# Higgs Pair Production with Large Missing ET at the LHC

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9/14/2017 @ Seoul National University
Seoul, Korea

**CRC**, Lin, Wu, Yue, arXiv: 1709.*****

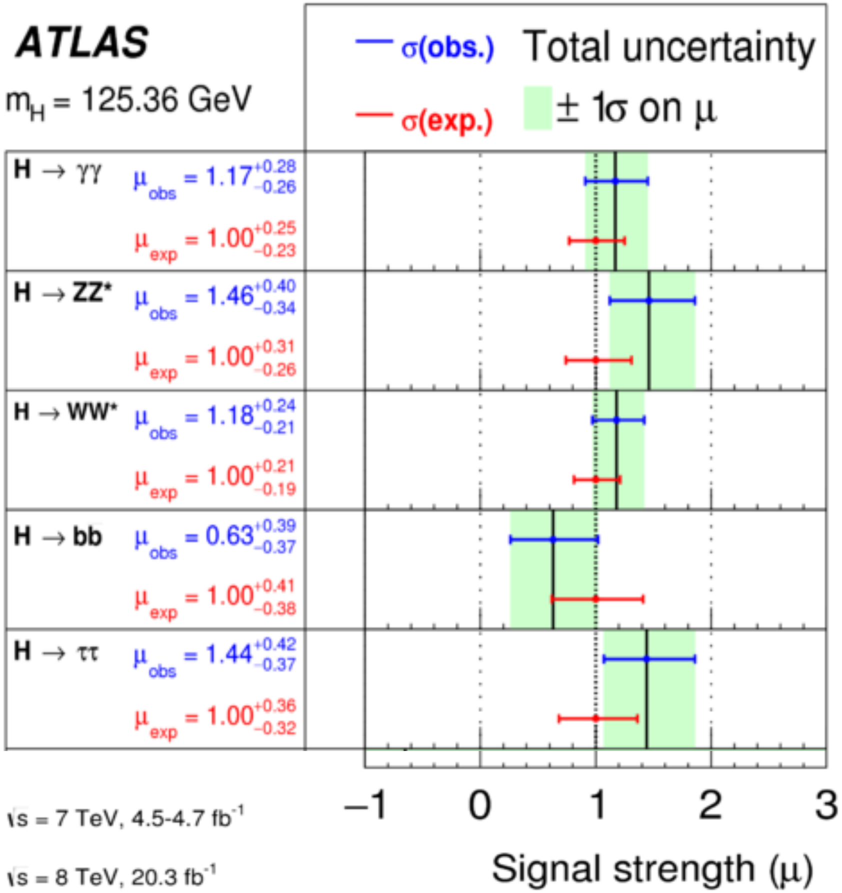
# Outline

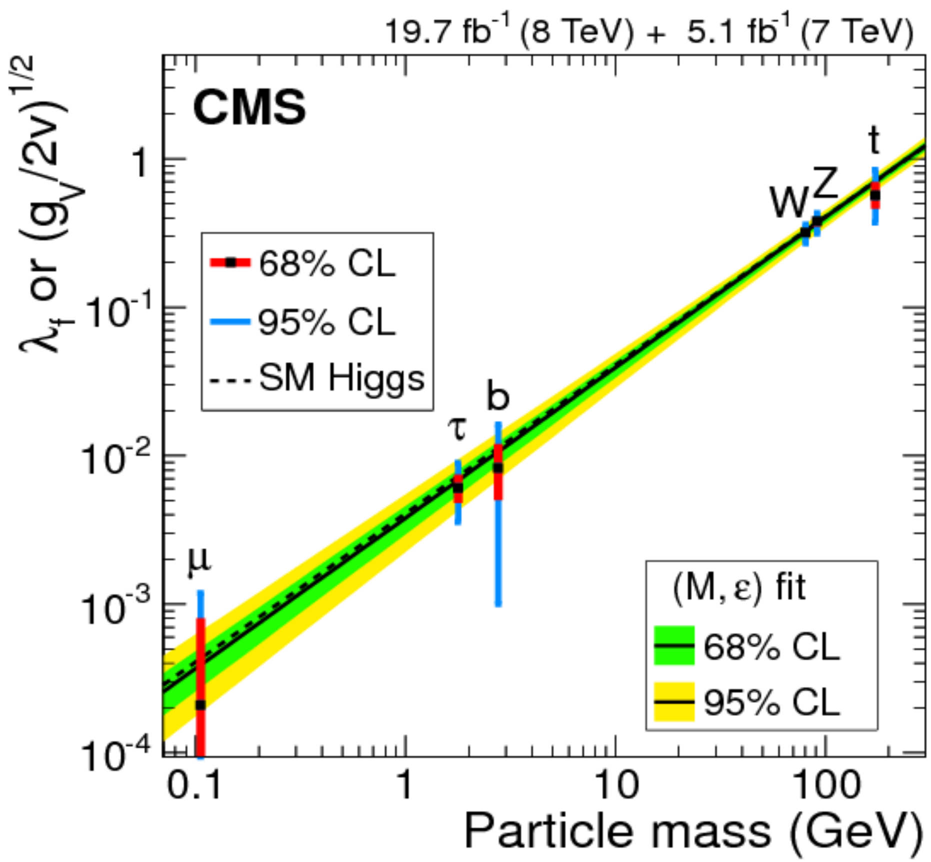
New physics effects in Higgs pair production at the LHC

- couplings
- resonance
- associated with other particles – Dark Matter

Summary

# Higgs boson @ LHC

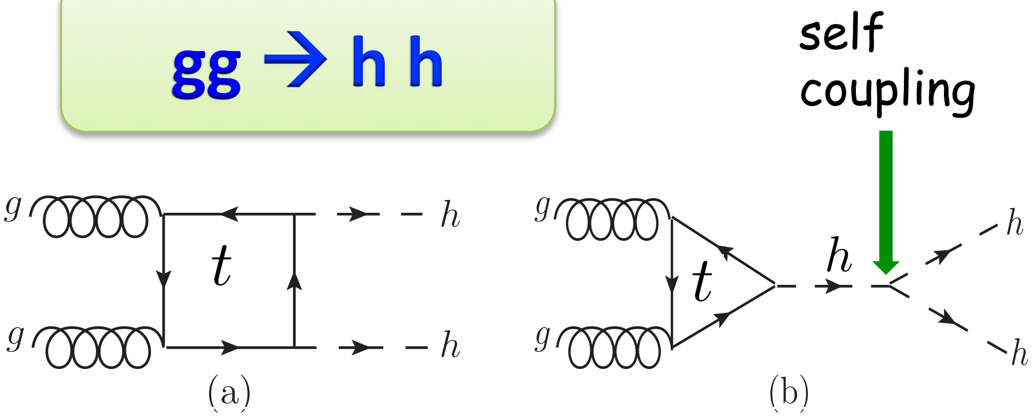


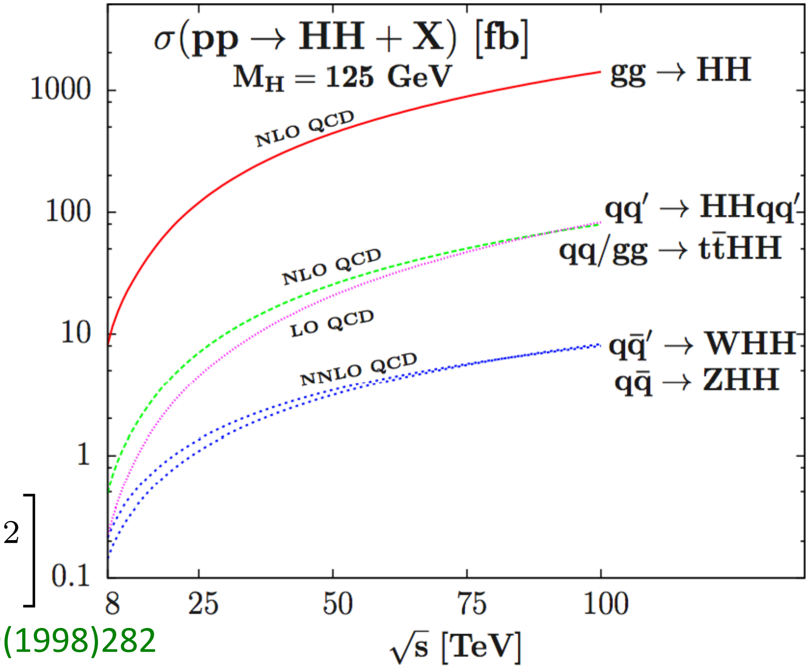




get information of interactions between
Higgs boson and other SM particles

HOWEVER, can NOT test/determine the Higgs boson self coupling!!

# gg → h h




$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3}\left[\left|\frac{3m_h^2}{\hat{s}-m_h^2}F_\triangle + F_\Box\right|^2 + |G_\Box|^2\right]$$

Plehn, Spira, Zerwas, NPB 479(1996)46 Glover, van der BIJ, NPB 309(1998)282

Dawson, Dittmaier, Spira, hep-ph/9805244 Djouadi, Kilian, Muhlleitner, Zerwas, hep-ph/9904287

Asakawa, Harada, Kanemura, Okada, Tsumura, 1009.4670 Dawson, Furlan, Lewis, 1210.6663

Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, 1212.5581 Yao, 1308.6302

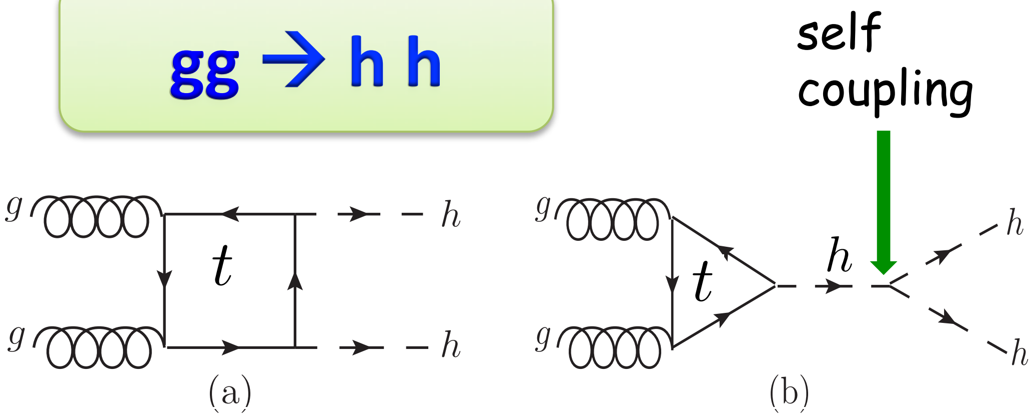
| $\sqrt{s}$ [TeV] | $\sigma^{NLO}_{gg\to HH}$ [fb] | $\sigma^{NLO}_{qq'\to HHqq'}$ [fb] | $\sigma^{NNLO}_{q\bar{q}'\to WHH}$ [fb] | $\sigma^{NNLO}_{q\bar{q}\to ZHH}$ [fb] | $\sigma^{LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb] |
|---|---|---|---|---|---|
| 8 | 8.16 | 0.49 | 0.21 | 0.14 | 0.21 |
| 14 | 33.89 | 2.01 | 0.57 | 0.42 | 1.02 |
| 33 | 207.29 | 12.05 | 1.99 | 1.68 | 7.91 |
| 100 | 1417.83 | 79.55 | 8.00 | 8.27 | 77.82 |

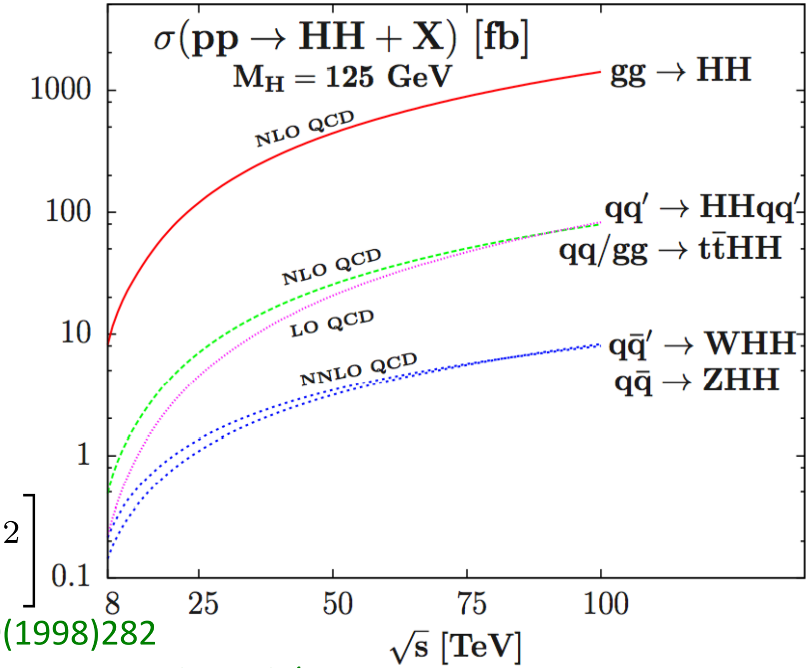
* quite promising that one can discover $gg \to hh \to \gamma\gamma b\bar{b}$

* w/ 3000 fb$^{-1}$ @ 100 TeV pp collider, hhh coupling can be measured with 8 % accuracy

Yao, 1308.6302

# gg → h h

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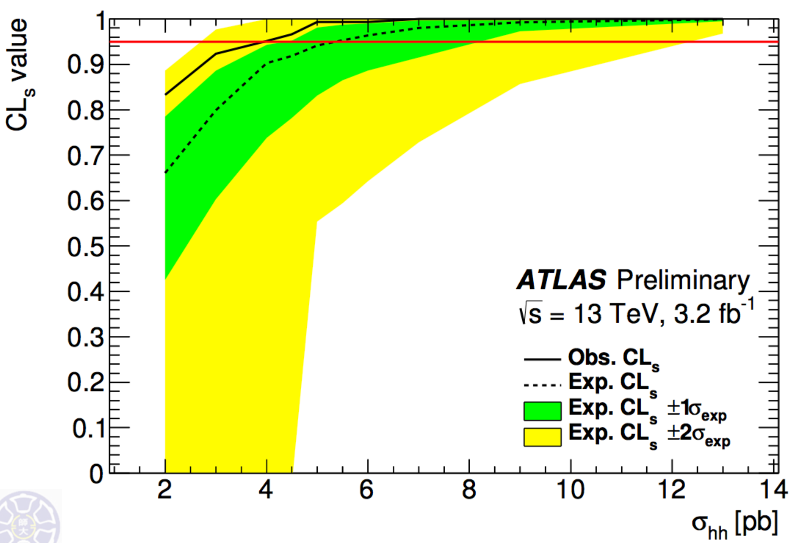



ATLAS:

"an upper limit of 3.9 pb on the cross section for non-resonant is extracted at 95% confidence level"

# tri-H coupling at ILC

$e^+e^- \rightarrow Zhh$

250 GeV, 1150 $fb^{-1}$ +
500 GeV, 1600 $fb^{-1}$ : ~46%

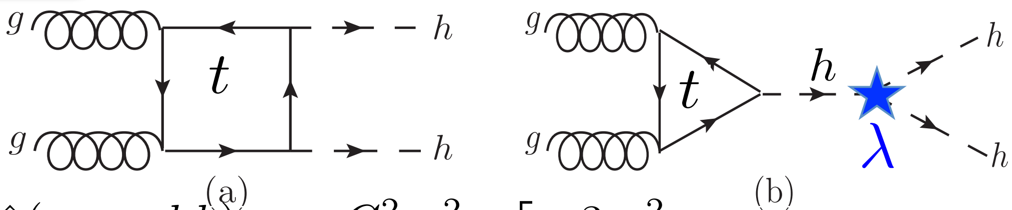
+ 1 TeV, 2500 $fb^{-1}$: ~13%

| | ILC(250) | ILC(500) | ILC(1000) | ILC(LumUp) |
|---|---|---|---|---|
| $\sqrt{s}$ (GeV) | 250 | 250 + 500 | 250 + 500 + 1000 | 250 + 500 + 1000 |
| L ($ab^{-1}$) | 0.25 | 0.25 + 0.5 | 0.25 + 0.5 + 1 | 1.15 + 1.6 + 2.5 |
| $\gamma\gamma$ | 18% | 8.4% | 4.0% | 2.4% |
| $gg$ | 6.4% | 2.3% | 1.6% | 0.9% |
| $WW$ | 4.8% | 1.1% | 1.1% | 0.6% |
| $ZZ$ | 1.3% | 1.0% | 1.0% | 0.5% |
| $t\bar{t}$ | – | 14% | 3.1% | 1.9% |
| $b\bar{b}$ | 5.3% | 1.6% | 1.3% | 0.7% |
| $\tau^+\tau^-$ | 5.7% | 2.3% | 1.6% | 0.9% |
| $c\bar{c}$ | 6.8% | 2.8% | 1.8% | 1.0% |
| $\mu^+\mu^-$ | 91% | 91% | 16% | 10% |
| $\Gamma_T(h)$ | 12% | 4.9% | 4.5% | 2.3% |
| $HHH$ | – | 83% | 21% | 13% |
| BR(invis.) | <0.9% | <0.9% | <0.9% | <0.4% |

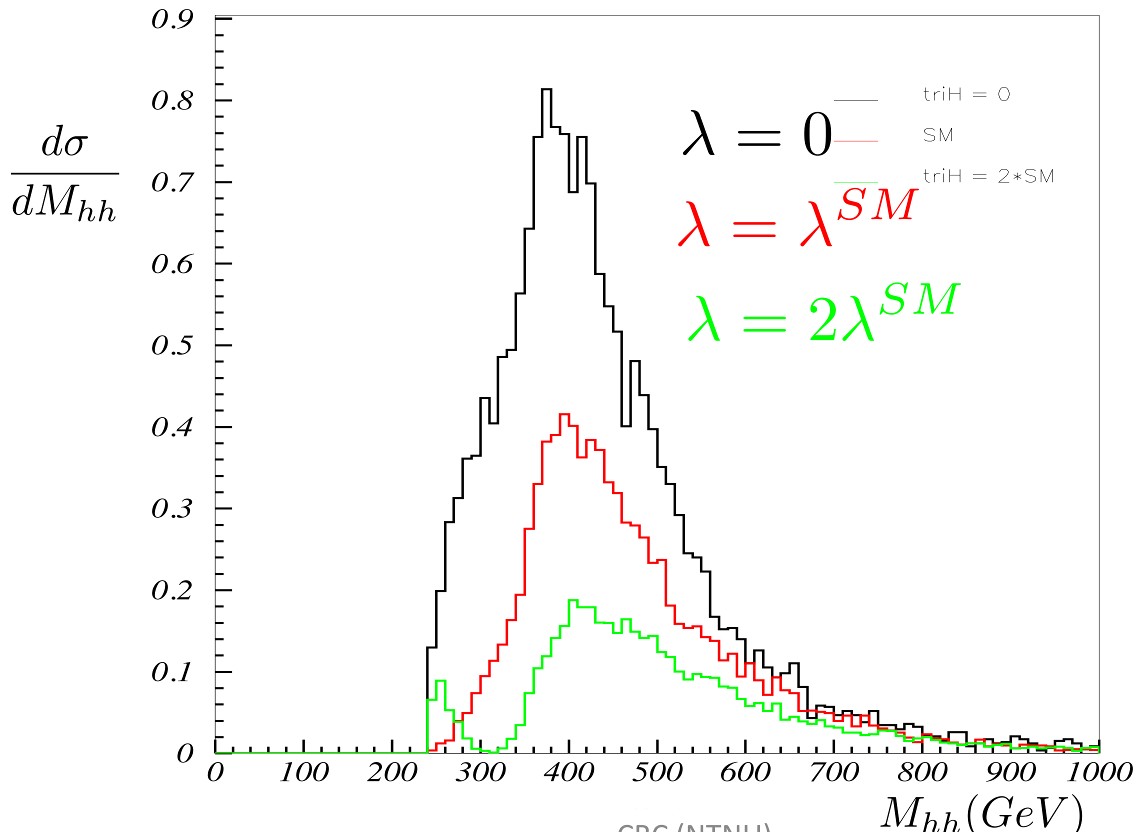
*For these estimates the value $m_H$ = 120 GeV was used.*

The measurement of the hhh coupling for mh ≃ 126 GeV is very challenging at the LHC and even at the high luminosity upgrade of the LHC. At the ILC, the hhh coupling can be measured via e+e− → Zhh and e+e− → hhνν̄ . As indicated in Chapter 9, for the combined data taken at the ILC with √s = 250 with 1150 fb−1 and 500 GeV with 1600 fb−1, the hhh coupling can be measured with an accuracy of about 46%. By adding additional data from a run of √s = 1 TeV with 2500 fb−1, one can determine the hhh coupling to an accuracy of about 13%. Therefore, the scenario for electroweak baryogenesis would be testable by measuring the triple Higgs boson coupling at the ILC.

# NP effects in gg → h h

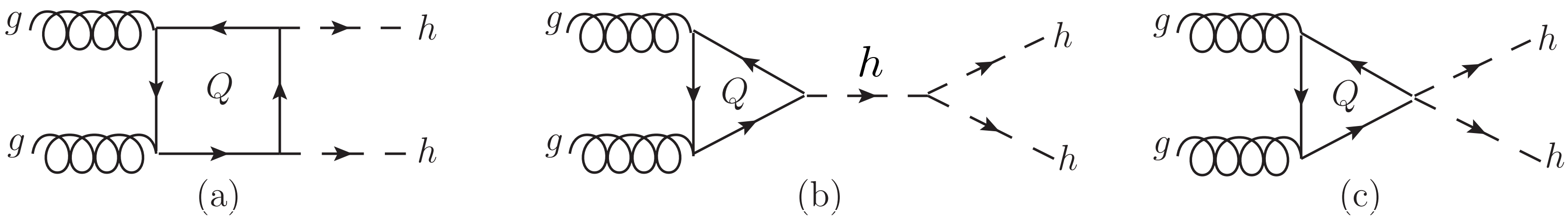



$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[ \left| \frac{3m_h^2}{\hat{s} - m_h^2} F_\triangle + F_\Box \right|^2 + |G_\Box|^2 \right]$$

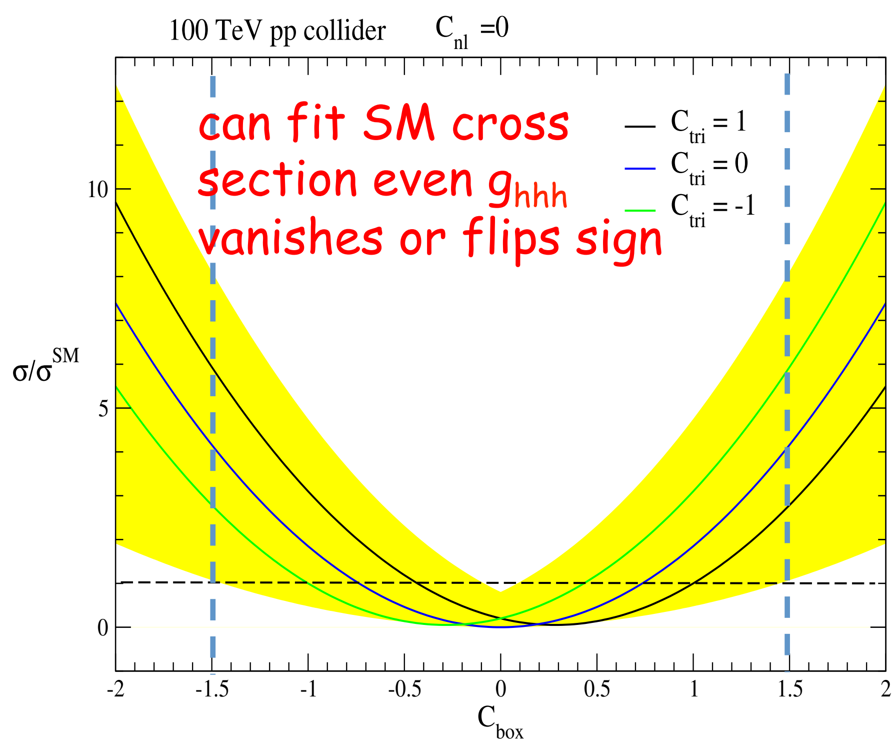


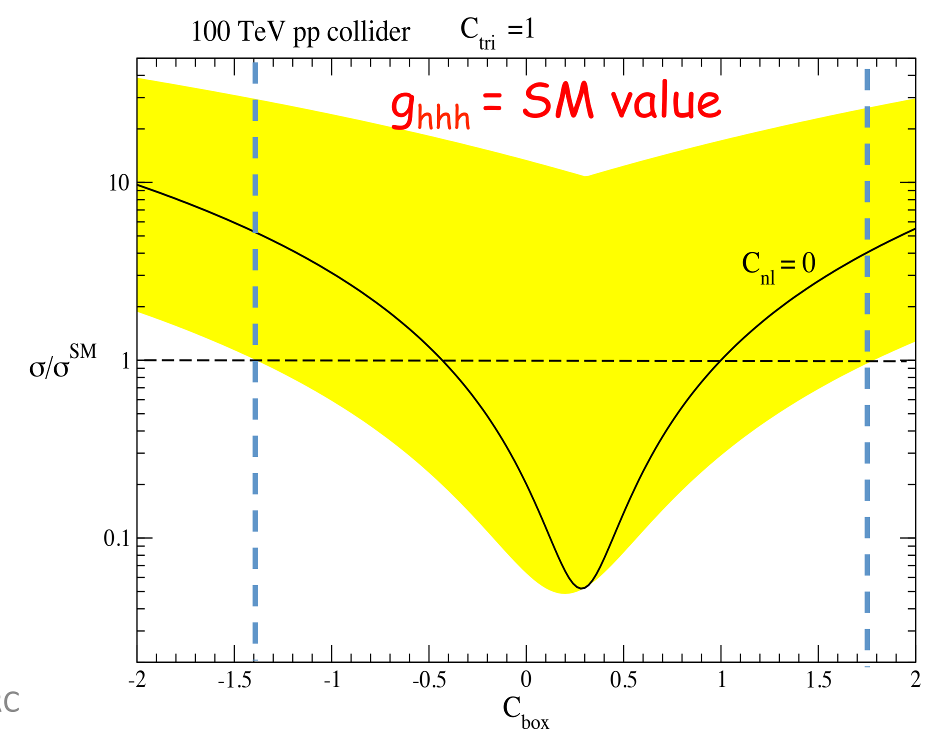
# NP effects in gg → h h (I)

CRC and Low, PRD 90. 013018




$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3}\left[\left|\left(c_{tri}\frac{3m_h^2}{\hat{s}-m_h^2} + c_{nl}\right)F_\triangle + c_{box}F_\square\right|^2 + \left|c_{box}G_\square\right|^2\right]$$

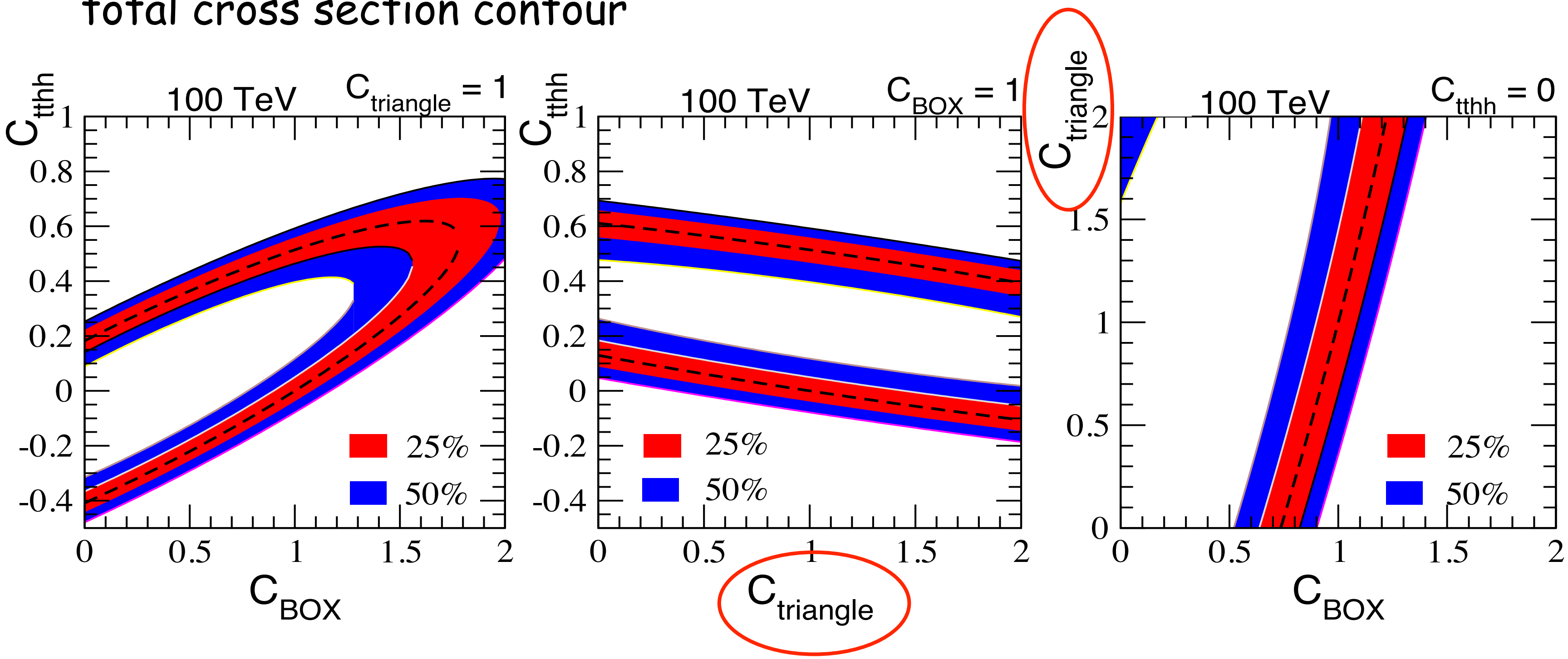



RC

# gg → h h

total cross section contour



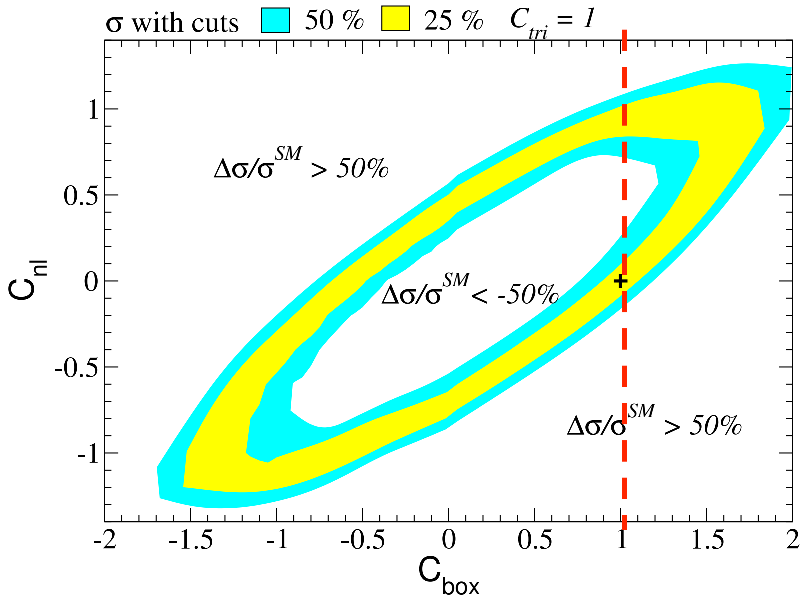

total cross section itself is insensitive to Higgs trilinear coupling!!

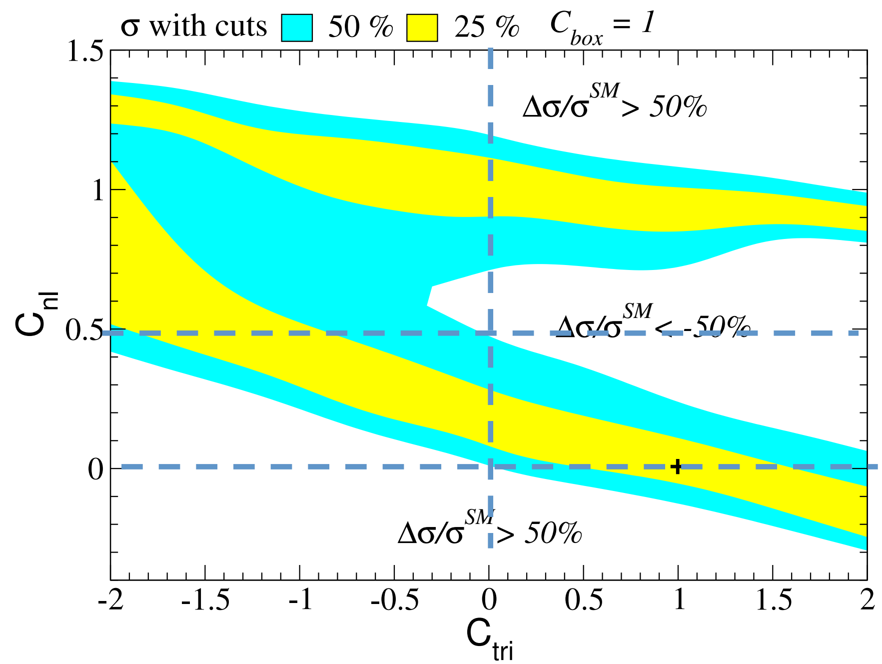
# gg → h h

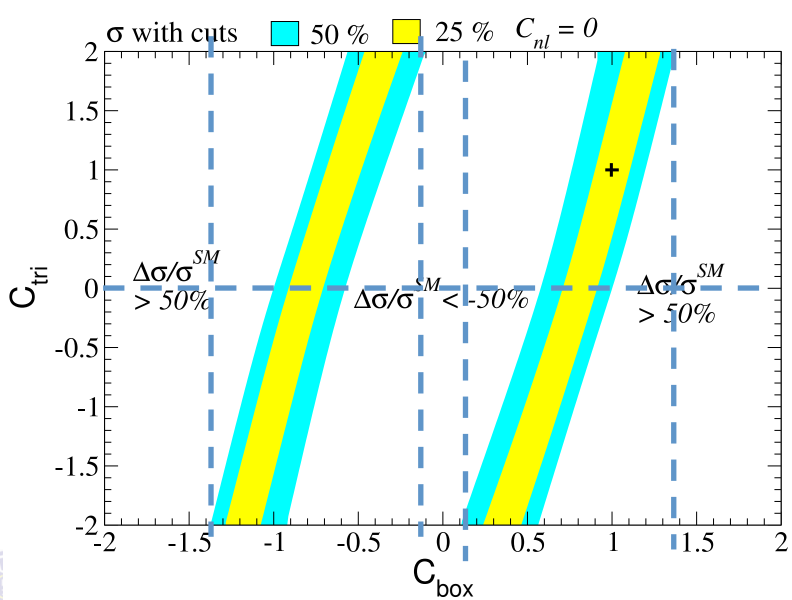
$$p_T^b > 35 \text{ GeV}, \quad |\eta_b| < 2, \quad 2.5 > \Delta R(b,b) > 0.4,$$

$$p_T^\gamma > 35 \text{ GeV}, \quad |\eta_\gamma| < 2, \quad 2.5 > \Delta R(\gamma,\gamma) > 0.4, \quad \Delta R(\gamma,b) > 0.4,$$

$$|\cos\theta_{\gamma\gamma}| < 0.8, \quad p_T^h > 100 \text{ GeV and } m_{hh} > 350 \text{ GeV},$$



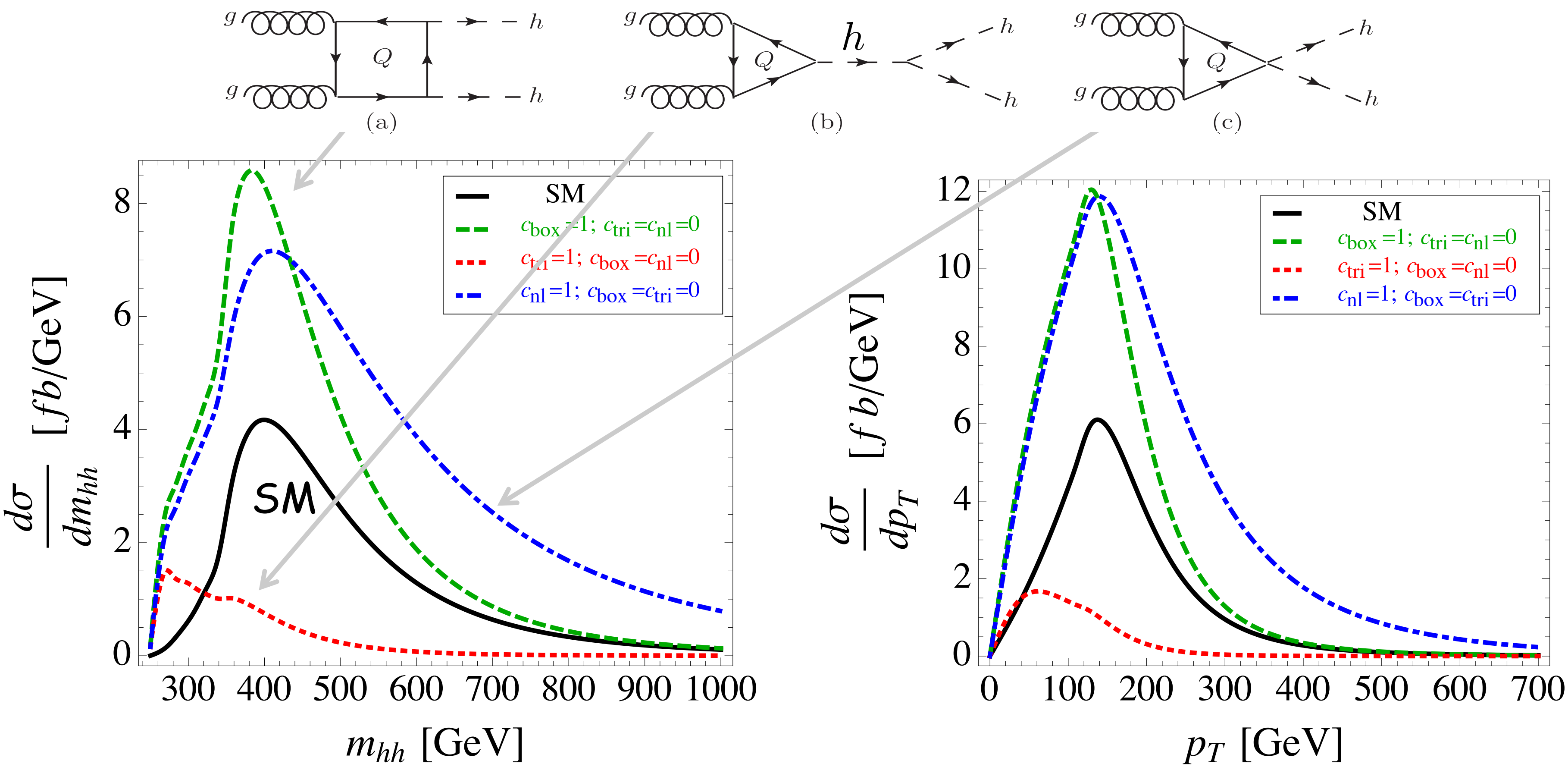




constrain on $C_{tri}$ is weak

w/ more assumptions, we can have more implications

# gg → h h



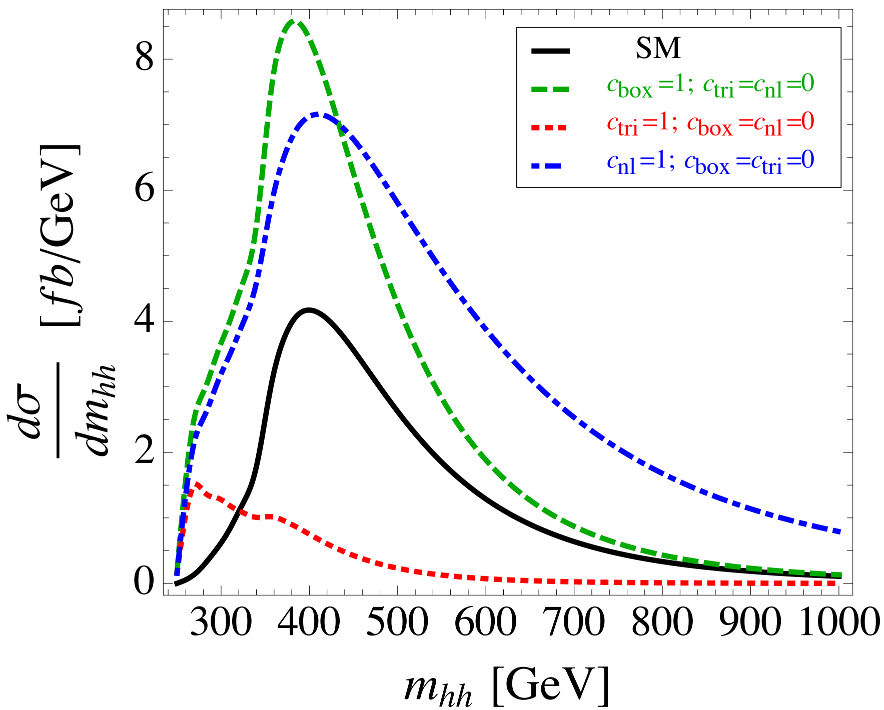

triangle → low $M_{hh}$ and low $p_t$

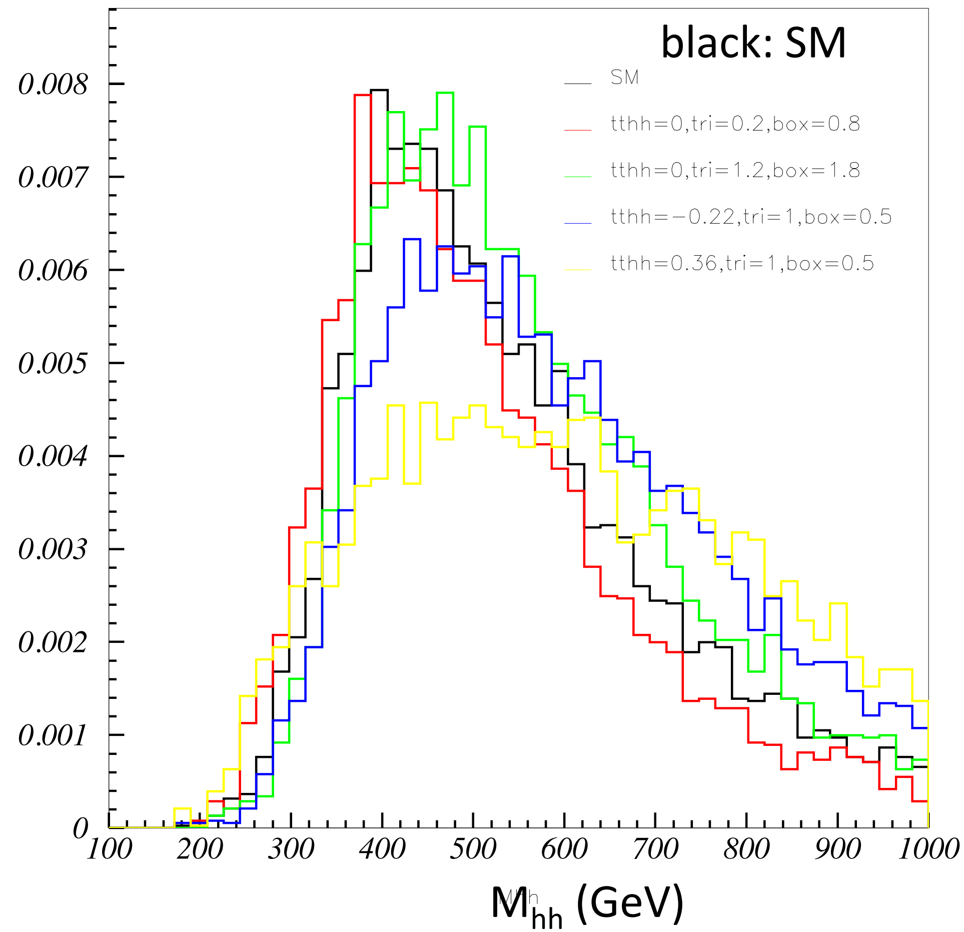
box diagram → higher $M_{hh}$ and higher $p_t$

tthh diagram →even higher $M_{hh}$ and even higher $p_t$

# gg → h h

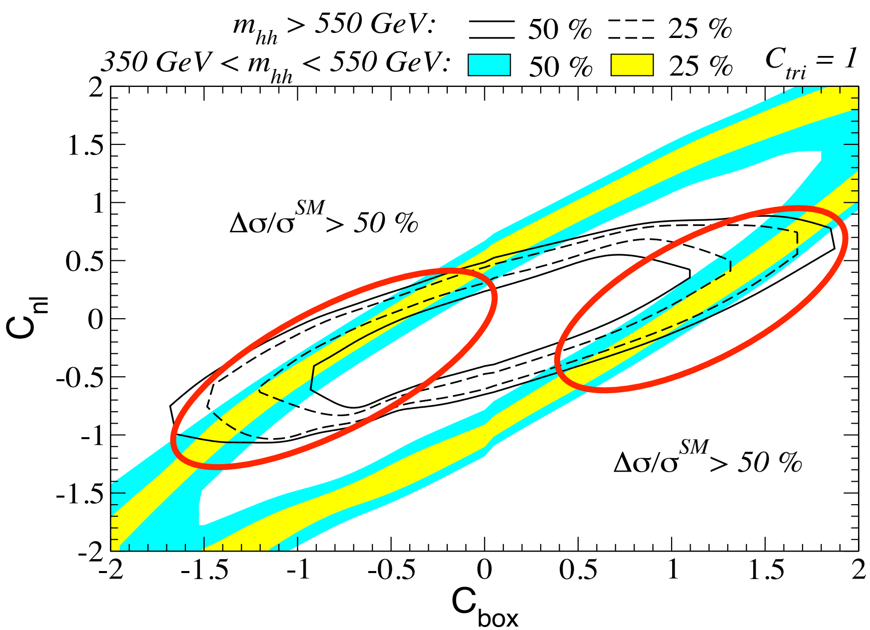
red: $C_{nl}$=0, $C_{tri}$=0.2, $C_{box}$=0.8
green: $C_{nl}$=0, $C_{tri}$=1.2, $C_{box}$=1.8
blue: $C_{nl}$=-0.22, $C_{tri}$=1, $C_{box}$=0.5
yellow: $C_{nl}$=0.36, $C_{tri}$=1, $C_{box}$=0.5



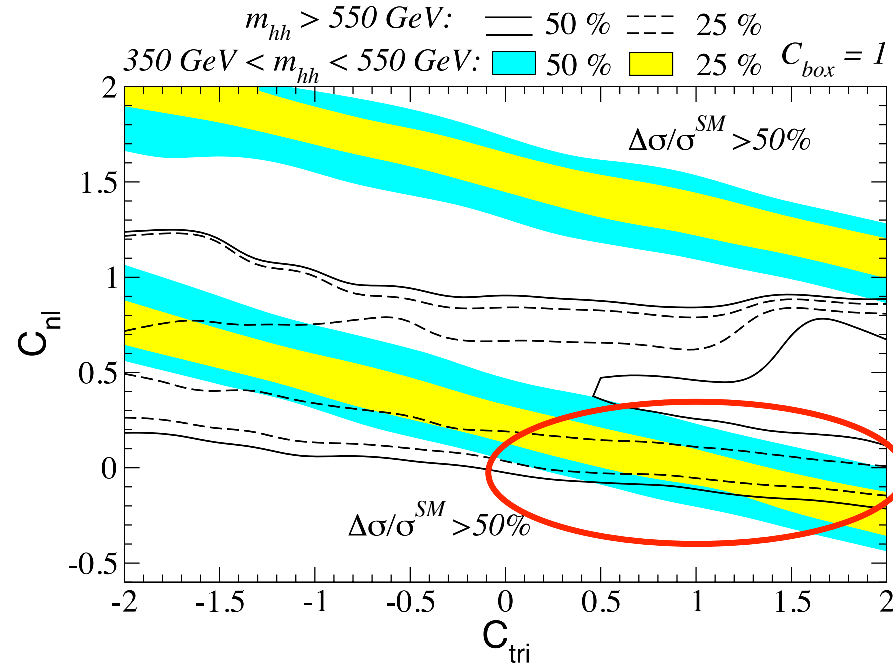



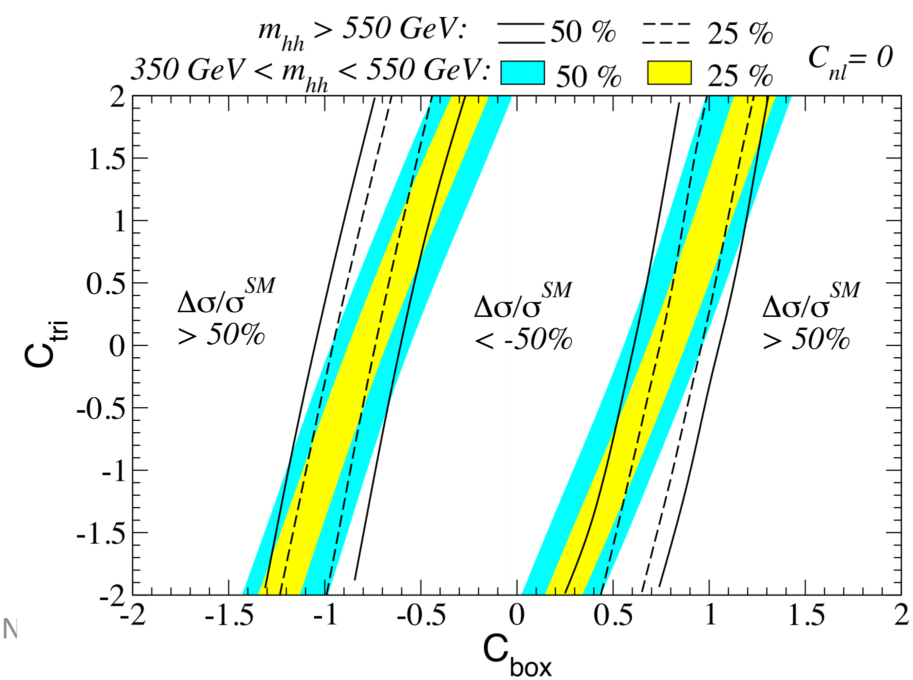

different combinations give same cross section, but
different $M_{hh}$ and $P_t$ distributions

# gg → h h

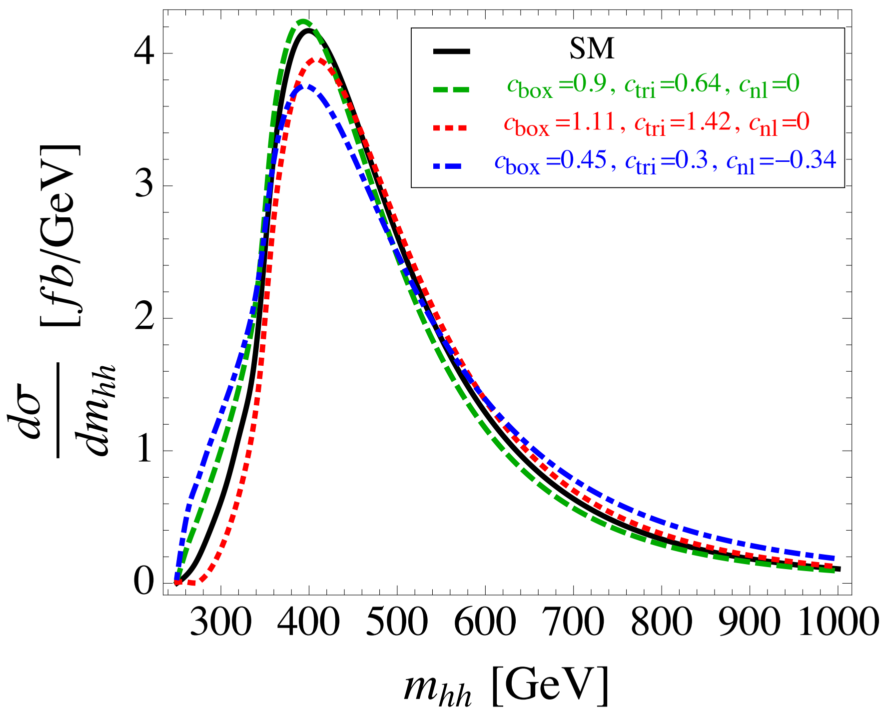


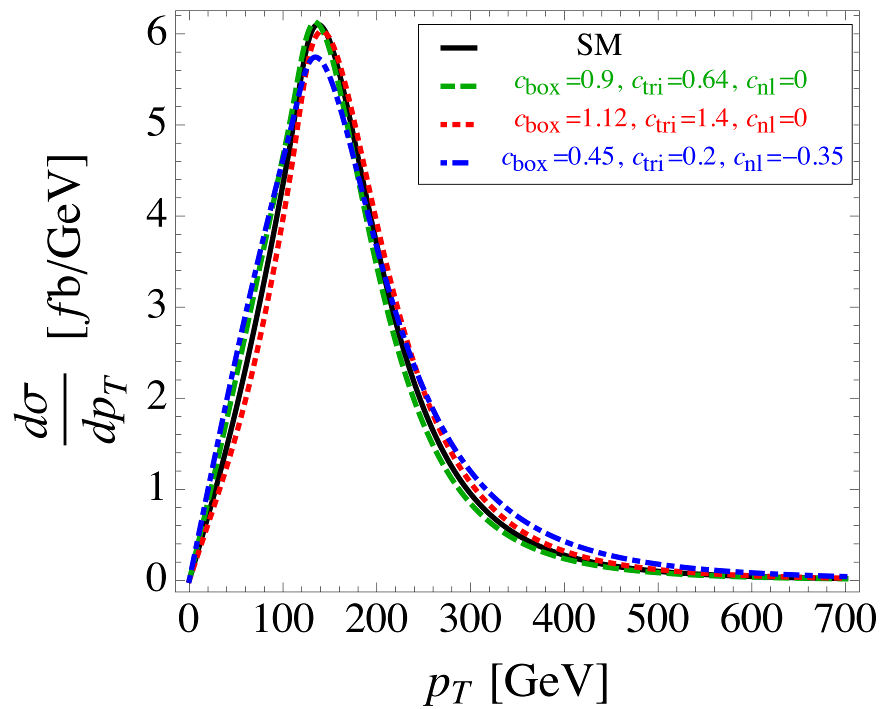

constrain some parameter space



# gg → h h

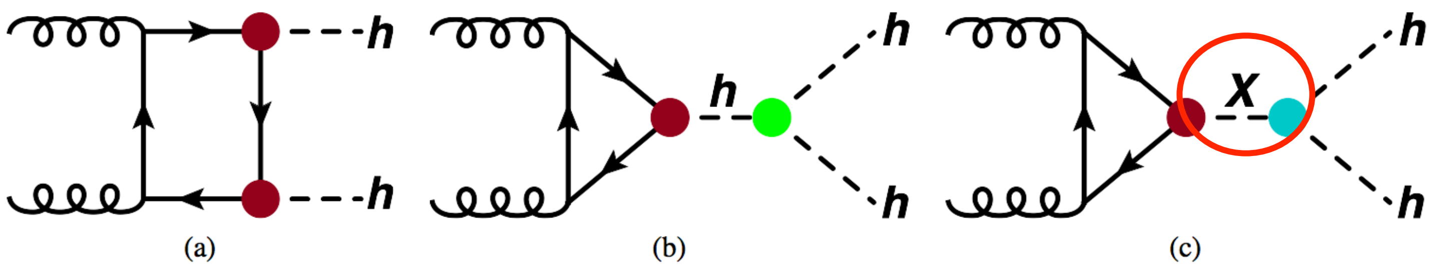



different combinations of $C_{tri}$, $C_{box}$ and $C_{NL}$ produce similar distributions

→ need more information to break the degeneracy

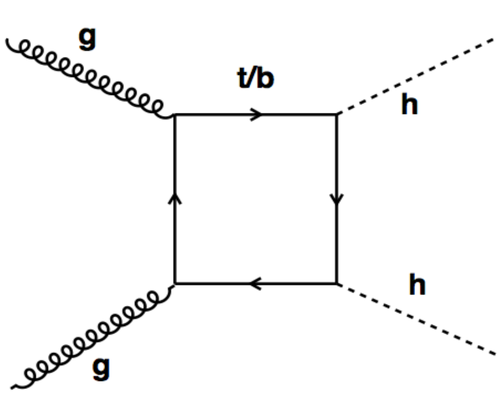
# NP effects in gg → h h (II)

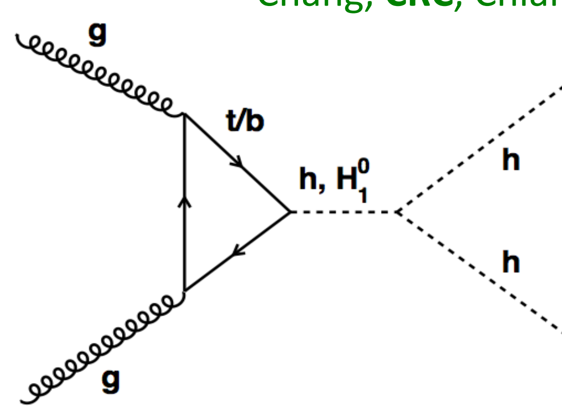



existence of a new resonance that decays into Higgs boson pair!

e.g. two doublet Higgs model, Gerogi-Machacek model, …

Chang, **CRC**, Chiang, JHEP 1703,137



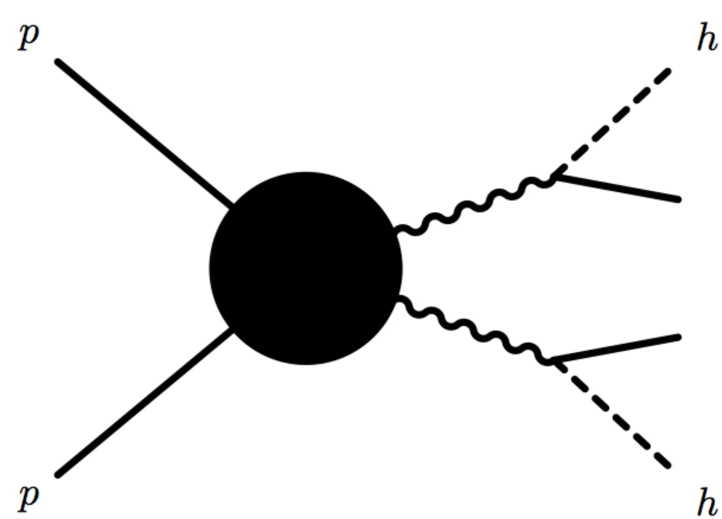

See Cheng-We's talk!!

# NP effects in gg → h h (III)

existence of a new resonance that decays into Higgs boson + some thing else!

IF because of symmetry, new resonance must be pair produced! → signals of Higgs boson pair !

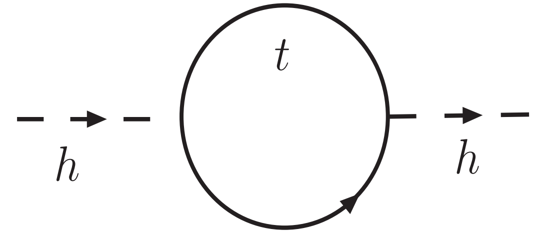
e.g. Little Higgs model with T-parity



# Naturalness "Problem"

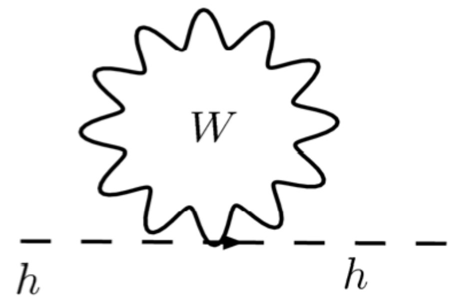
$$m_h^2 = m_{h0}^2 + \delta m_h^2$$

$$\delta^t m_h^2 \sim -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2$$




$$\delta^W m_h^2 \sim \frac{9g^2}{64\pi^2}\Lambda^2$$

$$\delta^h m_h^2 \sim \frac{\lambda^2}{16\pi^2}\Lambda^2$$

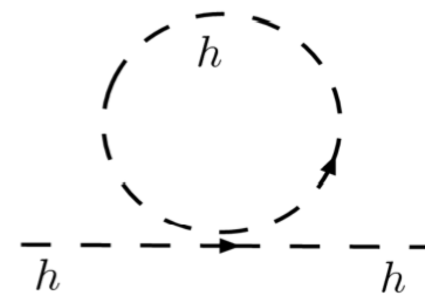



$$\delta m_h^2 \sim -(200\,GeV)^2\left(\frac{\Lambda}{1\,TeV}\right)^2$$

$\Lambda \sim 10^{19}$ GeV : Planck scale

$$\delta m_h^2 \sim -(200\,GeV)^2 \times 10^{32}$$

needs $m_{h0}^2 \sim (200\,GeV)^2 \times 10^{32}\left(1+\frac{1}{10^{32}}\right)$

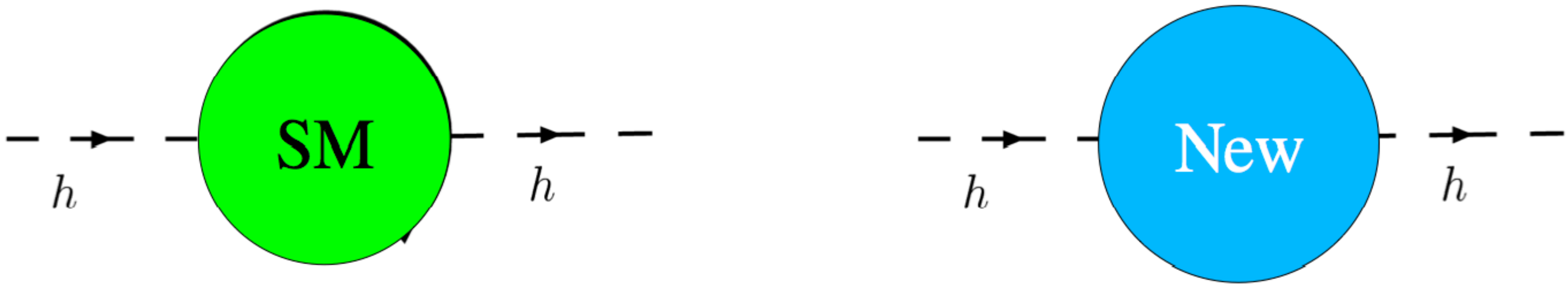



→ $m_h \sim 200\,GeV$

Highly fine-tuned !!

IF $\Lambda \sim 1$ TeV

→ Higgs is naturally ~ 200 GeV

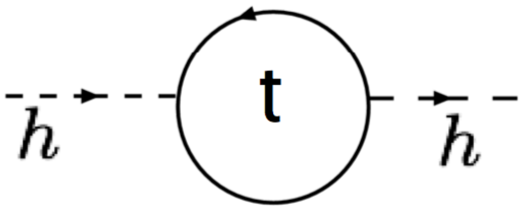



$\Lambda^2$ terms are canceled !!

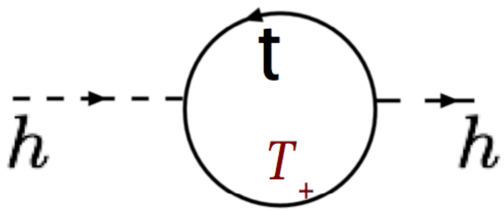
Only logarithmic divergence is left

e.g. Supersymmetry

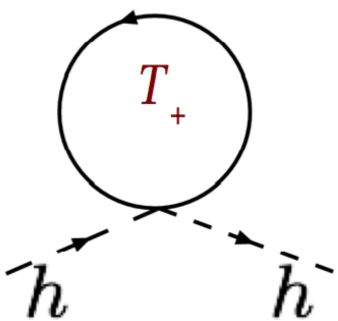
# LHT




$$-12\frac{\lambda_1^2\lambda_2^2}{\lambda_1^2+\lambda_2^2}\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2}$$




$$-12\frac{\lambda_1^4}{\lambda_1^2+\lambda_2^2}\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m_{T_+}^2}$$




$$12\frac{\lambda_1^2}{f\sqrt{\lambda_1^2+\lambda_2^2}}m_{T_+}\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m_{T_+}^2}$$

Sum $=0\bullet\Lambda^2+\bullet\bullet\bullet$

T-even heavy $T_+$ contributions cancel $\Lambda^2$

particle spectrum

**T-parity Even**

SM

$u \times 3$ $d \times 3$

$\ell \times 3$ $\nu \times 3$

$W^{\pm}$

$Z$

$\gamma$

$T_{+} \sim \sqrt{\lambda_1^2 + \lambda_2^2} f$

**T-parity Odd**

$d_{-} \gtrsim u_{-} \sim \sqrt{2}\kappa_q f$

$\ell_{-} \gtrsim \nu_{-} \sim \sqrt{2}\kappa_\ell f$

$Z_H \sim W_H \sim g f$

$A_H \sim g' f/\sqrt{5}$

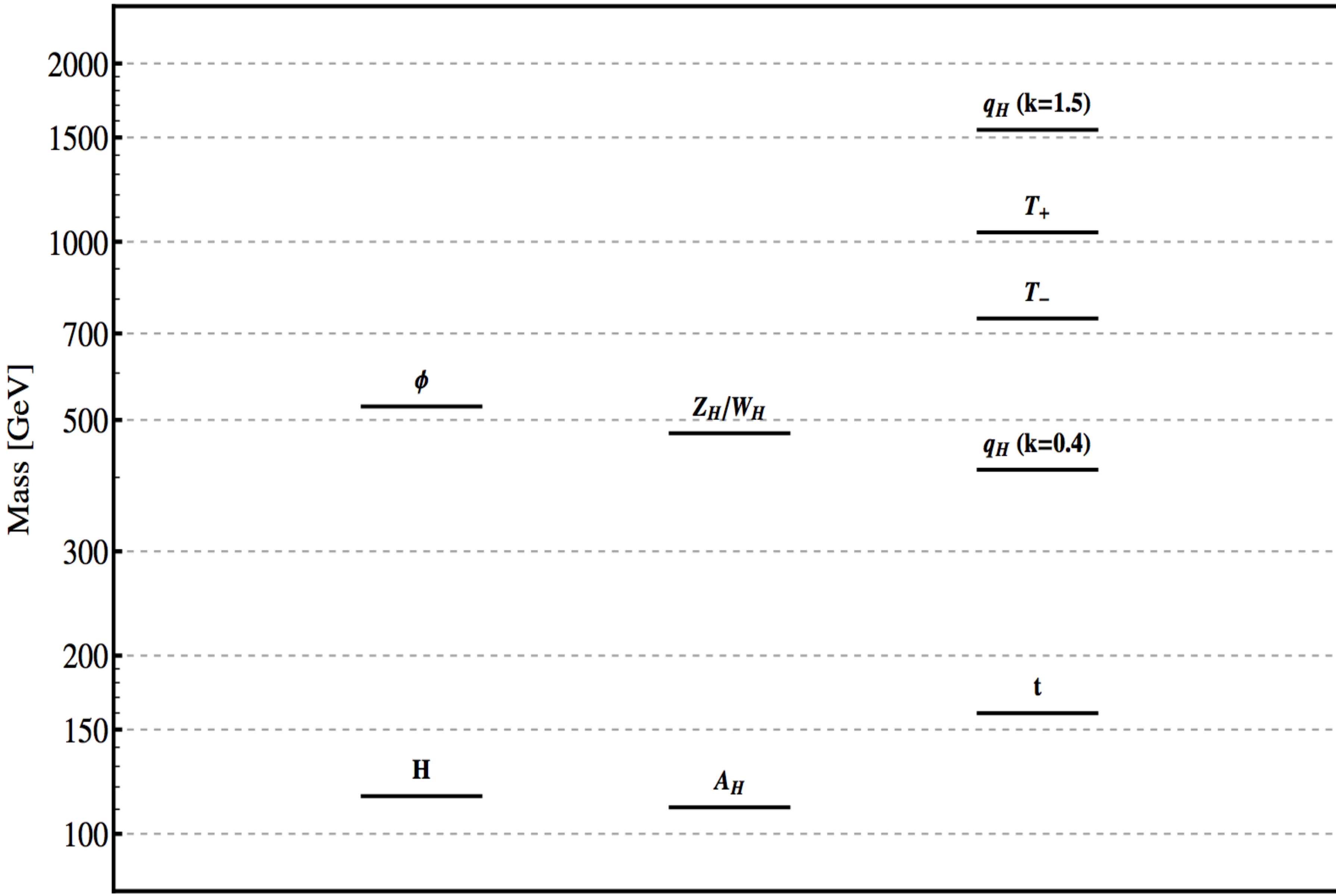
$T_{-} \sim \lambda_2 f$

**measurement of mass of gauge bosons measures f !**

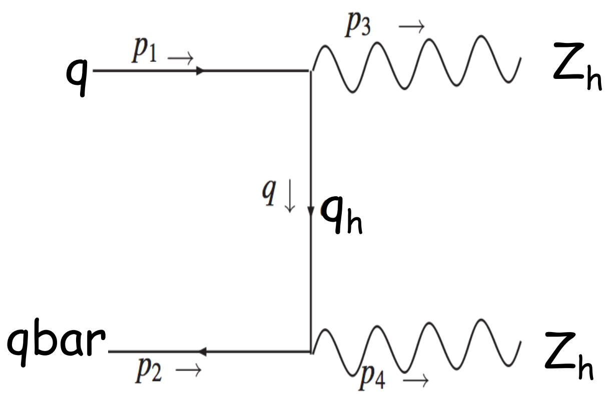
* parameters: **f**, $k_q$, $k_\ell$, $\lambda_1$, $m_h$

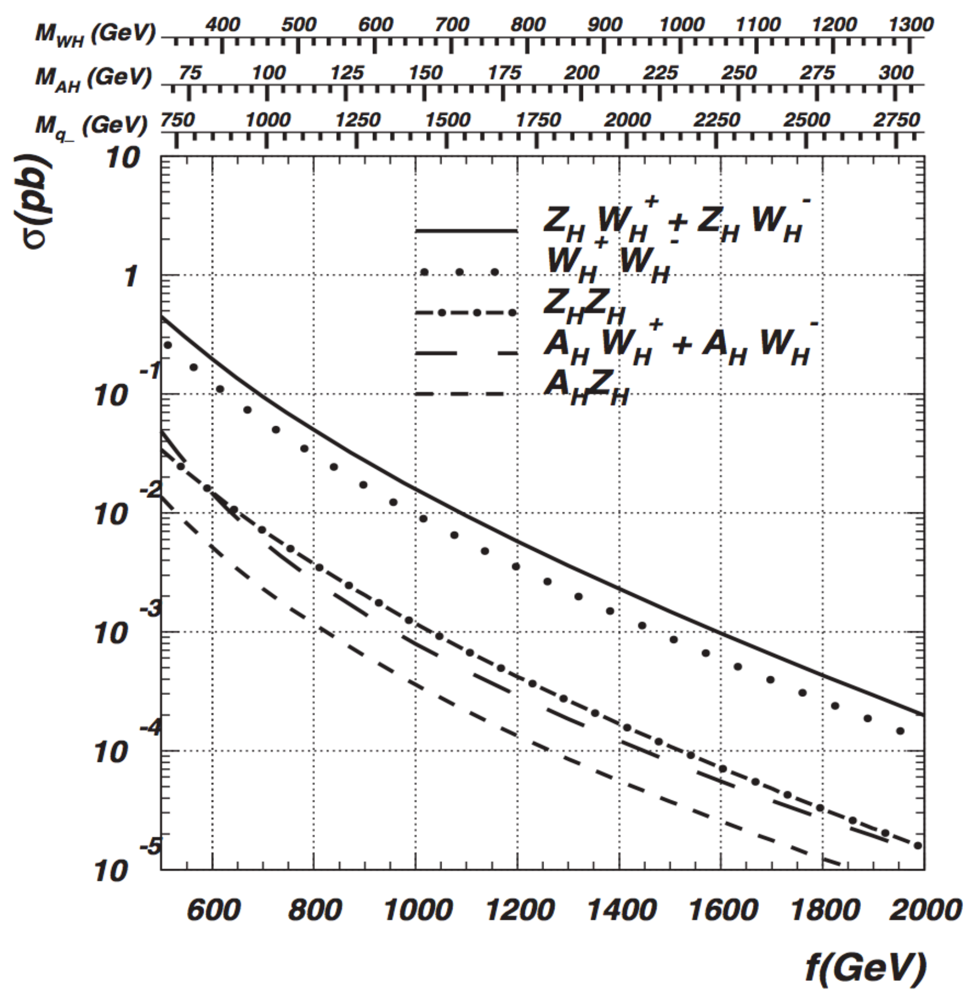
* The lightest T-odd particle is stable → dark matter candidate $A_H$

# particle spectrum



# Z' & h pair




$Z_h \rightarrow h + A_h$ : BR = 100 %

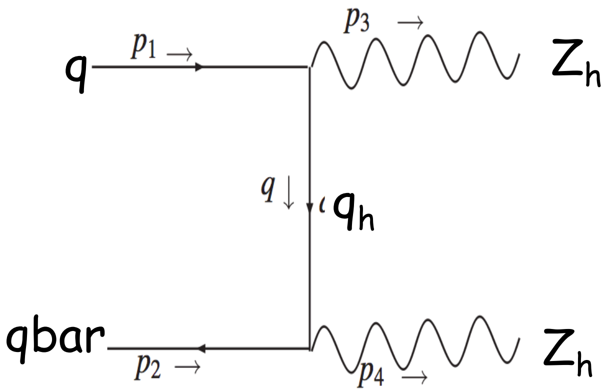
dark matter

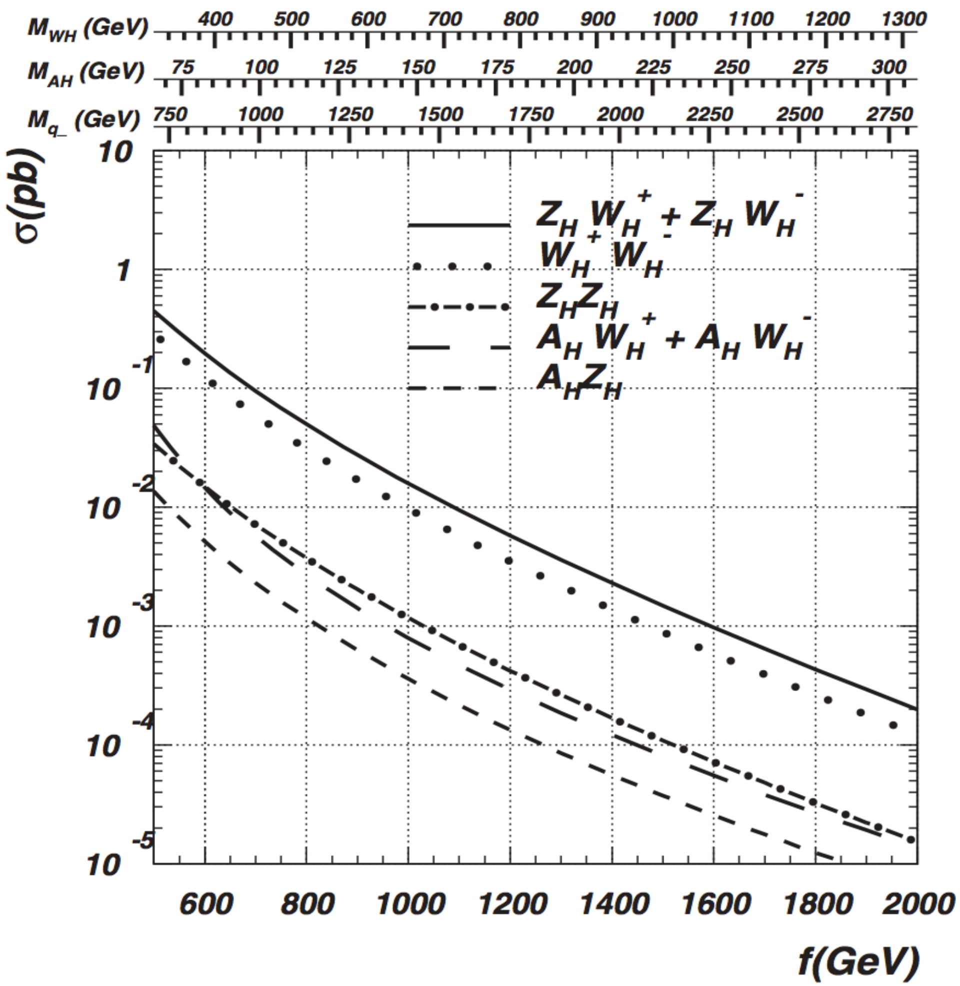
Therefore, we have di-Higgs associated missing ET

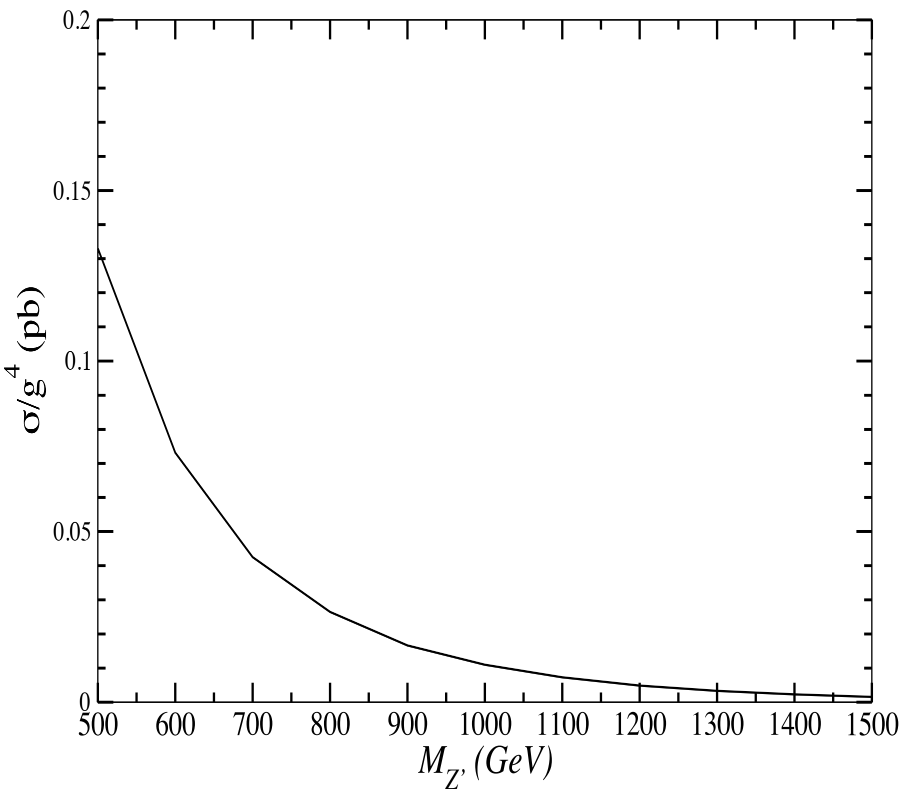
# Z' & h pair

Zh → h + $A_h$ : BR = 100 %

we have di-Higgs associated missing ET

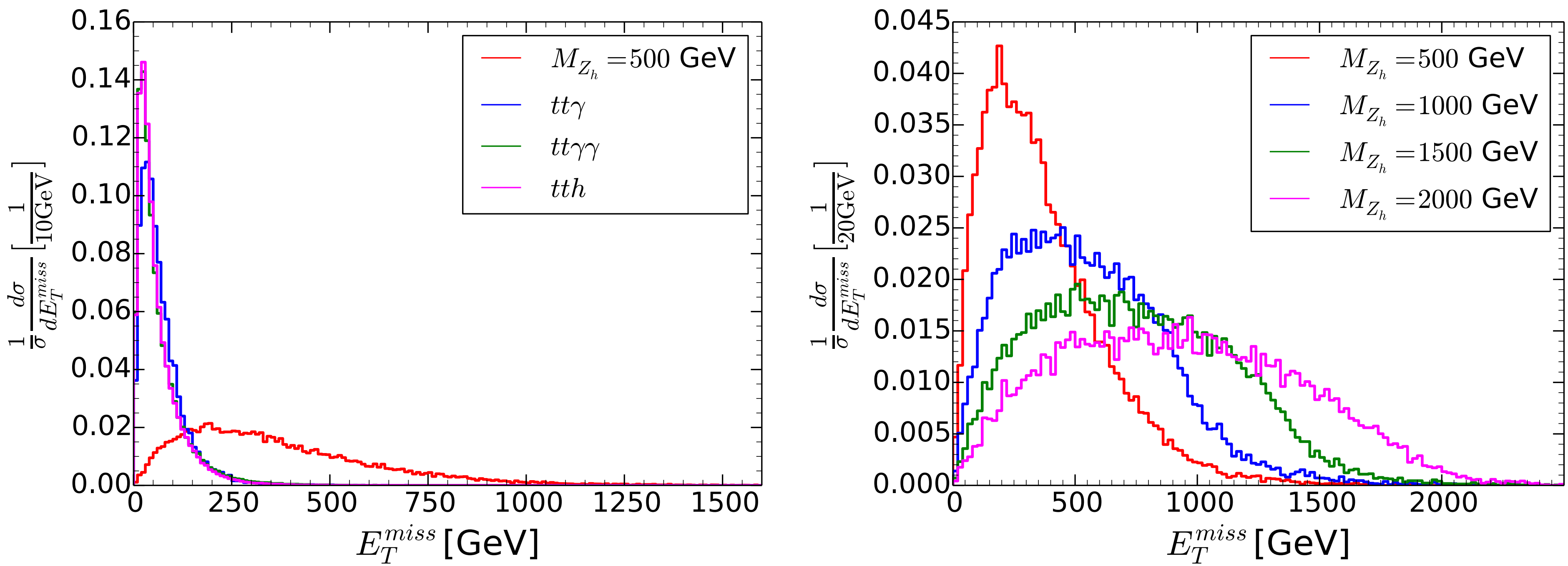


# Z' & h pair

$$pp \to Z'Z' \to h\ h\ dm\ dm$$




Large missing energy compared to the SM background!

$$hh \to \gamma\gamma b\bar{b}$$

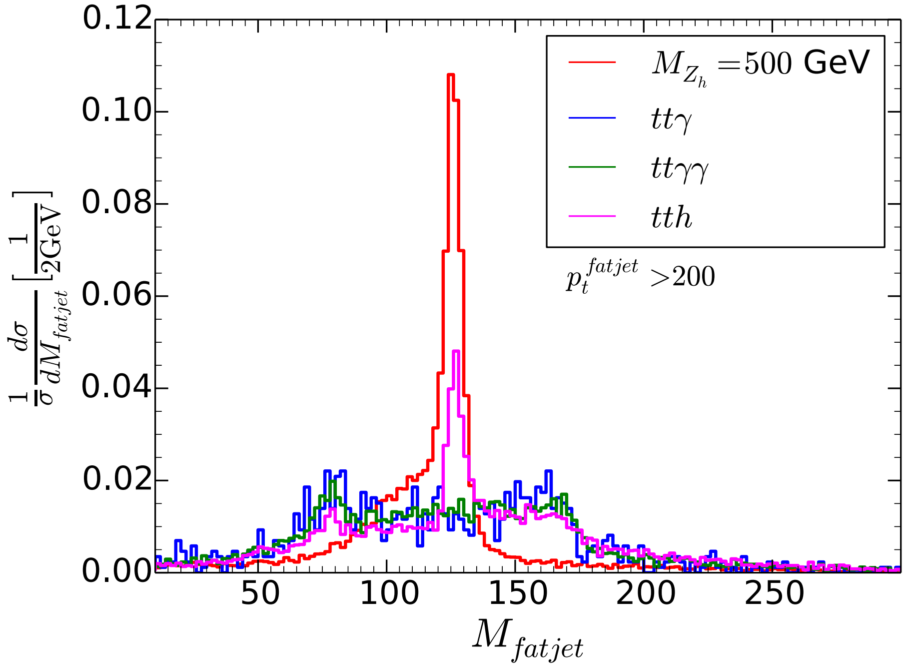
## Z' & h pair

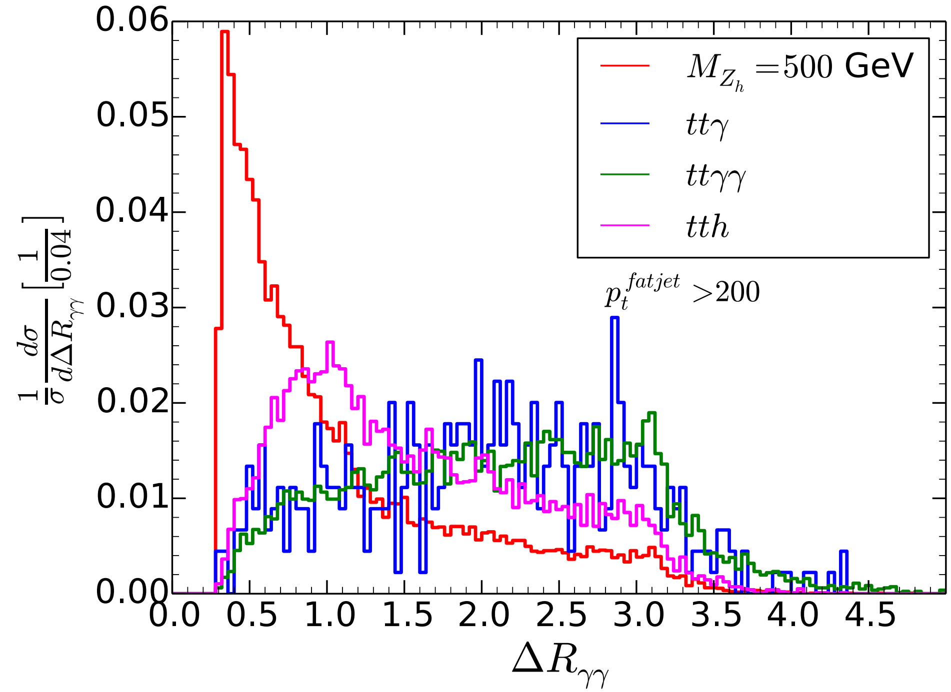
Other tricks to suppress SM background?

some thoughts:

$M_{Z'} \gg M_h, M_{dm}$ ➡ Higgs boson is boosted

➡ two bs ( and photons) in Higgs boson decay are collimated and jet-substructure can be adopted



# Z' & h pair

2 photons

1 fast jet (mass drop, CA algorithms, R=1.2) w/ PT > 200 GeV

lepton veto

MET > 150 GeV

| Mγγ –125 | < 10 GeV

| M(fat jet) – 125 | < 30 GeV

one b-tag inside the fat jet

$M_{hh}$ > 252 GeV

background: $b\bar{b}\gamma\gamma \sim 0$ $\quad h b\bar{b} \sim 0$ $\quad t\bar{t}\gamma\gamma \sim 2.7 \times 10^{-2}\ \%$

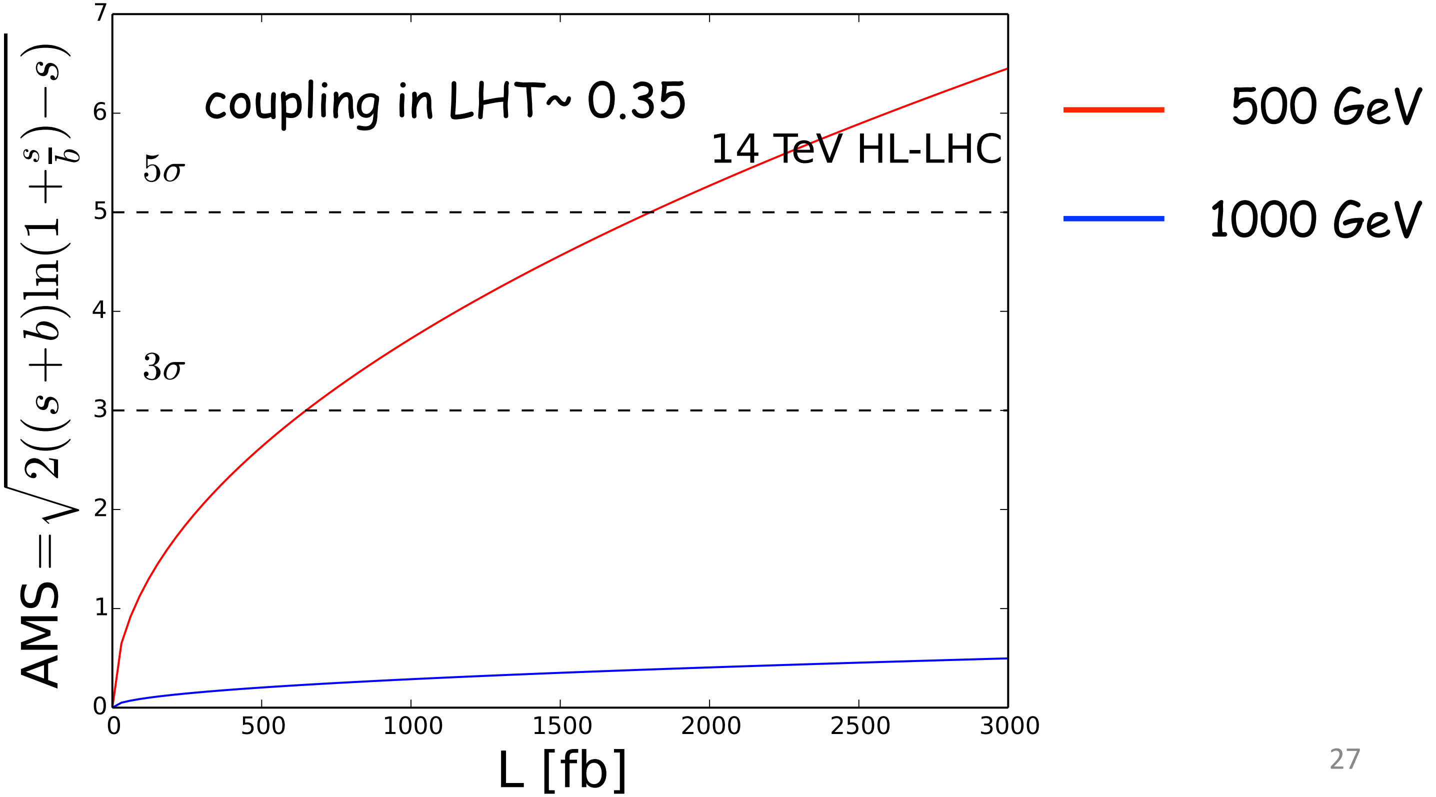
$t\bar{t}\gamma \sim 10^{-3}\ \%$ $\quad t\bar{t}h \sim 0.27\%$ $\quad Zh \sim 2.3 \times 10^{-3}\%$

Z' : ~ 12%

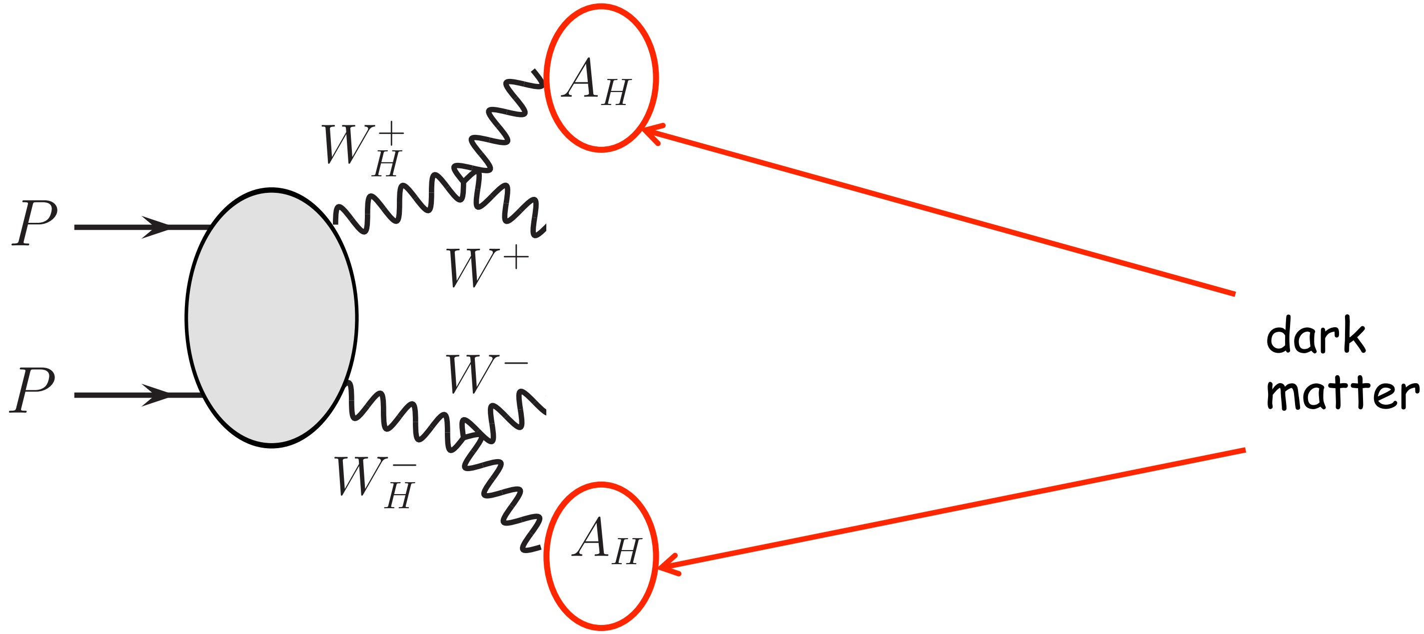
# Z' & h pair

AMS (approximate median significance)

$$\sqrt{2\left((s+b)\ln\left(1+\frac{s}{b}\right)-s\right)} \sim \frac{s}{\sqrt{b}}$$



# Another di-heavy boson




$W^+ W^-$ in association with missing energy!

again, when $M_{W_H} \gg M_{A_H}, \quad M_W$

➡ W boson is boosted

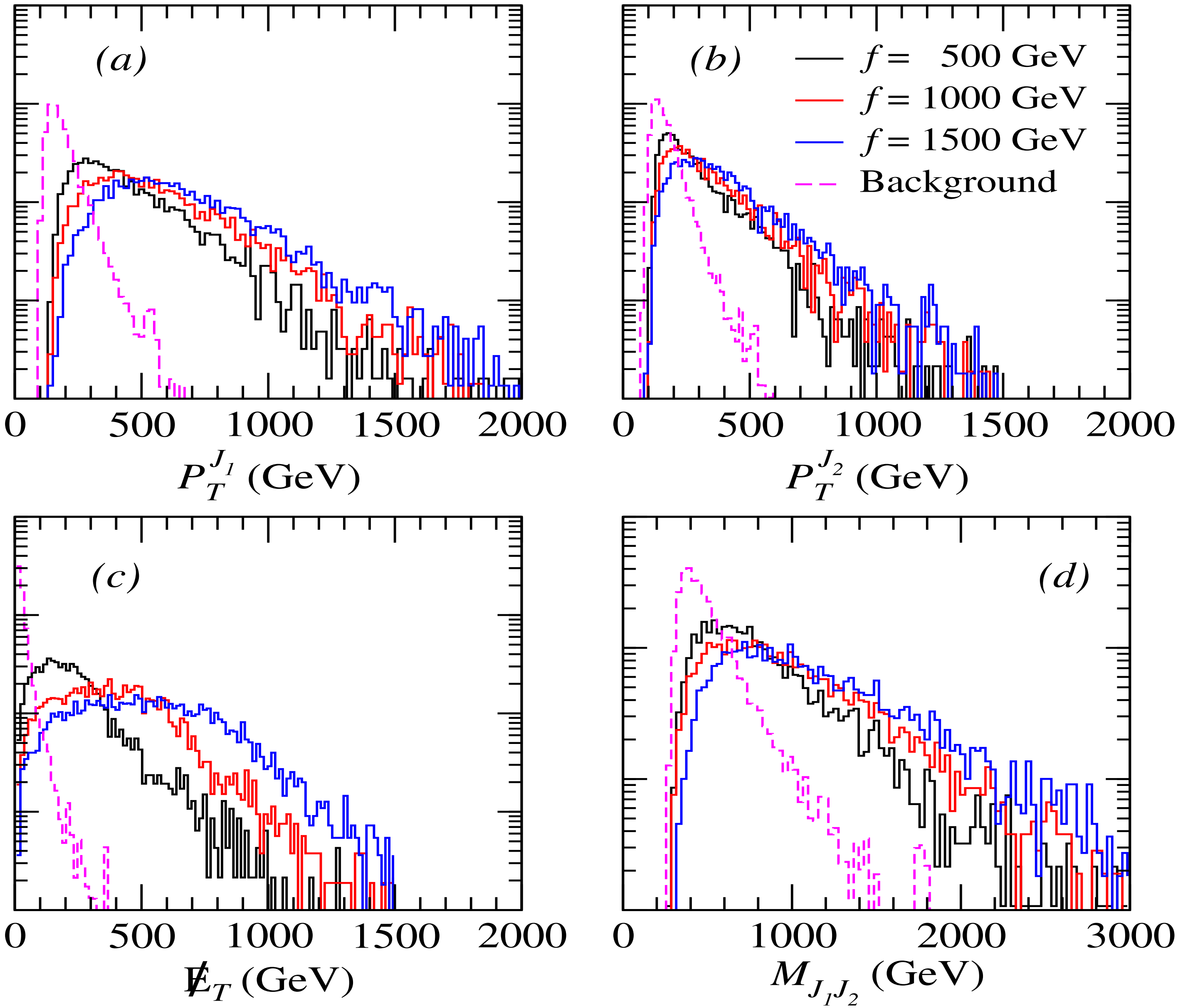
Cao, **CRC**, Liu, PRD94 (2016), 055033

➡ decay products of W-boson are collimated and jet-substructure can be adopted

# Another di-heavy boson

Signal in larger

$P_T \quad \not{E}_T \quad M_{JJ}$

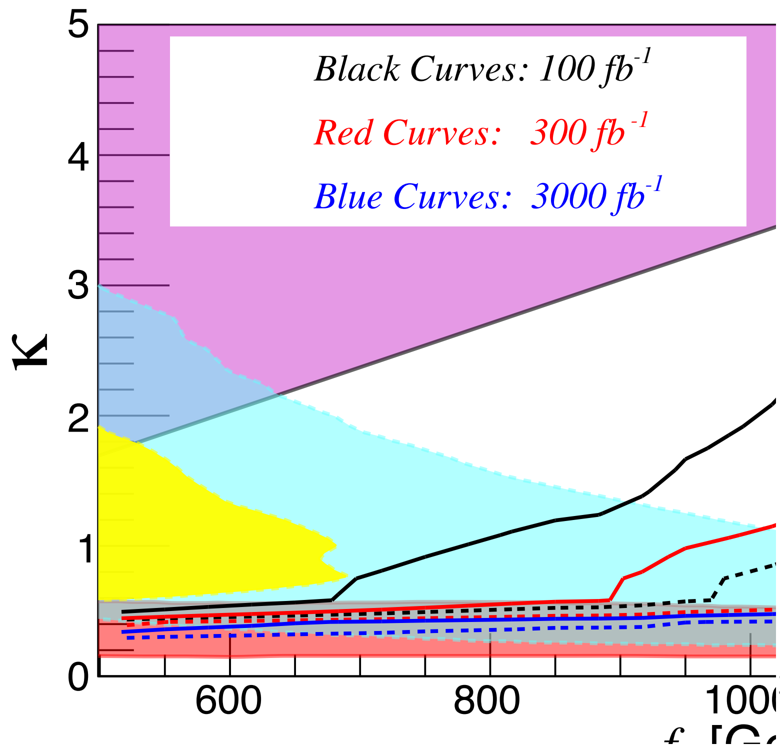


cuts

$$m_W - 13\ \text{GeV} \le M_J \le m_W + 13\ \text{GeV},$$
$$p_T^{J_1} \ge 200\ \text{GeV},\ p_T^{J_2} \ge 100\ \text{GeV},\ \left|\eta^{J_{1,2}}\right| \le 3,$$
$$M_{J_1 J_2} \ge 500\ \text{GeV},\ \not{E}_T \ge 400\ \text{GeV}$$ and lepton veto

| | $f = 0.5$ TeV | $f = 1.0$ TeV | $f = 1.5$ TeV | $t\bar{t}$ | $WW$ | $WZ$ | $ZZ$ |
|---|---|---|---|---|---|---|---|
| No cut | 88698 | 2735.04 | 244.32 | $5.5 \times 10^7$ | $9.54 \times 10^6$ | $4.36 \times 10^6$ | $1.25 \times 10^6$ |
| $\not{E}_T$, $W_{\text{jet}}$-tagging and $M_{JJ}$ | 295.33 | 38.51 | 5.51 | 13.31 | 4.77 | 6.43 | 1.17 |

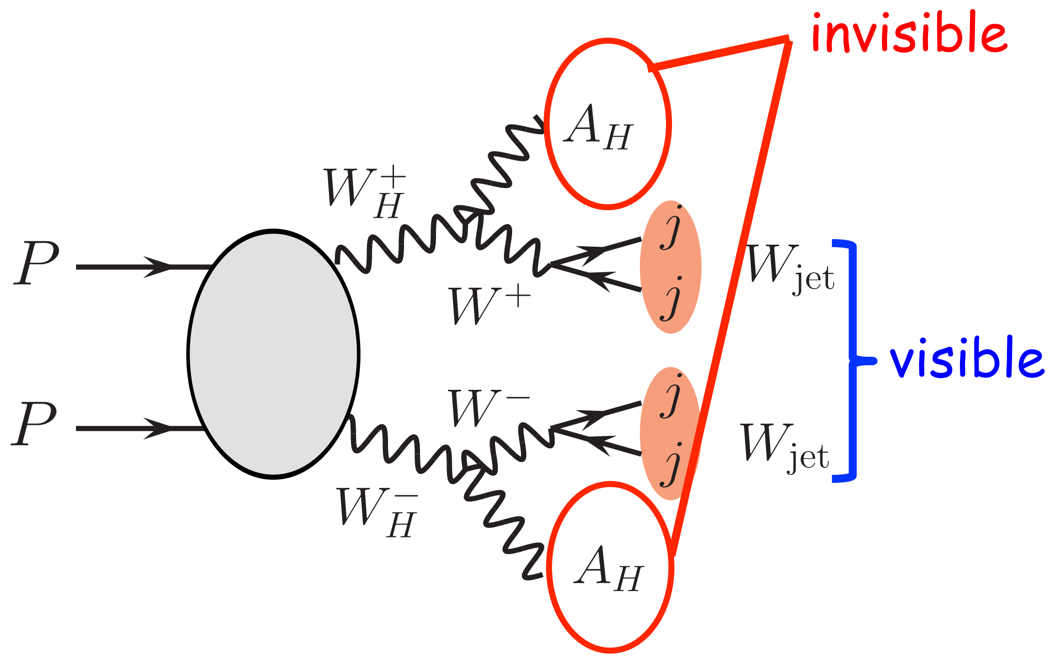
$$M_{W'} \sim 0.65 f$$



can reach > 3σ level for most of the parameter space

However, another difficulty – How can we measure the mass of $W_H$ (i.e. determine f ) with two missing $A_H$ (dark matter) ?

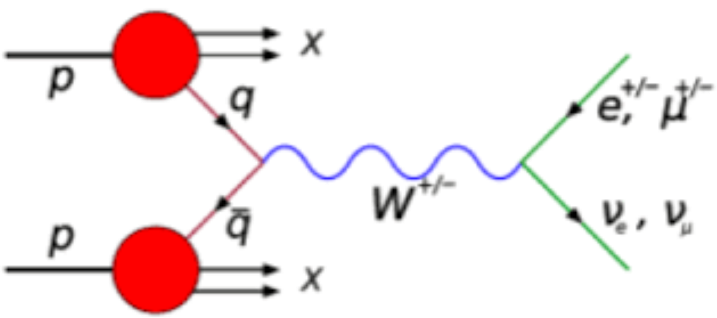
→ no resonance can be reconstructed!



# MT2 method

How can one measure the mass of a heavy particle if it is produced in pairs and its decay products include invisible particles?

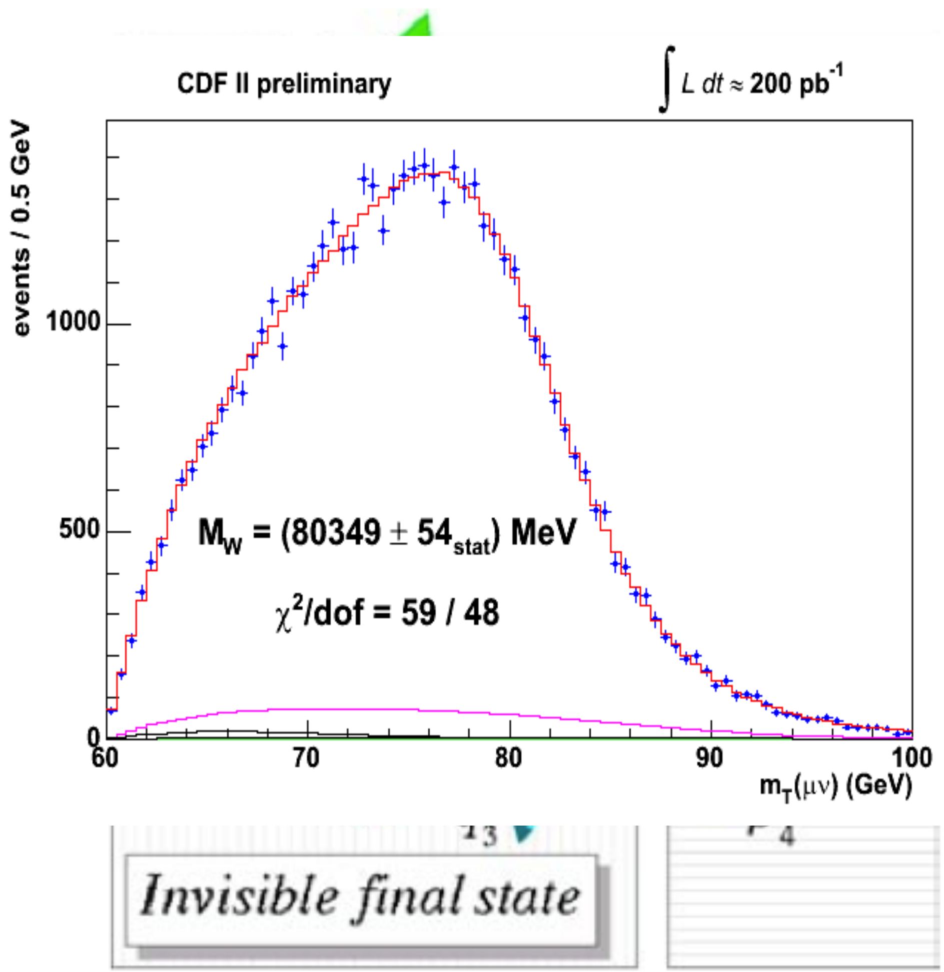
- Warm up: measuring the mass of the W boson in the leptonic decay channel -- MT variable.




$$m_T^2 = 2\left(E_T^e \not{E}_T - \mathbf{p}_T^e \cdot \not{\mathbf{p}}_T\right)$$

- The true mass of the W boson satisfies $m_T^2 \leq m_W^2$

- The end point of the transverse mass distribution is the W boson mass.



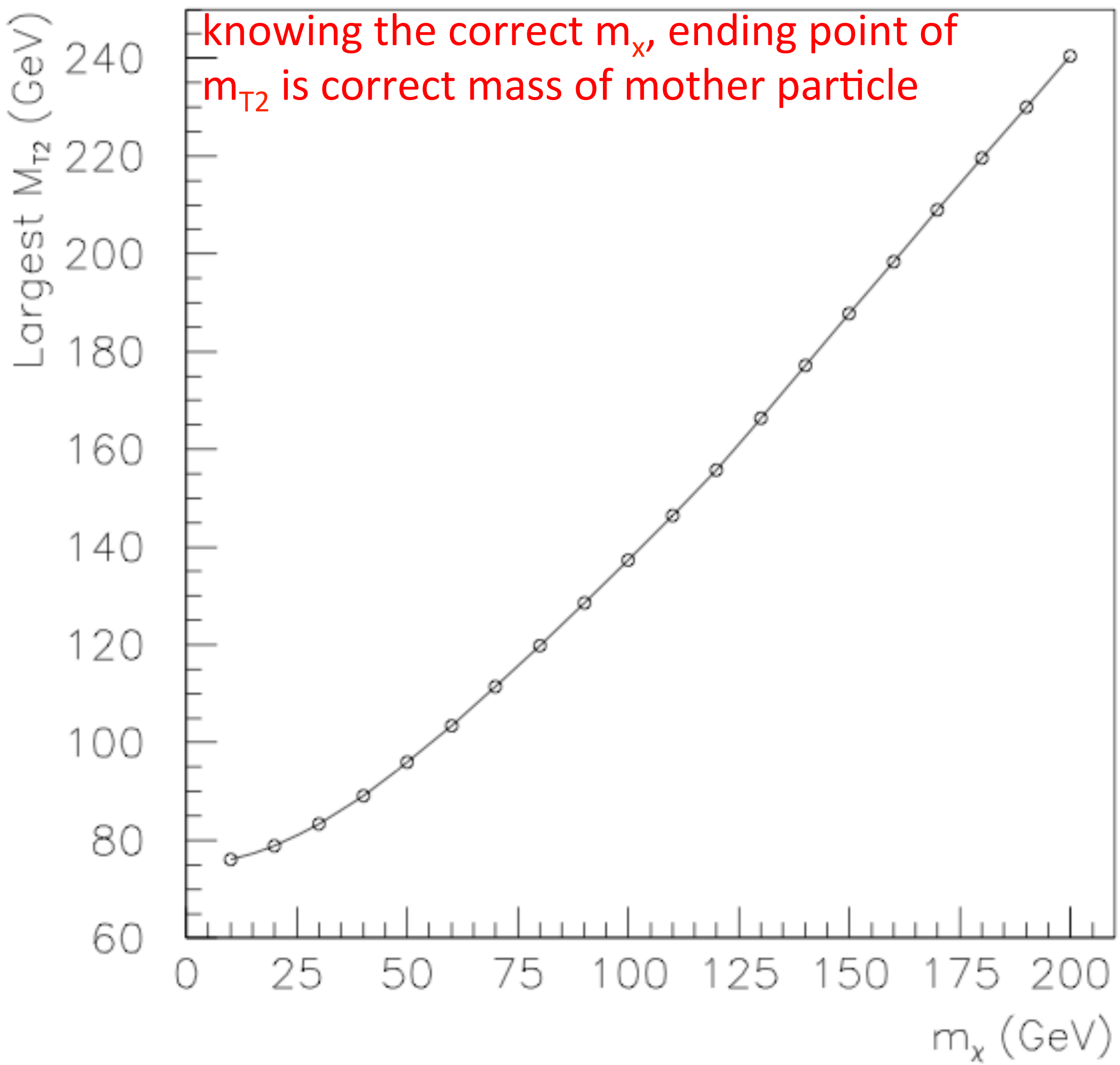
# MT2 method

- When there ... d
invisible parti ... s of
their parent. ...h/9906349

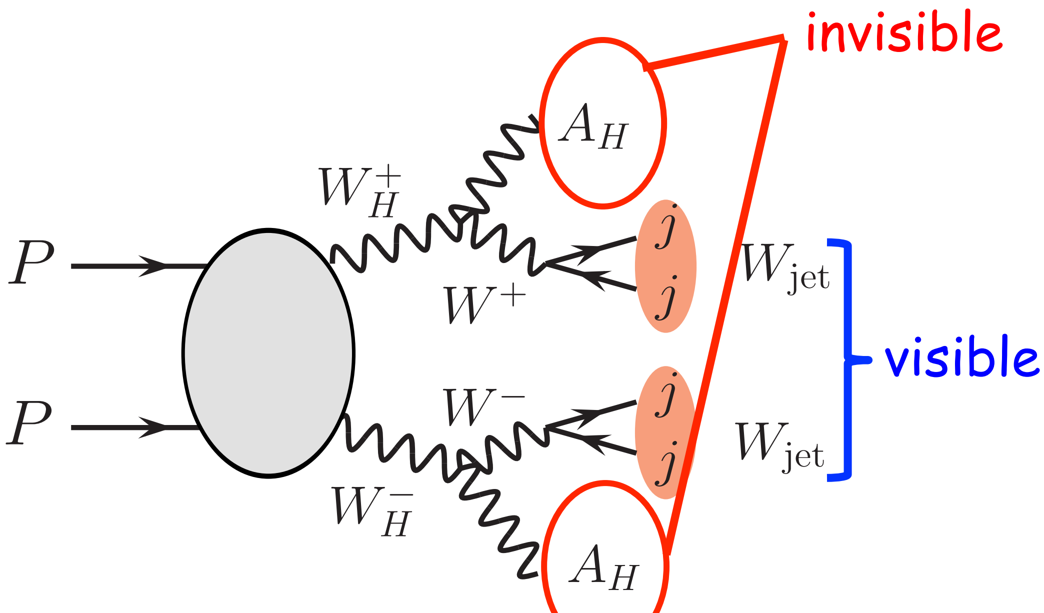
$m_{T2}(m_{invis})$ =
$\min_{\mathbf{p}_T^{(1)},\mathbf{p}_T^{(2)}} \left[ \max \right.$

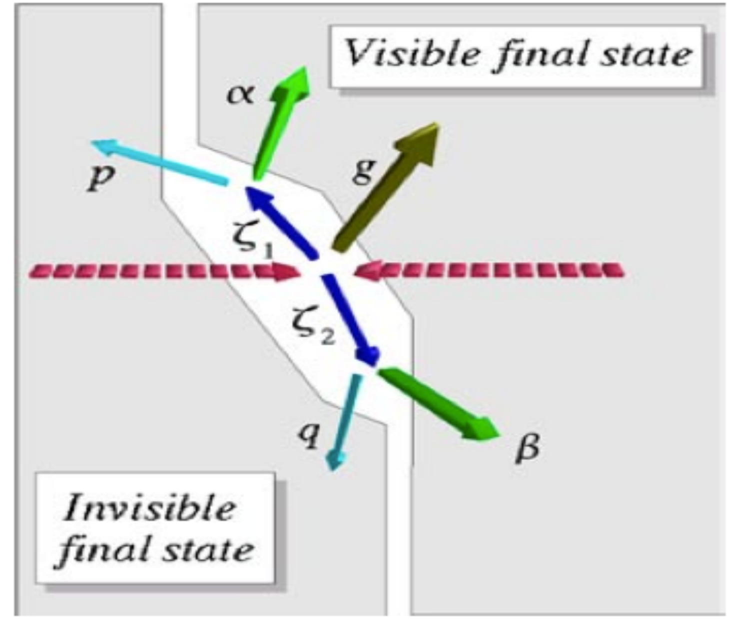
$m_T(m_{invis}; \mathbf{p}_T^{invis}$
$\sqrt{m_{vis}^2 + m_{invis}^2}$

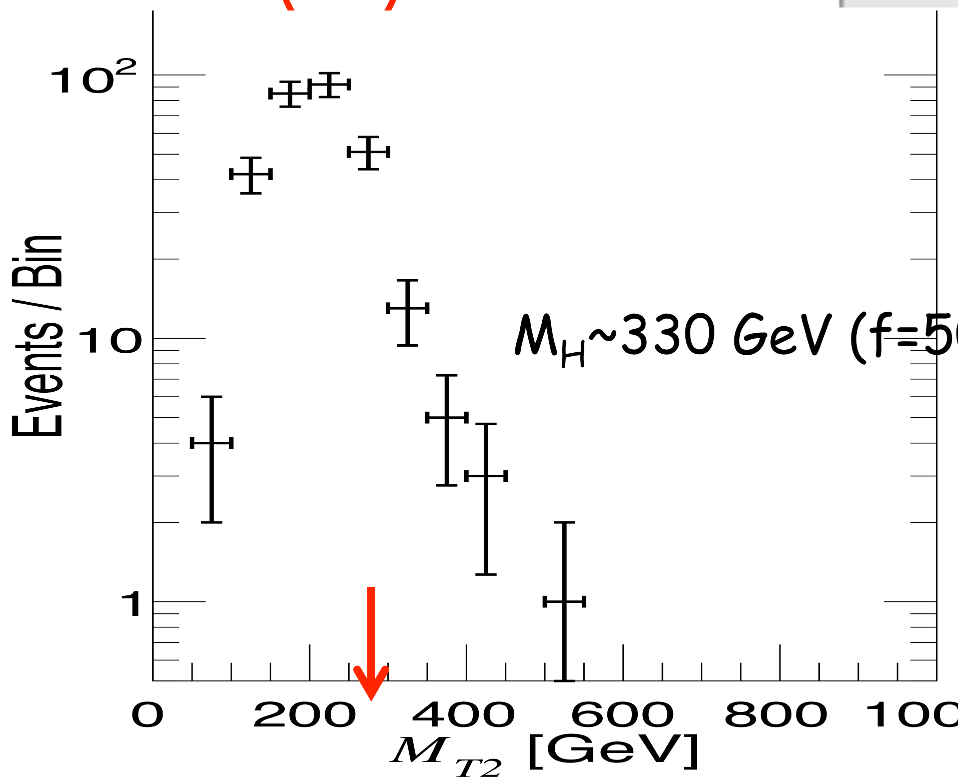
★ The MT2 vari
momenta of v
and missing tr
Its upper bou
parent particl




...al state




$M_H$~330 GeV (f=500 GeV)

## Summary

* A new scalar with mass ~ 125 GeV is discovered and its properties are consistent with SM Higgs boson.

* Higgs self-coupling is crucial to test SM and find NP!! → not measured yet.

* Higgs pair production is important for the Higgs self-coupling, however, total cross section is not that sensitive to it, and NP may hide there.

* Kinematic distributions can break some degeneracy but more information is needed for a significant improvement!!

* With new resonance, the Higgs pair production can be significantly enhanced!!

* As NP contains "parity-odd" particles, di-boson signals can be produced in association with dark matter, e.g. Higgs pair, W-boson pair production → jet substructure can be adopted.

* May be challenging to search NP in di-boson production, HL-LHC or future hadron collider is highly desired!