BSM theories & signals

ISTAPP 2011 - Gökhan Ünel / U.C.Irvine

Last Lecture of week 1, prelude to week 2
=> what should you get out of it?
+ A review of the BSM theories on the “Market”
+ Typical signatures of most prominent models
  - Expected results for $\sqrt{s} = 14\text{TeV}$, ATLAS, (CMS is very similar)
+ No homework, sit back and relax but don’t snore!
A brief summary of popular models:

- **Grand Unified Theories:**
  - SM gauge group is embedded into a larger one like SO(10), to unify EW and QCD.
  - Additional fermions and bosons predicted.

- **Little Higgs models:**
  - Spontaneously broken global symmetry to impose a cut-off ~10 TeV.
  - Additional bosons and quarks introduced to cure the hierarchy problem.

- **Extra Dimensions:**
  - Low Planck scale in d dimensional theory solves the hierarchy problem between EW and Gravitational couplings.
  - Excitations of SM bosons and fermions are predicted.

- And Many More like Fourth Generation, Hidden Valley, Unparticles.....

Most of these models do **not** exclude supersymmetry.
SM ingredients

- *Fermions* as matter particles
  - Quarks & Leptons

- *Gauge group structure*
  - Gauge bosons as force carriers

- *EW Symmetry Breaking*
  - Mass via Higgs bosons

- 3+1 space-time

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**SM can not be the final theory:**

- Hierarchy problem: $\delta H \sim M_H$
- EW and Strong forces not unified
- Arbitrary fermion masses & mixings
- Arbitrary number of families
- Unknown source of baryogenesis

**SM is like your old car: you like it but you also know it has problems...**
SM to BSM

- **Fermions** as matter particles
  - Quarks & Leptons
    - new quarks
    - new leptons
    - lepto-quarks
    - new constituents

- **Gauge group structure**
  - gauge bosons as force carriers
    - new gauge bosons

- **EW Symmetry Breaking**
  - mass via Higgs bosons
    - new scalars
    - new EWSB

- **3+1 space-time**
  - new dimensions

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**Fourth Family**

**GUTs**

**Gauge G**

**Little Higgs**

**2HDMs**

**Super Symmetry**

**Dynamical Symmetry Breaking**

**Technicolor**

**ADD Models**

**RS Model**
SM to BSM

- **Fermions as matter particles**
  - Quarks & Leptons
  - New quarks
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- **Super Symmetry**
  - Fourth Family
  - GUTs
  - Gauge G
  - Little Higgs
  - 2HDMs
  - New gauge bosons
  - New scalars
  - New EWSB
  - New dimensions
  - New constituents

- **Gauge group structure**
  - Gauge bosons as force carriers

- **EW Symmetry Breaking**
  - Mass via Higgs bosons
  - New EWSB

- **3+1 space-time**
  - New gauge bosons
  - Technicolor
  - Dynamical Symmetry Breaking
  - RS Model
  - ADD Models
New constituents excited Vs

predicted by: composite (preonic) models
produced as: single ($\nu\nu^*/\nu^*e$) via $Z,W,\gamma$
decay via: boson + lepton: $\nu\gamma, \nu Z, eW$

• Fast MC based study
• scan neutrino mass: [500,..,2500]
• consider 2 coupling possibilities:
  • with and w/o $\nu\gamma$ decay (same disc. limit)

\[ \ell \rightarrow e^+e^- \rightarrow eeW \rightarrow ee\mu \nu \]
\[ \Lambda = \text{Mass} \]
\[ P_{\text{trk}} > 50 \text{ GeV} \]
\[ \eta_{\text{trk}} < 2.5 \]

Backgrounds

- WZ
- WWW
- Total

\[
\begin{align*}
\text{Events/(300 fb^{-1})/20 GeV} & \leq 10^5
\end{align*}
\]

\[
\begin{align*}
\text{Mass (e\mu\nu), GeV} & \leq 3.5
\end{align*}
\]

\[
\begin{align*}
\Lambda, \text{ TeV} & \leq 9
\end{align*}
\]

\textbf{with 300fb^{-1} data}

\[
\begin{align*}
\sigma & > 3
\end{align*}
\]

\[
\begin{align*}
9 \text{ TeV @ 300GeV} \\
2.5 \text{ TeV @ 2 TeV}
\end{align*}
\]

\[
\begin{align*}
\sigma & > 5
\end{align*}
\]

eW ($W\rightarrow jj$ $e/\mu\nu$) AND

\textbf{eZ ($Z\rightarrow jj$ $\mu\mu$) considered}

\textbf{* other excited fermions (e^*,q^*) also studied, but not reported here.}
New quarks: \( q = -\frac{1}{3} \) singlets

- predicted by: \( E_6 \) GUT
- produced as: pairs from gluon (quark) fusion
- decay via: boson + light jet

- Fast MC based study
- scan new quark mass
- pair production is mixing independent

\[
D \bar{D} \rightarrow Z j Z j \rightarrow 4\ell 2j
\]
about \( q=-\frac{1}{3} \) singlets

**E\(_6\) model introduces new particles:**

\[
SU_C(3) \times SU_W(2) \times U_Y(1) \subset E_6
\]

- one iso-singlet quark per family:
  \[
  \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R, D_L, D_R \begin{pmatrix} c_L \\ s_L \end{pmatrix}, c_R, s_R, S_L, S_R \begin{pmatrix} t_L \\ b_L \end{pmatrix}, t_R, b_R, B_L, B_R
  \]

**Assumptions:**

1. In-family mixing bigger than between family mixing
2. D quark is the lightest, like SM: most accessible in LHC
3. E\(_6\) gauge bosons heavy & don’t interact w/ SM bosons

\[
D \rightarrow Zd \\
\text{BR} \quad 33\% \quad 66\% \quad 50\%
\]

\[
D \rightarrow Wu \quad \text{if there is no Higgs}
\]

\[
\text{25}\% \quad 50\% \quad \text{if Higgs is light}
\]
Higgs search & $q=\mp^{1/3}$ quarks

- d-D mixing leads to dDh vertex at tree level
- this can be exploited for a double discovery: light H & D
- pair production mode considered for ATLAS using FastMC
  - $m_D = 250 - 1000$ GeV range scanned

<table>
<thead>
<tr>
<th>$D_1$</th>
<th>$D_2$</th>
<th>BR</th>
<th>expected final state</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D \rightarrow h_j$</td>
<td>$D \rightarrow h_j$</td>
<td>0.029 (0.053)</td>
<td>$2j \ 4j_b$</td>
</tr>
<tr>
<td>$D \rightarrow h_j$</td>
<td>$D \rightarrow Z_j$</td>
<td>0.092 (0.120)</td>
<td>$2j \ 2j_b \ 2l$</td>
</tr>
<tr>
<td>$D \rightarrow h_j$</td>
<td>$D \rightarrow W_j$</td>
<td>0.190 (0.235)</td>
<td>$2j \ 2j_b \ l \ E_{T,miss}$</td>
</tr>
</tbody>
</table>

- 5$\sigma$ Higgs discovery in $DD \rightarrow Whjj$ channel can be made using 100 fb$^{-1}$ if $m_D < 700$ GeV
- If $m_D < 630$ GeV, this channel becomes as efficient as $h \rightarrow \gamma\gamma$. (i.e. 8$\sigma$ in 100 fb$^{-1}$)
New quarks \( q = 2/3 \) singlets

- **predicted by:** Little Higgs
- **produced as:** single from W exchange
- **decay via:** boson + (t or b) jet

\[
qb \rightarrow q'T \rightarrow q' \, Wb \ (ht, Zt)
\]

- Fast MC based study
- function of T quark mass and t-T mixing
- all 3 decay channels studied.

\[
Zt \rightarrow \ell\ell\nu j_b \\
Wb \rightarrow \ell\nu j_b
\]

ATLAS

T is observable with 300 fb\(^{-1}\):
- up to ~2.5 TeV via Wb,
- up to ~1.4 TeV via Zt.

at maximum t-T mixing
New quarks doublets

- predicted by: DMM
- produced as: pairs from gluon (quark) fusion
- decay via: $W + \text{jet}$ (no FCNC)

- Fast MC based study
- scan new quark mass
- results for 100 fb$^{-1}$ shown

$u_4 \rightarrow W^+ b$

- 61σ signal from 320 GeV $u_4$
- 13σ signal from 640 GeV $u_4$

$d_4 \rightarrow W^- t$

- broad signal at 320 GeV $d_4$
- Exact knowledge of BG shape needed

* new studies for other CKM mixings done, but not yet made public.
CPV source (for BAU)
- 3x3 CKM is $10^{10}$ too short to match WMAP data
- new quarks of (300) 600 GeV would give $(10^{13})10^{15}$ more CPV

Alternative EW symmetry breaking
- 4th generation fermion condensate can play the Higgs role
- 5D AdS, K.K. excitations of gauge bosons interacting w/ 4th generation fermions $\Rightarrow$ Yukawa couplings & mass hierarchy

Fermion mass hierarchy
- observed masses of fermions in the first 3 families arise from perturbations to a flavour-blind 4x4 mass matrix.

Dark Matter candidates
- hadrons from stable $t'$, $\nu'$, additional fermions of spin-charge unification models
New Leptons

- predicted by: Fourth family, $\text{E}_6$ GUT, technicolor.
- produced as: pairs from gluon (quark) fusion
- decay via: boson + lepton

• Fast MC based study
• function of $L$, $Z'$ mass

Higher $Z'$ mass increases the $L$ mass reach: $Z' = 2\text{TeV}$, $L = 1\text{TeV}$ accessible
**Lepto-quarks**

- **predicted by:** GUTs & composite models
- **produced as:** pairs + single from g-g (q) fusion
- **decay via:** $e$(type1) or $\nu$(type2) + light jet

- Fast MC based study for Scalar & Vector LQs
- Coupling $\kappa, \lambda = e$ (for V)
- LQ-mass scanned

### Fast MC Study

- **Scalar & Vector LQs**
- **Coupling:** $\kappa, \lambda = e$ (for V)
- **LQ-mass scanned:**
  - 1.2 TeV reach for S LQs
  - 1.5 TeV reach for V LQs

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**Graphs:**

- **Events/300 fb$^{-1}$:**
  - Vector LQ
  - Scalar LQ
  - $Z+jets$
  - $t\bar{t}$
  - Total bg
  - $M_{LQ}=750$ GeV
  - $P_T^{jet} > 90$ GeV
  - $P_T^{elec} > 130$ GeV
  - $\eta < 2.5$
  - $H_T > 1000$ GeV
  - $S/B$ @ $3 \times 10^5$ pb$^{-1}$

- **Signal Region:**
  - 1.2 TeV reach for S LQs
  - 1.5 TeV reach for V LQs

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**Diagram:**

- **Diagram Description:**
  - Predictions and decay mechanisms for lepto-quarks
  - Fast Monte Carlo (MC) study for Scalar and Vector LQs
  - Couplings and mass scans
  - Event distributions with cuts
  - Signal-to-background ($S/B$) analysis
  - Mass scan with detection limits

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**Additional Information:**

- **SN-ATLAS-2005-051**
- **ISTAPP 2011**
SM to BSM

- **Fermions** as matter particles
  - Quarks & Leptons
    - new quarks
    - new leptons
    - lepto-quarks
    - new constituents

- **Gauge group structure**
  - gauge bosons as force carriers

- **GUTs**

- **Gauge G**

- **Little Higgs**

- **2HDMs**
  - new scalars
  - new EWSB

- **EW Symmetry Breaking**
  - mass via Higgs bosons

- **3+1 space-time**

- **Super Symmetry**
  - new gauge bosons
  - new dimensions
  - new constituents

- **Dynamical Symmetry Breaking**
  - Technicolor
  - new scalars
  - new dimensions

- **3+1 space-time**

- **RS Model**

- **ADD Models**
New bosons $W'/W_H$

- **predicted by:** SO(10), E$_6$, GUTs, Little Higgs, EDs
- **produced as:** s channel from q-q' annihilation
- **decay via:** top-b $q\bar{q}' \rightarrow W' \rightarrow tb \rightarrow \ell\nu bb$

- Fast MC based study
- $W-W_H$ coupling via $\cot \theta$
- $W_H$ mass 1 & 2 TeV considered

**Discovery plane for 300fb$^{-1}$ data**

Discovery reach is 6.5 TeV depending on the $W-W_H$ mixing.
New bosons: $Z'$

- **predicted by:** SO(10), E$_6$, GUTs, Little Higgs, EDs
- **produced as:** from q-q annihilation
- **decay via:** fermion pairs

- Dileptons (ee, $\mu\mu$) provide a clear search channel
- Current lower limits: 700-800 GeV from Tevatron
- CMS example of 1.5 TeV $Z'$ from electrons (clean signal)

LHC will allow $\sim 4.5$ TeV $m_{Z'}$ reach

![Graph showing CMS $Z'$ discovery reach with dielectrons and dimuons](image)
leptophobic $Z'$

- $Z'$ that couples to hadrons only, hadrophilic
- Could explain $2.8\sigma$ discrepancy in $A_{FB}^b$ (world average)
- CMS search w/ full simulation for $Z' \rightarrow$ di-jets
  - $Z^{(1)} = 2 \ldots 3$ TeV
  - Model independent search

Discovery up to $\sim 3.5$ TeV possible using data from $\int Lumi = 10 fb^{-1}$
but which $Z'$?

Once discovered (!) how to determine which particle / model:

1. particle identification from spin is “easy”

2. model identification from $A_{FB}$

$$\frac{d\sigma}{d\cos \theta} = \frac{3}{8}(1 + \cos^2 \theta) + A_{FB} \cos \theta$$

$$\theta = \frac{\vec{\ell} \cdot \vec{q}}{|p| \cdot |q|}$$

$$A_{FB} = \frac{\ell_F - \ell_B}{\ell_F + \ell_B}$$

$A_{FB}$: coupling dependent, predicted by theory

$Z' = 3$ TeV, $\int L = 400$ fb$^{-1}$

not so easy!! (for some models)
Various E₆ Z’s

- From E₆ down to SM, but how?
  - E₆→SO(10)×U(1)ψ→SU(5)×U(1)χ×U(1)ψ
  - E₆→SU(3)C×SU(2)L×U(1)Y×U(1)η=SM×U(1)η
- Available neutral bosons: Zψ, Zχ, Zη
- Define mass eigenstates: Z’, Z”
  - Z’ = Zψ cosθ - Zχ sinθ & & Z” = Zχ cosθ + Zψ sinθ
    - θ=0 : Z’ψ
    - θ=−π/2 : Z’χ
    - θ=arcsin(√3/8) : Z’η

- How about W’?
  - E₆→SU(3)C×SU(2)L×SU(2)R×U(1)L×U(1)C: Left-Right symmetric model 4+1+1=6
  - E₆→SU(3)C×SU(2)L×U(1)Y×SU(2)×U(1)’: each SU(2) introduces W±
  - selected breaking down of E₆ to SM determines the predicted particles & couplings
**New bosons $Z^n$**

- **Predicted by:** RS, ADD models
- **Produced as:** from q-q annihilation
- **Decay via:** lepton pairs

- FULL simulation based study
- 3 Parameter sets to reproduce the fermion masses & mixings (A, B, C)
- only electrons were reconstructed

\[ pp \rightarrow \gamma^n/Z^n \rightarrow \ell^+\ell^- \]

**Discovery reach is about 6 TeV depending on the model for 100 fb^{-1} data.**
SM to BSM

- **Fourth Family**
  - Fermions as matter particles
    - Quarks & Leptons
    - New quarks
    - New leptons
    - Lepto-quarks
    - New constituents
    - Composite models

- **GUTs**
  - Gauge group structure
    - New gauge bosons

- **Gauge G**
  - EW Symmetry Breaking
    - Mass via Higgs bosons
    - New scalars
    - New EWSB

- **Little Higgs**
  - New gauge bosons

- **2HDMs**
  - New scalars

- **3+1 space-time**

- **Super Symmetry**
  - new dimensions
  - Super Symmetry
    - New constituents
    - Lepto-quarks
    - New leptons
    - New quarks

- **Dynamical Symmetry Breaking**
  - Technicolor
  - RS Model
  - ADD Models
New Scalars $q=\pm 2$

- **predicted by:** Little Higgs, LRSM
- **produced as:** pair via q-q annihilation & single via W fusion
- **decay via:** lepton pairs
  - Fast MC based study
  - $W^+_R$ & $\Delta^{++}$ mass scanned for min 10 evts
  - $e, \mu$ & $\tau$ channels separately studied
  - results for 100(a) & 300(b) fb$^{-1}$ shown

Single production reach $\sim 1.8$ TeV depending on $mW^+$

Pair production reach $1.1$ TeV depending on $mZ_R$ with 3 and 4 leptons
New EWSB no scalar

- **predicted by:** Dynamical SB models, technicolor
- **produced as:** from q-q annihilation
- **decay via:** boson pairs

- Fast MC based study
- Scan $\rho_T$ mass for different $\pi_T$

Discovery with 30fb$^{-1}$ data possible depending on model parameters
New EWSB SUSY

Give up the (so far) observed “spin” asymmetry between matter and force carriers: s-partners for all SM particles

• solves Fine Tuning, DM.. problems

SUSY not observed: sparticles heavy: broken symmetry

Rich phenomenology (even with Rparity):

• large # of parameters: >100 in MSSM case*
• many SB options: MSSM, mSUGRA, GMSB, AMSB..

Common properties:

• cascade decays of sparticles to high $p_T$ objects,
• stable LSP escapes undetected: large $E_T^{miss}$.

Look for: jets + $E_T^{miss}$ and leptons + jets + $E_T^{miss}$

* 

#parameters=124 given in SN-ATLAS-2006-058
New EWSB mSUGRA

- mSUGRA's LSP is DM candidate
- Model should be consistent with WMAP data
- R parity imposes pair production
  \[ pp \rightarrow \tilde{g}\tilde{g} \]
  \[ \tilde{g} \rightarrow \tilde{\chi}^+_1 t\bar{b} \]
  \[ \tilde{g} \rightarrow \tilde{\chi}^-_1 \bar{t}b \]
  \[ \tilde{g} \rightarrow \tilde{\chi}^0_1 t\bar{t} \]

• Fast MC based study
• \( m_{1/2} - m_0 \) parameter space scanned

ISAJET 7.71 \( m_t = 175 \text{ GeV}, \tan\beta = 54 \text{ A=0 GeV} \mu > 0 \)

jets + \( E_T \)_{miss}

Invariant mass best selected tt pair

7 σ significance with 1fb\(^{-1}\) of data
New EWSB GMSB

Susy breaking scale close to weak scale
- LSP is gravitino, FCNC is suppressed

Reference points with different model parameters & NLSP
- Fast MC based study @ G3 (NLSP is stau)
- G3b: NLSP is quasi-stable
- G3a: NLSP immediately decays

Negligibly small

\[ \tilde{q} \rightarrow \tilde{\chi}_{1,2}^0 q \rightarrow \ell\ell q \rightarrow \tilde{\tau}(\tau)\ell\ell q \rightarrow \tilde{G}(\tau)\ell\ell q \]

leptons + jets + $E_T^{\text{miss}}$

SM background

G3b: stau detected in the muon chambers

Excellent signal with few fb$^{-1}$ in both cases

G3a: stau decays before detection but dips can be calculated & fit:

\[ M_{\tau,l}^{\text{max}} = \sqrt{M_{l_B}^2 - (M_{\tilde{\tau}_1} + M_\tau)^2} \]
**SM to BSM**

- **Fermions as matter particles**
  - Quarks & Leptons
  - new quarks
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  - lepto-quarks
  - new constituents
  - composite models

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- **3+1 space-time**
  - new dimensions

- **Dynamical Symmetry Breaking**

- **Technicolor**

- **RS Model**

- **ADD Models**

- **Fourth Family**

- **GUTs**

- **Gauge G**

- **Little Higgs**

- **2HDMs**
some ED concepts

- Large Extra Dimensions (LED, ADD):
  - compactified, flat
  - $M_{Pl}^2 \sim R_n M^2 S_n$, $M_S$: string scale
  - Graviton in bulk

- TeV-I ED (DDG):
  - $M_C$: compactification scale
  - Gauge & Higgs bosons in bulk as well

- Warped Extra Dimensions (RS):
  - 2-branes solution: RS typeI
  - $k/M_{Pl}$, $k$: curvature, warp factor
  - narrow spin-2 resonances: Graviton

- Universal Extra Dimensions (UED):
  - KK-number conservation
  - $M_C$ and cut-off scale $\Lambda$
  - All SM particles in the bulk
  - Lots of KK spectra (similar to SUSY signatures)

$G^{ab,n, M_C, R}$: model parameters
EDs graviton

predicted by: all ED models
produced as: from q-q annihilation, q-g/g-g fusion
decay via: - (stable) $gg/gq/qq \rightarrow gG$

- Fast MC based study
- #EDs=2,3,4 & ED scale scanned

<table>
<thead>
<tr>
<th>$M_{Pl(4+d)}^{MAX}$ (TeV)</th>
<th>$\delta=2$</th>
<th>$\delta=3$</th>
<th>$\delta=4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30fb$^{-1}$</td>
<td>7.7</td>
<td>6.2</td>
<td>5.2</td>
</tr>
<tr>
<td>100fb$^{-1}$</td>
<td>9.1</td>
<td>7.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>
**EDs** Excited gluons

- **predicted by:** TEV\(^{-1}\) EDs (DDG)
- **produced as:** from q-q annihilation
- **decay via:** heavy quark pairs

\[ q\bar{q} \rightarrow g^* \rightarrow t\bar{t} \rightarrow b\bar{b} \]

- *Fast MC based study*
- *g*\(^*\) mass scanned [1..3] TeV

---

**300 fb\(^{-1}\) allows reaching 3.3 TeV with 5\(\sigma\)**
Randall Sundrum (Type I)

- Brane metric scales as function of bulk position
- Coupling constant: $c = k/M_{Pl}$, $k$: curvature scale
- Well separated narrow-width graviton mass spectrum with masses

$$m_n = k x_n e^{krc} \left( J_1(x_n) = 0 \right)$$

$$ds^2 = e^{-2ky} \eta_{uv} dx^u dx^v - dy^2$$

$c > 0.1$ actually forbidden

$\text{pp} \rightarrow G^{KK} \rightarrow \Pi$

$c = 1$
$c = 0.5$
$c = 0.1$
$c = 0.05$
$c = 0.01$
μ-Blackholes

- Arise from models with ED
- Could be produced when $E_{CM} > M_{Pl}$
- Need QT of gravity as $M_{BH}$ approaches $M_{Pl}$
- $\sigma \sim \pi R_{S}^{2} \sim 1$ TeV$^{-2} \sim 10^{-38}$ m$^2 \sim O(100)$pb
- LHC could be a Black Hole Factory with rates as high as 1 Hz.

If the impact parameter of a 2-parton collision $<\text{Schwarzschild radius } R_{S}$, then a black hole with $M_{BH}$ is formed.
μBH Detection

- BH lifetime \(\sim 10^{-27} - 10^{-25}\) seconds!
- Decays with equal probability to all particles via Hawking Radiation (roughly a blackbody spectrum)
- evaporates into (hadron : lepton) = (5 : 1) accounting for t, W, Z and H decays

Distinguishing features
- High Multiplicity, \(\Sigma E_T\), Sphericity, \(MP_T\)
- Democratic Decay

6.1 TeV \(M_{\text{BH}}\) Decay

Giddings, Thomas PRD65(2002)056010
Harris, et al. JHEP05 (2005) 053

J. Tanaka, “Search for Black Holes”, 24/05/03 Athens

Harris, et al. JHEP05 (2005) 053

N=6 gives a larger yield than n=2

\(p p \rightarrow \text{QCD} (P_\tau > 600 \text{ GeV})\)

SUSY (SUGRA point 5)

5 TeV BH (n=6)

5 TeV BH (n=2)

Arbitrary Scale

Missing \(P_\tau\) (GeV)

10^{-6}

10^{-5}

10^{-4}

10^{-3}

10^{-2}

10^{-1}

10^0

10^1

10^2

10^3

10^4

10^5

10^6

0

1000

2000

3000

0

10

100

1000

10000

100000

1000000

Giddings, Thomas PRD65(2002)056010
LHC experiments have very rich discovery potential for BSM physics.

Concentrated on a small selection of BSM possibilities;
- some models (e.g. micro BHs) not mentioned,
- differentiation between models not shown,
- boost to standard searches from BSM physics not shown.

Only summary results shown
- From scientific or pub notes, mostly published
- Mostly from Fast MC simulation results (next week more on MCs)

Experiments will tell us which model is closer to the truth
Back up slides:

- a few slides about Higgs Searches
- a few words about susy
Higgs production

- gg fusion
- VBF WW/ZZ fusion
- associated WH, ZH
- ttH
Higgs decay

Low mass

- \( H \to \gamma\gamma \)
- \( ttH, H \to bb \)
- \( qqH, H \to \tau\tau \) VBF

High mass

- \( H \to ZZ (\ast), Z \to 4\ell \) Golden discovery channel
- \( qqH, H \to WW (\ast) \) VBF
1. $H \rightarrow \gamma\gamma$ $S/B \sim 10^{-2}$ despite $BF \sim 10^{-3}$

2. $ttH$ (WH, ZH) with $H \rightarrow bb$ (b-tagging, 4 b-jets) DIFFICULT due to systematic errors

   $ttH \rightarrow tt\, bb \rightarrow b\bar{b}$$\nu\bar{\nu} \, bb$

3. $qqH \rightarrow qq\tau\tau$ VBF: jets over $|\eta| < 5$ forward jet tag + central jet veto for $\tau$ ID

   $qqH \rightarrow qq\tau\tau$
The golden channel

$130 \leq m_H < 700 \text{ GeV}$

$H \rightarrow ZZ^{(*)} \rightarrow 4 \text{ leptons}$

Discovery with less than 10 fb$^{-1}$ for
$130 < m_H < 160 \text{ GeV}, \ 2m_Z < m_H < 550 \text{ GeV}$

combining various channels for $m_{\text{Higgs}} < 200 \text{ GeV}$

exclusion from LEP and Tevatron shown in shaded areas
GMSB susy

Parameters (general model has 124):

- $\Lambda$: Breaking scale
- $M$: Mass scale of the messengers
- $\tan\beta$: Ratio of Higgs vacuum expectation values
- $N$: Number of messenger chiral supermultiplets
- $\text{sign}(\mu)$: Sign of the Higgs mass parameter
- $C_{grav}$: Scale factor of the Gravitino mass $\rightarrow$ lifetime of NLSP

Masses of the gauginos are produced via couplings to a massive messenger sector.

REF: Mark Terwort
mSUGRA

5 Parameters

- $m_0$: scalar mass
- $m_{1/2}$: gaugino mass
- $A_0$: H sf sf coupling const.
- $\tan\beta$: vev ratio of 2 Hs
- $\text{sgn}(\mu)$: sign of H mass parameter

Ref: Gilly Elor and Andre Bach