Fermilab

Composite quarks and leptons with low-scale $SO(10)$ unification

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Work in progress with Bogdan Dobrescu

Substructure

Quark and lepton compositeness

Can we write down such a model?

SM fermions chiral ⇒ composite dynamics also chiral

A spectrum of light bound states arises

Model in a nutshell

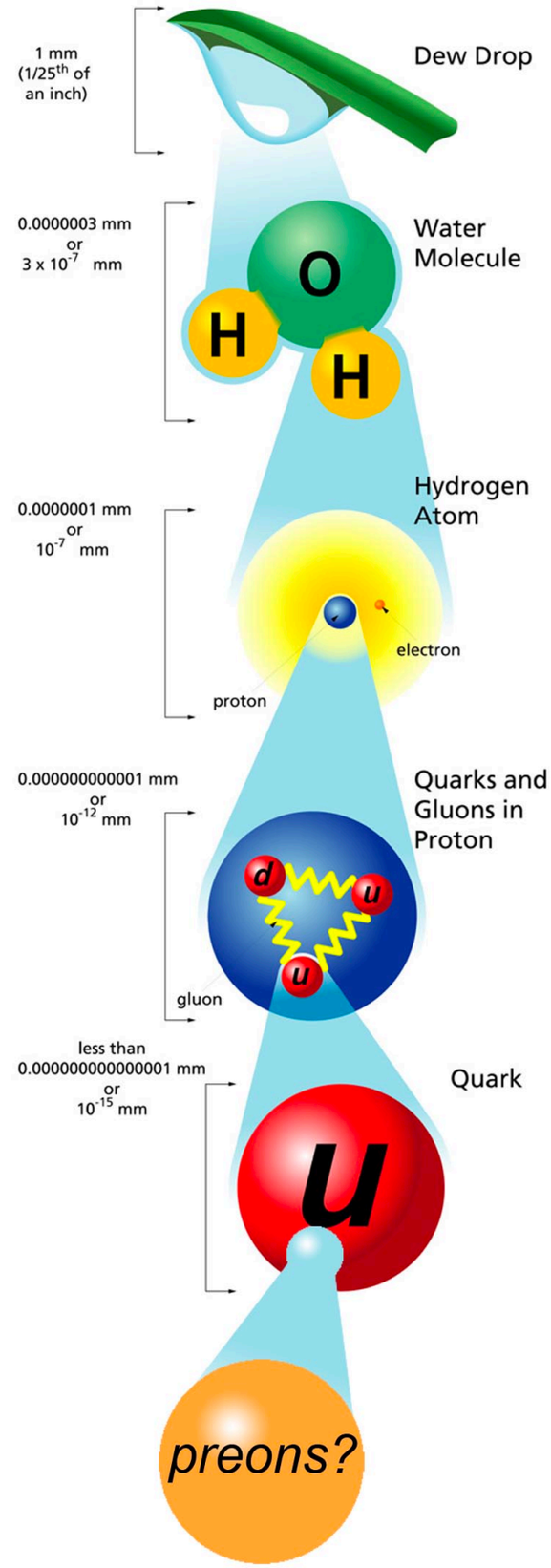
Preons bind into prebaryons under $SU(15)$

Prebaryons include all 3 SM generations of matter

Higgs doublets are di-prebaryon bound states

Implications

Low-scale unification, mass hierarchies, new proton decay modes.



UV model

Preons $(\Psi, \psi_{2,3,4}, \Omega)$ are massless chiral fermions

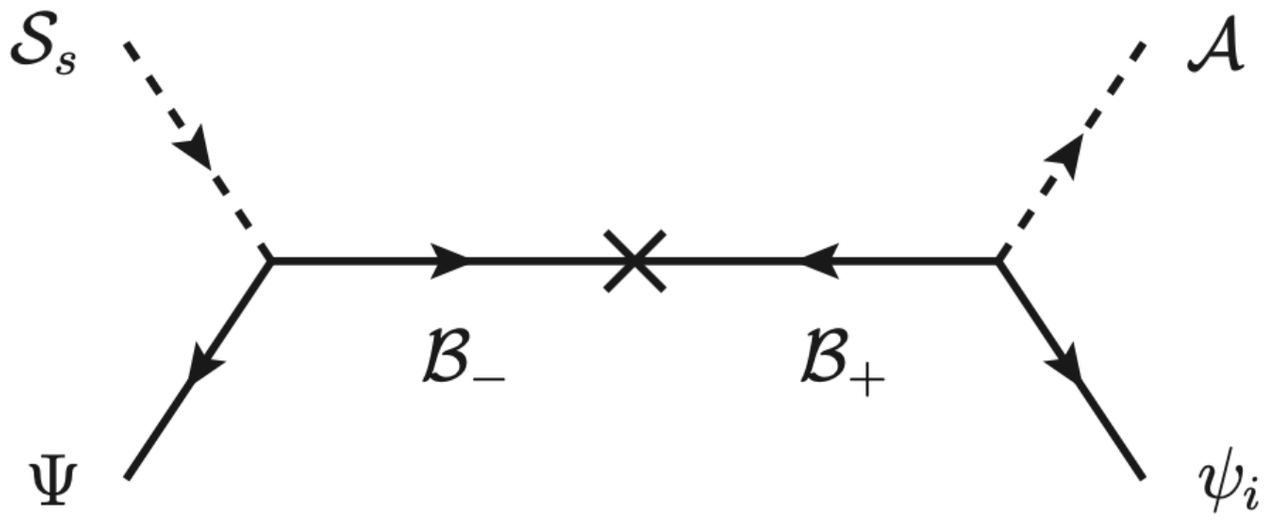
$SU(15)_p$ confines the preons below confining scale Λ_{pre}

Scalars break flavor and $SO(10)$ symmetry at Λ_{10}

Fields charged under $SU(15) \times SO(10)$ gauge group

field	spin	$SU(15)_{\text{p}}$	$SO(10)$	comments
Ψ	$1/2$	15	16	massless preons
ψ_2, ψ_3, ψ_4	$1/2$	15	1	massless preons
Ω	$1/2$	$\overline{120}$	1	massless preons
$\mathcal{A}$	0	$\overline{105}$	1	flavor-dependent couplings
$\mathcal{S}_a$	0	1	45	$SO(10)$ breaking VEVs
$\mathcal{S}_s$	0	1	16	$SO(10)$ breaking VEVs
$\mathcal{B}_+$, $\mathcal{B}_-$	$1/2$	15 , $\overline{15}$	1	Dirac mass $> \Lambda_{10}$

Light first SM generation since no direct coupling to A exists. Suppressed by dimension 5 effective Yukawa operator.



Theory below GUT scale

$SU(N)$ gauge theory, with $(N+4)$-fund. and 1-symm. rep. $\Rightarrow$ massless chiral baryons form

Ω LH fermion in symm. rep. anomaly cancelled by 19 LH fermions in fund. reps.

Fields charged under $SU(15)_p \times SU(3)_c \times SU(2)_W \times U(1)_Y$

Fermion	$SU(15)_{\mathrm{p}}$	$SU(3)_c \times SU(2)_W$	$U(1)_Y$
ψ_Q	15	$(3,2)$	$+1/6$
ψ_U	15	$(\overline{3},1)$	$-2/3$
ψ_D	15	$(\overline{3},1)$	$+1/3$
ψ_L	15	$(1,2)$	$-1/2$
ψ_E	15	$(1,1)$	$+1$
$\psi_1, ..., \psi_4$	15	$(1,1)$	0
Ω	$\overline{120}$	$(1,1)$	0

$SO(10)$ symmetry breaking $\psi_{4\ldots19}$ and re-labelling w.r.t SM charges:

$$\Psi = \psi_U + \psi_Q + \psi_E + \psi_D + \psi_U + \psi_1$$

The SM-singlet LH fermion $\psi_1 \leftrightarrow \psi_N$ and is conjugate of RH neutrino

Prebaryons below confinement scale

$SU(15)_p$ interactions give rise to composite chiral **prebaryons**: $(\Psi\psi_i\Omega, \psi_i\psi_j\Omega, \Psi\Psi\Omega)$

Bound states of **SM fermions**: $(\Omega_{Qi}, \Omega_{Li}, \Omega_{Ui}, \Omega_{Di}, \Omega_{Ei})$

Additional bound states:

12 Dirac fermions which are vectorlike under SM gauge

6 gauge singlet Weil fermions: $(\Omega_{ij}, \Omega_{Ni})$

vectorlike fermion	component LH , RH	$SU(3)\times SU(2)\times U(1)$
$\Omega_{8,2}$	$\Omega_{QU}^{(8,2)}$, $\overline{\Omega}_{QD}^{(8,2)}$	$(8,2,-1/2)$
$\Omega_{6,1}$	$\Omega_{QQ}^{(6,1)}$, $\overline{\Omega}_{UD}^{(\bar{6},1)}$	$(6,1,+1/3)$
$\Omega_{3,3}$	$\Omega_{QL}^{(3,3)}$, $\overline{\Omega}_{QQ}^{(\bar{3},3)}$	$(3,3,-1/3)$
$\Omega_{3,2}$	Ω_{QE} , $\overline{\Omega}_{UL}$	$(3,2,+7/6)$
$\mathcal{L}_2$	$\Omega_{QU}^{(1,2)}$, $\overline{\Omega}_{QD}^{(1,2)}$	$(1,2,-1/2)$
$\Omega_{3,1}$	Ω_{UU} , $\overline{\Omega}_{DE}$	$(3,1,-4/3)$
$\mathcal{Q}$	Ω_{Q4} , $\overline{\Omega}_{DL}$	$(3,2,+1/6)$
$\mathcal{D}_2$	$\Omega_{QL}^{(3,1)}$, $\overline{\Omega}_{UE}$	$(3,1,-1/3)$
$\mathcal{D}_1$	$\Omega_{UD}^{(3,1)}$, $\overline{\Omega}_{D4}$	$(3,1,-1/3)$
$\mathcal{L}_1$	Ω_{L4} , $\overline{\Omega}_{LE}$	$(1,2,-1/2)$
$\mathcal{U}$	Ω_{DD} , $\overline{\Omega}_{U4}$	$(3,1,+2/3)$
$\mathcal{E}$	Ω_{E4} , $\overline{\Omega}_{LL}$	$(1,1,+1)$

Di-prebaryons and mass hierarchy

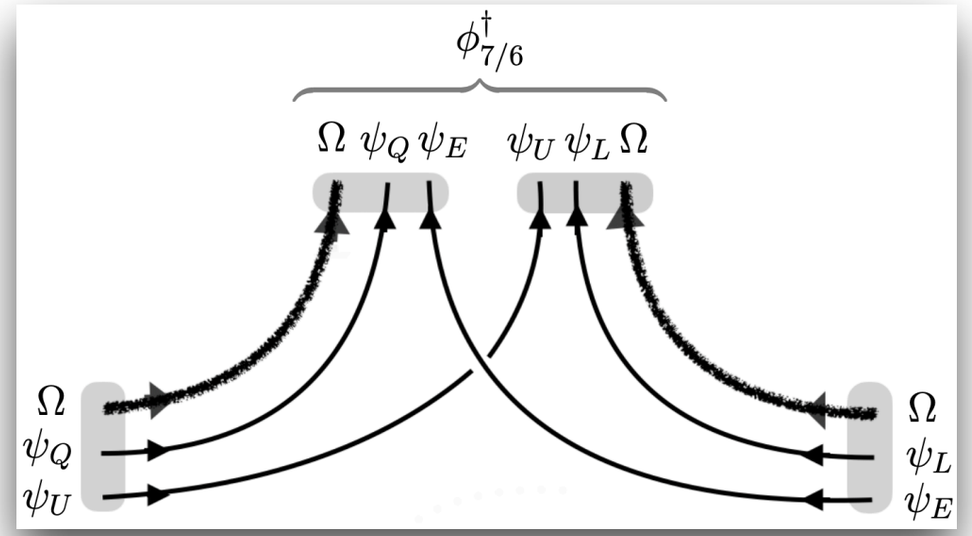
Scalars lighter than $\Lambda_{\rm pre}$ are **di-prebaryons** bound by remnant $SU(15)$ + SM gauge + A exchange (think deuteron)

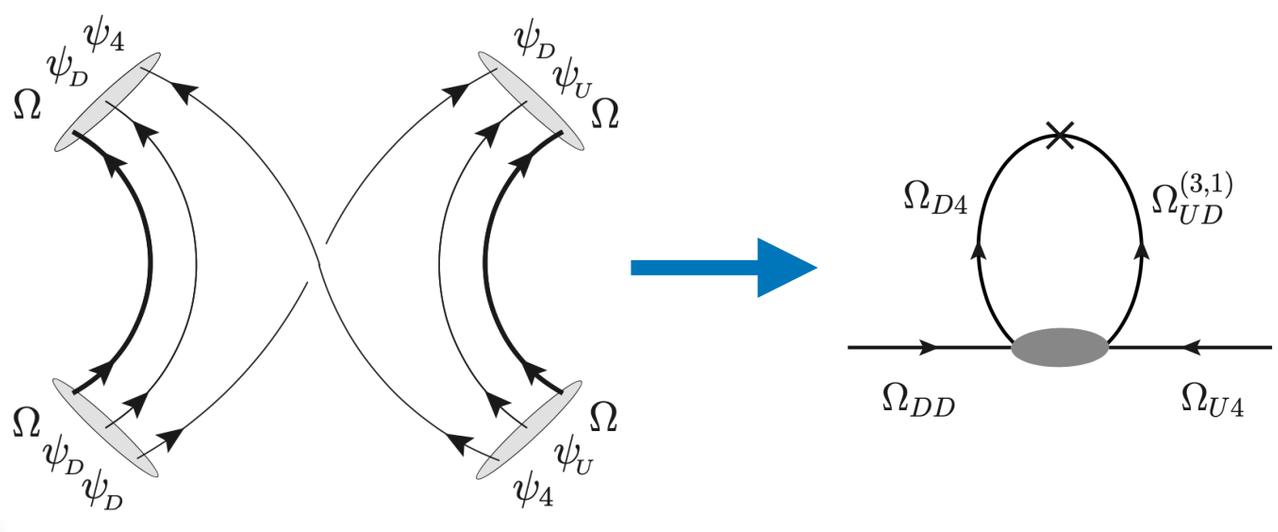
Vfermions of $(8,2,+1/2)$ most deeply bound with largest Dirac mass and Yukawa-couple as: $y_{88}\phi^*_{88}\Omega^{(8,2)}_{QU}\Omega^{(8,2)}_{QD}$

Additional mass generating mechanism can arise from loop-effects of non-planar $SU(15)$ interactions at $\Lambda_{\rm pre}$

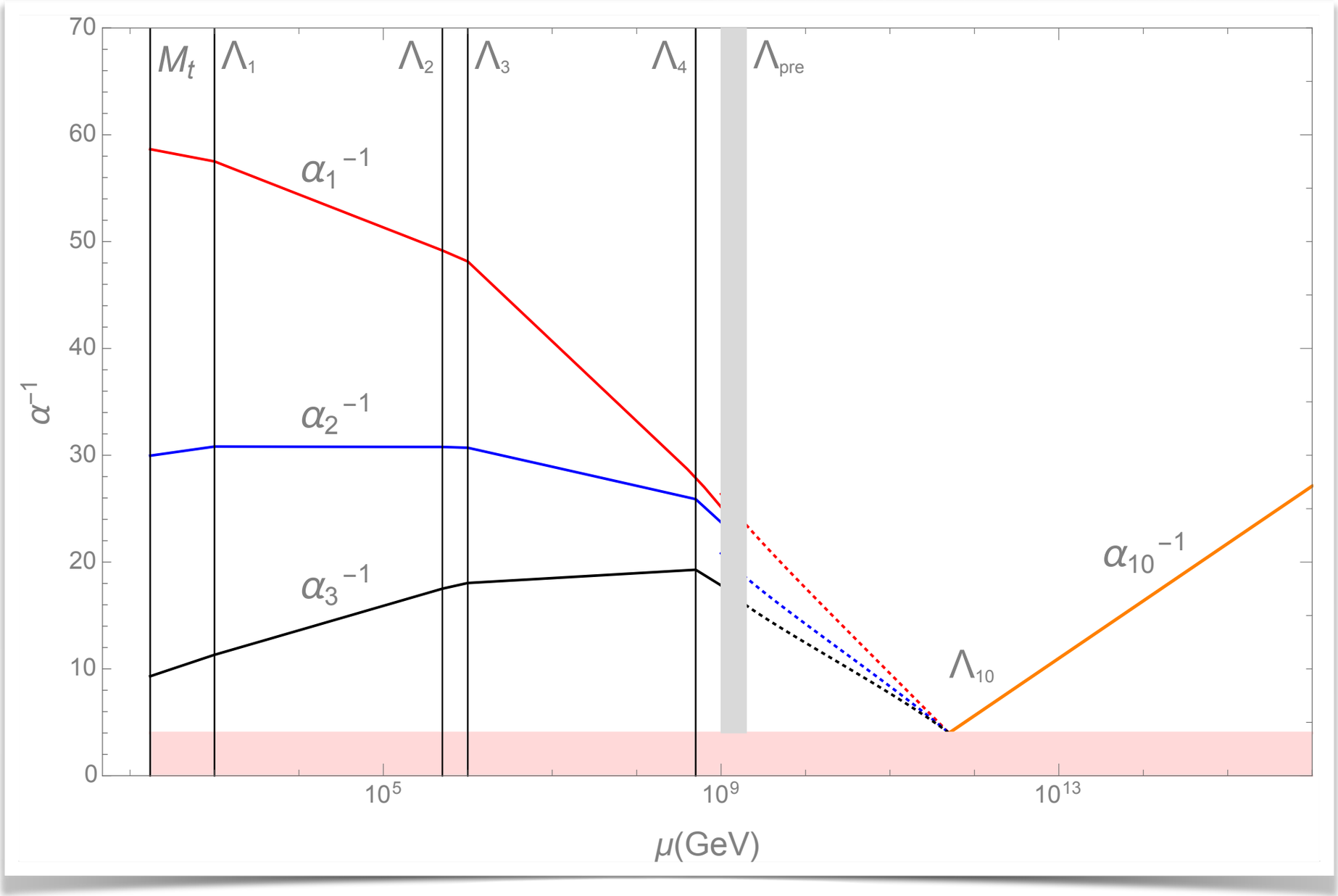
$H_{(u,d)}(1,2,\pm 1/2) \equiv \Omega_{(U,D)4}\Omega_{Q3}(1,2,\mp 1/2)$ give rise to up (down)-type quark masses.

vectorlike fermion	mass
$\Omega_{8,2}$	$y_{88}\,\langle\phi_{88}\rangle$
$\Omega_{6,1}$	$y_{6\bar{6}}\,\langle\phi_{6\bar{6}}\rangle$
$\Omega_{3,3}$	$y_{33}\,\langle\phi_{33}\rangle$
$\Omega_{3,2}$	$y_{7/6}\,\langle\phi_{7/6}\rangle$
$\mathcal{L}_2$	$y'_{88}\,\langle\phi_{88}\rangle + y'_{6\bar{6}}\langle\phi_{6\bar{6}}\rangle$
$\Omega_{3,1}$	$y_{4/3}\,\langle\phi_{4/3}\rangle$
$\mathcal{Q}$	$y_{1/6}\,\langle\phi_{1/6}\rangle$
$\mathcal{D}_2$	$y'_{7/6}\langle\phi_{7/6}\rangle$
$\mathcal{D}_1$	$y'_{1/6}\,y'_{4/3}\langle\phi_{1/6}\rangle\dfrac{\langle\phi_{4/3}\rangle}{m_{\mathcal{D}_2}}$
$\mathcal{L}_1$	$y'_{1/6}\,y'_{7/6}\langle\phi_{1/6}\rangle\dfrac{\langle\phi_{7/6}\rangle}{m_{\mathcal{L}_2}}$
$\mathcal{U}$	$\dfrac{m_{\mathcal{D}_1}}{N_c N}$
$\mathcal{E}$	$\dfrac{m_{\mathcal{L}_1}}{N}$





Unification



Below Λ_{10} **mass hierarchy**:

$\Lambda_1 \leftrightarrow (\Omega_{U4}, \Omega_{DD}; \Omega_{E4}\Omega_{LL}; H_{u,d})$

$\Lambda_2 \leftrightarrow (\Omega_{D4}, \Omega_{UD}, \Omega_{UE}, \Omega_{QL}; \Omega_{L4}\Omega_{LE})$

$\Lambda_3 \leftrightarrow (\Omega_{DE}, \Omega_{UU}, \Omega_{Q4}, \Omega_{DL}, \Omega_{QE}\Omega_{UL}; \phi_{76,16,43})$

$\Lambda_4 \leftrightarrow (\Omega_{D4}, \Omega_{UD}, \Omega_{UE}, \Omega_{QL}; \Omega_{LE}\Omega_{L4}; \phi_{88,66,33})$

Low-scale unification possible due to $SU(15)$ symmetry protection against rapid proton decay

Passed Λ_4 **asymptotic freedom** lost but couplings unify under SO(10) at $\Lambda_{10} \Rightarrow$ Freedom regained!

Proton decay

Proton decay at $\Lambda_{\rm pre}$ occurs, e.g. 8-baryon operator:

$$\frac{C_8}{\Lambda^8_{\rm pre}}\left(\bar{\Omega}_{43}\bar{\Omega}_{43}\right)\left(\bar{\Omega}^{\bar{3},3}_{QQ}\bar{\Omega}^{(3,3)}_{QL}\right)\left(\Omega_{Q3}\Omega_{Q3}\right)\left(\Omega_{Q4}\Omega_{L4}\right)$$

Leads to $(su)(ue)$ operator with suppression:

$$\frac{1}{M^2_{suue}} \approx 10^{-16}\left(\frac{\langle\phi^\dagger_M\rangle\langle\phi^\dagger_{33}\rangle}{\Lambda^6_{\rm pre}}\right)$$

Additional (B, L)-violating operators also arise

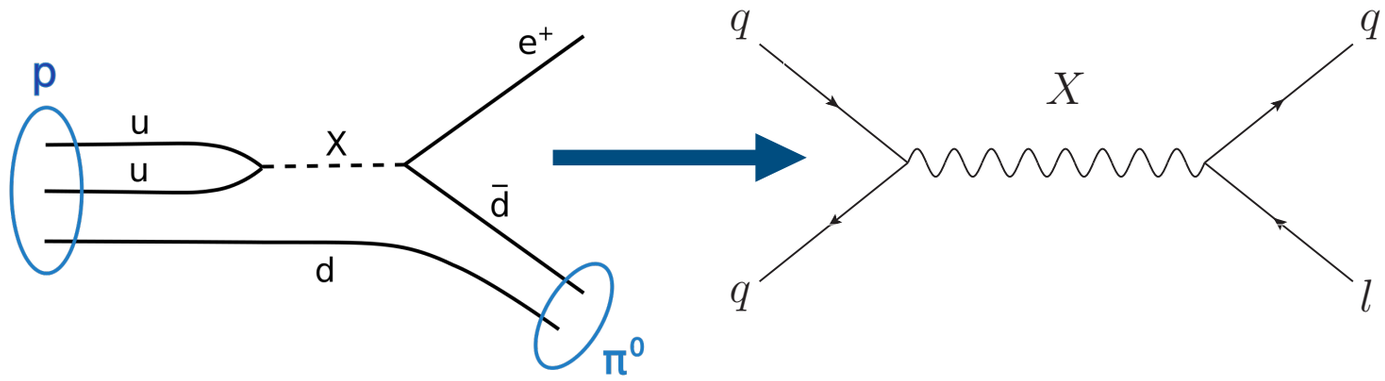
GUTs unify matter and forces ⇒ (B, L) not conserved ⇒ **Proton decay = GUT probe**

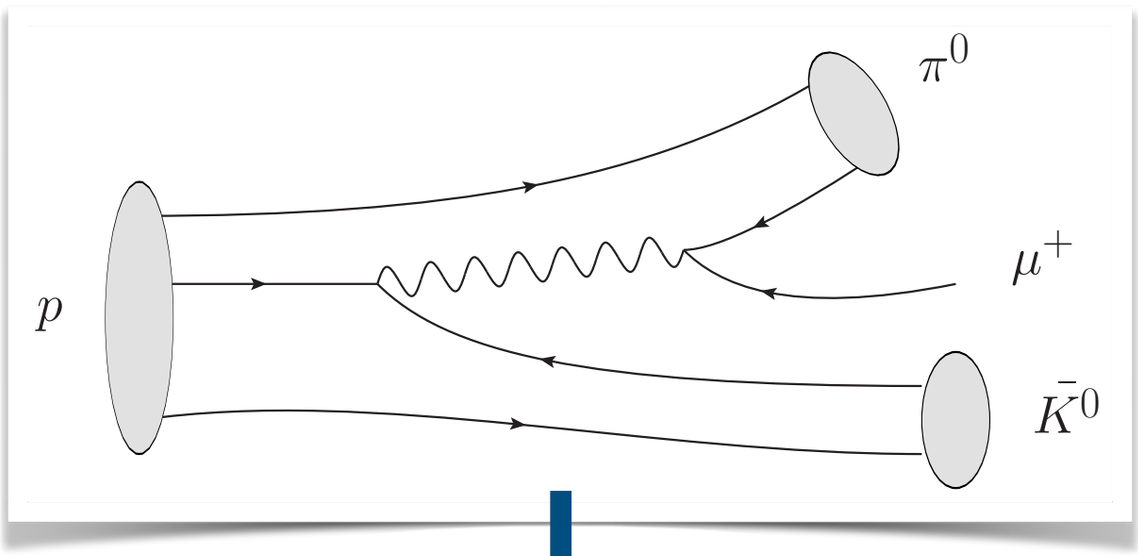
Dominant X^μ-mediated decay by dimension 8 operators: $\mathcal{O}_8 = \frac{y_u y_d}{\Lambda^2_{\rm pre}\Lambda^2_{10}}(H_u H_d)^\dagger(Q\sigma^\mu Q)(Q\sigma_\mu L)$

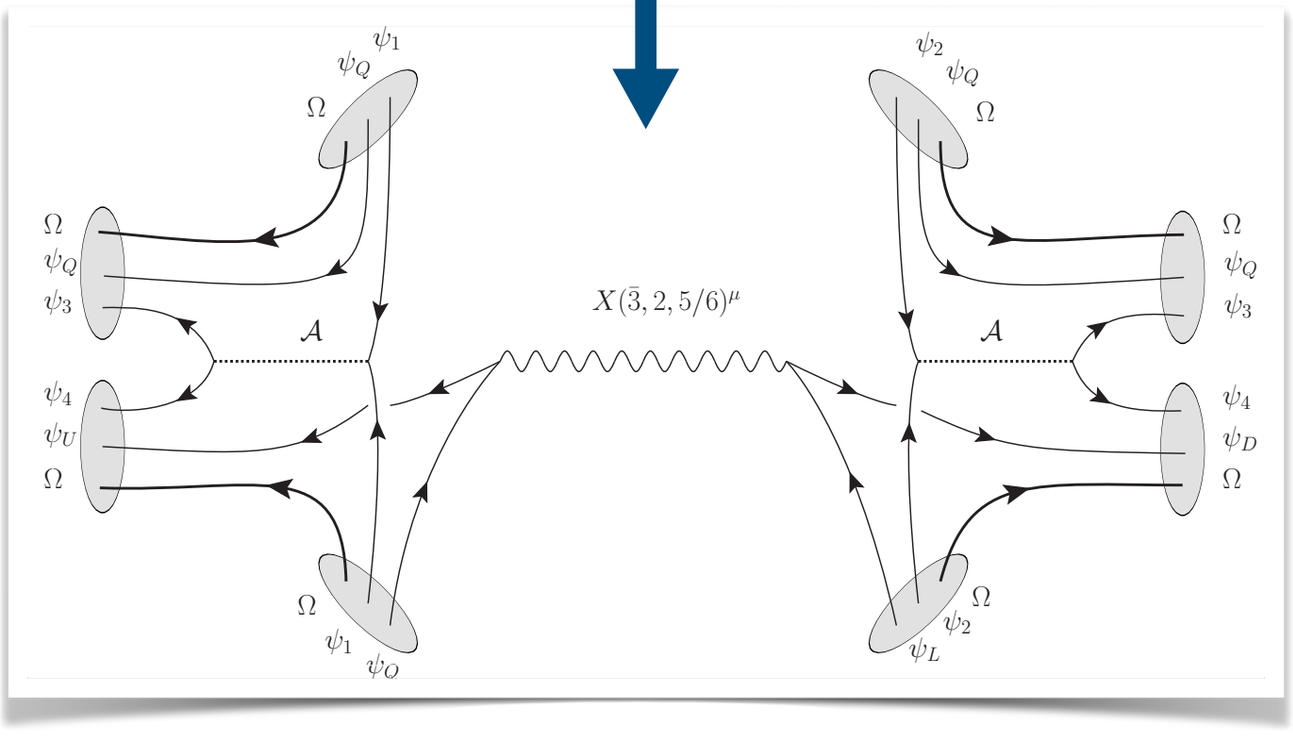
$$\Lambda_{10} > 10^8 \text{GeV} \Rightarrow \tau(p \to e^+\pi^0) \geq 2.4 \times 10^{34} y$$

Novel signatures: $p \to (\bar{K}^0\pi^0(\mu/e)^+, K^+\pi^-(\mu/e)^+)$

$$\tau(p \to e^+\pi^0) > \tau(p \to \bar{K}^0\pi^0(\mu/e)^+) > \tau(p \to K^+\bar{\nu})$$







Summary

A preonic $SU(15) \times SO(10)$ gauge theory was proposed.

Preon confinement gives rise to exactly **3 generations** of SM fermions.

Running of SM couplings leads to **low-scale** unification.

Proton decay by both GUT-mediated and confinement scale fields can lead to **novel signatures**.

Outlook

Improved understanding of strongly coupled chiral gauge theories.

Composite vectorlike fermions and scalars within reach of the LHC.

Proton decay signatures can be searched for at DUNE and other future experiments.