Physics Beyond The (Minimal Supersymmetric) Standard Model

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Introduction

What have we seen?

- **all collider experiments** are compatible with a renormalization of some 18 parameters of the dim $\leq 4$ operators invariant under

$$\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$$

standard model

- the $\text{SU}(2)_L \times \text{U}(1)_Y$ gauge symmetry appears to be spontaneously broken and vector bosons get their masses by eating a Goldstone boson, i.e. from a Higgs mechanism

- **all current data** are compatible with an elementary Higgs boson as the source of the Goldstone bosons

- if and only if interpreted as a fundamental renormalizable field theory, the data strongly favor a light Higgs boson

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Introduction

What have we seen?

- **(cold) dark matter**
  - several independent observations (WMAP, rotation curves, gravitational lensing, structure formation, &c.)
  - very little wiggle room, any serious BSM model must leave room for CDM candidates

- **(almost all) neutrinos have mass**
  - structurally not really BSM, b/c we can always add right handed singlets to obtain Dirac masses
  - still: elegance of the seesaw mechanism(s) suggest Majorana masses w/associated higher mass scale $\approx 10^{10}$ TeV
  - lepton flavor violation (e.g. $\mu^\pm \rightarrow e^\pm \gamma$) not unlikely

- **dark energy**
  - solid evidence (WMAP, type IA supernova), but no *hot* particle physics candidates yet

- **gravity**
  - the granddaddy of BSM physics
  - there *must* be a new scale $m_{\text{Planck}} \gg \nu$ (w/ $m_{\text{Planck},4D} \approx (10^{16}) \cdot \nu_F$)
Introduction

What do most of us expect?

*Grand unification* in some form is a central tenet of our discipline: “stuff becomes simpler at high energies — for a suitable notion of *simple*”, e.g. $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{SU}(5)$

*requires* BSM physics — some even at the *Terascale*

- assume gauge and Yukawa coupling unification
- there *should* be yet another new high scale
- does not work w/a *desert* above $v_F = 254$ GeV
- there *should* be yet another new *threshold*:
  $$m_{\text{Planck}} \gg m_{\text{threshold}} > v_F$$

coexistence of widely separated scales raises *naturalness* concerns

- if there is a new much higher scale, we *should* explain the *origin* and *stability* of the lower scales
- new *symmetries/particles* for the protection of the EWSB scale

*caveat*: viewed from the earth, the diameters of sun and moon appear to very finely tuned (anthropic principle: no astronomy, physics and higher mathematics w/o prediction of eclipses) . . .

- most fertile ground for Terascale BSM models to date . . .

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Introduction

What do some of us hope for?

*theoretical solution of the *flavor problem*

- number of generations
- mass and mixing hierarchies
- CP-violation

*observation of lepton flavor violation* beyond $\nu$-mixing

- do we owe our existence to leptogenesis?
- is there a seesaw mechanism?
- are there Majorana masses?
Introduction

What might take us by surprise?

- Occam’s razor might be dull: BSM physics can be a combination some or all of the above
  - nature is often more messy than we hope
    - be prepared!
  - there are examples for “strange” stuff that doesn’t fit nicely with (most of) our orthodoxy:
    - Unparticles
      - did anybody anticipate these propagators?
    - Noncommutativity
      - Lorentz invariance is hardwired in our brains . . .
  - nothing but the minimal SM plus an ad-hoc WIMP CDM candidate would be the biggest surprise of all

Perturbative

All the Way Up To the Planck Scale
Perturbative

- ironic: the ultimate **new physics** at LHC: the Higgs and nothing but the Higgs — the first **fine-tuned** theory that we once “understood”!
- NB: the fine tuning of the **cosmological constant** $\Lambda$ is worse, but nobody(?) claims to understand it . . .

∴ current consensus: two options
  - find a **symmetry** that protects the EWSB scale, and/or
  - explain EWSB **dynamically**

- many scenarios allow to maintain our successful approach to new physics all the way up to the Planck scale:
  - new physics in **contact interactions** $\propto 1/m_{NP}^2$
    ![Contact interactions diagram]
    - can be interpreted as new particles of mass $m_{NP}$

- examples: $Z'$, see-saw mechanism

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Supersymmetry

- for many (most?) SUSY is already contained in **release 2.0** of the **Standard Model**, which will be launched after a few $10^{-1}$ of LHC collisions have been analyzed in 201x
- very well motivated and well studied extension of the SM
- $\exists$ rich set of tools (dedicated and multi purpose) available — often very well tested in real applications
- $\exists$ multiple independent **cross checked** implementations of constrained versions of the MSSM, extensions in the works

∴ perturbatively renormalizable field theory allows clean factorization of tasks related to different scales, interfaces available, in particular SLHA
  - couplings from spectrum generators
  - scattering amplitudes from diagrammatic tools

∴ all-in-one packages for LO event samples feasible (new model $\lesssim$ MA-thesis)
Perturbative

Extended Higgs Sectors

- SUSY extensions of the SM require more than one Higgs doublet, but more general Higgs representations do not require SUSY
- just demand that
  - $\rho \approx 1$ naturally
  - FCNCs are naturally suppressed
- Glashow-Weinberg Criterion ['77] satisfied by 2HDM, w/mass eigenstates in reach of collider experiments
- popular source of CP-violation
  - many phenomenological studies
  - implemented in most (all?) all-in-one packages

Nonperturbative

Perturbative
Up To the Terascale
(but not much further)
Nonperturbative Extra Dimensions

- extra dimensions have been with us for a long, long time [Kaluza, Klein '21, '26] and string theory made them a necessity at the Planck scale
- Terascale extra dimensions became respectable in the late '90s [ADD '98, RS '99] (see also [Antoniadis '90])
- XDs play many (sometimes incompatible) rôles in Terascale particle physics
  - real XD:
    - can solve the hierarchy problem by a Terascale Planck mass
    - introduce infinite Kaluza-Klein towers
    - allow symmetry breaking by boundary conditions
    - unitarize VV scattering by exchange of KK partners
    - (ab)use the Xtra components of gauge fields as naturally light scalars
  - metaphorical XD: symmetries in deconstructed dimensions
  - holographical XD: powerful new description of strongly interacting models using the (conjectured!) AdS/CFT correspondence

Nonperturbative Real XD

- all degrees of freedom in XD represented by infinite Kaluza-Klein towers $m_n = n/R$:

\[
\Phi(x, y) = \sum_{n \in \mathbb{Z}} f_n(y) \phi_n(x)
\]

- orbifolding: identify points in the XD, e.g. $\Phi(x, y) = \Phi(x, 2\pi - y)$

\[
\Phi(x, y) = \sum_{n \in \mathbb{Z}} f_n(y) \phi_n(x)
\]

- “odd” modes are projected out
- fixed points (e.g. $y = 0, \pi$) correspond to branes
  $\therefore$ boundary conditions at the branes ($f_n(0) = 0, \partial_x f_n(0) = 0$, etc.)
Nonperturbative Metaphoric XD

- replace continuous XD by discrete XD

\[ \Phi(x, y) \rightarrow \{ \phi_n(x) = \Phi(x, 2\pi n/N) \}_{n=0,1,\ldots,N-1} \]

- finite dimensional representations of translation symmetry in XD
- can be combined with orbifolding, of course
- 5D gauge theory is equivalent to a collection of 4D gauged nonlinear sigma models

\[ \int dy \frac{1}{4} \text{tr}(F_{\mu\nu}F^{\mu\nu}) \Rightarrow \text{“lattice”} \Rightarrow \frac{1}{4} \sum_{n=1}^{N} \text{tr}(D_\mu \Phi^\dagger(x, y_n)D^\mu \Phi(x, y_n)) \]

- NB: one loop quadratic divergencies for uneaten goldstone bosons cancel from remnant of translational symmetry!

Nonperturbative Holographic XD

- replace flat XD by warped XD:

\[ y = 0 \quad \text{UV} \quad g_{\mu\nu} = e^{-2Rky} \eta_{\mu\nu} \quad \text{IR} \quad y = \pi \]

- NB: warped XD play a dual rôle
  - warp factor creates hierarchy \( m/M \approx e^{-Rk\pi} \)
  - if the AdS/CFT correspondence is correct, we can describe a strongly coupled 4D theory by a dual weakly coupled 5D theory!

- the technicolor and composite Higgs models of the ’70s and ’80s have been resurrected as models on AdS5!
- can be combined with deconstruction, of course
Nonperturbative Little Higgs

- **Little Higgs** started life as *deconstructed XD*

\[ \sum_n \frac{n}{\Lambda^2} \propto \sum_{-N/2 < n \leq N/2} \cos \left( 2\pi \frac{n}{N} + \phi \right) + g \ln \Lambda \]

- can be reproduced by internal symmetry breaking pattern, e.g.

\[
\text{SU(5)} \rightarrow \text{SO(5)}
\]

- drawbacks:
  - hierarchy problem merely postponed
  - two loop contributions remain quadratically divergent:

\[ \Lambda : 1 \text{ TeV} \rightarrow 10 \text{ TeV} \]

Nonperturbative Higgsless Models (a. k. a. (E)TC)

- Randall-Sundrum started with *only gravity* in the bulk (motivation: open string endpoints confined to D-branes)

- **warp factor** softens hierarchy from power to logarithm

- also: smallness of $\rho - 1$ (& other EW precision observables) not natural in EWSB by boundary conditions in flat XD

- can be explained by similar exponential suppression of the symmetry breaking sector [Csaki et al. '03]

\[
\begin{align*}
\text{SU(2)}_L \times \text{U(1)}_Y & \rightarrow \text{SU(2)}_D \times \text{U(1)}_X \\
\text{UV} & \quad \text{IR}
\end{align*}
\]

- couplings from overlap integrals in the extra dimension
Nonperturbative XD w/SUSY

- even higgsless models must provide reasonable CDM candidates
  - warp factors destroy Kaluza-Klein parity
  - ∄ stable Lightest KK Particle (LKP)
  - some additional physics BSM required
    - two branes with parity [Agashe et al. '07, Panico et al. '08]

- R-parity conserving SUSY in warped 5D [Knochel, TO '08]
  - SUSY well motivated to appear in UV completions of any effective model, including higgsless models

flat 5D \( N = 1 \) can be mapped to 4D \( N = 2 \)

- \( N = 2 \) SUSY broken by warp factor, only one \( y \)-dependent global
- \( N = 1 \) SUSY compatible with the metric (“killing spinors”)

\[
\xi(y) = e^{-Rky/2} \begin{pmatrix} \xi_0^\alpha \\ 0 \end{pmatrix}
\]

- remaining degeneracy must be lifted by soft breaking
- most elegantly by boundary conditions on the UV-brane
Nonperturbative XD w/SUSY

- spectrum of gauge bosons and matter together with KK and SUSY partners:

- couplings of the heavy gauge scalars ("sgauginos"),

\[ \approx m_f, \quad \langle \sigma (\chi \chi \rightarrow ff) \rangle \approx 0 \]

\therefore \text{ Higgs-like w/o vector boson fusion}

Nonperturbative XD w/SUSY

- estimate neutralino relic density freezeout at \( \approx \frac{m_\chi}{20} \)

\[
\frac{1}{\Omega h^2} \propto \langle \sigma (\chi \chi \rightarrow WW) \rangle + \langle \sigma (\chi \chi \rightarrow ff) \rangle \\
\approx 0 \text{ for } m_\chi < m_t, \quad m_\chi \ll m_f
\]

\[
\frac{1}{\Omega h^2} \\
\text{vs. } m_\chi \text{ GeV}
\]

\( m_\chi = 100 \)  
(\( m_\chi = 114 \))

\therefore \text{ Very good agreement with current WMAP data possible}
Nonperturbative

The Sgaugino $\Sigma^0$

- scalar $\Sigma$ as $N = 2$ partner of the gauge bosons
- no $\Sigma A_\mu A_\mu$ interaction $\implies$ no Vector boson fusion
- Interaction with fermions $\mathcal{L}_{\Sigma f\bar{f}} = g \frac{1}{(kz)} \chi(\Sigma_0 + iA_5) \eta + \text{h.c.}$

$$y^0_{\text{eff}} \propto \langle \Sigma_0 \eta_L \chi_L \rangle + \langle \Sigma_0 \eta_R \chi_R \rangle \begin{cases} m_f = 0 : & \eta_R = \chi_L = 0 \\ m_f > 0 : & \text{contributions from } \eta_R, \chi_L \end{cases}$$

- $y^0_{\text{eff}}$ grows with fermion mass, similar to SM Higgs: $y^0_{\text{eff}} \approx \frac{y_H}{3}$
- $\Sigma_0$ production similar to SM

- However: the sfermion partners of SM fermions are projected out by boundary conditions

- (potentially) large mass corrections

Nonperturbative

LHC

- tree level contributions to associated heavy quark and LSP pair production with a $q\bar{q}$ initial state.
Nonperturbative LHC

- tree level contributions to associated heavy quark and LSP pair production with a $gg$ initial state.

Model implemented by in WHIZARD [Kilian/TO/Reuter]

- commercial break:
  - fully automated Monte Carlo event generator generator (emphasis on BSM physics, w/and w/o SUSY)
    - http://whizard.event-generator.org (or hepforge.org)
  - $\alpha$-Version of Version 2 recently completed (still working out Fortran 2003 compiler kinks)
  - hadron colliders no longer an afterthought (Version 1 sometimes revealed its TESLA/ILC origins)

Kinematic cuts

<table>
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<tr>
<th>Variable</th>
<th>I</th>
<th>II.1</th>
<th>II.2</th>
<th>II.3</th>
</tr>
</thead>
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<td>$P_T(q),P_T(\bar{q})$</td>
<td>-</td>
<td>&gt; 100 GeV</td>
<td>&gt; 300 GeV</td>
<td>&gt; 100 GeV</td>
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<tr>
<td>$\Delta\phi(q,\bar{q})$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[0, 140°]</td>
</tr>
</tbody>
</table>

II.3 suppress SM background with back-to-back $t\bar{t}$ pairs
Nonperturbative LHC

- Missing energy in neutralino LSP pair production in association with top pairs (SM background: $\sqrt{s} t \bar{t}$):

\[ \frac{dN}{dE} \left( \frac{1}{\text{GeV}} \right) \]

<table>
<thead>
<tr>
<th>$P_T/\text{TeV}$</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
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<tbody>
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<td>80</td>
<td>70</td>
<td>60</td>
<td>50</td>
<td>40</td>
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<td>60</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>70</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>SM (N=14396)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
</tbody>
</table>

- Cuts II.1: $pp \rightarrow \chi^0 \chi^0 t \bar{t}$
  - 200 fb$^{-1}$ @ 14 TeV

\[ \frac{dN}{dE} \left( \frac{1}{\text{GeV}} \right) \]

<table>
<thead>
<tr>
<th>$P_T/\text{TeV}$</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
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<th>0.8</th>
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<td>10</td>
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<td>12</td>
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<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
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</table>

- Cuts II.2: $pp \rightarrow \chi^0 \chi^0 t \bar{t}$
  - 200 fb$^{-1}$ @ 14 TeV

\[ \frac{dN}{dE} \left( \frac{1}{\text{GeV}} \right) \]

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<thead>
<tr>
<th>$P_T/\text{TeV}$</th>
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<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

- Cuts II.3: $pp \rightarrow \chi^0 \chi^0 t \bar{t}$
  - 200 fb$^{-1}$ @ 14 TeV

\[ \frac{dN}{dE} \left( \frac{1}{\text{GeV}} \right) \]

<table>
<thead>
<tr>
<th>$P_T/\text{TeV}$</th>
<th>0</th>
<th>0.2</th>
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<td>$P_1^b$ quarks</td>
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<td>10</td>
<td>12</td>
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</tbody>
</table>

EFT

Model Independent EFT Approach
Most conservative approach:

- use only observed degrees of freedom
- implement observed exact and broken symmetries

\[ \mathcal{L} = \frac{1}{4} \text{tr} ( [D_\mu, D_\nu] [D^\mu, D^\nu] ) + \frac{v_F^2}{2} \text{tr} ( D_\mu U D^\mu U ) + \ldots \]

dependence of \( VV \to VV \) and \( VV \to t\bar{t} \) scattering on dim-4 operators

studied for ILC (\( e^+ e^- \to 6f/8f \)) and LHC (\( pp \to 6f/8f \))

custodial \( SU(2)_c \) conserving:

\[ \mathcal{L}_4 = \alpha_4 \text{tr} [V_\mu V_\nu] \text{tr} [V^\mu V^\nu] \]
\[ \mathcal{L}_5 = \alpha_5 \text{tr} [V_\mu V^\mu] \text{tr} [V_\nu V^\nu] \]

where \( V_\mu = U^\dagger D_\mu U \)

\[ \sigma \text{ [fb]} \]
\[ e^+ e^- \to \bar{\nu} \nu W^+ W^- \]

\[ +1\sigma \]

\[ [\alpha_4 = 0, \alpha_5] \]
\[ [\alpha_4, \alpha_5 = 0] \]
our 1997 Dream Machine could probe $\alpha_{4,5}$ at the "magic"
$\Theta(10^{-3}) \lesssim 1/(16\pi^2)$ suggested by naive dimensional analysis

\[
e^{-e^-} \to \nu W^-W^-
\]
\[
e^+e^- \to \bar{\nu}W^+W^-
\]
\[
e^+e^- \to \bar{\nu}ZZ
\]

\[
\sqrt{s} = 1.6 \text{ TeV}
\int \mathcal{L} = 500 \text{ fb}^{-1}
100\%/50\% \text{ pol.}
\]

custodial $SU(2)_c$ violation:

\[
\mathcal{L}_6 = \alpha_6 \operatorname{tr} [V_\mu V_\nu] \operatorname{tr} [\mathcal{T} V^\mu] \operatorname{tr} [\mathcal{T} V^\nu]
\]
\[
\mathcal{L}_7 = \alpha_7 \operatorname{tr} [V_\mu V^\mu] \operatorname{tr} [\mathcal{T} V^\nu] \operatorname{tr} [\mathcal{T} V^\nu]
\]

where \( \mathcal{T} = U\tau_3 U^\dagger \).
Who Ordered That?

PoS(LCPS2009)003

Th. Ohl (Würzburg)

Who Ordered That?

Noncommutative Space Time

Quantum mechanics: measurements of coordinate and momentum are complementary

\[
\Delta x_i \cdot \Delta p_j \geq \hbar / 2 \cdot \delta_{ij}
\]

More formal: the corresponding operators don’t commute

\[
[x_i, p_j] = x_i p_j - p_j x_i = i\hbar \delta_{ij}
\]

Currently no exp. evidence for complementary coordinate pairs:

\[
\Delta x_\mu \cdot \Delta x_\nu \neq 0 \iff [x_\mu, x_\nu] \neq 0
\]

nevertheless

\[
[x_\mu, x_\nu] = i\theta_{\mu\nu} = \frac{iC_{\mu\nu}}{\Lambda_{NC}^2}
\]

possible, as long as characteristic energy scale \( \Lambda_{NC} \) large and corresponding minimal area in the \( e_\mu \land e_\nu \)-plane

\[
a_{NC} = l_{NC}^2 = 1 / \Lambda_{NC}^2
\]

small compared to the resolution of present experiments.

Th. Ohl (Würzburg)
Who Ordered That? Noncommutative Space Time

Why is it interesting?

- Fundamental length scale
  - $x_\mu$-continuum $\Rightarrow$ lattice of eigenvalues of operators $\hat{x}_\mu$
    (lattice constant $\sim 1/\Lambda_{NC}$) [Snyder, Wess]
  - smooth cut off of some divergent contributions $E > \Lambda_{NC}$ in quantum gravity (cf. $\hbar$ and black body radiation)
  - internal and space-time symmetries do not commute any more
  - richer symmetry structure

- String theory
  - NCQFT is low energy limit of certain string theories [Seiberg, Witten]
  - more than 2000 citations for a single paper written in 1999...
  - no prediction for the value of $\Lambda_{NC}$

- special (simplest) case: $\theta^{\mu\nu}$ constant $4 \times 4$-matrix:

  \[
  [\hat{x}^\mu, \hat{x}^\nu] = i\theta^{\mu\nu} = i\frac{1}{\Lambda_{NC}^2} C^{\mu\nu} = i\frac{1}{\Lambda_{NC}^2} \begin{pmatrix}
  0 & -E^1 & -E^2 & -E^3 \\
  E^1 & 0 & -B^3 & B^2 \\
  E^2 & B^3 & 0 & -B^1 \\
  E^3 & -B^2 & B^1 & 0
  \end{pmatrix}
  \]

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- simpler, but equivalent realization: replace all point products of functions of noncommuting coordinates
  \[
  (f \cdot g)(\hat{x}) = f(\hat{x})g(\hat{x})
  \]

  by Moyal-Weyl-\*$-$products of functions of commuting coordinates:

  \[
  (f \ast g)(x) = f(x)e^{i\frac{\theta^{\mu\nu}}{\Lambda_{NC}^2} \partial^\mu \partial^\nu} g(x) = f(x)g(x) + \frac{i}{2} \theta^{\mu\nu} \frac{\partial f(x)}{\partial x_\mu} \frac{\partial g(x)}{\partial x_\nu} + O(\theta^2)
  \]

- then $(x_\mu \ast x_\nu)(x) = x_\mu x_\nu + \frac{i}{2} \theta^{\mu\nu}$ and in particular

  \[
  [x_\mu \ast x_\nu](x) = (x_\mu \ast x_\nu)(x) - (x_\nu \ast x_\mu)(x) = i\theta^{\mu\nu}
  \]

- new interaction vertices among gauge and matter fields from expanding Moyal-Weyl-$\ast$-$products$ and Seiberg-Witten-Maps as determined by gauge invariance

  \[
  g(\bar{\psi} \ast \hat{A} \ast \psi)(x) = g(\bar{\psi}(x)\hat{A}(x)\psi(x) + O(\theta)
  \]

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e.g. at $\mathcal{O}(\theta)$ with all momenta outgoing

\[
\begin{align*}
\text{canon. NC extension of the SM known to } &\mathcal{O}(\theta^2) \\
\text{standard acceptance cuts and } &85 \text{ GeV} < m_{\ell^+\ell^-} < 97 \text{ GeV,} \\
&200 \text{ GeV} < m_{\ell^+\ell^-\gamma} < 1 \text{ TeV, } 0 < \cos \theta_Z^* < 0.9, \\
&\cos \theta_Z > 0 \text{ and } \cos \theta_{\gamma} > 0 \text{ (favoring } \bar{q}q \text{ over } q\bar{q}!)
\end{align*}
\]
Who Ordered That? Noncommutative Space Time

likelihood fits for $\Lambda_{NC} = 500 \text{ GeV}$ [Alboteanu, T. O., Rückl, PRD74]

- only the expected kinematical correlations of $(E_1, B_2)$ and $(E_2, B_1)$
- $\Lambda_{NC} \gtrsim 1 \text{ TeV}$ can be easily probed at the LHC
- unfortunately, hard to reconcile with Lorentz violation bounds from atomic physics and astronomy

Facts of Life . . .

- Light fermions couple very weakly to the Electroweak Symmetry Breaking sector
  
  - Standard Model Yukawa Couplings

  \[
  \mathcal{L} \supset \frac{m_f}{v_F} H \bar{\psi}_f \psi_f \implies \frac{d\sigma}{d\Phi} (f\bar{f} \to H) \propto \frac{m_f^2}{v_F^2}
  \]

  - generically in any chiral Effective Field Theory description

  \[
  \mathcal{L} \supset m_f \bar{\psi}_f \psi_f \exp \left( \frac{i}{v_F} \Phi \right) \implies \frac{d\sigma}{d\Omega} (f\bar{f} \to \Phi) \propto \frac{m_f^2}{v_F^2}
  \]

∴ cross sections for the direct excitation of the EWSB sector at LHC ($u, d$) and ILC ($e^\pm$) are strongly suppressed
Couplings of all fermions except top have been measured very precisely at LEP 1.

All observed Flavor Changing Neutral Currents can be explained by penguin and box diagrams.

New particles in models of any new physics are very likely to be fermiophobic (with an exception for top quarks).

Direct production cross sections for new gauge bosons &c. at ILC and LHC strongly suppressed again!

New physics appears to suffer from fermiophobia!

Produce excitations of the EWSB sector (e.g. Higgs bosons) in association with heavy particles (i.e. \( m = \mathcal{O}(v_F) \)) via their known gauge couplings.

- e.g. top-quarks

- or W and Z bosons

At a 500 GeV LHC, the cost of producing an additional \( t\bar{t} \)-pair pushes it back to the threshold of a light Higgs:

\[
500 \text{ GeV} - 2m_t = 150 \text{ GeV}
\]

LHC advantage: colored new physics must have a large cross section in gluon-gluon scattering.

NB: guaranteed by universality of the strong coupling.
Trick: generate almost real massive gauge bosons ($W^\pm$ and $Z$) with known gauge couplings by bremsstrahlung off light fermions and let them scatter.

- Cross section suppressed by additional gauge couplings

\[
\left( \frac{\alpha}{\pi} \right)^2 \approx 5 \cdot 10^{-6}
\]

- But enhanced by

\[
\left( \frac{m_{W,Z}}{m_e} \right)^2 \approx 3 \cdot 10^9
\]

Net gain of $\mathcal{O}(10^3)$

Drawback: lower energy available in the CMS of the vector bosons, because of soft bremsstrahlung spectrum (see below)

Upper Higgs mass reach of linear collider dominated by Vector Boson Fusion:

- $e^+e^- \rightarrow H +$ neutrinos

\[
\sigma [\text{fb}] \quad \sqrt{s} = 500 \text{ GeV}
\]
Conclusions

- 1990s: LEP enforced **triumph** of the minimal **standard model**
- 2000s: theorists running wild due to lack of supervision from experimentalists: plethora of new and **repackaged** BSM models
- 2010s: LHC
  - will most of the content of arXiv.org be obsolete soon, or
  - will we have to come up with completely new ideas?
- 2020s: ILC/CLIC: **Will the fog be lifted?**