A theory of quark and lepton compositeness

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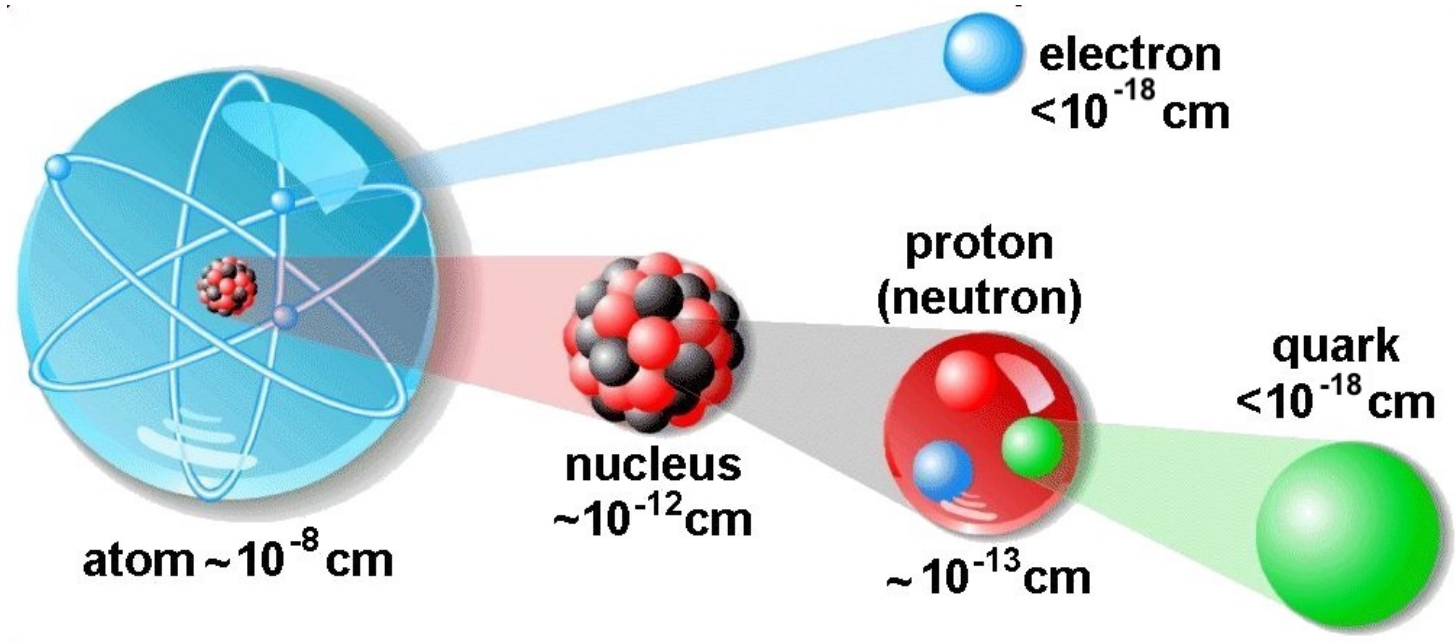
Based on 2112.15132, and on work with Ben Assi (Univ. of Cincinnati):
2211.02211, 2501.11607

Lepton-Photon Conference – Fermilab – August 25, 2025

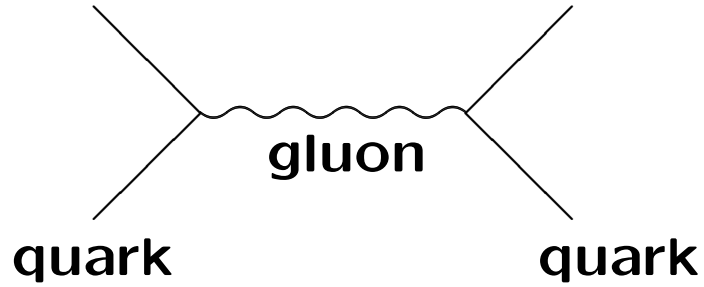


Does the electron have substructure?

How about the quarks?

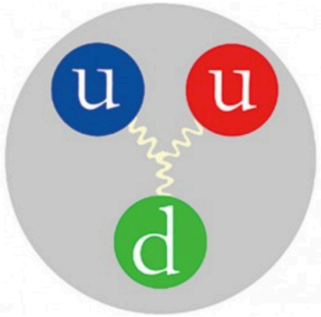
?

QCD



⋆ *strongly coupled at the QCD scale:* $\Lambda_{\rm QCD} \sim 200$ *MeV*

⋆ **it forms** $\langle \bar{q} q \rangle$ **condensates** *(chiral symmetry breaking)*.

⋆ **it forms the proton** 

, other baryons, and mesons.

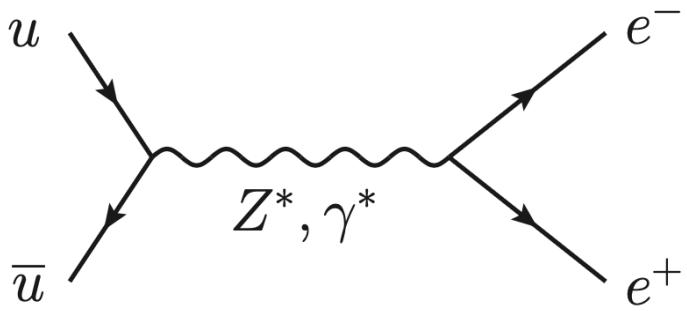
(confinement at $\Lambda_{\rm QCD}$*)*

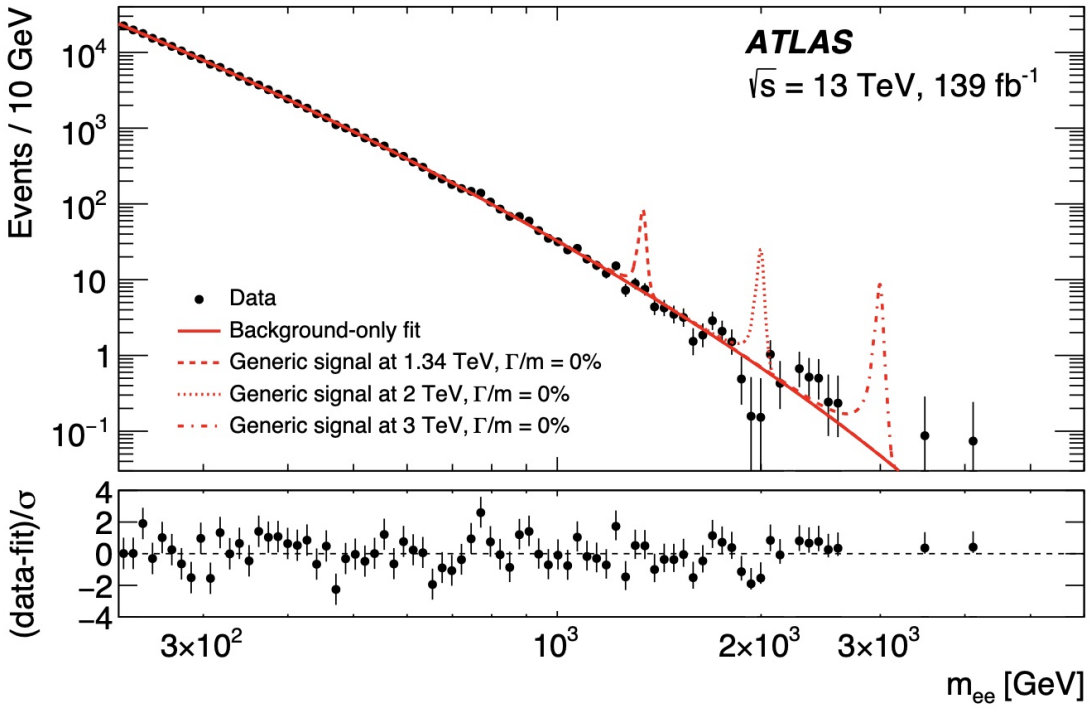
Up and down quark masses: $m_u, m_d \ll \Lambda_{\rm QCD}$

Proton mass: $m_p = 938$ **MeV** $> \Lambda_{\rm QCD}$

If the electron has substructure, it cannot be due a QCD-like interaction:

scale of electron compositeness is > 5 TeV (inferred from CMS and ATLAS searches at the LHC), so $> 10^7 m_e$.





1903.06248

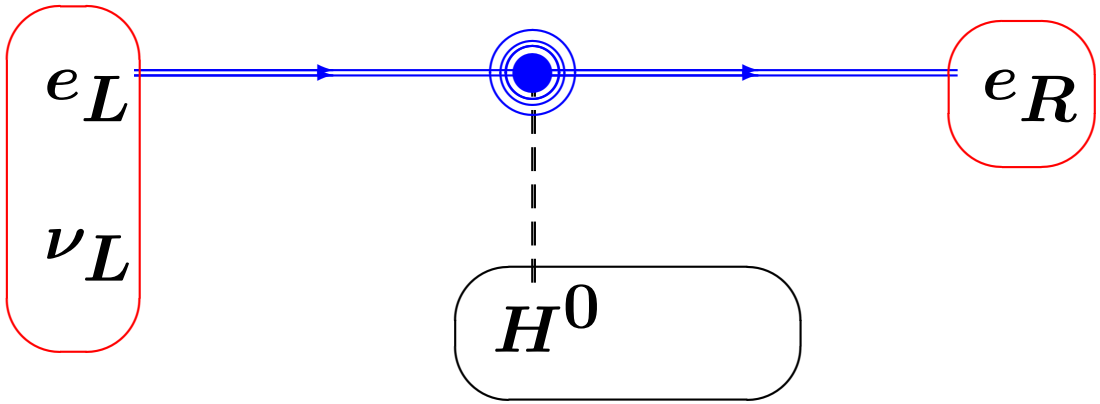
Chiral fermions

All Standard Model fermions are chiral: left- and right-handed components have different $SU(2)_W \times U(1)_Y$ charges.

E.g., **electron:**

e_L *(feels the weak interaction),* e_R *(no interaction with* $W^{\pm}$*)*

Electron mass: e_L turns into e_R and vice-versa due to its interaction with the Higgs field:



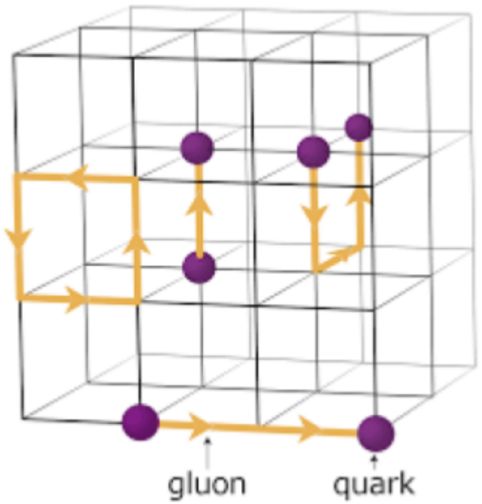
⋆ **If the electron is a composite particle, then the ν_e neutrino must also be composite!**

⋆ **Any theory that predicts electron compositeness must be a strongly-coupled chiral theory.**

So far, nobody knows how to compute observables in a chiral theory at large coupling.

QCD (not a chiral theory): computations at $\alpha_s \approx 1$ are done (heroic progress over 50 years) using simulations on a space-"time" Lattice.

Same methods don't work (yet) for chiral theories.



There are, however, some methods for guessing the spectrum of light composite particles ...

Standard Model

Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
quark doublet: $q_L^i = (u_L^i,\, d_L^i)$	3	2	$1/6$
right-handed up-type quark: u_R^i	3	1	$2/3$
right-handed down-type quark: d_R^i	3	1	$-1/3$
lepton doublet: $l_L^i = (\nu_L^i,\, e_L^i)$	1	2	$-1/2$
right-handed charged lepton: e_R^i	1	1	-1
Higgs doublet: H	1	2	$1/2$

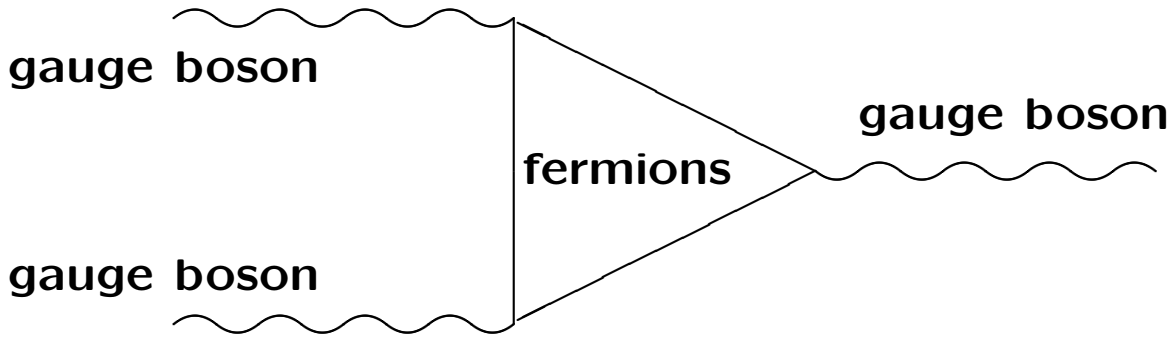
$i = 1, 2, 3$ *labels the fermion generations.*

There are $2 \times 3 + 3 + 3 + 2 + 1 = 15$ fermions per generation.

Charge conservation $\rightarrow$ gauge anomaly cancellation

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



Standard Model – anomalies cancel within each fermion generation:

$[SU(3)_c]^2\, U(1)_Y$: $\quad 2(1/6) + (-2/3) + (1/3) = 0$

$[U(1)_Y]^3$: $\quad 3\left[2(1/6)^3 + (-2/3)^3 + (1/3)^3\right] + 2(-1/2)^3 + (-1)^3 = 0$

... $\qquad (u_L, d_L) \qquad u_R \qquad d_R \qquad (\nu_L, e_L) \qquad e_R$

If the electron is a composite particle, then the u and d quarks must also be composite!

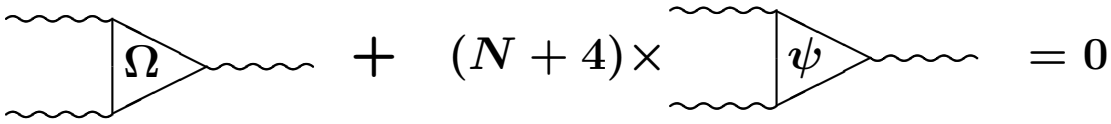
Example of strongly-coupled chiral theory

$SU(N)$ gauge symmetry with:

- **a chiral fermion (Ω) in the symmetric representation $\overline{\square\square}$,**
- **$N+4$ chiral fermions (ψ_k) in the fundamental representation $\square$**

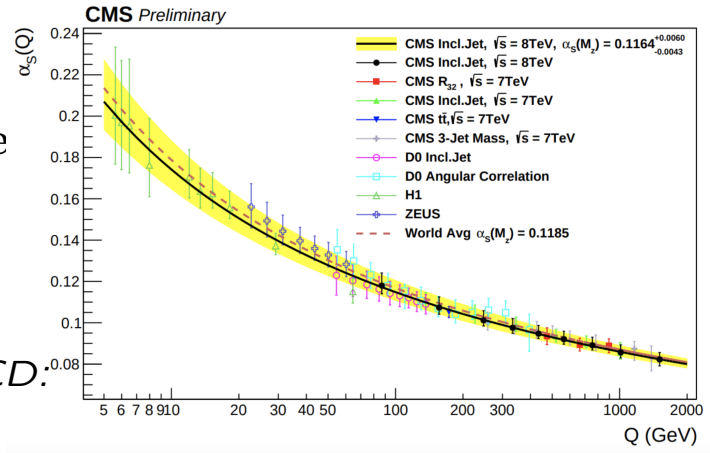
(Dimopoulos, Raby, Susskind, 1980; Eichten, Peccei, Preskill, Zeppenfeld, 1986)

Free of gauge anomalies:



Asymptotic freedom: α_N grows at smaller energy scales, until it becomes strong at $\Lambda_{\rm pre}$

similar to QCD:



Most likely forms $\Omega\,\psi_k\,\psi_\ell$ bound states: massless <u>chiral</u> "baryons" !

↓

based on consistency checks
('t Hooft anomaly matching; large N arguments; ...)

A model of quark and lepton compositeness

B. Dobrescu, Phys.Rev.Lett. (2022)

Preons: hypothetical left-handed fermions charged under the confining gauge group $SU(15)_{\rm p}$

Preons	$SU(15)_{\rm p}$	$SU(3)_c \times SU(2)_W \times U(1)_Y$	
ψ_Q	$\square$	$(3,\ 2,\ +1/6)$	*same charges as one generation of SM fermions*
ψ_U	$\square$	$(\bar{3},\ 1,\ -2/3)$	
ψ_D	$\square$	$(\bar{3},\ 1,\ +1/3)$	
ψ_L	$\square$	$(1,\ 2,\ -1/2)$	
ψ_E	$\square$	$(1,\ 1,\ +1)$	
$\psi_1, ..., \psi_4$	$\square$	$(1,\ 1,\ 0)$	*SM singlets*
Ω	$\overline{\square\square}$	$(1,\ 1,\ 0)$	

Chiral "pre-baryons" (bound states of 3 preons) have exactly the quantum numbers of the Standard Model fermions:

electron = $\Omega\,\psi_E\,\psi_1$ 

down quark = $\Omega\,\psi_D\,\psi_1$  , up quark = $\Omega\,\psi_U\,\psi_1$ 

...

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electron = $\Omega\,\psi_E\,\psi_1$ 

down quark = $\Omega\,\psi_D\,\psi_1$  **, up quark =** $\Omega\,\psi_U\,\psi_1$ 

...

Prediction **– much heavier new fermions must also exist:**

vectorlike down-type quarks = $\Omega\,\psi_U\,\psi_E \leftrightarrow \Omega\,\psi_U\,\psi_D$  

...

ongoing searches at the LHC!

Chiral "pre-baryons" of $SU(15)_{\rm p}$

Preon flavor index $i = 1, ..., 4$ implies 3 generations of SM fermions!

pre-baryons	$SU(3)_c \times SU(2)_W \times U(1)_Y$	name
$\Omega\,\psi_Q\,\psi_i \;\; (i = 1, 2, 3)$	$(3, 2, +1/6)$	$(u_L, d_L)_i$
$\Omega\,\psi_U\,\psi_i$	$(\overline{3}, 1, -2/3)$	u_i^c
$\Omega\,\psi_D\,\psi_i$	$(\overline{3}, 1, +1/3)$	d_i^c
$\Omega\,\psi_L\,\psi_i$	$(1, 2, -1/2)$	$(\nu_L, e_L)_i$
$\Omega\,\psi_E\,\psi_i$	$(1, 1, +1)$	e_i^c
$\Omega\,\psi_i\,\psi_j \;\; (i \neq j)$	$(1, 1, 0)$	N_{ij}
$\Omega\,\psi_D\,\psi_4 \leftrightarrow \Omega\,\psi_U\,\psi_D$	$(3, 2, +1/6)$	$\mathcal{D}$
$\Omega\,\psi_L\,\psi_4 \leftrightarrow \Omega\,\psi_L\,\psi_E$	$(1, 2, -1/2)$	$\mathcal{L}$
$\Omega\,\psi_E\,\psi_4 \leftrightarrow \Omega\,\psi_L\,\psi_L$	$(1, 1, +1)$	$\mathcal{E}$
■ ■ ■		■ ■ ■

3 generations of SM quarks and leptons

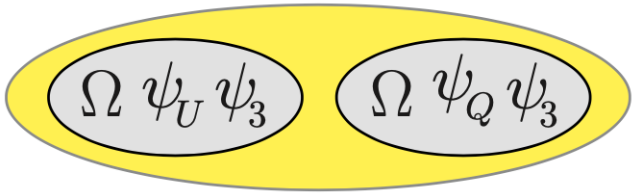
6 "right-handed" neutrinos

vectorlike fermions

Composite Higgs field

Deuteron: proton-neutron bound state due to nuclear forces (a remnant of QCD)

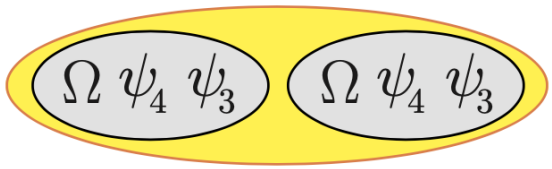
Similarly, there must be bound states of two pre-baryons:



$= \boldsymbol{H}$ *same quantum numbers as the Higgs doublet in the Standard Model*

If the $SU(15)_{\rm p}$ remnant interaction (preonic-"nuclear" force) is strong enough, then H breaks the electroweak symmetry.

There are also composite pseudoscalar particles: (potentially light gauge-singlets)

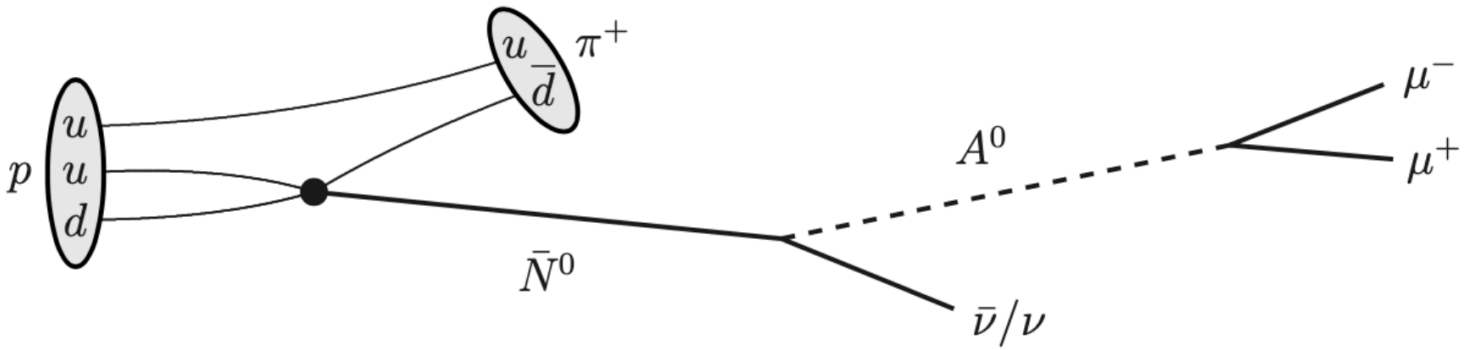
$A^0 =$ 

Another indirect test of electron & quark substructure:

Ben Assi, B.D., JHEP (2022)

Compositeness scale constrained by proton lifetime: $\Lambda_{\rm pre} \gtrsim 10^3$ **TeV**

Exotic proton decay $p \to \bar{N}^0 \pi^+$ followed by a displaced decay of "right-handed neutrino" via a axion-like particle A^0 (if $M_A < m_N$):



Signal can be probed at future proton decay experiments:

HyperKamiokande and especially DUNE *(liquid Argon detector allows reconstruction of the resonances)*

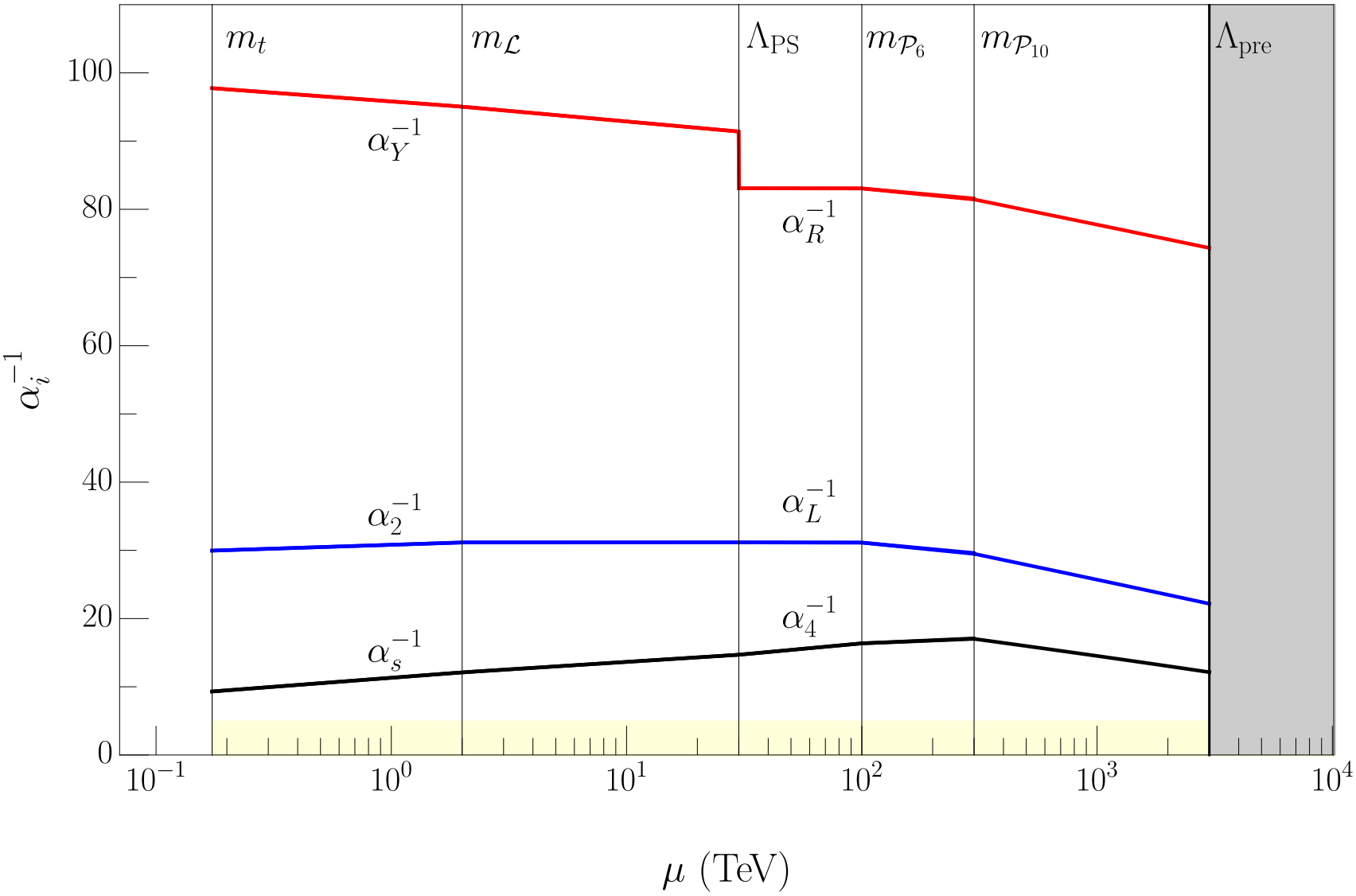
QCD looses asymptotic freedom

$\rightarrow$ UV behavior softened by embedding the SM gauge group:

Ben Assi, B. Dobrescu: 2501.11607

field	spin	$SU(15)_{\rm p}$	$SU(4)_{\rm PS} \times SU(2)_L \times SU(2)_R$
Ψ_W	1/2	$\square$	$(4, 2, 1)$
$\Psi_{W'}$	1/2	$\square$	$(\bar{4}, 1, 2)$
ψ_1, ψ_2, ψ_3	1/2	$\square$	$(1, 1, 1)$
Ω	1/2	$\overline{\square\square}$	$(1, 1, 1)$
$\mathcal{A}$, $\mathcal{A}'$	0	$\overline{\begin{array}{l}\square\\\square\end{array}}$	$(1, 1, 1)$

Running of the SM gauge couplings:

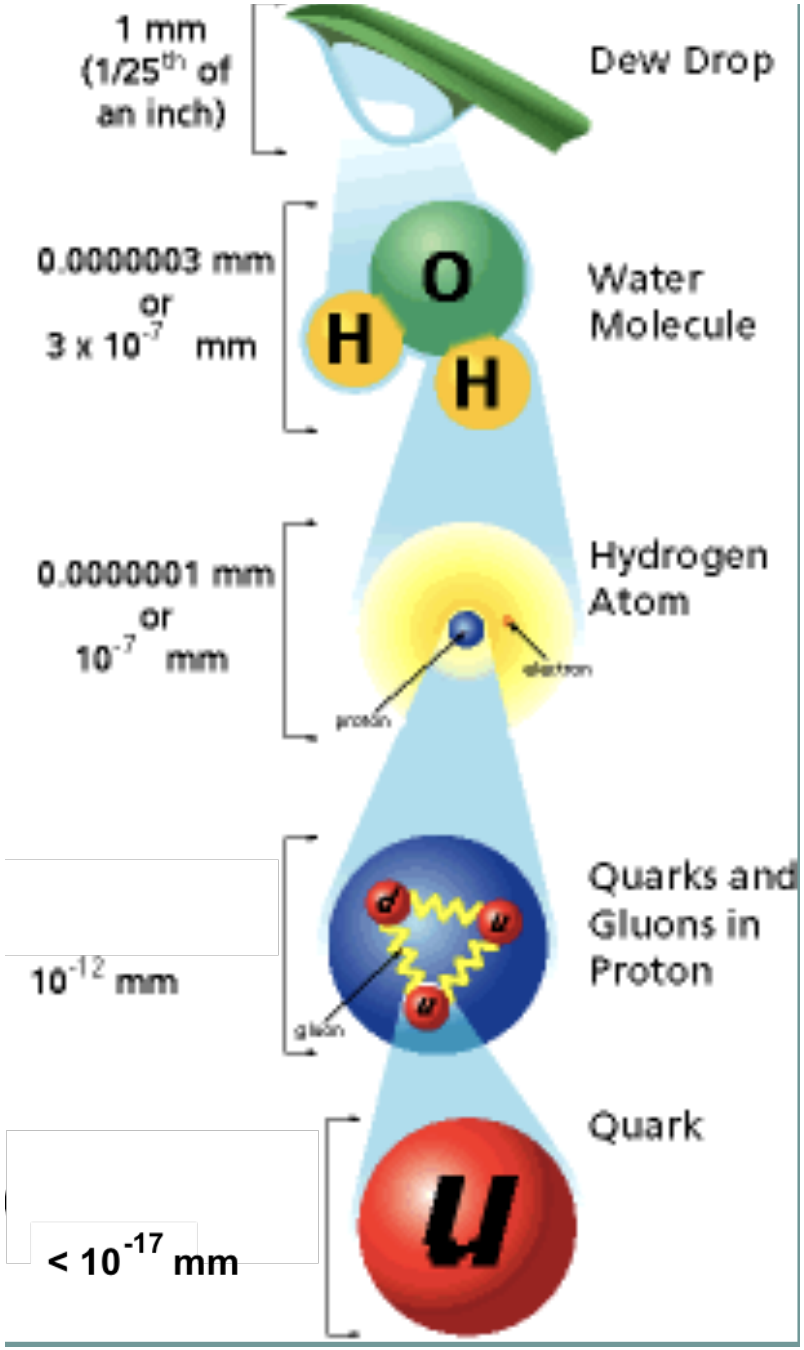


Conclusions

- **Not known if the leptons & quarks are elementary particles (point-like) or composite particles.**

- **In a theoretical model where the all Standard Model fermions are made of preons:**
  - *vectorlike quarks and leptons also form and will be probed at the LHC*
  - *rich sterile neutrino sector and axion-like particles to be probed at DUNE*

Bogdan Dobrescu (Fermilab)



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