Mixed gluinos and sgluons from a new $SU(3) \times SU(3)$ gauge group

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No SUSY at LHC so far, but no other resolution of hierarchy problem, either.

Consider extensions of minimal SUSY at the energy frontier. Possibilities include:

- Extra chiral supermultiplets (vectorlike reps of the gauge group):
  - NMSSM (extra singlet)
  - extended Higgs sector
  - vectorlike quark and lepton supermultiplets
- Extra gauge supermultiplets
  - new U(1) (Z')
  - extended electroweak gauge sector
  - **extend color group**

This talk: QCD color from $SU(3)_A \times SU(3)_B \to SU(3)_C$ in SUSY.

QCD color from $SU(3)_A \times SU(3)_B \to SU(3)_C$ in SUSY.

Chiral supermultiplets: $\Phi_j^k \sim (\mathbf{3},\, \overline{\mathbf{3}})$ and $\overline{\Phi}_k^j \sim (\mathbf{3},\, \overline{\mathbf{3}})$ will get VEVs that preserve the diagonal $SU(3)_C$.

Scalar components expanded around VEVs v and $\overline{v}$:

$$\Phi_j^k = \delta_j^k (v + \phi_0) + T_j^{ak} \phi^a, \qquad \overline{\Phi}_k^j = \delta_k^j (\overline{v} + \overline{\phi}_0) + T_k^{aj} \overline{\phi}^a.$$

Gluon, heavy octet vector X are mixtures of $SU(3)_A$ and $SU(3)_B$ vector bosons:

$$\begin{pmatrix} G_\mu^a \\ X_\mu^a \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A_\mu^a \\ B_\mu^a \end{pmatrix}, \qquad \tan\theta = g_A/g_B.$$

with

$$g_C = \frac{g_A g_B}{\sqrt{g_A^2 + g_B^2}}, \qquad M_X^2 = (g_A^2 + g_B^2)(v^2 + \overline{v}^2),$$

Extensive literature in non-SUSY models for this symmetry breaking pattern: axigluon, topcolor, coloron models.

Most general renormalizable superpotential of this theory is:

$$W = \frac{1}{6}\epsilon^{jkl}\epsilon_{mnp}\left(y\,\Phi_j^m\Phi_k^n\Phi_l^p + \overline{y}\,\overline{\Phi}_j^m\overline{\Phi}_k^n\overline{\Phi}_l^p\right) - \mu_\Phi\Phi_j^k\overline{\Phi}_k^j + W_{\rm MSSM},$$

Existence of y, $\overline{y}$ Yukawa couplings relies on $N_c = 3$.

Assume all MSSM quark+squark superfields transform under $SU(3)_A$.

Soft SUSY-breaking Lagrangian:

$$\begin{aligned}\mathcal{L}_{\rm soft} &= -\frac{1}{2}M_A\lambda_A\lambda_A - \frac{1}{2}M_B\lambda_B\lambda_B \\ &\quad -\frac{1}{6}(a\phi\phi\phi + \overline{a}\,\overline{\phi}\,\overline{\phi}\,\overline{\phi}) + b_\phi\phi\overline{\phi} - m^2|\phi|^2 - \overline{m}^2|\overline{\phi}|^2 \\ &\quad + \text{(MSSM part)}\end{aligned}$$

Note: a, $\overline{a}$, b_ϕ couplings all favor $SU(3)_A \times SU(3)_B$ breaking. However, if $|b_\phi|$ is **too** large, will have a dangerous unbounded from below (UFB) instability.

Can the resulting potential give the correct symmetry breaking pattern?

Warm-up exercise: the potential in the SUSY limit

The D-flat direction of the scalar potential is:

$$V(v, \overline{v}) \quad = \quad 3|yv^2 - \mu_\Phi \overline{v}|^2 + 3|\overline{y}\,\overline{v}^2 - \mu_\Phi v|^2$$

Two distinct, disconnected, degenerate, SUSY-preserving minima, at:

- $v = \overline{v} = 0$ (gauge symmetry unbroken)
- $v = \mu_\Phi/(y^2\overline{y})^{1/3}$ and $\overline{v} = \mu_\Phi/(\overline{y}^2 y)^{1/3}$ (SU(3)$_A \times$ SU(3)$_B \rightarrow$ SU(3)$_C$)

In the latter vacuum, the particle spectrum is:

- Massless SU(3)$_C$ gluon/gluino
- Color octet vector and fermion: $M_X^2 = (g_A^2 + g_B^2)(v^2 + \overline{v}^2)$
- Color octet scalar and fermion: $M^2_{\rm octet} = R^2|\mu_\Phi|^2$
- Singlet scalar and fermion: $M^2_{\rm singlet} = (2R^2 - 3 \pm 2R\sqrt{R^2 - 3})|\mu_\Phi|^2$

where $R = |y/\overline{y}|^{1/3} + |\overline{y}/y|^{1/3} > 2.$

Now include SUSY breaking terms in the potential.

Possible vacua:

- No vacuum: potential unbounded from below **(not our world)**
- SU(3)$_A\times$ SU(3)$_B$ unbroken **(not our world)**
- SU(3)$_A\times$ SU(3)$_B$ $\rightarrow$ SU(2)$\times$SU(2)$\times$U(1) **(not our world)**
  Only occurs in small sliver: $(|\mu_\Phi|^2+m^2)(|\mu_\Phi|^2+\overline{m}^2) \;<\; |b_\phi|^2 \;<$ $(|\mu_\Phi|^2+m^2)(|\mu_\Phi|^2+\overline{m}^2)+\frac{1}{4}(m^2-\overline{m}^2)^2.$
- SU(3)$_A\times$ SU(3)$_B$ $\rightarrow$ SU(3)$_C$ **(could be our world)**
  If $y, \overline{y}, a, \overline{a}, \mu_\Phi, b_\phi$ are all real, then depending on their magnitudes could have:
  - $v, \overline{v}$ real ("Good Vacuum")
  - $v, \overline{v}$ complex (spontaneous CP violation)

In general, the conditions for a Good Vacuum are very complicated, but can be analyzed numerically.

One simple case can be done analytically. . .

Consider for simplicity: $\overline{y} = y$ and $\overline{a} = a$ and $\overline{m}^2 = m^2$, and define:

$$A = \frac{a}{y\mu_\Phi}, \qquad B = \frac{b_\phi}{\mu_\Phi}, \qquad C = \frac{m^2}{\mu_\Phi^2}.$$

Avoiding an unbounded from below runaway direction in potential requires:

$$|B| < 1 + C.$$

A stable Good Vacuum $v = \overline{v}$ with

$$x \quad \equiv \quad \frac{v\mu_\Phi}{y} \quad = \quad \frac{3-A}{4}\left(1 + \sqrt{1 + 8(B - C - 1)/(3-A)^2}\right)$$

requires:

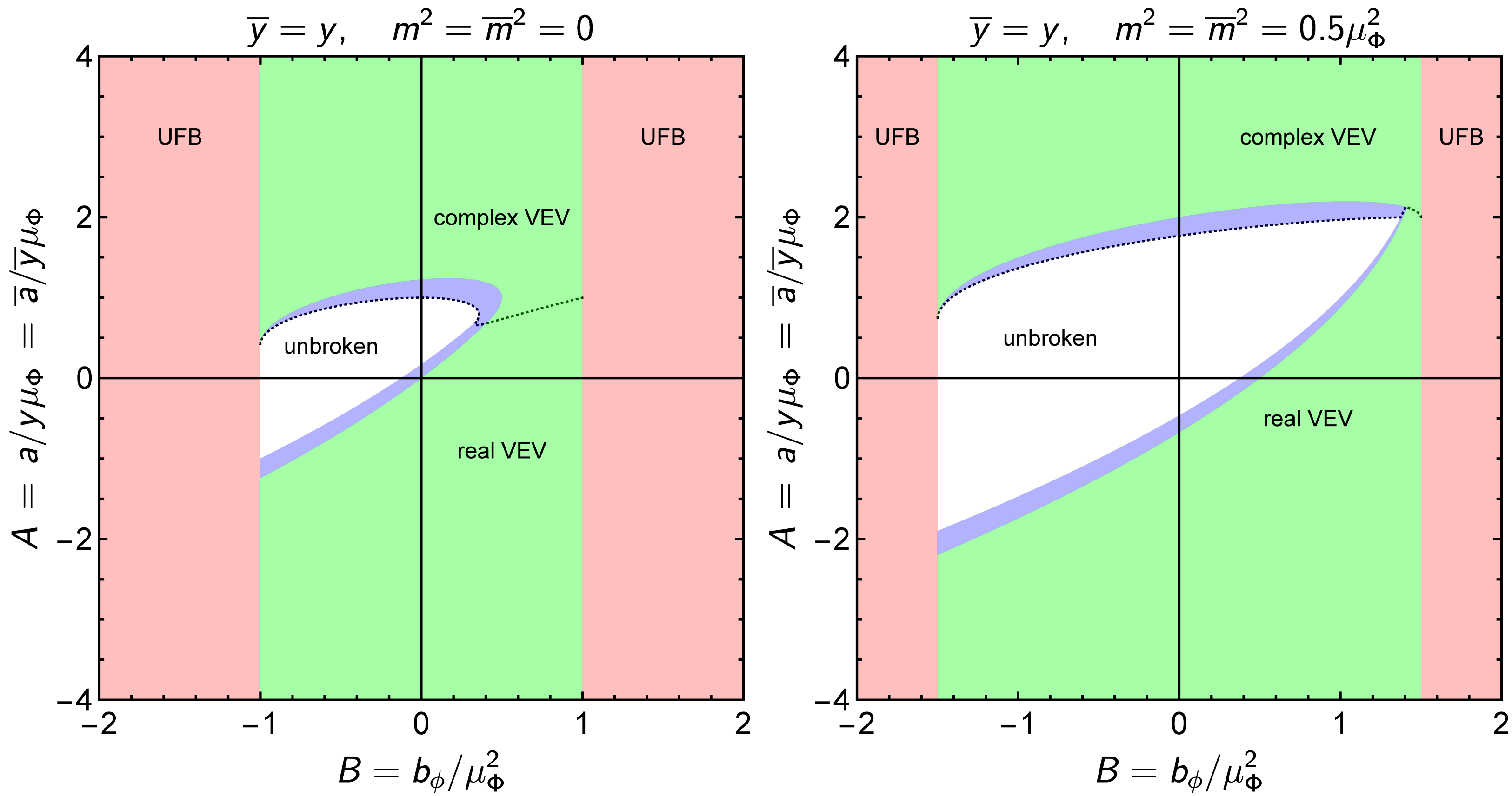
$$\begin{aligned} (3-A)^2 \quad &> \quad 8(1 - B + C) \qquad \text{(local minimum)} \\ (3-A)^2 \quad &> \quad 9(1 - B + C) \qquad \text{(global minimum)} \end{aligned}$$

and four more conditions:

$$(1 + nx)^2 + C \;>\; |B + nx(A + x - 1)| \qquad \text{for } n = 1, 2, -2, \text{ and}$$
$$(g_A^2 + g_B^2)x^2 + (1 - x)^2 \;>\; -C.$$

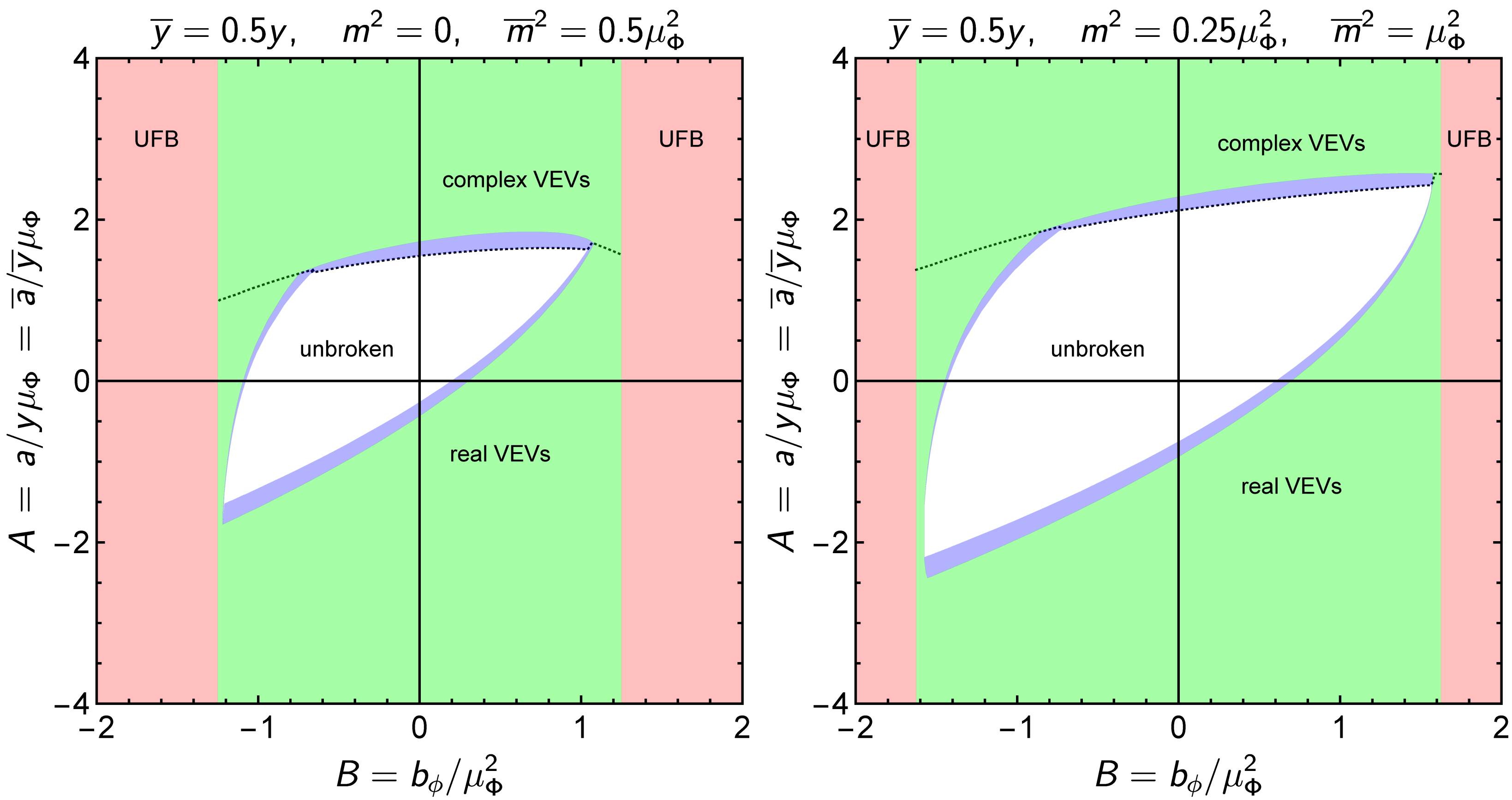
Together, these are necessary and sufficient for a Good Vacuum.

Phase diagrams for $SU(3)_A \times SU(3)_B$ breaking:



The SUSY limit occurs at the origin of the left panel; there the local broken minimum is exactly degenerate with the local unbroken minimum (blue meets green).

Phase diagrams for sample models with $y \neq \overline{y}$ and $m^2 \neq \overline{m}^2$:



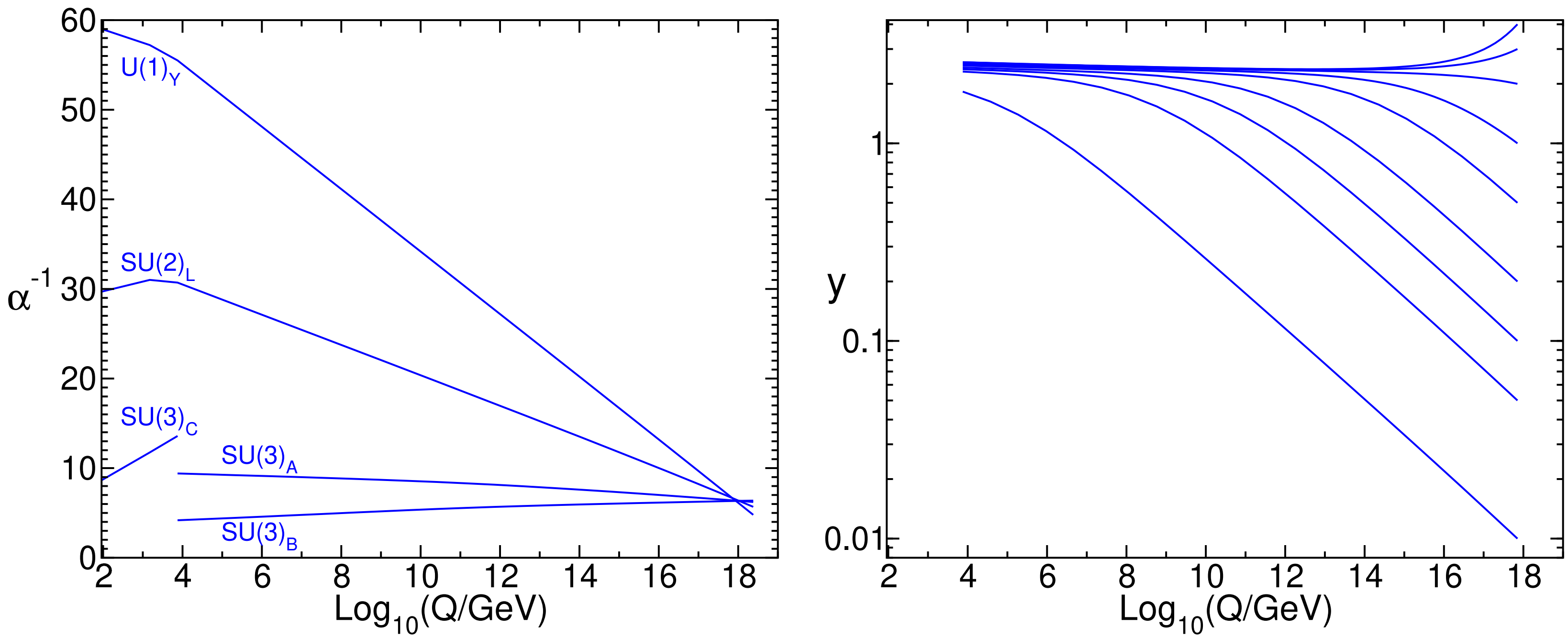
Recall we chose MSSM quarks+squarks to live in $SU(3)_A$. Gauge coupling unification can be achieved by adding vectorlike quark and lepton superfields, for example, with reps under $SU(3)_A \times SU(3)_B \times SU(2)_L \times U(1)_Y$:

$(\mathbf{1}, \mathbf{3}, \mathbf{2}, \frac{1}{6}) + (\mathbf{1}, \overline{\mathbf{3}}, \mathbf{2}, -\frac{1}{6}) + 3 \times \left[(\mathbf{1}, \mathbf{3}, \mathbf{1}, -\frac{1}{3}) + (\mathbf{1}, \overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})\right] +$
$(\mathbf{1}, \mathbf{1}, \mathbf{1}, -1) + (\mathbf{1}, \mathbf{1}, \mathbf{1}, 1)$.

Consequences:

- Unification scale at 7×10^{17} GeV.
- Both $SU(3)_A$ and $SU(3)_B$ gauge couplings g_A, g_B run slowly, are rather strongly coupled up to unification scale.
- Yukawa couplings y and $\overline{y}$ have IR-attractive quasi-fixed point renormalization group running.
  $\beta_y \sim y(6y^2 - 8g_A^2 - 8g_B^2)$
- $A = a/y\mu_\Phi$ and $B = b/\mu_\Phi^2$ are driven to negative values.
  Good Vacuum conditions are achieved!

Renormalization group running of gauge couplings (left panel) and Yukawa coupling for various different high-scale values (right panel):



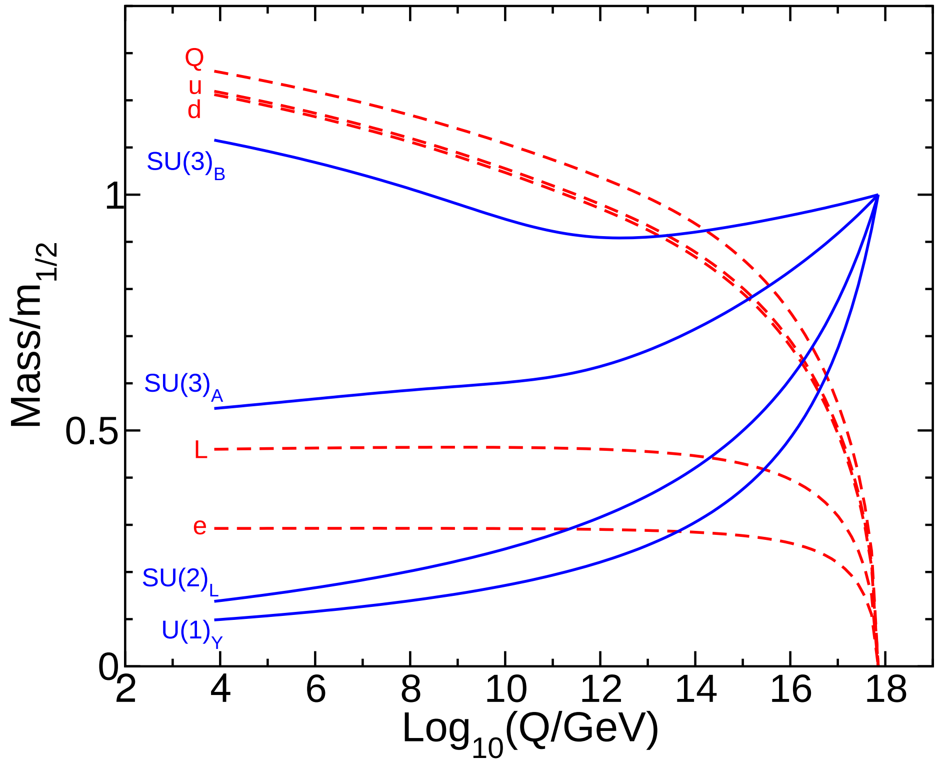
Need $SU(3)_A$ and $SU(3)_B$ fairly strongly coupled, because of

$$g_C = \frac{g_A g_B}{\sqrt{g_A^2 + g_B^2}}.$$

Note IR quasi-fixed point for Yukawa coupling is then strongly attractive.

Renormalization group running of soft gaugino and sfermion masses

Sample case with scalar masses vanishing at high scale:



Even in this no-scale (gaugino mass dominated) scenario:

- Squarks are heavier than gauginos.
- Sleptons are heavier than electroweakinos.

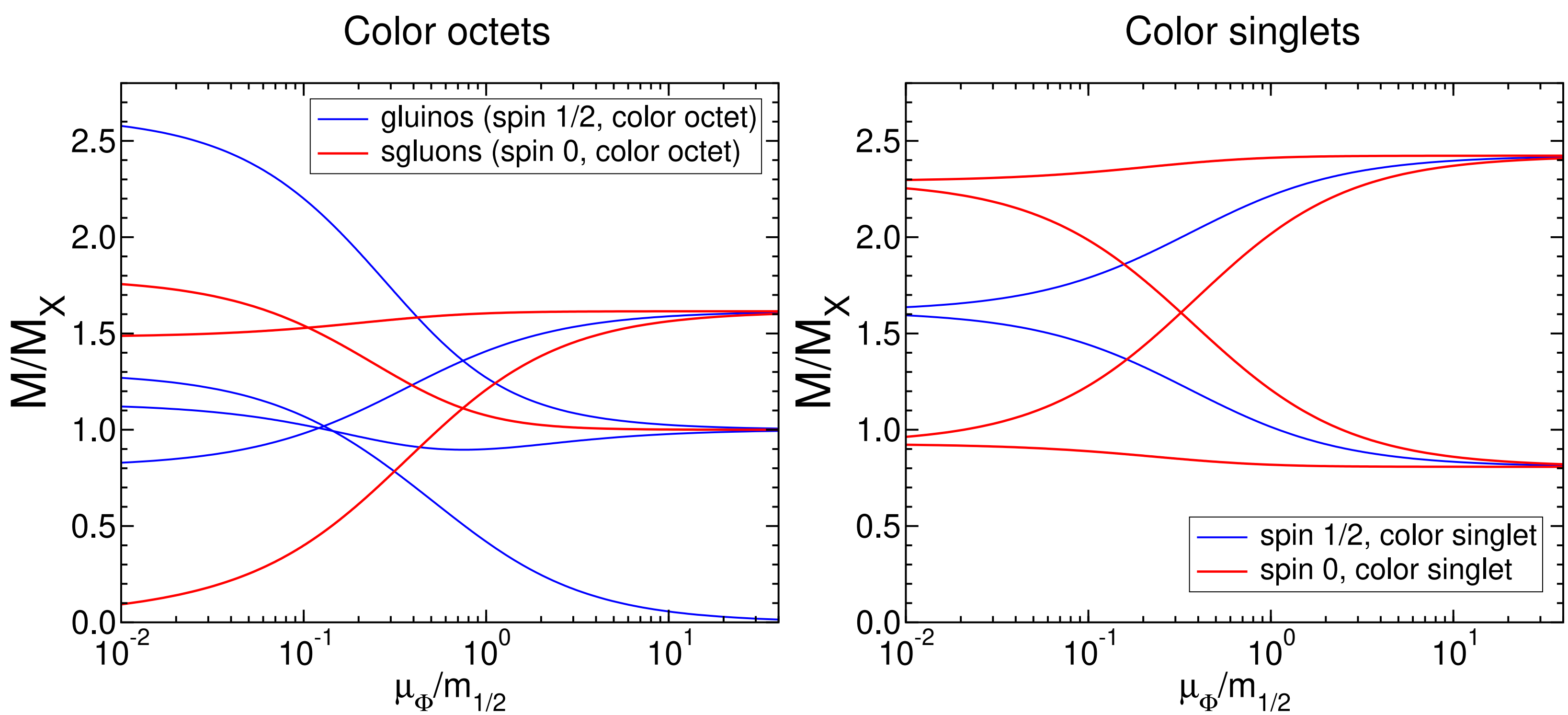
New particles beyond the MSSM:

$$\begin{aligned}
X &= \text{color octet massive vector} \\
\tilde{g}_j &= \textbf{four} \text{ color octet gluinos, } (j = 1,2,3,4) \\
\tilde{\chi}_j &= \text{two color singlet fermion singlinos, } (j = 1,2) \\
S_j &= \textbf{three} \text{ color octet real scalar sgluons, } (j = 1,2,3) \\
\varphi_j &= \text{four color singlet real scalars, } (j = 1,2,3,4).
\end{aligned}$$

The gluinos have a mixed Majorana-Dirac mass matrix:

$$M_{\tilde{g}} = \begin{pmatrix} M_A & 0 & g_A v & -g_A \overline{v} \\ 0 & M_B & -g_B v & g_B \overline{v} \\ g_A v & -g_B v & -y v & -\mu_\Phi \\ -g_A \overline{v} & g_B \overline{v} & -\mu_\Phi & -\overline{y}\,\overline{v} \end{pmatrix}.$$

Mass spectrum (normalized to the heavy vector mass M_X) as a function of the ratio $\mu_\Phi/m_{1/2}$, where $m_{1/2}$ = gaugino mass parameter:



SUSY preserving limit is large $\mu_\Phi/m_{1/2}$, one gluino much lighter than others.

If $\mu_\Phi/m_{1/2} \ll 1$, lightest gluino doesn't couple to MSSM quark-squark pairs.

One gluino is (almost) always lighter than heavy vector octet.

Lightest color octet scalar sgluon could be heavier or lighter.

Lightest color singlet is always heavier than at least one gluino or sgluon.

Brief comments on phenomenology for LHC

Massive spin-1 color octet produced in $q\overline{q}$, can decay in the dijet channel:

$$q\overline{q} \to X \to q\overline{q}$$

Limit from dijet resonance search CMS 1911.04947: $M_X > 6.6$ TeV, assuming $g_A = g_B$. But in the present case, the limit will be weaker, for two reasons:

- Here, $g_A < g_B$, so coupling to ordinary quarks is weaker, production cross-section will be smaller.
- Could have other decays, including sgluon pairs or gluino pairs.

ex

Four gluinos (color octet fermions) can be pair-produced in gluon fusion and $q\bar{q}$ at LHC.

Just as in MSSM, can decay to neutralinos and charginos:

$$\tilde{g}_j \quad \rightarrow \quad q\overline{q}\tilde{N} \;\; \underline{\text{or}} \;\; q\overline{q}\tilde{C}$$

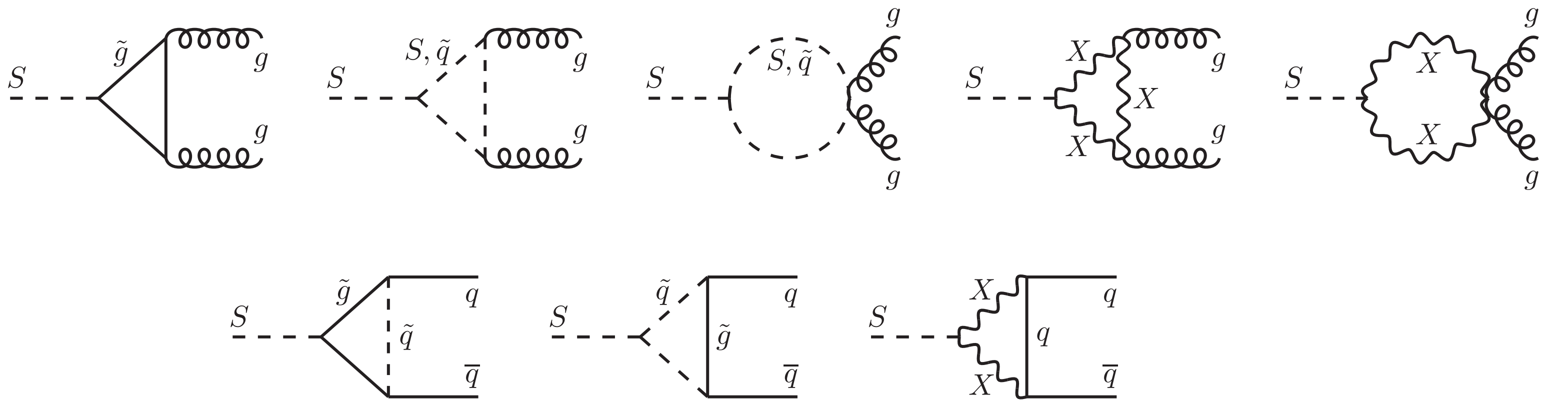
However, may also decay in a variety of 2-body modes, if kinematically allowed: $\tilde{g}_k X$ or $\tilde{\chi}_k X$ or $\tilde{g}_k S$ or $\tilde{\chi}_k S$ or $\tilde{g}_k \varphi_l$.

As in the MSSM, final states of pair-produced gluino always have at least four jets plus missing transverse energy signatures, sometimes with leptons from chargino or neutralino decays, and often with bottom jets from the kinematic enhancement of lighter bottom and top squarks in the cascade decays.

Unlike the case of pure or mostly Dirac gluinos, one of the gluinos often has an **enhanced** coupling to quark-squark pairs. But, this need not be the lightest of the four gluinos.

When the lightest gluino is not gaugino-like and has very small couplings to quark-squark pairs, it is accompanied by a much lighter sgluon.

Three sgluon (scalar octet) mass eigenstates can be pair-produced, but also singly produced from the following effective Sgg and $Sq\overline{q}$ couplings:



Some selection rules and suppressions noted in previously considered models of sgluons (Plehn and Tait 0810.3919, Choi, Drees, Kalinowski, Kim, Popenda, Zerwas, 0812.3586) do not apply here, so single production of sgluons could be larger than previously considered. First BSM signal: a dijet resonance?

CMS has limits on dijet resonances, but if the sgluon mainly decays in the gg channel, signal/background interference could be significant. (See Prudhvi Bhattiprolu's talk, and 2004.06181.)

The talk was its own conclusion!

Thanks for your attention.