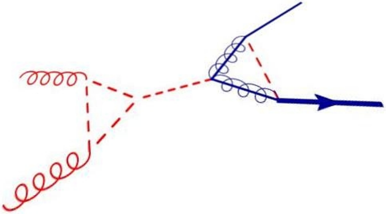
Supersymmetric Single Top Production with a $U(1)_R$ Symmetry

Robert Knegjens



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Supersymmetry (SUSY)

Standard Model with SUSY

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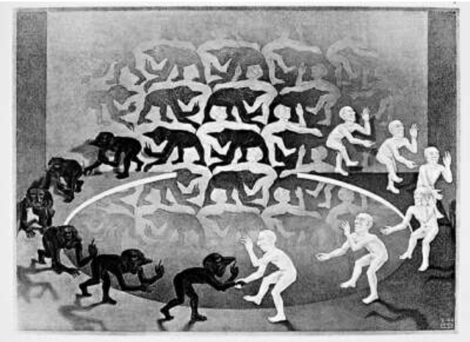
Supersymmetry (SUSY)



Motivation for SUSY

Supersymmetry (SUSY):

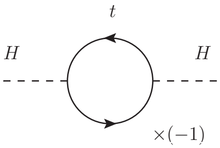
$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle \quad , \quad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

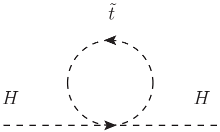
SUSY + Standard Model:

- Solves the fine-tuning problem

$$m_H^2 = m_{\text{tree}}^2 - \frac{\lambda_t^2}{8\pi^2}\Lambda_{\text{UV}}{}^2 + \ldots \sim (200\text{GeV})^2$$

- Can unify gauge coupling constants of the SM (e.g MSSM)
- Broken SUSY theory with R symmetry gives a stable dark matter candidate





Spacetime Symmetries

- The Poincaré group:
  - Translations generated by P_μ
  - Rotations generated by J_i
  - Boosts generated by K_i

$$M_{ij} = \epsilon_{ijk} J_k \quad \text{and} \quad M_{i0} = K_i,$$

- The Poincaré **Lie algebra**:

$$\begin{aligned}
[P_\mu, P_\nu] &= 0 \\
[M_{\mu\nu}, P_\lambda] &= i(\eta_{\nu\lambda} P_\mu - \eta_{\mu\lambda} P_\nu) \\
[M_{\mu\nu}, M_{\rho\sigma}] &= -i(\eta_{\mu\rho} M_{\nu\sigma} - \eta_{\mu\sigma} M_{\nu\rho} - \eta_{\nu\rho} M_{\mu\sigma} + \eta_{\nu\sigma} M_{\mu\rho})
\end{aligned}$$

Additional Spacetime Symmetries?

NO-GO Theorem: Coleman and Mandula (1967)

The most general **Lie algebra** for symmetries of an S-matrix can have **only Poincare group generators** along with Lorentz **scalar generators** of a compact Lie group.

- Bypass theorem by going to **graded (super)** Lie algebras

$$\{Q, Q'\} = X, \quad [X, X'] = X'', \quad [Q, X] = Q'$$

X: original commuting Poincaré generators $(P_\mu, M_{\mu\nu})$
Q: new anti-commuting generators

- **Super-Poincaré algebra** (N=1), Q Majorana fermions:

$$\boxed{\{Q, \bar{Q}\} = 2\gamma^\mu P_\mu}\,, \quad [M_{\mu\nu}, Q] = -\tfrac{1}{2}\sigma_{\mu\nu} Q, \quad [P_\mu, Q] = 0$$

Superfields

- Define a generic **superfield** using an expansion in anti-commuting coordinates θ_a

$$\{\theta_a, \theta_b\} = 0 \quad , \quad \{\theta_a, \psi_b\} = 0$$

$$\hat{\Phi}(x,\theta) = \mathcal{S}(x) + \bar{\theta}\psi(x) + (\bar{\theta}\gamma_\mu\theta)V^\mu(x) + (\bar{\theta}\theta)\bar{\theta}\lambda(x) + \ldots\{\mathcal{F},\mathcal{D}\}$$

- SUSY transformation: $\hat{\Phi}'(x,\theta) = e^{i\bar{\alpha}Q}\,\hat{\Phi}\,(x,\theta)e^{-i\bar{\alpha}Q}$

$$\begin{aligned} \delta\mathcal{S} &= -i\sqrt{2}\bar{\alpha}\psi_L \\ \delta\psi_L &= -\sqrt{2}\mathcal{F}\alpha_L + \sqrt{2}\partial\!\!\!/\mathcal{S}\alpha_R \\ \delta\mathcal{F} &= i\sqrt{2}\bar{\alpha}\partial_\mu(\gamma^\mu\psi_L) \\ \delta(\ldots) & \ldots \quad \ldots \end{aligned}$$

- Irreducible representations are **chiral superfield** $\hat{\mathcal{S}} \equiv \{\mathcal{S}, \psi_L, \mathcal{F}\}$ and **vector superfield** $\hat{V} \equiv \{V^\mu, \lambda, \mathcal{D}\} = \hat{V}^\dagger$

Building a SUSY Lagrangian

- Build from combination of superfields

$$\hat{\Phi}\hat{\Phi}' = \hat{\Phi}'', \quad \hat{\mathcal{S}}\hat{\mathcal{S}}' = \hat{\mathcal{S}}'', \quad \hat{\mathcal{S}}^\dagger\hat{\mathcal{S}} = \hat{\Phi}$$

- Action must be SUSY invariant

$$\delta S = \int d^4x\, \delta\mathcal{L} = 0 \quad \Rightarrow \quad \boxed{\begin{cases} \delta\mathcal{L} = 0 \\ \delta\mathcal{L} = \partial_\mu(\dots) \end{cases}}$$

- $\delta\hat{\mathcal{S}} \neq 0$ but $\delta\mathcal{F} = \not{\partial}(\dots)$

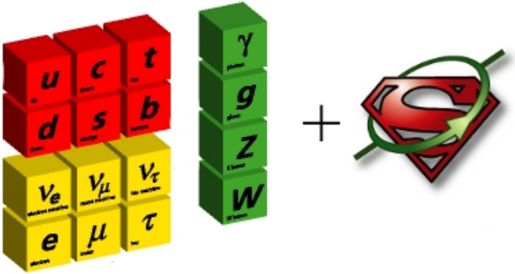
$$\text{Superpotential} \;:\quad \hat{f}(\hat{\mathcal{S}}) \to \hat{f}(\hat{\mathcal{S}})\Big|_{\mathcal{F}\text{-term}} \in \mathcal{L}$$

- Similarly, $\delta\hat{\Phi} \neq 0$ but $\delta\mathcal{D} = \partial_\mu(\dots) \quad \Rightarrow \quad K(\hat{\Phi})\Big|_{\mathcal{D}\text{-term}} \in \mathcal{L}$

A Master SUSY Lagrangian

$$\begin{aligned}\mathcal{L} = &\sum_i (D_\mu \mathcal{S}_i)^\dagger (D^\mu \mathcal{S}_i) + \frac{i}{2}\sum_i \bar{\psi}_i \not{D} \psi_i + \sum_\alpha \left[\frac{i}{2} \bar{\lambda}_\alpha (\not{D}\lambda)_\alpha - \frac{1}{4} F_{\mu\nu\alpha} F^{\mu\nu}_\alpha \right] \\ &- \sqrt{2} \sum_{i,\alpha} \left(\mathcal{S}_i^\dagger g_\alpha t_\alpha \bar{\lambda}_\alpha \psi_{Li} + \text{h.c.} \right) \\ &- \frac{1}{2} \sum_\alpha \left[\sum_i \mathcal{S}_i^\dagger g_\alpha t_\alpha \mathcal{S}_i + \xi_\alpha \right]^2 - \sum_i \left| \frac{\partial \hat{f}(\hat{\mathcal{S}})}{\partial \hat{\mathcal{S}}_i} \right|^2_{\hat{\mathcal{S}} = \mathcal{S}} \\ &- \frac{1}{2} \sum_{i,j} \bar{\psi}_i \left[\left(\frac{\partial^2 \hat{f}(\hat{\mathcal{S}})}{\partial \hat{\mathcal{S}}_i \partial \hat{\mathcal{S}}_j} \right)_{\hat{\mathcal{S}} = \mathcal{S}} P_L + \left(\frac{\partial^2 \hat{f}(\hat{\mathcal{S}})}{\partial \hat{\mathcal{S}}_i \partial \hat{\mathcal{S}}_j} \right)^\dagger_{\hat{\mathcal{S}} = \mathcal{S}} P_R \right] \psi_j\end{aligned}$$

Standard Model with SUSY



Minimal Supersymmetric Standard Model

- Keep $SU(3)_c \times SU(2)_L \times U(1)_Y$. Promote SM gauge fields to **vector superfields**

$$\text{e.g } B_\mu \to \hat{B} \ni (B_\mu, \lambda_0)$$

- Promote SM fermion fields to **chiral superfields**

$$\text{e.g } \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \to \begin{pmatrix} \hat{\nu} \\ \hat{e} \end{pmatrix} \equiv \hat{L}_e \quad \text{where } \hat{e} \ni (\tilde{e}_L, \psi_{eL}) \text{ etc.}$$

- Higgs potential must enter via superpotential $\hat{f}(\hat{\mathcal{S}})$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \to \hat{H}_u = \begin{pmatrix} \hat{h}_u^+ \\ \hat{h}_u^0 \end{pmatrix} \quad \text{but} \quad \hat{H}_u^\dagger \not\in \hat{f}(\hat{\mathcal{S}}) \Rightarrow \text{add } \hat{H}_d$$

- Minimal superpotential (with **R-parity**):

$$\hat{f}(\hat{\mathcal{S}}) = \mu \hat{H}_u \hat{H}_d + \mathbf{f}_u \epsilon \underbrace{\hat{Q}}_{\frac{1}{3}} \underbrace{\hat{H}_u}_{1} \underbrace{\hat{U}}_{-\frac{4}{3}} + \mathbf{f}_d \underbrace{\hat{Q}}_{\frac{1}{3}} \underbrace{\hat{H}_d}_{-1} \underbrace{\hat{D}}_{\frac{2}{3}} + \mathbf{f}_e \hat{L} \hat{H}_d \hat{E}$$

MSSM Particles

SM Particles		**Superpartners**	
Fermions		Scalar Fermions	
Quarks:	u, c, t, d, s, b	Squarks:	$\tilde{u}$, $\tilde{c}$, $\tilde{t}$, $\tilde{d}$, $\tilde{s}$, $\tilde{b}$
Leptons:	e, μ, τ, ν_e, ν_μ, ν_τ	Sleptons:	$\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$, $\tilde{\nu_e}$, $\tilde{\nu_\mu}$, $\tilde{\nu_\tau}$
Gauge Bosons		Gauginos	
Photon:	A_μ	Photino:	$\sin\theta_w \lambda_3 + \cos\theta_w \lambda_0$
W,Z Bosons:	${W^\pm}_\mu$	W-ino:	$\frac{1}{\sqrt{2}}(\lambda_1 \mp i\lambda_2)$
	Z_μ	Z-ino	$-\cos\theta_w \lambda_3 + \sin\theta_w \lambda_0$
Gluon:	G_μ	Gluino:	$\tilde{g}$
Higgs Bosons		Higgsinos	
h_u^+ h_u^0 $(h_d^-$ $h_d^0)$		$\tilde{h}_u^+$ $\tilde{h}_u^0$ $\tilde{h}_d^-$ $\tilde{h}_d^0$	

Breaking of the MSSM

- $[Q, P_\mu] = 0 \Rightarrow$ SUSY states have **equal mass**

$$Q(P^2\psi) = Q(m_\psi^2\psi) \quad \Rightarrow \quad P^2(Q\psi) = m_\psi^2(Q\psi)$$

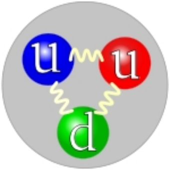
$$\Rightarrow \text{SUSY must be broken!}$$

- **Soft breaking** protects scalar masses

$$\mathcal{L}_{\text{soft}} = \left[\tilde{L}_i^\dagger \mathbf{m}_{Lij}^2 \tilde{L}_j + \ldots + m_{H_u}^2 |H_u|^2 + \ldots\right] - \frac{1}{2}\left[M_1 \bar{\lambda}_0 \lambda_0 + \ldots\right] + \left[(\mathbf{a_e})_{ij}\epsilon_{ab}\tilde{L}_i H_d \tilde{e}_{Rj}^\dagger + \ldots\right] + \left[(\mathbf{c_e})_{ij}\epsilon_{ab}\tilde{L}_i H_d^* \tilde{e}_{Rj}^\dagger + \ldots\right] + [bH_u H_d + h.c]$$

- MSSM with all soft breaking terms: **178 parameters!!**

R Symmetry



Baryon/Lepton Number Conservation

- SM + SUSY doesn't naturally conserve B/L numbers:

$$\epsilon\,\hat{L}\hat{Q}\hat{D}^c + \epsilon\,\hat{L}\hat{L}\hat{E}^c + \epsilon\,\hat{L}\hat{H}_u \in \hat{f}_{\Delta L=1}$$
$$\hat{U}^c\hat{U}^c\hat{D}^c \in \hat{f}_{\Delta B=1}$$

- This gives unobserved phenomena such as rapid proton decay

$$P \rightarrow \pi^0 + e^+$$

- MSSM introduces a $\mathbb{Z}_2$ symmetry: **R parity**

$$R[\text{SM particles}] = 1 \qquad R[\text{Superpartners}] = -1$$

A Continuous R Symmetry

- N=1 SUSY has a U(1) R symmetry

$$[Q, R] = i\gamma_5 Q$$

$$\hat{\mathcal{S}}^{(1)}(\hat{x},\theta) = \mathcal{S}^{(1)} + i\sqrt{2}\bar{\theta}^{(1)}\psi_L^{(0)} + i\bar{\theta}\theta_L^{(2)}\mathcal{F}^{(-1)}$$

Quantity	$U(1)_R$
$\theta_{L/R}$	± 1
$\hat{\mathcal{S}}$	$+1$
$\hat{h}$	0
$\hat{V}$	0

- B and L violating terms forbidden:

$$R\left[\bar{\psi}\left(\frac{\partial^2 \hat{f}}{\partial\hat{\mathcal{S}}_i\partial\hat{\mathcal{S}}_j}\right)\psi_L\right] = 0 \quad \Rightarrow \quad R\left[\hat{f}\right] = +2$$

$$\cancel{\epsilon\,\hat{L}^{(1)}\hat{Q}^{(1)}\hat{D}^{c(1)}} + \cancel{\epsilon\,\hat{L}^{(1)}\hat{L}^{(1)}\hat{E}^{c(1)}} + \cancel{\epsilon\,\hat{L}^{(1)}\hat{H}_u^{(0)}} \in \hat{f}^{(2)}_{\Delta L=1}$$

$$\cancel{\hat{U}^{c(1)}\hat{U}^{c(1)}\hat{D}^{c(1)}} \in \hat{f}^{(2)}_{\Delta B=1}$$

A Continuous R Symmetry

- $U(1)_R$ symmetry reduces the parameter space:

$$\hat{f}^{(2)} = \cancel{\mu \hat{H}_u^{(0)} \hat{H}_d^{(0)}} + \mathbf{f}_u \epsilon_{ab} \hat{Q}^{(1)a} \hat{H}_u^{(0)a} \hat{U}^{c(1)} + \mathbf{f}_d \hat{Q}^{(1)} \hat{H}_d^{(0)} \hat{D}^{c(1)} + \mathbf{f}_e \hat{L}^{(1)} \cdot \hat{H}_d^{(0)} \hat{E}^{c(1)}$$

$$\mathcal{L}_{\text{soft}}^{(0)} = \left[\tilde{Q}_i^{\dagger(-1)} \mathbf{m}^2_{Qij} \tilde{Q}_j^{(1)} + \ldots + m^2_{H_u} |H_u|^{2(0)} + \ldots \right] - \frac{1}{2} \left[\cancel{M_1 \bar{\lambda}_0^{(1)} \lambda_0^{(1)}} + \ldots \right] + \left[\cancel{(\mathbf{a_u})_{ij} \epsilon \tilde{Q}_i^{(1)} H_u^{(0)} \tilde{u}_{Rj}^{\dagger(1)}} + \ldots \right] + \left[\cancel{(\mathbf{c_u})_{ij} \epsilon \tilde{Q}_i^{(1)} H_d^{*(0)} \tilde{u}_{Rj}^{\dagger(1)}} + \ldots \right] + \left[b H_u^{(0)} H_d^{(0)} + \text{ h.c} \right]$$

- Problem: massless gauginos...

The MRSSM

- Solution: The Minimal R-symmetric Supersymmetric Standard Model [Kribs, Poppitz and Weiner, Phys. Rev. D78 (2008) 055010]
- Add chiral superfields with adjoint gauge representation

$$\hat{\Phi}_A \ni (\phi_A, \psi_{LA}, \mathcal{F}_A)$$

- The two Majorana spinors combine to give a **Dirac spinor**:

$$\tilde{g}_A \equiv \psi_{LA} + \lambda_{RA}$$

- Dirac mass is generated by breaking of a spurion field

$$\hat{Y} \rightarrow \ldots - i\theta_L \langle D' \rangle + \ldots$$

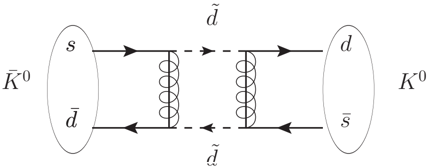
$$\left(\overline{\hat{Y}^c} \hat{W}_A \hat{\Phi}_A + \text{ h.c} \right) \Big|_{\mathcal{F}\text{-term}} \quad \in \mathcal{L}$$

$$\rightarrow \quad -\langle D' \rangle \bar{\tilde{g}} \tilde{g}$$

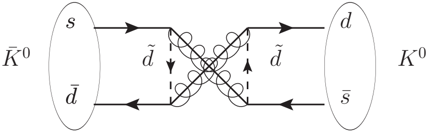
Squark Flavour Mixing

$$\tilde{Q}_i^\dagger \mathbf{m}^2_{Qij} \tilde{Q}_j \in \mathcal{L}_{\text{soft}}$$

- Squark flavour mixing gives contributions to meson mixing experiments
- Heavily suppressed in the MSSM: $\sqrt{\delta_{LL}\delta_{RR}} \leq 9.6 \times 10^{-4}$ [Ciuchini *et al.*]



$$\propto \left(\frac{\not{k}}{m_{\tilde{g}}{}^2}\right)^2$$



$$\propto \left(\frac{m_{\tilde{g}}}{m_{\tilde{g}}{}^2}\right)^2$$

Squark Flavour Mixing

- In MRSSM gluino is a **Dirac fermion**, so the dominant mixing diagram is forbidden
- The remaining box diagram has an additional factor

$$\left(\frac{\not{k}}{m_{\tilde{g}}}\right)^2 \sim \left(\frac{m_{\tilde{q}}}{m_{\tilde{g}}}\right)^2$$

- Thus squark flavour mixing in MRSSM not phenomenologically suppressed when $m_{\tilde{g}} > m_{\tilde{q}}$

$$\tilde{q}_a = \sum_i \left(U_{\tilde{q}}^{\dagger}\right)_{ai} \tilde{q}_i$$

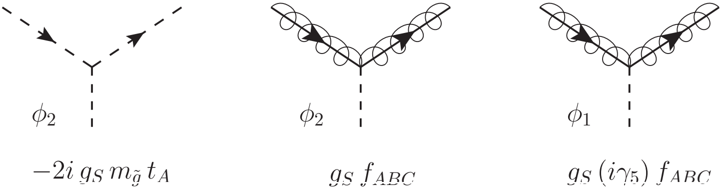
Scalar Gluons (sgluons)

$$\hat{\Phi}_A \ni (\phi_A, \psi_{LA}, \mathcal{F}_A)$$

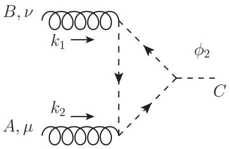
- In MRSSM QCD we have a colour octet complex scalar field:

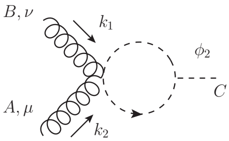
$$\phi_{GA} \equiv \frac{\phi_{2A} + i\phi_{1A}}{\sqrt{2}}$$

- ϕ_2 and ϕ_1 are the physical mass eigenstates: **sgluons**
- At tree level, sgluons couple to squarks and gluinos

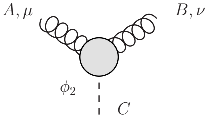


Gluons-Sgluon One Loop Coupling





Effective vertex:

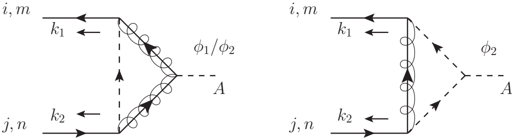


$$= \quad \mathcal{M}^{\mu\nu}_{ABC}$$

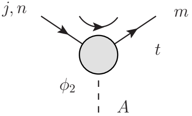
$$\mathcal{M}^{\mu\nu}_{ABC} = \quad 2\, m_{\tilde{g}}\, g_S^3\, d_{ABC} \left[g^{\mu\nu} - \frac{2 k_1^\mu k_2^\nu}{(k_1 + k_2)^2} \right]$$

$$\times \left\{ \sum_{\tilde{q}} m^2_{\tilde{q}L}\, C_0(k_1, k_2; m_{\tilde{q}L}, m_{\tilde{q}L}, m_{\tilde{q}L}) - (L \leftrightarrow R) \right\}$$

Quarks-Sgluon One Loop Coupling



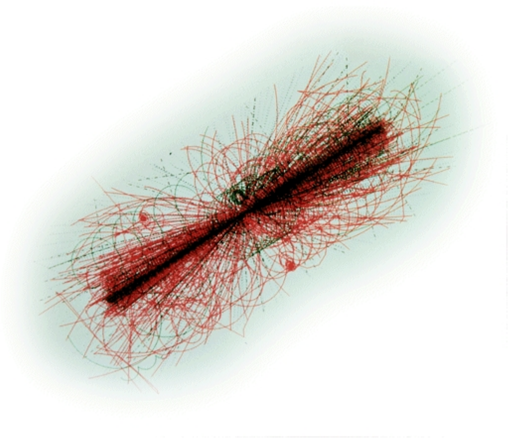
Effective vertex:



$= \mathcal{M}_t^{\phi_2}$

$$\mathcal{M}_t^{\phi_2} = \frac{ig_S^3}{8\pi^2}\frac{m_{\tilde{g}}m_t}{s-m_t^2}(t_A)_{mn}\Bigg\{ \bar{u}_{3m}(k_1)P_L v_{jn}(k_2) \times \left(\sum_{\tilde{q}a}(U_{\tilde{q}L})_{3a}(U^{\dagger}_{\tilde{q}L})_{aj} f_t(s; m_{\tilde{q}aL})\right) + (L \leftrightarrow R)\Bigg\}$$

Numerical Methods



Multi-dimensional Integration

$$\hat{\sigma} = \frac{(2\pi)^4}{\mathcal{F}} \int \prod^{n}{}_{j=1} \frac{d^3\mathbf{p}_j}{(2\pi)^3 2E_j} \; \delta^{(4)}(q - \sum_{j=1}^{n} p_j) \; |\overline{\mathcal{M}}|^2$$

- 3n - 4 integration variables $\Rightarrow$ numerical integration
- Convergence of Monte Carlo integration independent of dimension

Monte Carlo Integration

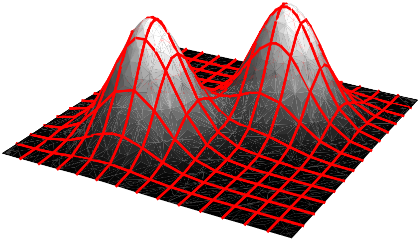
- By the law of large numbers can integrate over a hypercube by picking random points:

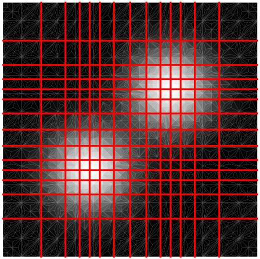
$$I = \int d^d\mathbf{x}\, f(\mathbf{x}) = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} f(\mathbf{x}_n)$$

- Large N gives an estimate E with variance: $E - I \propto \frac{1}{\sqrt{N}}$

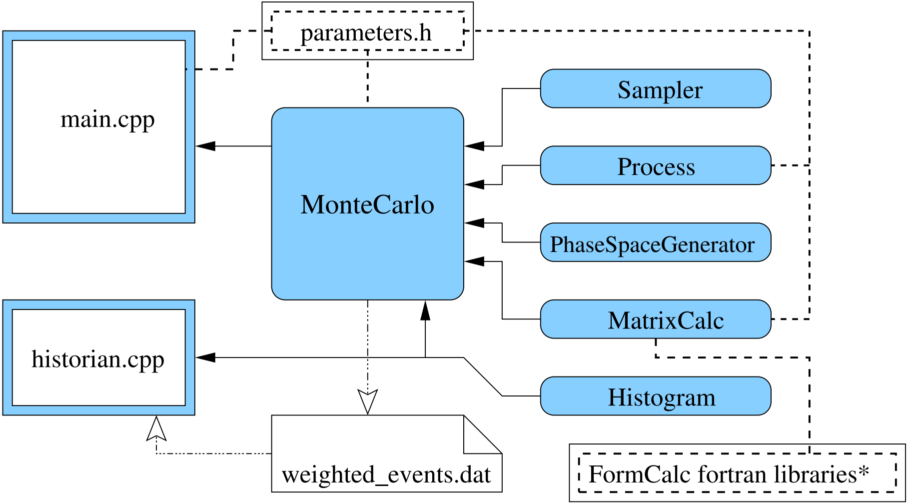
Improving Convergence

- Use adaptive algorithm to bias the sampling to regions with greater variance.
- The adaptive **VEGAS algorithm**:
  - Splits domain into a grid. Each subspace has uniform probability density
  - Shifts grid lines towards regions of higher variance after each iteration





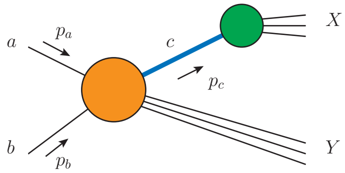
Our Monte Carlo Program



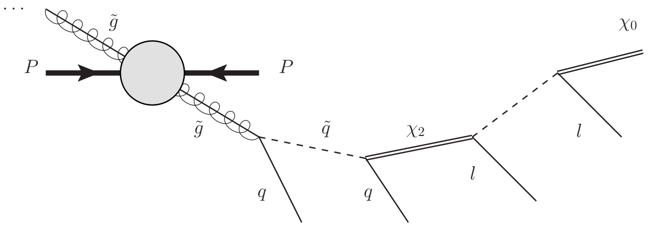
*[T. Hahn and M. Perez-Victoria, arXiv:hep-ph/9807565v1]

Breit-Wigner Factorization Implemented

- Dominant contribution when particle c close to mass-shell
- Arbitrary decay chains straightforward



$$d\sigma^{\text{tot}} \simeq \mathbf{d}\sigma^{\text{prod}} \cdot \left\{ \frac{1}{\pi} \frac{m_c \Gamma}{(s_c - m_c^2)^2 + m_c^2 \Gamma^2} \right\} \mathbf{ds_c} \cdot \frac{\sqrt{s_c + \mathbf{p_c}^2}\, \mathbf{d\Gamma(p_c)}}{m_c \Gamma}$$



Validity Check

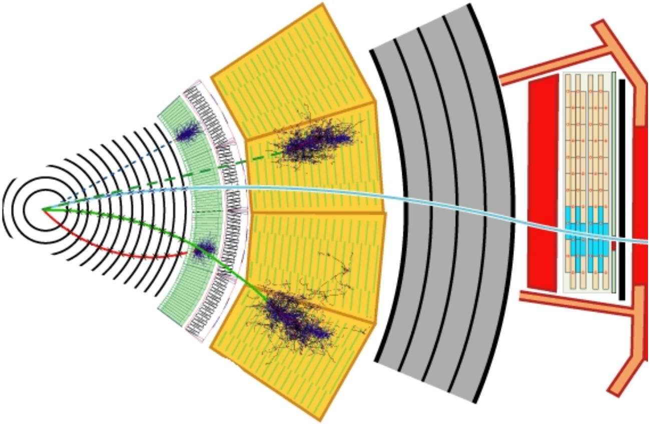
- Compare with analytical solution for the process

$$q + \bar{q} \to \tilde{g} + \tilde{g}$$

Method	$\hat{\sigma}$ [fb] (2 TeV)
Analytical	691.693
Our Monte Carlo	691.754 ± 0.069
Madgraph/MadEvent†	693.610 ± 3.102

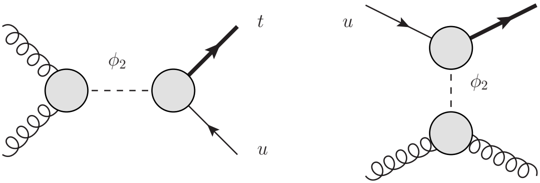
†[Alwall, Demin, Visscher, Frederix, Herquet, Maltoni, Plehn, Raindwater and Stelzer, JHEP0709 028 (2008)]

Phenomenology

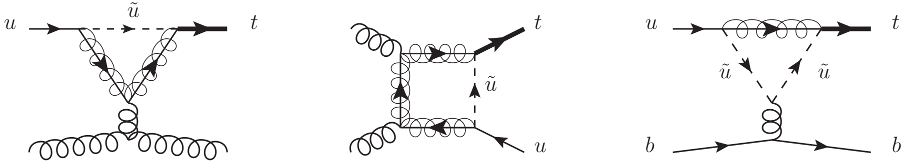


Strong Flavour Changing Interactions

- QCD sector of MRSSM has flavour changing interactions
  - **Single top quark production** possible
- Sgluon mediated: 2 diagrams

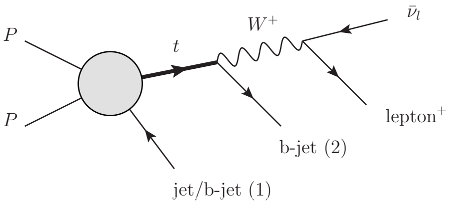


- Non-sgluon mediated: 60 diagrams (FeynArts/FormCalc)



Detection of Single Top Production

- Top has large decay width, thus decays quickly: $\mathrm{Br}(t \to W\, b) \sim 1$
- Most interesting decay of W boson is to leptons: $\mathrm{Br}(W \to l^+\, \nu_l) = 0.11$

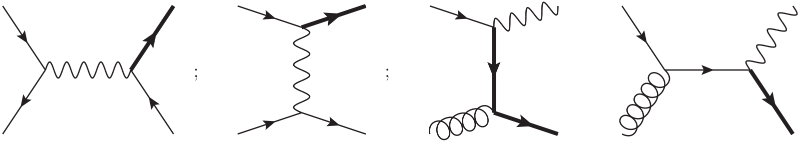


- Detectors have a b-tagging efficiency of ∼50%. Signals of interest are thus
  - $2\, b\text{-jets} + l^+ + \not{E}_T$
  - $b\text{-jet} + \text{jet} + l^+ + \not{E}_T$

Background: Standard Model Single Top

- Standard Model has flavour changing interactions in the **electroweak** sector:

$$\frac{g}{\sqrt{2}} V_{tb} \bar{t} \gamma^{\mu} P_L b W_{\mu} + \text{ h.c} \in \mathcal{L}_{\text{SM}}$$



(s) (t) (Wt)

- **Irreducible background** will be given by the s and t channels

MRSSM Parameter Space

- Assume two mixed squark flavours for simplicity

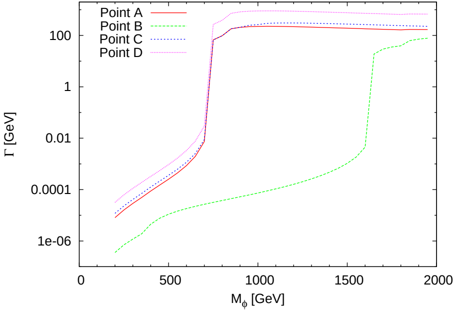
$$U_{\tilde{u}L} = \begin{pmatrix} \cos\theta_L & 0 & \sin\theta_L \\ 0 & 1 & 0 \\ -\sin\theta_L & 0 & \cos\theta_L \end{pmatrix}$$

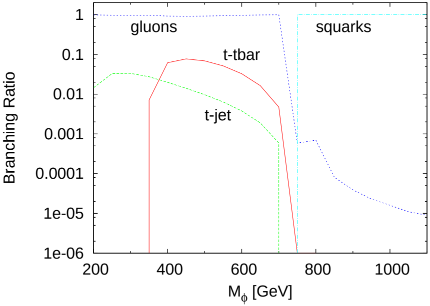
- Pick six points in parameter space:

Benchmark	$m_{\tilde{g}}$	$m_{\tilde{u}L} = m_{\tilde{d}L}$	$m_{\tilde{q}R}/m_{\tilde{q}L}$	$\theta_L = \theta_R$
Point A	1000	{400, 400, 1000}	0.9	$\pi/4$
Point B	1000	{900, 900, 1500}	0.9	$\pi/4$
Point C	1000	{400, 400, 500}	0.9	$\pi/4$
Point D	2000	{400, 400, 1000}	0.9	$\pi/4$
Point E	500	{400, 400, 1000}	0.9	$\pi/4$
Point F	1000	{400, 400, 1000}	0.9	$\pi/3$

Sgluon Mediated Single Top

- Sgluon has very narrow decay width when squark/gluino decays kinematically forbidden



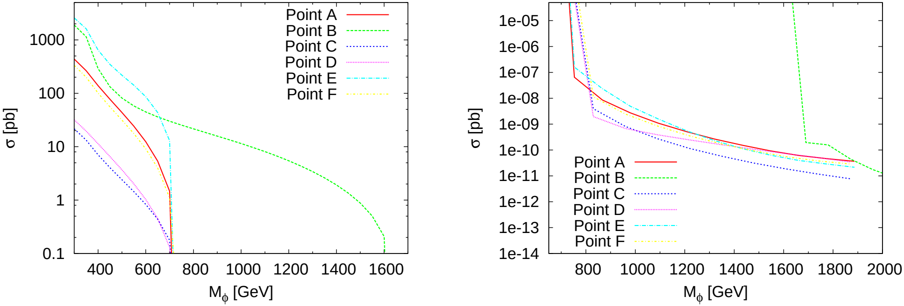


- Can therefore use **narrow width approximation** in this region

$$\sigma(gg \to t\bar{q})\Big|_{s=M_\phi^2} = \frac{\pi}{M_\phi^2}\mathrm{Br}(\phi_2 \to gg)\mathrm{Br}(\phi_2 \to t\bar{q})$$

Sgluon Mediated Single Top

- Cross section of s-channel sgluon mediated single top production:



- **Ideal detector** would give a single spiked bin on invariant mass distribution plots

Non-sgluon Mediated Single Top

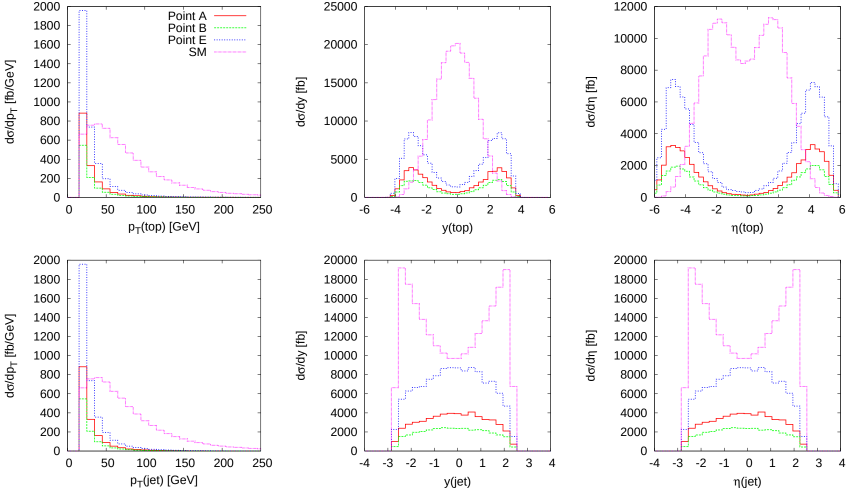
- $t +$ jet dominates $t +$ b-jet:

	$\sigma_{\text{LO}}(t + \text{jet})$ [pb]	$\sigma_{\text{LO}}(t + \text{b-jet})$ [pb]
Point A	16.3 ± 0.2	0.449 ± 0.002
Point B	10.16 ± 0.05	0.282 ± 0.001
Point C	0.46 ± 0.03	0.0152 ± 0.0001
Point D	4.0 ± 0.3	0.115 ± 0.009
Point E	36.0 ± 0.3	0.991 ± 0.004
Point F	12.06 ± 0.05	0.336 ± 0.002
Standard Model	69.1 ± 0.2	3.39 ± 0.01

- Standard Model gives sizable background

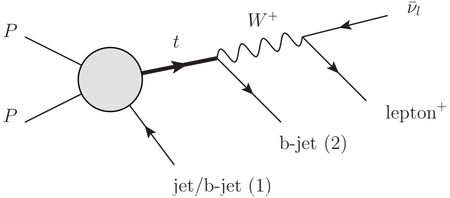
Non-sgluon Mediated Single Top

- $t +$ jet: top quark is very forward



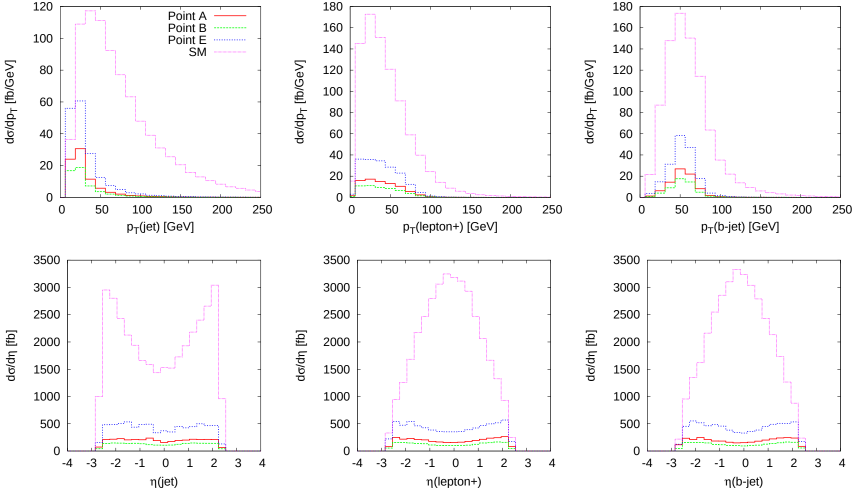
Signals at the LHC

- Consider signal of non-sgluon mediated single top at the LHC
- Take as background **irreducible** Standard Model processes



Signals at the LHC

- b-jet + jet + l^+ + $\not{E}_T$



Signals at the LHC

- Place **kinematic cuts**:
  - 1. $p_T(\text{jet}/b\text{-jet } 1) \leq 75$ GeV.
  - 2. $|\eta(l^+)| \geq 0.5$ and $|\eta(b\text{-jet } 2)| \geq 0.5$.
- Assume b-tagging efficiency of 50%. For integrated luminosity L:
  - $2\, b\text{-jets} + l^+ + \not{E}_T$:

$$S = (0.5)^2 \times \sigma(\text{2b-jets}) \times L$$
$$B = (0.5)^2 \times \sigma_{\text{SM}}(\text{2b-jets}) \times L$$

  - $b\text{-jet} + \text{jet} + l^+ + \not{E}_T$:

$$S = 0.5 \times \sigma(\text{b-jet}) \times L + 2 \times (0.5)^2 \times \sigma(\text{2b-jets}) \times L,$$
$$B = 0.5 \times \sigma_{\text{SM}}(\text{b-jet}) \times L + 2 \times (0.5)^2 \times \sigma_{\text{SM}}(\text{2b-jets}) \times L.$$

- For signal discovery, need $S/B \gtrsim 10\%$ and statistical significance $S/\sqrt{B} \geq 5$

Signals at the LHC

- 2 b-jets + l^+ + $\not{E}_T$: luminosity of 10 fb^{-1}

		No Cuts†	Cut 1	Cuts 1 & 2
Point A	S/B	0.05	0.10	0.14
	$S/\sqrt{B}$	1.8	2.4	2.5
Point B	S/B	0.03	0.06	0.09
	$S/\sqrt{B}$	1.1	1.5	1.6
Point C	S/B	0.00	0.00	0.00
	$S/\sqrt{B}$			
Point D	S/B	0.01	0.03	0.04
	$S/\sqrt{B}$	0.5	0.7	0.8
Point E	S/B	0.11	0.21	0.31
	$S/\sqrt{B}$	4.0	5.3	5.6
Point F	S/B	0.04	0.07	0.10
	$S/\sqrt{B}$	1.3	1.8	1.9

Signals at the LHC

- b-jet + jet + l^+ + $\not{E}_T$: luminosity of 10 fb^{-1}

		No Cuts†	Cut 1	Cuts 1 & 2
Point A	S/B	0.09	0.16	0.23
	$S/\sqrt{B}$	22.2	27.7	28.3
Point B	S/B	0.06	0.10	0.15
	$S/\sqrt{B}$	14.2	17.8	18.3
Point C	S/B	0.00	0.01	0.01
	$S/\sqrt{B}$			
Point D	S/B	0.03	0.05	0.07
	$S/\sqrt{B}$	6.6	8.3	8.6
Point E	S/B	0.20	0.35	0.49
	$S/\sqrt{B}$	48.6	60.5	61.5
Point F	S/B	0.07	0.12	0.17
	$S/\sqrt{B}$	16.9	21.1	21.8

Signals at the Tevatron

- Tevatron recently detected single top production at D0 and CDF
- Can Tevatron 2-jets $+ l^+ + \not{E}_T$ data rule out MRSSM? **...No**

		CDF (3.2 fb^{-1})	D0 (2.3 fb^{-1})
Tevatron data		3315	2579
Standard Model	B	3377 ± 505	2615 ± 192
Point A	S/B	0.01	0.01
	$S/\sqrt{B}$	0.6	0.5
Point B	S/B	0.01	0.01
	$S/\sqrt{B}$	0.4	0.3
Point E	S/B	0.02	0.02
	$S/\sqrt{B}$	1.4	1.1
Point F	S/B	0.01	0.01
	$S/\sqrt{B}$	0.5	0.4

Summary

- Derived Feynman rules and mass spectrum for QCD sector of the MRSSM
- Developed a Monte Carlo program to calculate cross sections
- Studied single top phenomenology of the MRSSM
- Outlook:
  - Check parameter points w.r.t meson mixing: $\mathbf{m_{\tilde{g}}} > \mathbf{m_{\tilde{q}}}$
  - Add reducible backgrounds
  - Add hadronization effects