New Physics at the LHC

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Universität Heidelberg

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Outline
The LHC

LHC — Large Hadron Collider: starting Summer 20XX
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- Einstein: beam energy to particle mass $E = mc^2$
  - smash 7 TeV protons onto 7 TeV protons [energy unit GeV: proton mass]
  - produce anything that couples to quarks and gluons
  - search for it in decay products
  - repeat every 25 ns

- huge detectors, computers, analysis... $\rightarrow$ experimental particle physics
- prejudice, fun and smart comments... $\rightarrow$ theoretical particle physics
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life as an experimentalist

life as a theorist
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Everything you always wanted to know...

- Atlas/CMS: measure anything flying around
- signal: everything new, exciting and rare
- background: yesterday’s signal
- Standard Model: theory of background
- QCD: evil background theory trying to kill us

- \( N_{\text{events}} = \sigma \cdot L \)  ['cross section times luminosity']
- trigger: soft jets — not on tape
- jet: everything except for leptons/photons
- crucial: what is inside a jet  \( [q, g, b, \tau \text{ tagged?}] \)
- discovery \( N_S / \sqrt{N_B} > 5 \)
Standard–Model effective theory

A brief history of our Standard–Model mess...

– Fermi 1934: theory of weak interactions \([n \rightarrow pe^- \bar{\nu}_e]\)
  
  (2 → 2) transition amplitude \(A \propto G_F E^2\)
  
  probability/unitarity violation
  
  pre-80s effective theory for \(E < 600\) GeV

– Yukawa 1935: massive particle exchange
  
  four fermions unitary for \(E \gg M\): \(A \propto g^2 E^2 / (E^2 - M^2)\)
  
  unitarity violation in \(WW \rightarrow WW\)
  
  current effective theory for \(E < 1.2\) TeV \([\text{LHC energy!!}]\)
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- Higgs 1964: spontaneous symmetry breaking
  unitarity for massive \(W, Z\)
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  fundamental scalar below TeV
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- ’t Hooft & Veltman 1971: renormalizability  
  beware of \(1/M\) couplings  
  gauge theories without cut-off  
  truly fundamental theory

⇒ 35 years later — no sign of weakness...
What is the Standard Model?

- gauge theory with local $SU(3) \times SU(2) \times U(1)$
- massless $SU(3)$ and $U(1)$ gauge bosons
  massive $W, Z$ bosons  
  [Higgs mechanism]
- Dirac fermions in doublets with masses = Yukawas
  generation mixing in quark and neutrino sector
- renormalizability $\mathcal{L} \sim -m^2_W W^\mu W^\mu - m_f \bar{\psi} \psi + g H \bar{\psi} \psi + \frac{g}{M} H W_{\mu \nu} W^{\mu \nu}$

$\Rightarrow$ fundamental theory: particle content, interactions, renormalizability
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⇒ fundamental theory: particle content, interactions, renormalizability

And how complete experimentally?

- dark matter?  [solid evidence for low–scale new physics!]
- quark mixing — flavor physics?  [new operators above $10^4$ GeV?]
- neutrino masses and mixing?  [see-saw at $10^{11}$ GeV?]
- matter–antimatter asymmetry?  [universe mostly matter?]
- gauge coupling unification real?
- gravity missing?  [mostly negligible but definitely unrenormalizaby]

⇒ physical cut-off unavoidable, size negotiable, renormalizability desirable
⇒ who the hell cares???
Standard–Model effective theory

Theorists care!!

– Heisenberg: compute quantum corrections to Higgs mass... \[ \Delta t \Delta E < 1 \]
Standard–Model effective theory

Theorists care!!

- Heisenberg: compute quantum corrections to Higgs mass...
  ...and watch the field–theory desaster unfold

\[ m_H^2 \longrightarrow m_H^2 - \frac{g^2}{(4\pi)^2} \frac{3}{2} \frac{\Lambda^2}{m_W^2} \left[ m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 \right] + \cdots \]

- Higgs mass pulled to physical cut-off \( \Lambda \) [where Higgs at \( \Lambda \) is not a Higgs]

\[ \Rightarrow \text{hierarchy problem — Higgs without stabilization incomplete} \]
Standard–Model effective theory

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\( \Rightarrow \) hierarchy problem — Higgs without stabilization incomplete

Starting from data which...

...indicates a light Higgs [e–w precision data]
...indicates higher–scale physics

- easy solution: counter term — but gauge theories don’t do tuning
- or new physics at TeV scale: supersymmetry extra dimensions little Higgs composite Higgs, TopColor [wish they were gone...]
YourFavoriteNewPhysics...

\( \Rightarrow \) typically cancellation by new particles or discussing away high scale
\( \Rightarrow \) beautiful concepts, but problematic in reality
\( \Rightarrow \) TeV–scale models in baroque state
Standard–Model effective theory

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\Rightarrow \text{hierarchy problem — Higgs without stabilization incomplete}

Expectations from the LHC

– find light Higgs?
– find new physics stabilizing Higgs mass?
– see dark–matter candidate?
Example: TeV–scale supersymmetry

Supersymmetry

- partner for each Standard–Model particle
- SUSY obviously broken by masses, mechanism unknown
- not an LHC paradigm: maximally blind mediation \([\text{MSUGRA, CMSSM}]\)
  - scalars — \(m_0\)
  - fermions — \(m_{1/2}\)
  - tri-scalar — \(A_0\)
  - Higgs sector — \(\text{sign}(\mu), \tan\beta\)
- assume dark matter, stable lightest partner

\[\Rightarrow\] measure BSM spectrum with missing energy at LHC
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⇒ measure BSM spectrum with missing energy at LHC

LHC searches: MSSM

- conjugate Higgs field not allowed
  - give mass to \(t\) and \(b\)?
  - five Higgs bosons
- SUSY–Higgs alone interesting

⇒ would be another talk...

⇒ list of SUSY partners

<table>
<thead>
<tr>
<th></th>
<th>spin</th>
<th>d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>fermion</td>
<td>(f_L, f_R)</td>
<td>1/2</td>
</tr>
<tr>
<td>→ sfermion</td>
<td>(\tilde{f}_L, \tilde{f}_R)</td>
<td>0</td>
</tr>
<tr>
<td>gluon</td>
<td>(G_\mu, \tilde{g})</td>
<td>1</td>
</tr>
<tr>
<td>→ gluino</td>
<td></td>
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<tr>
<td>gauge bosons</td>
<td>(\gamma, Z)</td>
<td>1</td>
</tr>
<tr>
<td>Higgs bosons</td>
<td>(h^0, H^0, A^0)</td>
<td>0</td>
</tr>
<tr>
<td>→ neutralinos</td>
<td>(\tilde{\chi}_i^0)</td>
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Supersymmetric signatures

New physics at the LHC

(1) discovery — signals for new physics
(2) measurements — spectrum, quantum numbers
(3) parameters — TeV-scale Lagrangian, underlying theory
⇒ approach independent of new physics model

Special about LHC, except bigger than Tevatron

– beyond inclusive searches [that was Tevatron]
  lots of strongly interacting particles
cascade decays to DM candidate
– general theme: try to survive QCD
– rates not good in $\frac{\alpha_s}{4\pi} \sim 0.01$
  (collinear) jets everywhere
  good LHC observables needed
⇒ aim at underlying theory
Supersymmetric signatures

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New physics measurements

Spectra from cascade decays

- more than $10^7$ squark–gluino events
- thresholds & edges

\[ m_{ij}^2 = E_i E_j - |\vec{p}_i| |\vec{p}_j| \cos \theta_{ij} \]

\[ 0 < m_{\mu\mu}^2 < \frac{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\mu}}^2}{m_{\tilde{\mu}}} \frac{m_{\tilde{\mu}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\mu}}} \]

- the longer decay chain the better

⇒ new–physics mass spectrum from cascade decays
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  - the longer decay chain the better
  ⇒ new–physics mass spectrum from cascade decays

Cascade masses from kinematics
- all decay jets $b$ quarks [otherwise dead by QCD]
- gluino mass to $\sim 1\%$
  ⇒ what’s more in $m_{ij}$?
New physics measurements

When do I believe it’s SUSY–QCD?

– gluinos: strongly interacting Majorana fermions
  Majorana = its own antiparticle
– first jet in gluino decay: $q$ or $\bar{q}$
– final–state leptons with charges $50\% - 50\%$
⇒ gluino = like–sign dileptons in SUSY–like events

\[
\tilde{g} \rightarrow \tilde{u} \rightarrow \tilde{\chi}^+ \rightarrow \mu^+ \\
\tilde{g} \rightarrow \tilde{u}^* \rightarrow \tilde{\chi}^- \rightarrow \mu^-
\]
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All new physics is hypothesis testing

– loop hole: ‘gluino is Majorana if it is a fermion’
– assume gluino cascade observed
– straw–man model where ‘gluino’ is a boson: universal extra dimensions
  [spectra degenerate — ignore; cross section larger — ignore]
⇒ compare angular correlations
New physics measurements

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Asymmetries

- shorter sqark decay chain
- shape between endpoints: $\hat{m} = m_{q\mu}/m_{q\mu}^{\text{max}} \sim \sin \theta/2$
- dominant $pp \rightarrow \tilde{q}\tilde{g}$ with $\tilde{q} : \tilde{q}^* \sim 2 : 1$
- production asymmetry with reduced errors

$$A(m_{\mu j}) = \frac{\sigma(j\mu^+) - \sigma(j\mu^-)}{\sigma(j\mu^+) + \sigma(j\mu^-)}$$

- kind of similar for gluino decay

$\Rightarrow$ gluino = fermion with like-sign dileptons
Weak boson fusion

Illustrating useful jets: spin of LSP

- Majorana LSP with like-sign charginos?
- hypotheses: like–sign charginos (SUSY)
  like–sign scalars (scalar dark matter)
  like–sign vector bosons (little–Higgs inspired)
- chargino decay/kinematics not used
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Like-sign scalars or fermions?

- charged Higgs in 2HDM
- $H^+ H^-$ same as simple $H^0$
- $W$ radiated off quarks [Goldstone coupling to Higgs]

$$P_T(x, p_T) \sim \frac{1 + (1 - x)^2}{2x} \frac{1}{p_T^2}$$

$\Rightarrow$ scalars with softer $p_{T,j}$
Weak boson fusion

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\[ P_T(x, p_T) \sim \frac{1}{2x} \left( \frac{1 - x}{x} \right)^2 \frac{1}{p_T^2} \]

\[ P_L(x, p_T) \sim \frac{(1 - x)^2}{x} \frac{m_W^2}{p_T^4} \]

$\Rightarrow$ scalars with softer $p_T, j$

Like-sign vectors or fermions?

- little–Higgs inspired
- start with copy of SM, heavy $W', Z', f'$
- Lorentz structure reflected in angle between jets

$\Rightarrow$ vectors with peaked $\Delta \phi_{jj}$
Weak boson fusion

Like-sign scalars or fermions?

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\( \Rightarrow \) vectors with peaked \( \Delta \phi_{jj} \)

Or else...

- nightmare: strongly interacting \( WW \)
Fundamental parameters

From kinematics to weak–scale parameters

– parameters: weak-scale Lagrangian
– measurements: better edges than masses,
  branching fractions, rates,...
  flavor, dark matter, electroweak constraints,...
– errors: general correlation, statistics & systematics & theory
– problem in grid: huge phase space, no local maximum?
  problem in fit: domain walls, no global maximum?
  problem in interpretation: bad observables, secondary maxima?

Probability maps of new physics

– want probability of model being true $p(m|d)$
  have exclusive likelihood map $p(d|m)$ over $m$
– Bayesian: $p(m|d) \sim p(d|m) \, p(m)$ with theorists’ bias $p(m)$  [cosmology, BSM]
  frequentist: best–fitting point $\max_m p(d|m)$  [flavor]
– getting rid of parameters: integration vs projection
– LHC era: (1) compute high-dimensional map $p(d|m)$
  (2) find and rank local best-fitting points
  (3) predict additional observables
Markov chains

Define set of representative points in new–physics space

– measure of ‘representative’: likely to agree with data  [Markov chain]
– evaluate any function over chain

(1) probability to agree with data

(2) Higgs mass from LEP and DM relic density
   LHC rates from LEP and DM relic density
   dark matter detection from LEP and/or LHC
   dates of birth of people on shift...

⇒ anything goes
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Bayesian probabilities vs profile likelihood

- ‘Which is the most likely parameter point?’
- ‘How does dark matter annihilate/couple?’

![Graph showing m₀ vs M₁/₂]
Fundamental parameters

MSSM map for LHC

- four neutralinos with (diagonal) mass parameters $M_1, M_2, \mu$
- three of four mass-eigenstate neutralinos observed
- alternative solutions in parameter space
Fundamental parameters

MSSM map for LHC

- four neutralinos with (diagonal) mass parameters $M_1, M_2, \mu$
- three of four mass-eigenstate neutralinos observed
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- quality of fit not useful: all the same...

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<th>$\mu &gt; 0$</th>
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<tbody>
<tr>
<td>$M_1$</td>
<td>96.6 175.1 103.5  365.8</td>
<td>98.3 176.4 105.9  365.3</td>
</tr>
<tr>
<td>$M_2$</td>
<td>181.2 98.4 350.0  130.9</td>
<td>187.5 103.9 348.4  137.8</td>
</tr>
<tr>
<td>$\mu$</td>
<td>-354.1 -357.6 -177.7 -159.9</td>
<td>347.8 352.6 178.0  161.5</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>14.6 14.5 29.1  32.1</td>
<td>15.0 14.8 29.2  32.1</td>
</tr>
<tr>
<td>$M_3$</td>
<td>583.2 583.3 583.3  583.5</td>
<td>583.1 583.1 583.3  583.4</td>
</tr>
<tr>
<td>$M_{\mu L}$</td>
<td>192.7 192.7 192.7  192.9</td>
<td>192.6 192.6 192.7  192.8</td>
</tr>
<tr>
<td>$M_{\mu R}$</td>
<td>131.1 131.1 131.1  131.3</td>
<td>131.0 131.0 131.1  131.2</td>
</tr>
<tr>
<td>$A_t (-)$</td>
<td>-252.3 -348.4 -477.1 -259.0</td>
<td>-470.0 -484.3 -243.4 -465.7</td>
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<tr>
<td>$A_t (+)$</td>
<td>384.9 481.8 641.5  432.5</td>
<td>739.2 774.7 440.5  656.9</td>
</tr>
<tr>
<td>$m_A$</td>
<td>350.3 725.8 263.1  1020.0</td>
<td>171.6 156.5 897.6  256.1</td>
</tr>
<tr>
<td>$m_t$</td>
<td>171.4 171.4 171.4  171.4</td>
<td>171.4 171.4 171.4  171.4</td>
</tr>
</tbody>
</table>

⇒ let’s try to not miss too many particles...
Beyond the LHC

Why theorists involved?

– want to learn statistics
– know about theory errors
– know about link with other observations and models

Beyond the LHC

– remember: unknown sign(µ), believe–based tan β from \( m_h \)

(1) maybe it’s new physics: \((g − 2)_µ \sim tan \beta\)

– strongly correlated and promising

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<th>LHC ( \otimes (g − 2) )</th>
<th>SPS1a</th>
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</thead>
<tbody>
<tr>
<td>( \tan \beta )</td>
<td>10.0± 4.5</td>
<td>10.3± 2.0</td>
<td>10.0</td>
</tr>
<tr>
<td>( M_1 )</td>
<td>102.1± 7.8</td>
<td>102.7± 5.9</td>
<td>103.1</td>
</tr>
<tr>
<td>( M_2 )</td>
<td>193.3± 7.8</td>
<td>193.2± 5.8</td>
<td>192.9</td>
</tr>
<tr>
<td>( M_3 )</td>
<td>577.2±14.5</td>
<td>578.2±12.1</td>
<td>577.9</td>
</tr>
<tr>
<td>( M_{\tilde{\mu}_L} )</td>
<td>193.2± 8.8</td>
<td>194.0± 6.8</td>
<td>194.4</td>
</tr>
<tr>
<td>( M_{\tilde{q}_3 L} )</td>
<td>481.4±22.0</td>
<td>485.6±22.4</td>
<td>480.8</td>
</tr>
<tr>
<td>( M_{\tilde{b}_R} )</td>
<td>501.7±17.9</td>
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<tr>
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<td>353.7</td>
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</tbody>
</table>
Beyond the LHC

Why theorists involved?

– want to learn statistics
– know about theory errors
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(1) maybe it’s new physics: $(g - 2)_\mu \sim \tan \beta$
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<table>
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<tr>
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<th>LHC $\otimes (g - 2)$</th>
<th>SPS1a</th>
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<tr>
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New Physics at the LHC

Tilman Plehn

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$\Rightarrow$ fundamental theory at all scales — happy neighbors!
New physics at the LHC

Need for new physics

- there is physics beyond Standard Model
- Higgs and new physics the same question
- LHC should find and study it

Supersymmetry one well-studied example

- solves the hierarchy problem
- easily explains dark matter
- cascade decays rule
- LHC to determine underlying model

LHC not only the biggest, but also the coolest machine!
New Physics at the LHC
Tilman Plehn