(Still Waitin' For) Some Physics Beyond the Standard Model

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

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

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- gravity
  - the granddaddy of BSM physics
  - $\therefore$ there must be a new scale $m_{\text{Planck}} \gg v$ (w/ $m_{\text{Planck,4D}} = \mathcal{O}(10^{16}) \cdot v_F$)

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$\therefore$ most fertile ground for Terascale BSM models to date ...

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$\because$ implementing the *model du jour* and interfacing must become even more user friendly, i. e. even less error prone

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- *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

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$\therefore$ automatized TOOLS need no fundamental change of architecture ("just more of the same")

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

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- non collider applications
  - DarkSUSY, MicrOmegas, Torino Code ...

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- popular source of CP-violation
  - many phenomenological studies
  - implemented in most (all?) all-in-one packages

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(but not much further)

Nonperturbative Extra Dimensions

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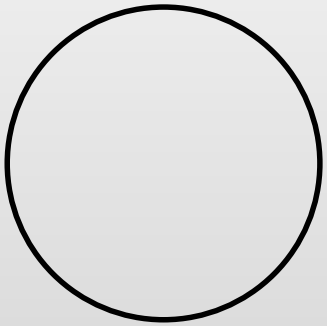
  - holographical XD: powerful new description of strongly interacting models using the (conjectured!) AdS/CFT correspondence

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



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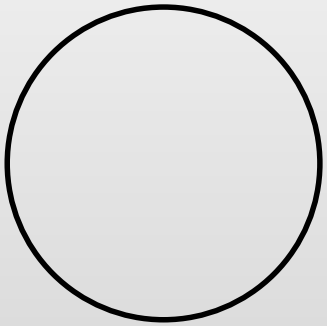

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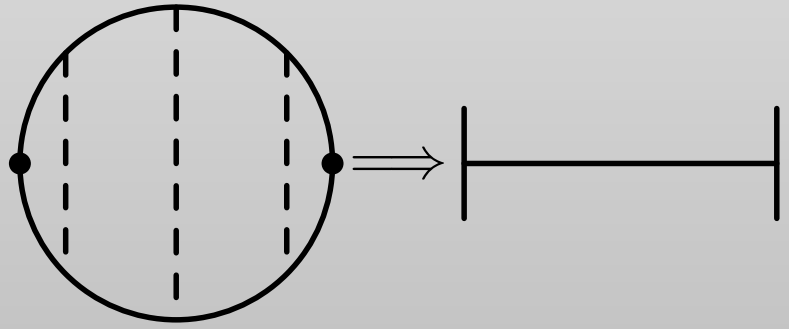

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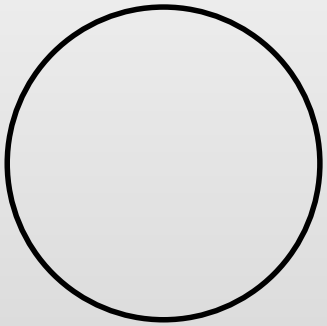

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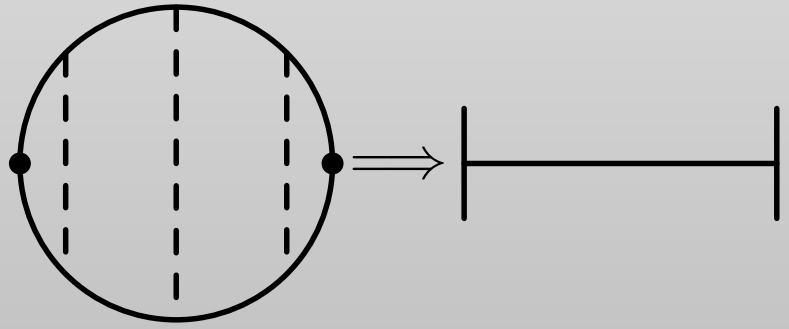

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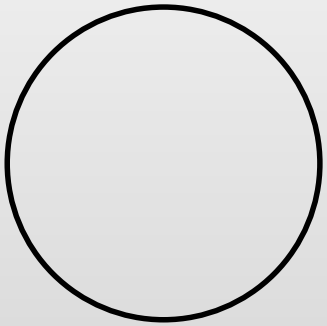

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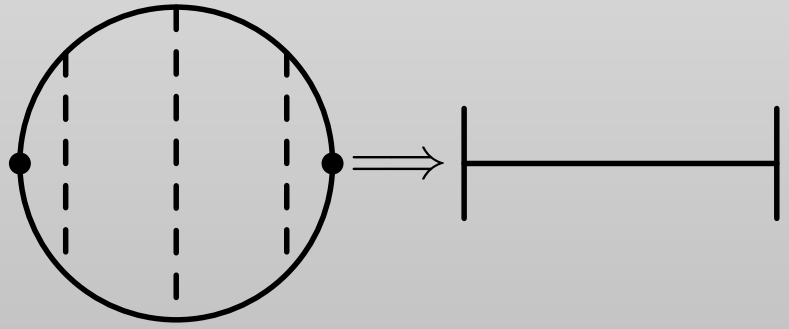

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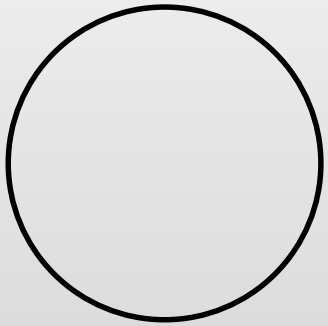

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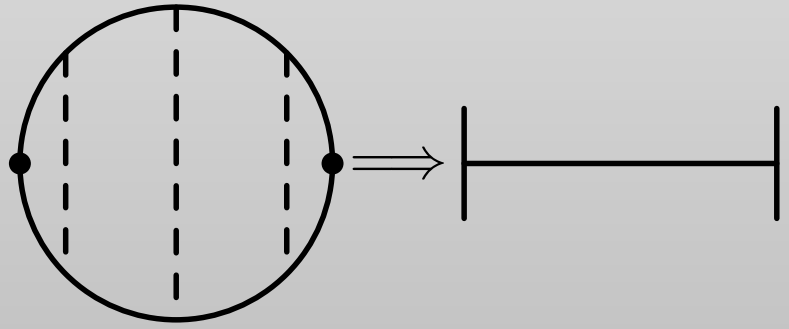

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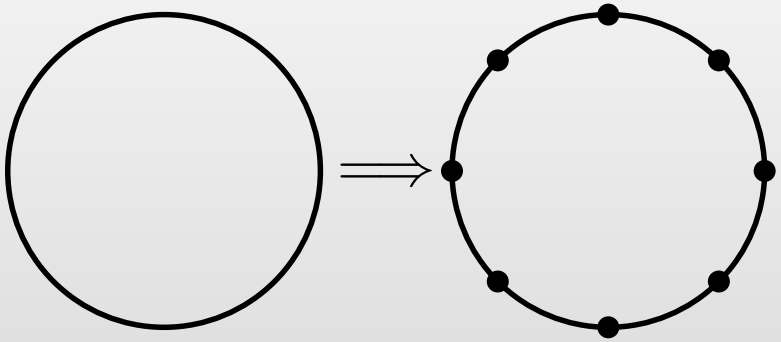
$\therefore$ boundary conditions at the branes

- replace continuous XD by discrete XD



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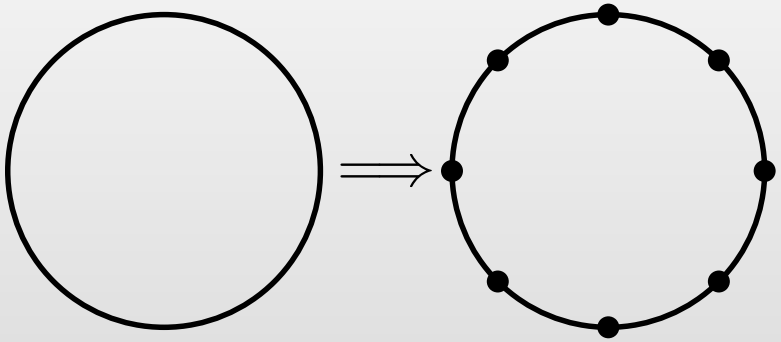

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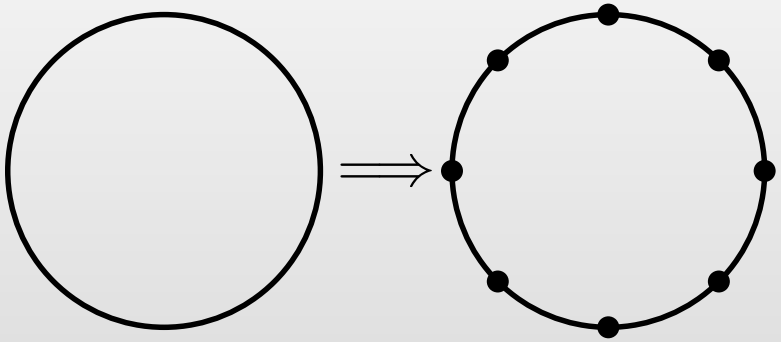

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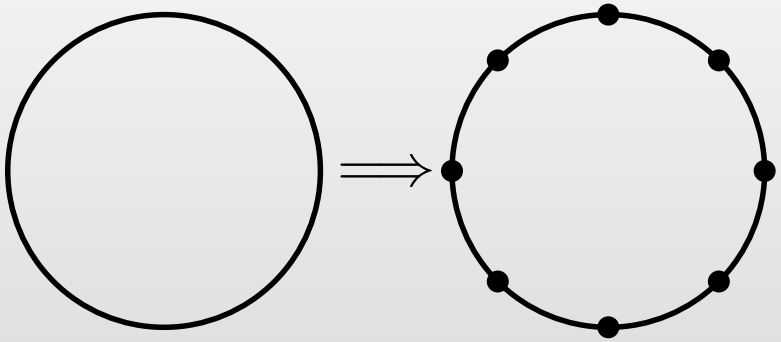

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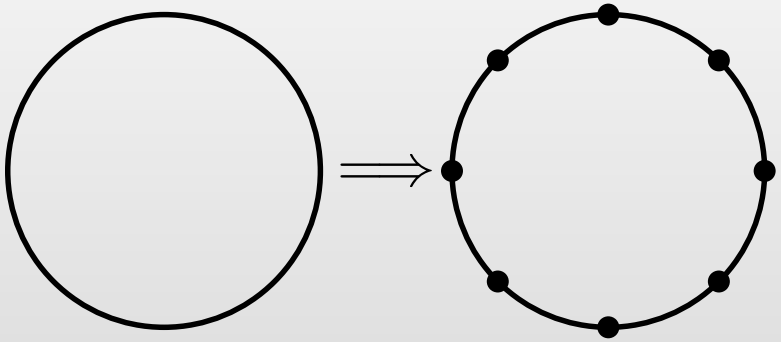

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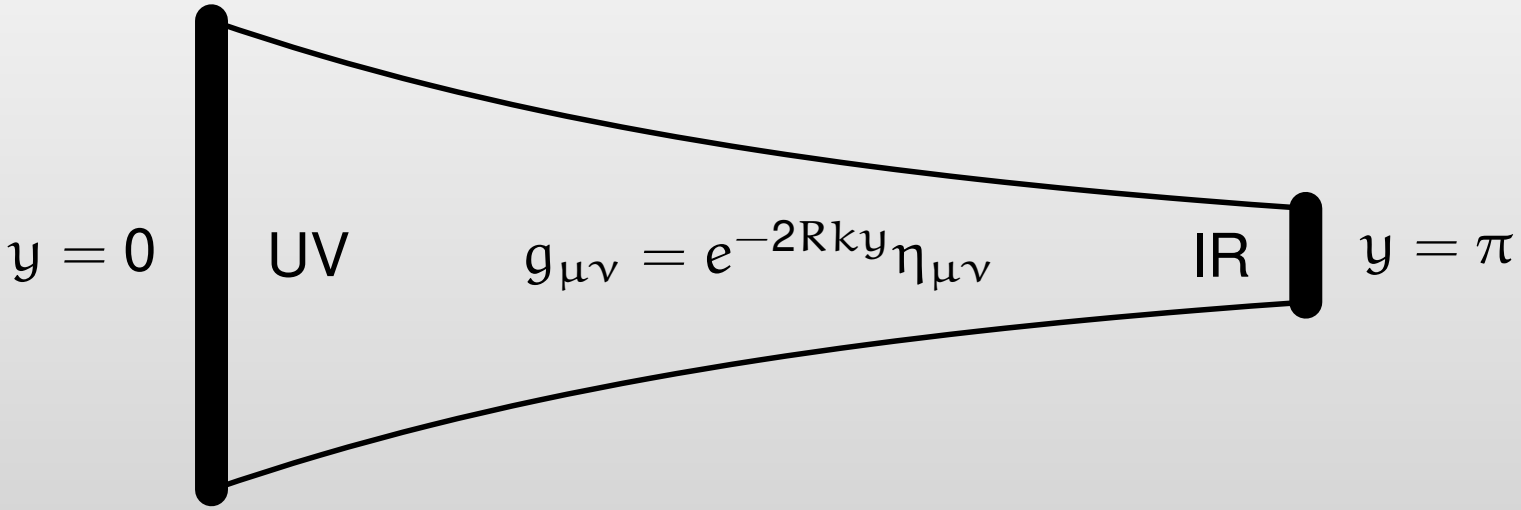

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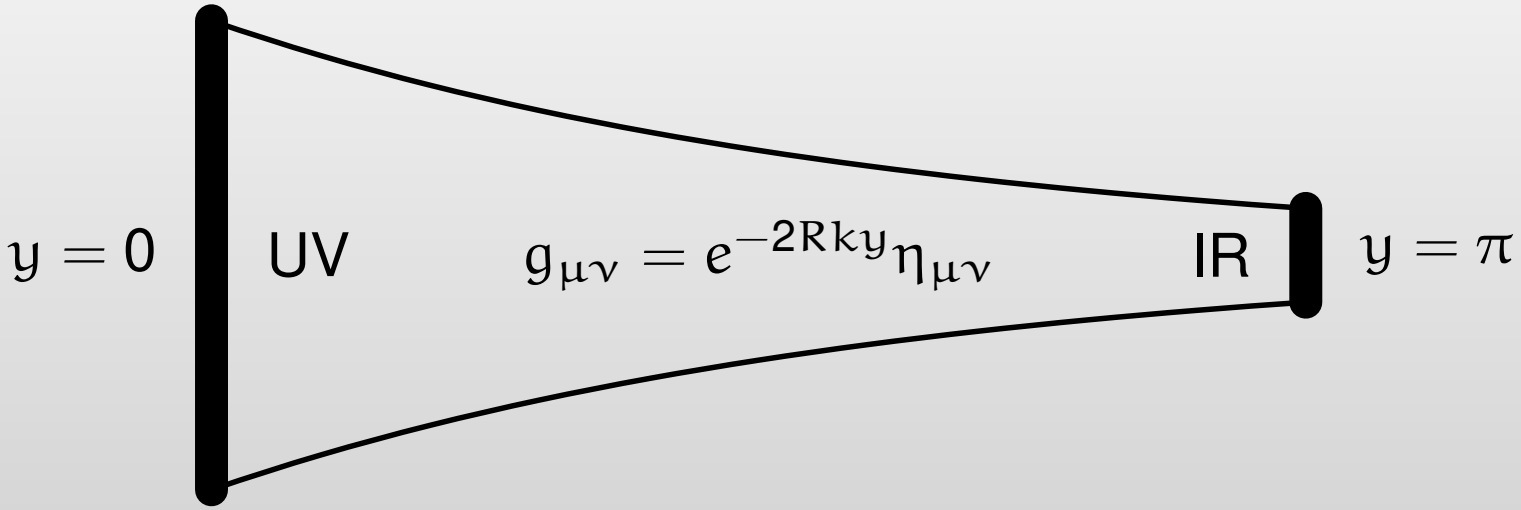

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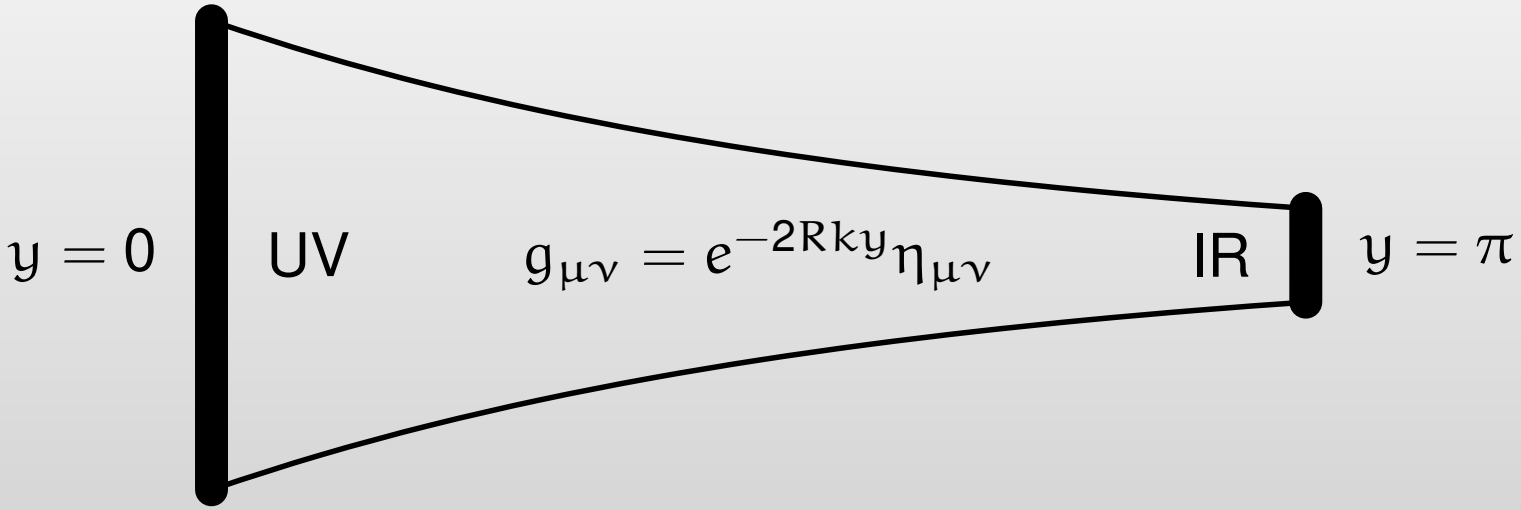

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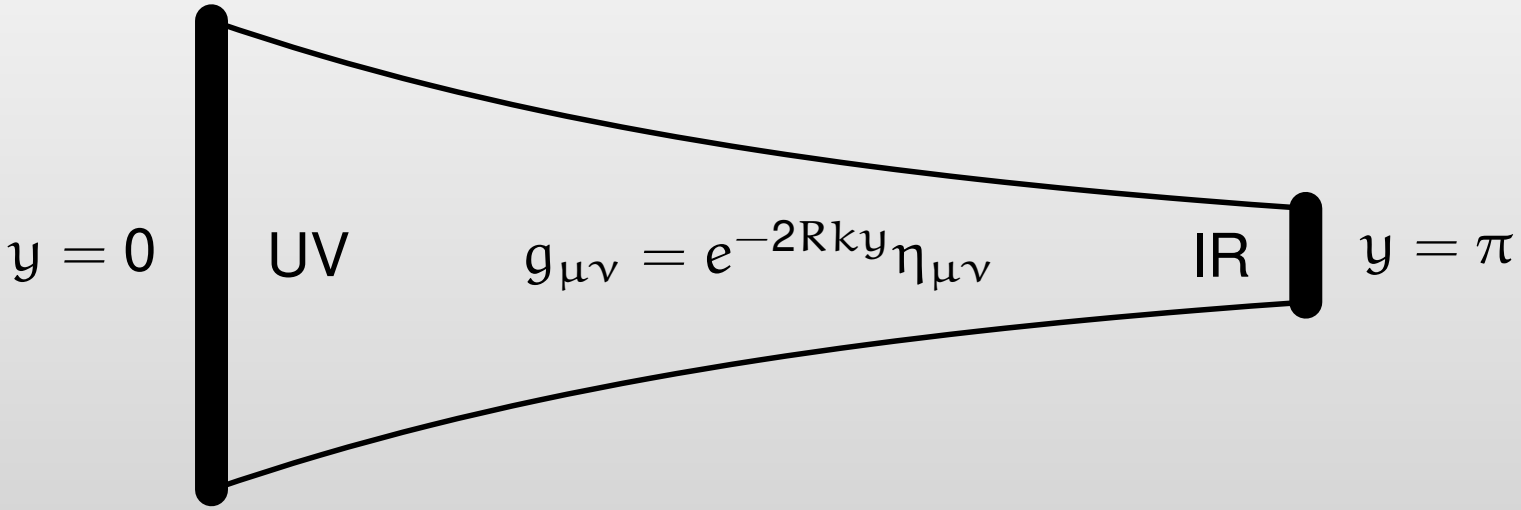

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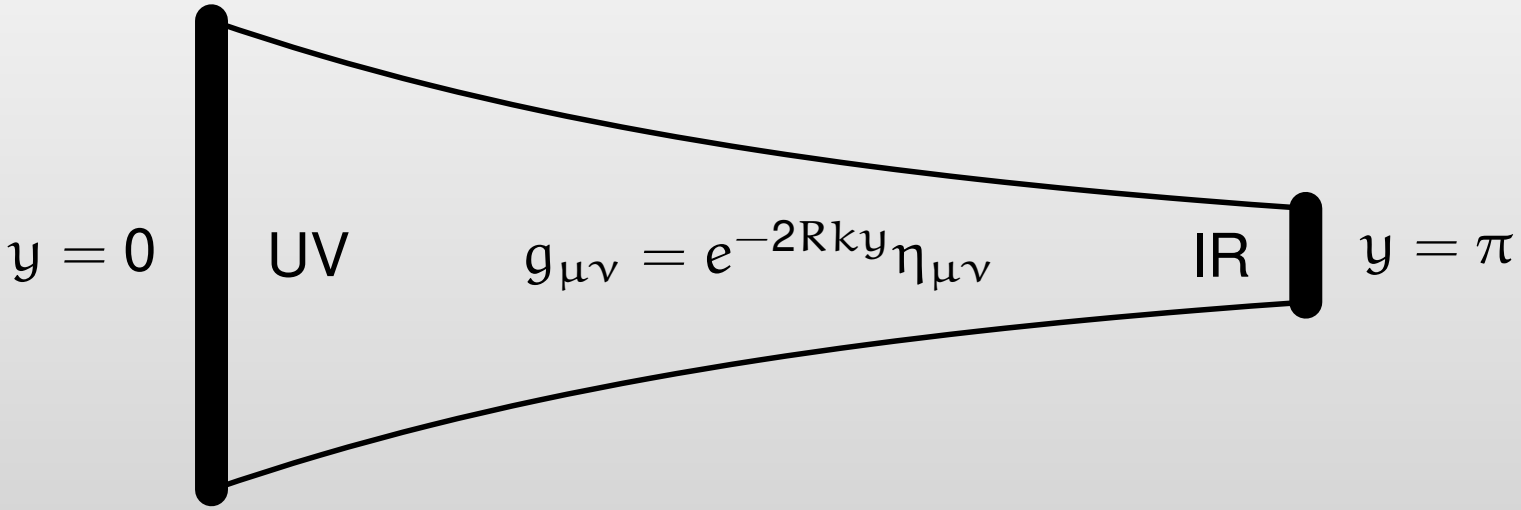

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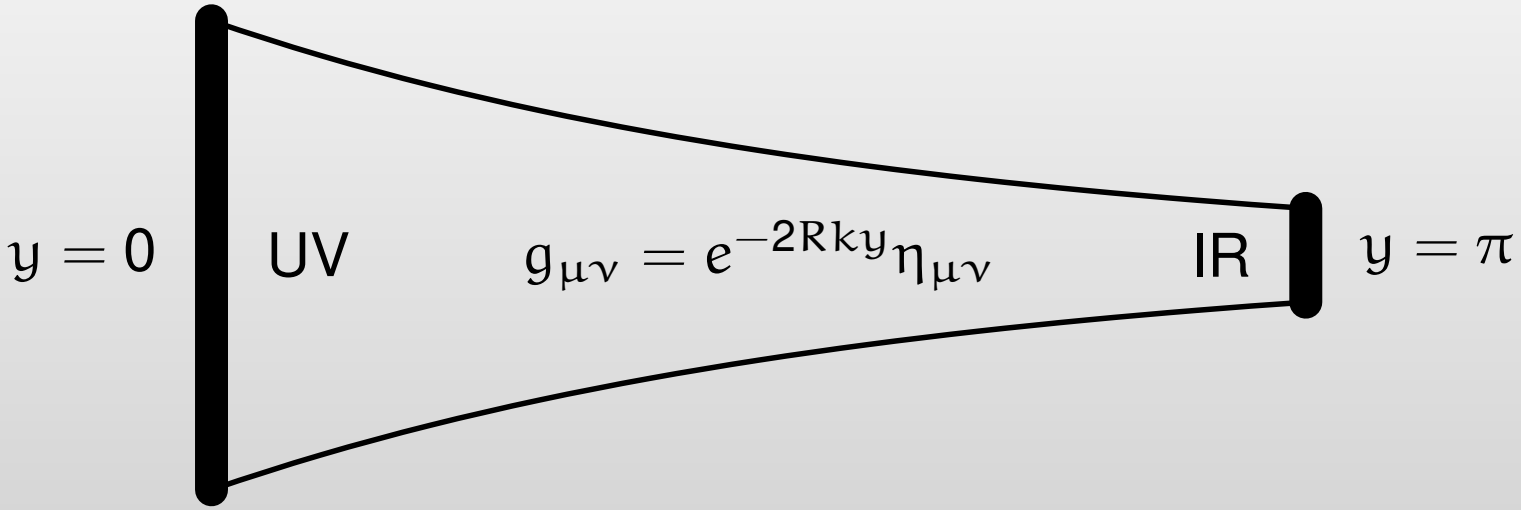

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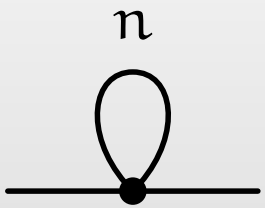
- can be combined with deconstruction, of course

- Little Higgs started life as deconstructed XD

$$\sum_n$$ 

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

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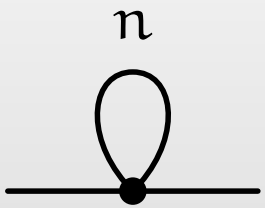
$$\sum_{n}$$ 

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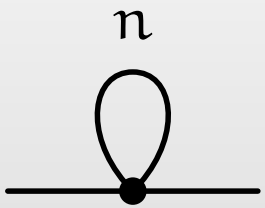
$$\sum_n$$ 

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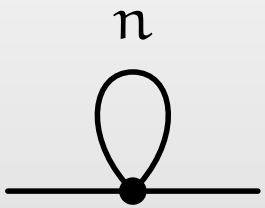
$$\sum_n$$ 

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

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

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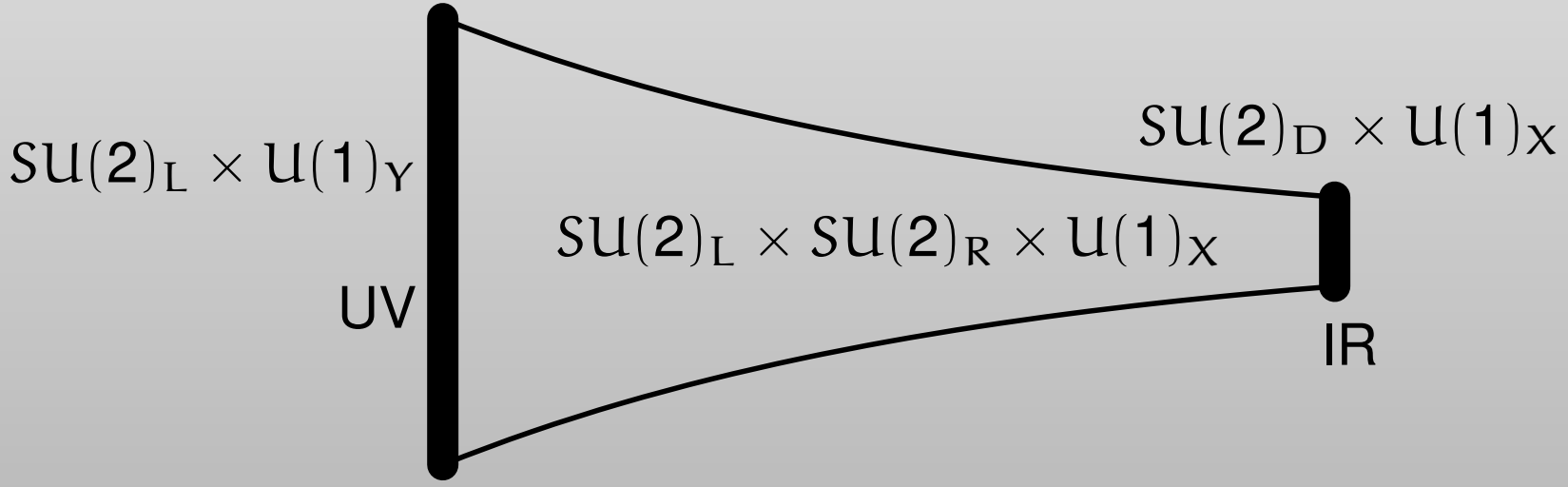
- can be explained by similar exponential suppression of the symmetry breaking sector [Csaki et al. '03]



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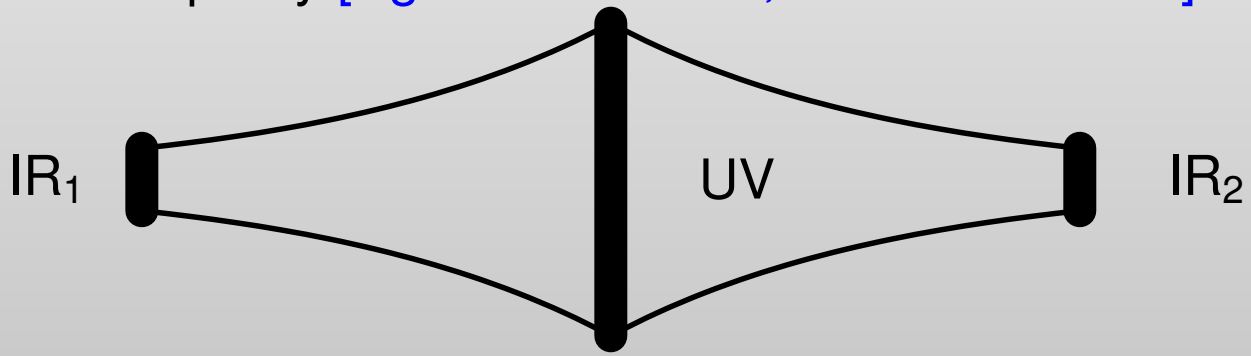

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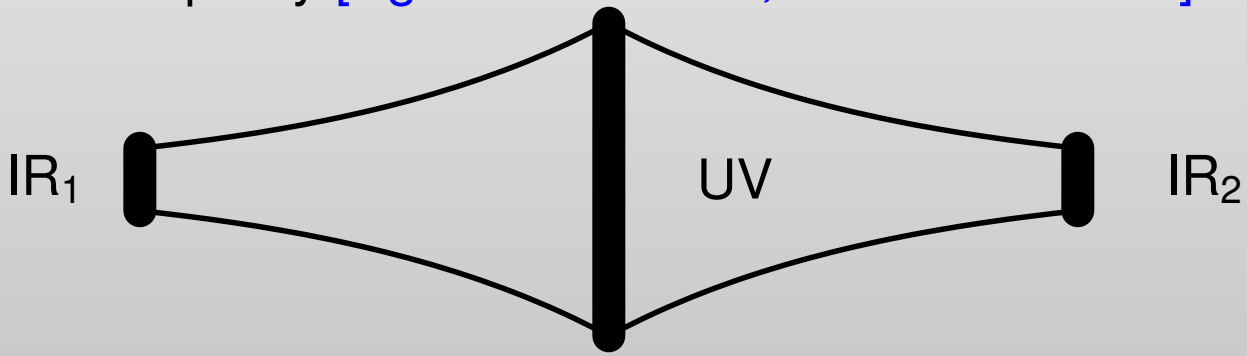

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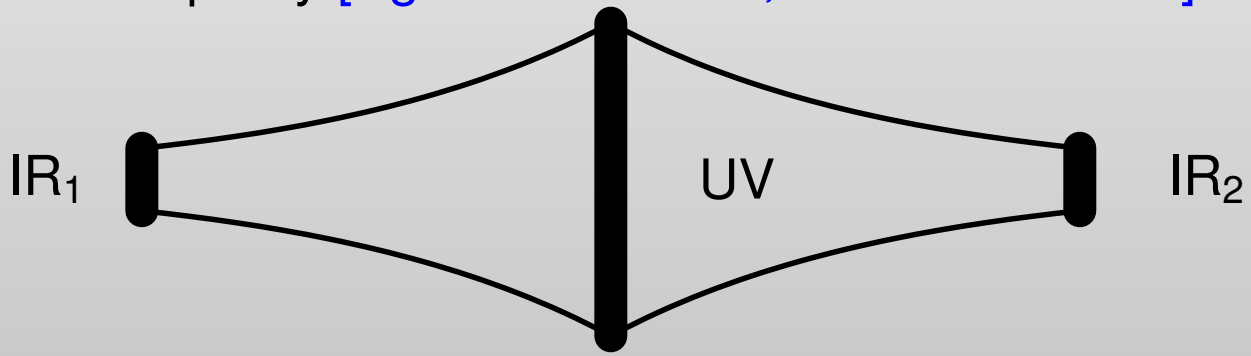

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$\because$ SUSY well motivated to appear in UV completions of any effective model, including higgsless models

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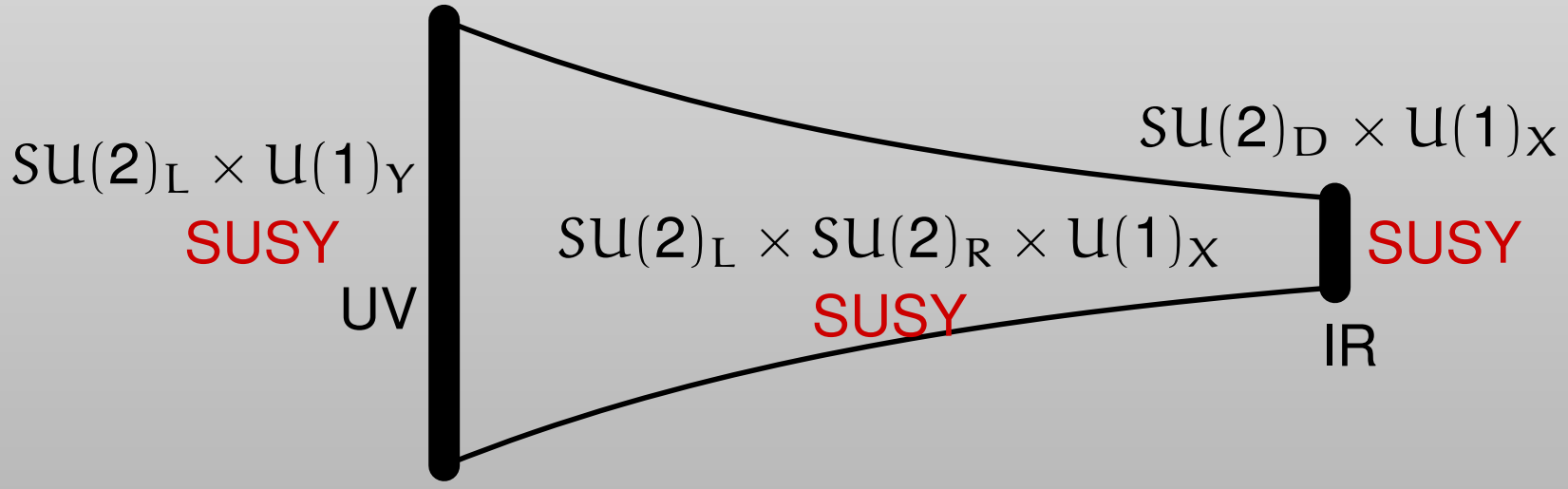

Nonperturbative XD w/SUSY

- flat 5D $N = 1$ can be mapped to 4D $N = 2$
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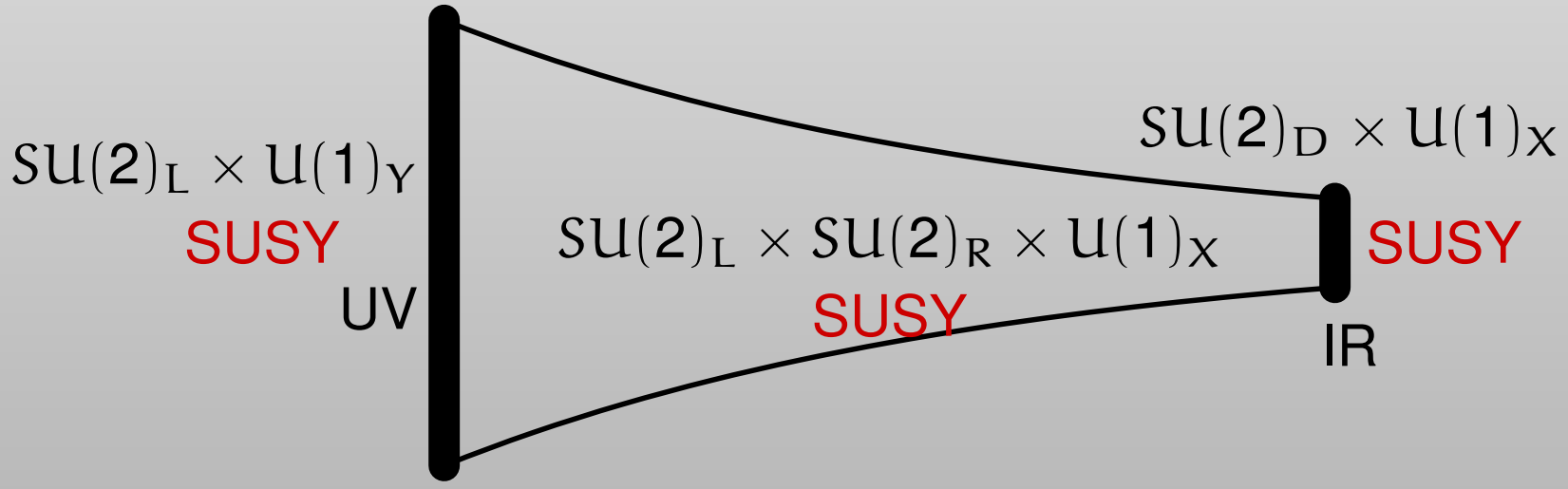
$$\xi(y) = e^{-Rky/2} \begin{pmatrix} \xi^0_\alpha \\ 0 \end{pmatrix}$$



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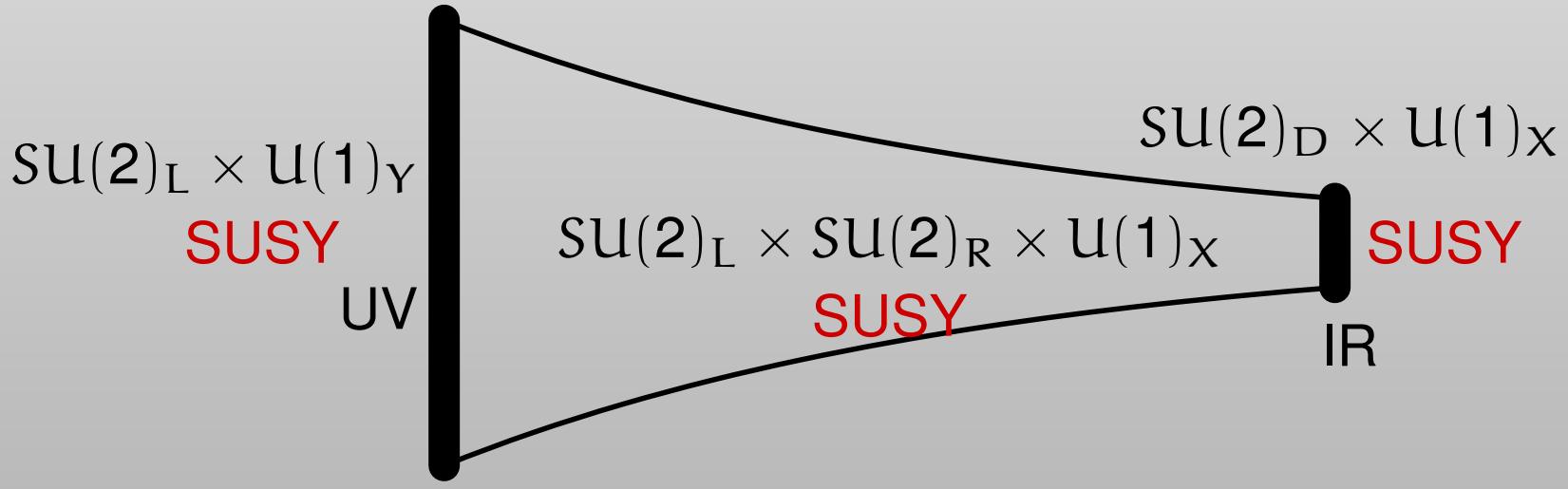

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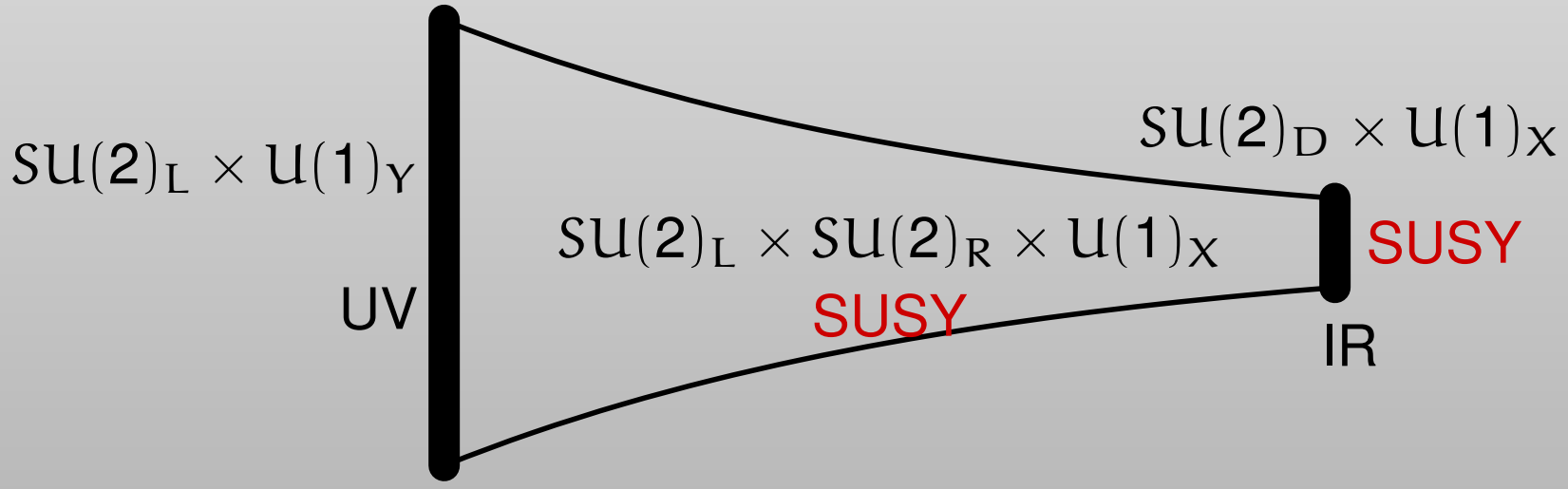
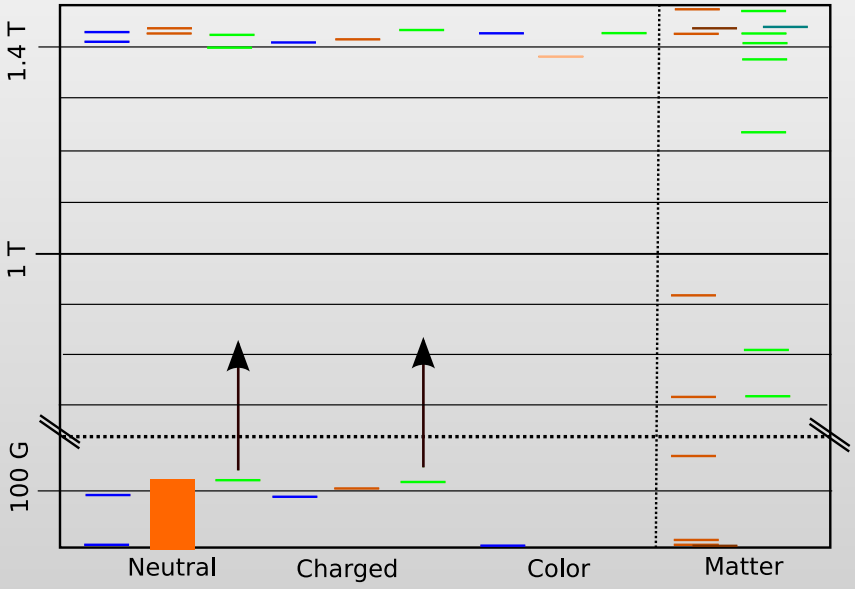
- most elegantly by boundary conditions on the UV-brane



Nonperturbative XD w/SUSY

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



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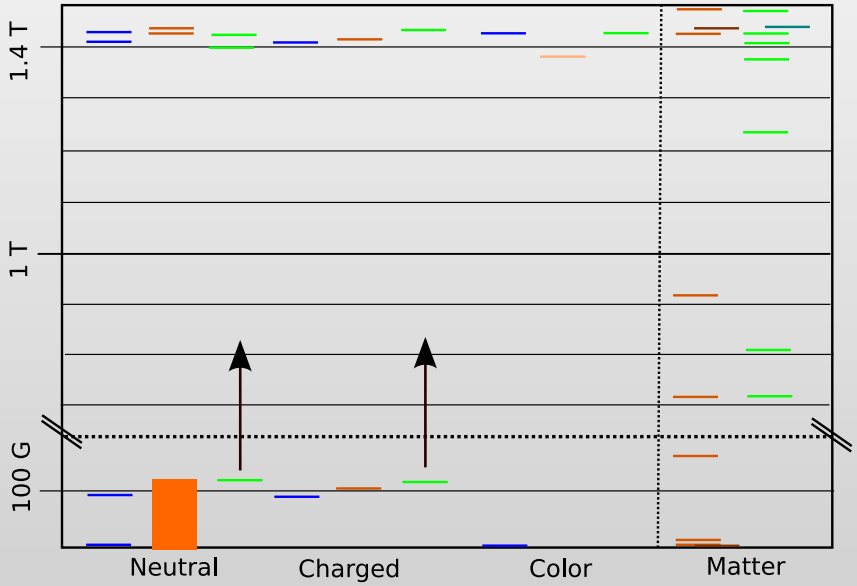

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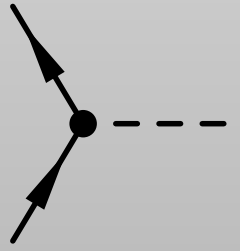

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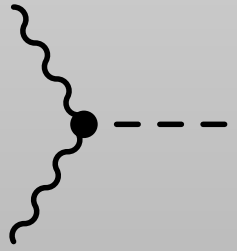

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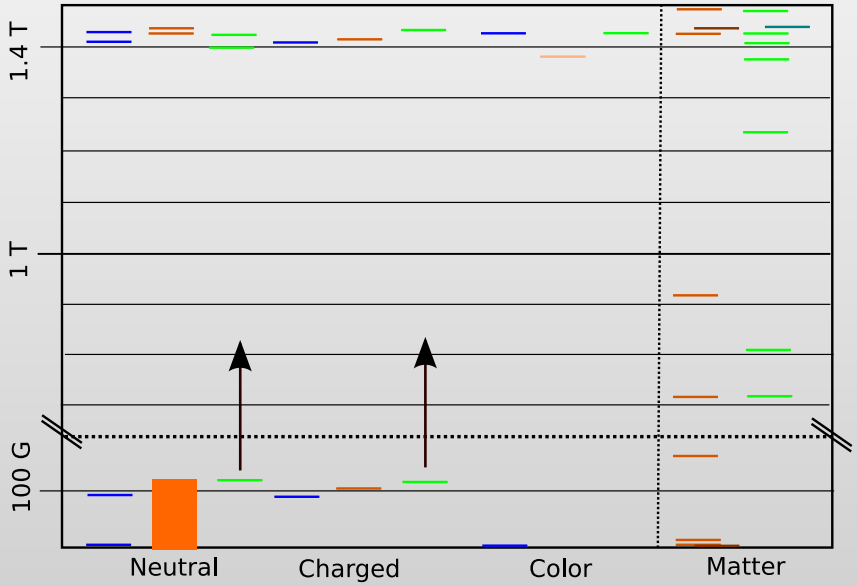

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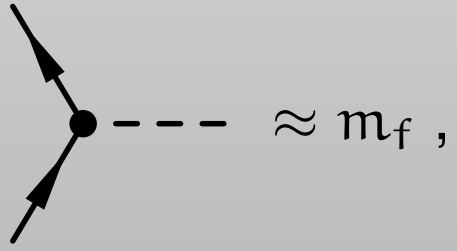
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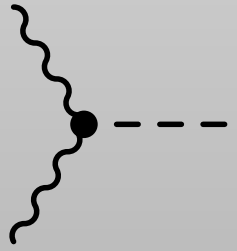
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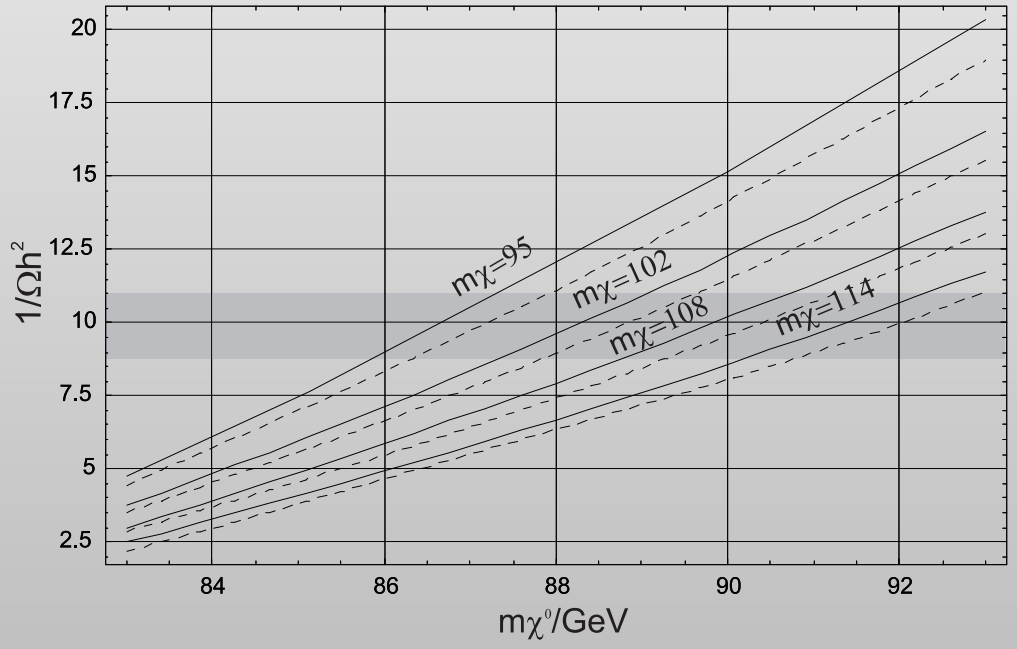
$\therefore$ Higgs-like w/o vector boson fusion

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

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



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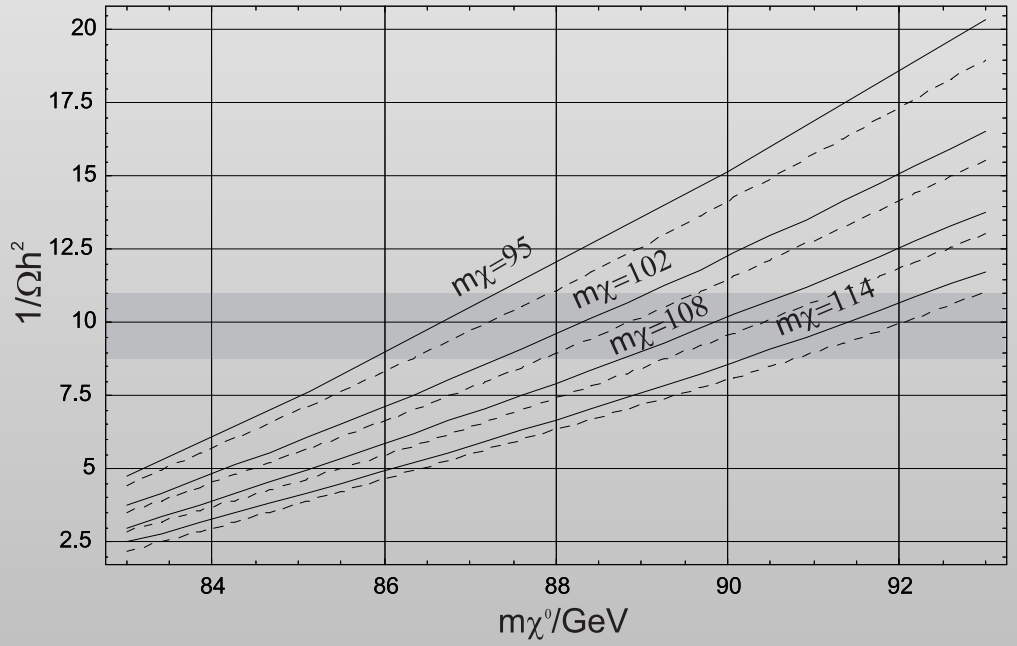

- Very good agreement with current WMAP data possible

Nonperturbative XD w/SUSY

- Model partially implemented in WHIZARD [Reichert '08]

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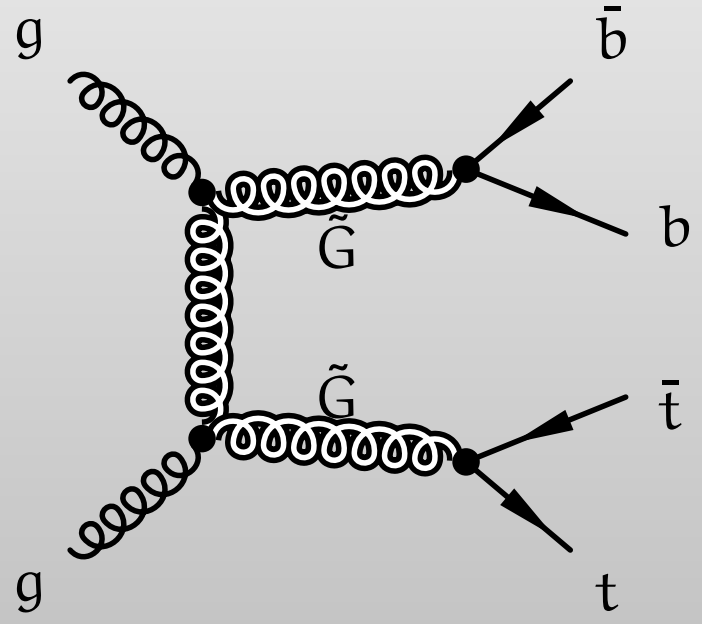
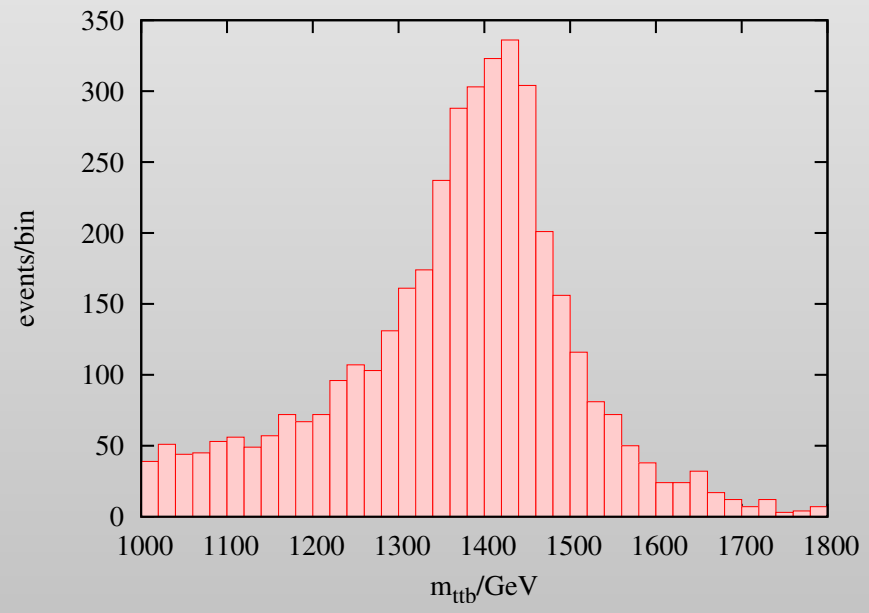
- Production of heavy colored scalars and gluons at LHC
- Invariant mass of the $t\bar{t}$ pair in $gg \to b\bar{b}t\bar{t}$ for $\int \mathcal{L} = 100\,\mathrm{fb}^{-1}$





(the colored scalar Σ is degenerate with the first KK gluon $\tilde{G}$)

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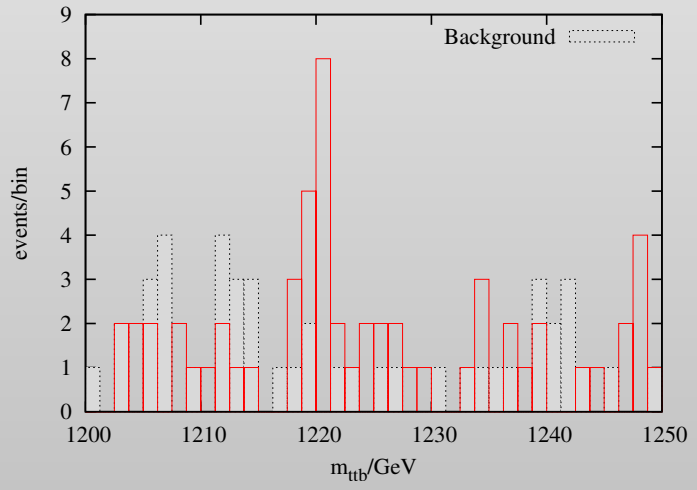

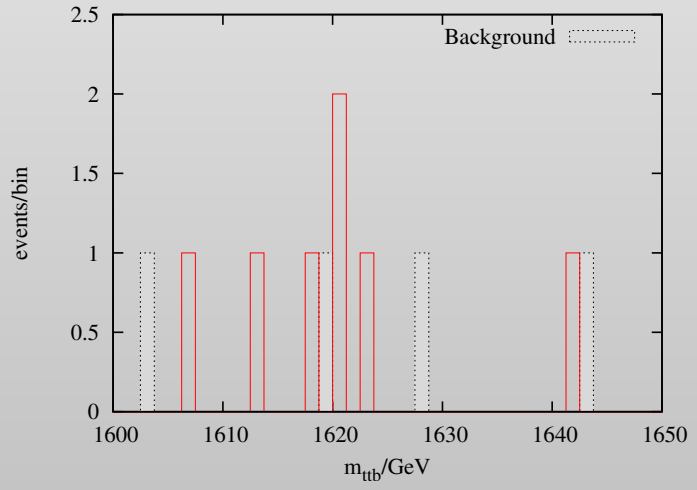

Model Independent EFT Approach

Chiral Lagrangian

- Most conservative approach:
  - use only observed degrees of freedom
  - implement observed exact and broken symmetries
  - $\therefore$ effective chiral Lagrangian for $SU_L(2) \times SU_R(2) \to SU_C(2)$ breaking

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

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- straightforward to implement in all TOOLS

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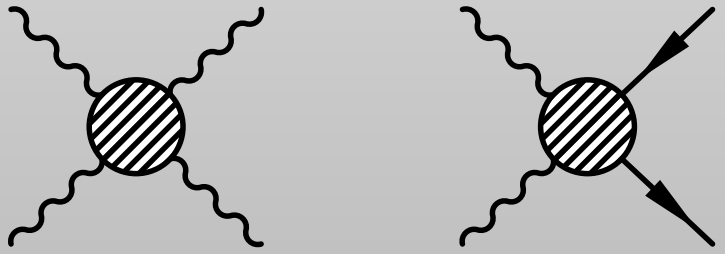
  - ∴ effective chiral Lagrangian for $SU_L(2) \times SU_R(2) \to SU_C(2)$ breaking

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

- straightforward to implement in all TOOLS
- 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 ($pp \to 6f/8f$)

Who Ordered That?

- 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

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

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

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

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

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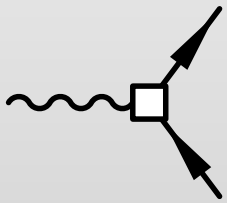
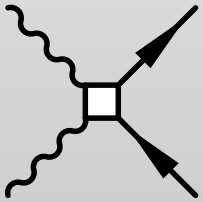
- new interaction vertices among gauge and matter fields from expanding Moyal-Weyl-$*$-products and Seiberg-Witten-Maps as determined by gauge invariance

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

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



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



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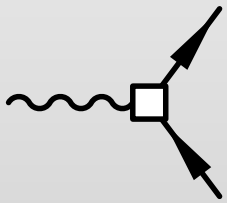

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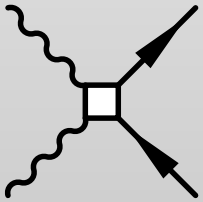

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- canonical NC exstension of the SM known to $\mathcal{O}(\theta^2)$

standard acceptance cuts and 85 GeV $< m_{\ell^+\ell^-} <$ 97 GeV,
200 GeV $< m_{\ell^+\ell^-\gamma} <$ 1 TeV, $0 < \cos\theta^*_\gamma < 0.9$,
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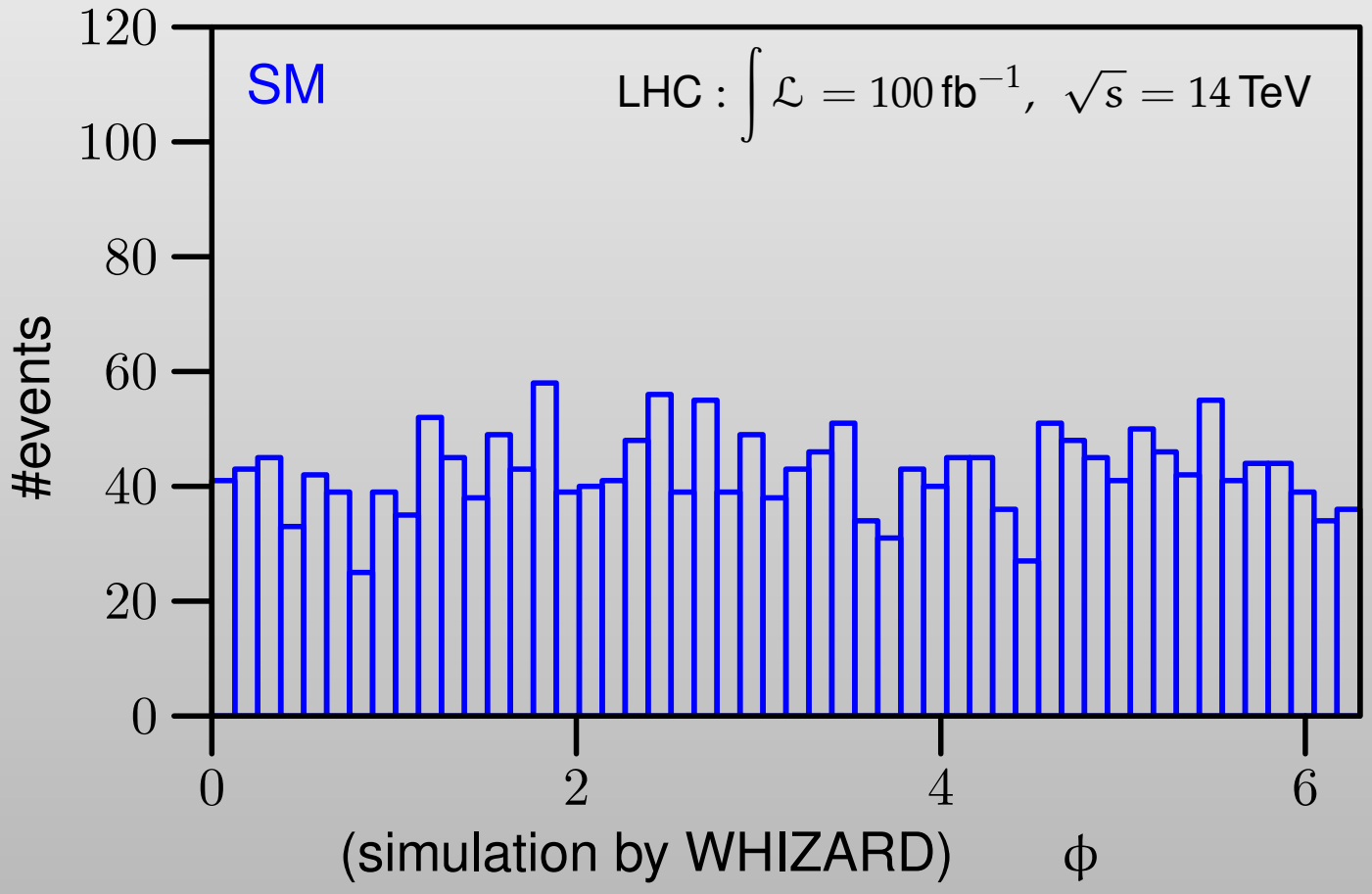

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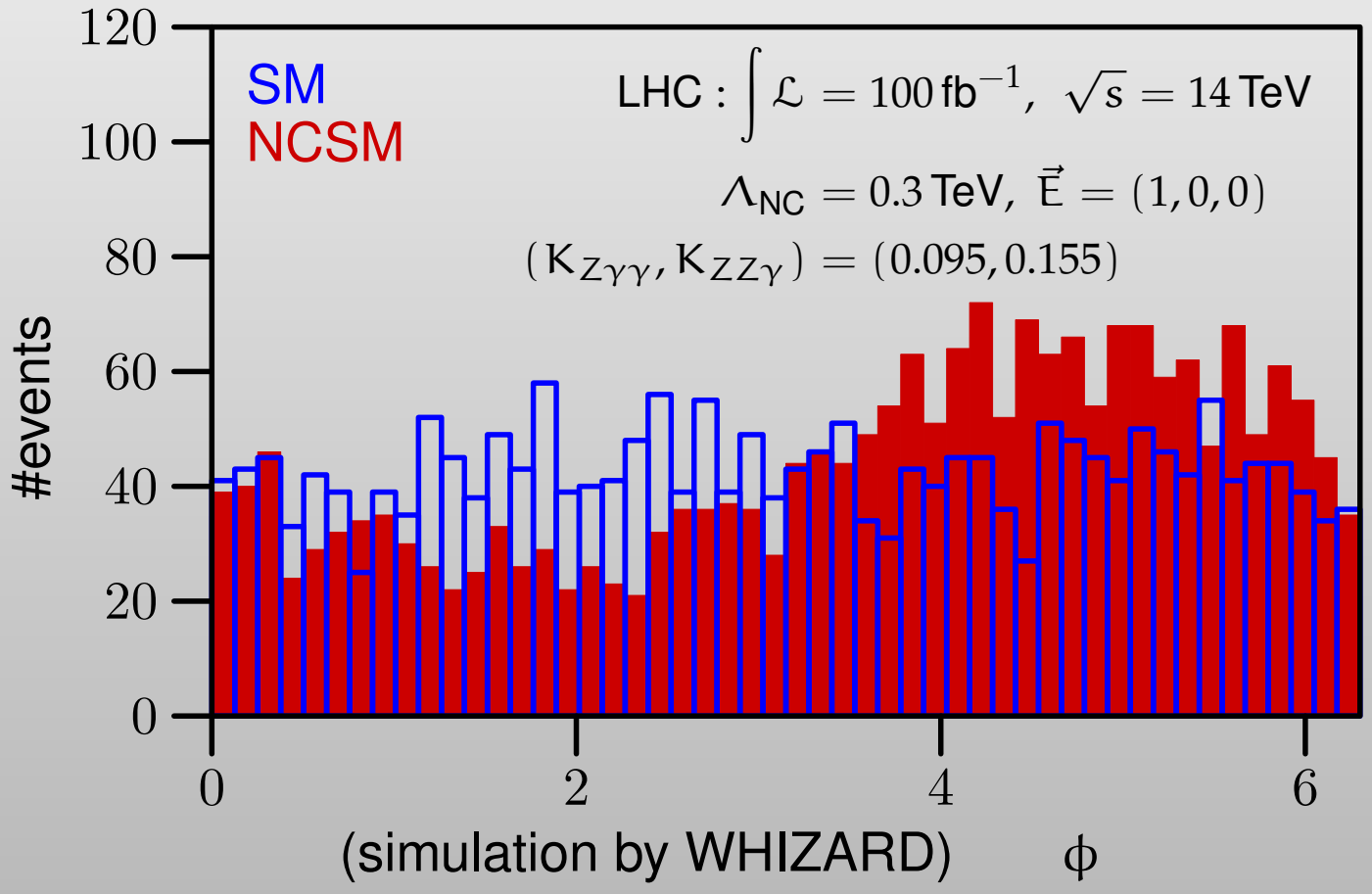

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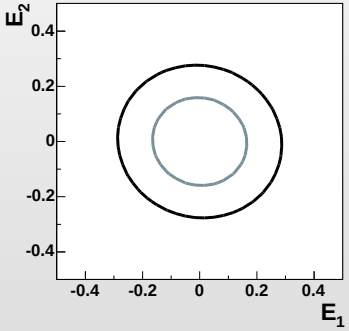

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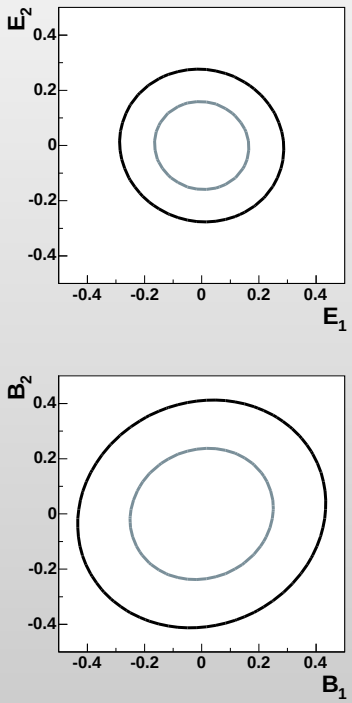

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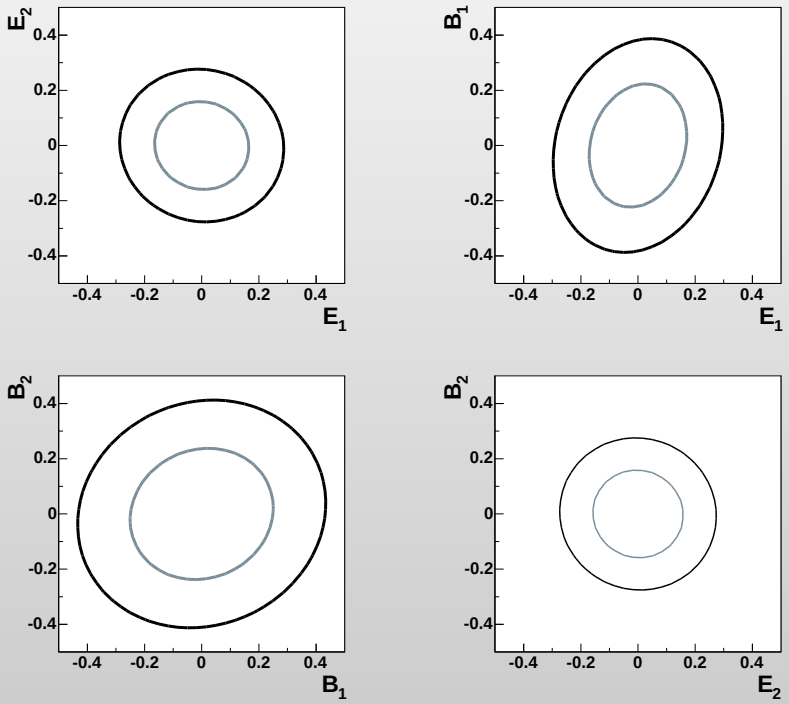

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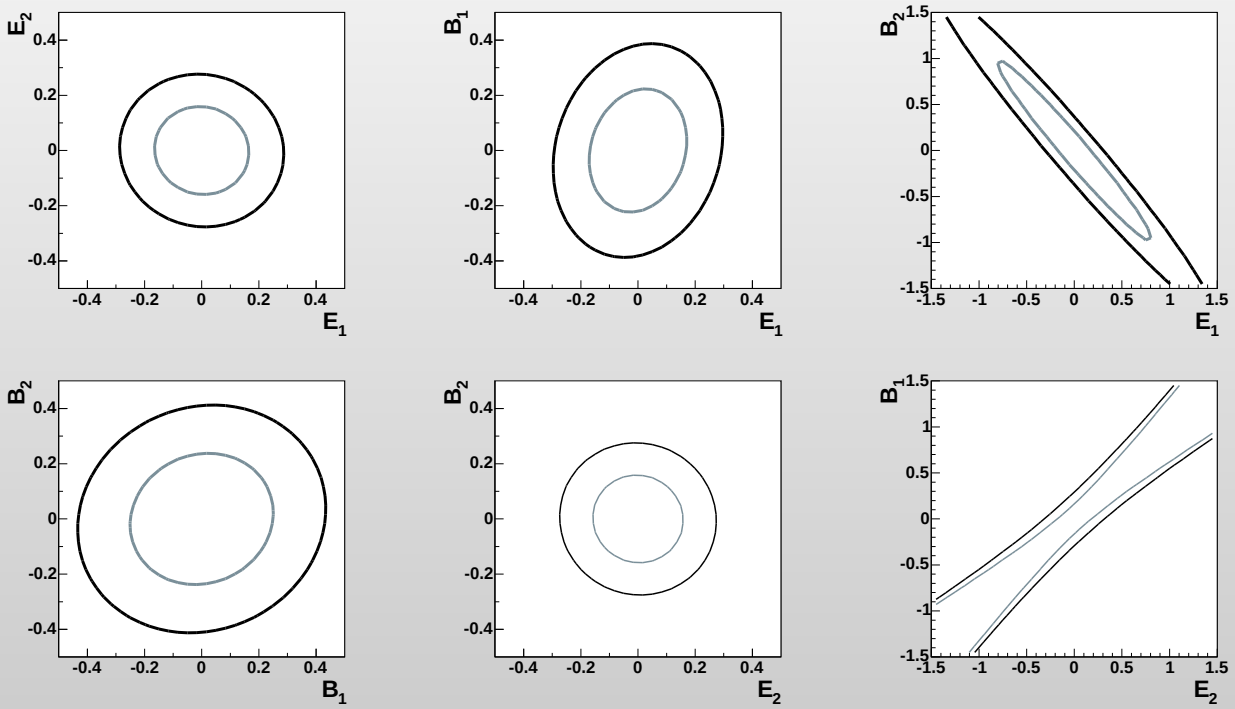

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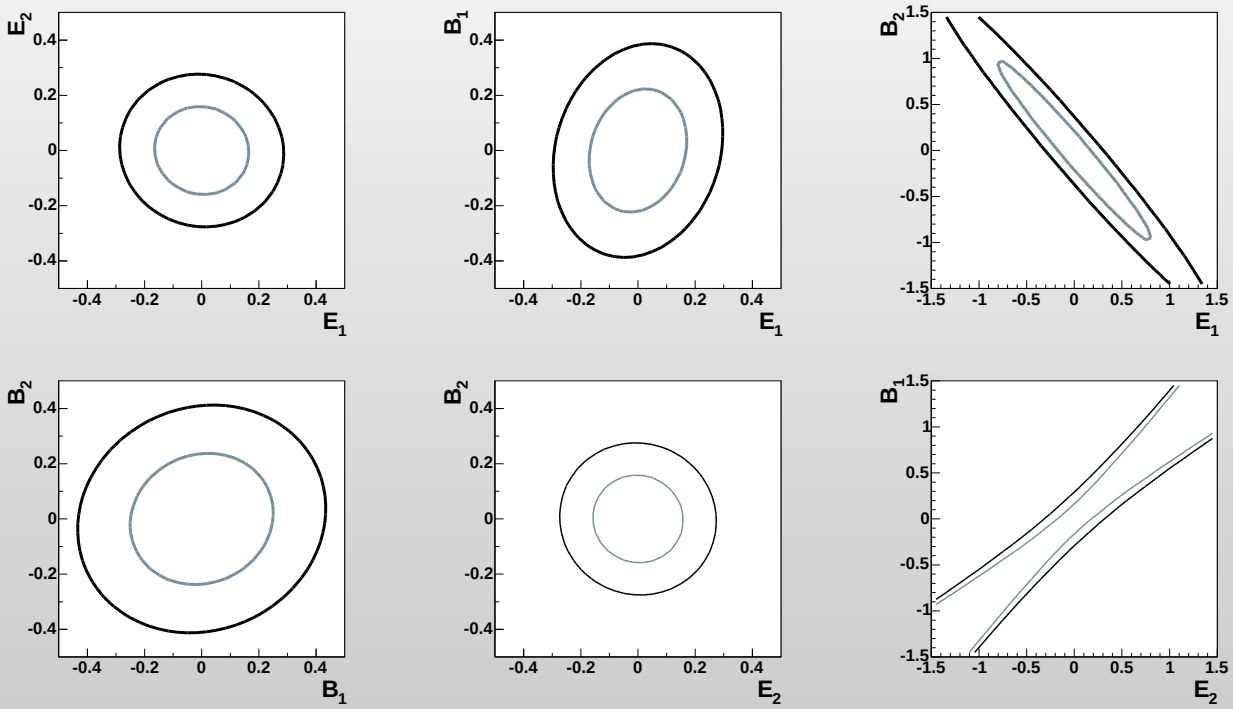

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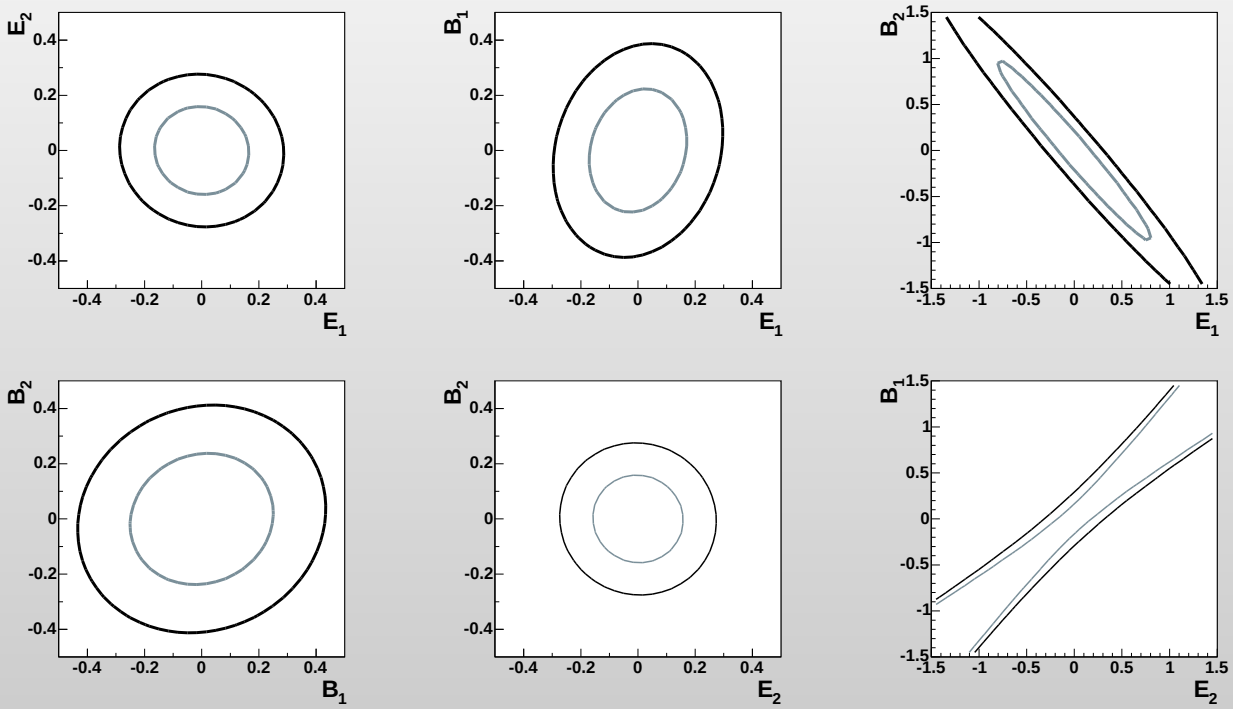

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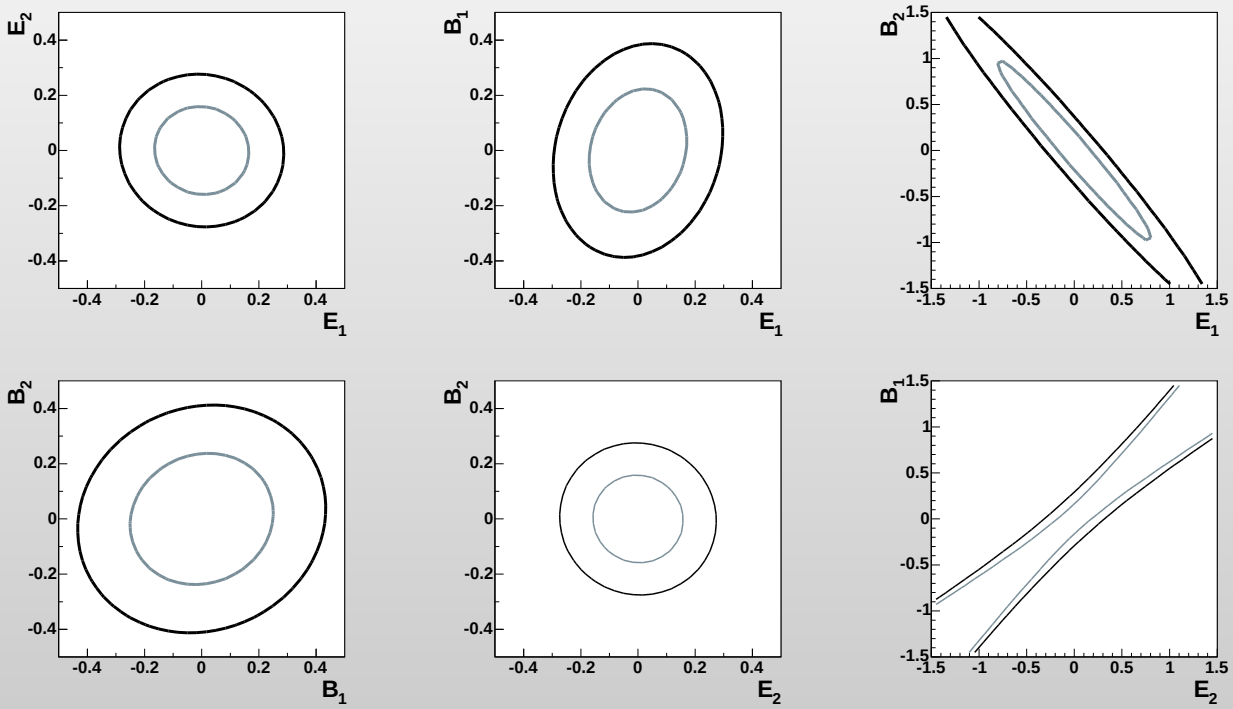

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- unfortunately, hard to reconcile with Lorentz violation bounds from atomic physics and astronomy

From Models To Event Samples

- not practical for matrix element tools to compute parameters in the low energy effective lagrangian (i. e. masses and couplings) from input parameters themselves

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- ∵ there a several well tested programs for SUSY extensions of the SM that do the heavy liftung for the RG evolution and in many cases we can use SLHA
- ∵ XD models require other non-trivial computations, e. g. wave function overlaps

$$g_{ijk} = \int dy \, \sqrt{|g(y)|} f_i(y) f_j(y) f_k(y)$$

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