Phenomenology of Littlest Higgs Model with T-parity

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(Based on the talk given by Chuan-Ren Chen at Argonne National Laboratory, 12/12/07)

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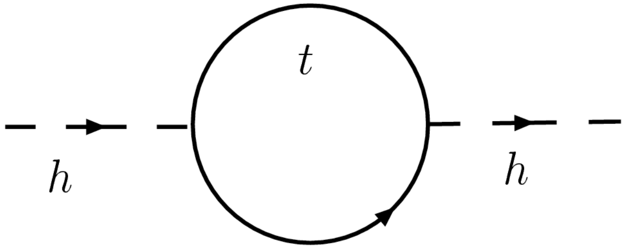
Phys. Lett. B640, 263 (2006)
Phys. Rev. D74, 115020 (2006)
Phys. Rev. D76, 075007 (2007)
hep-ph/0612243

Outline

- Motivation and Model
  - Little Hierarchy Problem
  - Littlest Higgs Model with T-parity
- Higgs Physics in the LHT
- Top Physics in the LHT
- Production and Decay of new particles at the LHC
- Searching for the T-odd gauge boson at the LHC and LC
- Summary

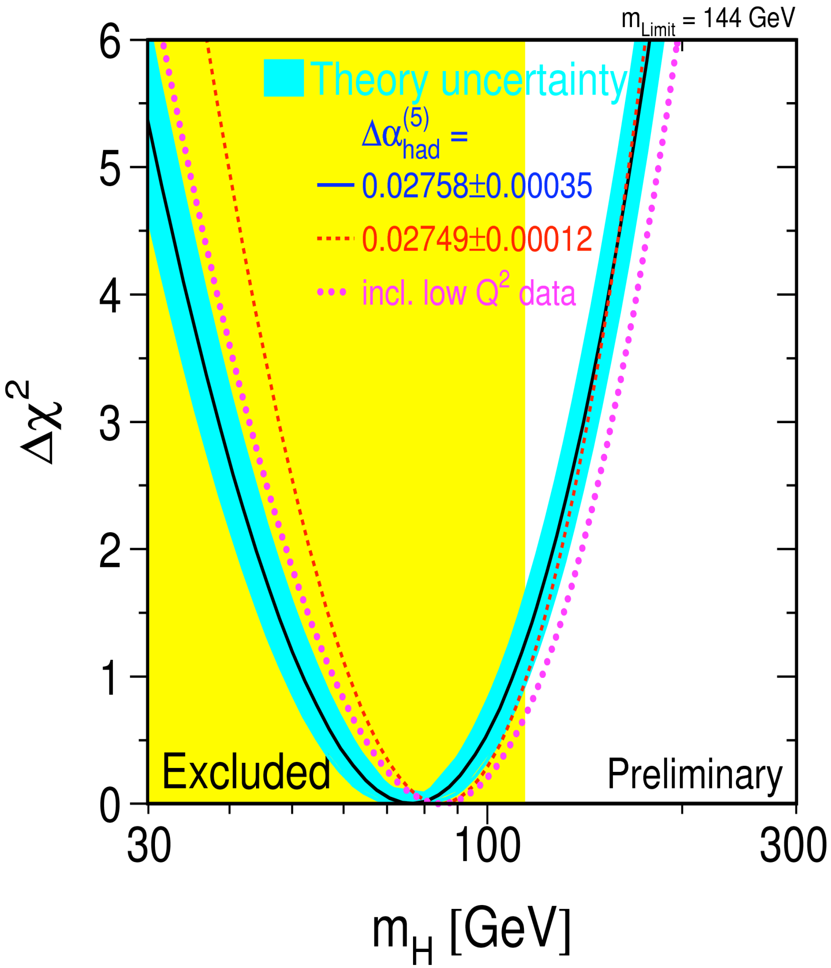
- Electroweak precision measurements prefer a light Higgs boson

$$m_H \leq 182\, GeV \quad @95\%\ \text{C.L.}$$



$$\delta m_h^2 \sim -\frac{y_t^2}{16\pi^2}\Lambda^2 \sim -\left(100\, GeV\right)^2$$

$$\Rightarrow \quad \Lambda \sim 1\, TeV$$

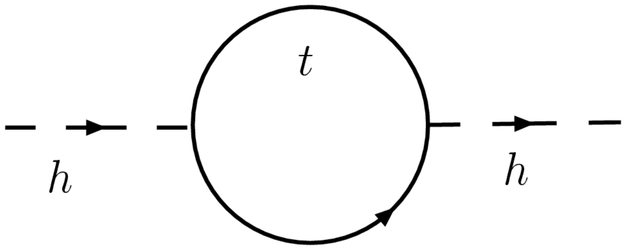


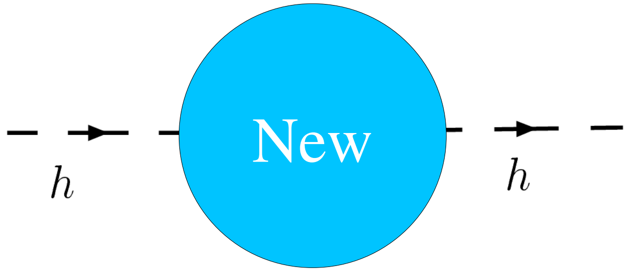
Schmaltz et al, hep-ph/0502182,
and references therein

broken symmetry	operators	scale Λ (TeV)
B, L	$(QQQL)/\Lambda^2$	10^{13}
flavor (1&2), CP	$(\bar{d}s\bar{d}s)/\Lambda^2$	1000
flavor (2&3)	$m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$	50
Custodial SU(2)	$(h^\dagger D_\mu h)^2/\Lambda^2$	5
non (S-parameter)	$(D^2h^\dagger D^2h)/\Lambda^2$	5

- NO new physics is needed up to ~5 TeV

Summary → tension between 1 TeV and 5 TeV !!
(fine-tunning)





Λ^2 Canceled !! at least, at one-loop level

$$\delta m_h^2 \sim -\frac{1}{16\pi^2} m_{new}^2 \ln\frac{\Lambda^2}{m_{new}^2}$$

$$m_{new} \sim 1\,TeV \Rightarrow \delta m_h^2 \sim -(100\,GeV)^2$$

e.g. Supersymmetry, ***Little Higgs models***

Little Higgs mechanism
(collective symmetry breaking)

- Higgs is a pseudo-Nambu-Goldstone boson Georgi, Pais
- The quadratic divergences are canceled by the particles with the same spin statistics
- Higgs mass is protected by two independent symmetries, i. e., Higgs is massless unless two or more couplings exist simultaneously (collective symmetry breaking) Arkani-Hamed, Cohen, Georgi, hep-ph/0105239

$$\mathcal{L} = \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$

$$\delta m_h^2 \sim -\frac{\lambda_1^2 \lambda_2^2}{16\pi^2} f^2 \ln \frac{\Lambda^2}{f^2}$$

$$\lambda_1 = 0 \ \text{or} \ \lambda_2 = 0 \quad \Rightarrow \quad \delta m_h^2 \to 0$$

$$if\ \lambda_1 \sim \lambda_2 \sim 1,\ f = 1\ TeV,\ \Lambda \sim 4\pi f$$

$$\Rightarrow \quad \delta m_h^2 \sim -O(100\, GeV)^2$$

- SU(5) / SO(5) non-linear sigma model

Arkani-Hamed, Cohen, Katz, Nelson
hep-ph/0206021

Global SU(5) → SO(5)
Gauged $[SU(2) \times U(1)]^2$ → SU(2) x U(1)

at scale f

VEV $\Sigma_0 = \begin{bmatrix} & & 1_{2\times2} \\ & 1 & \\ 1_{2\times2} & & \end{bmatrix}_{5\times5}$

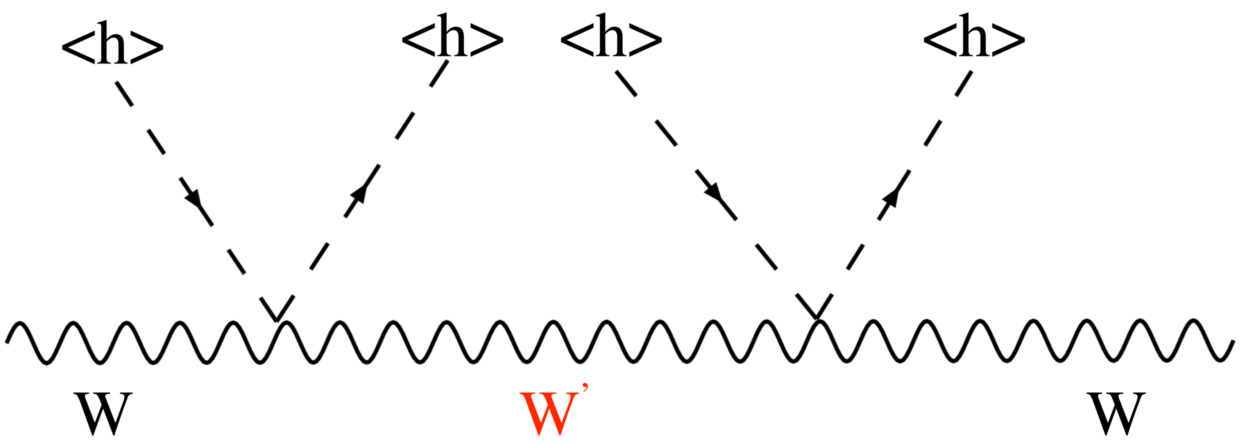
GB fields $\Pi = \begin{bmatrix} \omega_{2\times2} & h & \phi_{2\times2} \\ h^\dagger & \eta & h^T \\ \phi^\dagger_{2\times2} & h^* & \omega^T_{2\times2} \end{bmatrix}_{5\times5}$

$$\Sigma = \exp\{\frac{2i\Pi}{f}\}\Sigma_0$$

- The Higgs boson is an exact GB under both $SU(3)_1$ and $SU(3)_2$

- Mixing between the SM gauge bosons and heavy gauge bosons
- ρ parameter ≠ 1 at tree level

Chen, Dawson, hep-ph/0311932



→ Contribute significantly to EW observables

→ $f \geq 4 \; TeV$

→ new particle ~ few TeV, need fine-tunning again

Csaki, Hubisz, Kribs, Meade and Terning, hep-ph/0211124

Hewett, Petriello and Rizzo, hep-ph/0212228

T-parity

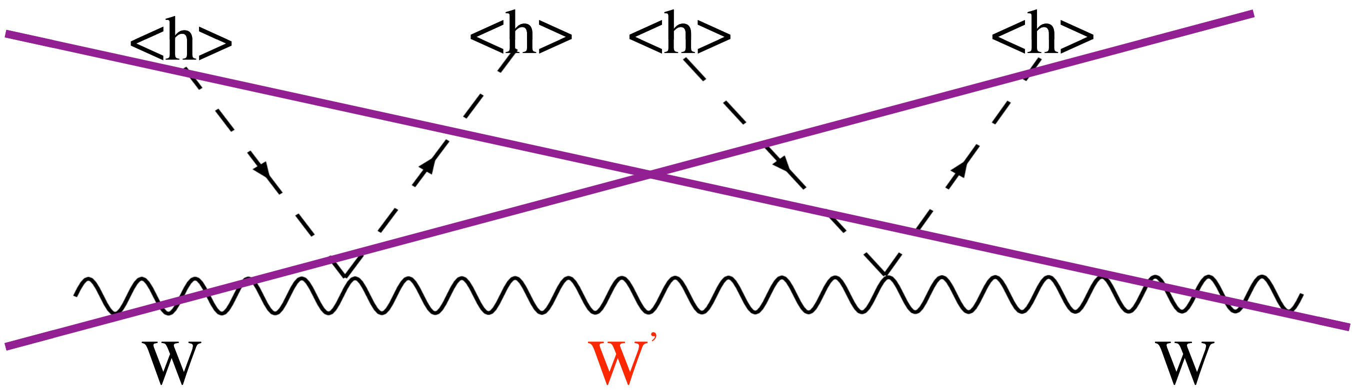
- A discrete symmetry

Cheng, Low, hep-ph/0308199, hep-ph/0405243
Low, hep-ph/0409025

$$SU(2)_1 \times U(1)_1 \longleftrightarrow SU(2)_2 \times U(1)_2$$

- **NO** mixing between the SM gauge bosons and heavy gauge bosons
  (T-even) (T-odd)

- ρ parameter = 1 at tree level



- Contributions to EW observables are loop suppressed

$$\Rightarrow \quad f \geq 500 \ GeV$$

Hubisz, Meade, Noble, Perelstein, hep-ph/0506042

- Dark Matter candidate

Chen, Cheung, Yuan, hep-ph/0605314
Perelstein, Spray, hep-ph/0610357
Hubisz, Meade, hep-ph/0411264
Asano, Matsumoto, N. Okada, Y. Okada, hep-ph/0602157
Birkedal, Noble, Perelstein, Spray, hep-ph/0603077

Low, hep-ph/0409025

Hubisz, Meade, hep-ph/0411264

$$\mathcal{L}_t = -\frac{\lambda_1 f}{2\sqrt{2}}\epsilon_{ijk}\epsilon_{xy}\left[(\bar{Q}_1)_i\Sigma_{jx}\Sigma_{ky} - (\bar{Q}_2\Sigma_0)_i\tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right]u_R$$

$$-\lambda_2 f\left(\bar{U}_1 U_{R_1} + \bar{U}_2 U_{R_2}\right) + \text{h.c.}$$

i,j,k summed over 1,2,3

x,y summed over 4,5

$$Q_1 = (q_1, U_1, 0, 0)^{\mathrm{T}}, \quad Q_2 = (0, 0, U_2, q_2)^{\mathrm{T}}$$

$$Q_1 \overset{\mathrm{T}}{\longleftrightarrow} -\Sigma_0 Q_2 \qquad \Sigma \to \tilde{\Sigma} \overset{\mathrm{T}}{\equiv} \Sigma_0\Omega\Sigma^\dagger\Omega\Sigma_0$$

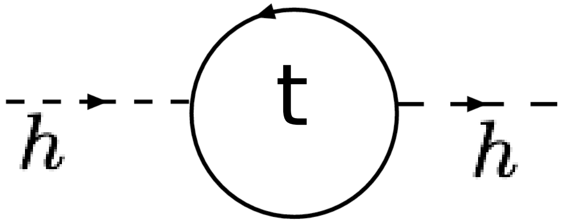
$$\mathcal{L}_t = \frac{-\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{t}\,t\,h + \frac{\lambda_1^2}{2\sqrt{\lambda_1^2+\lambda_2^2}f}\bar{T}_+T_+hh - \frac{\lambda_1^2}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{t}_L T_{+R}h$$

$$-\sqrt{\lambda_1^2+\lambda_2^2}f\,\bar{T}_+T_+ - \lambda_2 f\,\bar{T}_-T_- + \cdots$$

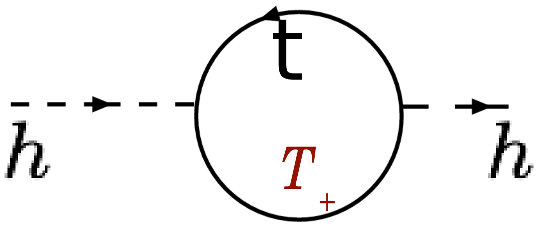
Before EWSB: T-even $\quad m_t = 0 \quad m_{T_+} = \sqrt{\lambda_1^2+\lambda_2^2}f$

T-odd $\quad m_{T_-} = \lambda_2 f$

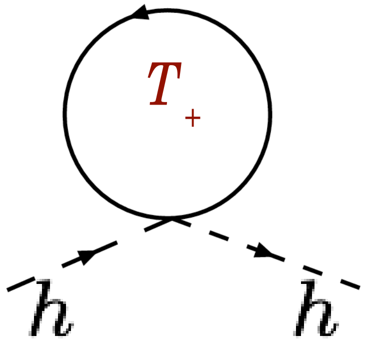
Top sector



$$-3\frac{\lambda_1^2\lambda_2^2}{\lambda_1^2+\lambda_2^2}\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2}$$



$$-3\frac{\lambda_1^4}{\lambda_1^2+\lambda_2^2}\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m_{T_+}^2}$$



$$3\frac{\lambda_1^2}{f\sqrt{\lambda_1^2+\lambda_2^2}}m_{T_+}\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m_{T_+}^2}$$

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

T-even heavy T_+ contributions cancel Λ^2

Low, hep-ph/0409025
Hubisz, Meade, hep-ph/0411264

- Additional T-odd fermion fields

$$L_\kappa = -\kappa f \left(\bar{\Psi}_2 \xi \Psi_c + \bar{\Psi}_1 \Sigma_0 \Omega \xi^\dagger \Omega \Psi_c \right) + h.c.$$

$$\Psi_1 = (q_1, 0, 0, 0)^T \qquad \Psi_2 = (0, 0, 0, q_2)^T \qquad \Psi_c = (q_c, \chi_c, \tilde{q}_c)^T$$

$$\xi = \exp\{ i \Pi / f \}$$

includes Higgs

$$\Psi_1 \xleftrightarrow{T} -\Sigma_0 \Psi_2 \qquad \Psi_c \xleftrightarrow{T} -\Psi_c \qquad \xi \xleftrightarrow{T} \Omega \xi^\dagger \Omega$$

$$m_{odd} = \sqrt{2} \kappa f$$

T-odd fermions are unique for the model with T-parity!

Low, hep-ph/0409025
Hubisz, Meade, hep-ph/0411264

summary: Little Higgs models solve the little hierarchy problem

T-parity relaxes EWPO constrains, new particles could be light

Particle spectrum

T-even : $u\times 3,\ d\times 3,\ e\times 3,\ \nu\times 3,\ T_+,$
$W^\pm,\ Z,\ \gamma,\ h$

T-odd : $u_-\times 3,\ d_-\times 3,\ e_-\times 3,\ \nu_-\times 3,\ T_-,$
$W_H^\pm,\ Z_H,\ A_H,\ \phi$

" heavy photon "
(dark matter candidate)

triplet Higgs

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

$$m_{u_-}\sim m_{d_-}\sim\sqrt{2}k_q f$$

$$m_{e_-}\sim m_{\nu_-}\sim\sqrt{2}k_l f$$

$$m_{T_-}\sim\lambda_2 f$$

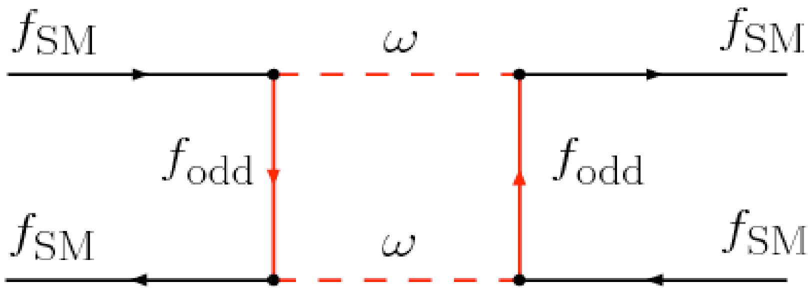
$$m_{W_H}\sim m_{Z_H}\sim g f$$

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

$$m_\phi\sim\sqrt{2}m_h f/v$$

- 4 fermion operators

Hubisz, Meade, hep-ph/0411264
Hubisz, Meade, Noble, Perelstein, hep-ph/0506042

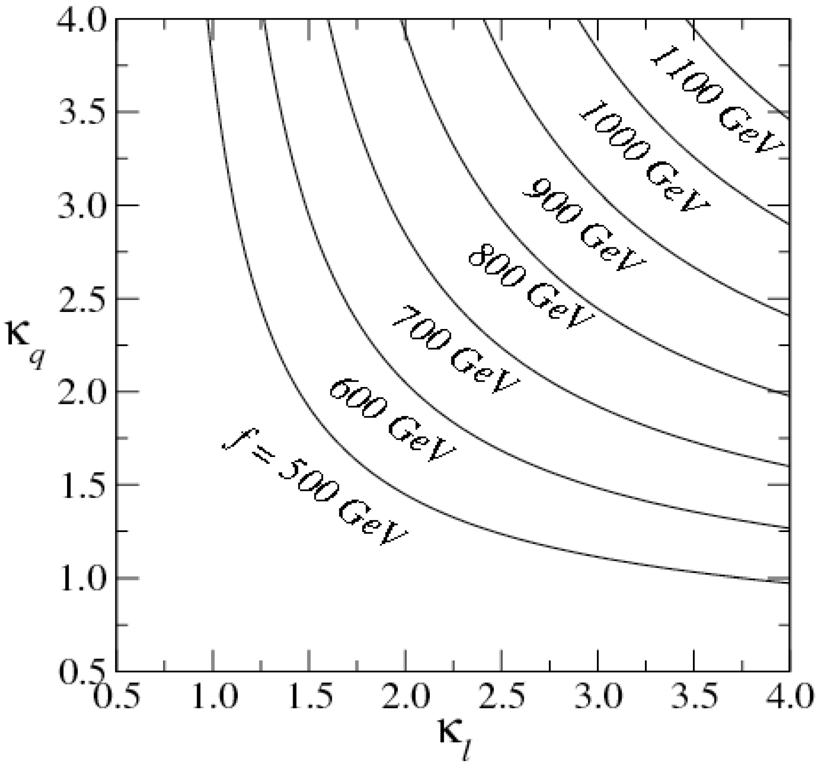


$$\sim \frac{-\kappa^2}{128\pi^2 f^2}\bar{f}\gamma^\mu f\,\bar{f}\gamma_\mu f$$

universal κ

$$m_{odd} \leq 4.8\left(\frac{f}{1\,TeV}\right)^2 TeV$$

$$m_{odd} \sim \sqrt{2}\kappa f$$



non-universal κ

$O(eedd)$

(lepton ≠ quark)

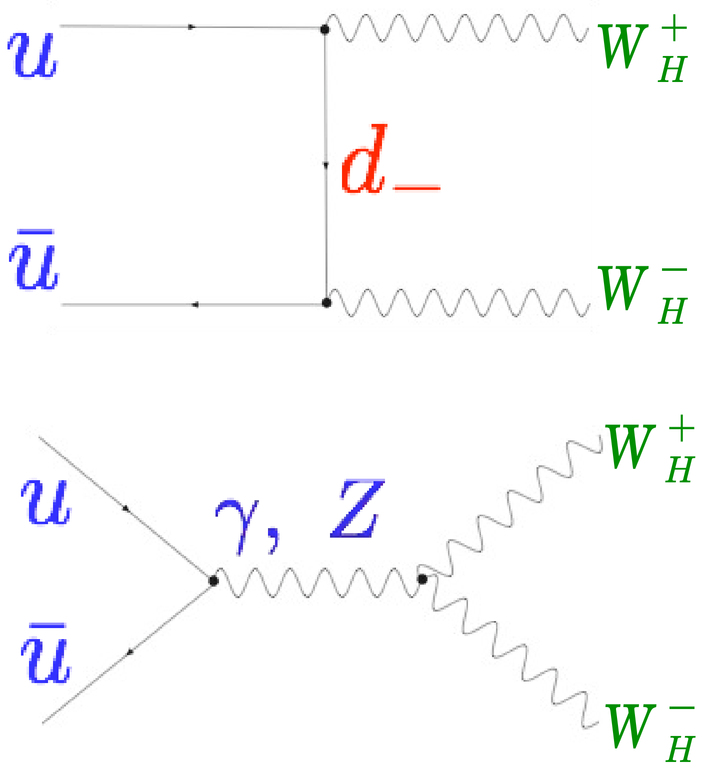
Cao, Chen, arXiv: 0707.0877[hep-ph]

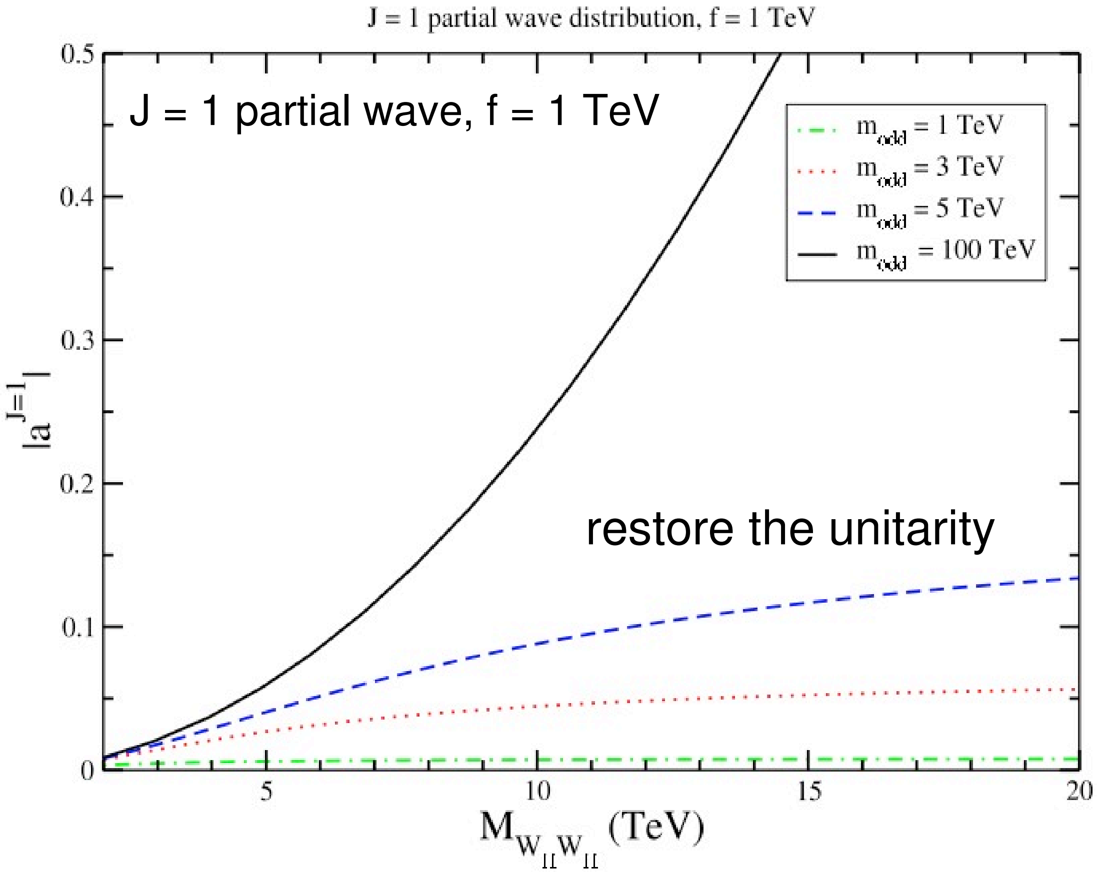
$$\frac{\kappa_l^2\kappa_q^2}{\kappa_l^2-\kappa_q^2}\ln\left(\frac{\kappa_l}{\kappa_q}\right) \leq \frac{128\pi^3 f^2}{(26.4\,TeV)^2}$$

- High energy behavior of $q\bar{q} \to W_H^+ W_H^-$ $s \gg m_{W_H}^2$

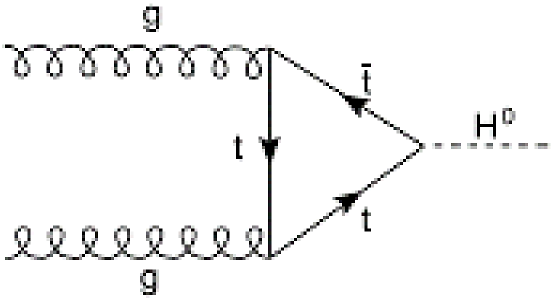
Belyaev, Chen, Tobe, Yuan, hep-ph/0609179

$$A^\gamma = -\frac{s_w^2 \sin\theta}{3f^2} s \quad A^Z = -\left(1 - \frac{4}{3} s_w^2\right) \frac{\sin\theta}{4f^2} s \quad A^t = \frac{\sin\theta}{4f^2} s \Rightarrow A^\gamma + A^Z + A^t = 0$$

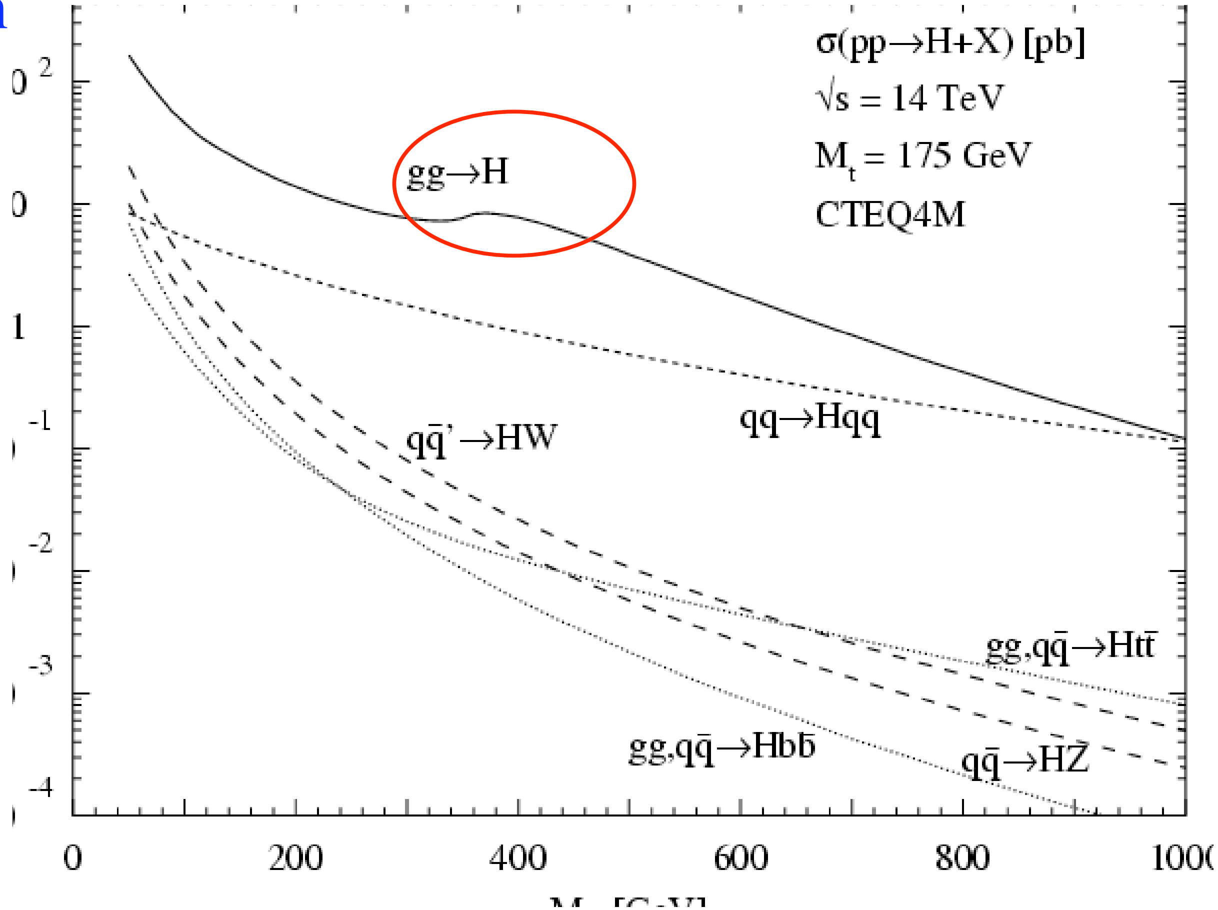




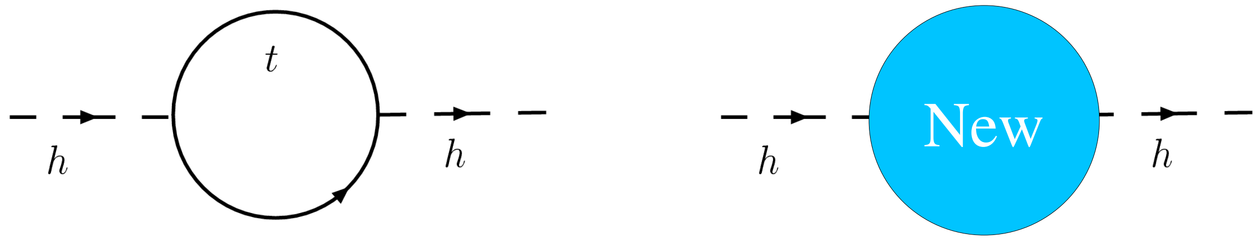
gluon-gluon fusion dominates !!



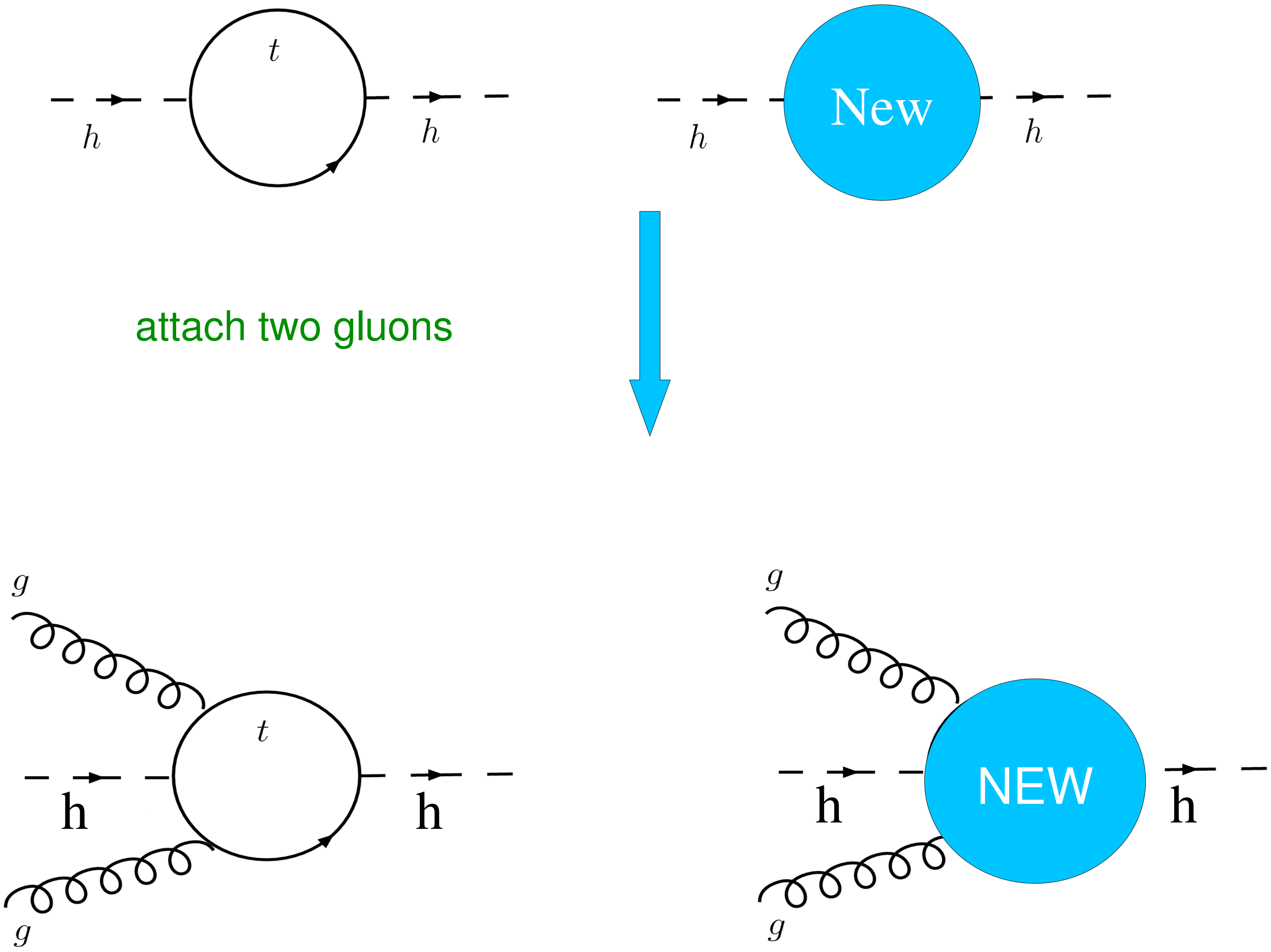
~ factor 5 larger than the 2nd largest one (WW fusion), when Higgs is light



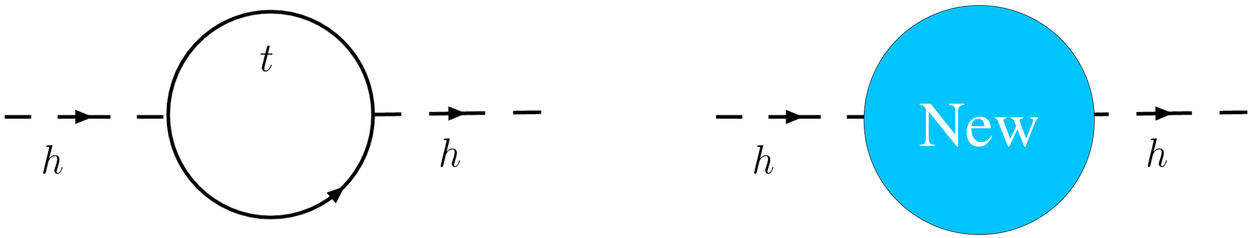
cancellation of quadratic divergences



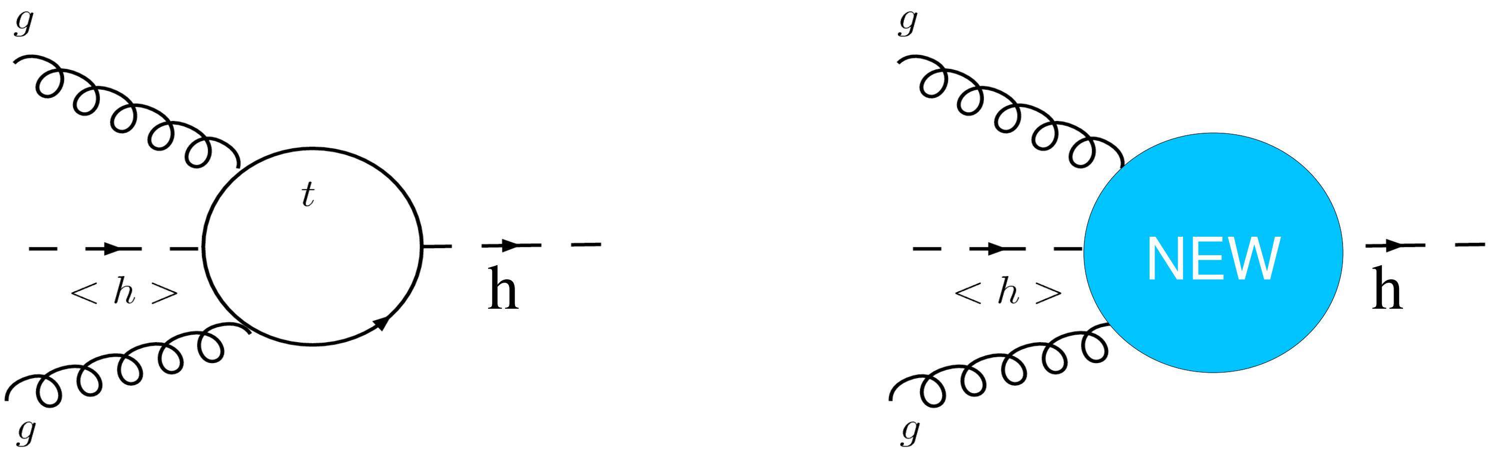
cancellation of quadratic divergences



cancellation of quadratic divergences

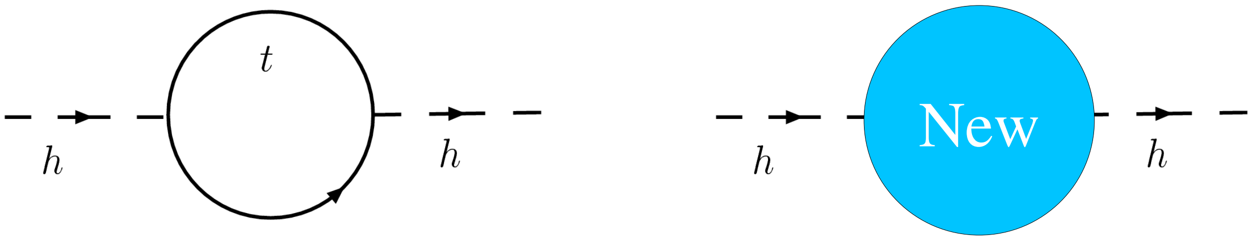


attach two gluons and one of the Higgs fields take its vev



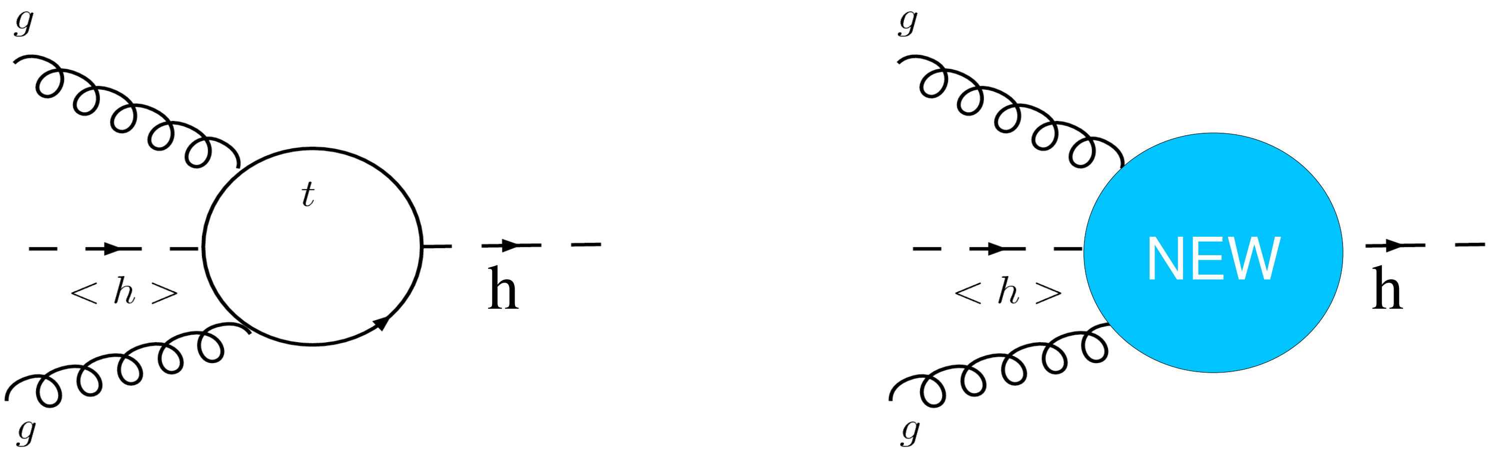
Chen, Tobe, Yuan, hep-ph/0602211

cancellation of quadratic divergences



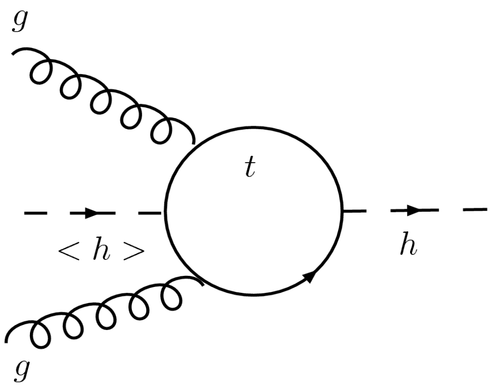
attach two gluons and one of the Higgs fields take its vev

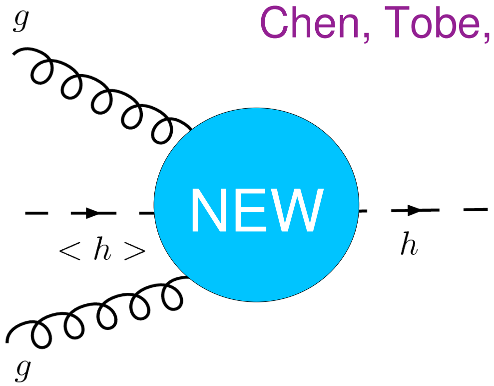
Higgs production via gluon-gluon fusion



Contributions form new particles

Chen, Tobe, Yuan, hep-ph/0602211

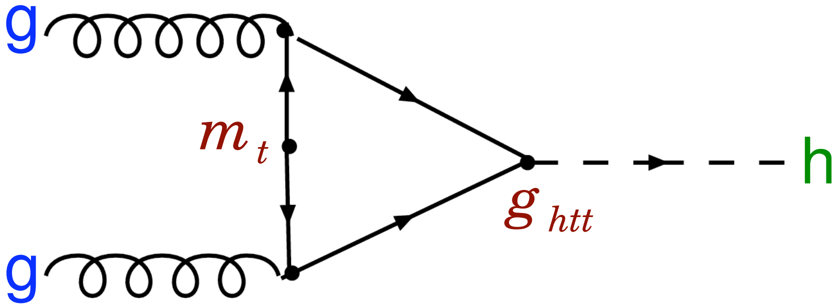




both T-even and T-odd particles will contribute

the contributions from new particles in LHT will reduce the production rate via gluon-gluon fusion process

top loop

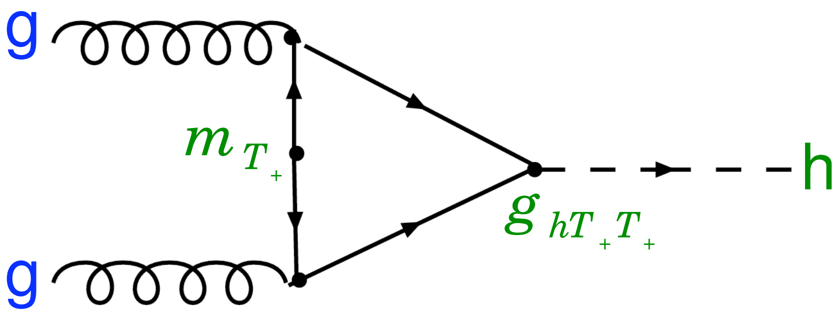


$$A_t^{SM} \propto m_t g_{htt}^{SM} \frac{1}{m_t^2} \quad \text{for } m_t \gg \frac{m_h}{2}$$

$$A_t^{LHT} \propto m_t g_{htt}^{LHT} \frac{1}{m_t^2} \qquad R = \frac{\lambda_1}{\lambda_2}$$

$$g_{htt}^{LHT} \sim g_{htt}^{SM} \left[1 - \frac{3 + 2R^2 + 3R^4}{4(1+R^2)^2} \frac{v^2}{f^2} + \cdots \right]$$

Heavy T-even top loop



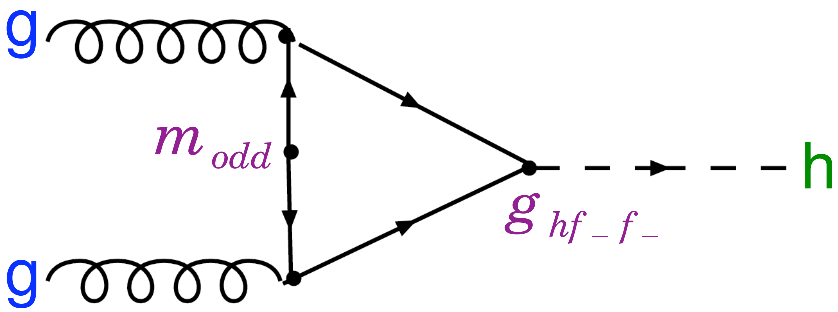
$$g_{hT_+T_+} \sim -\frac{m_t}{v}\frac{R}{1+R^2}\frac{v}{f}$$

$$A_{T_+}^{LHT} \propto m_{T_+} g_{hT_+T_+} \frac{1}{m_{T_+}^2}$$

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

$$\frac{\delta A_{T+t}}{A_{SM}} = \frac{-3}{4}\frac{v^2}{f^2}$$

Heavy T-odd quark loop



$$g_{hf_-f_-} \sim -\frac{\kappa}{2\sqrt{2}}\frac{v}{f}$$

$$A_{odd}^{LHT} \propto m_{odd}\, g_{hf_-f_-} \frac{1}{m_{odd}^2}$$

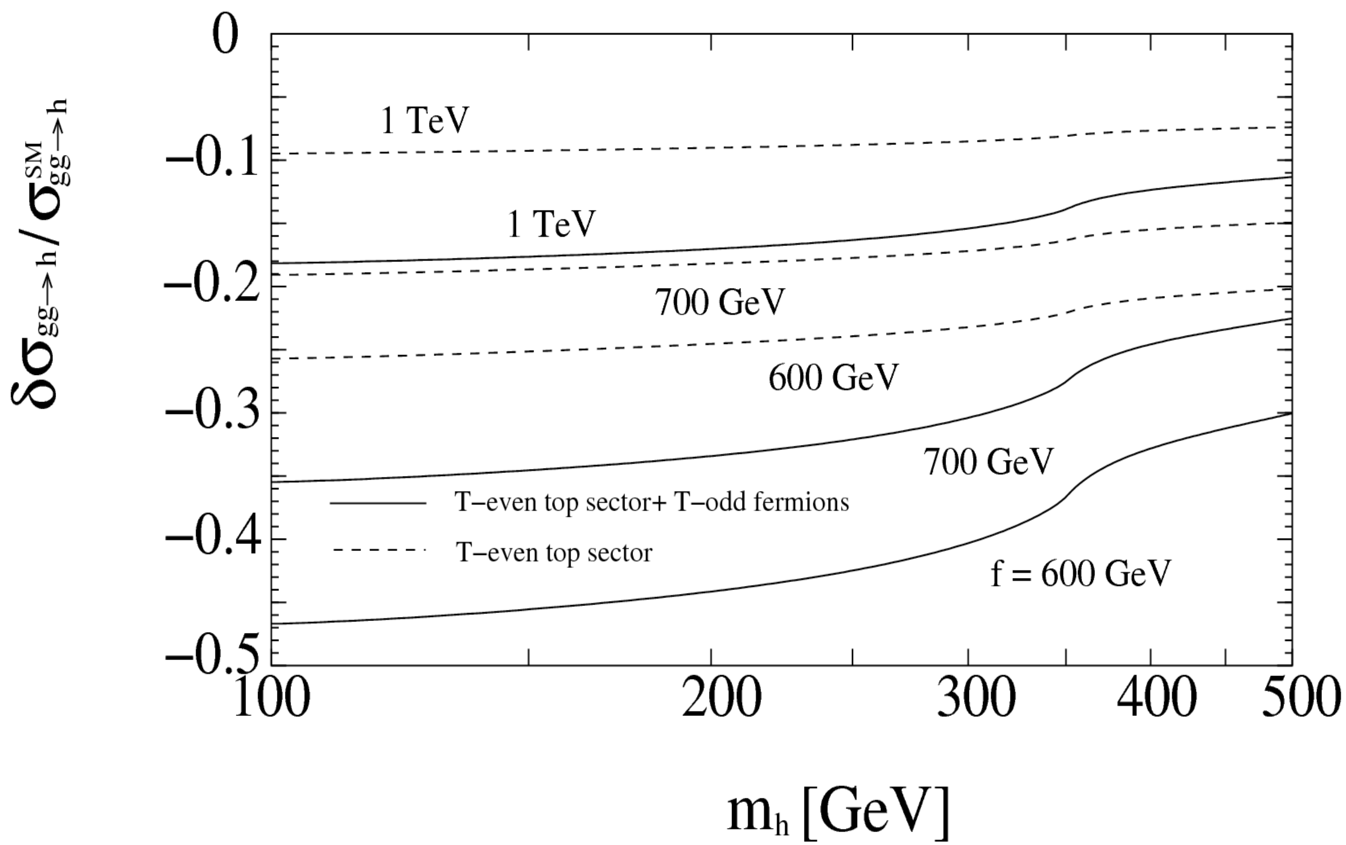
$$m_{odd} \sim \sqrt{2}\,\kappa f$$

$$\frac{\delta A_{odd}}{A_{SM}} = \frac{-1}{4}\frac{v^2}{f^2}$$

$$\frac{\delta A_{total}}{A_{SM}} = \frac{-3}{4}\frac{v^2}{f^2} + \frac{-1}{4}\frac{v^2}{f^2}\times 3 = \frac{-3}{2}\frac{v^2}{f^2}$$

Corrections to the Higgs boson production total cross section via gluon-gluon fusion at the LHC

$$\delta\sigma_{gg\to h} \equiv \sigma^{LHT}(gg\to h) - \sigma^{SM}(gg\to h)$$

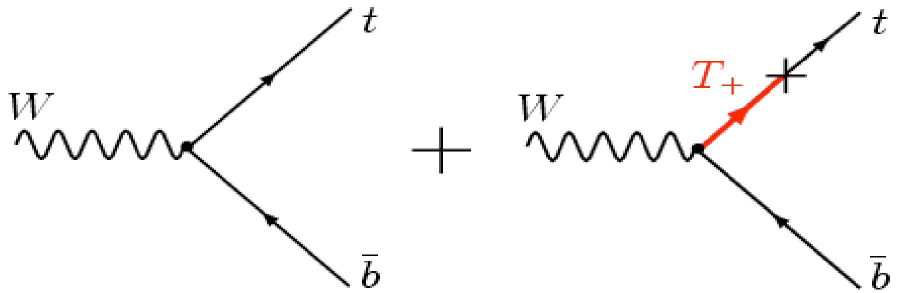


The production rate could be significantly suppressed !

Chen, Tobe, Yuan, hep-ph/0602211

- Shift in W-t-b coupling

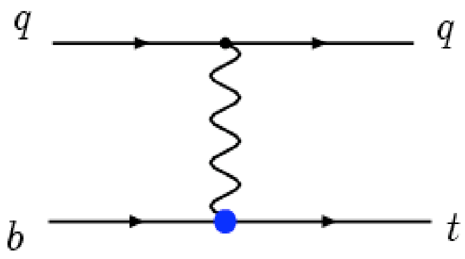
Cao, Li, Yuan, hep-ph/0612243



$$iV_{tb}\frac{g}{\sqrt{2}}\gamma_\mu\left(1-\frac{s_\alpha^4}{2}\frac{v^2}{f^2}\right)P_L$$

$$s_\alpha \equiv \sin\alpha = \frac{\lambda_1}{\sqrt{\lambda_1^2+\lambda_2^2}}$$

- t-channel single-top production

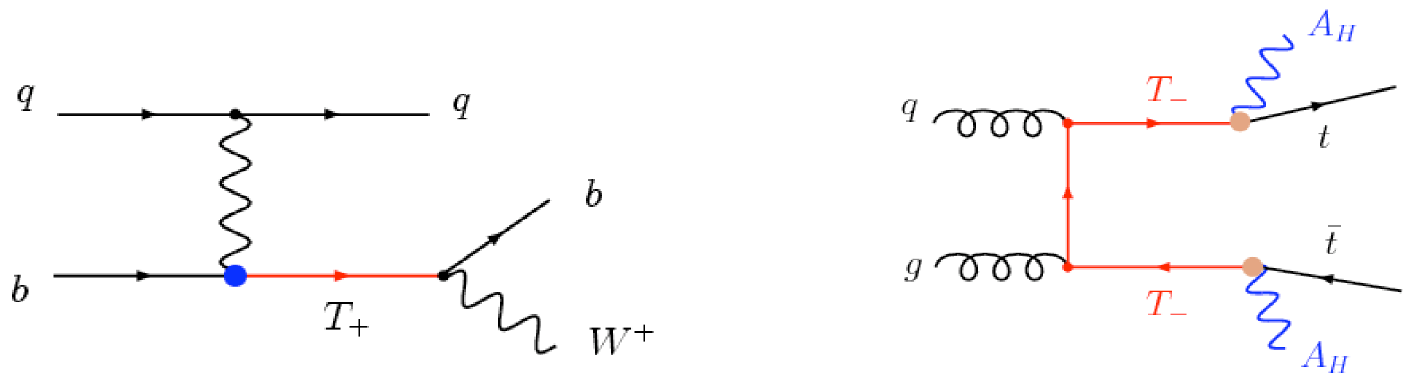


$$\sigma(t) \propto g_{Wtb}^2$$

➡ deviation from SM prediction

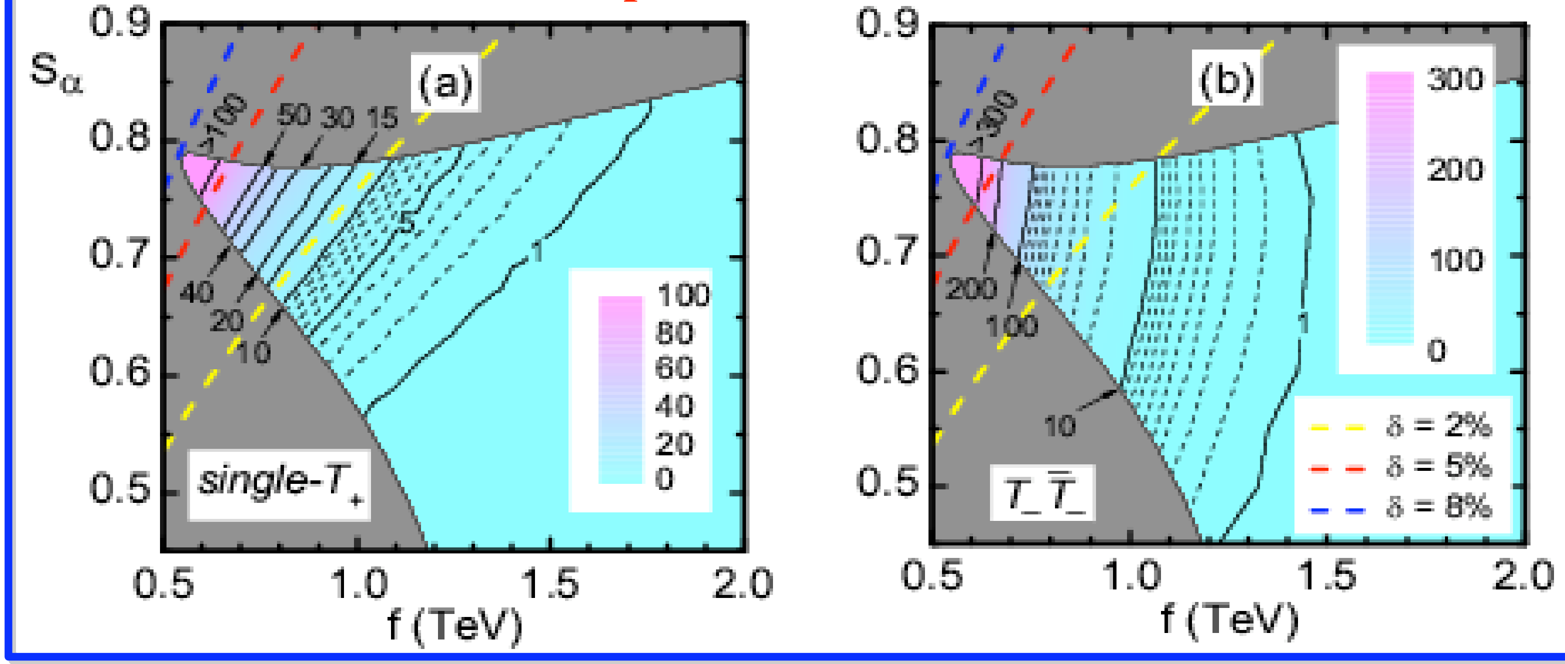
$$\delta = \frac{\sigma_{SM}-\sigma_{LHT}}{\sigma_{SM}} = 2\delta g_{Wtb} = s_\alpha^4\frac{v^2}{f^2}$$

Correlation between the deviation in single-top production and new particle productions



Cao, Li, Yuan, hep-ph/0612243

contours of production cross sections (fb)



Gray region: excluded by EWPT.

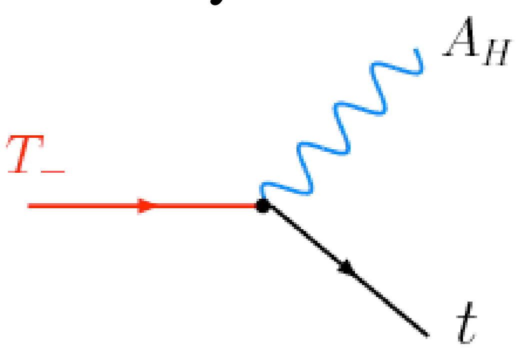
Hubisz, Meade, Nobel, Perelstein hep-ph/0506042

If deviation in single-top production rate is large

⇒ single T_+ and T_- pair rates are also large.

Cao, Li, Yuan, hep-ph/0612243

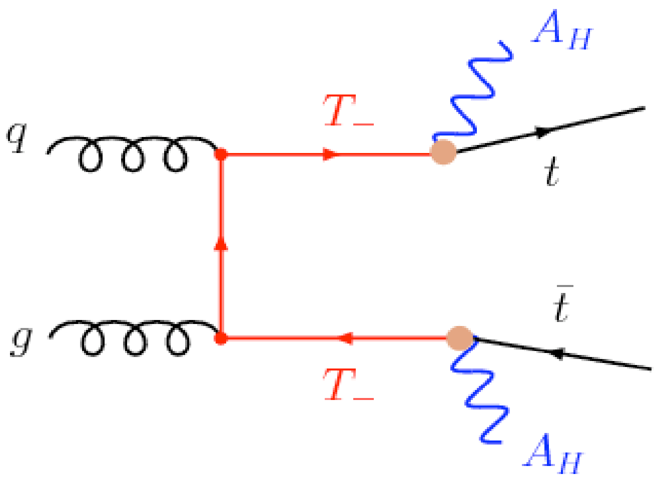
- T_- decay



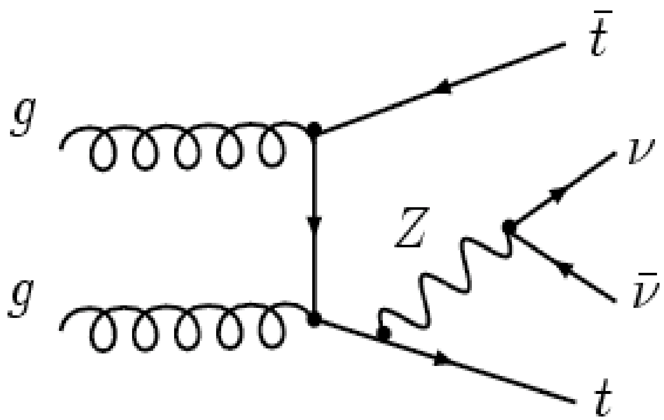
$$\frac{2}{5} g' s_\alpha \gamma_\mu \left(s_\alpha \frac{v}{f} P_L + P_R \right)$$

predominately **right-handed** polarized top

- Signal



- Background



Right-handed top is preferred in LHT while left-handed top in SM background

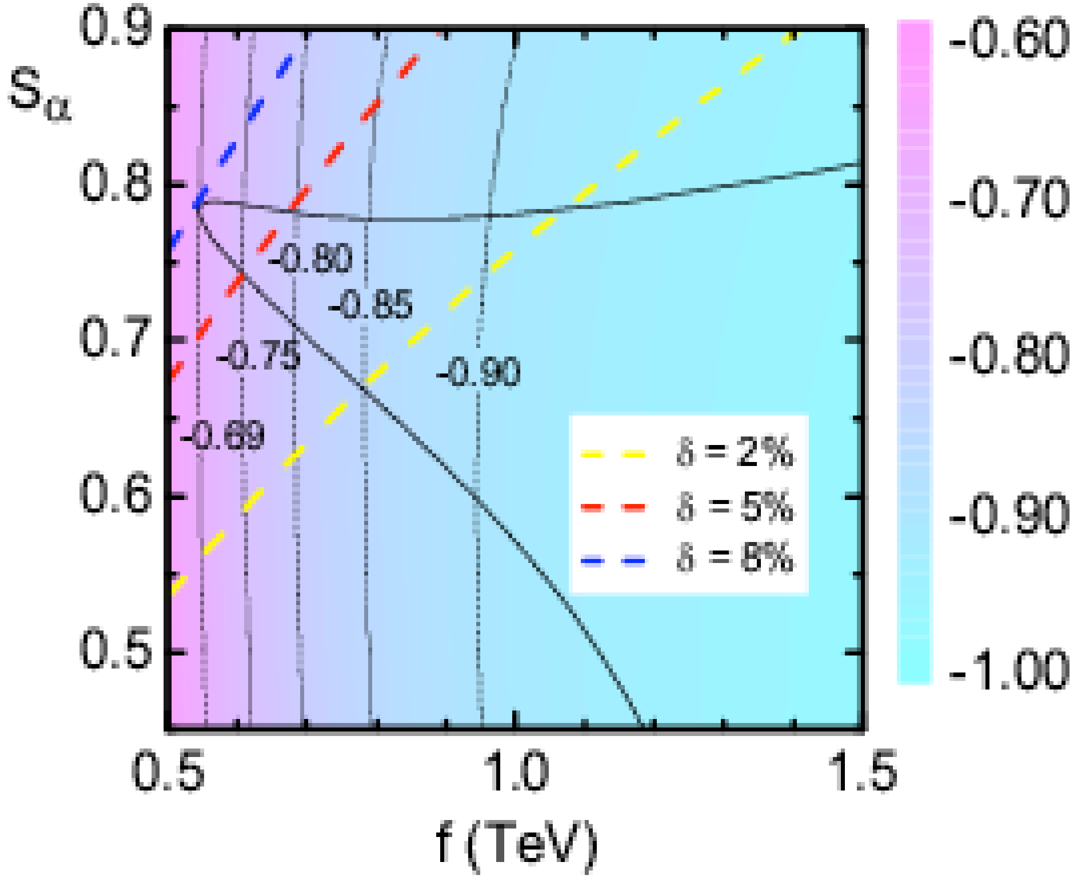
Spin correlation of top quarks in T-odd T_ pair production

$$\mathcal{A}_{LR} \equiv \frac{\sigma(t_L) - \sigma(t_R)}{\sigma(t_L) + \sigma(t_R)}$$

LHT	SM
$\mathcal{A}_{LR} < 0$	$\mathcal{A}_{LR} > 0$

- Powerful tool to kill SM backgrounds
- A good probe to the symmetry breaking scale f

Cao, Chen, Li, Yuan,
detailed phenomenology study
in progress.



For the mass measurement of T-, see
Meade, Reece, hep-ph/0601124; Matsumoto, Nojiri, Nomura, hep-ph/06112249.

Hubisz, Meade, hep-ph/0411264

Freitas, Wyler, hep-ph/0609103

Belyaev, Chen, Tobe, Yuan, hep-ph/0609179

http://hep.pa.msu.edu/LHT/

Lagrangian

↓

LanHEP : generate Feynman rules for input Lagrangian

↓

CalcHEP : calculate production cross sections and decay
decay branching ratios

↓

Numerical results

We categorize productions of all the new heavy particles and their signatures at the LHC.

f = 1 TeV

$\kappa = 1$

$m_h = 120$ GeV

A_H	$Z(W)_H$	T_+	T_-	$u(d)_-$	ϕ	
0.15	0.65	1.4	1	1.4	0.69	(TeV)

Heavy particle decay branching ratios

Particle	Decay mode	BR (%)	Particle	Decay mode	BR (%)
u_-	$W_H^+ d$	61	d_-	$W_H^- u$	62
	$Z_H\ u$	30		$Z_H\ d$	31
	$A_H\ u$	8.6		$A_H\ d$	6.3
b_-	$W_H^- t$	60	t_-	$W_H^+ b$	62
	$Z_H\ b$	32		$Z_H\ t$	29
	$A_H\ b$	6.6		$A_H\ t$	8.2
T_+	$W^+\ b$	46	T_-	$A_H\ t$	100
	$Z\ t$	22	W_H^+	$A_H W^+$	100
	$h\ t$	20	Z_H	$A_H\ h$	100
	$A_H\ T_-$	12	ϕ^+	$A_H W^+$	100
ϕ^p	$A_H\ h$	100	ϕ^0	$A_H Z$	100

T-odd quark productions (1st and 2nd generation)

Belyaev, Chen, Tobe, Yuan, hep-ph/0609179

Carena, Hubisz, Perelstein, Verdier, hep-ph/0610156

signatures:

a gauge boson pair + $\not{E}_T$ + jets :

LSL + $\not{E}_T$ +jets ,

OSL + $\not{E}_T$ +jets ,

1L + $\not{E}_T$ +jets

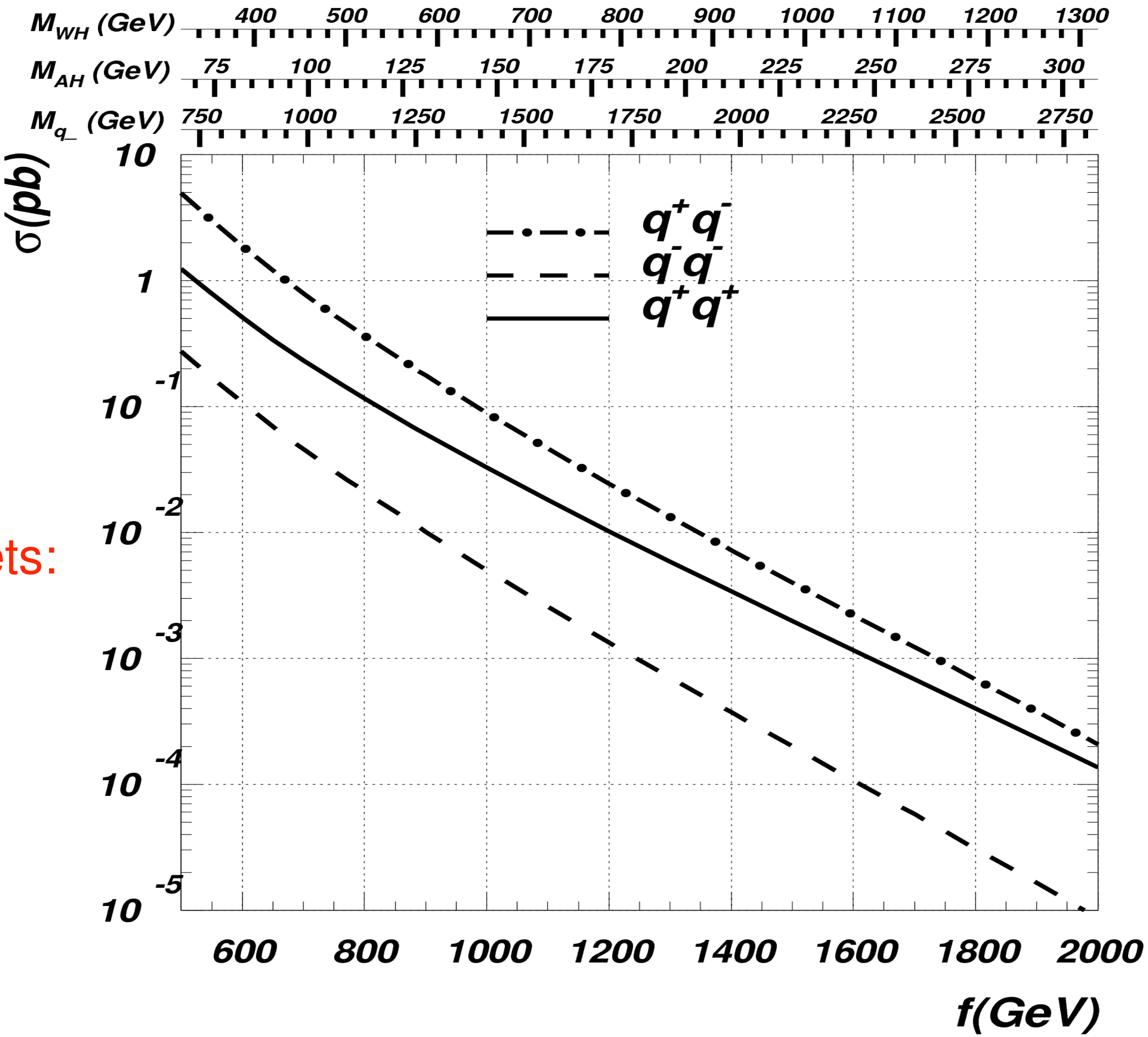
a gauge boson + Higgs + $\not{E}_T$ + jets:

1L +Higgs + $\not{E}_T$ + jet,

Higgs + $\not{E}_T$ + jets,

Higgs pair + $\not{E}_T$ + jets

$$\left(q_- \to Z_H q\,,\;\; Z_H \to h\, A_H\right)$$



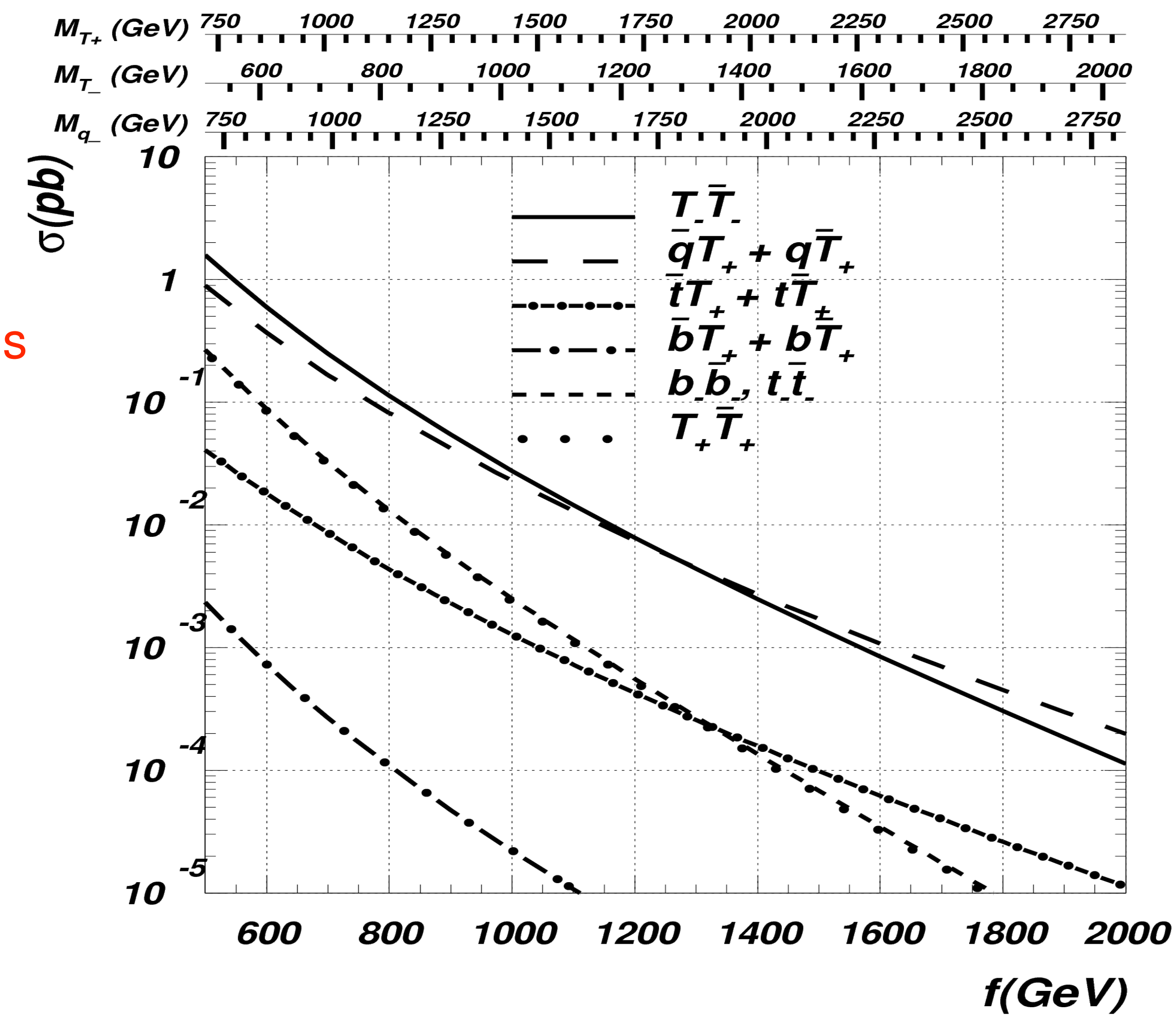
3^{rd} generation heavy quarks

signatures:

a top pair + $\not{E}_T$

Single Heavy T-even T_+

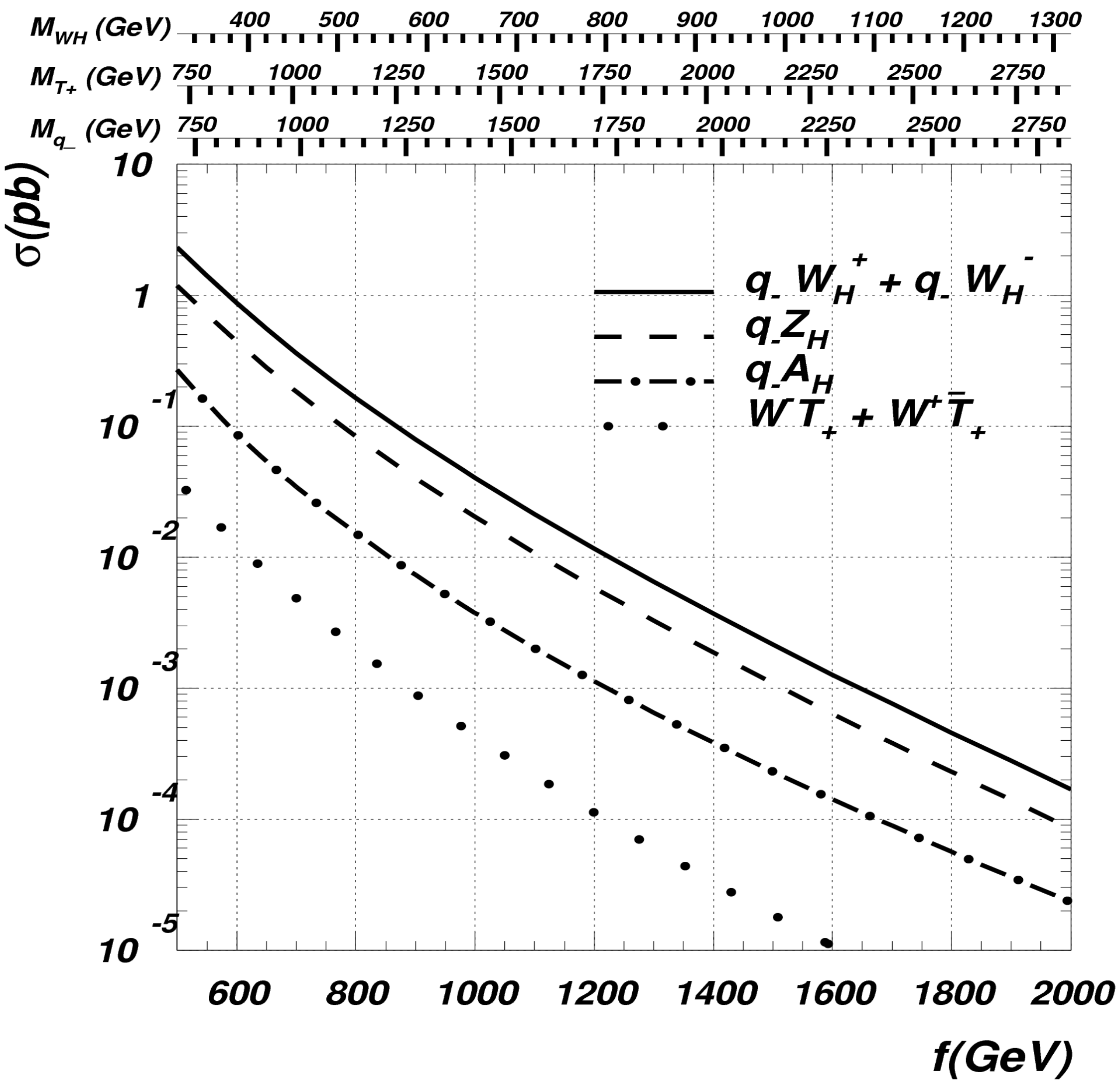
A top pair + Z-boson and Higgs



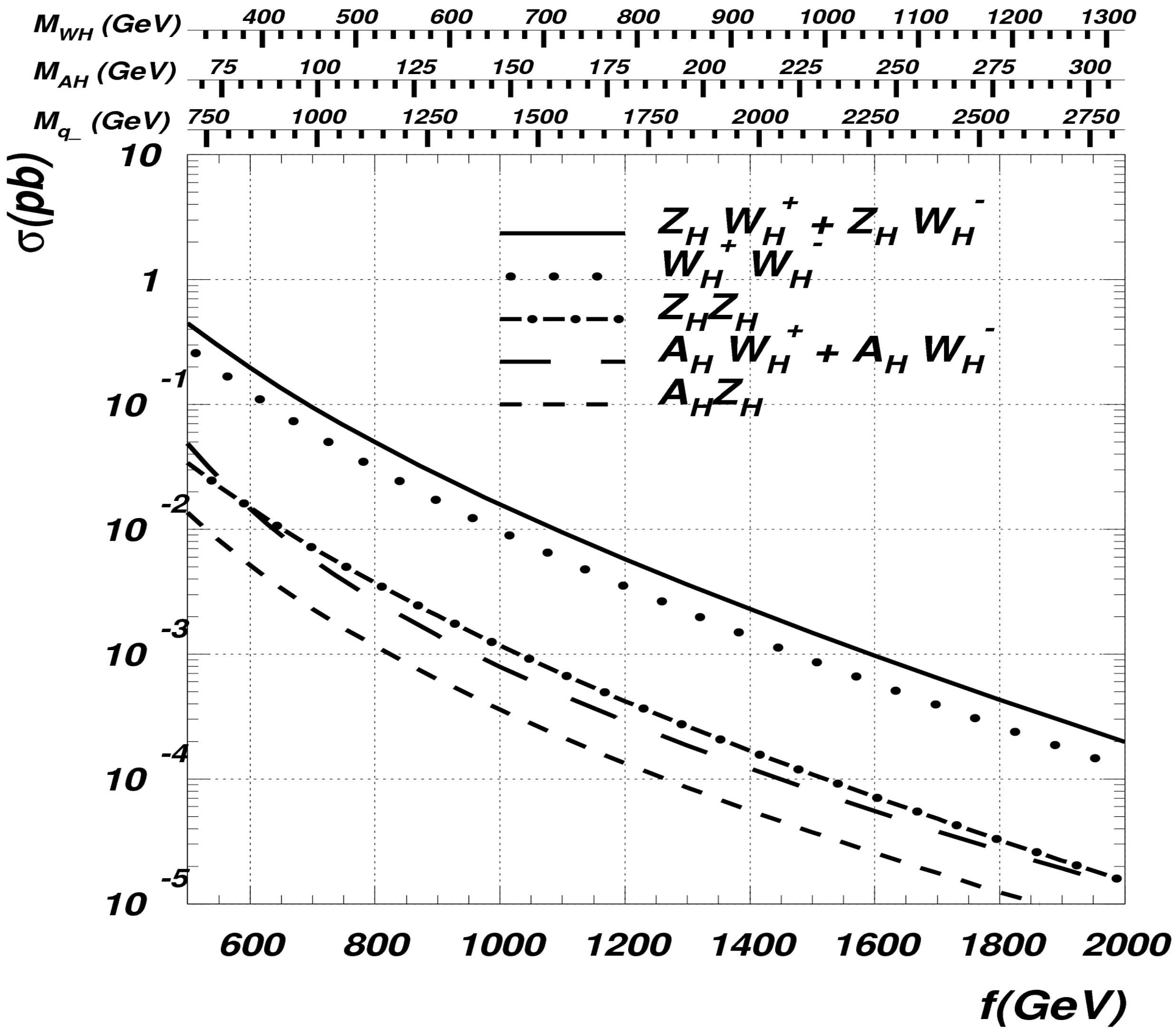
Boson-quark associated production

signatures:

* gauge boson pair + jets + $\not{E}_T$
* a Higgs + a gauge boson +jets + $\not{E}_T$
* a Higgs pair + 1 Jet + $\not{E}_T$
* a gauge boson + 1 Jet + $\not{E}_T$
* a Higgs + 1 Jet + $\not{E}_T$



Boson pair production



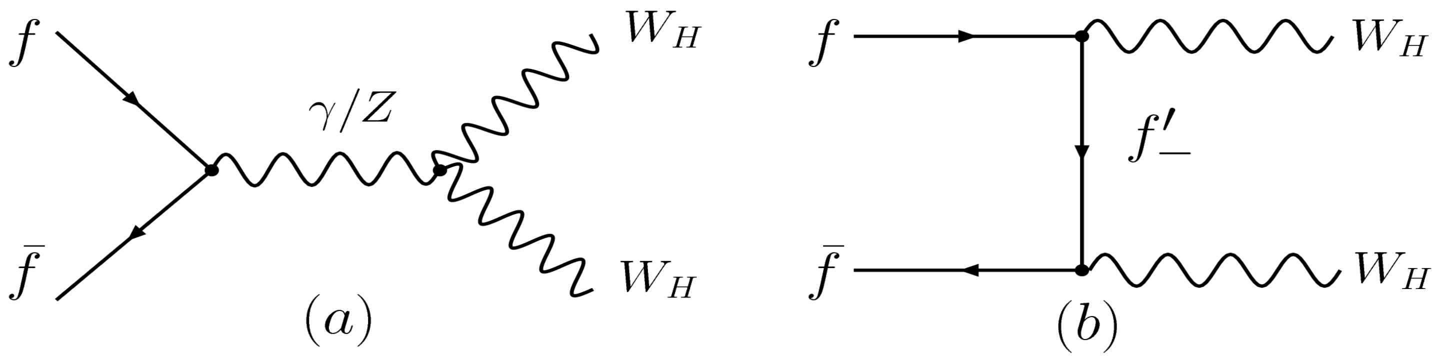
Signatures:

* a gauge boson
+ a Higgs boson + $\not{E}_T$

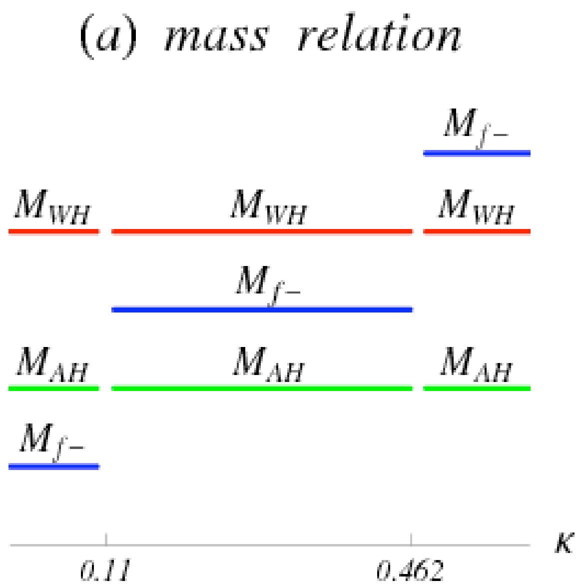
* a gauge boson pair + $\not{E}_T$

Cao, Chen, arXiv: 0707.0877[hep-ph]

Production of $W_H W_H$



Decay of W_H

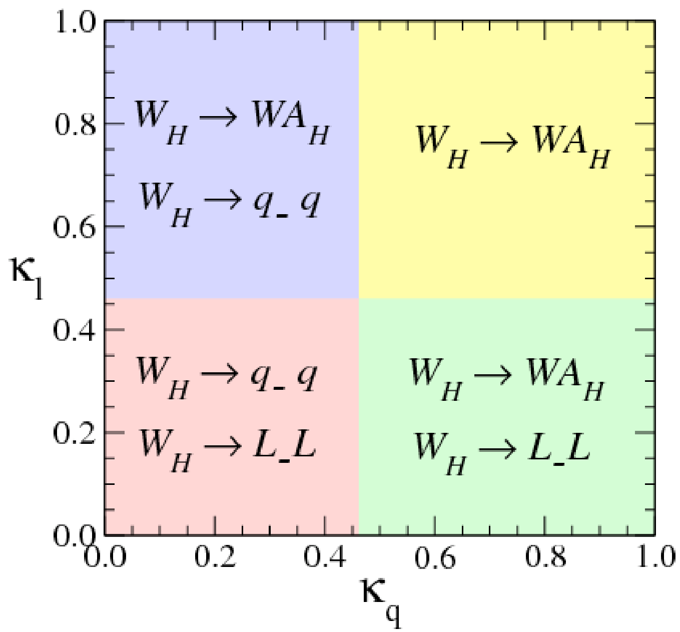


$$M_{AH} \approx 0.156 f$$

$$M_{WH} \approx 0.653 f$$

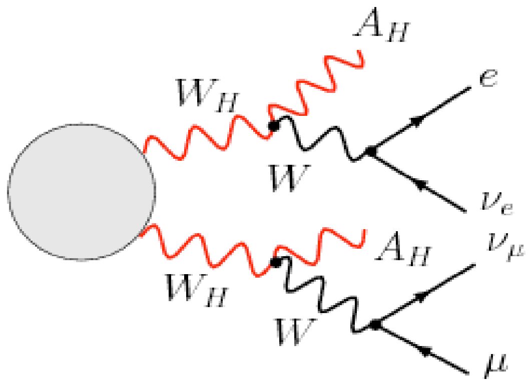
$$M_{L-} \approx 1.414 \kappa_l f$$

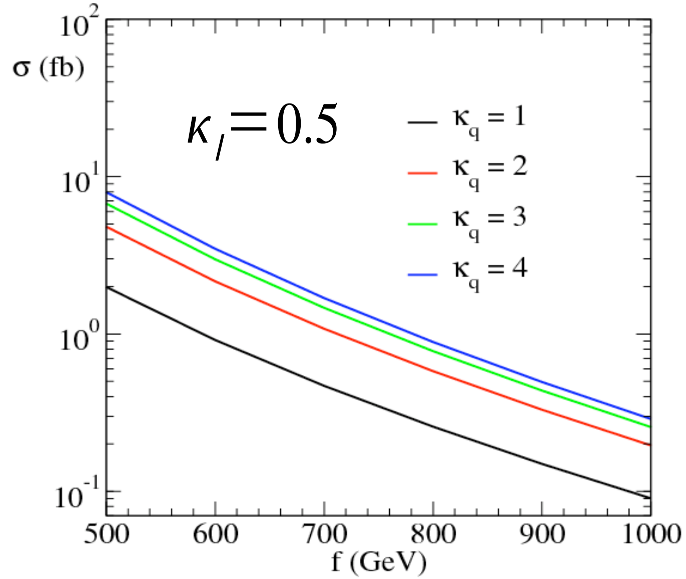
$$M_{q-} \approx 1.414 \kappa_q f$$



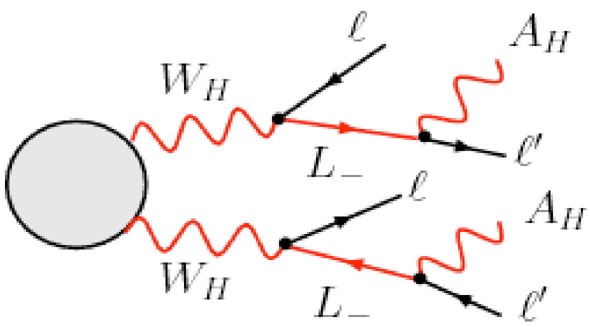
Signature $e\,\mu + \not{E}_T$:

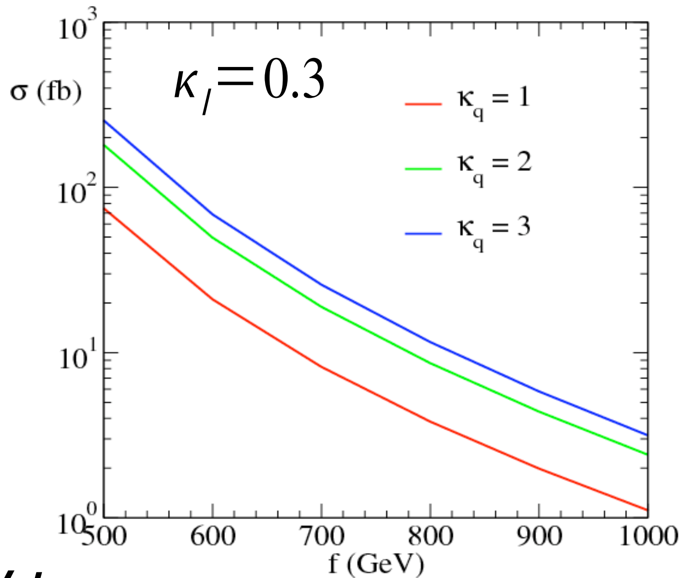
$$pp \to W_H W_H \to A_H W(\to e\nu_e) A_H W(\to \mu\nu_\mu)$$





$$pp \to W_H W_H \to \nu_e E_-(\to e A_H) \nu_\mu M_-(\to \mu A_H)$$

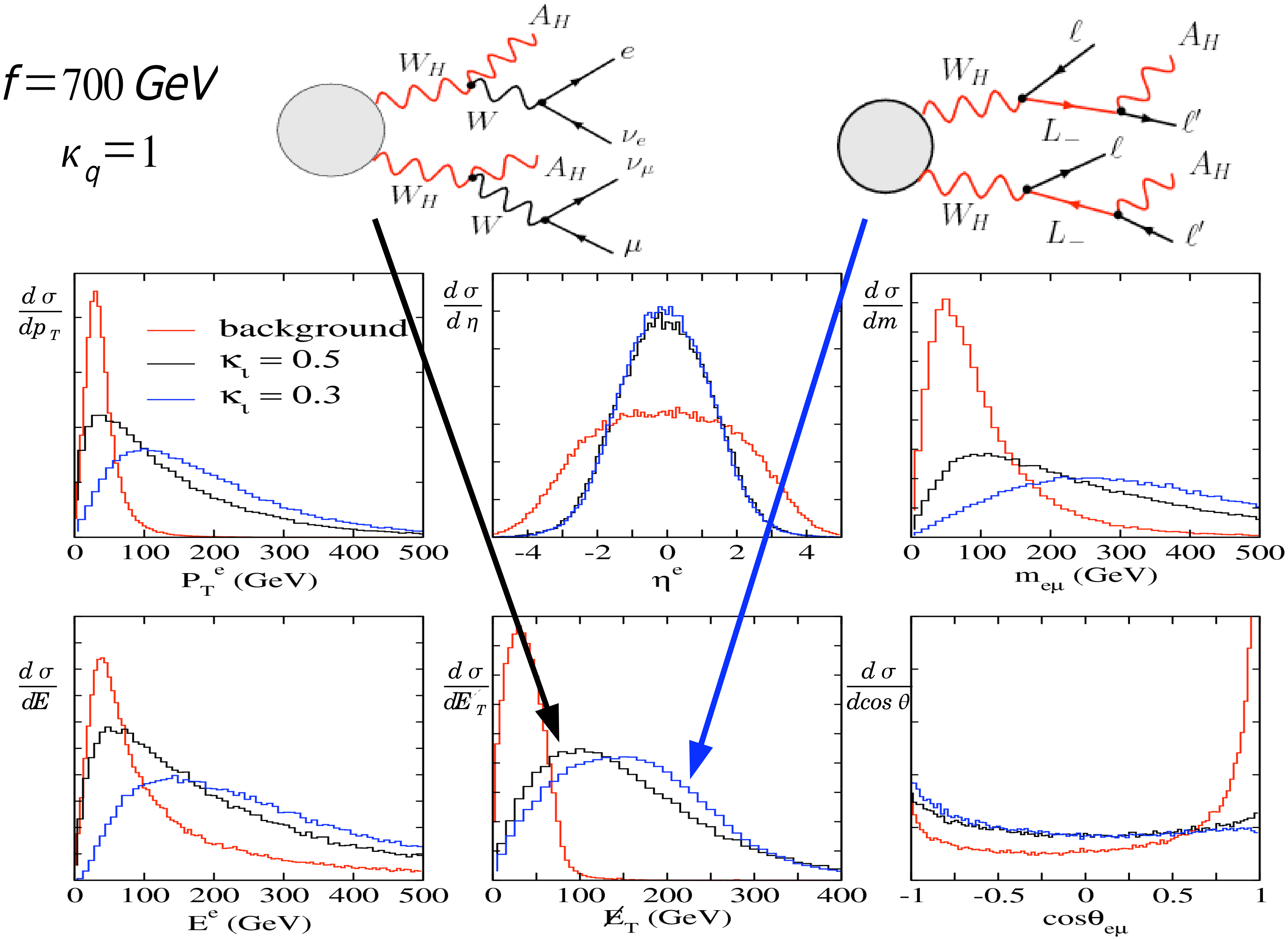




Backgrounds: $pp \to WW, WWZ, t\bar{t}, Wt$

$f = 700$ GeV

$\kappa_q = 1$

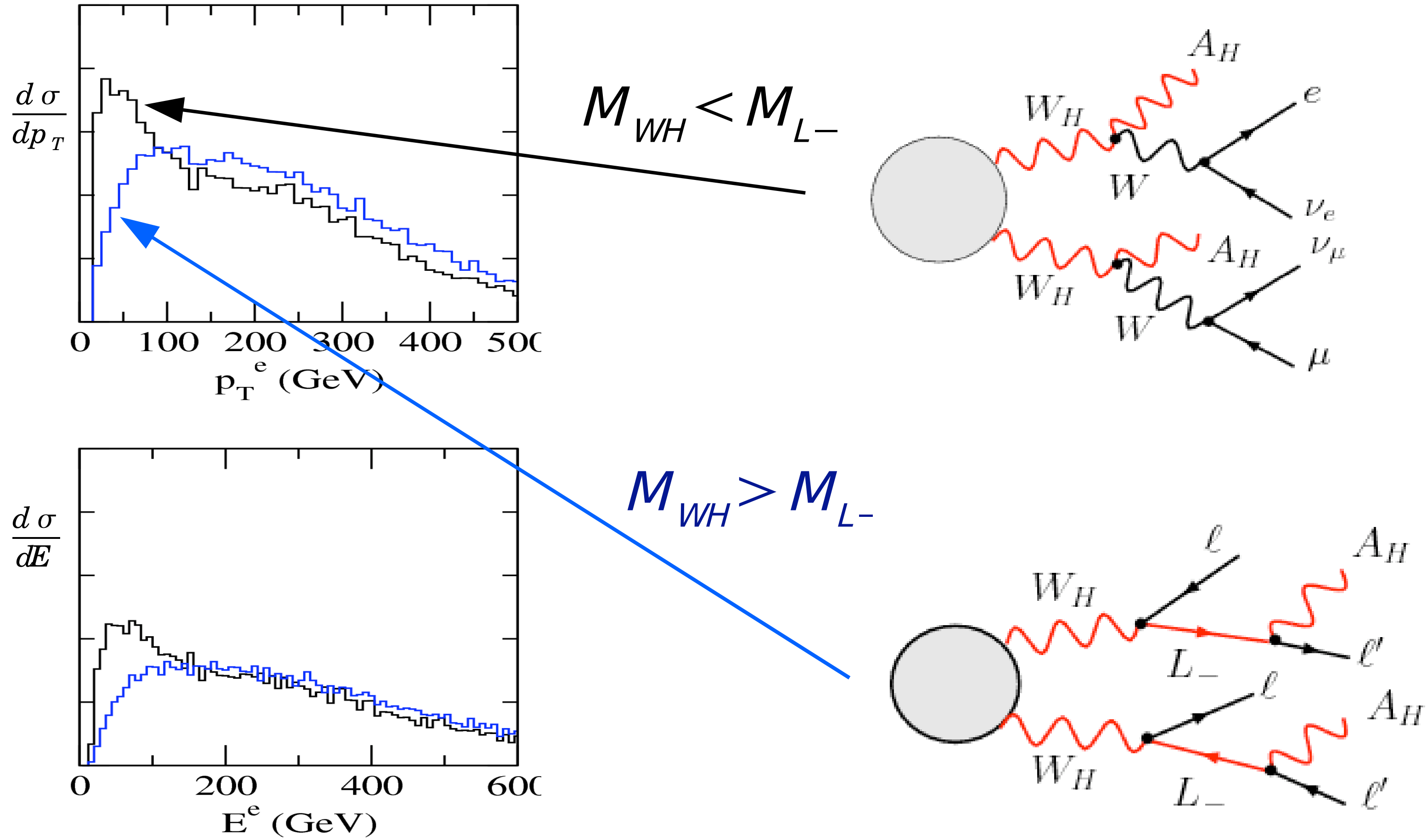


T-odd W-boson

Kinematics after cuts

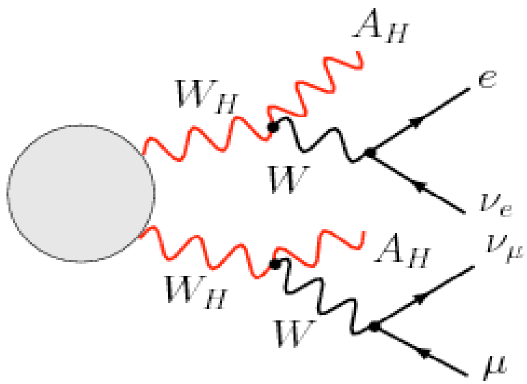
$$\text{cuts}: \quad p_T^e > 20\,GeV,\ p_T^\mu > 20\,GeV,\ |\eta^e| < 2.0,\ |\eta^\mu| < 2.0$$

$$\not{E}_T > 175\,GeV,\ \cos\theta_{e\mu} < 0.6$$

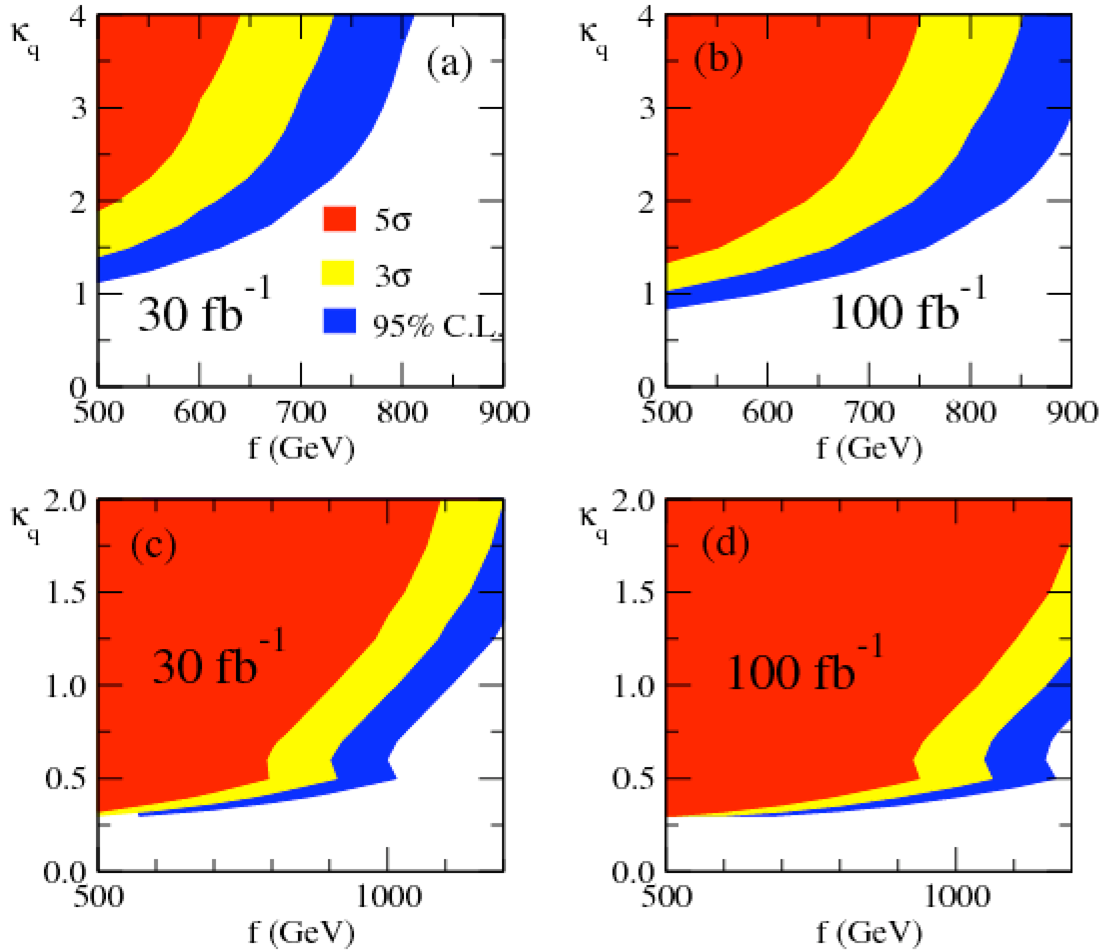


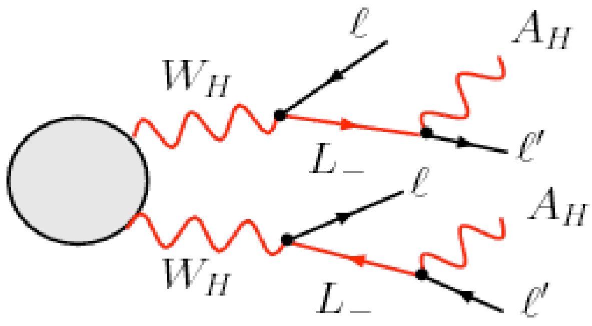
cuts : $p_T^e > 20\ GeV,\ p_T^\mu > 20\ GeV,\ |\eta^e| < 2.0,\ |\eta^\mu| < 2.0$

$$E_T > 175\ GeV,\ \cos\theta_{e\mu} < 0.6$$



$S/\sqrt{B}$ contour





LHC : di-lepton + $\not{E}_T$

→ Has a great discovery potential !!

BUT ...

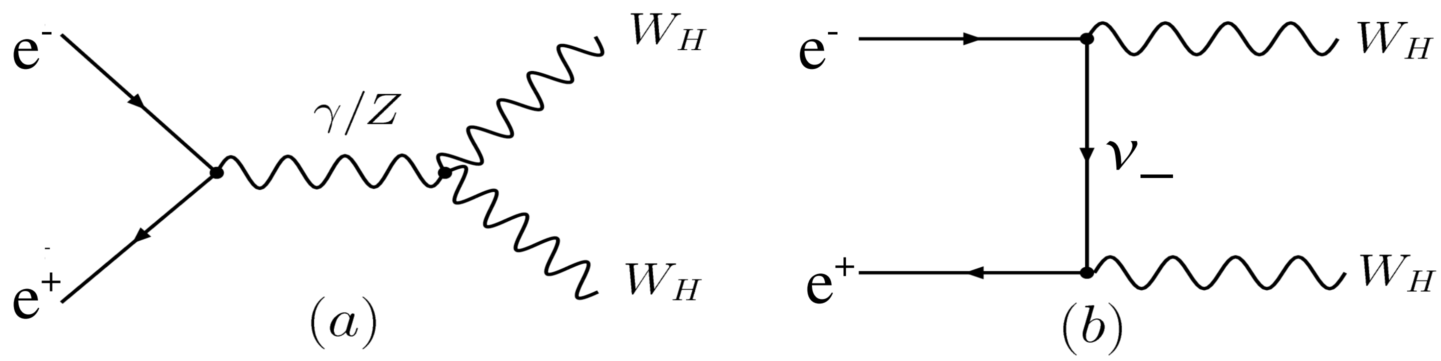
- Can NOT determine masses of W_H and A_H
- Can NOT reconstruct kinematics of A_H
- Can NOT measure the spin of W_H

~~LHC~~ LC :

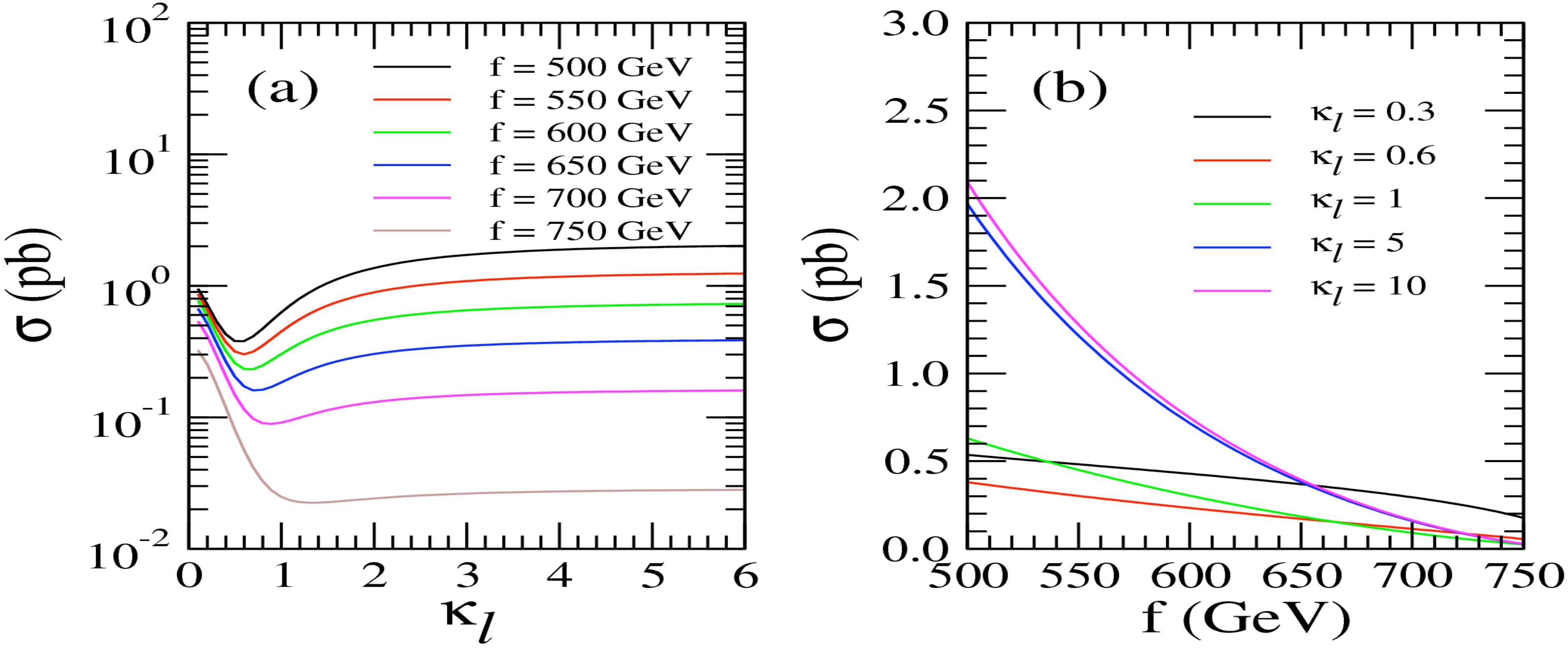
- Can ~~NOT~~ determine masses of W_H and A_H
- Can ~~NOT~~ reconstruct kinematics of A_H
- Can ~~NOT~~ measure the spin of W_H

With 4 jets + $\not{E}_T$ signature

$$e^+ e^- \rightarrow W_H W_H \rightarrow A_H W(\rightarrow j\, j) A_H W(\rightarrow j\, j)$$

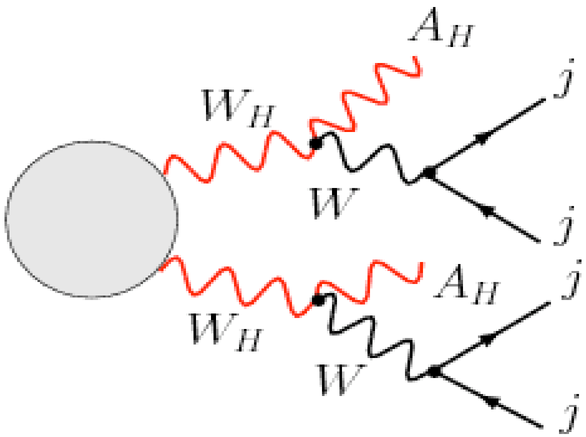


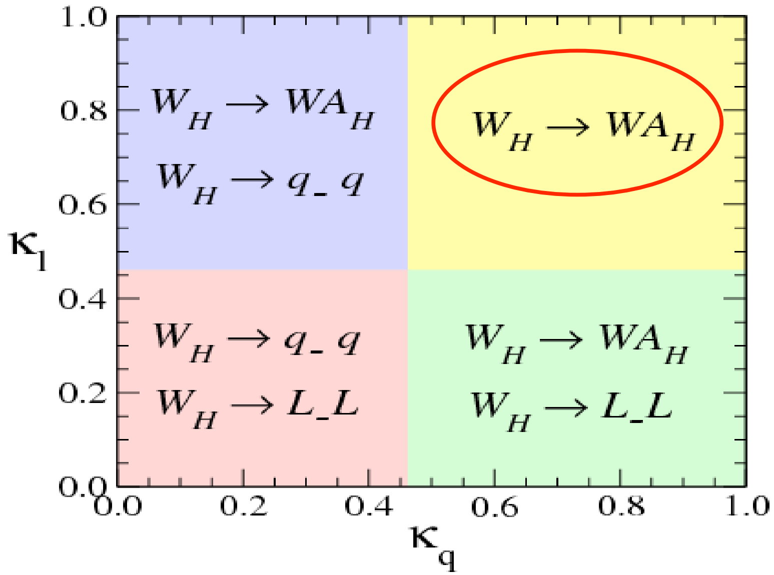
$$\sqrt{s}=1\,TeV \qquad m_{W_H}\sim g\,f \qquad m_{\nu_-}\sim\sqrt{2}\kappa_l f$$

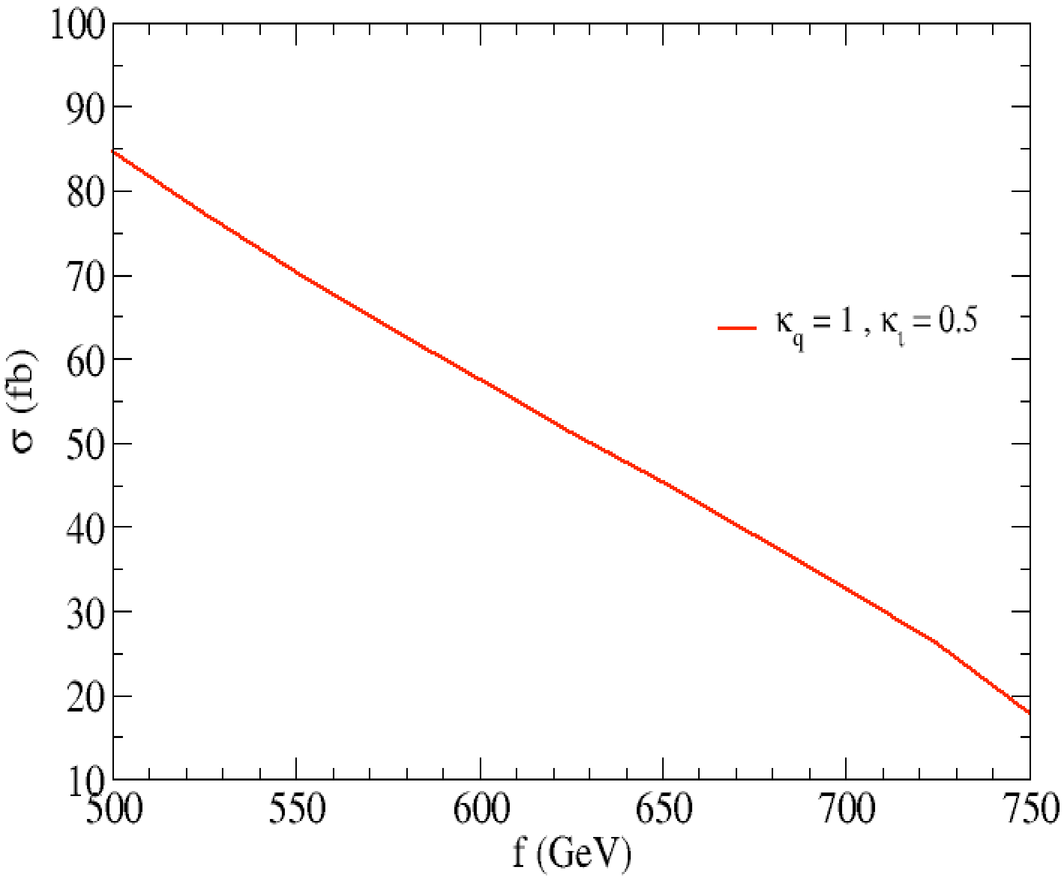


Signature $4\ jets + \not{E}_T$

$$e^+ e^- \to W_H W_H \to A_H W(\to j\,j) A_H W(\to j\,j)$$



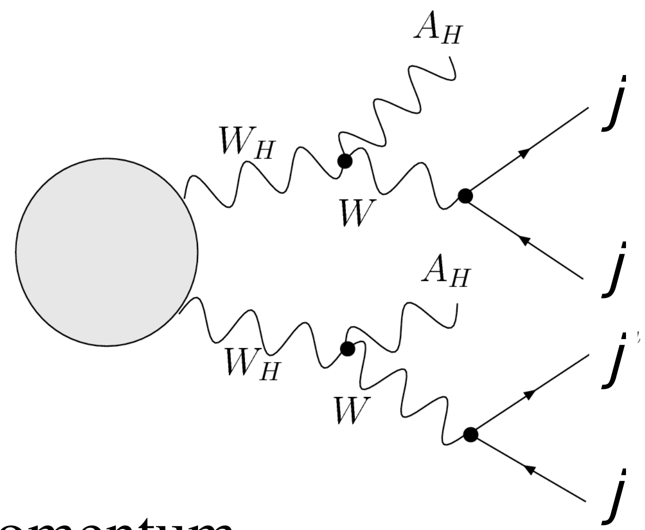




Intrinsic background : $e^+ e^- \to Z\,W\,W \to \nu\,\bar{\nu}\;j\,j\,j\,j\;\;(\sim 5.6\,fb)$

Require :

$$p_T^j \geq 15\, GeV\,,\ |\eta| \leq 3.0\,,\ \Delta R > 0.5$$



Reconstruct W boson

* order 4 jets with respect to their transverse momentum

$$p_T^{j_1} > p_T^{j_2} > p_T^{j_3} > p_T^{j_4}$$

* also require $MIN\left(\Delta = \sqrt{(m_1(jj) - m_W)^2 + (m_2(jj) - m_W)^2}\right)$

* identify Ws : $W_1 \equiv m(j_1 j_x)$, the other one is W_2

→ > 99 % accuracy

Kong, Park, hep-ph/0703057

At the rest frame of W_H

$$E_w^{res} = \frac{m_{W_H}^2 - m_{A_H}^2 + m_w^2}{2m_{W_H}} \qquad p_w^{res} = \frac{\sqrt{[m_{W_H}^2 - (m_{A_H} + m_w)^2][m_{W_H}^2 - (m_{A_H} - m_w)^2]}}{2m_{W_H}}$$

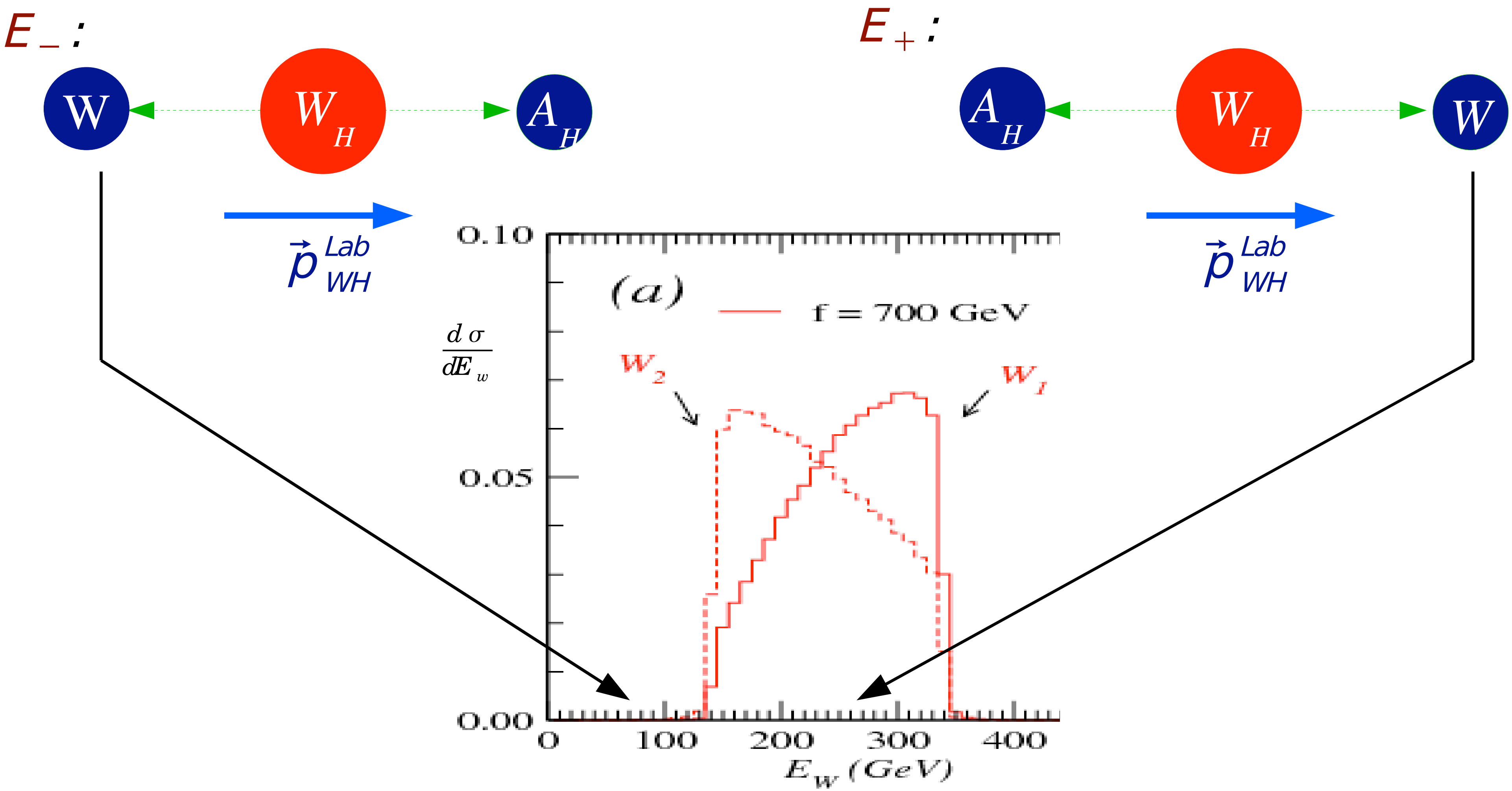
$$E_\pm = \gamma (E_w^{res} \pm \beta p_w^{res}) \qquad \beta = \sqrt{1 - \frac{m_{W_H}^2}{s}}$$

(+ : max. — : min.)

$$M_{W_H} = \sqrt{\frac{s}{2} \frac{\sqrt{E_+ E_-}}{E_+ + E_-}} \sqrt{1 + \frac{m_w^2}{E_+ E_-} + \sqrt{\left(1 - \frac{m_w^2}{E_+^2}\right)\left(1 - \frac{m_w^2}{E_-^2}\right)}}$$

$$M_{A_H} = M_{W_H} \sqrt{1 - 2\frac{(E_+ + E_-)}{\sqrt{s}} + \frac{m_w^2}{M_{W_H}^2}}$$

(Similar technique has been widely used in SUSY analysis.)

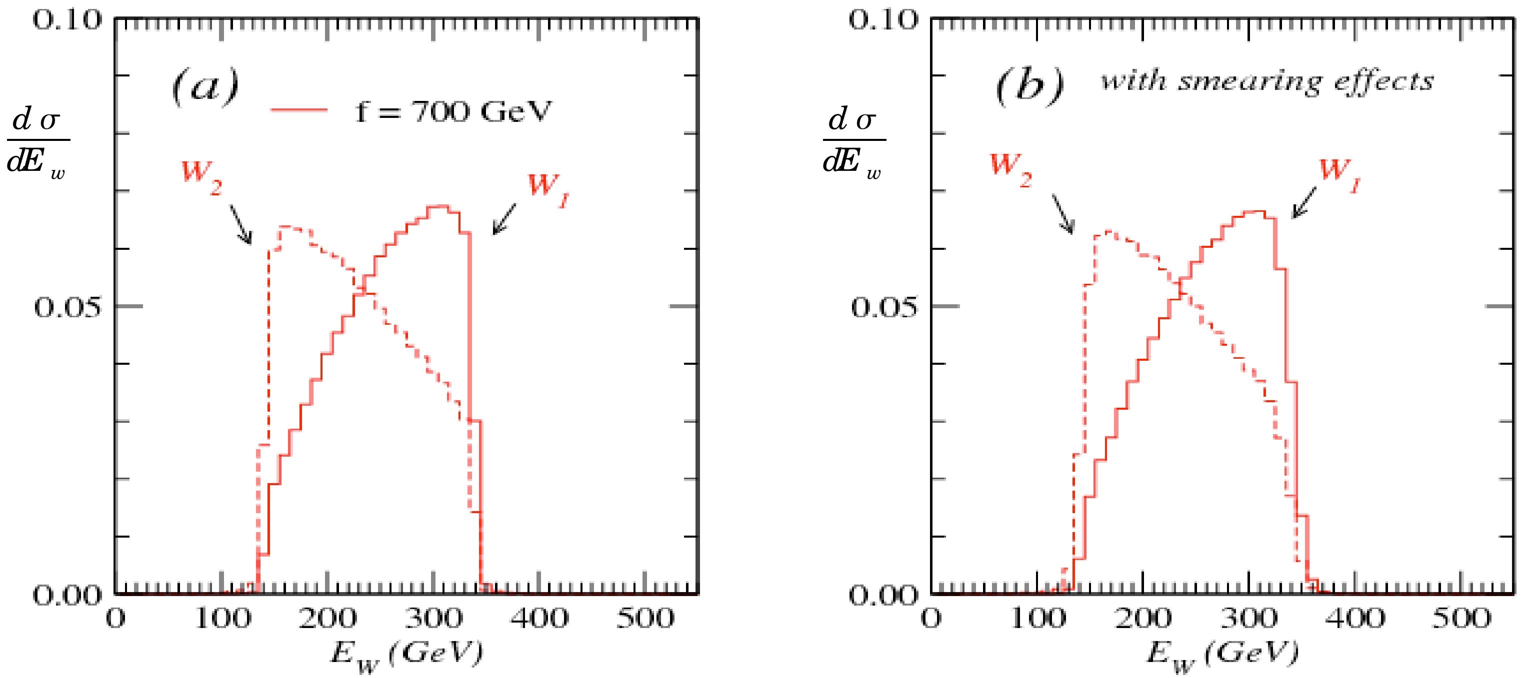


$$M_{W_H}=\sqrt{\frac{s}{2}}\frac{\sqrt{E_+E_-}}{E_++E_-}\sqrt{1+\frac{m_w^2}{E_+E_-}+\sqrt{\left(1-\frac{m_w^2}{E_+^2}\right)\left(1-\frac{m_w^2}{E_-^2}\right)}}$$

$$M_{A_H}=M_{W_H}\sqrt{1-2\frac{(E_++E_-)}{\sqrt{s}}+\frac{m_w^2}{M_{W_H}^2}}$$

Reconstruct the mass of W_H

$$\frac{\Delta E}{E} = \frac{0.5}{\sqrt{E}}$$



$E_+ = 345\,GeV,\ E_- = 130\,GeV$ smeared → $E_+ = 355\,GeV,\ E_- = 130\,GeV$

$(M_{W_H}, M_{A_H}) \approx (435, 126)\,GeV$ $(M_{W_H}, M_{A_H}) \approx (432, 109)\,GeV$

true $(450, 101)\,GeV$ $\delta \approx 4\%\,,\ 8\%$

Probing the Weak Boson Sector in $e^+e^- \rightarrow W^+W^-$

K. Hagiwara, R. D. Peccei and D. Zeppenfeld,
Nucl.Phys.B282:253,1987.

On shell condition
Momentum conservation
Known C.M. energy

→ reconstruct the momentum of A_H

→ reconstruct the momentum of W_H

→ boost back to the rest frame of W_H

→ Study spin of W_H

$$e^+ e^- \to A A' \to B' C'$$
$$\hookrightarrow B C$$

Hagiwara, Peccei, Zeppenfeld, Nucl.Phys.B282:253,1987.

$$p_{e^+} = (E_t,\ 0,\ 0,\ E_t) \quad p_{e^-} = (E_t,\ 0,\ 0,\ -E_t) \quad m_A = m_{A'}\ ,\ m_B = m_{B'}\ ,\ m_C = m_{C'}$$

$$\vec{p}_A = \vec{p}_B + \vec{p}_C\ ,\quad \vec{p}_{A'} = \vec{p}_{B'} + \vec{p}_{C'}\ ,\quad E_A = E_B + E_C\ ,\quad E_{A'} = E_{B'} + E_{C'}$$

$$\vec{p}_B + \vec{p}_C + \vec{p}_{B'} + \vec{p}_{C'} = 0$$

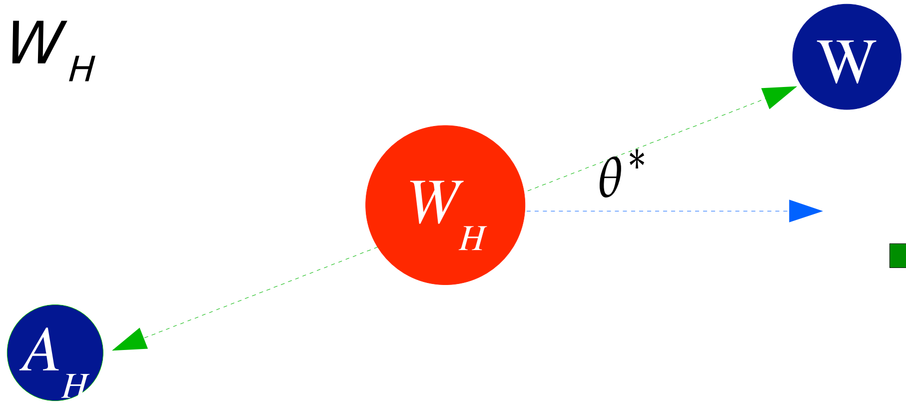
$$2\vec{p}_B \cdot \vec{p}_C = E_A^2 - m_A^2 - (E_B^2 - m_b^2) - (E_C^2 - m_C^2)\ ,\ 2\vec{p}_B \cdot \vec{p}_C = E_A^2 - m_A^2 - (E_B^2 - m_b^2) - (E_C^2 - m_C^2)$$

$$2\vec{p}_{B'} \cdot \vec{p}_C = (E_{c'}^2 - m_{c'}^2) - (E_A^2 - m_A^2) - (E_B^2 - E_{B'}^2) - 2\vec{p}_B \cdot \vec{p}_{B'}$$

$$p_C^2 = E_C^2 - m_C^2$$

$$\vec{p}_C = \alpha \vec{p}_B + \beta \vec{p}_{B'} + \gamma \vec{p}_B \times \vec{p}_{B'}$$

rest frame of W_H

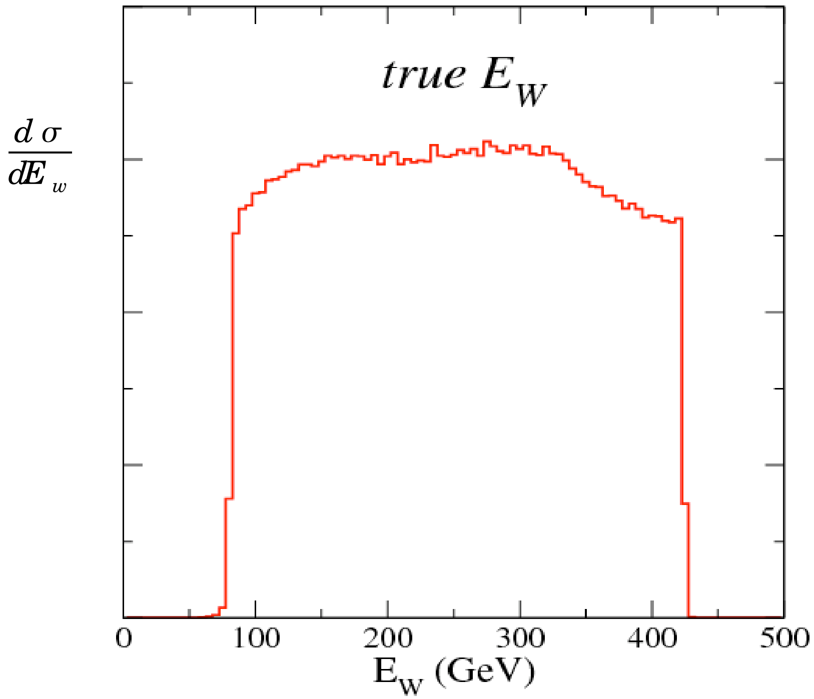


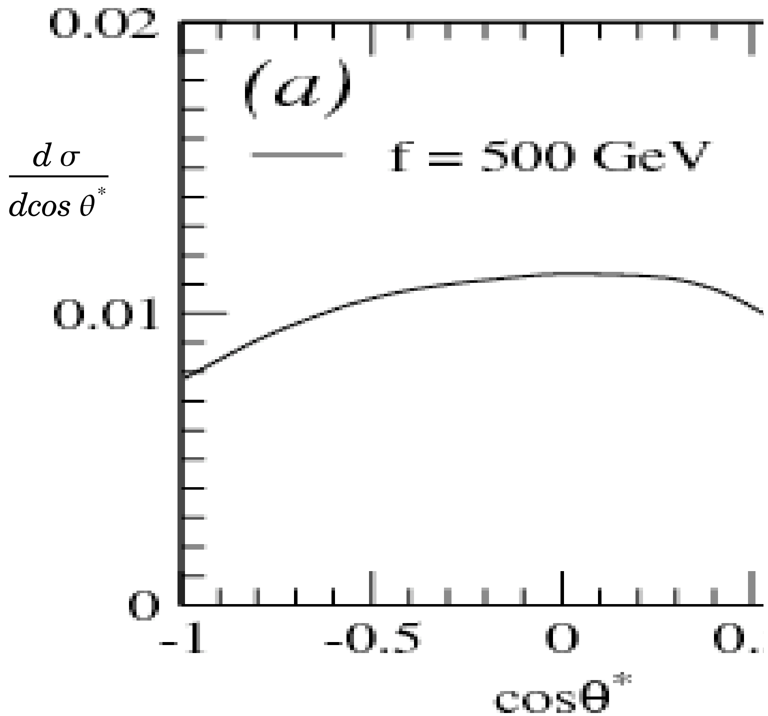
spin-1 to 2 scalars

P-wave dominates

$\sim \sin^2 \theta^*$

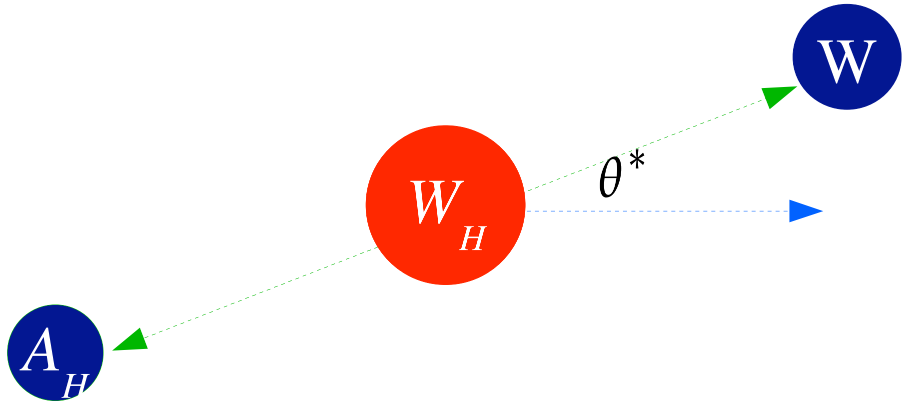
true



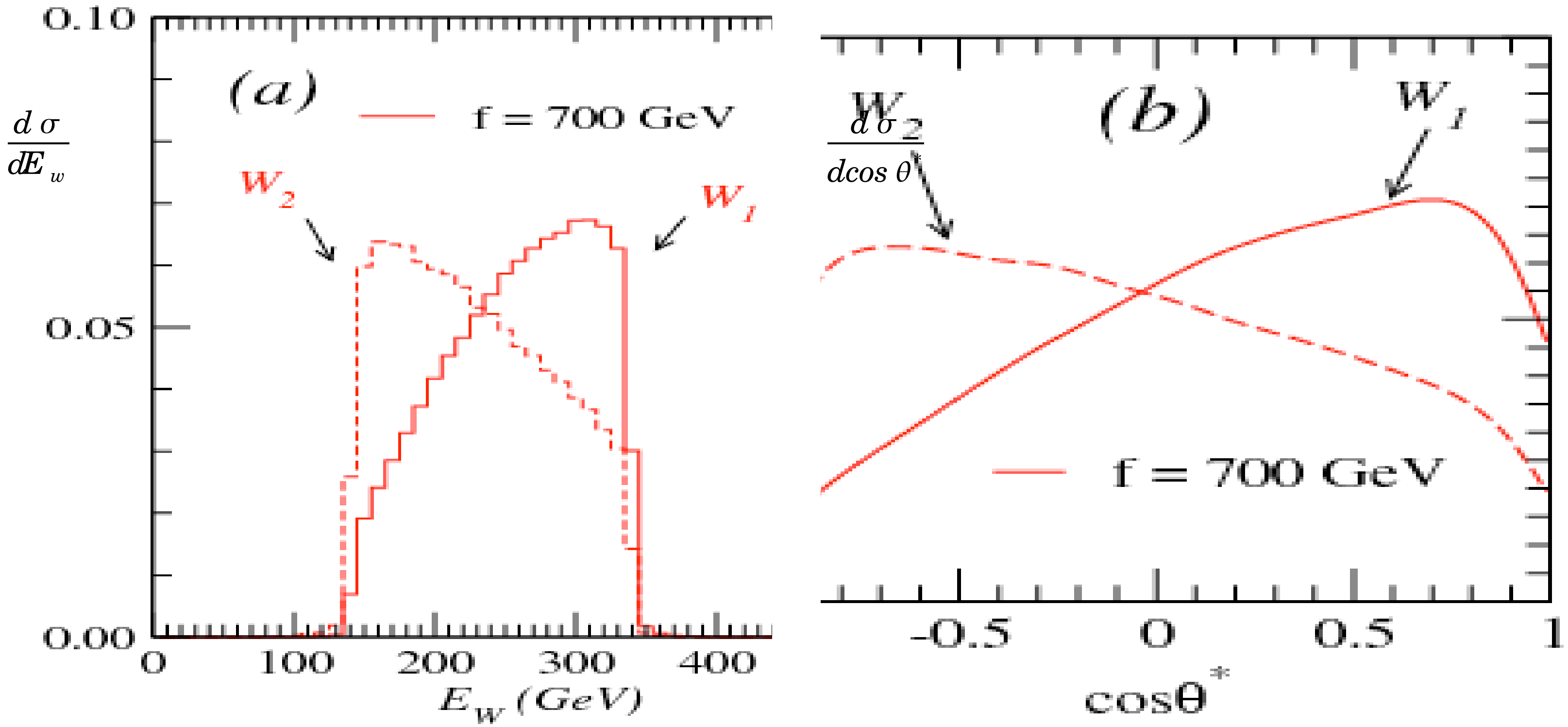


Spin of W_H

rest frame of W_H



After reconstruction

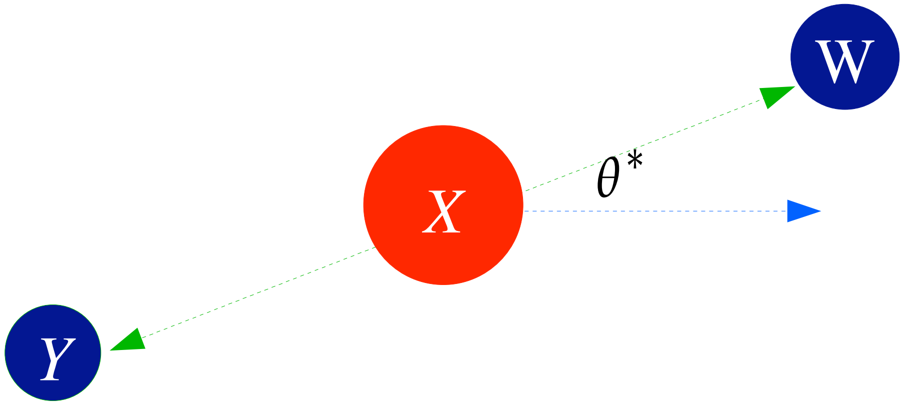


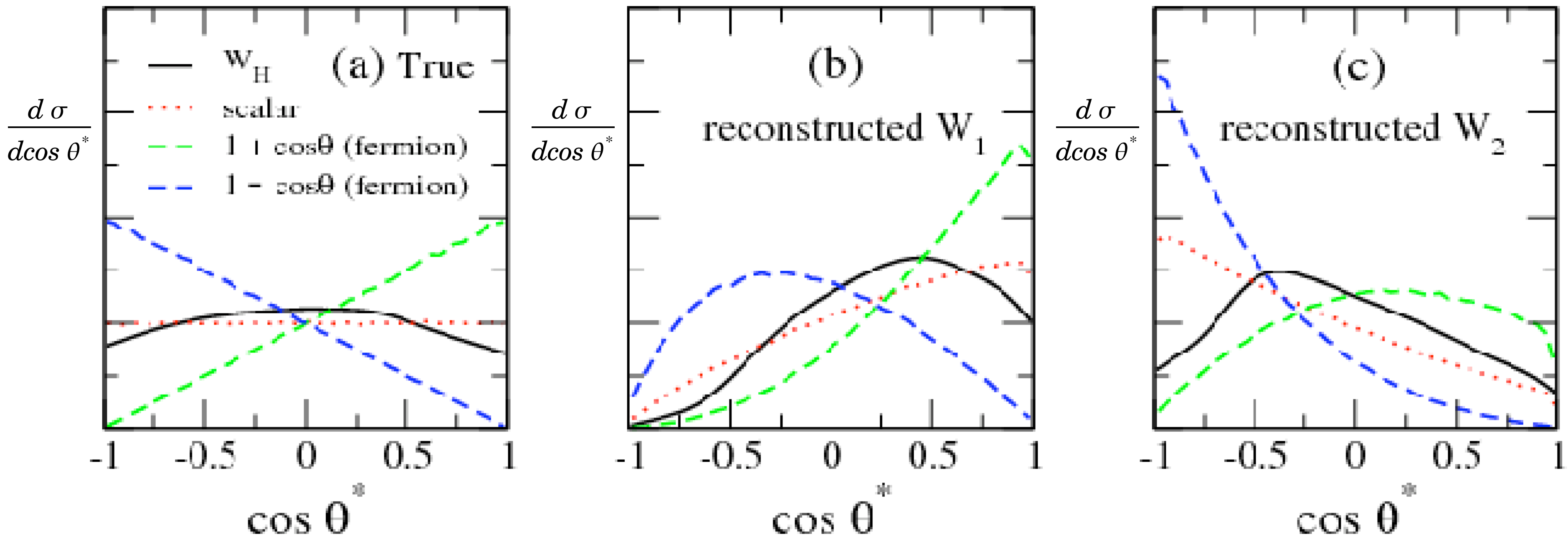
LHT

scalar

fermion

fermion





Summary

- Little Higgs mechanism provides a solution for solving the " little hierarchy " problem.
- T-parity forbids the mixing btw the SM and heavy gauge bosons
  → avoiding EWPT, lowering f, LHC could copiously produce new particles.
- The Higgs boson production rate via gluon fusion is suppressed.
- Polarization states of top quarks could provide the evidence of LHT.
- The LHC has a great potential to discover the signatures of new particles (W_H) predicted in the LHT.
- The physics quantities (mass, spin) could be measured at the LC, different models could be distinguished.