Searches Beyond the Standard Model

Experimental Summary of the results from the B-factories, HERA, Tevatron, LHC, and Super-Kamiokande

Pavel Murat

1 Fermilab

ICHEP, Jul 27 2010, Paris

Special thanks to: all speakers,
even if particle content of the SM was complete, we’d know that there is something beyond

understanding of the elementary particles interactions has been based on understanding their symmetries

search for new particles = search for the new symmetries

searches from the Tevatron use datasets up to 6.3 $fb^{-1}$

HERA experiments continue to finalize their results

results from the B-factories

Super-Kamiokande analysed full dataset of 173 kton·yrs

first searches at LHC used up to $\sim 300\ nb^{-1}$
Outline

1. Super-Kamiokande
2. BSM Searches at the Tevatron, HERA, B-factories
3. First Results from the LHC
Super-Kamiokande: probing the Grand Unification scale

- if measured, the proton lifetime may tell about the Grand Unification scale

Newly analyzed (this talk).

by M. Miura
Summary of the Super-Kamiokande Results

- SK1-SK3 data: 173 kton·yrs
- No evidence for proton decay found
- Proton lifetime limits (90% CL):
  - $p \rightarrow e^+\pi^0$: $T_p > 1.0 \times 10^{34}$ yrs
  - $p \rightarrow \bar{v}K^+$: $T_p > 3.3 \times 10^{33}$ yrs
- Other modes:
  - SK1-SK2, 141 kton·yrs
  - $T_p > (6.6 - 0.04) \times 10^{33}$ yrs

<table>
<thead>
<tr>
<th></th>
<th>SK-1</th>
<th>SK-2</th>
<th>SK-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff.(%)</td>
<td>$44.6 \pm 8.5$</td>
<td>$43.5 \pm 8.3$</td>
<td>$45.2 \pm 8.6$</td>
</tr>
<tr>
<td>BKG</td>
<td>0.20 evts/1489 days</td>
<td>0.11 evts/799 days</td>
<td>0.06 evts/518 days</td>
</tr>
<tr>
<td>Obs</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Lifetime limit (90% C.L):
- Super-Kamiokande has reached to $10^{34}$ years!
- Total BKG is 0.37 events (still low enough).
- SK-2 has almost same efficiency even though with a half PMT density.
Super-Kamiokande

BSM Searches at the Tevatron, HERA, B-factories

First Results from the LHC
SUSY

- A symmetry between fermions and bosons
- One of the most motivated symmetries
- Introduces framework for multiple models
- A broken symmetry, different symmetry breaking mechanisms (GMSB, mSUGRA, AMSB)
- Rich new particle contents and many choices
- R-parity assumed to be conserved in most scenarios
- Searched for very extensively over the last decades
in GMSB, the LSP is the gravitino $\tilde{G}$, $M_{\tilde{G}}$ in a KeV range.

- If NLSP is $\tilde{\chi}^0_1$, gaugino / stau pair production can cascade to $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow \gamma \gamma \tilde{G} \tilde{G}$

- SM background ($W/Z + \gamma \gamma$) very low

- assuming $t_{\tilde{\chi}^0_1} = 0$, $M(\tilde{\chi}^0_1) > 175$GeV at 95% CL (D0, 6.3fb$^{-1}$, Jul’2010)

- for a long-lived $\tilde{\chi}^0_1$, $M(\tilde{\chi}^0_1) > 101$GeV for $t_{\tilde{\chi}^0_1} = 5$ns at 95% CL (CDF, PRD 78, 032015 (2008))
Searches for $\tilde{b}$ quarks

- due to mixing, 3rd generation squark, $\tilde{b}_1$, can be light
- direct $\tilde{b}\tilde{b}$ pair production (assuming R-parity conservation): $p\bar{p} \rightarrow \tilde{b}\tilde{b}$
- mSUGRA, $B(\tilde{b} \rightarrow b\chi^0_1)=100\%$ : 2 b-jets and $E_T$

$M(\tilde{b}) > 247$ GeV for $M_{\chi^0_1} = 0$ (D0, 5.2 fb$^{-1}$, arXiv:1005.2222 [hep-ex])

previous limit: $M(\tilde{b}) > 230$ GeV (CDF, 2.65 fb$^{-1}$, arXiv:1005.3600 [hep-ex])
Searches for Broken Symmetries: R-parity violation

- RPV models: single resonant production of sparticles
- assume only $\lambda'_{311}$ and $\lambda_{312}$ non-zero
- D0’2010 search for $\tilde{\nu} \rightarrow e\mu$

$$B(\tilde{\nu}_\tau \rightarrow e\mu) = \frac{2\lambda^2_{312}}{(3\lambda'^2_{311} + 2\lambda^2_{312})}$$
Searches for Leptoquarks

- $N(\text{lepton generations}) = N(\text{quark generations})$ - a coincidence or an additional symmetry?
- Leptoquarks naturally appear in GUTs, RPV SUSY, ..

- D0'2010 (5.2 fb$^{-1}$): exclude scalar $LQ_3 \ M(LQ_3) > 247$ GeV @ 95%CL (arXiv.org:1005.2222)
Search for the Lepton Flavor Violating Scalar Leptoquarks

\[ \lambda_{\text{eq}} = 0.3, \text{ excluded at 95\% CL are:} \]

- \( e q \rightarrow LQ \rightarrow \mu q \):
  - \( M_{LQ} \) in [304 GeV, 530 GeV]

- \( e q \rightarrow LQ \rightarrow \tau q \):
  - \( M_{LQ} \) in [272 GeV, 450 GeV]

- complementary to the Tevatron results
analysed channels: $t \rightarrow b l \nu$ and $t \rightarrow b q \bar{q}$

95% CL limits:

- $\sigma(ep \rightarrow etX) < 0.25pb$
- $K_{tU\gamma} < 0.18$

HERA limit on $K_{tU\gamma}$ complementary to the Tevatron
Search for additional symmetries

- Introducing an additional U(1) leads to a new neutral vector boson ($Z'$)

$Z' \rightarrow ee : M(Z'_{SM}) > 1023 \text{ GeV} \, @ \, 95\% \, CL \, (D0'2010)$

$Z' \rightarrow \mu\mu : M(Z'_{SM}) > 1071 \text{ GeV} \, @ \, 95\% \, CL \, (CDF'2010)$
Searches for Heavy Vector Bosons: $W'$

- $SU(2)_L \times SU(2)_R$, KK excitations of the $W$ in UED: new charged vector bosons ($W'$)
- D0 search for $W'$ in $W' \rightarrow WZ \rightarrow 3l + \nu$ channel (PRL 104, 061801 (2010))

$W'$ mass range [188 GeV, 520 GeV] is excluded @ 95% CL, assuming SM couplings

Technicolor $\rho_T \rightarrow WZ : M_{\rho_T}$ in [208 GeV, 408 GeV] excluded at 95% CL

Comparable sensitivity to $W'$ in $W' \rightarrow WZ \rightarrow l\nu q\bar{q}$ channel:
  - excluded at 95% CL mass range [285 GeV, 516 GeV] (CDF, PRL 104, 241801 2010)
Search for Heavy Vector Bosons: $W' \rightarrow tb$

- D0’2010: $p\bar{p} \rightarrow W' \rightarrow tb$ (2.3fb$^{-1}$)

**95% CL exclusions:**

- $M(W') > 863$ GeV, $a^L = 1$, $a^R = 0$
- $M(W') > 885$ GeV, $a^L = 0$, $a^R = 1$, $M(W') < m(\nu_R)$
- $M(W') > 890$ GeV, $a^L = 0$, $a^R = 1$, $M(W') > m(\nu_R)$
- $M(W') > 916$ GeV, $a^L = 1$, $a^R = 1$
Search for $t\bar{t}$ resonances

- CDF’2010: search for $R \rightarrow t\bar{t}$ in lepton + jets+$E_T$ channel ($4.8 fb^{-1}$)
- additional U(1): topcolor-assisted $Z'$ (hep-ph/9911288)

- 95% CL exclusion: $M_{Z'} > 900 GeV$, $\Gamma_{Z'} = 0.012 M_{Z'}$
- previous 95% CL limit: $M_{Z'} > 820 GeV$, D0’2009
4-th Generation Quarks: Search for Heavy $t'$

- 4th generation of fermions arises in a set of models
- if mass splitting is small, $M(t') - M(b') < M(W)$, $B(t' \to Wq) = 100$
- search for a pair-produced heavy top-like quark

- excluded at 95% CL: $M_{t'} < 335\text{GeV}$ (CDF’2010), $M_{t'} < 296\text{GeV}$ (D0’2010)
4th Generation Quarks: Search for Heavy $b'$

- search for a pair-produced heavy $b'$: $p\bar{p} \rightarrow b'\bar{b'} \rightarrow WW\ell\bar{\ell} \rightarrow WWWWb\bar{b} \rightarrow l + E_T + \text{jets}$
- final states with multiple (5,6,7) jets, very large $H_T = \Sigma E_T + E_T$

$M_{b'} < 385\text{GeV}/c^2$ excluded at 95% CL (CDF’2010)
for $M_Q$ approaching $\sqrt{s}$, $\sigma(qq' \rightarrow Qq)$ could be significantly larger than $\sigma(qq', gg \rightarrow Q\bar{Q})$

- assume gauge interactions with the 1st generation SM quarks

- parameterization of the couplings: $\sigma(qq' \rightarrow Qq') = k_{qQ}^2 \sigma_{SM}(qq' \rightarrow qQ)$

- CDF’2010 search for $qq' \rightarrow Qq$:
Extra Dimensions

- a solution to a hierarchy problem (Arkani-Hamed, Dimopulous, Dvali’99)
- warped extra dimensions (Randall, Sundrum’99):
  - Kaluza-Klein excitations of a graviton, $G^*$, are coupled to SM particles and narrow
  - $B(G^* \rightarrow \gamma\gamma) \approx 2B(G^* \rightarrow l^+l^-)$

excluded at 95% CL for $k/M_{Pl} = 0.1$:
- D0’2010: $G^* \rightarrow \gamma\gamma, e^+e^- : M_{G^*} < 1050$ GeV PRL 104, 241802
- CDF’2010: $G^* \rightarrow \gamma\gamma : M_{G^*} < 976$ GeV arXiv:0910.5170 [hep-ex]
Search for Heavy Quarks: Quirks

- additional strong SU(N) with $M_Q \gg \Lambda$
  - large non-perturbative effects in strong dynamics (Okun, 1979)
  - heavy quark and antiquark can form a macroscopic “molecule”, $L \sim M_Q/\Lambda^2$
  - an example: “electric dipole” with a size of $\sim 10$-100 microns
- D0’2010: search for events with highly-ionizing tracks with very large $p_T$

$M_Q > 124 \text{ GeV}$ for $10 \text{ KeV} < \Lambda < 1\text{ MeV}$ (95%CL)
"hidden valley" SUSY models (Strassler, Zurek 2007):

- weakly coupled sector with low mass particles
- $\gamma_D$, a force carrier, is light and decays predominantly into SM fermions
- $B(\tilde{\chi} \rightarrow \tilde{X} \gamma_D)$ is a free parameter

D0'2010: search for final states with a photon, 2 close leptons and $E_T$

Assume $B(\tilde{\chi} \rightarrow \tilde{X} \gamma_D) = 0.5$
Constraining Hidden Symmetries: Lepton Jets

- if \( B(\tilde{\chi} \rightarrow \tilde{X} \gamma_D) \) is large, both SM LSP's decay into this channel
- D0’2010: search for final states with 2 pairs of close leptons and \( E_T \) from \( \tilde{X} \)'s

\[
\text{D0 Preliminary 5.8 fb}^{-1}
\]

- for \( M_{\gamma_D} < 2.5 \text{ GeV} \) \( \sigma(p\bar{p} \rightarrow \gamma_D \gamma_D \tilde{X} \tilde{X} + X) < \sim 200 \text{ fb} \),
Charged Lepton Flavor Violation:
\[ \tau \rightarrow l\gamma \ (l=e,\mu) \]
\[ \tau \rightarrow 3l \ (l=e,\mu) \]
\[ Y(2S,3S) \rightarrow l\tau \ (l=e,\mu) \]

Light Higgs (A^0) decays:
\[ Y(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^- \]
\[ Y(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^- \]
\[ Y(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible} \]
\[ Y(2S) \rightarrow \pi^+\pi^- Y(1S), Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible} \]

Lepton Non-Universality:
\[ Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow l^+l^- \]

Invisible Bottomonium decays:
\[ Y(3S) \rightarrow \pi^+\pi^- Y(1S), Y(1S) \rightarrow \text{invisible} \]

Dark Sector Gauge Boson mediated decays:
\[ e^+e^- \rightarrow W_D^+W_D^- \rightarrow l^+l^-l^+l^- \]
Search for invisible decays of $\Upsilon(1S)$

- $\Upsilon(1S)$ can potentially decay into the dark sector
  - via an intermediate scalar: $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \text{invisible}$
  - or via 3-body decay: $\Upsilon(1S) \to \gamma \chi \bar{\chi}$

New 90% CL limits, BaBar’2010

- $B(\Upsilon(1S) \to \gamma A^0) \cdot B(A^0 \to \text{invisible}) < (1.9 - 37) \cdot 10^{-6}$
- $B(\Upsilon(1S) \to \gamma \chi \bar{\chi}) < (0.5 - 24) \cdot 10^{-5}$
1. Super-Kamiokande

2. BSM Searches at the Tevatron, HERA, B-factories

3. First Results from the LHC
LHC: Getting ready for the first SUSY searches

- largest cross section SUSY channels: \((2+)\) jets + \(E_T\)
- understanding of backgrounds at large \(E_T\) critical
- focus on simple and robust experimental techniques
- event with 2 jets: 
  \[
  \alpha_T = \frac{p_{T2}}{M_{T12}} = \sqrt{\frac{p_{T2}}{2p_{T1}(1-\cos\Delta\phi_{12})}}
  \]
- for QCD events at large \(H_T\) expect \(\alpha_T \leq 0.5\)

\[
\text{CMS preliminary}
\]
\[
\sqrt{s} = 7 \text{ TeV}
\]
\[
L = 11 \text{ nb}^{-1}
\]

\[
\text{Events / 0.05}
\]

\[
\text{2 Calo Jets}
\]
\[
80 \leq HT < 120 \text{ GeV}
\]

\[
\text{Data}
\]
\[
\text{Pythia8 QCD}
\]

- successfully tested at the level of \(10^{-3}\), few more orders of magnitude to go!
Dijet angular distributions at LHC

\[ \sqrt{s} = 7 \text{ TeV} \]

- Data, \( \int L dt \sim 61 \text{nb}^{-1} \)
- Pythia QCD LO

**ATLAS** Preliminary

\[ \chi = e^{y_1 y_2} \]

- first 95% CL results on compositness: ATLAS: \( \Lambda > 875 \text{ GeV} \), CMS: \( \Lambda > 1900 \text{ GeV} \)

- Best published limit: \( \Lambda > 2800 \text{ GeV} \) (D0, PRL 103, 191803)

- all the tools needed to deal with higher luminosities are in place!
First Search for Excited Quarks

- select event with 2 or more jets
- require $|\Delta \eta_{12}| < 1.3$ to improve sensitivity to the high-mass signal

**ATLAS** Preliminary

- $\sqrt{s}=7$ TeV
- Data $\int L dt=296$ nb$^{-1}$
- Fit

**ATLAS** Preliminary

**ATLAS’2010 excluded @ 95% CL**

- $M_{Q^*}$ in [400 GeV, 1180 GeV] with CTEQ6 L1 PDF’s
- $M_{Q^*}$ in [400 GeV, 1290 GeV] with MRST’2007 PDF’s

improving best published limit $M_{Q^*} > 870$ GeV (CDF, 1.1 fb$^{-1}$, PRD79(2009)112002)
Search for Heavy Stable Charged Particles (HSCP) by CMS

CMS Preliminary 2010 $\sqrt{s} = 7$ TeV 198 nb$^{-1}$

- Search for heavy gluino, hadronizing into a charged R-hadron
- Reconstruct R-hadron mass based on measured $dE/dX$
- CMS’2010 95% CL exclusion:
  - $M_{\tilde{g}} < 271(284)$ GeV/c$^2$ for track (muon)
Searches for Stopped Gluino

- gluino, hadronized into a charged R-hadron, can stop and decay in the calorimeter
- trigger on large “out-of-collision” energy depositions
- sensitive to the large lifetimes
- assume $BR(\tilde{g} \rightarrow g\tilde{\chi}^0) = 100\%$, $M_{\tilde{g}} - M_{\tilde{\chi}^0} > 100$ GeV
- CMS’2010 95% CL limits on gluino lifetime $\tau_{\tilde{g}}$:
  - counting experiment excludes $\tau_{\tilde{g}}$ within [120ns, 6µs]
  - time profile analysis improves low limit down to 75ns
Summary

- extensive searches for physics beyond the SM
- multiple new constraints on the new physics from the Tevatron, HERA, B-factories
- maturity and breadth of the ongoing program
- first search results from the LHC - impressive!
- expect searches at the Tevatron and LHC to complement each other in the future
- anticipate the new results
Summary

- extensive searches for physics beyond the SM
- multiple new constraints on the new physics from the Tevatron, HERA, B-factories
- maturity and breadth of the ongoing program
- first search results from the LHC - impressive!
- expect searches at the Tevatron and LHC to complement each other in the future
- anticipate the new results beyond the 95%CL!
The highest-$m_{jj}$ central event observed

$m_{jj} = 1.77$ TeV. $p_T^1 = 1.1$ TeV. $p_T^{j2} = 480$ GeV, partly in calorimeter gap.
CMS: the highest dijet mass event

Run: 138919
Event: 32253996
Dijet Mass: 2.130 TeV

Jet 1 $p_T$: 585 GeV
Jet 2 $p_T$: 557 GeV
CMS: early searches with dijets

**Measured cross-section**

- $\sqrt{s} = 7$ TeV
- anti-$k_T$ $R = 0.7$ CaloJets
- $M_{jj} > 354$ GeV
- $|\eta_1, \eta_2| < 1.3$

**Graphs:**

1. **Data vs. Fit**
   - CMS Preliminary (120 nb$^{-1}$)
   - Data ($L = 120$ nb$^{-1}$)
   - QCD Pythia + CMS simulation
   - 10% JES uncertainty

2. **Signal Scenarios**
   - $S (0.7$ TeV$)$
   - $q^* (0.7$ TeV$)$
   - $q^* (0.5$ TeV$)$
   - String
   - Excited quark

---

*Pavel Murat (Fermilab)*

**Searches Beyond the Standard Model**

ICHEP, Jul 27 2010, Paris