Prospects of probing Right-handed neutrinos via Semileptonic Higgs decays @ LHC

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Outline

- Searches for right-handed neutrinos
- Brief discussion on collider searches & bounds
- A search channel from $pp \to h\,j$ and semileptonic h decays

Why RH neutrinos & where to look

Allahverdi, Campbell, Dutta, Gao
PRD 90, 073002 (2014)

- Understanding neutrino masses: heavy Majarona fermion(s) for see-saw mechanism
- Cosmology: Relativistic species (N_{eff}), reheat, dark matter, etc.
- EW theories: Extended symmetry requirements

- Indirect search cosmic ray signals: **γ**, **e**, ap, **ν** (flavors), and spectral features
- Correction to W, Z properties (EWPD)
- Weakly(and strongly, too) produced at collider
- Associated production with (model dependent) other BSM partners

`Common' see-saw features in RH Neutrinos

- See-saw: A finite Majorana RH neutrino mass
- RH neutrino talks to SM via Yukawa (Dirac mass) terms
- Leads to a (small) mixing into SM neutrinos, hence W, Z, couplings, etc.
- Identify with "economical" SM extensions with fermion(s)

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{N}_i i\partial\!\!\!/ N_i + (\lambda_N^{ij}\, N^i L^j H + \frac{M_N^{ij}}{2} N_i N_j + \text{h.c.})$$

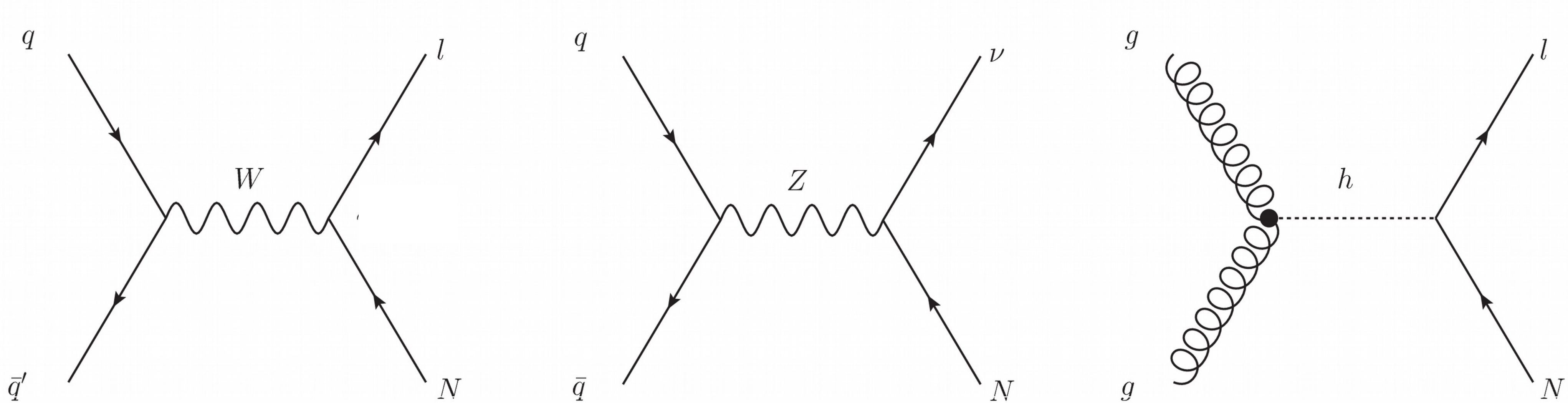
(Type-I) see-saw

Minkowski (1977) Yanagida(1979)
Gell-Mann, Ramond, & Slansky (1979)
Glashow (1980)

$$\begin{array}{cc} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} 0 & \boldsymbol{\lambda}_N^T v \\ \boldsymbol{\lambda}_N v & \boldsymbol{M}_N \end{pmatrix} \end{array} \qquad \theta \approx \left(\frac{m_\nu}{M_N}\right)^{1/2}$$

How to produce a heavy neutrino at collider?

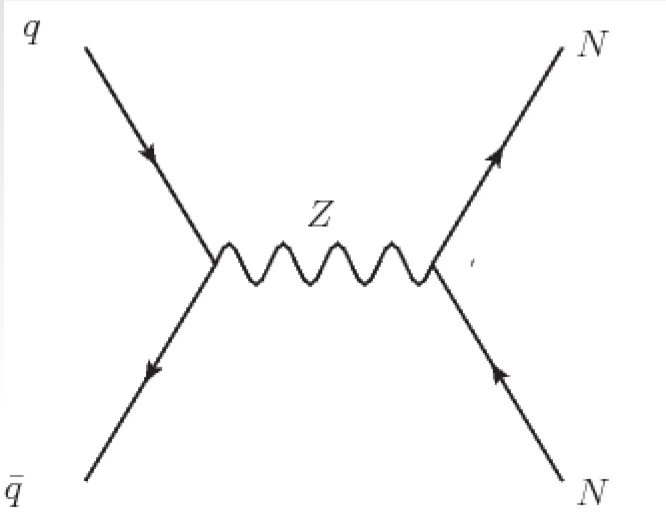
- Via mixing with the SM left-handed neutrino.
- Leading channel : Drell-Yan
- Resonant W, Z, h production (for $M_N < M_{W/Z/h}$)
- Need significant mixing



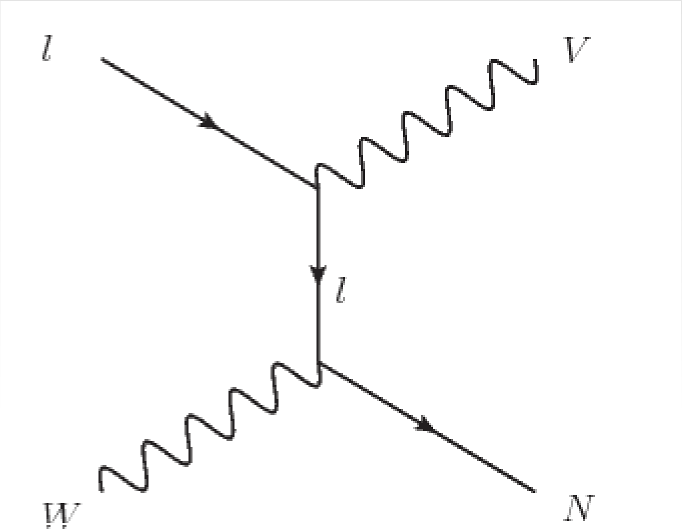
Drell – Yan

Gluon fusion

and a few other ways ...

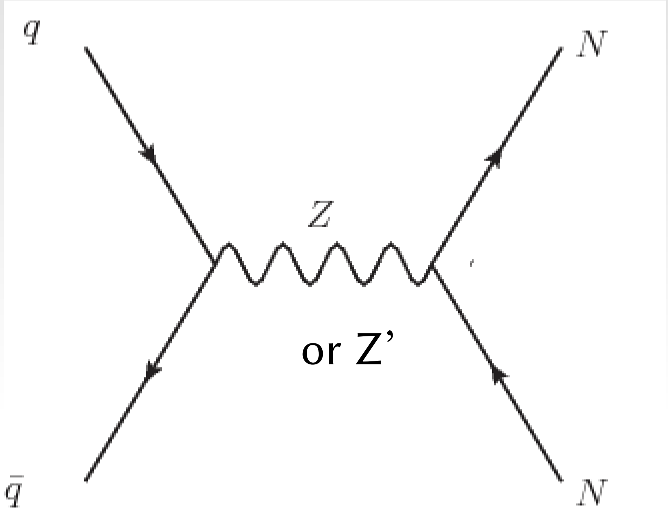


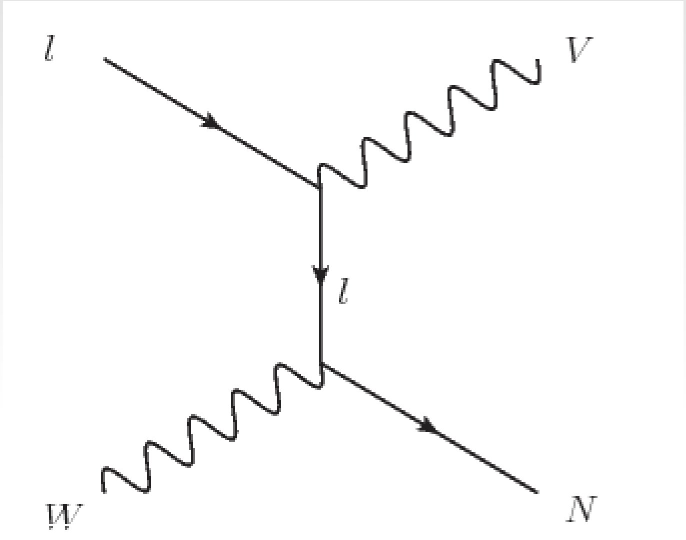
N pair production suppressed by mixing^4



Vector-boson and/or lepton fusion: need lepton and/or VB luminosity

and a few other less blessed ways ...





N pair production suppressed
by mixing^4
Note: Z' are not mixing-suppressed
but ($m_{Z'}/g_{z'}$) must be large

Or maybe go after associated
N partners instead

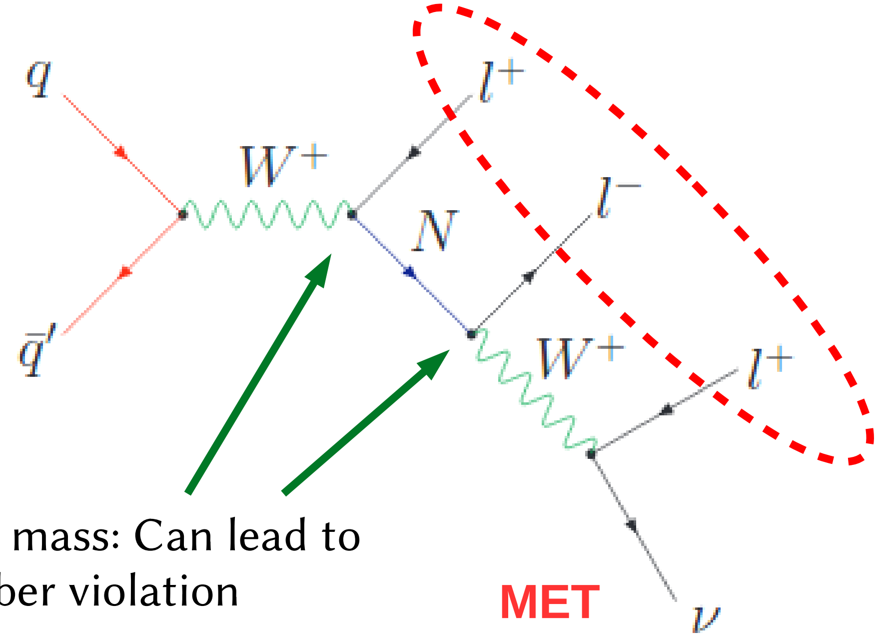
Vector-boson and/or lepton fusion:
need lepton and/or VB luminosity

VBF has cleaner bkg, yet
suffers from small signal

VB-*l* fusion at e+e- collider
or even at CR experiments:
needs larger Ecom

Drell-Yan channels

- pp$\rightarrow$ $l\,N$, $N\rightarrow$ $l\,l\nu$, final state: `Trilepton' $lll\nu$
- pp$\rightarrow$$\nu\,N$, $N\rightarrow$ $l\,l\nu$, final state: two lepton $ll\nu\nu$
- Semileptonic N decays $N\rightarrow$ $j\,j\nu$, mass reconstruct-able
- Mediator can be on shell (resonance) for light N



A Majorana mass: Can lead to lepton number violation
e.g. $e^+e^+\mu^-\bar{\nu}$

Heavy N decays: Missing energy, or prompt decays?

- (Mostly RH) *N* decays weakly via its mixing into SM neutrino, yet its lifetime varies greatly...

Type I mixing is very tiny

$$\begin{array}{cc} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} 0 & \boldsymbol{\lambda}_N^T v \\ \boldsymbol{\lambda}_N v & \boldsymbol{M}_N \end{pmatrix} \end{array} \qquad \theta \approx \left(\frac{m_\nu}{M_N} \right)^{1/2}$$

M_D

Suppress production rate / decay branching fraction
N may become completely invisible at LHC

May search for other `associated' particles, like charged scalars in Type II, heavy Z' in extra U(1), etc.

When RH *N*'s lifetime is very long and *N* becomes MET at collider, leadings to mono-lepton signals, but measuring its mass and identifying the N can be difficult.

NOTE: A long-lived heavy N can be useful in indirect searches

- In a 1 – 5 GeV mass range, (Type-I) RH neutrinos can escapes the Sun before decaying [with a Lorentz boost from TeV -scale dark matter annihilations]

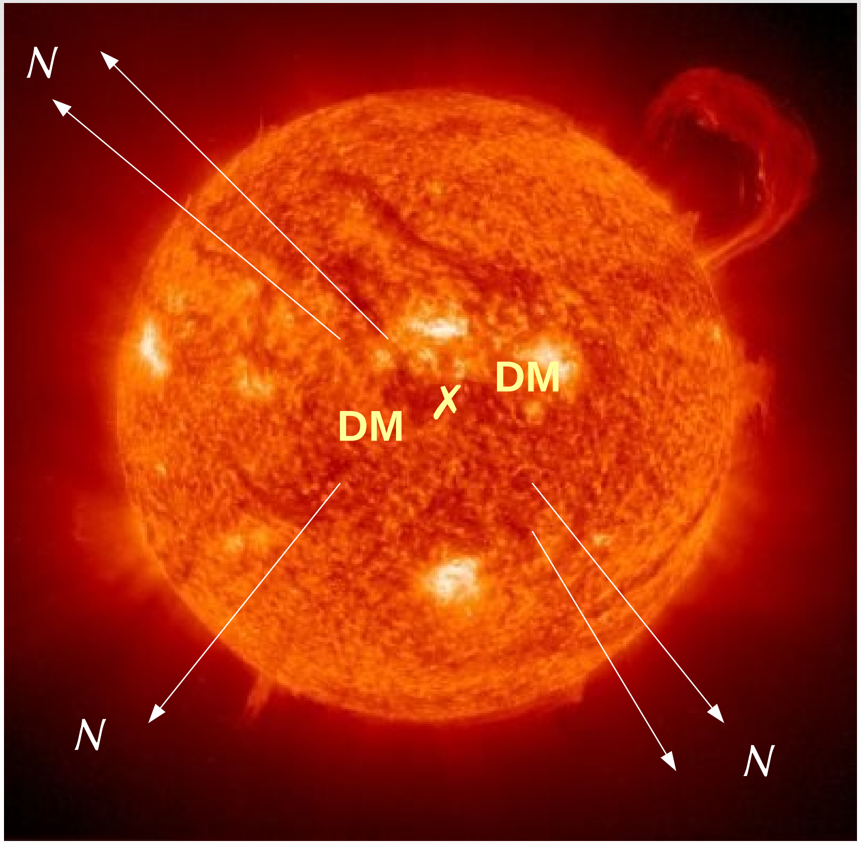
- Signal in both high-energy γ-ray & neutrinos in the Sun’s direction

$$\Delta\mathcal{L} \supset y_{\rm D}(L^{\dagger} \cdot i\tau_2 H)N + \mathbf{h.c.},$$

$$\Gamma_N \propto \theta^2 G_{\rm F}^2 M_N^5 \frac{M_N}{M_{\rm DM}}$$

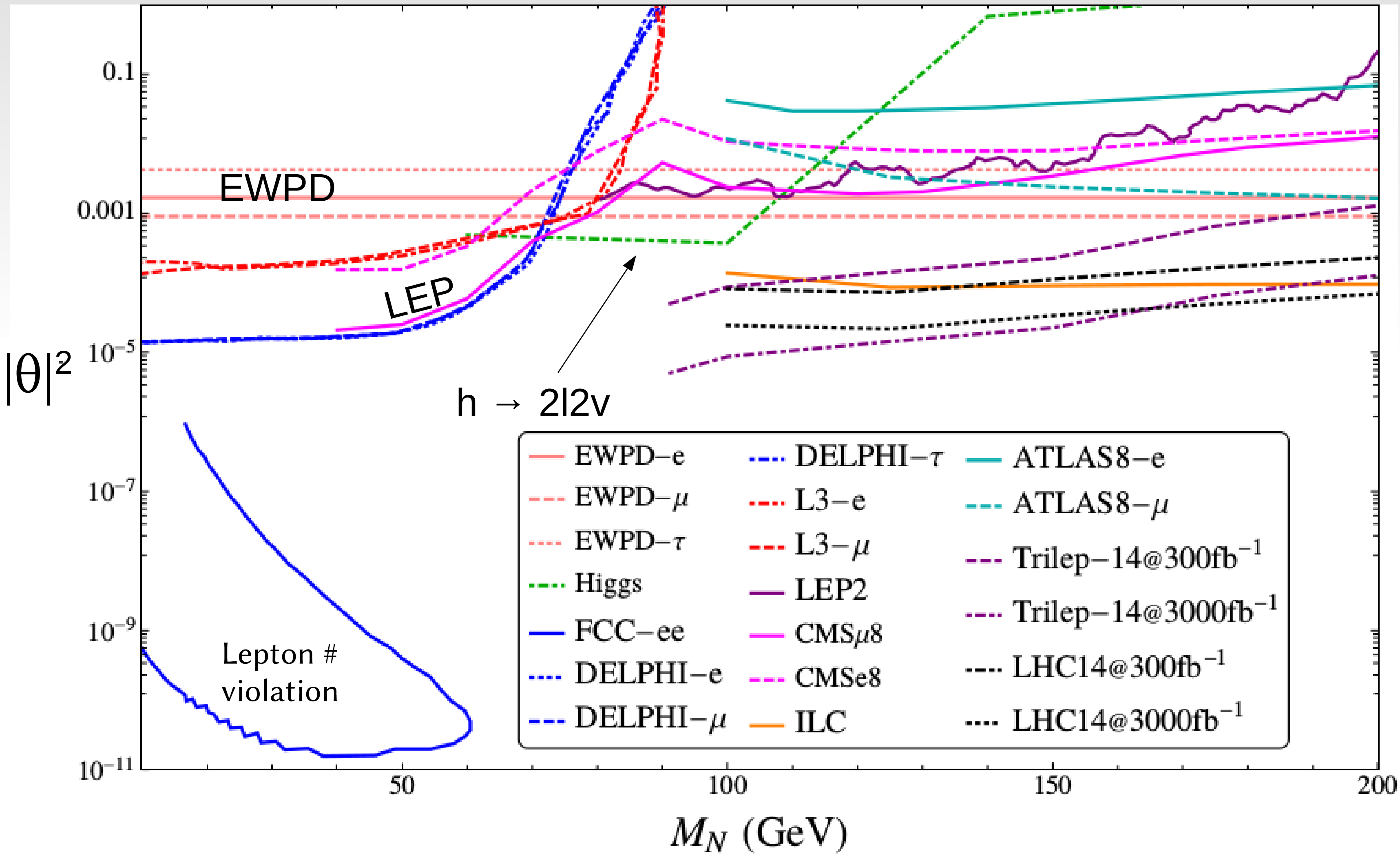
boosted $\tau_N \propto \frac{M_{\rm DM} m_\nu}{M_N^5}$

- Leads to strong bounds from both Fermi-LAT and IceCube



R. Allahverdi, YG , B. Knockel, S. Shalgar, 1612.03110, PRD 95 no. 7, 075001 (2017)
For neutrino sector’s DM, aslo see
R. Allahverdi, S.Campbell, B.Dutta, YG
PRD 90, no. 7, 073002 (2014)

A quick look at the present and future at colliders...



Higgs can be sensitive to New Physics

Higgs versus W & Z mediation:

SM Higgs width is small, (potentially) sensitive to mixing

Higher resonance mass than W, Z.

$$\Gamma(h \to N\nu) = \frac{Y_N^2}{8\pi m_h^3}(m_h^2 - M_N^2)^2$$

$$\mathcal{BR}_{h\to N\nu} = \frac{\Gamma(h \to N\nu)}{\Gamma_h^{\rm SM} + \Gamma(h \to N\nu)}$$

~4MeV

Future Higgs Precision data can be powerful

Signal $\sigma = \sigma(hj)\ \mathrm{Br}_{h\to N\nu}\ \mathrm{Br}_{N\to X}\ A_{\rm eff}$

N mostly (80^{+}%) decays via W

Optimizes cuts for a semi-leptonic N⟶ljj channel

The semileptonic channel

- Higgs leptonic, DY searches by LHC exist.
- Gluon fusion has a good Higgs production rate.
- Production: p p ⟶ h j, with a high PT triggering jet.
- Higgs decays semileptonically h ⟶ ν N, N ⟶ l W, W⟶j j
- Can see the *N* mass: fully reconstructible from l j j
- Requires high-PT jet for triggering, and on-shell (and separate) W, N mass windows, M_T for bkg suppression
- SM bkg: channels with (real & fake) W+jets.

Production at loop level

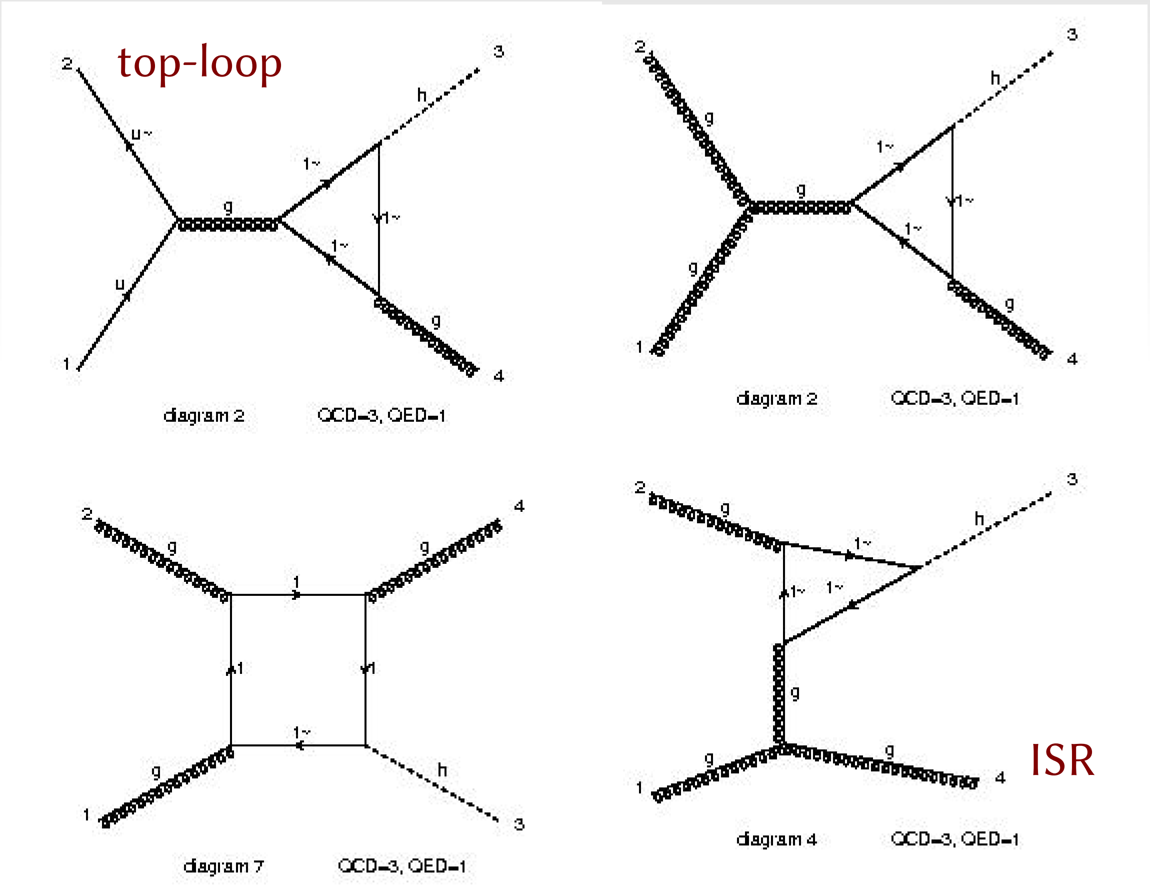
1 loop pp→hj at LO

High PT jet originates from loop and ISR

j1 $P_T > M_{top}$: Need loop calc

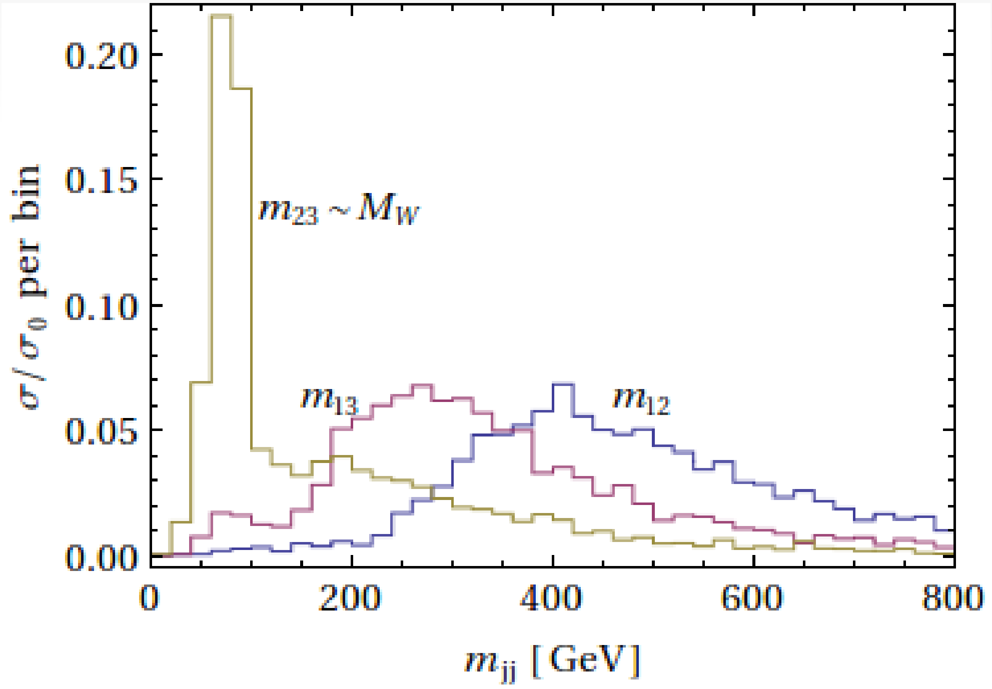
MG5+pythia6+PGS4

MadGraph NLO model:
Degrande, Mattelaer, Ruiz, Turner, PRD 94, 053002 (2016)



Final state kinematics

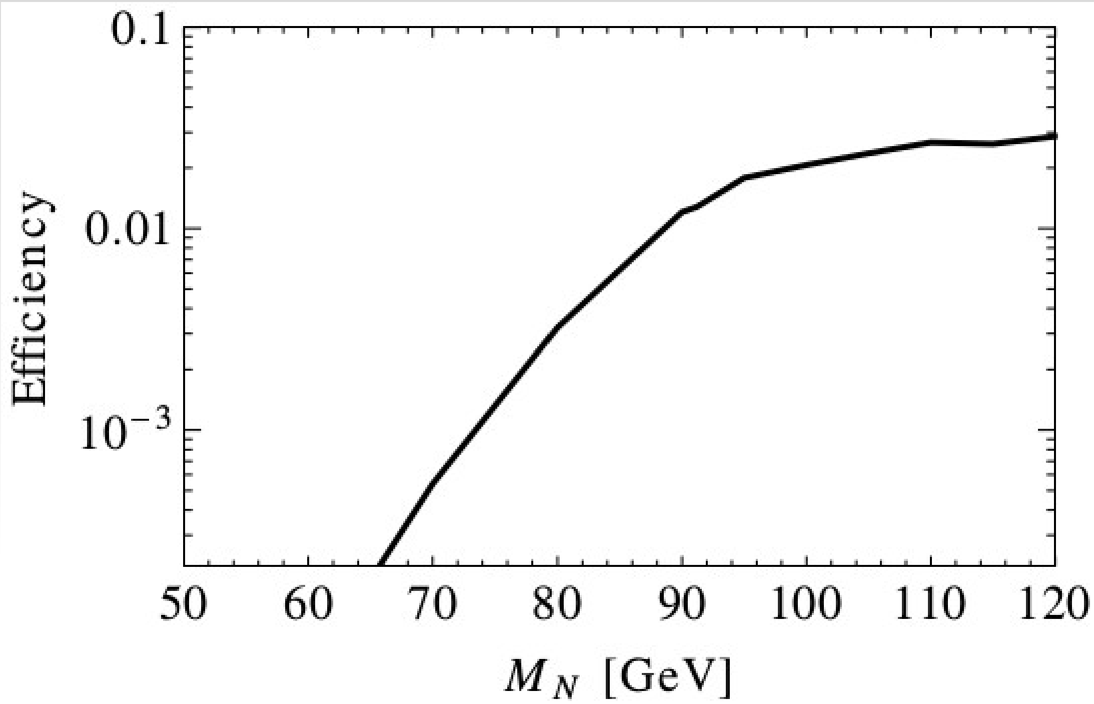
- *N* mass fully reconstructible
- No large PT leptons, needs jet for triggering
- High P_T jet transversely boosts *h* system – higher l, $j_2\, j_3\ P_T$



A large j1 PT separates M(j2j3) from M(j1j2) and M(j1j3)

A dijet (j2j3) mass cut around W mass helps.

LO pp→hj, after a 200 GeV leading jet cut for |eta(j)|<2.5



A percent level selection efficiency is expected for signal
In the near M_h mass range.

Lower mass harder to pass M_W window cut

Signal cut flow

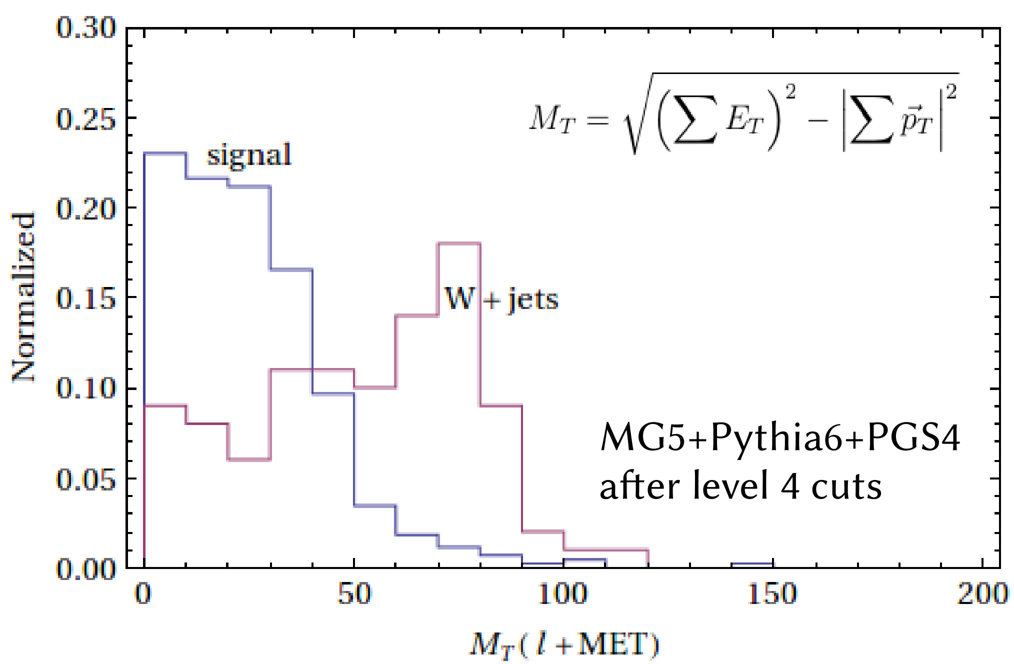
(1) leading jet p_T^j >200 GeV; — Trigger & j_1 - j_2j_3 separation

(2) at least three jets and exactly one lepton; — Remove Z bkgs

(3) $|M(j_2j_3) - M_W| < 20$ GeV; — A physical W mass

(4) $|M(l_1j_2j_3) - M_N| < 20$ GeV. — M_N mass window

(5) $|M_T(l_1\not{E}_T)| < 45$ GeV — Suppress leptonic W



σ / $\mathrm{Br}_{h\to N\nu}$

Cut #	M_N=110	M_N=100
1	0.19pb	0.19pb
2	34 fb	28 fb
3	13 fb	10 fb
4	11 fb	8 fb
5	9.5 fb	7.3 fb

Leptons become soft

Backgrounds & significance...

M_N Mass window	ttbar (+0,1,2 jets)	W+jets (+1,2,3 jets)	Z+jets (+1,2,3 jets)	Others (tj, vvj)	Signal/$Br_{h\to N\nu}$ (LO)
100	63	23	12	12	7.3
110	101	94	19	18	9.5

V+jets from large stat. simulations,
MG5+Pythia+PGS4

Leading order: for $BR(h\to N\nu)$ =10% / 5% / 1 %

M_N=100GeV: $S/\sqrt{S+B}$ at 3 ab^{-1} = 3.5[5.2] / 1.7[2.6] / 0.3[0.5]

M_N=110GeV: $S/\sqrt{S+B}$ at 3 ab^{-1} = 3.7[5.6] / 1.9[2.8] / 0.4[0.6]

Higher signal corrections from NLO ? (50%) NLO enhancements

Inverse seesaw: Can accomendate for large $N\nu$ mixing in flavor diagonal cases
maximally allowed $h\to N\nu$ BR= 4%(100 GeV) and 3%(110 GeV) $\to$ 2.1σ and 1.7σ @3ab^{-1}

Summary

- A complementary channel for HL-LHC, optimal N mass range 100-110 GeV
- A triggering high j_1 P_T (200 GeV) : for both triggering & *N* mass reconstruction
- Signal O(10) fb * Br($h \to N\nu$) at LO, Bkg at O(10^2) fb
- RH neutrino mass reconstructible in semileptonic pp$\to$*hj* channel, dedicated kin. analysis can help.

Backups

Collider friendly scenario: Inverse seesaw

R. N. Mohapatra, 1986

- Outsource Maj. mass to an additional singlet fermion
- Larger mixing angle into RH *N*, but no LNV in *N* decay
- Can be flavor-diagonal in ν-*N* mixing (m_D terms)

$$\mathcal{L} \supset -Y_D^{\alpha\beta}\overline{\ell_L^\alpha}\tilde{H}N_R^\beta - M_N^{\alpha\beta}\overline{S_L^\alpha}N_R^\beta - \frac{1}{2}\mu_{\alpha\beta}\overline{S_L^\alpha}S_L^{\beta^C} + H.c.$$

	SU(2)	U(1)$_Y$
ℓ	**2**	$-1/2$
H	**2**	$+1/2$
N_R	**1**	0
S_L	**1**	0

$$M_\nu = \begin{array}{cc} \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_N^T \\ 0 & M_N & \mu \end{pmatrix} & \begin{array}{c} \nu \\ N \\ S \end{array} \end{array}$$

$$m_\nu \simeq (m_D M_N^{-1})\mu(M_N^{-1^T} m_D^T)$$

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M_N=110GeV: $S/\sqrt{S+B}$ at 3 ab^{-1} = 3.7[5.6, 7.5]/1.9[2.8, 3.7]/0.4[0.6, 0.7]

Higher signal corrections from NLO ? (50%, 100%) NLO enhancements