1st Symposium
of the Division for Physics of Fundamental Interactions
of the Polish Physical Society

Various Faces of QCD

Institute of Physics, Jan Kochanowski University
Kielce, Poland
May 10-11, 2014

Supersymmetric QCD: N=0, 1, or N>1?

Jan Kalinowski
University of Warsaw

Motivation

Fantastic first three years of LHC run 1 with plenty of data

- from the first $\pi \to \gamma\gamma$ reconstructed
  - to „rediscovery" of the SM
    - precise SM measurements
      - culminated with the discovery of a Higgs ~ 125 GeV

A new era has begun

- already quite precise measurement of properties consistent with SM prediction within errors
- searches beyond the SM
- ultimately: understand the nature of EWSB

A great triumph of a weakly coupled SM

Although very successful, the SM is not the ultimate theory

- the Higgs sector unnatural
- matter-antimatter asymmetry
- dark matter/energy

➡ Hints for new physics at a TeV scale

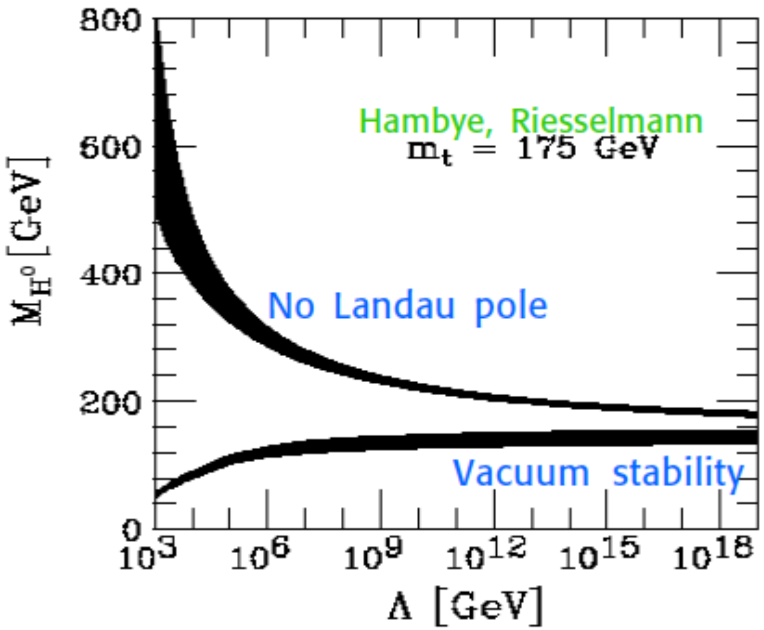
A great triumph of a weakly coupled SM

Although very successful, the SM is not the ultimate theory

- the Higgs sector unnatural
- matter-antimatter asymmetry
- dark matter/energy

➡ Hints for new physics at a TeV scale

- and a light Higgs implies a cutoff below M_{GUT}

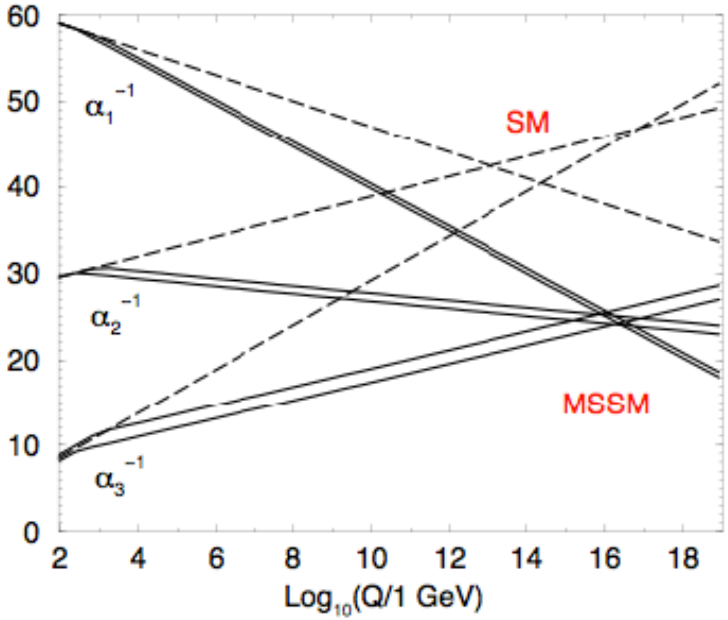


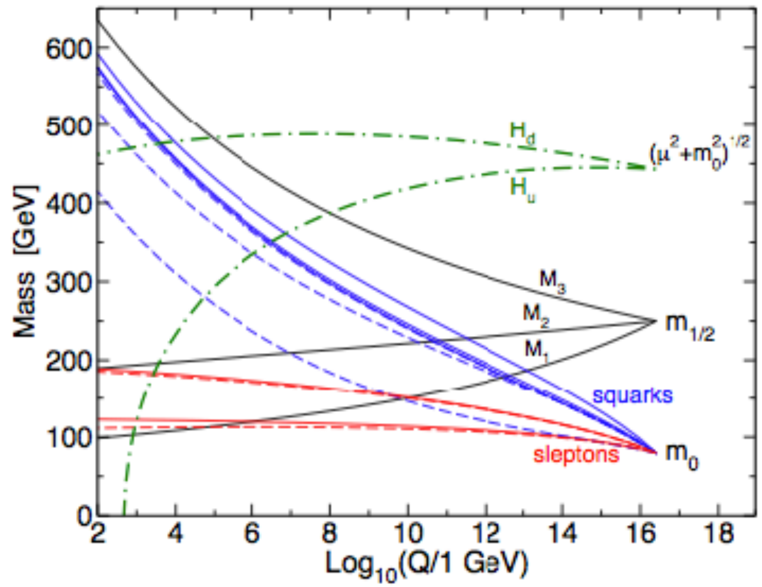
Supersymmetry – the preferred proposition for the beyond SM physics

- solves the SM hierarchy problem $\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$

  in broken SUSY Λ^2 replaced $(m_{stop}^2 - m_t^2)\log\Lambda$

- explains gauge coupling unification and EWSB





other BSM models (little Higgs, composite Higgs, Higgsless) become strongly interacting and non-perturbative at a few TeV scale

- provides candidates for dark matter (e.g. neutralino)

In the simplest realisation each SM particle is paired with a sparticle that differs in spin by ½:

- fermions – sfermions
- gauge bosons – gauginos
- Higgses – higgsinos

gluinos, neutralinos are Majorana fermions
to be checked experimentally!

- Exact supersymmetry: no new parameters!

  but inconsistent with experiment

- Must be broken: this is where many arbitrary parameters enter

- Once parameters fixed: completely computable, mathematically consistent theory up to M_{GUT}

The mass of the Higgs boson ~125 GeV consistent with SUSY

however it requires large radiative corrections from supersymmetric partners, some of which should be relatively light

The mass of the Higgs boson ~125 GeV consistent with SUSY

however it requires large radiative corrections from supersymmetric partners, some of which should be relatively light

But LHC searches do not show any direct sign of supersymmetry!

should we give up supersymmetry????

The mass of the Higgs boson ~125 GeV consistent with SUSY

however it requires large radiative corrections from supersymmetric partners, some of which should be relatively light

But LHC searches do not show any direct sign of supersymmetry!

should we give up supersymmetry????

Even before the LHC the minimal SUSY was under severe pressure:

- dim-4 B- and L-violating operators → extra symmetry (e.g. R-parity)
- possible flavor and CPV → strong constraints on the parameter space
- already LEP2 limit on Higgs mass >114 GeV requires fine tuning

Question: how many SUSY do we need?

Question: how many SUSY do we need?

- N=0 (i.e. none)

Question: how many SUSY do we need?

- N=0 (i.e. none)
- 0<N<1 (split SUSY, not-so split SUSY, ...)

Question: how many SUSY do we need?

- N=0 (i.e. none)
- 0<N<1 (split SUSY, not-so split SUSY, ...)
- N=1 (squashed, extra matter, NMSSM, extra gauge factors, ...)

Question: how many SUSY do we need?

- $N=0$ (i.e. none)
- $0<N<1$ (split SUSY, not-so split SUSY, ...)
- $N=1$ (squashed, extra matter, NMSSM, extra gauge factors, ...)
- $N>1$??

Supersymmetry with R-symmetry

All nice features of SUSY do not rely on the simplest realisation

Continuous R-symmetry can ameliorate the above problems by removing

- dim-4 B- and L-violating terms as well as dim-5 mediating proton decay
- soft tri-linear scalar couplings
- mu-term
- Majorana gaugino masses

Outline

- R-symmetry
- Structure of the Minimal R-symmetric Supersymmetric Standard Model
- Expectations at the LHC (and ILC)
  - testing the Dirac nature of gauginos
  - production and decay modes of new states
  - searches for sgluons

  based on:

  Choi, Drees, JK, Kim, Popenda, Zerwas, Phys.Lett.B 672 (2009) 246
  Choi, Choudhury, Freitas, JK, Kim,Zerwas, JHEP 1008 (2010) 025
  Choi, Choudhury, Freitas, JK, Zerwas, Phys.Lett. B697 (2011) 215
  Kotlarski, JK, Acta Phys. Polon.B 42 (2011) 2485
  Kotlarski, JK, Kalinowski, Acta Phys. Polon. B44
- Summary

Supersymmetry

Supersymmetry: superspace $\{x^\mu, \theta, \bar{\theta}\}$

superfields

matter and Higgs – chiral $\hat{\Phi}(x^\mu, \theta) = \{\varphi, \psi^\alpha\}$

gauge fields – vector $\hat{G}(x^\mu, \theta, \bar{\theta}) = \{\tilde{G}^\alpha, G^\mu\}$

Lagrangian

- kinetic terms $\int d^2\theta\, d^2\bar{\theta}\, \hat{\Phi}^\dagger\, e^{-2g\hat{G}}\hat{\Phi} + (\int d^2\theta\, \hat{G}^\alpha \hat{G}_\alpha + h.c.)$

  where $\hat{G}^\alpha \sim \bar{D}^2\, D^\alpha \hat{G}$ field-strength superfield

- potential $\int d^2\theta\, W$ where superpotential

  $$W \sim \mu \hat{H}_d \hat{H}_u + y_d \hat{H}_d \hat{Q} \hat{D}^c + \ldots$$

- soft-SUSY breaking: tri-linear scalar couplings and soft masses

R-symmetry

R-symmetry – a continuous U(1) global symmetry under $\theta \to e^{i\alpha}\theta$

[Fayet; Salam & Strathdee, ...]

Grassmann coordinates have non-trivial R-charge

$$R(\theta) = +1, \quad R(d\theta) = -1, \quad R(\bar\theta) = -1, \quad R(d\bar\theta) = +1$$

superfields $\hat{X}_i(x^\mu, \theta, \bar\theta) \to e^{i\xi_i \alpha}\, \hat{X}_i(x^\mu, e^{i\alpha}\theta, e^{-i\alpha}\bar\theta)$

component fields have different R-charge

for vector gauge $R(\hat{G}) = 0 \quad \Rightarrow \quad R(G^\mu) = 0, \quad R(\tilde{G}^\alpha) = 1$

kinetic terms $\int d^2\theta\, d^2\bar\theta\ \hat\Phi^\dagger\, e^{-2g\hat{G}}\hat\Phi + (\int d^2\theta\ \hat{G}^\alpha \hat{G}_\alpha + h.c.)$

$\hat{G}^\alpha \sim \bar{D}^2\, D^\alpha \hat{G}$

➡ are automatically R-symmetric

R-symmetry

- Nelson-Seiberg theorem: R-sym needed for F-term SUSY breaking
- R-symmetry cannot be broken spontaneously
- two options: exact or broken explicitly

in the MSSM is broken by soft gaugino masses $M_{\tilde{G}} \tilde{G}^{\alpha} \tilde{G}_{\alpha}$

- for exact we need

R(superpotential)=2 $\quad \int d^2\theta \, W$

R(soft terms) =0

- freedom to assign the R-charges to chiral superfields

e.g.

matter $\quad R(\hat{Q}) = 1 \quad \Rightarrow \quad R(\tilde{q}) = 1, \quad R(q) = 0$

Higgs $\quad R(\hat{H}) = 0 \quad \Rightarrow \quad R(H) = 0, \quad R(\tilde{H}) = -1$

(superpartners carry non-zero R-charge)

Constraints from R-symmetry

terms forbidden

superpotential R=2	mu-term	$\mu \hat{H}_d \hat{H}_u$	(R=0)
	L- and B-violation	$\hat{L}\hat{Q}\hat{D}^c \, , \, \hat{H}_u \hat{L}$	(R=3,1)
soft terms R=0	tri-linear scalar couplings	$A_d H_d \tilde{Q} \tilde{d}^*$	(R=2)
	Majorana gaugino masses	$M_{\tilde{G}} \tilde{G}^{\alpha} \tilde{G}_{\alpha}$	(R=2)

terms allowed:

superpotential	Yukawa	$y_d \hat{H}_d \hat{Q} \hat{D}^c$
soft terms	scalar masses	$M^2_{\tilde{q}} \lvert\tilde{q}\rvert^2$

also ΔL=2 Majorana neutrino mass $\hat{H}_u \hat{L} \hat{H}_u \hat{L}$ allowed

Since mu-term and Majorana masses are forbidden, need new means to give masses to gauginos/higgsinos

Minimal R-symmetric SSM

[Kribs Poppitz Weiner 2007]

The field content of MRSSM: fields of the MSSM with addition of

- chiral superfields in the adjoint rep. of the corresponding gauge group

$$\hat{\Sigma} = \sigma + \sqrt{2}\theta\tilde{G}' + \theta\theta F_\Sigma$$

(like in N=2 SUSY)

$$R(\hat{\Sigma}) = 0 \qquad \Rightarrow R(\sigma) = 0, \quad R(\tilde{G}'^\alpha) = -1$$

to build a Dirac gaugino $\tilde{G}_D = \tilde{G}'_L + \tilde{G}_R$

- super-soft Dirac mass can be generated by Giudice-Masiero

$$\int d^2\theta \, \frac{\hat{W}'^\alpha}{M} \mathrm{Tr}\, \hat{G}^\alpha \hat{\Sigma} \to \; M^D \tilde{G}\tilde{G}'$$

with D-type spurion $\langle \hat{W}'^\alpha \rangle = \theta^\alpha D'$

- heavier gauginos, no A-terms and/or Dirac nature of gauginos relax flavour constraints

- new scalar fields in adjoint representations, e.g. sgluons

Minimal R-symmetric SSM

[Kribs Poppitz Weiner 2007]

The field content of MRSSM: fields of the MSSM with addition of

- chiral superfields in the adjoint rep. of the corresponding gauge group

- two chiral iso-dublets $\hat{R}_u, \hat{R}_d$ with R-charge 2

  to build a mu-type term $\mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u$

  - the mu-type term can be generated by $\int d^4\theta \frac{\hat{X}^\dagger}{M} \hat{H}_i \hat{R}_i$

    with F-type spurion $\langle \hat{X} \rangle = \theta^2 F_X$

  - other couplings allowed $\lambda_d^i \hat{H}_d \hat{\Sigma}^i \hat{R}_d + \lambda_u^i \hat{H}_u \hat{\Sigma}^i \hat{R}_u, \quad i = I, Y$

  - R-Higgs bosons

➡ impotrant consequences for collider physics, dark matter, flavour physics,...

MRSSM

R-charges of the superfields and their component fields

Field	Superfield		Boson		Fermion	
Matter	$\hat{Q}, \hat{D}^c, \hat{U}^c$	$+1$	$\tilde{Q}, \tilde{D}^c, \tilde{U}^c$	$+1$	Q, D^c, U^c	0
Higgs	$\hat{H}_{d,u}$	0	$H_{d,u}$	0	$\tilde{H}_{d,u}$	-1
	$\hat{R}_{d,u}$	$+2$	$R_{d,u}$	$+2$	$\tilde{R}_{d,u}$	$+1$
Gauge Vector	$\hat{G}$	0	G_μ	0	$\tilde{G}$	$+1$
Gauge Chiral	$\hat{\Sigma}$	0	σ	0	$\tilde{G}'$	-1

Physical fields: matter, gauge and Higgs fields as in the MSSM
Dirac gluinos and neutralinos
additional pair of charginos
gauge-adjoint scalars (e.g. sgluons)
R-Higgs bosons

Colored sector

In the MSSM gluinos are Majorana particles with two degrees of freedom to match gluons in a vector super-multiplet.

$$\hat{G}^a_\alpha = \tilde{g}^a_\alpha + D^a\theta_\alpha + (\sigma^{\mu\nu})_\alpha{}^\beta\theta_\beta G^a_{\mu\nu} + \ldots$$

R=1

$$\tilde{g}_M = \tilde{g}_L + \tilde{g}_R = \tilde{g}^c_M \quad \Leftrightarrow \quad \tilde{g}_R = (\tilde{g}_L)^c$$

In R-symmetric realisation, the N=1 gauge vector super-multiplet is paired with the additional N=1 gauge chiral super-multiplet

$$\hat{\Sigma}^a = \sigma^a + \sqrt{2}\theta\,\tilde{g'}^a + \theta\theta\,F^a$$

R=0

$$\tilde{g}_D = \tilde{g}'_L + \tilde{g}_R \neq \tilde{g}^c_D$$

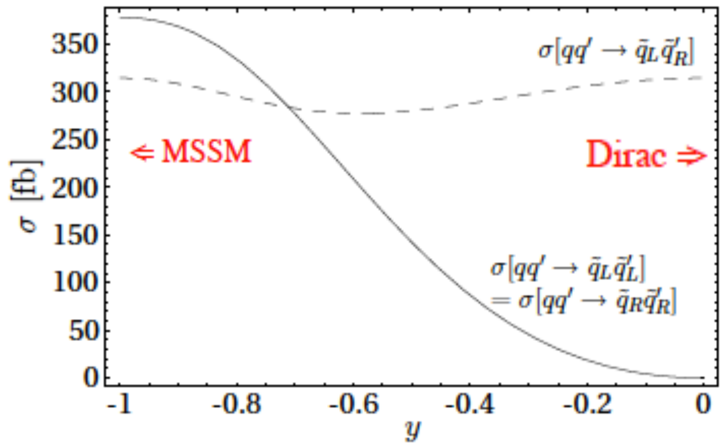
(both form a vector hyper-multiplet of N=2 supersymmetry)

Fayet 1976
Del Aguila ea, 1985
Alvarez-Gaume, Hassan 1997
Fox, Nelson, Weiner 2002
…….

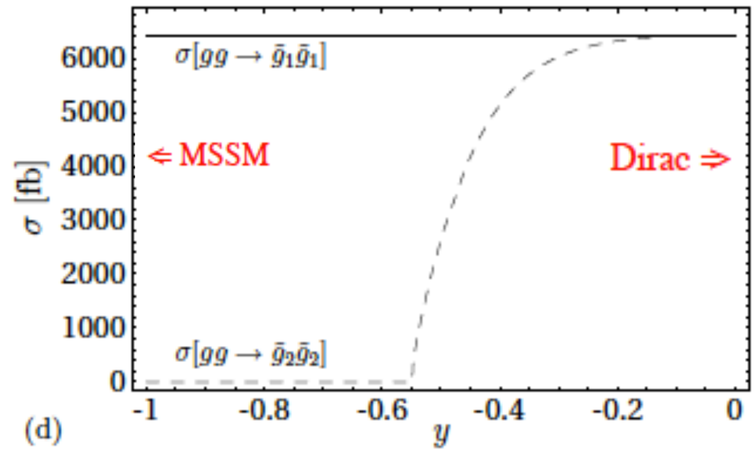
Dirac gluinos

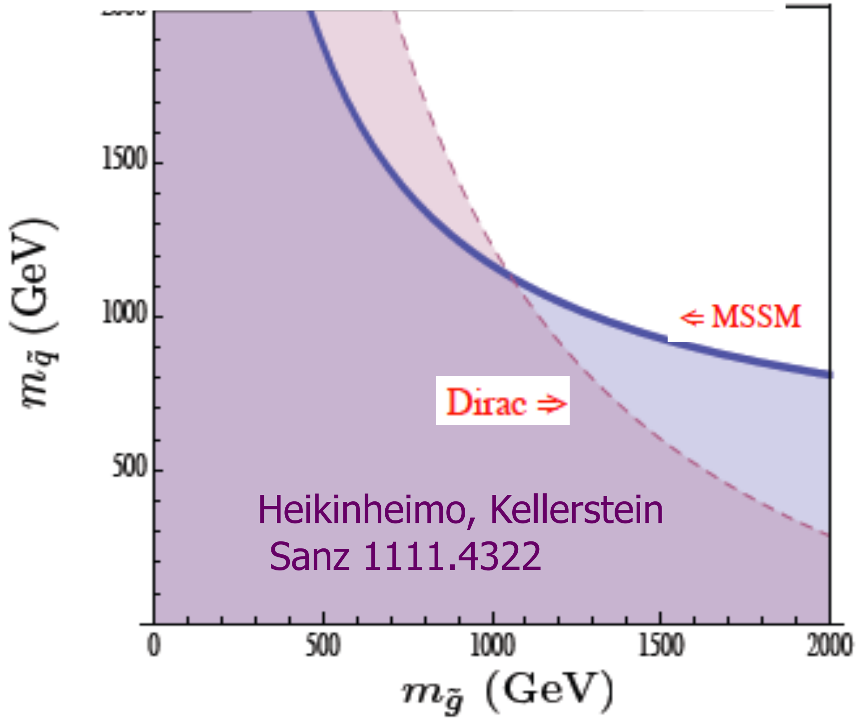
Choi Drees Freitas Zerwas '08

Dirac gluino cannot flip chirality



Dirac gluino has more d.o.f





- compared to MSSM, for Dirac gluino at the LHC
  - lower senstivity to squarks
  - increased sensitivity to gluinos

Colored scalars: sgluons

Tree-level couplings

- $\sigma\sigma^* g$ and $\sigma\sigma^* gg$ couplings as required by gauge invariance
- to gluinos $-\sqrt{2}\, i\, g_s\, f^{abc}\, \overline{\tilde{g}'^a_L}\, \tilde{g}^b_R\, \sigma^c_C + \text{h.c.}$
- Dirac gluino mass => trilinear scalar couplings to squarks

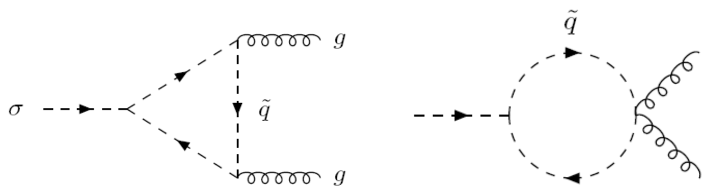
$$-\sqrt{2}\, g_s\, M^D_C\, (\sigma^a_C + \sigma^{a*}_C) \left(\tilde{q}^*_L \frac{\lambda^a}{2} \tilde{q}_L - \tilde{q}^*_R \frac{\lambda^a}{2} \tilde{q}_R \right)$$

vanish for degenerate L/R squarks

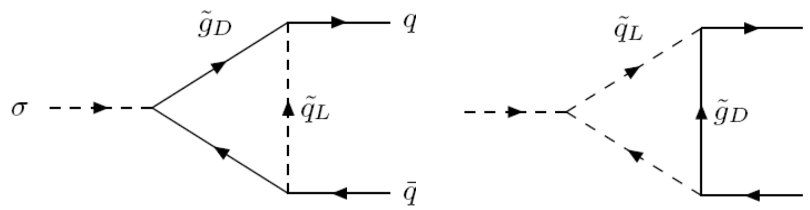
Although R=0, single sgluon cannot be produced at treel level

Loop-induced couplings

- to a gluon or quark pair through diagrams with squarks or gluinos



(gluino loops vanish)

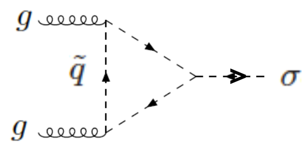


$\sim m_q$

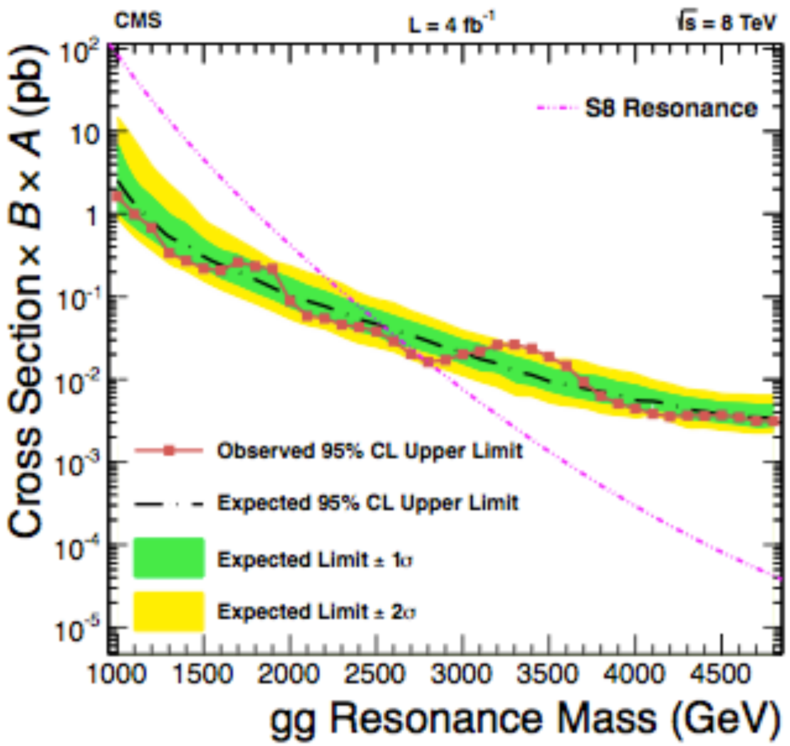
Choi, Drees, JK, Kim, Popenda, Zerwas '09
Plehn,Tait '09

Searching for sgluons

- At the LHC sgluons can be produced singly via



→ exciting possibility of resonant s-channel sgluon production

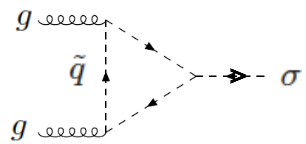


exclusion up to ~ 2.5 TeV for a state s8
with full strength coupling

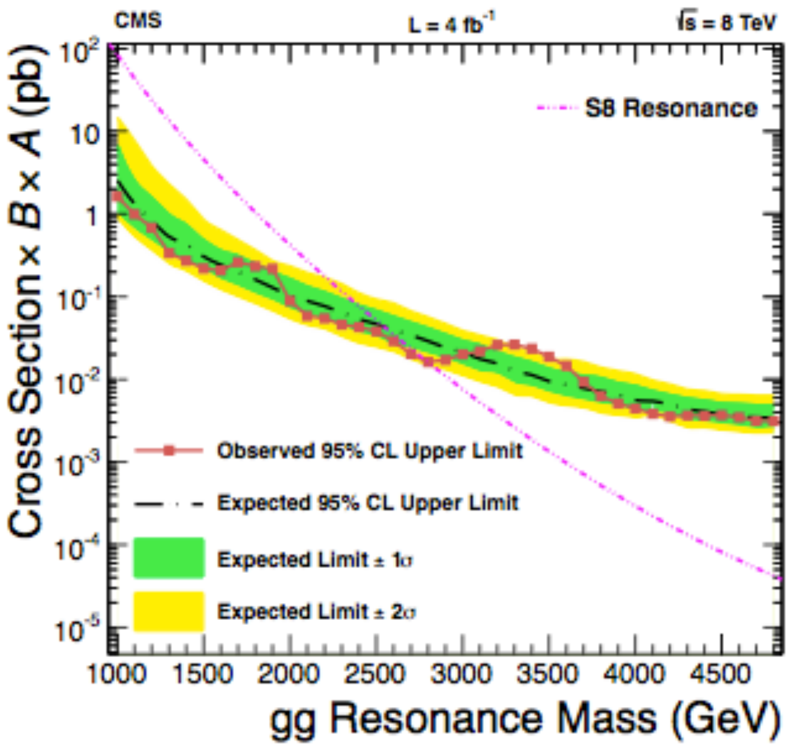
Han, Lewis, Liu, 1010.4309

Searching for sgluons

❖ At the LHC sgluons can be produced singly via



exciting possibility of resonant s-channel sgluon production

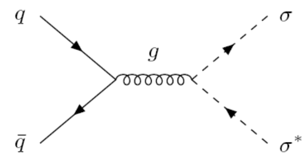


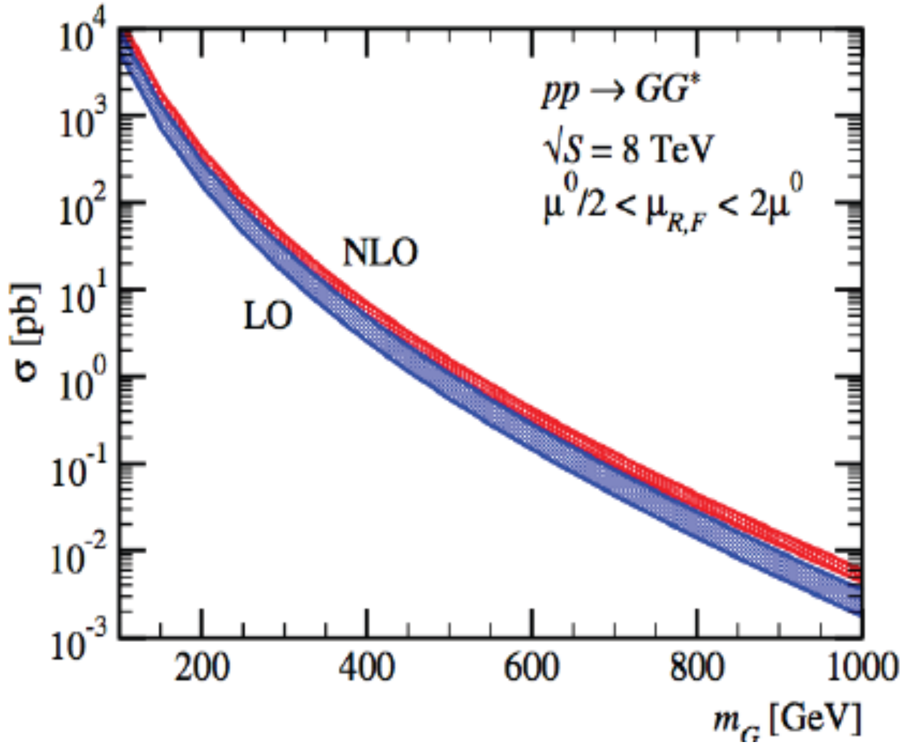
exclusion up to ~ 2.5 TeV for a state s8 with full strength coupling

Han, Lewis, Liu, 1010.4309

however, for loop-induced coupling factor ~ 10^{-5} suppression

❖ At the LHC sgluons can be also produced in pairs





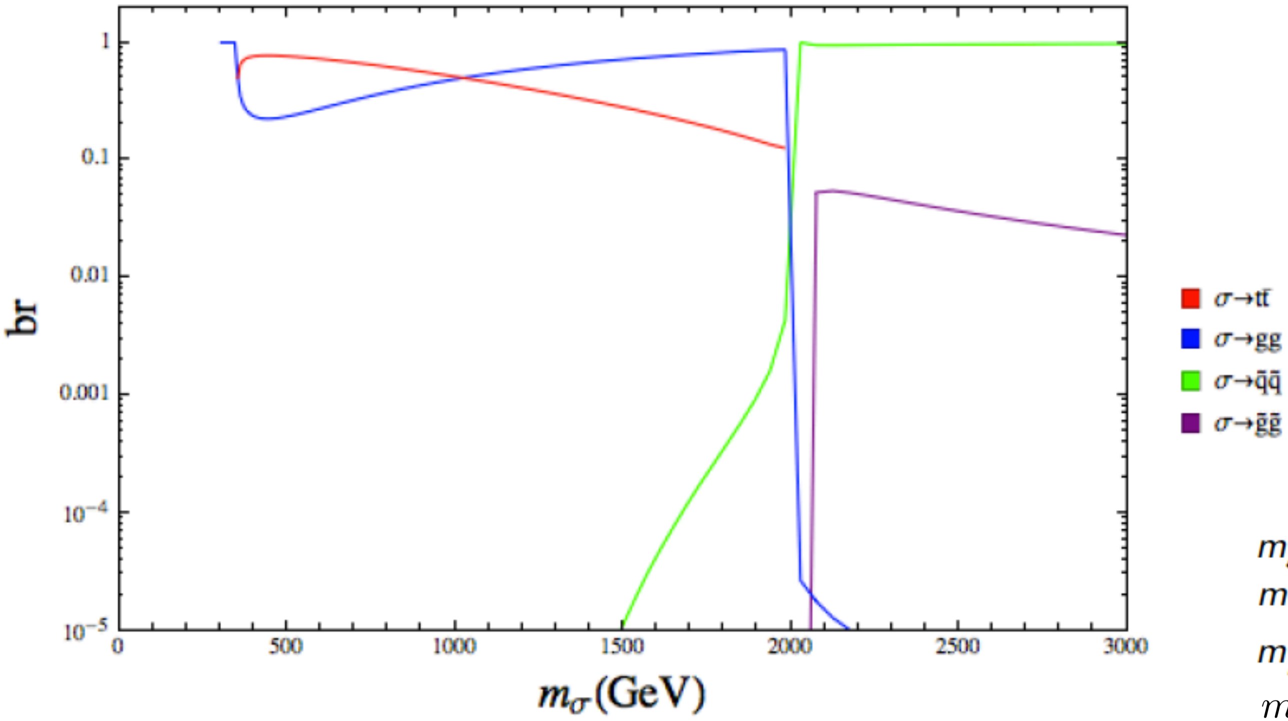
MadGolem coll, arXiv:1203.6358.

	$\sqrt{S} = 8$ TeV			$\sqrt{S} = 14$ TeV		
m_G [GeV]	σ^{LO}[pb]	σ^{NLO}[pb]	K	σ^{LO}[pb]	σ^{NLO}[pb]	K
200	2.12×10^{2}	3.36×10^{2}	1.58	9.77×10^{2}	1.48×10^{3}	1.52
350	8.16×10^{0}	1.36×10^{1}	1.66	5.44×10^{1}	8.46×10^{1}	1.56
500	7.64×10^{-1}	1.34×10^{0}	1.75	7.14×10^{0}	1.14×10^{1}	1.60
750	3.40×10^{-2}	6.54×10^{-2}	1.93	5.56×10^{-1}	9.29×10^{-1}	1.67
1000	2.47×10^{-3}	5.29×10^{-3}	2.15	7.31×10^{-2}	1.28×10^{-1}	1.75

Experimental signature depends on decay modes, which are model dependent

- below top-pair threshold $Br(\sigma \to gg) \sim 1$
- above top-pair $Br(\sigma \to gg) + Br(\sigma \to t\bar{t}) \sim 1$
- close or above sparticle-pair $Br(\sigma \to susy) \sim 1$

e.g.



$m_{\tilde{g}} = 1$ TeV

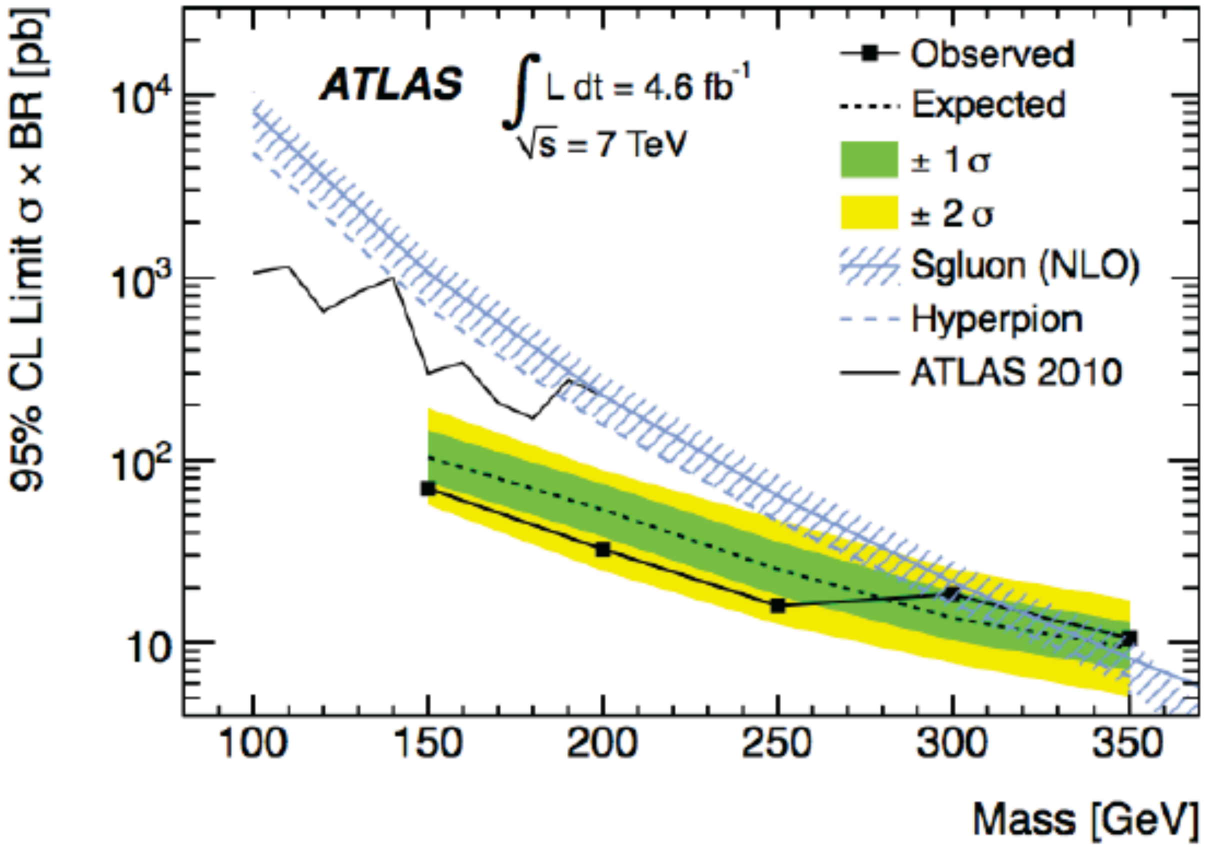
$m_{\tilde{q}_L} = 4$ TeV, $m_{\tilde{q}_R} = 0.95 m_{\tilde{q}_L}$

$m_{\tilde{b}_R} = 0.35 m_{\tilde{q}_L}$, $m_{\tilde{b}_L} = 0.4 m_{\tilde{q}_L}$

$m_{\tilde{t}_R} = 0.25 m_{\tilde{q}_L}$, $m_{\tilde{t}_L} = 0.4 m_{\tilde{q}_L}$

❖ low mass range $m_\sigma < 2m_t$: di-jet signature $\sigma \to gg$

dedicated ATLAS search for a pair of colored scalars in 4-jet final states



ATLAS 1210.4826

❖ medium mass range between top and SUSY thresholds: possible signature

$$pp \to \sigma\sigma \to t\bar{t}\,t\bar{t}$$

SM production of $t\bar{t}\,t\bar{t}$ small, but hard to reconstruct four tops

our strategy (W. Kotlarski, A. Kalinowski and S. Prestel)

look for events

- with same-sign dileptons
- large hadron activity
- „fat jets"

at 8 TeV => sensitivity to ~800 GeV (Acta Phys.Polon.B44,2149)
in agreement with ATLAS

at 14 TeV => next presentation by W. Kotlarski

Summary

- Supersymmetry still attractive, although not so simple as hoped
- Well motivated R-symmetric SUSY model discussed
- Ameliorates MSSM flavour and CP problems

  interesting FV processes in squark and slepton decays at the LHC
- Gauginos become Dirac particles, new scalar partners
- Conserved R-charge restricts production channels and decay modes

  distinct phenomenology at colliders

  sgluons can be light and seen at the LHC

- high mass range, when SUSY channels open:
  the tree-level decays to gluino or squark pair dominate

  - a pair of Dirac gluinos $$\Gamma[\sigma \to \tilde{g}_D \bar{\tilde{g}}_D] = \frac{3\alpha_s M_\sigma}{4} \beta_{\tilde{g}} (1 + \beta_{\tilde{g}}^2)$$
  - a pair of squarks $$\Gamma[\sigma \to \tilde{q}_a \tilde{q}_a^*] = \frac{\alpha_s}{4} \frac{|M_3^D|^2}{M_\sigma} \beta_{\tilde{q}_a} ,$$

$$\sigma \to \tilde{g}\tilde{g} \to qq\tilde{q}\tilde{q} \to qqqq + \tilde{\chi}\tilde{\chi} ,$$

$$\sigma \to \tilde{q}\tilde{q} \to qq + \tilde{\chi}\tilde{\chi} ,$$

where $\tilde{\chi}$ chargino or neutralino

For σ pair production at the LHC a spectacular signature

$$pp \to 8\,\mathrm{jets} + 4\,\mathrm{LSP's}$$

however, with current limits on gluinos and squarks difficult to expect