Detection of Superparticles – Electroweak Contributions to Squark Pair Production

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Promotionskolloquium

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Outline

1 Introduction

The Standard Model (SM) of Particle Physics...

- is a relativistic, renormalizable quantum field theory, which based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$
- describes the matter particles, leptons and quarks (an electron is a lepton; a proton consists of three quarks)
- describes interactions of the matter particles:
  - electromagnetic interaction (force on charged particles)
  - weak interaction (decay of particles)
  - strong interaction (glue together protons)

Particle content of the Standard Model

- there are three generations of quarks and leptons (spin 1/2)
- there are gauge bosons (spin 1), which transfer the interations
- there is one hypothetical (not yet found) higgs boson (spin 0), which gives rise to the masses of the particles

Standard Model

(“http://www.hep.ucl.ac.uk/postgrad/“)

BUT, the Standard Model cannot be the "final answer" since it does NOT...

- predict neutrino masses
- give an answer to the question why we have three generations of particles
- account for Dark Matter in the Universe
- include the fourth known fundamental interaction, gravity
- ...

Extension of the SM due to Supersymmetry (SUSY); SUSY...

- connects fermions (half–integer spin) and bosons (integer spin)
- each SM particle gets a Superpartner ("sparticles"), e.g. quark q $\Longrightarrow$ squark $\tilde{q}$
- simplest possible realization of SUSY is given within the "Minimal Supersymmetric extension of the SM" (MSSM)
- MSSM provides a candidate for Dark Matter, enables the exact unification of the three couplings constants, ...

The MSSM and its particle spectrum

- there is second SU(2)-Higgs doublet with hypercharge $Y = -1$
- SUSY is not exact, sparticles do not have the same mass as their SM partners $\Longrightarrow$ SUSY have to be broken $\Longrightarrow$ adding soft-terms
- MSSM has 105 extra free parameters
- has "R-parity" conservation, sparticles will be produced always in pairs

Names	Boson Fields	Fermion Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
gluons&gluinos	g^a	$\tilde{g}^a$	8	0	0
W bosons&winos	W^i	$\tilde{W}^i$	1	3	0
B boson&bino	B	$\tilde{B}$	1	1	0
sleptons&leptons	$\tilde{L}^j = (\tilde{\nu}, \tilde{e})_L$	$(\nu, e)_L$	1	2	-1
	$\tilde{E} = \tilde{e}_R^*$	$e_R^\dagger$	1	1	2
squarks&quarks	$\tilde{Q}^j = (\tilde{u}, \tilde{d})_L$	$(u, d)_L$	3	2	$\frac{1}{3}$
	$\tilde{U} = \tilde{u}_R^*$	$u_R^\dagger$	3^*	1	$-\frac{4}{3}$
	$\tilde{D} = \tilde{d}_R^*$	$d_R^\dagger$	3^*	1	$\frac{2}{3}$
Higgs&Higgsinos	H_1^i	$(\tilde{H}_1^0, \tilde{H}_1^-)_L$	1	2	-1
	H_2^i	$(\tilde{H}_2^+, \tilde{H}_2^0)_L$	1	2	1

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Gaugino Mass Eigenstates

particles with same $SU(3) \times U(1)_{EM}$ quantum numbers can mix after breaking electroweak symmetry breaking of $SU(2)_L \times U(1)_Y$:

- charginos $\chi_i^{\pm}$ are linear combination of charged winos ($\tilde{W}^+, \tilde{W}^-$) and charged higgsinos ($\tilde{H}_1^-, \tilde{H}_2^+$)
- neutralinos χ_i^0 are linear combinations of neutral wino ($\tilde{W}^3$), bino ($\tilde{B}$) and neutral higgsinos ($\tilde{H}_1^0, \tilde{H}_2^0$)

mSUGRA

- MSSM has 105 (!) new parameter $\Longrightarrow$ work within a constrained MSSM: mSUGRA, here only 5 free parameter left:
  - $m_0, m_{1/2}$: scalar and gaugino mass
  - A_0: trilinear coupling
  - $\tan\beta$: ratio of vaccum expectation values of the Higgses
  - $\mathrm{sgn}(\mu)$: sign of the Higgsino mass parameter
- after choice of the five parameters $\Longrightarrow$ you get masses of the sparticles, parameters for mixing, ...

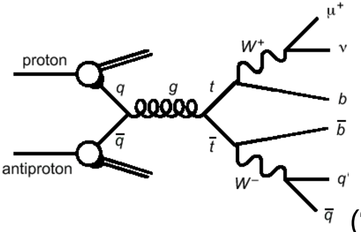
Search for Supersymmetry

- no direct experimental evidence for SUSY until now
- expectation that some of the SUSY particles will be found at the Large Hadron Collider (LHC) at CERN:
  - is a proton–proton circular collider
  - is the world‘s largest particle accelerator (circle of 27km)
  - is the world‘s highest–energy particle accelerator ($E_{cm} = 14 TeV$)
  - will be go on line in the end of 2008

(very) simplified picture of a proton–proton collision at the LHC:

- one quark of each proton (uud) interact with each other
- probability to find a special quark within a proton is described by so called ”parton–distribution functions“ (pdf’s) $f(x, Q^2)$
- probability for an interaction between two quarks is given by the corresponding cross section $\hat{\sigma}$
- the cross section $\hat{\sigma}$ can be calculated with the help of Feynman diagrams

(very) simplified picture of a p–p collision continue



("http://hep.uchicago.edu/ arahlin/")

cross section σ for an process is given by:

$$\sigma = \int dx_1 \int dx_2 f(x_1, \mu^2) f'(x_2, \mu^2) \hat{\sigma}(\hat{s}, \mu^2)$$

- μ: factorization scale
- $f(x_i, \mu^2)$: pdf for proton i; fraction x_i of the proton energy was given to the corresponding quark
- $\hat{\sigma}(\hat{s}, \mu^2)$ parton cross section for the interaction of the two quarks ($\hat{s} = x_1 x_2 s, \sqrt{s} = E_{cm}$)

Squark Pair Production at the LHC

- TeV scale Supersymmetry will be decisively tested at the LHC ($E_{cm} = 14 TeV$)
- squark pairs can be produced via leading order strong interactions
- 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.

$\Longrightarrow$

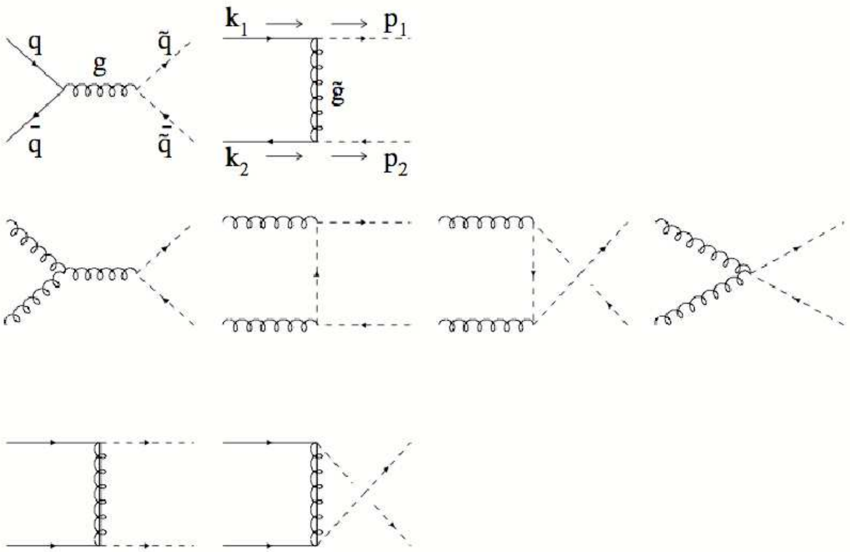
We need accurate theoretical predictions:

- NLO QCD corrections in addition to the LO cross section (Beenakker, Hopker, Spira and Zerwas, 1995)
- remaining uncertanity from yet higher order QCD corrections should be at 10% level

Thus EW corrections at leading order might be important since:

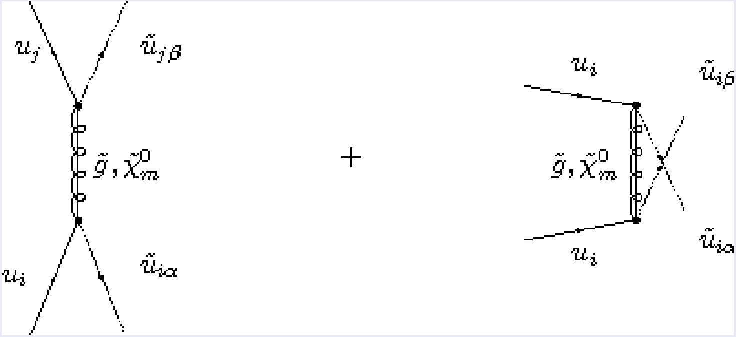
- the interference terms between QCD and EW can be quite sizable
- they can give rise to an increase up to 20% for mSUGRA scenarios and two SU(2) doublet squarks
- they can give rise to an increase up to 50% for scenarios without gaugino mass unification and two SU(2) doublet squarks

QCD: Diagrams for Leading Order Squark Pair Production



2 Electroweak Contributions

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



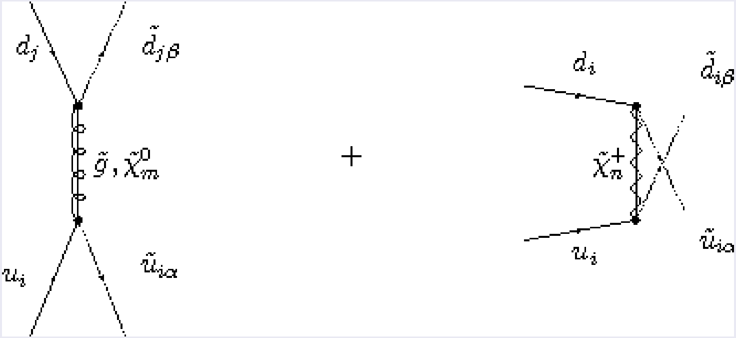
Notation:

- 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

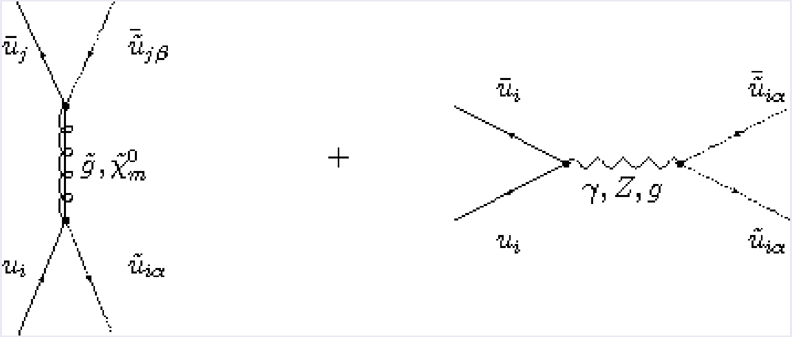
$qq' \to \tilde{q}\tilde{q}'$: t– or u–channel chargino exchange



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 $i \neq j$

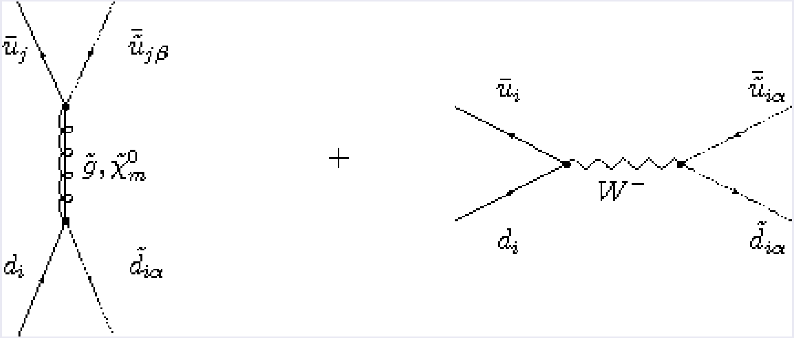
$q\bar{q}' \to \tilde{q}\bar{\tilde{q}}'$: γ, Z, g boson s–channel exchange



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

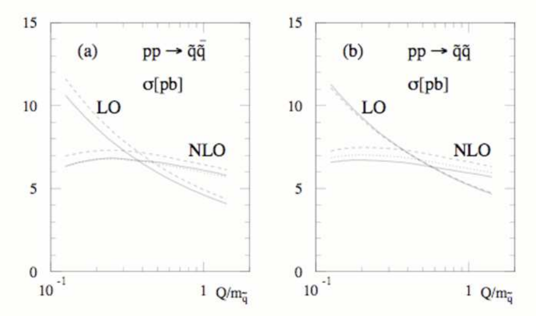


Remarks:

- 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 $i \neq j$

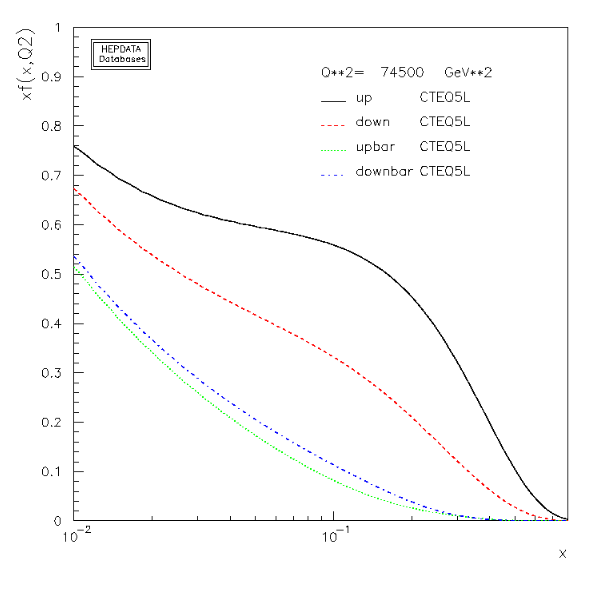
Parameter choice

- 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	QCD + EW[pb] Total	QCD + 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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- 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

Helicity flip and threshold behaviour:

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

- 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 $u_L u_R \to \tilde{u}_L \tilde{u}_R$:

- 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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Electroweak Contributions, 2nd category:

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8	$u\bar{u} \to \tilde{u}_L\bar{\tilde{u}}_L$	s, t	s, t	no	β^3	0.165	0.140	0.848
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
- 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, 2nd category:

No.	Process	diagrams QCD	EW	helicity flip?	thre–shold	cross section [pb] QCD	QCD + EW	ratio
8	$u\bar{u} \to \tilde{u}_L \bar{\tilde{u}}_L$	s, t	s, t	no	β^3	0.165	0.140	0.848
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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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	$u\bar{u} \to \tilde{u}_L \bar{\tilde{u}}_R$	t	t	yes	β	0.569	0.569	1.000
19	$d\bar{d} \to \tilde{d}_L \bar{\tilde{d}}_R$	t	t	yes	β	0.331	0.331	1.000
20	$u\bar{d} \to \tilde{u}_L \bar{\tilde{d}}_R$	t	t	yes	β	0.491	0.491	1.000
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22	$u\bar{d} \to \tilde{u}_R \bar{\tilde{d}}_R$	t	t	no	β^3	0.202	0.203	1.004
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24	$d\bar{d} \to \tilde{u}_R \bar{\tilde{u}}_R$	s	s	–	β^3	0.0240	0.0240	1.000

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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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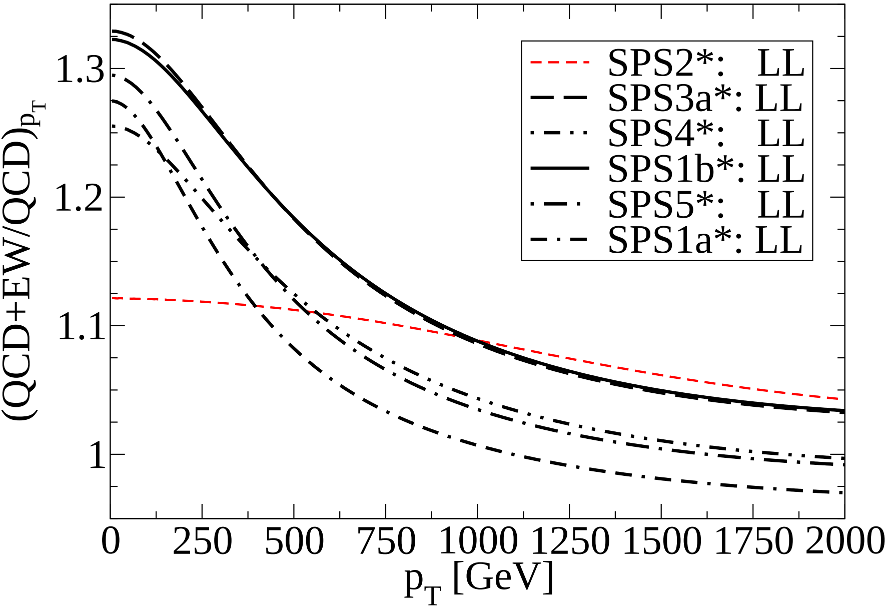


SPS2*: LL
SPS3a*: LL
SPS4*: LL
SPS1b*: LL
SPS5*: LL
SPS1a*: LL
(QCD+EW/QCD)$_{p_T}$
1.3
1.2
1.1
1
0
250
500
750
1000
1250
1500
1750
2000
p_T [GeV]

Dependence on squark mass

Larger squark masses give rise to:

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

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

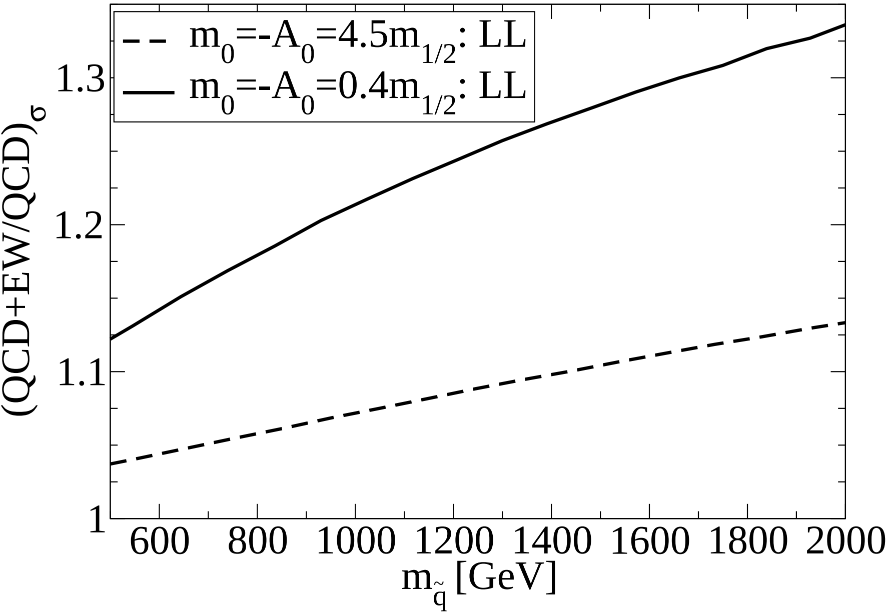
- anti–quarks suffer higher suppression than quarks (Bjorken–x)

$$\hat{s} = 4\left(m_{\tilde{q}}^2 + \frac{p_T^2}{\sin^2\theta}\right), \hat{s} = x_1 x_2 s$$

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
(QCD+EW/QCD)σ
1
1.1
1.2
1.3
600
800
1000
1200
1400
1600
1800
2000
mq̃ [GeV]

Dependence on gaugino masses

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

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

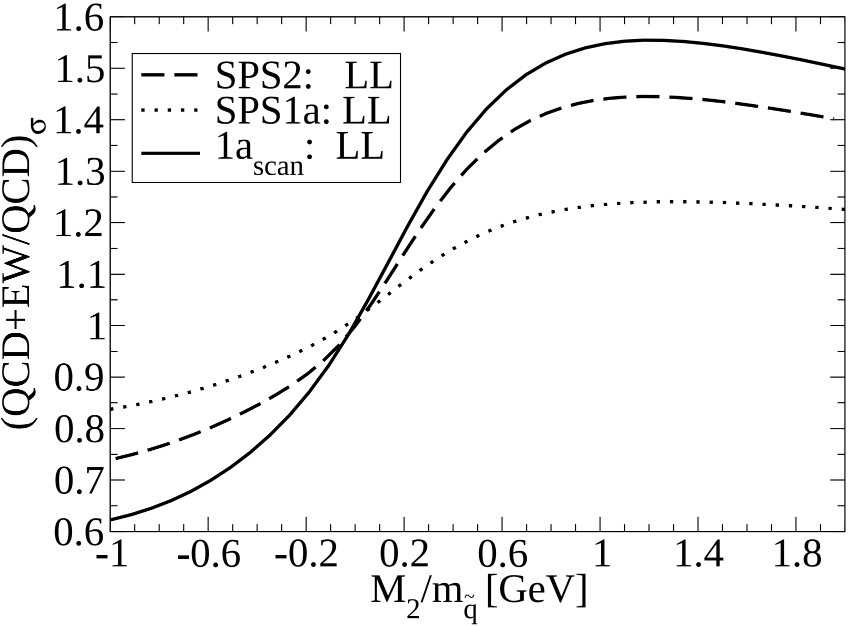
$\Longrightarrow$ larger EW contributions without gaugino mass unification

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 $M_{\tilde{g}}$) leads 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
M_2/m_q̃ [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

3 Summary

Summary

- MSSM: each SM particle gets a superpartner
- TeV scale SUSY will be tested at the LHC
- squark pair production will be important; determination of the production cross section with a high precision
- even leading order EW contributions might be important
- 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
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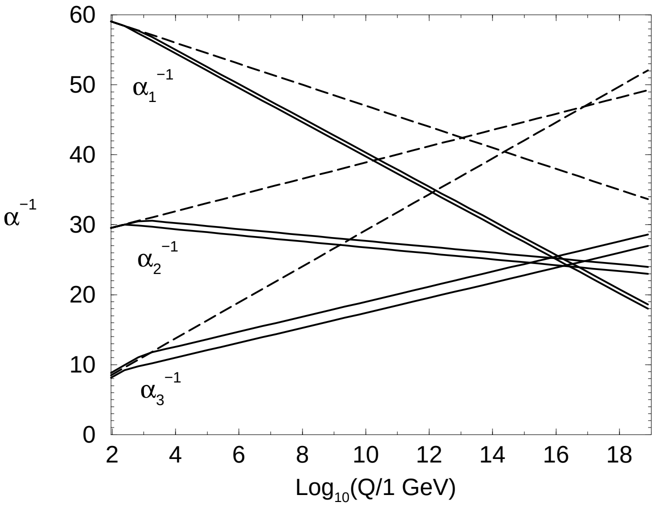
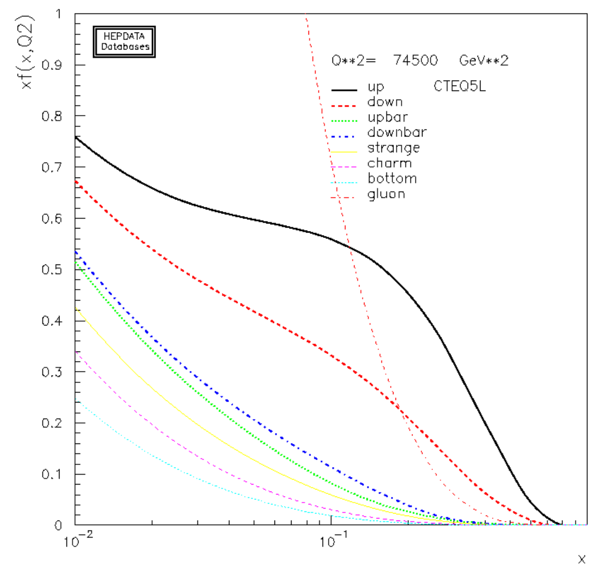
- **Thank you!! Questions?!**

Backup Slides

Gauge coupling unification

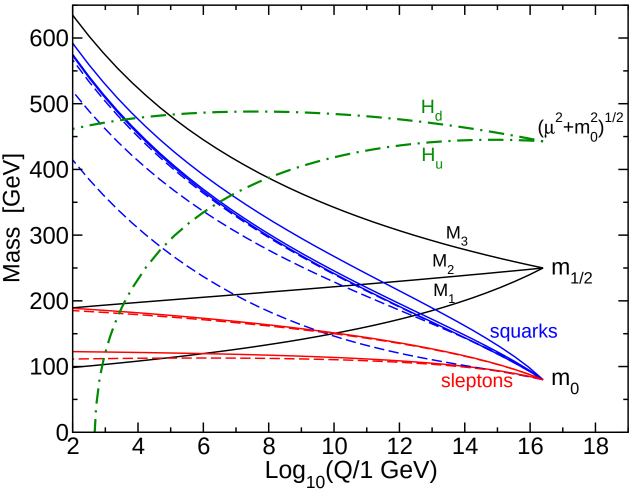


Parton Distribution Functions



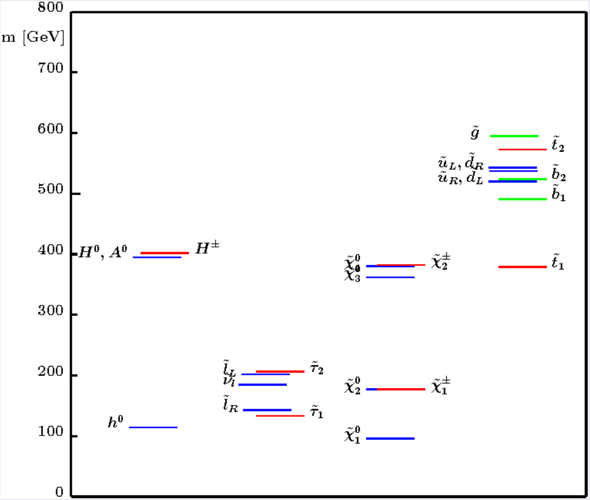
(Durham University On–line Plotting and Calculation page)

mSUGRA



Mass [GeV]
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16
18
Log10(Q/1 GeV)
Hd
Hu
(μ2+m02)1/2
M3
M2
M1
m1/2
squarks
sleptons
m0

Mass eigenstates



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

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

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 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

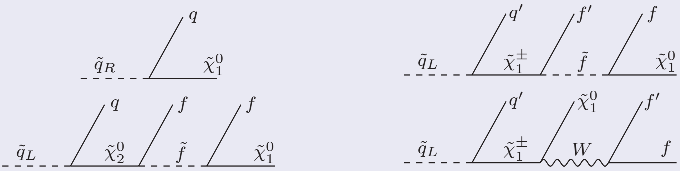
$$\frac{1}{\hat{t} - M_{\tilde{q}}^2} = \frac{1}{m_{\tilde{q}}^2 - \frac{\hat{s}}{2}(1 - \beta\cos\theta) - M_{\tilde{g}}^2},$$

$\Longrightarrow$ highest contributions for large $\beta|\cos\theta|$

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

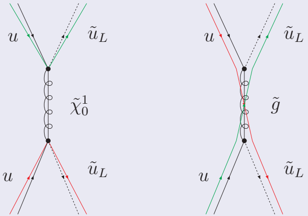
Signal I

- EW contribution is much smaller for SU(2) singlet final states
- for $m_{\tilde{g}} > m_{\tilde{q}} > |M_2|, |M_1|$
- SU(2) doublets decay into charginos and neutralinos dominated by SU(2) gaugino components, in mSUGRA: $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$
- SU(2) singlets decay into bino–like neutralinos, in mSUGRA: $\tilde{\chi}_1^0$



- the rate for doublet squarks can therefore be experimentally enhanced by the presence of energetic, isolated charged leptons, ≥ 2 jets and missing transverse momentum

Rapidity gaps



- in EW channels, both partons are not color–connected
- if both jets are not color–connected, gluons will fill the phase space between the jets and the beam remnants
- if both jets are color–connected, the phase space between both jets will be filled by gluons