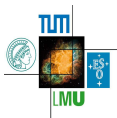


# Grand Unification without Proton Decay

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Universe Cluster Munich

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String Pheno 2016 - Ioannina

Based on:

arXiv:1606.02303 [hep-ph] by Andreas Mütter, Michael Ratz and P. V.

## Outline and Motivation

- ▶ Understand the structure of matter
- ▶ Unification of forces: GUT
- ▶ Proton decay operators of various (mass-) dimensions
- ▶ Extra spatial dimensions: Local GUTs
- ▶ Local GUT breaking vs. non-local GUT breaking
- ▶ Non-local GUT breaking: no dimension 6 proton decay via  $X$  boson:

$$p \not\rightarrow \pi^0 e^+$$

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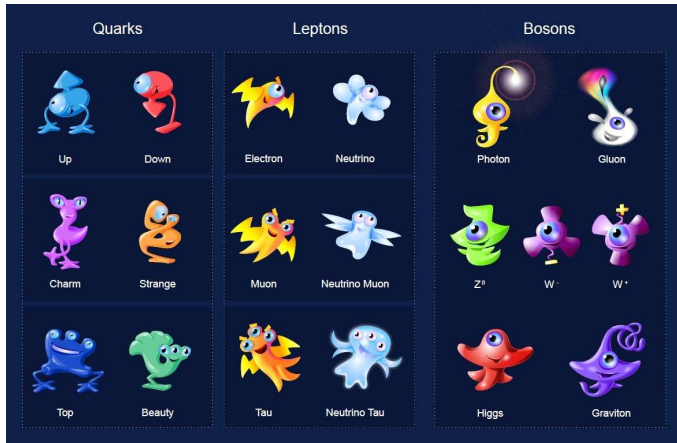


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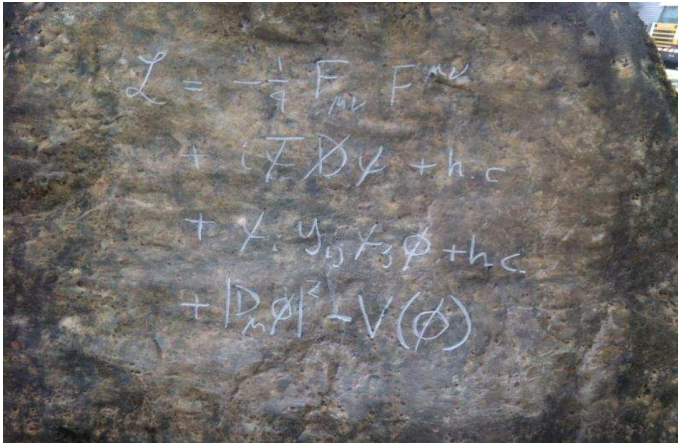
# Standard Model of Particle Physics



Cern web page

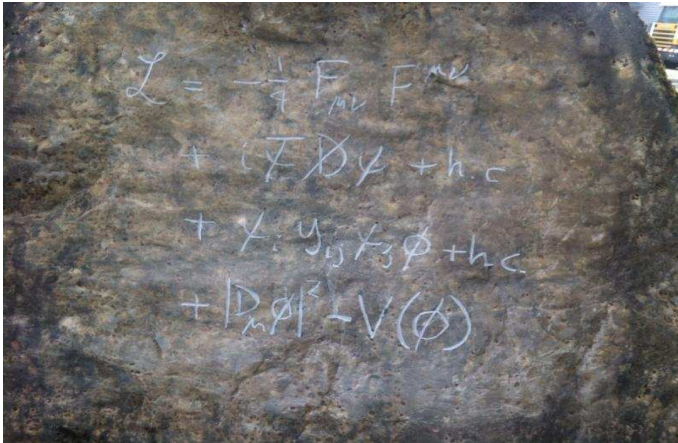
- gauge group  $SU(3)_C \times SU(2)_L \times U(1)_Y$
- masses, mixings, CP-phases, ...

# Standard Model of Particle Physics

A photograph of a dark, textured rock surface with the Lagrangian of the Standard Model of particle physics written on it in white chalk. The equation is written in four lines, with some terms appearing to be written over others. The first line is  $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$ . The second line is  $+ \bar{\psi} \not{D} \psi + h.c$ . The third line is  $+ \chi_1 \psi_1 \chi_2 \psi_2 + h.c$ . The fourth line is  $+ |D_\mu \phi|^2 - V(\phi)$ .
$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ \bar{\psi} \not{D} \psi + h.c \\ &+ \chi_1 \psi_1 \chi_2 \psi_2 + h.c \\ &+ |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

Cern web page

# Standard Model of Particle Physics



The image shows a chalkboard with the Lagrangian of the Standard Model of particle physics written in white chalk. The equation is:

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + \bar{\psi} \not{D} \psi + h.c. \\ & + \chi_i y_{ij} \chi_j \phi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

Cern web page

⇒ Are there hints for physics beyond the SM?

## Unification of particles

weight of <b>16</b>	Y		
++ - +- + - + +- - + + +- ++ - -+ + - + -+ - + + -+	$\frac{1}{6}$	<b>(3, 2)</b>	$_{1/6}$
+ - - ++ - + - ++ - - + ++	$-\frac{2}{3}$	<b>(<math>\bar{3}</math>, 1)</b>	$_{-2/3}$
+ - - --- - + - --- - - + ---	$\frac{1}{3}$	<b>(<math>\bar{3}</math>, 1)</b>	$_{1/3}$
- - - +- - - - -+	$-\frac{1}{2}$	<b>(1, 2)</b>	$_{-1/2}$
+++ --	1	<b>(1, 1)</b>	$_1$
+++ ++	0	<b>(1, 1)</b>	$_0$

using  $\pm$  for  $\pm\frac{1}{2}$  and  $t_Y = (\frac{1}{3}, \frac{1}{3}, \frac{1}{3}, -\frac{1}{2}, -\frac{1}{2})$

## Unification of particles

weight of <b>16</b>	Y		
$+ + - + -$			
$+ - + + -$			
$- + + + -$	$\frac{1}{6}$	$(\mathbf{3}, \mathbf{2})_{1/6}$	
$+ + - - +$			
$+ - + - +$			
$- + + - +$			
$+ - - ++$	$-\frac{2}{3}$	$(\bar{\mathbf{3}}, \mathbf{1})_{-2/3}$	
$- + - ++$			
$- - + ++$			
$+ - - ---$	$\frac{1}{3}$	$(\bar{\mathbf{3}}, \mathbf{1})_{1/3}$	
$- + - ---$			
$- - + ---$			
$- - - +-$	$-\frac{1}{2}$	$(\mathbf{1}, \mathbf{2})_{-1/2}$	
$- - - - +$			
$+ + + --$	$1$	$(\mathbf{1}, \mathbf{1})_1$	
$+ + + ++$	$0$	$(\mathbf{1}, \mathbf{1})_0$	

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## Unification of particles

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+ - - ++ - + - ++ - - + ++	$-\frac{2}{3}$	$(\bar{\mathbf{3}}, \mathbf{1})_{-2/3}$
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++ - +- + - + +- - + + +- ++ - -+ + - + -+ - + + -+	$\frac{1}{6}$	$(\mathbf{3}, \mathbf{2})_{1/6}$
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$$\mathbf{10} = \underbrace{(\mathbf{3}, \mathbf{2})_{1/6}}_q \oplus \underbrace{(\bar{\mathbf{3}}, \mathbf{1})_{-2/3}}_{\bar{u}} \oplus \underbrace{(\mathbf{1}, \mathbf{1})_1}_{\bar{e}} \quad \bar{\mathbf{5}} = \underbrace{(\bar{\mathbf{3}}, \mathbf{1})_{1/3}}_{\bar{d}} \oplus \underbrace{(\mathbf{1}, \mathbf{2})_{-1/2}}_{\ell}$$



## Unification of particles

weight of <b>16</b>	Y	
++ - +- + - + +- - + + +- ++ - -+ + - + -+ - + + -+	$\frac{1}{6}$	$(\mathbf{3}, \mathbf{2})_{1/6}$
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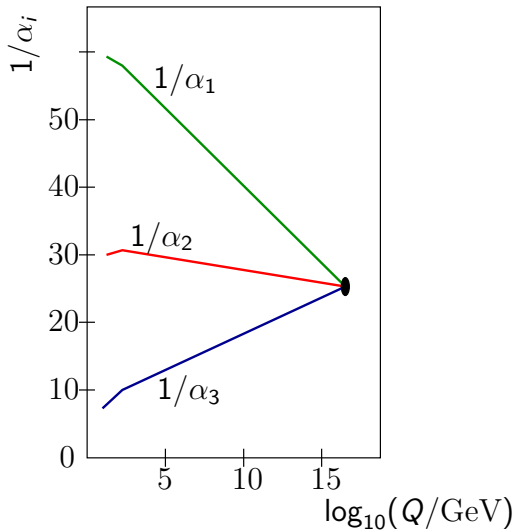
## Unification of particles (!)

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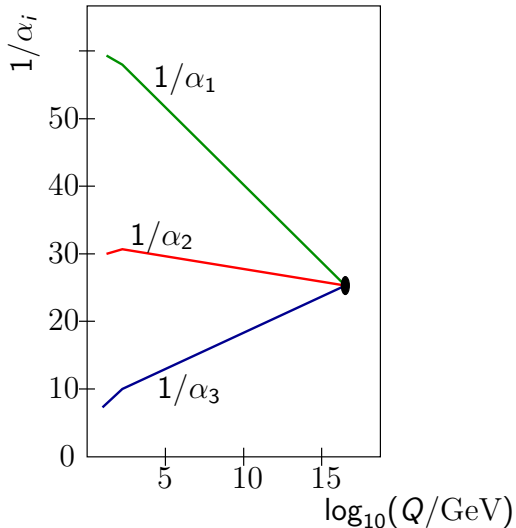
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## Gauge couplings in the MSSM



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⇒ gauge couplings unify at about  $3 \times 10^{16}$  GeV

## Grand Unified Theories in 4D

- Simplest GUT SU(5) Georgi, Glashow 1974
- Three copies of  $\mathbf{10} \oplus \bar{\mathbf{5}}$  for quarks and leptons
- SUSY GUTs:  $\mathbf{5}_H \oplus \bar{\mathbf{5}}_H$  for Higgses  
$$\mathcal{W} \supset \mathbf{10} \times \bar{\mathbf{5}} \times \bar{\mathbf{5}}_H + \mathbf{10} \times \mathbf{10} \times \mathbf{5}_H$$

where  $\mathbf{5}_H = \underbrace{(\mathbf{3}, \mathbf{1})_{-1/3}}_{\text{Higgs triplets}} \oplus (\mathbf{1}, \mathbf{2})_{1/2}$
- In general for (SUSY) GUTs: proton decay operators of various dim.

### Dimension 4 Operators

- $\mathcal{W} \supset \bar{u}\bar{d}\bar{d} + \ell\bar{\ell}\bar{e} + \ell q\bar{d}$  from  $\mathbf{10} \times \bar{\mathbf{5}} \times \bar{\mathbf{5}}$
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  - Forbidden by matter parity  $\mathbb{Z}_2^m$  Farrar, Fayet 1978  
( $\equiv$  R-parity) Dimopoulos, Georgi 1981  
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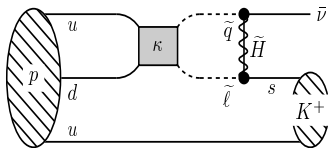
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# Grand Unified Theories in 4D

## Dimension 5 Operators

$$\mathcal{W} \supset \frac{1}{M_{\text{Pl}}} qqql + \frac{1}{M_{\text{Pl}}} \bar{u}\bar{u}\bar{d}\bar{e} \quad \text{from } \mathbf{10} \times \mathbf{10} \times \mathbf{10} \times \bar{\mathbf{5}}$$

- Decay mode:  $p \rightarrow K^+ \bar{\nu}$



Fast proton decay  $\Rightarrow$  additional suppression  $\approx 10^{-8}$  needed

- Symmetries:

- Baryon triality  $B_3$

Ibáñez, Ross 1991

- Proton hexality  $P_6 \equiv \mathbb{Z}_2^m \times B_3$

Dreiner, Luhn, Thormeier 2006  
Förste, Nilles, Ramos-Sánchez, P.V. 2010

- $\mathbb{Z}_4^R$  with  $R$ -charges (from extra dimensions):

matter	1
Higgs	0
$\mathcal{W}$	2

Lee, Raby, Ratz, Ross, Schieren,  
Schmidt-Hoberg, P.V. 2010

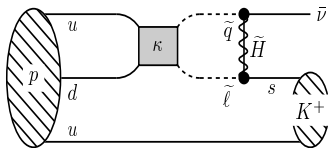
- Furthermore e.g. Babu, Barr 1993, Hall, Nomura 2001

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**GUT** Ibáñez, Ross 1991

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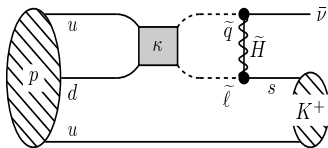
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# Grand Unified Theories in 4D

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$$\mathcal{W} \supset \frac{1}{M_{\text{Pl}}} qqql + \frac{1}{M_{\text{Pl}}} \bar{u}\bar{u}\bar{d}\bar{e} \quad \text{from } \mathbf{10} \times \mathbf{10} \times \mathbf{10} \times \bar{\mathbf{5}}$$

- Decay mode:  $p \rightarrow K^+ \bar{\nu}$



Fast proton decay  $\Rightarrow$  additional suppression  $\approx 10^{-8}$  needed

- Symmetries:

- Baryon triality  $B_3$

**GUT** Ibáñez, Ross 1991

- Proton hexality  $P_6 \equiv \mathbb{Z}_2^m \times B_3$

**GUT** Dreiner, Luhn, Thormeier 2006  
Förste, Nilles, Ramos-Sánchez, P.V. 2010

- $\mathbb{Z}_4^R$  with  $R$ -charges (from extra dimensions):

matter	1
Higgs	0
$\mathcal{W}$	2

Lee, Raby, Ratz, Ross, Schieren,  
Schmidt-Hoberg, P.V. 2010

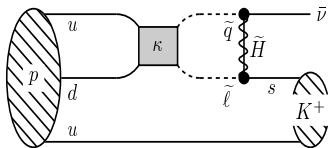
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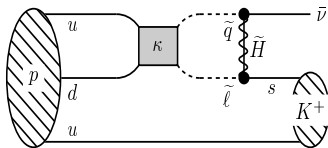
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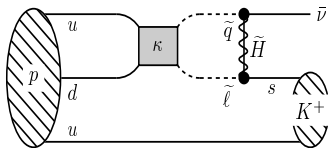


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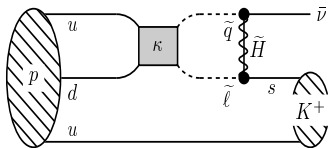
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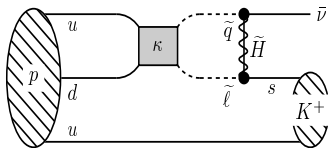
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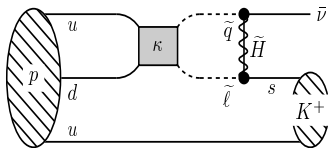
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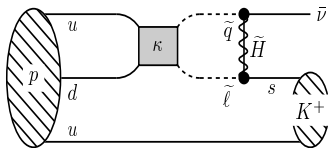
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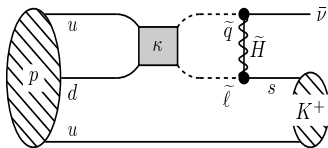
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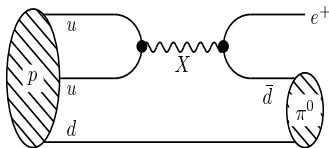
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## Dimension 6 Operators

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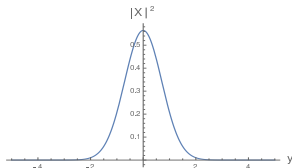
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Smoking gun signature of GUTs

- Attempt: avoid this in extra dimensions

Localize  $X$  boson wavefunction in extra dimension,  $n = 0$



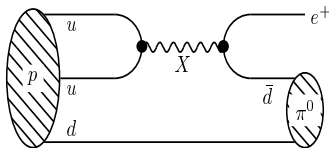
Hebecker, Unwin 2014

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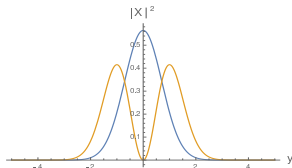
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Hebecker, Unwin 2014

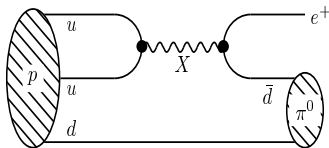


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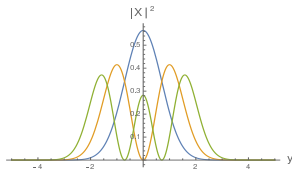
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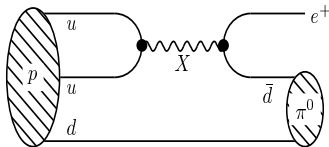
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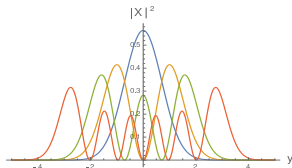
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Smoking gun signature of GUTs

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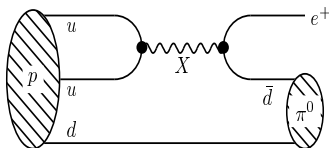
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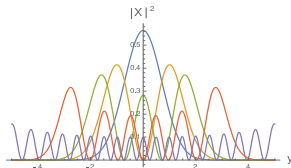
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Smoking gun signature of GUTs

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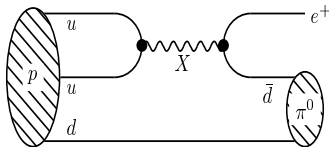
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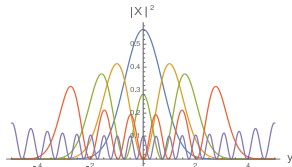
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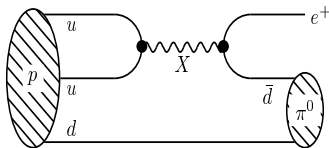
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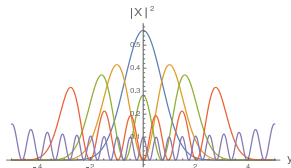
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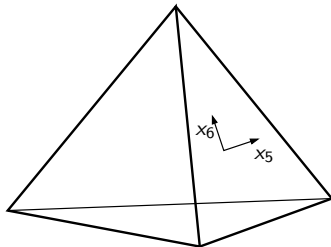


Hebecker, Unwin 2014

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$\Rightarrow$  orbifolds, e.g.  $T^2/\mathbb{Z}_2$



- bulk and brane fields

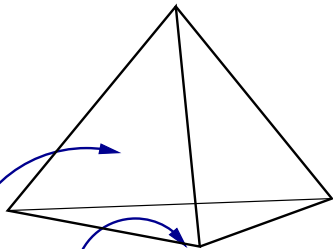
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e.g. Nilles, Ratz and P.V. 2012

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from enhanced gauge symmetry

Biermann, Ratz and P.V. in prep. 2016

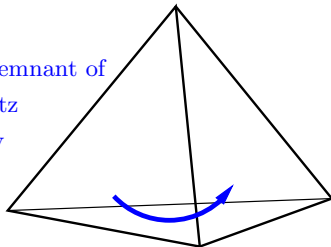
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discrete remnant of  
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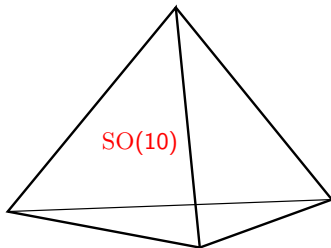
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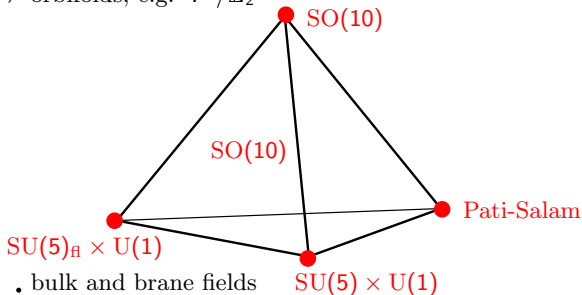
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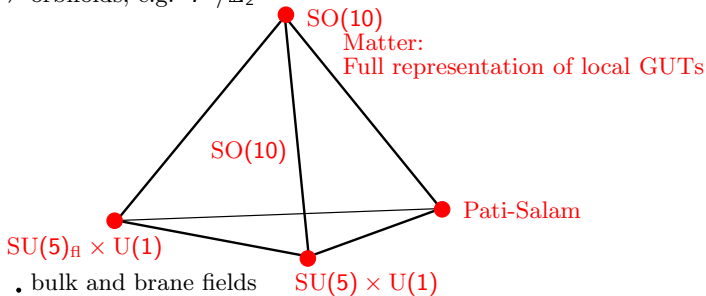
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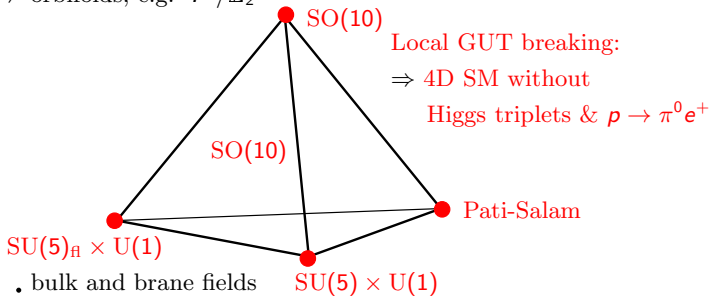
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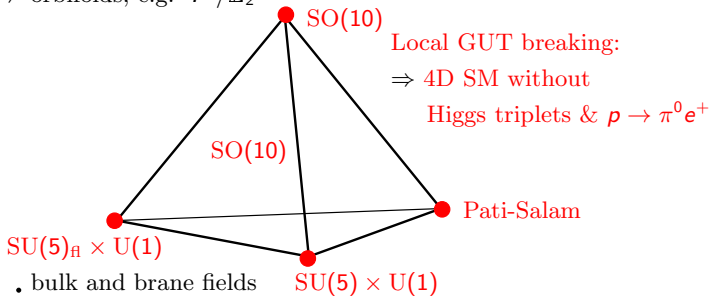
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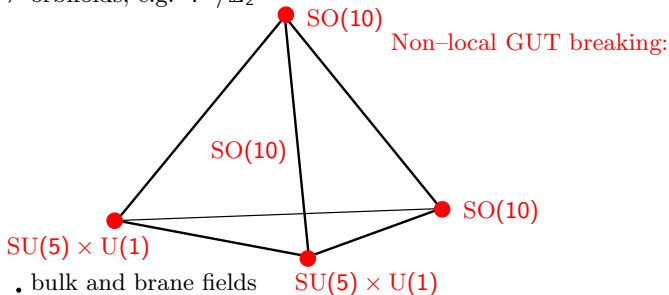
MiniLandscape & OrbifoldLandscape  
 $10^4$  MSSMs Talk by Nilles & Nilles, P.V. 2014

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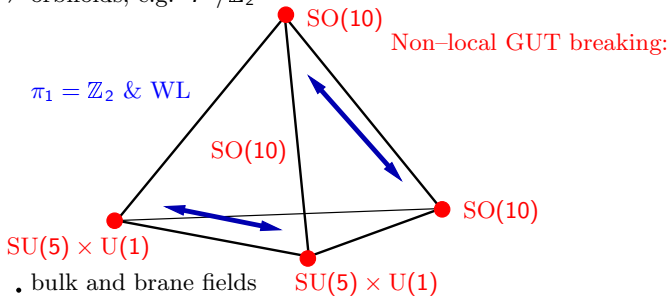
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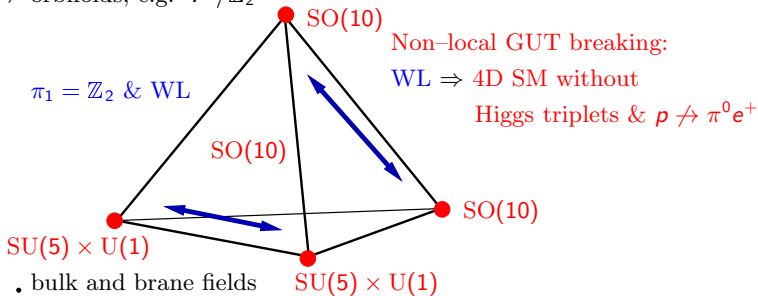
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- want: discrete  $R$  symmetry  $\Rightarrow$  Dim. 4 & 5 proton decay suppressed
- need: compact space with discrete symmetries

$\Rightarrow$  orbifolds, e.g.  $T^2/\mathbb{Z}_2$



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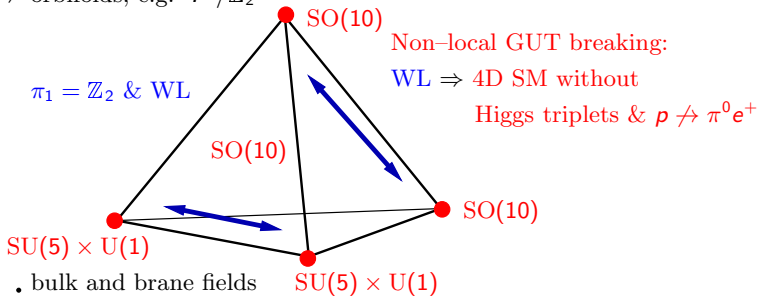
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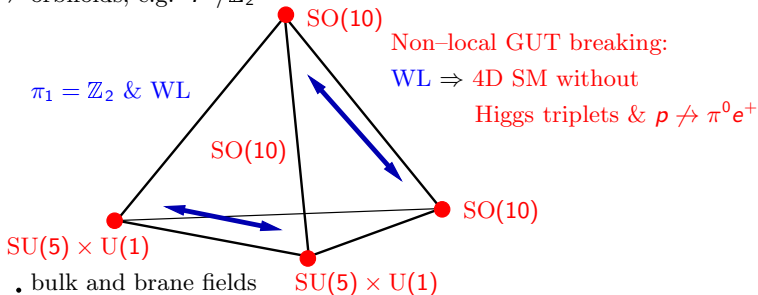
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$\mathbb{Z}_2 \times \mathbb{Z}_2$  + freely acting  $\mathbb{Z}_2$  Blaszczyk,  
Groot Nibbelink, Ratz, Ruehle, Trapletti, P.V. 2009

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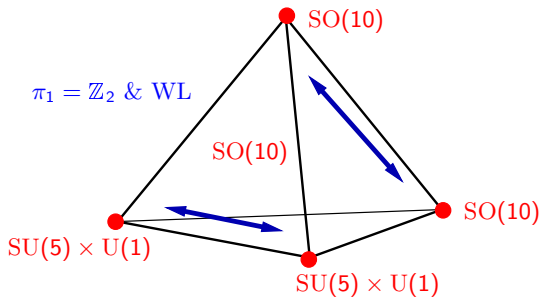
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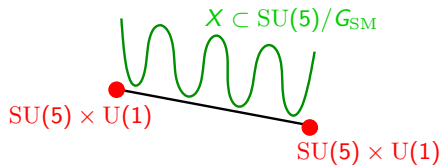
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$\pi_1 \neq 1$  for smooth Calabi-Yau MSSMs

Talks by Anderson, Gray, Lukas, ...

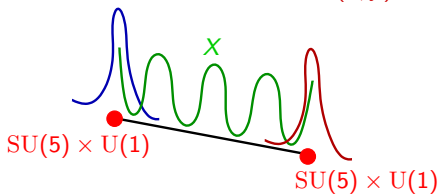






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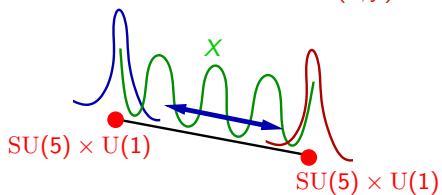
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$\pi_1 = \mathbb{Z}_2$  & WL

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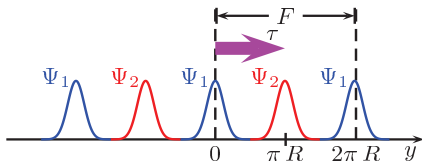


## Non-local GUT breaking and dimension 6 proton decay:

- Upstairs: SU(5) with  $n_G = 6$  generations
- $\ell_i$  and  $\bar{d}_i$  from  $\bar{\mathbf{5}}_s$

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- Consider localization of  $i = 1, 2$  in  $F$



- $X$  boson exchange, e.g.

$$\mathcal{L}_{\text{eff}} \supset \int dy g_{5D} \sum_{i=1}^{n_G} \bar{\ell}_i(x, y) \gamma^\mu X_\mu(x, y) \bar{d}_i(x, y)$$

- Quotient by  $\tau$  (generates  $\pi_1 = \mathbb{Z}_2$ )

$$A^\mu(x, y) \xrightarrow{\tau} A^\mu(x, y + \tau) \stackrel{!}{=} P A^\mu(x, y) P^{-1}$$

with  $P = \text{diag}(-1, -1, +1, +1, +1) \Rightarrow X$  massive

Mütter, Ratz and P.V. 2016

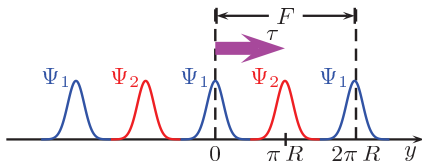


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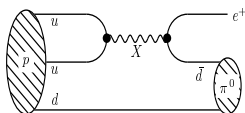
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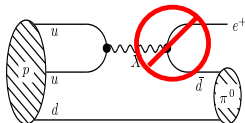
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