Aspects of Higgs searches in CP-violating & CP-conserving SUSY scenarios at the LHC and ILC

Priyotosh Bandyopadhyay
Korea Institute for Advanced Study

March 28, 2010

LCWS10 and ILC 10

In collaboration with
Amitava Datta, Asesh K. Datta, Biswarup Mukhopadhyaya

Phys. Rev. D 78, 015017 (2008), PLB(670) 5 (2008), JHEP 0907:102 2009

Plan

1. Motivation
2. Higgs from SUSY cascade
3. Universality and non-universality
4. Prospect at LHC & ILC
5. CP violation in MSSM
6. Probing the CPX 'hole' at LHC
7. Prospects at ILC
8. Conclusions

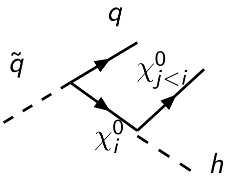
Motivation

- Higgs bosons are to be looked for in as many possible channels to know the underlying theory correctly
- Higgs from the SUSY cascades of strongly interacting particles (squarks & gluinos): Large production cross-section at the LHC.
- ILC will be indispensable in order to provide complementary information in particular slepton, netralino/chargino sectors.

Motivation

- Conventional searches are highly $\tan\beta$ dependent: they are significant only in high and low values of $\tan\beta$. more
- Cascade Higgs production rates are more or less independent of $\tan\beta$
- Many interaction vertices of different kind, viz, gauge-gaugino-Higgsino, gaugino-Higgsino-Higgs, sfermion-gaugino-fermion involve in a cascade
  ILC can be more effetive in determining these vertices.

Universal and non-universal gaugino masses



- Masses & Compositions (couplings) of the (EW) charginos/neutralinos play the crucial role.
- Governed mainly by,

  μ: which appears in the superpotential,

  M_2, M_1 mass parameters corresponding to SU(2)& U(1) gaugino masses.

and $\tan\beta = v_2/v_1$

Universal and non-universal gaugino masses

- Conventional (mSUGRA motivated) scenario: $M_1 = M_2/2$ at the weak scale
  $\Rightarrow$ assumes gaugino mass unification ($M_{1/2}$) at a high (GUT) scale
  $\Rightarrow$ In general, universality may be absent
  (minimal form of the gauge-kinetic function is assumed to have unification of gaugino-masses)

- Cascade Br $\propto f(\mu, M_1, M_2)$ (mainly)
  $\Rightarrow$ Can differ very much from universal to non-universal scenario, i.e., $M_1 = M_2/2$ to arbitrary M_1 (w.r.t M_2)

Sources of non-universalities

- The issue of non-universality of SUSY breaking gaugino masses arises under the influence of different GUT representations responsible for the SUSY breaking terms.
- In Supergravity frame work all the gauge and matter terms depends on two fundamental functions
  $\Rightarrow$ the gauge kinetic function $f_{\alpha\beta}(\Phi)$
  and the Kähler function $G(\Phi_i, \Phi_i^*)$ given by:

$$G = K + ln|W| \quad (1)$$

where, K is the Kähler potential. and W is the superpotential.

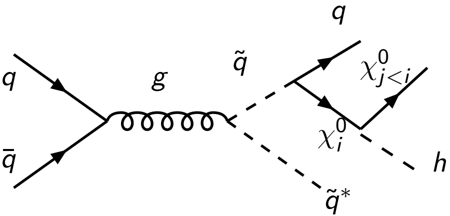
Sources of non-universalities

- The VEV of $< \partial_j f_{\alpha\beta} >$ determines the gaugino masses. ▸ more
- mSUGRA,

  $\Rightarrow$ Unification of the gaugino masses and couplings at the GUT scale.
- In models with minimal supergravity, the gaugino masses evolve from a common mass at high scale. At EW scale the gaugino masses follow the relation:

$$M_3 : M_2 : M_1 \approx 6 : 2 : 1 \qquad (2)$$

Typical Cascade decays



Typical Cascade decays

- The Big cascades

$$
\begin{aligned}
pp \longrightarrow\quad & \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \\
\longrightarrow\quad & \chi_2^{\pm}, \chi_3^0, \chi_4^0 + X \\
\longrightarrow\quad & \chi_1^{\pm}, \chi_2^0, \chi_1^0 + h, H, A, H^{\pm} \; + X
\end{aligned}
$$

- The Little cascades

$$
\begin{aligned}
pp \longrightarrow\quad & \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \\
\longrightarrow\quad & \chi_1^{\pm}, \chi_2^0 + X \\
\longrightarrow\quad & \chi_1^0 + H^{\pm}, h, H, A \; + X
\end{aligned}
$$

Datta, Djouadi, Guchait, Mambrini, Moortgat: 2001, 2003

Typical Cascade decays

- Gaugino sector depends on M_1, M_2, μ
- More importantly the relative values of M_1, M_2, μ play a crucial role in determining the cascade final states.
- Production cross-section of first two generations squark is larger.

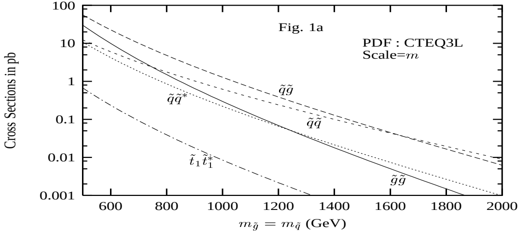


Figure: cross-section at the LHC

- High cross-section compensate for low Brs
  $\Rightarrow$ A good effective cross-section =cross-section$\times$ Brs

Datta et. al.

Higgsino limit:

- $|\mu| \ll M_2$

$$m_{\chi_2^0} \sim m_{\chi_1^\pm} \sim m_{\chi_1^0} \sim |\mu|$$

$\Rightarrow$ Gives the lighter charginos and neutralinos.
whereas,

$$2m_{\chi_3^0} \sim m_{\chi_2^\pm} \sim m_{\chi_4^0} \sim M_2$$

$\Rightarrow$ Gives the heavier charginos and neutralinos.

- However, because the higgsinos couple proportionally to the quark masses, squarks will dominantly decay into the heavier chargino and neutralinos, $\tilde{q_{1,2}} \rightarrow q'_{1,2}\chi_2^\pm, q_{1,2}\chi_3^0$ and $q_{1,2}\chi_4^0$.

Gaugino limit:

- When $|\mu| \gg M_2$ and $M_2 \sim 2M_1$ (as in mSUGRA)

$$m_{\chi_2^0} \sim m_{\chi_1^\pm} \sim 2m_{\chi_1^0} \sim M_2$$

$\Rightarrow$ Gives the lighter charginos and neutralinos.
whereas,

$$m_{\chi_3^0} \sim m_{\chi_2^\pm} \sim m_{\chi_4^0} \sim \mu$$

$\Rightarrow$ Gives the heavier charginos and neutralinos.

- In this case the squarks will decay to lighter ino states not only because of phase-space but also because of couplings.

Inputs

- We first work in $m_{\tilde{g}} > m_{\tilde{q}}$
  with $m_{\tilde{q}} \simeq 800$ GeV $\quad m_{\tilde{g}} = 900$ GeV.
- Next we will go to $m_{\tilde{g}} < m_{\tilde{q}}$
  with $m_{\tilde{q}} \simeq 900$ GeV $\quad m_{\tilde{g}} = 800$ GeV.
- We do not keep slepton decoupled from the scenario
  i.e., $m_{\tilde{\ell}} \simeq 400$ GeV
- Other parameters: $\quad m_t = 172$GeV $\quad \tan\beta = 10$,
  variation of $\tan\beta$ is also examined.
- We have analysed the system to two sets of Higgs mass spectrum

$m_{H^\pm}$ (in GeV)	m_h (in GeV)	m_A (in GeV)	m_H (in GeV)
180	109	162	164
250	109	238	239

Table: The Higgs mass spectra

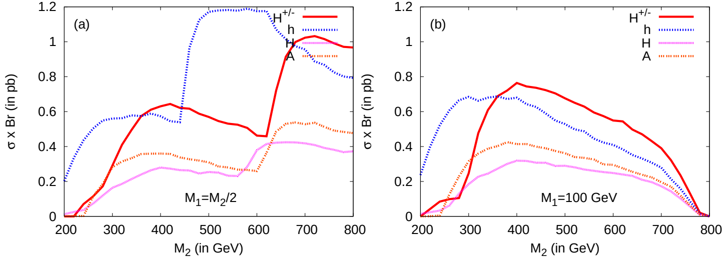


Figure: Effective cross-sections for Universal scenario $M_1 = M_2/2$(left)and Non-universal with $M_1 = 100$ GeV (right) at $\mu = 150$ GeV

- The 'cross-over' points for the rates of the charged Higgs and the lightest neutral Higgs boson are also different for universal and non-universal cases ▸ more

PLB (670) 5 (2008)

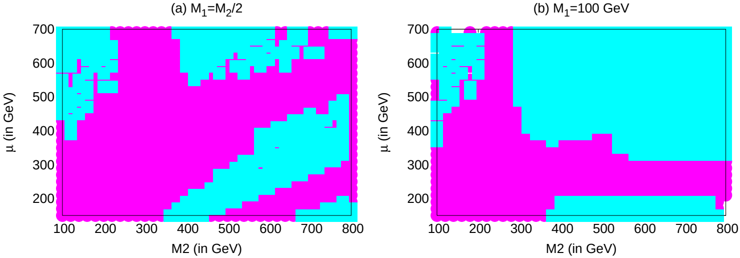


Figure: Pink region is the region where $H^{\pm}$ is less than h production and sky-blue region represents the opposite case, for M1=M2/2(left) and M1=100 GeV(right)

- Scanning of the relative rates for different M_2, μ values lead us to the contrasting regions for universal and non-universal ones.
- A detailed analysis of background shows that we can probe some of the region of the parameter space

JHEP 0907:102, 2009

- Some benchmark point

Benchmark Point	M2 (in GeV)	μ (in GeV)
BP1	600	150
BP2	350	700
BP3	700	550
BP4	350	400

- BP1 and BP2 are from Higgsino and gaugino like regions respectively.
- For BP3 and BP4 are heavy mixture of gauginos higgsinos respectively.

Chargino, neutralino mass spectrum for the Benchmark Points

Benchmark Point	$m_{\chi_1^\pm}$ (in GeV)	$m_{\chi_2^\pm}$ (in GeV)	$m_{\chi_1^0}$ (in GeV)	$m_{\chi_2^0}$ (in GeV)	$m_{\chi_3^0}$ (in GeV)	$m_{\chi_4^0}$ (in GeV)
BP1(U)	145.0	612.0	135.3	155.2	308.2	611.8
BP2(U)	341.7	713.2	173.6	341.9	703.3	712.8
BP3(U)	529.6	724.5	345.0	533.5	552.9	724.4
BP4(U)	311.3	445.5	171.0	312.9	404.8	445.8
BP1(NU)	145.0	612.0	84.3	156.6	160.6	611.7
BP2(NU)	341.7	713.2	99.0	341.9	703.4	712.5
BP3(NU)	529.6	724.5	98.6	530.4	553.2	724.2
BP4(NU)	311.3	445.5	97.7	312.2	405.0	445.5

Table: The gaugino mass spectrum for the universal (U) and the non-universal (NU) scenarios corresponding to the benchmark points. For the universal case M_1 is taken to be $M_2/2$ while for non-universal case $M_1 = 100$ GeV is set.

back

Effective cross-sections corresponding to Benchmark Points

	Universal		Non-universal	
Benchmark Points	Effective cross -section (in fb)		Effective cross -section (in fb)	
	σ_h	σ_{H^+}	σ_h	σ_{H^+}
BP1	765.3	312.8	220.0	304.1
BP2	657.2	1.7	350.0	1198.7
BP3	290.4	124.0	231.4	375.7
BP4	948.0	14.5	582.5	694.0

Table: An estimate is given for the h and $H^{\pm}$ production rates for $m_H^{\pm} = 180$ GeV

back

Signal

- $n_{jet} \geq 5$, $\not{p}_T \geq 150$ GeV, $M_{eff} \geq 1200$ GeV, $p_T^{hardest-jet} \geq 300$ GeV
  along with invariant mass of two tagged b-jets defines the signal for the neutral Higgses.
- For charged Higgs boson along with the basic cut we demand a τ-jet of $p_T > 100$ GeV.
- With some advance cut the signal can reproduce the rate level observations with enough significance over background depending on the benchmark points.

- Unlinke LHC it is very difficult produce these strongly interacting supersymetric particles because of two reasons
  1. ILC has less reach compared to LHC in pair producing these heavy particles
  2. It does not have any strongly interacting particle at the initial states (like q, g in the case of LHC)
- Here we have a comparison in the production cross-sections

@LHC	@ILC
3.5 pb with $m_{\tilde{q},\tilde{g}} \simeq 800$ GeV	few fb with $m_{\tilde{q},\tilde{g}} \simeq 400$ GeV

Talk by Thomas G. Rizzo

Higgs from SUSY Cascades Prospect at ILC

- There is advantage at the 2nd stage of the cascade at the ILC.
  1. Can produce EW gauginos unlike strongly interacting ones
  2. Total gaugino production $\sim$ 290 fb
     Talk by Yiming Li
  3. Having the required mass splitting Higgs production at the cascade could be still possible in relatively higher luminosity.
- Gaugino masses and mixings (in the context of mSUGRA scenario) can be extracted at ILC
  Choi et. al, Eur.Phys.J.C8:669-677,1999
- Precise measurements of the gaugino masses effectively can give more knowledge

Sparticle masses at ILC

	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^{\pm}$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^{\pm}$	378.2	3	estimate $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$, spectra $\tilde{\chi}_2^{\pm} \to Z\tilde{\chi}_1^{\pm}$, $W\chi_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	176.8	1.2	simulation threshold scan $\tilde{\chi}_2^0\tilde{\chi}_2^0$, 100 fb^{-1}
$\tilde{\chi}_3^0$	358.8	3 – 5	spectra $\chi_3^0 \to Z\chi_1^0, 2,\ \chi_2^0\chi_3^0, \chi_3^0\chi_4^0$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{\chi}_4^0$	377.8	3 – 5	spectra $\chi_4^0 \to W\tilde{\chi}_1^{\pm},\ \chi_2^0\chi_4^0, \chi_3^0\chi_4^0$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{e}_R$	143.0	0.05	e^-e^- threshold scan, 10 fb^{-1}
$\tilde{e}_L$	202.1	0.2	e^-e^- threshold scan 20 fb^{-1}
$\tilde{\nu}_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde{\mu}_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde{\mu}_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1}
$\tilde{\tau}_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde{\tau}_2$	206.1	1.1	estimate threshold scan, 60 fb^{-1}
$\tilde{t}_1$	379.1	2	estimate b-jet spectrum, $m_{\rm min}$, 1TeV, 1000 fb^{-1}

Table: Sparticle masses and their expected precisions in Linear Collider experiments, SPS 1a mSUGRA scenario (hep-ph/0410364).

$\Rightarrow$ Combining with LHC it could be very effective to probe cascade Higgs searches as well as the universality, non-universality issues of the gaugino masses.

Conclusions

- Higgs production under SUSY cascades (already known) is a useful complementary mode for Higgs search
- Could provide useful information on the underlying scenario, i.e, the couplings, relative masses from LHC and ILC
- Imprint of non-universality in the gaugino masses likely to be reflected in the Signal
- The distinguishability of universality from non-universality is again very clear for lower values of M_1 (for a given value of M_2) and for low Charged Higgs mass.

Higgs CPV-MSSM

- CP violation in the Higgs potential of the MSSM leads to mixing terms between the CP-even and CP-odd Higgs fields. Pilaftsis, etal; 88,98
- The mixing term :

$$\mathcal{M}^2_{SP} \quad \propto \quad -\frac{T_a}{v} \simeq \mathcal{O}\left(\frac{m_t^4}{v^2}\frac{|\mu||A_t|}{32\pi^2 M^2_{\rm SUSY}}\right) \sin\phi_{\rm CP}$$

where,

$\phi_{\rm CP} = \arg(A_t\mu) + \xi \quad M^2_{\rm SUSY} = \frac{1}{2}\left(m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}\right)$

$m_t =$ Mass of top quark

- CP-phases of gluino mass parameter also contribute through the threshold corrections $\sim f(M_3^*\mu^*)$.

The CPX scenario

- The mixing become significant when $(\mu A_t/M^2_{SUSY})$ is large.
- Motivated by this following CP-violating benchmark scenario CPX was introduced in the literature.
  Carena,Pilaftsis, Ellis, Wagner

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\rm SUSY} \, ,$$
$$|\mu| = 4\, M_{\rm SUSY} \, , \quad |A_{t,b,\tau}| = 2\, M_{\rm SUSY} \, , \quad |M_3| = 1 \;\; {\rm TeV}.$$

- The parameter $\tan\beta$, $M_{H^\pm}$, and $M_{\rm SUSY}$ can be varied.

- For CP phases, $\Phi_A = \Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau}$, we have two physical phases to vary: Φ_A and $\Phi_3 = {\rm Arg}(M_3)$.

The CPX scenario

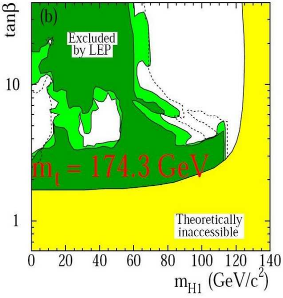
- Special case:

$$M_{SUSY} = 500 \text{ GeV}, \quad \Phi_A = \Phi_{M_3} = 90^\circ$$
$$M_2 = 2M_1 = 200 \text{ GeV},$$

- We vary $\tan\beta = 5 - 10$ and $M_{H^\pm}$.
- $\Rightarrow$ low lightest Higgs(h_1, $m_{h_1} \leq 60$ GeV)
- $Z - Z - h_1$ coupling goes down.
- First two generation scalars ($\geq$10 TeV) $\Rightarrow$ to satisfy the experimental constraint on the Electric Dipole Moment of electron and neutron

The Experimental constraints

- LEP put a lower bound on SM Higgs: $m_H \geq 114.4$ GeV.
- Similar bound on CPC MSSM Higgs: $m_h \geq 92.9$ GeV.
- The 'LEP hole' in CPX scenario



CPX:"LEP-hole" and Earlier works

- $Z - Z - h_1$ coupling goes down.

  $\Rightarrow$ can not probe the CPX.

- $g_{t\bar{t}h_1}$ also goes down.

- Need to find out a channel to probe CPX.

- Sum rule:

$$g^2_{h_i VV} + \mid g_{h_i H^- W^+} \mid^2 = 1$$

$$g^2_{h_i VV} \downarrow \quad \Rightarrow \quad g_{h_i H^- W^+} \uparrow$$

where, V=W, Z

CPX:"LEP-hole" and works at the LHC

- As $M_{h_1} < 50$ GeV $\Rightarrow$ BR($H^{\pm} \rightarrow h_1 W$)$>$ 90%
- Again ($M_{H^{\pm}} < M_t$)
- At the LHC

$$pp \rightarrow t + \bar{t} + X$$

$\Rightarrow$ The signal:

$\geq$ 3 b-tagged jets + 2 untagged jets + 1 lepton + $\not{p}_T$

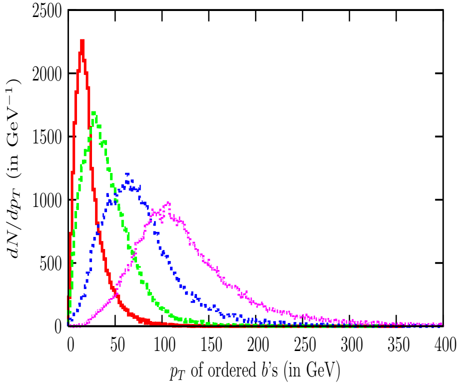
Moretti, Gosh, Roy and Godbole

CPX:"LEP-hole" and works at the LHC

- CPX $\Rightarrow$ relatively lighter $\tilde{t}_1$
  $\Rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$ a large rate @ LHC: $\sigma_{\tilde{t}_1 \tilde{t}_1^* h_1} = 440$ fb
- $$\tilde{t}_1 \longrightarrow b\chi_1^+ \longrightarrow bW^+\chi_1^0 \longrightarrow b\ell^+\nu_\ell\chi_1^0$$
  $$h_1 \longrightarrow b\bar{b}$$
- $\Rightarrow$ parton level signal:
  4-b partons + dilepton + missing p_T

b-jet p_T distribution

- Are all the 4-bs in the parton level, taggable after hadronization ?
- b-p_T distribution from $\tilde{t}_1 \tilde{t}_1^* h_1$.



Search for realistic signal:

- The soft 'b' jet is rather soft: can escape detection
- A plausible signal:
  3 *tagged b-jets* + *dilepton* + *other untagged jets* + *missing* p_T
- Backgrounds: $t\bar{t}H$, $t\bar{t}, t\bar{t}Z, t\bar{t}b\bar{b}$
  and main SUSY background $\tilde{g}\tilde{g}$
- Cuts: $n_jet \leq 5, \not{p}_T \geq 110$ GeV
  $\Rightarrow$A suitable signal:
  dilepton $+ \leq 5$ *jets including three tagged b-jets* $+ \not{p}_T$
- results: At $\mathcal{L}$=30fb^{-1}, signal size (7.2 σ) is still larger than CPC-MSSM or SM with one advance cut.

Phys.Rev.D78:015017,2008

Prospect at ILC

- $\sigma_{\tilde{t}_1 \tilde{t}_1^* h_1} \simeq 4$ fb with $\sqrt{S} = 1$ TeV
  $\Rightarrow$ can be produced at relatively higher luminosities.
- No $\tilde{g}\tilde{g}$ backgrounds and $t\bar{t}$ is also less.
- less chance of b-jet mistagging.
- All this could really increase the signal significance.
- At the end precision mass measurements and reach to third generation scalar quarks add to this as discovery channel.

Conclusions:

- IF CP is violated maximally via loop effects, the 'hole' can be probed via this channel provided we have some idea about the squark masses
- If this happens: could be a solid indication the low mass of lightest Higgs
- ILC reach to the signal and low backgrounds can really probe this better.
- Third generation cascade which could be under the reach of ILC and can have very interesting phenomenology.

Take home:

THANK YOU

Channels responsible

- For universal case:
  $\chi_3^0 \to h/H/A\,\chi_1^0$ & $\chi_3^0 \to H^{\pm}\,\chi_1^{\mp}$ are open
- For non-universal case these channel are not open
  $\Rightarrow$ Changes the cross-over points back

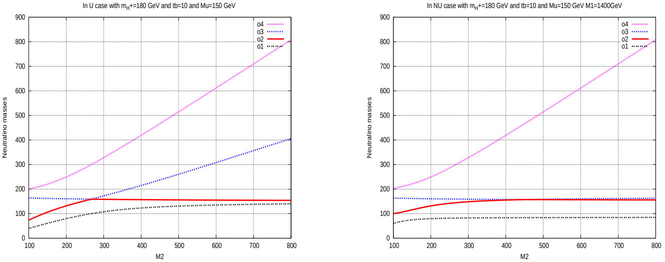
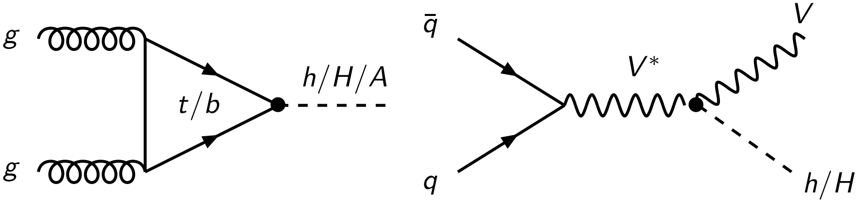


Figure: Neutralino mass spectrum for universal(left) and non-universal(right) scenarios

Direct Higgs production:

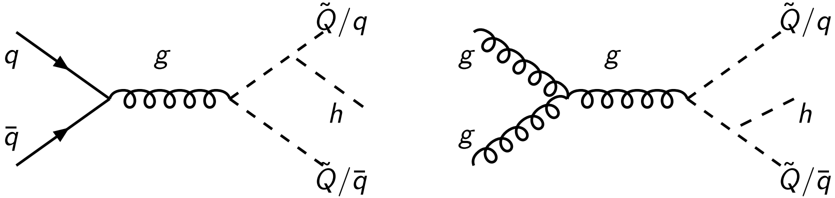
- Resonant Higgs production via gluon-gluon fusion and associated production with gauge boson.



back

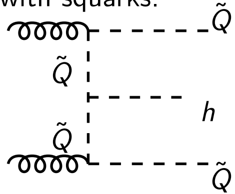
Direct Higgs production:

- The associated production processes with squarks or quarks.



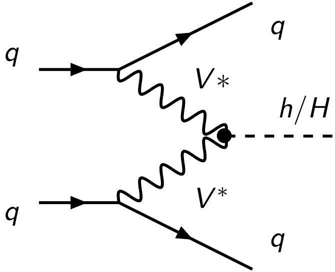
Direct Higgs production:

- The associated production with squarks.



Direct Higgs production:

- Higgs production associated with gauge boson and via gauge boson fusion.



◂ back

Higgs decay Modes

- Canonical SM Higgs decay Modes:
  $H \rightarrow b\bar{b} \qquad H \rightarrow \tau\bar{\tau} \qquad H \rightarrow W^+W^-$
  $H \rightarrow ZZ \qquad H \rightarrow \gamma\gamma$
- 2HDM and MSSM sector will differ via

$$H^{\pm} \rightarrow \tau\nu_\tau$$

- *CP*-odd A Higgs will not decay into gauge boson pair unlike CP-even Higgs.
- But for *CP*-violating MSSM neutral Higgses do not have definite *CP* parity.
- For MSSM gauginos decay to Higgs play a crucial role. back

Sources of non-universalities

- $$f_{\alpha\beta}(\Phi^j) = f_0(\Phi^S)\delta_{\alpha\beta} + \sum_N \xi_N(\Phi^s)\frac{\Phi^j{}_{\alpha\beta}}{M} + \mathcal{O}(\frac{\Phi^j}{M})^2 \qquad (3)$$

  where f_0 and ξ_N are functions of chiral singlet superfields, and M is the reduced Planck mass= $M_{Pl}/\sqrt{8\pi}$.
- Φ^j s can be of two categories: a set of GUT singlet Φ^S and a set of non-singlet ones Φ^N.
- $f_{\alpha,\beta}$ can have contributions from the singlet and non-singlet representations or could as well have a linear combination of singlet and non-singlet representations. back