Beyond the Standard Model at HERA II

Hubert Spiesberger
DESY Forum
14.5.2002

- High luminosity and polarization . . .
- tests of the electroweak interactions
- future searches, mainly:
- supersymmetry
  - production processes and decays
  - signatures and generic searches
  - model scenarios: $\not{R}_p$ MSSM, GMSB

HERA II upgrade

- Luminosity
  focussing magnets inside detector
  $\rightarrow \mathcal{L}$ increased by factor ~ 3.5
  expect $\int dt \mathcal{L} \simeq 1000$ pb^{-1} till 2006

$\Rightarrow$ high precision for NC / CC DIS cross sections, structure functions, parton distributions

$\Rightarrow$ small cross sections of rare processes accessible

- Polarization
  spin rotators and polarimetry,
  degree of polarization up to $P_L = 0.7$

$\Rightarrow$ test helicity structure of electroweak interactions

$\Rightarrow$ diagnostic tool for new physics

- Detector upgrades
  vertex, tracking, luminosity system

Electroweak tests

Example: charged current DIS cross section
quantify agreement of data with SM by W-mass
(strategies for a determination of m_W)

$$\left.\frac{d\sigma}{dQ^2}\right|_{CC} = \frac{1}{\left(Q^2+m_W^2\right)^2}\Phi(x,Q^2) \quad (1)$$

$$\uparrow \text{ pdf, normalization}$$

$$= \frac{1}{\left(Q^2+m_W^2\right)^2}\frac{G_\mu^2 m_W^4}{2\pi}\Phi'(x,Q^2) \quad (2)$$

$$\updownarrow\ G_\mu \to G_\mu^{\text{SM}} \text{ at tree-level}$$

$$= \frac{1}{\left(Q^2+m_W^2\right)^2}\frac{\pi\alpha^2}{4\left(1-m_W^2/m_Z^2\right)^2}\Phi''(x,Q^2) \quad (3)$$

$$= \frac{1}{\left(Q^2+m_W^2\right)^2}\frac{\pi\alpha^2}{4s_W^4}\Phi'''(x,Q^2)\times \quad (4)$$

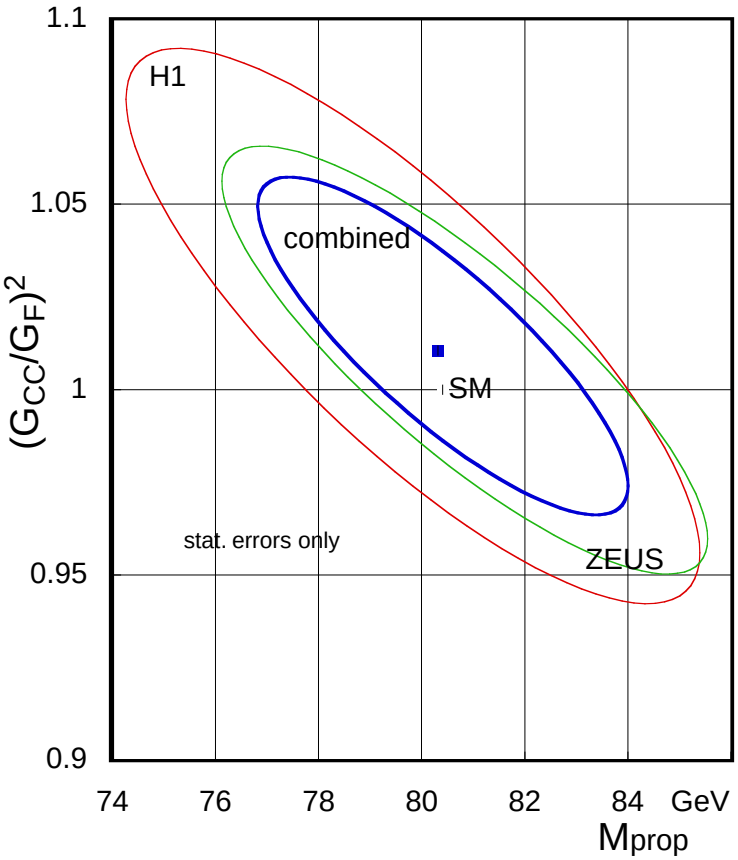
$$\rho_{CC}^{1-\text{loop}}(\alpha, m_Z, m_W, m_t, m_H, \ldots)$$

$\rho_{CC}^{1-\text{loop}}$ takes account of one-loop electroweak radiative corrections

SM predictions are function of a set of independent parameters, e.g. α, m_W, m_Z, m_{top}, m_{Higgs}, ...

m_W determination: propagator mass

2-parameter fit: G_μ and m_W

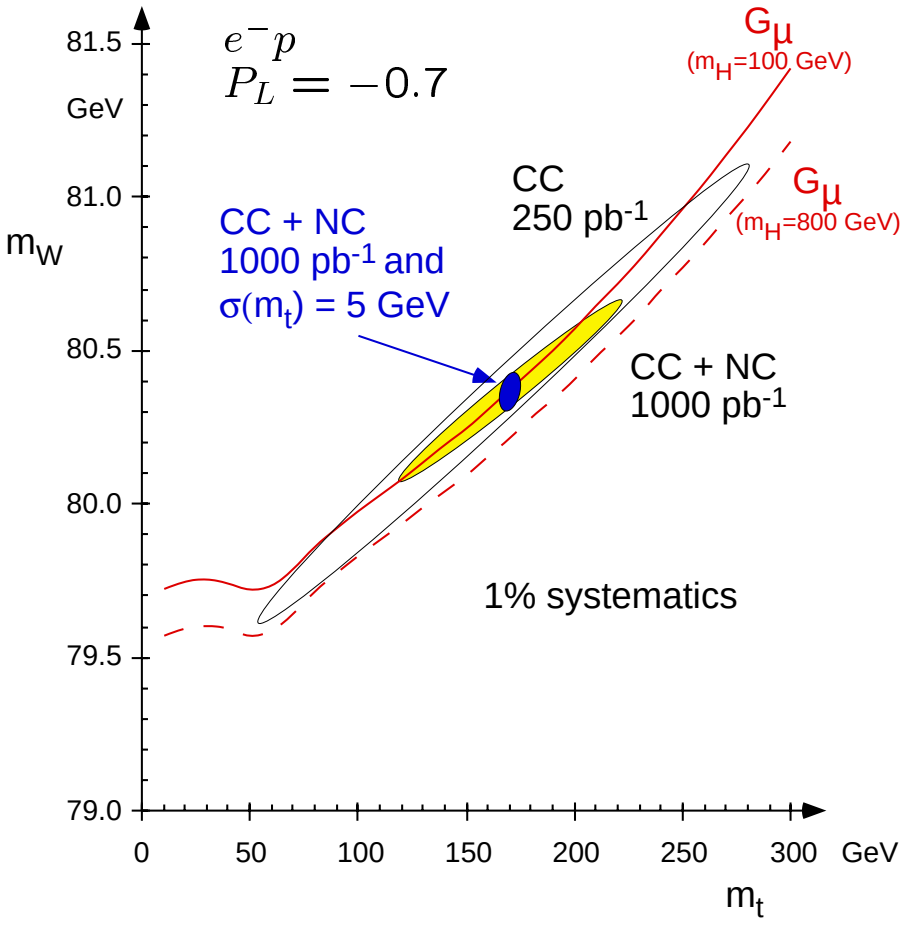


E. Elsen, Tampere '99

constrained fit, fixing G_μ:

$$m_W = 79.9 \pm 2.2_{\text{stat}} \pm 0.9_{\text{sys}} \pm 2.1_{\text{pdf}} \qquad (e^- p)$$

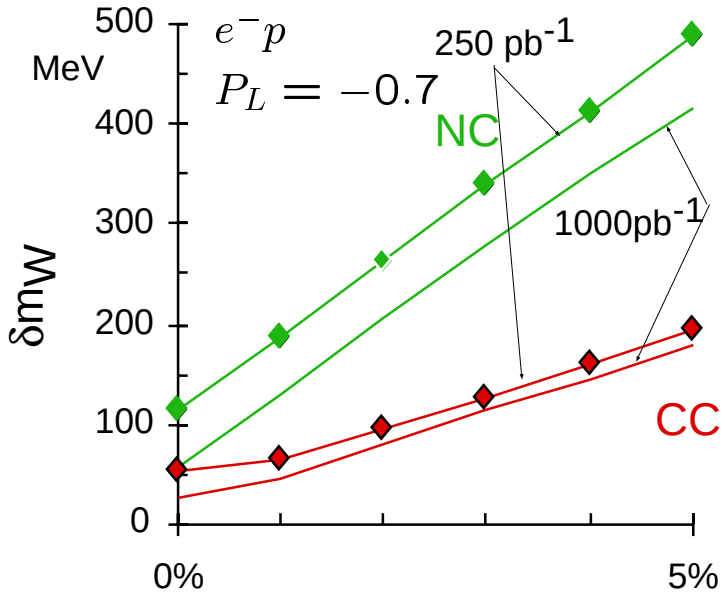
$$m_W = 80.9 \pm 3.3_{\text{stat}} \pm 1.7_{\text{sys}} \pm 3.7_{\text{pdf}} \qquad (e^+ p)$$



constrained fit:
insert
$G_\mu = G_\mu^{\mathrm{SM}}(m_W, m_t)$

high-Q^2 NC/CC
HERA data
combined with
direct m_{top}

G_μ constraint
(CC at $Q^2 = 0$)



Systematic
uncertainty

Beware: in case of a disagreement with other measurements → need to convince that no large systematic effects are responsible

Electroweak tests

Example: utilizing polarized beams

Charged current:

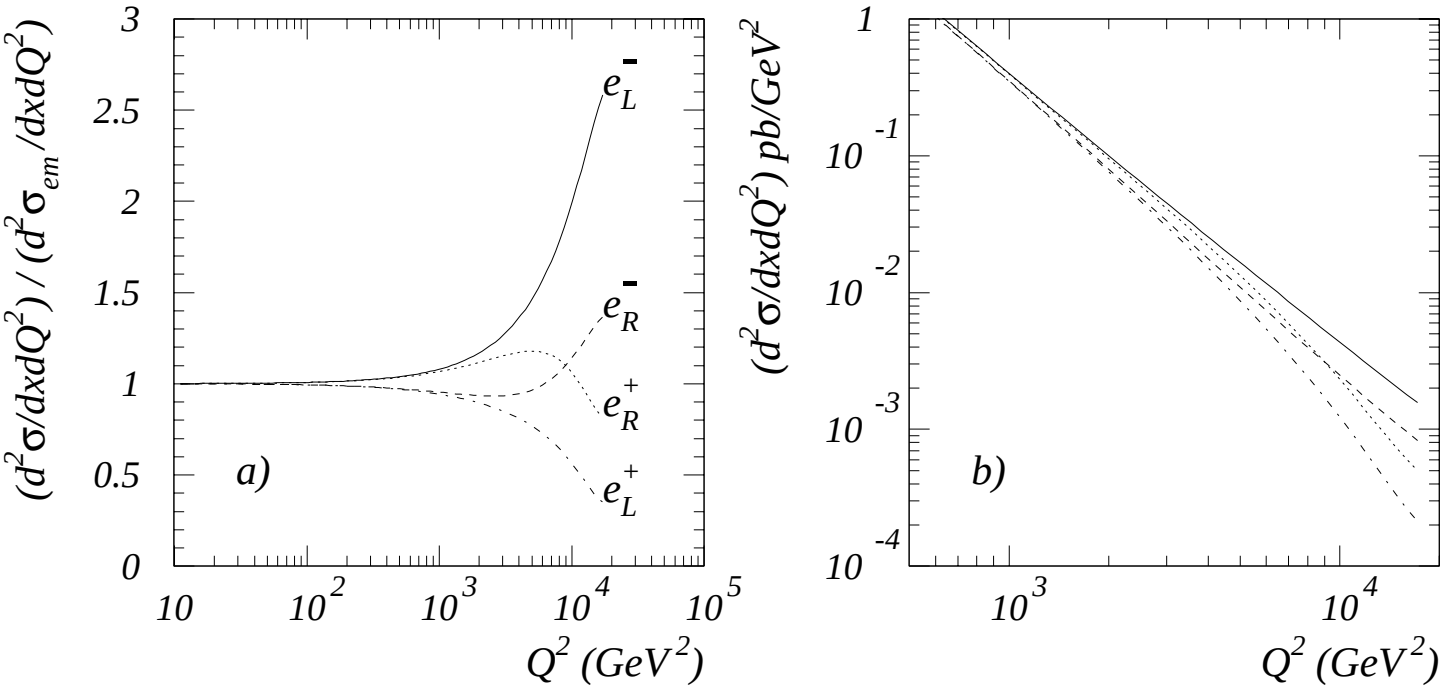
$$\sigma \propto (1 - P_L)$$

→ easy straight-line fits,
→ limits on right-handed currents (m_{W_R})

Neutral current:

$$\frac{d^2\sigma^{\pm}}{dxdQ^2} = \tilde{\sigma}_0^{\pm} + P_L \tilde{\sigma}_L^{\pm}$$

$\sigma_0^{\pm}$ and $\sigma_L^{\pm}$ are functions of lepton and quark coupling constants g_V, g_A

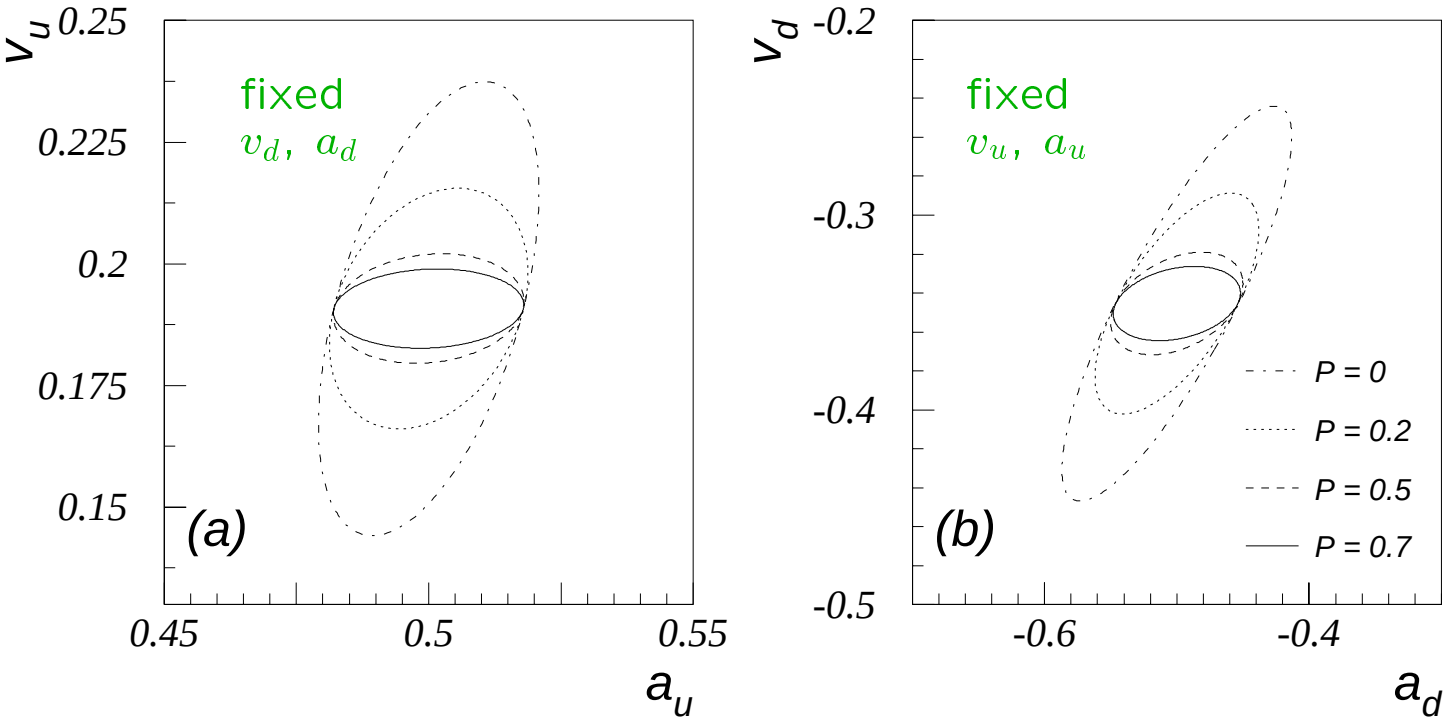


fit coupling constants

with 250 pb^{-1} / beam e^-_L, e^-_R, e^+_L, e^+_R
(assume pdf's known to within $< 5\,\%$ unc.)
4-parameter fit to quark coupling constants $\rightarrow$

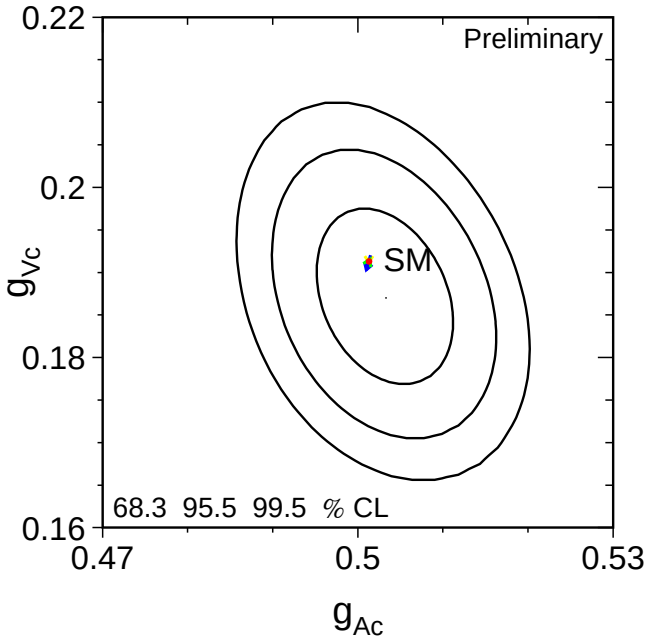
v_u : 13 %, v_d : 17 %
a_u : 6 %, a_d : 17 %

2-parameter fits

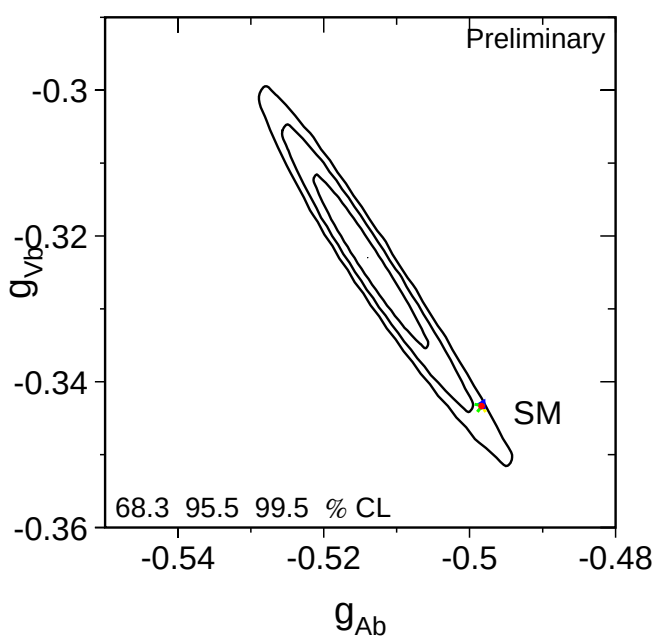


LEP results

for c-quarks



for b-quarks



Rare SM processes

- W production
  $\rightarrow$ anomalous $WW\gamma$ couplings $\Delta\kappa$, λ
  see Proc. Future Physics at HERA '96
- Z production

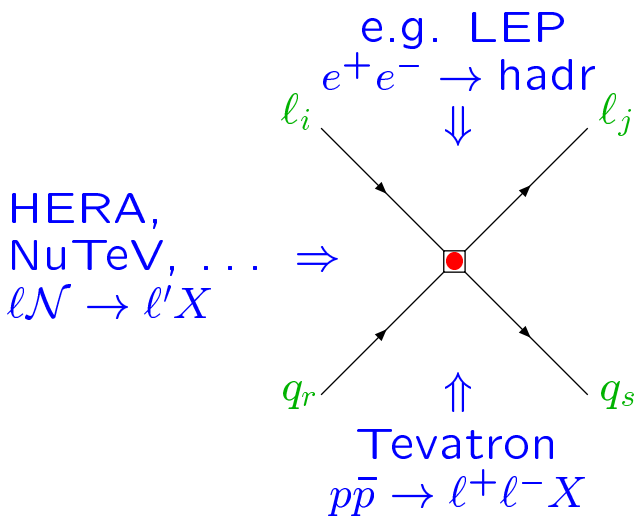
- Lepton pair production
  from various mechanisms
  see Proc. Future Physics HERA '96, DIS2002
- Radiative processes
  $ep \rightarrow \gamma + X$ in NC, CC

$\Rightarrow$ Background for non-SM physics

Search for new physics

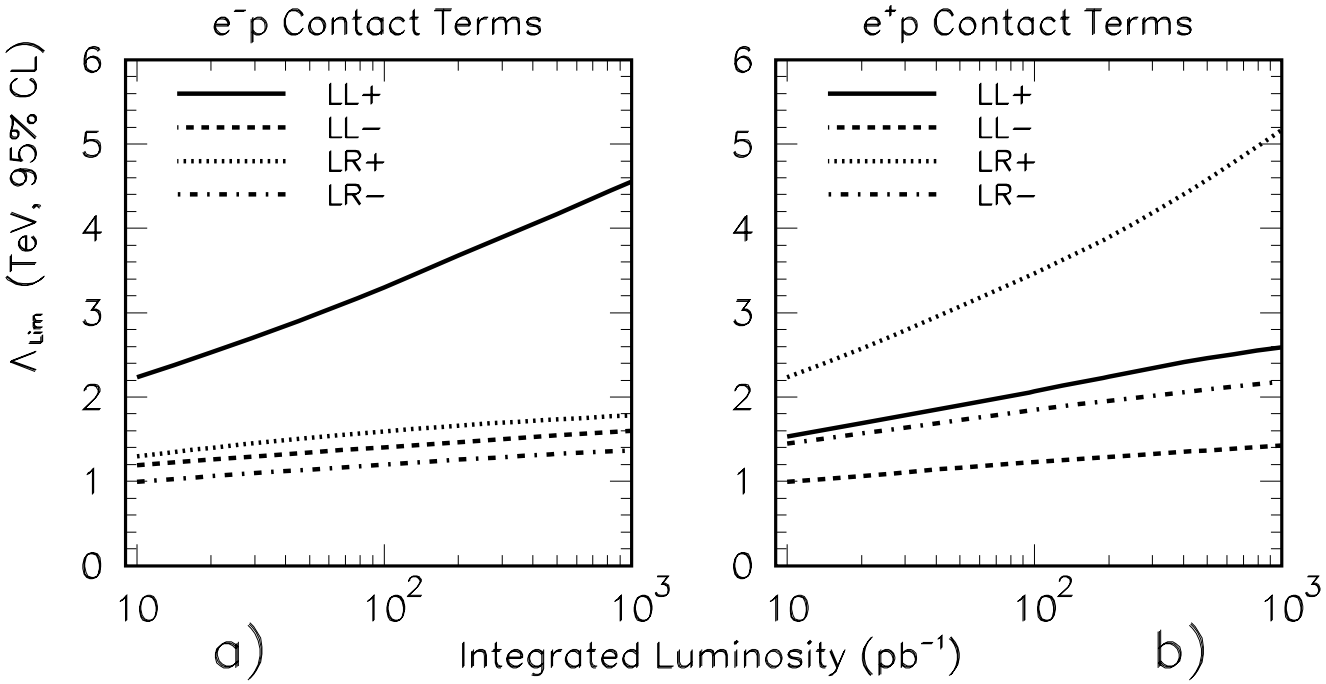
see Proc. Physics at HERA '91
and Future Physics at HERA '96

- Contact interactions
- Extra Z', W
- Heavy Majorana neutrinos, W_R
- Excited fermions (leptons, neutrinos, quarks; substructure)
- Large extra dimensions
- Doubly charged Higgs
- Light gluinos
- Leptoquarks
- Lepton flavor violation
- Supersymmetry (various model scenarios)



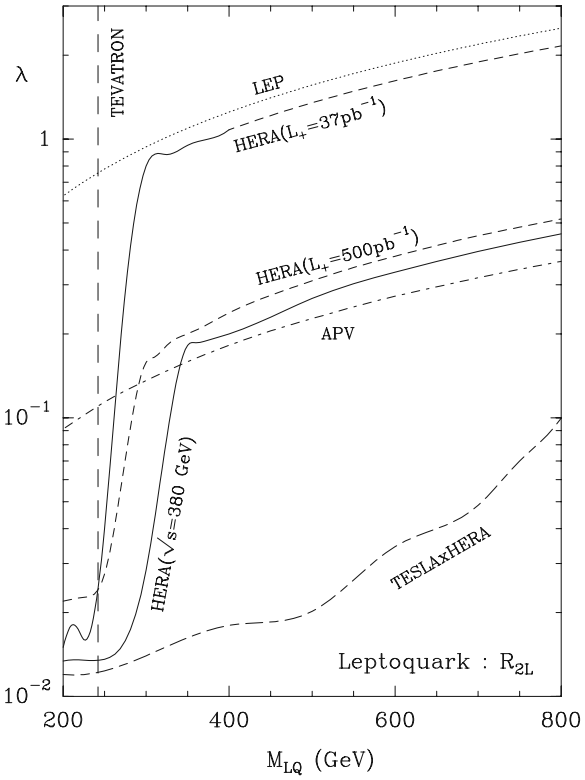
$$\mathcal{L}_{\rm CI} = \sum_{i,j,r,s} \frac{4\pi}{\left(\Lambda^{AB}_{ijrs}\right)^2} \eta_{ijrs} \left(\bar{\ell}_i \Gamma^A \ell_j\right) \left(\bar{q}_r \Gamma^B q_s\right)$$

with i, j, r, s denoting flavor and L, R and $\Gamma^A = \gamma_\mu,\ \gamma_\mu\gamma_5$



Gilmore '96

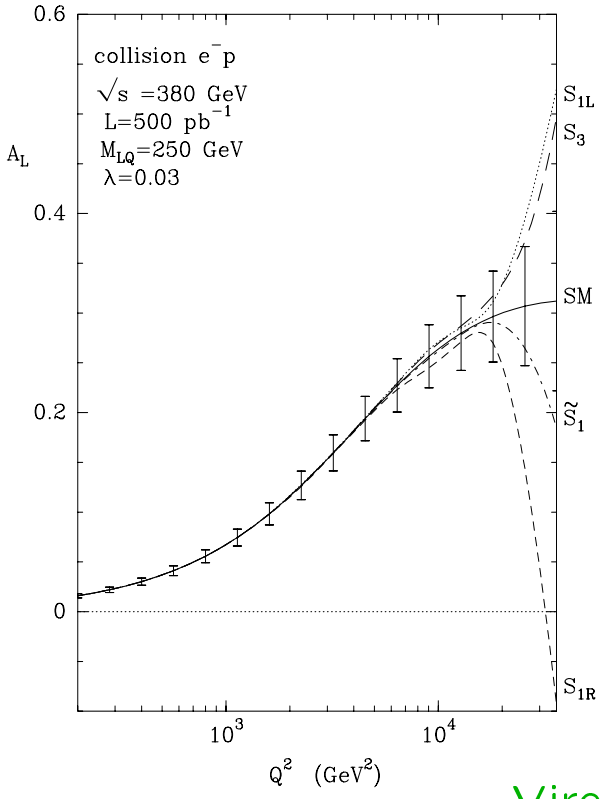
Future: leptoquarks

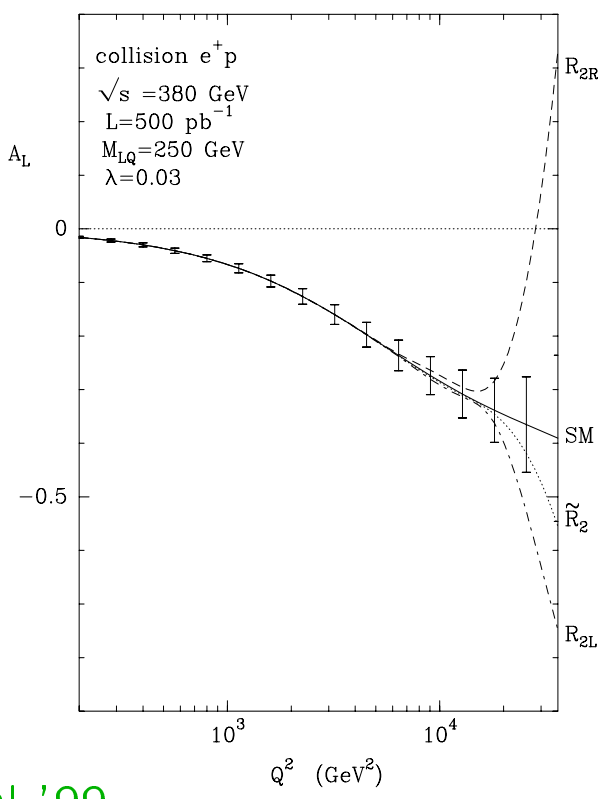


Improved limits from higher luminosity

Virey '98

if there is an effect → polarization may help to distinguish different types of leptoquarks



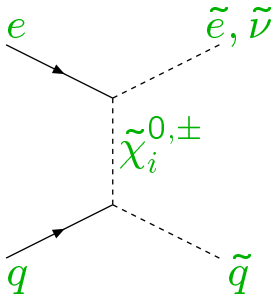


Virey et al '99

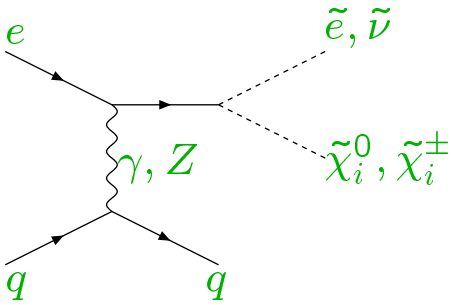
Search for supersymmetry

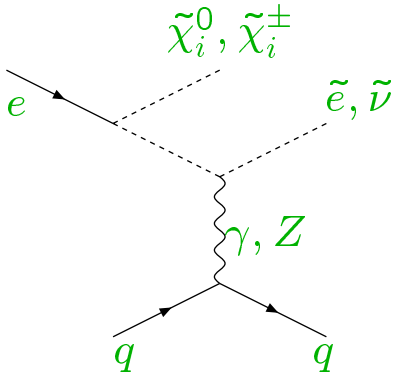
production processes

- $eq \to \tilde{e}\tilde{q}$
- $eq \to \tilde{\nu}\tilde{q}'_L$



- $eq \to \tilde{e}\tilde{\chi}_i^0 q$
  $eq \to \tilde{\nu}\tilde{\chi}_i^{\pm} q$

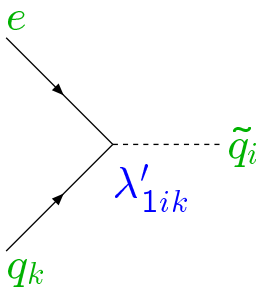




- $eq \to e\tilde{q}\tilde{\chi}_i^0$
  $eq \to e\tilde{q}'\tilde{\chi}_i^{\pm}$
- $\gamma g \to \tilde{t}\bar{\tilde{t}}$

with R_p violation also resonant production

- $eq \to \tilde{q}$



polarization:
only e_L^-, e_R^+

Search for supersymmetry

decays $\rightarrow$ signatures

$$\tilde{q} \rightarrow eq \quad \text{with } \not{R}_p$$

$$\begin{array}{lcl} \tilde{q}_L & \rightarrow & q\tilde{\chi}_i^0, \quad q'\tilde{\chi}_i^{\pm} \\ \tilde{q}_R & \rightarrow & q\tilde{\chi}_i^0 \end{array} \qquad \begin{array}{lcl} \tilde{e}_L & \rightarrow & e\tilde{\chi}_i^0, \quad \nu\tilde{\chi}_i^{\pm} \\ \tilde{e}_R & \rightarrow & e\tilde{\chi}_i^0 \end{array}$$

heavier $\tilde{\chi}^{0,\pm}$ cascading to

$$\begin{array}{lcl} \tilde{\chi}_i^0 & \rightarrow & f\bar{f}\tilde{\chi}_{i-1}^0, \quad f\bar{f}'\tilde{\chi}_j^{\pm} \\ \tilde{\chi}_i^{\pm} & \rightarrow & f\bar{f}'\tilde{\chi}_j^0 \end{array}$$

MSSM: lightest supersymmetric particle (LSP)

$$\tilde{\chi}_1^0 \text{ is stable}$$

MSSM+ $\not{R}_p$: LSP decays with R_p violation

$$\begin{array}{lcl} \tilde{\chi}_1^0 & \rightarrow & e^- u\bar{d}, \; e^+ d\bar{u}, \; \nu d\bar{d} \\ \tilde{\chi}_1^+ & \rightarrow & e^+ d\bar{d}, \; \nu u\bar{d} \end{array} \qquad \text{via } \lambda'_{111}$$

$\Rightarrow$ signatures are combinations of

$$\not{E}_T, \; \ell^{\pm}, \text{ jets}$$

maybe also τ, γ, Z $(= \ell^+\ell^-)$, W $(= \ell\nu)$, b- and c-jets

Generic search ?

motivation: very time-consuming to perform dedicated searches for every specific model
may overlook the unexpected new

problem: if a number of outstanding, seemingly atypical events is found: how to evaluate unbiased statistical significance?

example: SLEUTH, see D0: hep-ex/0006011

- choose set of final states (composed of objects $\not\!\!E_T$, $\ell^{\pm}$, γ, jets, ...)
- choose kinematical variables (like $\not\!\!E_T$, p_T's)
- define regions about data points (after variable transformation to obtain uniform background)
- calculate probabilities of background fluctuating up to (or above) the observed number of events
- find interesting regions
- interpretation: badly modeled background or new physics

requires precise SM predictions including higher-order corrections

Deriving limits

measurements provide limits on $\sigma \cdot B$

interpretation within specific models

e.g. MSSM: $\sigma B(\tilde{m}) \longrightarrow$ mass limits

e.g. MSSM + $\not{R}_p$: $\sigma B(\tilde{m}, \lambda') \longrightarrow$ exclusion plots
mass vs. coupling
(depending on additional parameters)

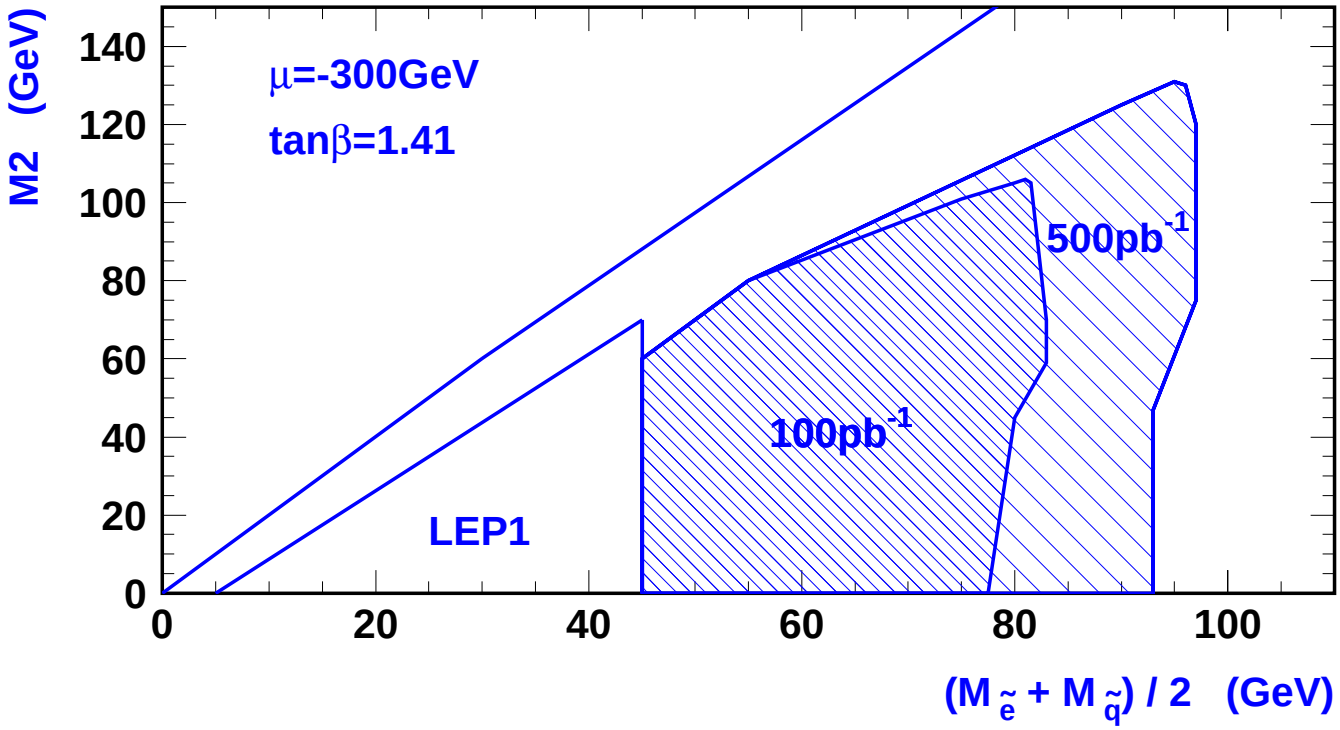
e.g. mSUGRA with REWSB, independent parameters: m_0, $m_{1/2}$, signμ, tan β, (λ'_{ijk})

$\sigma B(m_0, m_{1/2}, \tan\beta, \lambda') \longrightarrow$ exclusion plots
e.g. m_0 vs. $m_{1/2}$
(with tan β and λ' as parameters)

other models ?

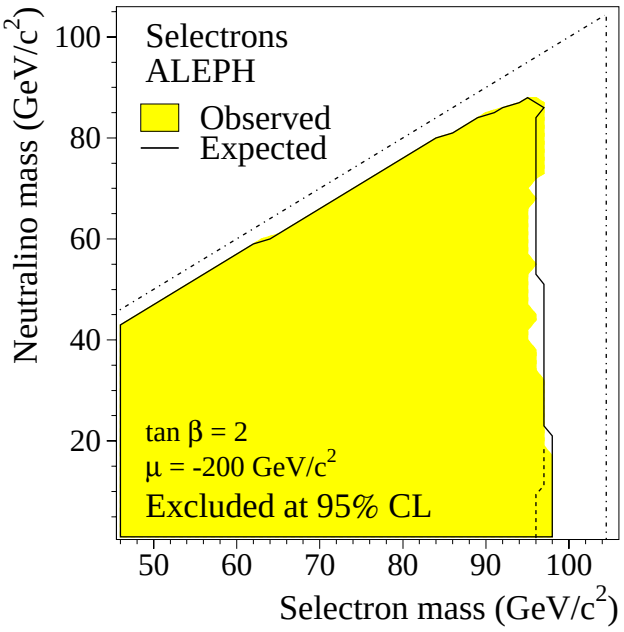
MSSM: mass limits

Schleper, '96: $eq \to \tilde{e}\tilde{q}$



compare recent limits from LEP2

ALEPH, hep-ex/0112011:



$\tilde{e}^{\pm}_R \to e^{\pm}\tilde{\chi}^0_1$

$\tilde{e}^{\pm}_R$: $m > 95$ GeV

$\tilde{\mu}^{\pm}_R$: $m > 88$ GeV

$\tilde{\tau}^{\pm}_R$: $m > 79$ GeV

Supersymmetry with R_p violation

Motivation: consider fermion mass generation in the MSSM

Yukawa superpotential

$$W_\Upsilon = \lambda^E_{ij} H L_i E^c_j + \lambda^D_{ij} H Q_i D^c_j + \lambda^U_{ij} \bar{H} Q_i U^c_j + \mu H \bar{H}$$

with superfields $L \to \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$, $H \to \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$ + superpartners

L and H have same weak isospin and hypercharge $\to$ additional term suggested

$$W_{\not{R}_p} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} D^c_i D^c_j U_k + \mu' H L$$

↑ lepton number violation

↑ lepton number violation

↑ baryon number violation
$\lambda'' = 0$ avoids p decay

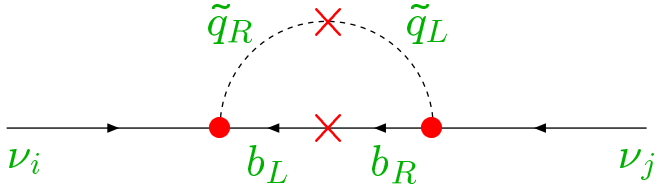
Analogy $W_\Upsilon \leftrightarrow W_{\not{R}_p}$ may even suggest relation between coupling constants ?

$$\lambda'_{ijk} = \lambda'_i \; \lambda^D_{jk} \quad \text{with} \quad \lambda'_i = O(1) \qquad (5)$$

flavor alignment

Consequences of R_p violation

$\Rightarrow$ neutrino masses radiatively generated



mass matrix $(m_\nu)_{ij} = m_\nu^D \lambda'_i \lambda'_j$
with m_ν^D from loop factor, $\propto 1/m_{\tilde{q}}^2$

framework for ν-mixing and ν-masses

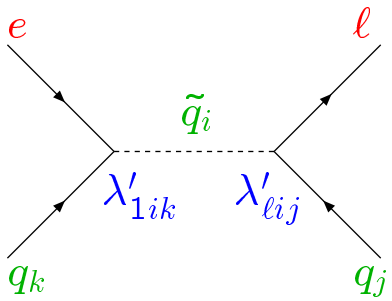
$\Rightarrow$ allows resonant squark production at HERA

$$e_L^- \bar{d}^k \to \bar{\tilde{u}}_L^j, \qquad e_R^+ d^k \to \tilde{u}_L^j$$
$$e_L^- u^j \to \tilde{d}_R^k, \qquad e_R^+ \bar{u}^j \to \bar{\tilde{d}}_R^k$$

via λ'_{1jk}

framework for leptoquarks with masses at the electroweak scale

$\Rightarrow$ generates lepton-flavor violation



$$\to \quad \sum_k \frac{\lambda'_{1ik}\lambda'_{\ell ij}}{\tilde{m}_i^2}$$

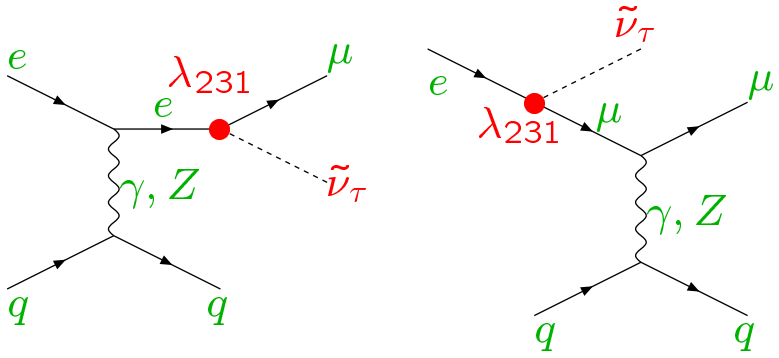
may also exploit relation to λ_{ij}^D: CKM quark mixing

R_p violation: the LLE-term

Kon et al., hep-ph/0203262

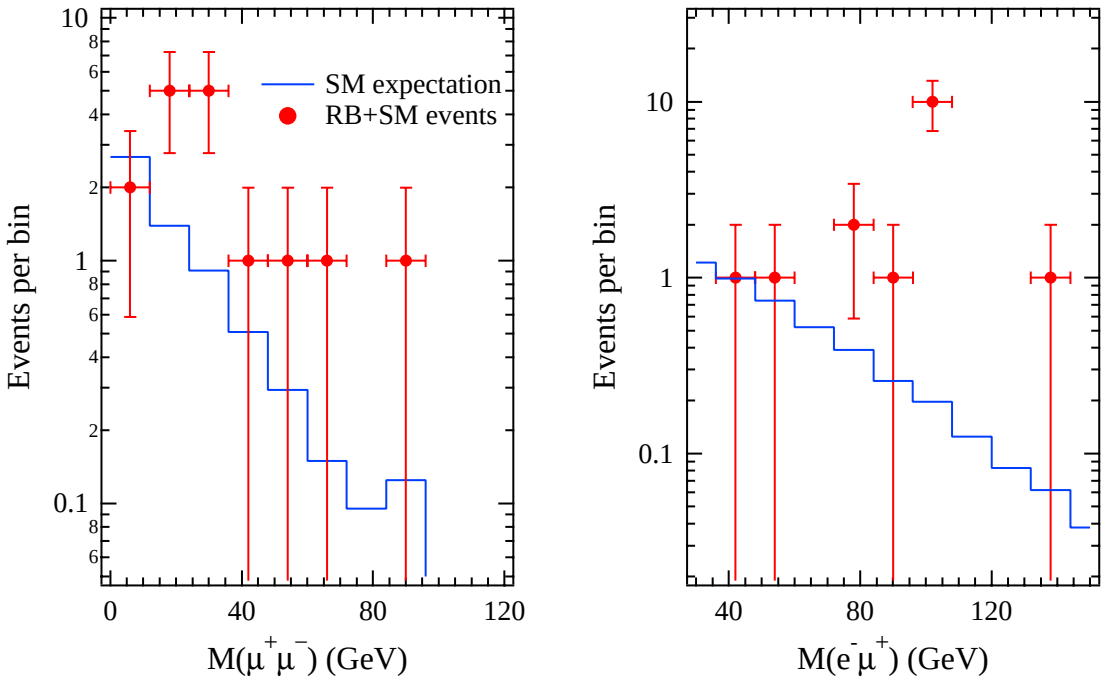
consider LLE-term with $\lambda_{231} \neq 0$
contains $e - \mu - \tilde{\nu}_\tau$ coupling
bound from τ decay: $\lambda_{231} < 0.07$ for $m_{\tilde{e}_R} = 100$ GeV
$\Rightarrow$ sneutrino production at HERA

$e^- p \to \mu \tilde{\nu}_\tau X$
with
$\tilde{\nu}_\tau \to e\mu$



final state: $\mu^+\mu^- e^-$

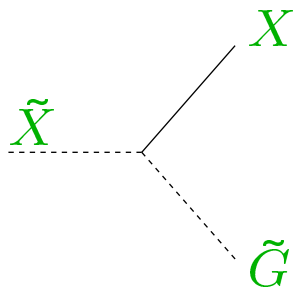
cross section: $O(10)$ fb, $BR \simeq 1$ for large M_2, μ
SM-background mainly 2γ and γ, Z production



- super-Higgs mechanism active in secluded sector
  (broken local supersymmetry $\rightarrow$ Goldstino-gravitino order parameter (vev) of SB: F
- coupled to messenger sector with N generations of fields with Susy mass $\propto M_m$
- gauge interactions transfer Susy breaking to observable sector

model parameters:

- $\Lambda = F/M_m$
- N
- M_m
- $\tan\beta$, signμ
- C_G: Goldstino coupling



$$\Gamma(\tilde{X} \rightarrow X\tilde{G}) = \frac{\kappa m_{\tilde{X}}^5}{16\pi(C_G F)^2}\left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)^4$$

(κ: model-dependent mixing parameter)

mass of Goldstino: $m_{\tilde{G}} = F/\sqrt{3}M_{\text{Planck}}$ very small

$\Rightarrow$ LSP is Goldstino-gravitino
NLSP is relevant for accelerator physics

examples ("model lines") see e.g. hep-ex/0008070

- neutralino NLSP: $\tilde{\chi}_1^0 = \tilde{\gamma}/\tilde{Z}$ or $\tilde{h}$

$$\tilde{\chi}_1^0 \to (\gamma, Z, h) + \tilde{G}$$

- slepton NLSP (maybe stau):

$$\tilde{\ell} \to \ell + \tilde{G}$$

- squark NLSP:

$$\tilde{q} \to q + \tilde{G}$$

  for stop with $m_{\tilde{t}} < m_t$: $\tilde{t} \to bW + \tilde{G}$

- gluino NLSP:

$$\tilde{g} \to g + \tilde{G}$$

phenomenology and signatures classified by decay length:

$$c\tau \simeq \left(\frac{100\mu\text{m}}{\kappa}\right)\left(\frac{100\,\text{GeV}}{m_{\tilde{X}}}\right)^5\left(\frac{\sqrt{F}}{100\,\text{TeV}}\right)^4\left(1-\frac{m_X^2}{m_{\tilde{X}}^2}\right)^{-4}$$

- prompt decay: $c\tau$ small
  various signatures with $\not{E}_T$, γ, $\ell^\pm$, jets
  spectrum usually harder than in conventional scenarios since $\tilde{G}$ is essentially massless
- macroscopic decay length: $\mu\text{m} < c\tau <$ few m
  decay inside detector
  signatures with displaced vertices, tracks with kinks
- decay outside detector: $c\tau \gg$ m
  if NSLP is neutralino: conventional $\not{E}_T$ signature
  otherwise: heavy stable charged particles

GMSB new signatures

- photons
- displaced vertices, tracks with kinks
- heavy stable charged particles

GMSB limits

searches at LEP2 and Tevatron

for example:
$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ with slepton NLSP

prompt decays to final states with 2, 4 or 6 leptons and $\not\!\!E_T$; displaced vertex; stable sleptons (independent of $\tau(\tilde{G})$)

$$
\begin{aligned}
m_{\tilde{e}} &> 66 \text{ GeV} \\
m_{\tilde{\mu}} &> 95.2 \text{ GeV} \\
m_{\tilde{\tau}} &> 86.1 \text{ GeV}
\end{aligned}
$$

ADLO prel. (De Filippis, DIS2002)

not (yet) studied for HERA

can HERA be competitive?

Summary

- Tests of the electroweak interactions at large Q^2: W mass and neutral current quark couplings
- Improved limits from higher luminosity
- Polarization as a diagnostic tool for new physics
- Searches for supersymmetry
- Generic searches ?
- R_p violation: LQD and LLE terms
- New signatures from GMSB ?

Maybe there is more physics

Beyond the Standard Model

at HERA II ?