Electroweak Contributions to Squark Pair Production at the LHC

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LHC focus week
IPMU

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Outline

MSSM particle spectrum

- each SM particle has a superpartner
- add a SU(2)-Higgs doublet with hypercharge $Y = -1$
- SUSY is not exact⇒have to be broken⇒adding soft-terms
- MSSM has 105 extra free parameters
- in mSUGRA 5 free parameters left ($m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sgn}(\mu)$)

Superfield	Boson Fields	Fermionic Partners	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\hat{G}$	g	$\tilde{g}$	8	0	0
$\hat{V}$	W^a	$\tilde{W}^a$	1	3	0
$\hat{V}'$	B	$\tilde{B}$	1	1	0
$\hat{L}$	$\tilde{L}^j = (\tilde{\nu}, \tilde{e})_L$	$(\nu, e)_L$	1	2	-1
$\hat{E}$	$\tilde{E} = \tilde{e}_R^*$	$e_R^\dagger$	1	1	2
$\hat{Q}$	$\tilde{Q}^j = (\tilde{u}, \tilde{d})_L$	$(u, d)_L$	3	2	$\frac{1}{3}$
$\hat{U}$	$\tilde{U} = \tilde{u}_R^*$	$u_R^\dagger$	3^*	1	$-\frac{4}{3}$
$\hat{D}$	$\tilde{D} = \tilde{d}_R^*$	$d_R^\dagger$	3^*	1	$\frac{2}{3}$
$\hat{H}_1 = \hat{H}_d$	H_1^i	$(\tilde{H}_1^0, \tilde{H}_1^-)_L$	1	2	-1
$\hat{H}_2 = \hat{H}_u$	H_2^i	$(\tilde{H}_2^+, \tilde{H}_2^0)_L$	1	2	1

Gaugino Mass Eigenstates

- charginos $\chi_i^\pm$, $i = 1, 2$ are linear combination of charged winos and charged higgsinos
- neutralinos χ_i^0, $i = 1, 2, 3, 4$ are linear combinations of neutral wino, bino and neutral higgsinos
- gluinos $\tilde{g}$ are mass eigenstates

Squark Pair Production at the LHC

- TeV scale supersymmetry will be decisively tested at LHC
- cross section is $\mathcal{O}(\alpha_s^2)$, e.g.:

$$\begin{aligned} m_{\tilde{q}} &\approx 1000\,\mathrm{GeV} \\ \sigma &\approx 0.5\,\mathrm{pb} \\ \mathcal{L} &\approx 10\,\mathrm{fb}^{-1}\,\mathrm{per\,year} \\ N_{\mathrm{events}} &= \mathcal{L}\,\sigma \end{aligned}$$

- 5000 events are expected at low luminosity

Role of electroweak (EW) contributions

5000 events $\Longrightarrow$

It should be possible to measure the squark pair production cross section with a statistical uncertainty of a few percent.

$\Longrightarrow$

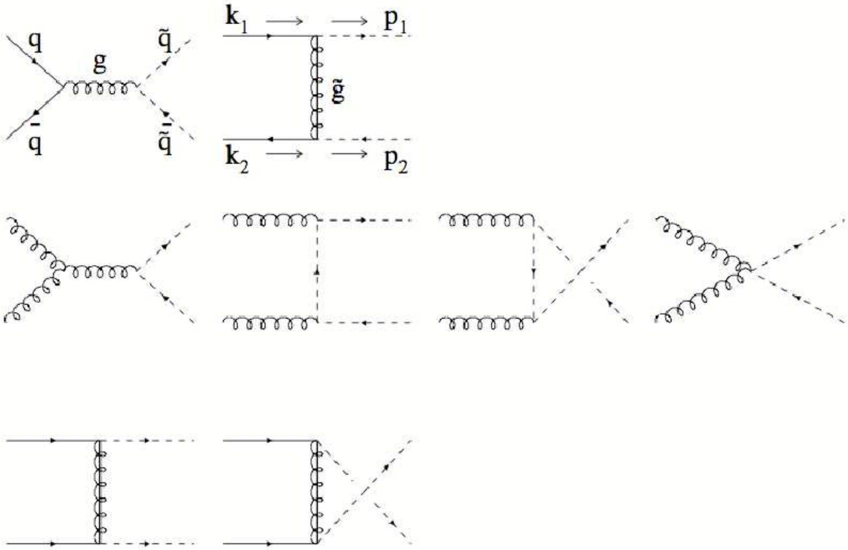
We need accurate theoretical predictions:

- NLO QCD corrections in addition to the LO cross section (NLO: Beenakker, Hopker, Spira and Zerwas, 1995; LO: Harrison and Llewellyn Smith, 1983 & Dawson, Eichten and Quigg 1985)
- remaining uncertainty from yet higher order QCD corrections should be at 10% level

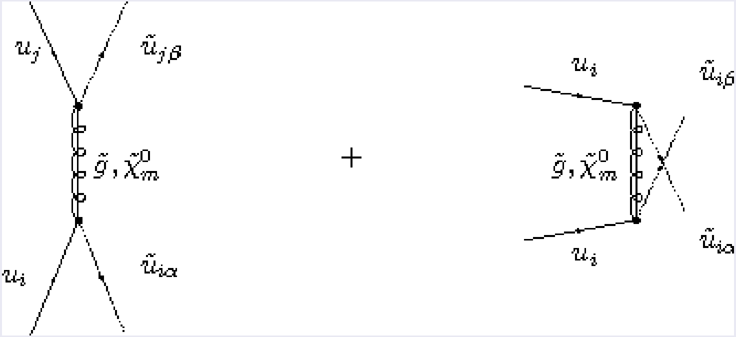
Thus EW corrections at leading order might be important since:

- they can give rise to an increase up to 20% for mSUGRA scenarios and two SU(2) douplet squarks
- they can give rise to an increase up to 50% for scenarios without gaugino mass unification and two SU(2) douplet squarks

QCD: Diagrams for Leading Order Squark Pair Production



$qq' \to \tilde{q}\tilde{q}'$: t– or/and u–channel neutralino exchange



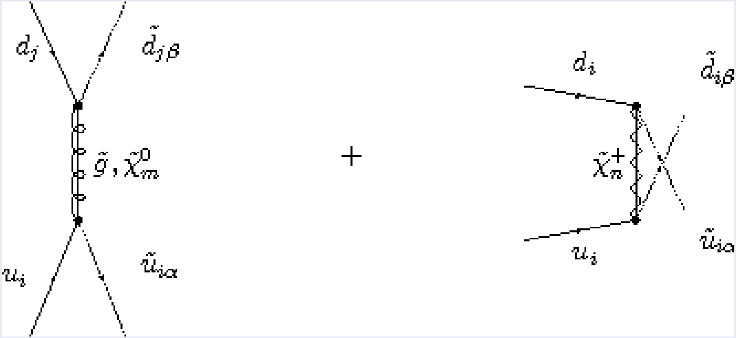
Notation:

- i, j: denotes the generation
- α, β: denotes the chirality (L– and R–type) of the squarks
- m: labels the exchanged neutralino mass eigenstate

Remarks:

- there are no s–channel contributions
- there are t– and u–channel (i=j) diagrams for neutralino exchange

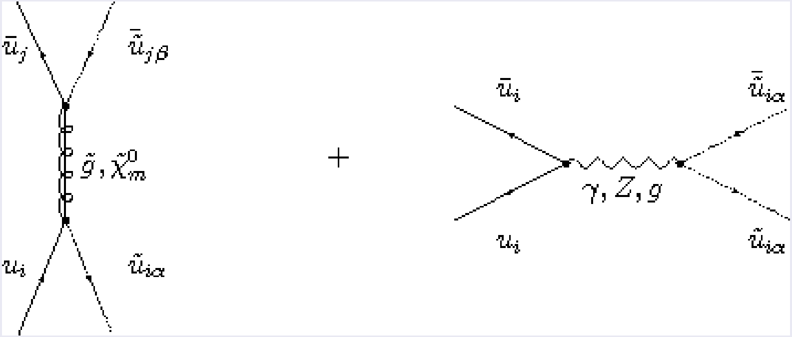
$qq' \to \tilde{q}\tilde{q}'$: t– or u–channel chargino exchange



Remarks:

- there is no gluino u–channel contribution
- u–channel chargino diagrams exist only for $i = j$
- sole chargino t– channel contribution for $u_i d_j \to \tilde{d}_{i\alpha}\tilde{u}_{j\beta}$ and $i \neq j$

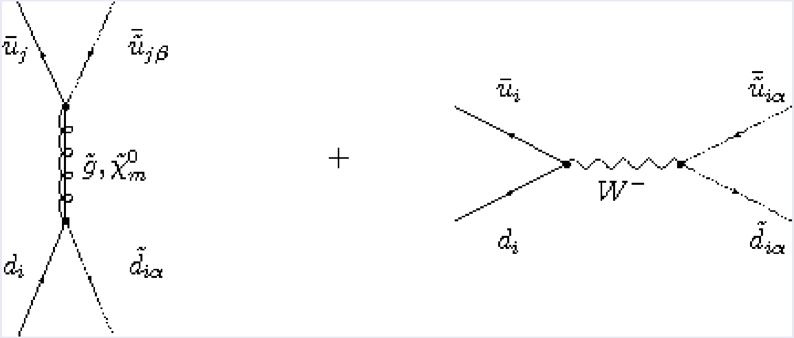
$q\bar{q}' \rightarrow \tilde{q}\bar{\tilde{q}}'$: γ, Z, g boson s–channel exchange



Remarks:

- there are s–channel diagrams for $q\bar{q}'$ initial states
- γ, Z, g boson s–channel conntributions for $i = j$

$q\bar{q}' \to \tilde{q}\bar{\tilde{q}}'$: W boson s–channel exchange

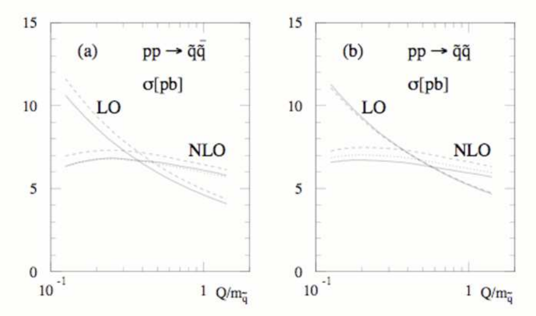


Remarks:

- W boson s–channel conntributions for $i = j$
- sole W boson s–channel conntribution for $d_i\bar{u}_i \to \tilde{d}_{j\alpha}\bar{\tilde{u}}_{j\beta}$ and $i \neq j$

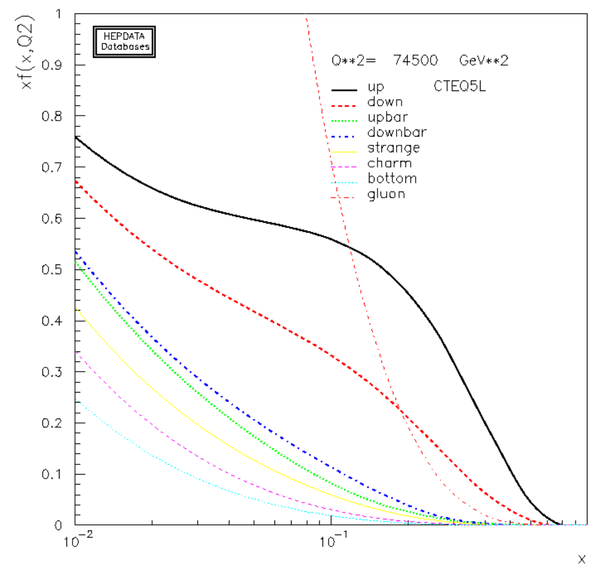
Parameter choice

- we take equal factorization and renormalization scales: $\mu_F = \mu_R = m_{\tilde{q}}/2$
- we do not consider 3. generation squarks (have no mentionable EW contributions)
- we do not consider gluon fusion contributions in the initial states (have no EW contributions in LO)



(Beenakker, Hopker, Spira and Zerwas)

Parton Distribution Functions



(Durham University On–line Plotting and Calculation page)

Numerical Results

Results

mSUGRA	m_0 [GeV]	$m_{1/2}$ [GeV]	$m_{\tilde{q}}$ [GeV]	QCD[pb] Total	QCD[pb] LL	$\mathrm{QCD} + \mathrm{EW}$[pb] Total	$\mathrm{QCD} + \mathrm{EW}$[pb] LL	ratio Total	ratio LL
SPS 1a	100	250	560	12.11	3.09	12.55	3.50	1.036	1.133
SPS 1b	200	400	865	1.57	0.42	1.66	0.499	1.055	1.186
SPS 2	1450	300	1590	0.055	0.013	0.057	0.0144	1.025	1.091
SPS 3	90	400	845	1.74	0.464	1.83	0.551	1.055	1.188
SPS 4	400	300	760	3.10	0.813	3.22	0.927	1.040	1.141
SPS 5	150	300	670	5.42	1.41	5.66	1.62	1.042	1.152

Remarks

- EW contribution is more important for two SU(2) doublet squarks, due to $(g_2/g_Y)^2 = \cot^2\theta_W \approx 3.3$
- EW contribution depends on the ratio $m_{1/2}/m_0$
- EW contribution becomes more important for heavier squarks if ratio $m_0/m_{1/2}$ remains roughly the same

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Helicity flip and threshold behaviour:

Processes like $u_L u_L \rightarrow \tilde{u}_L \tilde{u}_L$:

- matrix element is proportional to mass of exchanged gaugino (helicity flip)
- both quarks have to be left–handed $\Longrightarrow$ total momentum $J = 0$; squarks are in a s–wave
- $\sigma_{\text{total}} \propto \beta$,

  where $\beta = v = \frac{p}{E} = \sqrt{1 - \frac{4m_{\tilde{q}}^2}{\hat{s}}}$

Processes like $u_L u_R \rightarrow \tilde{u}_L \tilde{u}_R$:

- matrix element is NOT proportional to mass of exchanged gaugino (no helicity flip)
- addition of right– and left–handed quark $\Longrightarrow$ total momentum $J = 1$; squarks are in a p–wave
- $\sigma_{\text{total}} \propto \beta^3$

Electroweak Contributions, 1st category:

No.	Process	diagrams QCD	diagrams EW	helicity flip?	thre–shold	cross section [pb] QCD	cross section [pb] QCD + EW	ratio
1	$uu \to \tilde{u}_L\tilde{u}_L$	t, u	t, u	yes	β	0.683	0.794	1.162
2	$uu \to \tilde{u}_R\tilde{u}_R$	t, u	t, u	yes	β	0.761	0.796	1.045
3	$uu \to \tilde{u}_L\tilde{u}_R$	t, u	t, u	no	β^3	0.929	0.931	1.002
4	$dd \to \tilde{d}_L\tilde{d}_L$	t, u	t, u	yes	β	0.198	0.232	1.171
5	$dd \to \tilde{d}_R\tilde{d}_R$	t, u	t, u	yes	β	0.234	0.237	1.012
6	$dd \to \tilde{d}_L\tilde{d}_R$	t, u	t, u	no	β^3	0.243	0.243	1.000
7	$ud \to \tilde{u}_L\tilde{d}_L$	t	t, u	yes	β	0.969	1.22	1.261

- possible interference between t– and u–channel diagrams
- processes with two SU(2) doublet squarks have:
  - constructive (positive) interference terms between QCD and EW
  - helictiy flip, so $\sigma \propto \beta$ and $\mathcal{M} \propto M_{\tilde{G}}$
- cross sections are sizable due to two valence quarks

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9	$u\bar{u} \to \tilde{u}_R \bar{\tilde{u}}_R$	s, t	s, t	no	β^3	0.187	0.170	0.909
10	$d\bar{d} \to \tilde{d}_L \bar{\tilde{d}}_L$	s, t	s, t	no	β^3	0.0925	0.0784	0.847
11	$d\bar{d} \to \tilde{d}_R \bar{\tilde{d}}_R$	s, t	s, t	no	β^3	0.109	0.106	0.972
12	$u\bar{u} \to \tilde{d}_L \bar{\tilde{d}}_L$	s	s, t	no	β^3	0.0341	0.0353	1.035
13	$d\bar{d} \to \tilde{u}_L \bar{\tilde{u}}_L$	s	s, t	no	β^3	0.0207	0.0219	1.057
14	$u\bar{d} \to \tilde{u}_L \bar{\tilde{d}}_L$	t	s, t	no	β^3	0.178	0.162	0.910

- possible interference between s– and t–channel diagrams
- nearly all processes have reduction of total cross section due to destructive interference terms between QCD and EW
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10	$d\bar{d} \to \tilde{d}_L \bar{\tilde{d}}_L$	s, t	s, t	no	β^3	0.0925	0.0784	0.847
11	$d\bar{d} \to \tilde{d}_R \bar{\tilde{d}}_R$	s, t	s, t	no	β^3	0.109	0.106	0.972
12	$u\bar{u} \to \tilde{d}_L \bar{\tilde{d}}_L$	s	s, t	no	β^3	0.0341	0.0353	1.035
13	$d\bar{d} \to \tilde{u}_L \bar{\tilde{u}}_L$	s	s, t	no	β^3	0.0207	0.0219	1.057
14	$u\bar{d} \to \tilde{u}_L \bar{\tilde{d}}_L$	t	s, t	no	β^3	0.178	0.162	0.910

- possible interference between s– and t–channel diagrams
- nearly all processes have reduction of total cross section due to destructive interference terms between QCD and EW
- all processes have no helictiy flip, so $\sigma \propto \beta^3$
- small size of the cross section due to an anti-quark as initial state

Electroweak Contributions, 3st category:

No.	Process	diagrams QCD	diagrams EW	helicity flip?	thre–shold	cross section [pb] QCD	cross section [pb] QCD + EW	ratio
15	$ud \to \tilde{u}_L \tilde{d}_R$	t	t	no	β^3	0.484	0.485	1.001
16	$ud \to \tilde{u}_R \tilde{d}_L$	t	t	no	β^3	0.477	0.479	1.002
17	$ud \to \tilde{u}_R \tilde{d}_R$	t	t	yes	β	1.113	1.114	1.001
18	$u\bar{u} \to \tilde{u}_L \tilde{\bar{u}}_R$	t	t	yes	β	0.569	0.569	1.000
19	$d\bar{d} \to \tilde{d}_L \tilde{\bar{d}}_R$	t	t	yes	β	0.331	0.331	1.000
20	$u\bar{d} \to \tilde{u}_L \tilde{\bar{d}}_R$	t	t	yes	β	0.491	0.491	1.000
21	$u\bar{d} \to \tilde{u}_R \tilde{\bar{d}}_L$	t	t	yes	β	0.480	0.480	1.000
22	$u\bar{d} \to \tilde{u}_R \tilde{\bar{d}}_R$	t	t	no	β^3	0.202	0.203	1.004
23	$u\bar{u} \to \tilde{d}_R \tilde{\bar{d}}_R$	s	s	–	β^3	0.0420	0.0421	1.002
24	$d\bar{d} \to \tilde{u}_R \tilde{\bar{u}}_R$	s	s	–	β^3	0.0240	0.0240	1.000

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- all electroweak contributions are positive but very small due to at least one initial SU(2) singlet
- cross sections for the first eight processes are sizable

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Dependence on transverse momentum p_T of the squarks

Ratio of EW and QCD t– or u–channel propagator is given by

$$\frac{EW}{QCD} \approx \frac{2p_T^2 + m_{\tilde{q}}^2 + M_{\tilde{g}}^2}{2p_T^2 + m_{\tilde{q}}^2 + M_{\tilde{W}}^2},$$

where

- p_T is the transverse momentum of the squarks
- $m_{\tilde{q}}/m_{\tilde{g}}$ is the squark/gluino mass
- $M_{\tilde{W}}$ is the relevant chargino or neutralino mass

Therefore:

- enhancement by a factor of 2 for small p_T for $m_{\tilde{q}} \approx M_{\tilde{g}} \gg M_{\tilde{W}}$ (nearly all SPS scenarios)
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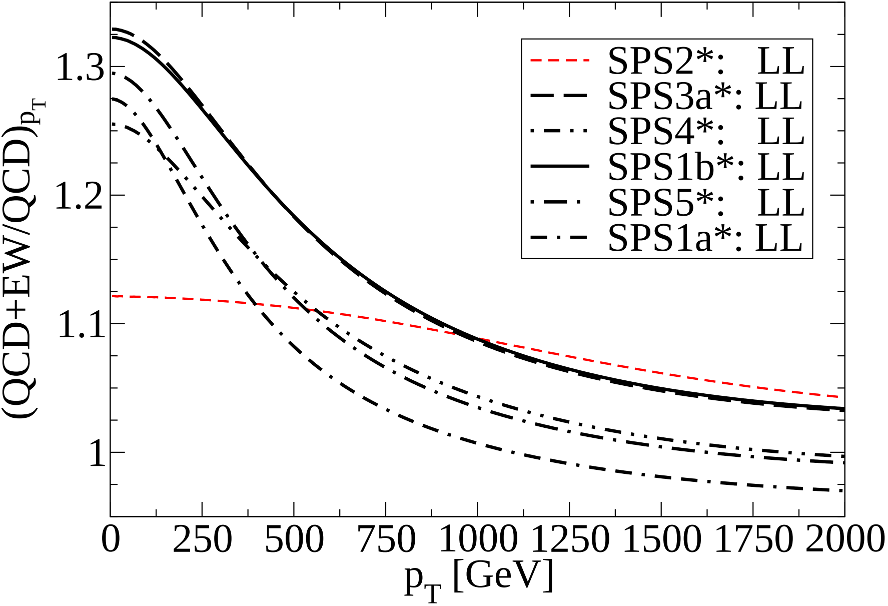

SPS2*: LL
SPS3a*: LL
SPS4*: LL
SPS1b*: LL
SPS5*: LL
SPS1a*: LL
(QCD+EW/QCD)$_{p_T}$
p_T [GeV]
0
250
500
750
1000
1250
1500
1750
2000
1
1.1
1.2
1.3

Dependence on p_T continue

There are three cases of decrease for large p_T; why?!:

- interference terms of category 1:

$$\propto M_{\tilde{g}} M_{\tilde{W}} \quad \text{(helicity flip)},$$

  this has to be compensated by an extra factor of p_T^{-2} for large p_T
- negative interference terms of category 2 (no helicity flip) have suppression for large p_T due to anti-quark in the initial state

$$\hat{s} = 4\left(m_{\tilde{q}}^2 + \frac{p_T^2}{\sin^2\theta}\right), \hat{s} = x s$$

Thus:

- category 1 and 2 have competing suppressions factors
- for the three cases: category 2 dominates slightly
- larger suppression of category 2 for larger squark masses

Dependence on squark mass

Larger squark masses give rise to:

- smaller values of β due to reduction of the phase space

$$\beta = \sqrt{1 - \frac{4m_{\tilde{q}}^2}{\hat{s}}}$$

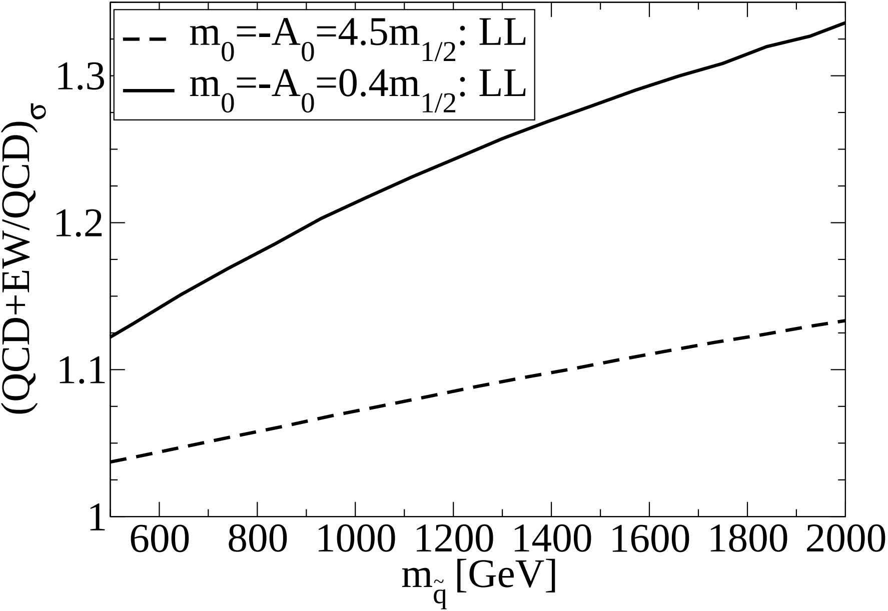
- anti–quarks suffer higher suppression than quarks (Bjorken–x)

$$\hat{s} = 4\left(m_{\tilde{q}}^2 + \frac{p_T^2}{\sin^2\theta}\right)$$

So larger squark masses lead to:

- higher suppression of the destructive interference terms of category 2, which have an anti–quark and $\sigma \propto \beta^3$
- nearly all processes of category 3 have anti–quark or/and $\sigma \propto \beta^3$ suppressions

$\Longrightarrow$ higher weighting of the positive contributions



m0=-A0=4.5m1/2: LL
m0=-A0=0.4m1/2: LL
1.3
1.2
1.1
1
600
800
1000
1200
1400
1600
1800
2000
(QCD+EW/QCD)σ
mq̃ [GeV]

Dependence on squark mass continue

Two further observations:

- increase of the cross section can be much different for a fixed squark mass
- maximal relative size of EW contributions larger than the most favorable single process of category 1

For smaller squark masses (larger β) the weighting of processes with squared t–channel and u–channel propagators is higher:

- t–channel propagator is given by

$$\frac{1}{\hat{t} - M_{\tilde{q}}^2} = \frac{1}{m_{\tilde{q}}^2 - \frac{\hat{s}}{2}(1 - \beta \cos\theta) - M_{\tilde{g}}^2} ,$$

  $\Longrightarrow$ highest contributions for large $\beta |\cos\theta|$
- pure QCD gives largest contributions to processes with non–mixed propagators (for u–channel replace $\cos\theta \to -\cos\theta$)
- pure QCD interference terms (mixed propagators) are destructive

Dependence on gaugino masses

- category 1 $\propto$ to $M_{\tilde{g}} M_{\tilde{W}}$, so sensitive to ratio of gaugino masses
- in mSUGRA:

$$M_1 : M_2 : M_3 \sim 1 : 2 : 7 \text{ at the weak scale}$$

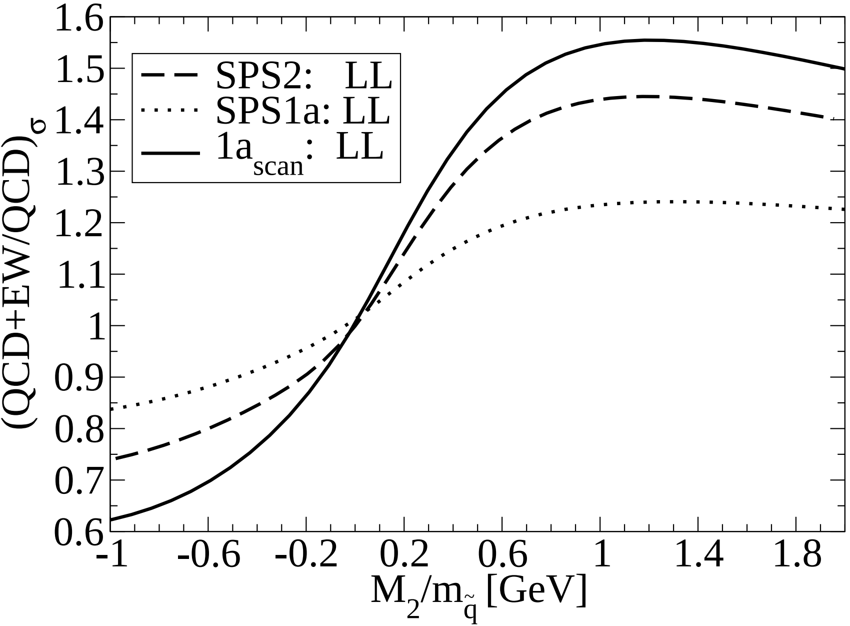
$\Longrightarrow$ larger EW contributions without gaugino mass unification

For example, vary M_2 at the weak scale:

- maximum of curve is at $M_2 = m_{\tilde{q}}$, since it maximizes

$$\frac{M_2}{\hat{t} - M_2^2}$$

- $M_2 < 0$ (keep sign of $M_{\tilde{g}}$) lead to negative EW contributions due to change of the sign of the interference terms of category 1



SPS2: LL
SPS1a: LL
1a scan : LL
(QCD+EW/QCD)σ
M2/mq̃ [GeV]
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
-1
-0.6
-0.2
0.2
0.6
1
1.4
1.8

Summary

- contribution with interference between t- and u-channel is dominant for SU(2)-doublets
- EW correction increases with the squark mass
- EW effects can reduce or enhance the total cross section by more than a factor of 1.55
- for gaugino mass unification, the enhancement factor is 1.4
- EW contribution might give a new, independent handle on the gaugino mass parameters