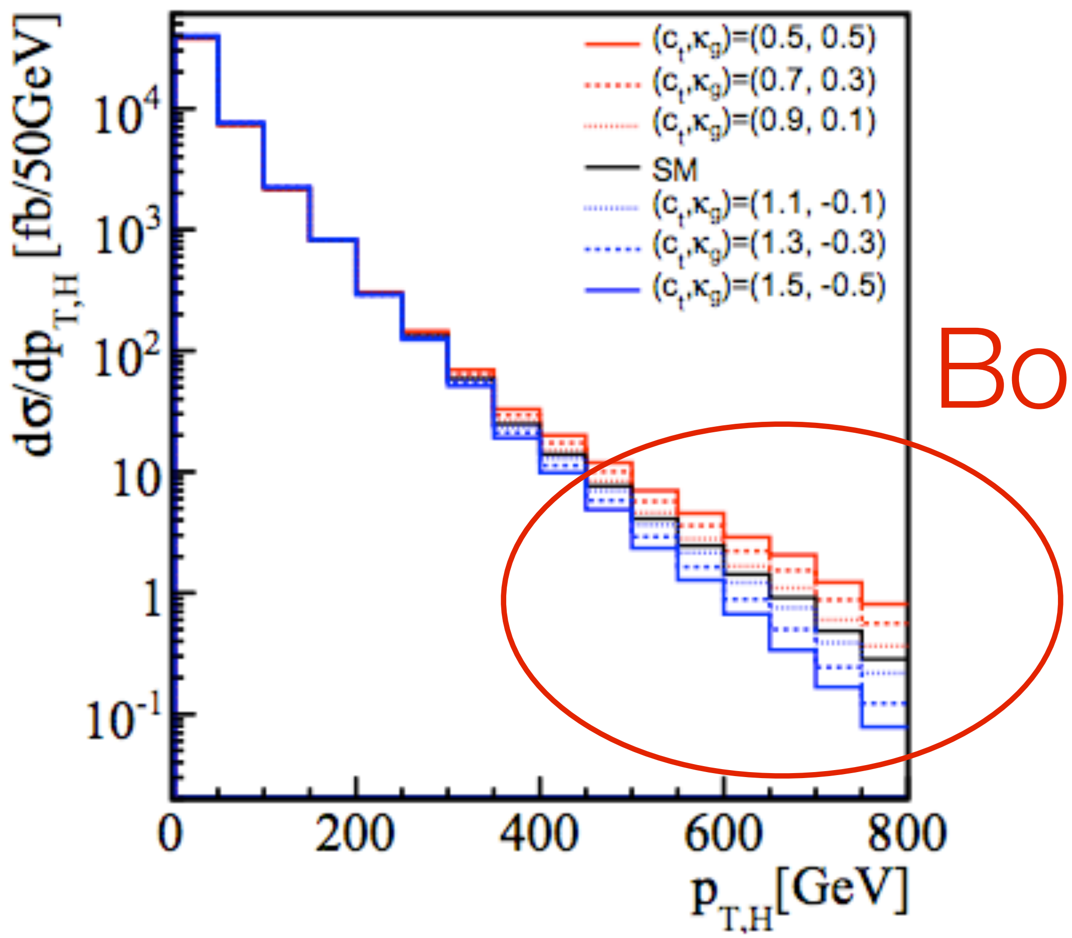

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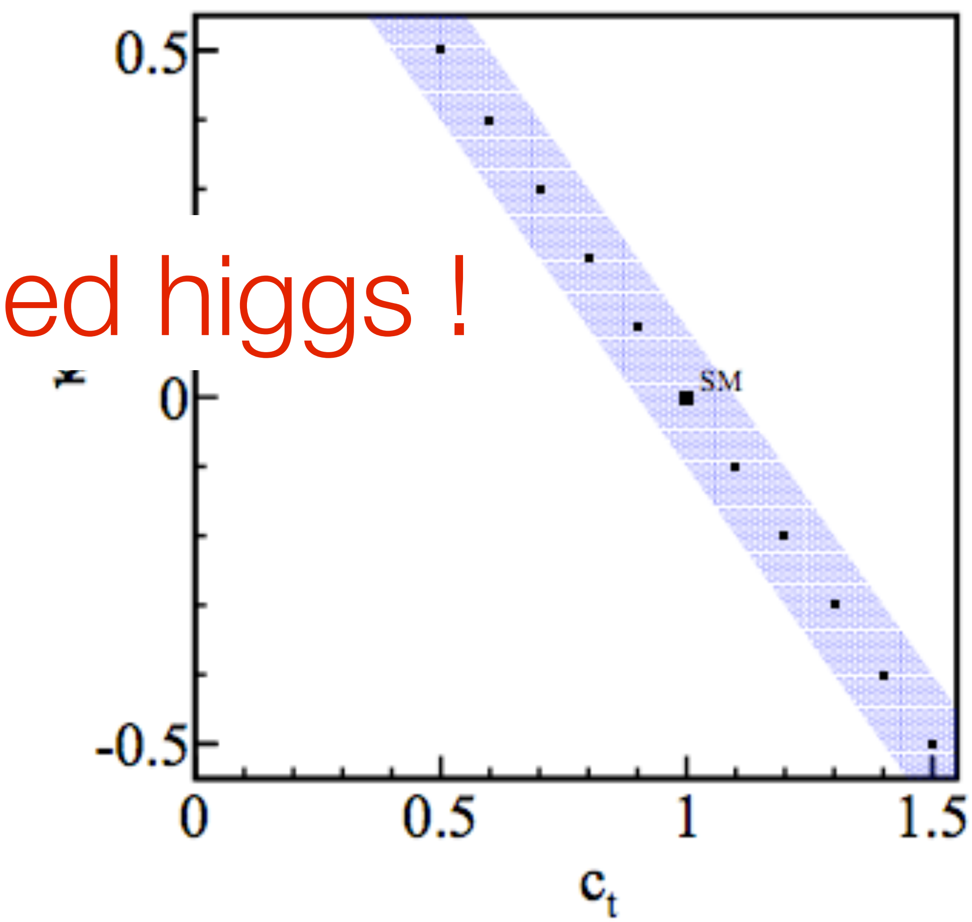
Boosted higgs !



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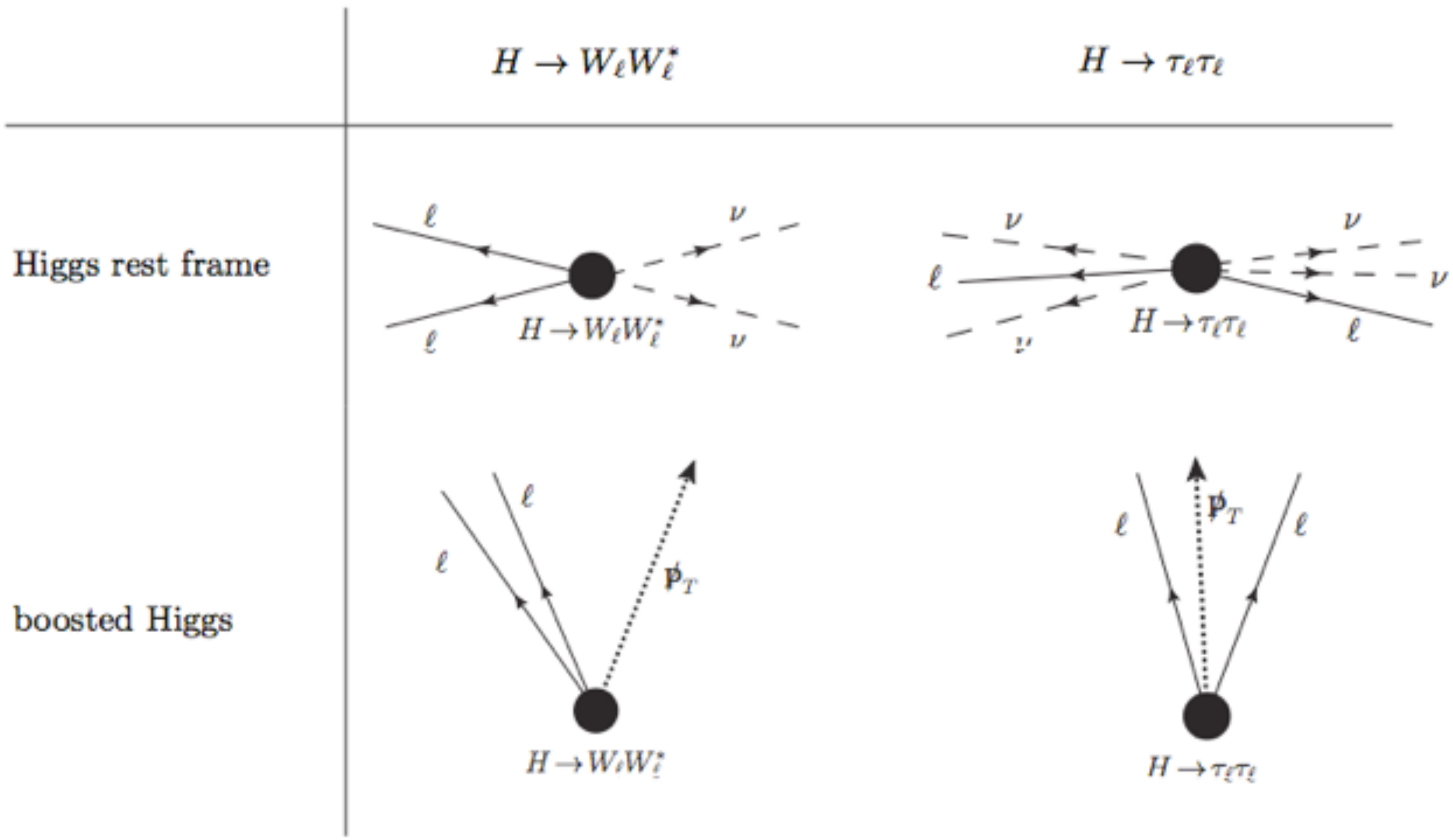
$H+\mathrm{j}:\quad p_{T,H}$ distribution is the observable

How higgs boost helps

arXiv:1405.4295 M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant

For 125 GeV higgs, $BR(b\bar{b}) \sim 60\%$, $BR(W^+W^-) \sim 20\%$, $BR(\tau^+\tau^-) \sim 6\%$,



$H \to \tau\tau$ BR is large and can reconstruct using $\not{E}_T$

Collinear approx. $\mathbf{p}_\nu = \alpha \mathbf{p}_\ell \quad (\alpha > 0)$ thanks to $m_\tau \ll m_H$

We consider di-lepton channel $(ee, e\mu, \mu\mu) + \not{E}_T$ from $\tau\tau$

How far can we measure under BG presence?

$H \to \tau\tau$ ($p_{T,H} > 0$ GeV) 3.15 pb

BG: WW+jets, Z+jets, $t\bar{t}$+jets,

- WW+jets: 2 jets merged, $p_{T,j_1} > 150$ GeV, $W \to e, \mu, \tau$ 0.6 pb
- Z+jets: 2 jets merged, $p_{T,j_1} > 150$ GeV, only $Z \to \tau\tau$ 10 pb
- $t\bar{t}$+jets: 0 + 1 jet merged 918 pb

Basic selection cut:

$$n_\ell = 2,\ \text{opposite-sign},\ m_{\ell\ell} > 20\text{GeV},\ p_{T,H}^{\rm rec} > 200\ \text{GeV},\ n_j^{\rm fat} = 1,\ n_b = 0$$

$$\mathbf{p}_{T,H}^{\rm rec} = \mathbf{p}_{T,\ell_1} + \mathbf{p}_{T,\ell_2} + \not{\mathbf{p}}_T$$

Cut flow

Event rate [fb]	$H\to\tau\tau$	$H\to WW^*$	$W_\ell W_\ell$+jets	$Z_{\to\tau\tau}$+jets	$t_\ell\bar{t}_\ell$+jets	S/B	$S/\sqrt{B}$
0. Nominal cross-section	3149.779	10719.207	580.000	$1.01\cdot10^4$	$1.02\cdot10^5$	–	–
1. $n_\ell=2$, opposite-sign	118.043	323.531	195.033	347.516	$3.72\cdot10^4$	–	–
2. $m_{\ell\ell}>20$ GeV	117.733	264.723	189.522	315.201	$3.57\cdot10^4$	–	–
3. $p_{T,H}^{\rm rec}>200$ GeV	1.987	3.834	91.273	104.434	$1.28\cdot10^3$	0.004	2.62
4. $n_j^{\rm fat}=1$ ($p_{T,j}>200$ GeV)	0.957	1.858	50.443	58.810	395.602	0.006	2.17
5. $n_b=0$	0.940	1.825	48.855	57.068	105.851	0.01	3.29

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$$\mathbf{p}_{T,H}^{\rm rec} = \mathbf{p}_{T,\ell_1} + \mathbf{p}_{T,\ell_2} + \not{\mathbf{p}}_T$$

WW, Z, $t\bar{t}$ contribute at similar level

Cut flow

Event rate [fb]	$H\to\tau\tau$	$H\to WW^*$	$W_\ell W_\ell$+jets	$Z_{\to\tau\tau}$+jets	$t_\ell\bar{t}_\ell$+jets	S/B	$S/\sqrt{B}$
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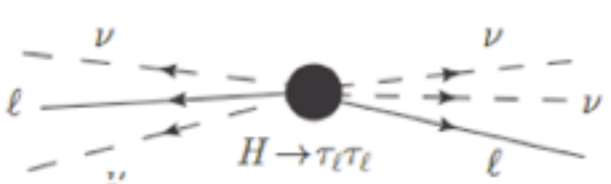
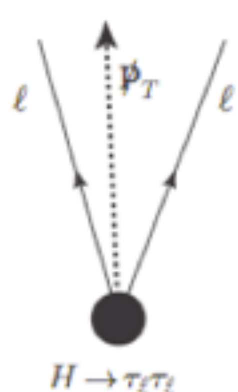
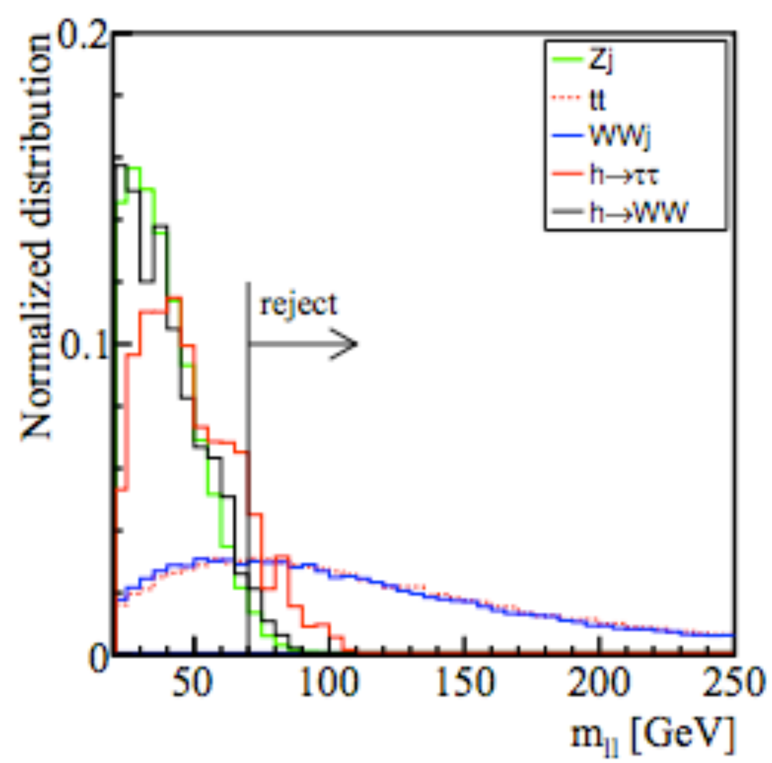
6. $\not{p}_T$ inside the two leptons	0.923	0.533	20.215	55.551	44.050	0.01	2.30
7. $m_{\ell\ell} < 70$ GeV	0.796	0.490	3.860	53.985	8.511	0.02	2.73







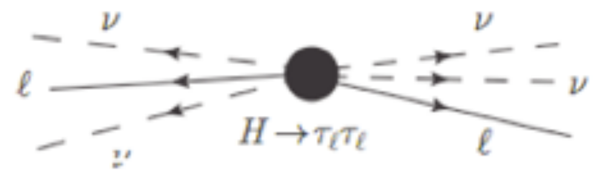
Z+jets becomes dominant BG

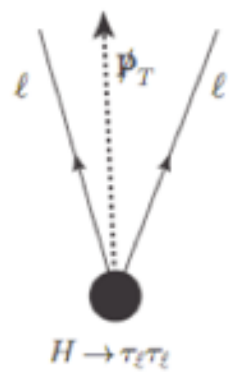
How boost helps, M_col distribution

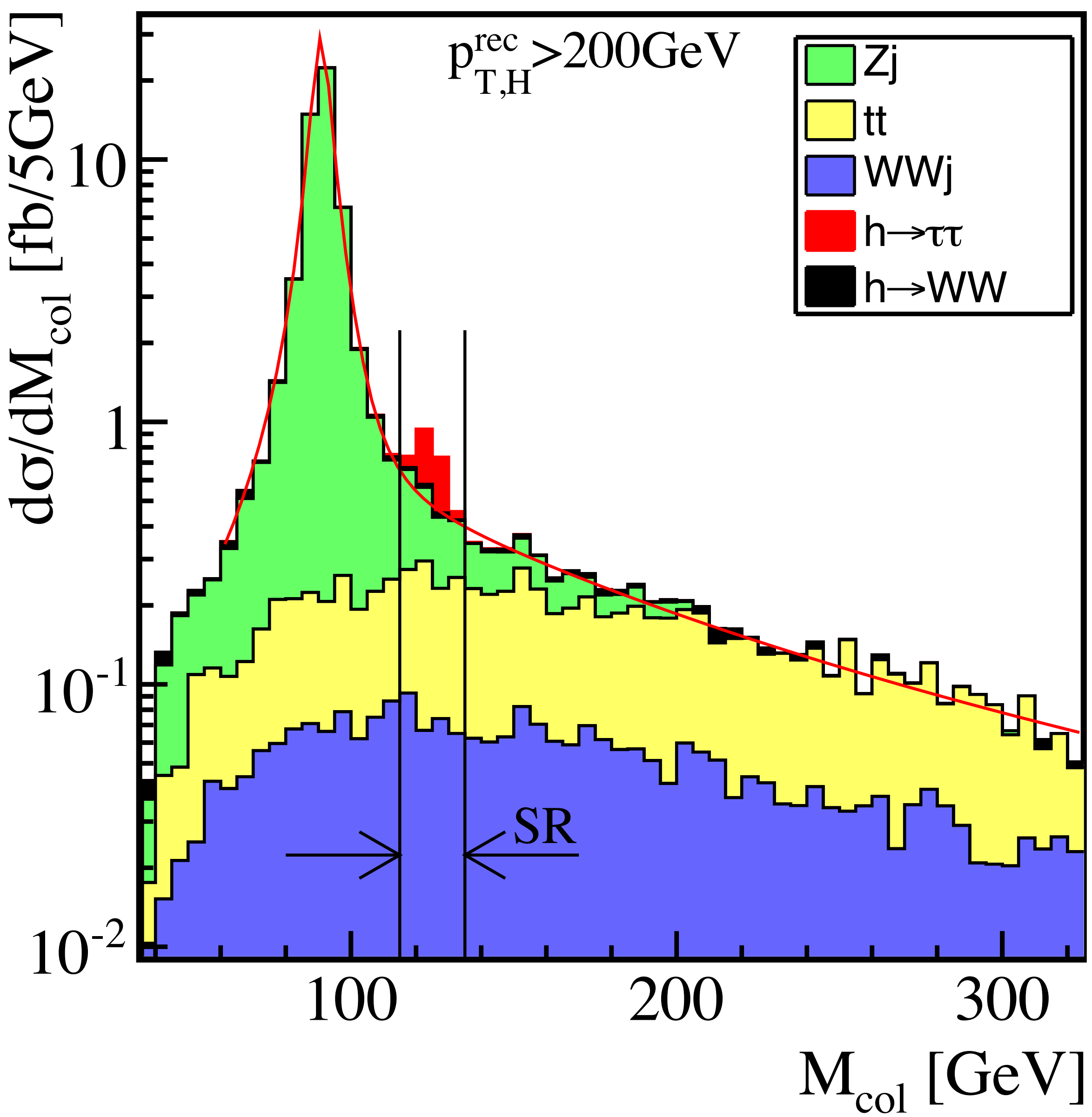
Collinear approx.

$$\not{\mathbf{p}}_T = \mathbf{p}_{T,\nu_1} + \mathbf{p}_{T,\nu_2}$$

$$\mathbf{p}_{\nu_1} = \alpha_1 \mathbf{p}_{\ell_1},\ \mathbf{p}_{\nu_2} = \alpha_2 \mathbf{p}_{\ell_2} \qquad (\alpha_1, \alpha_2 > 0)$$







$$p_{\text{col}} = p_{\nu_1} + p_{\nu_2} + p_{\ell_1} + p_{\ell_2}$$

$$M^2_{\text{col}} = p^2_{\text{col}}$$

thanks to $m_\tau \ll m_H$

We see also $m_Z \to \tau\tau$ peak

H to tau tau results

Event rate [fb]	$H \to \tau\tau$	$H \to WW^*$	$W_\ell W_\ell$+jets	$Z_{\to\tau\tau}$+jets	$t_\ell \bar{t}_\ell$+jets	S/B	$S/\sqrt{B}$
0. Nominal cross-section	3149.779	10719.207	580.000	$1.01 \cdot 10^4$	$1.02 \cdot 10^5$	–	–
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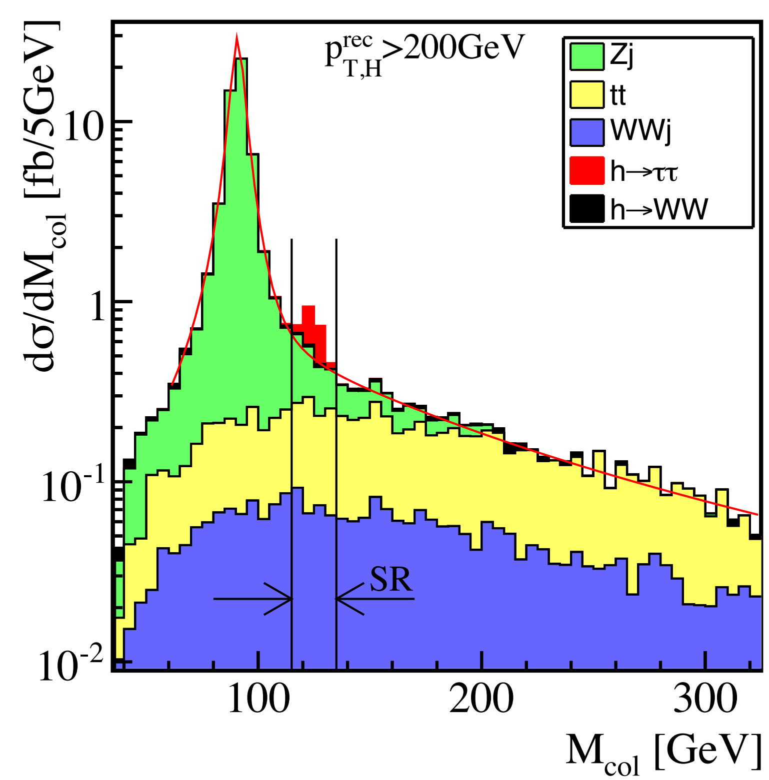
7. $m_{\ell\ell} < 70$ GeV	0.796	0.490	3.860	53.985	8.511	0.02	2.73
8. $\lvert M_{\rm col} - m_H \rvert < 10$ GeV	0.749	0.046	0.298	1.019	0.758	0.38	9.56

$S/B \sim 0.4$, $S/\sqrt{B} \sim 10$ for 300 fb^{-1}

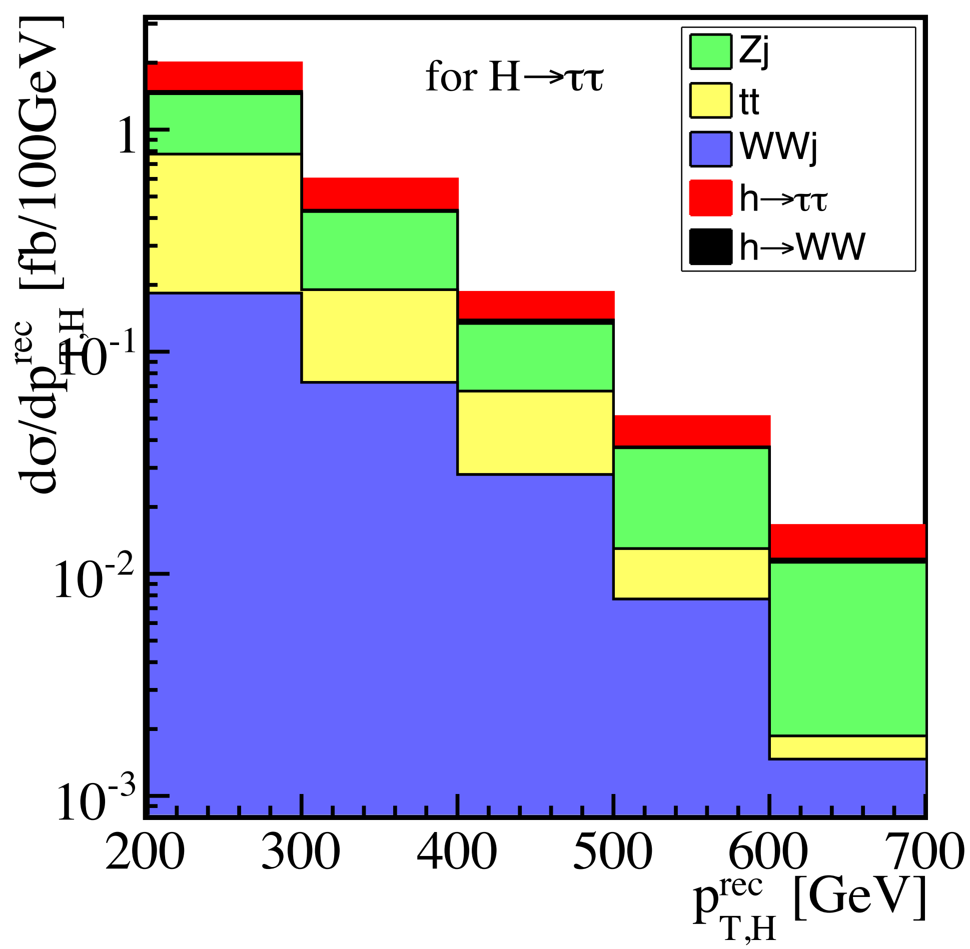
$H \to \tau\tau$ is visible



Higgs PT distribution

Event rate [fb]	$H \to \tau\tau$	$H \to WW^*$	$W_\ell W_\ell$+jets	$Z_{\to\tau\tau}$+jets	$t_\ell \bar{t}_\ell$+jets	S/B	$S/\sqrt{B}$
8. $\lvert M_{\rm col} - m_H \rvert < 10$ GeV	0.749	0.046	0.298	1.019	0.758	0.38	9.56
$p_{T,H}^{\rm rec} > 300$ GeV	0.234	0.012	0.115	0.343	0.166	0.39	5.40
$p_{T,H}^{\rm rec} > 400$ GeV	0.068	0.006	0.042	0.106	0.049	0.38	2.88
$p_{T,H}^{\rm rec} > 500$ GeV	0.021	0.001	0.014	0.038	0.010	0.36	1.55
$p_{T,H}^{\rm rec} > 600$ GeV	0.008	0.001	0.006	0.014	0.005	0.32	0.89

H momentum is reconstructed, we can observe $p_{T,H}$ dependence



$error$	$300fb^{-1}$	$3ab^{-1}$
$\sigma(p_{T,H} > 200\text{GeV})$	12%	4%
$\sigma(p_{T,H} > 300\text{GeV})$	22%	7%
$\sigma(p_{T,H} > 400\text{GeV})$	41%	13%

Event rate [fb]	$H \to \tau\tau$	$H \to WW^*$	$W_\ell W_\ell$+jets	$Z_{\to\tau\tau}$+jets	$t_\ell \bar{t}_\ell$+jets	S/B	$S/\sqrt{B}$
6. $\not{p}_T$ inside the two leptons	0.923	0.533	20.215	55.551	44.050	0.01	2.30
7. $m_{\ell\ell} < 70$ GeV	0.796	0.490	3.860	53.985	8.511	0.02	2.73
8. $\|M_{\rm col} - m_H\| < 10$ GeV	0.749	0.046	0.298	1.019	0.758	0.38	9.56
$p_{T,H}^{\rm rec} > 300$ GeV	0.234	0.012	0.115	0.343	0.166	0.39	5.40
$p_{T,H}^{\rm rec} > 400$ GeV	0.068	0.006	0.042	0.106	0.049	0.38	2.88
$p_{T,H}^{\rm rec} > 500$ GeV	0.021	0.001	0.014	0.038	0.010	0.36	1.55
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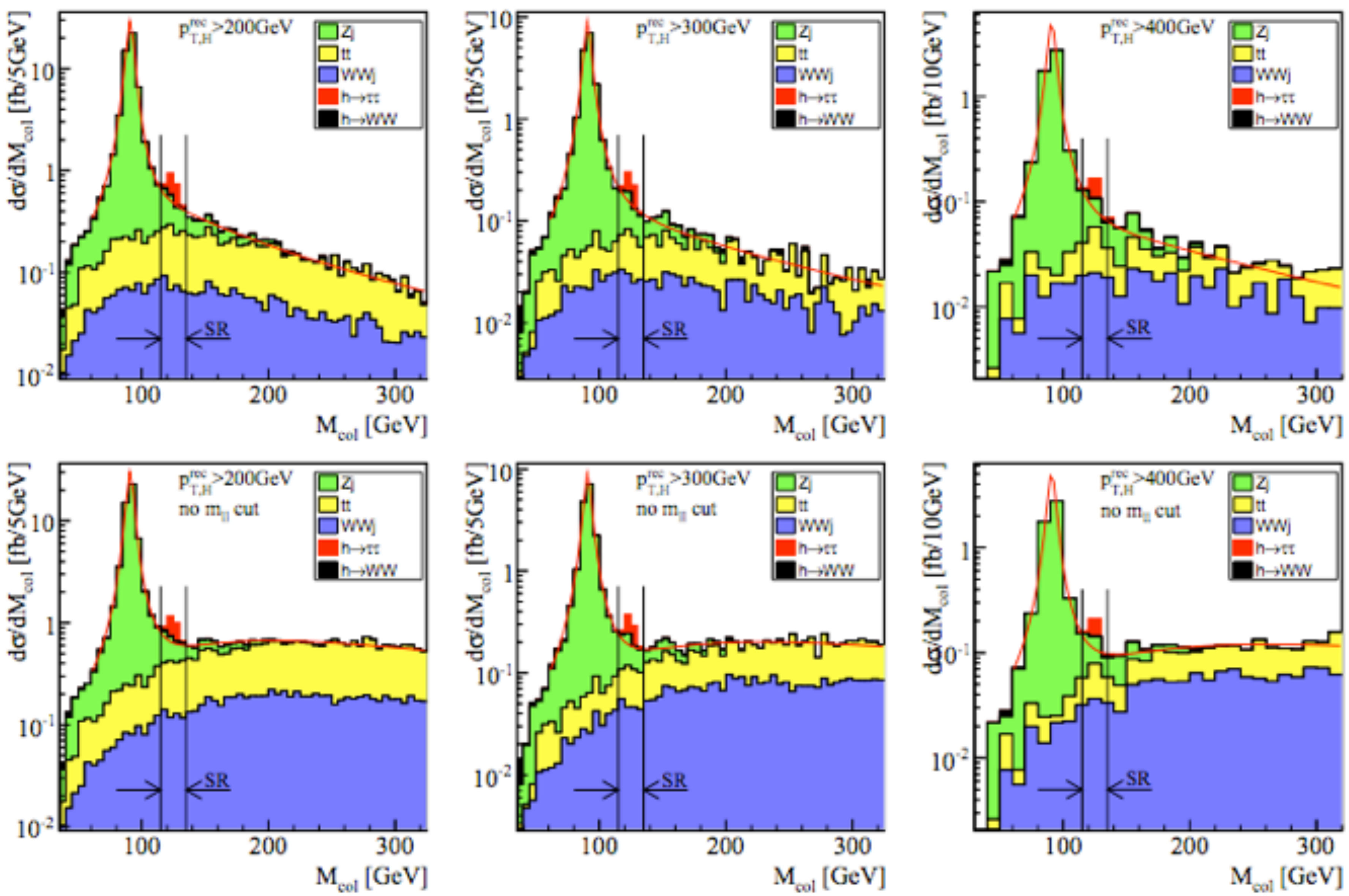


beautiful side band

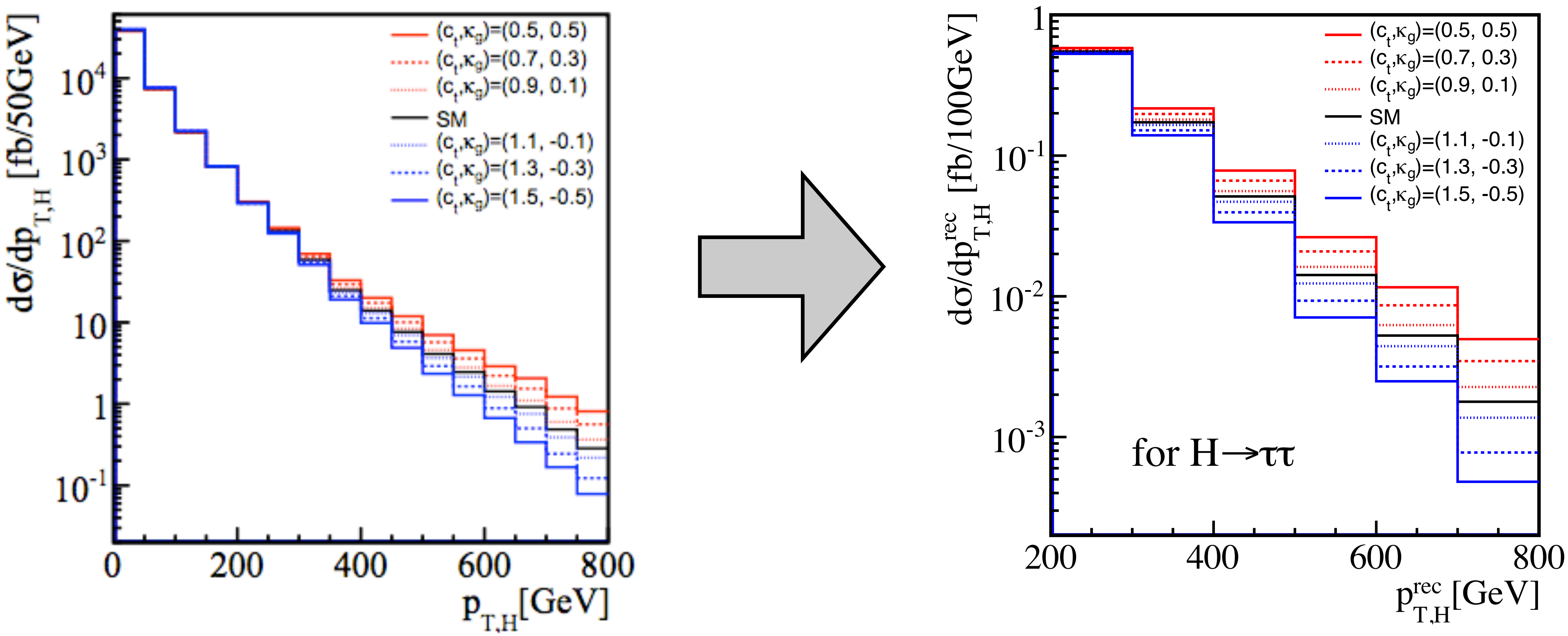
removing $m_{\ell\ell}$ cut

WW, $t\bar{t}$ contribution

we can estimate

New physics sensitivity

With the same cut flow, enhanced in high $p_{T,H}$ since optimised for boosted H



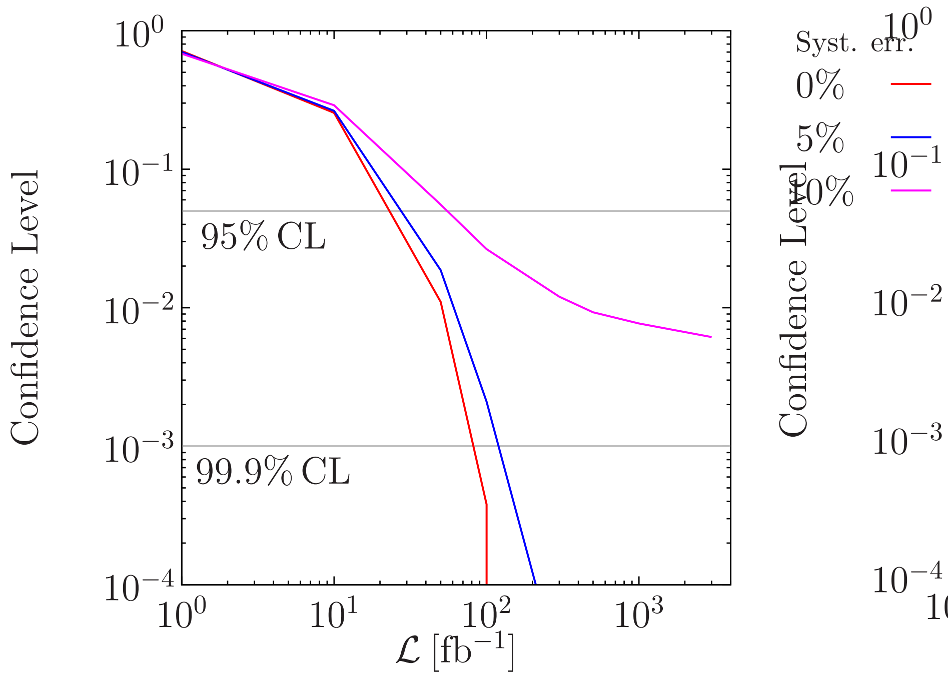
Model point (κ_g)	0.5	0.4	0.3	0.2	0.1	0 (SM)	-0.1	-0.2	-0.3	-0.4	-0.5
3. $p_{T,H}^{\rm rec} > 200$ GeV	1.109	1.084	1.061	1.039	1.019	1.000	0.983	0.968	0.954	0.942	0.932
4. $n_j^{\rm fat} = 1$	1.143	1.110	1.079	1.050	1.024	1.000	0.978	0.959	0.941	0.926	0.913
5. $n_b = 0$	1.143	1.110	1.079	1.050	1.024	1.000	0.978	0.959	0.941	0.926	0.913
6. $\not{p}_T$ inside two ℓs	1.156	1.120	1.086	1.055	1.026	1.000	0.976	0.954	0.935	0.918	0.903
7. $m_{\ell\ell} < 70$ GeV	1.157	1.121	1.087	1.056	1.027	1.000	0.976	0.954	0.934	0.917	0.902
8. $\|M_{\rm col} - m_H\| < 10$ GeV	1.163	1.125	1.091	1.058	1.028	1.000	0.974	0.951	0.930	0.912	0.896
$p_{T,H}^{\rm rec} > 300$ GeV	1.392	1.303	1.219	1.140	1.067	1.000	0.938	0.882	0.831	0.785	0.745
$p_{T,H}^{\rm rec} > 400$ GeV	1.711	1.544	1.389	1.247	1.117	1.000	0.895	0.802	0.722	0.653	0.597
$p_{T,H}^{\rm rec} > 500$ GeV	2.131	1.857	1.607	1.381	1.179	1.000	0.845	0.715	0.608	0.525	0.465
$p_{T,H}^{\rm rec} > 600$ GeV	2.602	2.201	1.840	1.520	1.240	1.000	0.801	0.642	0.523	0.445	0.407

$\kappa_g > 0$ enhance in high $p_{T,H}$

$\kappa_g < 0$ deficit in high $p_{T,H}$

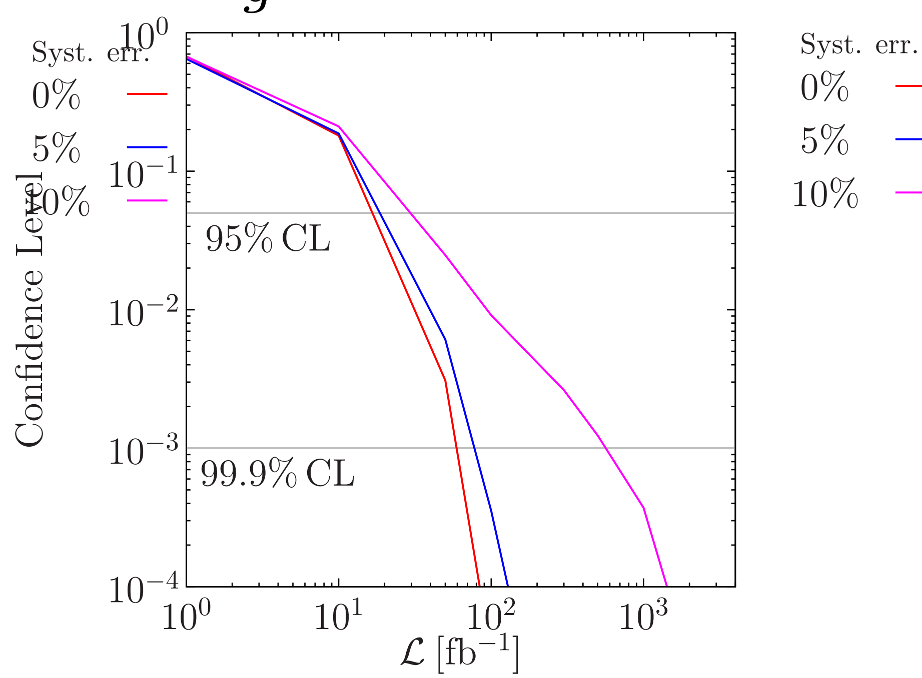
New physics sensitivity

SM vs. BG



$\mathcal{L} = 20 \sim 60\mathrm{fb}^{-1}$

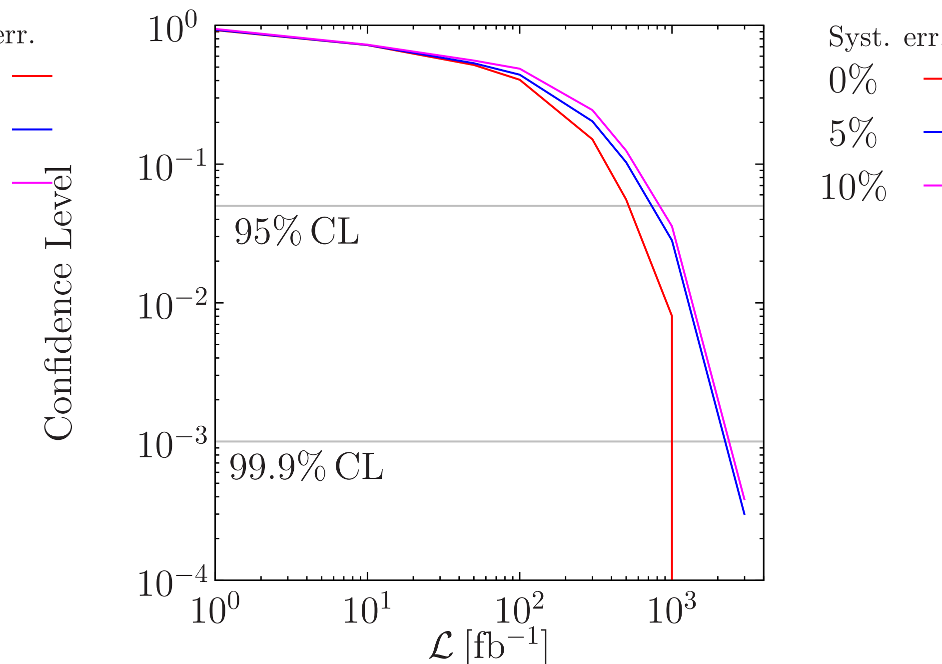
$\kappa_g = 0.5$ vs. BG



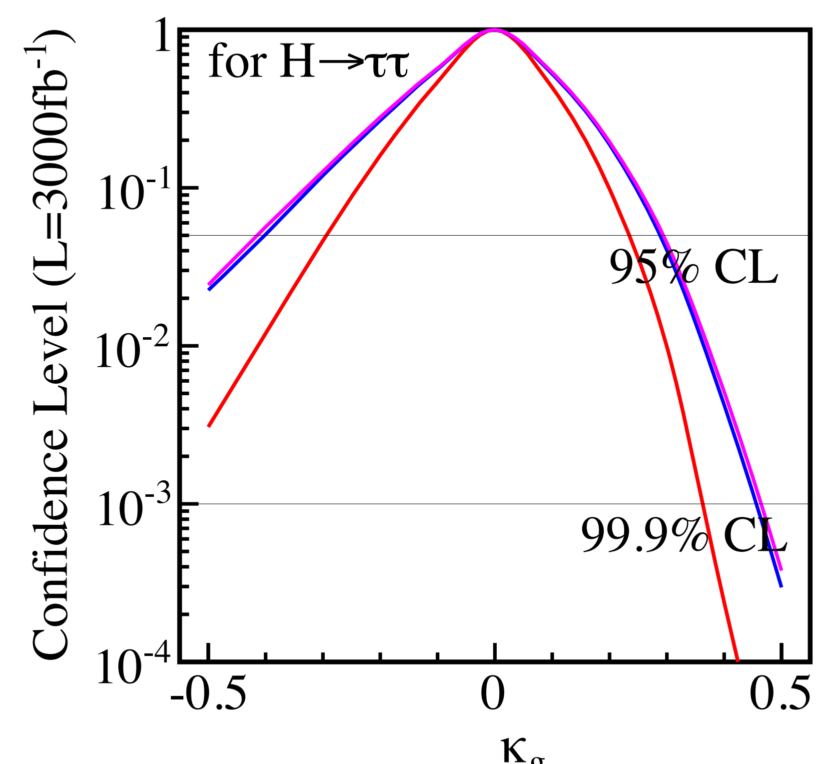
$\mathcal{L} = 15 \sim 30\mathrm{fb}^{-1}$

$\kappa_g < 0$: deficit is difficult to distinguish

$\kappa_g = 0.5$ vs. SM



$\mathcal{L} = 1000\mathrm{fb}^{-1}$



with 3000 fb^{-1}, $\kappa_g < -0.29$ and $\kappa_g > 0.24$ excluded

with 10% sys. err., $\kappa_g < -0.4$ and $\kappa_g > 0.3$ excluded

$\Delta\kappa_t$ by $t\bar{t}H$: $0.15(300\mathrm{fb}^{-1}), 0.12(3\mathrm{ab}^{-1})$

degeneracy in ggH and ttH couplings

$H \to gg$: sensitive to new physics, top partner in principle

but only combination $\kappa_g^{\text{eff}} = c_t + \kappa_g$ at low energy

cancellation in many models insensitive to top partner mass

$pp \to H + j$ breaks this degeneracy by pumping enough energy in the loops

alternative channel for c_t measurement, usually based on $t\bar{t}H$

We estimate how much we can measure the difference under presence of BGs

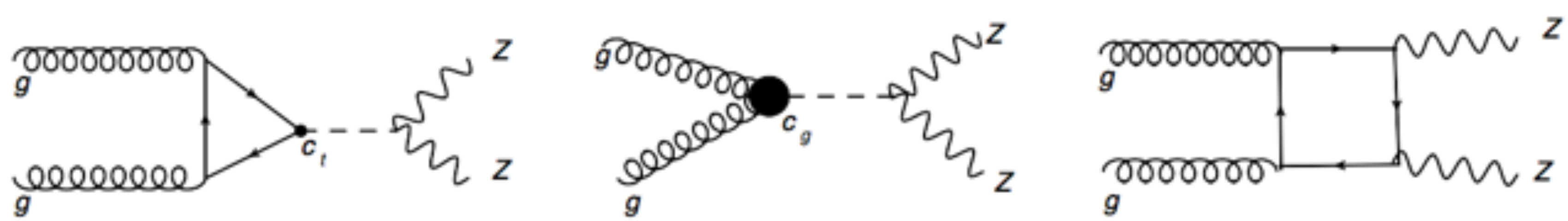
other following works

[Diptimoy Ghosh, Martin Wiebusch] Phys.Rev. D91 (2015) 3, 031701

$$\mathcal{L}_6 = \frac{C_g}{\Lambda^2} O_g + \frac{C_{3g}}{\Lambda^2} O_{3g} + \left(\frac{C_t}{\Lambda^2} O_t + \text{h.c.} \right) + \left(\frac{C_b}{\Lambda^2} O_b + \text{h.c.} \right) , \quad (1)$$

$$O_g = \Phi^\dagger \Phi \, G^a_{\mu\nu} G^{\mu\nu a} , \qquad O_t = Y_t (\Phi^\dagger \Phi)(\bar{Q}_{3L} t_R \tilde{\Phi}) ,$$
$$O_{3g} = f^{abc} G^{a\mu}{}_{\nu} G^{b\nu}{}_{\rho} G^{c\rho}{}_{\mu} , \quad O_b = Y_b (\Phi^\dagger \Phi)(\bar{Q}_{3L} b_R \Phi) . \quad (2)$$

[Aleksandr Azatov, Christophe Grojean, Ayan Paul and Ennio Salvioni] Zh.Eksp.Teor.Fiz. 147 (2015) 410-425, J.Exp.Theor.Phys. 120 (2015) 354-368



off-shell Higgs breaks degeneracy

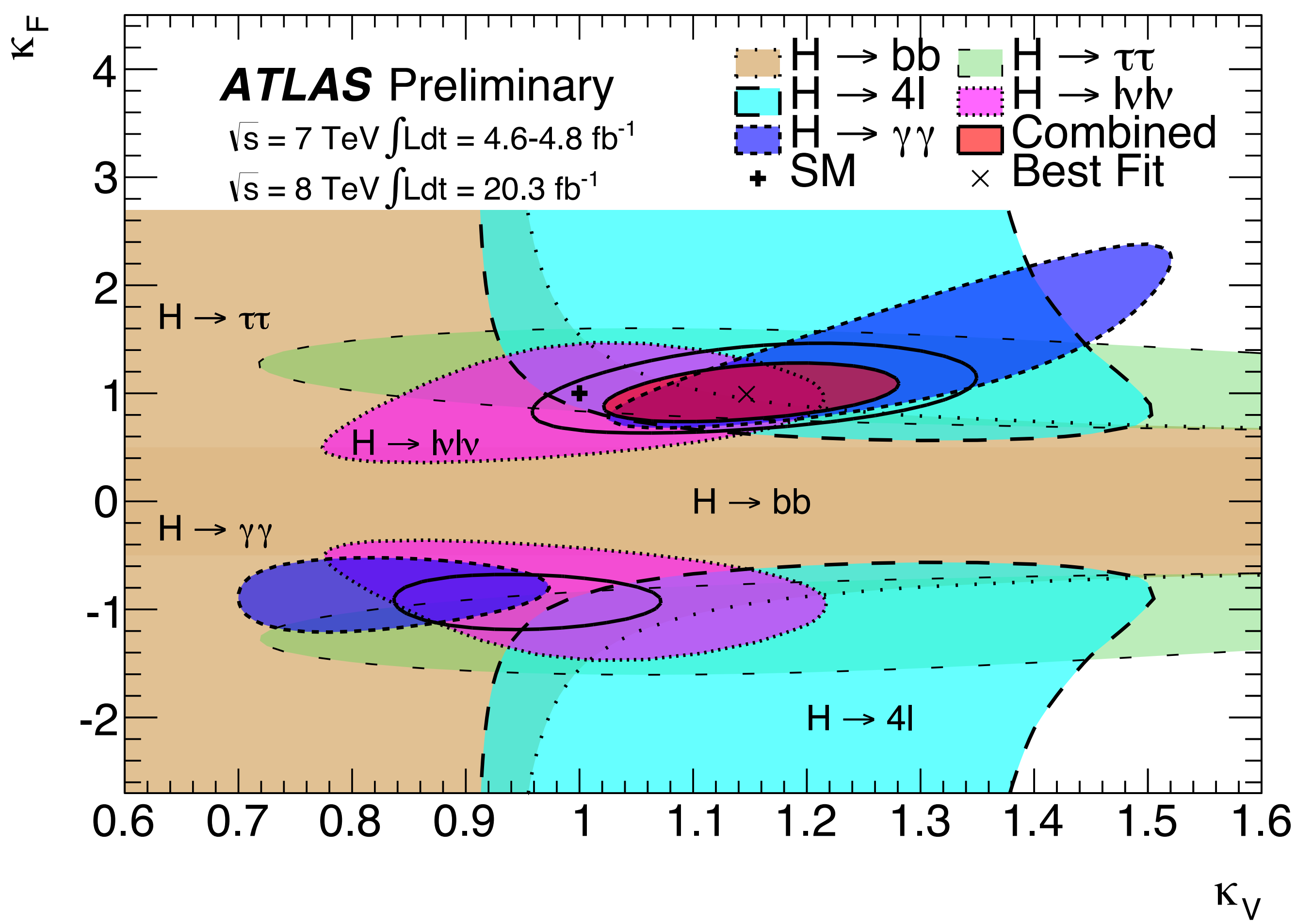
Degeneracy in ttH CP-even, CP-odd couplings

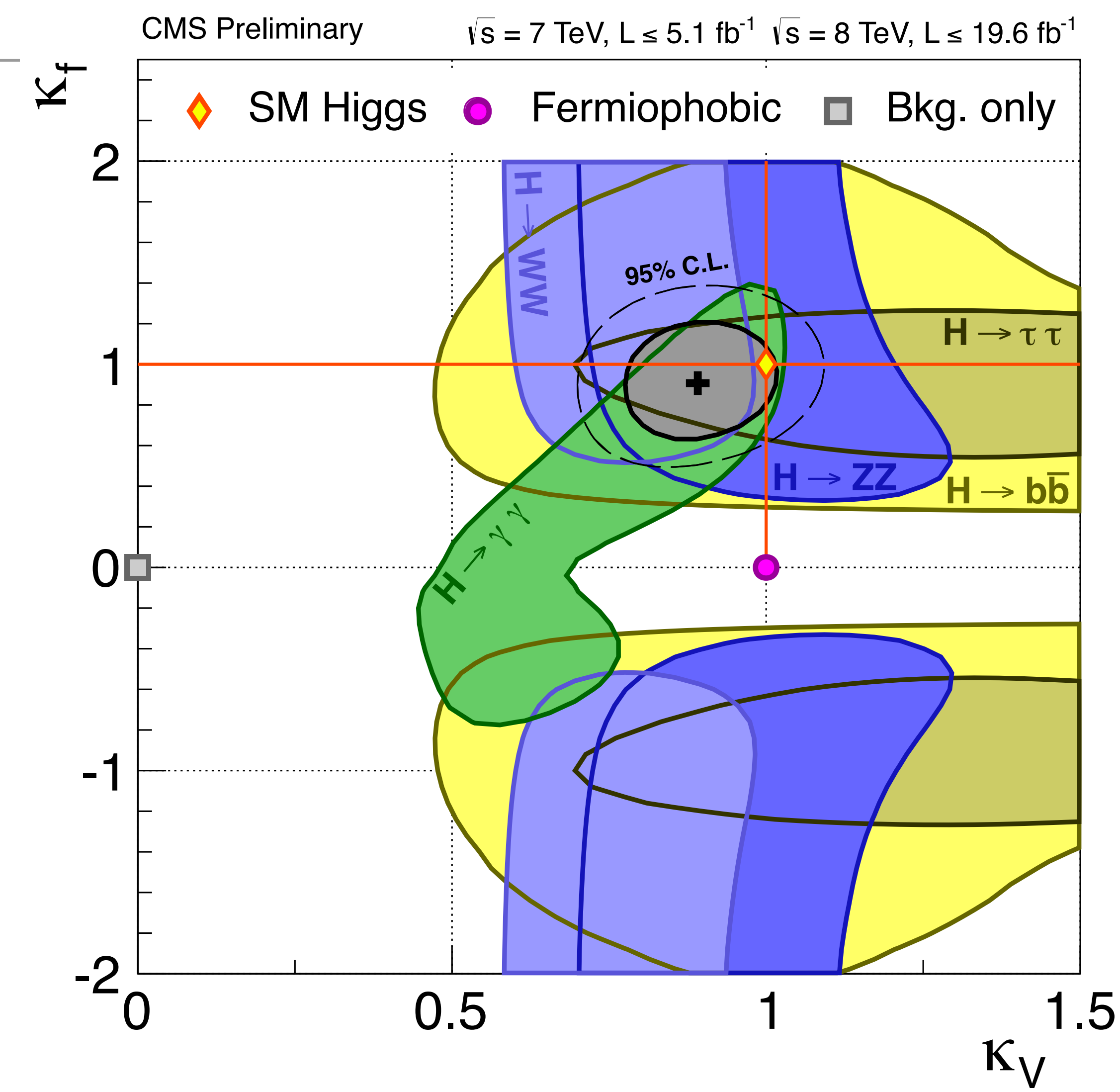
$$-\kappa_t \frac{m_t}{v}\bar{t}th + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu\,a} + i\tilde{\kappa}_t \frac{m_t}{v}\bar{t}\gamma_5 th + \tilde{\kappa}_g \frac{\alpha_s}{8\pi}\frac{h}{v}G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu} + \mathcal{L}_{\rm QCD}\,,$$

CMS-Hig-13-005

higgs results

ATLAS-CONF-2014-009





ATLAS: κ_V **[1.05,1.22] at 68% CL - κ_F [0.76,1.18] at 68% CL**
CMS: κ_V **[0.74,1.06] at 95% CL - κ_F [0.61,1.33] at 95% CL**

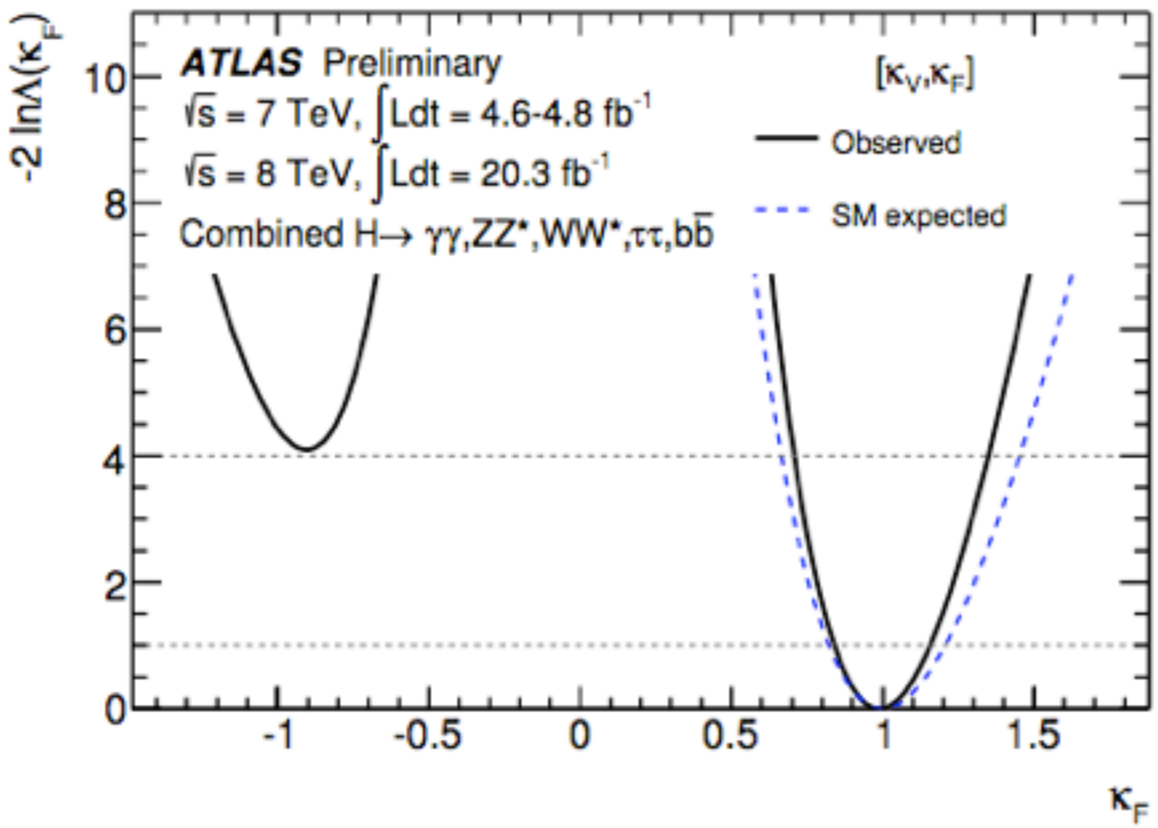
compatible in 10-20%

$$-\kappa_t \frac{m_t}{v}\bar{t}th + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu\, a} + i\tilde{\kappa}_t\frac{m_t}{v}\bar{t}\gamma_5 th + \tilde{\kappa}_g\frac{\alpha_s}{8\pi}\frac{h}{v}G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu} + \mathcal{L}_{\rm QCD}\,,$$

$$\kappa_t = -1 \text{ is excluded in } 2\sigma \;(\text{SM:}\kappa_t = 1)$$

What if ct = -1 ?

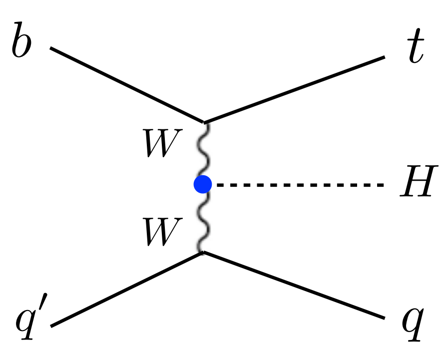
$$-\kappa_t \frac{m_t}{v}\bar{t}th + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu\, a} + i\tilde{\kappa}_t \frac{m_t}{v}\bar{t}\gamma_5 th + \tilde{\kappa}_g \frac{\alpha_s}{8\pi}\frac{h}{v}G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu} + \mathcal{L}_{\rm QCD}\,,$$

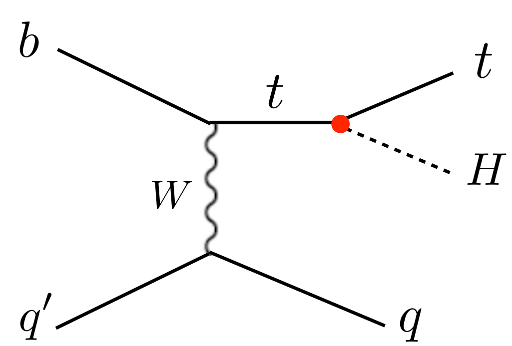


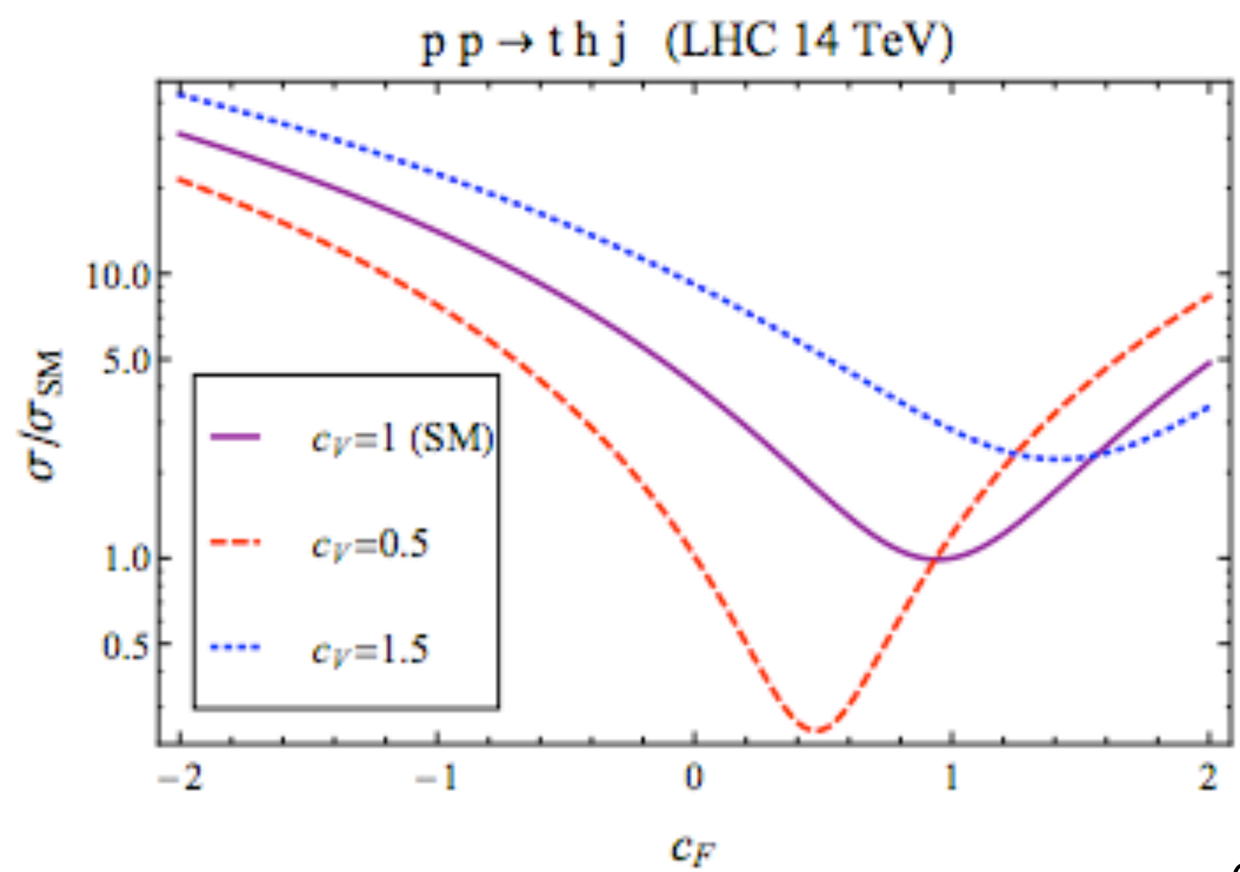
$\kappa_t = -1$ is excluded in 2σ (SM:$\kappa_t = 1$)

$$\mu_{gg} \propto |\kappa_t|^2, \mu_{\gamma\gamma} \propto |\kappa_V - \epsilon\kappa_t|^2$$

$\sigma(tH)$ would be enhanced by interference



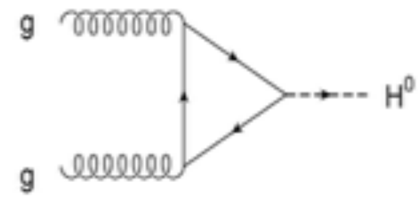


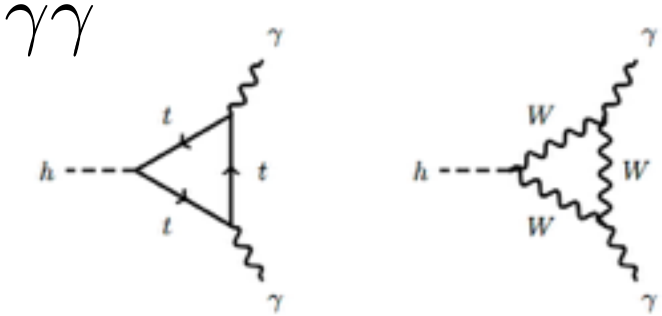


taken from JHEP 1305 (2013) 022

CPV ttH coupling

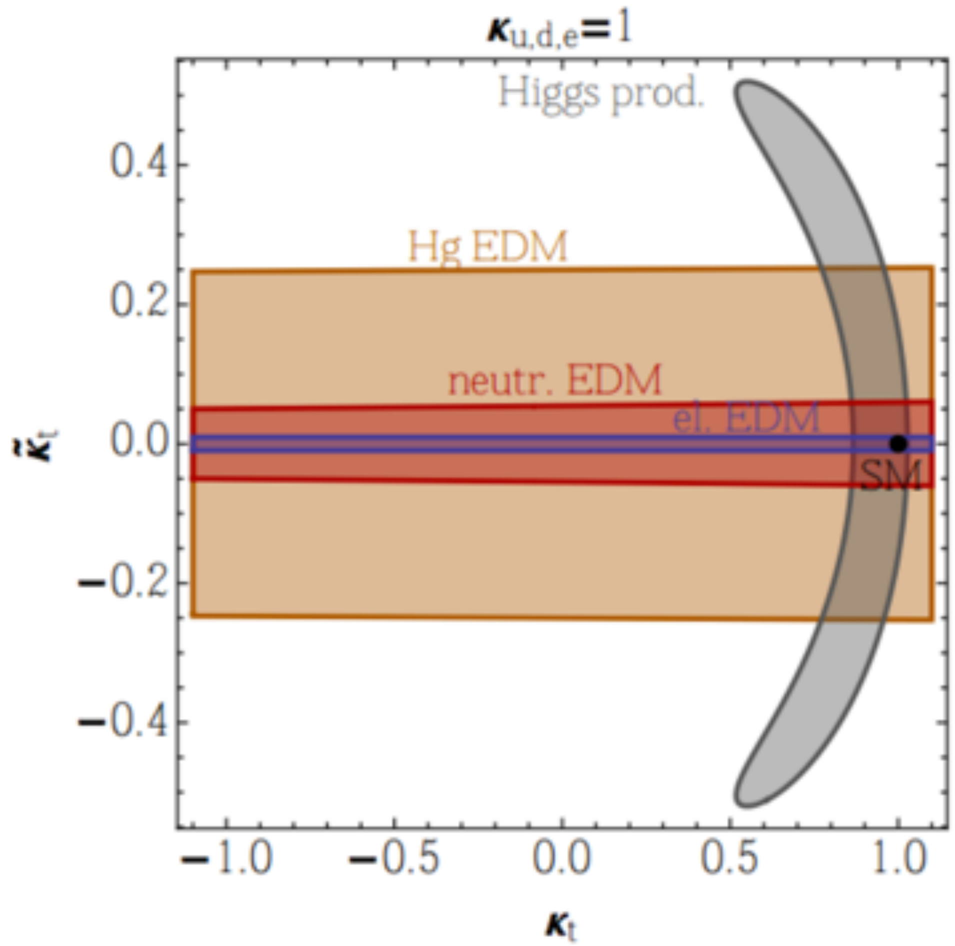
weakly constrained by $H \to gg$ and $H \to \gamma\gamma$





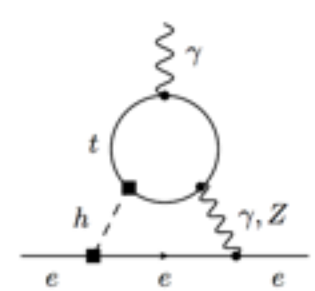
$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

$$\mathrm{SM}: \kappa_t = 1, \tilde{\kappa}_t = 0$$



$$\kappa_{g,\mathrm{WA}} = 0.91 \pm 0.08\,, \qquad \kappa_{\gamma,\mathrm{WA}} = 1.10 \pm 0.11\,,$$

[Joachim Brod,Ulrich Haisch and Jure Zupan]

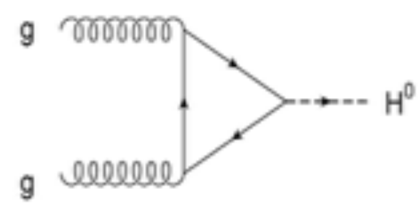


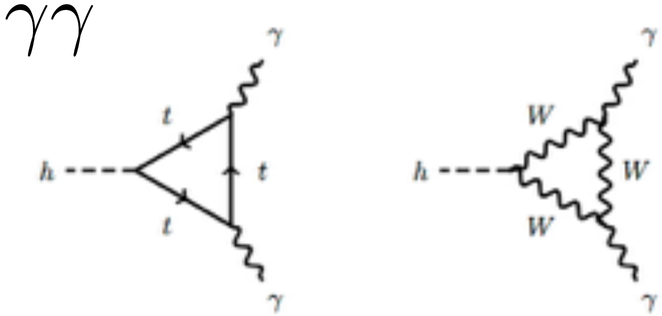
strongly constrained by EDM $|\tilde{\kappa}_t| < 0.01$

CPV ttH coupling

[arXiv:1312.5736[hep-ph] J. Ellis, D. Hwang, K. Sakurai, MT]

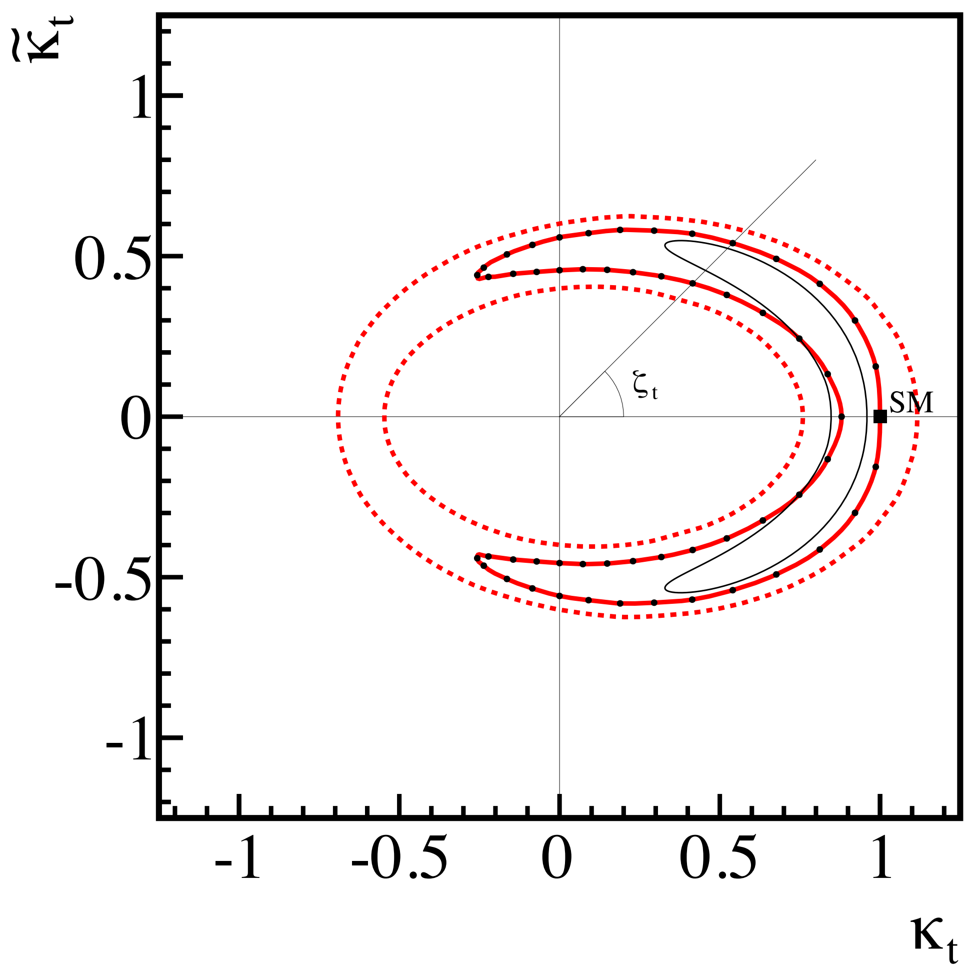
weakly constrained by $H \to gg$ and $H \to \gamma\gamma$

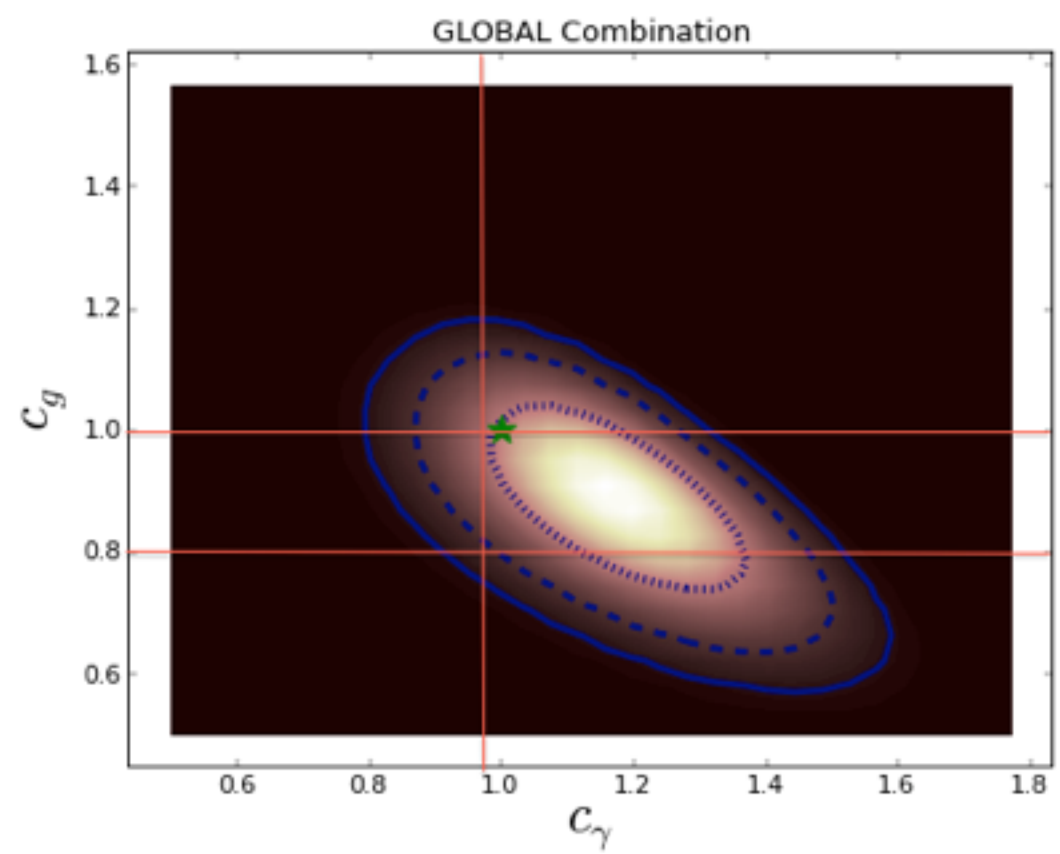




$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

$$\mathrm{SM}: \kappa_t = 1, \tilde{\kappa}_t = 0$$

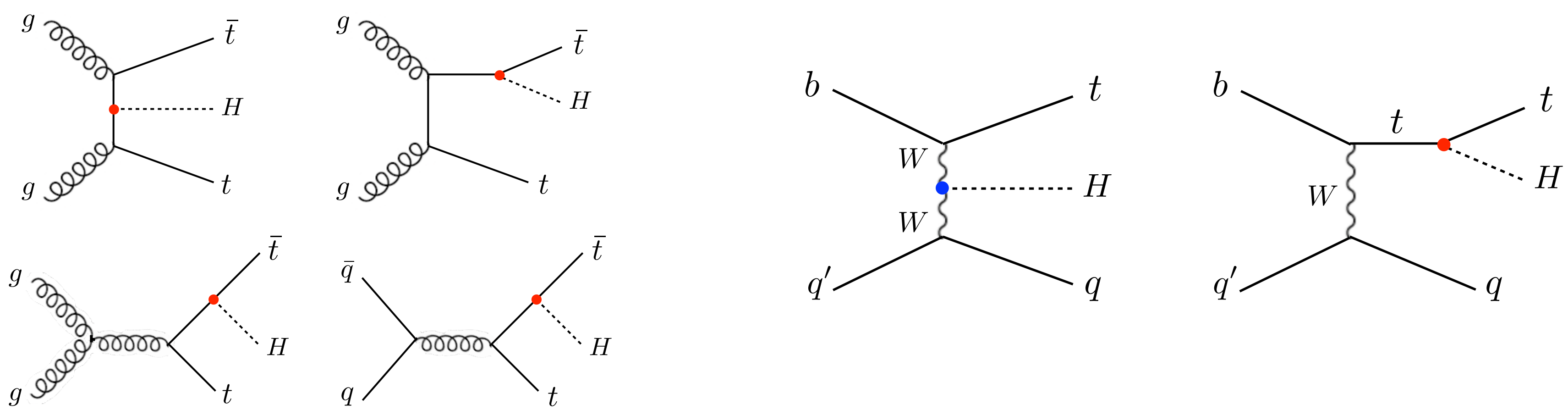




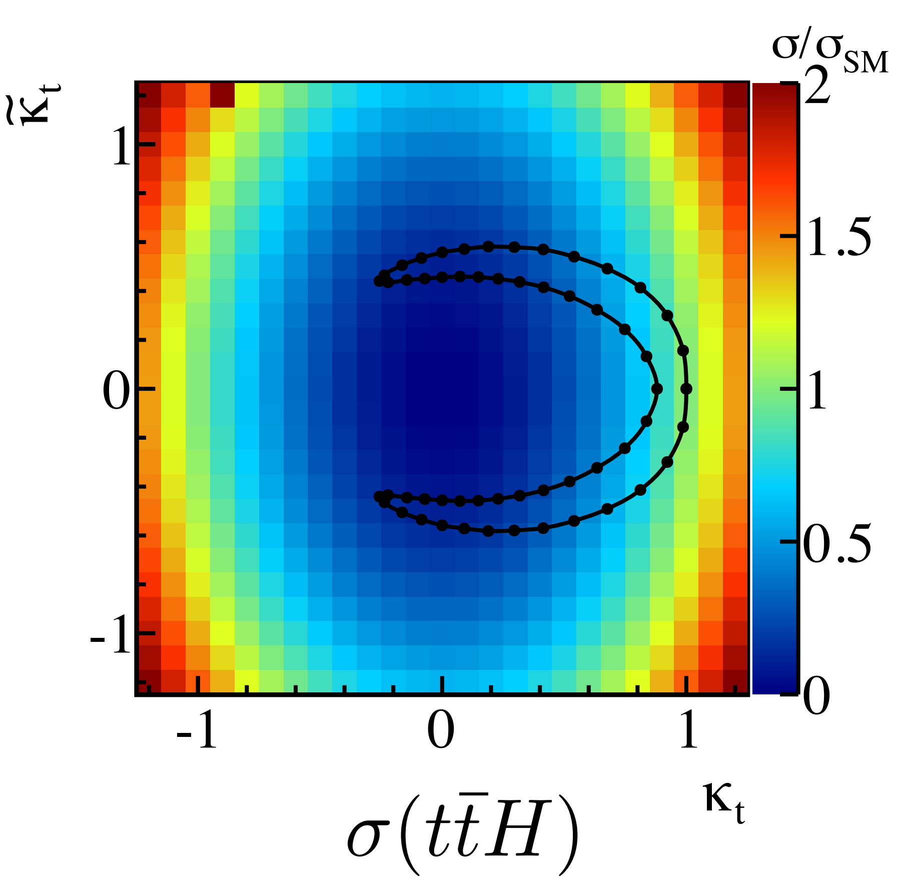
note: anti-correlation

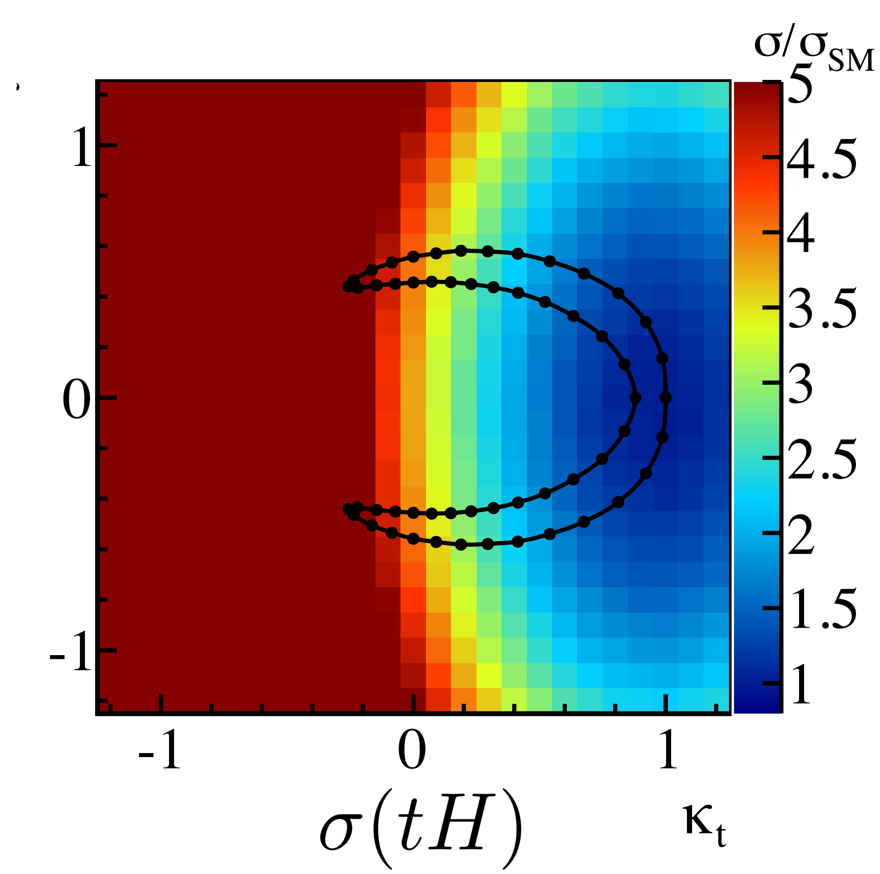
ttH, tHj production rate [arXiv:1312.5736[hep-ph] J. Ellis, D. Hwang, K. Sakurai, MT]

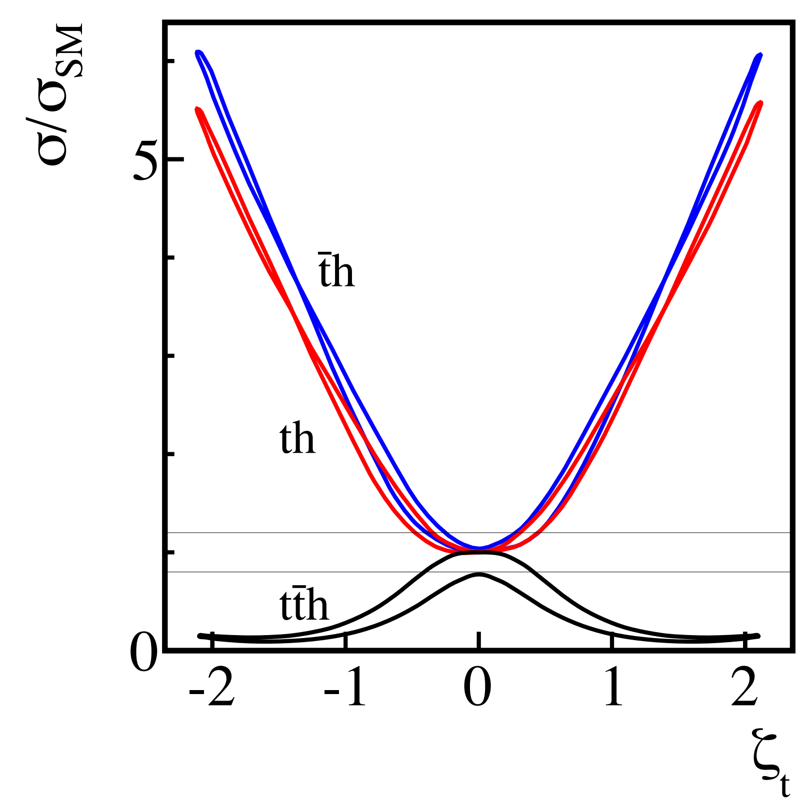
$$\mathcal{L}_t \;=\; -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$



20% $\sigma(t\bar{t}H)$ measurement
determine $\zeta_t < 30°$

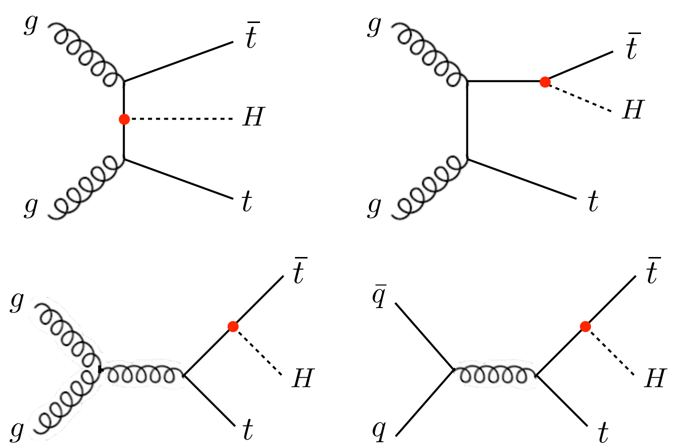


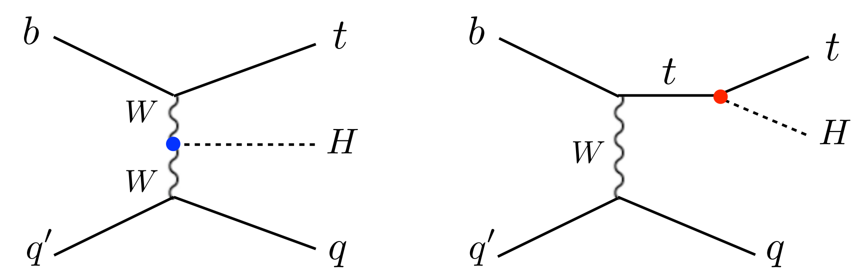




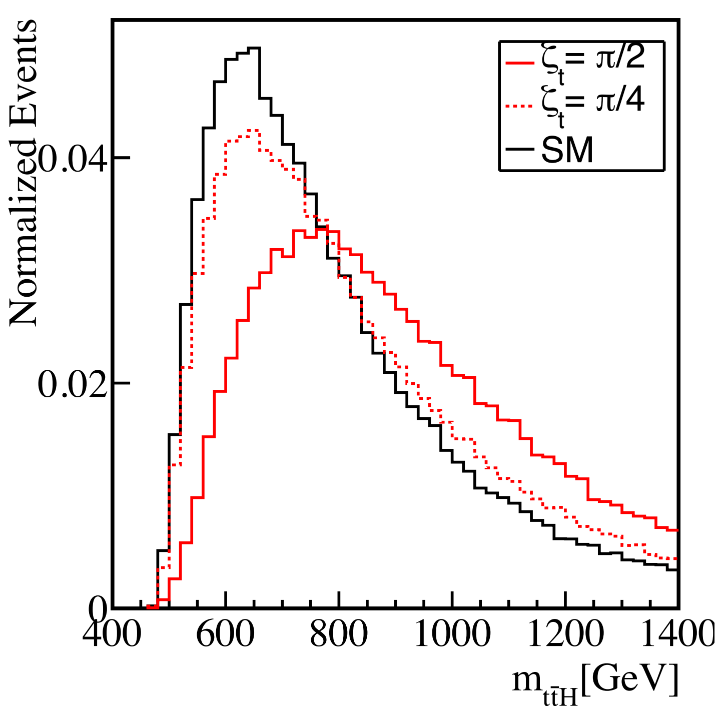
ttH, tHj invariant masses [arXiv:1312.5736[hep-ph] J. Ellis, D. Hwang, K. Sakurai, MT]

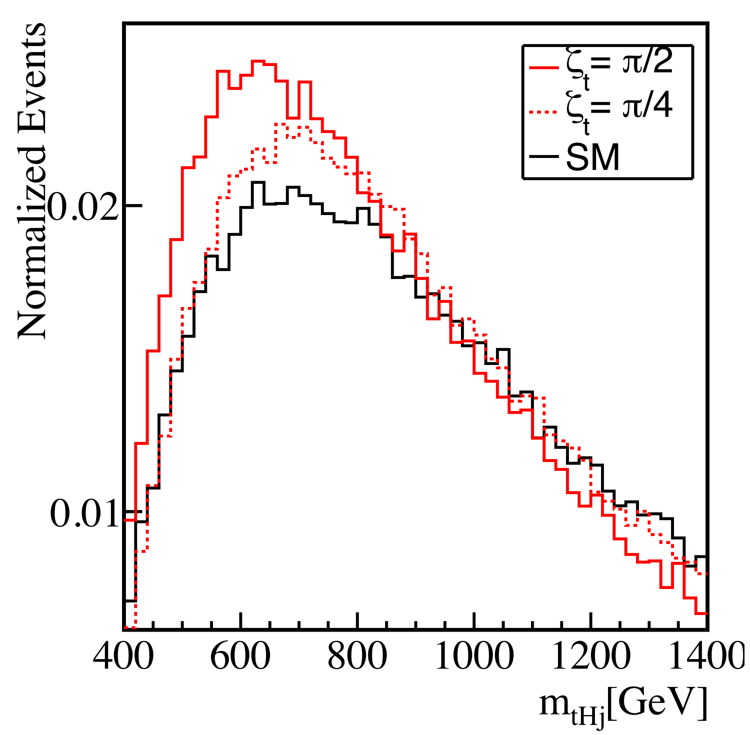
$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

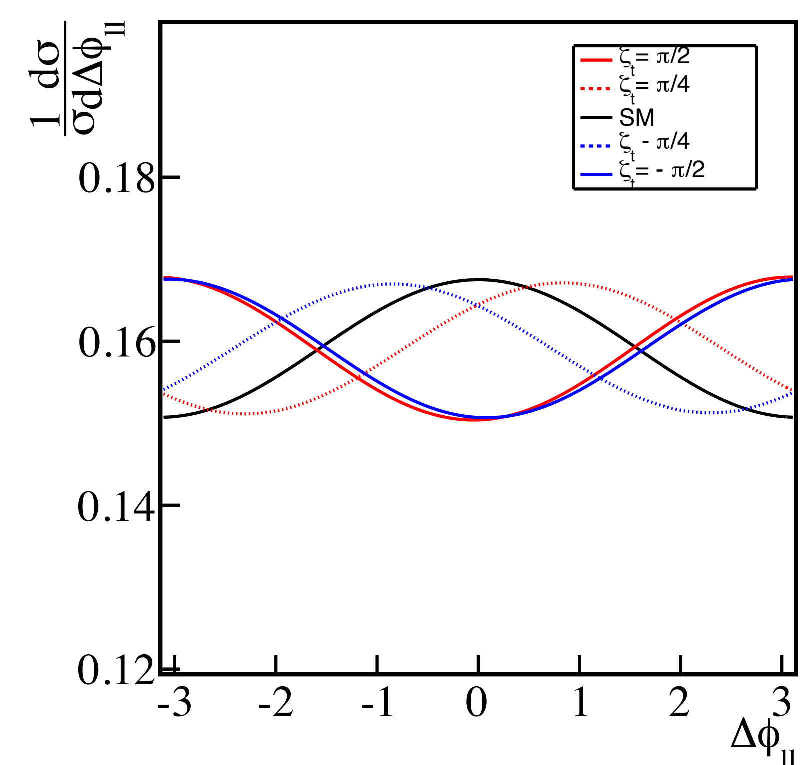




$$\alpha \equiv \mathrm{sgn}\left(\vec{p}_t^{\,t\bar{t}} \cdot (\vec{p}_{\ell^-}^{\,t\bar{t}} \times \vec{p}_{\ell^+}^{\,t\bar{t}})\right).$$



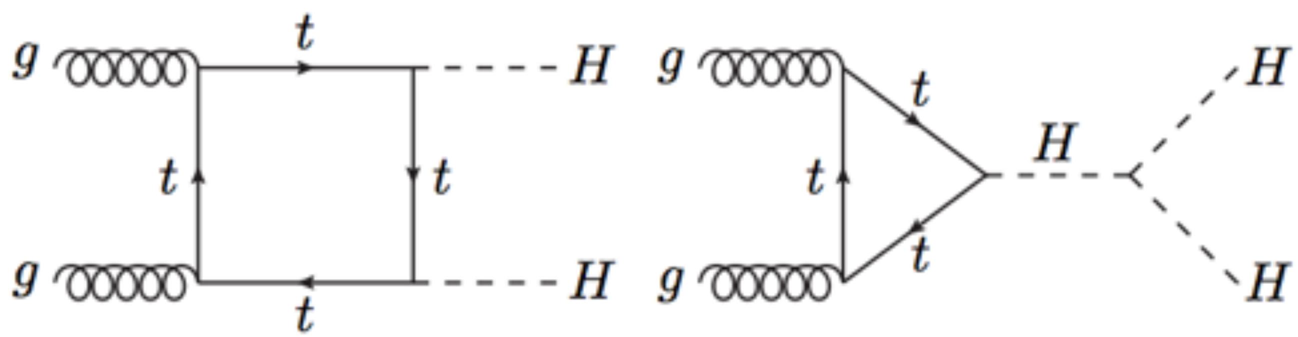


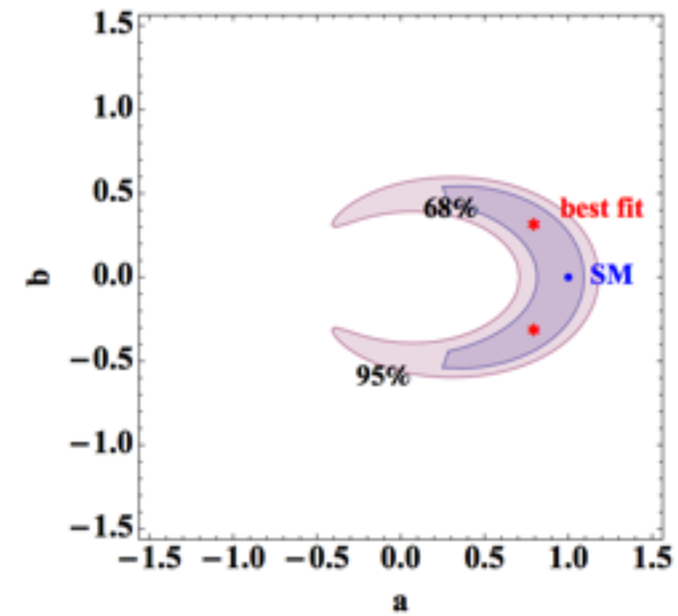


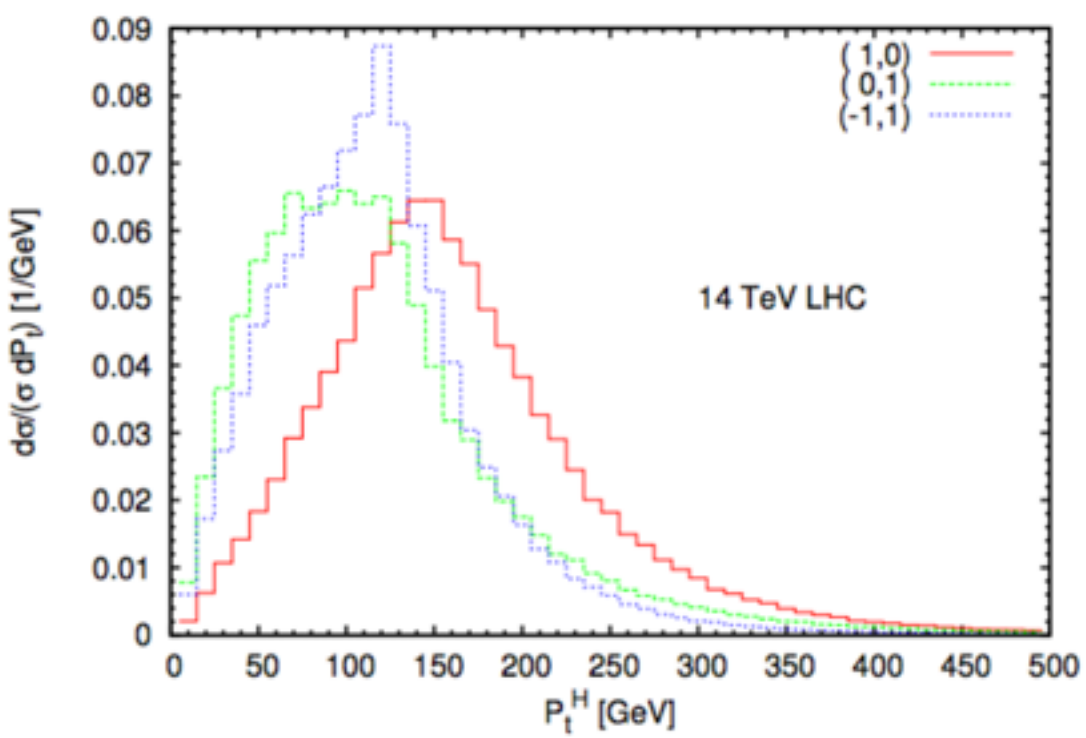
HH invariant masses

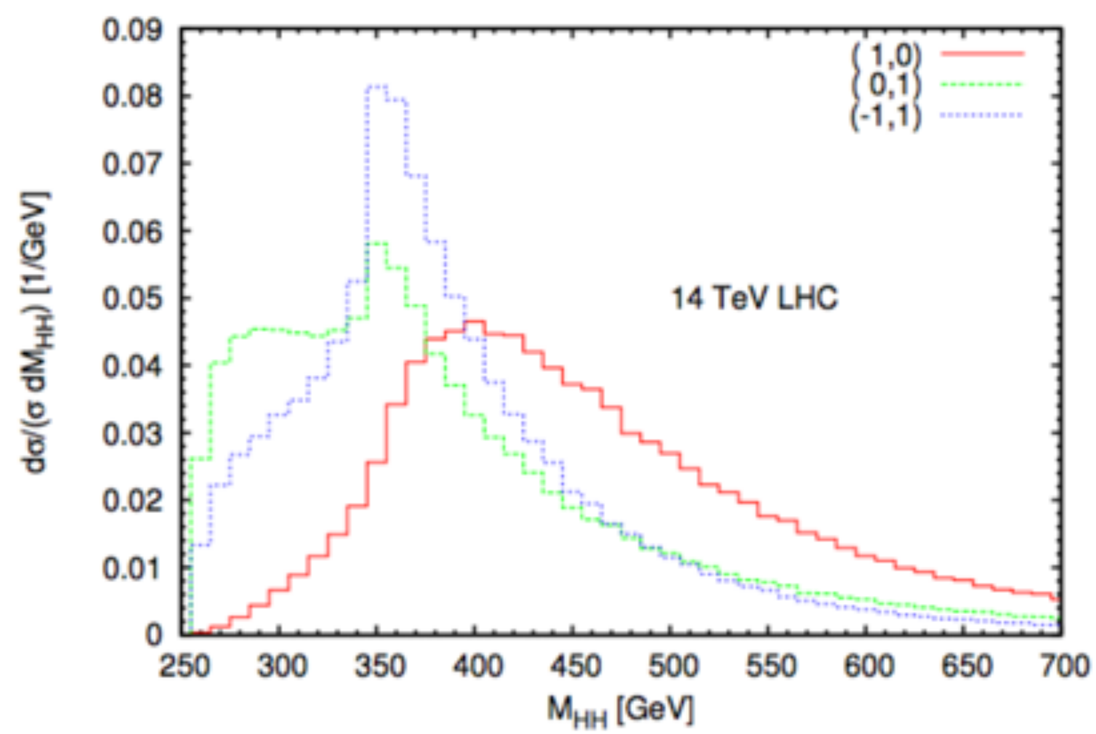
arXiv:1309.6907 [Kenji Nishiwaki, Saurabh Niyogi, Ambresh Shivaji]

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



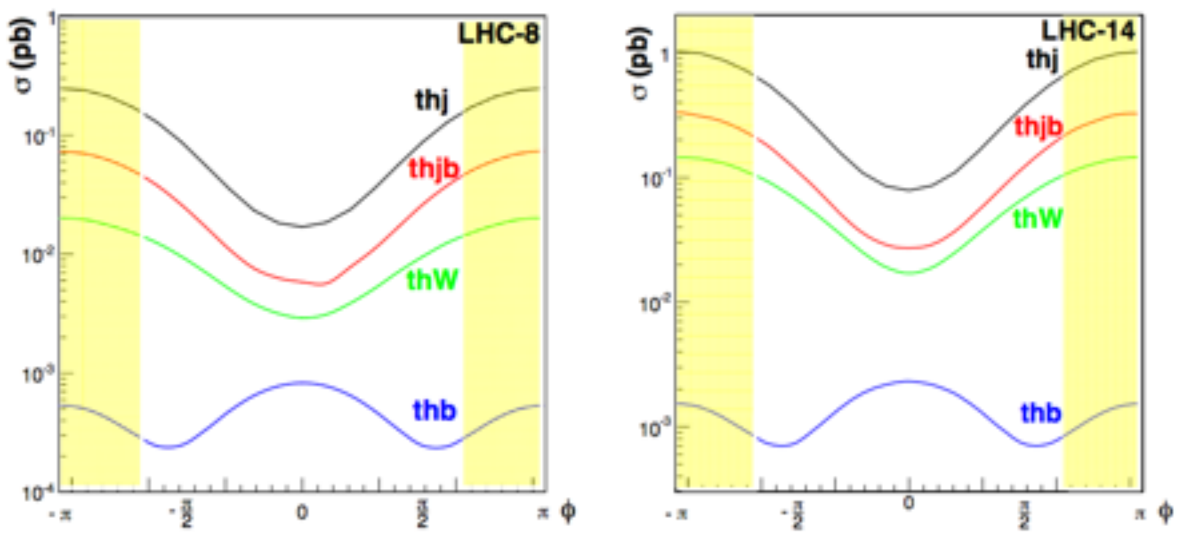






other processes, other observables

[Jung Chang, Kingman Cheung, Jae Sik Lee and Chih-Ting Lu]



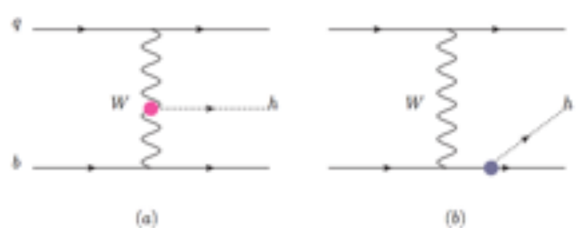


Figure 1. Contributing Feynman diagrams for $qb \to thq'$.

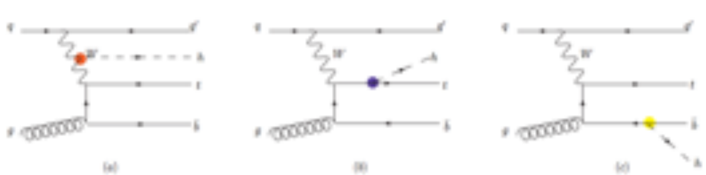


Figure 2. Some of the contributing Feynman diagrams for $qg \to thq'\bar{b}$.

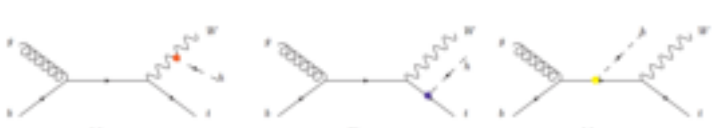


Figure 3. Some of the contributing Feynman diagrams for $gb \to thW^-$.

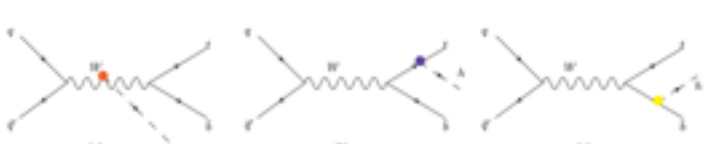


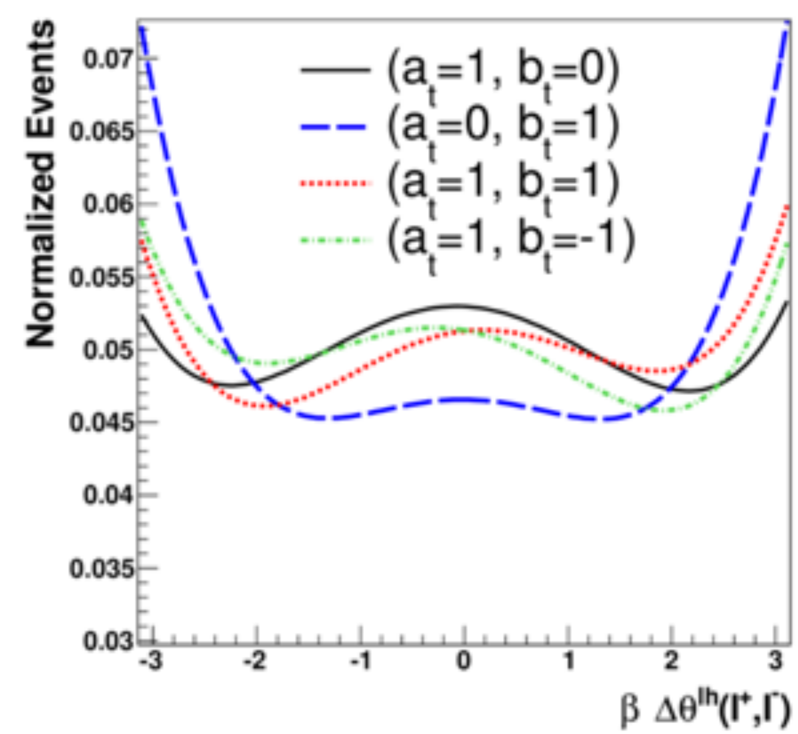
Figure 4. Contributing Feynman diagrams for $q\bar{q}' \to th\bar{b}$.

[Fawzi Boudjema, Rohini M. Godbole, Diego Guadagnoli, Kirtimaan A. Mohan]

$$\alpha \equiv \text{sgn}\left(\vec{p}_t^{\,t\bar{t}} \cdot (\vec{p}_{\ell^-}^{\,t\bar{t}} \times \vec{p}_{\ell^+}^{\,t\bar{t}})\right).$$

defined with lab frame observables

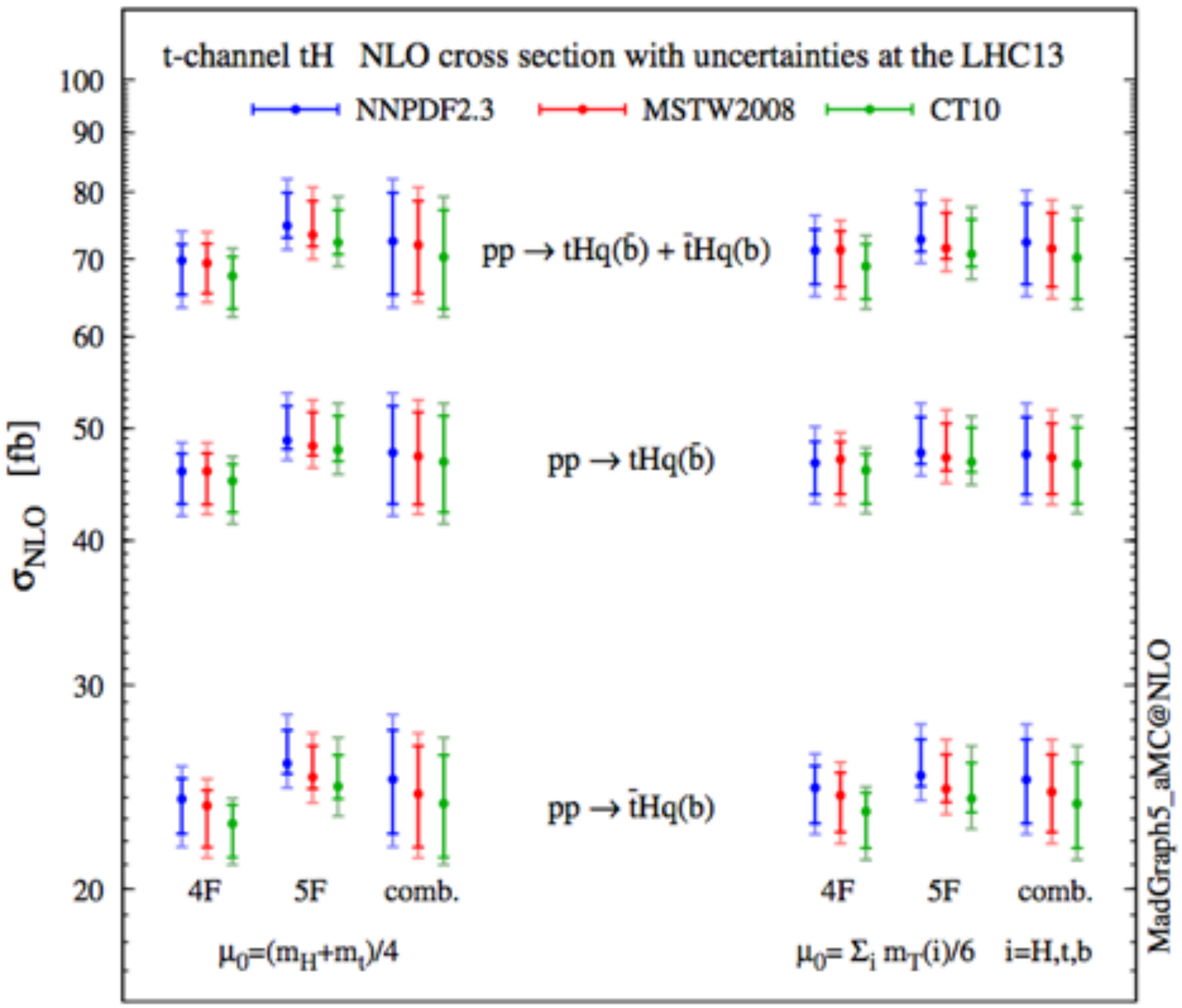
$$\beta \equiv \text{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right).$$

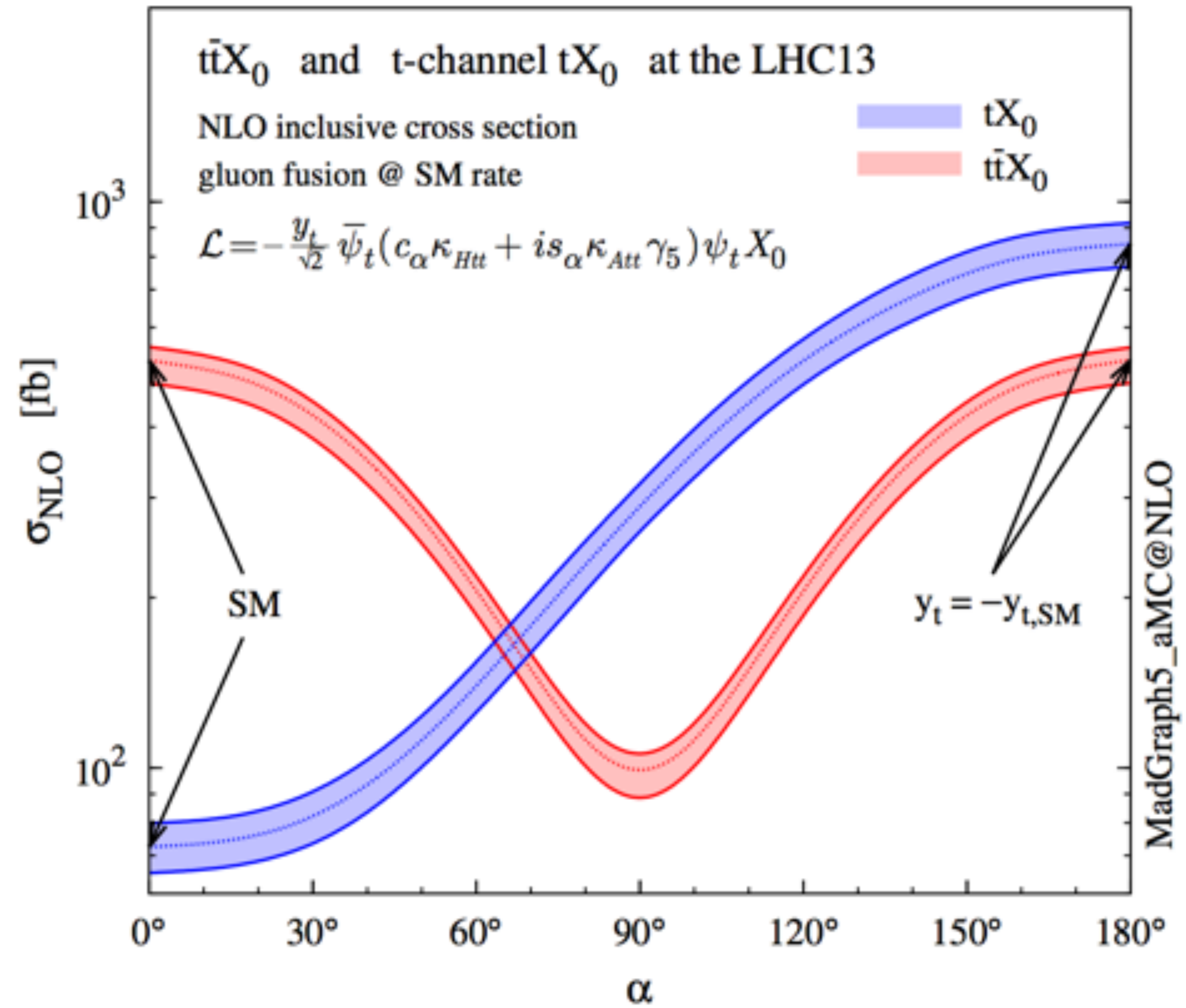


NLO prediction

[Federico Demartin, Fabio Maltoni, Kentarou Mawatari, Marco Zaro]

arxiv:1504.00611





NLO in QCD is available, more reliable prediction possible.

degeneracy in CP-even, CP-odd ttH couplings

Higgs signal strengths can be satisfied along the ellipse.

$\sigma(ttH)$ decreases, $\sigma(tH)$ increases as $ih\bar{t}\gamma^5 t$ coupling increases

invariant mass distribution m_{ttH}, m_{tHj} are sensitive.

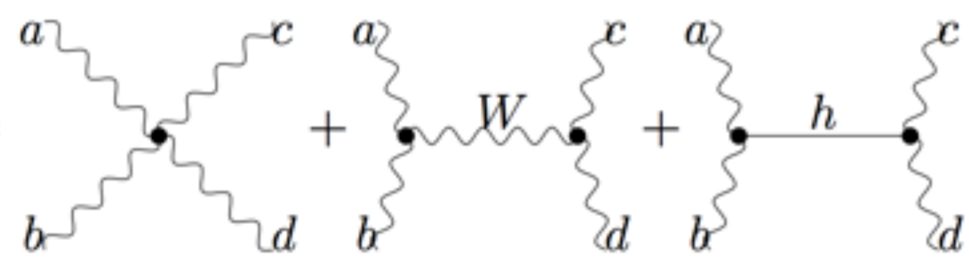
invariant mass distribution m_{HH} , m_{ZZ} are also sensitive.

lab frame observables useful. More studies welcome.

Unitarity-controlled resonances after Higgs discovery

arXiv: 1503.07459

$$i\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) =$$



$$\sim \frac{E^4}{m_W^4}$$

$$\epsilon_L^\mu = (\frac{p}{m_W}, 0, 0, \frac{E}{m_W})$$

$$g_{WWWW} = g_{WW\gamma}^2 + \sum_i g_{WWZ_i}^2$$

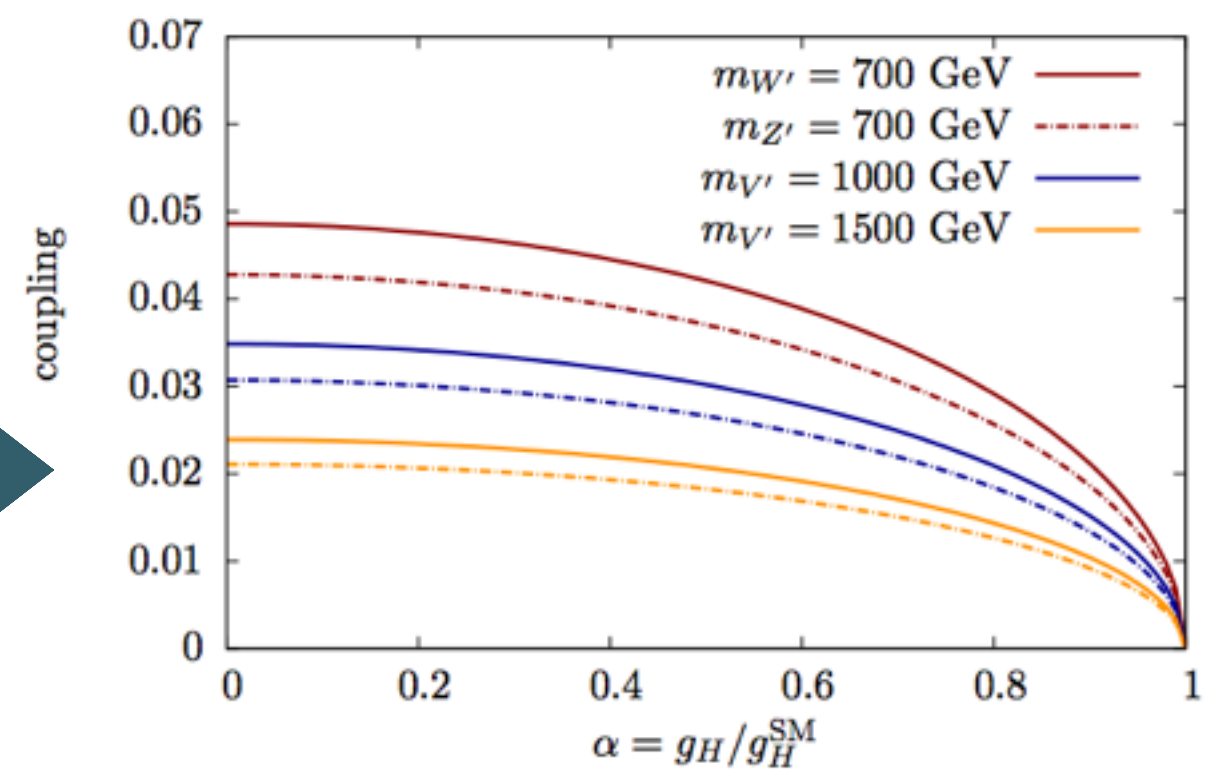
$$4m_W^2 g_{WWWW} = \sum_i 3m_i^2 g_{WWZ_i}^2 + \sum_i g_{WWH_i}^2 \,,$$

$$g_{WWZZ} = \sum_i g_{W_iWZ}^2$$

$$2(m_W^2 + m_Z^2) g_{WWZZ} = \sum_i \left(3m_i^2 - \frac{(m_Z^2 - m_W^2)^2}{m_i^2}\right) g_{W_iWZ}^2 + \sum_i g_{WWH_i} g_{ZZH_i} \,.$$

Unitarity constrains $W'WZ$, $Z'WW$ couplings

$$m_{W',Z'} = 700 \text{ GeV}, \quad \Gamma_{W',Z'} = 3 \text{ GeV}, \quad \alpha = 0.9,$$
$$m_{W',Z'} = 1000 \text{ GeV}, \quad \Gamma_{W',Z'} = 7 \text{ GeV}, \quad \alpha = 0.9,$$
$$m_{W',Z'} = 700 \text{ GeV}, \quad \Gamma_{W',Z'} = 10 \text{ GeV}, \quad \alpha = 0.5,$$
$$m_{W',Z'} = 1000 \text{ GeV}, \quad \Gamma_{W',Z'} = 30 \text{ GeV}, \quad \alpha = 0.5.$$



Unitarity-controlled resonances after Higgs discovery

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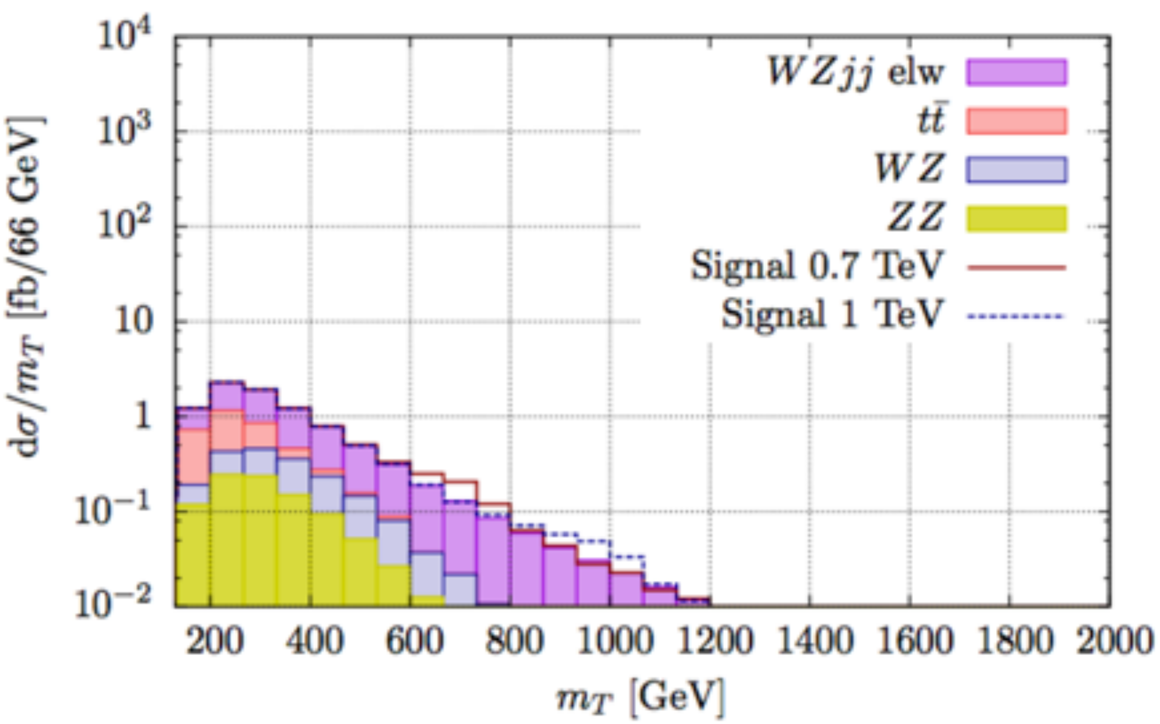
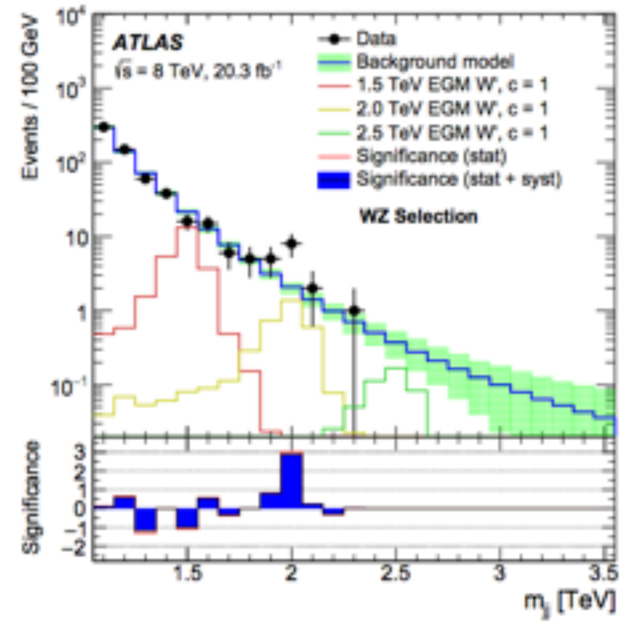
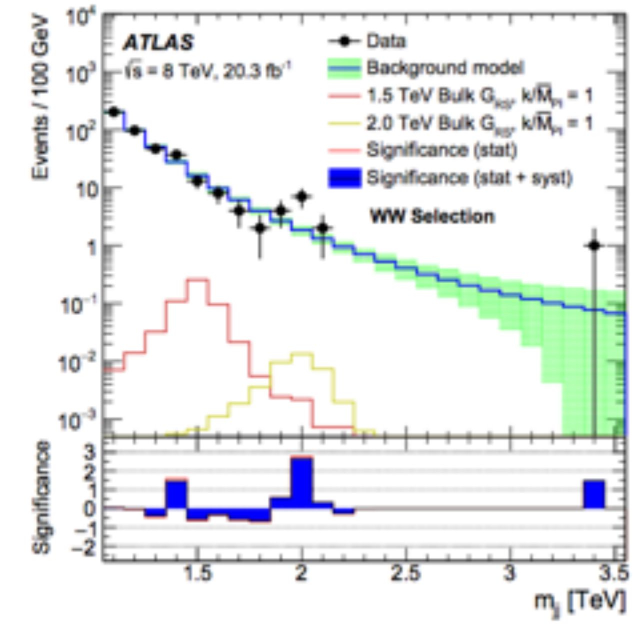


(b) Transverse mass distribution of the $3l + \not{E}_T + 2j$ final state



(a)



(b)