Physics Beyond the Standard Model
— Signals at Colliders

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CTEQ Summer School, Puebla, Mexico
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The Standard Model and the Need For Going Beyond
Our "Theory Bank"
New Physics Signals at Hadron Colliders
The Standard Model and the Need For Going Beyond
Our “Theory Bank”
New Physics Signals at Hadron Colliders

- Higgs bosons
- SUSY particles
- New gauge bosons
- New heavy fermions
- Extra dimensions
The Standard Model
as a Low-Energy Effective Theory

- $SU_c(3)$ QCD as the theory of strong interactions:
The Standard Model as a Low-Energy Effective Theory

- $SU_c(3)$ QCD as the theory of strong interactions:

QCD remarkably successful:
Perturbative QCD well tested and formed foundation for HEP;
Significant progress in lattice gauge calculations.
**SU_L(2) ⊗ U_Y(1) EW theory and precision measurements:**

### Summer 2003

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>(O^\text{meas} - O^\text{fit}/\sigma^\text{meas})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta\alpha^{(5)}_{\text{had}}(m_Z))</td>
<td>0.02767</td>
<td></td>
</tr>
<tr>
<td>(m_Z) [GeV]</td>
<td>91.1875</td>
<td>91.1875</td>
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<tr>
<td>(\Gamma_Z) [GeV]</td>
<td>2.4952</td>
<td>2.4960</td>
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<td>(\sigma^0_{\text{had}}) [nb]</td>
<td>41.540</td>
<td>41.478</td>
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<tr>
<td>(R_l)</td>
<td>20.767</td>
<td>20.742</td>
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<tr>
<td>(A_{t,b}^0)</td>
<td>0.01714</td>
<td>0.01636</td>
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<tr>
<td>(A_{t}(P_T))</td>
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<tr>
<td>(R_b)</td>
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<td>(R_c)</td>
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<td>(A_{t,b}^0)</td>
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<td>(A_{t,b}^0)</td>
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<td>(A_b)</td>
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<td>(A_c)</td>
<td>0.670</td>
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<td>(A_t(SLD))</td>
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<tr>
<td>(\sin^2\theta_{\text{eff}}(Q_{fb}))</td>
<td>0.2324</td>
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<td>(m_{W}) [GeV]</td>
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<tr>
<td>(\Gamma_{W}) [GeV]</td>
<td>2.139</td>
<td>2.093</td>
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<td>(m_{t}) [GeV]</td>
<td>174.3</td>
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<tr>
<td>(\sin^2\theta_{W}(vN))</td>
<td>0.2277</td>
<td>0.2229</td>
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<tr>
<td>(Q_W(Cs))</td>
<td>-72.84</td>
<td>-72.90</td>
</tr>
</tbody>
</table>

**Graph:**

- direct (1\(\sigma\))
- indirect (1\(\sigma\))
- all (90% CL)
\(SU_L(2) \otimes U_Y(1)\) EW theory and precision measurements:

EW precision data: \(m_H < 251\) GeV at 95% CL with \(m_t = 178\) GeV.
SM as an effective theory?

\[ V = -\mu^2 \Phi^2 + \lambda \Phi^4, \quad <\Phi> = \frac{v}{\sqrt{2}} = \sqrt{\frac{\mu^2}{2\lambda}}, \quad v^{-2} = \sqrt{2} G_F \]

\[ m_H = \sqrt{2\lambda} v \]
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All couplings \( g_{2,3}, \sin^2 \theta_W, \ g_f \) and masses \( \sim g_i v \) are in place.

SM with a light \( H \) could be an effective theory to \( \Lambda \sim M_{pl} \).

a stable vacuum;
non-trivial interactions;
renormalizability ...
Q: Would you need physics beyond the Standard Model?
A: ... ...

(The Garden of Aden)
The Need For Going Beyond SM?

Mass Spectrum in a Wide Range:

$M_{PL} \times 10^{15}$
The Need For Going Beyond SM?

Mass Spectrum in a Wide Range:

EW scale: \( v \approx \mathcal{O}(1 \text{ TeV}) \); \( m_\nu : 10^{-15} \) down? \( M_{\text{Pl}} : 10^{15} \) up?
Vastly Separated Scales for Fundamental Interactions:

- **QCD condensate:** $f_\pi$
  
  At the scale $\Lambda_{QCD}$, the interaction becomes non-perturbative:

  \[
  \alpha_s(Q^2) = \frac{1}{b \ln(Q^2/\Lambda^2)} \implies \Lambda_{QCD} \sim \Lambda \exp\left(-\frac{1}{2b\alpha_s}\right),
  \]

  \[
  f_\pi \propto \langle \bar{q}_L q_R \rangle_0^{1/3} \sim 100 \text{ MeV}.
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  Perfectly natural! We understand the dynamics.
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  Empirically (Fermi’s weak interaction) and theoretically (EWSB):
  
  $$v = \frac{1}{(\sqrt{2} \ G_F)^{1/2}} = \frac{2M_W}{g} \approx 250 \text{ GeV}.$$  

  We do NOT know the underlining dynamics!
  
  Scalar mass unstable against quantum corrections.
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- **Quantum Gravity?**

$$M_{Pl} = \hbar c/\sqrt{G_N} \approx 10^{19} \text{ GeV}.$$  

We have NO clue about it ...
Nontrivial fermion pattern: (observed)

Three fermion generations;
Quark small mixing;
Neutrino masses and (nearly) maximal mixing;
CP violation...
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Gauge interactions;
Yukawa couplings;
Mass relations...
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Gravity and Planck scale physics;
Particle cosmology:
inflation; baryogenesis; dark matter; dark energy ...
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⇒ All indicate the need for physics beyond the SM.
Our “theory bank”

Let’s focus on the EWSB sector: The key to new physics.
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(A). Supersymmetry:

Weak scale SUSY stabilizes the hierarchy $M_W - M_{pl}$

$$
\Delta m^2_H \sim (M^2_{SUSY} - M^2_{SM}) \frac{\lambda^2_f}{16\pi^2} \ln \left( \frac{\Lambda}{M_{SUSY}} \right).
$$

if the “soft-SUSY breaking”: $M_{SUSY} \sim O(M_{SM})$.

Predict TeV scale new physics:

light Higgs bosons $H^0, A^0, H^\pm$;

SUSY partners $\tilde{W}^\pm..., \tilde{g}, \tilde{q}, \tilde{\ell}^\pm...$

Lead to rich physics at the electroweak scale at colliders;

Accommodate SUSY GUTs $M_{GUT} \sim 5 \times 10^{16}$ GeV.
(B). Dynamical approach for mass generation:

- Technicolor and alike: a lesson from QCD
  \( \text{SU}(N_{TC}) \) gauge theory, TC fermions \( Q = U, D, \ldots \)
  EWSB by TC-fermion condensation at \( \Lambda_{TC} \):
  \[ v \sim \langle Q_L Q_R \rangle^{1/3} \sim 246 \text{ GeV}. \]
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- “Topcolor/Top-seesaw”: Top quark special?
  \[ m_t \approx v/\sqrt{2} = 174 \text{ GeV}. \]

Introducing an additional fermion pair $\chi_L, \chi_R$
to generate the condensation $H \sim (\bar{\chi}_R t_L, \bar{\chi}_R b_L)$

  Lead to a heavy Higgs $m_H \sim 1 \text{ TeV}$,
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- A less ambitious approach: Little Higgs Models
Accept the existence of a light Higgs;
keep the Higgs boson “naturally” light (at 1-loop level).
  Predicts new “partner particles”:
  \[ W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi. \]
A new approach to the hierarchy problem

- Large Extra-dimension Scenario; ADD*

In a world with $D = 4 + n$ dimensions, $n$ of them compactified,

*N. Arkani-Hamed, Dimopoulos, Dvali
(C). Extra-dimensions: A new approach to the hierarchy problem

- Large Extra-dimension Scenario; \( \text{ADD}^* \)

In a world with \( D = 4 + n \) dimensions, \( n \) of them compactified,

the 4-dim Planck scale is related to the D-dim one \( M_D \) as

\[
M_{PL}^2 \sim M_D^{n+2} \int dx^n = M_D^{n+2} V_n.
\]

Thus the fundamental scale in the theory:

\[
M_D \sim (M_{pl}^2/V_n)^{1/n+2} \rightarrow \mathcal{O}(1 \text{ TeV}).
\]

\*N. Arkani-Hamed, Dimopoulos, Dvali
• Extra dimensions and KK particles:

If an extra dimension $y$ becomes compact (a circle of radius $R$), then all fields (gravitational, electromagnetic etc.) in $y$-dimension are periodic functions:

$$F(x, y) = \sum_{n=-\infty}^{\infty} F^n(x) e^{iny/R}.$$  

Equation of motion:

$$\left(\partial^\mu \partial_\mu - \partial^y \partial_y\right) F(x, y) \Rightarrow \left(\partial^\mu \partial_\mu + \frac{n^2}{R^2}\right) F^n(x)$$

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\[
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No \( \gamma_{KK}, e^-_{KK}, \ldots \) found \( \Rightarrow R^{-1} \) large; or \( \gamma, e^- \ldots \) don’t go there.
Graviton Interactions With SM Fields:

The rule: gravitons couple to ANYTHING
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Although each graviton couples gravitationally \( \kappa^2 \sim G_N \), the high-degeneracy leads to

\[
\kappa^2 \rho(m) dm^2 \sim \kappa^2 R^n m^{n-2} dm^2 \sim E^n / M_S^{n+2}
\]

Effective coupling \( \kappa^2 \sim \frac{1}{M_{pl}^2} \rightarrow \frac{1}{M_S^2} \)
• The Randall-Sundrum Scenario
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The extra dimension $y$ is “warped”:

$$ds^2 = e^{2A(y)} \eta_{\mu \nu} \, dx^\mu dx^\nu - dy^2,$$

where the “warp” factor $A(y) = -ky$, with $k$ the curvature scale in the $5^{th}$-dim.

So the masses of the KK states are not equally-spaced.
We are entering a “data-rich” era:
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Electroweak precision constraints;

$K/B$ rare decays and CP violation: $B \rightarrow X_s \gamma$; $J/\psi K_S$, $\phi K_S$, $\eta' K_S$...

Neutrino masses and mixing;

muon $g - 2$; $\mu \rightarrow e\gamma$...; neutron/electron EDMs;

Nucleon stability;
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Yet more to come:

Tevatron: ($p\bar{p}$ at 1.96 TeV, current)

   EW, top sector, new particle searches, Higgs (?) ...

LHC: ($pp$ at 14 TeV, 2007)

   comprehensive Higgs studies, extensive new particle searches...

ILC: ($e^+e^-$ at 500 GeV – 1 TeV ?)

   more on top sector, precision Higgs and new light particles...
In high-energy hadron collisions,
In high-energy hadron collisions, "Hard" Scattering

- Higher energy threshold: $M_{\text{new}} \sim \sqrt{s}$.
- Multiple (strong, electroweak) channels: $q\bar{q}$, $gg$, $qg$, $b\bar{b}$, $WW$ ...
Scattering cross sections for various SM processes:
Scattering cross sections for various SM processes:

- Rare events: once every 1,000,000, there may be one interesting ...
- challenge to dig signals out of the backgrounds...
How to search for new particles?
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Distinctive decay products: (in high $p_T$)

- Leptons ($e, \mu$)
- Photons
- Taus
- Jets Missing $E_T$

Diagram:
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ \rightarrow l\ell\tau\tau$
- $H \rightarrow WW \rightarrow l\nu l\nu$
- $H \rightarrow ZZ \rightarrow l\ell l\ell$
- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow WW \rightarrow l\nu l\nu$
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Kinematical features:

- invariant mass of two-body $R \rightarrow ab$: $m_{ab}^2 = (p_a + p_b)^2 = M_R^2$.

Jacobian peak in transverse momentum:

$$\frac{d\sigma(R \rightarrow ab)}{dp_T^2} \propto \frac{1}{(m_{ab}^2 - 4p_T^2)^{1/2}}.$$
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- “transverse” mass of two-body $W^- \rightarrow e^-\bar{\nu}_e$:

  \[
  m_{e\nu T}^2 = (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2
  \]

  \[
  = 2E_{eT}E_{\nu T}(1 - \cos \phi) \leq M_W^2.
  \]
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- cluster transverse mass of multi-body $H^0 \rightarrow W^+W^- \rightarrow e^+\nu_e e^-\bar{\nu}_e$:
  \[ m_{WW}^2 = (E_{e1T} + E_{e2T} + E_{\nu1T} + E_{\nu2T})^2 - (\vec{p}_{e1T} + \vec{p}_{e2T} + \vec{p}_{\nu1T} + \vec{p}_{\nu2T})^2 \]
  \[ = (E_{e1T} + E_{e2T} + E_T^{\text{miss}})^2 - (\vec{p}_{e1T} + \vec{p}_{e2T} + \vec{p}_T^{\text{miss}})^2 \leq M_H^2. \]

  where $\vec{p}_T^{\text{miss}} = -\sum_{\text{obs}} \vec{p}_T^{\text{obs}}$. 
Kinematical features:

- **Invariant mass of two-body** \( R \rightarrow ab : \) \( m_{ab}^2 = (p_a + p_b)^2 = M_R^2. \)

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  \[
  \frac{d\sigma(R \rightarrow ab)}{dp_T^2} \propto \frac{1}{(m_{ab}^2 - 4p_T^2)^{1/2}}.
  \]

- **“Transverse” mass of two-body** \( W^- \rightarrow e^-\bar{\nu}_e : \)

  \[
  m_{e\nu T}^2 = (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 \\
  = 2E_{eT}E_{\nu T}(1 - \cos \phi) \leq M_W^2.
  \]

- **Cluster transverse mass of multi-body** \( H^0 \rightarrow W^+W^- \rightarrow e^+\nu_e e^-\bar{\nu}_e : \)

  \[
  m_{WW T}^2 = (E_{e1T} + E_{e2T} + E_{\nu1T} + E_{\nu2T})^2 - (\vec{p}_{e1T} + \vec{p}_{e2T} + \vec{p}_{\nu1T} + \vec{p}_{\nu2T})^2 \\
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  where \( \vec{p}_{T}^{\text{miss}} = -\sum_{\text{obs}} \vec{p}_T^{\text{obs}}. \)

YOU design an appropriate variable/observable for the search.
Higgs Searches at the Tevatron and the LHC:

The crucial features: Couplings proportional to masses.
Higgs Searches at the Tevatron and the LHC:

The crucial features: Couplings proportional to masses.

SM Higgs boson decay branching fractions:

preferably to heavier particles.
SM Higgs boson production rates:

\[ \sigma(pp \rightarrow h_{\text{SM}} + X) \ [\text{pb}] \]
\[ \sqrt{s} = 2 \ \text{TeV} \]
\[ M_t = 175 \ \text{GeV} \]
CTEQ4M

\[ \sigma(pp \rightarrow H + X) \ [\text{pb}] \]
\[ \sqrt{s} = 14 \ \text{TeV} \]
\[ M_t = 175 \ \text{GeV} \]
CTEQ4M
SM Higgs boson production rates:

- At the Tevatron: hundreds of Higgs bosons may have been produced, for $m_h \lesssim 200$ GeV, $500 \text{ pb}^{-1}$.
- At the LHC: hundreds of thousand may be produce, for $m_h \lesssim 700$ GeV, $100 \text{ fb}^{-1}$. 
• Higgs first shot at the Tevatron:

\[ q\bar{q}' \rightarrow Wh, Zh, \quad h \rightarrow b\bar{b} \]

\[ gg \rightarrow h, \quad h \rightarrow WW^*, ZZ^*, \tau^+\tau^- \]
SM Higgs fully covered at the LHC:

- $H \rightarrow γγ + WH, ttH (H \rightarrow γγ)$
- $ttH (H \rightarrow bb)$
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$
- $H \rightarrow WW^{(*)} \rightarrow lνlν$
- $H \rightarrow ZZ \rightarrow lνlν$
- $H \rightarrow WW \rightarrow lνjj$

Total significance $5σ$ observation achievable.

ATLAS report: combining multiple channels, $10σ$ observation achievable.
• SUSY Higgs fully covered at the LHC:

In MSSM, 5 Higgs bosons: $h^0$, $H^0$, $A^0$, $H^\pm$, two independent parameters: $\tan\beta - M_A$. 
Significance contours for SUSY Higgses

Regions of the MSSM parameter space \((m_A, \tan\beta)\) explorable through various SUSY Higgs channels

- 5\(\sigma\) significance contours
- two-loop / RGE-improved radiative corrections
- \(m_{\text{top}} = 175\) GeV, \(m_{\text{SUSY}} = 1\) TeV, no stop mixing;

\[
\begin{align*}
\text{CMS, } 3 \cdot 10^4 \text{ pb}^{-1} \\
H^\pm \to \tau \nu \\
10^4 \text{ pb}^{-1} \\
A, H, h \to \tau \tau \to e + \mu \pm X \\
A, H, h \to \tau \tau \to \tau^- + \tau^+ \text{ jet + } X \\
A, H \to \tau \tau \to h^+ + h^- + X \\
h \to \gamma \gamma \\
\text{LEP II, } \sqrt{s} = 200 \text{ GeV}
\end{align*}
\]
Weak Scale Supersymmetry

- **SUSY partners**

<table>
<thead>
<tr>
<th>particles</th>
<th>symbol</th>
<th>spin</th>
<th>mass param.</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluino</td>
<td>$\tilde{g}$</td>
<td>1/2</td>
<td>$M_3$</td>
</tr>
<tr>
<td>charginos</td>
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</tr>
<tr>
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<td>$M_1$, $\mu$, $B$</td>
</tr>
<tr>
<td></td>
<td>$\chi_1$, $\chi_2$, $\chi_3$, $\chi_4$</td>
<td></td>
<td>$m_{H_u}^2$, $m_{H_d}^2$</td>
</tr>
<tr>
<td>sleptons</td>
<td>$\tilde{e}_L$, $\tilde{\nu}_e$, $\tilde{\nu}_e$, $\tilde{\nu}_e$, $\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\tau}_L$</td>
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<tr>
<td></td>
<td>$\tilde{\mu}<em>L$, $\tilde{\nu}</em>\mu$, $\tilde{\nu}_\mu$, $\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\tau}_L$</td>
<td>0</td>
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<tr>
<td>squarks</td>
<td>$\tilde{u}_L$, $\tilde{d}_L$, $\tilde{u}_R$, $\tilde{d}_R$, $\tilde{c}_L$, $\tilde{s}_L$, $\tilde{c}_R$, $\tilde{s}_R$, $\tilde{t}_L$, $\tilde{b}_L$, $\tilde{b}_L$, $\tilde{b}_L$, $\tilde{b}_L$</td>
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<td>$\tilde{t}_1$, $\tilde{t}_2$, $\tilde{b}_1$, $\tilde{b}_2$</td>
<td>0</td>
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But where do they get their masses?

⇒ “soft” SUSY breaking

(many parameters put in by hand)

Also general Yukawa couplings

$A_{u,d,\ell}$, that lead to Sfermion mixings; CP phases etc.

$R$-parity violation couplings ...
Parameter count in the SM and MSSM

<table>
<thead>
<tr>
<th>model</th>
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<th>CP-viol. phases</th>
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Guidance and Assumptions:

Based on observation:

* Proton stability:
  \( \Rightarrow \) \( R \)-parity conservation; or \( B, L \) not broken simultaneously (in 1\( st \), 2\( nd \) generations).

* No large CP-violation/FCNC:
  \( \Rightarrow \) no (or small) phases; sfermion mass degenerate (or heavy).
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  \( \Rightarrow \) no (or small) phases; sfermion mass degenerate (or heavy).

Pure theoretical considerations:
* Gauge-coupling/Yukawa Unification:
  \( \Rightarrow \) universal masses at the GUT scale
* radiative E.W.S.B.;
* LSP cold dark matter; ...
Gauge coupling unification

\[ \alpha_1 = \alpha_2 = \alpha_3 = \alpha_G \text{ at } \mathcal{O}(10^{16} \text{ GeV}) \]

need the help of weak-scale SUSY threshold.
Hadron colliders can be a S-particle factory:

**QCD production:** \( q\bar{q}, gq, gg \rightarrow \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} \).

**E.W. production:** \( q\bar{q} \rightarrow \tilde{\chi}^+_1 \tilde{\chi}^-_1, \tilde{\chi}^0_1 \tilde{\chi}^-_1, \tilde{\chi}^+_1 \tilde{\chi}^-_2 \).

Typically,
\[
\sigma(Tevatron) \approx \mathcal{O}(0.1 - 1 \text{ pb}); \quad \sigma(LHC) \approx \mathcal{O}(10 - 100 \text{ pb}).
\]
New ball-game for signal searches:

The lightest SUSY particle (LSP $\tilde{\chi}_1^0$) is stable ($R$-parity), and nearly non-interacting (in detectors),

$\Rightarrow$ large missing energy is the characteristics;

difficult to reconstruct a mass peak for the sparticle.
New ball-game for signal searches:

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⇒ large missing energy is the characteristics;

difficult to reconstruct a mass peak for the sparticle.

Details depend on the model...
• mSUGRA scenario: SUSY breaking near $M_{GUT}$.

Supergravity as messenger to transmit SUSY breaking effects.

$m_0$, $m_{1/2}$, $A$, $\tan \beta$, and $\text{sign}(\mu)$

Sparticle decays:

$$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \ell^+ \nu, \quad \tilde{\chi}_1^0 q \bar{q}'$$
\[ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-, \quad \tilde{\chi}_1^0 q\bar{q} \]
\[ \tilde{g} \rightarrow \tilde{\chi}_2^0 q\bar{q}, \quad \tilde{g} \rightarrow \tilde{\chi}_1^+ q\bar{q}, \quad \tilde{g} \rightarrow \tilde{q}\bar{q}, \]
\[ \tilde{t}_1 \rightarrow \tilde{\chi}_1^0 t, \quad \tilde{t}_1 \rightarrow \tilde{\chi}_2^0 t, \quad \tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b. \]

Generically, \( \tilde{\chi}_1^0 \) leads to missing energy signal:

“missing \( E_T \) plus jets”: \( E_T + \text{jets} \)
“dilepton plus missing \( E_T \)” \( \ell\ell + E_T \) (\( \pm\pm \) or \( ++ \))
“trilepton plus missing \( E_T \)” \( \ell\ell\ell + E_T \)
mSUGRA: $\tan\beta=45$, $A_0=0$, $\mu<0$

LHC: $m_0 > 4000$ GeV, $m_{1/2} > 1400$ GeV, $\tan\beta \gtrsim 45$. 

Gauge mediation scenario: SUSY breaking at $\Lambda \sim 10 - 100$ TeV, Gauge interactions as messengers to mediate SUSY breaking effects.

$\Lambda$, $M$, $\tan \beta$, and $N_M$
Squarks and gluinos are typically heavier; Gravitino $\tilde{G}$ LSP.

The NLSP dominates phenomenology: \[ \tilde{x} \xrightarrow{1/F} \tilde{G} \]
Squarks and gluinos are typically heavier; Gravitino $\tilde{G}$ LSP.

The NLSP dominates phenomenology:

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<tr>
<th>NLSP</th>
<th>Decay to the $\tilde{G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bino-like Neutralino</td>
<td>$\tilde{\chi}_1^0 \to \gamma \tilde{G}$</td>
</tr>
<tr>
<td>Higgsino-like Neutralino</td>
<td>$\tilde{\chi}_1^0 \to (h, Z, \gamma) \tilde{G}$</td>
</tr>
<tr>
<td>Stau</td>
<td>$\tilde{\tau} \to \tau \tilde{G}$</td>
</tr>
<tr>
<td>Slepton Co-NLSP</td>
<td>$\tilde{\ell} \to \ell \tilde{G}$</td>
</tr>
<tr>
<td>Squark</td>
<td>$\tilde{q} \to (q, q'W) \tilde{G}$</td>
</tr>
<tr>
<td>Gluino</td>
<td>$\tilde{g} \to g \tilde{G}$</td>
</tr>
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</table>

$$c\tau(\tilde{x} \to x\tilde{G}) \approx 100 \ \mu m \left( \frac{100 \ \text{GeV}}{m_{\tilde{x}}} \right)^5 \left( \frac{\sqrt{F}}{100 \ \text{TeV}} \right)^4.$$  

could lead to a displaced vertex in decay, or quasi-stable charged track.
LHC reach:

\[ \Lambda (\text{TeV}) \]

\[ \sigma (\text{fb}) \]

Model Line B
\[ n_b = 2, \frac{M}{\Lambda} = 3, \tan \beta = 15, \mu > 0 \]

- \( \bar{g}g + \bar{g}q + \bar{q}q \)
- \( \bar{W}_i \bar{W}_j + \bar{W}_i \bar{Z}_j + \bar{Z}_i \bar{Z}_j \)
- \( \bar{l} + \bar{L} + \bar{\nu} \)

\[ \text{Max}(\sigma_S/\sqrt{\sigma_B}) \]

Model Line B
\[ n_b = 2, \mu > 0, \tan \beta = 15, \frac{M}{\Lambda} = 3 \]

- \( 0i \)
- \( 1i \)
- \( 2SS \)
- \( 2OS \)
- \( 3i \)
New gauge bosons and heavy fermions
New gauge bosons and heavy fermions

Little Higgs models as an example

In the Littlest Higgs model:*  

<table>
<thead>
<tr>
<th>Heavy particles</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_H$</td>
<td>$m_{A_H}^2 = m_W^2 \frac{f^2}{s_W^2 c^2 v^2}$</td>
</tr>
<tr>
<td>$Z_H$</td>
<td>$m_{Z_H}^2 = m_W^2 \frac{f^2}{s_W^2 c^2 v^2}$</td>
</tr>
<tr>
<td>$W_H$</td>
<td>$m_{W_H}^2 = m_W^2 \frac{f^2}{s_W^2 c^2 v^2}$</td>
</tr>
<tr>
<td>$\phi^0, \pm, \pm\pm$</td>
<td>$\frac{2m_W^2 f^2}{v^2} \frac{1}{1 - (4v'f/v^2)^2}$</td>
</tr>
<tr>
<td>$T$</td>
<td>$\sqrt{\lambda_1^2 + \lambda_2^2} f$ (where $m_W = g v/2$.)</td>
</tr>
</tbody>
</table>

\[
\tan \theta = \frac{s}{c} = \frac{g_2}{g_1}
\]
New \(SU(2)\) gauge coupling
(or equivalently mixing angle \(\theta\))

\[
\tan \theta' = \frac{s'}{c'} = \frac{g'_2}{g'_1}
\]
New \(U(1)\) gauge coupling
(or equivalently mixing angle \(\theta'\))

\(f\)
Symmetry breaking scale \(\mathcal{O}\) (TeV)

\(v'\)
Triplet \(\phi\) vacuum expectation value,
\(v'/v \lesssim v/4f\)

\(m_H\)
Regular SM Higgs mass

\(M_T\)
Heavy vector top mass, we trade \(\lambda_2\) for \(M_T\)
• New gauge bosons in DY process:
Recall CDF searches for a $Z' \rightarrow \mu^+\mu^-$: [PRL 79, (1997)]
New gauge bosons in DY process:
Recall CDF searches for a $Z' \rightarrow \mu^+ \mu^-$: [PRL 79, (1997)]

including:

- $p\bar{p} \rightarrow Z, \gamma \rightarrow \mu^+ \mu^- X$,
- $p\bar{p} \rightarrow W^+ W^- \rightarrow \mu^+ \nu_\mu \bar{\nu}_\mu X$,
- $p\bar{p} \rightarrow b\bar{b} \rightarrow \mu^+ \mu^- + \text{hadrons} + X$,
- $p\bar{p} \rightarrow t\bar{t} \rightarrow W^+ b \ W^- \bar{b} \rightarrow \mu^+ \nu_\mu \bar{\nu}_\mu b\bar{b} X$. 
New gauge bosons in DY process:
Recall CDF searches for a $Z' \rightarrow \mu^+\mu^-$: [PRL 79, (1997)]

including:

$p\bar{p} \rightarrow Z, \gamma \rightarrow \mu^+\mu^- X,$
$p\bar{p} \rightarrow W^+W^- \rightarrow \mu^+\nu\mu^-\bar{\nu}_\mu X,$
$p\bar{p} \rightarrow b\bar{b} \rightarrow \mu^+\mu^- + \text{hadrons} + X,$
$p\bar{p} \rightarrow t\bar{t} \rightarrow W^+b \ W^-\bar{b} \rightarrow \mu^+\nu\mu^-\bar{\nu}_\mu b\bar{b} \ X.$

$\sigma < 40 ~\text{fb} \Rightarrow M_{Z'} > 600 \text{ GeV}.$
\• \(A_H\) should be the lightest new state;

\• large DY production \(A_H \rightarrow \ell^+\ell^- (\ell = e, \mu)\)

\[pp \rightarrow A_H X\]
- $A_H$ should be the lightest new state;
- large DY production $A_H \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu$)

Tevatron: $M_{A_H} > 0.5$ TeV or $f > 3$ TeV;
LHC: $M_{A_H} \sim 3$ TeV or $f \sim 18$ TeV.
- $Z_H/W_H$ robust new state
- DY production rate large
- $Z_H/W_H$ robust new state  
- DY production rate large

Tevatron: not quite accessible (except for $A_H$);
LHC: $M_{Z_H} \sim 5$ TeV or $f \sim 8$ TeV.
ATLAS simulations for $Z \rightarrow \ell^+ \ell^-$:

Reach $M_{Z_H} \sim$ several TeV for $\cot \theta > 0.1$:
ATLAS simulations for $Z \rightarrow \ell^+ \ell^-$:

Reach $M_{ZH} \sim$ several TeV for $\cot \theta > 0.1$:

Cross-sections measure $\cot \theta : N(\ell^+ \ell^-)$ versus $N(Zh)$.

Mass peak $M_{ZH}$ determines $f$. 

$Z_{H \rightarrow ee}$ $5 \sigma$ reach for 300 fb$^{-1}$

$\cot \theta$ 

$m(Z_{H})$ (GeV)
Significant differences for FB asymmetry among $Z'$s:

$$A_{i,f}^{i,f} = \frac{3}{4} A_i A_f, \quad A_i = \frac{g_i^2 - g_R^2}{g_i^2 + g_R^2}.$$ 

$$A_{FB}^{\text{had}} = \frac{\int dx_1 \sum_{q=u,d} A_{FB}^{q} (F_q(x_1)F_{\bar{q}}(x_2) - F_{\bar{q}}(x_1)F_q(x_2)) \text{sign}(x_1 - x_2)}{\int dx_1 \sum_{q=u,d,s,c} (F_q(x_1)F_{\bar{q}}(x_2) + F_{\bar{q}}(x_1)F_q(x_2))}.$$
Black quark signals:

Recall the top-quark searches at hadron colliders

The leading production channels:

\[ q\bar{q} \rightarrow t\bar{t}, \quad \text{Tevatron 90%; LHC 10\%} \]
\[ gg \rightarrow t\bar{t}, \quad \text{Tevatron 10\%; LHC 90\%} \]

with \( t\bar{t} \rightarrow W^+ b \ W^- \bar{b} \rightarrow \ldots \)

Top-quark discovered (1993): \( m_t \approx 178 \text{ GeV} \).
• **Heavy quark signals:**

Recall the top-quark searches at hadron colliders
The leading production channels:

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with \( t\bar{t} \rightarrow W^+b \ W^-\bar{b} \rightarrow \ldots \)

Top-quark discovered (1993): \( m_t \approx 178 \) GeV.

Interesting sub-leading (electroweak) production channels: the single-top

\[ q\bar{q}' \rightarrow W^* \rightarrow t\bar{b}, \quad \text{a lot smaller}
\]
\[ gb \rightarrow tW, \quad \text{smaller too}
\]
\[ qb \rightarrow q'W^*b \rightarrow q' t \quad \text{1/3 of QCD}. \]
• Heavy quark signals:

Recall the top-quark searches at hadron colliders
The leading production channels:

\[ q\bar{q} \rightarrow t\bar{t}, \quad \text{Tevatron 90%; LHC 10\%} \]
\[ gg \rightarrow t\bar{t}, \quad \text{Tevatron 10\%; LHC 90\%} \]
with \( t\bar{t} \rightarrow W^+b \ W^-\bar{b} \rightarrow \ldots \)

Top-quark discovered (1993): \( m_t \approx 178 \) GeV.

Interesting sub-leading (electroweak) production channels: the single-top

\[ q\bar{q}' \rightarrow W^* \rightarrow t\bar{b}, \quad \text{a lot smaller} \]
\[ gb \rightarrow tW, \quad \text{smaller too} \]
\[ qb \rightarrow q'W^*b \rightarrow q' \ t \quad \text{1/3 of QCD.} \]

measure \( V_{tb} \) and test \( tbW_L \) coupling \( \leftarrow \) surely new at the Tevatron.
The heavy $T$ signal at the LHC

$gg \rightarrow T\bar{T}$ phase-space suppression;
$qb \rightarrow q'T$ via $t$-channel $W_Lb \rightarrow T$. 
ATLAS simulations for $T \rightarrow tZ, bW$:

Reach $M_T \sim 1 \ (2) \ \text{TeV}$ for $x_\lambda = 1 \ (2)$. 
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Cross-sections measure coupling $x_\lambda$.

Mass peak $M_T$ determines $f : v/f = m_t/M_T(x_\lambda + x_\lambda^{-1})$

$\Rightarrow$ check consistency with $f$ from $M_{ZH}$.
If there is either a $U$-type or $D$-type heavy quark, must observe $W^+d \rightarrow U$ or $W^-u \rightarrow D$:

Note that $\sigma_D \approx 1.2 \sigma_U$. 

![Graph showing the relationship between $M_U$ and $\sigma$ for different scenarios.](image)
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Interesting to note:

- $\sigma_U \approx 10\sigma_{\bar{U}}$; $\sigma_D \approx 10\sigma_{\bar{D}}$
- $U \to d\ell^+\nu \Rightarrow$ sequential fermion embedding;
  $D \to u\ell^-\bar{\nu} \Rightarrow$ anomaly-free fermion embedding.
Kinematical features: $W^+ d \rightarrow U \rightarrow \ell^+ \nu j$: 

\[ \begin{align*}
W^\pm & \rightarrow q \rightarrow l^\pm \rightarrow q' \nu \rightarrow \text{forward jet} \\
& \text{high } p_T \text{ jet}
\end{align*} \]
Kinematical features: $W^+ d \rightarrow U \rightarrow \ell^+ \nu j$:

$p_T$ jet

forward jet

$q'$

$q$

$LHC$ 14 TeV

$M_{U(Wd)}$

$M_{Tran}$
Deep into extra-dimensions at the LHC:

- Observable signatures for extra-dim models:
  - At “low” energies
    - “very low”: $E \ll 1/R, M_D$
  - 4d effective theory: as the Standard Model; weak effects from gravity.
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    - March into the extra-dimensions: \( 1/R < E \ll M_D \),
      - \((4+n)\)-dim physics directly probed, and gravity effects observable: mainly via light KK gravitons of mass
      \[ m_{KK} \sim 1/R, \]
      - discrete states in 5d viewpoint.
  - Or whatever propagate there \( \Rightarrow \) an effective theory \((\text{SM+KK})\).
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    \[ m_{KK} \sim 1/R, \leftrightarrow \text{discrete states in 5d viewpoint}. \]
    or whatever propagate there \( \Rightarrow \) an effective theory \((\text{SM}+\text{KK})\).
  - Intermediate energy regime \( E \sim M_D \):
    stringy states significant:
    \( s \)-channel poles as resonances:
    \[ M(s,t) \sim \frac{t}{s-M_n^2}, \quad M_n = \sqrt{n}M_S. \]
At “trans Planckian” energies $E > M_D, M_S$:

$(4 + n)$–dim physics directly probed;

gravity dominant: black hole production

$$\sqrt{s} = M_{BH} > M_D \text{ for } b < r_{bh}.$$
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$$r_{bh} = \frac{1}{\sqrt{\pi} M_D} \left[ \frac{M_{BH}}{M_D} \left( \frac{8 \Gamma \left( \frac{n+3}{2} \right)}{n + 2} \right) \right]^{\frac{1}{n+1}} \rightarrow \frac{M_{BH}}{M_{pl}^2} \text{ in 4d}$$

$$\sigma = \pi r_{bh}^2.$$ 

---

Collider Searches for Extra Dimensions:

A. Collider Signals I (ADD)

Real KK Emission: Missing Energy Signature

a. $e^+ e^- \rightarrow \gamma + KK$ ($\gamma+$missing energy)

\[ n - \text{dim: at LEP2} \]
\[ n = 4 \quad M_S > 730 \text{ (GeV)} \]
\[ n = 6 \quad M_S > 520 \text{ (GeV)} \]
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\end{align*}
\]

b. $p\bar{p} \rightarrow \text{jet} + KK \ (\text{mono-jet + missing energy})$

\[
\begin{align*}
&n - \text{dim: at Tevatron} \quad \text{at LHC} \\
&n = 4 \quad M_S > 900 \ \text{(GeV)} \quad 3400 \\
&n = 6 \quad M_S > 810 \ \text{(GeV)} \quad 3300
\end{align*}
\]
B. Collider Signals II (ADD)

Virtual KK Graviton Effects

On four-particle contact interactions:

\[
\begin{align*}
\bar{f}_1 & \rightarrow f_1, \\
\bar{f}_2 & \rightarrow f_2, \\
\bar{f}_1 & \rightarrow f_1, \\
\bar{f}_2 & \rightarrow f_2.
\end{align*}
\]

Sum over virtual KK exchanges:

\[
\begin{align*}
iM & \sim \bar{f} O_i f \bar{f} O_j f \int_0^\infty \frac{dm_{\mathbf{n}}^2}{s - m_{\mathbf{n}}^2 + i\epsilon} \\
& \sim \frac{s^2}{M^4_S} \bar{f} O_i f \bar{f} O_j f.
\end{align*}
\]

Again, effective coupling \( \kappa^2 \sim \frac{1}{M^2_{pl}} \rightarrow \frac{1}{M^2_S} \)!
Qualitative differences for signal/background distributions, due to the spin-2 exchange:

\[ e^+ e^- \rightarrow b \bar{b} \] at \( \sqrt{s} = 500 \text{ GeV} \).

LR asymmetry for \( e^+ e^- \rightarrow b \bar{b} \) at \( \sqrt{s} = 500 \text{ GeV} \).
Solid: SM; “data” points for \( \lambda = \pm 1 \) with \( = 75 \text{ fb}^{-1} \).
C. KK Resonant States at Colliders: (RS)

If the SM fields (photons, electrons, $Z, W, H^0 ...$) also propagate in extra dimensions, then they have KK excitations.

Direct search bounds:

$$M^*_{\gamma,Z,W} \sim \frac{1}{R} > 4 \text{ TeV}.$$
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Resonant production at the LHC:
D. Stringy States at Colliders

Future colliders may reach the TeV string threshold thus directly produce the “stringy” resonant states. Amplitude factor near the resonance

\[ M(s, t) \sim \frac{t}{s - nM^2_S}, \quad \text{its mass } M_n = \sqrt{nM_S}. \]
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where $T$ is an unknown gauge factor (Chan-Simon factor), typically $1 - 4$. 
Very rich structure of angular distributions:
LHC 95% C.L. sensitivity from $\ell^+\ell^-$ mode:
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With $300 \text{ fb}^{-1}$, if no signal seen, we expect to reach bounds for $M_S > 8 \ (10) \text{ TeV}$ for $T = 1 - 4$. 
E. Black Hole Production at Colliders

For a black hole of mass $M_{BH}$, its size is

$$r_{bh} \approx \frac{1}{M_D} \left( \frac{M_{BH}}{M_D} \right)^{\frac{1}{n+1}} \rightarrow \frac{M_{BH}}{M_{pl}^2} \text{ in } 4d.$$
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At higher energies and shorter distances (impact parameter)

$$E_{cm} > M_{BH} > M_D, \quad b_{impact} < r_{bh},$$

black holes formation is the dominant quantum gravity phenomena.
Black holes copiously produced at the LHC energies,

<table>
<thead>
<tr>
<th>$M_{BH}$</th>
<th>$n = 4$</th>
<th>$n = 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 TeV</td>
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Black holes “decay” via Hawking radiation:
\[ \gamma, \nu, e^\pm, \text{hadrons},... W^\pm, Z..., \text{gravitons} \]

Spectacular events:
- very luminous in the detector!
- lepton-number/baryon-number violation (?)
- spherical/angular momentum orientation (?) ... ...
Recap:
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  - Many free parameters, over incomprehensible ranges
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  - weak-scale SUSY
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Realize the Tevatron potential, go for the LHC!
Major breakthrough ahead of us!