Searches for New Phenomena at Current Colliders: Status and Prospects

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- Not Higgs, not SUSY (cf M. Schmitt’s talk)...
- Emphasis on recent results
- Selected topics ...

XXI International Symposium on Lepton and Photon Interactions at High Energies
Fermilab, 11-16 August 2003
“Exotic” Physics : Why ?

- SM works so far, but raises a crucial question:
  - Where/what is the Higgs boson?
  - Fundamental scalar field ??
  - Hierarchy pb
    - Yes
    - No
  - Dynamical Breaking of EW
    - Supersymmetry
    - Extra-dimensions
    - “Little” hierarchy
    - technicolor, topcolor

- Questions which the SM (or SM + SUSY) does not answer:
  - Quantization of EM charge
  - Mass terms for n’s ?
  - “Replication” of three families ?
  - Additionnal source of CP ?
  - Particle masses & their hierarchy
  - Strong CP problem ?
  - Flavor ?
  - Symmetry leptons-quarks ? Magnetic Monopoles ?
  - R, Higgs triplets, RpV SUSY ?
  - Compositeness ? Superstrings ?
  - SUSY (phases), additionnal quarks ?
  - Extra-dimensions ?
  - Axions, m_u = 0 ?
  - Horizontal Symmetries ?
  - Extra-dimensions?
Where to look for?

- In rare meson decays
- In Lepton Flavor Violating processes (e+ e- conversion in nuclei ...)
- In the sky (Cold Dark Matter, SN, red giants...) 
- Various other places, amongst which: High Energy Colliders
  - LEP
    - $e^+e^-$, $s = 91 - 209$ GeV, ended in nov 2000
    - ALEPH, DELPHI, L3, OPAL
    - “tail” of analyses
    - $\sim 900$ pb$^{-1}$ per experiment
  - HERA
    - $e^\pm p$, $s = 300 - 320$ GeV
    - H1 / ZEUS (colliding experiments)
    - until summer 2000: $\sim 120$ pb$^{-1}$ / expt
    - Restart (fall 01) more difficult than expected
    - Expect high $\mathcal{L}$ (high $I_e/I_p$) back in sep 03
  - Tevatron
    - $\sim 2$ fb$^{-1}$ in 06-07
    - Run I (92 - 96): $\sim 110$ pb$^{-1}$ / expt
    - Restart in may 2001 $\sim 300$ pb$^{-1}$ delivered by Tevatron.
    - > 210 pb$^{-1}$ delivered (mid-July) since detectors are fully operationnal
  - The subject of this talk
    - The subject of this talk
  - E. Perez

The subject of this talk

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Any Hints for New Physics?

Yes. Neutrinos do oscillate! But no strong implication in the charged sector...

- **Atomic Parity Violation**: weak charge in Cs measured to 0.6% (1997)
  - > 2σ discrepancy with expectation until last spring.
  - SM prediction revised - now very good agreement

- \(\sin^2 \theta_W\) at NuTev? Differs by \(\approx 3\)σ from global SM analysis
  - Not clear... theoretical uncertainty? e.g. asymmetry in s-\(\bar{s}\), violation of isospin in parton distributions?

- Excess in \(b\bar{b}\) production? May be not as large as initially suspected...
  - Tevatron & HERA: discrepancy reduced... Still excess in \(g\bar{g} \rightarrow b\bar{b}\) at LEP...

- \((g-2)\mu\)? KLOE & BaBar enter the game via radiative return data
  - BNL (ave.)

- Some interesting events / measurements at colliders... Some examples shown in the next slides...
New Physics in $B \rightarrow J/\psi K_S$?

At ICHEP '02 BaBar & Belle reported a measurement of $\sin(2\beta)$ from:

- $B \rightarrow J/\psi K_S$ dominated by a tree-level amplitude
  
  Average (2002): $\sin(2\beta) = 0.734 \pm 0.054$

- $B \rightarrow \phi K_S$ only penguin contributions

  BaBar: $\sin(2\beta) = -0.19^{+0.52}_{-0.50} \pm 0.09$
  
  Belle: $\sin(2\beta) = -0.73 \pm 0.64 \pm 0.22$

  Average: $\sin(2\beta) = -0.39 \pm 0.41$

In the SM both should be the same within < 4%  

Discrepancy of $\approx 2.7\sigma$

Hint of new physics in $B \rightarrow \phi K$? (NP effects might be large in loop induced processes)

Triggered various speculations...

- SUSY (non-universality), some 2HDM models, extra down quark...
- Constrained by $B$ mixing and $b \rightarrow s\phi$

Looking forward to reducing stat. error in $\sin(2\beta)_{J/\psi K}$!
(Run I) CDF events with $\square + E_{T,\text{miss}} + X$

Run I data: slight excess of events with high $E_T$ lepton & $\square + $ large $E_{T,\text{miss}}$

Run I ee$\square + E_{T,\text{miss}}$ event: triggered a lot of activity... ($10^{-6}$ evt expected !)

Run II data: look for events with two central $\square$s

Better hermiticity of Run II detector!

No such spectacular event observed so far! (CDF & D0)

Run II data, 84 pb$^{-1}$

Events/5 GeV

CDF RunII Prelim, 72 pb$^{-1}$

W $\square$ production at Run II: good agreement with SM
CDF “superjets” Events

Run I CDF data: excess of $W + 2,3$ jets where both a secondary vertex and a soft lepton are found in one jet (“superjets”)

13 events observed, $4.4 \pm 0.6$ expected

- atypical kinematic properties
- SM reproduces well closely related data samples
- many, many checks; e.g. that the correlation of SVX and SLT taggers are well described by simulation

No explanation for this excess. Probability (stat. fluctuation) $\leq 0.1\%$

No statement yet from Run II. Good performance of $b$-tagging in both experiments, but correlations between taggers not yet studied. Work is going on in both experiments.
HERA multilepton events

Search for events with several leptons in final state
Mainly produced via $\gamma$ collisions


$0.37 \pm 0.04$

$0.23 \pm 0.04$

No excess in $\text{ep} \rightarrow \ell^+ \ell^- \gamma X$

<table>
<thead>
<tr>
<th>selection</th>
<th>exp$^*$</th>
<th>H1 (115 pb$^{-1}$)</th>
<th>ZEUS (130 pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2$\ell$, $M &gt; 100$ GeV</td>
<td>3 / 0.30 ± 0.04</td>
<td>2 / 0.77 ± 0.08</td>
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</tr>
<tr>
<td>3$\ell$, $M &gt; 100$ GeV</td>
<td>3 / 0.23 ± 0.04</td>
<td>0 / 0.37 ± 0.04</td>
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</tr>
</tbody>
</table>

(different angular ranges in H1 / ZEUS analyses)
HERA events with isolated lepton + $P_T,\text{miss}$

- H1 e$^+ p$ data, 105 pb$^{-1}$
- Combined Electron and Muon

$e p \rightarrow l + \text{jet} + P_T,\text{miss}$

Main SM contribution:

\[ \frac{P_T}{X} \]

- $P_T > 40$ GeV
  - $2 / 0.12 \pm 0.02$
  - $1 / 0.06 \pm 0.01$

- Events observed / expected

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events</th>
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</thead>
<tbody>
<tr>
<td>H1 e$^+ p$ data</td>
<td>e channel</td>
</tr>
<tr>
<td>$P_T &gt; 25$ GeV</td>
<td>4 / 1.48 ± 0.25</td>
</tr>
<tr>
<td>$P_T &gt; 40$ GeV</td>
<td>3 / 0.54 ± 0.11</td>
</tr>
</tbody>
</table>

- No excess in H1 e$^-$ p data
- No excess in ZEUS data in e & $\square$ channels, $\square$ candidates
- Agreement in the had. channel (but large bckgd)
- $W$ prod: full NLO corrections included (recently available)

E. Perez

ZEUS Prelim

130 pb$^{-1}$
HERA events with isolated lepton + $P_{T,\text{miss}}$

$e p \rightarrow e + \text{jet} + X$

$e p \rightarrow e + \text{jet} + X$
**Complementarity of Experiments**

Statistical fluctuation in H1 / ZEUS data? The answer should come soon! Meanwhile, possible hint for new physics? i.e. should other expts see something?

- e-q resonance?

- New physics in $e\gamma$?

- New physics in $q\gamma$?

Most likely, something should have been seen at LEP!

(NB: unlikely to produce large $P_T,had$ at HERA)

May have large x-section at the Tevatron ...

But huge $W +$ jets background!

Illustrates the complementarity between the 3 colliders

To go further in such comparisons, one needs specific models ...

Adapted from P. Schleper

"Partonic luminosities"
Models for New Physics

Try to address one/several question(s) not solved by the SM...

Extend the SM by:

• More symmetry
  - SUSY - the only sym. which prevents to add $m^2 H^*H$ in $\mathcal{L}$
  - enlarge the gauge symmetry - unification of couplings, restore
    the parity symmetry at high energies, add some symmetry between
    the lepton & quark sectors...

• Enlarged/modified matter field content
  - neutrino masses, new fermions
to cancel $m^2_h$ divergences up to $\sim 10$ TeV ...
  - may arise in GUTs
  - possibly together with some new interaction(s) - dynamical EWSB

• Enlarged space-time
  - hierarchy problem, fermion masses, links with
    cosmology; links with string theories

Build models taking into account precision measurements & bounds from low E

Covered:
- Composite fermions
- Technicolor resonances (a bit...)
- Leptoquarks
- $Z'$ ($W'$) gauge bosons
- Models with extra dimensions

Not covered:
- Extra generations of leptons or/and quarks
- Lepton Flavor Violation
- some models with extra dim.
- ...

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A new scale of matter?

- First approach: assign a finite size to the EW charge distributions. E.g. in DIS at HERA,
  \[ f(Q^2) = 1 - \frac{<r^2>}{6} Q^2 \]

  where \( Q^2_{\text{max}} \leq 10^5 \text{ GeV}^2 \)

- Interaction between fermion constituents can be parameterized as a Contact Interaction (\( ff \leftrightarrow ff \))

- Unambiguous signature: direct observation of excited states
  (chiral) magnetic coupling \( \sim (\text{GeV})^{-1} \)
  \( R_q < 10^{-18} \text{ m} \)

  \( \text{Pair production of } f^* \text{ in } e^+e^- \text{ and } pp; \text{ single production depends on coupling} \)

Other possible approach IF leptons & quarks have common constituents:
\[ \mathcal{L} \supset \frac{4\alpha}{2} ( \bar{e}^* \bar{e} e)(\bar{q} q q) \]

Experimentally \( \sim \) similar, mainly \( \neq \) normalization


Excited Electrons: $e + V$ Resonances

- Pair production at LEP with masses below 100 GeV ruled out.
- Single production at LEP and HERA.

All $e^*$ decay modes considered at LEP & HERA.

Branching ratios of $e^*$, $eZ$, $eW$ depend on $f$ vs $f'$ at LEP & HERA.

$e^*$ decay at Tevatron.

My interpretation of CDF bounds:

- $f/\Lambda = 1/M(e^*)$

To fix the ideas:
- $M(e^*) > 250$ GeV

Interesting for Tevatron, esp. if $(g-2)_\mu$!

Hagiwara, $f/\Lambda = 1/M$, $M > 150$ GeV.

Take care of conventions!
Excited quarks & other j-j resonances

- Dijet resonances predicted in various models
  - New fermions, e.g. excited quarks
    - expect signal in $q\bar{q}/Z, qW$ depending on $f_s$ vs $f$ & $f'$
  - new gauge bosons, $Z', W'$ (but signal mainly in the dilepton channels)
  - new massive colored bosons, e.g. $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_{QCD}$
    (chiral color, colorons, topgluons...)
  - Look for a narrow resonance in the di-jet spectrum: use a simple background parametrization for $d\sigma/dM$ and search for bumps $\Delta$ resolution

- Axigluon & (flavor univ.) colorons:
  - assuming $\sigma(qqg) = \sigma(qqG)$
    - First direct bound $> 1$ TeV!!

- Excited quarks:
  - $M > 760$ GeV
    (f=f'=fs=1, $\overline{f} = M$)

CDF Run II, 75 pb$^{-1}$, Prelim.
New Physics in the Top Quark Sector?

Large top mass... *Might expect first hints of new physics in the top sector*

- **Topcolor**: introduced in DEWSB models to account for large $M_{top}$
  
  $SU(3)_1 \times SU(3)_2 \cong SU(3)_{QCD}$ with e.g. $SU(3)_2$ coupling strongly to $3^{rd}$ gene only
  
  - Topgluons coupling mainly to $bb, tt$
  
  Avoid a large mass for $b$?
  
  - e.g. a new Z boson, attractive to $tt$ & repulsive to $bb$  
    i.e. no $bb$ condensate

- **“ Little Higgs” models**
  
  New heavy $T$, could be observed in $q b \stackrel{q'}{\rightarrow} q' T$
  
  + $T \rightarrow tZ \rightarrow 3$ leptons

  **Look for a $tZ$ resonance**

  NB: “recent” model... experimental studies have already started!

- **Single Top production @ Tevatron**
  
  Should be observed with $\mathcal{L} \geq 2 \text{ fb}^{-1}$

  **Might bring surprises, eg $V_{tb}$, anomalous couplings**

\[ \mathcal{L} = 300 \text{ fb}^{-1} \]
FCNC couplings involving the top quark?

Anomalous couplings between top, $\gamma/Z$ and $u/c$ may arise in SM extensions. Would lead to:

- enhanced single top production @ Tevatron
- single top production at LEP & HERA (tiny rate within the SM) (HERA has no sensitivity on couplings top-c)
- $t \rightarrow u/c + \gamma/Z$ @ Tevatron

Possible explanation of HERA’s events?

$e\, q \rightarrow (e)\, t\rightarrow (e) + b + \text{lepton} + E_{T,\text{miss}}$

$H1: 5$ candidates, $1.7\pm0.4$ expected (Prelim.)

- not excluded by LEP & Run I data
- ZEUS vs H1: too few events so far... looking forward to doubling $\mathcal{L}$!

Sensitivity @Tevatron:

- mainly via radiative top decays
- $u/c \rightarrow t$: quite large but huge background!

for $\kappa \leq 0.2$, $\kappa \leq \kappa$(SM single $t$) $\leq 2$ pb...

E. Perez, Prelim., Contrib. Paper #181
Final DELPHI results, Contrib. Paper #53
L3, PLB 549 (2002) 290
Lepton + Quark Resonances: Leptoquarks

Apparent symmetry between the lepton & quark sectors?
Exact cancellation of QED triangular anomaly?

- LQs appear in many extensions of SM
  (enlarged gauge structure, compositeness, technicolor...)
- Connect lepton & quark sectors

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

ZEUS, DESY-03-041

• Single LQ prod at HERA

<table>
<thead>
<tr>
<th>Topologies</th>
<th>SM Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>e + jet</td>
<td>Neutral Current DIS</td>
</tr>
<tr>
<td>[ ] + jet</td>
<td>Charged Current DIS</td>
</tr>
</tbody>
</table>

Look for a resonant peak in $M$ spectra

No excess observed in both channels

(unknown) Yukawa coupling lepton-quark-LQ
First Generation Leptoquarks at Tevatron

- Pair production at Tevatron

<table>
<thead>
<tr>
<th>Topol.</th>
<th>SM Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>eejj</td>
<td>DY + jets, QCD &quot;fake&quot;, top</td>
</tr>
<tr>
<td>e[\not]{jj}</td>
<td>QCD, W + jets, top</td>
</tr>
<tr>
<td>[\not]{jj}</td>
<td>W ([\not]{\ell} [\not]{\ell} / \ell \ell) + jets, Z ([\not]{\ell} [\not]{\ell} / \ell \ell) + jets</td>
</tr>
</tbody>
</table>

- Mainly from the data

- Rate for a jet to "fake" an e
- Use of control/bckgd enriched samples
- Correct the $O(\alpha_s^0)$ MC to reproduce the observed jet mult.

- Require a good understanding of missing $E_T$!

- Mainly W+jets
- QCD dominates at large $M_T$ & $S_T$

- Bckgd well controlled

- No attempt to reconstruct the LQ mass
  Make use of $S_T = \not{E}_T$

<table>
<thead>
<tr>
<th></th>
<th>DO</th>
<th>CDF</th>
</tr>
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<tbody>
<tr>
<td>eejj</td>
<td>0 / 0.45 ± 0.12</td>
<td>0 / 3.4 ± 3.2</td>
</tr>
<tr>
<td></td>
<td>(135 pb(^{-1}))</td>
<td>(72 pb(^{-1}))</td>
</tr>
<tr>
<td>e[\not]{jj}</td>
<td>3 / 4.19 ± 1.00</td>
<td>2 / 1.73 ± 1.40</td>
</tr>
<tr>
<td></td>
<td>(121 pb(^{-1}))</td>
<td>(72 pb(^{-1}))</td>
</tr>
<tr>
<td>[\not]{jj}</td>
<td>—</td>
<td>42 / 42.5 ± 10.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(76 pb(^{-1}))</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary

$\int L \, dt = 76 \, \text{pb}^{-1}$

Missing $E_T$ (GeV)

Transverse mass ($e, \[\not]{\ell}$) (GeV)
Existing Bounds on 1st Generation LQs

\[ \square = \text{BR}(\text{LQ} \rightarrow \text{eq}) \]

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>Run II bounds</th>
<th>CDF (eejj)</th>
<th>D0 (eejj)</th>
<th>D0 (e(\bar{\nu})jj)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>231</td>
<td>D0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>230</td>
<td></td>
<td>CDF</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>166</td>
<td></td>
<td>CDF</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>169</td>
<td>D0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>156</td>
<td>D0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>107</td>
<td>CDF</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For \( \lambda = \sqrt{4 \lambda_{em}} \leq 0.3 \), HERA rules out LQ masses \( \lambda \leq 290 \text{ GeV} @ 95 \% \text{ CL} \)

D0 Run II + D0 Run I: \( M > 253 \text{ GeV} \) for \( \lambda = 1 \)

- Tevatron probes large masses for large \( \lambda \) (LQ \( \rightarrow \) eq) independently of \( \lambda \)
- HERA better probes LQs with small \( \lambda \) provided that \( \lambda \) not too small

\( \square \) Complementarity of both facilities

NB: at HERA, \( e^+ / e^- + \) polarisation could help in disentangling the LQ quantum nbs
Second and Third Generation Leptoquarks

So far, $LQ_{2,3}$ with $M > 100$ GeV can be probed exclusively at the Tevatron!

- **Search for $LQ_2$ in D0 Run II data:**
  - $m\bar{m} + \text{at least 2 jets}$
  - Signal at large $M_{\mu\mu}$ & $S_T$
  - SM bckgd $\leq$ only DY
  - $M > 186$ GeV for $LQ_2 \rightarrow m\bar{m}$

- **Search for $LQ_2$ & $LQ_3$ using heavy flavor tagging (Run I results):**
  - $LQ_2 \rightarrow c$,
  - $LQ_3 \rightarrow b$, $LQ_3 \rightarrow b$

Already competitive with Run I result (200 GeV) obtained from a NN analysis

- New physics might couple mainly to 3rd gene fermions

Run II will bring much more sensitivity (improved SVX)
Dilepton resonances

- New heavy gauge boson $Z'$, e.g. models with L-R symmetry or $E_6$ GUT inspired
- Kaluza-Klein gravitons in some extra-dim. models
- (Color-singlet) technirho in Technicolor models ...

Model couplings of $Z'$ to fermions; mixing with the $Z \to 0$ (mainly $Z$ peak data)

**DO & CDF searched for ee & $\mu\mu$ resonances:**

**Main bckgds @ high $M$:**

<table>
<thead>
<tr>
<th></th>
<th>DY, QCD &quot;fake&quot;</th>
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<tbody>
<tr>
<td>ee</td>
<td>DY</td>
</tr>
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</table>

**Run II direct bounds between 545 and 730 GeV**

Already competitive with indirect LEP bounds

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Status & Prospects on New Z' Bosons

Limits & sensitivities on Z' bosons often expressed in:

- **SSM**: Z' couples to fermions like the SM Z
- **E₆ inspired models**: E₆ \( \cong \) SO(10) \( \times \) U(1)\( ^c \) and SO(10) \( \cong \) SU(5) \( \times \) U(1)\( ^c \)
  \( Z' = Z_c \sin \theta_6 + Z_y \cos \theta_6 \)
  different models depending on mixing angle \( \theta_6 \)

<table>
<thead>
<tr>
<th>Indirect bounds</th>
<th>Run II prelim. results</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP Combined</td>
<td>APV (*)</td>
</tr>
<tr>
<td></td>
<td>CDF e⁺e⁻ (126 pb⁻¹)</td>
</tr>
<tr>
<td>SSM</td>
<td>1787</td>
</tr>
<tr>
<td></td>
<td>835</td>
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<tr>
<td></td>
<td>730</td>
</tr>
<tr>
<td></td>
<td>610</td>
</tr>
<tr>
<td></td>
<td>719</td>
</tr>
<tr>
<td></td>
<td>D0 e⁺e⁻ (100 pb⁻¹)</td>
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<tr>
<td></td>
<td>590 ( \text{my estimations from} )</td>
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<tr>
<td></td>
<td>605 ( \text{DO bounds on} e⁺e⁻ \times \text{BR} )</td>
</tr>
<tr>
<td></td>
<td>434 540</td>
</tr>
<tr>
<td></td>
<td>630 ( \Box 530 )</td>
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<tr>
<td></td>
<td>( \Box 605 )</td>
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</tbody>
</table>

\( (*) \) my estimations using Casalbuoni et al, PLB 460, 135 & Kuchiev & Flambaum, hep-ph/0305053

\( \Box (f f), A_{FB} \)

\( \chi \) (Prelim.)

Indirect bounds from LEP much more model dependent

\( Z' \) mass (TeV)

Tevatron 1 fb⁻¹
LHC, 100 fb⁻¹
LC, 0.5 TeV, 1 ab⁻¹
LC, 1 TeV, 1 ab⁻¹

APV \( Q_W \) would need to be measured within \( \Box 0.1\% \) to compete with LHC

E. Perez

1 10

LEP '03, 08 / 11 / 03
1^+1^+ Resonances? E.g. Doubly Charged Higgs

Appear in L- R symmetric models: \( SU(2)_L \times SU(2)_R \) broken by Higgs triplet
(or extended Higgs sector by a triplet with Y=2). Might explain small (Majorana) \( M \) masses.
\( H^{++} \) couples to fermions via unknown Yukawa couplings \( h_{ij} \), not related to masses
SUSY L - R models predict low \( H^{++} \) masses, below \( \sim 1 \) TeV

- Pair production at LEP: \( H \rightarrow ee, \mu \mu, \tau \tau, e\bar{e}, e\bar{\mu}, e\bar{\tau} \) considered
  \( M_H > 98.5 \) GeV

- LEP & Hera: single production via \( e^+ g \rightarrow e^- H^{++} \)
  \( H^{++} \) events at high \( M \): only one 2e evt fulfils charge requirement
  H1 2e & 3e events at high \( M \):

- Influence on Bhabha scattering at LEP
  Constraints at \( M > 200 \) GeV

- Tevatron: pair production dominates
  No sensitivity yet!

Run II should probe masses up to 180 GeV
Search for $H^{±±}$ at Tevatron

Look for events with at least 2 $\mu$ and one pair of $\mu$ with like-sign charges

- **Basic $\mu$ like-sign selection:**
  Mainly $bb$ events
  Rate well described by SM prediction when $bb$ expectation is rescaled following Run I (bb, inclusive) measurement

- **Signal selection**
  2 candidates (exp. $0.34 \pm 0.1$)
  $M_H > 116 (95) \text{ GeV}$ for $L (R) H^{±±}$
  (similar result from CDF)

- **CDF also looked at non-diagonal coupling**
  $H^{±±} \not\rightarrow e \not\rightarrow \ell$ for $H^{±±}$
  $M_H > 110 \text{ GeV}$

Could this be the 1st ZZ candidate in Run II?
Kaluza-Klein Gravitons

Why is the gravity so weak, i.e. $M_{Pl} \gg M_{EW}$?

All attempts in higher dim. space, with $n$ compactified extra dimensions

- "Localized gravity" on a "brane" at $d = 0$ from our brane; propagation of gravity in the extra dim is exponentially damped due to the (tuned) space-time metric
  - Randall & Sundrum models; "usual" version: $n=1$, $R_c \ll$ Planck length

- "Strong gravity"; fundamental scale $\sim$ TeV; gravity appears weaker in 4d because flux lines are "diluted" in large extra dimensions
  - Large $R_c \ll 0.1$ mm. Not excluded by gravity measurements

Arkani-Hamed, Dimopoulos, Dvali, PLB 429 (1998) 263

Graviton propagate in extra dim $\to$ Kaluza-Klein modes

In localized gravity:
- $G^{(k)}$ heavy, $G^{(1)} \ll$ TeV
- Coupling of $G^{(k)}$ to SM fields $\ll$ TeV
  (determined by some model param, $k/M_{Pl} \ll 0.1$)

CDF: $qq, gg \to ee, jj$

First direct constraints on Randall-Sundrum models!

PRL 83 (1999) 3370;
PRL 83 (1999) 4690

CDF Run II, Prelim, 126 pb$^{-1}$

Spin 2 resonance

Randall-Sundrum Graviton
95% C.L. Excluded Region
in dilepton decay mode

ee & $jj$ combined

Sensitivity for 2 fb$^{-1}$

$G^{(1)}$ mass (GeV)
**Kaluza-Klein Gravitons in Large Extra Dim**

Very different phenomenology if “large” extra dimensions.

\[ G(k) \text{ with quantized momentum } q_T = k/R \text{ in extra dim: } m^2 = 0 = (E^2 - p_{4d}^2 - q_T^2) \quad \square \quad m_{4d}^2 = q_T^2 \]

<table>
<thead>
<tr>
<th>4+n dim</th>
<th>4 dim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massless graviton ( G^{(k)} ) with momentum ( q_T = k/R )</td>
<td>Massive graviton ( G^{(k)} ) with ( m^2 = k^2/R^2 )</td>
</tr>
</tbody>
</table>

\( R \approx 0.1 \text{ mm i.e. } 1/R \approx 1 \text{ meV} \quad \text{Mass “continuum”,} \quad \text{“first” states very light!!!} \)

**Coupling of \( G^{(k)} \) to SM fields \( \square 1 / M_{Pl} \quad \square \quad G^{(k)} \text{ stable!} \)**

May be copiously produced at colliders

\[ e^+e^- \quad \square \quad G^{(k)} \]

**Direct probe of \( M_D \)**

- Hadronic colliders: mainly jet + Missing \( E_T \)
  - \( D0 \& CDF \) (Run I): bounds \( \square \) 1 TeV \( \square \) \((n=2)\)
  - \( LHC \) (100 fb\(^{-1}\)): reach \( \square \) 7 – 8 TeV
Kaluza-Klein Gravitons in Large Extra Dim

Interference of $G^{(k)}$ exchange with SM processes affects observables

$$\frac{1}{M_{Pl}^2}\frac{1}{s/t/u}m_k^2 \rightarrow \frac{\bar{e}}{M_S^4}$$

divergent for $n > 1$...

Effective coupling with

$$\sqrt{\phi} = O(1), M_S = O(M_D)$$

(i.e. not a direct probe of $M_D$)

• Bhabha & $\square$ at LEP
  $M_S > 1.35$ TeV
  (LEP combined, Bhabha)

• NC DIS at HERA
  $M_S > 0.82$ TeV

• $ee \& \square$ at Tevatron
  $M_S > 1.28$ TeV
  (D0 Run II, Prelim., ee & $\square$)

With $2 \text{ fb}^{-1}$, $M_S$ up to $2$ TeV can be probed at the Tevatron

1.38 TeV
combined with Run I

For the 1st time in $pp$

$\square = O(1), M_S = O(M_D)$

(Various formalisms...)

Effective coupling with

Effective coupling with

The D0 Run II preliminary results show a significant signal in the diEM cosine spectrum with $1.38$ TeV combined with Run I.

DO Run II with $100$ pb$^{-1}$

ee & $\square$ 128 pb$^{-1}$

Instr. bckgd
**New ED Searches from LEP: Branons & Radions**

- **LED**: Remind the DV problem in (tree-level) amplitudes involving $G^{(k)}$ exchange...
  - Allow the SM brane to "vibrate" in the extra dim, on a length $1/f$
  - Emission/absorption of KK modes \( \rightarrow \) brane deformation; larger deformations \( \rightarrow \) higher modes
  - Large $1/f$ (small tension) \( \rightarrow \) Strong suppression of $G^{(k)}$ emission for large \(|k|\)
    - might regularize the DVs, but suppress the standard signal!!

**Scalar field** associated to the brane vibrations: "branon" \( \rightarrow \)
- May be pair produced, e.g. $e^+e^- \rightarrow \text{branon}$, coupling \( \sim 1/f^4 \)
- Scalar field associated to the brane vibrations: "branon" \( \rightarrow \) $f \ll M_D$ : branon sig.
- Scalar field associated to the brane vibrations: "branon" \( \rightarrow \) $f \gg M_D$ : graviton sig.

- **L3 Limits on the Brane Tension**
  - Strong bounds set on $f$

- **Extra dim models**: also new scalars
  - In RS model: only one, the radion $R$
  - Mixes with the Higgs, large coupling to $gg$

- Re-interpretation of the flavor ind. Higgs searches
  - $M(h\text{-like}) > 58$ GeV
  - First collider bound on Higgs-radion

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“Signature Based” Searches for NP

(Quasi) “model-independent” search for new physics:
- definition of objects (e, ℓ, q, q jet, W, Z, ...)
- look at data vs SM in all “channels” with > 1 object
- in each channel, find the part of  placeholder space with largest deviation (e.g. in $M, q^n, p_T$)
- quantify the agreement using “Gedanken” (Mock, MC) expts

Pionnered by DZero with the full Run I sample
D0, PRD64, 012004 (2001)

Applied recently to the full sample of H1 data

# Events

2B
3B
4B

Requires a very good understanding of detector & backgrounds!
Searches for Magnetic Monopoles

(Dirac) Magnetic Monopoles may explain the quantization of $Q_{em}$

\[ \text{eg} = \frac{\hbar c}{4\pi} \]

Might affect $\perp$ via a Monopole (M) loop. Prediction ?? (non-perturbative...)

If light enough, could be produced at colliders: pp, ee, ep $\rightarrow$ MM (via $\perp$)

High energy loss $\perp$ might be stopped + trapped in material (e.g. beam pipe)

H1 used its (old !) beam pipe, cut it in strips & analyze with a SQUID

$\perp$ dipole

$\perp$ SC coil

Cabrera, PRL 48

Candidate !

Calibration using “pseudo-poles”; sensitivity of $\perp 0.2 \ g_D$

Similar studies using pieces of D0 & CDF detectors & BP


E. Perez
Conclusions

• Many new results from Tevatron experiments using Run II data. No signal for new physics observed so far. Constraints set on many models, often the most stringent up to date. Established the good performances of key components of the detector. Good understanding of SM physics as seen in the detectors.

• “Puzzling” events observed at HERA. Clarification (or discovery ?) should come soon with HERA-II luminosity.

• We do not know what form “new physics” will take, but expect to see something at the TeV scale. Could happen soon:
  • at Tevatron & HERA, within models & beyond models
  • in precision measurements, rare decays and LFV processes
  • or a bit later with the Large Hadron Collider…

Within the next 10 years we should have a much deeper understanding of fundamental physics at the highest energy scales!

Apologies for results I did not present, for mistakes, for missing references.