Seesaw Scalars at the LHC

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16 June 2022

good morning

and thank you for the invitation!

the big picture[1]

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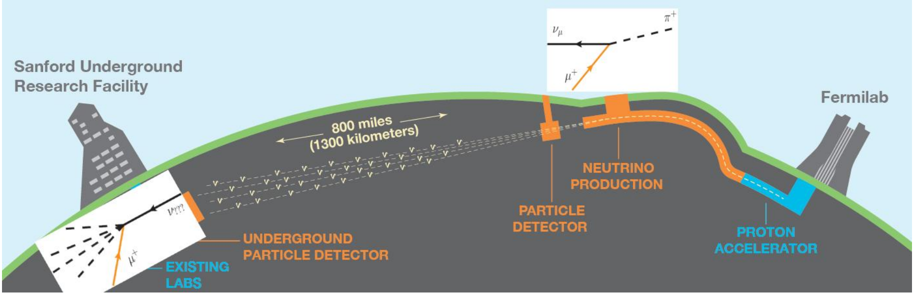
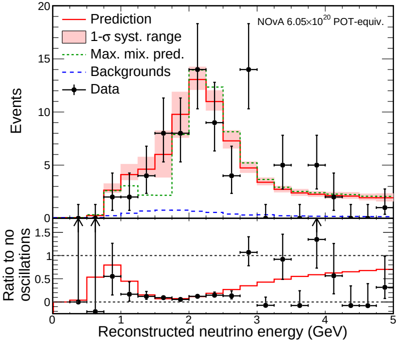
[1] (none of the next few slides are new, just an organization of my motivation)

In neutrino beamline experiments, ν_μ beams are made from collimated $\pi^\pm$





Count ν_μ at near detector (ND) and **compare** to # at far detector (FD)

ν_μ deficit + ν_e/ν_τ apperance at FD best described by $\nu_{\ell_1} \to \nu_{\text{mass}} \to \nu_{\ell_2}$ transitions/oscillations

← NOνA ν_μ disappearance [1701.05891]

$\Longrightarrow$ **evidence for ν masses!**

So, neutrinos have masses, with $m_\nu \lesssim \mathcal{O}(1)$ eV

Is this a problem?

Yes.

SM's guidance on m_ν

Problem: according to the SM, $m_\nu = 0$ (not enough ingredients!)

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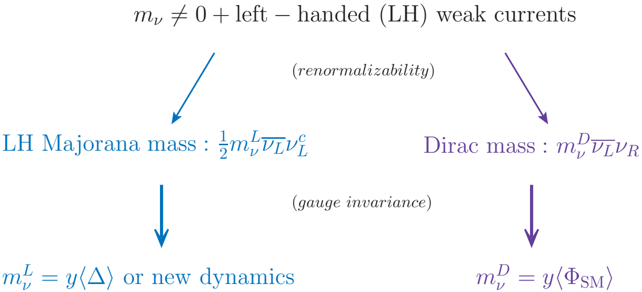

$$m_\nu \neq 0 + \mathrm{left-handed\ (LH)\ weak\ currents}$$

(*renormalizability*)

$$\mathrm{LH\ Majorana\ mass}: \frac{1}{2}m_\nu^L \overline{\nu_L}\nu_L^c \qquad \mathrm{Dirac\ mass}: m_\nu^D \overline{\nu_L}\nu_R$$

(*gauge invariance*)

$$m_\nu^L = y\langle\Delta\rangle \ \mathrm{or\ new\ dynamics} \qquad m_\nu^D = y\langle\Phi_{\mathrm{SM}}\rangle$$

$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\Longrightarrow$ **new particles!**

Ma('98) + others

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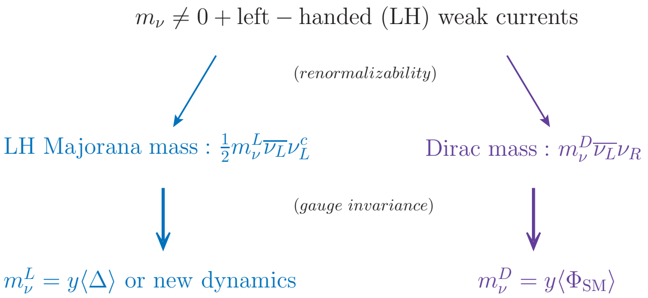

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$(renormalizability)$

LH Majorana mass : $\frac{1}{2} m_\nu^L \overline{\nu_L} \nu_L^c$

Dirac mass : $m_\nu^D \overline{\nu_L} \nu_R$

$(gauge\ invariance)$

$m_\nu^L = y\langle\Delta\rangle$ or new dynamics

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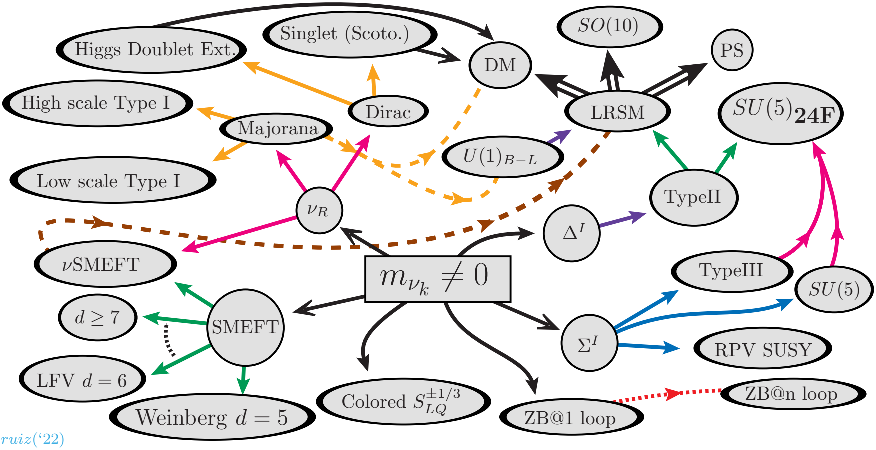
Ma('98) + others

New particles couple to ν_ℓ and $\ell^\pm$, usually H, and often mediate processes that violate **lepton number** and/or **lepton flavor** symmetries

These core ideas can be realized in ***many*** ways! [2]

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



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[2] For reviews, see Cai, et al [1706.08524]; Cai, Han, Li, RR [1711.02180]; Coy, Frigerio [2110.09126]

$m_\nu \neq 0$ + renormalizability + SM gauge inv. $\implies$ new particles!

[Ma ('98)]

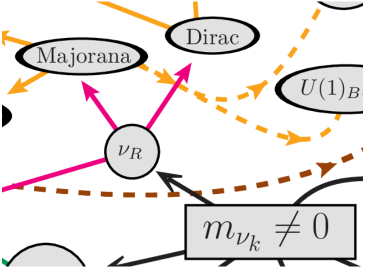
Incredibly powerful but also incredibly vague since new particles:

- ... can be light ☺ or heavy ☹
- ... can be short-lived ☺ or long-lived ☺
- ... can have SM gauge interactions, e.g., $H^{\pm\pm}$ in Type II, Zee-Babu

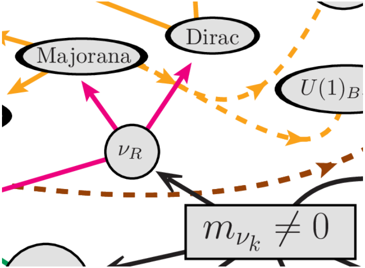
(ν_R not always needed!)

- ... can have new gauge interactions, e.g. ν_R and Z_{B-L} in $U(1)_{\mathrm{B-L}}$
- ... must couple to Φ_{SM} and L, often inducing collider processes that do not conserve **lepton number (LNV)** and/or **lepton flavor (LFV)**

what if right-handed neutrinos do not exist?



what if right-handed neutrinos do exist?

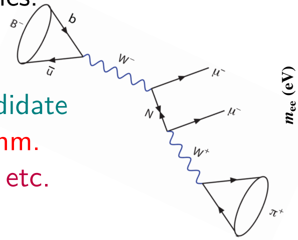


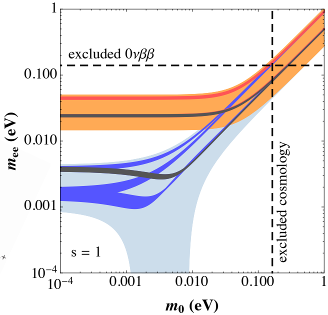
Consequences of ν_R

Obviously lots of rich physics:

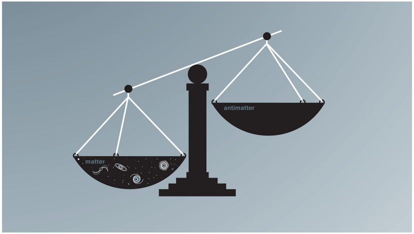
- m_ν and ν oscillations
- $0\nu\beta\beta$ decay (probably)
- particle dark matter candidate
- trigger matter-anti. asymm.
- stepping stone to GUTs, etc.

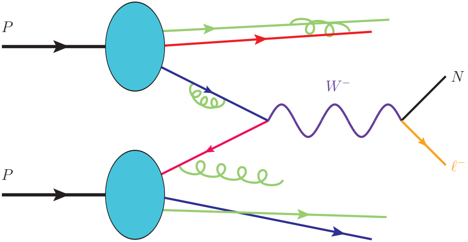
(see previous talks or papers by nearly everyone here)





Hagedorn, et al [1602.04206]





broad implications for the universe ☺

life with ν_R is probably more complicated ☺

Motivation for non-minimal scenarios

Little-known fact: $W_0^\pm W_0^\pm \to \ell_i^\pm \ell_i^\pm$ in Type I violates s-wave unitarity

Dicus & He ('04, '05); Fuks, RR, et al [2011.02547]

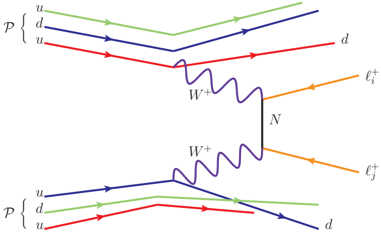
Working out the matrix element for $W_0^\pm W_0^\pm \to \ell_i^\pm \ell_i^\pm$, you get:

$$-i\mathcal{M} \sim g_W^2 \frac{V_{\ell N} V_{\ell N}}{m_N} \frac{M_{WW}^3}{m_W^2}$$

(in limit that $M_W, M_{WW} \ll m_N$)

Extracting the s-wave amplitude

$$a_{J=0} = \frac{1}{32\pi} \int_{-1}^{1} d\cos\theta \ \mathcal{M}$$



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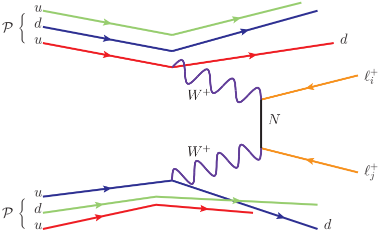


Extracting the *s*-wave amplitude

$$a_{J=0} = \frac{1}{32\pi} \int_{-1}^{1} d\cos\theta \ \mathcal{M}$$

and requiring $|a_{J=0}| < 1$ gives scale (M_{WW}) at which unitarity is violated:

$$(\text{scattering energy})^3 > \frac{32\pi M_W^2}{(2-\delta_{\ell_i \ell_j}) g_W^2} \frac{1}{|\sum_k \frac{V_{ik} V_{jk}}{m_{N_k}}|}$$

does this tell us anything? **(unsure)**

Unitarity violation in the Standard Model

1. In Fermi Theory, unitarity violation in $\nu\mathcal{N} \to \ell\mathcal{N}'$ suggests missing particle

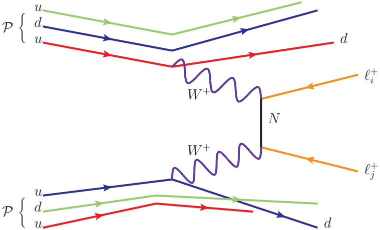
W boson!

2. In Fermi Theory w/ W (no Z), unitarity violation in $e^- e^+ \to W^- W^+$ suggests missing particle

Z boson!

3. In the SM without Higgs, unitarity violation in $V_0 V_0' \to V_0 V_0$ suggests missing particle

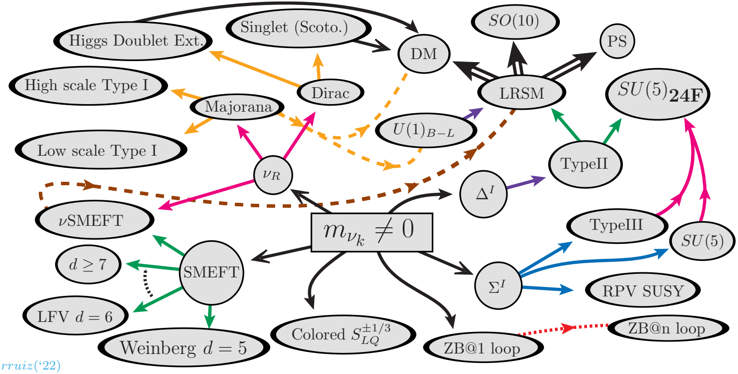
H^0 boson!



μ_R in $\Delta\mathcal{L} = (1/2)\mu_R\overline{\nu_R^c}\nu_R$ probably needs to be generated dynamically by **scalar carrying lepton number**... but maybe ν_R do not exist

(yes, this is a jump / "baby with the bath water" argument)

Type II Seesaw[3]



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[3] Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

The Type II Seesaw is special: generates m_ν ***without*** hypothesizing ν_R

- shows $m_\nu \neq 0 \nRightarrow$ that ν_R exist

The Type II Seesaw is special: generates m_ν ***without*** hypothesizing ν_R

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Hypothesize a **scalar** $\mathrm{SU}(2)_L$ triplet with **lepton number** $L = -2$

$$\hat{\Delta} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta} \left(\Phi^\dagger \hat{\Delta} \cdot \Phi^\dagger + \mathrm{H.c.} \right)$$

The mass scale $\mu_{h\Delta}$ breaks lepton number, and induces $\langle \Delta \rangle \neq 0$:

$$\sqrt{s} \langle \hat{\Delta} \rangle = v_\Delta \approx \frac{\mu_{h\Delta} v_{\mathrm{EW}}^2}{\sqrt{2} m_\Delta^2}$$

which leads to **left-handed Majorana masses** for neutrinos

$$\Delta\mathcal{L} = -\frac{y_\Delta^{ij}}{\sqrt{2}} \overline{L^c} \hat{\Delta} L = -\frac{y_\Delta^{ij}}{\sqrt{2}} \begin{pmatrix} \overline{\nu^{jc}} & \overline{\ell^{jc}} \end{pmatrix} \begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix} \begin{pmatrix} \nu^i \\ \ell^i \end{pmatrix}$$

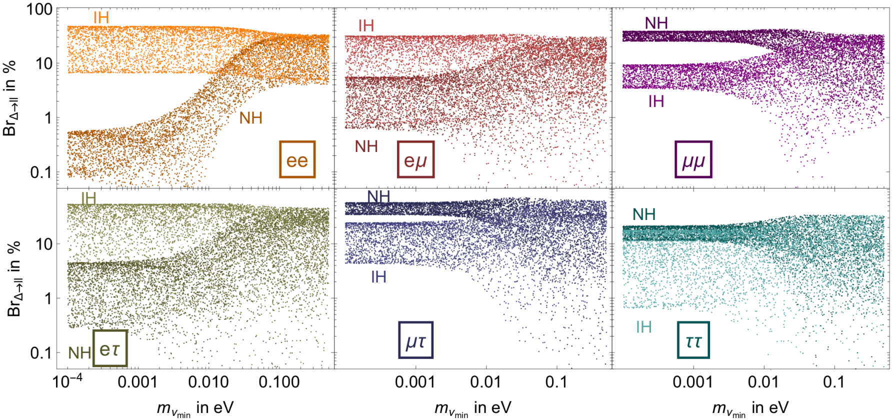
$$\ni -\frac{1}{2} \underbrace{\left(\sqrt{2} y_\Delta^{ij} v_\Delta \right)}_{= m_\nu^{ij}} \overline{\nu^{jc}} \nu^i$$

Fewer free parameters $\implies$ richer experimental predictions

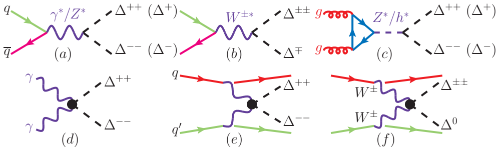
Fileviez Perez, Han, Li, et al, [0805.3536], Crivellin, et al [1807.10224], Fuks, Nemevšek, RR [1912.08975] + others

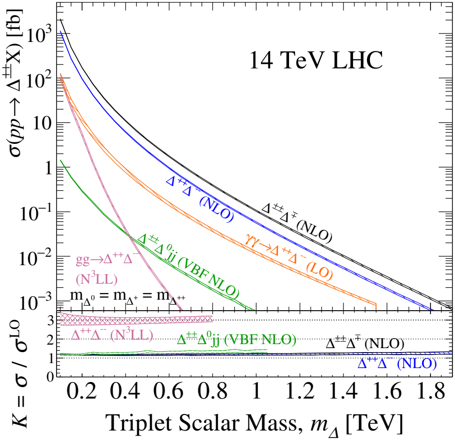
- **Example:** Δ decay rates encode inverse (IH) vs normal (NH) ordering of light neutrino masses

$$\Gamma(\Delta^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim y_{\Delta}^{ij} \sim (U_{\mathrm{PMNS}}^{*}\tilde{m}_{\nu}^{\mathrm{diag}} U_{\mathrm{PMNS}}^{\dagger})_{ij}$$



The **leptonic scalars** of the model $\Delta^{\pm\pm}$, $\Delta^{\pm}$, Δ^{0}, ξ^{0} all couple directly to W, Z, γ via gauge couplings ($\Longrightarrow$ unambiguous xsec prediction!)





Fuks, Nemevšek, RR [1912.08975]

Many production channels but most studies focus on $pp \to \Delta^{++}\Delta^{--}$

(unsure if studies on ξ^0 even exist ☹)

If $\Delta^{\pm\pm}$ is the lightest state, then decay rates set by oscillation parameters

(I find this really, really cool ☺)

If $\Delta^{\pm\pm}$ is not the lightest state, or v_Δ is large, then things get “interesting”

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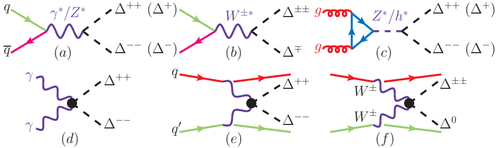

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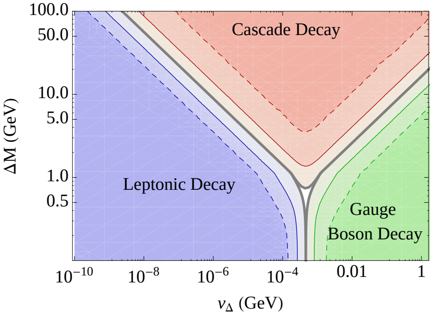
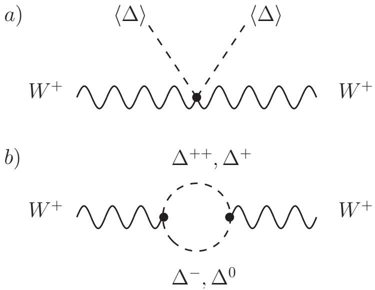
Preferred decay modes of $\Delta^{\pm\pm}$

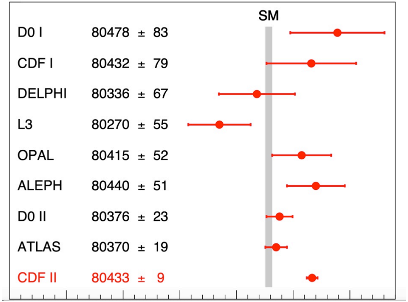
$(\Delta M = m_{++} - m_{+})$



Melfo, Nemevšek, Nesti, Senjanovic, Zhang [1108.4416]

the “large” v_Δ limit





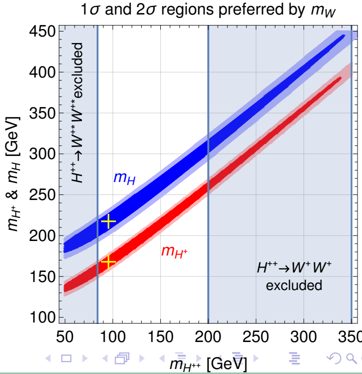
CDF's legacy measurement of the M_W is larger than EWPD suggests [Science('22)]

(not sure the experimental result should be discounted so quickly)

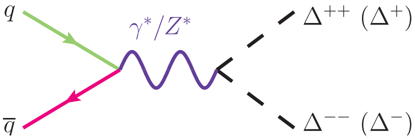
Interesting that Type II's correction to ρ param. accommodates measurement

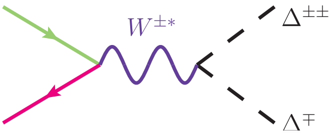
– favors $\Delta^{\pm\pm}$, $\Delta^{\pm}$ with lighter masses

Heeck [1108.4416]



strong(er) motivation for LHC searches

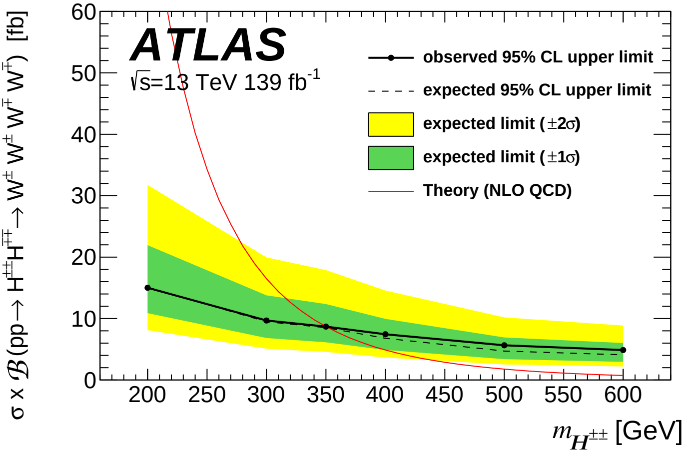




LHC limits on pair production

$$pp \rightarrow \Delta^{++}\Delta^{--} \rightarrow 4W^{\pm} \rightarrow 2-4\ell^{\pm} + \not{E}_T + X$$

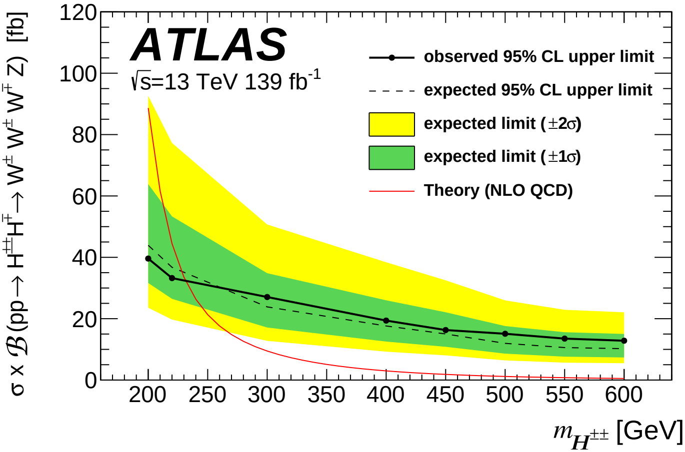
$(\ell = e, \mu)$ [2101.11961]



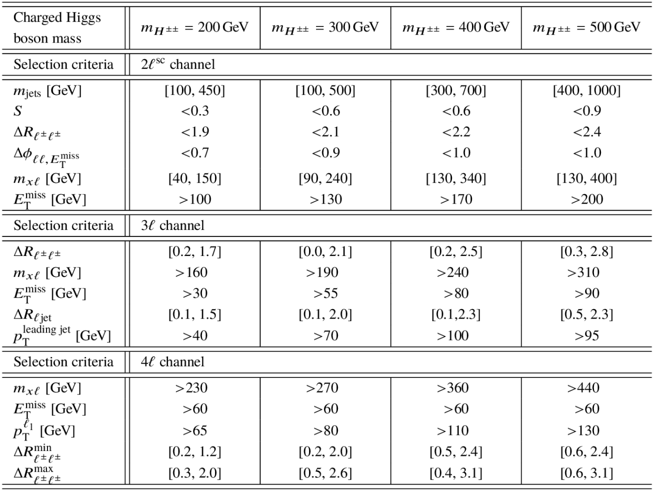
LHC limits on associated production

$$pp \rightarrow \Delta^{\pm\pm}\Delta^{\mp} \rightarrow 3W^{\pm}Z \rightarrow 2-4\ell^{\pm} + \not{E}_T + X$$

$(\ell = e, \mu)$ [2101.11961]



Details on event selection ($\ell = e, \mu$) [2101.11961]

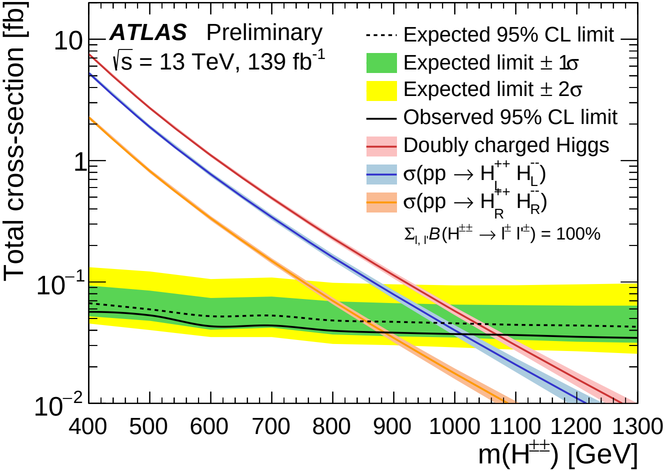


Charged Higgs boson mass	$m_{H^{\pm\pm}} = 200\,\mathrm{GeV}$	$m_{H^{\pm\pm}} = 300\,\mathrm{GeV}$	$m_{H^{\pm\pm}} = 400\,\mathrm{GeV}$	$m_{H^{\pm\pm}} = 500\,\mathrm{GeV}$
Selection criteria	$2\ell^{\mathrm{sc}}$ channel			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
S	<0.3	<0.6	<0.6	<0.9
$\Delta R_{\ell^{\pm}\ell^{\pm}}$	<1.9	<2.1	<2.2	<2.4
$\Delta\phi_{\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}}}$	<0.7	<0.9	<1.0	<1.0
$m_{x\ell}$ [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>100	>130	>170	>200
Selection criteria	3ℓ channel			
$\Delta R_{\ell^{\pm}\ell^{\pm}}$	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$m_{x\ell}$ [GeV]	>160	>190	>240	>310
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>30	>55	>80	>90
$\Delta R_{\ell\,\mathrm{jet}}$	[0.1, 1.5]	[0.1, 2.0]	[0.1,2.3]	[0.5, 2.3]
$p_{\mathrm{T}}^{\mathrm{leading\ jet}}$ [GeV]	>40	>70	>100	>95
Selection criteria	4ℓ channel			
$m_{x\ell}$ [GeV]	>230	>270	>360	>440
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>60	>60	>60	>60
$p_{\mathrm{T}}^{\ell_1}$ [GeV]	>65	>80	>110	>130
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{min}}$	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\mathrm{max}}$	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]

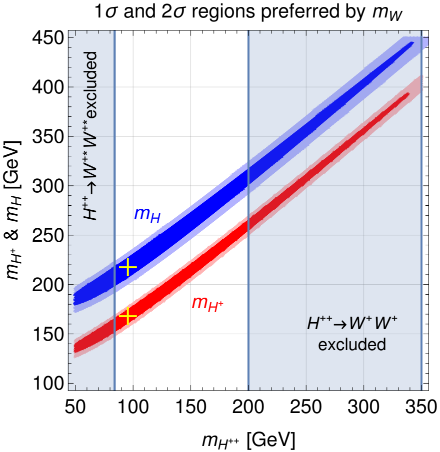
LHC limits on pair production (new!)

$$pp \rightarrow \Delta^{++}\Delta^{--} \rightarrow 4\ell^{\pm} + X$$

$(\ell = e, \mu)$ [ATLAS-CONF-2022-010]



What if $\Delta^{\pm\pm}$, $\Delta^{\pm}$ are discovered?



celebrate! ☺

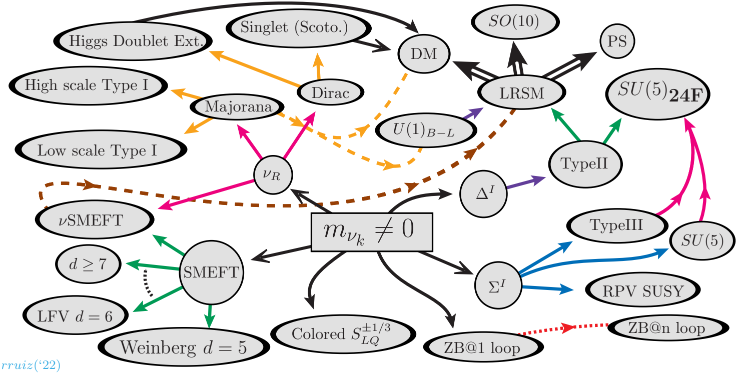
$\Delta^{\pm\pm}$, $\Delta^{\pm}$ are not unique in BSM models

context: the remainder of this talk is to show that

falsifying competing models will be difficult

(some guidance exists but personal hope is to inspire interest and new work)

Zee-Babu Model[4]



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[4] Zee ('85×2), Babu ('88)

Zee-Babu model generates m_ν radiatively ***without*** hypothesizing ν_R

again shows $m_\nu \neq 0 \not\Rightarrow$ that ν_R exist

Zee-Babu model generates m_ν radiatively ***without*** hypothesizing ν_R

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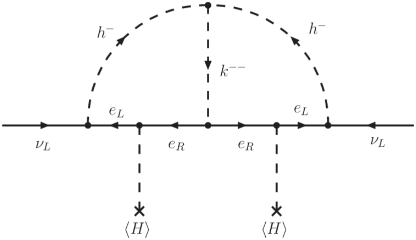
Hypothesize two **scalar** $\mathrm{SU}(2)_L$ singlets k, h with weak hypercharge $Y = -2, -1$ ($\implies Q_k = -2, Q_h = -1$) with **lepton number** $L = -2$

$$\mathcal{L}_{\rm ZB} = \mathcal{L}_{\rm SM} + (D_\mu k)^\dagger (D^\mu k) + (D_\mu h)^\dagger (D^\mu h) + + \left(\mu_{\not{L}}\ hhk^\dagger + \text{H.c.}\right)$$
$$\left[f_{ij}\ \overline{\tilde{L}^i} L^j h^\dagger + g_{ij}\ \overline{(e_R^c)^i} e_R{}^j k^\dagger + \text{H.c.}\right] + \ldots$$



[1402.4491]

The mass scale $\mu_{\not{L}}$ breaks lepton number, and induces $m_\nu \neq 0$:

$$\left(\mathcal{M}_\nu^{\rm flavor}\right)_{ij} = 16\mu_{\not{L}}\ f_{ia}\ m_a\ g^*_{ab}\ \mathcal{I}_{ab}(r)\ m_b\ f_{jb}.$$

Fewer free parameters $\Longrightarrow$ richer experimental predictions

Nebot,et al [0711.0483]; Ohlsson, Schwetz, Zhang [0909.0455]; Herrero-Garcia, Nebot, Rius, et al [1402.4491]; + others

- E.g., $k^{\pm\pm}$, $h^{\pm}$ couplings encode oscillation physics

Normal ordering:

$$\frac{f_{e\tau}}{f_{\mu\tau}} = \tan\theta_{12}\frac{\cos\theta_{23}}{\cos\theta_{13}} + \tan\theta_{13}\sin\theta_{23}e^{-i\delta}$$
$$\frac{f_{e\mu}}{f_{\mu\tau}} = \tan\theta_{12}\frac{\cos\theta_{23}}{\cos\theta_{13}} - \tan\theta_{13}\sin\theta_{23}e^{-i\delta}$$

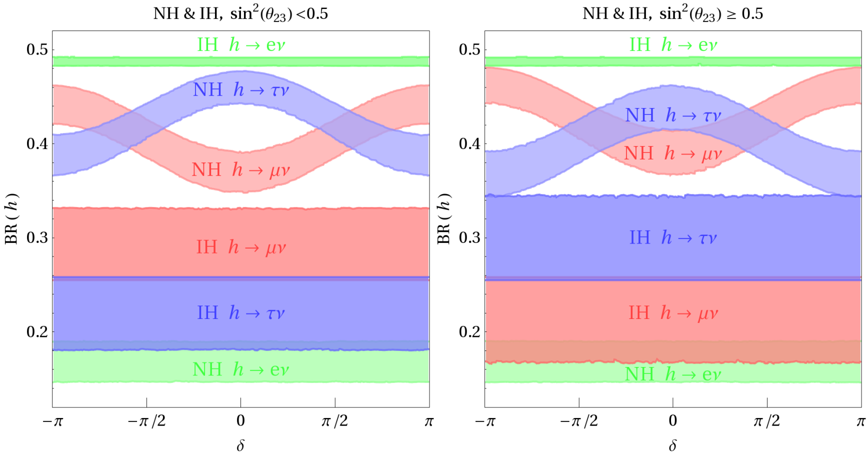
Inverse ordering:

$$\frac{f_{e\tau}}{f_{\mu\tau}} = -\frac{\sin\theta_{23}}{\tan\theta_{13}}e^{-i\delta},$$
$$\frac{f_{e\mu}}{f_{\mu\tau}} = \frac{\cos\theta_{23}}{\tan\theta_{13}}e^{-i\delta},$$
$$\frac{f_{e\tau}}{f_{e\mu}} = -\tan\theta_{23}.$$

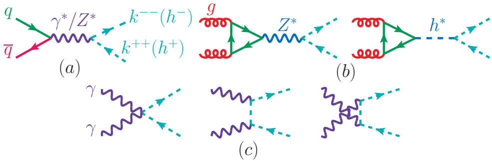
Fewer free parameters $\Longrightarrow$ richer experimental predictions

Nebot,et al [0711.0483]; Ohlsson, Schwetz, Zhang [0909.0455]; Herrero-Garcia, Nebot, Rius, et al [1402.4491]; + others

- E.g., $k^{\pm\pm}$, $h^{\pm}$ decay rates encode IH vs NO



The **leptonic scalars** of the model $k^{\pm\pm}$, $h^{\pm}$ couple directly to Z, γ via gauge couplings ($\implies$ unambiguous xsec prediction!)

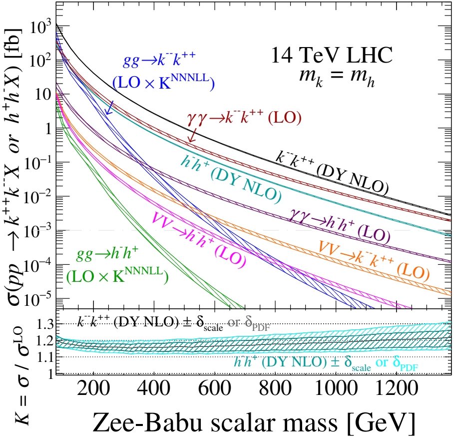


Many production channels but most studies focus on $pp \to k^{++}k^{--}$

If $k^{\pm\pm}$ is the lightest state, then decay rates set by oscillation parameters

(I find this really, really cool ☺)

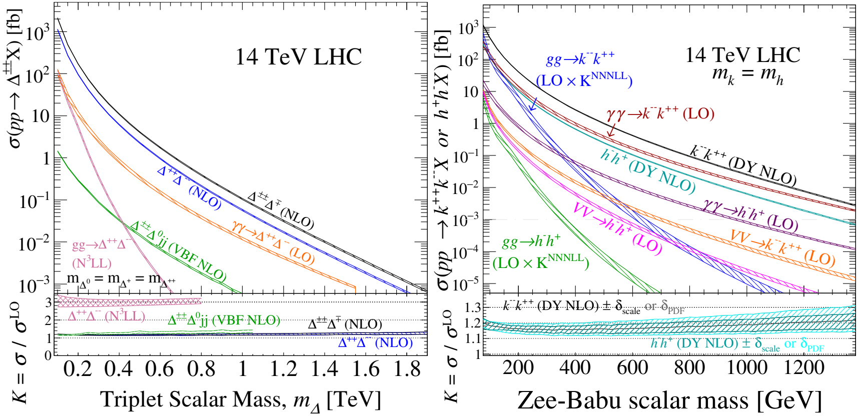
What about discerning from Type II Seesaw?



RR [$\mathcal{O}(1)$ week]

Usual argument: Different gauge quantum numbers $\implies$ different σ

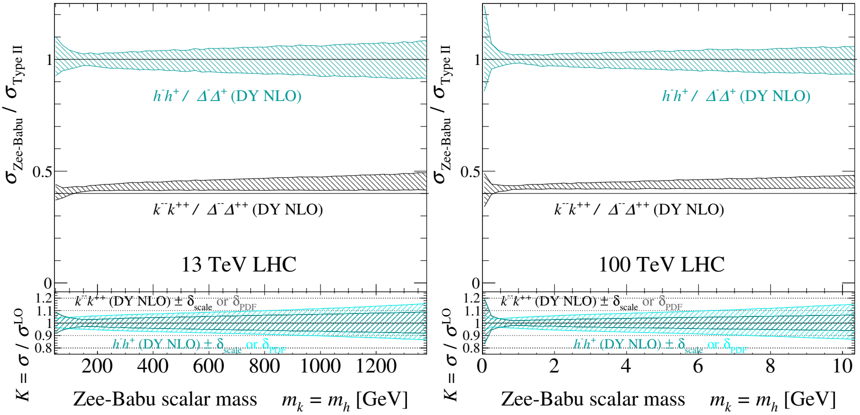
- In principle, this is a good arguement



(note: axes do not cover same domain/range)

Usual argument: Different gauge quantum numbers $\implies$ different σ

- In principle, this is a good arguement
- ... but difference ($1\times$ or $2\times$) can be absorbed by BR



Usual argument: Different gauge quantum numbers $\implies$ different $d\sigma$

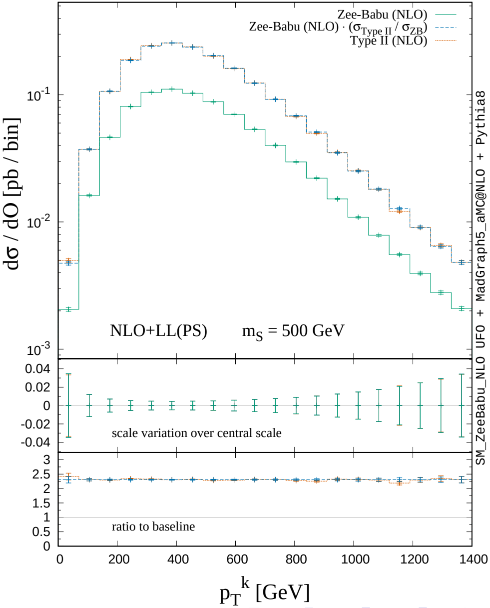
In principle, good argument...

Plotted: p_T^S in $pp \to S^{++}S^{--}$ for Type II and ZB

- Zee-Babu (solid, lower line)
- Type II (dotted, upper line)
- Zee-Babu $\times \left(\frac{\sigma_{\text{Type II}}}{\sigma_{\text{ZB}}}\right)$ (dash)

... except same shape

(note: this also holds for other models)



Usual argument: Different gauge quantum numbers $\implies$ different $d\sigma$

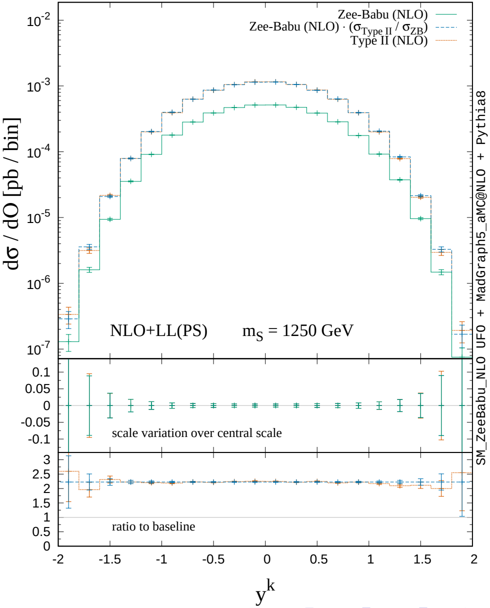
In principle, good argument...

Plotted: y^S in $pp \to S^{++}S^{--}$ for Type II and ZB

- Zee-Babu (solid, lower line)
- Type II (dotted, upper line)
- Zee-Babu $\times \left(\frac{\sigma_{\text{Type II}}}{\sigma_{\text{ZB}}}\right)$ (dash)

... except same shape

(note: this also holds for other models)



silver lining (pt 1)

Guidance from oscillation data

The ratios of $h^{\pm} \to \ell\nu$ couplings are fixed by oscillation data

- ν cannot be tagged at the LHC
- LHC only sensitive to sum over $\nu \implies$ inclusive w.r.t. ν!

From flavor-exclusive decay rates:

$$\Gamma(h^{\pm} \to \ell\nu'_{\ell}) = \frac{|f_{\ell\ell'}|^2}{4\pi}\ m_h \left(1 - \frac{m_\ell^2}{m_h^2}\right)$$

define flavor-inclusive decay rates:

$$\Gamma(h^{\pm} \to e^{\pm}\nu_X) = \sum_{\ell=e}^{\tau}\ \Gamma(h^{\pm} \to e^{\pm}\nu_\ell)$$

$$\Gamma(h^{\pm} \to \mu^{\pm}\nu_X) = \sum_{\ell=e}^{\tau}\ \Gamma(h^{\pm} \to \mu^{\pm}\nu_\ell)$$

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$$\Gamma(h^\pm \to \mu^\pm \nu_X) = \sum_{\ell=e}^{\tau}\ \Gamma(h^\pm \to \mu^\pm \nu_\ell)$$

$$\mathcal{R}^h_{e\mu} = \frac{\mathrm{BR}(h^\pm \to e^\pm \nu_X)}{\mathrm{BR}(h^\pm \to \mu^\pm \nu_X)}$$

$$= \frac{|f_{e\mu}|^2 + |f_{e\tau}|^2}{|f_{e\mu}|^2 + |f_{\mu\tau}|^2} = \frac{|\frac{f_{e\mu}}{f_{\mu\tau}}|^2 + |\frac{f_{e\tau}}{f_{\mu\tau}}|^2}{|\frac{f_{e\mu}}{f_{\mu\tau}}|^2 + 1}$$

(equivalent to measuring cross section ratio!)

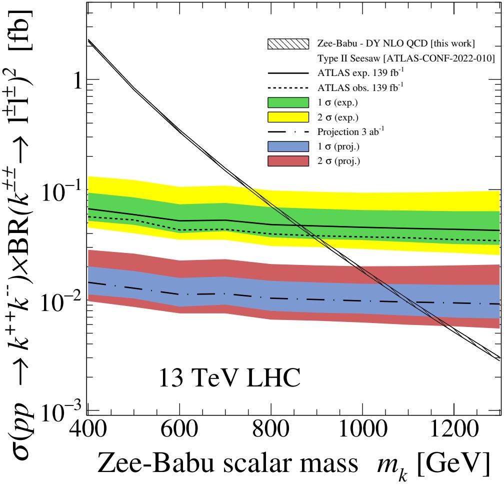
Using `NuFit`(v5.1)

$$\mathcal{R}^h_{e\mu}\Big|_{\mathrm{NO}} \approx 0.313$$ (+smallish unc.)

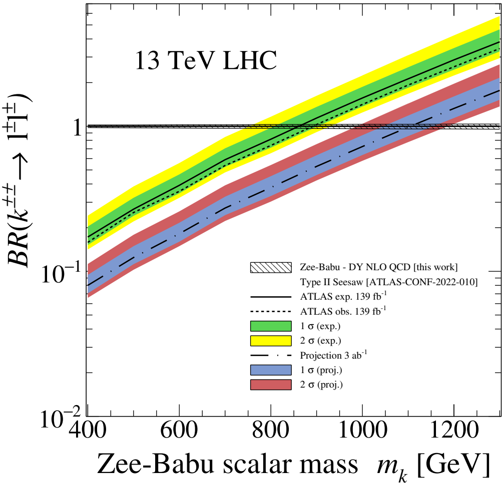
$$\mathcal{R}^h_{e\mu}\Big|_{\mathrm{IO}} \approx 0.715$$ (+smallish unc.)

silver lining (pt 2)

Identical kinematics $\Longrightarrow$ automatically obtain LHC limits (new!)



Identical kinematics $\Longrightarrow$ automatically obtain LHC limits (new!)



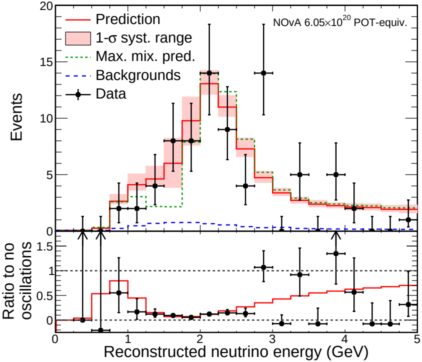
Summary and Conclusions

The origin and nature of $m_\nu \neq 0$ remain major puzzles for hep-ex/ph/th

– SM provides some (but limited) guidance on solution ☺

– While popular, models beyond "minimal" Type I Seesaw or w/o ν_R motivated by hep-ex and th ☺

– **Seesaw scalar models** turn oscillation data into collider predictions ☺



these models are testable at the LHC and dedicated flavor experiments! for reviews, see:
Cai, et al [1706.08524];
Cai, Han, Li, RR [1711.02180];
Coy, Frigerio [2110.09126]

Upon discovery, hypothesis- testing will be difficult ☹; further studies are encouraged

(oscillation data will provide strong guidance ☺)


mechanism
review
impact
veto
channel
system
leading
searche
epton
hadron
decay
heavy
LRSM
discovery
test
data
range
boson
neutrino
Monte
sses
cross
Type
order
GeV
current
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VBS
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QCD
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result
probe
available
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using
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Thank you.