Novel Signatures of New Physics at Frontiers

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Visiting at NCTS

NCTS Annual Theory Meeting 2019
Particles, Cosmology and Strings

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CP violating mode of the stoponium decay into Zh

with Kingman Cheung & Po-Yen Tseng

Lepton Number Violation and Majorana Heavy Neutrino at Colliders

with Goran Senjanovic, 1983

Dark annihilation with neutron underground

with Danny Marfatia & Po-Yen Tseng

NCTS Annual Theory Meeting 2019:
Particles, Cosmology and Strings

CP violating mode of the stoponium decay into *Zh*

with Kingman Cheung (NTHU/NCTS) and Po-Yen Tseng (IPMU)

Why no study on Zh?

Why CPX?

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e-Print: **arXiv:1804.06089**

Furry theorem:
The amplitude for n legs of external vectors (photon-like) vanishes for odd n.
(assuming the C-symmetry)

$$V^\mu \xrightarrow{C} -V^\mu \qquad \mathcal{M} = (-1)^n \mathcal{M}$$

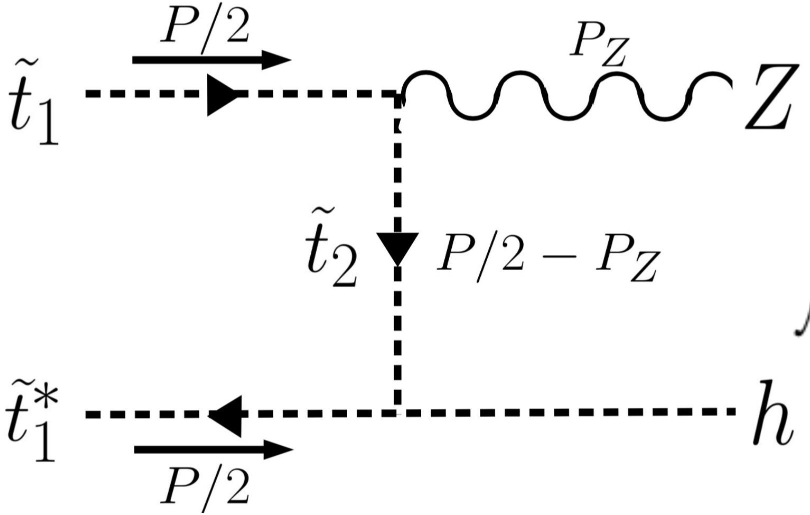
Diagrammatic proof requires the cancellation of a pair of loop diagrams of opposite flow of charge.

Z boson couplings to the stops $t_i (i = 1.2)$

$$J^\mu_{ij} = i\widetilde{t}^*_i \overleftrightarrow{\partial} \widetilde{t}_j \quad \text{where} \quad \overleftrightarrow{\partial} \equiv \overrightarrow{\partial} - \overleftarrow{\partial} \qquad \langle \widetilde{t}_i(p_i) | J^\mu_{ij} | \widetilde{t}_j(p_j) \rangle = (p_j + p_i)^\mu$$

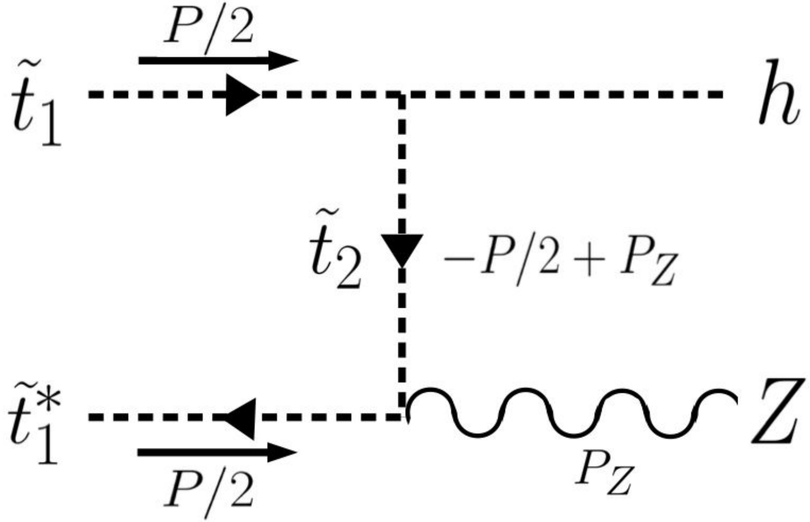
$$\text{charge conjugation } C,\ \widetilde{t}_i \xleftrightarrow{C} \widetilde{t}^*_i \qquad Z^\mu \xleftrightarrow{C} -Z^\mu \quad J^\mu_{ij} \xleftrightarrow{C} -J^\mu_{ji}.$$

hermiticity of the unitary interaction $\mathcal{L} \supset \sum_{ij} g^Z_{ij} J^\mu_{ij} Z_\mu$ requires $g^Z_{ij} = g^{Z*}_{ji}$



$$\mathcal{L} \supset g^{Z}_{\tilde{t}_1\tilde{t}_2}(\tilde{t}_2^* \overleftrightarrow{\partial_\mu} \tilde{t}_1) Z^\mu + y^{h}_{\tilde{t}_1\tilde{t}_2}(\tilde{t}_2^* \tilde{t}_1) h + \text{h.c.}$$

$$\mathcal{M}_1 = -\frac{\left[\frac{P}{2} + \left(\frac{P}{2} - p_Z\right)\right]}{\left(\frac{P}{2} - p_Z\right)^2 - \tilde{m}_2^2} \cdot \epsilon^Z \quad g^{Z}_{\tilde{t}_1\tilde{t}_2} y^{*h}_{\tilde{t}_1\tilde{t}_2}$$

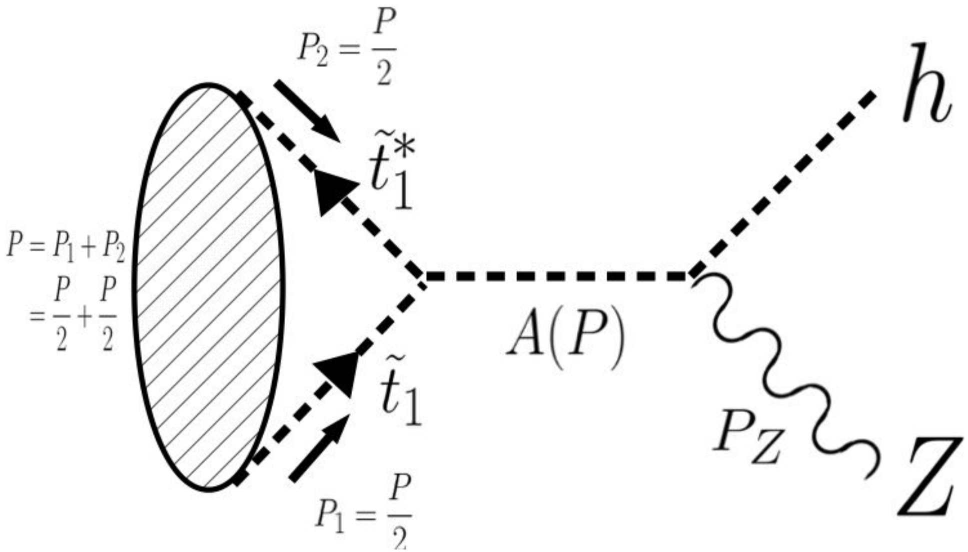


$$\mathcal{M}_2 = -\frac{\left[-\frac{P}{2} + \left(-\frac{P}{2} + p_Z\right)\right]}{\left(-\frac{P}{2} + p_Z\right)^2 - \tilde{m}_2^2} \cdot \epsilon^Z \quad \tilde{g}^{*Z}_{\tilde{t}_1\tilde{t}_2} \tilde{y}^{h}_{\tilde{t}_1\tilde{t}_2}$$

$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 = 4i \frac{\text{Im}(g^{*Z}_{\tilde{t}_1\tilde{t}_2} y^{h}_{\tilde{t}_1\tilde{t}_2}) \; P \cdot \epsilon^Z}{m_h^2 + m_Z^2 - 2(\tilde{m}_1^2 + \tilde{m}_2^2)}$$

$$\sum_{\epsilon_Z}|P\cdot\epsilon_Z| = P^\mu\left(-g_{\mu\nu}+p^Z_\mu p^Z_\nu/m_Z^2\right)P^\nu = \frac{1}{4m_Z^2}(s-m_h^2-m_Z^2)^2-m_h^2 = \frac{1}{4m_Z^2}\lambda(s,m_h^2,m_Z^2)$$

$$\lambda(a,b,c) = a^2+b^2+c^2-2ab-2bc-2ac$$



$$= -(P+p_h)\cdot\epsilon^Z y_{A\tilde{t}^*\tilde{t}}\frac{1}{P^2-m_A^2}g_{AhZ}$$

$$\mathcal{M}(\widetilde{t_1}\widetilde{t_1^*}\to hZ) = -\left[\frac{4i\mathrm{Im}(g^{Z*}_{\widetilde{t_1}\widetilde{t_2}}y^h_{\widetilde{t_1}\widetilde{t_2}})}{m_h^2+m_Z^2-2(m^2_{\widetilde{t_1}}+m^2_{\widetilde{t_2}})}+\frac{2y^A_{\widetilde{t_1}\widetilde{t_1}}g^Z_{Ah}}{4m^2_{\widetilde{t_1}}-m_A^2}\right](P\cdot\varepsilon_Z)$$

$$\Gamma(\widetilde{t}_1\widetilde{t}_1^* \to hZ) = \frac{1}{(2m_{\widetilde{t}_1})^2}\sum_{\varepsilon_Z}|\mathcal{M}(\widetilde{t}_1\widetilde{t}_1^* \to hZ)|^2|\psi(0)|^2\frac{3}{8\pi}\lambda^{\frac{1}{2}}(1, m_h^2/s, m_Z^2/s)$$

$$|\psi(0)|^2 = \frac{1}{27\pi}(\alpha_s 2m_{\widetilde{t}_1})^3$$

$$\Gamma(\widetilde{t}_1\widetilde{t}_1^* \to gg) = \frac{4\pi\alpha_s^2}{3m_{\widetilde{t}_1}^2}|\psi(0)|^2$$

SUSY Z-Gauge couplings

$$\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\delta_u} \end{pmatrix} \begin{pmatrix} \cos\theta_{\tilde{t}} & -\sin\theta_{\tilde{t}} \\ \sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$$

$$\begin{aligned} \mathcal{L} \supset & \frac{g}{\sqrt{1-x_W}} Z^\mu (\tilde{t}_L^*, \tilde{t}_R^*) i \overleftrightarrow{\partial}_\mu \begin{pmatrix} -\frac{1}{2} + Q_t x_W & 0 \\ 0 & Q_t x_W \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \\ = & \frac{g}{\sqrt{1-x_W}} Z^\mu \; (\tilde{t}_1^*, \tilde{t}_2^*) i \overleftrightarrow{\partial}_\mu \begin{pmatrix} -\frac{1}{2} c_{\theta_{\tilde{t}}} + Q_t x_W & \frac{1}{2} s_{\theta_{\tilde{t}}} c_{\theta_{\tilde{t}}} \\ \frac{1}{2} s_{\theta_{\tilde{t}}} c_{\theta_{\tilde{t}}} & -\frac{1}{2} s^2_{\theta_{\tilde{t}}} + Q_t x_W \end{pmatrix} \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} \\ \equiv & Z^\mu (\tilde{t}_1^*, \tilde{t}_2^*) i \overleftrightarrow{\partial}_\mu \begin{pmatrix} g^Z_{\tilde{t}_1 \tilde{t}_1} & g^Z_{\tilde{t}_1 \tilde{t}_2} \\ g^Z_{\tilde{t}_1 \tilde{t}_2} & g^Z_{\tilde{t}_2 \tilde{t}_2} \end{pmatrix} \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}, \end{aligned}$$

Higgs coupling to stops

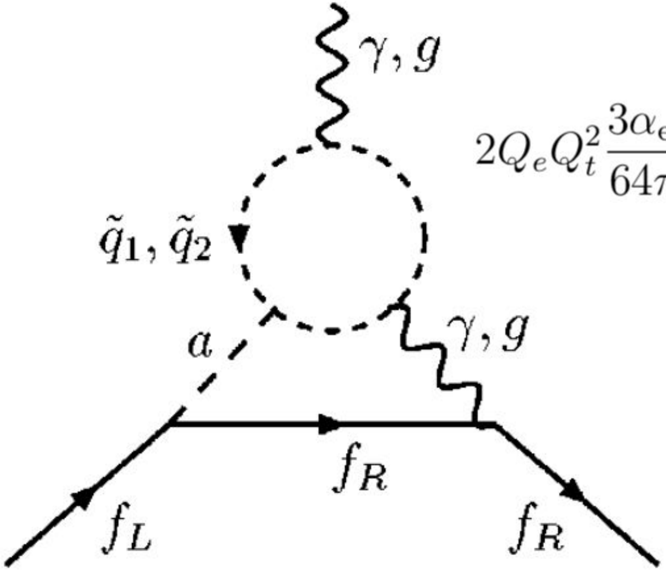
$$h(\widetilde{t}_L^*, \widetilde{t}_R^*) \begin{pmatrix} -\frac{gm_t^2 c_\alpha}{m_W s_\beta} + \frac{gm_Z}{\sqrt{1-x_W}}(\frac{1}{2} - \frac{2}{3}x_W)s_{\alpha+\beta} & -\frac{1}{2}\frac{gm_t}{m_W s_\beta}(A_t^* c_\alpha + \mu s_\alpha) \\ -\frac{1}{2}\frac{gm_t}{m_W s_\beta}(A_t c_\alpha + \mu^* s_\alpha) & -\frac{gm_t^2 c_\alpha}{m_W s_\beta} + \frac{gm_Z}{\sqrt{1-x_W}}(\frac{2}{3}x_W)s_{\alpha+\beta} \end{pmatrix} \begin{pmatrix} \widetilde{t}_L \\ \widetilde{t}_R \end{pmatrix}$$

$$\equiv h(\widetilde{t}_1^*, \widetilde{t}_2^*) \begin{pmatrix} y^h_{\widetilde{t}_1\widetilde{t}_1} & {y^h_{\widetilde{t}_1\widetilde{t}_2}}^* \\ y^h_{\widetilde{t}_1\widetilde{t}_2} & y^h_{\widetilde{t}_2\widetilde{t}_2} \end{pmatrix} \begin{pmatrix} \widetilde{t}_1 \\ \widetilde{t}_2 \end{pmatrix}$$

$$
\begin{aligned}
\mathcal{L} \supset & -\frac{im_t}{v\sin\beta}A^0(\widetilde{t_L^*},\widetilde{t_R^*})\begin{pmatrix} 0 & -(A_t^* c_\beta + \mu s_\beta) \\ A_t c_\beta + \mu^* s_\beta & 0 \end{pmatrix}\begin{pmatrix} \widetilde{t_L} \\ \widetilde{t_R} \end{pmatrix} \\
= & \frac{m_t}{v\sin\beta}A^0(\widetilde{t_1^*},\widetilde{t_2^*})\begin{pmatrix} 2s_{\theta_{\tilde{t}}}c_{\theta_{\tilde{t}}}\mathrm{Im}[\hat{A}_t] & i(c^2_{\theta_{\tilde{t}}}\hat{A}_t{}^* + s^2_{\theta_{\tilde{t}}}\hat{A}_t) \\ -i(c^2_{\theta_{\tilde{t}}}\hat{A}_t + s^2_{\theta_{\tilde{t}}}\hat{A}_t{}^*) & -2s_{\theta_{\tilde{t}}}c_{\theta_{\tilde{t}}}\mathrm{Im}[\hat{A}_t] \end{pmatrix}\begin{pmatrix} \widetilde{t_1} \\ \widetilde{t_2} \end{pmatrix} \\
\equiv & A^0(\widetilde{t_1^*},\widetilde{t_2^*})\begin{pmatrix} y^A_{\widetilde{t_1}\widetilde{t_1}} & y^A_{\widetilde{t_1}\widetilde{t_2}}{}^* \\ y^A_{\widetilde{t_1}\widetilde{t_2}} & y^A_{\widetilde{t_2}\widetilde{t_2}} \end{pmatrix}\begin{pmatrix} \widetilde{t_1} \\ \widetilde{t_2} \end{pmatrix}
\end{aligned}
$$

2-loop EDM constraint

$$\left(\frac{d_e}{e}\right)^{\widetilde{t}}_{2-\text{loop}}$$



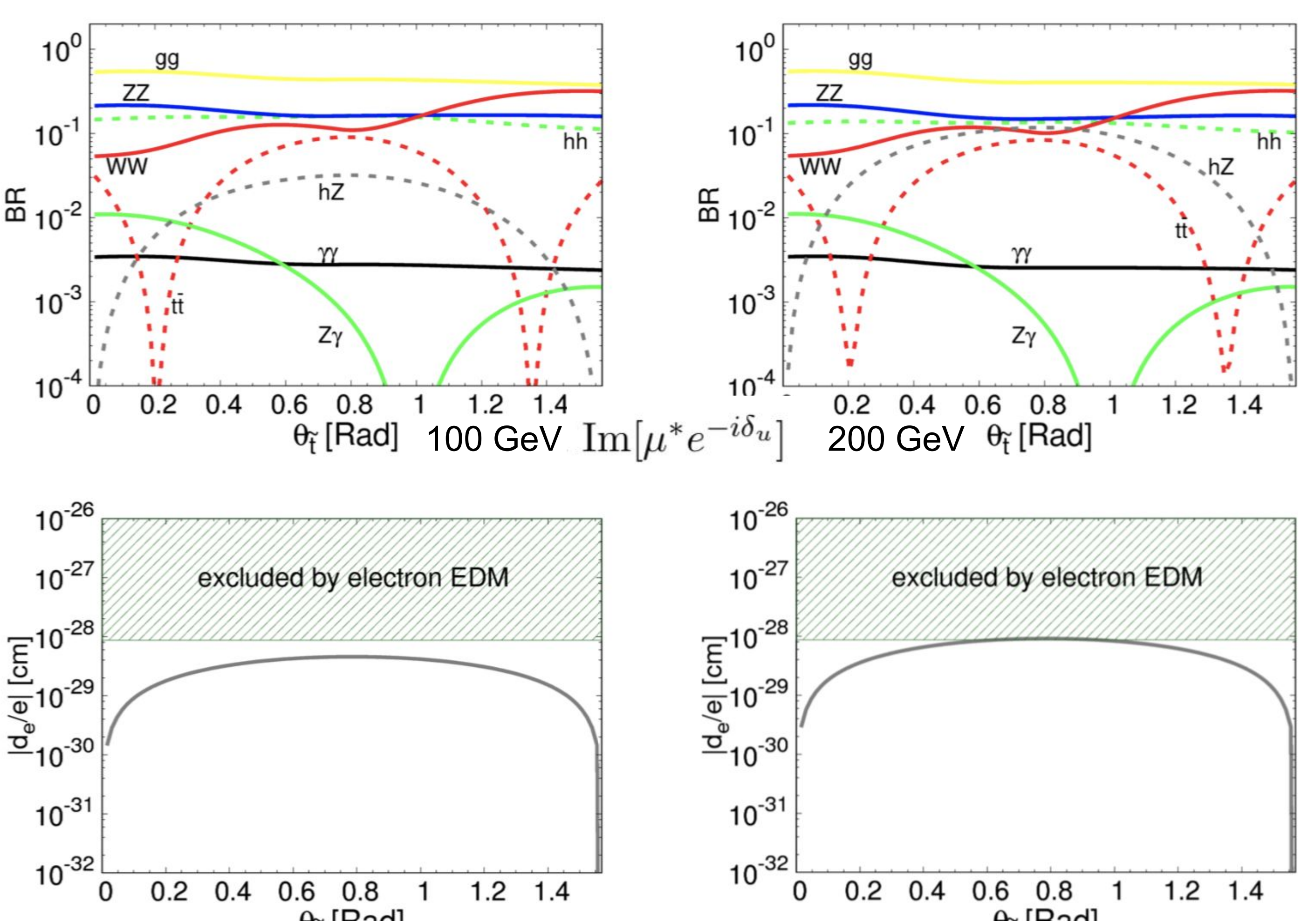
$$2Q_eQ_t^2\frac{3\alpha_{\rm em}}{64\pi^3}\frac{m_e}{m_A^2}\left(\frac{\sin 2\theta_{\widetilde{t}}\; m_t{\rm Im}[\mu^* e^{-i\delta_u}]}{v^2\sin\beta\cos\beta}\right)\left[F\left(\frac{m^2_{\widetilde{t}_1}}{m_A^2}\right)-F\left(\frac{m^2_{\widetilde{t}_2}}{m_A^2}\right)\right]$$

$$F(z)=\int_0^1 dx\frac{x(1-x)}{z-x(1-x)}\ln\left[\frac{x(1-x)}{z}\right]$$

VOLUME 82, NUMBER 5 PHYSICAL REVIEW LETTERS 1 FEBRUARY 1999

New Two-Loop Contribution to Electric Dipole Moments in Supersymmetric Theories

Darwin Chang,[1,2] Wai-Yee Keung,[3,2] and Apostolos Pilaftsis[4,2]



$|d_e| < 8.7 \times 10^{-29}\ e \cdot [\mathrm{cm}]$

90% CL ACME 2004

reduced by 8 in 2018

$m_{\tilde{t}_1} = 600\ \mathrm{GeV}$

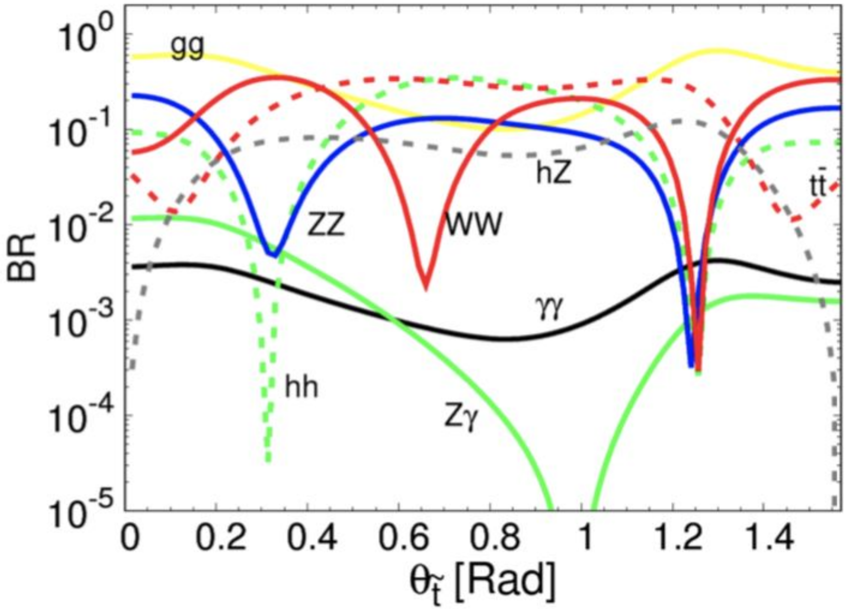
$m_{\tilde{t}_2} = 650\ \mathrm{GeV}$

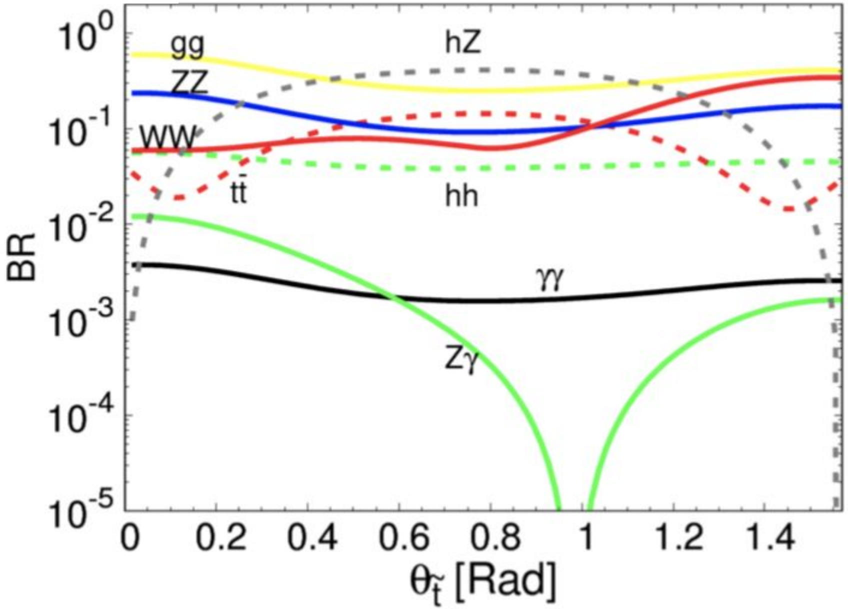
$m_{H,A} = 1.5\ \mathrm{TeV}$

$m_{\tilde{g}} = 2\ \mathrm{TeV}$

$$m_A \to \infty$$

$$m_{\tilde{t}_1} = 600 \text{ GeV}$$





$m_{\tilde{t}_2} =$ 1 TeV

$m_{\tilde{t}_2} =$ 650 GeV

$\mathrm{Im}[\mu^* e^{-i\delta_u}]$ = 5 TeV

Part 1 summary

We show how the stoponium can violate Furry theorem by CP violation with complex couplings.

We have demonstrated that the decay mode of the ground state of the stoponium to Zh, can have a dominant or significant branching ratio if we choose suitable CP violating mixing in the stop sector, which is still allowed by the eEDM measurement. Observation of such a decay mode of the stoponium is clean signal of CP violation.

Our framework for the decay mode Zh from the scalar pair in the ground state can be extended to other models that have fundamental colored scalar bosons, such as the technipion or the colored octet Higgs.

Majorana Neutrinos at Colliders

VOLUME 50, NUMBER 19 PHYSICAL REVIEW LETTERS 9 MAY 1983

Majorana Neutrinos and the Production of the Right-Handed Charged Gauge Boson

Wai-Yee Keung and Goran Senjanović
Physics Department, Brookhaven National Laboratory, Upton, New York 11973
(Received 14 February 1983)

A possibility of a very clean signature for the production of $W_R^{\pm}$ is pointed out. If the right-handed neutrino is lighter than $W_R^{\pm}$, left-right symmetric gauge theory predicts the decay $W_R^+ \to \mu^+\mu^+ + 2$ hadronic jets, with the branching ratio $\simeq 3\%$. The lack of neutrinos in the final state and the absence of a sizable background make $W_R^{\pm}$ rather easy to detect (if it exists). Detailed predictions regarding the production and decay rates of W_R^+ are presented.

PACS numbers: 14.80.Er, 12.10.Ck, 13.85.Qk, 14.60.Gh

We would like to thank . . . Larry Trueman for getting us involved with the physics study for the future CBA at the Brookhaven National Laboratory that led to this work.

Inverse process of the neutrinoless double beta decay at very high energy.

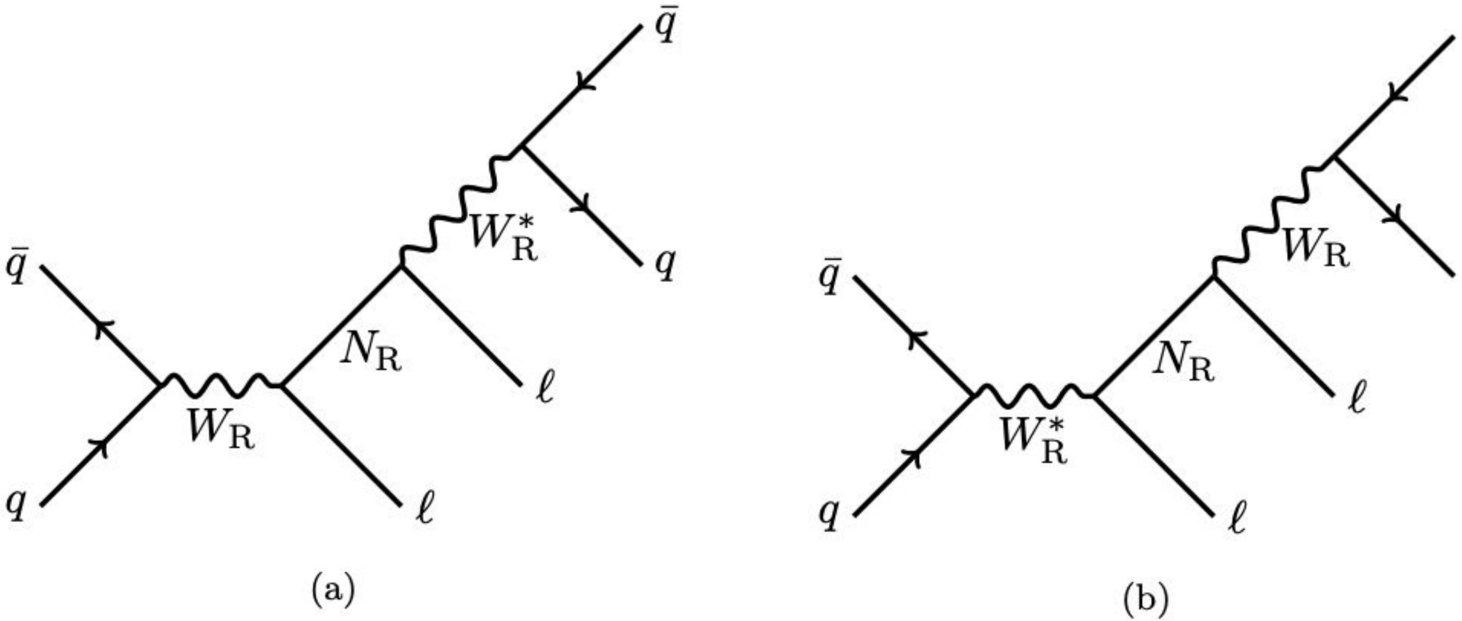


Figure 1. The KS process, for (a) the $m_{W_R} > m_{N_R}$ case and (b) the $m_{N_R} > m_{W_R}$ case.

- Fully reconstructed kinematics w/o $\not{p}$
- Majorana rules

Tao Han et al., Phys. Rev. Lett. 97, (2006)

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Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with two charged leptons and two jets at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: A search for heavy right-handed Majorana or Dirac neutrinos N_{R} and heavy right-handed gauge bosons W_{R} is performed in events with a pair of energetic electrons or muons, with the same or opposite electric charge, and two energetic jets. The events

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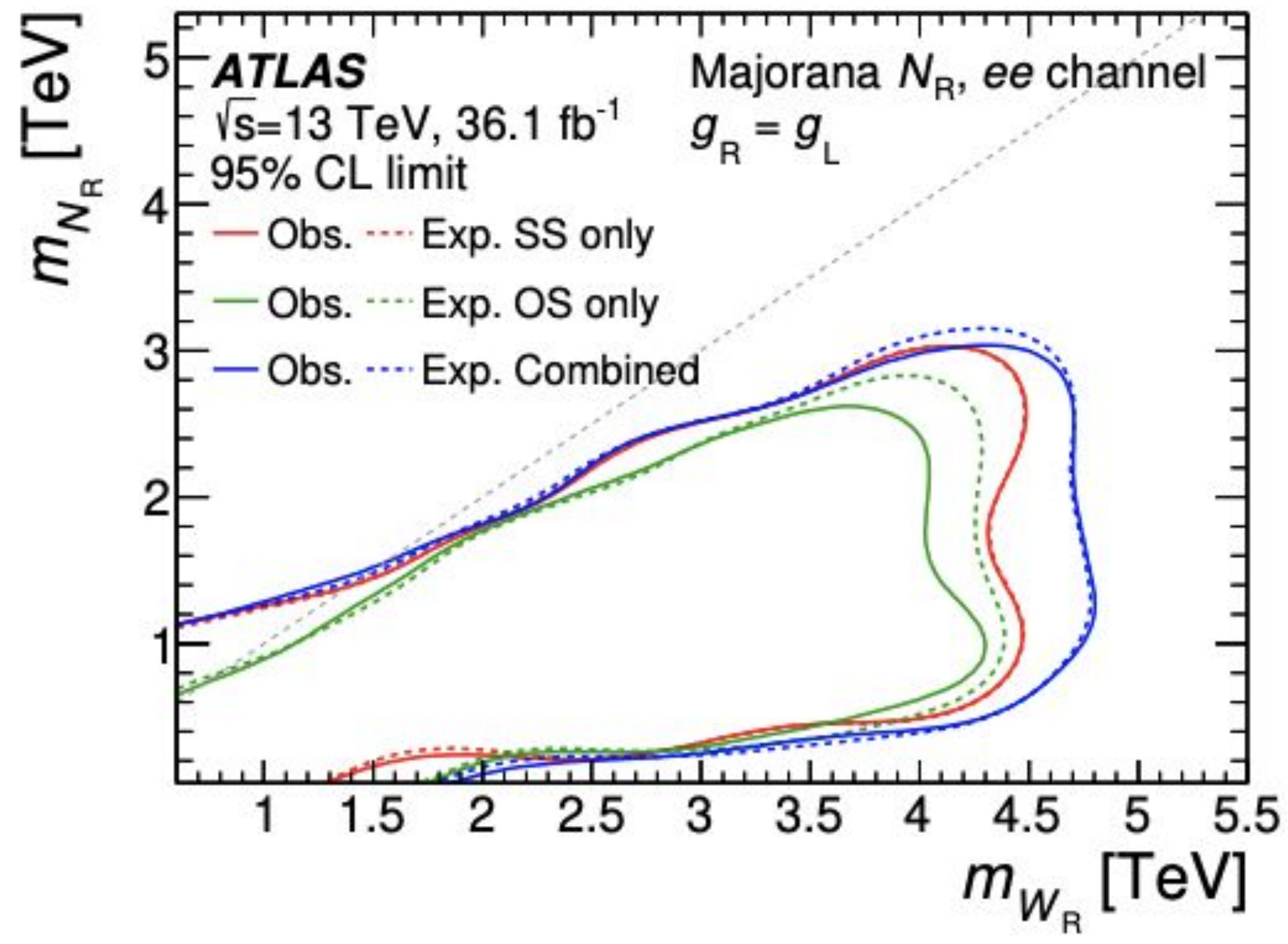


ATLAS
√s=13 TeV, 36.1 fb-1
95% CL limit
Majorana N_R, ee channel
g_R = g_L
Obs. Exp. SS only
Obs. Exp. OS only
Obs. Exp. Combined
m_N_R [TeV]
m_W_R [TeV]
1
2
3
4
5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5

Dark annihilation with neutron underground

with Danny Marfatia & Po-Yen Tseng

$$\tau_n^{\rm bottle} = 879.6 \pm 0.6 \ {\rm s}\,,$$
$$\tau_n^{\rm beam} = 888.0 \pm 2.0 \ {\rm s}\,.$$

$$\frac{1}{\tau_n^{\rm beam}} = {\rm Br}(n \to p + {\rm anything}) \underbrace{\left(-\frac{1}{N_n}\frac{dN_n}{dt}\right)_{\rm bottle}}_{\frac{1}{\tau_n^{\rm bottle}}}$$

$$\Delta\Gamma(n \to {\rm no\ proton}) \simeq 7.1 \times 10^{-30} \ {\rm GeV}$$

B. Fornal and B. Grinstein,

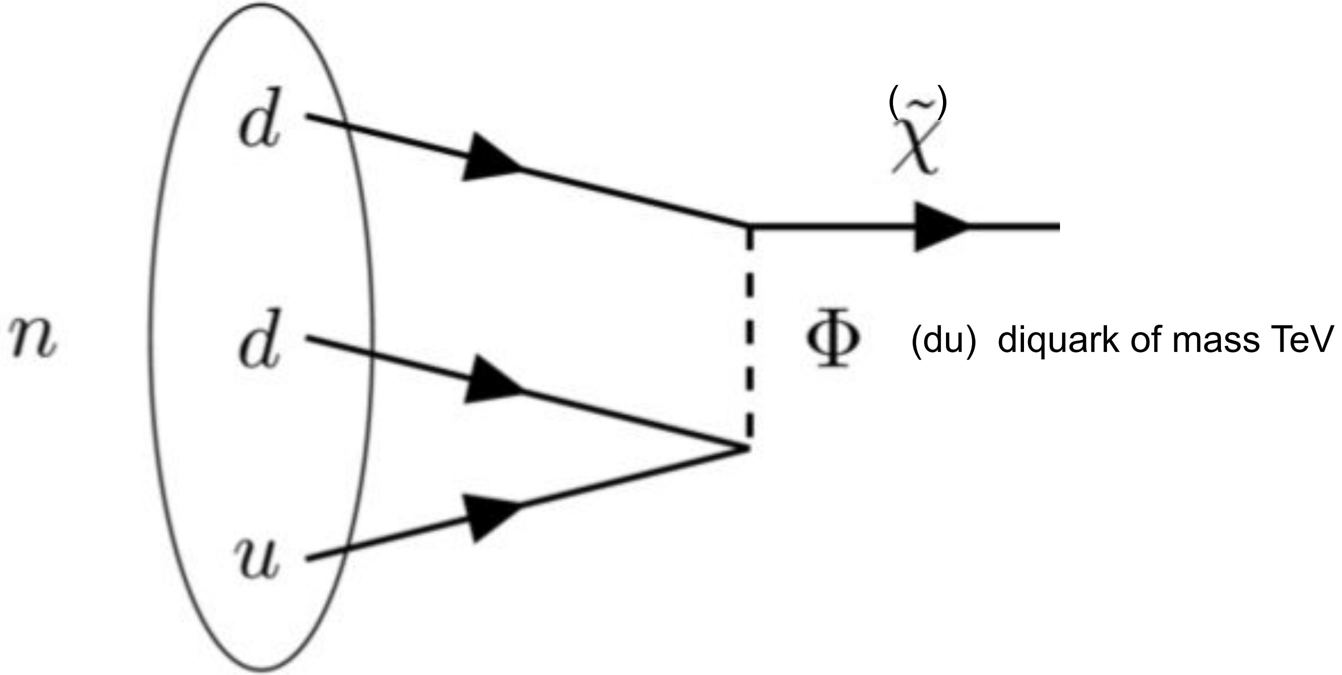
$$937.992 \ {\rm MeV} < m_\chi < 938.783 \ {\rm MeV}$$

$$\mathcal{L}_1^{\rm eff} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \varepsilon\left(\bar{n}\chi + \bar{\chi}n\right)$$

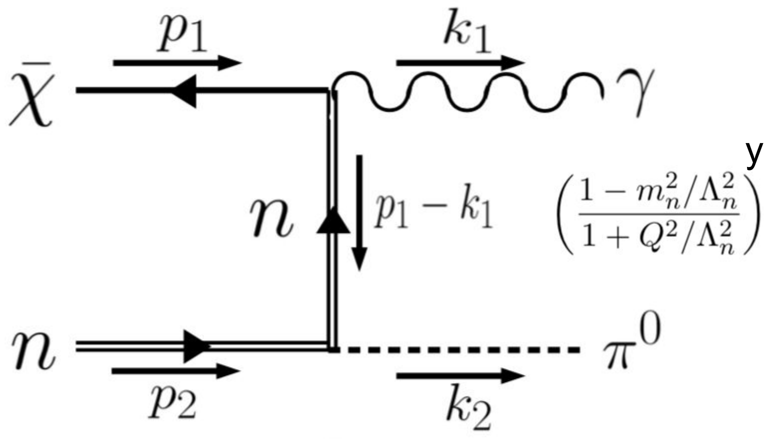
$$n \to \chi\,\gamma$$

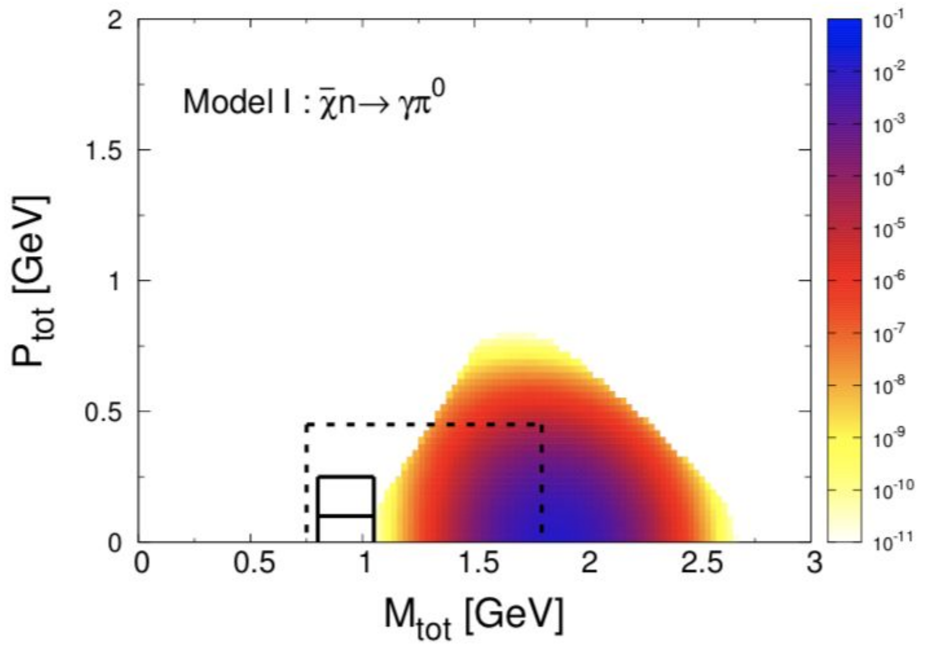
$$\mathcal{L}_2^{\rm eff} = \mathcal{L}_1^{\rm eff}(\chi \to \tilde{\chi}) + (\lambda_\phi\,\bar{\tilde{\chi}}\,\chi\,\phi + {\rm h.c.}) + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \partial_\mu\phi^*\partial^\mu\phi - m_\phi^2|\phi|^2$$

$$n \to \chi\phi$$


(~)
χ
n
d
d
u
Φ
(du) diquark of mass TeV

$$\bar{\chi} + n \rightarrow \gamma + \pi^0$$





	Kinematic cuts (in MeV)	$N_{\rm obs}$	$N_{\rm bkgd}$	$N^{3\sigma}_{\rm Super\text{-}K}$	$N^{3\sigma}_{\rm Hyper\text{-}K}$	$N^{3\sigma}_{\rm DUNE}$
cut-1	$P_{\rm tot} \subset [0, 450]$ $M_{\rm tot} \subset [750, 1800]$ [18]	24	24.1	$[0, 22.5]$	$[0, 75]$	$[0, 27]$
cut-2	$P_{\rm tot} \subset [0, 100]$, $M_{\rm tot} \subset [800, 1050]$ [17]	0	0.07	$[0, 7]$	$[0, 5.5]$	$[0, 4]$
cut-3	$P_{\rm tot} \subset [100, 250]$, $M_{\rm tot} \subset [800, 1050]$ [17]	0	0.54	$[0, 6.5]$	$[0, 7]$	$[0, 5.8]$

Expect 2 ~ 16 events in cut-1 for y=4

$$v\sigma(\bar{n}p \to \text{pions})_{\text{exp}} = 44 \text{ mb} = v\sigma(\bar{n}n \to \text{pions})$$

$$\frac{\sigma(\bar{n}n \to 3\pi^0)}{\sigma(\bar{n}n \to \text{pions})} = 0.065 \qquad \frac{\sigma(\bar{n}n \to 5\pi^0)}{\sigma(\bar{n}n \to \text{pions})} = 0.52$$

$$\sigma(\bar{n}n \to 3\pi^0)(y) \qquad \sigma(\bar{n}n \to 5\pi^0)(y),$$

$$y = 0.542 \qquad y = 0.337,$$

Model 1

	Model 1		P1	P2	P3
	$\bar{\chi}n \to 3\pi^0$ & $5\pi^0$		$\bar{\chi}n \to \phi 3\pi^0$ $(y = 0.542)$ & $\bar{\chi}n \to \phi 5\pi^0$ $(y = 0.337)$		
$\frac{v}{c}\sigma$ [cm^2]	9.71×10^{-47}	7.90×10^{-46}	2.51×10^{-51}	5.42×10^{-54}	7.04×10^{-50}
Super-K events	9.59×10^5	7.78×10^6	24.7	5.4×10^{-2}	693
Hyper-K events	2.32×10^7	1.88×10^8	601	1.30	16824
DUNE events	1.57×10^6	1.28×10^7	40.7	8.8×10^{-2}	1137

Near-GeV dark sector can annihilate with the underground nucleons and produce scintillating events.

Current measurement of Super-K has already disfavored certain scenarios, i.e. Model 1and Model 2, P3.

Future experiment efforts from Hyper-K or DUNE may discover this Near-GeV structure.

SUMMARY

CP violating mode of the stoponium decay into Zh

Lepton Number Violation and Majorana Heavy Neutrino at Colliders

Dark sector at GeV region to be probed by the underground scintillation.

Supplementary Slides

For the opposite sign process $\bar{u}d \to W_R^- \to e^- N$ plus $N \to e^+ jj$

$$\cdots \gamma^\mu \tfrac{1}{2}(1+\gamma_5) \frac{\not{p} + M}{p^2 - M^2 + i\Gamma_N M} \gamma^\nu \tfrac{1}{2}(1+\gamma_5) \cdots$$

if we look at the same sign process, $\bar{u}d \to W_R^- \to e^- N$ plus $N \to e^- j'j'$,

$$\cdots \gamma^\mu \tfrac{1}{2}(1+\gamma_5) \frac{\not{p} + M}{p^2 - M^2 + i\Gamma_N M} \gamma^\nu \tfrac{1}{2}(1-\gamma_5) \cdots$$

$\Sigma^{abs} = A \not{p} + B$

$$\cdots \not{p}(A \not{p} + B) \not{p} \cdots = \cdots p^2 (A \not{p} + B) \cdots$$

$$\cdots M(A \not{p} + B) M \cdots = \cdots M^2 (A \not{p} + B) \cdots$$

$$\frac{\text{Opposite sign}}{\text{Same sign}} = \frac{p^2}{M^2}$$