PHYSICS AT THE LHC

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DESY Summerstudent Programme
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Standard model (SM) of particle physics works remarkably well!

- No Higgs: divergence of SM at 1 TeV?
- SM NOT beautiful!
  Free parameters?
- SM: no coupling / mass unification!
- SM: No dark-matter candidate!
- Gravity?
- Gauge structure?
- Three generations?
- Hierarchy?
- Baryon asymmetry?
- Connection between quarks and leptons?
- …
For 40 years we have searched and produced models to be searched for …

Now we are (almost) there!!!
WHY THE LHC??????
NEW PHYSICS …

How to search for new physics ???
- model-independent or
- specific final-state signatures
(with large deviations from SM expectation)
NEW PHYSICS: MOTIVATION

Potential DM candidates (but disproved by new astrophysics results?): WIMPs (weakly interacting massive particles). WIMP candidates occur in many BSM models.
Kepler / Newton: \( v \sim \frac{1}{\sqrt{R}} \)
NEW PHYSICS: MOTIVATION

For reasons of simplicity and beauty: Want all 3 SM interactions to unite at high scale!
\[ \mathcal{L}_{GW} = \sum_f (\bar{\Psi}_f (i \gamma^\mu \partial_\mu - m_f) \Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \]
\[ + \frac{g}{\sqrt{2}} \sum_i (\bar{a}_i^L \gamma^\mu b_i^L W_{\mu}^+ + \bar{b}_i^L \gamma^\mu a_i^L W_{\mu}^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu_l (I_f^3 - 2 s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_{\mu} + \]
\[ - \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2} |\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ + \]
\[ - ie (W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu)|^2 + \]
\[ - \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 + \]
\[ - \frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 + \]
\[ + \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig'}{2 c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta \]

Neither simple nor beautiful?
We know: $m_H < 140 \text{ GeV}$!
But: loop corrections to $m_H$?

Expect: $\Delta m^2_H \propto \Lambda^2$

$m^2_H \approx M^2_{Pl} \approx 10^{2.19} \text{ GeV}^2$

Which “fine-tuning” can rearrange the “hierarchy”???

Solution: Introduce “shadow world”, related via symmetry!
One SUSY partner for each SM state!

Fermion loops cancel boson loops and $v v$!

Works as long as mass difference not too large
$\Rightarrow$ SUSY particles $< 1 \text{ TeV}$!!!
## INTRODUCING SUSY

<table>
<thead>
<tr>
<th>FERMIONS</th>
<th>BOSONS</th>
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<tbody>
<tr>
<td><strong>spin</strong></td>
<td><strong>Name</strong></td>
</tr>
<tr>
<td>½</td>
<td>leptons</td>
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<td></td>
<td></td>
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<tr>
<td>½</td>
<td>quarks</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>½</td>
<td>gluinos</td>
</tr>
<tr>
<td>½</td>
<td>charginos</td>
</tr>
<tr>
<td>½</td>
<td>neutralinos</td>
</tr>
</tbody>
</table>

SM particles (observed) | SM particles (not yet observed) | Super Partners (not yet observed)
SUSY: MOTIVATION

\begin{align*}
\frac{1}{\alpha_1}, \quad \frac{1}{\alpha_2}, \quad \frac{1}{\alpha_3}
\end{align*}

\begin{align*}
\text{SM} \\
\text{MSSM}
\end{align*}
• New symmetry between bosons and fermions
  ¬ Partner particle for each SM particle –
  • same quantum numbers and couplings except for spin!

• Solves many of the mentioned problems
  • natural light Higgs,
  • hierarchy
  • DM (e.g. neutralino $\chi_0$ as mixture of SUSY partners of Z,γ,H)
  • inclusion of gravitation
  • gauge structure
  • Unification

• Freedom: symmetry breaking,
  QN conservation
  • R parity: $R = (-1)^{3B+L+2S}$
    If $R$ violated ¬ proton decay!
  • RP conservation: Pairwise production,
    cascade decay, stable LSP (lightest SUSY particle)
SUSY: MODELS

• SUSY is a broken theory!!!
  Resulting disadvantage: many free parameters (masses, mixings, in MSSM 125!)

• Models for SUSY breaking:
  • … introduce assumptions --. Drastic reduction of parameters
  • … allow predictions for sparticle mass spectra
  • … examples: mSUGRA, GSMB, …

• Example mSUGRA:
  • … unification of SUSY spin-0 and SUSY spin-1/2 particle masses at GUT scale
  • … only 5 parameters left: \( \tan\beta, m_0, m_{1/2}, \text{sign}(\mu), A_0 \)

  \[
  \frac{1}{2} M_Z = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2 \beta}{\tan^2 \beta - 1} - |\mu|^2 > 0
  \]

  • … calculation of masses at lower scales (“running masses”)
  • … LSP as DM candidate!
RPC SUSY: pair production of (heavy) squarks and gluinos:
- large Xsection: 10-100 pb
- cascade decays to final state
⇒ inclusive search strategies with all relevant physics objects!

- $E_{T,\text{miss}}$ (MET, from LSP)
- hard jets (from coloured particles)
- hard leptons (from intermediate decays, OS, SS)

- MET + jets
- MET + jets + N leptons
- MET + jets + btag
- MET + jets + N $\gamma$
- …

In RPC models: lightest SUSY particle (LSP)
⇒ undetected ⇒ MET!
• Direct DM searches: e.g. cryogenic detectors and measurement of nuclear recoil. Issue: background! etc.
• Direct DM searches
• Indirect searches e.g. in astrophysics experiments
SUSY: SEARCHES (AT LEP)

- Direct DM searches
- Indirect searches e.g. in astrophysics experiments
- Searches at colliders: PETRA, SppS, HERA, LEP, Tevatron

- Fixed initial conditions
- Production of sparticles up to half CMS energy
- So far only exclusion of parameter regions!
SUSY: SEARCHES (AT LEP)

- Direct DM searches
- Indirect searches e.g. in astrophysics experiments
- Searches at colliders:

- Fixed initial conditions
- Production of sparticles up to half CMS energy
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SUSY: SEARCHES (TEVATRON)

- Direct DM searches
- Indirect searches e.g. in astrophysics experiments
- Searches at colliders
Do we see a significant excess of data over SM expectation? Or can we exclude a certain (mass) hypothesis?

Define test statistics $Q$ as ratio of likelihoods for $s$ / no $s$ hypotheses:

$$-2\ln Q = -2 \ln \frac{P_d(s+b)}{P_d(b)} = -2 \sum_i s_i + 2 \sum_i d_i \ln \left(1 + \frac{s_i}{b_i}\right)$$

Then perform toy experiments with and without $s$ for different parameters (e.g. $m_H$):

1-$CL_b$: Probability to observe more $s$-like outcome in $b$-only case

$CL_{s+b}$: Probability to observe more $b$-like outcome in signal case
Do we see a significant excess of data over SM expectation? Or can we exclude a certain (mass) hypothesis? Define test statistics $Q$ as ratio of likelihoods for $s$/no $s$ hypotheses:

$$1-\text{CL}_b: \text{Probability to observe more s-like outcome in b-only case}$$

$$\text{CL}_{s+b}: \text{Probability to observe more b-like outcome in signal case}$$

$$-2\ln Q = -2\ln P_d^{s+b} - 2\ln P_d^b$$

$$\text{Observed in data}$$

$$s+b \text{ like}$$

$$\text{b like}$$
1-\(\text{CL}_b\): Probability to observe more s-like outcome in b-only case
\(\text{CL}_{s+b}\): Probability to observe more b-like outcome in signal case
No excess in 1-\(\text{CL}_b\) \(\Rightarrow\) Look at \(\text{CL}_s = \text{CL}_{s+b} / \text{CL}_b\):
If \(\text{CL}_s\) small, then signal is very unlikely \(\Rightarrow\)
\(\text{CL}_s < 5\% \Rightarrow\) exclusion at 95% confidence level.
Ratio of X-section excluded at 95% CL ($CL_s = 5\%$) and predicted SM-Higgs X-section!

Equally the factor by which SM-Higgs X-section has to be scaled to be excluded at 95% CL.
SUSY AT LHC (1 EXAMPLE)

Inclusive spectra as fastest way to discovery of SUSY-like physics.

Challenging – requires excellent understanding of all detector components with little data!
SUSY discovery “easy”, but interpretation challenging (ILC!)
- need to measure masses to identify model (parameters)
- but 2 LSPs ➔ no mass peaks of decaying resonances!

One way: mass edges!
Intermediate states define max dilepton mass:
\[ m_{\ell\ell}^{\text{max}} = \frac{1}{m_{\tilde{\chi}_2^0}} \sqrt{\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_R^0}^2\right)\left(m_{\tilde{\chi}_R^0}^2 - m_{\tilde{\chi}_1^0}^2\right)} \]

Works also for other combinations, e.g.
\[ m_{q\ell\ell}^{\text{max}} = \frac{1}{m_{\tilde{\chi}_2^0}} \sqrt{\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_L^0}^2\right)\left(m_{\tilde{\chi}_L^0}^2 - m_{\tilde{\chi}_1^0}^2\right)} \]

Different end-points ➔ clues about masses!
Derived Mass Spectrum of SUSY Particles mSUGRA LE+LHC 1 fb⁻¹

1σ Environment
2σ Environment
3σ Environment
Most Probable Value
Mean Value

Derived Particle Mass [GeV]

h⁰ A⁰ H⁰ H⁺χ₁⁰χ₂⁰χ₃⁰χ₄⁰χ₁⁺χ₂⁺τᵣ Lᵣ τ₁ τ₂ q_R q_L b₁ b₂ τ₁ τ₂ g
SUSY: COMBINED CMS RESULTS

CMS Preliminary

\( \sqrt{s} = 7 \text{ TeV}, \int \text{Ldt} = 1 \text{ fb}^{-1} \)

- 2011 Limits
- 2010 Limits

\( \tan \beta = 10, \ A_0 = 0, \ \mu > 0 \)

\( \tilde{g}, \tilde{q}, \tilde{g} \)

CDF \( \tilde{g}, \tilde{q}, \tan \beta = 5, \ \mu < 0 \)

D0 \( \tilde{g}, \tilde{q}, \tan \beta = 3, \ \mu < 0 \)

LEP2 \( \tilde{\chi}_{1}^\pm \)

LEP2 \( \tilde{\tau} \)

LHC will deliver the answer to the SUSY question!
But we have to understand (interpret) it. Need precision (LC)?
Fittino results (thanks to P. Bechtle) for SM+mSUGRA fit to measured observables.

\[ \text{Chi}^2 = 20.6 \text{ at } 23 \text{ d.o.f} \]

**Parameter** | **Value and Uncertainty**
--- | ---
\( \tan \beta \) | \( 13.2 \pm 7.2 \)
\( M_{12} \) | \( 331.5 \pm 86.6 \)
\( M_0 \) | \( 76.2^{+79.8}_{-29.2} \)
\( A_0 \) | \( 383.1 \pm 647.0 \)
\( \alpha_s \) | \( 0.1177 \pm 0.0020 \)
\( \alpha_{em} \) | \( 127.924 \pm 0.014 \)
\( m_Z \) | \( 91.1871 \pm 0.0020 \)
\( m_t \) | \( 172.4 \pm 1.1 \)
\( G_F \) | \( 1.16637 \cdot 10^{-5} \pm 1 \cdot 10^{-10} \)
SUSY not only solution to SM problems! Also other models introduce some necessary new particles to achieve goals.

Requests:
- electrically neutral
- heavy to participate in gravitation
- stable

⇒ Weakly interacting massive particles (WIMPs) with masses 100 GeV – 1 TeV to satisfy requirements (mainly explain DM density via correct annihilation cross section).
GRAND UNIFIED THEORIES (GUTs)

1/α₁, 1/α₂, 1/α₃

Couplings “almost” unify at high scales

SM “almost” simple and beautiful!

\[ L_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial_\mu - m_f) \Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \]

\[ + \frac{g}{\sqrt{2}} \sum_i (a_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^2 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu + \]

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\[ - ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu)|^2 + \]

\[ - \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^- - W_\mu^+ W_\nu^+)|^2 + \]

\[ - \frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta}{8 M_W} \eta^3 - \frac{g' M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2 \eta} W_\mu^+|^2 + \]

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GRAND UNIFIED THEORIES (GUTs)

Assumption:
SM SU(3) × SU(2) × U(1) embedded in larger symmetry, e.g.

\[ SU(5) \supset SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \]

Spontaneous breaking of GUT symmetry \( G_{\text{GUT}} \) at high scale!

- Existence of leptoquarks!
- Explanation of electric charge:
  sum of charges in multiplet 0!
- Prediction for weak mixing angle.
- Proton should decay!
- Complex models: unification!

\[ SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \subset SU(5) \subset SO(10) \subset E(6) \]
LEPTOQUARKS (AT HERA)

In GUT-inspired models: (always) leptoquarks – bosons with \( L,B \neq 0 \).

At colliders: test of (general) models with certain assumptions
e.g. BRW model (renormalisable, LQ-coupling invariant under \( SU(3) \times SU(2) \times U(1) \)…)

Searches for LQ: resonant production @HERA:

Signature: high-\( p_T \) jets with and \( e/E_{T,\text{miss}} \). Indistinguishable from NC/CC!!
LEPTOQUARKS AT HERA

... but different kinematics → optimise selection.

Search for LQ in invariant-mass spectrum of jet and $e/E_{T,\text{Miss}}$.

Unfortunately no signal

⇒ for each mass hypothesis:

exclusion limit for coupling $\lambda$!

For $M_{LQ} < 320$ GeV in s channel: strong limits for large $q(x)$ because

$$\sigma_{\text{prod}} \propto \lambda^2 q(x = M_{LQ}^2 / s_{ep})$$

Higher masses: little sensitivity in t channel.
LEPTOQUARKS IN PP(BAR)

At Tevatron / LHC:
Search for 2j+2l
(note: $\sigma$ independent
of $\lambda$ because of gauge
couplings to gluons)

Tevatron: no indications,
limits at about 270 GeV

LHC: similar to Tevatron!
Issue: background suppression:
- QCD: require two high-\(p_T\) leptons!
- Drell-Yan: require high \(M_{ll}\) and \(M_{lq}\)!
- tt production: require low \(E_{T,\text{miss}}\)!

Simulations: clear resonance
peaks visible. Limit: 400 GeV!
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- \( tt \) production: require low \( E_{T,\text{miss}} \)!

Simulations: clear resonance peaks visible. Limit: 400 GeV!
Remember hierarchy problem:

\[ M_{Pl} = \sqrt{\frac{\hbar c}{G_N}} \approx 1.2 \cdot 10^{19} \text{ GeV} \gg M_{EW} \]

Or: why gravitation so weak?
Consequence: \( m_H \) unstable!

Arkani-Hamed, Dimopoulos, Dvali (ADD, 98): 4+n dimensions !!!
- \( n \) additional dimensions in which (only) gravitation is felt – gravitation weak because it is dilute!
- \( M_{Pl} \) seems large only in 4D; real fundamental scale \( M_D \) smaller, gravitation in 4+n stronger!

\( \Rightarrow \) Hierarchy problem solved if \( M_D \sim 1\text{TeV} \)

Without proof:

With \( M_D \sim 1\text{TeV} \):

\[ M_{Pl}^2 = 8\pi R^n M_D^{n+2} \]

<table>
<thead>
<tr>
<th>( n )</th>
<th>( R )</th>
<th>Change of law of gravity: ( n=1 ) excluded!</th>
<th>ED as solution? Now question: size of ( M_D )!</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( R \approx 10^{12} \text{ m} )</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>( R \approx 0.4 \text{ mm} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>( R \approx 1 \text{ nm} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>( R \approx 1 \text{ fm} )</td>
<td></td>
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</tbody>
</table>
ED curled up (compactified) \( \rightarrow \) gravitons behave like particle in box \( \rightarrow \) equidistant mass states: Kaluza-Klein towers!

Large extra dimensions: \( \Delta M \) small \( \rightarrow \) continuum of states!

Direct production: G couples weakly \( \rightarrow \) ET, Miss, mono-photons, monojets

Virtual KK exchange \( \rightarrow \) modification of Xsections.

Mass limits: \( O(2 \text{ TeV})! \)
ED curled up (compactified) $\rightarrow$ gravitons behave like particle in box $\rightarrow$ equidistant mass states: Kaluza-Klein towers!

Large extra dimensions: $\Delta M$ small $\rightarrow$ continuum of states!

**SEARCH FOR EXTRA DIMENSIONS**

![Graph showing the lower limit of $M_D$ versus the number of extra dimensions with different color bands for CDFII, D0 (RunI), and LEP Combined.](image)

![Graph showing the $M_D$ (TeV) versus $p_{T,\text{cut}}$ (GeV) with different curves for different values of $\delta$.](image)

**ATLFAST**

![Graph showing the mass limits for different values of $S_{\text{max}}$ and $S_{\text{min}}$.](image)

$\delta = n$

$100 \text{ fb}^{-1}$

$s = 14 \text{ TeV}, 1 \text{ year at } 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
ED searches with virtual gravitons: Deviation from SM expectation?

So far nothing observed ➔ limits!
ED searches with virtual gravitons: Deviation from SM expectation?

So far nothing observed \(\rightarrow\) limits!

**Final LHC discovery potential (depending on n):**
- \(10 \text{ fb}^{-1}\): \(M_D = 5.1-6.5 \text{ TeV}\)
- \(100 \text{ fb}^{-1}\): \(M_D = 6.5-7.8 \text{ TeV}\)
Z’, NEW PHYSICS IN DIJETS

Remember: Dijet spectra:
Excellent description by NLO pQCD!!

Many new physics models
decaying to a pair of jets
Example: Z’→qq (GUT-like models)
Z’, NEW PHYSICS IN DIJETS

Remember: Dijet spectra:
Excellent description by NLO pQCD!!

Many new physics models
decaying to a pair of jets
Example: $Z’ \rightarrow qq$ (GUT-like models)

Comparison of data and theories / models $\rightarrow$ limits?
- New heavy physics mainly central ($\chi = 1$).
- Complementarity: $\chi$ sensitive to spin, centrality ratio to mass
# Z’, NEW PHYSICS IN DIJETS

<table>
<thead>
<tr>
<th>Model and Analysis Strategy</th>
<th>95% C.L. Limits (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td><strong>Excited Quark q^</strong>*</td>
<td></td>
</tr>
<tr>
<td>Resonance in ( m_{jj} )</td>
<td>2.07</td>
</tr>
<tr>
<td>( F_\chi(m_{jj}) )</td>
<td>2.12</td>
</tr>
<tr>
<td>Randall-Meade Quantum Black Hole for ( n = 6 )</td>
<td></td>
</tr>
<tr>
<td>**Resonance in ( m_{jj} )</td>
<td>3.64</td>
</tr>
<tr>
<td>( F_\chi(m_{jj}) )</td>
<td>3.49</td>
</tr>
<tr>
<td>( \theta_{np} ) Parameter for ( m_{jj} &gt; 2 ) TeV</td>
<td>3.37</td>
</tr>
<tr>
<td>11-bin ( \chi ) Distribution for ( m_{jj} &gt; 2 ) TeV</td>
<td>3.36</td>
</tr>
<tr>
<td><strong>Axigluon</strong></td>
<td></td>
</tr>
<tr>
<td>**Resonance in ( m_{jj} )</td>
<td>2.01</td>
</tr>
<tr>
<td><strong>Contact Interaction ( \Lambda )</strong></td>
<td></td>
</tr>
<tr>
<td>( F_\chi(m_{jj}) )</td>
<td>5.7</td>
</tr>
<tr>
<td>( F_\chi ) for ( m_{jj} &gt; 2 ) TeV</td>
<td>5.2</td>
</tr>
<tr>
<td>11-bin ( \chi ) Distribution for ( m_{jj} &gt; 2 ) TeV</td>
<td>5.4</td>
</tr>
</tbody>
</table>
Possible explanations: quark substructure, compositeness, contact interactions, …

Later explained in terms of re-definition of gluon density of the proton.

Don’t see new physics where it is not; don’t hide new physics in re-parametrisation of old …
MODEL INDEPENDENT SEARCHES
Many ideas for physics beyond the Standard Model. The next 1.5 years will (hopefully) show us the path!