PROCEEDINGS OF SCIENCE

Physics Beyond The (Minimal Supersymmetric) Standard Model

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Who Ordered That?

What have we seen?

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

$$\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$$

  standard model
- the $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$ 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

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. $\mu^{\pm} \to e^{\pm}\gamma$) 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 $m_{\text{Planck}} \gg v$ (w/ $m_{\text{Planck,4D}} = \mathcal{O}(10^{16}) \cdot v_{\mathrm{F}}$)

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. $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{SU}(5)$
- 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 $v_F = 254\,\mathrm{GeV}$
  - ∴ there should be yet another new threshold:

    $m_{\mathrm{Planck}} \gg m_{\mathrm{threshold}} > v_F$
- 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 . . .

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

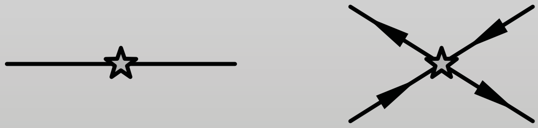
- Occam's razor might be dull: BSM physics can be a combination some or all of the above
  - nature is often more messy than we hope
  - ∴ be prepared!
- there are examples for "strange" stuff that doesn't fit nicely with (most of) our orthodoxy:
  - Unparticles
    - did anybody anticipate these propagators?
  - 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

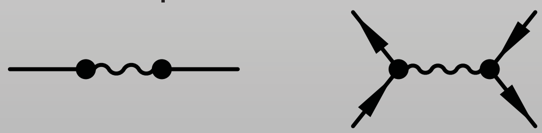
Perturbative

- 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 Λ 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 $\propto 1/m_{\text{NP}}^2$



  - can be interpreted as new particles of mass m_{NP}



- examples: Z', see-saw mechanism

Perturbative Supersymmetry

- for many (most?) SUSY is already contained in release 2.0 of the Standard Model which will be launched after a few 10 fb^{-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 SLHAn
  - couplings from spectrum generators
  - scattering amplitudes from diagrammatic tools

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

- 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

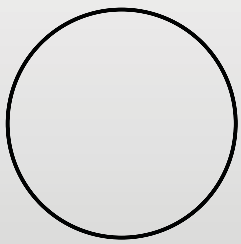
Perturbative
Up To the Terascale
(but not much further)

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

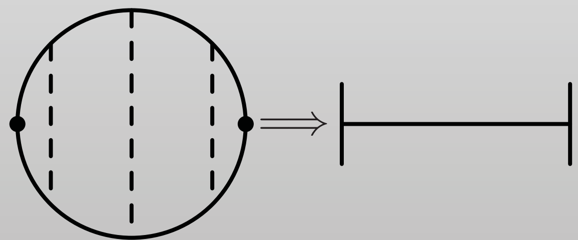
Nonperturbative — Real XD

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



$$: \Phi(x,y) = \sum_{n\in\mathbf{Z}} f_n(y)\phi_n(x)$$

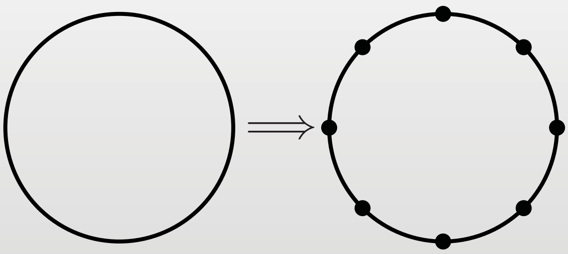
- orbifolding: identify points in the XD, e. g. $\Phi(x,y) = \Phi(x, 2\pi - y)$



$$: \Phi(x,y) = \sum_{n\in 2\mathbf{Z}} f_n(y)\phi_n(x)$$

  - "odd" modes are projected out
  - fixed points (e. g. $y = 0, \pi$) correspond to branes
  - $\therefore$ boundary conditions at the branes ($f_n(0) = 0$, $\partial_z f_n(0) = 0$, etc.

- replace continuous XD by discrete XD



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

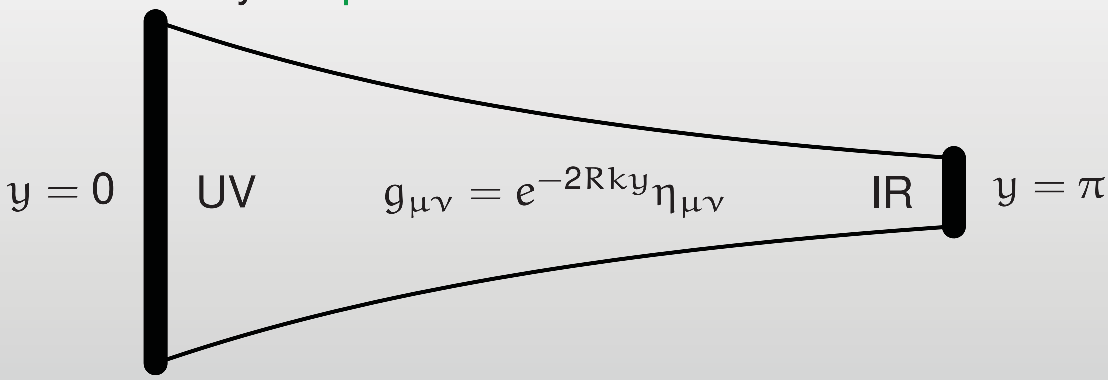
∴ finite dimensional representations of translation symmetry in XD

- can be combined with orbifolding, of course
- 5D gauge theory is equivalent to a collection of 4D gauged nonlinear sigma models

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

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

- replace flat XD by warped XD:



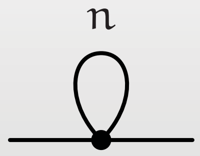
- NB: warped XD play a dual rôle
  - warp factor creates hierarchy $m/M \approx e^{-Rk\pi}$
  - if the AdS/CFT correspondence is correct, we can describe a strongly coupled 4D theory by a dual weakly coupled 5D theory!

∴ 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

- Little Higgs started life as deconstructed XD

$$\sum_n$$



$$\propto \Lambda^2 \cdot \underbrace{\sum_{-N/2<n\leqslant N/2} \cos\left(2\pi\frac{n}{N}+\phi\right)}_{=0} + g \ln \Lambda$$

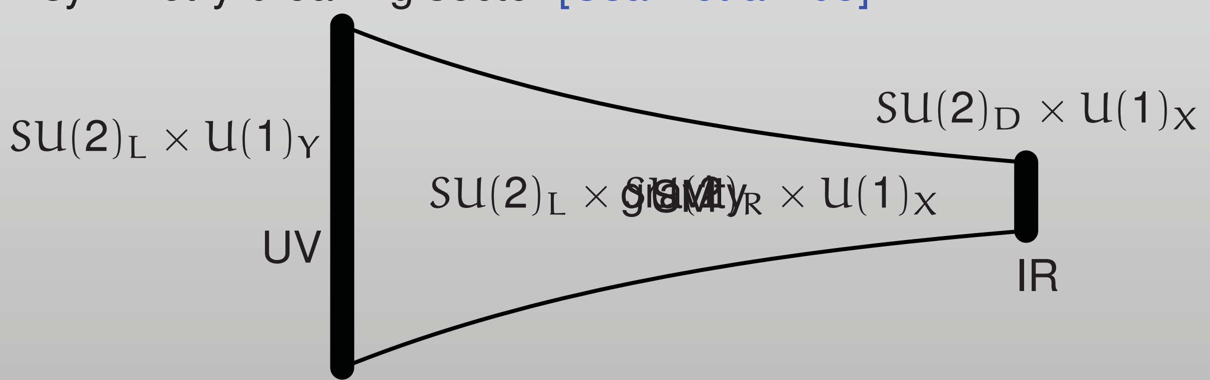
- can be reproduced by internal symmetry breaking pattern, e. g.

$$\mathrm{SU}(5) \to \mathrm{SO}(5)$$

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

$$\Lambda : 1\,\mathrm{TeV} \to 10\,\mathrm{TeV}$$

- 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]



- couplings from overlap integrals in the extra dimension

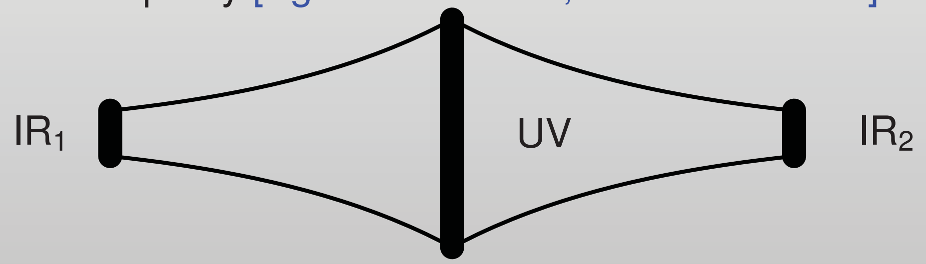
- even higgsless models must provide reasonable CDM candidates

$\because$ warp factors destroy Kaluza-Klein parity

$\therefore$ $\nexists$ stable Lightest KK Particle (LKP)

$\therefore$ some additional physics BSM required

  - two branes with parity [Agashe et al. ’07, Panico et al. ’08]



  - $\mathcal{R}$-parity conserving SUSY in warped 5D [Knochel, TO ’08]

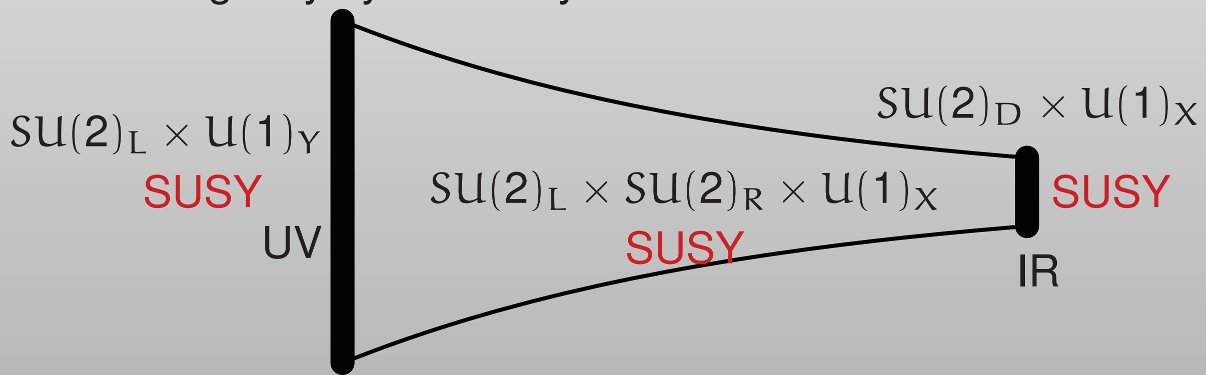
  $\because$ SUSY well motivated to appear in UV completions of any effective model, including higgsless models

- flat 5D $\mathcal{N} = 1$ can be mapped to 4D $\mathcal{N} = 2$
- $\mathcal{N} = 2$ SUSY broken by warp factor, only one y-dependent global $\mathcal{N} = 1$ SUSY compatible with the metric (“killing spinors”)

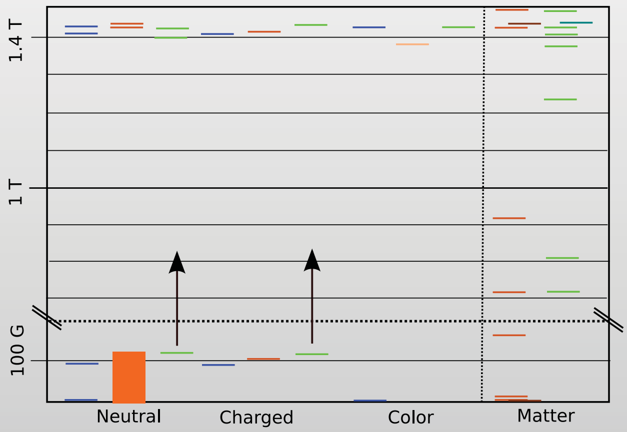
$$\xi(y) = e^{-Rky/2} \begin{pmatrix} \xi^0_\alpha \\ 0 \end{pmatrix}$$

$\therefore$ remaining degeneracy must be lifted by soft breaking

- most elegantly by boundary conditions on the UV-brane



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



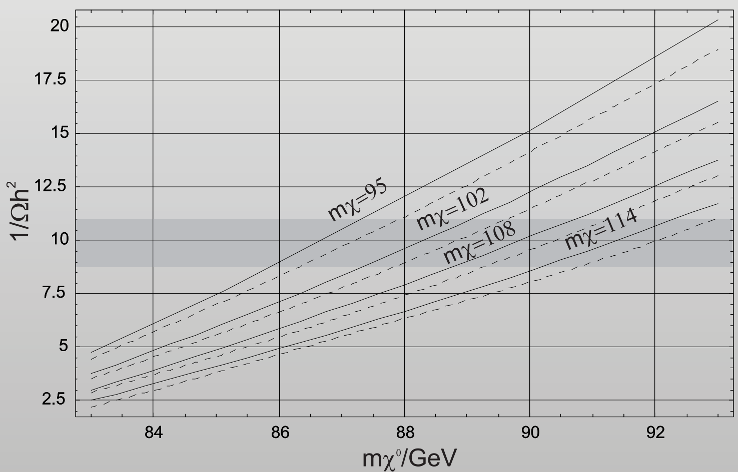
- couplings of the heavy gauge scalars ("sgauginos"),

$$\approx m_f \,, \qquad \approx 0$$

∴ Higgs-like w/o vector boson fusion

- estimate neutralino relic density freezeout at $\approx m_\chi/20$

$$1/\Omega h^2 \propto \langle v\sigma(\chi\chi \to WW)\rangle + \underbrace{\langle v\sigma(\chi\chi \to f\bar f)\rangle}_{\approx 0 \text{ for } m_\chi < m_t,\, m_\chi \ll m_{\tilde f}}$$



- Very good agreement with current WMAP data possible

The Sgaugino Σ^0

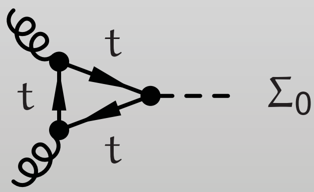
- scalar Σ as $\mathcal{N}=2$ partner of the gauge bosons
- no $\Sigma A_\mu A_\mu$ interaction $\Longrightarrow$ no Vector boson fusion

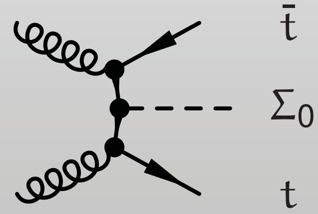
$\because$ Interaction with fermions $\mathcal{L}_{\Sigma f\bar{f}} = g\frac{1}{(kz)^5}\chi(\Sigma_0 + iA_5)\eta + \text{h. c.}$

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

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

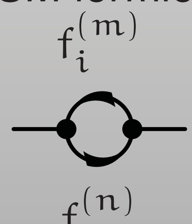
$\therefore$ Σ_0 production similar to SM

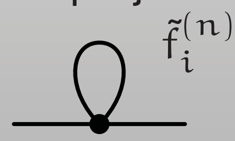




$\because$ However: the sfermion partners of SM fermions are projected out by boundary conditions

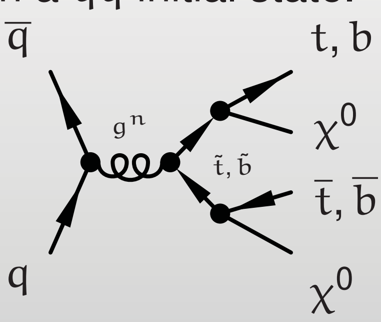
$\therefore$ (potentially) large mass corrections

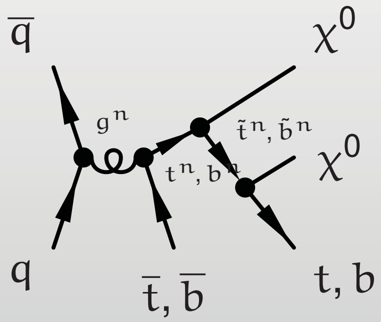


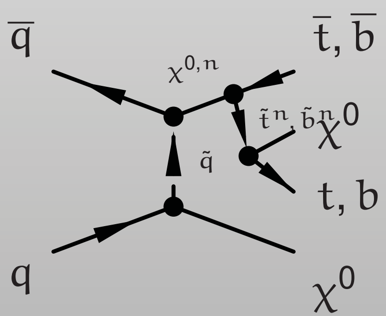


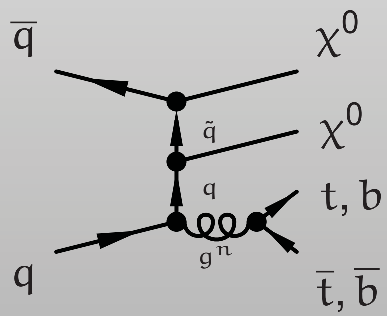
LHC

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

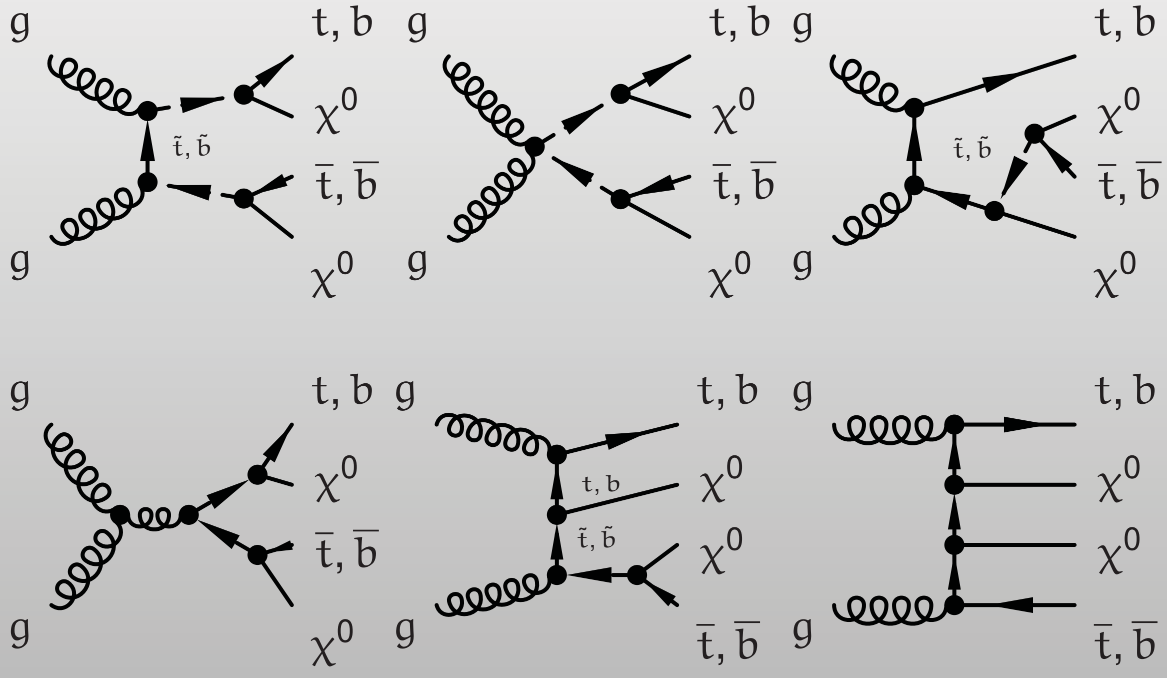








- tree level contributions to associated heavy quark and LSP pair production with a gg initial state.



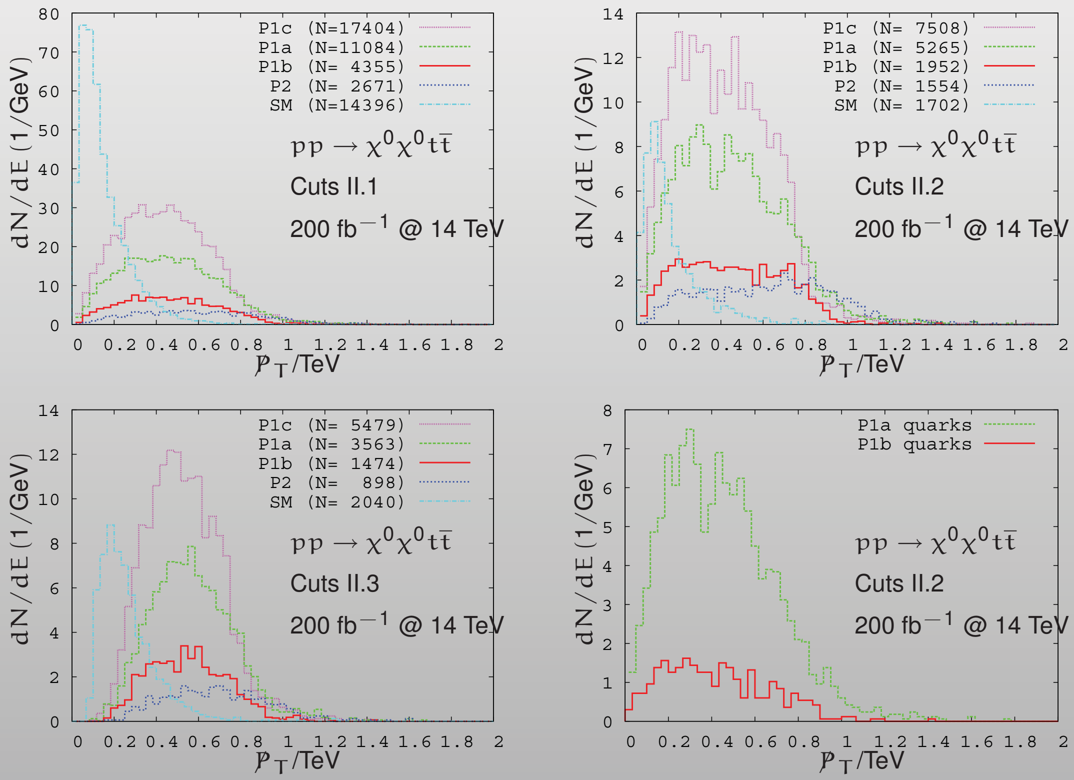
- Model implemented by in WHIZARD [Kilian/TO/Reuter]
- commercial break:
  - fully automated Monte Carlo event generator generator (emphasis on BSM physics, w/and w/o SUSY)

    `http://whizard.event-generator.org` (or `hepforge.org`)
  - α-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

Variable	I	II.1	II.2	II.3
$P_T(q)$,$P_T(\bar{q})$	-	$>$ 100 GeV	$>$ 300 GeV	$>$ 100 GeV
$\Delta\phi(q,\bar{q})$	-	-	-	$[0, 140^\circ]$

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

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



Model Independent EFT Approach

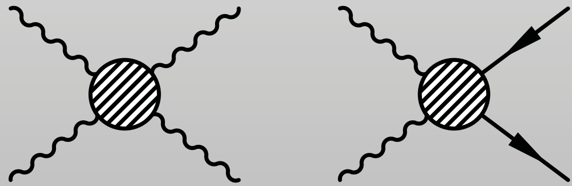
Chiral Lagrangian

- Most conservative approach:
  - use only observed degrees of freedom
  - implement observed exact and broken symmetries

  ∴ effective chiral Lagrangian for $SU_L(2) \times SU_R(2) \to SU_C(2)$ breaking

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

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



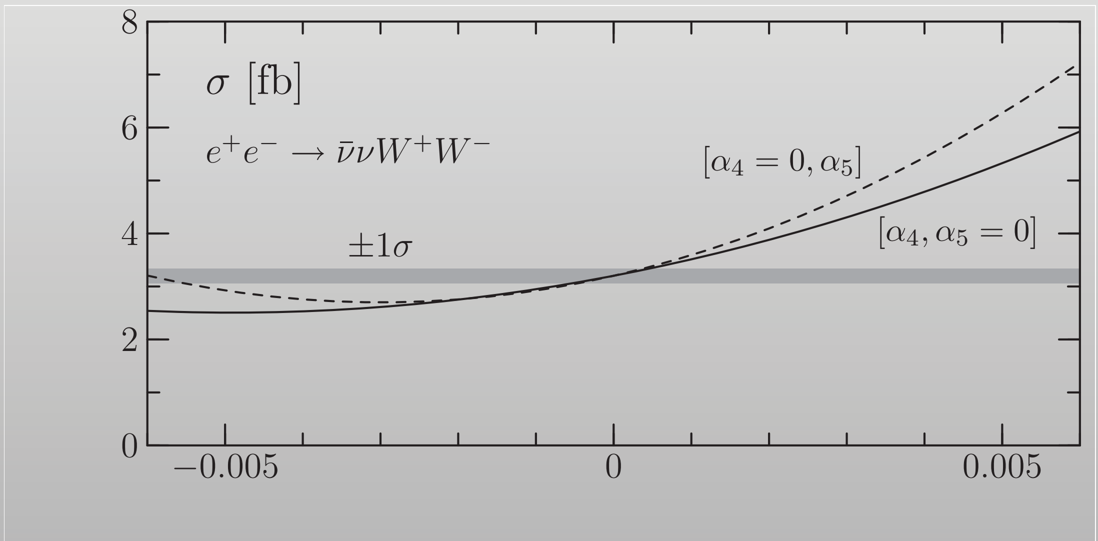
studied for ILC ($e^+e^- \to 6f/8f$) and LHC ($pp \to 6f/8f$)

$VV \to VV$ Below Threshold

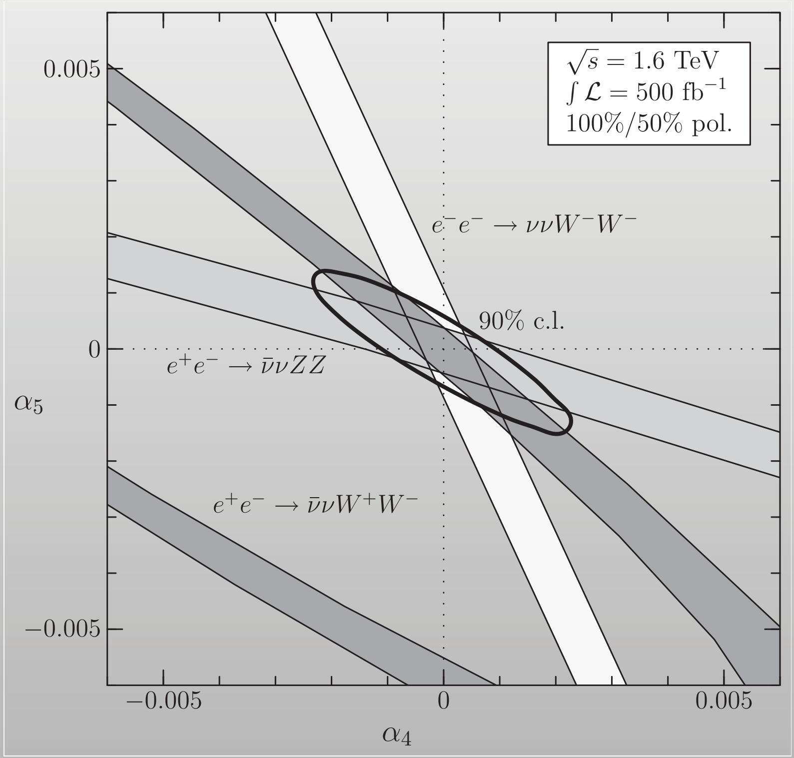
- custodial $SU(2)_c$ conserving:

$$\mathcal{L}_4 = \alpha_4 \operatorname{tr}\left[V_\mu V_\nu\right] \operatorname{tr}\left[V^\mu V^\nu\right]$$
$$\mathcal{L}_5 = \alpha_5 \operatorname{tr}\left[V_\mu V^\mu\right] \operatorname{tr}\left[V_\nu V^\nu\right]$$

where $V_\mu = U^\dagger D_\mu U$



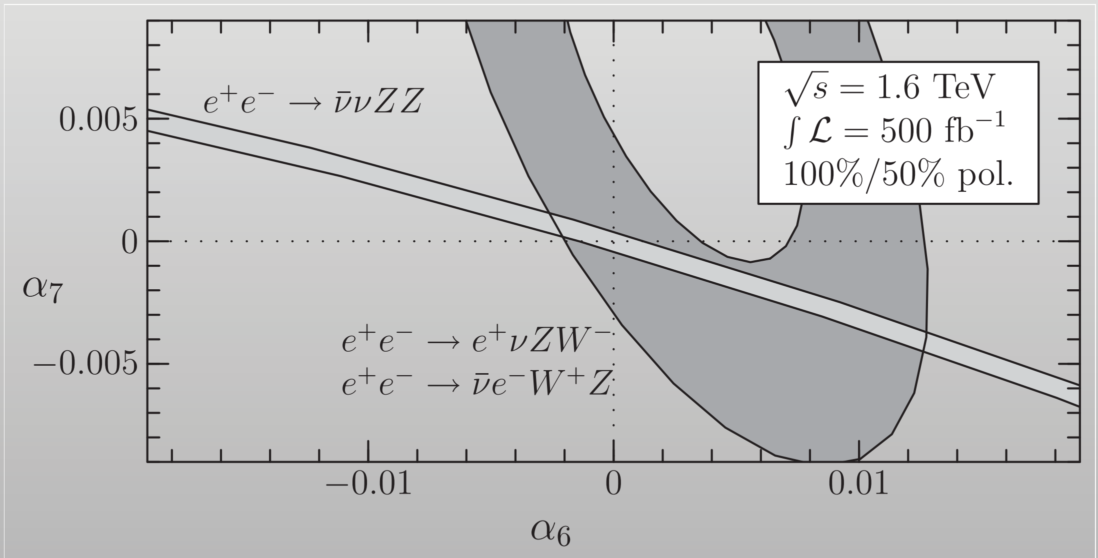
- our 1997 Dream Machine could probe $\alpha_{4,5}$ at the "magic" $\mathcal{O}(10^{-3}) \lesssim 1/(16\pi^2)$ suggested by naive dimensional analysis



- 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?

Noncommutative Space Time

- Quantum mechanics: measurements of coordinate and momentum are complementary

$$\Delta x_i \cdot \Delta p_j \geqslant \hbar/2 \cdot \delta_{ij}$$

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:

$$\Delta x_\mu \cdot \Delta x_\nu \stackrel{?}{=} 0 \quad \Leftrightarrow \quad [x_\mu, x_\nu] \stackrel{?}{=} 0$$

- nevertheless

$$[\hat{x}_\mu, \hat{x}_\nu] = i\theta_{\mu\nu} = i\frac{C_{\mu\nu}}{{\Lambda_{NC}}^2}$$

possible, as long as characteristic energy scale Λ_{NC} large and corresponding minimal area in the $e_\mu \wedge e_\nu$-plane

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

small compared to the resolution of present experiments.

Why is it interesting?

- Fundamental length scale
  - x_μ-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)
  - $\because$ internal and space-time symmetries do not commute any more
  - $\therefore$ 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 Λ_{NC}
- special (simplest) case: $\theta^{\mu\nu}$ constant 4×4-matrix:

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

- 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:

$$(f * g)(x) = f(x)e^{\frac{i}{2}\overleftarrow{\partial^\mu}\theta_{\mu\nu}\overrightarrow{\partial^\nu}}g(x) = f(x)g(x) + \frac{i}{2}\theta_{\mu\nu}\frac{\partial f(x)}{\partial x_\mu}\frac{\partial g(x)}{\partial x_\nu} + \mathcal{O}(\theta^2)$$

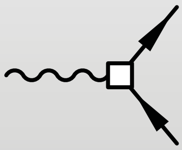
- then $(x_\mu * x_\nu)(x) = x_\mu x_\nu + \frac{i}{2}\theta_{\mu\nu}$ and in particular

$$[x_\mu \overset{*}{,} x_\nu](x) = (x_\mu * x_\nu)(x) - (x_\nu * x_\mu)(x) = i\theta_{\mu\nu}$$

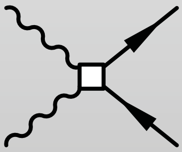
- new interaction vertices among gauge and matter fields from expanding Moyal-Weyl-$*$-products and Seiberg-Witten-Maps as determined by gauge invariance

$$g(\hat{\bar{\psi}} * \hat{\not{A}} * \hat{\psi})(x) = g\bar{\psi}(x)\not{A}(x)\psi(x) + \mathcal{O}(\theta)$$

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



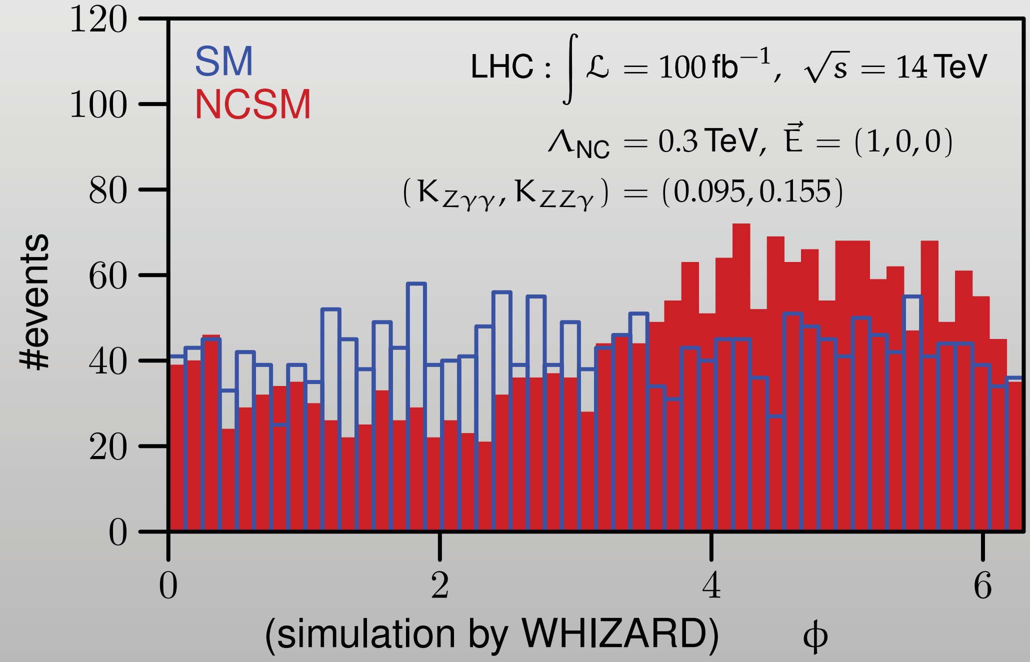
$$= ig \cdot \frac{i}{2}\left[(k\theta)_\mu \not{p} + (\theta p)_\mu \not{k} - (k\theta p)\gamma_\mu\right]$$



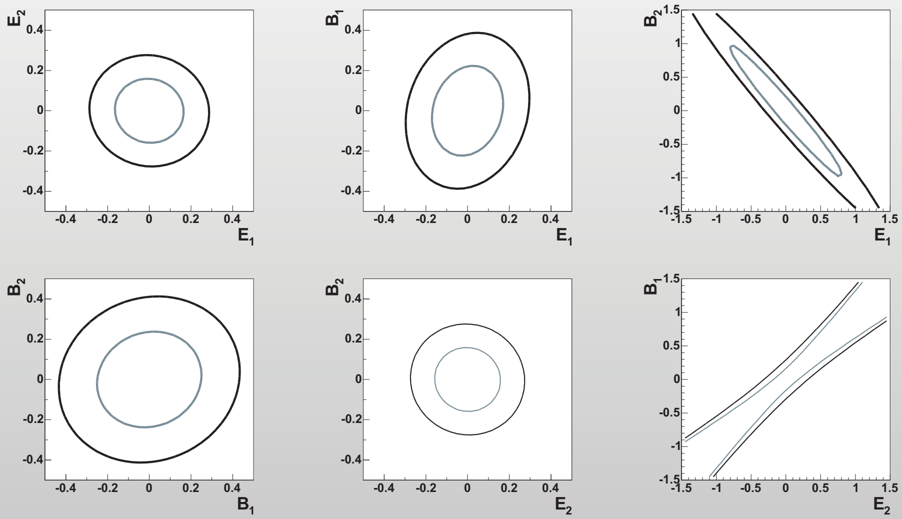
$$= ig^2 \cdot \frac{i}{2}\Big[(\theta(k_1 - k_2))_{\mu_1}\gamma_{\mu_2} - (\theta(k_1 - k_2))_{\mu_2}\gamma_{\mu_1} - \theta_{\mu_1\mu_2}(\not{k}_1 - \not{k}_2)\Big]$$

- canonical NC extension of the SM known to $\mathcal{O}(\theta^2)$

standard acceptance cuts and 85 GeV $< m_{\ell^+\ell^-} <$ 97 GeV,
200 GeV $< m_{\ell^+\ell^-\gamma} <$ 1 TeV, $0 < \cos\theta^*_\gamma < 0.9$,
$\cos\theta_Z > 0$ and $\cos\theta_\gamma > 0$ (favoring $\bar{q}q$ over $q\bar{q}$!)



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



- only the expected kinematical correlations of (E_1, B_2) and (E_2, B_1)

$\therefore$ $\Lambda_{NC} \gtrsim 1$ TeV can be easily probed at the LHC

- unfortunately, hard to reconcile with Lorentz violation bounds from atomic physics and astronomy

$\because$ Light fermions couple very weakly to the Electroweak Symmetry Breaking sector

- Standard Model Yukawa Couplings

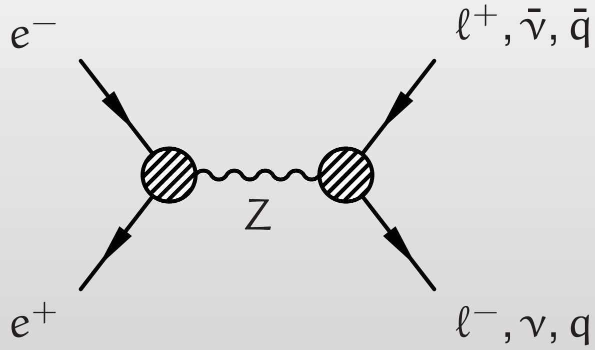
$$\mathcal{L} \supset \frac{m_f}{v_F} H\bar\psi_f\psi_f \Longrightarrow \frac{d\sigma}{d\Phi}(f\bar f \to H) \propto \frac{m_f^2}{v_F^2}$$

- generically in any chiral Effective Field Theory description

$$\mathcal{L} \supset m_f\bar\psi_f \exp\left(i\frac{\Phi}{v_F}\right)\psi_f \Longrightarrow \frac{d\sigma}{d\Omega}(f\bar f \to \Phi) \propto \frac{m_f^2}{v_F^2}$$

$\therefore$ 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



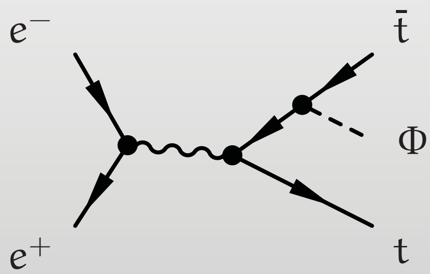
∵ all observed Flavor Changing Neutral Currents can be explained by penguin and box diagrams

∴ 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

… Vector Boson Fusion

- 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

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

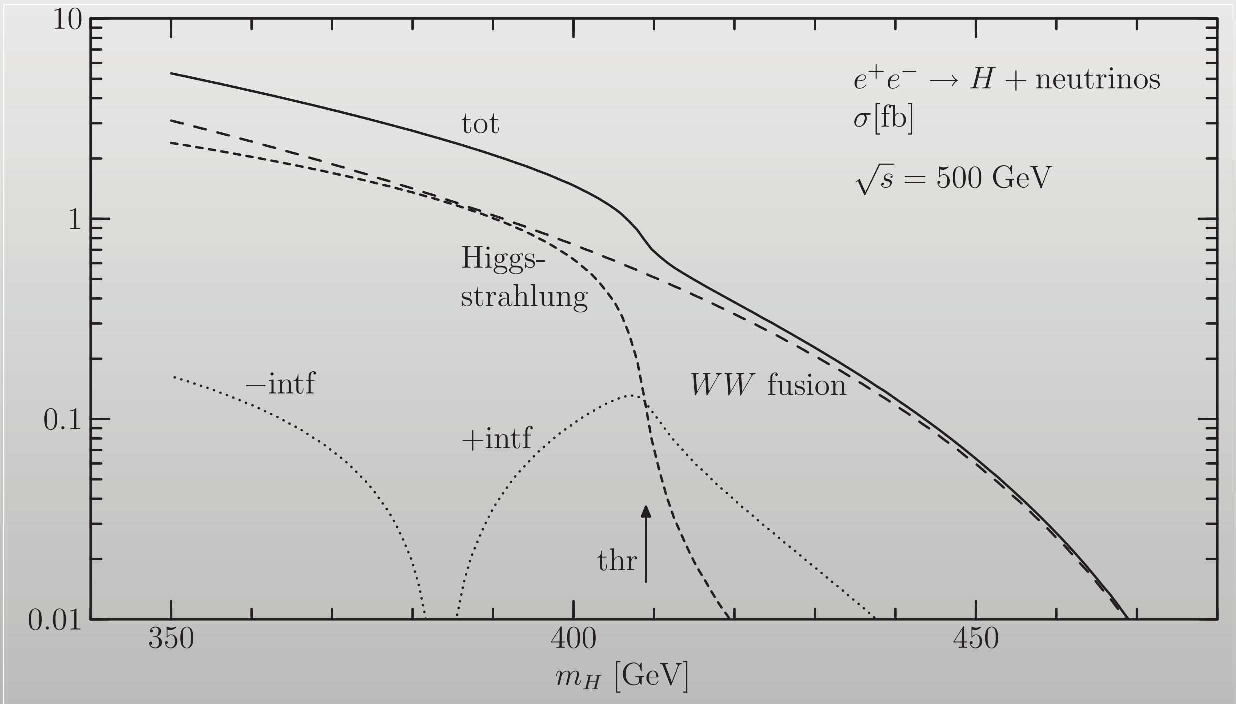
  - but enhanced by

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

- 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)

Higgsstrahlung vs. VBF

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



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?

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