Composite states in the Standard Model and beyond

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Based on: (2112.15132, 2211.02221) with co-authors: Michael Wagman and Bogdan Dobrescu

Composites of QCD and strongly-coupled dark matter

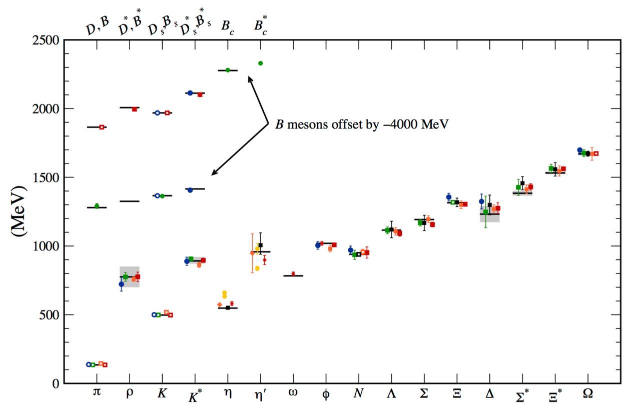
Hadrons and beyond

Lattice studies and pNRQCD motivation

pNRQCD for (multi-)hadron systems

Heavy meson and baryon spectra

Binding and N_c scaling for dark hadrons



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EFT treatment required

LQCD: Spectroscopy complete for most common hadrons

Exotic hadrons: recent experiments, BaBar, Belle, LHCb etc. E.g. tetra/pentaquarks, dibaryons etc.

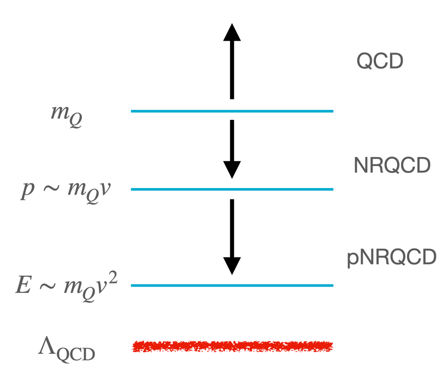
Weak coupling: $mv^2 \gg \Lambda_{\rm QCD}$ at $\mu \sim mv \Rightarrow$ perturbative pNRQCD estimates

Non-relativistic QCD

Heavy quarks and their bound states require **multi-scale** treatment ↔ Expansion at the Lagrangian level in $m_Q \gg v \sim \alpha_s \Rightarrow$ **EFT description**

HQET & NRQCD: Operators and matching known to $D=8$, NNLO and above [2]

pNRQCD: Static $1/r$ potentials known to $\mathrm{N^4LO}$, $m^2\mathrm{NNLO}$ [3,4]



Lagrangian operators

NRQCD: $\mathscr{L}_{\psi\chi} = \frac{d_1}{m_1 m_2}\psi_i^\dagger \psi_j \chi_k^\dagger \chi_l \delta_{ij}\delta_{kl} + \frac{d_8}{m_1 m_2}\psi_i^\dagger T^a_{ij}\psi_j \chi_k^\dagger T^a_{kl}\psi_l + \ldots$

pNRQCD: $\mathscr{L}_{\rm pNRQCD} = \mathscr{L}^{\rm ultrasoft}_{\rm NRQCD} + \int d^3r \sum_{n,k} \frac{c_n(\alpha_s,\mu)}{m^n} \mathscr{O}_k V^s_{n,k}(r,\mu,p,S_i)$

Degrees of freedom: Pauli spinors and ultra-soft gluons $(A^\mu(t,\boldsymbol{r}) : \boldsymbol{k}^\mu \ll mv)$

pNRQCD for arbitrary bound states

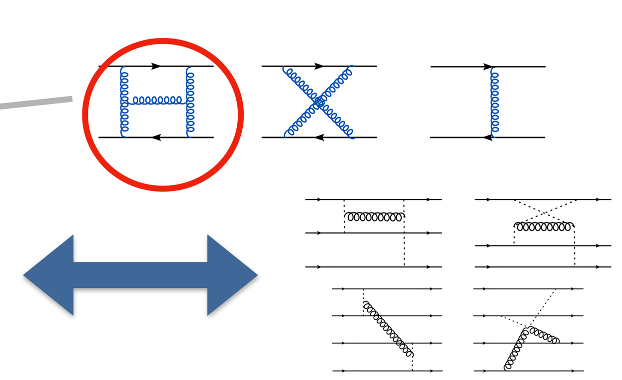
Meson and $N = N_c$ baryons : $\hat{H}_{\psi\chi} = -\frac{1}{2}\sum_i^N \nabla_{\boldsymbol{r}_i} + \hat{V}^{\psi\chi}_{\boldsymbol{1}}$ and $\hat{H} = -\frac{1}{2}\sum_i^N \nabla_{\boldsymbol{r}_i} + \hat{V}^{\psi\psi} + \hat{V}^{3\psi}$

2-body potential: $V^{\psi\psi}_{\boldsymbol{\rho}}(r) = -\mathscr{C}^{\rm tree}_{\boldsymbol{\rho}}\left(\frac{1}{C_F}V^{\psi\chi}_{\boldsymbol{1}}(r) - \frac{\alpha_s^3}{(4\pi)^2}\frac{\delta a_{\boldsymbol{\rho}}}{r}\right)$

3-body potential (NNLO):

$$V^{3\psi}_{\boldsymbol{\rho}} = \alpha\left(\frac{\alpha}{4\pi}\right)^2\left[\mathscr{C}^{3\psi,1}_{\rho uv}v_3(\boldsymbol{r}_{12},\boldsymbol{r}_{13}) + \mathscr{C}^{3\psi,2}_{\rho uv}v_3(\boldsymbol{r}_{12},\boldsymbol{r}_{23}) + \mathscr{C}^{3\psi,3}_{\rho uv}v_3(\boldsymbol{r}_{13},\boldsymbol{r}_{23})\right]$$

For $N > 3$ N-body operators contribute at NNLO+



Quantum MC methods

Variational MC: Vary $\boldsymbol{\alpha}$ with differential program to obtain $E_{\rm min}$ ↔ Hamiltonian of N-quark system and trial state

$$\Psi_T(\boldsymbol{r},\boldsymbol{\alpha}) = \sum_{i=1}^M \alpha_i \Phi_i(\boldsymbol{r})$$

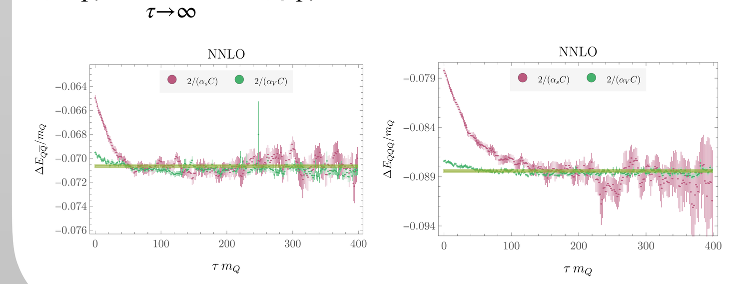
Simple N-baryon trial state:

$$H = -\frac{1}{2}\sum_i^N \nabla_{\boldsymbol{r}_i} + V^{\psi\psi}_{\bar{N}}(\boldsymbol{r}_{1\ldots N}) \Rightarrow \Psi_{\rm min}(\boldsymbol{r}_1,\ldots,\boldsymbol{r}_N) = \prod_{i<j}^N \psi_{100}(\boldsymbol{r}_{ij}, a_0 = 2/b_{N_c})$$

Green's function MC: We now have Ψ_T and $E_{\rm min}$ but what if ∃ *lower-lying states*?

Given Ψ_T from VMC, diffuse to true ground-state

$$|\Psi_T\rangle = \lim_{\tau\to\infty} e^{-\hat{H}\tau}|\psi_T\rangle$$

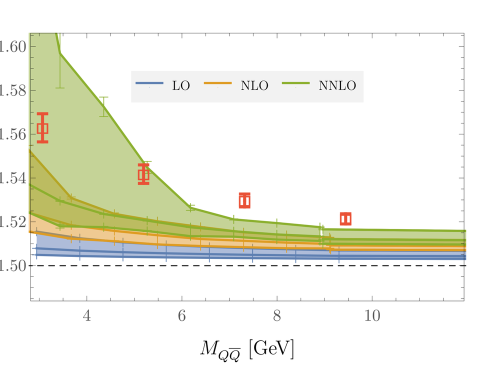


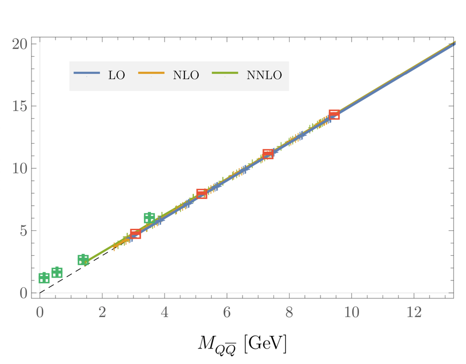
Heavy hadron spectrum and mass bound

$1S$ mesons	Order	$\alpha_s(\mu)$	m_Q	χ^2/dof	$M_{Q\bar{Q}}$	Measured $M_{Q\bar{Q}}$
(Υ,η_b)	LO (exact)	0.214850	4.77050	-	9.44295	9.44295(90)
(Υ,η_b)	NLO	0.227318	4.86886	1.09	9.44255(46)	9.44295(90)
(Υ,η_b)	NNLO	0.224750	4.96983	1.15	9.44386(40)	9.44295(90)
$(J/\psi,\eta_c)$	LO (exact)	0.282678	1.56206	-	3.06865	3.06865(10)
$(J/\psi,\eta_c)$	NLO	0.313613	1.65234	1.12	3.06870(33)	3.06865(10)
$(J/\psi,\eta_c)$	NNLO	0.297100	1.77092	0.59	3.06824(45)	3.06865(10)

Baryon	This work: M_{QQQ}	This work: χ^2/dof	Variational Methods	Lattice QCD
Ω_{ccc}	LO: 4.626723(8) NLO: 4.66561(42) NNLO: 4.69981(29)	LO: 1.0 NLO: 1.4 NNLO: 1.1	LO: 4.76(6) NNLO+mNLO: 4.97(20)	4.796(8)(18)
Ω_{ccb}	LO: 7.815284(14) NLO: 7.86032(34) NNLO: 7.91297(28)	LO: 1.3 NLO: 1.3 NNLO: 1.0	LO: 7.98(7) NNLO+mNLO: 8.20(15)	8.007(9)(20)
Ω_{cbb}	LO: 11.03611(1) NLO: 11.09206(28) NNLO: 11.110463(46)	LO: 1.5 NLO: 1.1 NNLO: 1.1	LO: 11.48(12) NNLO+mNLO: 11.34(26)	11.195(8)(20)
Ω_{bbb}	LO: 14.12990(3) NLO: 14.25397(4) NNLO: 14.25903(54)	LO: 1.2 NLO: 1.4 NNLO: 1.3	LO: 14.76(18) NNLO+mNLO: 14.57(25)	14.371(4)(12)

Previous works: [5,6]





Composite dark matter

Implicitly **stabile** due to global flavour symmetry

$$\mathscr{L}_{\rm dQCD} = -\frac{1}{2}{\rm Tr}G^2_{\mu\nu} + \bar{q}iDq + m_d\bar{q}q$$

New $SU(N_c)$ gauge sector **confines** at

$$\Lambda_{\rm dQCD} \sim \exp\left(-\frac{2\pi}{\beta_0\alpha_d}\right)$$

DM stability is maintained beyond Gyrs ∼ proton stability. SM-DM interactions **suppressed** in the EFT above confinement

Dark hadron spectra and scaling

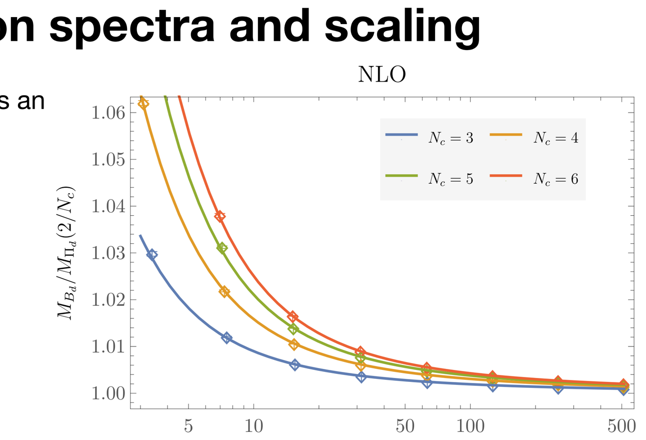
Obtained **precise** scaling relations for N_c mesons an baryons. E.g. for NLO barons:

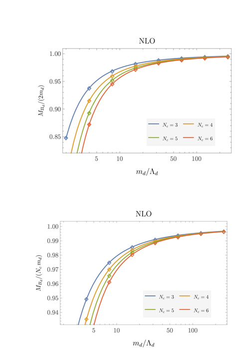
$$\frac{\Delta E^{\rm (NLO)}_{B_d}}{m_d\alpha_d^2 N_c^4} \approx -A^{\rm (LO,0)}_{B_d} - \alpha_d A^{\rm (NLO,1)}_{B_d} - \alpha_d^2 A^{\rm (NLO,2)}_{B_d}$$

$$A^{\rm (LO,0)}_{B_d} \approx \frac{0.013281(40)}{N_c} + \frac{0.02077(34)}{N_c^2} - \frac{0.0231(7)}{N_c^3}$$

$$A^{\rm (NLO,1)}_{B_d} \approx 0.0224(20) + \frac{0.179(18)}{N_c} - \frac{0.183(37)}{N_c^2}$$

$$A^{\rm (NLO,2)}_{B_d} \approx 0.0459(9)$$

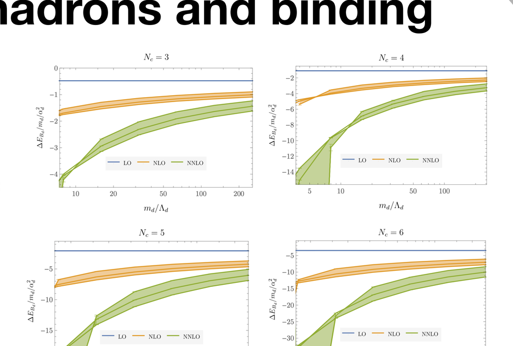




Dark hadrons and binding

We compute binding and spectra for heavy mesons and baryons to NNLO

We also provide the formalism to obtain properties of generic $SU(N_c)$ bound states



Outlook and summary

Extended pNRQCD for generic (multi-)hadronic computations. Combining VMC and GFMC is the ideal tool for determine hadronic properties

Compared QCD binding energies and mass spectra to lattice data as well as dark meson/baryon binding, spectra and color scaling

Next: Properties of states not yet obtained by lattice e.g. exotics, deuteron. Compute matrix elements for composite dark matter processes

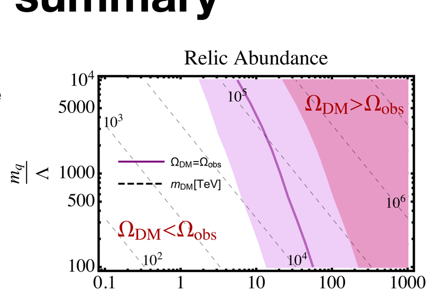


Image credit: [7]

References

[1] Kronfeld et. al. (2012), hep-lat/1203.1204
[2] M. Gerlach et al. (2019), hep-ph/1907.08227
[3] A. Pineda (2012), hep-ph/1111.0165
[4] N. Brambilla et al. (2010), hep-ph/0911.3541
[5] S. Meinel (2010), hep-lat/1008.3154
[6] Y. Jia (2006), hep-ph/0607290.
[7] P. Asadi et. al. (2021), hep-ph/2103.09822

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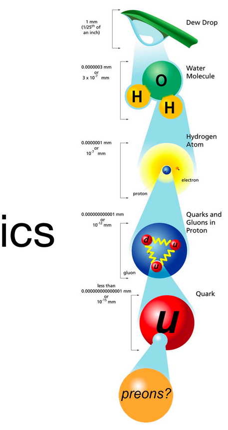
What if quarks and leptons are composite?

Quark and lepton compositeness

Can we write down such a model?

Fermions in SM chiral ⇒ chiral composite dynamics

A spectrum of light bound states can arise



Model in a nutshell

Preons bind into prehadrons under $SU(15)$

Prebaryons include all 3 SM generations of matter and heavy vector-like states

Higgs doublets are di-prebaryon bound states analogous to deuteron in QCD

UV model to composite EFT

Above GUT scale: massless chiral fermions $(\Psi, \psi_{2,3,4}, \Omega)$ charged under $SU(15)_p \times SO(10)$

Below GUT scale: scalars break flavor and $SO(10)$ symmetry at $\Lambda_{\rm GUT}$ and preons are charged under $SU(15)_p \times \mathrm{SM}$

Below confinement scale: confining $SU(15)_p$ interactions give rise composite chiral prehadrons below $\Lambda_{\rm pre}$

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

Fermion	$SU(15)_{\rm p}$	$SU(3)_c \times SU(2)_W$	$U(1)_Y$
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	$(1,1)$	$+1$
$\psi_1,\ldots,\psi_4$	15	$(1,1)$	0
Ω	$\overline{120}$	$(1,1)$	0

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

Formalism and bound states

$SU(N)$ gauge theory, with $(N+4)$ fundamental has **anomaly cancelled** by single symmetric representation

$SO(10)$ symmetry breaking $\psi_{4\ldots19}$ and relabelling according to SM charges $\Psi \to \psi_{U,Q,E,D,1}$ where SM-singlet LH fermion $\psi_1 \leftrightarrow \psi_N$ is conjugate of RH neutrino

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

Bound states: SM fermions $(\Omega_{Qi}, \Omega_{Li}, \Omega_{U,i}, \Omega_{D,i}, \Omega_{Ei})$ and 12 vectolrike fermions under SM gauge group.

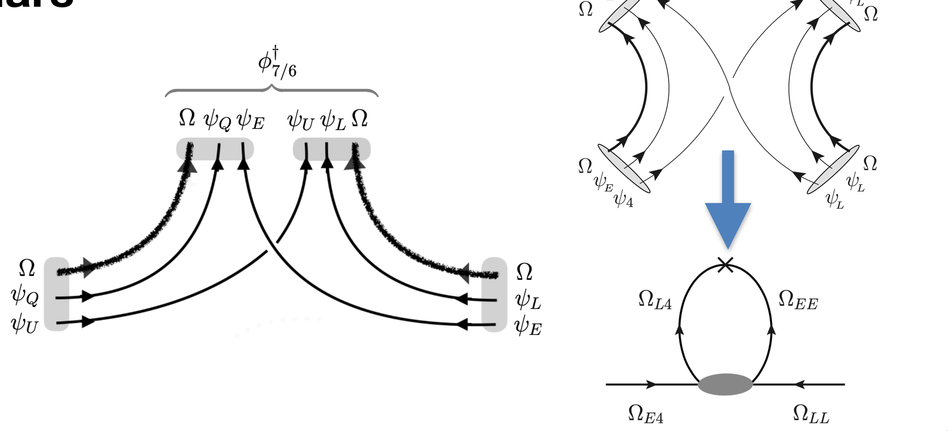
Additionally: 6 gauge singlet Weil fermions $(\Omega_{ij}, \Omega_{Ni})$ and premesons $(\Psi\sigma^\mu\Psi, \Psi\sigma^\mu\psi_i, \psi_i\sigma^\mu\psi_j)$

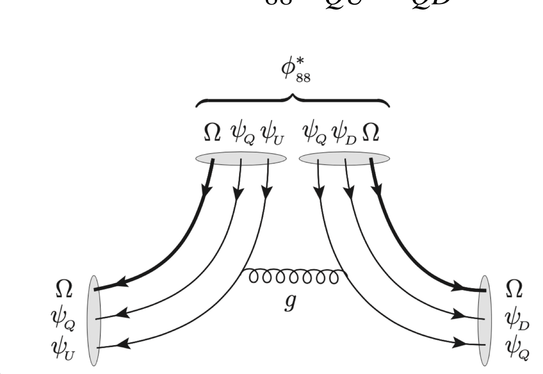
Higgs and other scalars

Di-prebaryons lighter than $\Lambda_{\rm pre}$ are bound by remnant $SU(15)$, SM gauge and A exchange

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

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





Compositeness scale proton decay

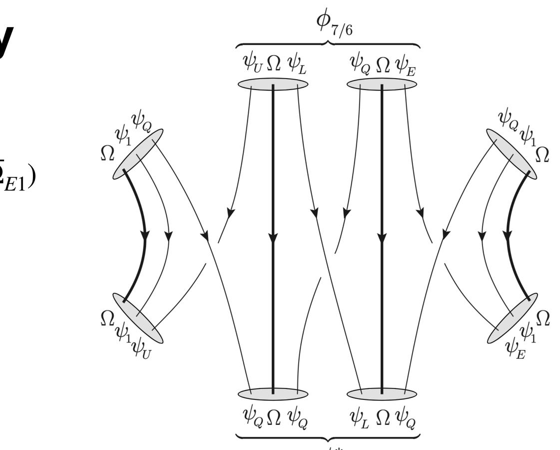
Proton decay at $\Lambda_{\rm pre}$ occurs, e.g. **8-baryon operator**:

$$\frac{\tilde{C}_8}{\Lambda^8_{\rm pre}}\left(\Omega_{Q4}\Omega_{DL}\right)\left(\overline{\Omega}^{\bar{3},3}_{QQ}\overline{\Omega}^{(3,3)}_{QL}\right)\left(\Omega_{Q1}\Omega_{Q1}\right)\left(\overline{\Omega}_{D1}\overline{\Omega}_{41}\right) \to \frac{\tilde{C}_8 c_\phi^2 y_{7/6}y^*_{33}}{2(4\pi)^4\Lambda^4_{\rm pre}}\phi_{7/6}\phi^\dagger_{33}(\Omega_{Q1}\Omega_{Q1})(\overline{\Omega}_{U1}\overline{\Omega}_{E1})$$

Identifying the prebaryons with corresponding SM fermions and scalars by their **VEVs:**

$$C_8\, c_\phi^2\, \frac{m_{7/6}m_{33}}{2(4\pi)^4 N^3 N_c^2 \Lambda^4_{\rm pre}}(q^1_L q^1_L)(\overline{u}^c\overline{e}^c)$$

Latest super-K limit: $\tau\left(p \to \pi^0 e^+\right) > 1.6\times 10^{34}\,{\rm yr} \Rightarrow \Lambda_{\rm pre} > 1.0\times 10^4\ {\rm TeV}\left(\frac{m_{7/6}m_{33}}{1\ {\rm TeV}^2}\right)^{1/4}$



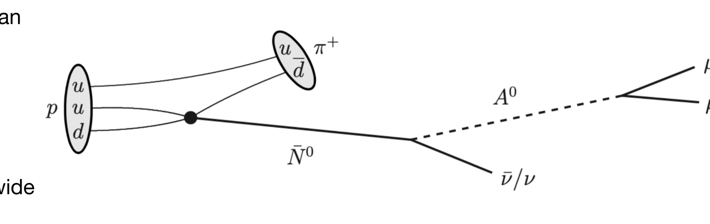
Novel baryon-number violating signatures

Neutral Ω_{ij} **RH neutrinos** may be lighter than the proton ⇒ **exotic** decay modes:

$[p \to \bar{N}^0\pi^+, p \to \bar{N}^0 K^+, n \to \bar{N}^0\pi^0]$

Dominant decay: $p \to \bar{N}^0\pi^+$ mode for a wide range of m_N with $D=6$ operator:

$$\frac{\tilde{C}_N}{\Lambda^8_{\rm pre}}\left(\Omega_{Q4}\Omega_{DL}\right)\left(\overline{\Omega}^{\bar{3},3}_{QQ}\overline{\Omega}^{(3,3)}_{QL}\right)\left(\Omega_{Q1}\Omega_{Q1}\right)\left(\overline{\Omega}_{D1}\overline{\Omega}_{41}\right)$$



Decay of $p \to \bar{N}^0\pi^+$ followed by the decay $\bar{N}^0 \equiv \Omega_{41}$ to a light pseudoscalar

Outlook and summary

A chiral preonic $SU(15)$ gauge theory was proposed in which preon confinement leads to exactly **3 generations** of SM fermions.

Proton decay by confinement scale fields can lead to **novel signatures** which can be searched for at DUNE and other future experiments