Phenomenology of Little Higgs Models

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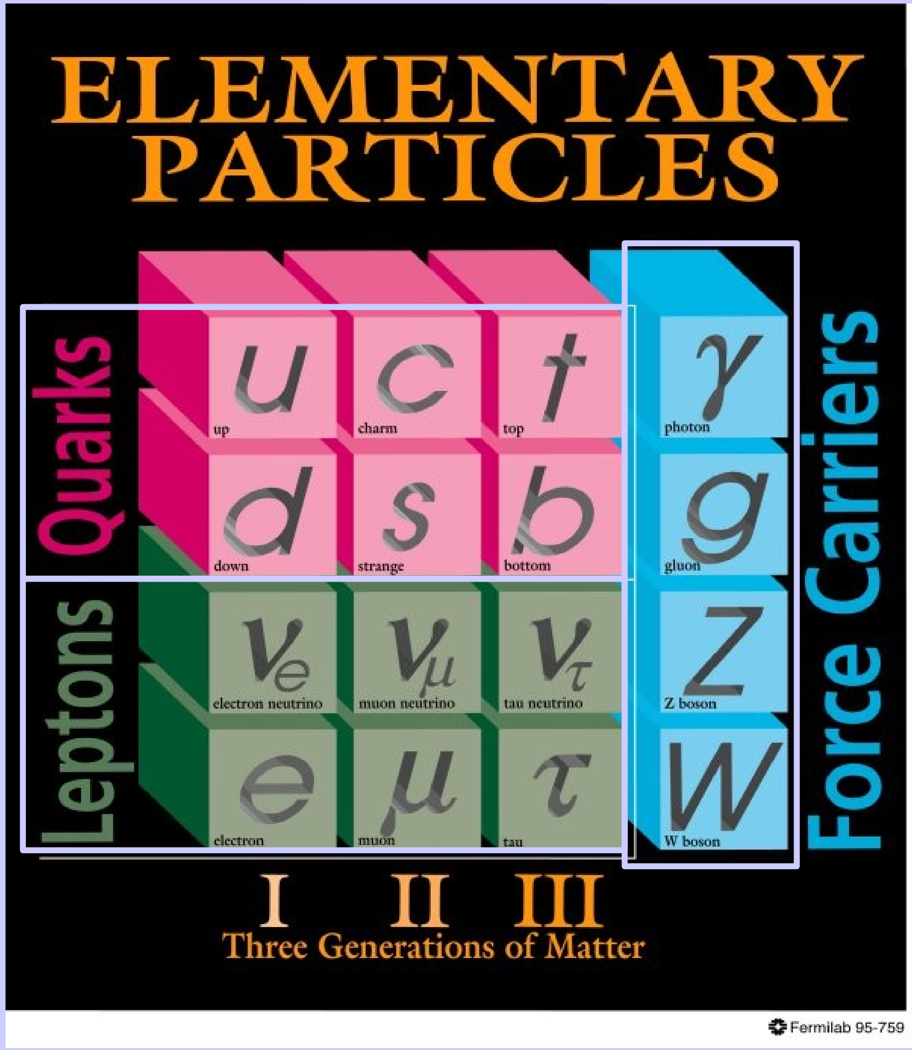
OUTLINE

- Motivation
- Little Higgs model: the idea
- Littlest Higgs model with T-parity (LHT)
- Phenomenology of LHT model
- Conclusions

The present status of the SM

- Based on SU(3)xSU(2)xU(1) symmetry spontaneously broken down to SU(3)xU(1):
- Matter: 3 generations of quarks and leptons
- One of the central role is played by Higgs field
  - *One complex Higgs doublet*
  - *3 degrees of freedom got eaten by massless W and Z, which acquire mass*
  - *1 DOF becomes the massive scalar, Higgs boson*
- Higgs boson is still unobserved, it is the most wanted particle!

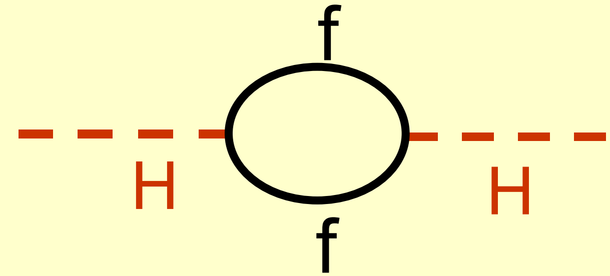


The present Higgs mass limit is 114.4 GeV from LEP2 e^+e^- collider

SM: Experimental/Theoretical problems

- *Theoretical problems*
  - *naturalness and gauge hierarchy problem*

$$M_H^2 = M_{H^0}^2 + \Delta M_H, \quad \text{SM: } \Delta M_H \sim \Lambda_{UV}^2$$



$$\delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}[-2\Lambda_{UV}^2 + \ldots]$$

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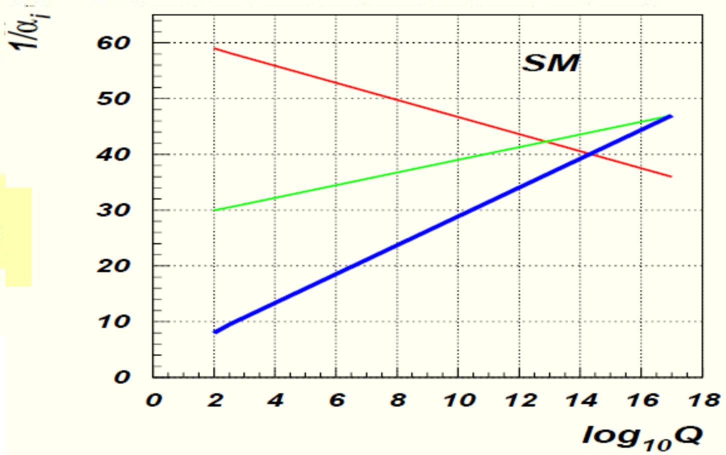
    $M_H^2 = M_{H^0}^2 + \Delta M_H$, SM: $\Delta M_H \sim \Lambda_{UV}^2$
  - gauge coupling unification is absent



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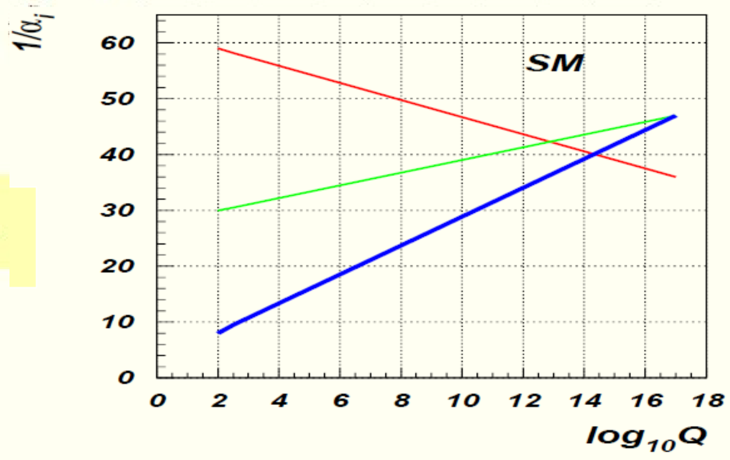
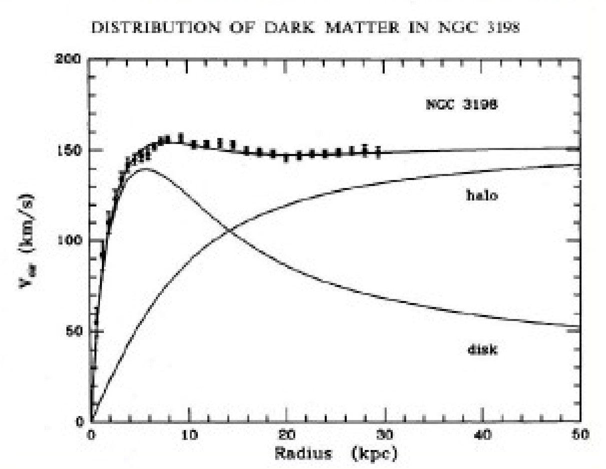
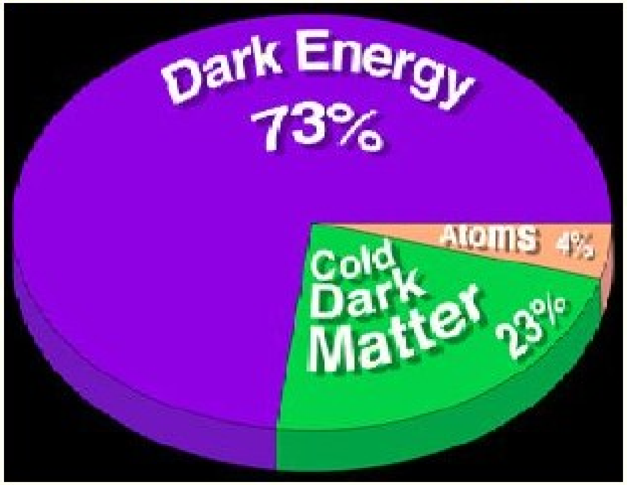


- Experimental Problems
  - Does not explain Dark Matter (WMAP results, galactic rotation curves, gravitational lensing)





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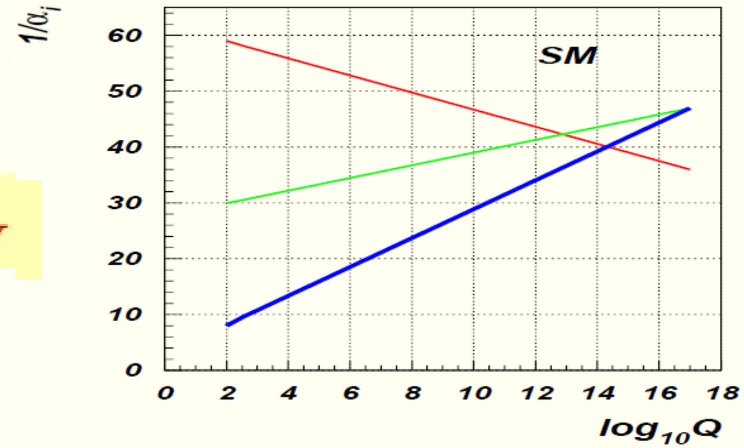

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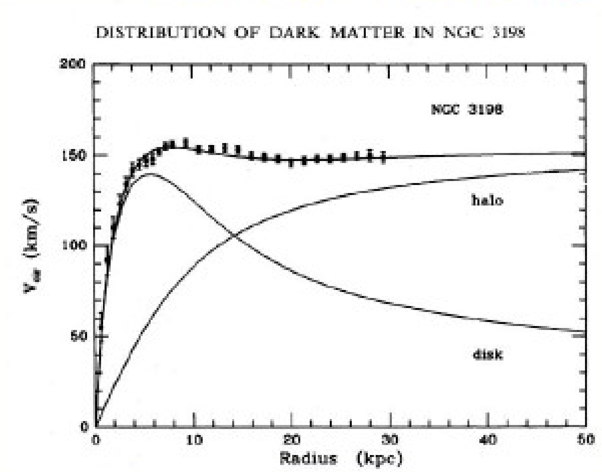
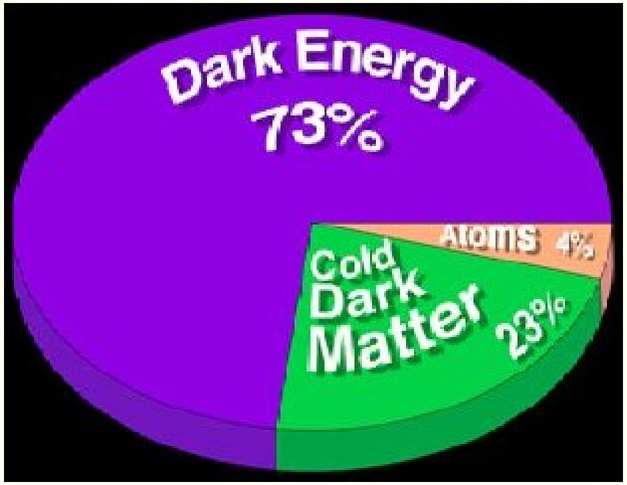




  - *Baryogenesis: the amount of CP violation is not enough because it predicts baryon asymmetry 10 orders of magnitude below the observed one*

Consequences of SUSY

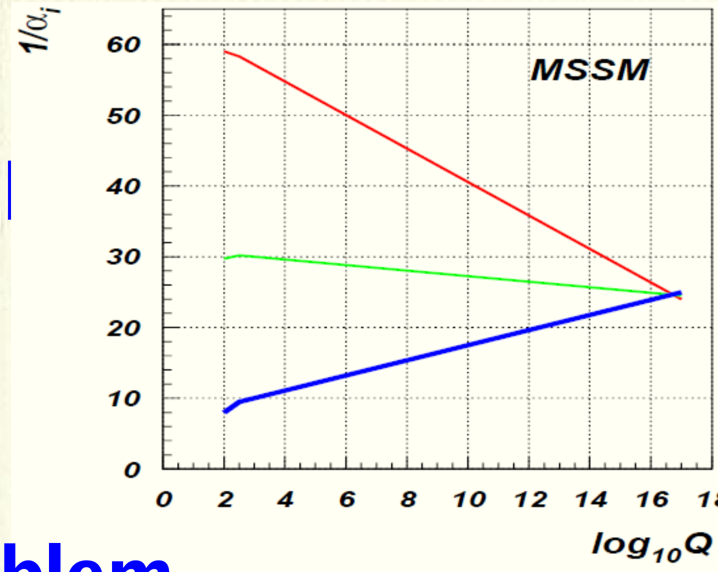
- local SUSY transformations introduce spin-2 graviton

$$spin2 \to spin3/2 \to spin1 \to spin1/2 \to spin0$$

- Provides connection to superstring models: crucial ingredient - allows to include fermions
- Solves fine-tuning problem of SM

$$M_H^2 = M_{H^0}^2 + \Delta M_H, \quad SM: \Delta M_H \sim \Lambda_{UV}^2, \quad SUSY: \Delta M_H \sim m_{soft}^2 \log(\Lambda_{UV}/m_{soft})$$

- Provides unification of gauge couplings
- EW symmetry is broken radiativel via RGE running H_u and H_D
- Provides perfect DM candidate: stable LSP



- Potentially solves baryogenis problem

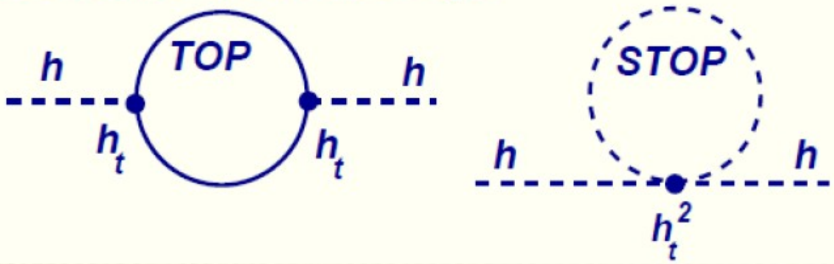
"Little" Fine Tuning in MSSM

- **Tree-level lightest Higgs boson mass is below Z-boson mass**

$$M_h^2 = \frac{1}{2}\left[m_A^2 + M_Z^2 - \sqrt{(M_A^2+M_Z^2)^2 - 4m_A^2M_Z^2\cos^2 2\beta}\right] \Rightarrow M_h \simeq M_Z|cos2\beta| \text{ for } M_a \gg M_Z$$

Top-stop Radiative corrections to the light Higgs mass drive its mass up!

$$\delta M_h = \frac{3g^2m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$



- **SUSY scale ~ 1 TeV and above is required to satisfy LEP2 constraints**
- **~ 1% of tuning to get Z-mass right**

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

Little Higgs model as an alternative to SUSY

Arkani-Hamed, Cohen, Georgi hep-ph/0105239

- "Little Higgs" is a pseudo-Nambu-Goldstone boson of spontaneously broken global symmetry
- This symmetry is also explicitly broken but only "collectively": when two or more couplings in the Lagrangian are non-vanishing: $\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$
- Setting any of these couplings to zero restores the symmetry and therefore the masslessness of the of the "little Higgs"
- Thus, little Higgs acquires its mass at second loop

$$\delta m_H^2 \sim \left(\frac{\lambda_1^2}{16\pi^2}\right)\left(\frac{\lambda_2^2}{16\pi^2}\right)\Lambda^2 \quad \sim O(100)\mathrm{GeV} \text{ for } \Lambda \sim 10 \text{ TeV}$$

Littlest Higgs: a minimal realization of Little Higgs

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

SU(5) global symmetry is spontaneously broken to SO(5) by the VEV of

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix}$$

at the scale f

SU(5) $\supset [SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$

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

VEV = f ~ O(1) TeV

SO(5) $\supset SU(2) \times U(1)$

(N^2-1) [24] – N(N-1)/2 [10] =
14 goldstone bosons

$\mathbf{1_0 \oplus 3_0} \oplus \mathbf{2_{\pm 1/2} \oplus 3_{\pm 1}}$

$A_H, \; Z_H, \; W_H^{\pm}$

$$\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \Phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \Phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}$$

Goldstone boson matrix parameterization in non-linear sigma model

$$\Sigma = \exp(i\Pi/f)\Sigma_0$$

Higgs is exact NG boson under either global SU(3)

Collective Symmetry Breaking

$[SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2$ ***are embedded in global SU(5)***

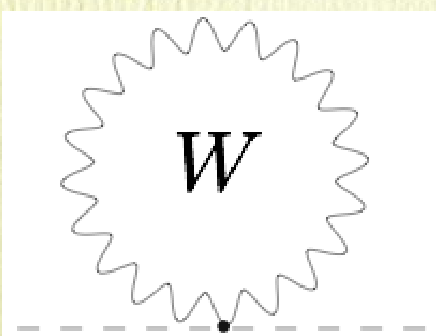
$$Q^a_{SU(2)_1} = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad Y_1 = \frac{1}{10}\begin{pmatrix} 3 & & & & \\ & 3 & & & \\ & & -2 & & \\ & & & -2 & \\ & & & & -2 \end{pmatrix}$$

preserves SU(3)

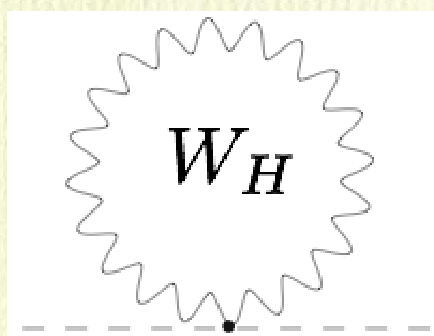
$$Q^a_{SU(2)_2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix} \qquad Y_2 = \frac{1}{10}\begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix}$$

preserves SU(3)

Either SU(3) is enough to keep Higgs massless. Sum of all gauge interactions break both SU(3)s and generate the Higgs mass.



$$\frac{g^2}{2}$$



$$-\frac{g^2}{2}$$

Λ^2 corrections are canceled.

Littlest Higgs: scalar kinetic term

$$\mathcal{L}_\Sigma = \frac{1}{2}\frac{f^2}{4}\mathrm{Tr}|\mathcal{D}_\mu \Sigma|^2$$ with covariant derivative given by

$$\mathcal{D}_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^{2} \left(g_j (W_j \Sigma + \Sigma W_j^T) + g'_j (B_j \Sigma + \Sigma B_j^T) \right)$$

where Σ expanded around its vacuum expectation value

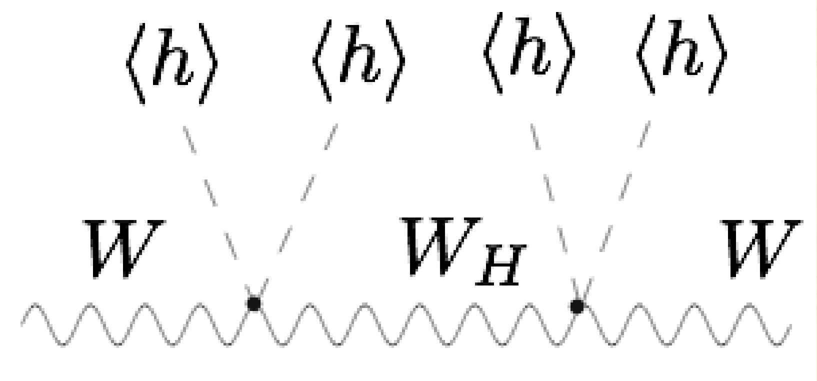
$$\Sigma = \Sigma_0 + \frac{2i}{f} \begin{pmatrix} \phi^\dagger & \frac{h^\dagger}{\sqrt{2}} & \mathbf{0}_{2\times 2} \\ \frac{h^*}{\sqrt{2}} & 0 & \frac{h}{\sqrt{2}} \\ \mathbf{0}_{2\times 2} & \frac{h^T}{\sqrt{2}} & \phi \end{pmatrix} + \mathcal{O}(\frac{1}{f^2}),$$

Lagrangian contains non-renormalizable interactions:
can be only low energy effective description of physics.

The loop contribution becomes as important as tree-level diagram at the scale $\Lambda \lesssim 4\pi f$: theory becomes strongly coupled

Little Higgs Model with T -parity (LHT)

- Large tree-level corrections e.g. due to the exchange of additional heavy gauge bosons and non-vanishing VEV of triplet higgs:
  f > 5 TeV, fine-tuning again !



- T-parity ***(Cheng, Low 2003),*** *Z_2 symmetry forbids mixing with SM*

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

$$\begin{array}{lcl} \text{SM particles} & \rightarrow & +\,\text{SM particles} \\ (W_H, Z_H, A_H, \Phi, Q) & \rightarrow & -(W_H, Z_H, A_H, \Phi, Q) \end{array}$$

$$g_1 = g_2 = \sqrt{2}g \text{ and } g_1' = g_2' = \sqrt{2}g'$$

- ***No tree-level to EW observables***
- ***The lightest T-odd particle is a good DM candidate***
- ***New scale f can be lower then 1 TeV***

interesting phenomenology ! *(Hubisz et al., 2004)*

LHT Model

Hsin-Chia Cheng, Ian Low,

Jay Hubisz, Patrick Meade,

Andrew Noble, Maxim Perelstein,

Claudio O. Dib, Rogerio Rosenfeld,

Alfonso Zerwekh, Seung J. Lee, Gil Paz,

Chuan-Ren Chen, Kazuhiro Tobe,

C.-P. Yuan, Andreas Birkedal, ...

LHT: new particles

Gauge sector

$$A_H,\ m \sim g' f/\sqrt{5}$$ DM candidate!

$$Z_H,\ W_H^{\pm},\ m \sim g f$$

Higgs sector

$$\Phi:\quad \phi^{++},\quad \phi^{+},\quad \phi^{0},\quad \phi^{P};\quad m \sim \sqrt{2} m_h f/v$$

$SU(2)_L$ doublets

Fermion sector

$$t'_{+},\quad m \sim \sqrt{\lambda_1^2+\lambda_2^2} f$$ singlet, the only T-even

$$t'_{-},\quad m \sim \lambda_2 f$$ singlet

$$Q_L^{(-)},\quad L_L^{(-)},\quad m \sim \sqrt{2}\kappa f$$ $SU(2)_L$ doublets

Have not been included in the previous phenomenological studies! Do not decouple.

LHT Model: Yukawa interactions

$$-\frac{\lambda_1}{2\sqrt{2}} f \epsilon_{ijk}\epsilon_{xy}\left[(\bar{Q}_1)_i \Sigma_{jx}\Sigma_{ky} - (\bar{Q}_2\Sigma_0)_i \tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right] u_{R_+}$$
$$-\lambda_2 f(\bar{U}_{L_1}U_{R_1} + \bar{U}_{L_2}U_{R_2}) + \text{h.c.},$$

with $Q_1 = (q_1, U_{L_1}, 0_2)^{\mathrm{T}}$ **and** $Q_2 = (0_2, U_{L_2}, q_2)^{\mathrm{T}}$

giving $t,\ t_+,\ \ t_-$ with $\sin\alpha = \lambda_1/\sqrt{\lambda_1^2+\lambda_2^2}$

$M_t \simeq (\lambda_2 \sin\alpha)v, \quad M_{t_-} \simeq \lambda_2 f, \quad M_{t_+} \simeq (\lambda_2/\cos\alpha) f$

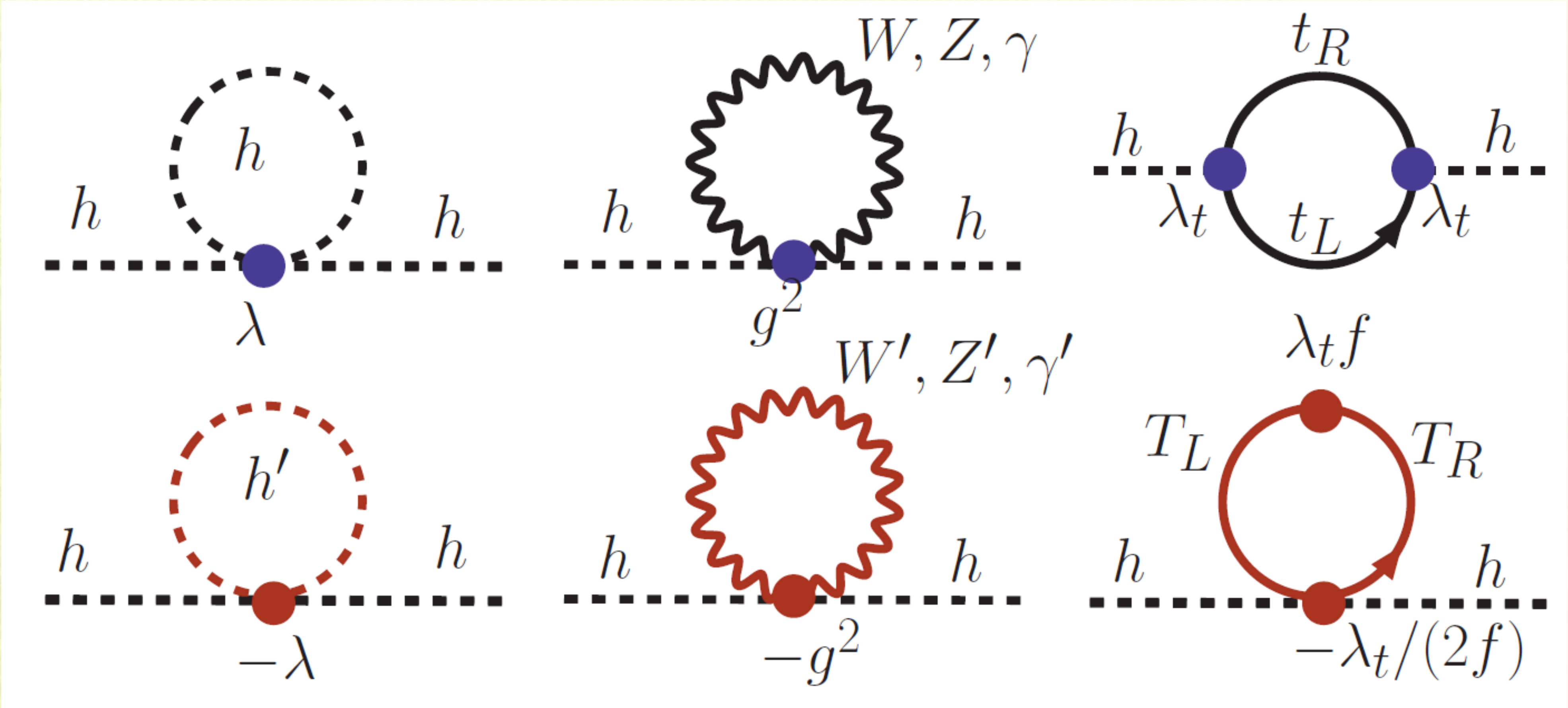
$$-\kappa f(\bar{\Psi}_2\xi\Psi_c + \bar{\Psi}_1\Sigma_0\Omega\xi^\dagger\Omega\Psi_c) + \text{h.c.}$$

fermion $SU(2)$ **doublets** q_1 **and** q_2**:**

$\Psi_1 = (q_1, 0, 0_2)^{\mathrm{T}}$ **and** $\Psi_1 = (0_2, 0, q_2)^{\mathrm{T}}$

giving U_-**,** D_-**, with** $M_{Q_-} = \sqrt{2}\kappa f$

Cancellation of quadratic divergences



New heavy particles bosons,top-quarks, scalars
cancel the respective SM one-loop quadratic divergences

LHT: model parameters and mass spectrum

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

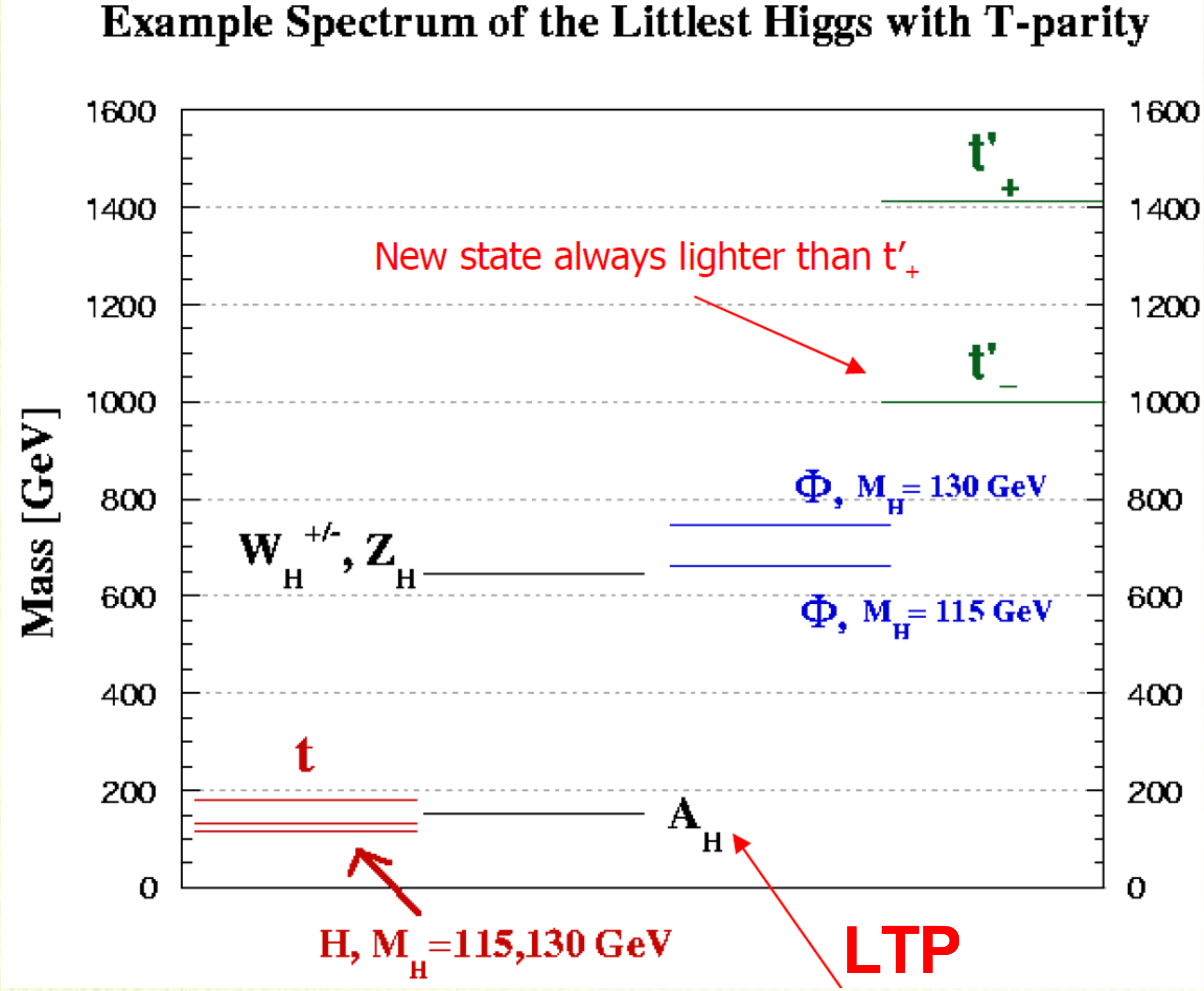
$Z_H, \; W_H^\pm, \; m \sim g f$

$\phi^{++}, \; \phi^+, \; \phi^0, \; \phi^P;$
$m \sim \sqrt{2} m_h f/v$

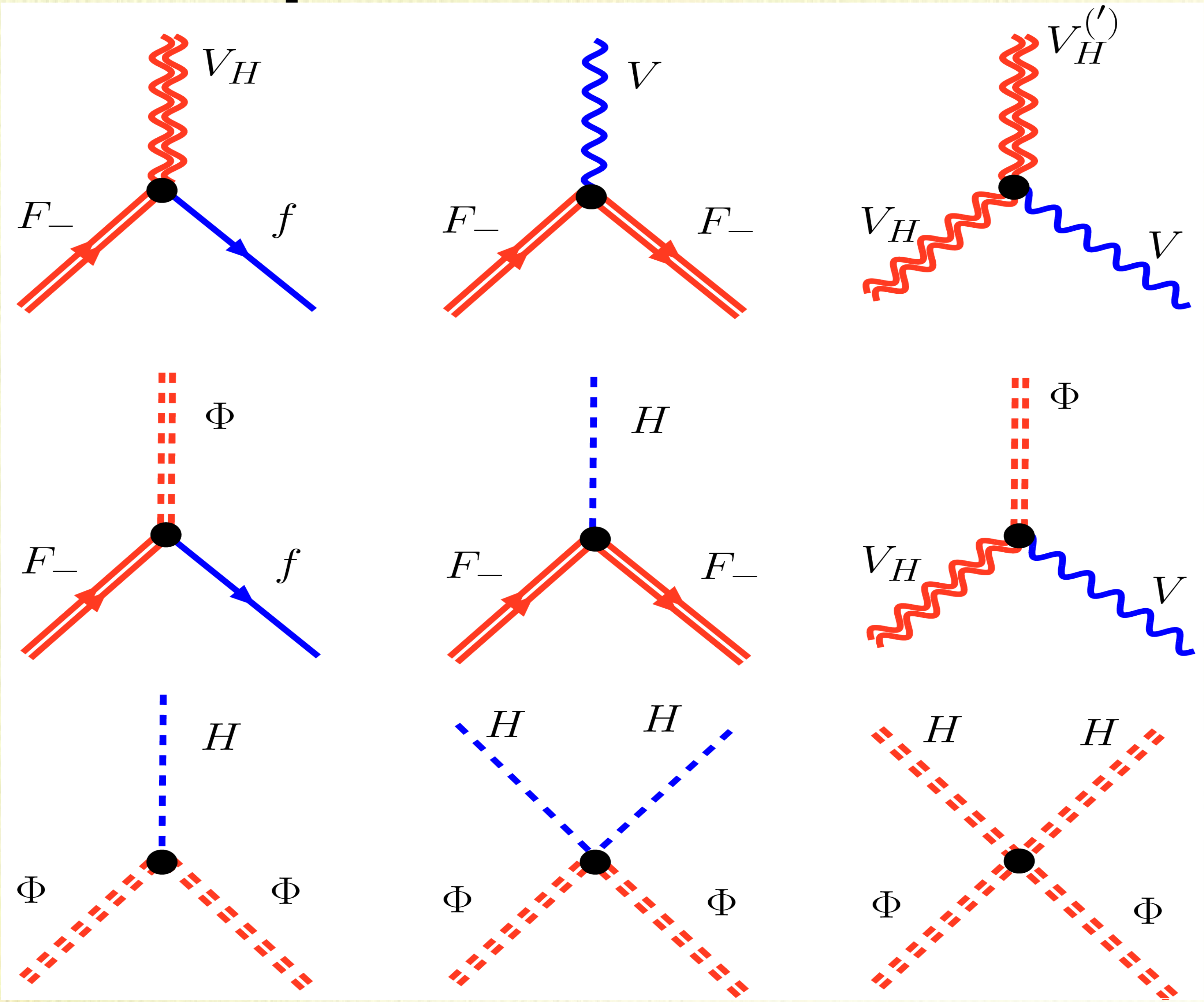
$\sin\alpha = \lambda_1/\sqrt{\lambda_1^2 + \lambda_2^2}$
$M_t \simeq (\lambda_2 \sin\alpha) v,$
$M_{t_-} \simeq \lambda_2 f,$
$M_{t_+} \simeq (\lambda_2/\cos\alpha) f$

$Q_L^{(-)}, L_L^{(-)},$
$m \sim \sqrt{2}\kappa f$

Model parameters:
$f, \quad M_h, \quad \sin\alpha, \quad \kappa$



LHT: particle interactions



Phenomenology of LHT model

- **Model implementation**

Lanhep → CalcHEP

Lanhep *(A.Semenov)* **is the package for automatic generation of Feynman rules (model) for CompHEP/CalcHEP**

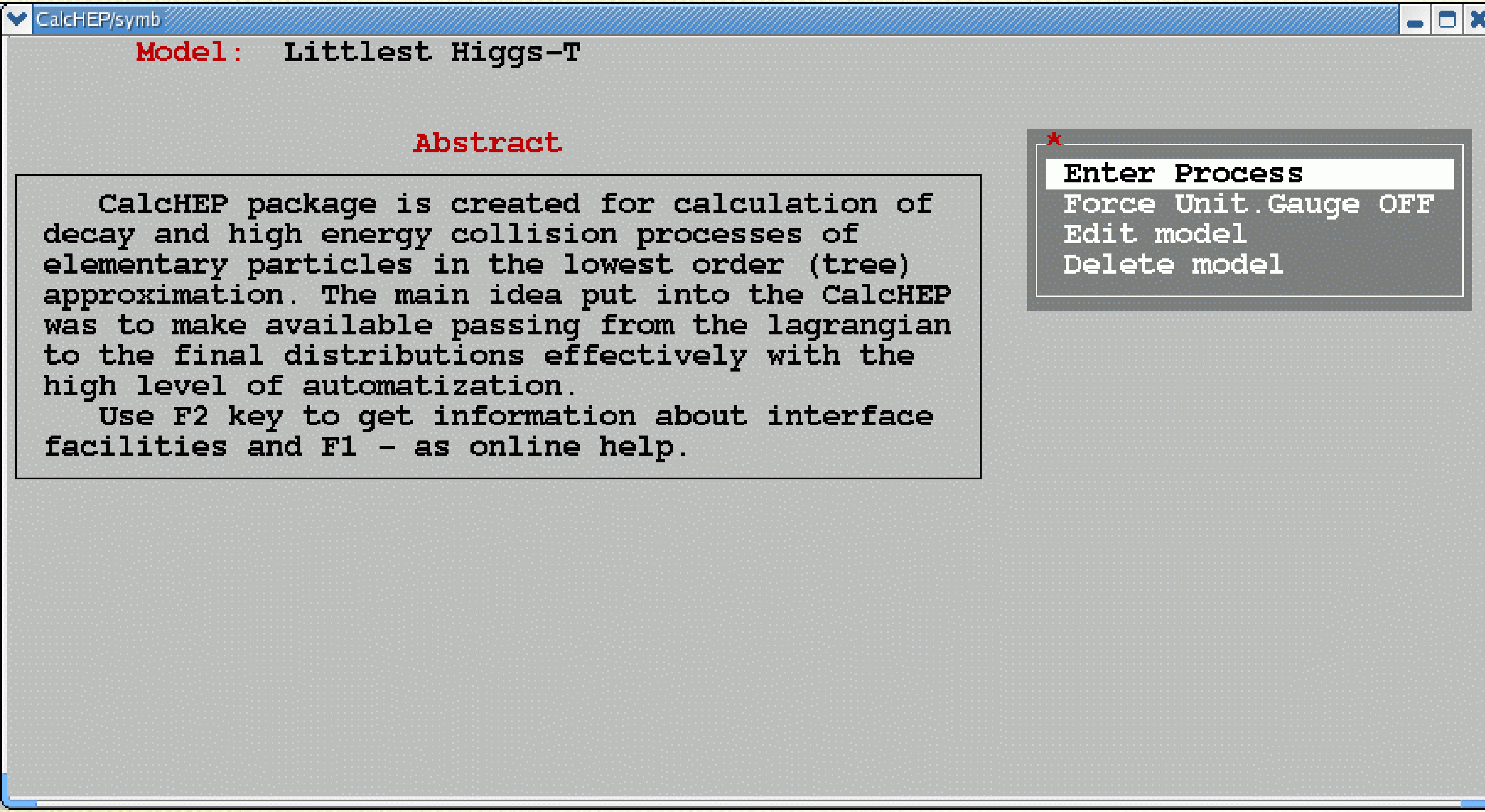
lowers down a lot the possibility of human mistake

- **Previously, the essential part of the model**

has been implemented by *J. Hubisz and P. Meade in hep-ph/0411264*

- **Our study aims**
  - ***to implement the complete model***
  - ***to check the previous studies***
  - ***to systematise all possible phenomenology***
  - ***to apply CalcHEP-PYTHIA for multibody final states***
  - ***To calculate DM relic density within the complete model using MicroMEGAs 2.0*** **(A. Pukhov et al)**

LHT implementation using LanHEP(1)



LHT implementation using LanHEP(2)

CalcHEP/symb

Variables

Clr Del Size Read ErrMes

Name	Value	> Comment <
EE	0.307885	Electromagnetic coupling constant (<->1/128)
GG	1.21772	Strong coupling constant (Z point) (PDG-94)
SW	0.4713	sin of the Weinberg angle (PDG-94,"on-shell")
s12	0.221	Parameter of C-K-M matrix (PDG-94)
s23	0.04	Parameter of C-K-M matrix (PDG-94)
s13	0.0035	Parameter of C-K-M matrix (PDG-94)
MZ	91.1876	Z-boson mass
f	1000	
sa	0.707107	
zero0	0	
Mt	175	
MH	120	
kappa	1	
Mb	4.7	
Mc	1.3	
Ms	0.2	
wW	2.502	width of W boson
wWh	10	width of W heavy
wZ	2.502	width of Z boson
wZh	10	width of Z heavy
Mm	0.1057	mass of muon

F1 F2 Xgoto Ygoto Find Write

LHT implementation using LanHEP(3)

CalcHEP/symb

Constraints

Clr Del Size Read ErrMes

Name	> Expression
CW	sqrt(1-SW^2)
MW	MZ*CW
v	2*MW*SW/EE
del	v/f
vh	v*(1+del^2/12)
ca	sqrt(1-sa^2)
mtcorr	(1-2*sa^4)*del^2/4
lam1	Mt/ca/v*(1+mtcorr)
lam2	Mt/sa/v*(1+mtcorr)
g	EE/SW
gp	EE/CW
xh	5/4*g*gp/(5*g^2-gp^2)
MWL	MW*sqrt(1)
MZL	MZ*sqrt(1)
MAH	gp*f/sqrt(5)*(1-5/8*del^2)
MZH	g*f*(1-del^2/8)
MWH	g*f*(1-del^2/8)
Mtp	sqrt(lam1^2+lam2^2)*f*(1-ca^2*sa^2/2*del^2)
Mt1	lam2*f
MH3	Sqrt2*MH/del
Muo	Sqrt2*kappa*f*(1-del^2/8)

F1 F2 Xgoto Ygoto Find Write

LHT implementation using LanHEP(4)

CalcHEP/symb

Particles 32

Clr Del Size Read ErrMes

Full name	P	aP	number	2*spin	mass	width	color	aux	> LaTeX(A)
p++ higgs	~++	~--	0	0	MH3	0	1		(++)
neutrino	n1	N1	0	1	0	0	1		n1
electron	e1	E1	0	1	0	0	1		e1
mu-neutrino	n2	N2	0	1	0	0	1		n2
muon	e2	E2	0	1	Mm	0	1		e2
tau-neutrino	n3	N3	0	1	0	0	1		n3
tau-lepton	e3	E3	0	1	Ml	0	1		e3
u-quark	u	U	2	1	0	0	3		u
d-quark	d	D	1	1	0	0	3		d
c-quark	c	C	4	1	Mc	0	3		c
s-quark	s	S	3	1	Ms	0	3		s
t-quark	t	T	6	1	Mt	wtop	3		t
b-quark	b	B	5	1	Mb	0	3		b
tp-quark	tp	Tp	0	1	Mtp	wtp	3		tp
u-todd	~u	~U	0	1	Muo	wtq	3		(u)
d-todd	~d	~D	0	1	Mdo	wtq	3		(d)
c-todd	~c	~C	0	1	Muo	wtq	3		(c)
s-todd	~s	~S	0	1	Mdo	wtq	3		(s)
b-todd	~b	~B	0	1	Mdo	wtq	3		(b)
T2-todd	~t2	~T2	2000006	1	Mt2	wt2	3		(t2)
T1-todd	~t1	~T1	1000006	1	Mt1	wt1	3		(t1)

F1 F2 Xgoto Ygoto Find Write

LHT implementation using LanHEP(5)

CalcHEP/symb

Lagrangian 51

Clr Del Size Read ErrMes

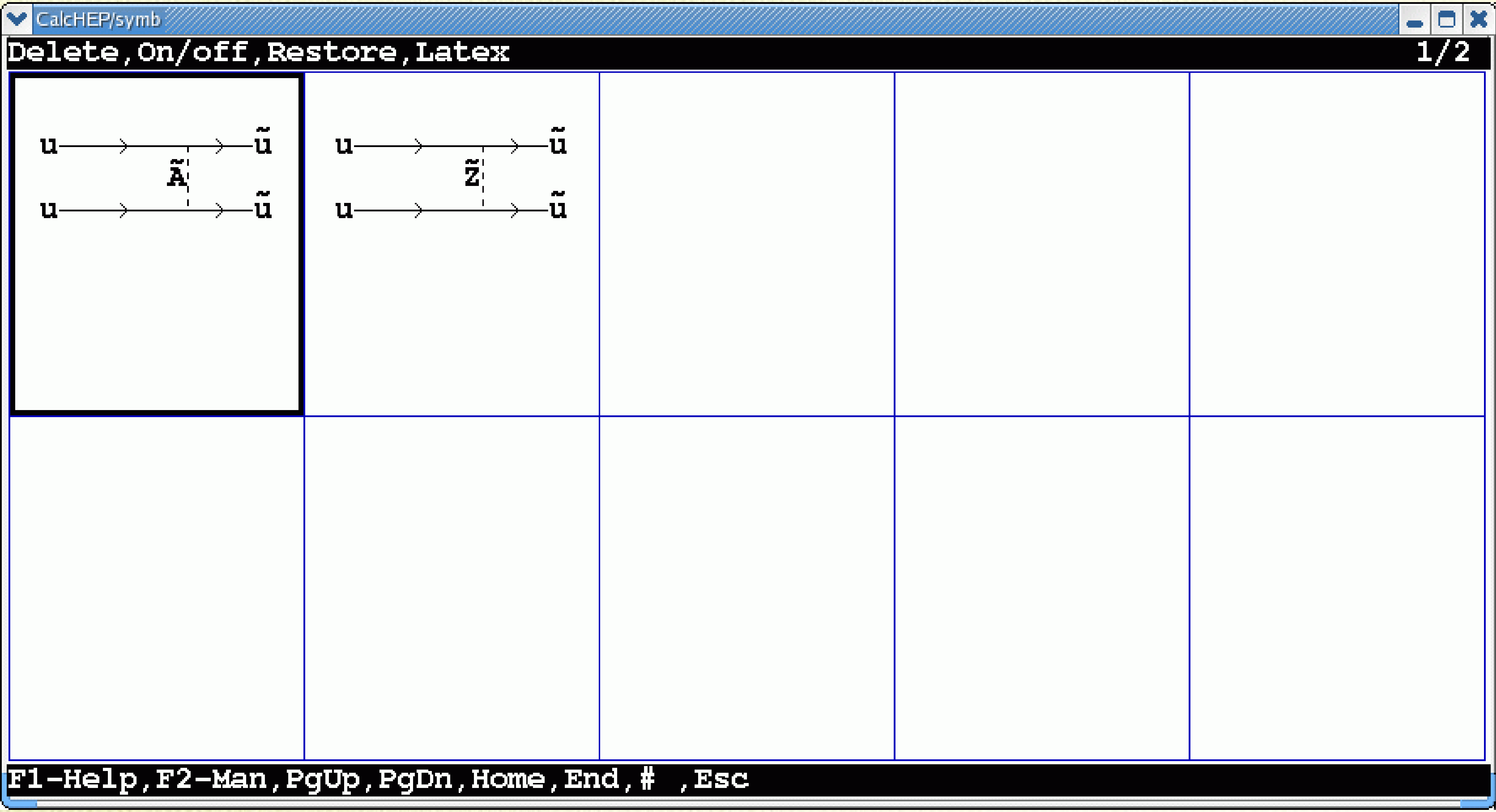
P1	P2	P3	P4	> Factor <	> dLagrangian/ dA(p1) dA(p2) dA(p3)
D	u	W-		EE*Sqrt2/(4*SW)	G(m3)*(1-G5)
D	~d	~A		EE/(20*CW*SW)	-SW*G(m3)*(1-G5)+5*del^2*CW*xh*(1-G5)*G(m3)
D	~d	~Z		EE/(20*CW*SW)	5*CW*G(m3)*(1-G5)+del^2*SW*xh*(1-G5)*G(m3)
D	~u	~W-		-EE*Sqrt2/(4*SW)	G(m3)*(1-G5)
E1	e1	A		-EE	G(m3)
E1	e1	Z		-EE/(4*CW*SW)	(1-2*SW^2)*G(m3)*(1-G5)-2*SW^2*G(m3)*(1+G5)
E1	n1	W-		EE*Sqrt2/(4*SW)	G(m3)*(1-G5)
E2	e2	A		-EE	G(m3)
E2	e2	H		-Mm/v	1
E2	e2	Z		-EE/(4*CW*SW)	(1-2*SW^2)*G(m3)*(1-G5)-2*SW^2*G(m3)*(1+G5)
E2	n2	W-		EE*Sqrt2/(4*SW)	G(m3)*(1-G5)
E3	e3	A		-EE	G(m3)
E3	e3	H		-Ml/v	1
E3	e3	Z		-EE/(4*CW*SW)	(1-2*SW^2)*G(m3)*(1-G5)-2*SW^2*G(m3)*(1+G5)
E3	n3	W-		EE*Sqrt2/(4*SW)	G(m3)*(1-G5)
G	G	G		GG	m2.p3*m1.m3-m1.p3*m2.m3+m3.p1*m1.m2-m2.p1*m1.m3-m3
G.C	G.c	G		GG	m3.p2
H	H	H		4*lamh4*vh	1
H	W+	W-		EE^2*vh/(2*SW^2)	m2.m3
H	Z	Z		EE^2*vh/(2*CW^2*SW^2)	m2.m3
H	~A	~A		-EE^2*vh/(2*CW^2*SW^2)	SW^2*m2.m3+(zero0*CW^2*xh^2*m2.m3+2*del^2*SW*CW*xh

F1 F2 Xgoto Ygoto Find Write

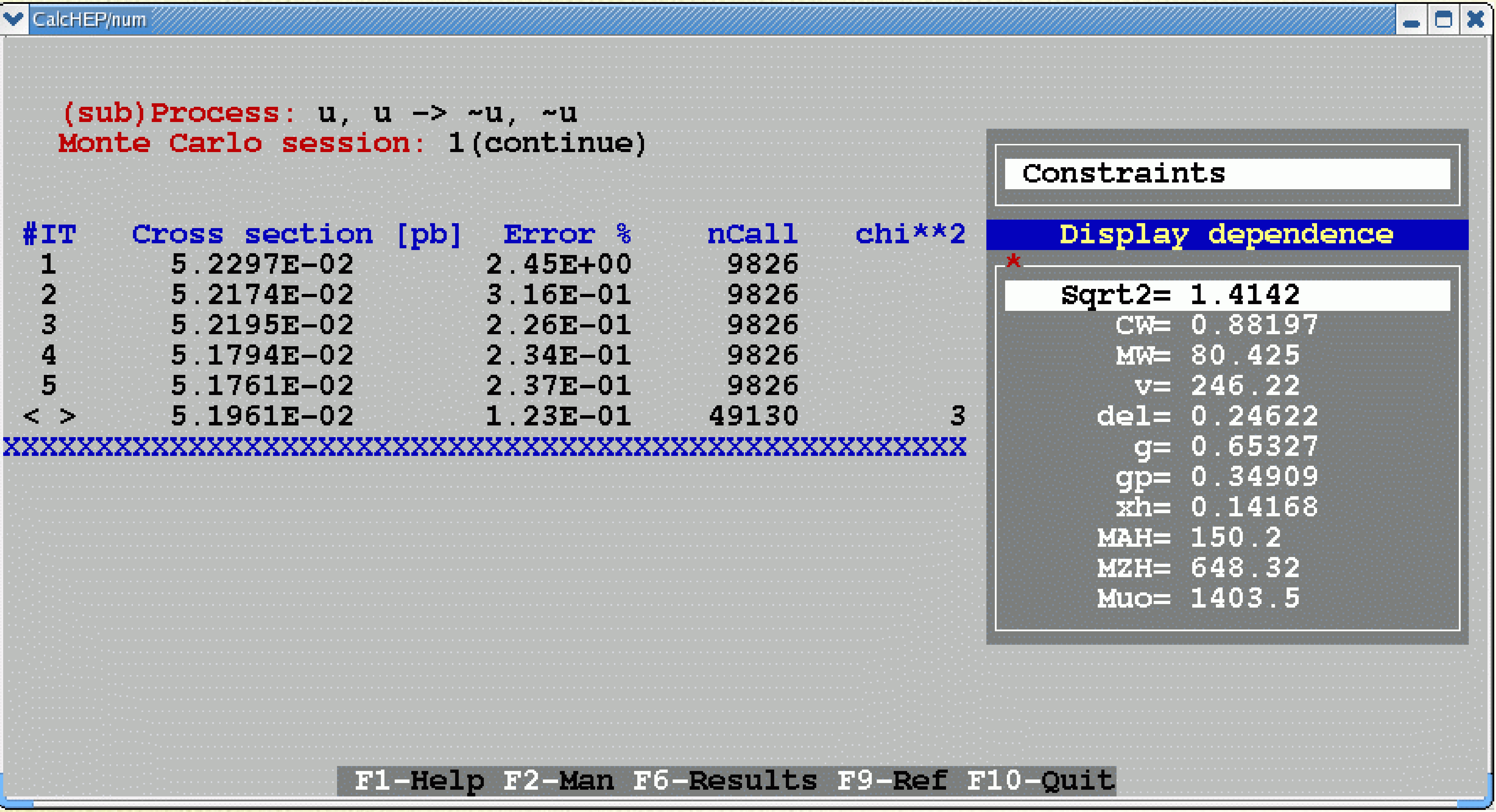
LHT implementation using LanHEP(6)

```
CalcHEP/symb

      Model:  Littlest Higgs-T

            List of particles (antiparticles)

 W+(W- )- W boson          ~W+(~W-)- W heavy          A(A  )- photon
 Z(Z  )- Z boson           ~A(~A )- photon heavy      ~Z(~Z )- Z heavy
 G(G  )- gluon             H(H  )- H  higgs           ~P0     - P0  higgs
 ~PS     - pp higgs        ~P+(~P-)- p+  higgs        ~++(~--)- p++  higgs
 n1(N1 )- neutrino         e1(E1 )- electron          n2(N2 )- mu-neutrino
 e2(E2 )- muon             n3(N3 )- tau-neutrino      e3(E3 )- tau-lepton
 u(U  )- u-quark           d(D  )- d-quark            c(C  )- c-quark
 s(S  )- s-quark           t(T  )- t-quark            b(B  )- b-quark
 tp(Tp )- tp-quark         ~u(~U )- u-todd            ~d(~D )- d-todd
 ~c(~C )- c-todd           ~s(~S )- s-todd            ~b(~B )- b-todd
 ~t2(~T2)- T2-todd         ~t1(~T1)- T1-todd

Enter  process: u,u ->~u,~u
```

LHT implementation using LanHEP(7)



LHT implementation using LanHEP(8)

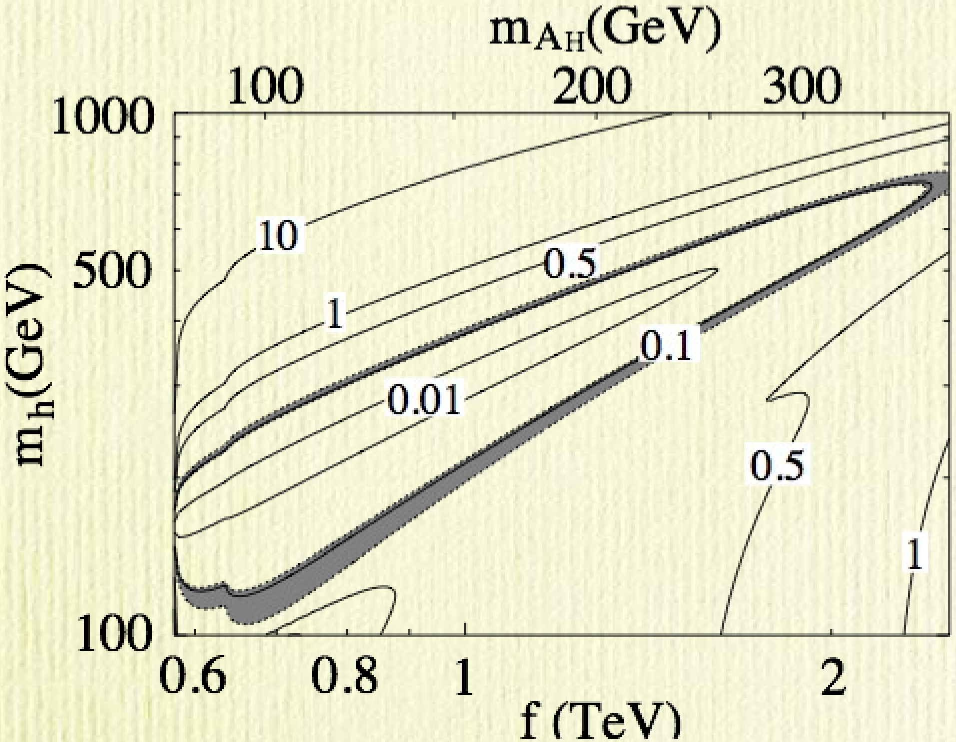


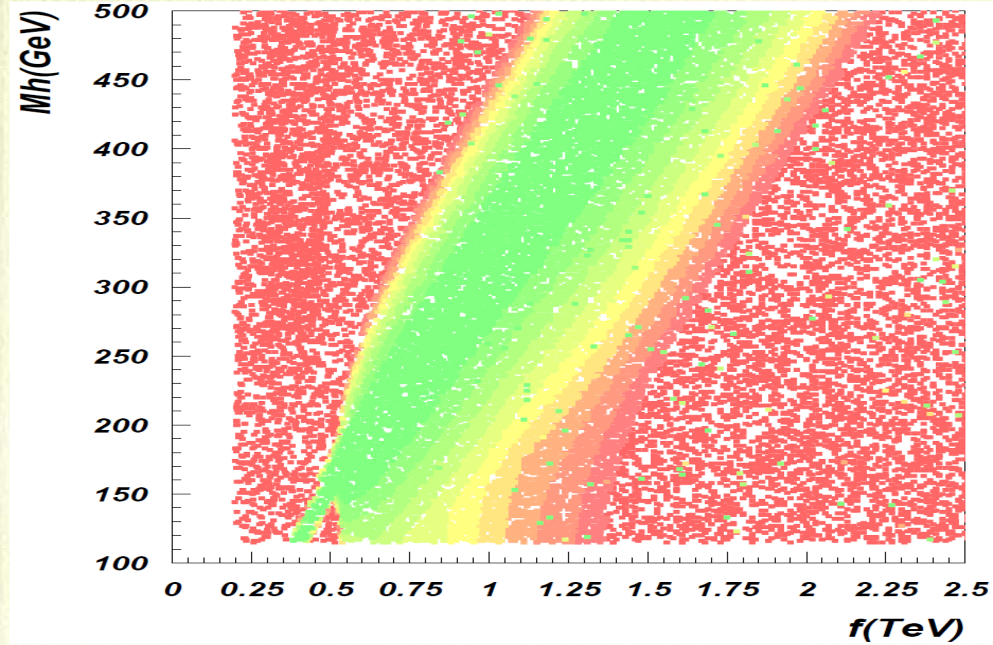
LHT: relic density abundance results

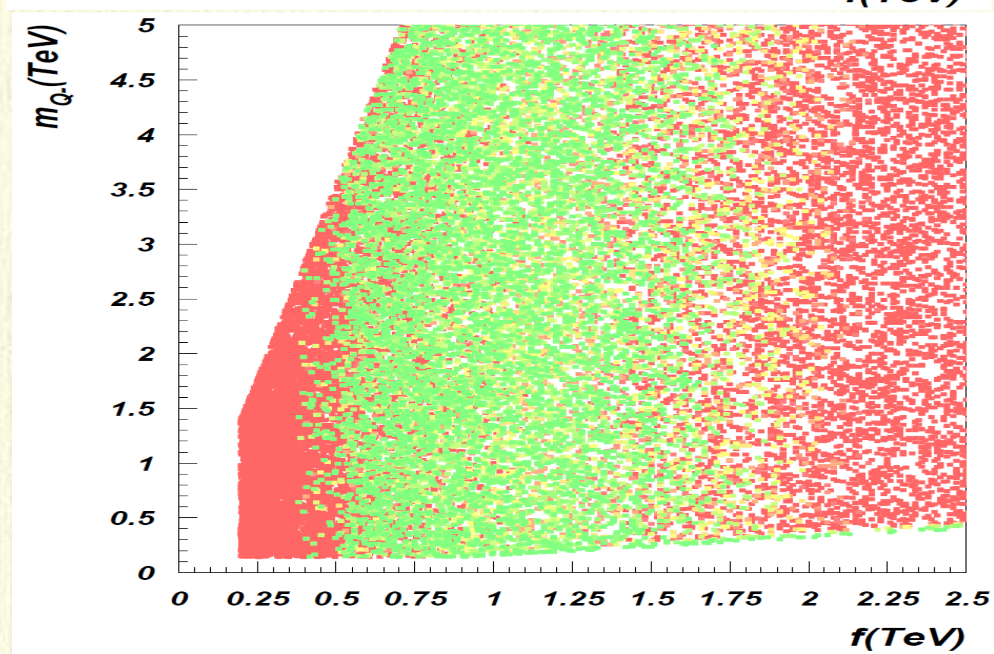
$0.094 < \Omega h^2 < 0.129$

A.B, A. Pukhov (preliminary)

Asano, Matsumoto, Okada, Okada, hep-ph/0602157



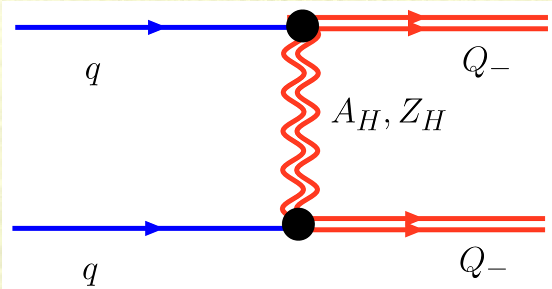




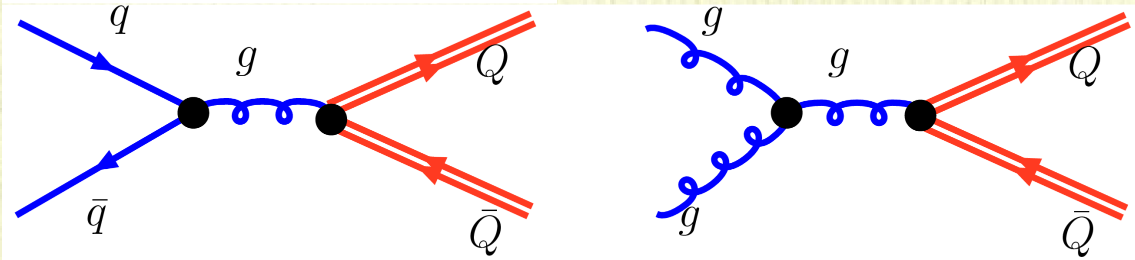
Model parameters:

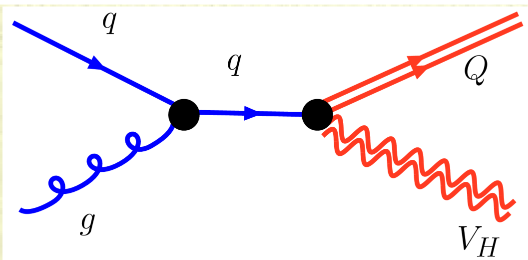
$$f, \quad M_h, \quad \sin\alpha, \quad \kappa$$

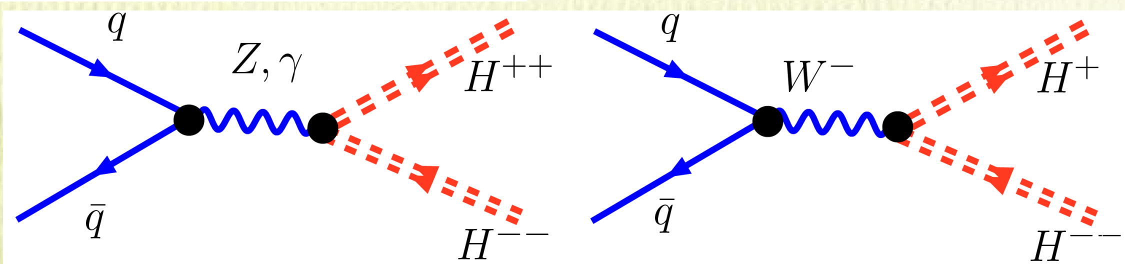
LHT: processes

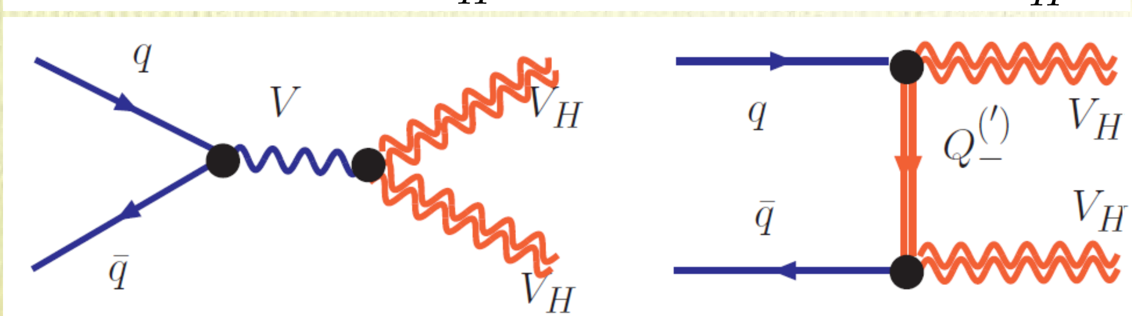


like-sign leptons!



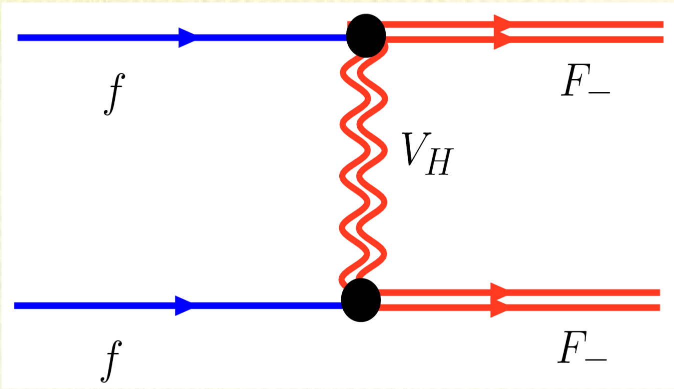


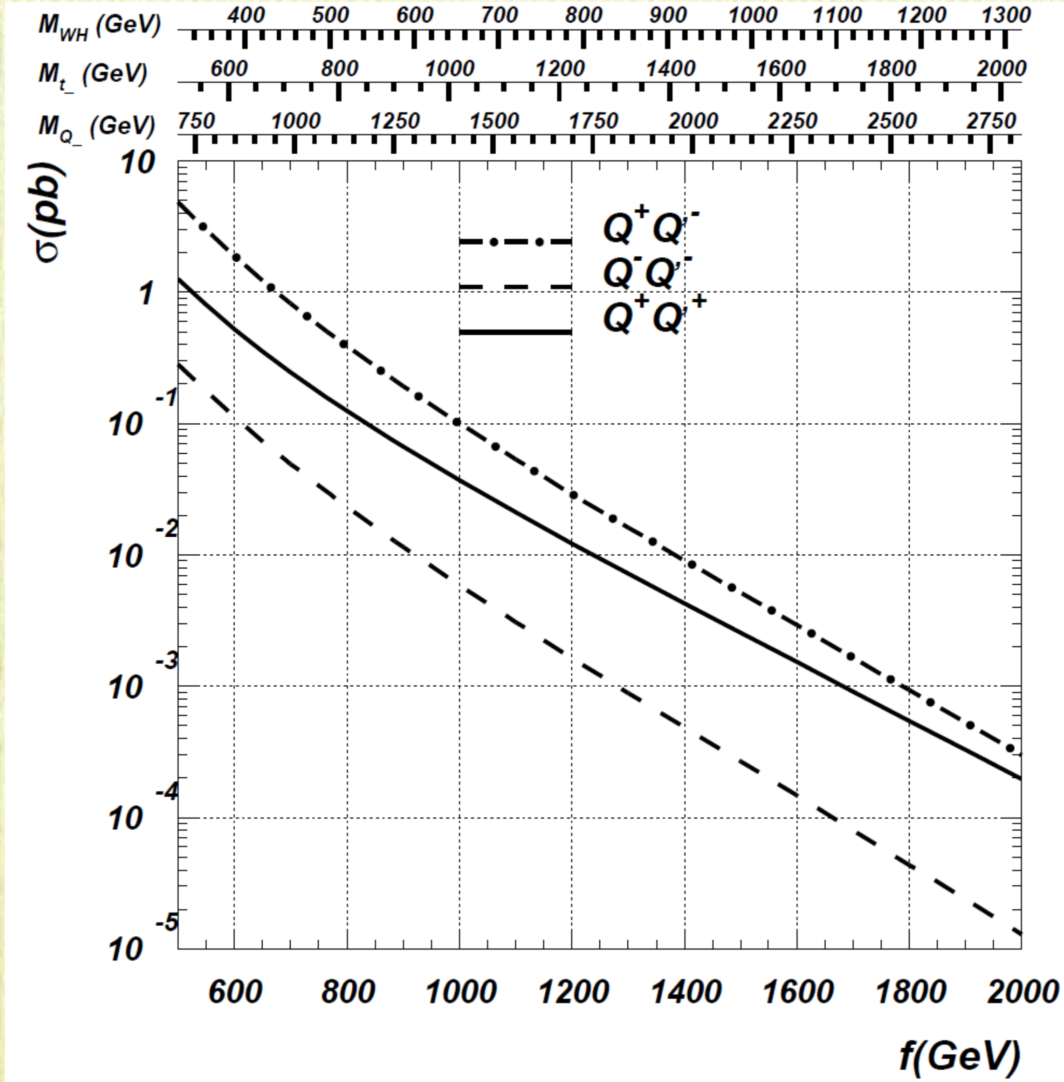




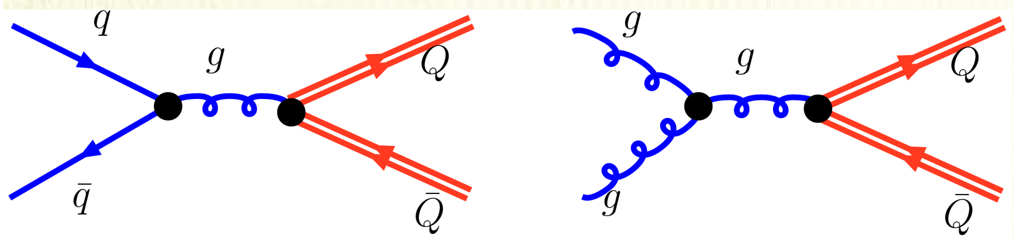
Heavy quarks production rates and signatures

$$\sin\alpha = 1/\sqrt{2}\ \ (\lambda_1 = \lambda_2), \kappa = 1$$

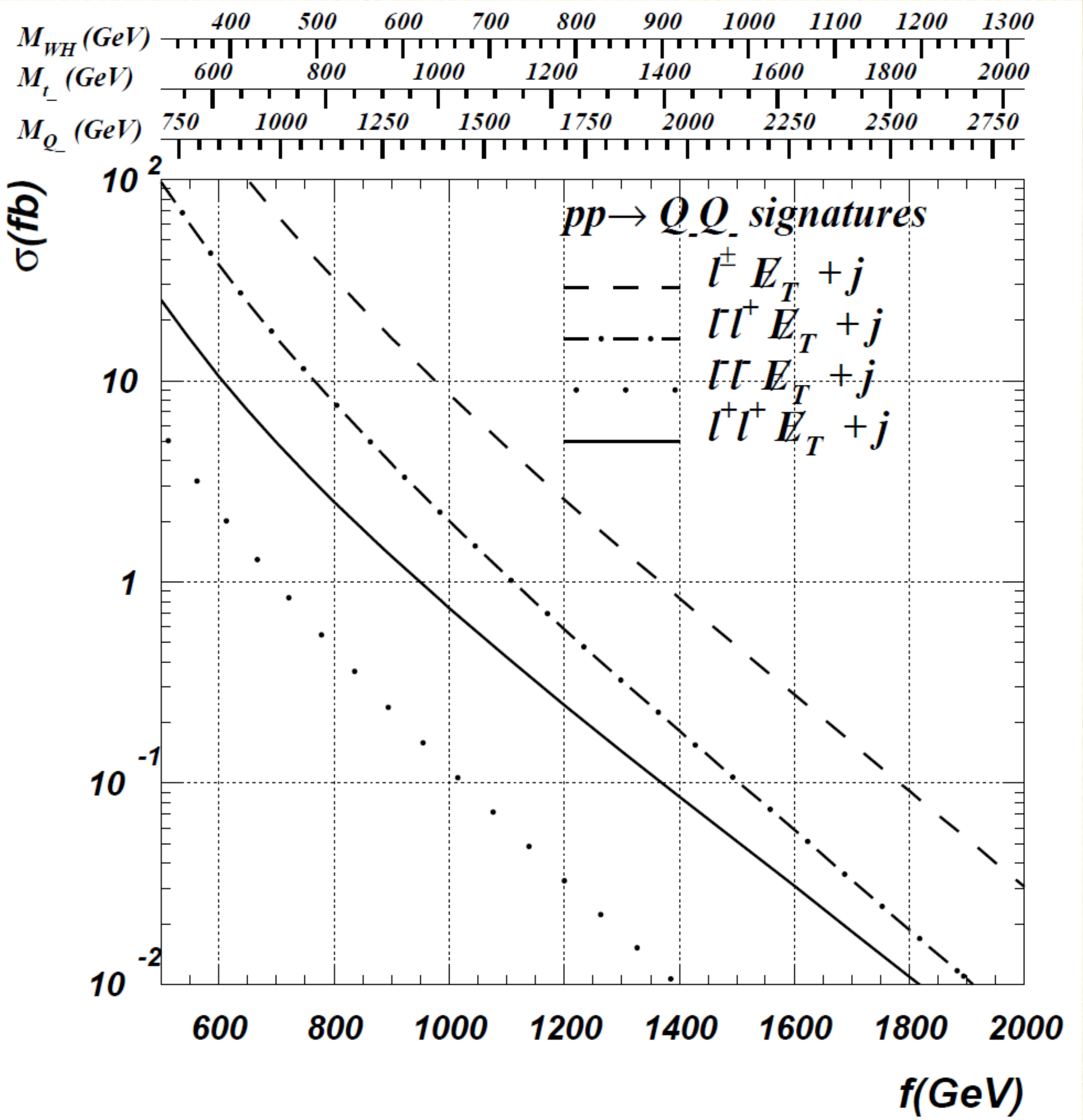


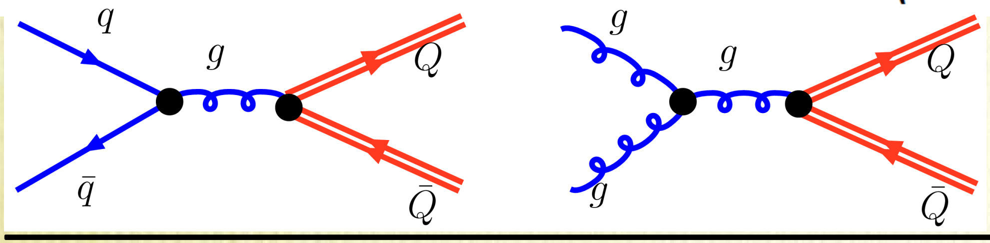


EW production due to the initial double valence quarks leads to like sign lepton signature (LSL), it is comparable to strong production and becomes even more important for heavier masses due to parton luminosity behavior!



Heavy quarks production rates and signatures





$$\lambda_1 = \lambda_2 = 1$$
$$f = 1\,TeV, \quad \kappa = 1$$
$$Br(Q \to W_H q') = 0.62$$
$$Br(W_H \to W A_H) = 1$$

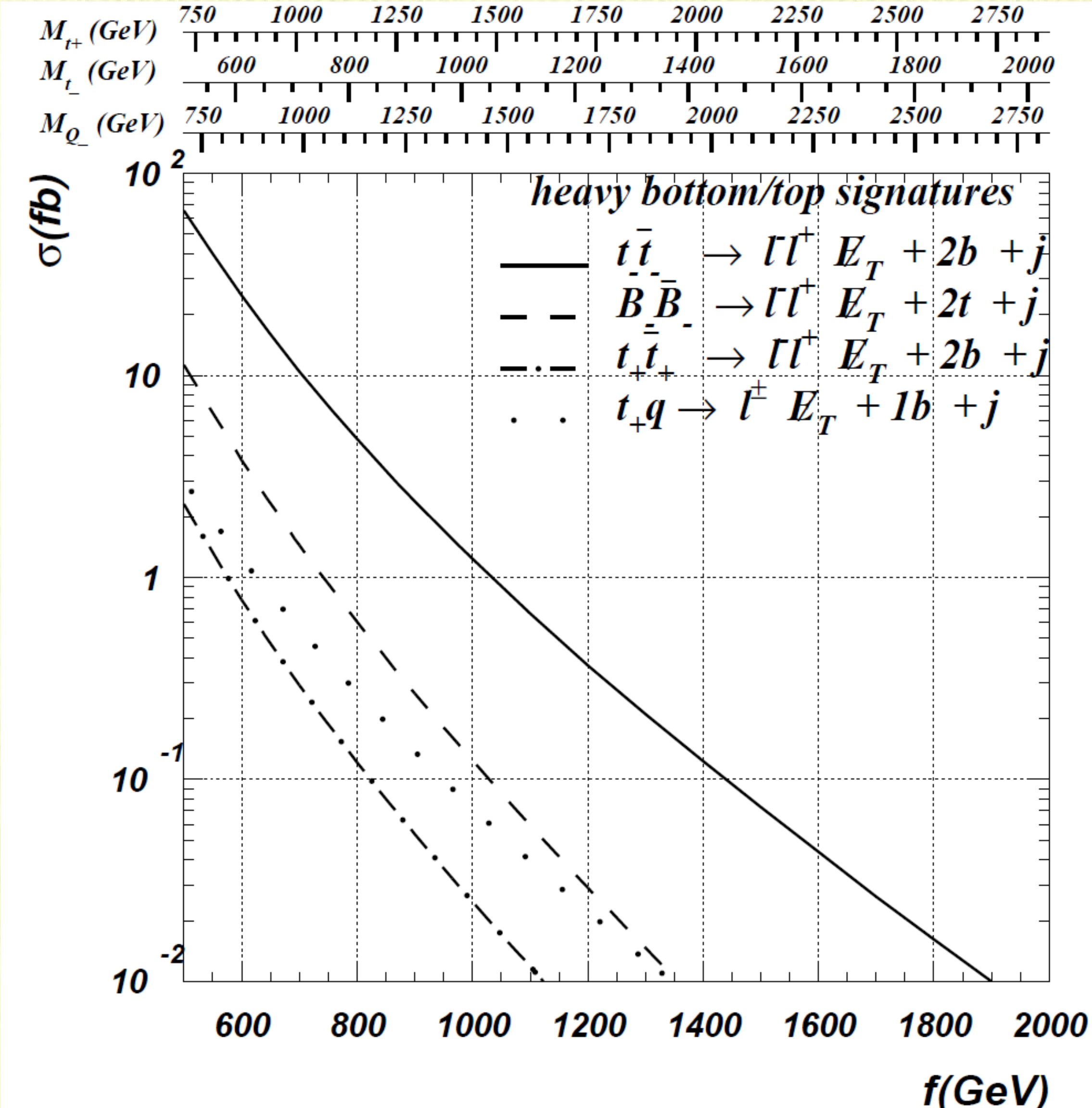
Like-sign lepton signature (LSL)

$$qq \longrightarrow QQ$$
$$(Q \to W_H^+ q') \to W_H^+ W_H^+ q' q'$$

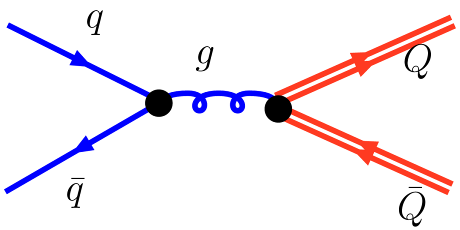
Opposite sign lepton signature and 1-lepton signature (1L)

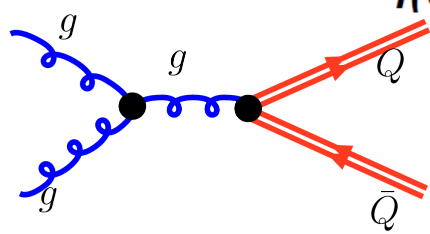
$$q\bar{q}(gg) \to Q\bar{Q} \to W_H^+ W_H^- q' \bar{q}'$$

Heavy top/bottom production rates and signatures



$$f = 1\ TeV, \quad \kappa = 1$$
$$Br(T \to W_H b) = 0.62$$
$$Br(B \to W_H t) = 0.62$$
$$Br(t_- \to A_H t) = 1$$
$$Br(t_+ \to W b) = 0.44$$
$$Br(t_+ \to H t) = 0.19$$
$$Br(t_+ \to Z t) = 0.21$$
$$Br(t_+ \to A_H t_-) = 0.16$$





OSL + 2b (2t) signature

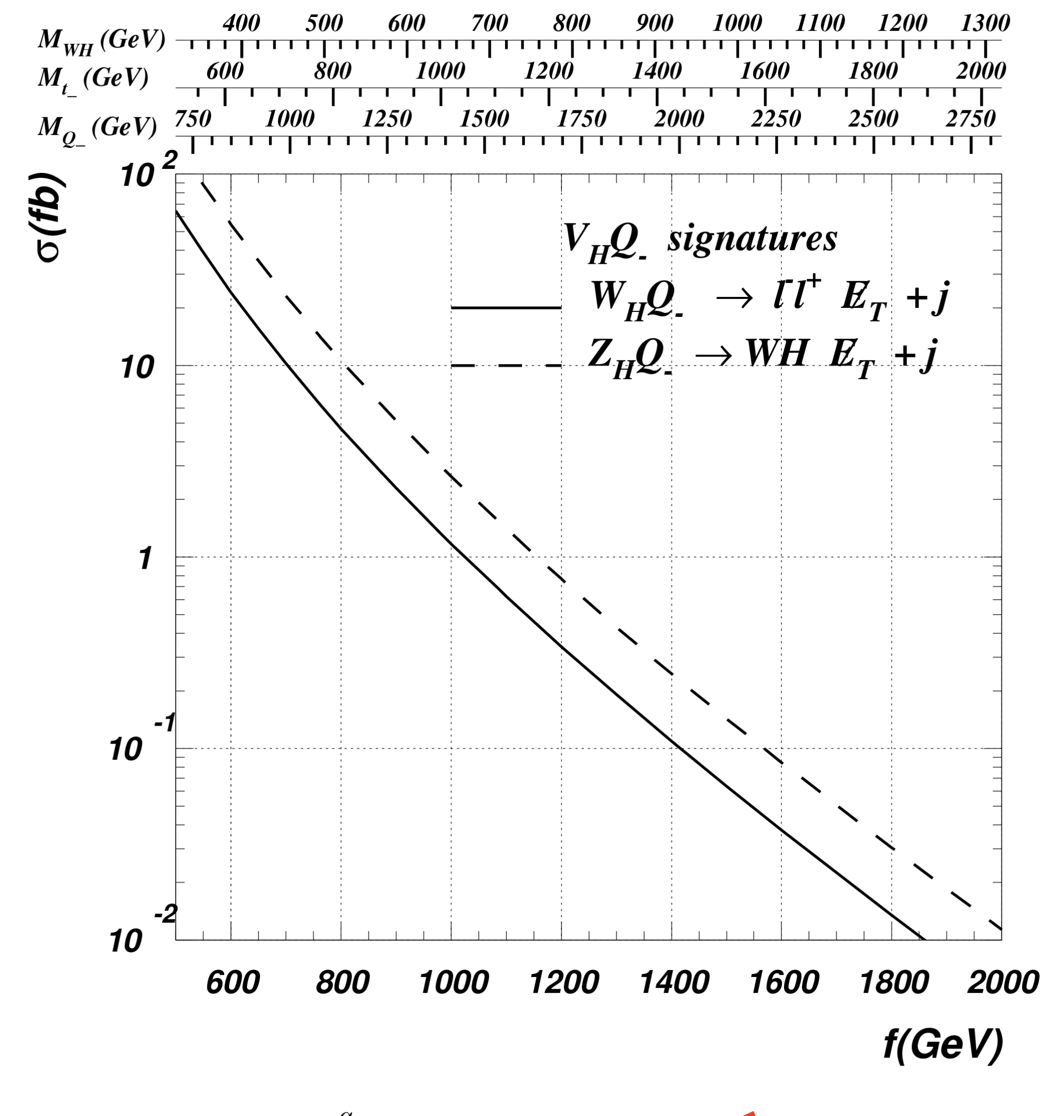
$$q\bar{q}(gg) \to T\bar{T} \to W_H^+ W_H^- b\bar{b}$$

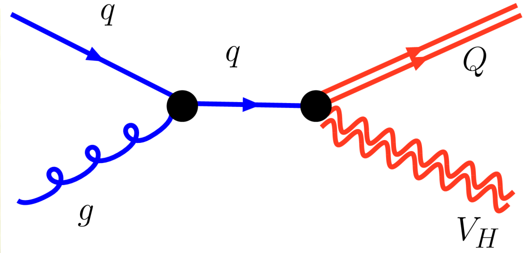
$$q\bar{q}(gg) \to B\bar{B} \to W_H^+ W_H^- t\bar{t}$$

Single top 1L + 1b signature

$$bq \to t_+ q \to W_H bq$$

Heavy quark-vector boson associate production





$$f = 1\ TeV, \quad \kappa = 1$$
$$Br(Q \to W_H q') = 0.62$$
$$Br(W_H \to A_H W) = 1.0$$
$$Br(Z_H \to A_H H) = 1.0$$

OSL, 1L signatures

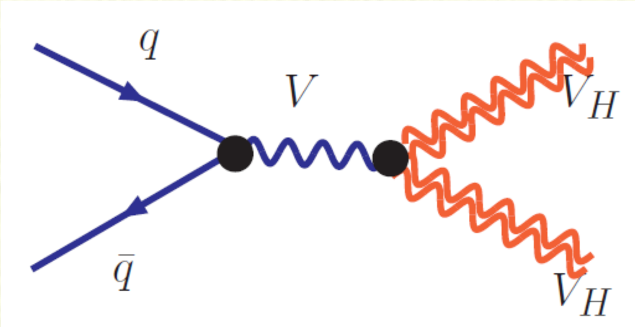
$$qg \to Q_- W_H \to W_H W_H q'$$

Indirect Higgs production as a result of cascade decays

$$qg \to Q_- Z_H \to W_H Z_H q' \to W q' A_H A_H H$$

$$M_H = 120\ GeV$$

Heavy vector boson pair production



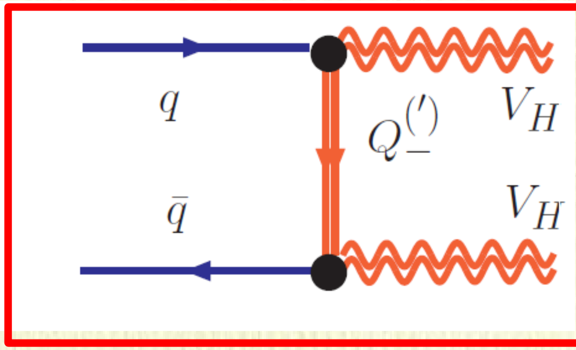
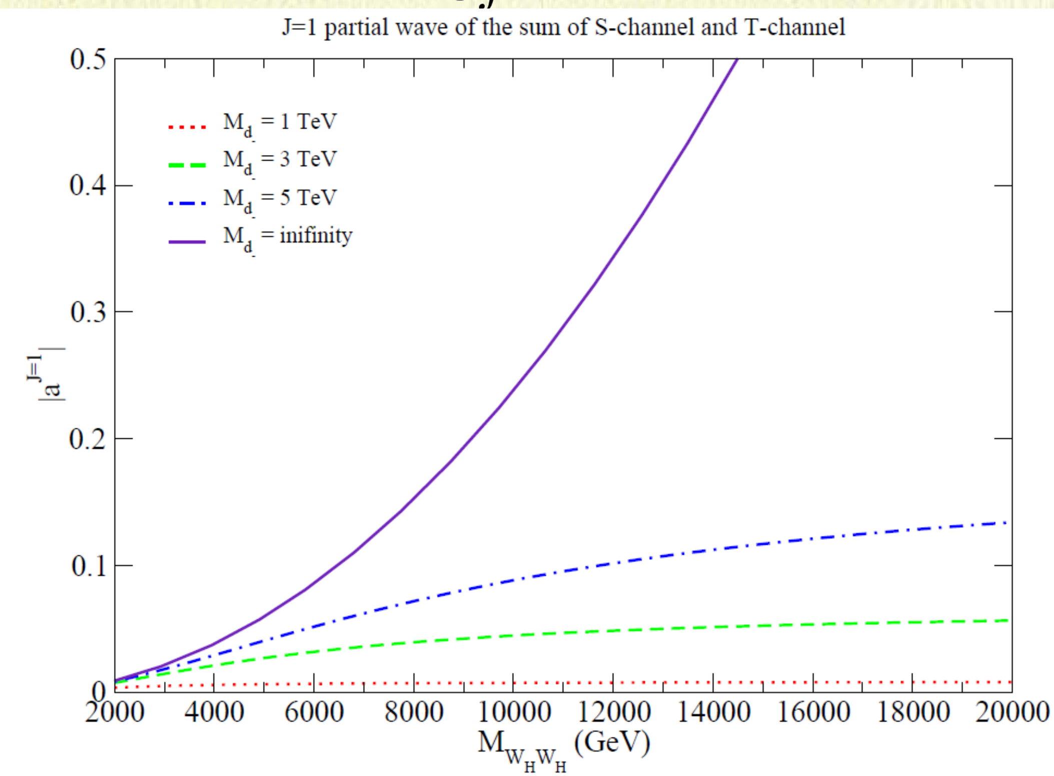
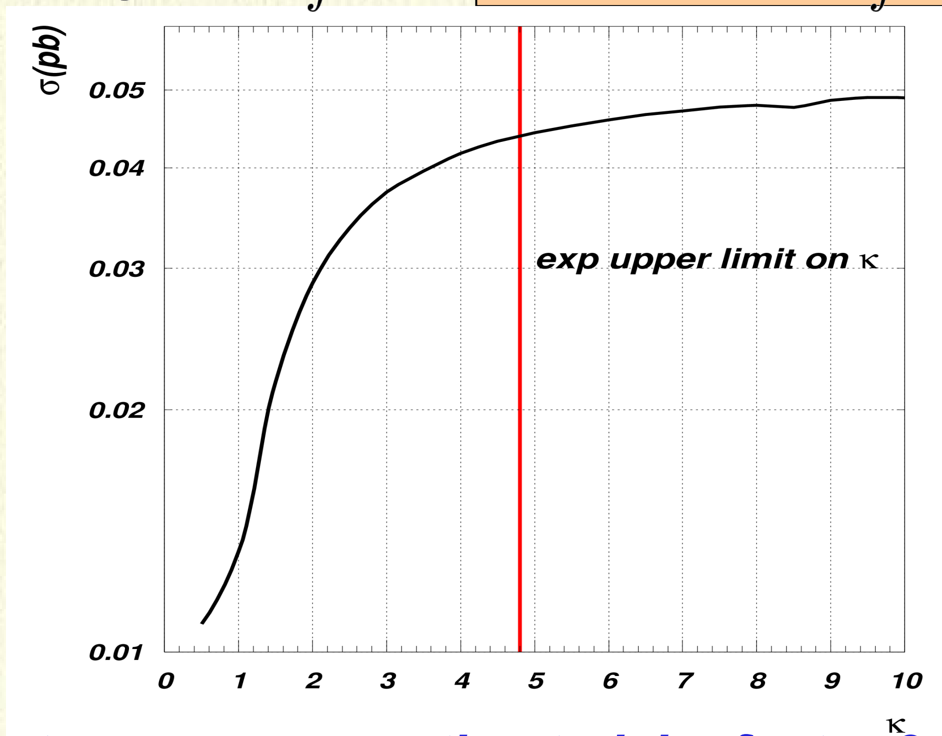


diagram was neglected in previous studies, but crucial for the correct rate prediction, gauge invariance and unitarity

There is no decoupling (Hubisz et all) $M_Q < 4.8(f^2/1\ TeV)^2 TeV, M_Q = \sqrt{2}\kappa f$

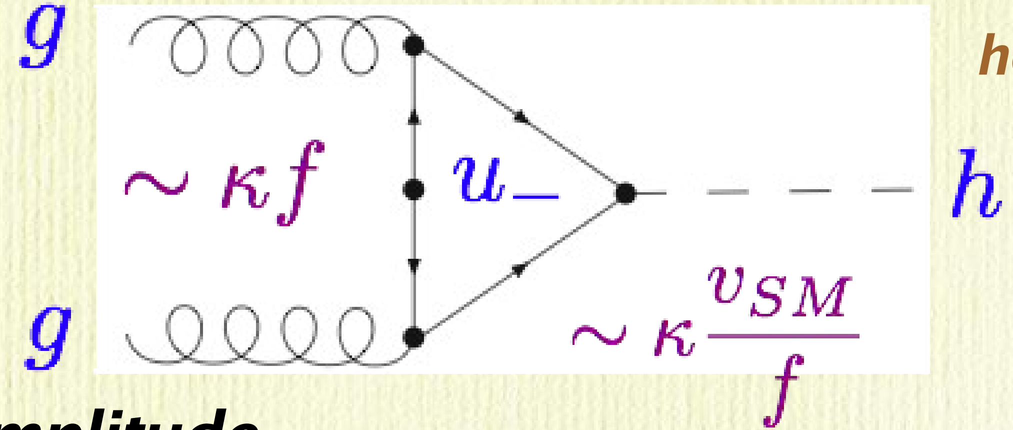
$$A^\gamma(-+) = -\frac{s_W^2 \sin\theta}{3f^2}s, \quad A^Z(-+) = -(1-\frac{4}{3}s_W^2)\frac{\sin\theta}{4f^2}s, \quad A^{d-}(-+) = \frac{\sin\theta}{4f^2}s$$





rates were overestimated by factor 2-5

Important T-odd fermion contribution to Higgs production via gluon-gluon fusion



hep-ph/0602211 Chen, Tobe, Yuan

Amplitude

$$A(\text{T odd fermins}) \propto m_{u_-}\; g_{hu_-u_-} \frac{1}{m_{u_-}^2} \sim \frac{v_{SM}}{f^2}$$

no κ dependence!

<u>(Once f is fixed, the T-odd fermion can not decouple.)</u>

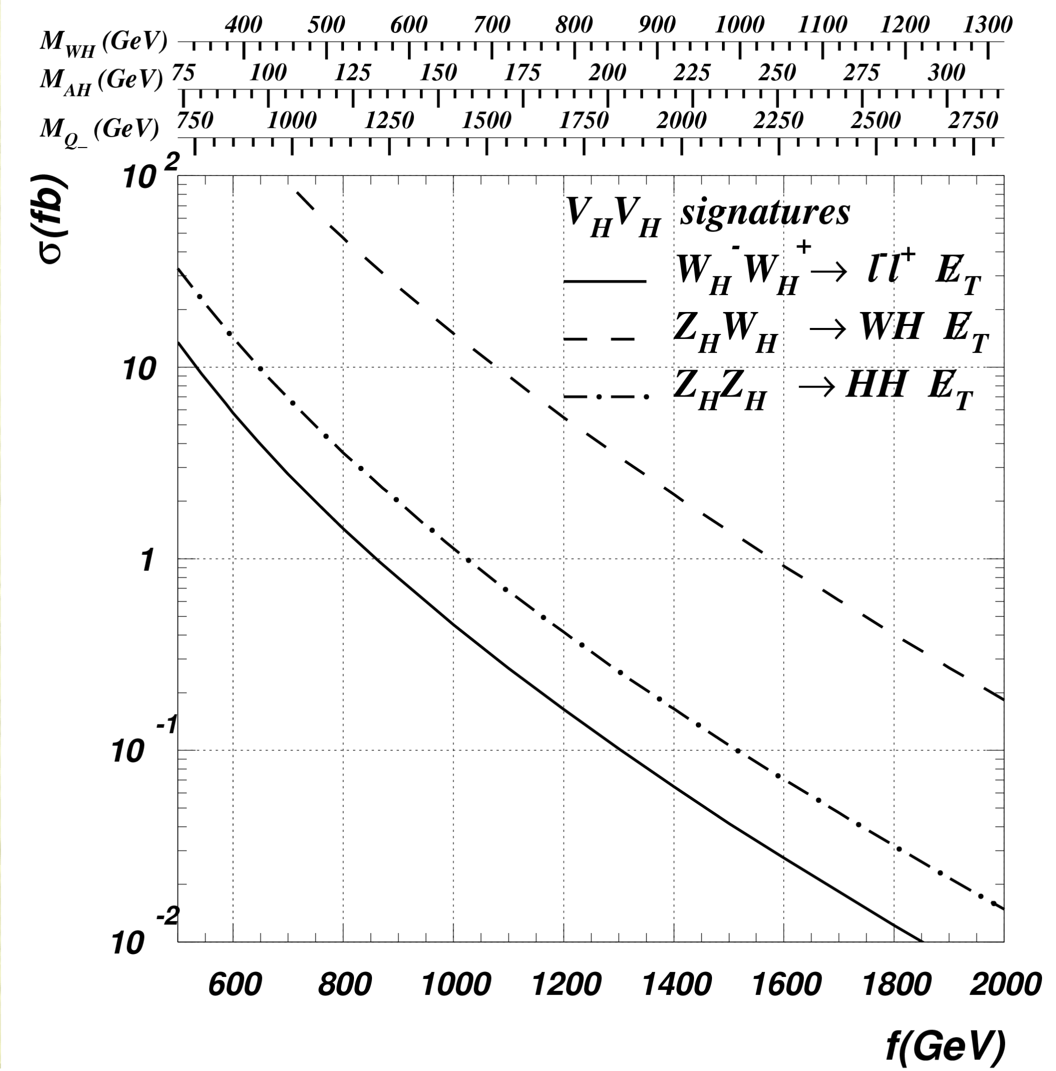
Correction to the cross section

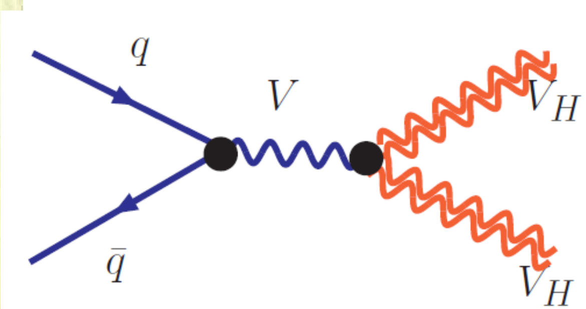
$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \simeq -\left(\frac{3}{2}+\frac{3}{2}\right)\frac{v_{SM}^2}{f^2} \simeq \begin{cases} -37\% \text{ for } f = 700 \text{ GeV}, \\ -18\% \text{ for } f = 1000 \text{ GeV}. \end{cases}$$

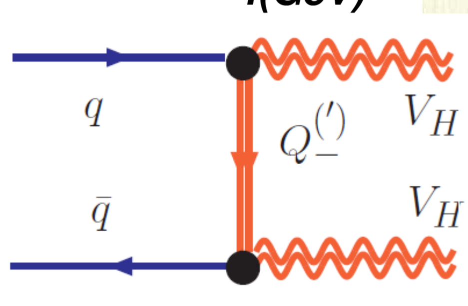
for $m_H < 2m_t$

top sector ↗ ↖ ***T-odd fermions***

Heavy vector boson pair production







$$f = 1\ TeV, \quad \kappa = 1$$
$$Br(Q \to W_H q') = 0.62$$
$$Br(W_H \to A_H W) = 1.0$$
$$Br(Z_H \to A_H H) = 1.0$$

OSL, 1L signatures

$$W_H^+ W_H^- \to W^+ A_H W^- A_H$$

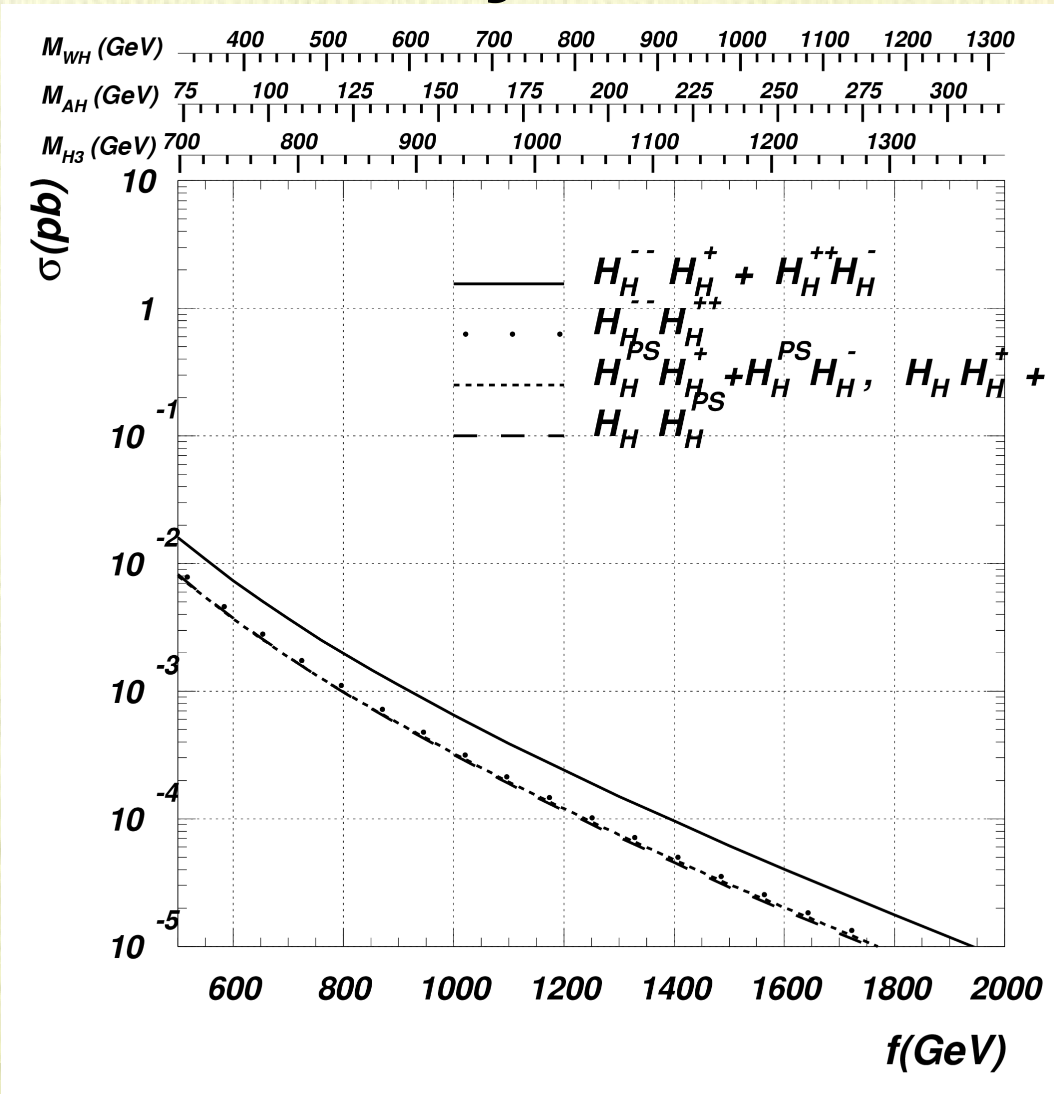
Associate Higgs production

$$Z_H W_H \to H W A_H A_H$$

Higgs pair production

$$Z_H Z_H \to H H A_H A_H$$

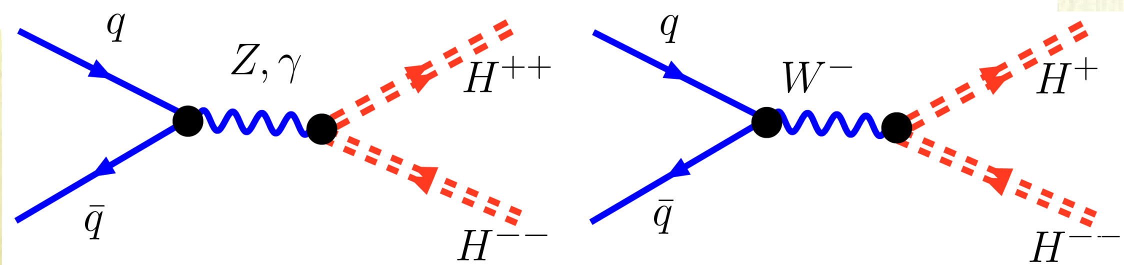
Heavy scalar boson pair production



$$Br(H^+ \to A_H W^+) = 1$$

$$q\bar{q} \to H^{++}H^{--}$$
$$q\bar{q}' \to H^{++}H^{-}$$

Study of 3-body tree-level decays for Heavy Higgs bosons is needed!



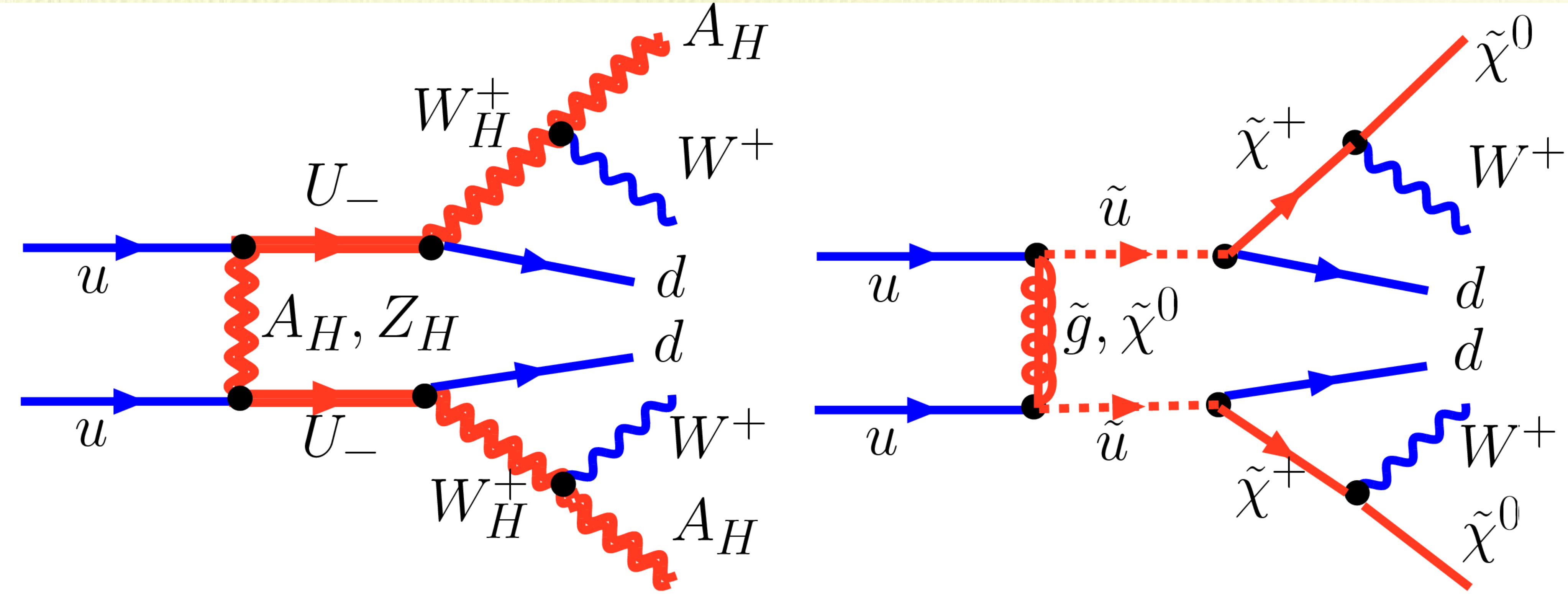
The signal observability

- CalcHEP – PYTHIA interface is crucial for further analysis beyond the parton level
- PYTHIA allows now to include new particles and their decay in easy fashion

(thanks to Peter Skands and Sasha Pukhov)

```
BLOCK QNUMBERS 90024 # WH+
    1    3  # 3 times electric charge
    2    3  # number of spin states (2S+1)
    3    1  # colour rep (1: singlet, 3: triplet, 8: octet)
    4    1  # Particle/Antiparticle distinction (0=own anti)
BLOCK MASS  # Mass Spectrum
    90024   5.000000E+02  # WH+
DECAY   90024      1.000000E+00 # WH+ width
    1.0000E-00    2       24       90022 # Br(WH -> W+ AH)
```

Lets look at LHT vs SUSY cascade decays

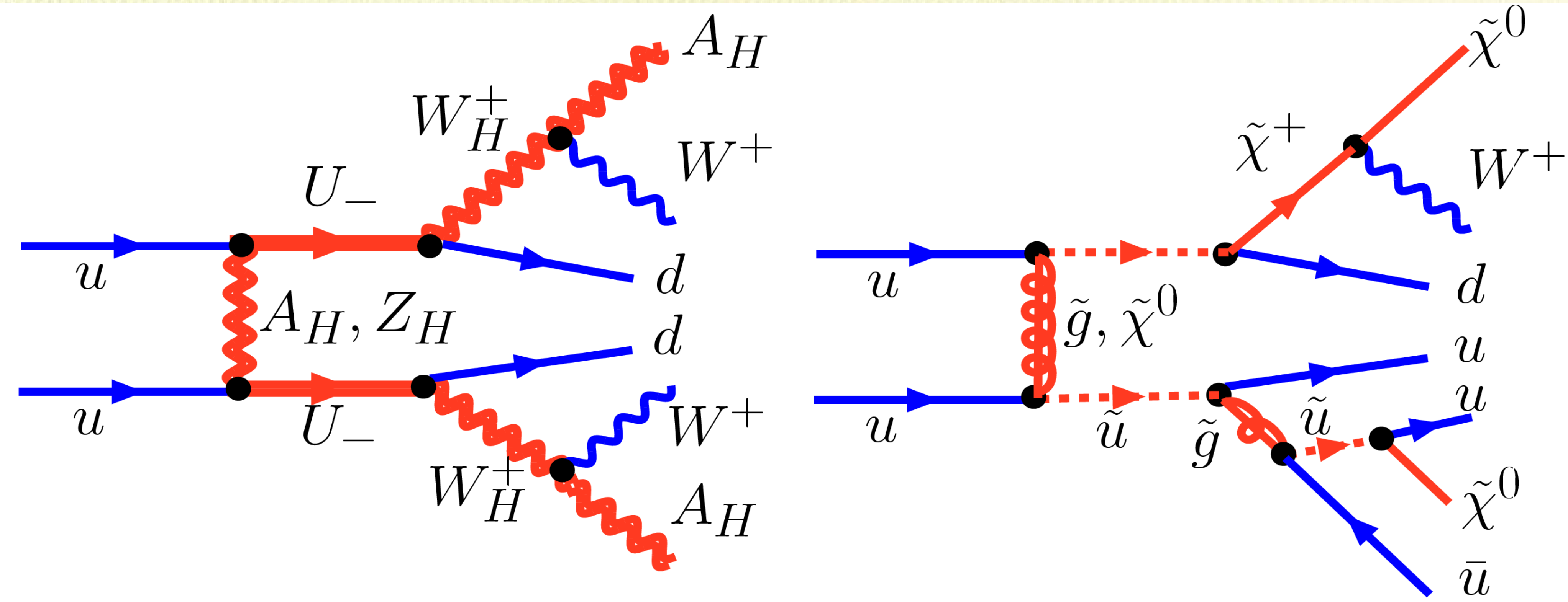


- **Both, SUSY and LHT could give the same signature pattern**

$\lambda_1 = \lambda_2 = 1$
$f = 1\ TeV, \quad \kappa = 1$
$Br(Q \to W_H q') = 0.62$
$Br(W_H \to W A_H) = 1$

- **One should look closely: various decay channels, spin correlations, couplings**

Lets look at LHT vs SUSY cascade decays



- **Gluon has no partner in LHT model!**

$$\lambda_1 = \lambda_2 = 1$$
$$f = 1\ TeV, \quad \kappa = 1$$
$$Br(Q \to W_H q') = 0.62$$
$$Br(W_H \to W A_H) = 1$$

- **Study of spins and couplings is quite a challenge at the LHC**

Conclusions

- **LHT model is well motivated and leads to an exciting phenomenology at the LHC**
- **The complete LHT model has been implemented into CalcHEP, independent implementation was important!**
- **New results**
  - ***all relevant LHC signatures are classified***
  - ***κ – term quark production has been suggested***
  - ***new signatures, including LSL has been pointed out***
  - ***Importance of non-decoupling effects: especially for heavy boson pair and higgs boson production***
- **CalcHEP-PYTHIA interface: understanding the signal observability and including spin correlations is important**
- **Relic density abundance has been evaluated for the complete model with MicroMEGAs - important constraint**

LHT Model: Yukawa interactions

$$-\frac{\lambda_1}{2\sqrt{2}} f \epsilon_{ijk}\epsilon_{xy}\left[(\bar{Q}_1)_i\Sigma_{jx}\Sigma_{ky} - (\bar{Q}_2\Sigma_0)_i\tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right] u_{R_+}$$

$$-\lambda_2 f(\bar{U}_{L_1}U_{R_1} + \bar{U}_{L_2}U_{R_2}) + \text{h.c.},$$

with $Q_1 = (q_1, U_{L_1}, 0_2)^T$ **and** $Q_2 = (0_2, U_{L_2}, q_2)^T$

giving $t,\ t_+,\ \ t_-$ with $\sin\alpha = \lambda_1/\sqrt{\lambda_1^2+\lambda_2^2}$

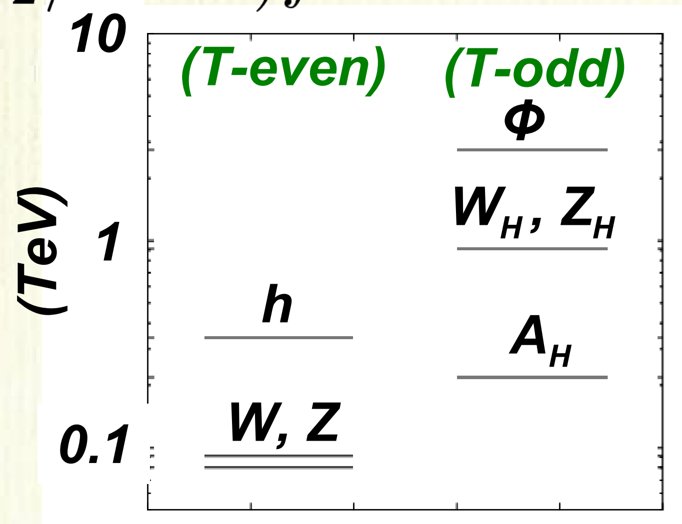
$M_t \simeq (\lambda_2 \sin\alpha)v,\quad M_{t_-} \simeq \lambda_2 f,\quad M_{t_+} \simeq (\lambda_2/\cos\alpha)f$

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

fermion $SU(2)$ **doublets** q_1 **and** q_2**:**

$\Psi_1 = (q_1, 0, 0_2)^T$ **and** $\Psi_1 = (0_2, 0, q_2)^T$

giving U_-**,** D_-**, with** $M_{Q_-} = \sqrt{2}\kappa f$



SUSY LHwTP dictionary

squarks, sleptons	⟷	mirror fermions
gauginos	⟷	heavy gauge bosons
2 Higgs	⟷	scalar triplet
gluino	⟷	NONE
NONE	⟷	Singlet quarks