Phenomenology of Little Higgs Model with T-parity with CalcHEP

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OUTLINE

- Little Higgs model with T-parity (LHT)
- Implementation of the complete model
- LanHEP → CalcHEP → PYTHIA chain
- Phenomenology of LHT model
  - *Direct production rates*
  - *Decay branchings*
  - *Promising signatures*
- Conclusions

Problems of the Standard Model

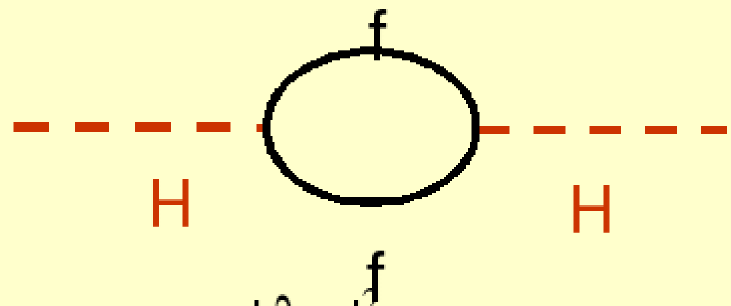
- Problem of large quantum corrections to the Higgs mass in SM (Hierarchy problem)
- Coupling Unification
- The origin of Electroweak Symmetry breaking.

  Higgs boson is not found yet

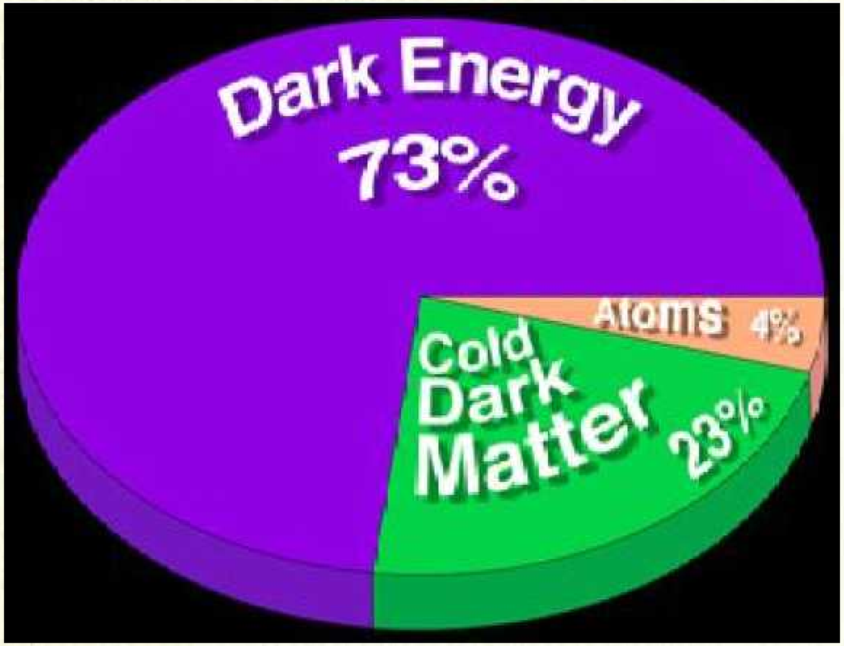
  ...
- The origin and Nature of

  Dark Matter and Dark Energy

  No explanation within SM ...
- Baryogenesis problem



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



Little Higgs Model as alternative to SUSY

Little Higgs scenario

New-Physics < 10TeV + EW ~ 0.1 TeV

Special arrangement for the cancellation of Λ^2 at 1-loop

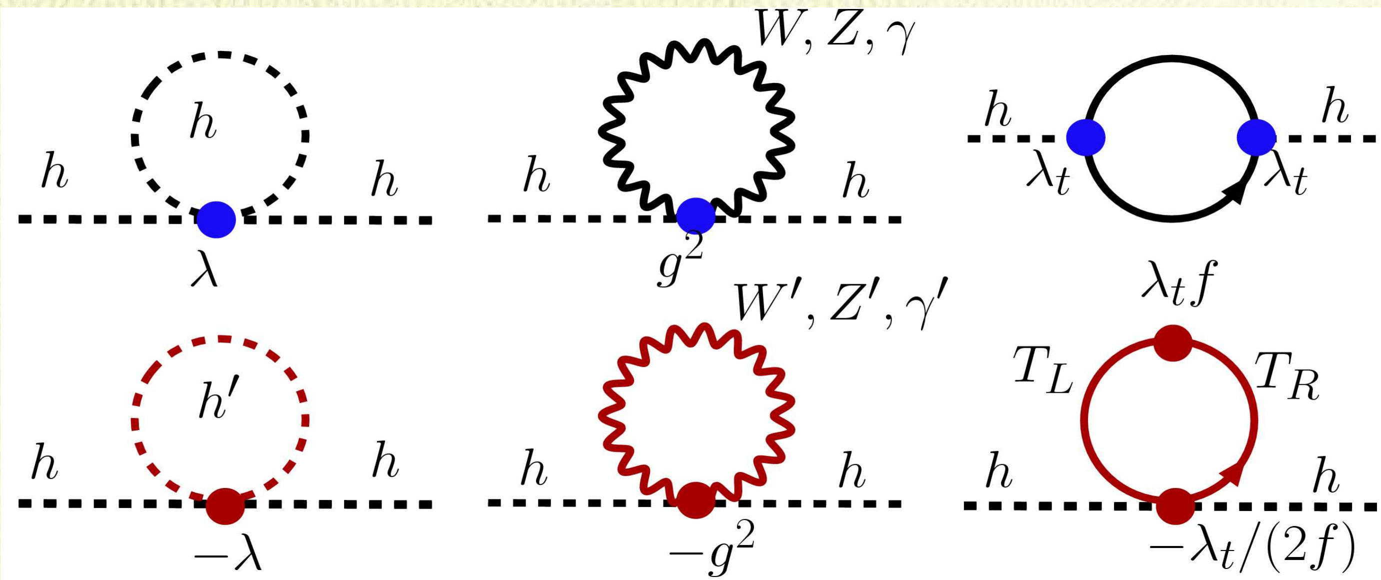
Littlest Higgs model

Arkani-Hamed, Cohen, Katz and Nelson (2002)

SU(5)⊃[SU(2)×U(1)]²(gauged)

VEV = f ~ O(1) TeV

SO(5)⊃SU(2)×U(1) (diagonal)



New heavy particles

-

bosons,top-quarks, scalars

-

cancel the one-loop quadratic divergences

Little Higgs Model with T -parity

- Original LHM is suffered from severe constraints from EW observables. Tree-level corrections are due to the exchange of additional heavy gauge bosons and non-vanishing VEV of triplet higgs.
  f must be larger than 5 TeV, fine-tuning again !
- **T-parity:** Cheng, Low 2003

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

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

- ***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!

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 Model

The Littlest Higgs model is based on an $SU(5)/SO(5)$ non-linear sigma model (Arkani-Hamed et al, 2002). A vacuum expectation value an $SU(5)$ symmetric tensor field (Σ_0) breaks the $SU(5)$ to $SO(5)$ at the scale f with

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

$[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$ it is broken into the SM electroweak symmetry $SU(2)_L \times U(1)_Y$ at the scale f. The 14 Nambu-Goldstone bosons Π^a decompose under $SU(2)_L \times U(1)_Y$ as $\mathbf{1_0} \oplus \mathbf{3_0} \oplus \mathbf{2_{1/2}} \oplus \mathbf{3_{\pm 1}}$ and parametrized by nlσ model field $\Sigma = \xi^2 \Sigma_0$, where $\xi = e^{i\Pi^a X^a/f}$. $M_\Phi = \sqrt{2} M_H f/v$

Scalar kinetic term

$\frac{f^2}{8} \mathrm{Tr} D_\mu \Sigma (D^\mu \Sigma)^\dagger$ where

$\Sigma = \partial_\mu \Sigma - i \sum_j \left[g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) + g'_j B_j (Y_j \Sigma + \Sigma Y_j) \right]$

$$M_{A_H} = \frac{g' f}{\sqrt{5}} \left[1 + O\left(\frac{v_{SM}^2}{f^2} \right) \right], \quad M_{Z_H} \simeq M_{W_H} = gf \left[1 + O\left(\frac{v_{SM}^2}{f^2} \right) \right]$$

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 $\sin\alpha = \lambda_1/\sqrt{\lambda_1^2+\lambda_2^2}$

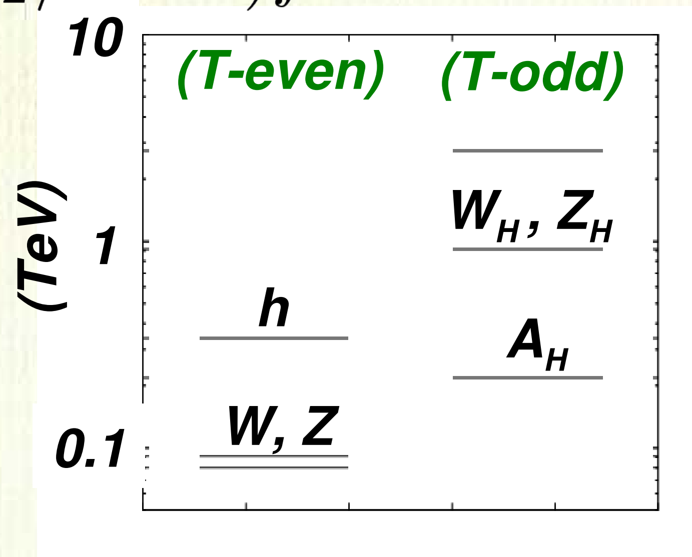
$M_t \simeq (\lambda_2 \sin\alpha)v,\quad M_{t_-} \simeq \lambda_2 f,\quad M_{t_+} \simeq (\lambda_2/\cos\alpha) f$

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

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** $M_{Q_-} = \sqrt{2}\kappa f$



Phenomenology of LHT model

- **Model implementation**

Lanhep → CalcHEP

Lanhep 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

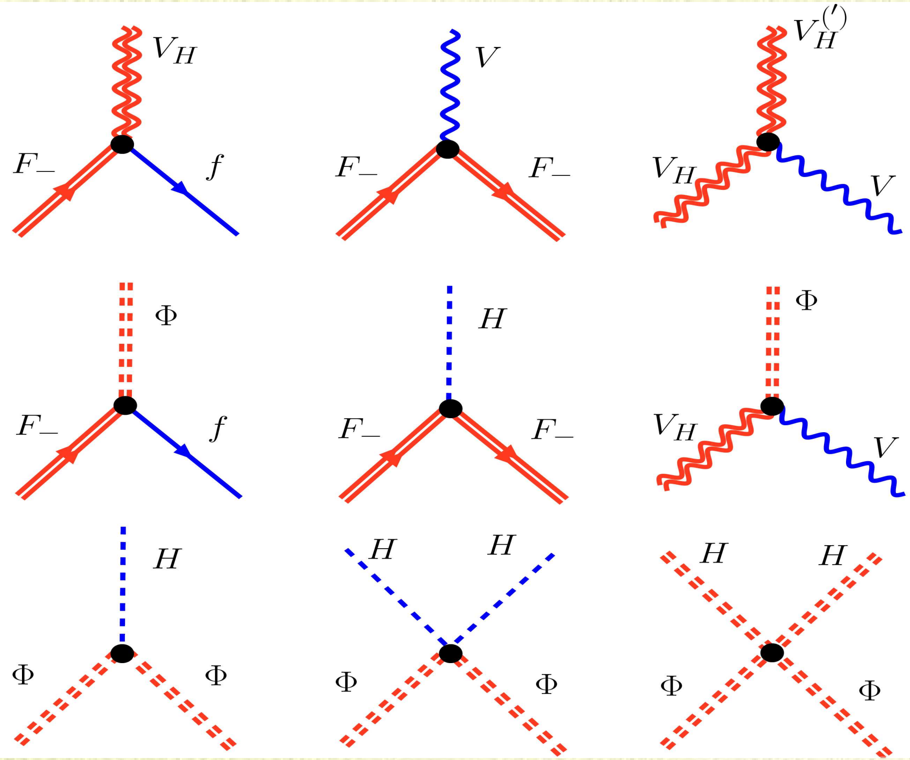
- **The present study aims**
  - *to implement the comple model*
  - *to check the previous studies*
  - *to systematise all possible phenomenology*
  - *to apply CalcHEP-PYTHIA for multibody final states*

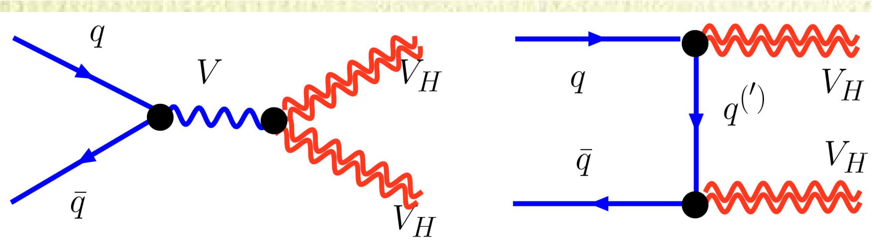
Phenomenology of LHT model

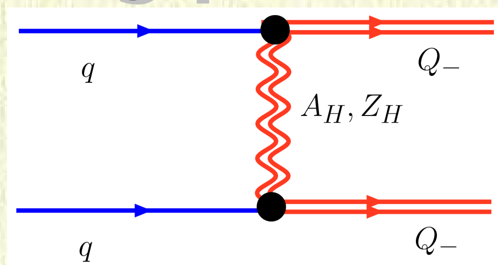
- **Parameters**

$$f, \quad sin\alpha = \frac{\lambda_1}{\sqrt{\lambda_1^2 + \lambda_2^2}}, \quad \kappa$$

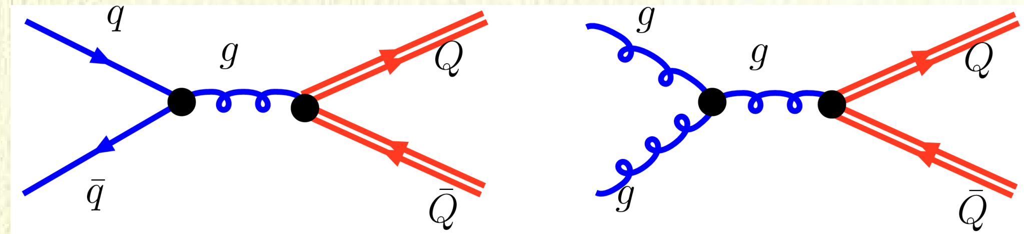
- **Interactions and promising production processes**

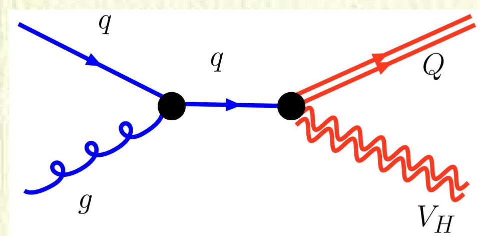


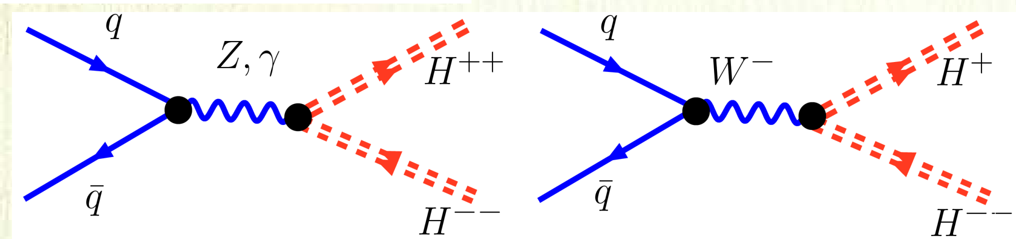




like-sign leptons!

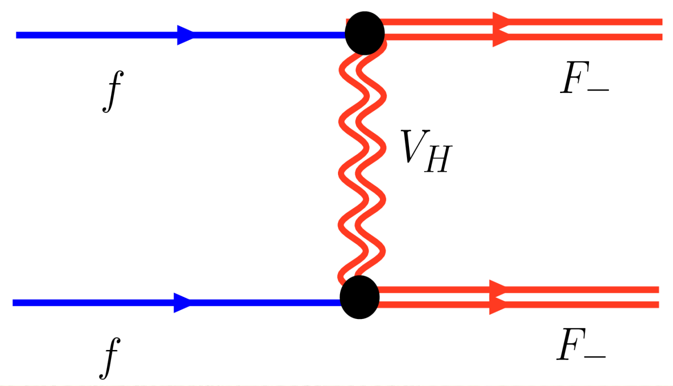


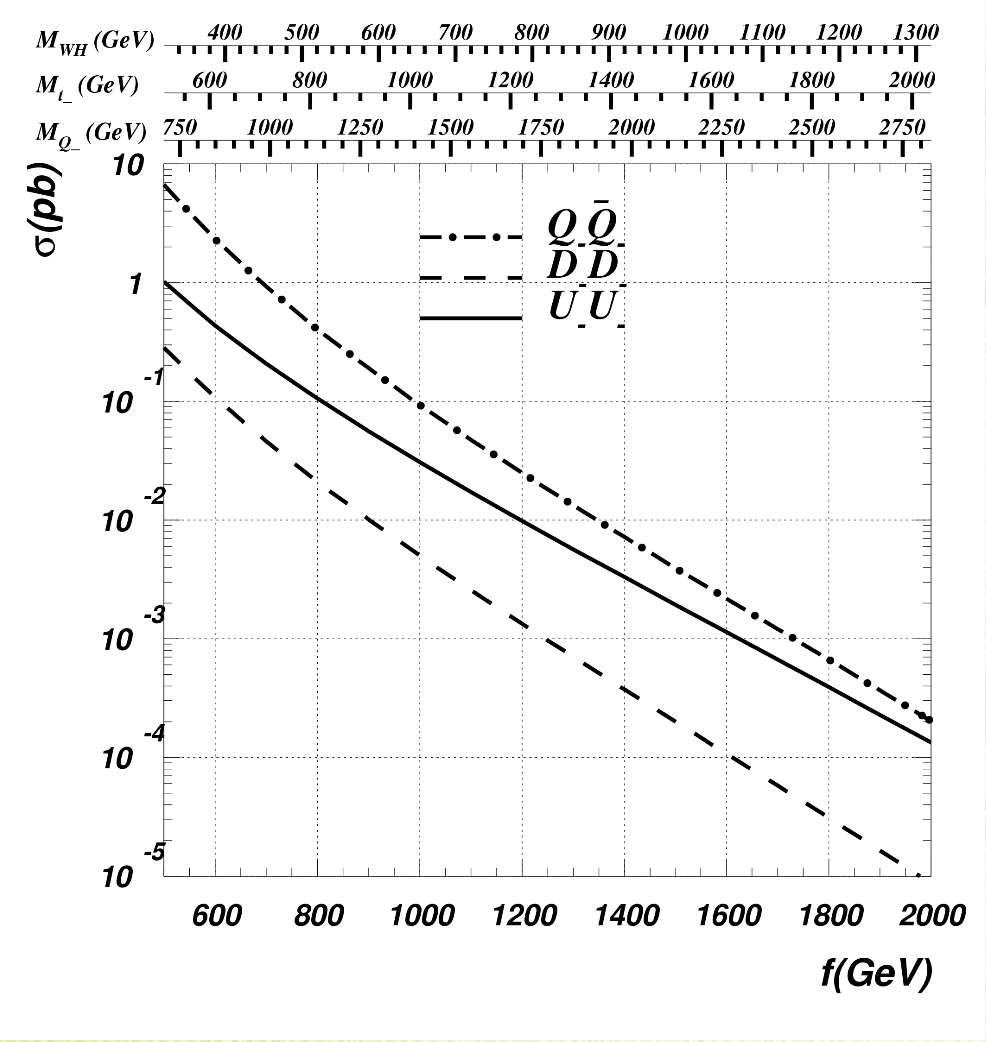




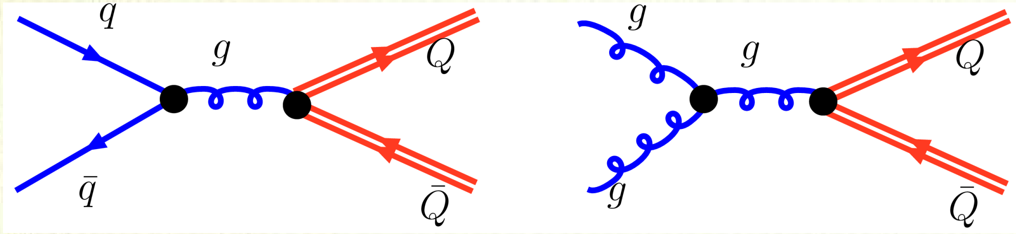
Heavy quarks production rates and signatures

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

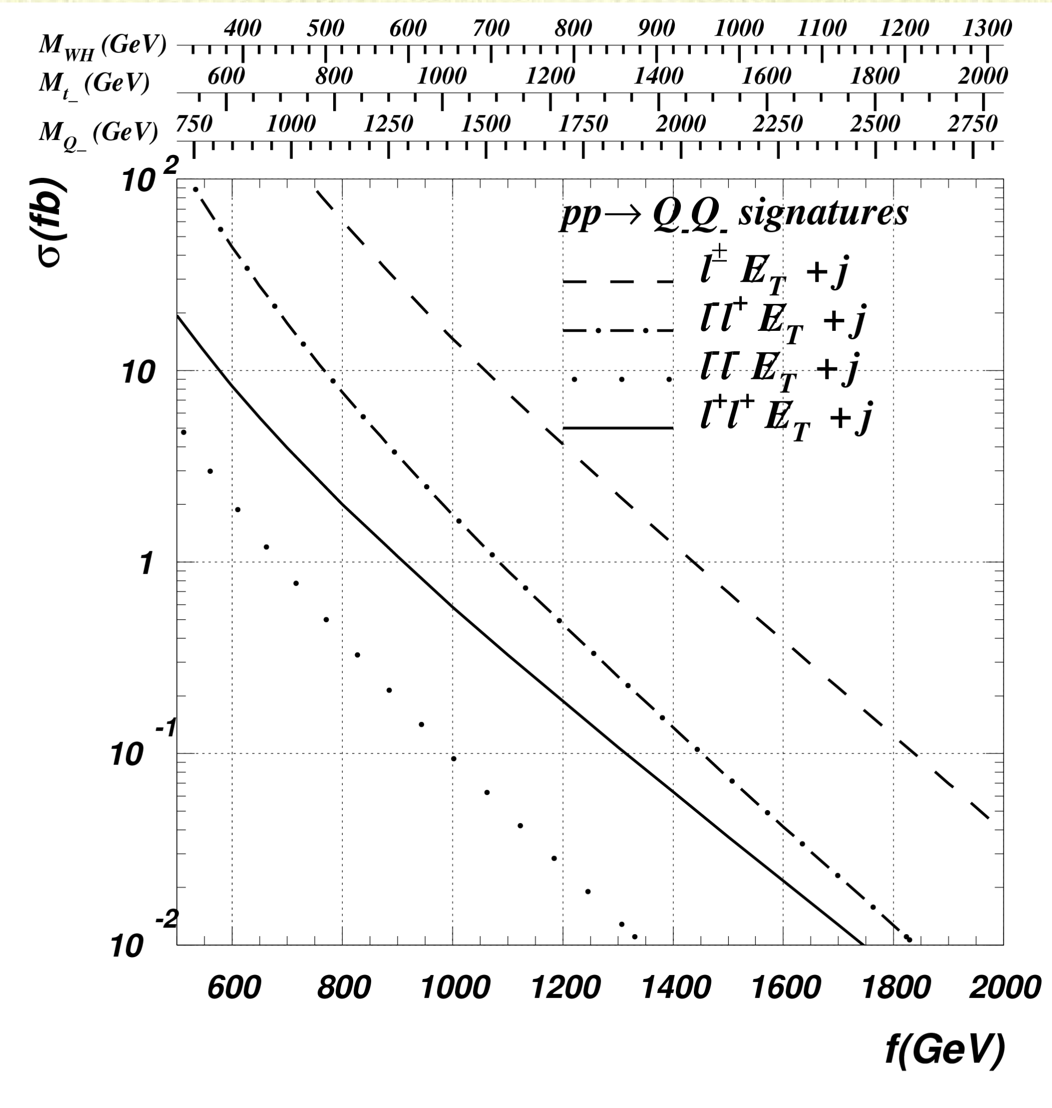




EW production due to the initial double valence quarks leads to like sign lepton signature (LSL), it is comparable to strong production and becomes even more important for heavier masses due to parton luminosity behavior!



Heavy quarks production rates and signatures



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

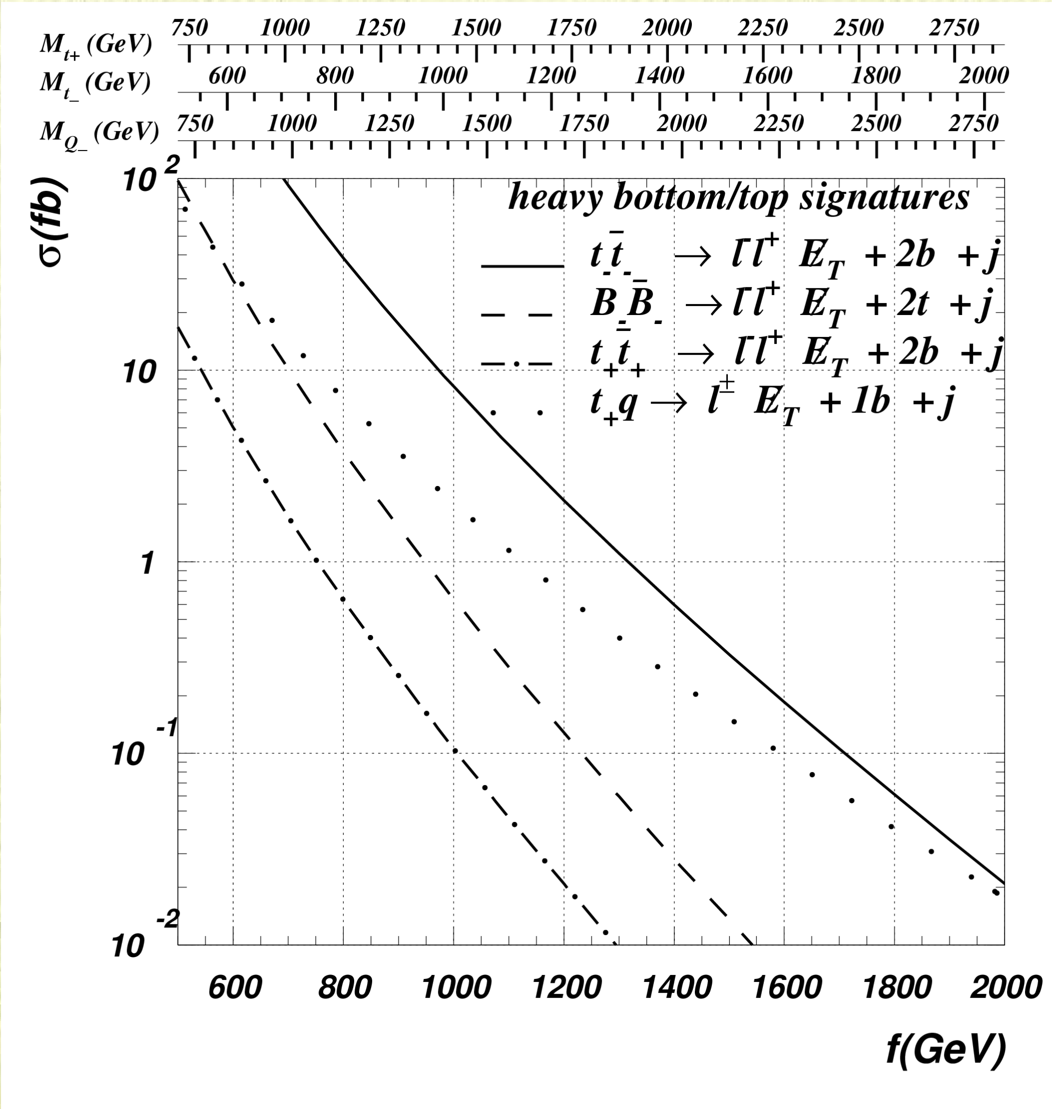
Like sign lepton signature (LSL)

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

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

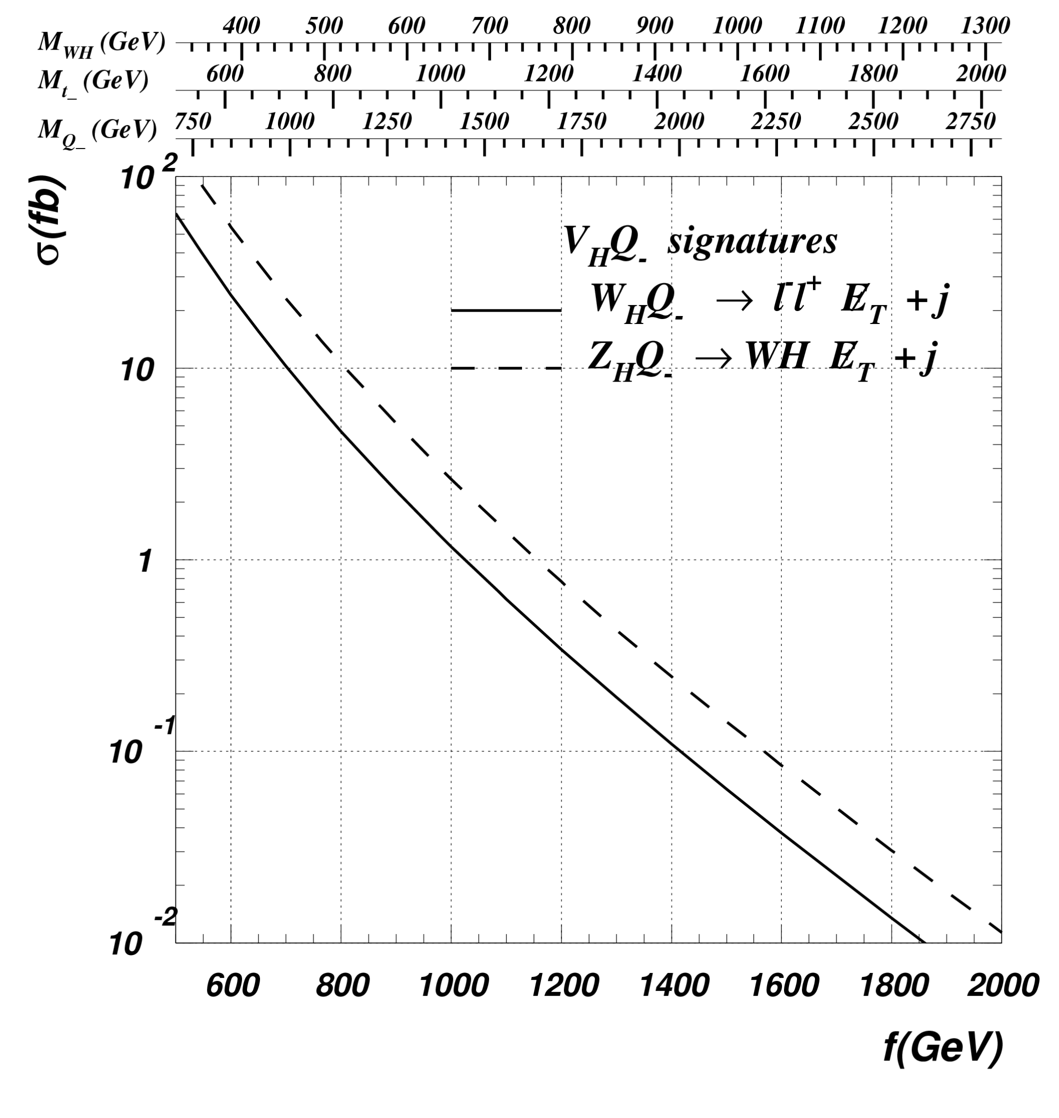
$$q\bar{q}(gg) \to T\bar{T} \to W_H^+ W_H^- b\bar{b}$$

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

Single top 1L + 1b signature

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

Heavy quark-vector boson accosiate 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

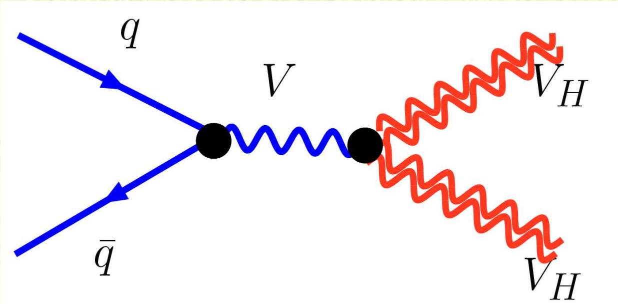
$$qg \to Q_- W_H \to W_H W_H q'$$

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



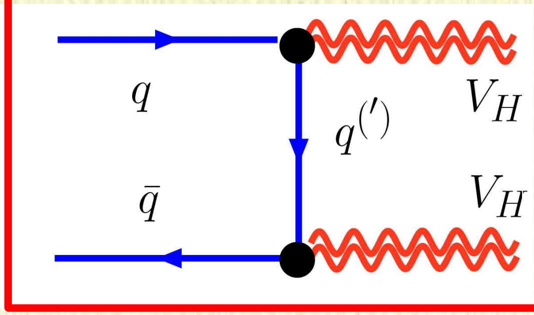
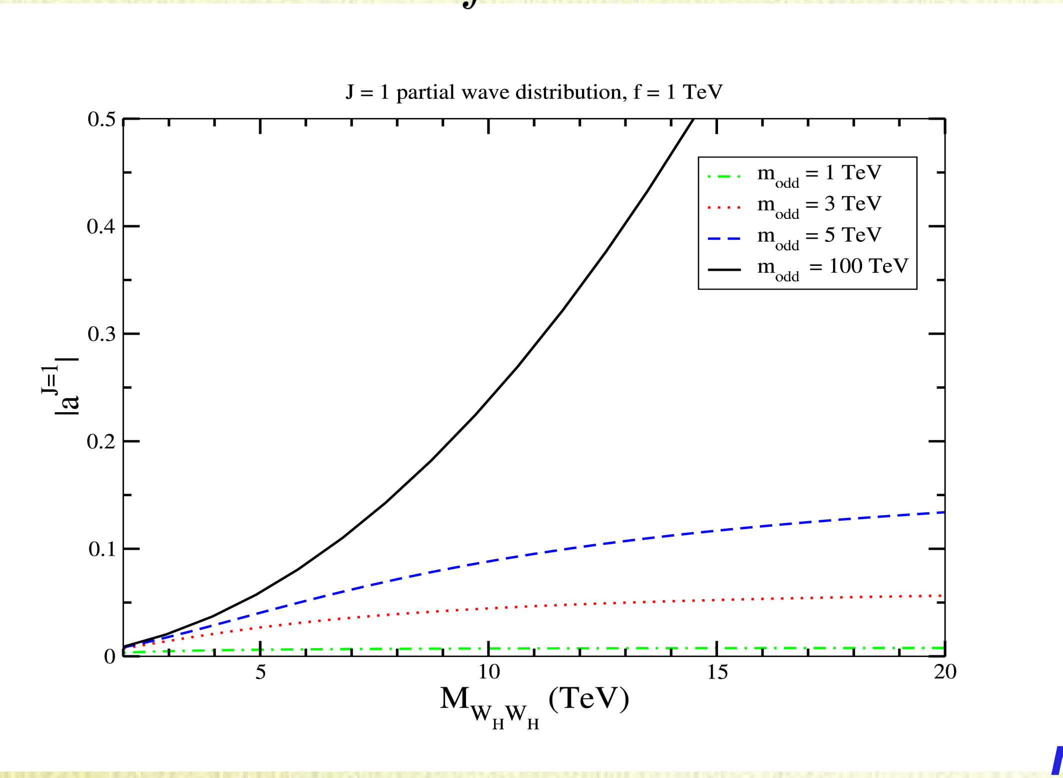
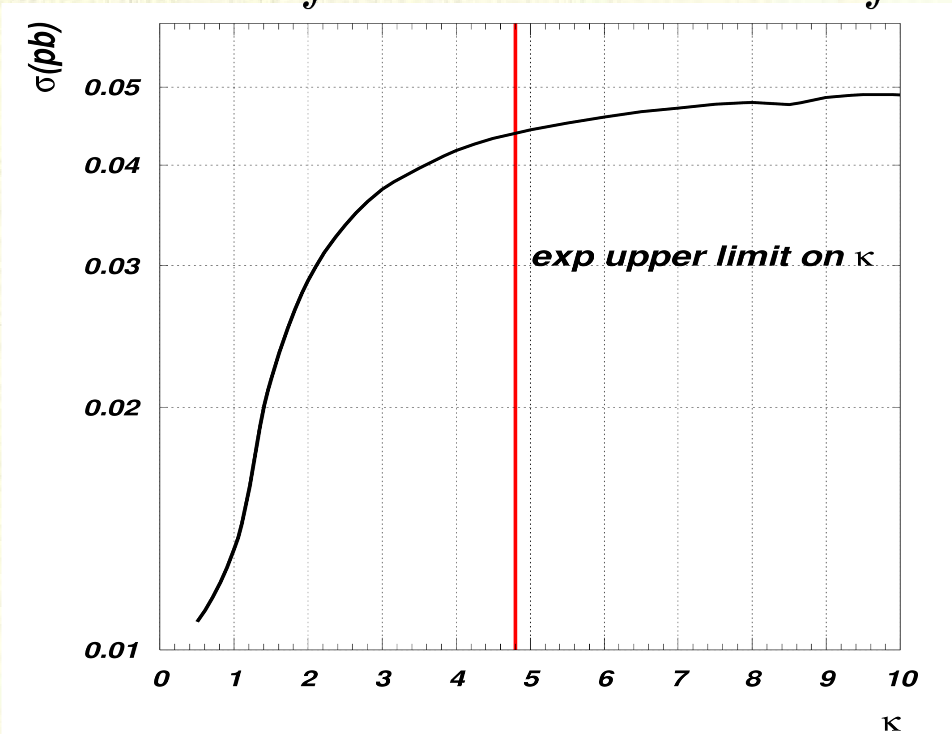


diagram was neglected in previous studies, but crucial for the correct rate prediction, gauge invariance and unitarity

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

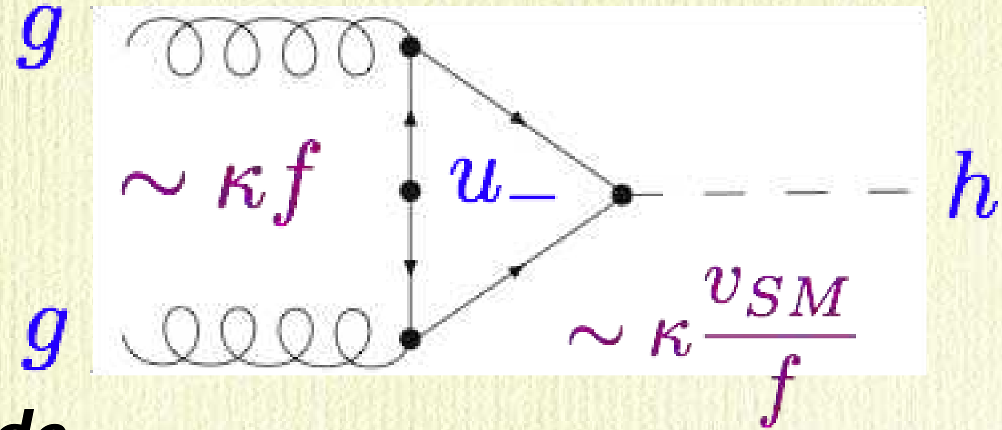
$$A^{\gamma}(-+) = -\frac{s_W^2 \sin\theta}{3f^2}s, \quad A^Z(-+) = -(1-\frac{4}{3}s_W^2)\frac{\sin\theta}{4f^2}s, \quad A^{d-}(-+) = \frac{\sin\theta}{4f^2}s$$





rates were overestimated by factor 2-5

Important T-odd fermion contribution to Higgsproduction 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 κdependence!

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

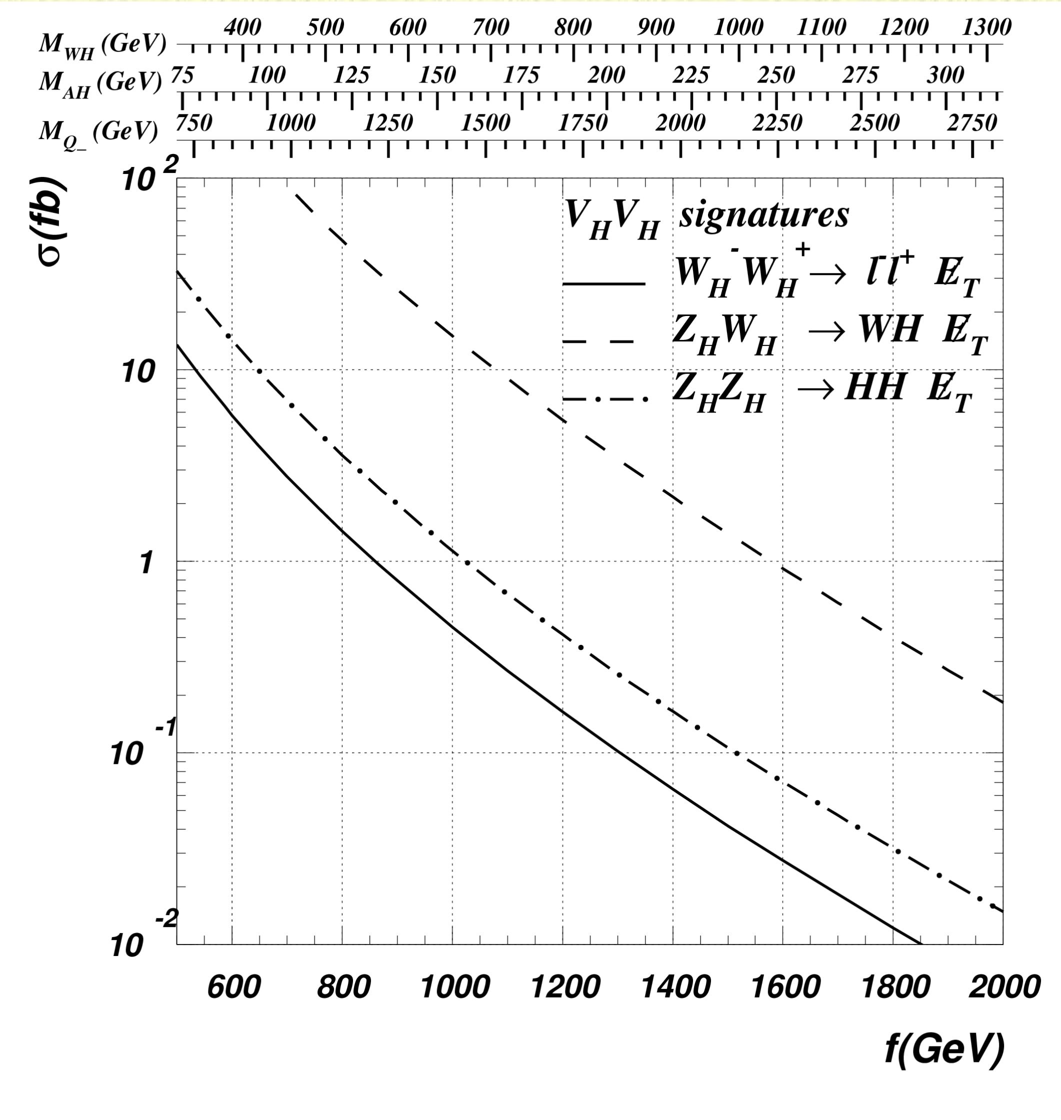
Correction to the cross section

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

top sector ↑ ↑ **T-odd fermions**

for $m_H < 2m_t$

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

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

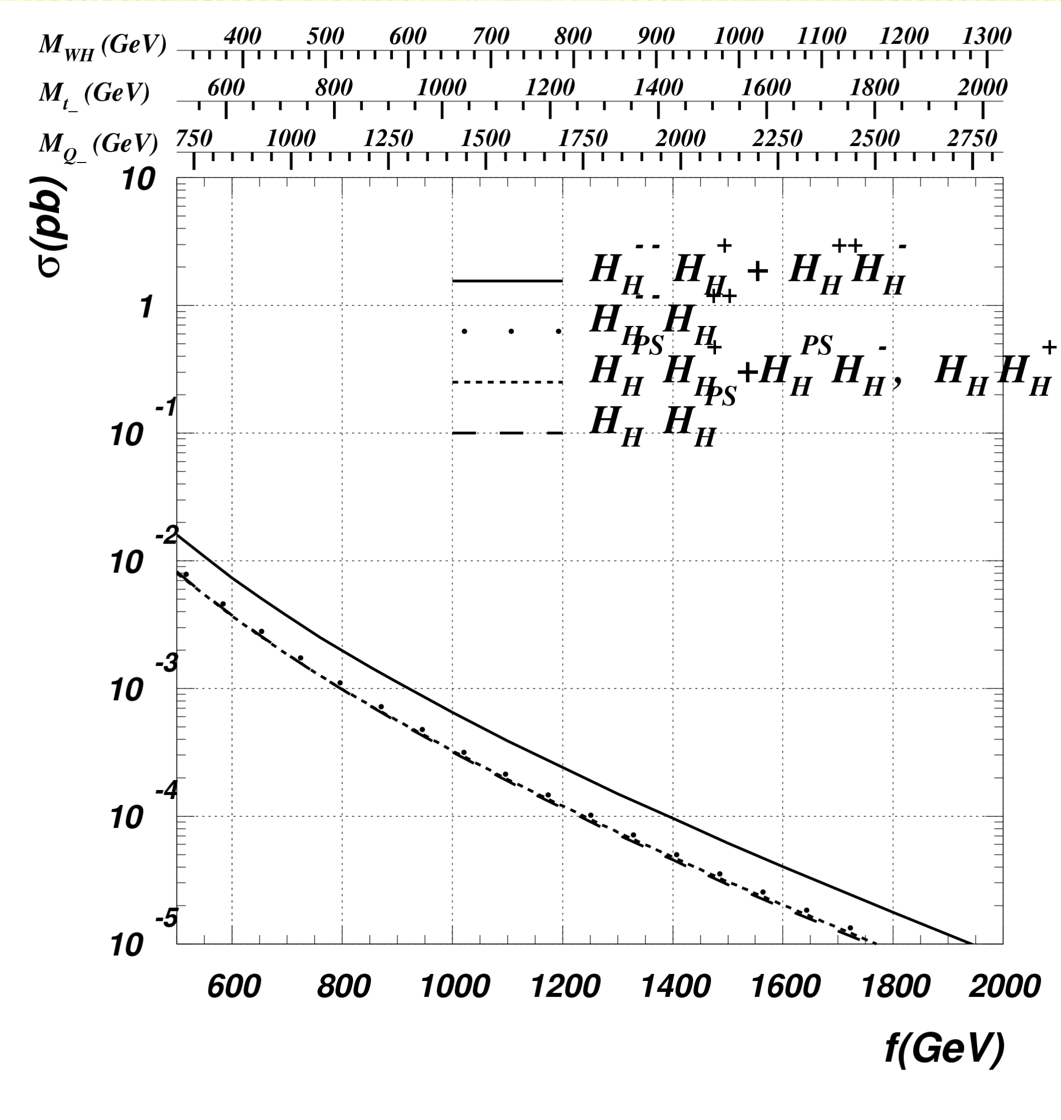
Associate Higgs production

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

Higgs pair production

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

Heavy scalar boson pair production



$$f = 1\ TeV, \quad \kappa = 1$$
$$H^{++} \to H^+W^+ \ \textbf{is closed}$$
$$H^+ \to \bar{b}T_- \quad \textbf{is closed}$$

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

Study of radiative decays and 3-body tree-level decays for Heavy Higgs bosons and 1-loop corrected mass spectrum is required !

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 Scands 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)
```

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 resuls
  - *all relevant to LHC signatures are classified*
  - *κ–term quark production has been suggested*
  - *new signatures, incl LSL has been pointed out*
  - *Importance of non-decoupling effects for heavy boson pair production has been shown*
- CalcHEP-PYTHIA interface - to go beyond the parton level and understand the signal observability – analysis are in progress