New physics in rare decays

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“Rare decays” in this talk…

#1. New Physics (NP) in Neutrinoless Double Beta Decays (0v2b)

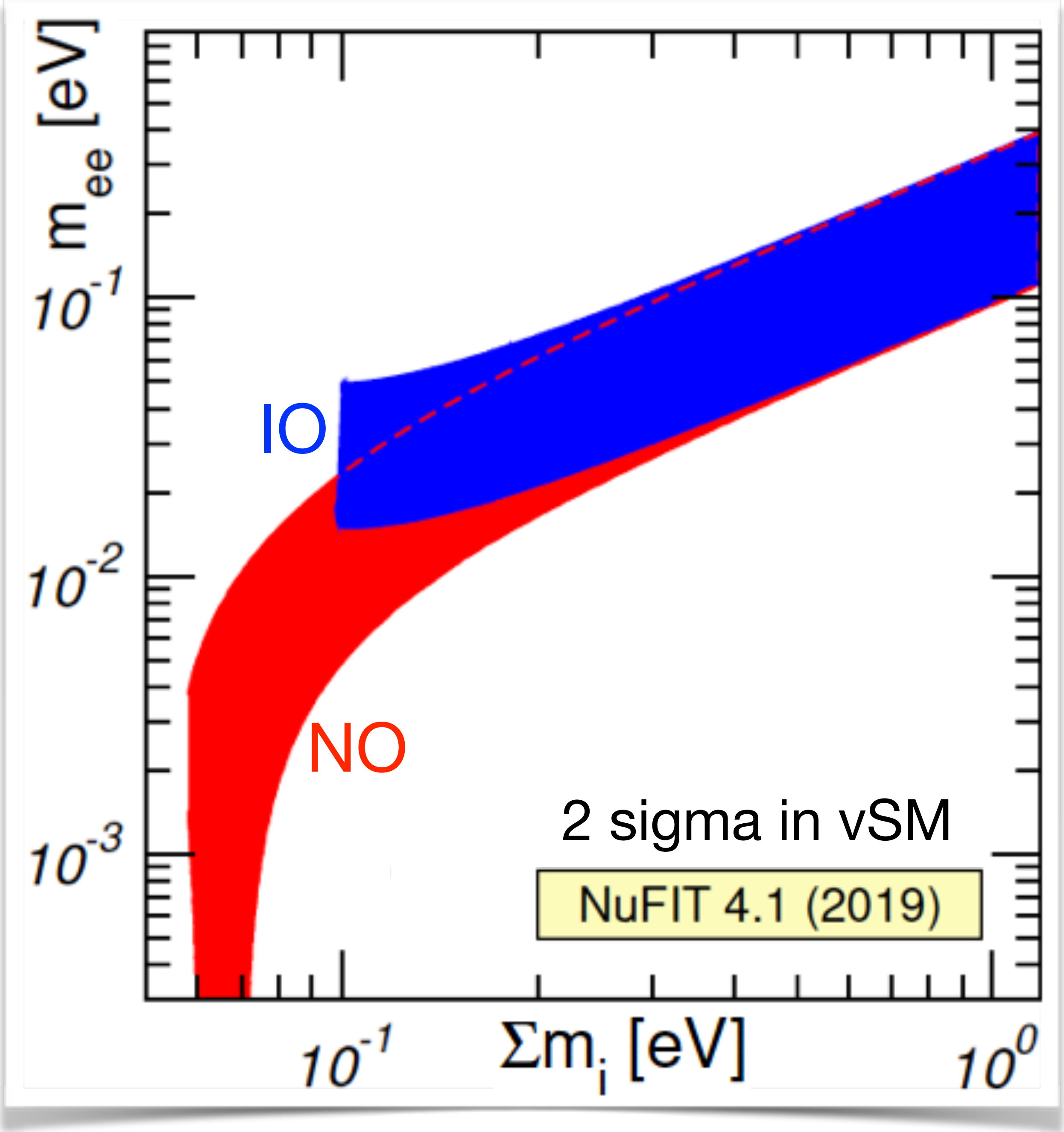
cf. Talk by Deppisch

#2. A bottom-up approach to the origin of Proton Decays

Rare decay #1: 0v2b

Chasing v into the corner…

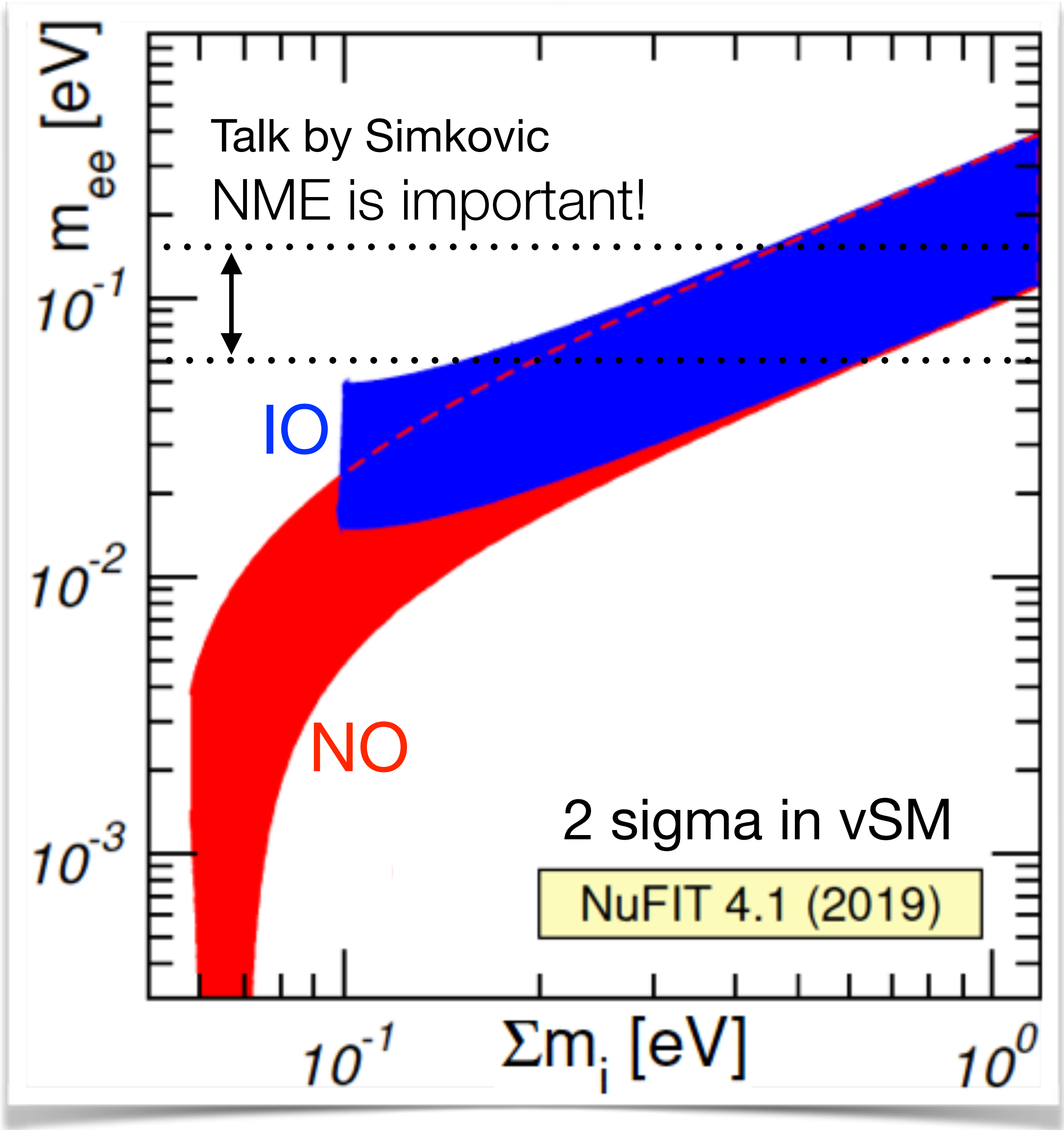
Playground of the νSM $(+\Lambda\text{CDM} + \Sigma m_\nu)$



Playground of the νSM $(+\Lambda\mathrm{CDM} + \Sigma m_\nu)$

cf. Tab.2 in 1902.04097
Tab.3 in 1901.11342

0ν2b
CUORE
EXO-200
GERDA
Kam.-Zen
more



Playground of the vSM $(+\Lambda\mathrm{CDM} + \Sigma m_\nu)$

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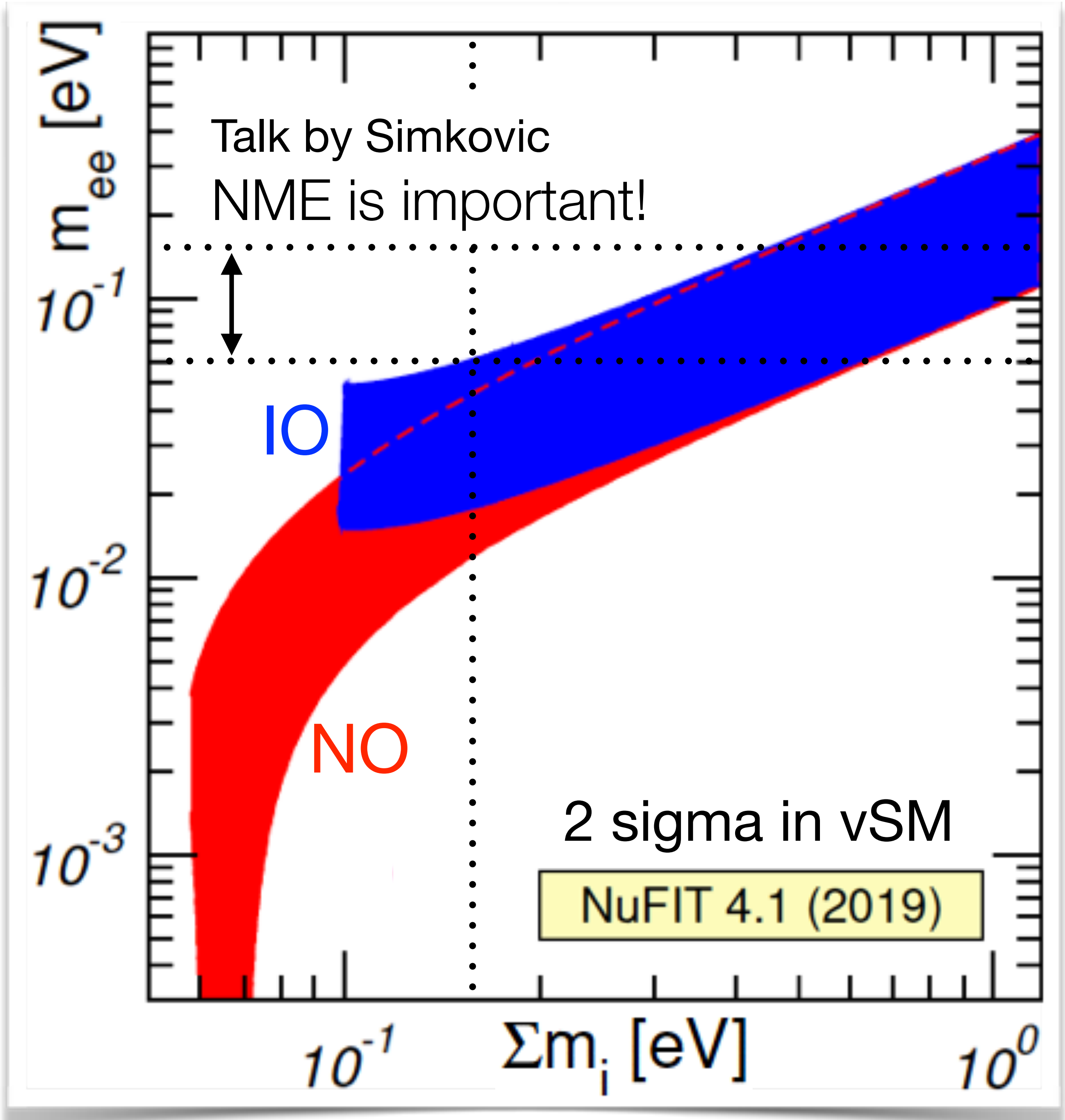

Talk by Oldengott Cosmology

$\Lambda\mathrm{CDM} + \Sigma m_\nu (+N_{\mathrm{eff}})$

CMB+LSS+BAO+…

cf. Tab.2 in 1907.12598 Tab.25.2 PDG review

Playground of the νSM $(+\Lambda\mathrm{CDM}+\Sigma m_\nu)$

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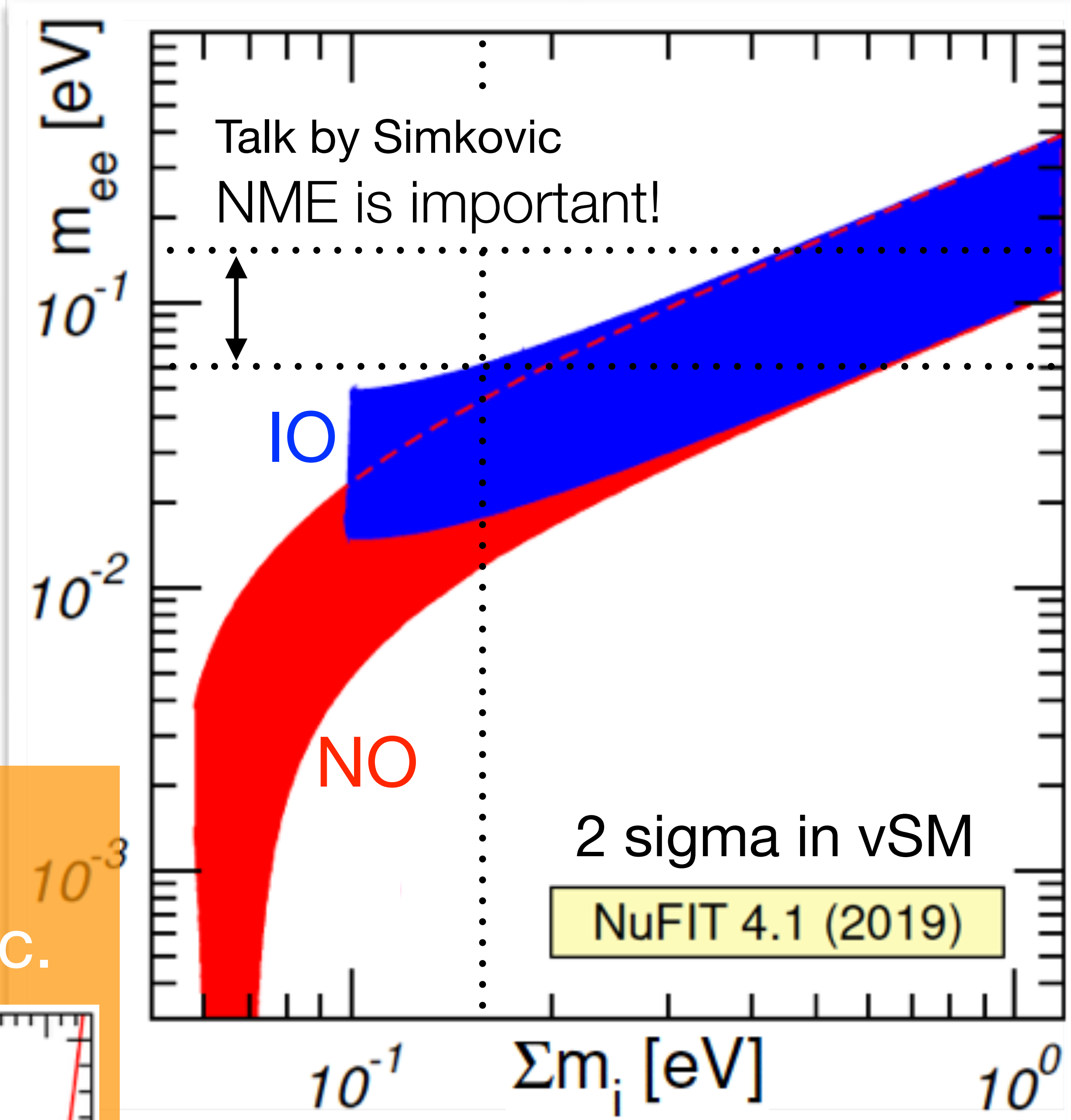
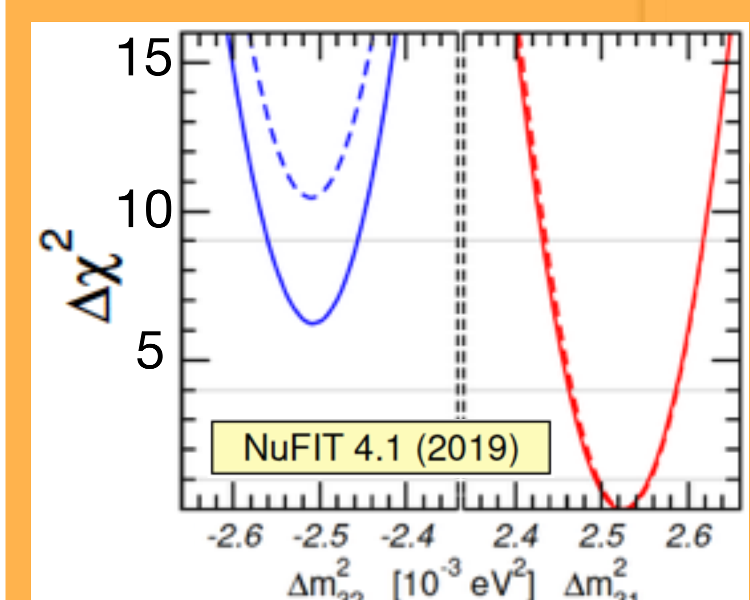


ν osc.

MINOS, NOvA
T2K, (atm.) + reac.



Talk by Oldengott **Cosmology**

$$\Lambda\mathrm{CDM}+\Sigma m_\nu(+N_{\mathrm{eff}})$$

CMB+LSS+BAO+…

cf. Tab.2 in 1907.12598 Tab.25.2 PDG review

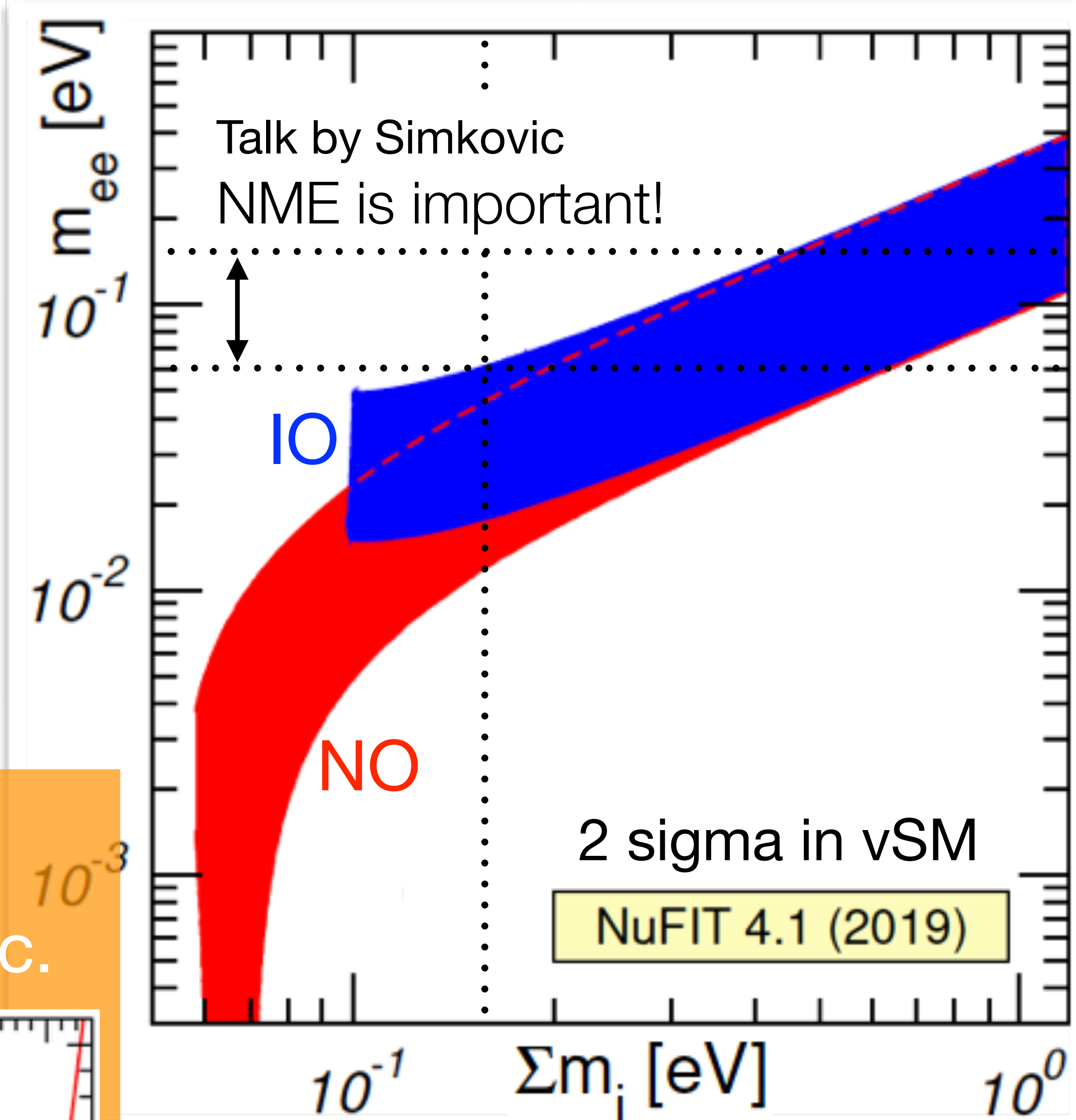
Playground of the νSM (+ ΛCDM)

Please excuse me for the incomplete list.

cf. Tab.2 in 1902.04097
Tab.3 in 1901.11342

0ν2β

CUORE
EXO-200
GERDA
Kam.-Zen
more



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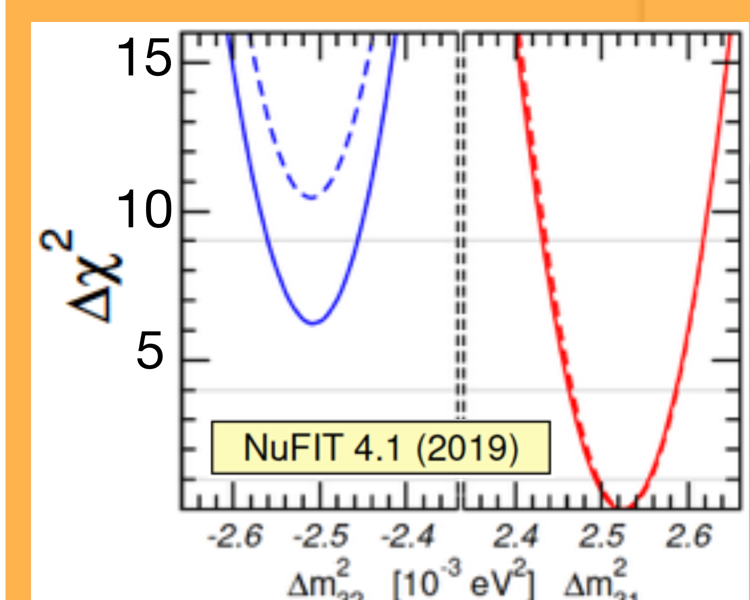


Talk by Oldengott

Cosmology

$$\Lambda\text{CDM} + \Sigma m_\nu (+N_{\text{eff}})$$

CMB+LSS+BAO+…

cf. Tab.2 in 1907.12598 Tab.25.2 PDG review

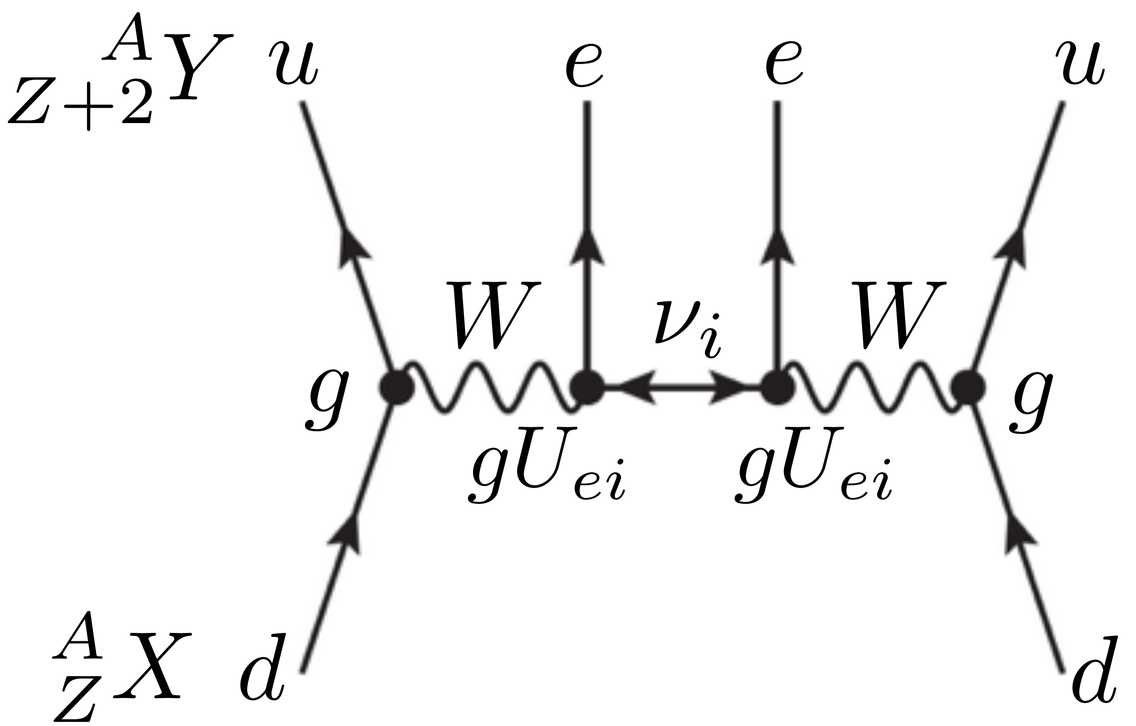
- 2019 KATRIN 1st result
- 2020(-2030) LSST
  LSS, BAO nearby
- 2021(-2026)
  LEGEND-200
  $m_{\beta\beta} = 0.034 - 0.09\text{eV}$
  JUNO
  LHC run-3 (L=300/fb)
- 2022(-2028) Euclid
  z~2
- 2024- HL-LHC (L=3k/fb)
- 2026(-2036)
  DUNE, HK
- 2027- SKA
  Cosmic dawn z~10
- 2030?-
  LEGEND-1000
  $m_{\beta\beta} = 0.011 - 0.028\text{eV}$

If we will face a conflict…

...New Physics in 0v2b?

cf. Talk by Deppisch

e.g., LBL&Cosmo: NH, 0v2b: Discovered at $m_{\beta\beta} \simeq 0.05 \text{ eV}$



$$\mathscr{L}_{\nu\text{SM}} \sim G_F^2 \frac{m_{\beta\beta}}{p^2} \bar{u}\bar{u}dd\bar{e}\bar{e}$$

$p \simeq 0.1[\text{GeV}]$

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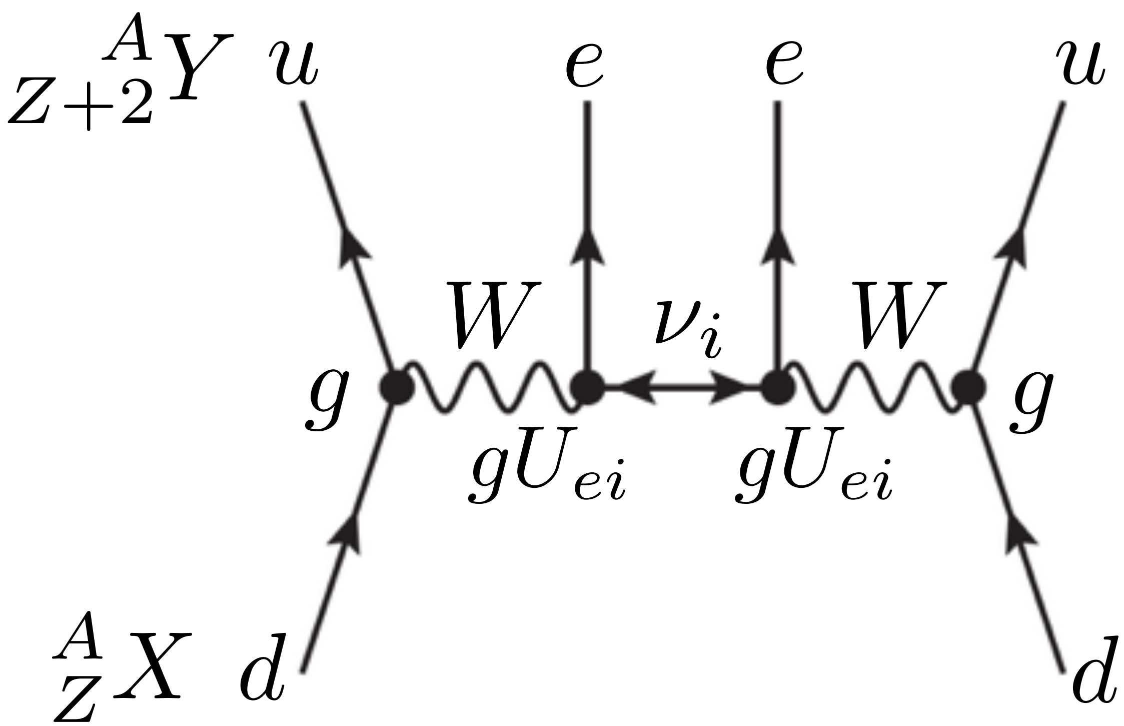
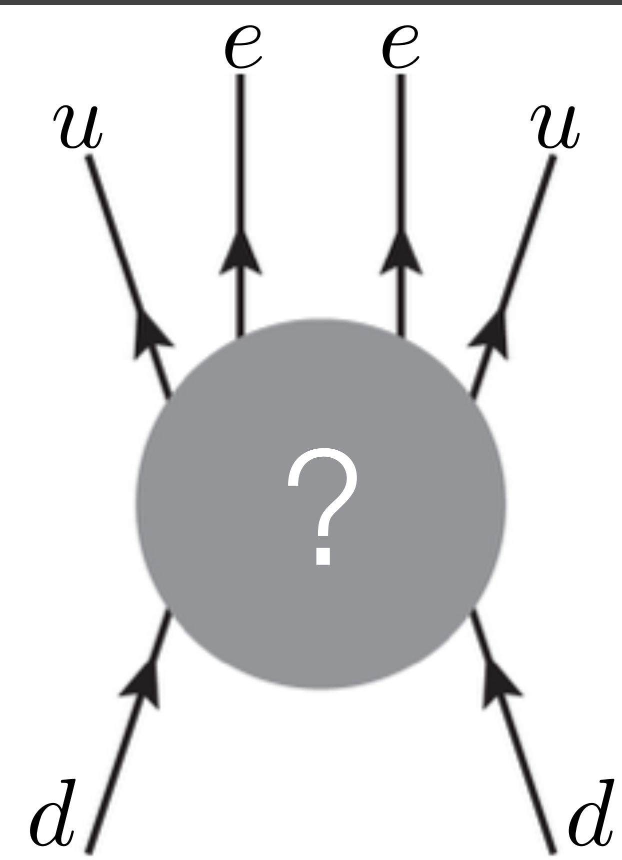


+



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$p \simeq 0.1[\mathrm{GeV}]$

$$\mathscr{L}_{\mathrm{NP}} = \frac{\mathcal{C}}{\Lambda_{\mathrm{NP}}^5} \bar{u}\bar{u}dd\bar{e}\bar{e}$$

Sensitivity to $m_{\beta\beta}$ = Sensitivity to NP at the scale Λ_{NP}

$$G_F^2 \frac{|m_{\beta\beta}|_{\mathrm{exp.}}}{p^2} \stackrel{!}{=} \frac{\mathcal{C}}{\Lambda_{\mathrm{NP}}^5}$$

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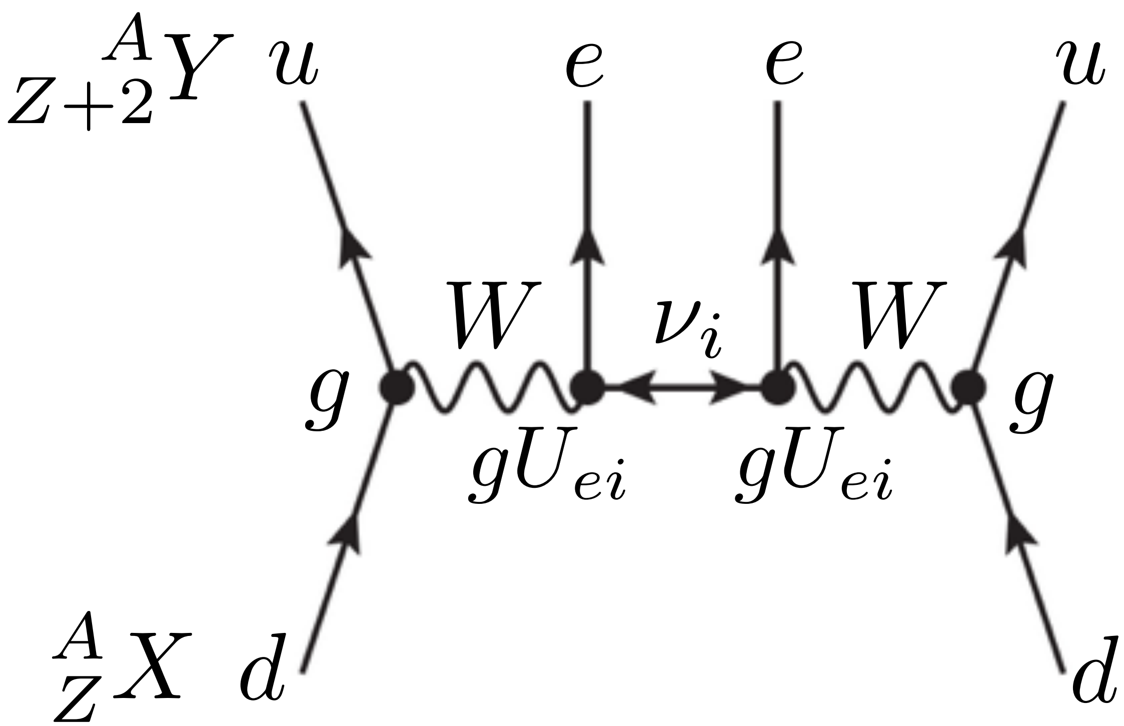
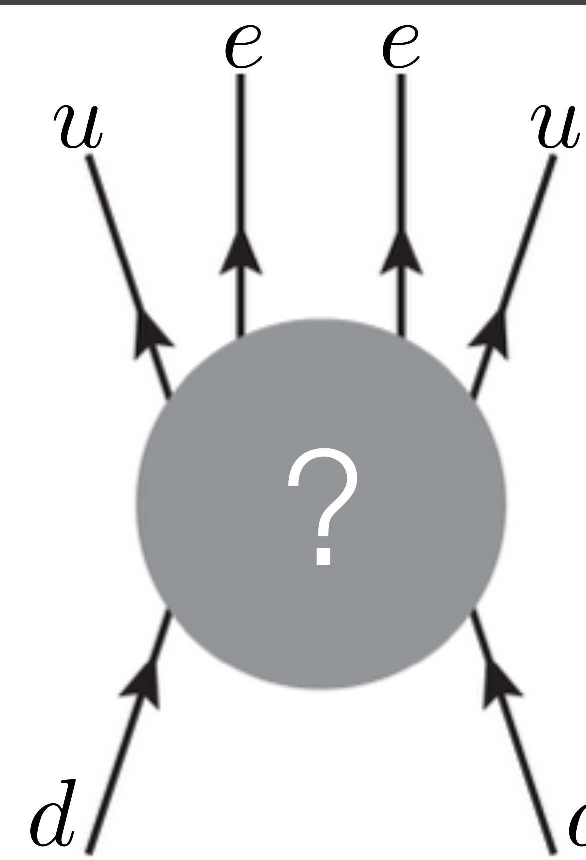


$$\mathscr{L}_{\nu\mathrm{SM}} \sim G_F^2 \frac{m_{\beta\beta}}{p^2} \bar{u}\bar{u}dd\bar{e}\bar{e} \qquad p \simeq 0.1[\mathrm{GeV}]$$

+



$$\mathscr{L}_{\mathrm{NP}} = \frac{\mathcal{C}}{\Lambda_{\mathrm{NP}}^5} \bar{u}\bar{u}dd\bar{e}\bar{e}$$

Sensitivity to $m_{\beta\beta}$ = Sensitivity to NP at the scale Λ_{NP}

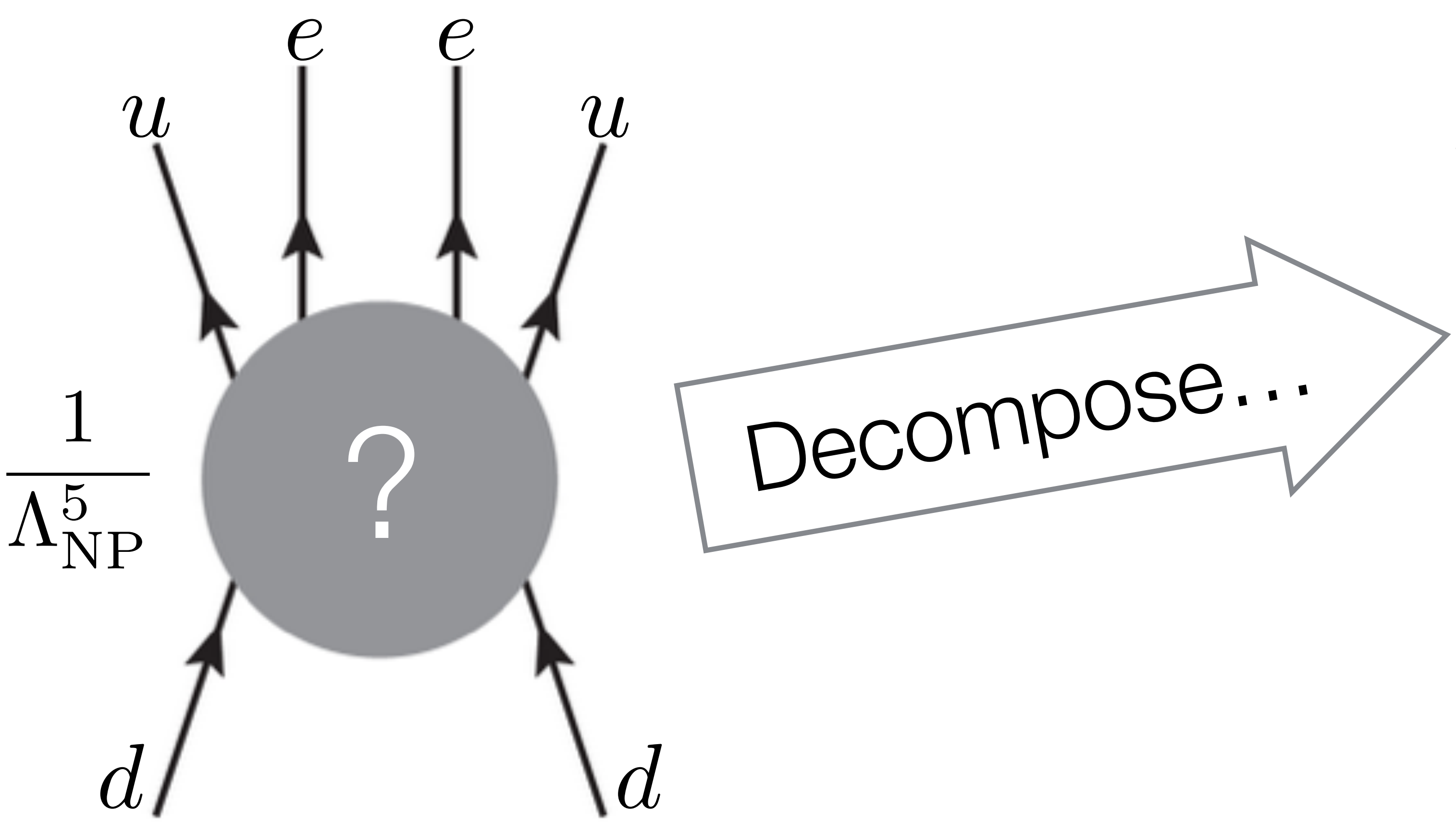
$$G_F^2 \frac{|m_{\beta\beta}|_{\mathrm{exp.}}}{p^2} \stackrel{!}{=} \frac{\mathcal{C}}{\Lambda_{\mathrm{NP}}^5} \quad \xrightarrow{\mathcal{C}=1} \quad \Lambda_{\mathrm{NP}} = 4\ \mathrm{TeV} \left[\frac{0.05\mathrm{eV}}{|m_{\beta\beta}|_{\mathrm{exp.}}}\right]^{1/5}$$

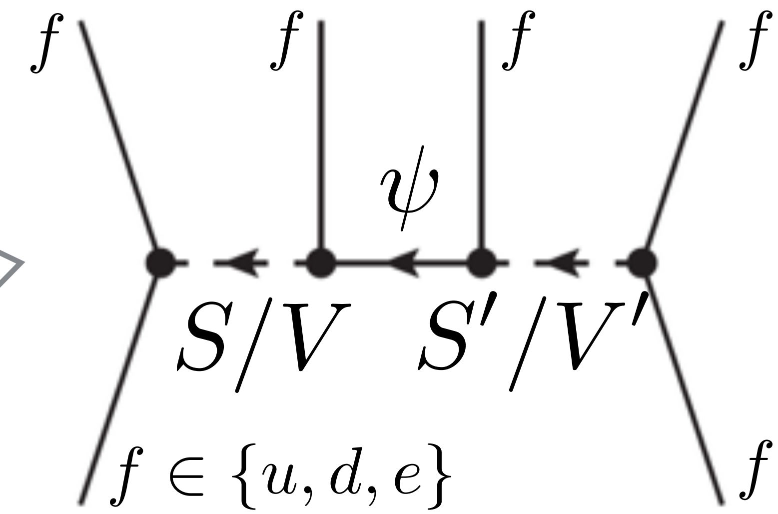
For early studies, e.g., Riazuddin et al. (1981), Rizzo (1982), Keung&Senjanovic (1983)

0v2b exp. are sensitive to NP@TeV

What are the effective op.s made of?

Bonnet et al., 1212.3045





What are the effective op.s made of?

#	Decomposition	Long Range?	Mediator $(U(1)_{\mathrm{em}}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
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2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
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			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ and V'_ρ
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3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	only with V_ρ
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5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
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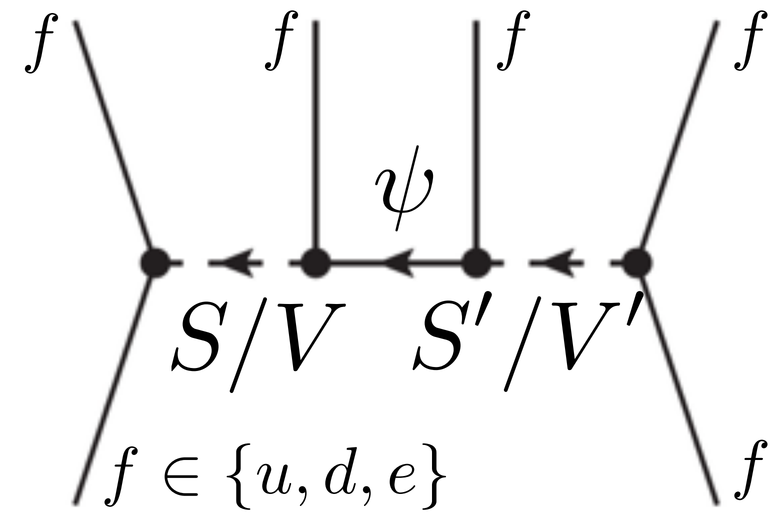
Bonnet et al., 1212.3045



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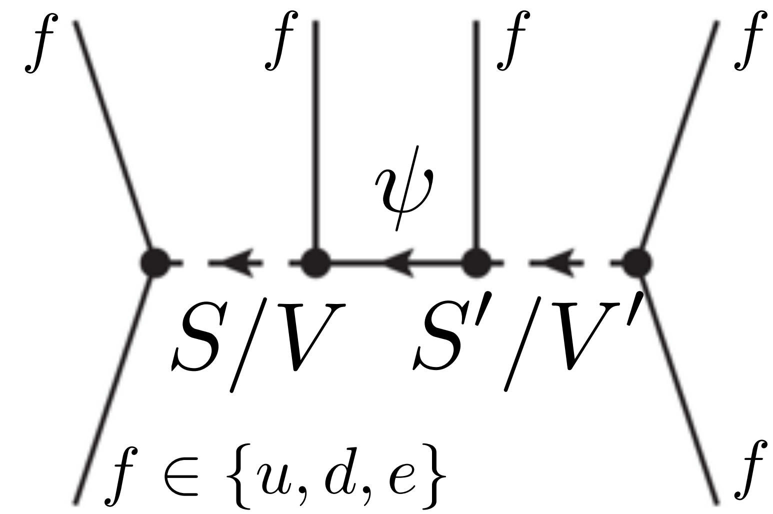


bosons

- Colored diquark
- Colour-1 diquark — $W^\pm, W'^\pm$, and $H^\pm$
- Dilepton
- Leptoquarks

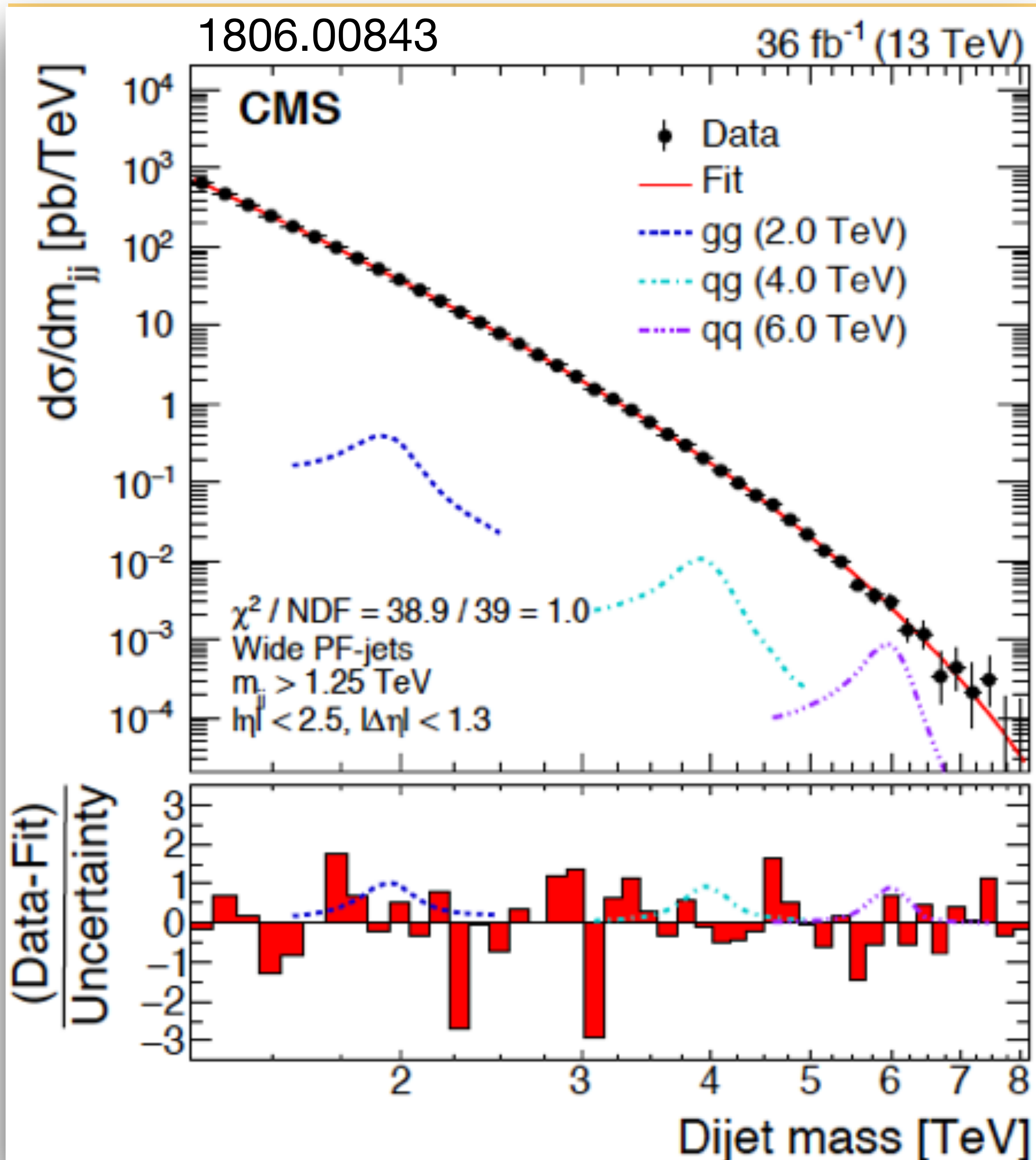
fermions

- Gluino-like
- Vector-like quarks
- Neutral fermion, ν, N

Searches for the mediators at the LHC

Diquarks

cf. Han et al., 1010.4309

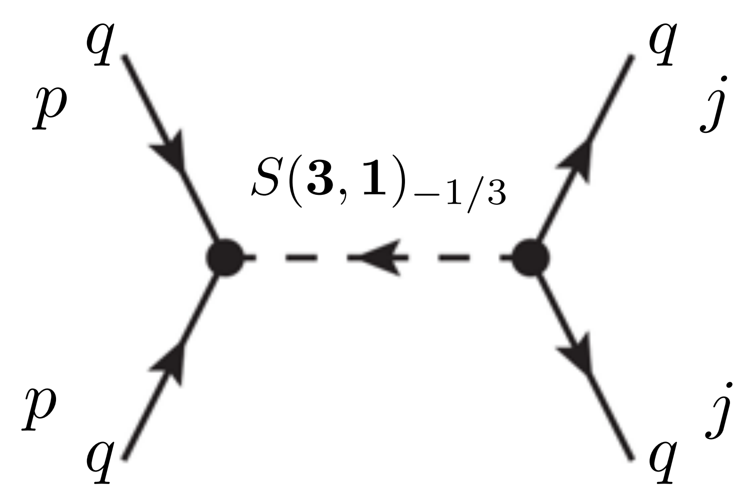


Production: qqS int.

e.g., QQS & $u_R d_R S$ — E_6 GUT inspired

Coupling with the size of the EM int.

Signal: Resonance in M_{jj}



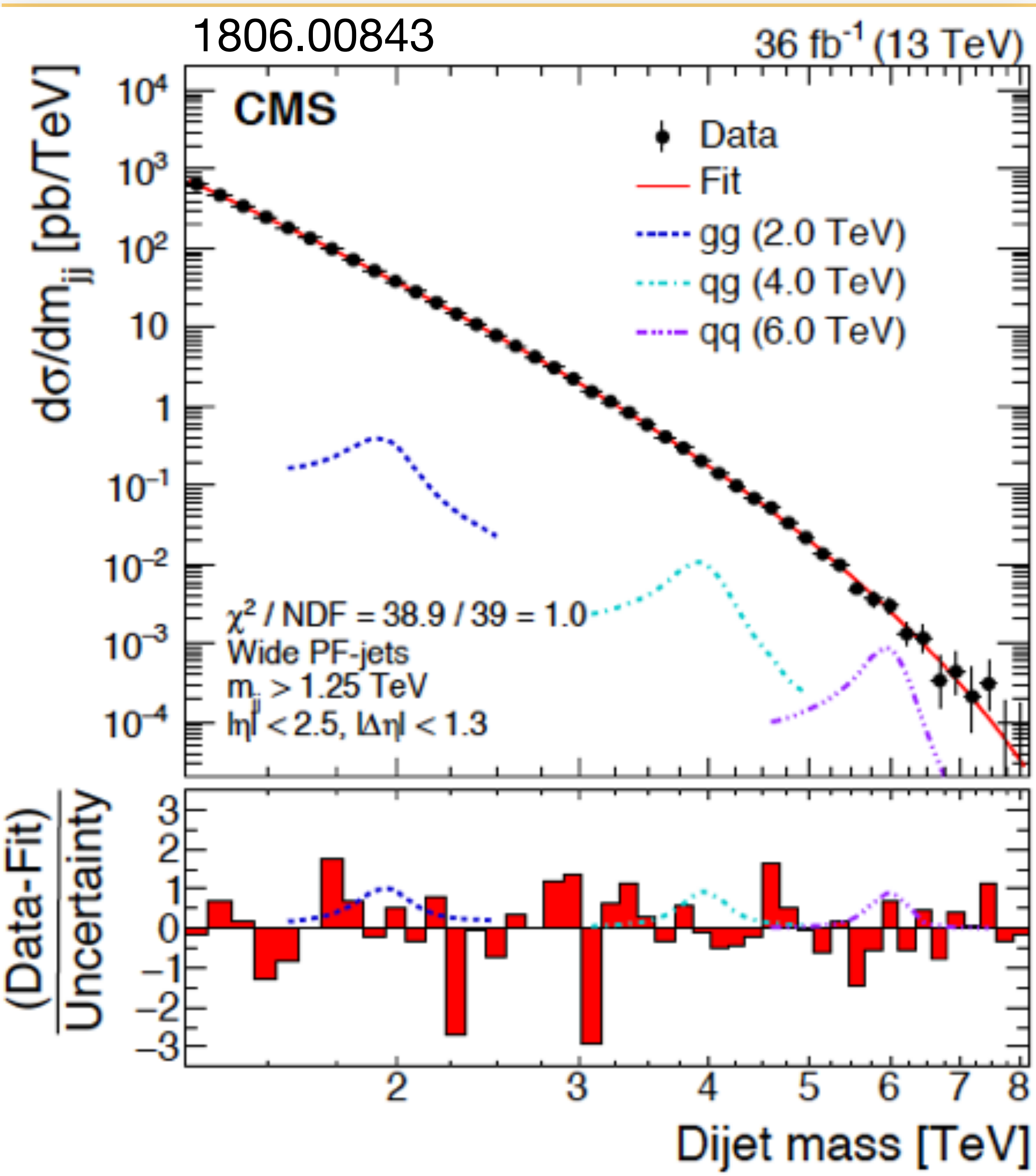
* Same for the Colour-1 one $\overline{u}\gamma^\rho d W'^+_\rho$ (with the SM W-like coupling)

LHC: $M_S > 7.2\mathrm{TeV}$ $M_{W'} > 3.3\mathrm{TeV}$

$C = 1$

Diquarks

cf. Han et al., 1010.4309



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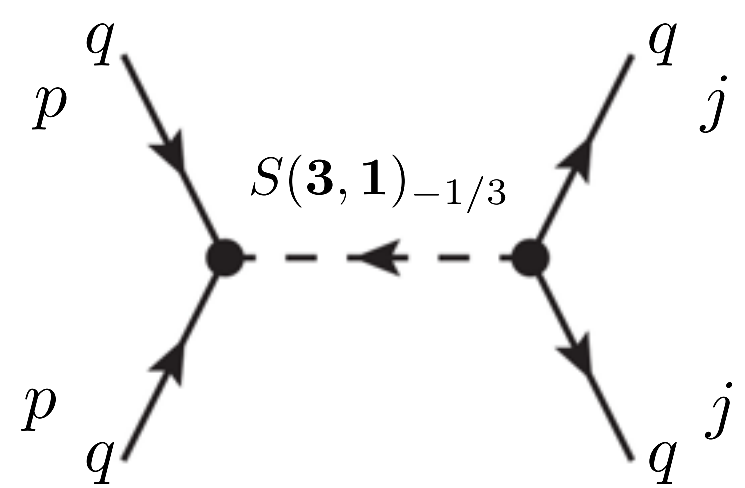
Coupling with the size of the EM int.

Signal: Resonance in M_{jj}



* Same for the Colour-1 one $\overline{u}\gamma^{\rho} d W'^{+}_{\rho}$ (with the SM W-like coupling)

LHC: $M_S > 7.2\mathrm{TeV}$ $M_{W'} > 3.3\mathrm{TeV}$

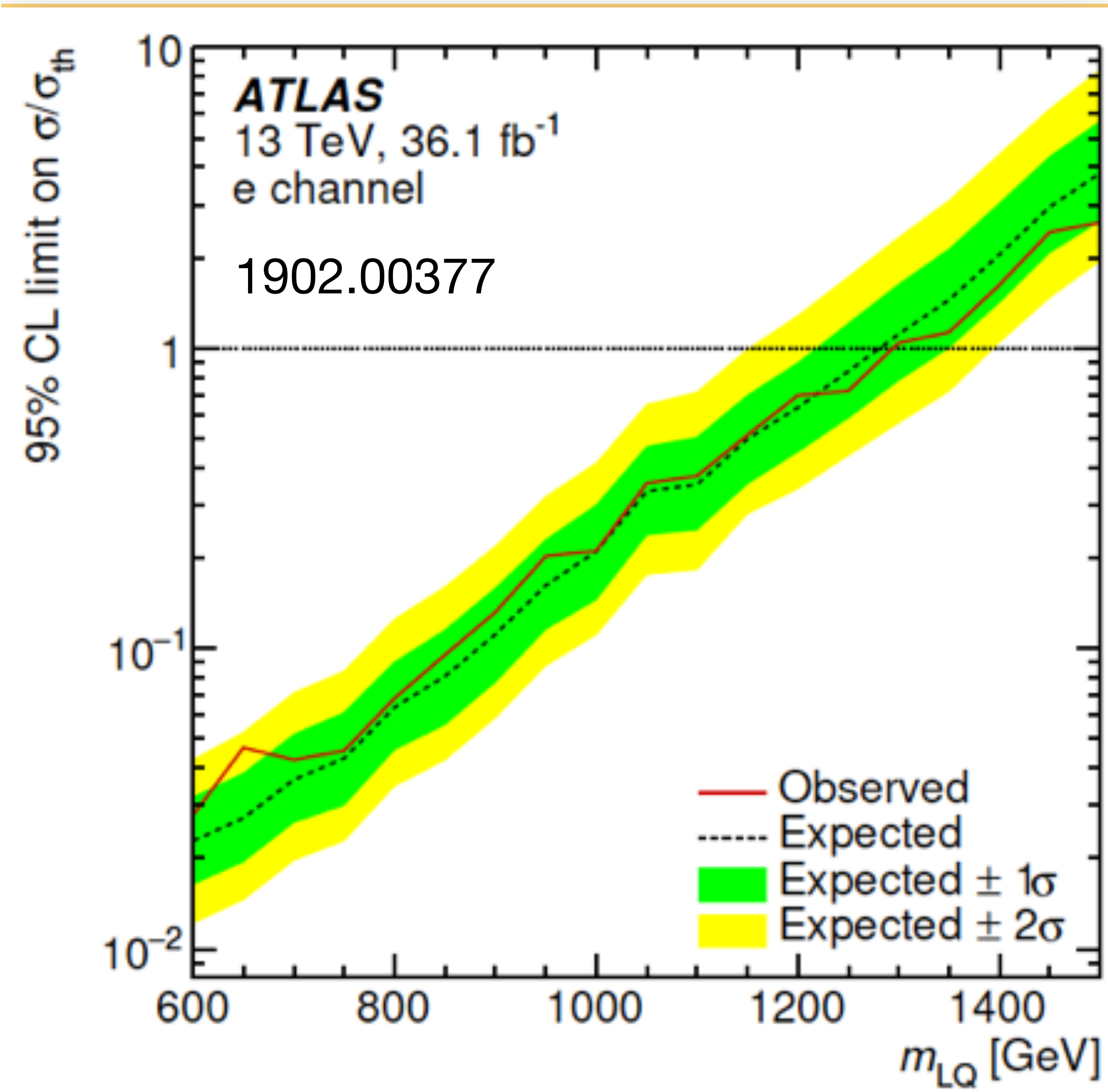
Sensitivity at 0v2b exps. (with $c = 1$)

$$\Lambda_{\mathrm{NP}} = 4\ \mathrm{TeV}\left[\frac{0.05\mathrm{eV}}{|m_{\beta\beta}|_{\mathrm{exp.}}}\right]^{1/5}$$

comparable to the LHC's.

Leptoquarks

cf. Buchmueller Rueckl Wyler (1987)
Belyayev et al., hep-ph/0502067

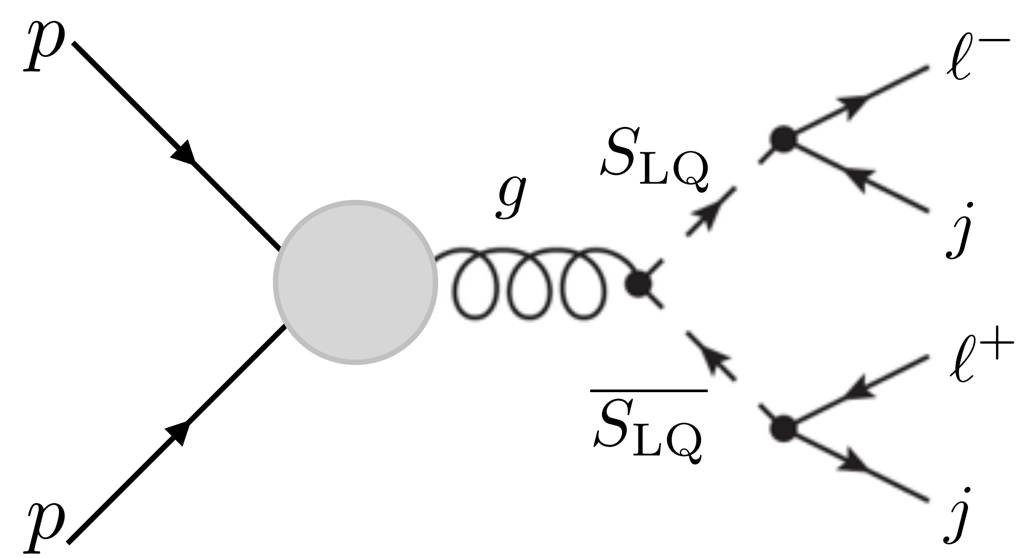


$*\,\mathrm{Br}(S_{\mathrm{LQ}} \to q\ell) = 0.5$ is assumed

Production: Strong interaction

Pair-production with g

Signal: $g \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to 2j2\ell$



LHC: $M_{S_{\mathrm{LQ}}} > 1.25\mathrm{TeV}$

for the 1st gen. scalar LQ

To bound LQs with $M_{\mathrm{LQ}} > 2$ TeV

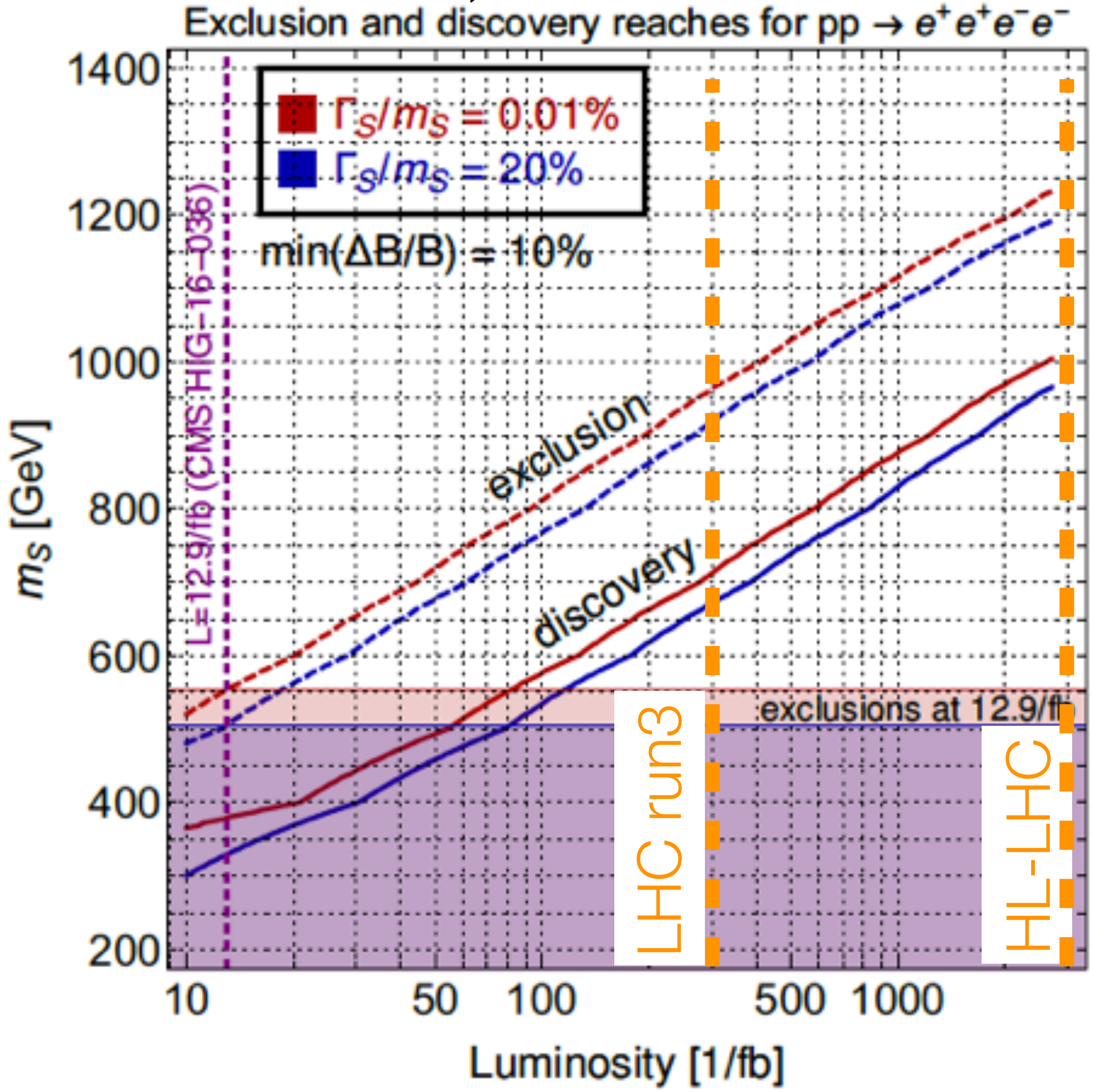
Pair-production suffers from the phase space suppression.

Single production $gq \to q^* \to S_{\mathrm{LQ}} + \ell$ at HL-LHC $\sigma_{\mathrm{single}} < 10^{-1}\mathrm{fb}$

Dilepton, aka Doubly charged boson

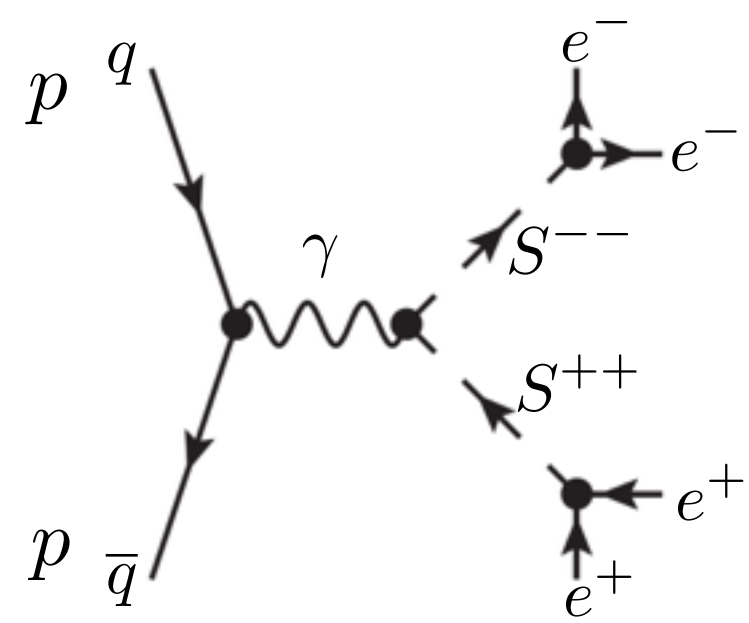
cf. Han et al. 0706.0441

Crivellin et al., 1807.10224



Production: EM Drell-Yan

Signal: $pp \to 4e$, resonance in M_{ee}



There is a dilepton search at ATLAS [1903.06248]. However, it assumed that the dilepton also couples to quarks: $q\bar{q} \to S \to ee$

We have only $q\psi S$

Future prospects of the searches for heavier dileptons

To produce a pair of them, we need high $\sqrt{s}$ = HE-LHC

$M_S > 8\mathrm{TeV}$ (with O(1) coupling) @ILC-250 (through Bhabha scattering)

Crivellin et al., 1807.10224

Coloured fermion mediators

Colour-8 fermion (gluino-like)

cf. Octet boson@LHC, Chen et al.,1410.8113

Production: Pair-produced through g

Signal: $\psi(\mathbf{8}) \to qS_{\rm LQ} \to q\bar{q}\ell$ 2j+a lepton

Gluino in SUSY $\tilde{g} \to q\tilde{q}^* \to q\bar{q}\chi_1^0$ 2j+Missing E

Gluino in RpV SUSY $\psi(\mathbf{8}) \to qqq$ 3j

ATLAS, 1804.03568

$pp \to \psi(\mathbf{8})\overline{\psi}(\mathbf{8}) \to 2q2\overline{q}\ell^+\ell^-$

Carquin et al., 1904.07257

LHC run-III will set the bound at $M_\psi > 2.5\mathrm{TeV}$

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LHC run-III will set the bound at $M_\psi > 2.5\mathrm{TeV}$

……………………………………

Colour-3 fermion (vector-like quark)

* Search for 6 should be essentially the same

Production: Pair-produced through g

Signal: Depends on the int. VLQs have

e.g., $\psi(\mathbf{3}) \to uS \to uue$

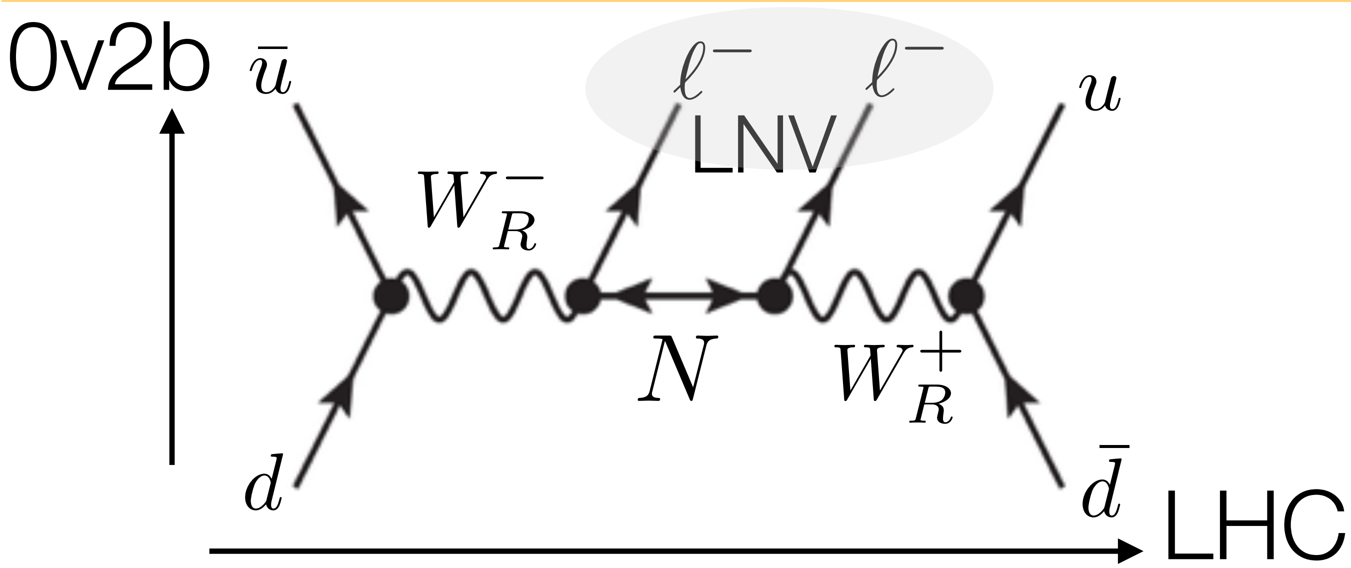
Typically the bounds are around ~1 TeV cf. Nikiforou, 1808.04695

Neutral fermion mediators

cf. Talk by Deppisch
cf. Talk by Drewes

SM ν, sterile ν, TeV N, etc…

Typical signal for TeV N is $pp \to \ell\ell jj$ through the EW Drell-Yan

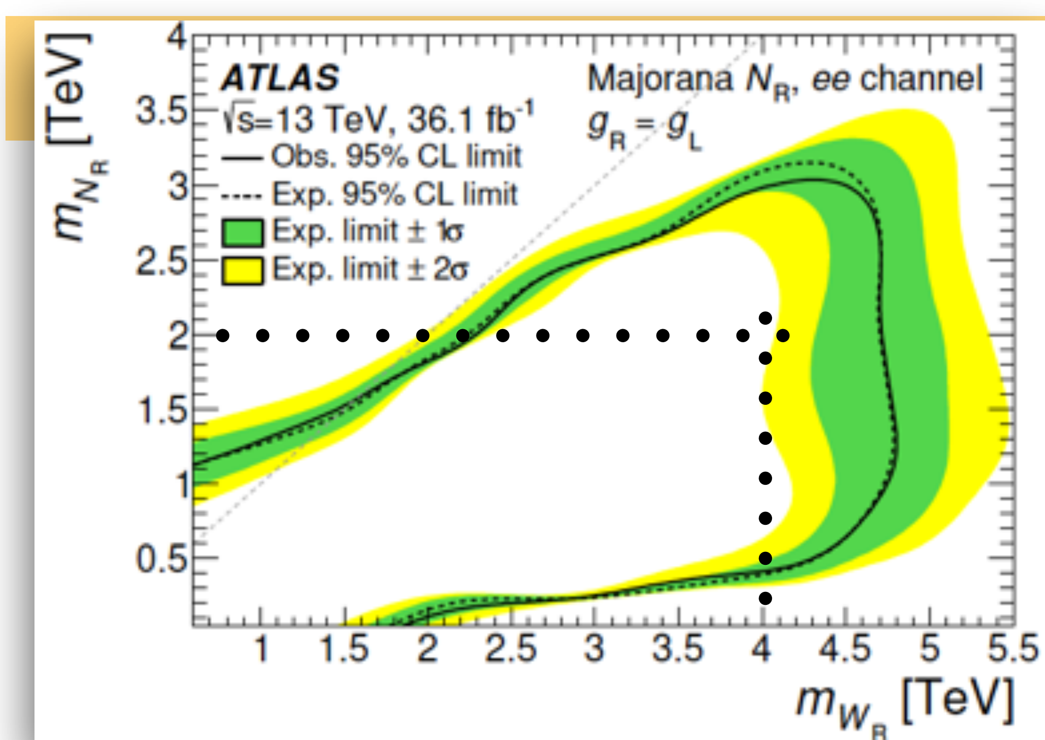


$\ell^\pm\ell^\pm$ Direct test of NP contribution to 0ν2b

LHC bounds depend on the "ingredients"

W_R-N-W_R inspired by LR sym.

WR-N-WR, CMS 1803.11116, ATLAS 1809.11105.



W_R = colour-1 diquark $M_{W_R} \gtrsim 4$ TeV

0ν2b amp. mediated by W_R-N-W_R

$$\mathcal{A}_{0\nu2\beta}^{W_R N} = 10^{-20}[\mathrm{GeV}^{-5}]\left[\frac{4\mathrm{TeV}}{M_{W_R}}\right]^4\left[\frac{2\mathrm{TeV}}{M_N}\right]$$

comparable with

$$\mathcal{A}_{0\nu2\beta}^{\mathrm{SM}} = 6.8\cdot 10^{-19}[\mathrm{GeV}^{-5}]\left[\frac{m_{\beta\beta}}{0.05\mathrm{eV}}\right]$$

Neutral fermion mediators

cf. Talk by Deppisch
cf. Talk by Drewes

SM ν, sterile ν, TeV N, etc…

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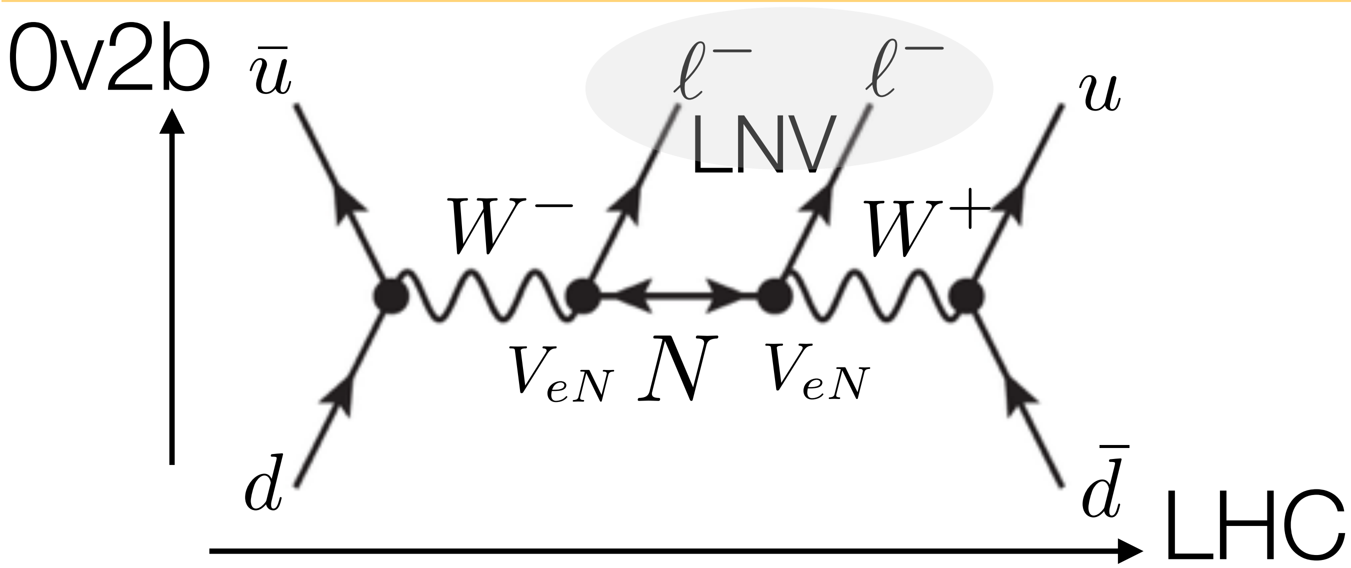
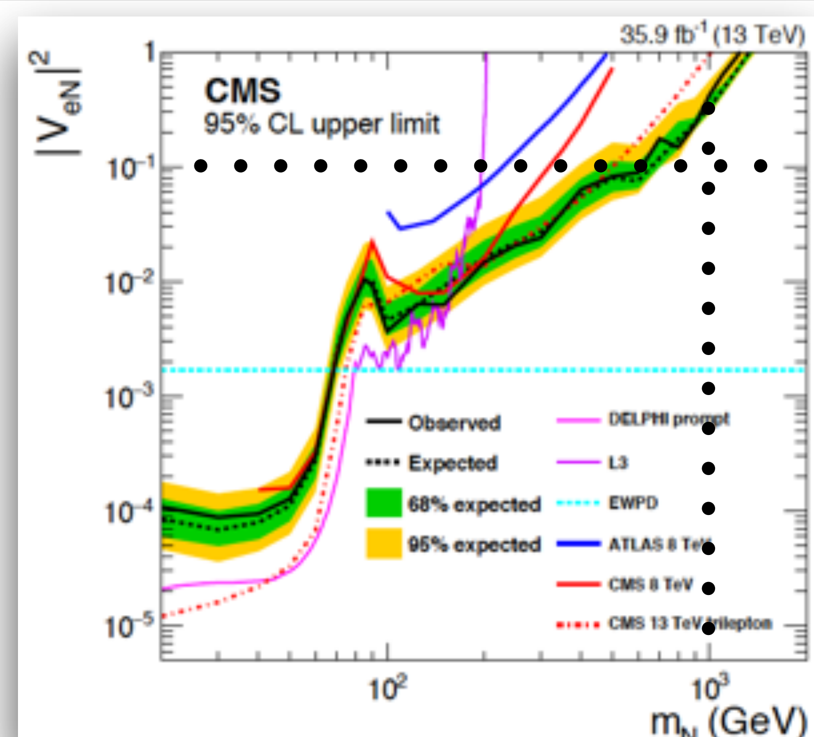


$\ell^\pm\ell^\pm$ Direct test of NP contribution to 0ν2b

LHC bounds depend on the “ingredients”

W-N-W inspired by TeV seesaw

W-N-W, CMS 1806.10905



Bound is weaker than W_R-N-W_R

$$\mathcal{A}^{WN}_{0\nu2\beta} = 10^{-14}[\mathrm{GeV}^{-5}]\left[\frac{V_{eN}^2}{0.1}\right]\left[\frac{1\mathrm{TeV}}{M_N}\right]$$

If LHC sees that N, 0ν2b has already seen it.

cf. e.g., Blennow et al., 1005.3240

$$\mathcal{A}^{\mathrm{SM}}_{0\nu2\beta} = 6.8\cdot 10^{-19}[\mathrm{GeV}^{-5}]\left[\frac{m_{\beta\beta}}{0.05\mathrm{eV}}\right]$$

Summary for Part 1: NP in 0v2b

Conflict in neutrino mass searches may suggest NP in 0v2b

0v2b experiments are sensitive to NP at TeV

$$\Lambda_{\rm NP} = 4\ {\rm TeV} \left[\frac{0.05{\rm eV}}{|m_{\beta\beta}|_{\rm exp.}}\right]^{1/5}$$

complementary with LHC, ILC, etc.

cf. Talk by Deppisch

Collider searches for the Mediators

- Decompositions with a diquark (or two) have already been strongly constrained at LHC $M_S > 7.2{\rm TeV}$
- HL-LHC may help bound high mass LQ (Single production)
- ILC can exclude the possibilities with a doubly charged scalar

etc…

Caveat: Long-range mediator bound is different, search strategy is different

Caveat: Neutrino mass bound from cosmology is based on the SM of cosmology.
H0 tension - ΛCDM is missing something?
Σm bound in the solutions for the H0 tension…?

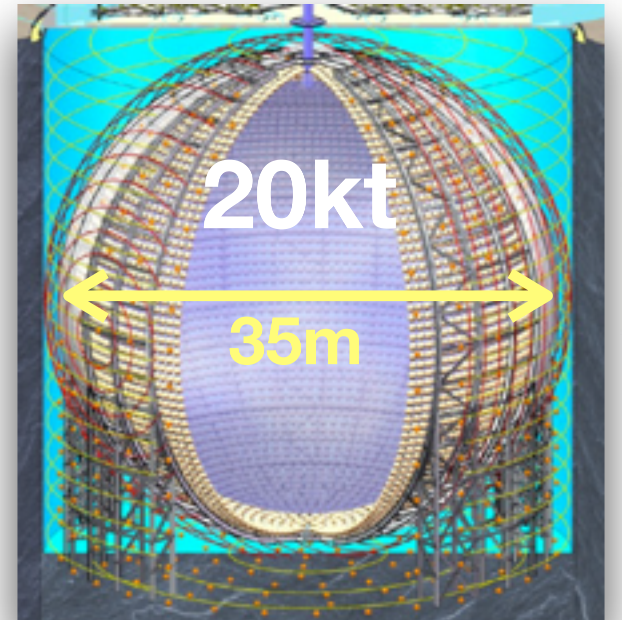
Rare decay #2: Proton decays

What does “NDE” originally stand for?

of Kamioka-NDE

ν detectors in 2020s

ν Detection Experiments
||
Nucleon Decay Experiments



JUNO

20 kt liquid scintillator
(35kt water Cherenkov veto)

$$\frac{\Delta m^2_{\mathrm{sol.}} L}{4E} \sim \frac{\pi}{2}$$

Start taking data in 2021

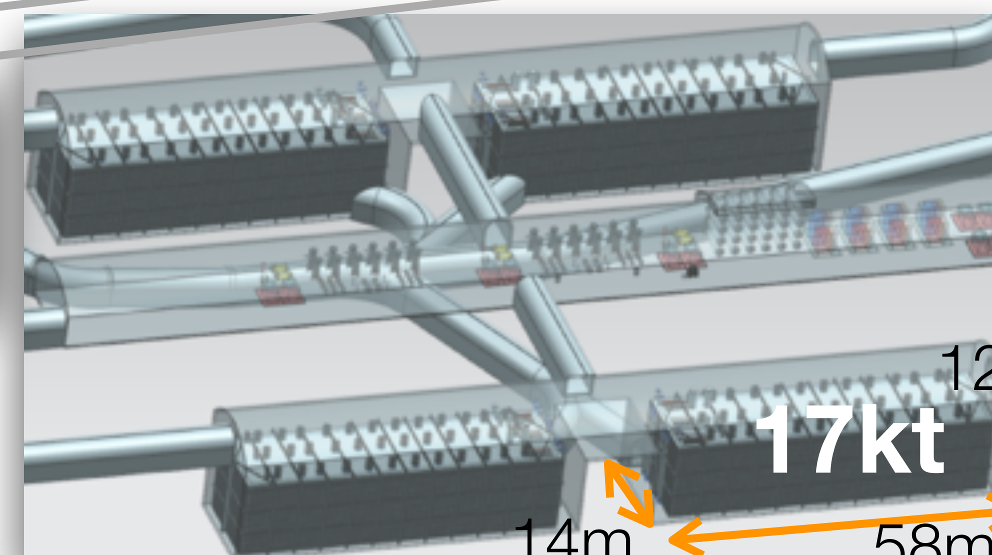
DUNE

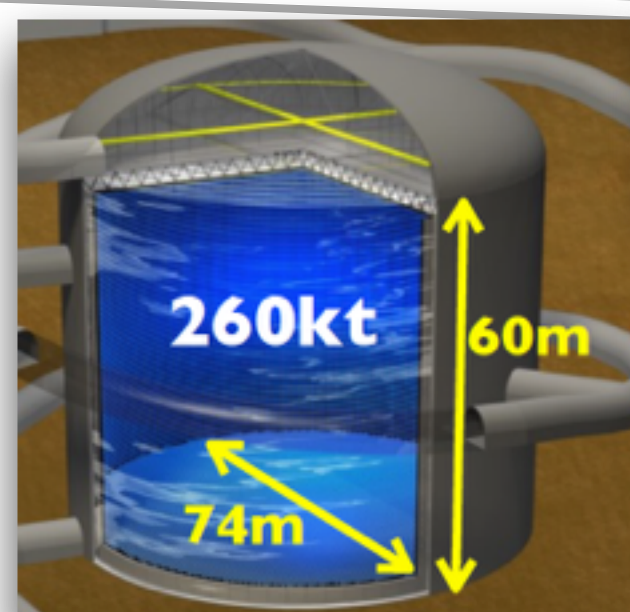
Talk by De Roeck

Liquid Ar TPC

4×17 kt (Fiducial 10 kt) modules

Installation of the 1st module in 2025





Hyper-Kamiokande

$$\frac{\Delta m^2_{\mathrm{atm.}} L}{4E} \sim \frac{\pi}{2}$$

260 kt (Fiducial 190 kt)
Water Cherenkov

Expected to start in 2026

MEXT: green-light to the construction

Proposal:
2nd detector in Korea

European Spallation Source ν SuperBeam

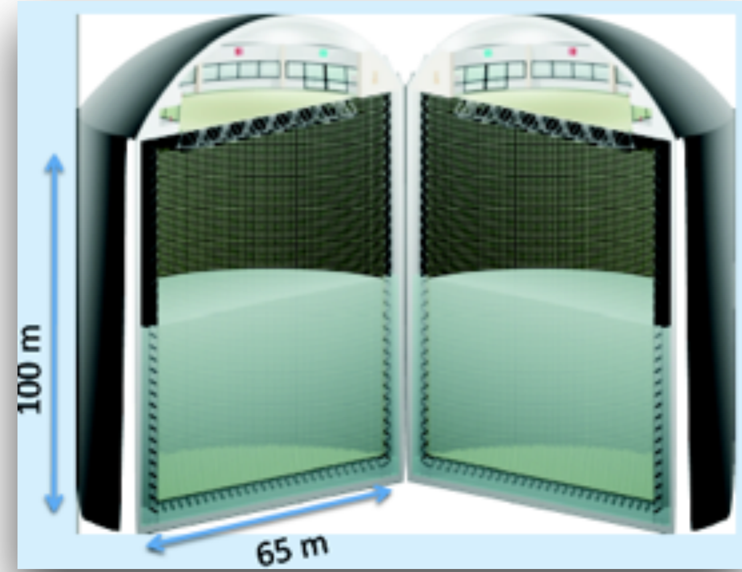
https://essnusb.eu

MEMPYHS (MEga-ton Mass PHYSics) proposal

LAGUNA, hep-ex/0607026

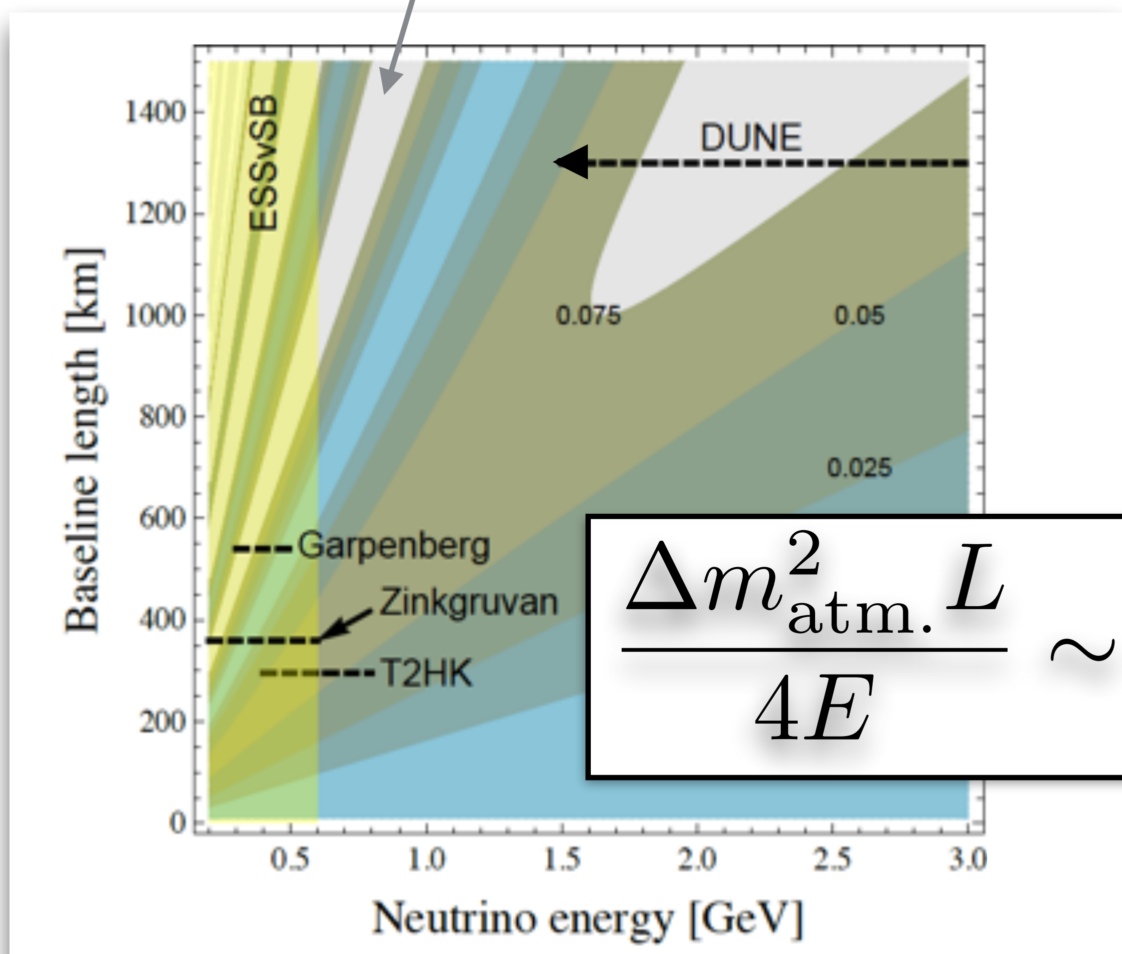
0.5 Mt (fiducial) WC

(240k 8”PMTs, 30% photo cover.)



cf. Talk by Dracos @ICHEP 2018

2nd osc. maximum



$$\frac{\Delta m^2_{\mathrm{atm.}} L}{4E} \sim \frac{3\pi}{2}$$

People who started NDEs were motivated by the grand unifications…

GUT → Proton decay

Why GUT? —— $q_p + q_e = 0$

GUT → Proton dec

Why GUT? —— $q_p + q_e = 0$

— Quarks and leptons in a box

$$\mathbf{10} \ni \{u_R{}^c, Q, e_R{}^c\}$$

$$\bar{\mathbf{5}} \ni \{d_R{}^c, L\}$$

Georgi Glashow (1974)

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

N BARYONS
$(S = 0, I = 1/2)$

$p, N^+ = uud; \quad n, N^0 = udd$

p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646688 \pm 0.00000000009$ u
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\bar{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\bar{p}}}{m_{\bar{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.7928473446 \pm 0.0000000008\ \mu_N$

GUT → Proton dec

Why GUT? —— $q_p + q_e = 0$

— Quarks and leptons in a box

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$$\overline{\mathbf{5}} \ni \{{d_R}^c, L\}$$

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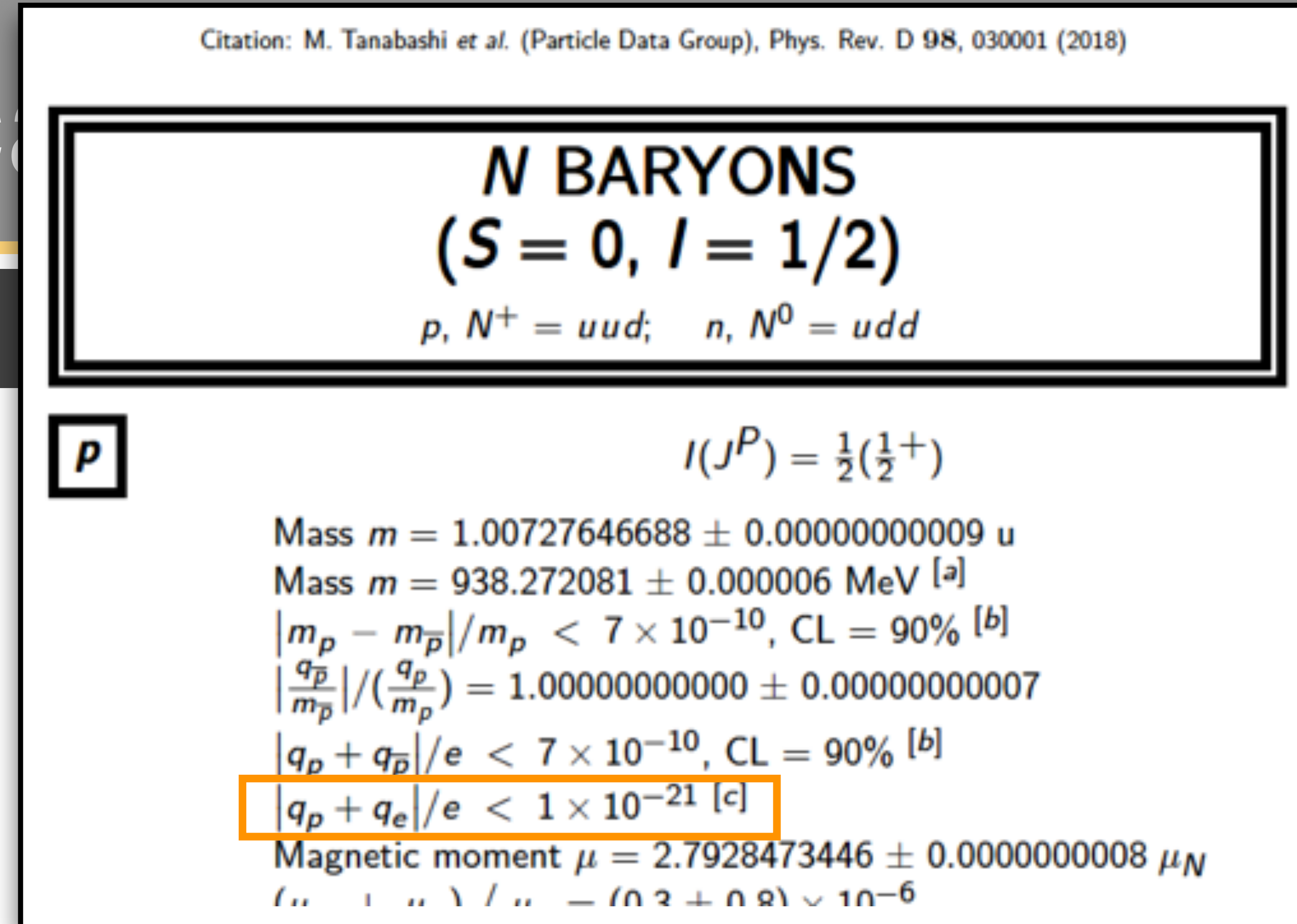
Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

***N* BARYONS**
($S = 0$, $I = 1/2$)
p, $N^+ = uud$; n, $N^0 = udd$

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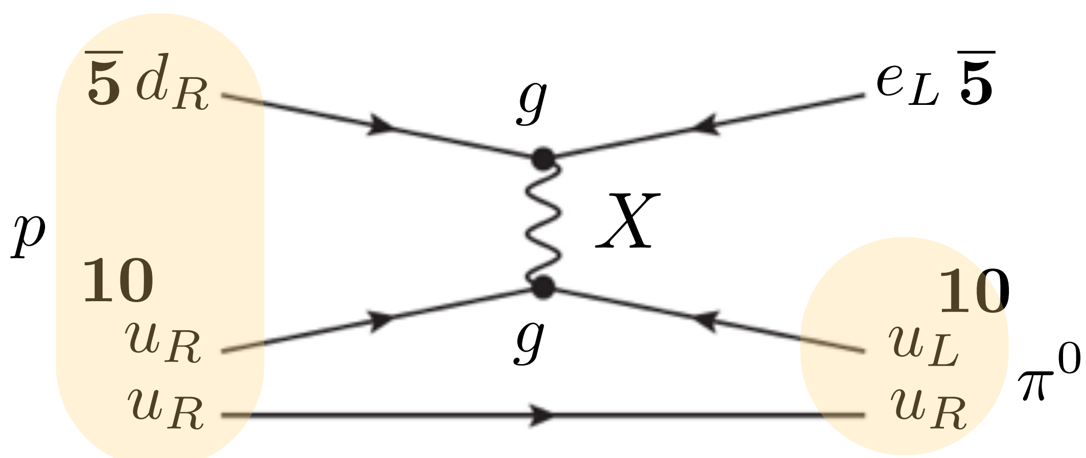
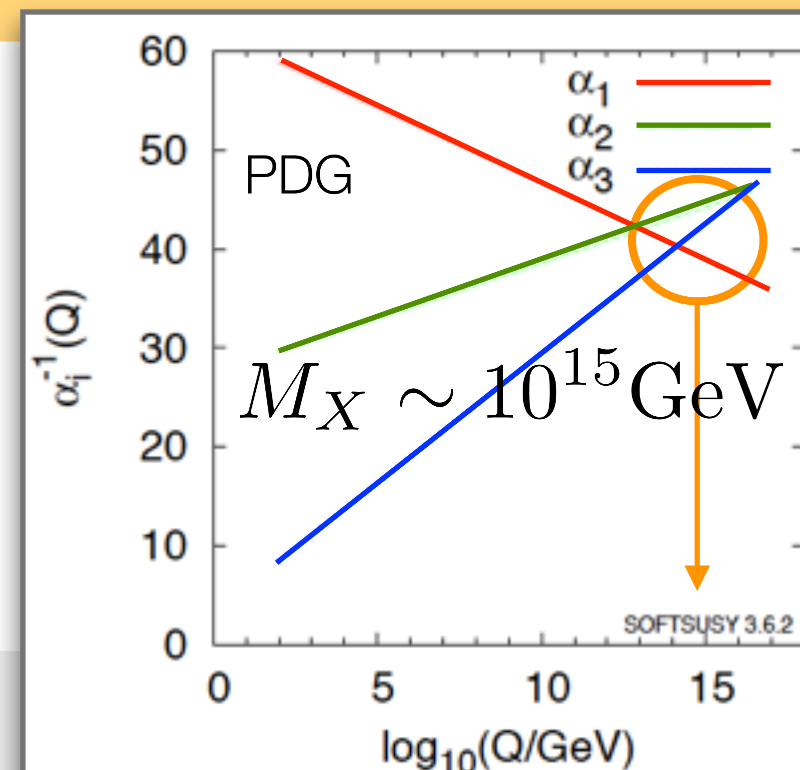
It suggests…



Georgi Quinn Weinberg (1974)

Lifetime is roughly…

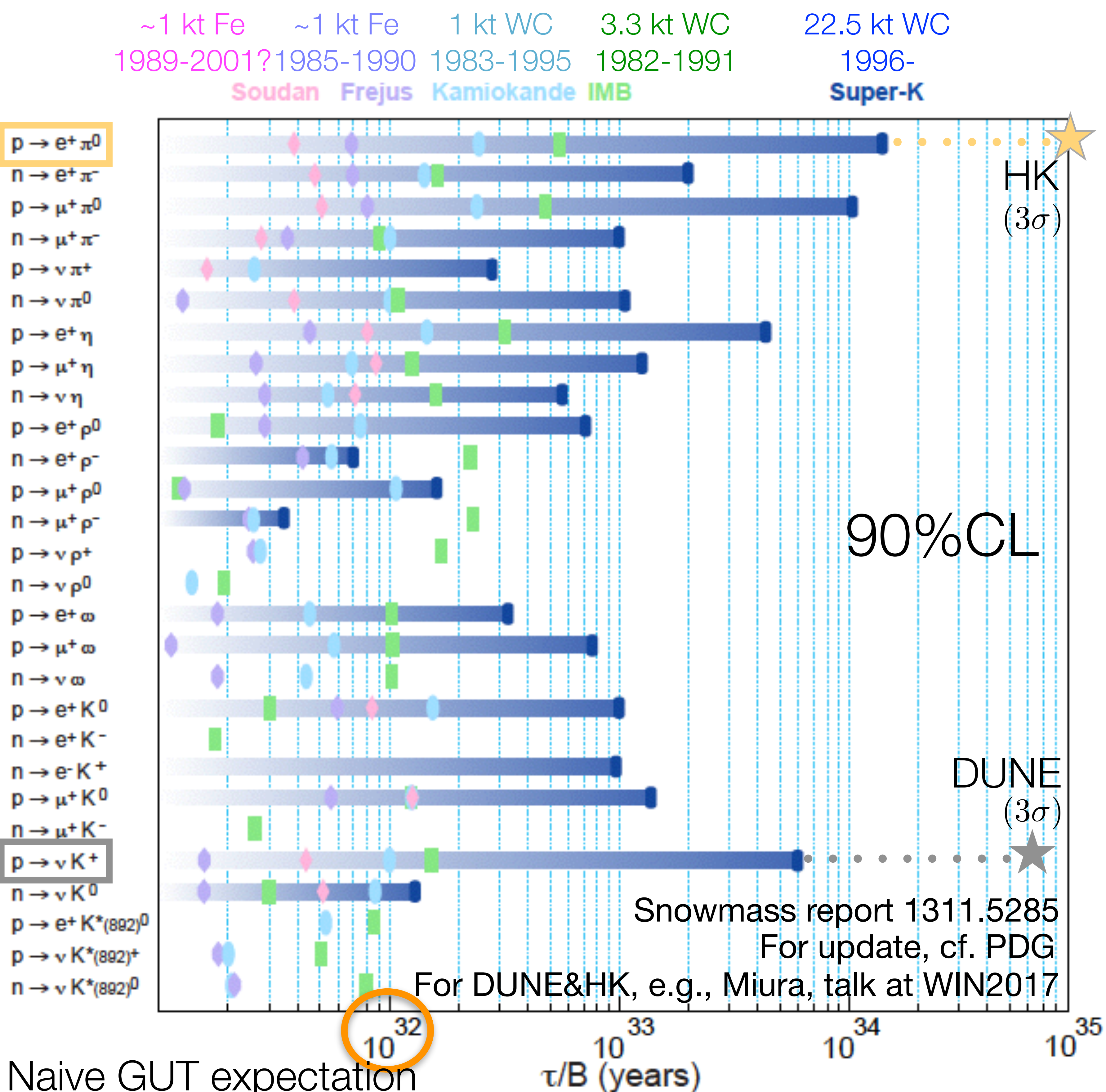
$$\frac{1}{\tau_p} \sim m_p^5 \left| \frac{g^2}{M_X^2} \right|^2$$



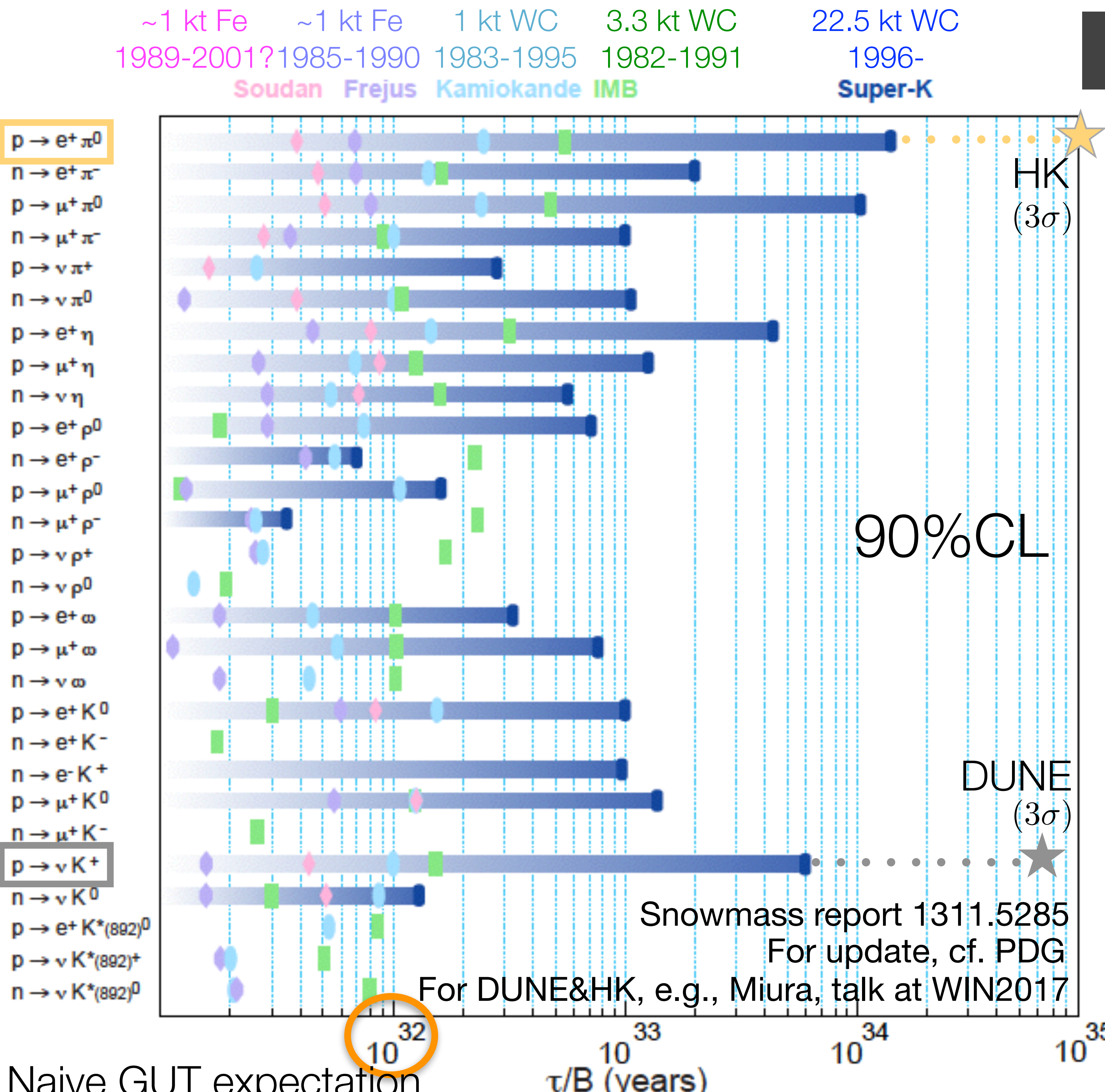
$$\tau(p \to \pi^0 e^+) \sim \mathcal{O}(10^{32})\ \mathrm{yrs}$$

which is reachable with an O(1) kt detector in a year.

Past, now and future of “NDEs”



Past, now and future of “NDEs”



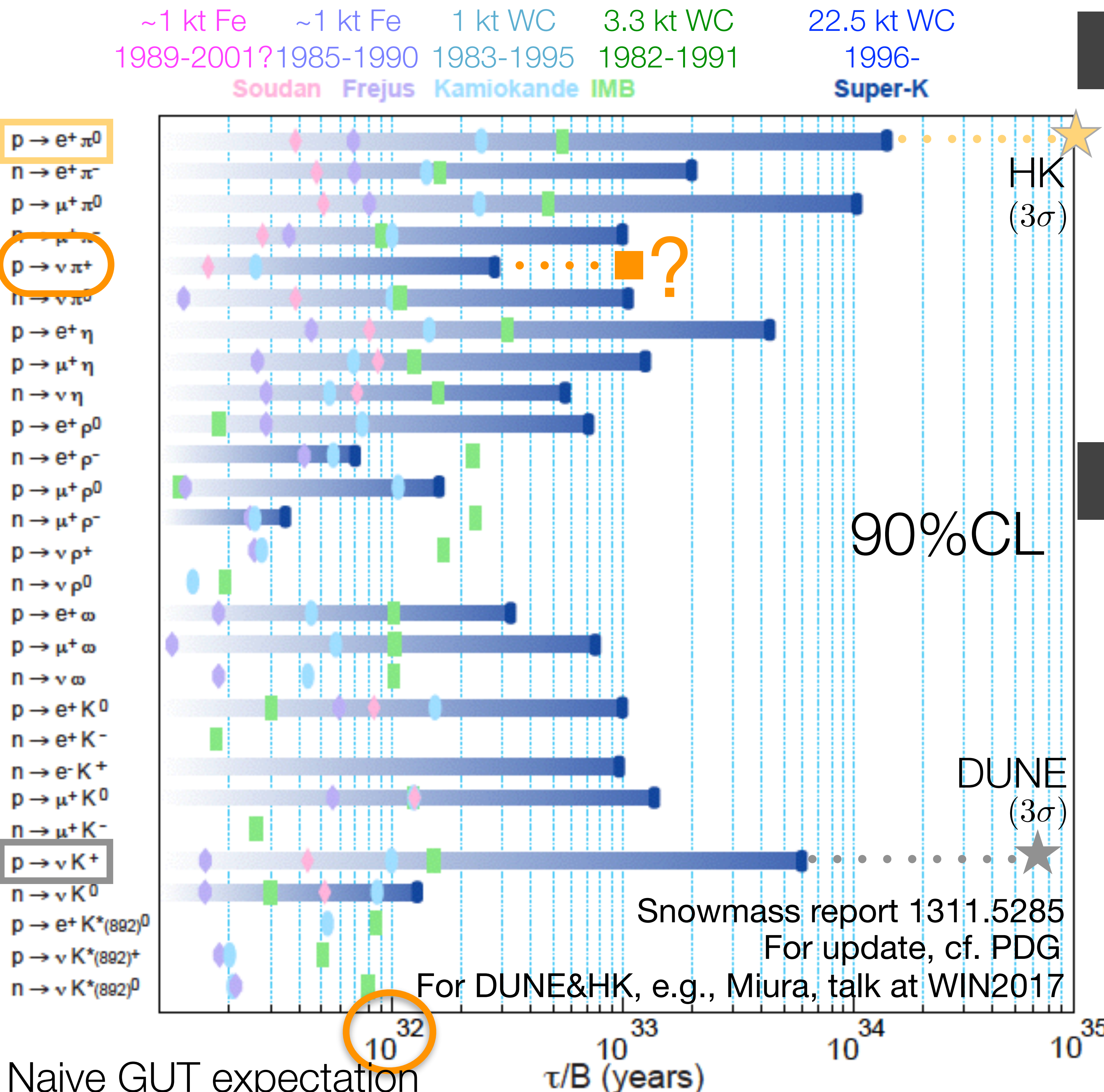
GUT → Proton decay

Proton decay → GUT?

Review the possibilities

w. a bottom up app.

Past, now and future of “NDEs”



GUT → Proton decay

Proton decay → GUT?

Review the possibilities w. a bottom up app.

Benchmark modes

$$p \to \pi^0 + e^+$$

for GUT

$$p \to K^+ + \bar{\nu}$$

for SUSY-GUT

Can the other modes tell us something?

Bottom up approach - SMEFT

At d=4, SM conserves B and L (at the perturbative level)

At d=5, SMEFT accommodates Majorana masses for neutrinos,

$$\mathscr{L}_5 = \frac{\mathcal{C}}{\Lambda}(\overline{L^c}\mathrm{i}\tau^2 H)(H\mathrm{i}\tau^2 L) + \mathrm{H.c.} \qquad \Delta L = 2$$

Weinberg (1979)

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Weinberg (1979)

At d=6, SMEFT violates B+L (conserves B-L)

$$\mathscr{L}_6 \supset \frac{1}{\Lambda^2}\sum_i \mathcal{C}_i \mathcal{O}_i + \mathrm{H.c.}$$

$$\mathcal{O}_1 = \epsilon^{IJK}(\overline{d_R{}^c}_I u_{RJ})(\overline{Q^c}_K \mathrm{i}\tau^2 L)$$

$$\mathcal{O}_2 = \epsilon^{IJK}(\overline{Q^c}_I \mathrm{i}\tau^2 Q_J)(\overline{u_R{}^c}_K e_R)$$

$$\mathcal{O}_3 = \epsilon^{IJK}(\overline{Q^c}_I \mathrm{i}\tau^2 Q_J)(\overline{Q^c}_K \mathrm{i}\tau^2 L)$$

$$\mathcal{O}_4 = \epsilon^{IJK}(\overline{Q^c}_I \mathrm{i}\tau^2 \tau^a Q_J)(\overline{Q^c}_K \mathrm{i}\tau^2 \tau^a L)$$

$$\mathcal{O}_5 = \epsilon^{IJK}(\overline{d_R{}^c}_I u_{RJ})(\overline{u_R{}^c}_K e_R)$$

Four-Fermi ops. with

3 quarks & 1 lepton

$\Delta B = 1 \quad \Delta L = 1$

Weinberg (1979), Wilczek&Zee (1979), Abbott&Wise (1980)

They lead to 2-body proton decays, $p \to$ meson + anti-lepton

The effective operators suggest…

If we have $p \to \pi^+ + \mathrm{missing}$ at the next NDEs… $\tau_p \sim 10^{33}\mathrm{yrs}$

$$\nu \subset [d_R u_R][QL], [QQ][QL]$$

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$\nu \subset [d_R u_R][QL], [QQ][QL]$

We should also have $p \to \pi^0 + \ell^+$

but…

$p \to \pi^0 + e^+/\mu^+$ have already been constrained at $\tau_p > 10^{34}\text{yrs}$

$p \to \pi^+ + \bar{\nu}_{e,\mu}$ should be suppressed at the same level.

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Then, if we will discover solely

$$p \to \pi^+ + \mathrm{missing}$$

which may be caused by

$$p \to \pi^+ + \bar{\nu}_\tau$$

B+L is violated only with the 3rd gen. lepton.

- A hint to the flavor structure

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which may be caused by

$p \to \pi^+ + \bar{\nu}_\tau$ — B+L is violated only with the 3rd gen. lepton.
- A hint to the flavor structure

or

$p \to \pi^+ + \bar{\nu}_s$ — No charged lepton counterpart

SM singlet fermion, aka sterile neutrino

A model for $p \to \pi^+ + N$

There are two additional effective operators with $N = \nu_s$

$$\mathcal{O}_{N1} = (QQ)(d_R N) \qquad \mathcal{O}_{N2} = (u_R d_R)(d_R N)$$

cf. e.g., Alonso et al., 1405.0486

Light N has rich phenomenology

A model for $p \to \pi^+ + N$

There are two additional effective operators with $N = \nu_s$

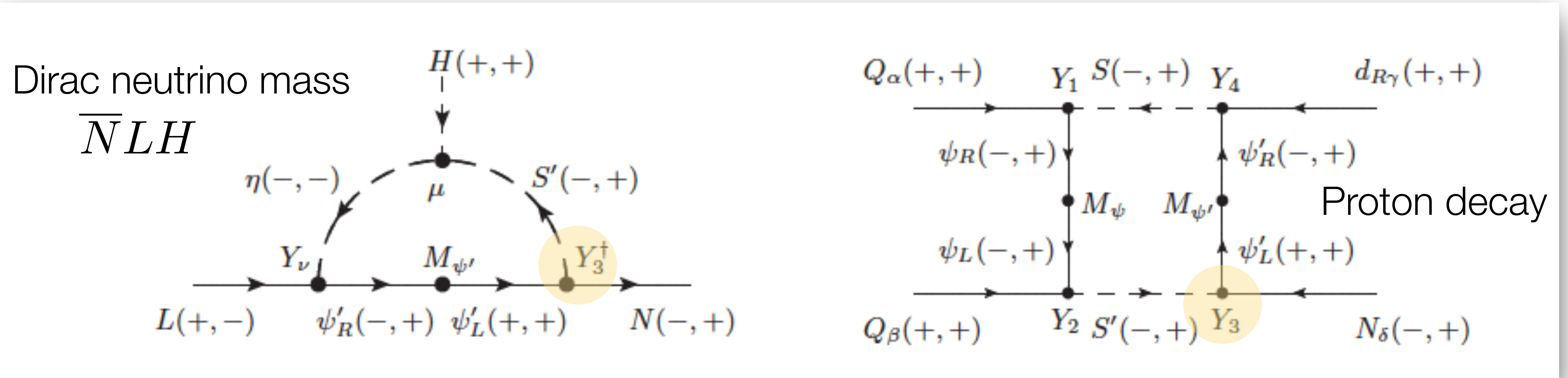
$$\mathcal{O}_{N1} = (QQ)(d_R N) \qquad \mathcal{O}_{N2} = (u_R d_R)(d_R N)$$

cf. e.g., Alonso et al., 1405.0486

Light N has rich phenomenology

Smallness of neutrino masses $\longleftrightarrow$ Longevity of protons

Helo et al., 1803.00035



with 2 vector-like fermions and 3 scalars

$$\psi'(\mathbf{1},\mathbf{1})_0 \quad \psi(\overline{\mathbf{3}},\mathbf{2})_{-1/6} \qquad \eta(\mathbf{1},\mathbf{2})_{+1/2} \quad S'(\mathbf{1},\mathbf{1})_0 \quad S(\mathbf{3},\mathbf{1})_{-1/3}$$

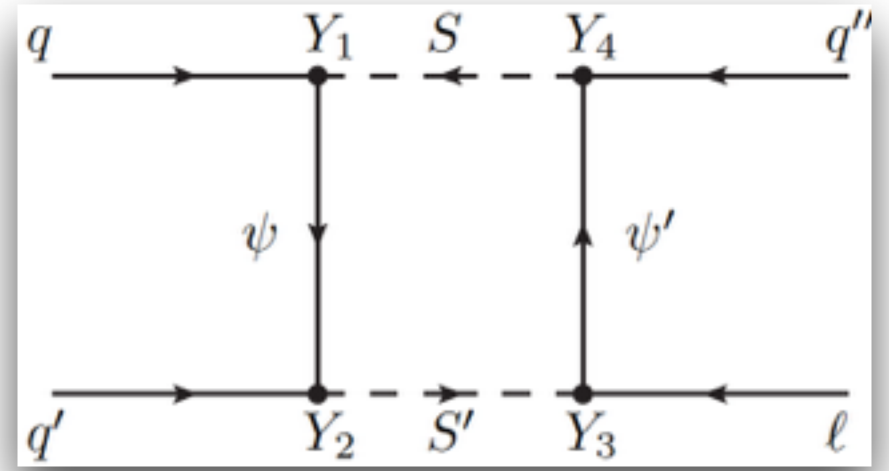
If M, μ ~TeV, the size of the couplings Ys are roughly $\mathcal{O}(10^{-5})$

for $m_\nu \sim \mathcal{O}(0.1)$ eV $\qquad \tau_p \sim \mathcal{O}(10^{32})$ yrs

A systematic list of the models…

*Decomposition at tree = Leptoquarks

Decompose the eff. ops into…



Helo et al.,
1904.00036

List of the models…

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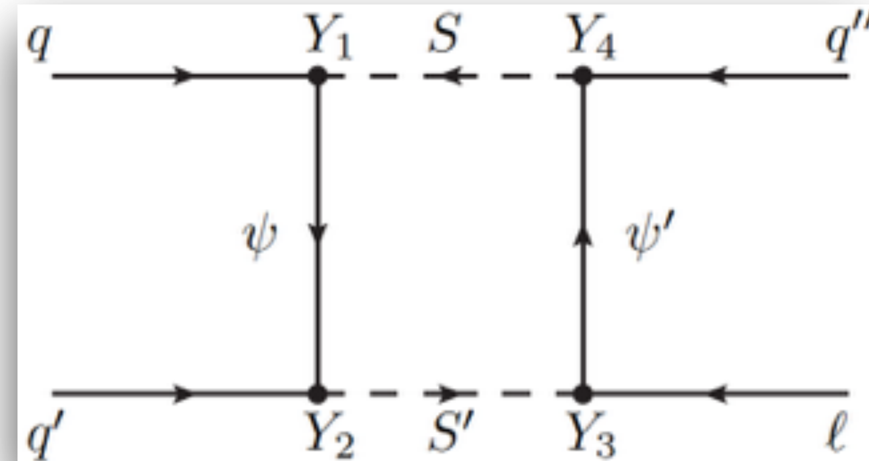


Helo et al.,
1904.00036

Mediators
$\psi \quad S \quad \psi' \quad S'$

Choices for the SU(3) colour

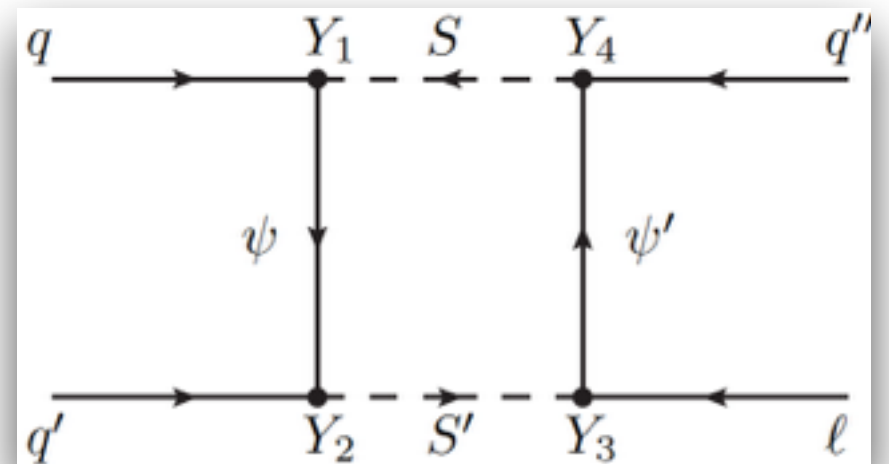
Common for all $\mathcal{O}$s

	Mediators				
	ψ	S	ψ'	S'	$SU(3)$ coeff.
#1	1	$\bar{3}$	3	3	-1
#2	3	1	$\bar{3}$	$\bar{3}$	1
#3	3	8	$\bar{3}$	$\bar{3}$	$-\frac{8}{3}$
#4	3	8	6	6	4
#5	$\bar{3}$	3	1	1	1
#6	$\bar{3}$	3	8	8	$-\frac{8}{3}$
#7	$\bar{3}$	$\bar{6}$	8	8	-4
#8	6	3	8	8	4
#9	$\bar{6}$	8	$\bar{3}$	$\bar{3}$	-4
#10	8	$\bar{3}$	3	3	$\frac{8}{3}$
#11	8	$\bar{3}$	$\bar{6}$	$\bar{6}$	-4
#12	8	6	3	3	4

List of the models…

*Decomposition at tree = Leptoquarks

Decompose the eff. ops into…



Helo et al., 1904.00036

$(qq')(q''\ell)$

Mediators

ψ S ψ' S'

Common for all $\mathcal{O}$s

Choices for the SU(3) colour

	Mediators ψ	S	ψ'	S'	$SU(3)$ coeff.
#1	1	$\bar{3}$	3	3	−1
#2	3	1	$\bar{3}$	$\bar{3}$	1
#3	3	8	$\bar{3}$	$\bar{3}$	$-\frac{8}{3}$
#4	3	8	6	6	4
#5	$\bar{3}$	3	1	1	1
#6	$\bar{3}$	3	8	8	$-\frac{8}{3}$
#7	$\bar{3}$	$\bar{6}$	8	8	−4
#8	6	3	8	8	4
#9	$\bar{6}$	8	$\bar{3}$	$\bar{3}$	−4
#10	8	$\bar{3}$	3	3	$\frac{8}{3}$
#11	8	$\bar{3}$	$\bar{6}$	$\bar{6}$	−4
#12	8	6	3	3	4

$\otimes$

For $\mathcal{O}_1 = [d_R u_R][QL]$

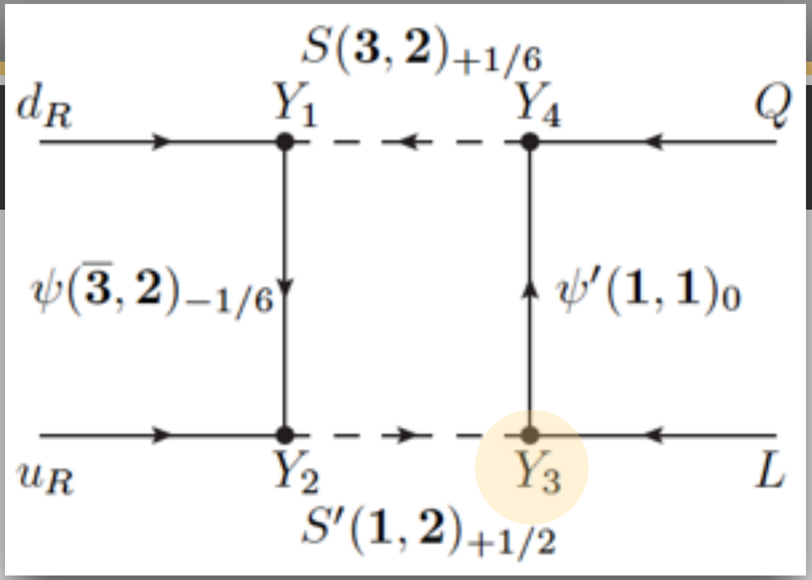
Choices for the SU(2)×U(1)

$\mathcal{O}_1$ Decom.	Mediators $SU(2)_{U(1)}$ ψ	S	ψ'	S'	$SU(2)$ coeff.	Fierz×Loop factors	$SU(3)$ sign
$(du)(QL)$	$\mathbf{1}_\alpha$	$\mathbf{1}_{\alpha+\frac{1}{3}}$	$\mathbf{2}_{\alpha+\frac{1}{6}}$	$\mathbf{1}_{\alpha+\frac{2}{3}}$	1	$M_\psi M_{\psi'} I_4$	+
	2	2	1	2	−1		
	2	2	3	2	−3		
	3	3	2	3	3		
$(ud)(QL)$	$\mathbf{1}_\alpha$	$\mathbf{1}_{\alpha-\frac{2}{3}}$	$\mathbf{2}_{\alpha-\frac{5}{6}}$	$\mathbf{1}_{\alpha-\frac{1}{3}}$	1	$M_\psi M_{\psi'} I_4$	−
	2	2	1	2	−1		
	2	2	3	2	−3		
	3	3	2	3	3		
$(dQ)(uL)$	$\mathbf{1}_\alpha$	$\mathbf{1}_{\alpha+\frac{1}{3}}$	$\mathbf{1}_{\alpha-\frac{1}{3}}$	$\mathbf{2}_{\alpha+\frac{1}{6}}$	−1	$-\frac{1}{2}J_4$	−
	2	2	2	1	−1		
	2	2	2	3	3		
	3	3	3	2	−3		
$(Qd)(uL)$	$\mathbf{1}_\alpha$	$\mathbf{2}_{\alpha-\frac{1}{6}}$	$\mathbf{2}_{\alpha-\frac{5}{6}}$	$\mathbf{1}_{\alpha-\frac{1}{3}}$	1	$\frac{1}{2}J_4$	+
	2	1	1	2	−1		
	2	3	3	2	−3		
	3	2	2	3	3		
$(uQ)(dL)$	$\mathbf{1}_\alpha$	$\mathbf{1}_{\alpha-\frac{2}{3}}$	$\mathbf{1}_{\alpha-\frac{1}{3}}$	$\mathbf{2}_{\alpha+\frac{1}{6}}$	−1	$-\frac{1}{2}J_4$	+
	2	2	2	1	−1		
	2	2	2	3	3		
	3	3	3	2	−3		
$(Qu)(dL)$	$\mathbf{1}_\alpha$	$\mathbf{2}_{\alpha-\frac{1}{6}}$	$\mathbf{2}_{\alpha+\frac{1}{6}}$	$\mathbf{1}_{\alpha+\frac{2}{3}}$	1	$\frac{1}{2}J_4$	−
	2	1	1	2	−1		
	2	3	3	2	−3		
	3	2	2	3	3		

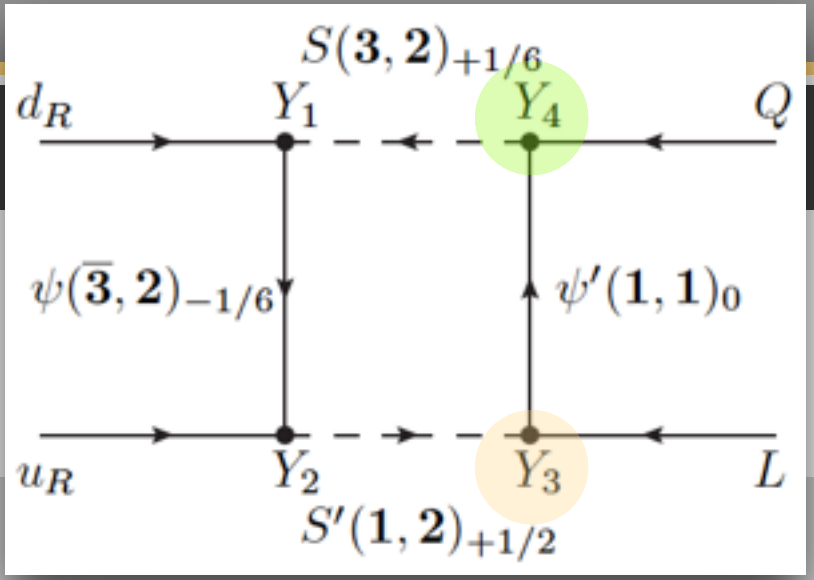
Inspired by Scotogenic models

Proton decays $p \to \pi^0 \ell^+ / \pi^+ \bar{\nu}_\ell$

$$\tau_p \sim 10^{34}[\text{yrs}] \left[\frac{\overline{M}}{1\text{TeV}}\right]^4 \left[\frac{3\cdot 10^{-6}}{\overline{Y}}\right]^8$$



Inspired by Scotogenic models



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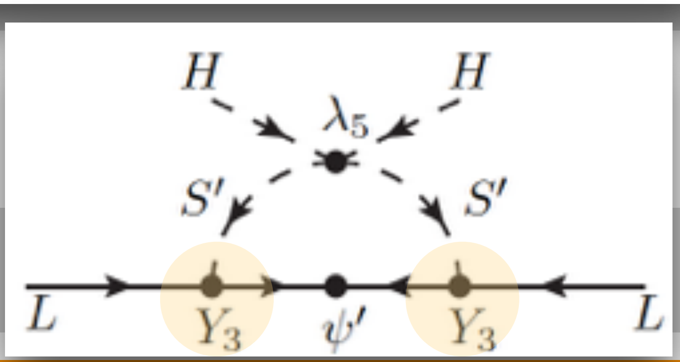
ν mass a la scotogenic models $\overline{M} \sim \text{TeV}$

$Y_3 \sim 10^{-5}$ for $\lambda_5 \sim 1$ Ma (2006)

$\psi'(\mathbf{1},\mathbf{1})_0$



To reproduce the correct DM relic density,

$Y_4 \gtrsim 0.1$ $\tau_p \sim 10^{-34}\text{yrs}$ ⇒ $Y_{1,2} \lesssim 10^{-7}$

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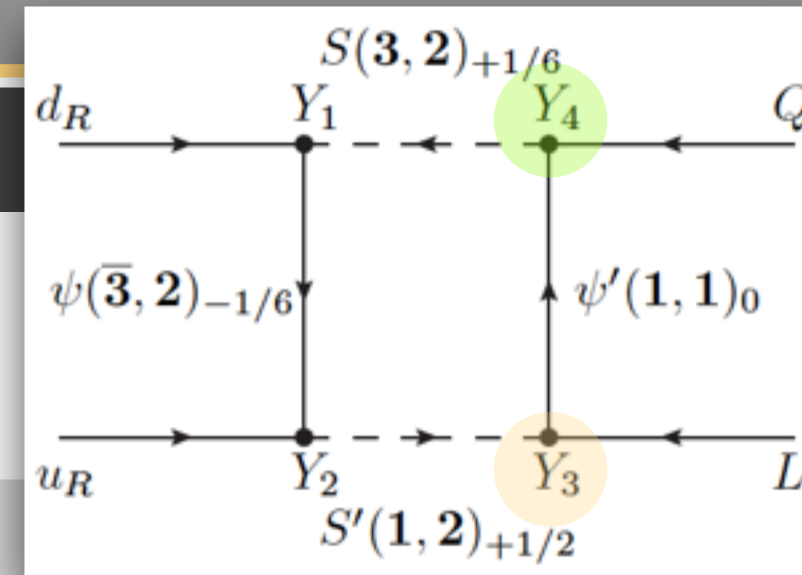

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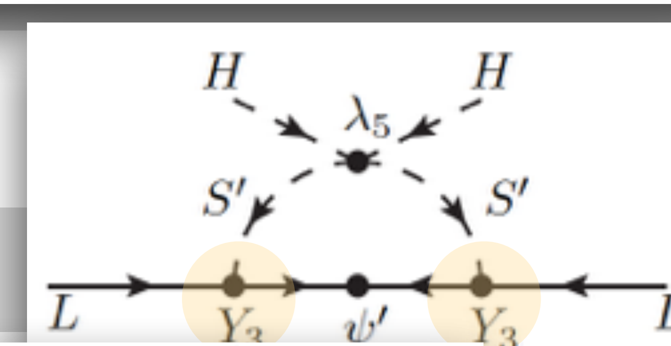

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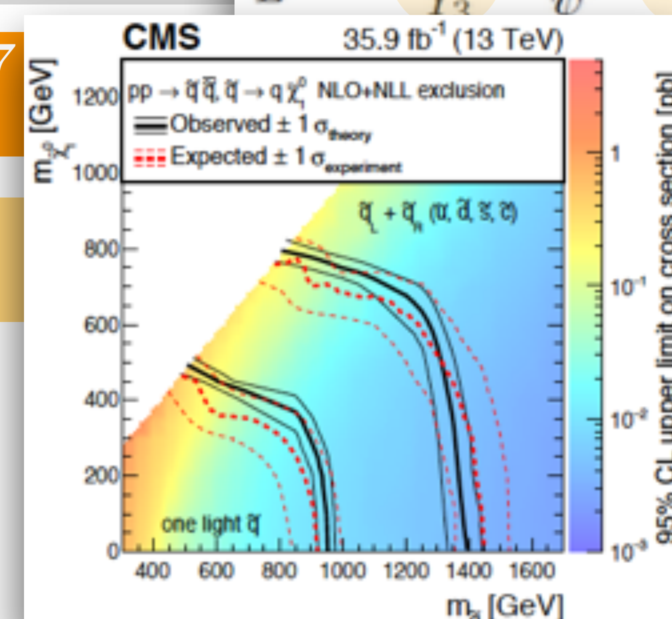
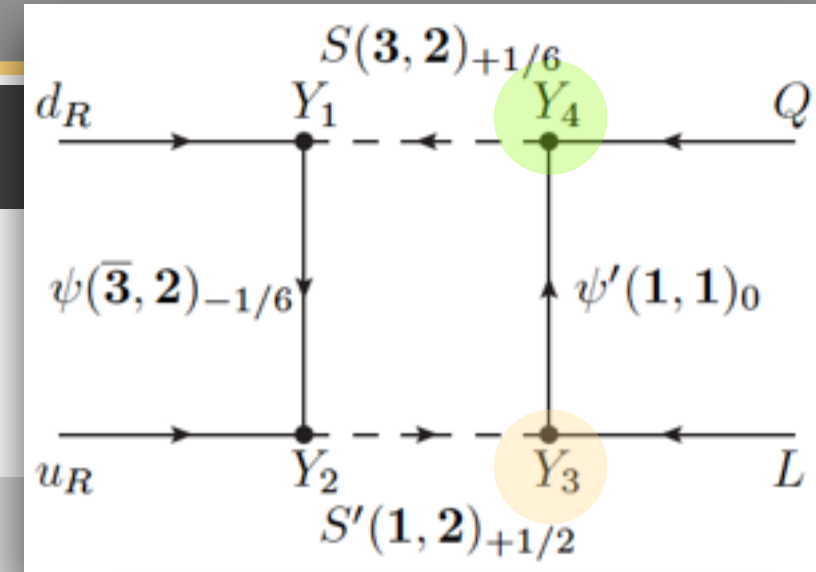
"Squark" @LHC

1704.07781 (CMS)
1712.02332 (ATLAS)



$S \xrightarrow{Y_4} Q\psi'$ =jet+missing

Inspired by Scotogenic models



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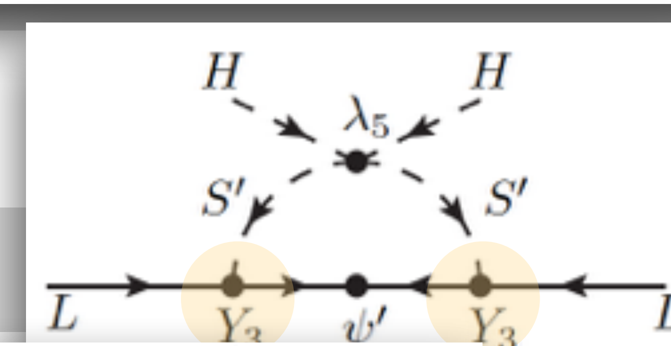

Ma (2006)

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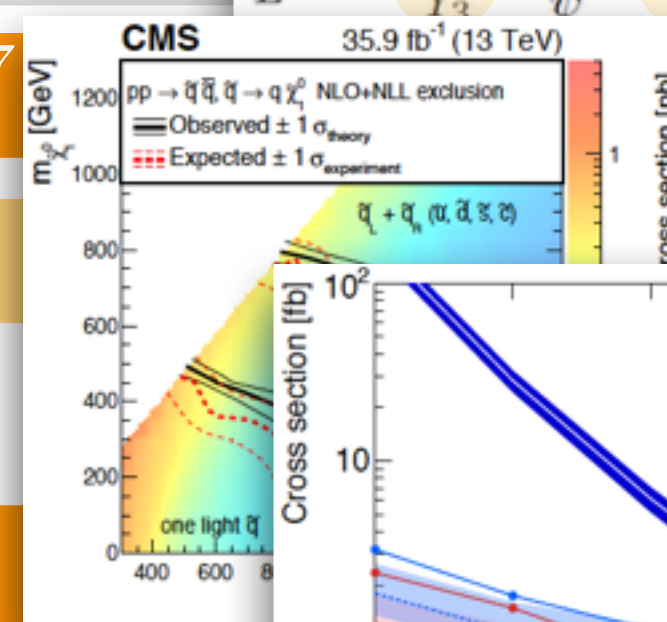

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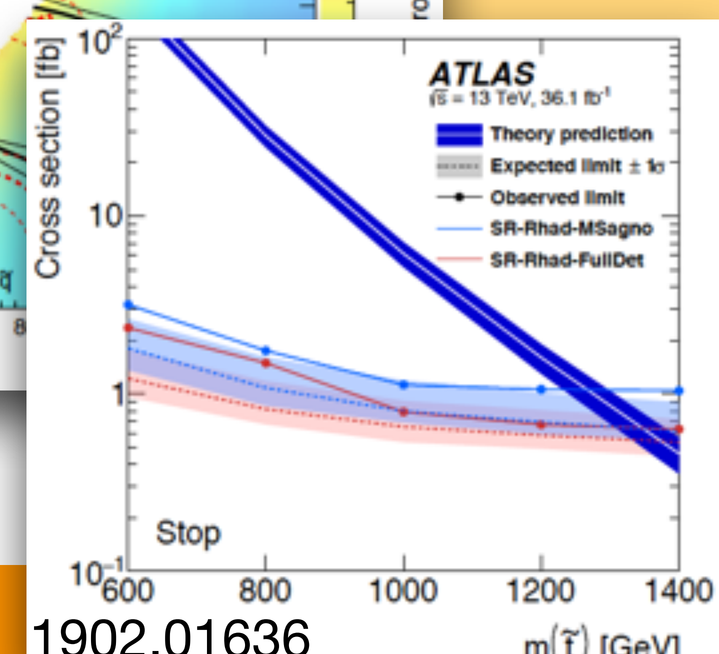
$S \xrightarrow{Y_4} Q\psi'$ =jet+missing

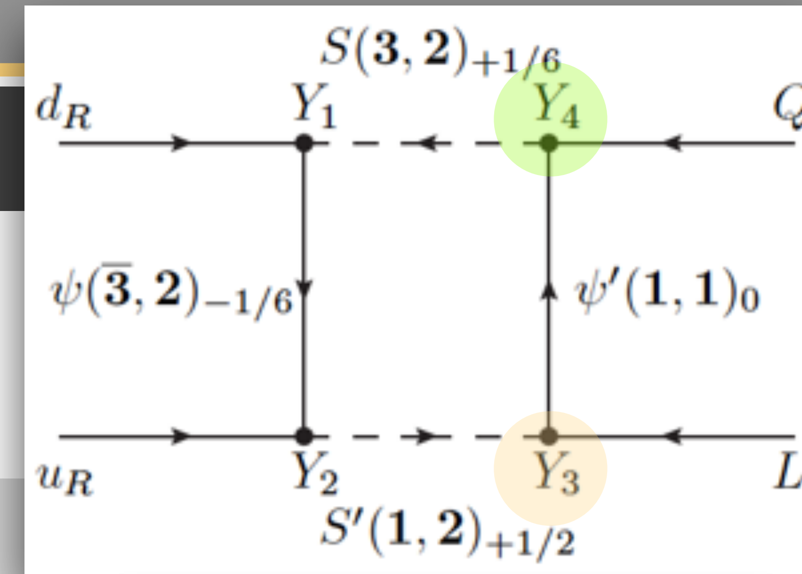
Long-lived colored&charged particle

$\overline{\psi} \to d_R Q \psi'$ =2jets+missing with $\tau_\psi \gtrsim 10$ s



"Heavy ionizing track" ("R-hadron") searches…

Inspired by Scotogenic models



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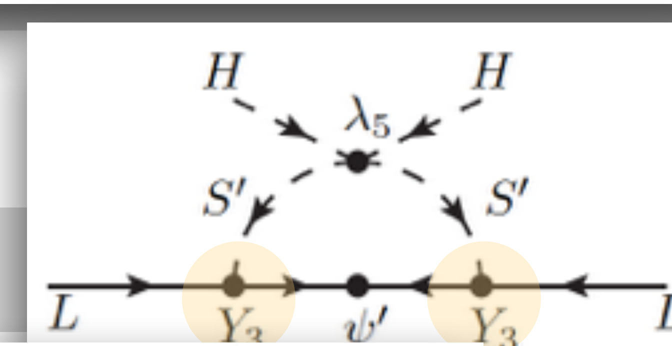

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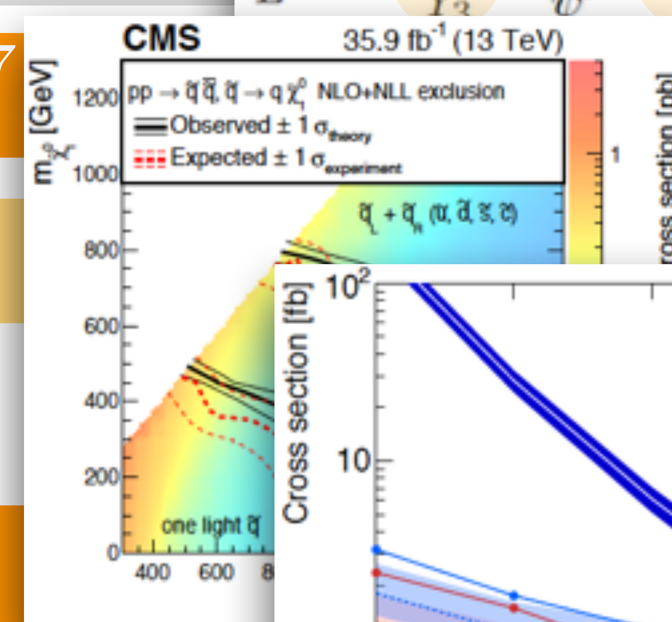

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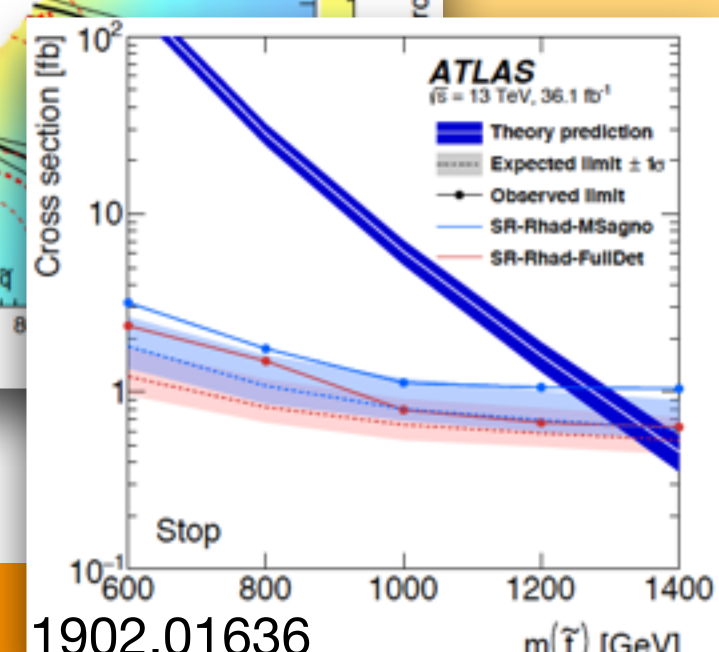
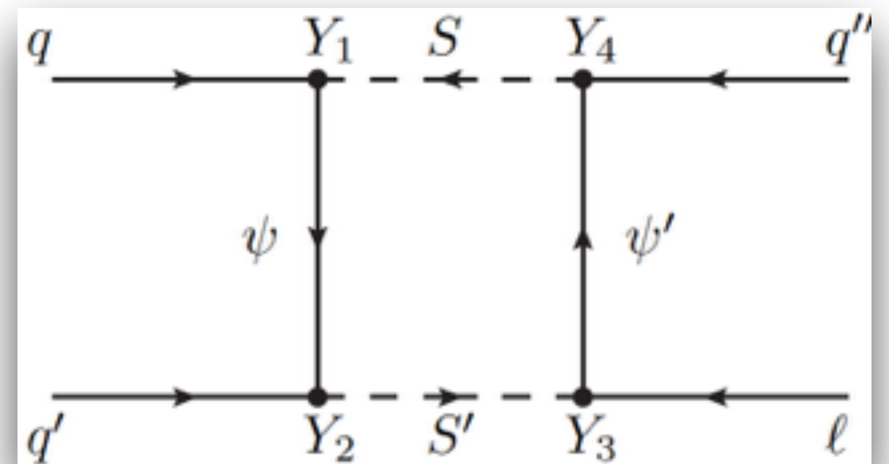


"Heavy ionizing track" ("R-hadron") searches…

List of the models…

*Decomposition at tree = Leptoquarks

Decompose the eff. ops into…



Helo et al., 1904.00036

$(qq')(q''\ell)$

Mediators ψ S ψ' S'

Choices for the SU(3) colour

Common for all $\mathcal{O}$s

	Mediators ψ	S	ψ'	S'	$SU(3)$ coeff.
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$\bigotimes$

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For $\mathcal{O}_1 = [d_R u_R][QL]$

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	2	2	1	2	−1		
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$(dQ)(uL)$	1_α	$1_{\alpha+\frac{1}{3}}$	$1_{\alpha-\frac{1}{3}}$	$2_{\alpha+\frac{1}{6}}$	−1	$-\frac{1}{2}J_4$	−
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	2	2	2	1	−1		
	2	2	2	3	3		
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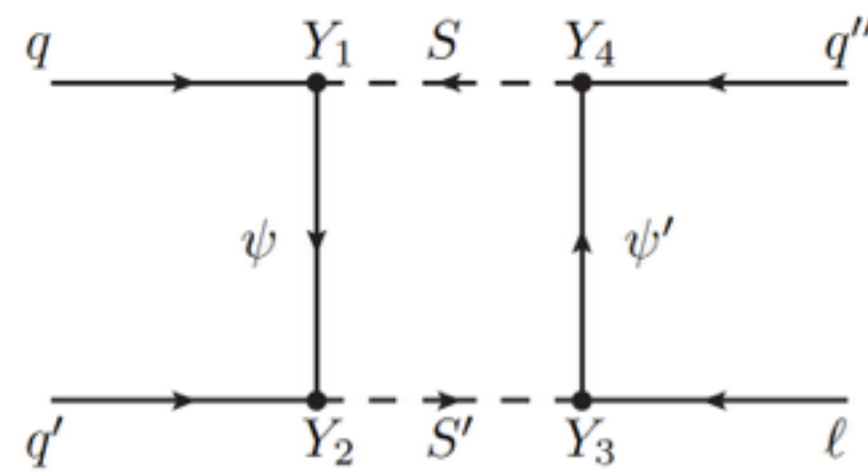
$(Qu)(dL)$	1_α	$2_{\alpha-\frac{1}{6}}$	$2_{\alpha+\frac{1}{6}}$	$1_{\alpha+\frac{2}{3}}$	1	$\frac{1}{2}J_4$	−
	2	1	1	2	−1		
	2	3	3	2	−3		
	3	2	2	3	3		

How to use the tables…

Fundamental Lagrangian: Yukawa interactions

$$\mathscr{L} \supset Y_1 \overline{q^c} \psi^c S + Y_2 \overline{\psi^c} q' S'^{\dagger} + Y_3 \overline{\psi'} \ell S' + Y_4 \overline{q''^c} \psi' S^{\dagger} + \mathrm{H.c.}$$



Effective Lagrangian for proton decays is…

e.g., Aoki et al., 1705.01338
Hadron matrix element given from lattice calc.

$$\mathscr{L}_{\mathrm{eff}} = [Y_1 \overline{q^c} \psi^c S][Y_2 \overline{\psi^c} q' S'^{\dagger}][Y_4 \overline{q''^c} \psi' S^{\dagger}][Y_3 \overline{\psi'} \ell S']$$

$$= \mathrm{coeff.} \times \mathcal{O}(\mathrm{s}) \quad \text{eff. ops}$$

Tables

$$\Gamma_p = \frac{m_p}{32\pi} \left[1 - \frac{m_M^2}{m_p^2} \right]^2 |W \times \mathrm{coeff.}|^2$$

Yukawa couplings times…

Group theory coef., Loop int., Fierz trans.

Helo et al., 1904.00036

Summary for Part 2: Proton decays

- We will have large neutrino detectors…

  NDEs are also Nucleon Decay Experiments.

- GUTs are the best motivation for nucleon decays, but…

  the GUT-benchmark modes may be too much emphasized.

  e.g., Non-benchmark mode $p \to \pi^+ + \mathrm{missing}$

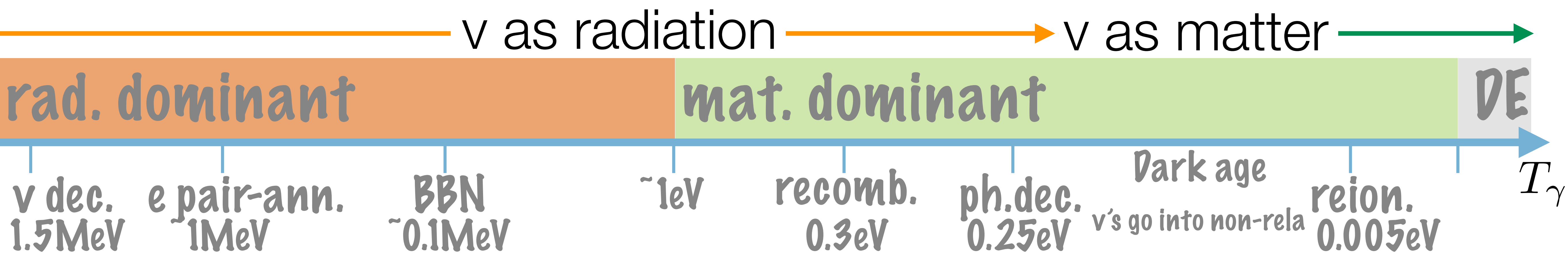
  can give hints of flavour structures / sterile ν.

- A bottom-up approach to explore the origin of nucleon decays:

  SMEFT ⟶ List of 1-loop decomposition of the effective ops

Backup

Bound to Σm from cosmology



CMB $\theta_{\rm obs.} \equiv r_s/d_A$

"Sound horizon" $r_s(z_{\gamma\rm dec.}) = \int_{z_{\gamma\rm dec.}}^{\infty} \frac{c_s \mathrm{d}z'}{H(z')}$

"Angular distance" $d_A(z_{\gamma\rm dec.}) = \int_0^{z_{\gamma\rm dec.}} \frac{\mathrm{d}z'}{H(z')}$

e.g., $\Sigma m \nearrow$ ⇨ r_s stays & $d_A \searrow$ ⇨ $\theta_{\rm obs.} \nearrow$

LSS Free streaming of ν disturbs the structure formation.

The structures with the scale smaller than a particular size are suppressed.

BAO Standard rular $r_s(z_{\gamma\rm dec.})$

in galaxy (z<2) LyA (z~3)

21cm (10<z<20)

Schoenberg et al.,1907.11594

Tension btw galaxy+LyA&SN

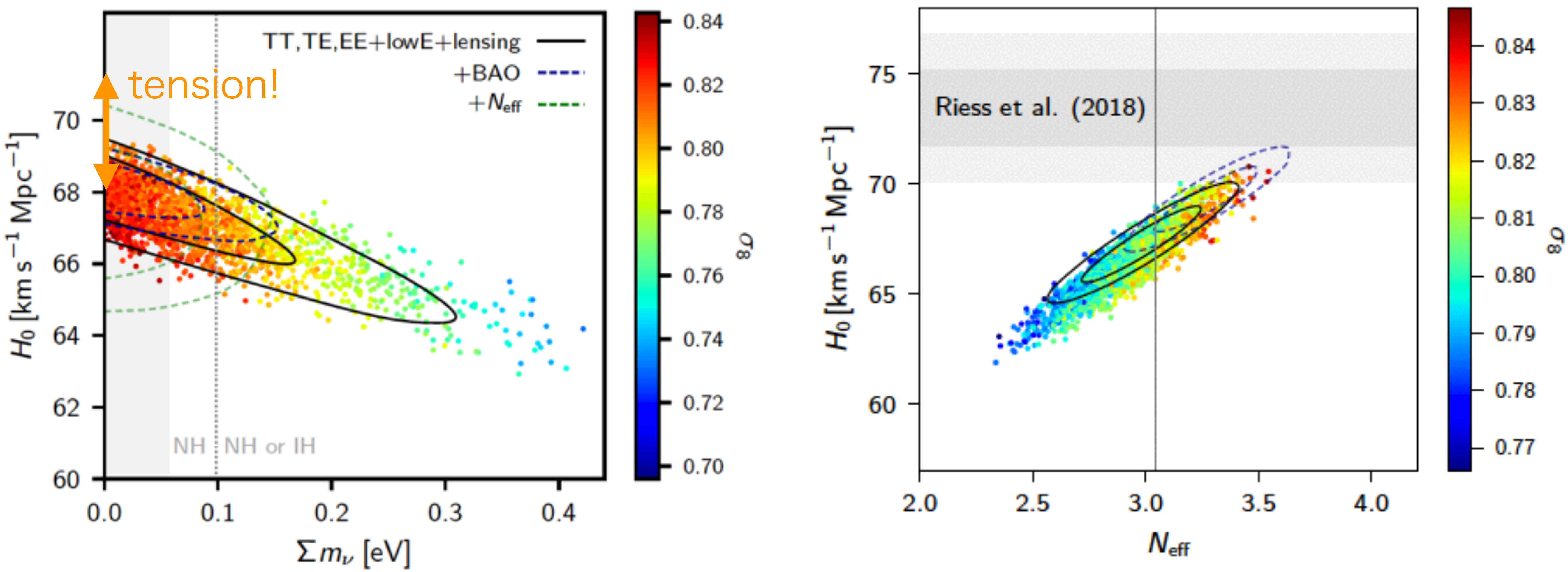
H0 tension - Possibly something is missing in LambdaCDM?

cf. Bernal et al., 1607.05617,
Jee et al., 1909.06712.

Incl. of "something" may change the bound…

H0 tension and ν parameters

Planck collaboration, 1807.06209



$\Sigma m \nearrow$ → $H_0 \searrow$ —— H0 tension gets higher

→ Inclusion of the H0 measurement with SNs

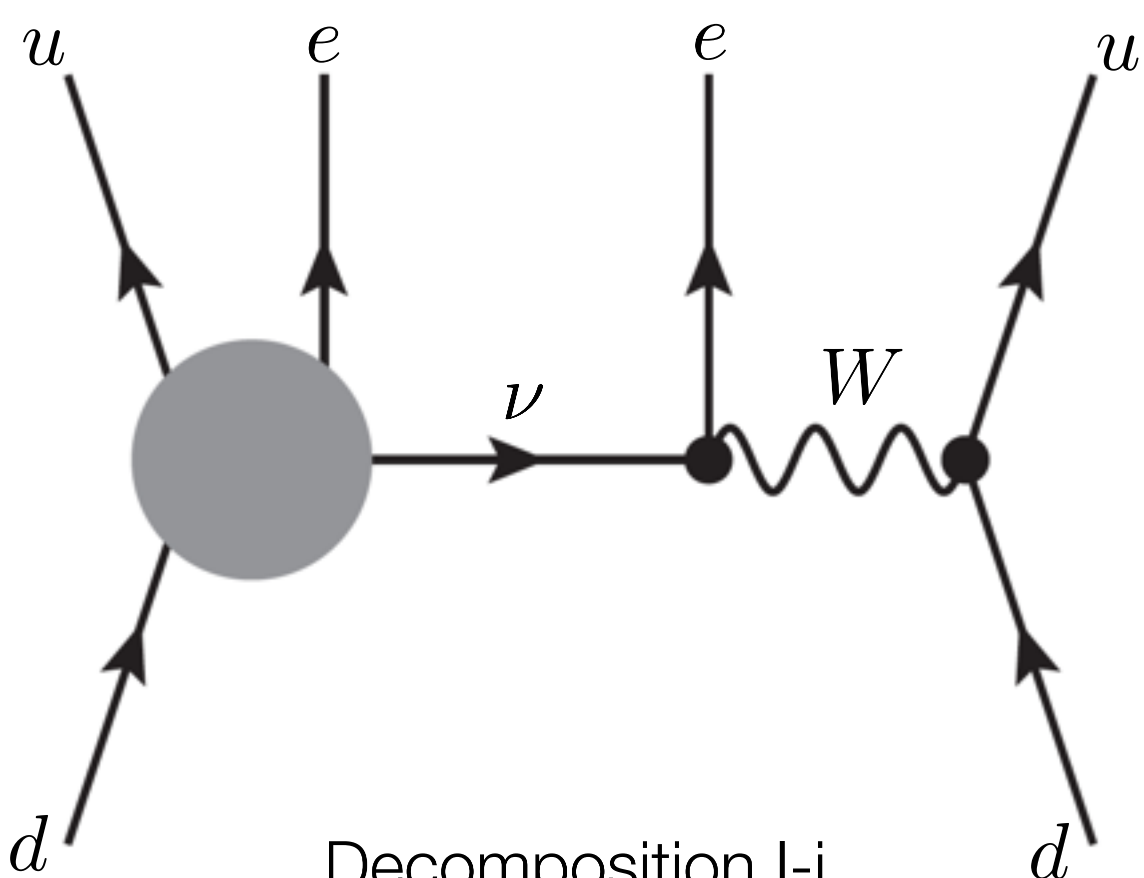
→ Σm bound stronger

Extra radiation relaxes the H0 tension.

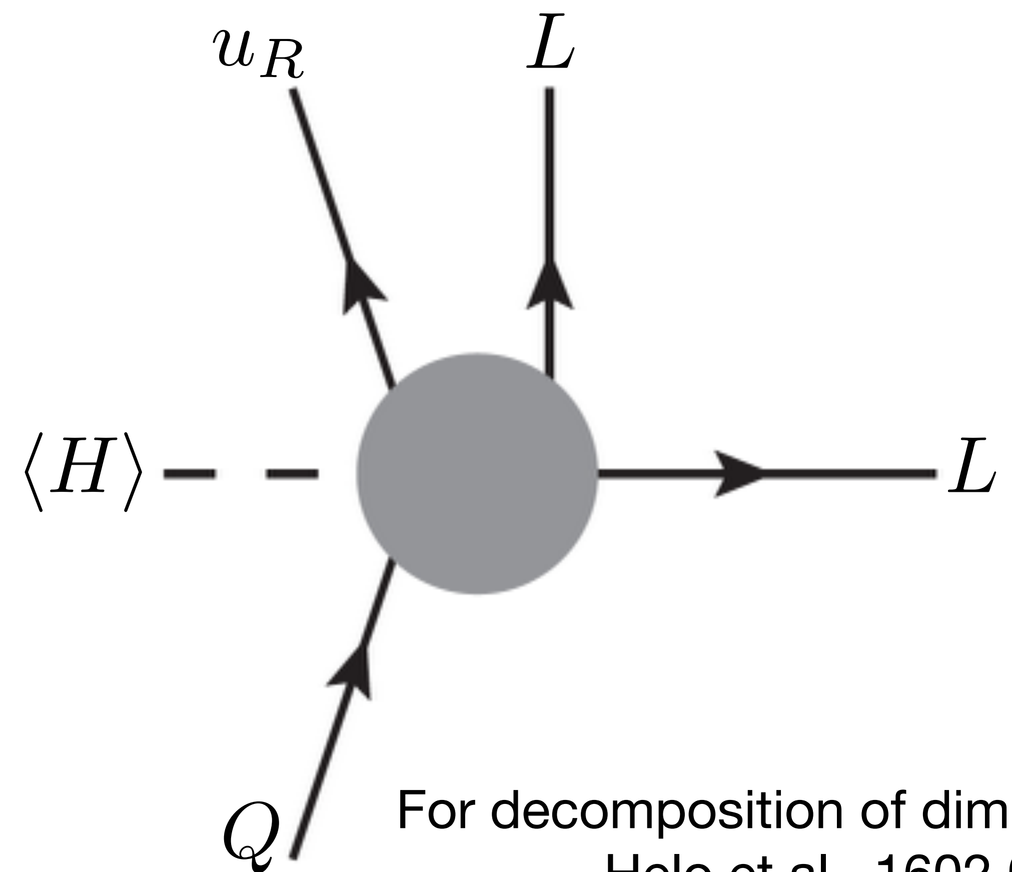
Long-range contribution to 0v2b

No suppression with $m_{\beta\beta}$

Based on LNV dim.=7 operator



Decomposition I-i



For decomposition of dim.7 ops, Helo et al., 1602.03362

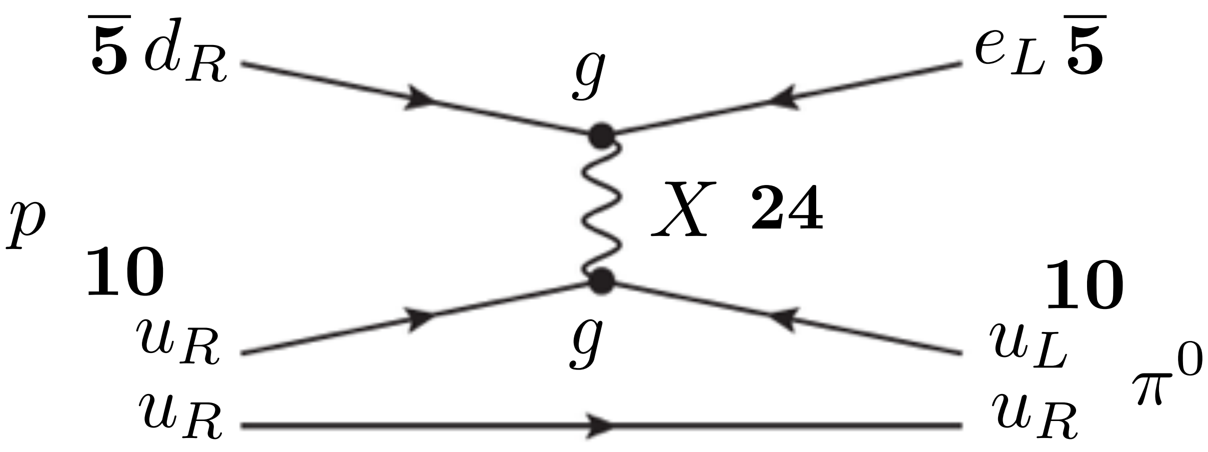
$$\mathscr{L}_{\text{Long-range}} \overset{!}{=} \mathscr{L}_{\nu\text{SM}}$$

$$\mathscr{L}_{\text{Long-range}} = \frac{\mathcal{C}}{\Lambda_{\text{NP}}^3} G_F \frac{1}{p} \Rightarrow \Lambda_{\text{NP}} = 56[\text{TeV}] \left[\frac{0.05\text{eV}}{m_{\beta\beta}}\right]^{1/3}$$

0v2b exps are sensitive to NP at O(10) TeV.

Proton decays in GUT&SUSY-GUT

GUT: Dim.6 mediated by a GUT gauge boson

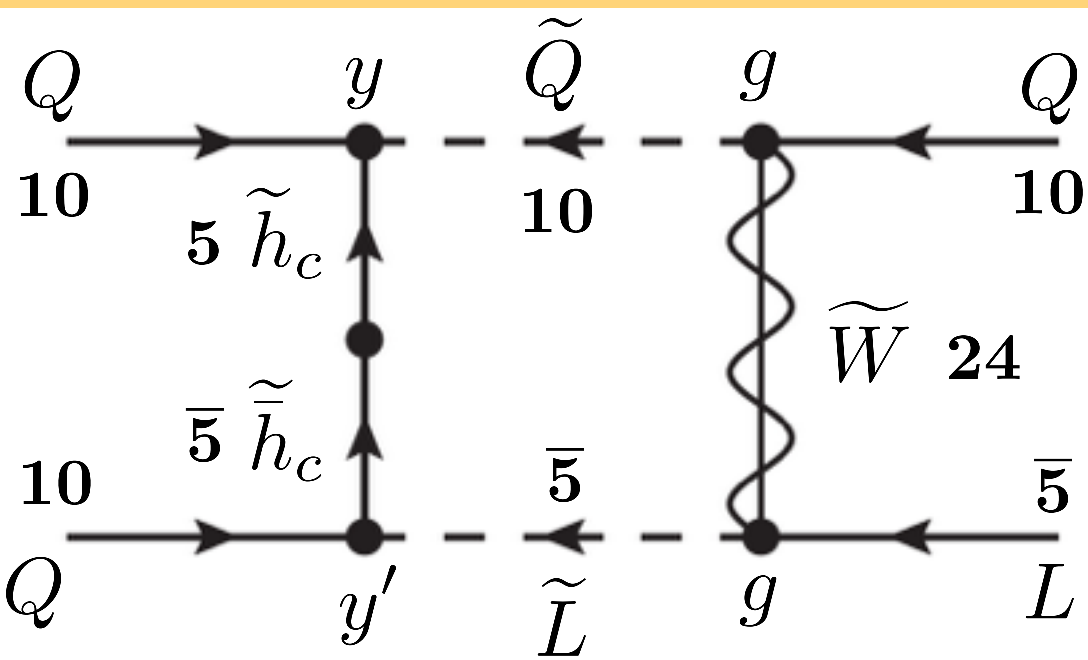


gauge int.

$$g = 0.1 \qquad M_{\mathrm{GUT}} = 10^{15}\mathrm{GeV}$$

$$\tau_p \sim \frac{1}{m_p^5 \left| \frac{g^2}{M_{\mathrm{GUT}}^2} \right|^2} = 3 \cdot 10^{32}[\mathrm{yrs}]$$

SUSY-GUT: Dim.5 mediated by a coloured higgsino + Dressing



Yukawa ints.

$$g = 0.1 \qquad y = y' = 10^{-4}$$

$$M_{\mathrm{SUSY}} = 1\mathrm{TeV} \qquad M_{\mathrm{GUT}} = 10^{16}\mathrm{GeV}$$

$$\tau_p \sim \frac{1}{m_p^5 \left| \frac{1}{16\pi^2} \frac{g^2 y y'}{M_{\mathrm{GUT}} M_{\mathrm{SUSY}}} \right|^2} = 7 \cdot 10^{30}[\mathrm{yrs}]$$