Higgs & Supersymmetry

Orsay, March 21, 2001

Exotic Searches at HERA and Tevatron : Status and Prospects

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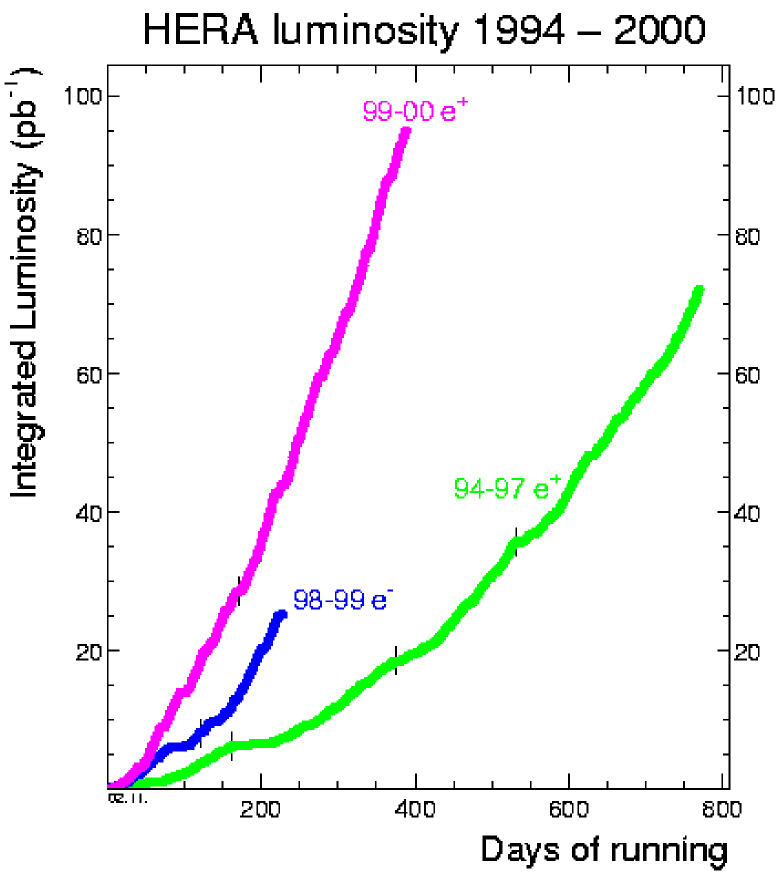
Besides Higgs & minimal SUSY :
What could we discover before the start of the LHC ?

The H1 and ZEUS experiments at the HERA ep collider



Year	Beam	$\sqrt{s}$ (GeV)	$\mathcal{L}$ per exp. (pb^{-1})
94-97	e^+p	300	~ 40
98-99	e^-p	320	~ 15
99-00	e^+p	320	~ 80

$\Sigma = \sim 135$ pb^{-1}

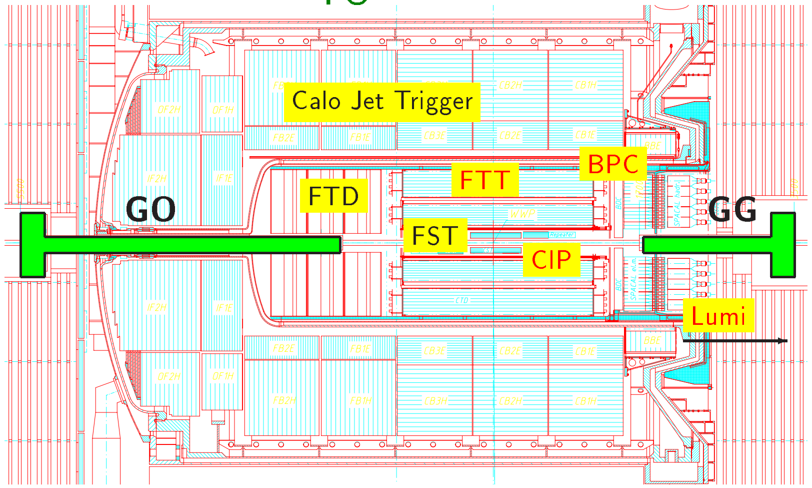
HERA stopped in sept 00, restarts in summer 2001

Upgrade :
- new magnets
- β functions reduced by a factor 4-5
- increased I_e and I_p

$\Rightarrow \sim$ 5-fold increase of luminosity

$\oplus$ Longitudinal polarisation of e beam

The H1 upgraded Detector



Upgrades of detectors, mainly :
- New μ-vertex detector (H1 + ZEUS)
- New Forward Tracking (H1 + ZEUS)
- New Luminosity systems (H1 + ZEUS)
- Improved Track & Jets Triggers (H1)

The CDF and DØ experiments at the TEVATRON $p\bar{p}$ collider

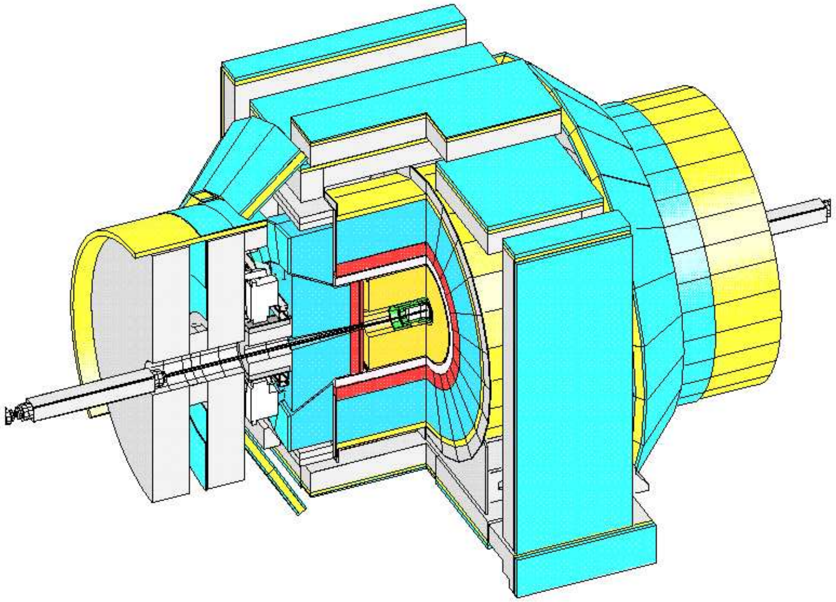
1992-1996 : Tevatron delivered ~ 110 pb^{-1}, $\sqrt{s} = 1.8$ TeV
1997-now : major upgrade of accelerator + detectors.

- Higher energy $\sqrt{s} = 2$ TeV
- New Main Injector $\Rightarrow$ more beam; more $\bar{p}$ production
  + $6\times$ more bunches, $\mathcal{L} \times \sim 10$

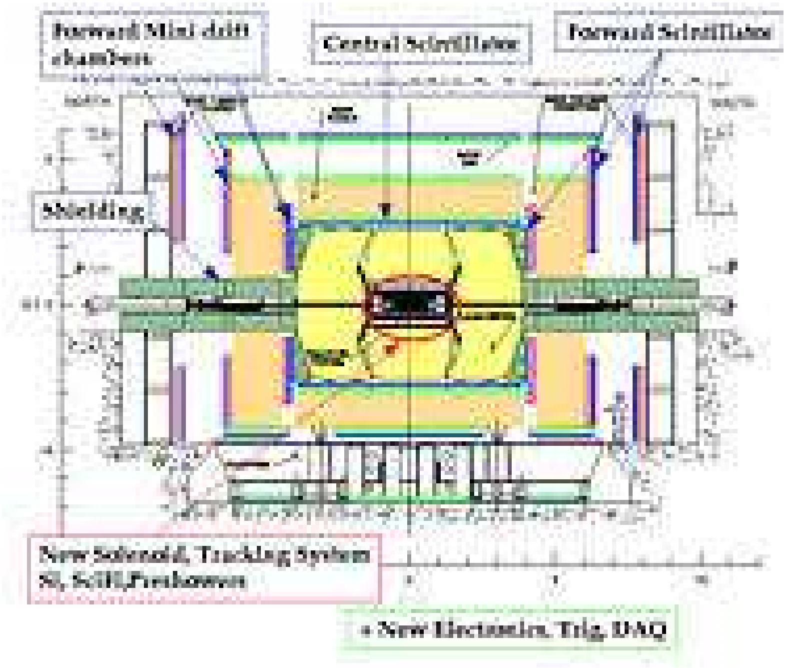
$\Rightarrow$ 20-fold increase of $\int$ luminosity

New machine $\Rightarrow$ p & $\bar{p}$ studies (began this month)
First collisions mid-april, expect ~ 0.5 fb^{-1} by 12/01

The CDF detector



The DØ detector



	DØ	CDF
Run I	good calorimetry good hermeticity $\Rightarrow E_{miss}$, e, γ no central $\vec{B}$	Charged particle tracking Si vertex detector $\Rightarrow l^{\pm}, b, \tau$..
Run II	Central magnet New tracker Si vertex detector Improved μ det.	New tracker More Silicon More hermetic calos and μ detectors

Both experiments look more like each other.

Beyond the Standard Model...

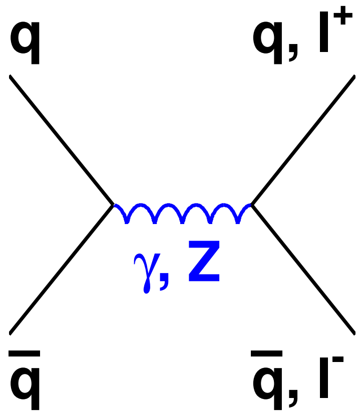
- More symmetry
  - $\rightarrow$ SUSY
    - not necessary *minimal* ! e.g. $\not{R}_p$
  - $\rightarrow$ connect lepton and quark sectors
    - (GUT, technicolor, compositeness, $\not{R}_p$ SUSY)
    - $\hookrightarrow$ LQ bosons
  - $\rightarrow$ enlarge gauge symmetry
    - $\hookrightarrow$ new gauge bosons
- Enlarged/modified matter field content
  - $\rightarrow$ "Technifermions" T (technicolor)
    - $< T\bar{T} > \Rightarrow$ Dynamical EWSB
    - $\hookrightarrow$ TC resonances
  - $\rightarrow$ composite fermions
    - $\hookrightarrow$ l^*, q^*
- Enlarged space-time
  - $\hookrightarrow$ Kaluza-Klein gravitons

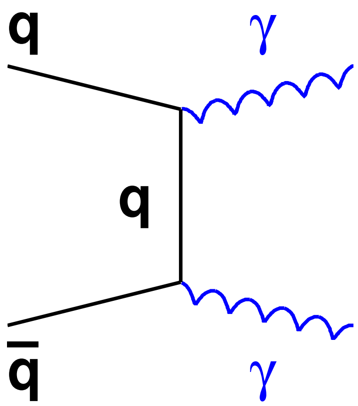
deviations from σ_{SM}

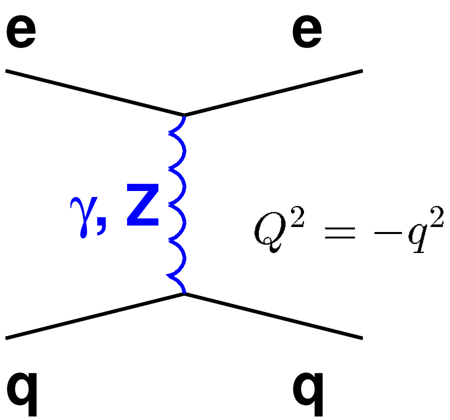
new resonances (ll, lj, jj)

exclusive final states (large multiplicity)

Deviations from SM in basic high E_T processes







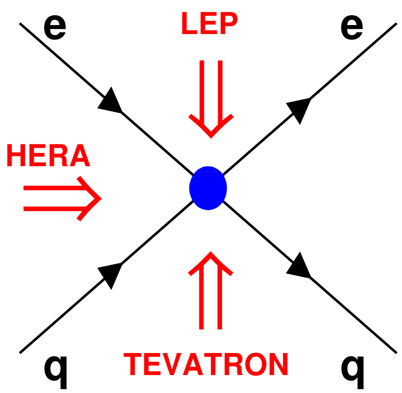
Drell-Yan or dijet (incl. jets) — diphoton — Deep Inelastic Scattering

$d\sigma$'s would deviate from SM predictions if new currents or exchange of heavy bosons.

Examples :

- composite fermions
- leptoquark bosons $(LQ - l - q)$

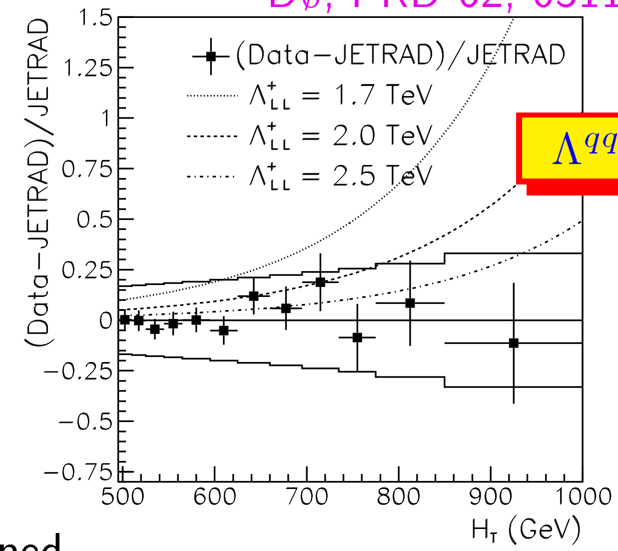
e.g. $\mathcal{L}_{CI} = \sum_{i,j=L,R} \varepsilon_{ij}^{eq} \frac{4\pi}{\Lambda^2} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j)$



- quark compositeness (quark form factor)
- exchange of virtual Kaluza-Klein gravitons in models with large extra-dimensions

Searches for $qqqq$ and $llqq$ Contact Interactions

D∅, PRD 62, 031101

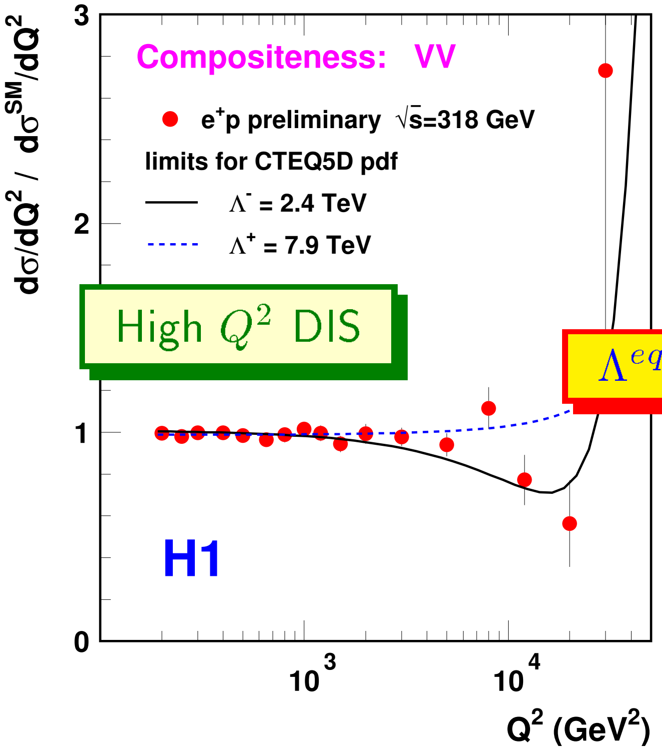


$\Lambda^{qq} > 2$ TeV

$qqqq$ contact interactions would manifest at Tevatron in :

- di-jet mass spectrum and angular distributions
- H_T distribution, $H_T = \sum_{jets} E_T^i$
  shape of H_T does not depend on choice of μ_r.

$eeqq$ contact interactions would manifest in :

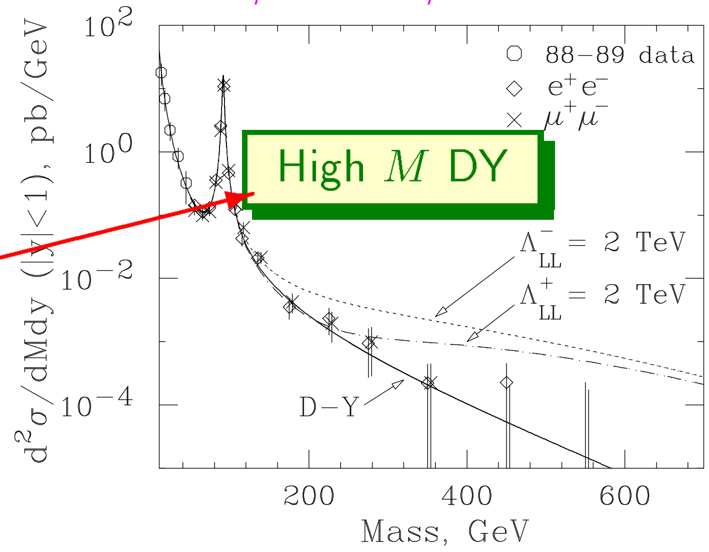


High Q^2 DIS

$\Lambda^{eq} > 1.5 \; - \; 9$ TeV

Many models constrained
Some $(VV, AA, ...)$
not constrained by APV

CDF, PRL 79, 2198



High M DY

$\Lambda^{eq} > 3.3 \; - \; 6.1$ TeV

(D∅, PRL 82, 4769)

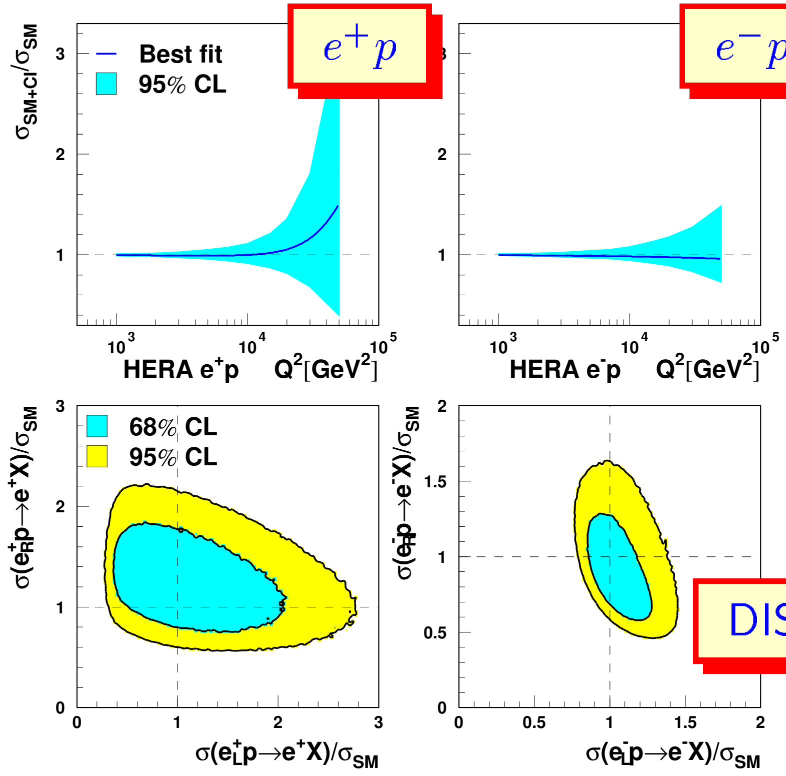
corresponds to distances
$\Delta x \sim$ few 10^{-17} cm

HERA & Tevatron bounds largely independent on flavor sym. hypothesis ($\neq$ LEP)

Future prospects for $eeqq$ contact interactions

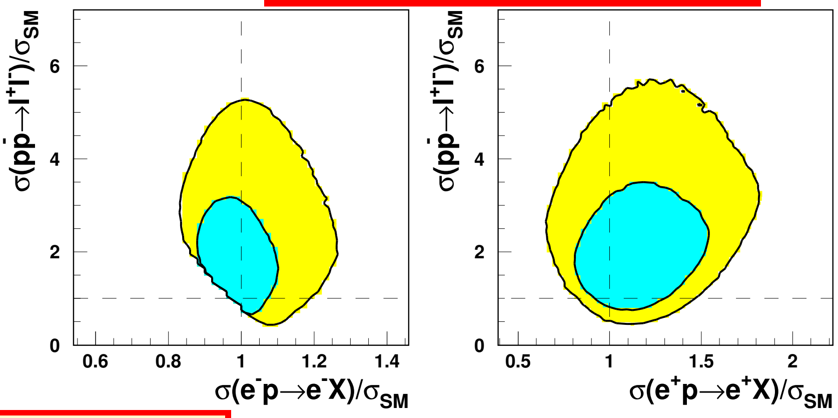
Taking into account existing measurements sensitive to $eeqq$ contact terms, compare allowed deviations in high Q^2 DIS and in high M_{ee} DY :

A.F. Zarnecki, EPJ C11 (1999) 539



DIS @ $Q^2 = 30000$ GeV^2

DY @ $M_{ee} - 500$ GeV

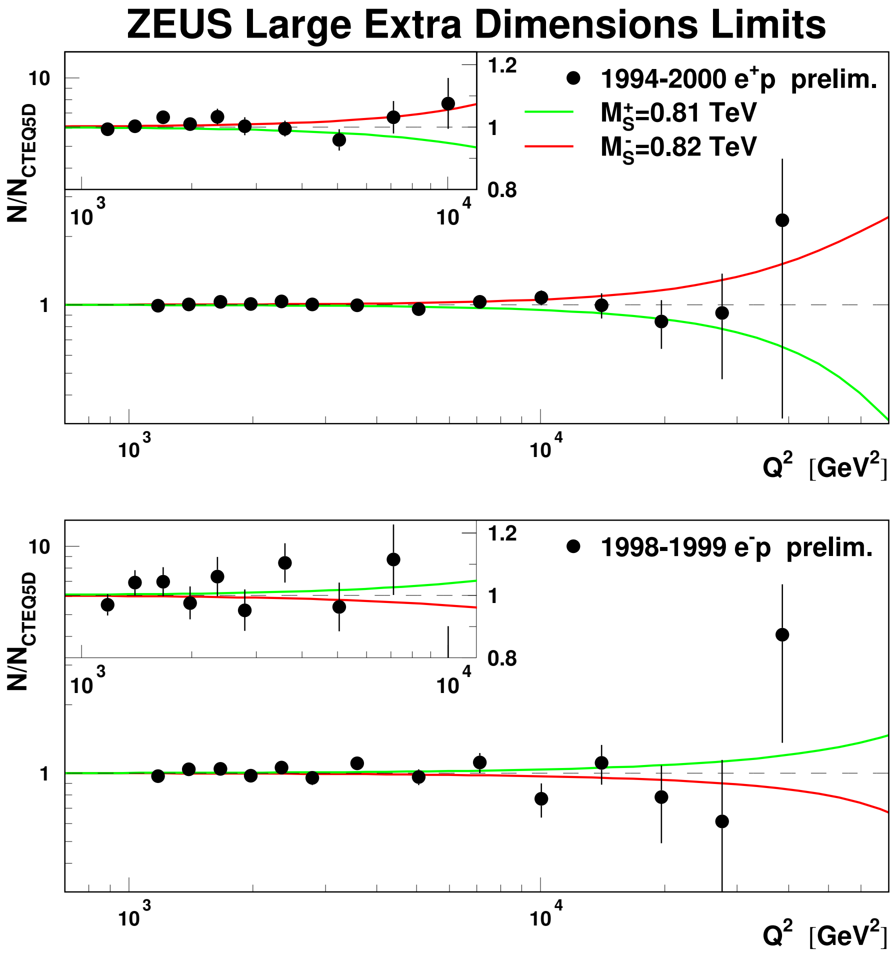


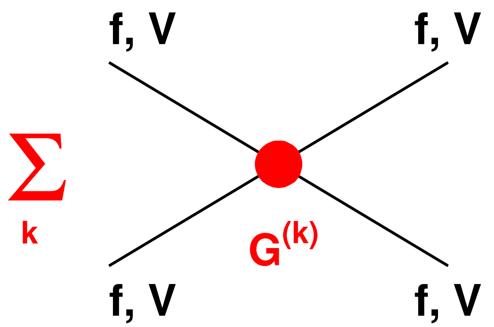
- Unpolarised $\sigma(e^-p)$ more constrained than e^+p $\Rightarrow$ more likely to see a deviation in e^+p data.
- Larger deviations could be observed with polarised e : $e^+_L > e^+_R > e^-_R > e^-_L$

- $\sigma(e^-p)$ and $\sigma(DY)$ cannot $\searrow$ simultaneously
- $\sigma(e^+p)$, $\sigma(e^-p)$ and $\sigma(DY)$ weakly correlated (# $\sigma(DY)$ and $\sigma(ee \to$ had.)) i.e. CI searches at HERA and Tevatron are largely independent

Searches for Effects of Large Extra-Dimensions

Large (compactified) extra dimensions where only gravity propagates





$\boxed{\longrightarrow \lambda/M_s^4}$

effective coupling

- $\lambda = \pm 1 \rightarrow G^{(k)}$ exchange can interfere constructively or destructively with SM
- $M_s \sim M_D$ fundamental scale characterising the gravity in the full space
  Could be $\sim$ TeV

At HERA : would affect high Q^2 DIS
H1, PLB 479 (2000) 358

ZEUS prelim., combined 94-00 data : $\boxed{M_s > 0.81\ (0.82)\ \text{TeV for } \lambda = +1\ (-1)}$

Similar to LEP sensitivity from $ee \rightarrow had.$

Searches for Effects of Large Extra-Dimensions

DØ, PRL86 (2001) 1156

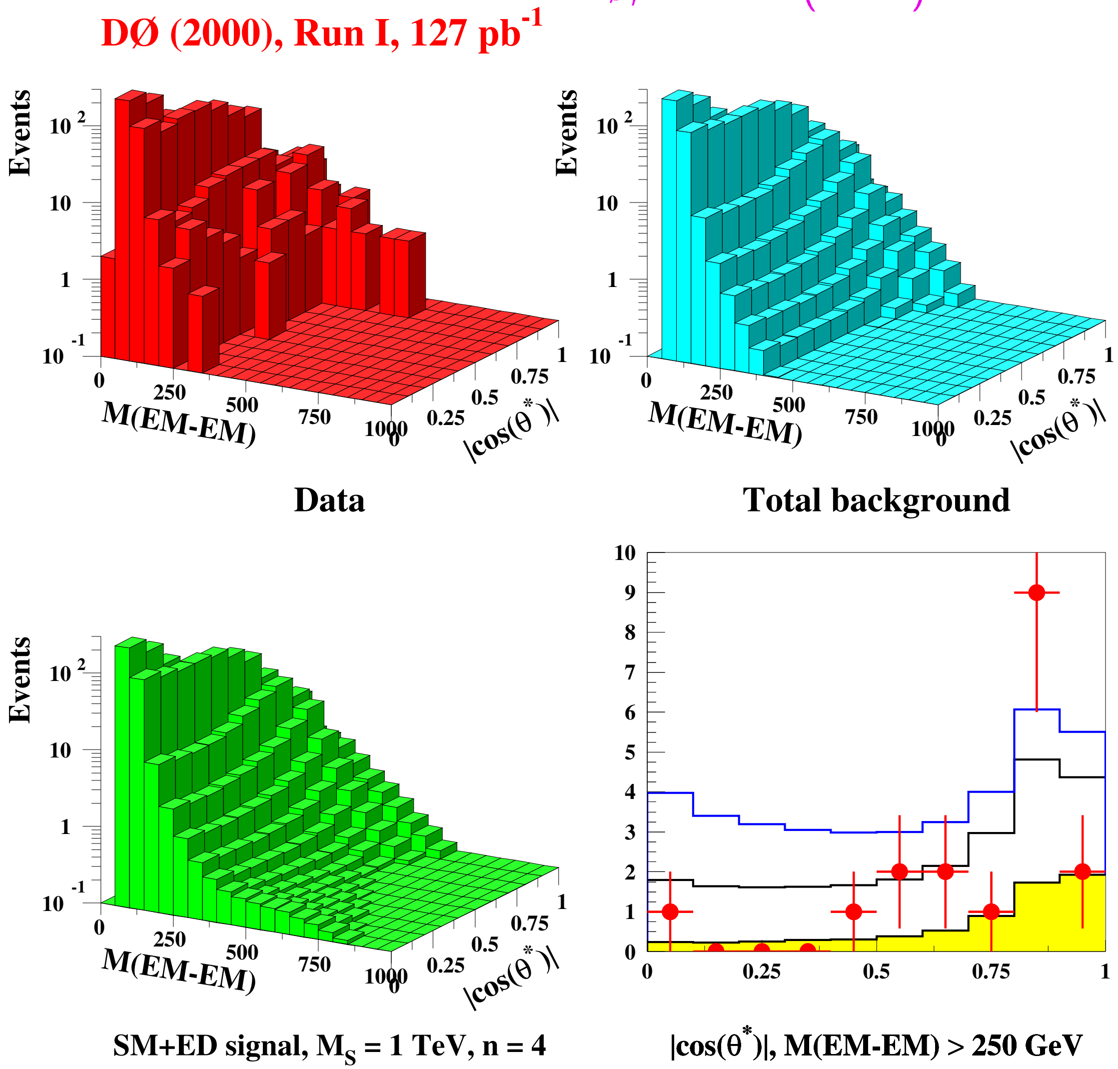
- First search for Edim at the Tevatron : Look for deviation in ee and $\gamma\gamma$ events induced by virtual exchange of KK gravitons ($\gamma\gamma$ = most sensitive)

$\Longrightarrow M_s > 1.2$ TeV

Run IIa, 2 fb^{-1} : reach $\sim$ 1.9 TeV
(K.Cheung & G.Landsberg, PRD62,076003)

- Direct production of $G^{(k)}$ also possible ($\rightarrow$ jet + missing energy)
Expected Run I sensitivity :

$M_D >\sim 1$ TeV for $n = 2$
(S.Cullen et al., PRD62,055012)



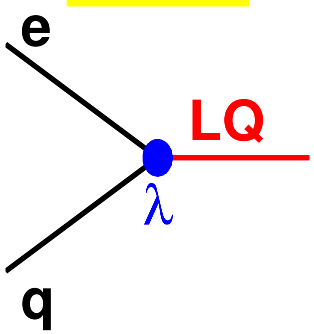
Direct searches for Leptoquarks

- Scalar or Vector color triplet bosons
- Carry both L and B, frac. e charge

- Appear in many extensions of SM
- Connect lepton and quark sectors

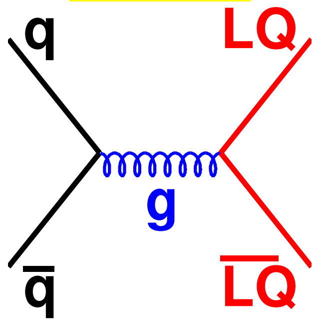
- λ Yukawa coupling lepton-quark-LQ

e p



$$\sigma_{ep} = f(M_{LQ}, \lambda)$$

p p



$$\sigma = f(M_{LQ})$$
$$(\sigma_{single} << \sigma_{pair})$$

$\longrightarrow$ Classified by Buchmüller,Rückl and Wyler according to their quantum numbers

Assumptions : LQs couple only to SM fermions & bosons
pure chiral couplings
family diagonal couplings
$\hookrightarrow$ 1st, 2nd and 3rd generation LQs

$\hookrightarrow$ 7 scalar LQs, 7 vector LQs.

BRW model : if $LQs \subset$ isospin multiplet are degenerate : $\begin{cases} \beta(LQ \to lq) & = & 1 \text{ or } 1/2 \\ \beta(LQ \to \nu_l q) & = & 0 \text{ or } 1/2 \end{cases}$

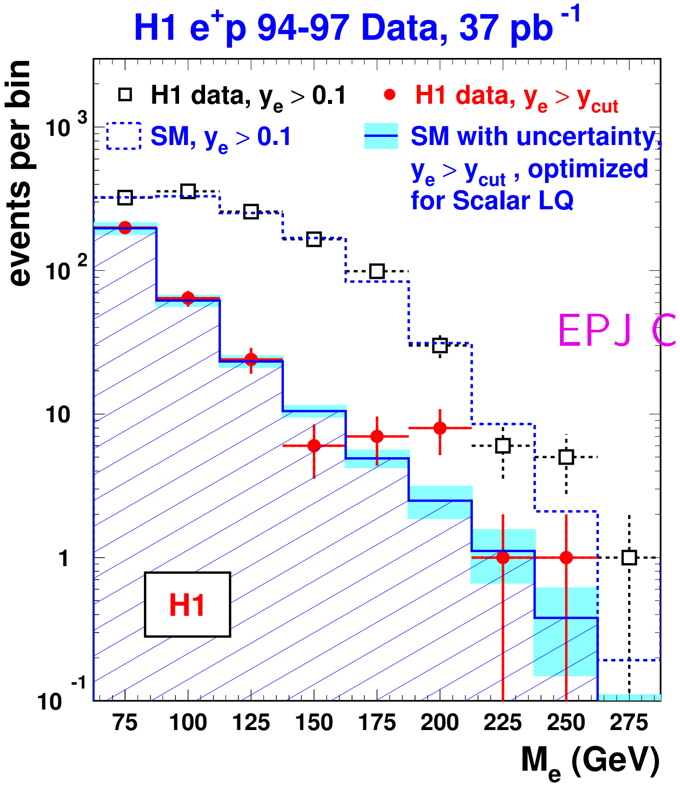
$\longrightarrow$ BRW assumptions can be relaxed $\Longrightarrow$ “Generic models”

$\hookrightarrow$ $\beta_l = \beta(LQ \to lq)$ and $\beta_\nu = \beta(LQ \to \nu q)$ can be free parameters

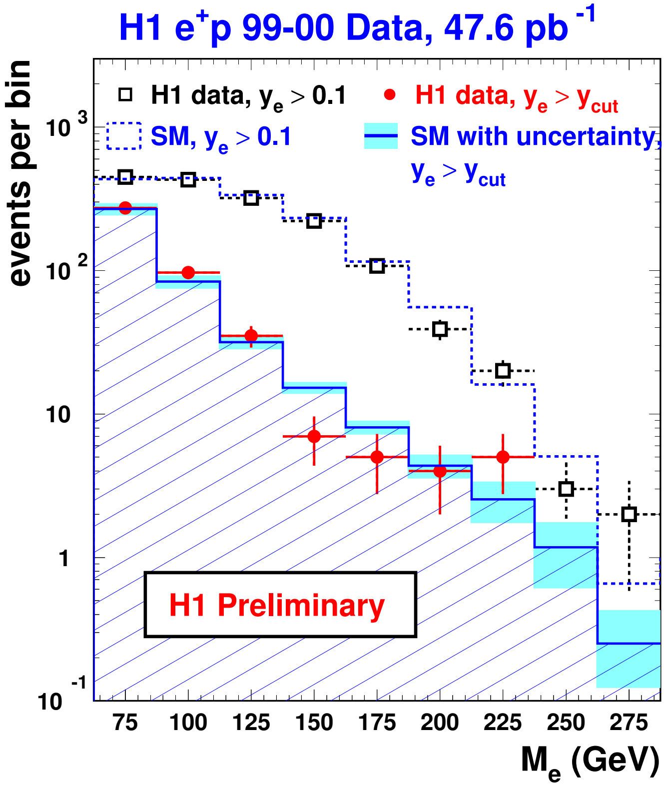
$\hookrightarrow$ Possibility to have Lepton Flavor Violating LQs (LQs couplings to $e_i q$ and $e_j q$, $i \neq j$)

First Generation LQs at HERA

Starting point = high Q^2 DIS events; exploit specific angular (y) distributions in NC channel.



EPJ C11, 447



EPJ C16, 253

ZEUS e^+p 94-97 data, 48 pb^{-1} :

4 events observed at $M > 220$ GeV, $y > 0.25$
1.9 expected from SM

Preliminary

ZEUS e^+p 99-00 (April) data, 39 pb^{-1} :

0 event observed in same kine. range
1.6 expected from SM

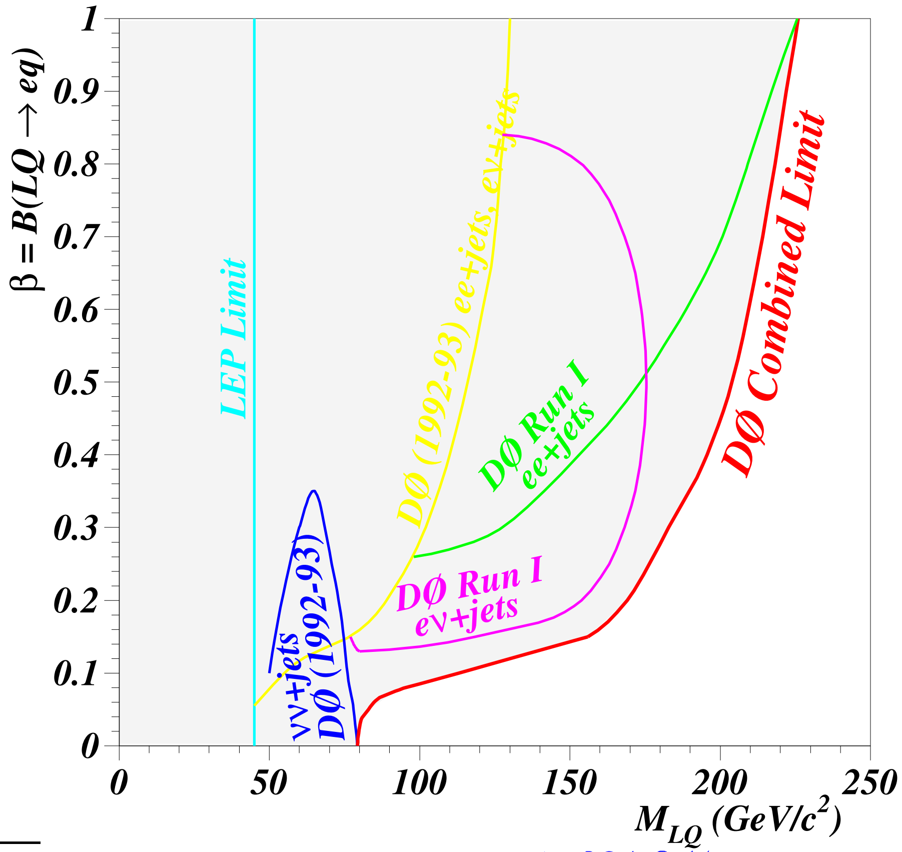
Excess in old e^+p data is not confirmed by new e^+p data by both experiments.

CC Channel : good agreement data/SM.

Searches for 1st generation LQs at TeVatron

DØ, PRL 80, 2051

For $\beta = 1.0$, $M_{SLQ} > 225$ GeV



For $\beta = 0.5$, $M_{SLQ} > 204$ GeV

HERA "anomaly" in 1997 triggered a lot of activity on LQs :

$\rightarrow$ CDF + DØ, full RunI statistics

$\rightarrow$ σ_{NLO} for scalar LQ production

Topologies	Main SM backgrounds
$eejj$	Drell-Yan $Z\ \gamma\ \rightarrow ee$ + jets
$e\nu jj$	W + jets, $t\bar{t}$
$\nu\nu jj$	$W\ /Z$ + jets

$\Rightarrow$ Event yield consistent with SM expectation

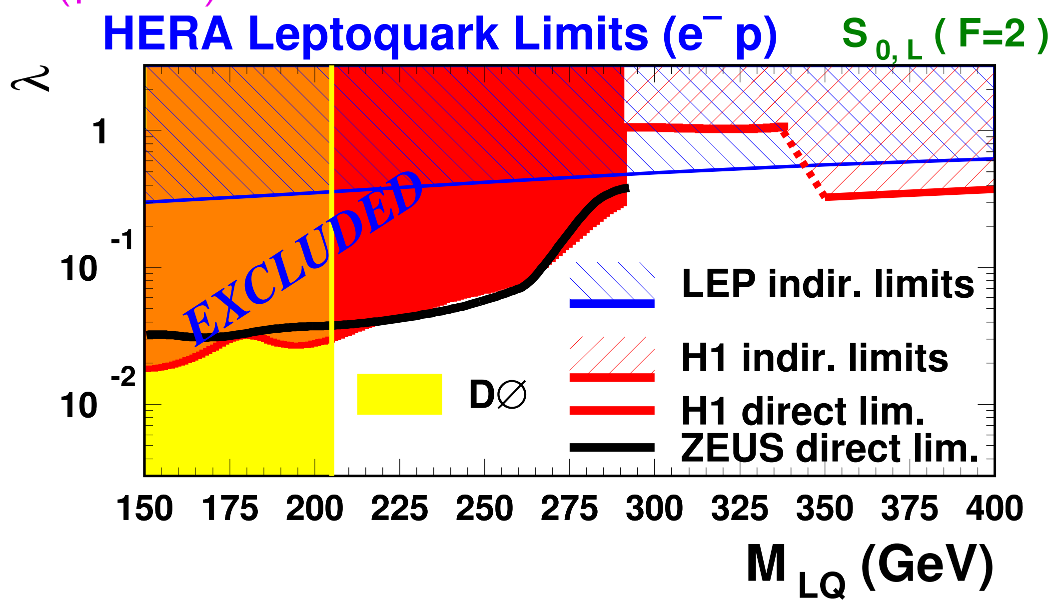
Mass bounds (GeV) on 1st generation LQs :

β_e	Scalar	Vector Yang-Mills	Vector Minimal σ	
1	242	-	-	CDF + DØ
1	213	-	-	CDF $eejj$
1	225	340	290	DØ $eejj$
1/2	204	325	275	DØ combined
0	79	200	145	DØ $\nu\nu jj$

NB : usually $\sigma_V \sim 10 \times \sigma_S$ but model dependent (for $\beta_e + \beta_\nu = 1$)

Existing constraints on 1st generation LQs

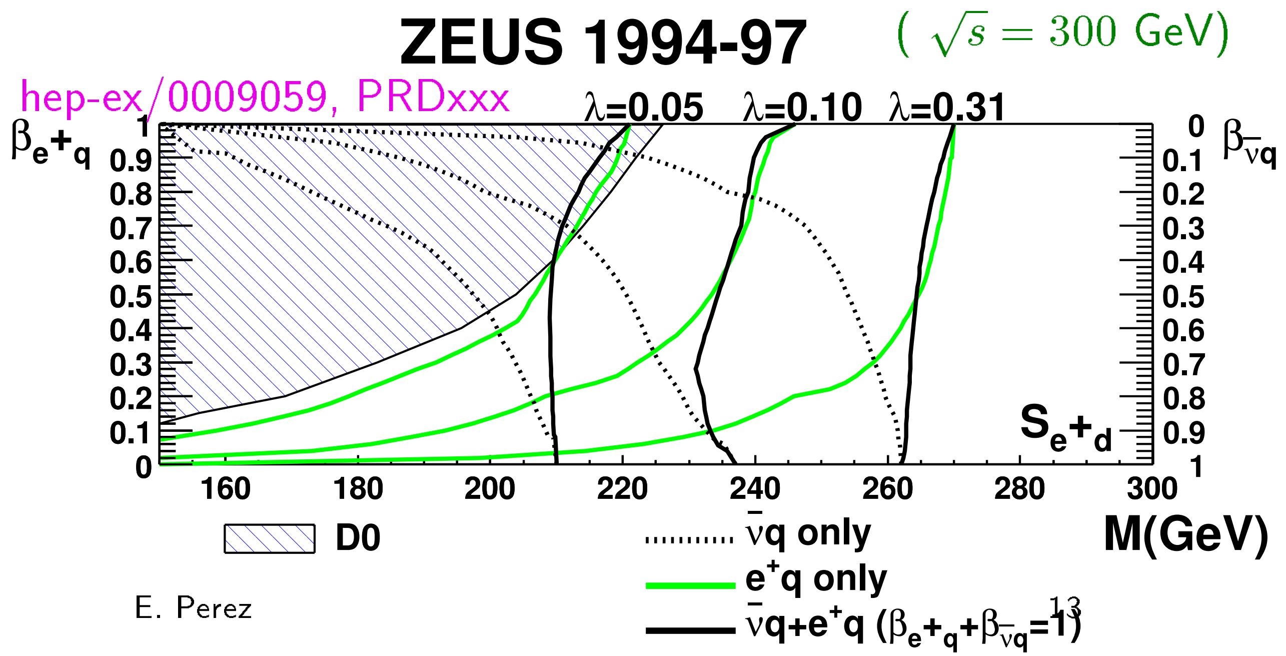
(prelim.)



Limits in BRW model : $\beta(LQ)$ known
(for this LQ, $\beta(eq) = \beta(\nu q) = 0.5$)

For $\lambda = \sqrt{4\pi\alpha_{em}} \sim 0.3$:
LQs can be ruled out
up to 290 GeV

(data at $\sqrt{s} = 320\mathrm{GeV}$)

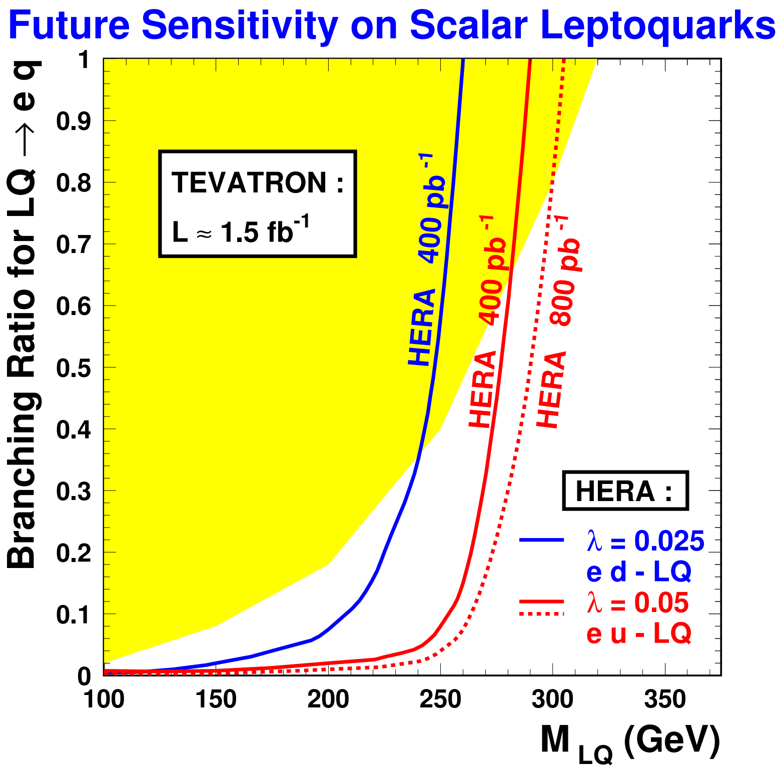


General case : $\beta(LQ)$ are free parameters. At given λ :
NC/CC channel $\Rightarrow$ β_e / β_ν vs M_{LQ}

For $\beta_e + \beta_\nu = 1$:
Combine NC & CC channels
$\Rightarrow$ limits $\sim$ indep. on β's

High mass LQs with small β_e and large β_ν are mainly probed by HERA.

Future sensitivities on 1st generation LQs



- Tevatron RunIIa (2 fb^{-1}) : probe large masses for large β_e independently of λ
- HERA better probes LQs with small β_e (need λ not too small)

$\Longrightarrow$ complementarity of both facilities

After 2004 : Tevatron $\rightarrow \sim$ 400 GeV with 10 fb^{-1}

At HERA : e^+ / e^- + polarisation could help in disentangling the LQ types

in BRW model : NC + CC brings additional information

	$S_{0,L}$	$S_{1,L}$	$\tilde{S}_{0,R}$	$S_{0,R}$	$S_{1/2,L}$	$\tilde{S}_{1/2,L}$	$S_{1/2,R}$
$S_{0,L}$		β_ν	P_e	P_e			
$S_{1,L}$	β_ν		P_e	P_e		e^+/e^-	
$\tilde{S}_{0,R}$	P_e	P_e		P_p			
$S_{0,R}$	P_e	P_e	P_p				
$S_{1/2,L}$						P_p	P_e
$\tilde{S}_{1/2,L}$		e^+/e^-			P_p		P_e
$S_{1/2,R}$					P_e	P_e	

Searches for 2nd generation LQs at Tevatron

$LQ \to \mu s$ or $LQ \to \nu c$ Possible final states : $\mu\mu ss$, $\mu\nu_\mu sc$, $\nu_\mu\nu_\mu cc$

- DØ : $\mu\mu jj + \mu\nu jj$

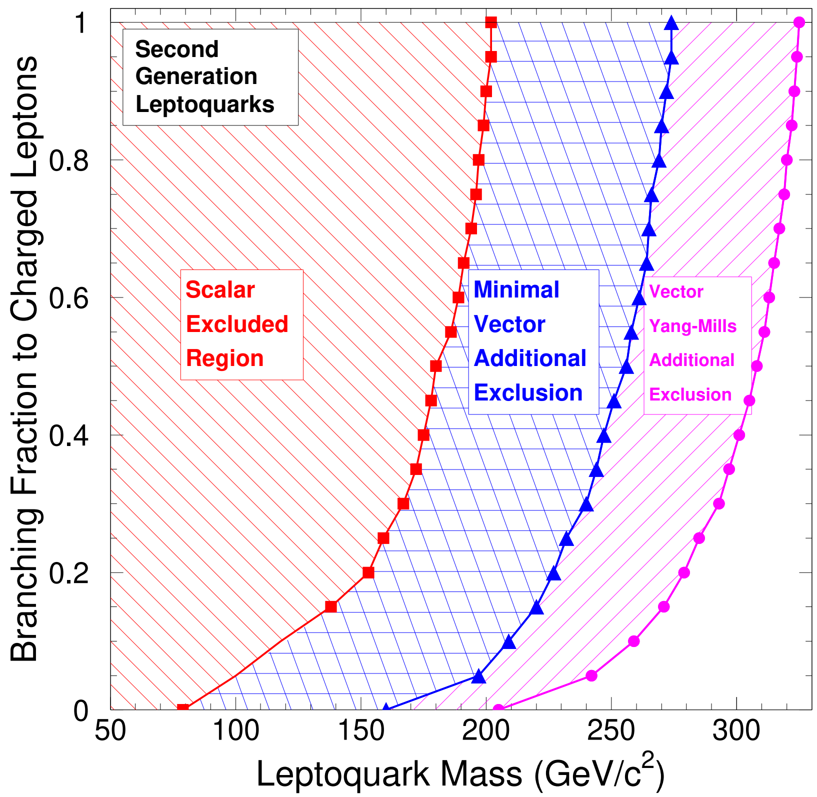
$\rightarrow$ NN to optimise signal signicance

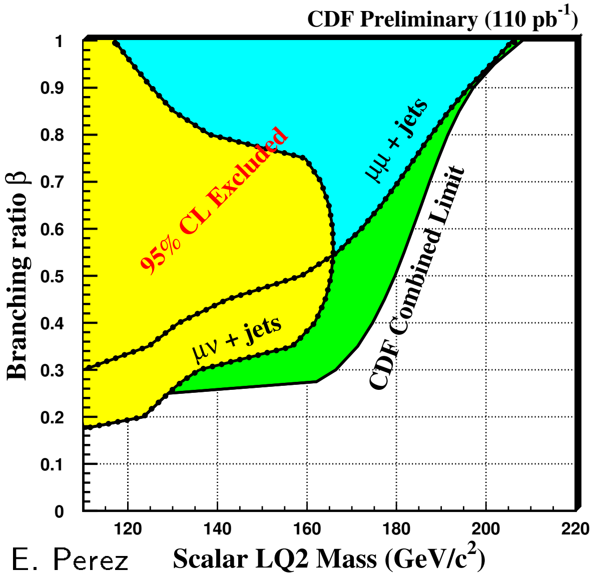
$\rightarrow$ combine $\mu\mu jj + \mu\nu jj +$ (earlier) $\nu\nu jj$

Resulting mass bounds (GeV) :

β_μ	Scalar	YM	MV
1	200	325	275
1/2	180	310	260
0	79	205	160

DØ, PRL 84 (2000) 2088





- CDF : $\mu\mu jj + \nu\bar{\nu}c\bar{c}$ $+ \mu\nu jj$ (CDF Preliminary)

$\rightarrow$ $\mu\mu jj$, $\mu\nu jj \sim$ DØ

$\rightarrow$ $\nu\bar{\nu}c\bar{c}$ by heavy flavour jet tagging ("jet probability")

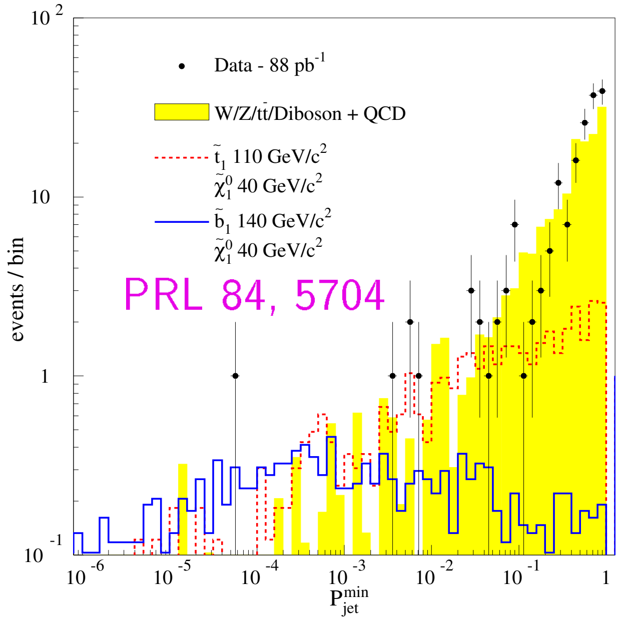
$\Longrightarrow$ improved sensitivity : $M_S > 123$ GeV for $\beta_\mu = 0$

CDF, PRL 85 (2000) 2056

2nd and 3rd generation LQs by HF tagging

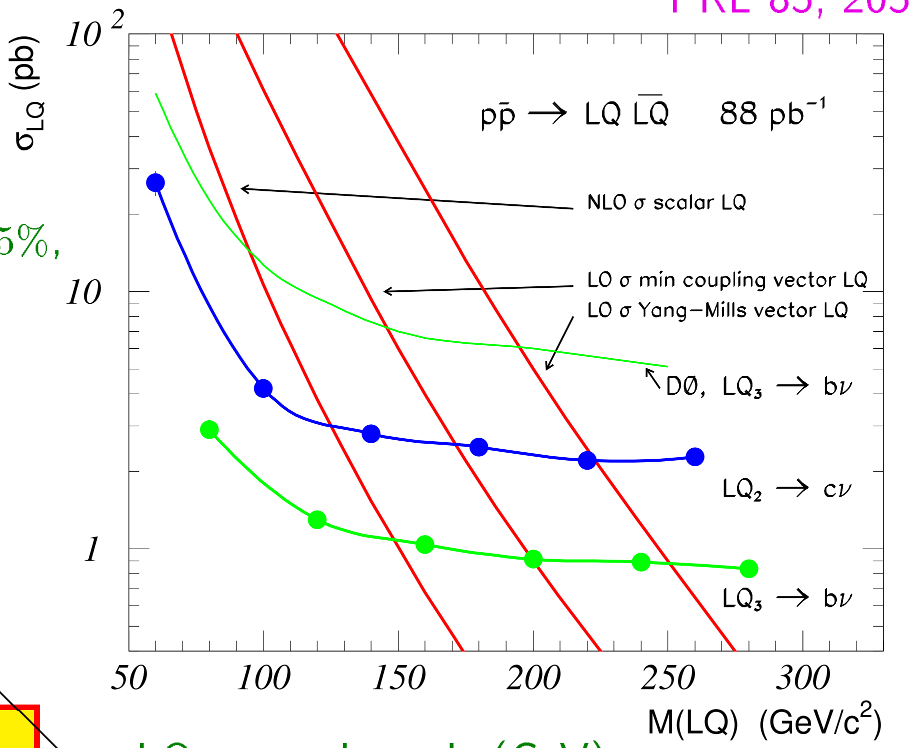
D∅ : search for 3rd gene LQ in $\nu\nu bb$ using soft muon tag $(b \to \mu)$

CDF : $P_{jet} = \otimes$ of track probabilities from signed impact parameters measured with SVX
$\Rightarrow P_{jet}$ flat $\in [0,1]$ for primary jets; P_{jet} peaks at 0 for b, c jets



allows $\varepsilon_{b\ tag} \sim 45\%$, $\varepsilon_{c\ tag} \sim 25\%$ (developped for $\tilde{t} \to c\chi^0$ and $\tilde{b} \to b\chi^0$)

PRL 85, 2056



Also $\tau\tau b\bar{b}$ (CDF) for 3rd generation LQs

LQ_3 mass bounds (GeV):

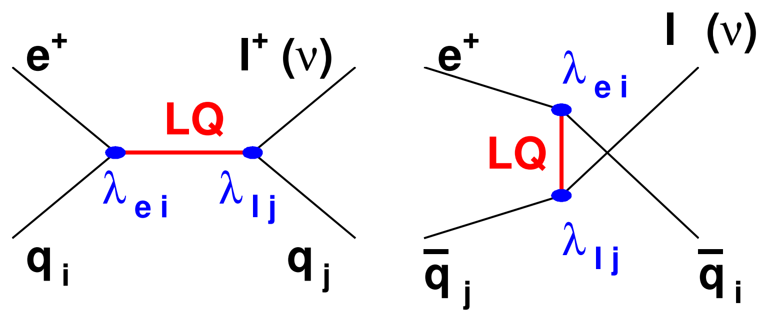
β_τ	Scalar	YM	MV
0	149	253	199
1	99	225	170

NB : New Physics is likely to couple strongly to third generation fermions
$\Longrightarrow$ Important to identify b, τ (c)
Feasability shown in Run I; will be better (better tracking, μvtx) in Run II (both experiments).

Lepton Flavor Violating LQs

LQs could couple both to (e,q) and (μ,q) or (τ,q) $e \longleftrightarrow \tau$ R. Kerger, DIS'2000

• LFV at HERA in General Model :



$\Rightarrow$ (μ,jet) or (τ , jet), b.t.b.
No candidate observed $\rightarrow$ bounds on $\lambda_e \lambda_l / M^2_{LQ}$

$q_i q_j$	$S^L_{1/2}$	$S^R_{1/2}$	$\tilde{S}^L_{1/2}$	V^R_0	V^L_0	$\tilde{V}^R_0$	V^L_1
1 1							
1 2	red	red	red	orange	orange	red	
1 3	-	yellow	yellow	yellow	yellow	-	yellow
2 1	red	red	red	orange	orange	red	
2 2		orange	red	red	red	red	red
2 3	-	yellow	yellow	yellow	yellow	-	yellow
3 1	-	yellow	yellow	yellow	yellow	-	yellow
3 2	-	yellow	yellow	yellow	yellow	-	yellow
3 3	-	red	red	red	red	-	red

Stringent bounds when heavy quarks involved

red: H1 & ZEUS (40 pb^{-1}) $>$ indir. limits
orange: HERA (1 fb^{-1}) $>$ indir. limits
yellow: will compete with limits from rare B decays

• Pati-Salam LQs : $SU(4)_c \rightarrow SU(3)_c \otimes U(1)_{B-L}$
$SU(4)$ multiplets = (q_R, q_B, q_G, l / ν_l)
e.g if $(e \leftrightarrow b)$ and $(\mu \leftrightarrow s$ / $d)$: leads to $B^0_{s,d} \rightarrow e\mu$
CDF upper bound on $\beta(B^0_{s,d} \rightarrow e\mu)$: $\boxed{M_{LQ,PS} > 20 \text{ TeV}}$

Upgraded H1 & ZEUS will allow :
better τ id,
High P_T b,c tagging in fwd region

(My) interpretation of current HERA bounds in PS model : with $\lambda_e = \lambda_\mu = g_s(M_{LQ})$
$\Longrightarrow M_{LQ,PS} > 20 - 30$ TeV

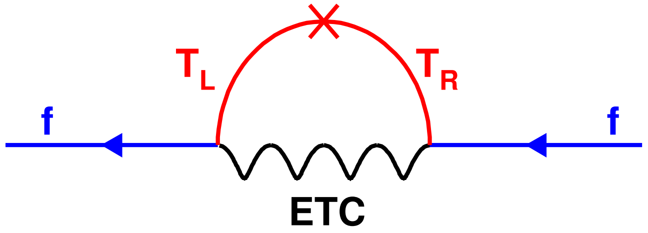
Technicolor Models

- Alternative to Higgs mechanism : dynamical EWSB

- Remind : breaking of chiral symmetry in QCD :
  strong interaction $\Rightarrow \langle u\bar{u}\rangle \neq 0$
  $SU(2)_L \otimes SU(2)_R \to SU(2)_V \Rightarrow$ 3 GB, π^0, $\pi^\pm$
  W, Z couple to $u \Rightarrow m_V \propto f_\pi$ 2000 $\times$ too small !

- idea = scaled up version of QCD
  New fields : Technifermions T, coupled to W, Z
  New interaction : Technicolor $(\Lambda_{TC} >> \Lambda_{QCD})$
  condensate $\langle T\bar{T}\rangle$ triggers DEWSB (79)

- Mass of fermions ? Need new gauge bosons (ETC)



- FCNC problem : avoided if g_{TC} runs slowly
  $\Rightarrow$ "Walking Technicolor" (89)

- large $M_{top} \Rightarrow$ "Topcolor" (95)

- Topcolor assisted walking extended technicolor : (TC2)
  OK for now !

Quantum nbs of fermions carried by T or ETC $\Rightarrow$ many possible models.

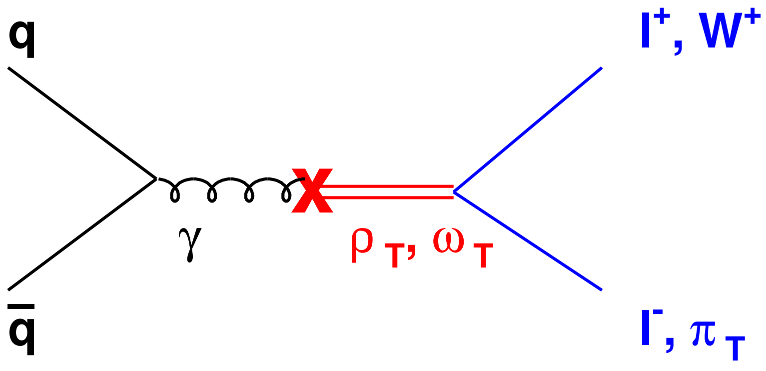
Example : technileptons (N, E)
or (N, E) + techniquarks (U, D)
$\Rightarrow$ possible bound states :

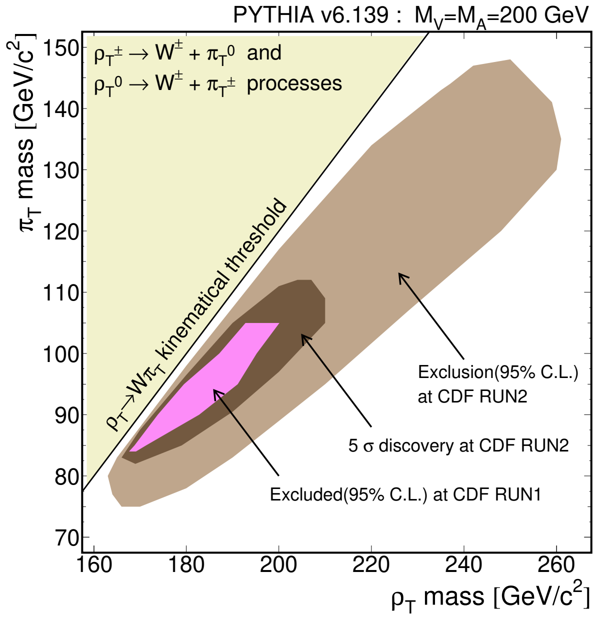
$$\begin{cases} X_T & \text{color singlet } (\bar{E}E) \\ X_{T,8} & \text{color octet } (\bar{Q}Q) \\ X_{T,3} & \text{color triplet } (\bar{Q}E) \quad \Rightarrow LQ \end{cases}$$

$\Rightarrow$ rich spectrum of technimesons labelled according to their q.n. : $\pi_T, \rho_T, \omega_T, \ldots$

- $\rho, \omega \sim \gamma$ or $g \Rightarrow$ Large σ at Tevatron
- $\pi \to f + f'$: Higgs-like coupling $(\propto m_f + m_{f'})$
  $\rho, \omega \to f\bar{f},\ G\pi,\ \ldots$

Searches for Technimesons (color singlets)





T. Handa

ρ_T up to ~ 250 GeV can be probed via $\rho_T \to \pi_T W$ at Run II a

- CDF : μvtx $\Rightarrow$ $\rho_T \to W\pi_T$, $\pi_T \to b\bar{b}$
  and $\omega_T \to \gamma\pi_T$

- DØ : calo $\Rightarrow$ $\rho_T, \omega_T \to e^+e^-$ ($\nearrow \varphi$ space for ρ_T)

Based on Drell-Yan compositeness search

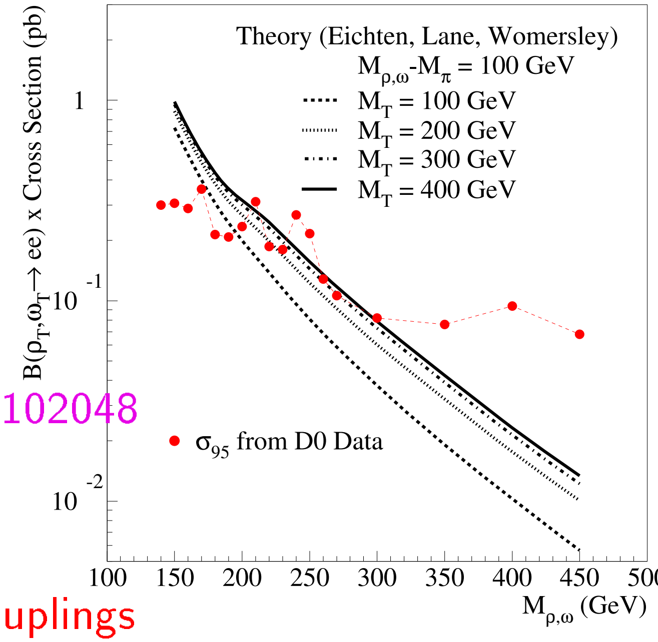
NB : Uses revised calculations for $\Gamma(\rho_T, \omega_T \to G_L \pi_T)$

lower bound on $M(\rho_T) = 200$-250 GeV

depending on model parameters.

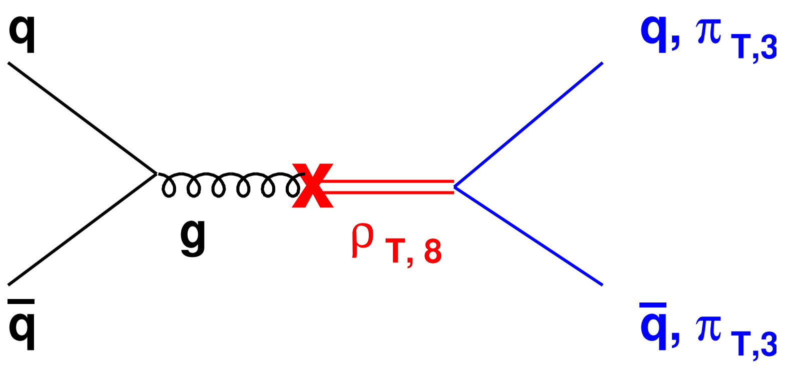
Run IIa : up to $420 - 500$ GeV

DØ, hep-ex/0102048



$\Longrightarrow$ also sets $Z' > 690$ GeV (CDF, $ee + \mu\mu$) for equal Z and Z' couplings

Searches for Technirhos (color octets) & Technicolor LQs



- Searches in dijet channel rule out (CDF) $260 < M(\rho_{T,8}) < 470$ GeV (PRD55, R5263)

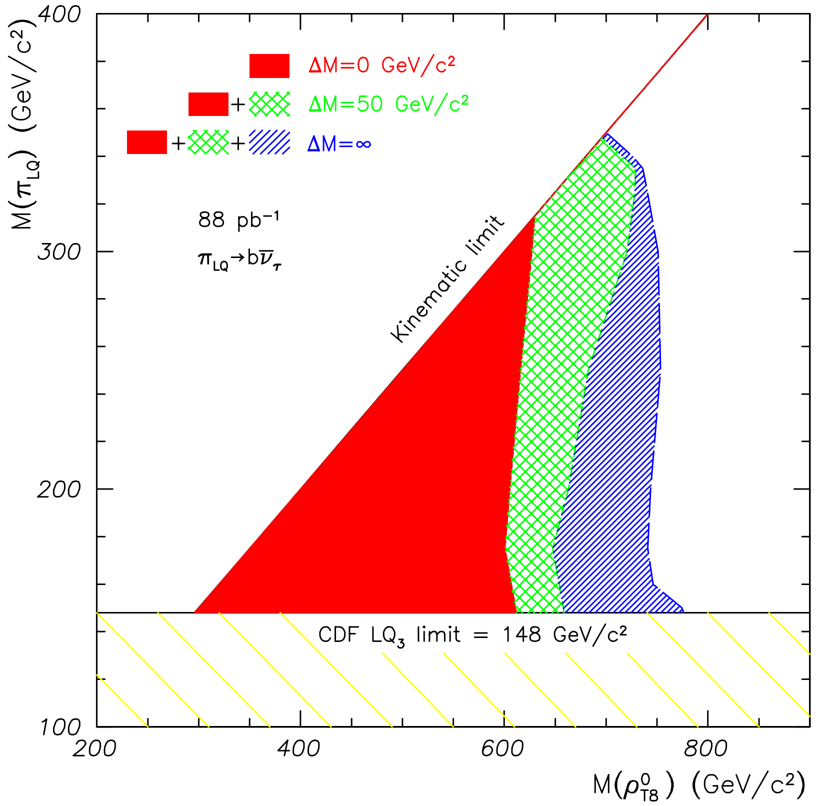
- Searches in $b\bar{b}$ probe $\rho_{T,8}$ between 350 and 440 GeV (CDF, PRL82, 2038)

- Decay into $\pi_{T,3}$: $\pi_{T,3} \to \nu b$ or $\to \nu c$ or $\to \tau b$ $\simeq$ pair-production of 2nd or 3rd generation LQs
Better sensitivity at large ΔM (higher ε)

$$\boxed{\Delta M = 0 : M(\rho_{T,8}) > 600 \text{ GeV}}$$

- t-channel exchange of $\pi_{T,3}$ at HERA : could lead to LFV processes ($eq \to \tau b$)

CDF, PRL 85, 2056



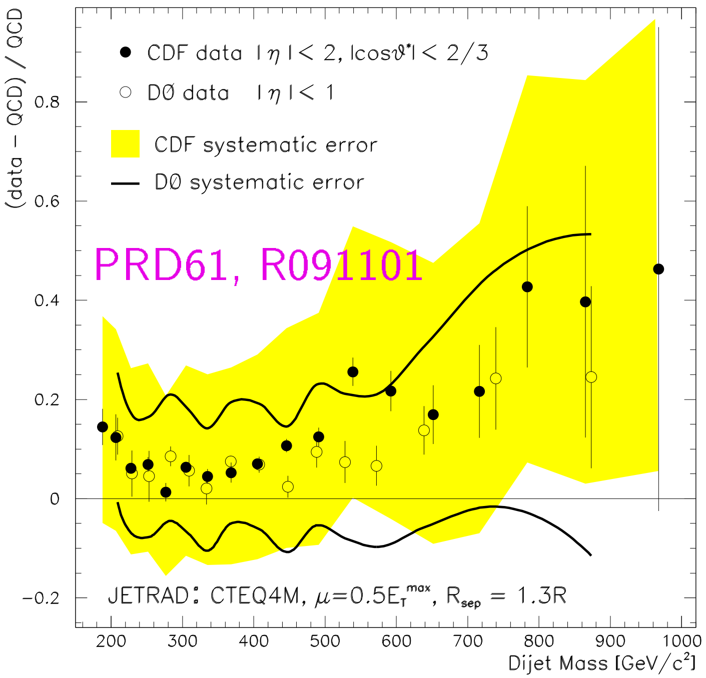
Bounds depend on $\Gamma(\rho_{T,8})$ which depends on $\Delta M = M(\pi_{T,8}) - M(\pi_{T,3})$

NB : Based on a simple (no TC2) WTC model with (U, D, N, E). Complications when $\oplus$ top-color, e.g. decays into 2 $\pi_{T,3}$ may be closed or smaller. Could affect the bounds.

Other jet-jet resonances in $p\bar{p}$ collisions : Z', W', q^*

- New bosons Z', W' could decay to jj [limits for same couplings as SM bosons] :
  - $\Rightarrow$ exclude W' for $300 < M_{W'} < 680$ GeV   CDF, PRD55 (1997)R5263; DØ Preliminary
  - $\Rightarrow$ exclude Z' for $365 < M_{Z'} < 615$ GeV   DØ Preliminary
- Phenomenological approach of compositeness : composite fermions $\Rightarrow$ Excited l, q

Model (Hagiwara et al.) : $\mathcal{L} = \frac{1}{\Lambda} \bar{f}^*{}_R \left[f SU(2)_L + f' U(1)_Y + f_s SU(3)_c \right] f_L$

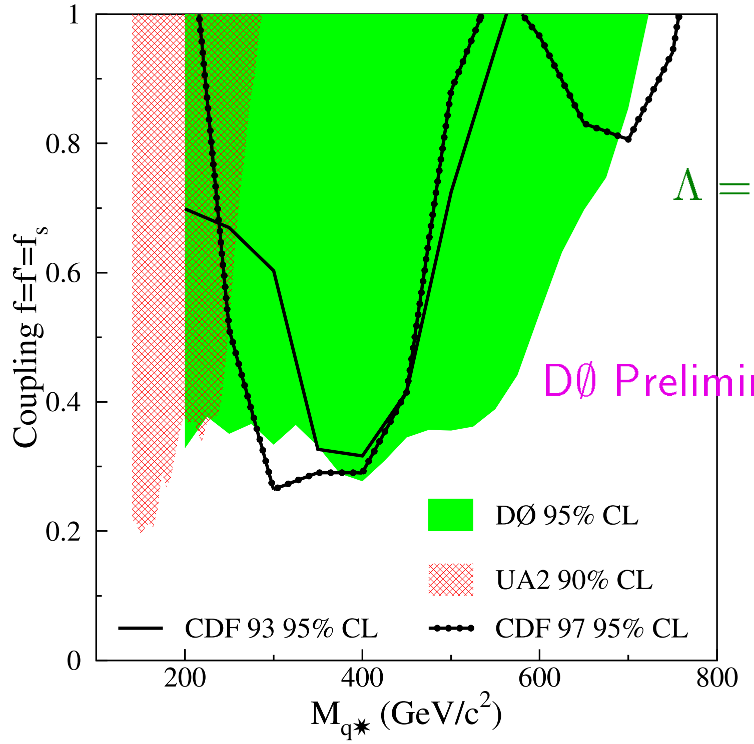


if f_s large enough :

$\boxed{gq \rightarrow q^* \rightarrow gq}$

For $f_s/\Lambda = 1/M_{q^*}$, $f = f' = f_s$:

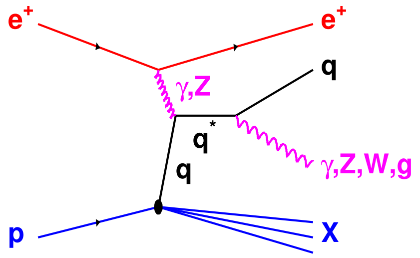
$\boxed{M_{q^*} > 725 \text{ GeV}}$



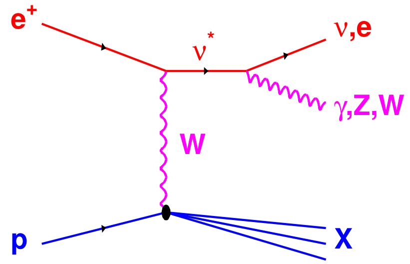
$\Lambda = M_{q*}$

For small f_s : smaller σ for $qg \rightarrow q^*$
decay modes in $q + V$, $V = \gamma, Z, W$ important
$\hookrightarrow$ exclusive final states, larger multiplicity

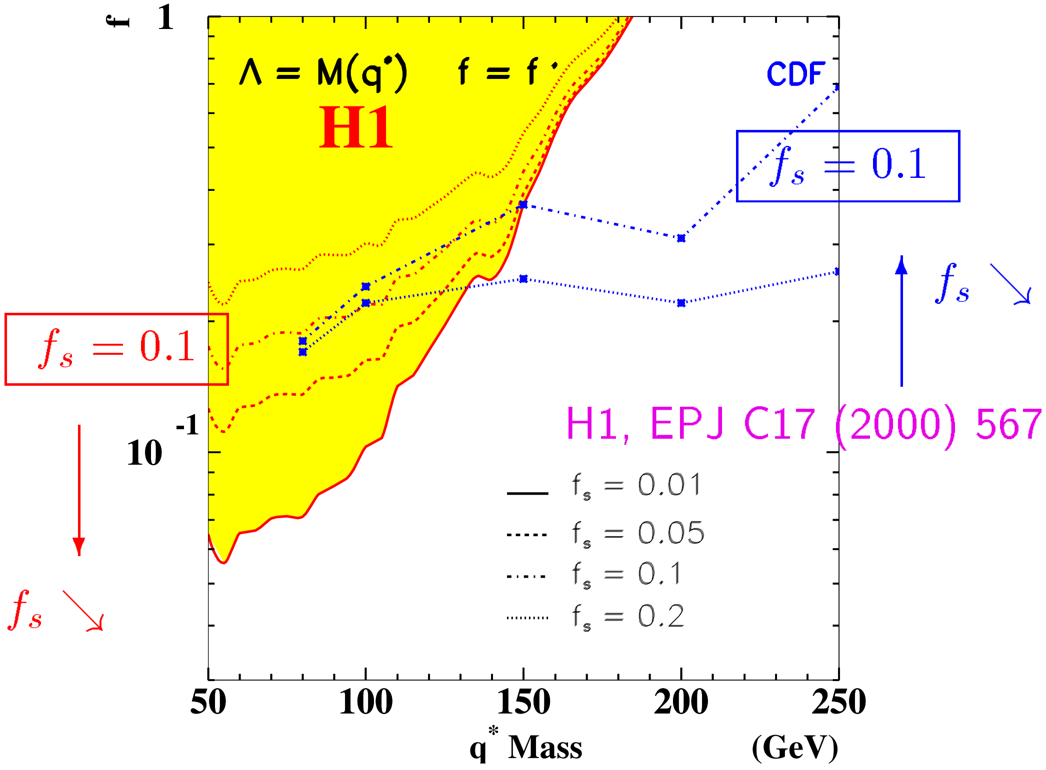
Searches for excited quarks and leptons in ep collisions

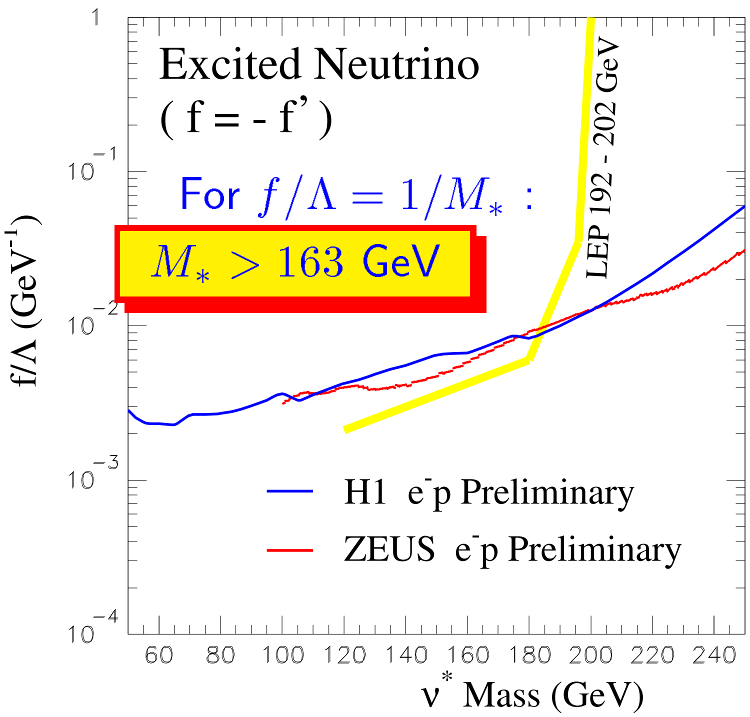


HERA's searches for q^* :
Look for $q^* \to$ EW boson
$+W, Z \to$ had., leptons
Many final states !



HERA's searches
for ν^*, e^* :
$l^* \to \gamma, Z, W$





When $f_s \searrow$: HERA's sensitivity $\nearrow$ ($q^* \to qg \searrow$)
Tevatron's sensitivity $\searrow$ ($\sigma \searrow$)

Complementarity; $f_s << f, f'$ better probed by HERA

HERA > LEP sensitivity for large masses.

No search at Tevatron yet. But e^*, ν^* could be pair-produced via $\gamma, Z \to$ indep. on f, f'

Searches for (non-MSSM) Supersymmetry

- Minimal SUSY :
  Tevatron $\rightarrow$ M. Carena's talk
  HERA : $eq \rightarrow \tilde{e}\tilde{q}$, $(M_{\tilde{e}} + M_{\tilde{q}})/2 >\sim 77$ GeV (ZEUS, PLB434, 214; H1, PLB380, 461)

- Minimal field content + R-parity violation : General superpotential contains :

$$W_{\not{R}_p} = \begin{array}{cccc} \lambda_{ijk} L_i L_j \bar{E}_k & +\lambda'_{ijk} L_i Q_j \bar{D}_k & +\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k & +\mu_i L_i H_2 \\ \not{L} & \not{L}_i & \not{B} & \not{L}_i \end{array}$$

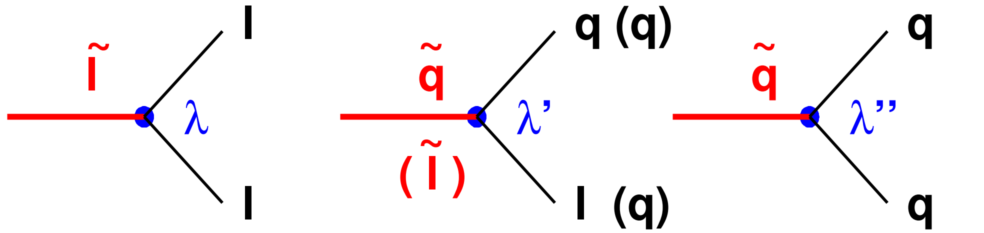
both R_p and $\not{R}_p$ equally well motivated if $\not{L}$ or $\not{B}$ only. And $\not{R}_p$ may be desirable, e.g. :
$\rightarrow$ For neutrinos : ν's masses (Majorana) without new fields
$\rightarrow$ For Cosmology : LSP not CDM candidate ! But could help EW baryogenesis

Main consequences of $\not{R}_p$ at colliders :

- **LSP can decay** i.e. LSP $\neq E_{miss}$ $\quad \lambda$: 3 leptons $\quad \lambda'$: l + 2 jets $\quad \lambda''$: 3 jets

- **single sparticle production**

$\Rightarrow$ probe larger masses



$\Rightarrow$ Final states with large multiplicities
$\Rightarrow$ If $\not{R}_p$ couplings sizeable : resonant $\tilde{f}$ production

Pair production + $R\!\!\!/_p$ decays via λ : multi (≥ 3) lepton events

Multileptons at Tevatron = clear signatures. Exploited e.g. in $\chi_1^{\pm}\chi_2^0$ MSSM searches.

$R\!\!\!/_p$ decay of χ_1^0 via λ_{ijk} : $\chi^0 \rightarrow \nu_{i,j}\ l_{j,i}\ l_k$

Pair production of sparticles (e.g. $\chi\chi$) $\rightarrow$ 2 χ_1^0 $(+X)$ $\rightarrow$ 4 leptons $(+X)$

- DØ : trileptons (e or μ) induced by $R\!\!\!/_p$ decays

Sensitivity to λ couplings involving τ's via leptonic decays of τ's.

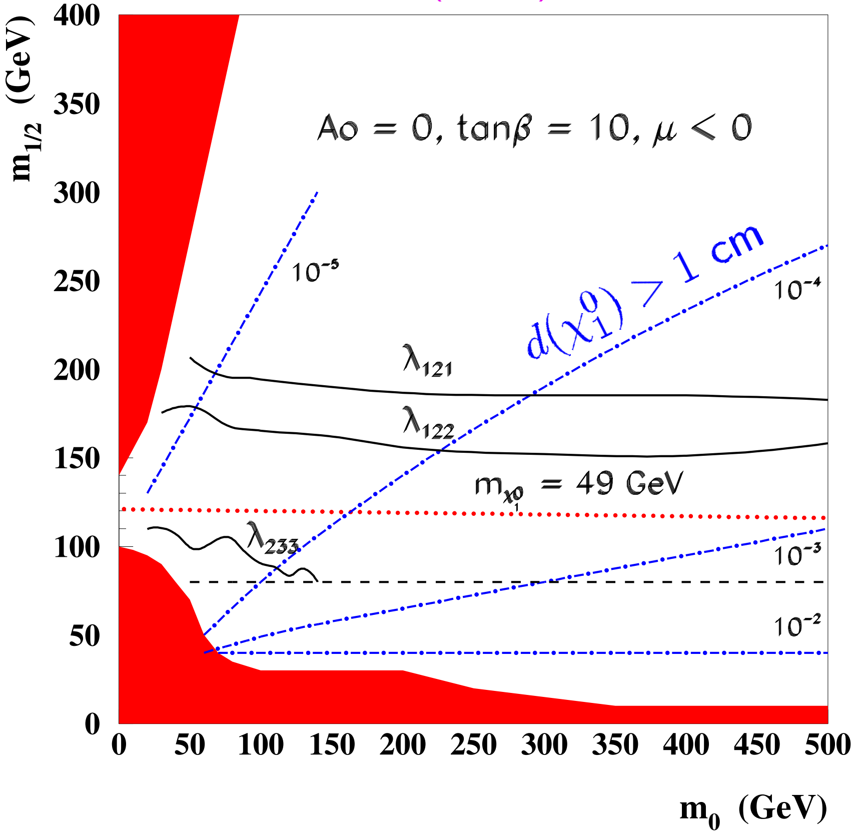
λ_{121}	$\rightarrow$ largest # of e	$\varepsilon \sim 20\%$
λ_{233}	$\rightarrow$ many τ's	$\varepsilon \sim 0.3\%$

For small λ : $\Gamma(\chi_1^0) \rightarrow 0$ and $d(\chi_1^0)$ large
(no analysis of track impacts)

New domain probed extending that excluded by LEP (but for couplings involving τ's)

Quite independent on $sgn(\mu)$ and $\tan\beta$

DØ, PRD 62 (2000) 071701



- CDF : tetraleptons induced by $R\!\!\!/_p$ decays

only $\chi_1^0\chi_1^0$ production considered
+ $4l$ requirement

Pair Production + $\not R_p$ decays via λ' : dilepton events

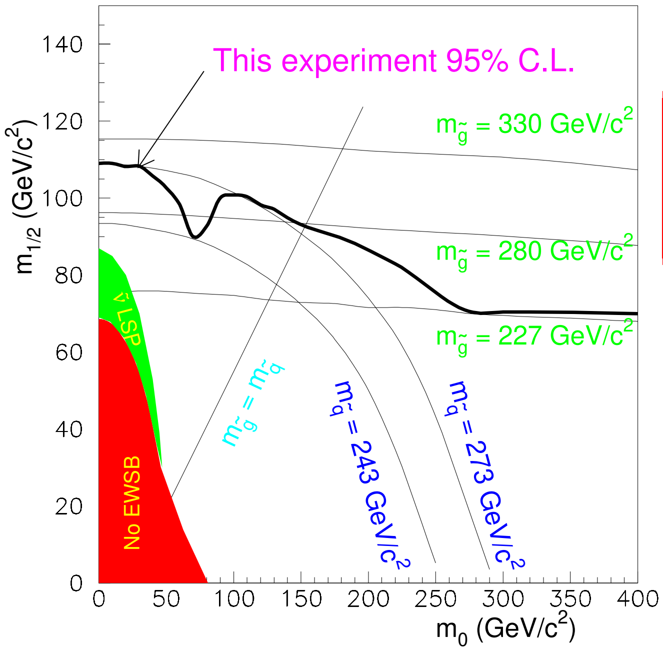
Pair produced sparticles (e.g. $\tilde{q}\tilde{q}^*$) cascade decay to the LSP, then LSP $\rightarrow \not R_p$ decay

Assume one λ'_{1jk} or $\lambda'_{2jk} \neq 0$ $(j \neq 3)$: $\boxed{\chi_1^0 \rightarrow e\ (\mu)\ + 2 \text{ quarks}}$ (not top)

DØ Run I analysis : (PRL 83, 4476)
$\lambda'_{1jk} \neq 0$: $\geq 2\ e\ +\ \geq 4$ jets
Main background = QCD fakes + DY

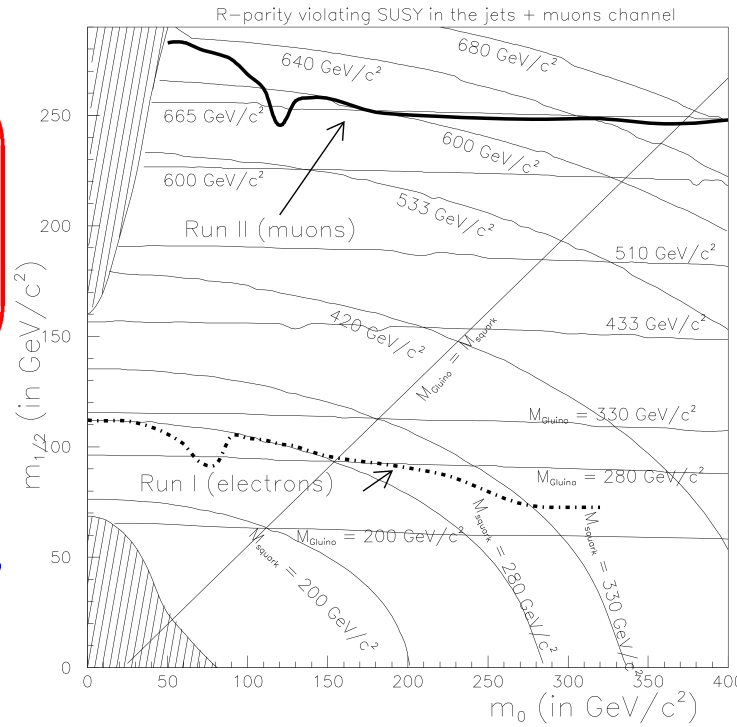
Prospects for Run II, 2 fb^{-1} :
(S. Banerjee et al., hep-ex/9904397)
e.g. $\lambda'_{2jk} \neq 0$: $2\mu\ +\ \geq 4$ jets

$\tan\beta = 2,\ \mu < 0,\ A_0 = 0$:



NB : for larger $\tan\beta$
Large BR for :
$\chi_1^0 \rightarrow \nu jj$
i.e. ll analysis is
less sensitive

(also CDF, PRL 83, 2133
LS dileptons)



$\boxed{M_{\tilde{q}} > 243 \text{ GeV},\ M_{\tilde{g}} > 227 \text{ GeV}}$

$\tilde{q}$ and $\tilde{g}$ probed up to $\sim 0.4 - 0.6$ TeV

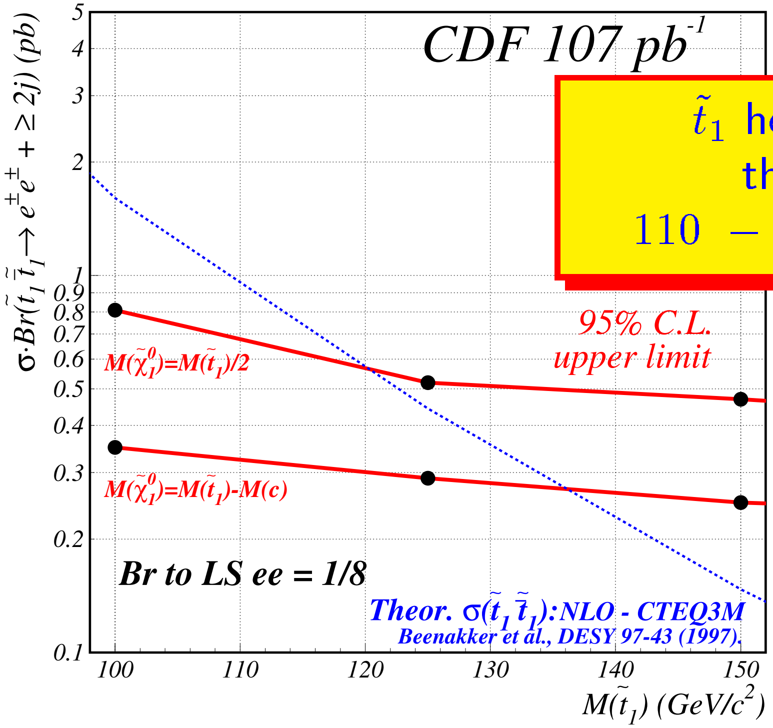
Pair Production of stops + $\not{R}_p$ decays via λ'

Consider only $\tilde{t}_1\tilde{t}_1^*$ pair production ($\tilde{t}_1$ could be lightest $\tilde{q}$!). Analysed Stop decay modes :

- $\tilde{t}_1 \to c\chi_1^0$ followed by $\chi_1^0 \to ejj$ ($\lambda'_{1jk}, j \neq 3$)

Look for LS dileptons (CDF, PRL 83, 2133)
"unconstrained" model :
assume χ_1^0 mass + $BR(\chi_1^0 \to ejj) = 1/2$

$\not{R}_p \quad \tilde{t}_1\bar{\tilde{t}}_1 \to c\,\tilde{\chi}_1^0\,\bar{c}\,\tilde{\chi}_1^0 \to e^\pm e^\pm + \geq 2j$

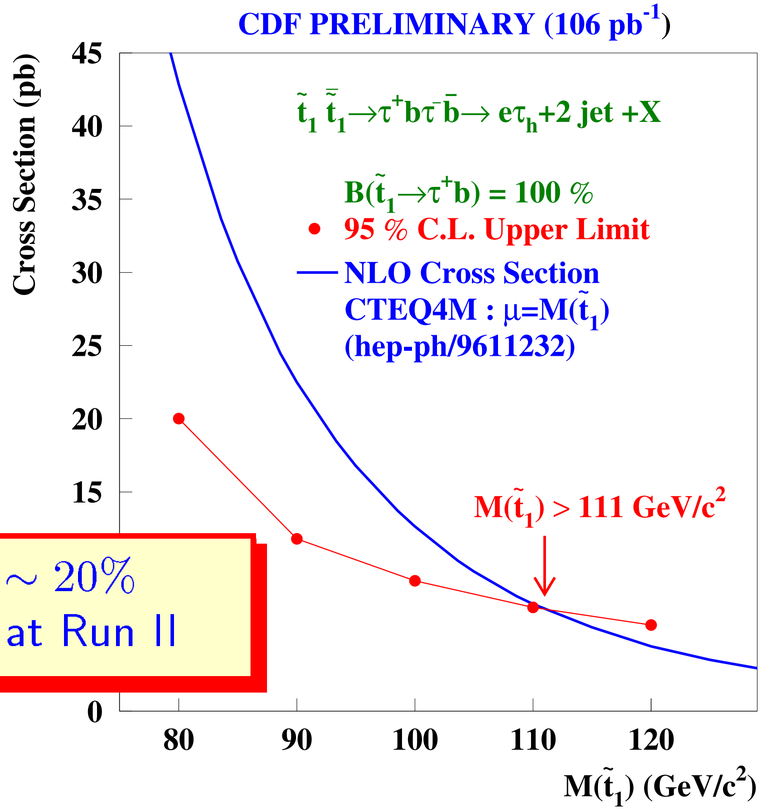


$\tilde{t}_1$ heavier than 110 – 130 GeV

- $\tilde{t}_1 \to b\tau$ via λ'_{333} or bilinear $\not{R}_p$

Look for $b\,\bar{b}$ $\quad \tau^\pm \hookrightarrow l^\pm$ $\quad \tau^\mp \hookrightarrow \tau^\mp_{had}$.

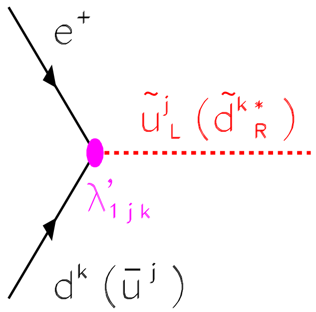
Tracker to perform τ id. and charge meas.
σ_{lim} by normalizing to $Z \to \tau\tau \to l\tau_{had}$



$\varepsilon(\tau_{id}) \sim 20\%$
Improve at Run II

Resonant squark production via λ' at HERA

Non-vanishing λ'_{1jk} coupling allows single resonant $\tilde{q}$ production at HERA :



$$\sigma \propto \lambda'^2_{1j1} q(x = M^2_{\tilde{q}}/s)$$

$\rightarrow$ eq LQ-like decay

$\rightarrow$ $q\chi^0$, $q\chi^+$, $q\tilde{g}$ many possible final states lepton(s) + multijets

Analysis covers $\sim 100\%$ of decay modes.

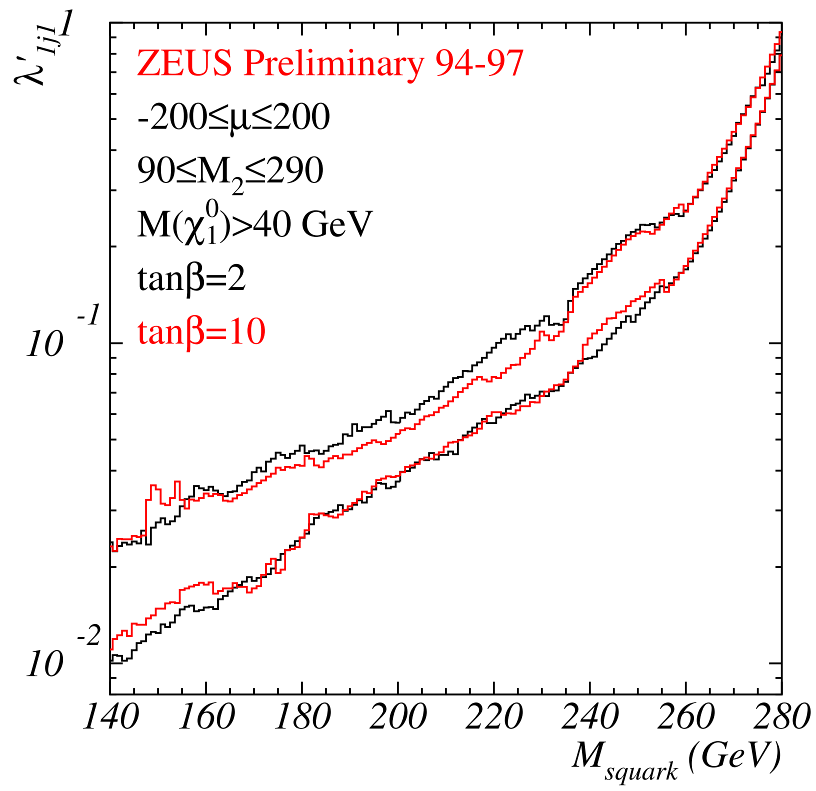
- Consider first an "unconstrained" model : sfermions & gauginos sectors not related i.e. $M_{\tilde{f}}$ free parameter

- Limits on λ'_{1jk} do not depend strongly on MSSM parameters

- For $\lambda'_{1j1} = 0.3$ (em coupling) : squarks can be ruled out **up to ~ 260 GeV**

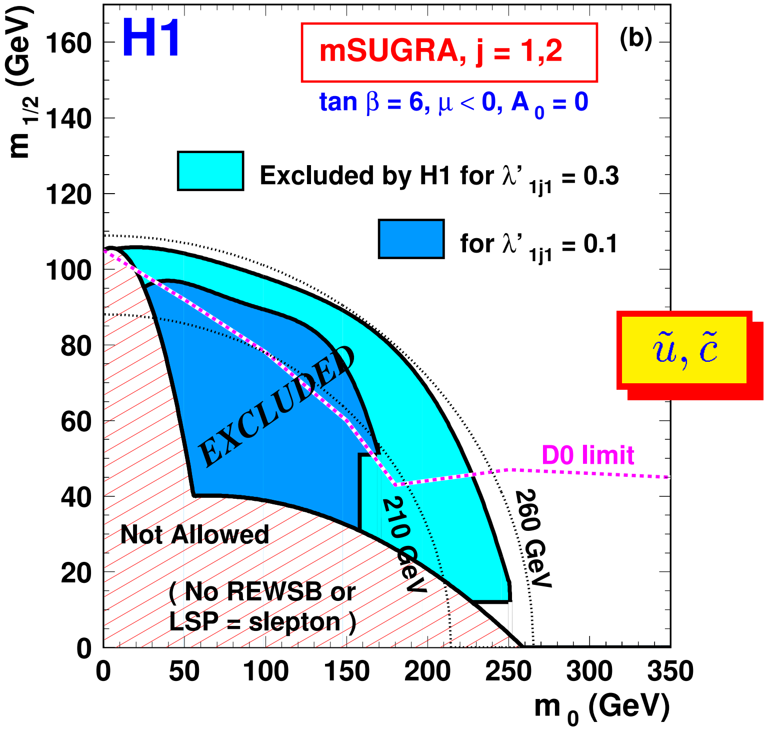
- HERA's sensitivity extends beyond the indirect limits from low energy experiments for $\tilde{c}$, $\tilde{t}$.

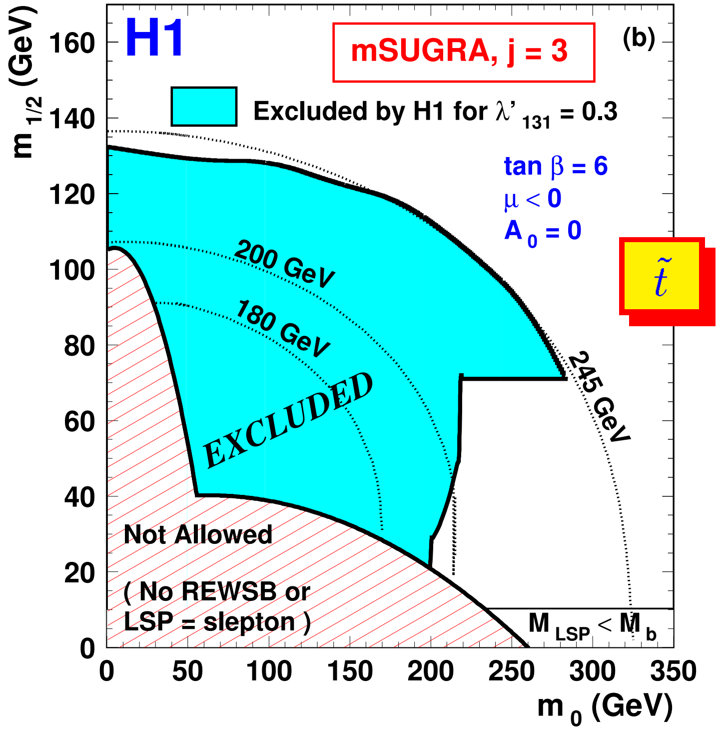
(also H1, hep-ex/0102050)



Resonant squark production via λ' at HERA

Results also interpreted in the framework of mSUGRA + $\not R_p$ for given λ' (H1, hep-ex/0102050)





- For medium $\tan\beta$: HERA's sensitivity extends beyond the domain probed by Tevatron (large BR for $\chi_1^0 \rightarrow \nu jj$, difficult at Tevatron !)
- HERA's constraints depend on the value of λ' coupling; Tevatron probes larger m_0 (via $\tilde{g}$)

$\Rightarrow$ HERA and Tevatron complement each other

Searches at LEP very sensitive. Competitive with HERA for intermediate values of m_0 for non-vanising λ'_{131} coupling ($\tilde{t}$ prod.)

Prospects for resonant sparticle production via $R\!\!\!/_p$ at HERA and Tevatron

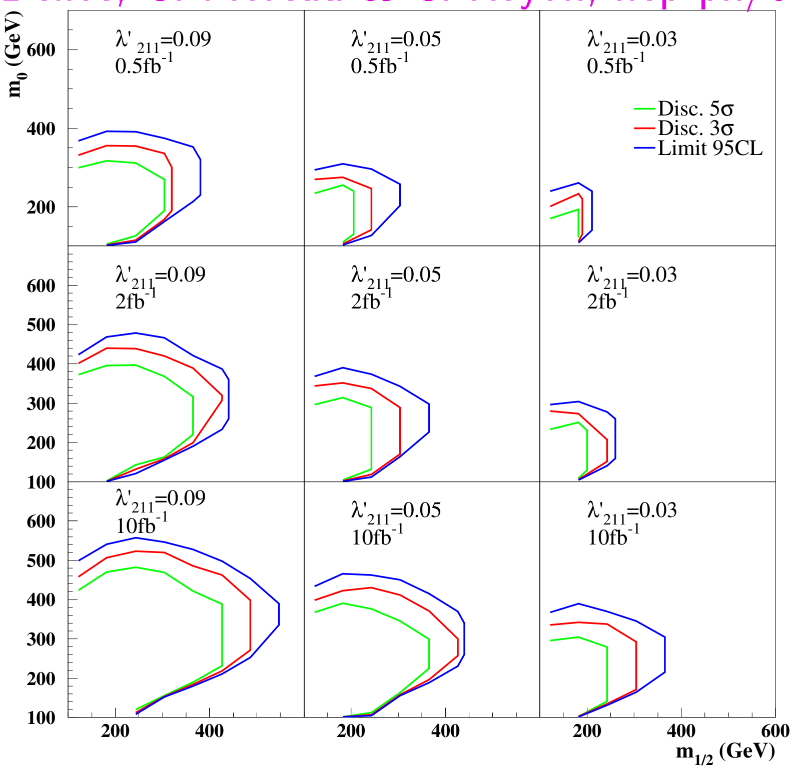
A non-vanishing λ' coupling could also lead to resonant slepton production at Tevatron, e.g. : $d_j \bar{d}_k \to \tilde{\nu}_i$. Slepton decays into χ^+ (χ_1^0) would lead to final states with trileptons (LS dileptons).

λ' needs to be sizeable. Resonant processes which could be observed at future HERA and Tevatron, taking into account indirect bounds ?

- HERA : 250 pb^{-1} of $e_R^+ \; p$ for λ'_{1j1}
  250 pb^{-1} of $e_L^- \; p$ for λ'_{11k}
  take squark mass = 250 GeV
- Tevatron : 2 fb^{-1}, take slepton mass = 250 GeV

e	HERA	Tev.	μ	Tev.	τ	Tev.
λ'_{111}	-	-	λ'_{211}		λ'_{311}	
λ'_{112}			λ'_{212}		λ'_{312}	
λ'_{113}			λ'_{213}		λ'_{313}	
λ'_{121}			λ'_{221}		λ'_{321}	
λ'_{122}	-	-	λ'_{222}		λ'_{322}	
λ'_{123}	-	-	λ'_{223}		λ'_{323}	-
λ'_{131}			λ'_{231}		λ'_{331}	
λ'_{132}			λ'_{232}		λ'_{332}	-
λ'_{133}	-	-	λ'_{233}		λ'_{333}	-

F. Déliot, G. Moreau & C. Royon, hep-ph/0007288



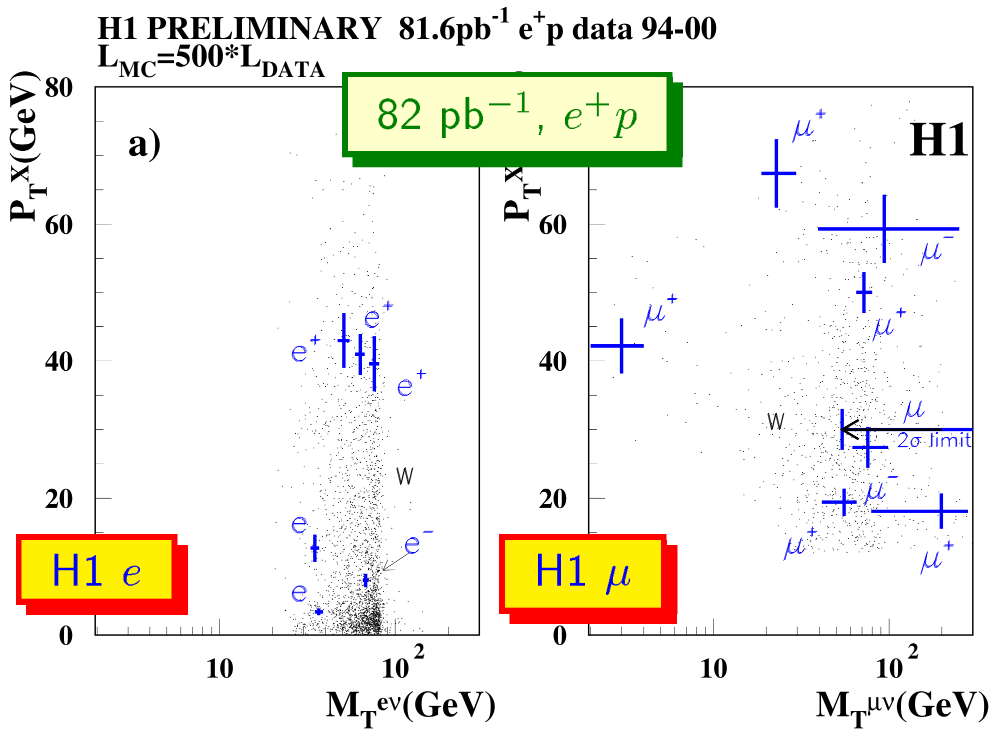
Probe large part of param. space

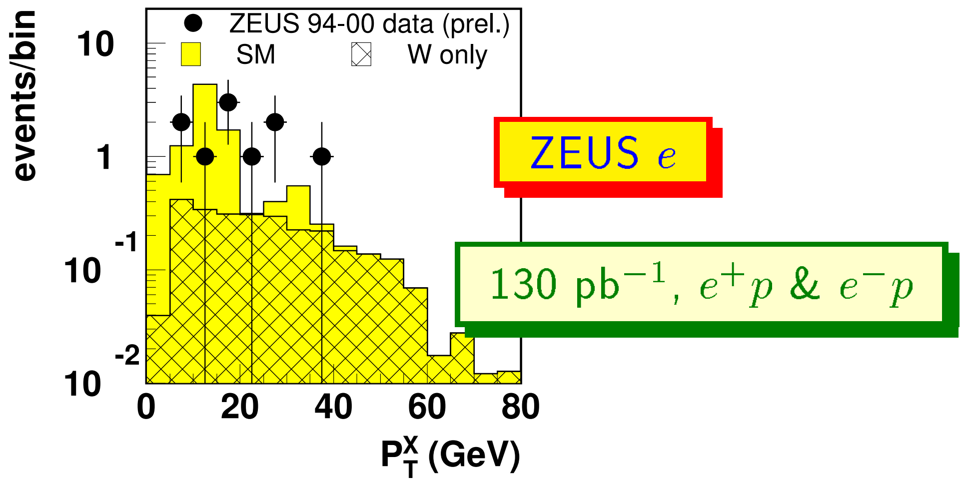
HF tagging at HERA & Tevatron, $\nearrow$ μ acceptance + better meas. at Tevatron, τ id. at Tevatron

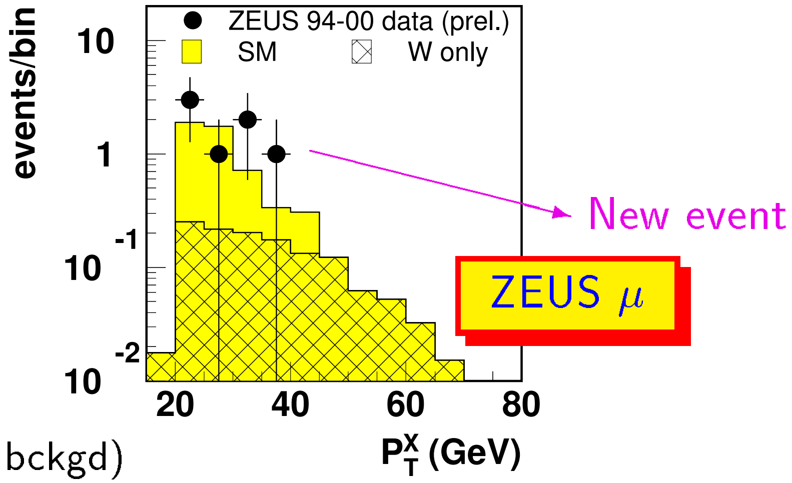
The Unexpected (?) $ep \to l + P_{T,miss}$ + had. at HERA

H1 & ZEUS observed events with high P_T isolated lepton and missing P_T : $l\ +\ P_{T,miss}\ +$ had.

At large P_T^X = hadronic P_T, SM prediction dominated by W production







$P_T^X > 25$ GeV, H1 sees 9 evts, expects 2.3 ± 0.6

(error $\subset 30\%$ on W prod)

ZEUS sees 2 candidates, expects 2.4

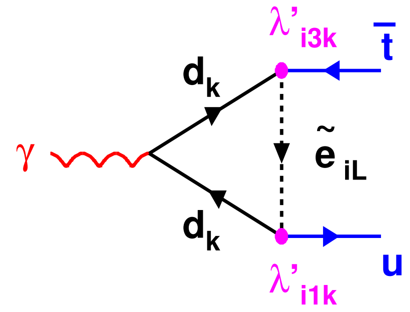
(after add. cuts to suppress non W bckgd)

$P_T^X > 40$ GeV, H1 sees 6 evts $(e + \mu)$, expect 0.8 ± 0.2

ZEUS observes no candidate

Excess observed by H1 at large P_T^X
Not confirmed by ZEUS
Wait for $\nearrow \mathcal{L}$!!

Anomalous couplings of the top quark



Anomalous couplings for the top quark often arise in models extending the SM. E.g. SUSY with two $\not{R}_p$ couplings :

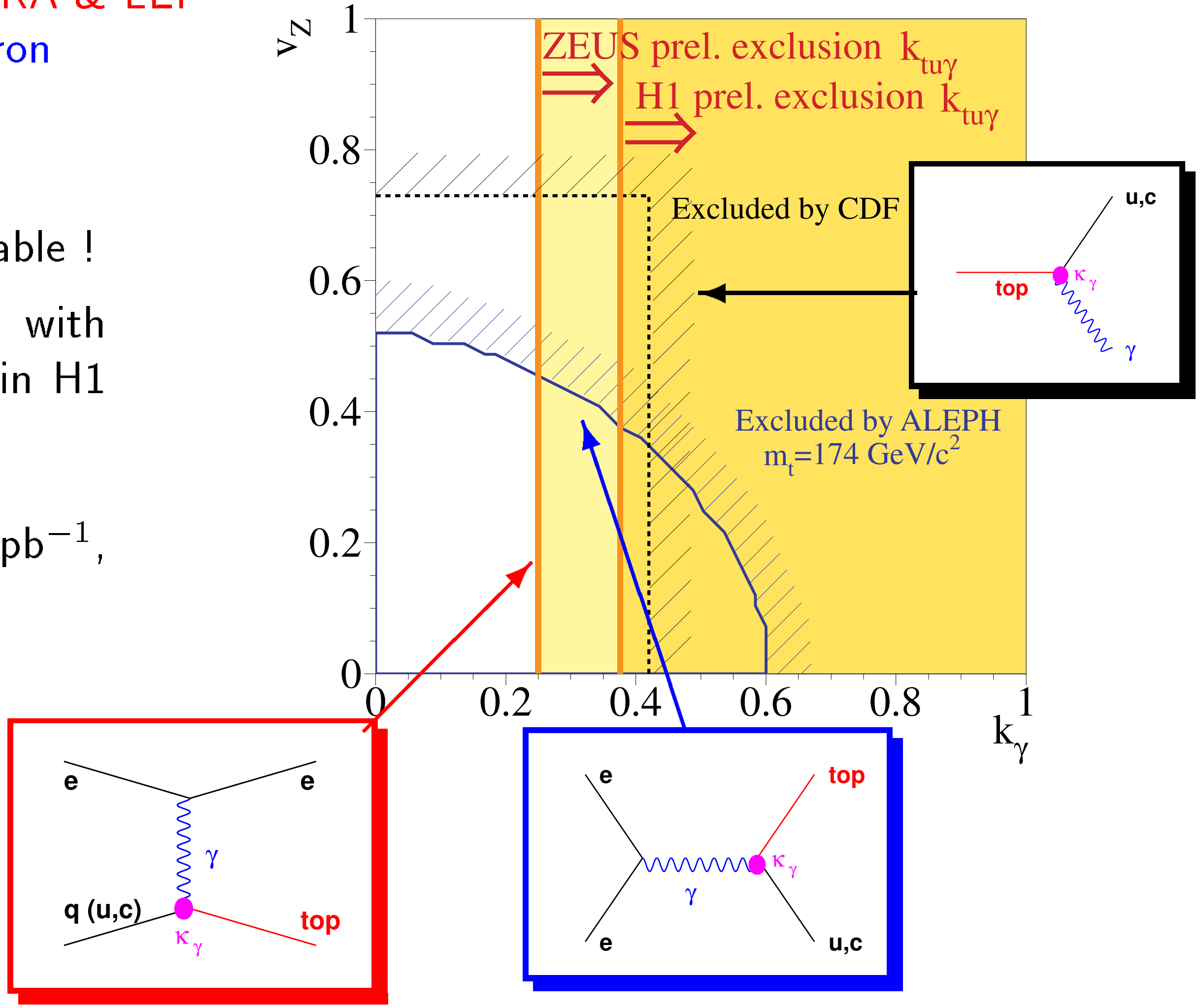
$$\mathcal{L}_{eff} = ee_q \frac{1}{m_{top}} \bar{t}\sigma^{\mu\nu} q_\nu \kappa_\gamma A_\mu u$$

Could lead to
- single top prod. at HERA & LEP
- $\nearrow$ single top at Tevatron
- $t \to u\gamma$ at Tevatron

$BR(t \to q\gamma) \Rightarrow \sigma(t, \text{HERA}) <\sim 1$ pb
i.e. production rate at HERA could be sizeable !

- $W \to l\nu$: $l + P_{T,miss} + X$ events, with large P_T^X. No candidate in Zeus, 5 in H1 (82 pb^{-1}, prel.)

- $W \to had$: 10 candidates in H1 (40 pb^{-1}, prel.), expect 8 ± 5



HERA gives the strongest bounds on $\kappa_{t,u,\gamma}$ coupling !

(see J. Dingfelder talk tomorrow)

Conclusions

- Intensive searches for new physics have been carried out at "HERA-1" and Tevatron Run I. No evidence for new physics so far (although some H1 events are "puzzling").

Searches at both facilities often show a large complementarity.

- This was a fruitful training for the second phase of our experiments :

$\rightarrow$ particle identification, calibration methods, understanding of SM physics as seen in our detectors;

$\rightarrow$ NLO calculations, hadronisation models,...

- The future experiments will provide in particular :

$\rightarrow$ possibility to (better) identify heavy fermions (τ, b, c) (H1, ZEUS, DØ, CDF), especially in geometrical regions relevant for new physics (H1, ZEUS);

$\rightarrow$ better measurement of E_{miss} (CDF) and of μ's (DØ, CDF);

$\rightarrow$ and a much larger luminosity

i.e. ideally suited to search for (and may be find) new phenomena before the start of the LHC.