Neutrino Physics at the LHC

MadGraph School 2019
Institute of Mathematical Sciences, Chennai

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Universite Catholique de Louvain

22 November 2019

Good Morning!

Thank you for the invitation and thank you for being here

Most important rule: This is an informal lecture, so ask questions!

You are encouraged to interrupt and ask questions

Lecture Plan

Lecture I (Thursday): Intro to Neutrino BSM ✓

- Neutrino Oscillations ✓
- Neutrino Masses and Possible Origins ✓

Lecture II (Friday): Neutrino Physics at the LHC

- Lecture I Review
- Test of ν Mass Models: Left-Right Symmetric Model Case Study
- Monte Carlo Tool Chain

Coffee and tea break at 11:30ish

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Lecture I Review:

The Massive ν Problem

Neutrinos Masses and New Physics

To generate Dirac masses for ν like other SM fermions, we need N_R

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi} N_R + H.c. = -y_\nu \left(\overline{\nu_L} \quad \overline{\ell_L}\right) \begin{pmatrix} \langle\Phi\rangle + h \\ 0 \end{pmatrix} N_R + H.c.$$

$$= \underbrace{-y_\nu \langle\Phi\rangle}_{=m_D} \overline{\nu_L} N_R + H.c. + \ldots$$

However, N_R^i do not exist in the SM, implying $m_D = 0$

Significance of Neutrino Oscillations:

- Neutrino masses $\implies \mathcal{L}_{\text{Universe}} \neq \mathcal{L}_{\text{SM}} \quad (+\mathcal{L}_{\text{gravity}})$
- Instead, $\mathcal{L}_{\text{Universe}} \approx \mathcal{L}_{\text{SM}} + \underbrace{\mathcal{L}_{\nu\ \text{masses}}}_{BSM\ physics!} + \ldots$

Neutrino masses $\implies$ existence of physics beyond the SM!

Seesaw Mechanisms: Pathways to Naturally Small m_ν

Spinor/gauge algebra + renormalizability restrict ways to build m_ν [Ma'98]

"Type 0": Add SM-singlet N_R with $y_\nu \sim 10^{-12}$ and forbid Majorana mass

- Possible, but tiny y_ν is theoretically unsatisfying

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- $\mathcal{L} \ni \; -y_\nu \overline{L}\tilde{\Phi} N_R \; - \; \frac{m_R}{2}\overline{N_R{}^c} N_R \implies \; m_\nu \propto m_D^2/m_R, \quad m_D = y_\nu \langle \Phi \rangle$

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- $\mathcal{L} \ni y_\Delta \overline{L}(i\sigma_2)\Delta L^c \implies m_\nu \propto y_\Delta \langle \Delta \rangle \overline{\nu^c}\nu, \quad \langle \Delta \rangle <$ few GeV

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Type III: Add fermion $SU(2)_L$ triplet ($T^{0,\pm}$)

- $\mathcal{L} \ni y_T \overline{L} T^a \sigma^a (i\sigma^2)\Phi \ + \ \frac{m_T}{2}\overline{T^{0c}} T^0 \ \Longrightarrow \ \ m_\nu \propto m_D^2/m_T$

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Less Minimal Models: Hybrid, Inverse, Radiative, ..., all with rich pheno

Collider Connection to Neutrino Mass Models

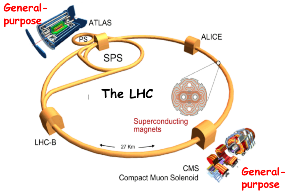
Neutrino mass models (aka Seesaw models) **hypothesize** new particles of all shapes, spins, charges, and color:

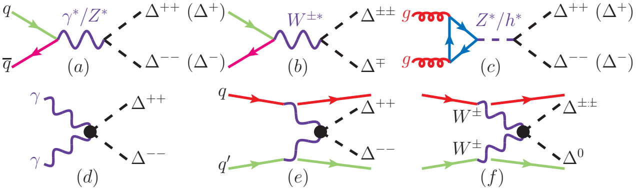
$$N \text{ (Type I)}, \ T^{0,\pm} \text{ (Type III)}, \ Z_{B-L}, \ H_R^{\pm,\pm\pm} \text{ (Type I+II)}, \ \ldots$$

that can be **produced in collisions** through gauge couplings and mixing:

$$\textbf{DY}: q\overline{q} \to \gamma^*/Z^* \to T^+T^- \quad \text{and} \quad q\overline{q'} \to W_R^\pm \to N\ell^\pm$$

$$\textbf{VBF}: W^\pm W^\pm \to H^{\pm\pm} \qquad \textbf{GF}: gg \to h^*/Z^* \to N\nu_\ell$$



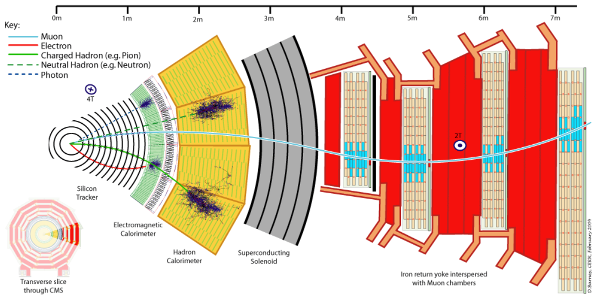


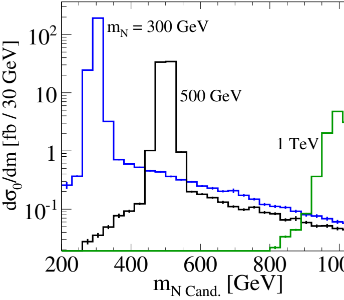
Collider Connection to Neutrino Mass Models

Seesaw particles then decay to SM particles, which are observed/inferred by detector subsystems (e.g., γ/j via calorimetry; μ from μChambers)

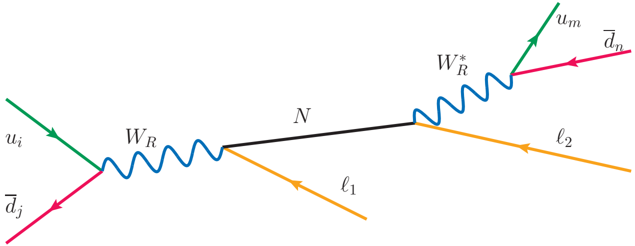
$$N/T^0 \to W^\pm \ell^\mp, \ Z\nu, \ h\nu,$$

Identification is possible through reconstruction of final-state kinematics

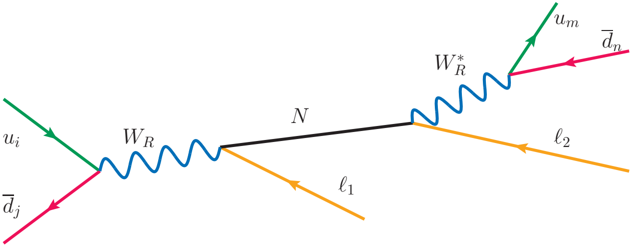




Lecture II: Neutrino Physics at the LHC



Lecture II: Left-Right Symmetric Model at the LHC



Left-Right Symmetric Models (LRSM) postulate that the SM's $V - A$ structure originates from the spontaneous breakdown of parity symmetry:

$$\mathcal{G} = \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \underbrace{\mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}}$$

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With N_R, all SM fermions can be grouped in $\mathrm{SU}(2)_L$ *and* $\mathrm{SU}(2)_R$ doublets.
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Neutrinos obtain LH (RH) Majorana masses from triplet scalar Δ_L (Δ_R):

$$m^{\nu}_{\mathrm{light}} = \underbrace{y_L \langle \Delta_L \rangle}_{\text{Type II}} - \underbrace{\left(y_D y_R^{-1} y_D^T \right) \langle \Phi \rangle^2 \langle \Delta_R \rangle^{-1}}_{\text{Type I a la Type II}} \sim \mathcal{O}(0) + \text{symm.-breaking}$$

Major pheno: heavy N, W'/Z' ($\approx W_R/Z_R$), and $H_i^{\pm\pm}$, $H_j^{\pm}$, H_k^0

W_R coupling to quarks analogous to SM W_{SM} couplings ($\gamma^\mu P_L \to \gamma^\mu P_R$):

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W^-_{R\mu} \sum_{q=u,d,...} [\overline{d_j}\ V_{ij}^{CKM'}\ \gamma^\mu P_R u_i] + \text{H.c.}$$

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In **chiral/gauge** basis, couplings to leptons is given by:

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W^-_{R\mu} \sum_{a=1}^{3} [\bar{l}^a \gamma^\mu P_R \underbrace{N^a_R}_{Note:\ |N_R\rangle = X|\nu_m\rangle + Y|N_{m'}\rangle}] + \text{H.c.}$$

Chiral/interaction basis is not a practical basis for scattering calculations.

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In **mass** basis, coupling to leptons can be generically parametrized as:

Atre, Han, Pascoli, Zhang [0901.3589]; Han, Lewis, RR, Si [1211.6447]

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W^-_{R\mu} \sum_{\ell=e}^{\tau}\ \overline{\ell}\gamma^\mu P_R \underbrace{\left[\sum_{m=1}^{3} \underbrace{X_{\ell m}}_{\mathcal{O}(m_\nu/m_N)} \nu_m + \sum_{m'=4}^{6} \underbrace{Y_{\ell m'}}_{\mathcal{O}(1)} N_{m'}\right]}_{Note:\ |N_R\rangle = X|\nu_m\rangle + Y|N_{m'}\rangle} + \text{H.c.}$$

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Benchmark: Simply consider only the lightest $N \equiv N_{m'=4}$ and that the N mass state is aligned with $\ell = e$ flavor state, i.e., $|Y_{eN}| = 1$.

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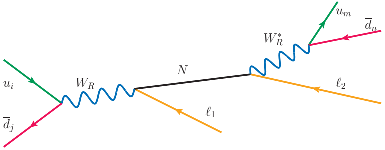
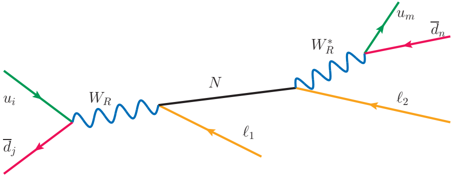
- $W_R \to Ne$ decay rate is BR $\approx 10\%$ for $M_{W_R} \gg m_N$ (90% to quarks)

- $N \to W_R^{*\pm}\ell^\mp \to \ell^\mp q\overline{q'}/tb$ are dominant decay channels with BR $\approx 100\%$



Hallmark LRSM collider signature is the spectacular same-sign lepton pairs:

$$q\overline{q'} \to W_R^{\pm} \to N\ell_1^{\pm} \to \ell_1^{\pm}\ell_2^{\pm}q'\overline{q}$$



Proposed by Keung & Senjanovic ('83) and basis for most Seesaw searches

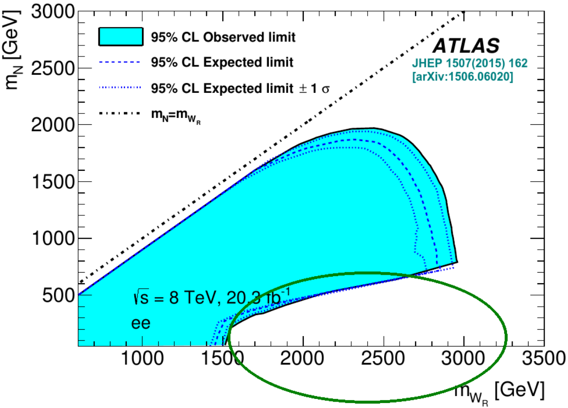
- $W_R^{\pm}$ is heavy[1]. If kinematically accessible, s-channel $q\overline{q'} \to W_R^{\pm}$ production rate is largest at LHC
- L-**violating process**! $\Rightarrow \nu$ are Majorana [Black Box Theorem]
- $W_R^* \to q'\overline{q}$ allows for full reconstruction of kinematics $\Rightarrow$ **properties**
- High-p_T $\ell^{\pm}$ without light $\nu \Rightarrow$ no transverse mom. imbalance (**MET**)

[1] ATLAS [1506.06020; 1512.01530] and CMS [1407.06020; 1512.01224]

Searches for LRSM at $\sqrt{s}$ =8 TeV

Signaure: $pp \to e^{\pm}e^{\pm} + nj + X + p_T^{\ell} \gtrsim \mathcal{O}(M_{W_R}) \sim 1$ TeV + no **MET**

Plotted: excluded (m_{N_R}, M_{W_R}) from searches for resonant W_R, N



Loss of sensitivity when $m_N \ll M_{W_R}$ (Lets simulate to investigate)

Simulating LHC Collisions

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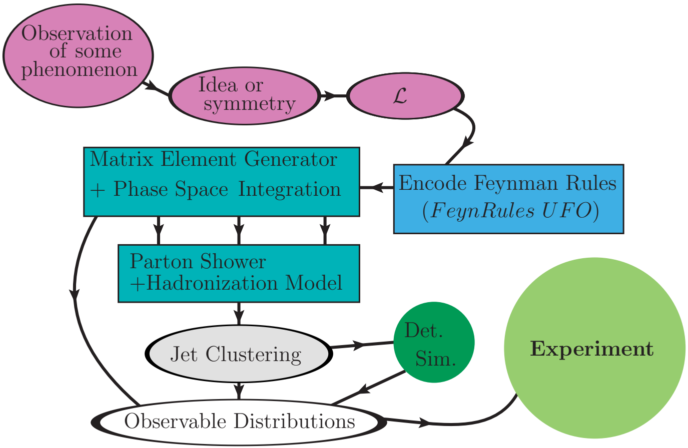
To simulate LHC collisions and model new physics, we get to use all the tools we learned this week

(See pretty much every talk this week!)



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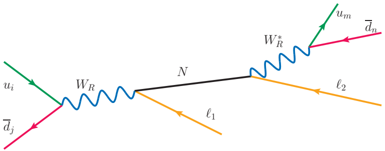


From Lagrangian to FeynRules

Given the relevant $\mathcal{L}_{Int.}$, one can build up an effective `FeynRules` model

(See Benjamin's Lectures and FeynRules Tutorial!)

Warning: $\mathcal{L}$ here contains only W_R, Z_R, N_i

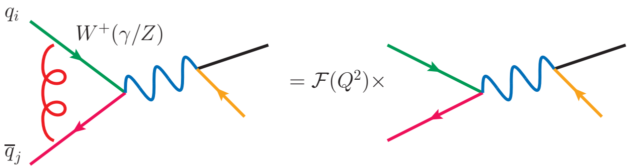
- Neglects $SU(2)_R$ non-Abelian couplings and scalar sector
- Okay for our study, usless for other types

```
(* ************************* *)
(* *** Kinetic+Mass Terms *** *)
(* ************************* *)
LNKin :=   I/2 N1bar[s1].Ga[v,s1,s2].del[N1[s2],v] - 1/2 mN1 N1bar[s1]N1[s1] \
       +  I/2 N2bar[s1].Ga[v,s1,s2].del[N2[s2],v] - 1/2 mN2 N2bar[s1]N2[s1] \
       +  I/2 N3bar[s1].Ga[v,s1,s2].del[N3[s2],v] - 1/2 mN3 N3bar[s1]N3[s1];


(* ************************* *)
(* *** Interaction Terms *** *)
(* ************************* *)
(* WR Currents *)
LWRTmp := ee/sw/Sqrt[2]*WR[mu]*( kRq*uqbar.VCKMR.Ga[mu].ProjP.dq \
                              + kRl*Nlbar.YlN.Ga[mu].ProjP.l    );

(* ZR Currents *)
LZRTmpU := kRq*ee/sw/Sqrt[1-tw2/kRq2]*ZR[mu]*(gZRuR* uqbar.Ga[mu].ProjP.uq \
                                            + gZRuL* uqbar.Ga[mu].ProjM.uq );
LZRTmpD := kRq*ee/sw/Sqrt[1-tw2/kRq2]*ZR[mu]*(gZRdR* dqbar.Ga[mu].ProjP.dq \
                                            + gZRdL* dqbar.Ga[mu].ProjM.dq );
LZRTmpN := kRl*ee/sw/Sqrt[1-tw2/kRl2]*ZR[mu]*(gZRNR* Nlbar.Ga[mu].ProjP.Nl \
                                            + gZRNL* Nlbar.Ga[mu].ProjM.Nl );
LZRTmpV := kRl*ee/sw/Sqrt[1-tw2/kRl2]*ZR[mu]*(gZRvR* vlbar.Ga[mu].ProjP.vl \
                                            + gZRvL* vlbar.Ga[mu].ProjM.vl );
LZRTmpE := kRl*ee/sw/Sqrt[1-tw2/kRl2]*ZR[mu]*(gZReR*  lbar.Ga[mu].ProjP.l  \
                                            + gZReL*  lbar.Ga[mu].ProjM.l  );
LZRTmp  := LZRTmpU + LZRTmpD + LZRTmpN + LZRTmpV + LZRTmpE;


(* Combine everything *)
LagLRSM := LNKin + LWRTmp + LZRTmp + HC[LWRTmp];
LagFull := LSM + LagLRSM;
```

```
  YlN == {        ParameterType->External,
                  ComplexParameter->False,
                  Indices->{Index[Generation],Index[Generation]},
                  BlockName->LeptonMixingYlN,
                  Value-> {
                          YlN[1,1]->1.0, YlN[1,2]->0.0, YlN[1,3]->0.0,
                          YlN[2,1]->0.0, YlN[2,2]->1.0, YlN[2,3]->0.0,
                          YlN[3,1]->0.0, YlN[3,2]->0.0, YlN[3,3]->1.0 },
                  TeX->Subscript[Y,lN],
                  Description->"Right-handed Lepton Mixing Matrix"
  },

        (* INTERNAL PARAMETERS *)
  tw2    == {
    ParameterType -> Internal,
    Value         -> sw2/(1-sw2),
    Description   -> "Squared Tan of the Weinberg angle"
  },
  kRq2   == {
    ParameterType -> Internal,
    Value         -> kRq*kRq,
    Description   -> "Square of kRq = gRQuarks/gSM"
  },
  kRl2   == {
    ParameterType -> Internal,
    Value         -> kRl*kRl,
    Description   -> "Square of kRq = gRLeptons/gSM"
  },

(* ZR coupling to RH fermions: gZR,f_R =  TR3 - Qf*tw2/kR2  *)
(* ZR coupling to LH fermions: gZR,f_L = (TL3 - Qf)*tw2/kR2 *)
```

Feynman Rules Beyond LO in QCD

QCD corrections to colorless currents with massless quarks are special



Importantly, at one-loop, corrections for *generic* V-A structure are UV-finite (contain only IR single and double poles)

$$
\begin{aligned}
\overline{v}(p_d)\gamma^\mu\left(g_L P_L + g_R P_R\right)u(p_u) &\to \overline{v}(p_d)\Gamma^\mu(p_u,p_d)u(p_u),\\
\overline{v}(p_d)\Gamma^\mu(p_u,p_d)u(p_u) &= \overline{v}(p_d)\gamma^\mu\left(g_L P_L + g_R P_R\right)u(p_u)\times\mathcal{F}\\
\mathcal{F} &\equiv \frac{\alpha_s(\mu_r^2)}{4\pi}C_F C_\varepsilon(\hat{s})(-1)^\varepsilon\Gamma\left(1+\varepsilon\right)\Gamma\left(1-\varepsilon\right)\left(\frac{-2}{\varepsilon^2}-\frac{3}{\varepsilon}-8\right)\\
C_\varepsilon(\hat{s}) &= \left(\frac{4\pi\mu_r^2}{\hat{s}}\right)^\varepsilon\frac{\Gamma\left(1-\varepsilon\right)}{\Gamma\left(1-2\varepsilon\right)},\quad C_F = 4/3.
\end{aligned}
$$

UV counterterms for our $\mathcal{L}_{Int.}$ at NLO in QCD are same for SM

Feynman Rules Beyond LO in QCD

Using FeynRules+NLOCT, a FeynRules@NLO model file can be generated

- See refs. in feynrules.irmp.ucl.ac.be/wiki/NLOModels for details

```
$FeynRulesPath = SetDirectory["~/Scripts/FeynRules/FeynRules"];
<< FeynRules`;
SetDirectory[NotebookDirectory[]];

(*Load default SM with Eff LRSM extension.*)

In[∘]:= LoadModel["sm.fr", "effLRSM.fr"];
LoadRestriction["massless.rst", "diagonalQuarkMixing.rst"];
(*LoadRestriction["massless.rst","diagonalMixing.rst"];*)
FeynmanGauge = True;
```

On-Shell Renormalization with FeynArts

```
LRen = OnShellRenormalization[LagFull, QCDOnly → True,
   FlavorMixing → False, Exclude4ScalarsCT → True];
SetDirectory["~/Scripts/FeynArts/FeynArts/Models"];
WriteFeynArtsOutput[LRen, GenericFile → False,
  FlavorExpand → True, Output → "EffLRSM_NuMixing_FA"];
```

```
In[∘]:= SetDirectory["~/Scripts/FeynArts/FeynArts"]
<< FeynArts`
SetDirectory["~/Scripts/FeynRules/FeynRules"]
<< NLOCT`
$CurrentPath = Directory[];
SetDirectory[$CurrentPath];

(*Note: Grab some coffee; this will take a few minutes. Output is located in FeynRules directory.*)

WriteCT["EffLRSM_NuMixing_FA/EffLRSM_NuMixing_FA", "Lorentz", Output → "EffLRSMct_NuMixing",
  ZeroMom → {{aS, {F[7], V[4], -F[7]}}}, ComplexMass → False,
  QCDOnly → True, Exclude4ScalarsCT → True];
```

Load BSM.nlo and Generate UFO at NLO

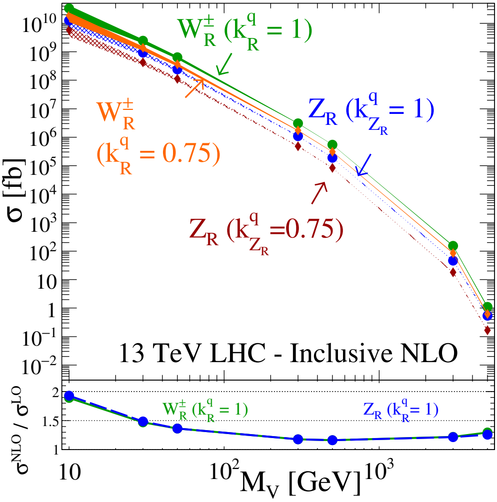
```
(* quit kernel before continuing *)

In[∘]:= Quit[];

In[∘]:= $CurrentPath = Directory[];
$FeynRulesPath = SetDirectory["~/Scripts/FeynRules/FeynRules"];
<< FeynRules`;
SetDirectory[NotebookDirectory[]];

In[∘]:= LoadModel["sm.fr", "effLRSM.fr"];
LoadRestriction["massless.rst", "diagonalQuarkMixing.rst"];
(*LoadRestriction["massless.rst","diagonalMixing.rst"];*)
FeynmanGauge = True;

Get["~/Scripts/FeynRules/FeynRules/EffLRSMct_NuMixing.nlo"];
WriteUFO[LagFull, UVCounterterms → UV$vertlist, R2Vertices → R2$vertlist, Output → "EffLRSM_NuMixing_NLO"];
```

FeynRules to MadGraph5aMC@NLO

Given an effective `FeynRules@NLO` model file, one can run `mg5amc`

(See Oliver's and HS's Lectures!)

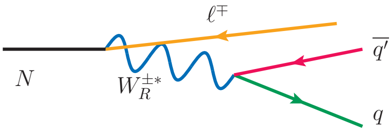
```
> import model EffLRSM_NLO
> define p  = u c d s b u~ c~ d~ s~ b~ g
> define j  = p
> define wr = wr+ wr-
> generate p p > wr [QCD]
> output PP_WR_NLO; launch
> order=NLO
> fixed_order=ON
> set MWR scan:range(1000,6001,1000)
> set dynamical_scale_choice 3
```



mg5amc+MadSpin+Parton Shower

If the narrow width approximation holds ($\Gamma_{W_R}/M_{W_R} \ll 1$), efficient generation of $pp \to W_R \to N\ell^\pm \to \ell^\pm\ell^\pm q\overline{q'}$ possible with `MadSpin`:

In `madspin_card.dat`, write:




```
set spinmode onshell

define  q = u c d s u~ c~ d~ s~

define ee = e+ e-

decay  n1 > ee q q

launch
```

Parton showering with `PY8` or `HERWIG` straightforward (See Leif's talks!)

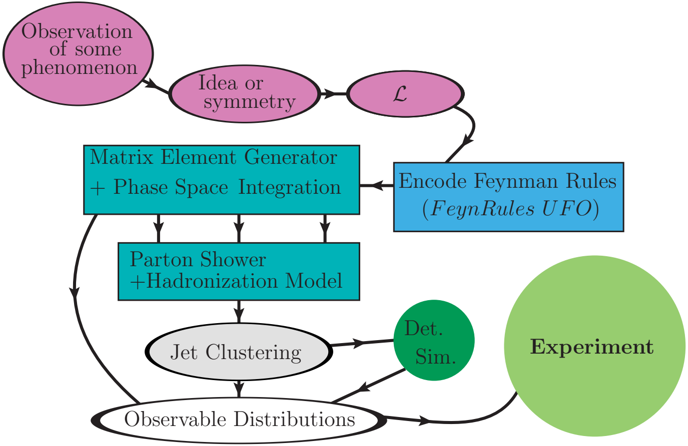
Fun Fact: possible to steer entire process with a script $\to$

```
rruiz@mac-1R0-359:~/Scripts/MG5aMC$ more runEffLRSMnlo_pp_Ne_Update.txt
launch EffLRSMnlo_pp_wr_Ne_NLO
order=NLO
shower=PY8
madspin=ON
done
set mwr 4000
set mn1 100
compute_widths wr+
compute_widths n1
set no_parton_cut
set nevents 100k
set LHC 13
set shower_card nsplit_jobs 100
set shower_card ue_enabled true

launch EffLRSMnlo_pp_wr_Ne_NLO
order=LO
shower=ON
madspin=ON
rruiz@mac-1R0-359:~/Scripts/MG5aMC$ ./bin/mg5_aMC ./runEffLRSMnlo_pp_Ne_Update.txt
```

Building Your Analysis

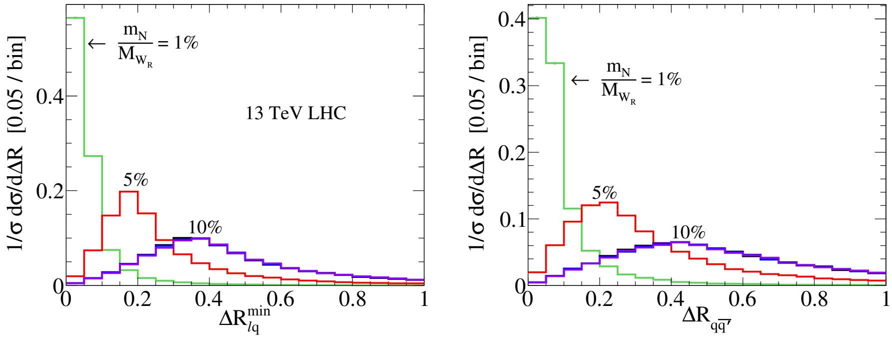
Regardles of the path, one always builds "an analysis" to impose "off-line" phase space cuts, and produce differential distributions ("plots")

(See Benj's talks and MA5 tutorial!)



Plotted: Separation $\Delta R_{ij} \equiv \sqrt{(\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2}$ between

(L) ℓ from N and nearest q and (R) $q\overline{q}$ pair



For a $1 \to 2$ decay, $m_{ij}^2 = (p_i + p_j)^2 \approx 2E_iE_j(1 - \cos\theta_{ij}) \approx E_iE_j \underbrace{\theta_{ij}^2}_{=\Delta R_{ij}^2}$

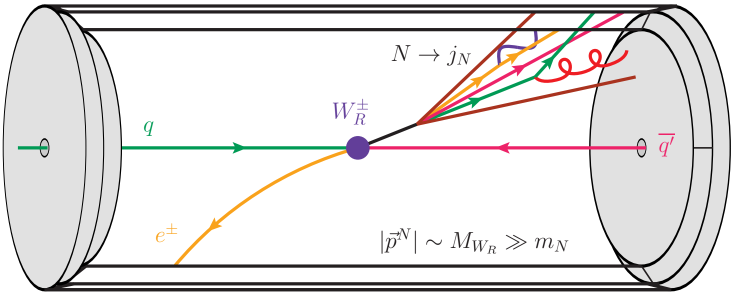
$\Rightarrow$ Angle between e and $(q\overline{q'})$-system $= \Delta R_{ij} \sim \frac{m_N}{\sqrt{E_iE_j}} \sim \frac{4m_N}{M_{W_R}}$

As $(m_N/M_{W_R}) \to 0$, N is more boosted, and its decay *more collimated:*

$$\Delta R_{ij} \sim\sim \frac{2m_N}{(M_{W_R}/2)} = 2/\gamma$$

For $\left(\frac{m_N}{M_{W_R}}\right) < 0.1, \theta_{e(q\overline{q'})}$ falls below $\theta^{\min}_{\ell X} = 0.4$ det. isolation threshold

Question: Is it necessary to identify the second lepton or jet multiplicity?

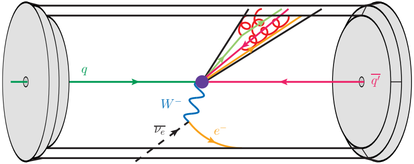


Fun Idea: Why not treat second $e^\pm$ like any other poorly isolated particle bathed in QCD radiation and label it as constituent of a jet?

Jets

What is a jet?

Suggestions? Intuitively: boosted, collimated hadronic activity.



Sterman-Weinberg jets: Cones with opening angle $\delta \ll 1$ containing up to $(E_{Tot.} - \epsilon)/N$ energy from hadrons.

To study jets, we consider the partial cross section $\sigma(E, \theta, \Omega, \epsilon, \delta)$ for e^+e^- hadron production events, in which all but a fraction $\epsilon \ll 1$ of the total e^+e^- energy E is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, lying within two fixed cones of solid angle Ω (with $\pi\delta^2 \ll \Omega \ll 1$) at an angle θ to the e^+e^- beam line.

Sterman, Weinberg ('77)

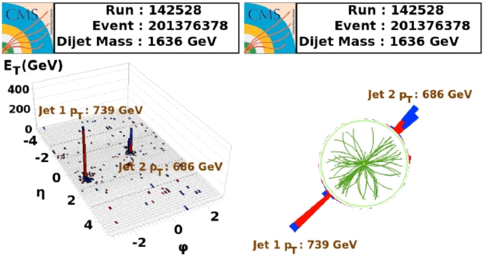
Since 1977, our understanding of jets and their constituents has evolved.

In particular,

- Application of ***infrared and collinear (IRC) safety***
- Invention of ***sequential jet clustering algorithms***

Infrared and Collinear Safety

Idea: physical quantities do not change under the emission of a single soft $(E_{rad} \to 0)$ and/or collinear $(\theta_{ij} \to 0)$ radiation



Eg., Theoretically and experimentally, a soft/collinear parton splitting should not change the number of jets.

It would be silly if adding a 1 GeV hadron to this $pp \to jj$ event made a difference.

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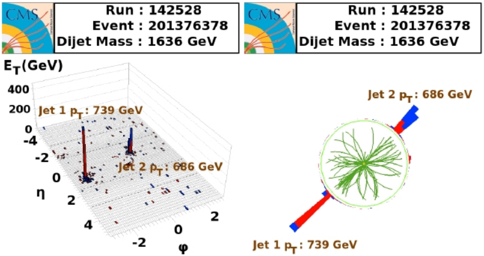


Eg., Theoretically and experimentally, a soft/collinear parton splitting should not change the number of jets.

It would be silly if adding a 1 GeV hadron to this $pp \to jj$ event made a difference.

Formally, for momenta $p_i = p_j + p_k$, an observable $\mathcal{O}$ is **IRC-safe** if

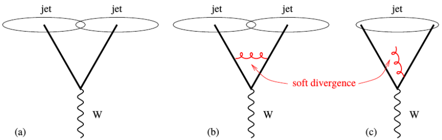
$$\mathcal{O}_{n+1}(p_1, \dots, p_j, p_k, \dots, p_{n+1}) = \mathcal{O}_n(p_1, \dots, p_j + p_k, \dots, p_{n+1})$$

when $E_j \to 0$, $E_k \to 0$, or $\hat{p}_i \cdot \hat{p}_j = \cos\theta_{ij} \to 1$.

Summary: collimated/soft objects are unresolvable

Breakdown of the Cone Clustering Algorithm

Consider two SW jets of radius R with their centers separated by R.



G. Salam [0906.1833]

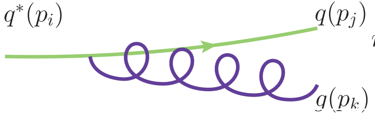
A single soft radiation may cause the two jets to merge into one, or the appearance of a third jet (SW jets do not require a minimum energy)

Recall: In soft/collinear limit, $(n+1)$-body kinematics map to the n-body configuration $\implies$ cancellation of radiation and loop IR poles [KLN Thm]

- If the number of jets changes in the soft limit, then **phase spaces** are different $\implies$ IR poles do not cancel [violation of KLN Thm]

Sequential Clustering Algorithms (1/3)

Consider a very energetic $1 \to 2$ parton splitting with $p_i = p_j + p_k$



$$m_{jk}^2 = (p_j + p_k)^2 = 2E_j E_k (1 - \cos\theta_{jk})$$
$$\approx 2p_T^j p_T^k [1 - (1 - \frac{\theta_{jk}^2}{2})] \approx z(1-z)(p_T^i)^2 \theta_{jk}^2$$

If $E_X \approx p_T^X$, then the parent's mass $\propto$ product of children's p_T

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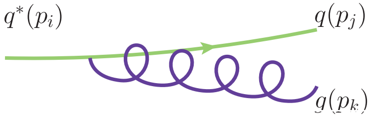

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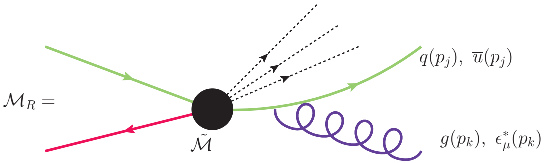
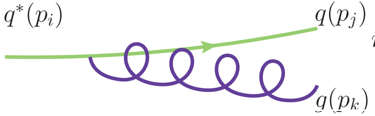
Lets define the *dimensionless* momentum fraction $z \equiv E_j/E_i \approx p_T^j/p_T^i$.



Since $\mathcal{M}_R \propto 1/m_{jk}^2$, the largest contribution to the matrix element is when $\theta, z \rightarrow 0$ or $z \rightarrow 1$. Unbroken gauge theories prefer soft/collinear radiation.

Sequential Clustering Algorithms (2/3)

Consider a very energetic $1 \to 2$ parton splitting with $p_i = p_j + p_k$



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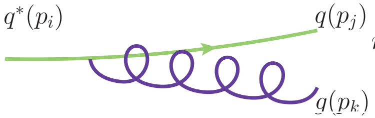

$$m_{jk}^2 = (p_j + p_k)^2 = 2E_jE_k(1-\cos\theta_{jk})$$
$$\approx 2p_T^jp_T^k[1-(1-\tfrac{\theta_{jk}^2}{2})] \approx z(1-z)(p_T^i)^2\theta_{jk}^2$$

Now, lets **define** the "distance" measure:

$$d_{jk} = \min(p_T^j, p_T^k)^p \Delta R_{jk}^2 / R^2, \qquad \Delta R_{jk} = \sqrt{(\Delta\phi_{jk})^2 + (\Delta\eta_{jk})^2}$$

- For $p = 2$, $d_{jk} \propto m_{jk}^2$, where $\min(z, 1-z) \approx z(1-z)$ as $z \to 0, 1$
- For $p = 0$, $d_{jk} \propto \theta_{jk}^2 \implies$ distance to geometric neighbors
- For $p = -2 \implies$ distance from hardest object to geometric neighbor

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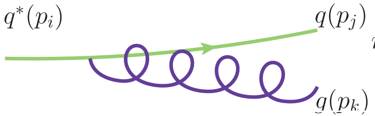

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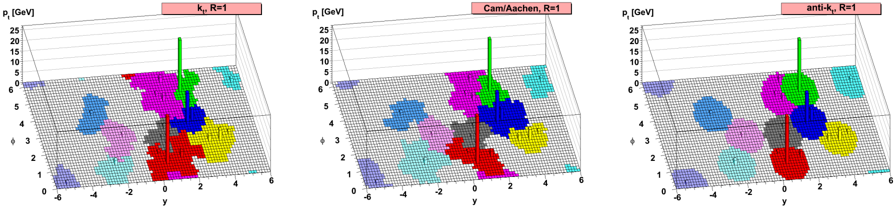
Sequential clustering/recombination algorithm:

1. For constituents j, k, calculate d_{jk}
2. For j, calculate "distance" to beam axis $d_{jB} = (p_T^j)^{2p}$
3. Find smallest d_{jB}, d_{jk}. If d_{jB}, call j a jet; else, merge (j, k) and restart

Sequential Clustering Algorithms (3/3)

Choice of momentum weighting p changes pheno appreciably

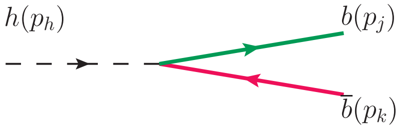
- $p = 2$ is the k_T-algo. and clusters softer/more col. neighbors first
- $p = 0$ is the Cambridge/Aachen algo. and clusters closest neighbors
  - Useful for studying jet substructure since no momentum scale bias
- $p = -2$ is the anti-k_T-algo. and clusters hardest object to neighbors
  - "Ideal" properties and reproduces cone-like jet structure



By construction, all k_T-style algorithms are IRC-safe. [0802.1189]

Jet Structure and Substructure

Consider the Higgs decay $h \to b\overline{b}$ with $p_h = p_j + p_k$



$$m_h^2 = (p_j + p_k)^2 \approx z(1-z)E_h^2\theta_{jk}^2$$

$$\to \Delta R_{jk} \sim \theta_{jk} = \frac{m_h}{\sqrt{z(1-z)}E_h} = \frac{2m_h}{E_h}$$

In $1 \to 2$ decays we have $z = (1-z) = 0.5 \implies \frac{1}{\sqrt{z(1-z)}} = 2.$

Decays of boosted objects are collimated: $\gamma = E/m > 2 \implies \Delta R_{jk} < 1$

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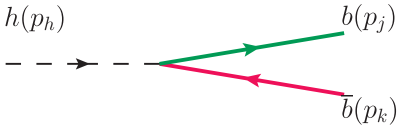

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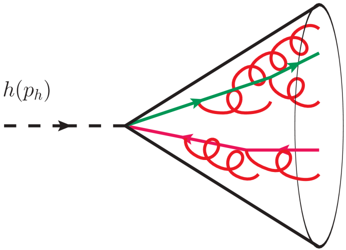
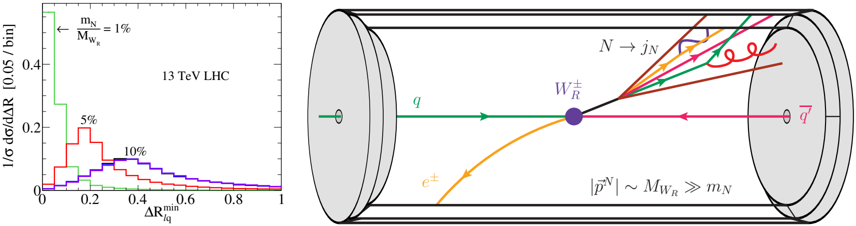


Collimated objects are difficult to resolve.

Solution: Instead of treating decay products as individual objects, consider them as a single object, a *Higgs jet*.

Boosted Heavy Neutrinos

Treat $\ell_2^\pm$ like any other poorly isolated parton bathed in QCD radiation and cluster via a sequential jet algorithm



For $m_N \ll M_{W_R}$, we consider a different collider search

$$pp \rightarrow W_R \rightarrow e^\pm N \rightarrow e^\pm j_{\rm Fat}$$

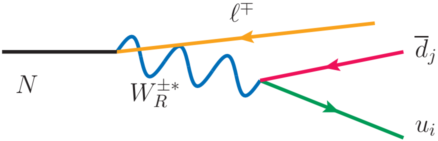
Procedure: After event generation check if $\ell^\pm$ is hadronically isolated

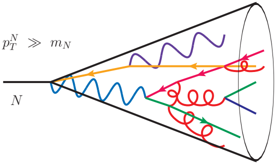
- If $\ell^\pm$ not hadronically isolated, label as QCD parton
- Cluster all QCD partons with $R = 1$ anti-k_T algorithm

Neutrino Jets (n):

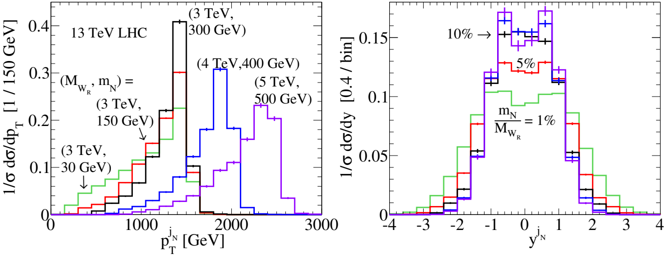
(i) hadronically decaying, high-p_T heavy neutrinos;

(ii) a jet with substructure originating from a heavy neutrino

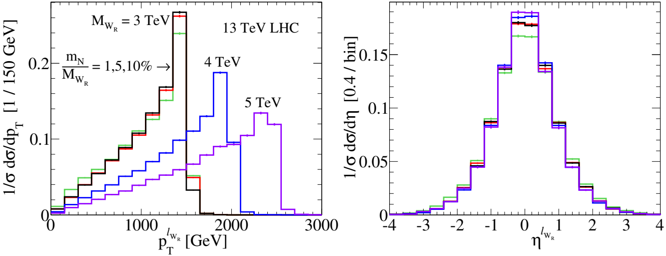




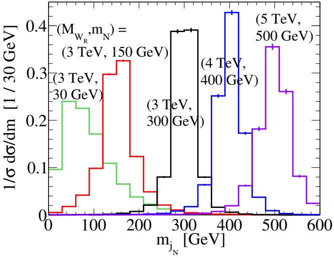
First sanity check: Up to mass effects, kinematics of j_N:

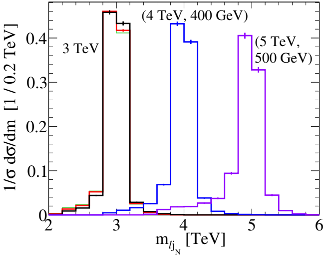


match the kinematics of $\ell^{\pm}_{W_R}$ (the charged lepton from the W_R decay):

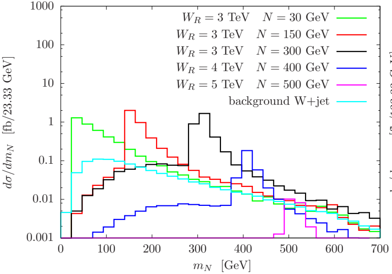


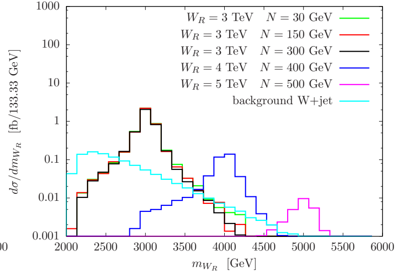
At parton-level + smearing, expected invariant mass peaks are visible:





+ parton shower + P.U. + detector simulation, structures are retained:





Studying the Backgrounds

- For $pp \to \ell^\pm + j + X$, **lots** of SM backgrounds
  - $V + 1j + X$, VV, tX, $t\bar{t}X$
- Apply standard particle identification + fiducial criteria:
  - Generator-level cuts to regulate matrix elements
  - Decay + $p_T^{\ell\ (\mathrm{Gen.})} > 1$ TeV + improve MC efficiency
  - Electron particle ID + second charged lepton veto
  - MET $= |\sum \vec{p}_T^{\mathrm{vis}}| < 35$ GeV (no intrinsic MET, inherited from $\ell\ell jj$)

Cut \ σ^{LO} [ab]	Wj	WZ	$t\bar{t}$	$t\bar{t}j$	tbj	eej	WWj
$p_T^{j,b} > 30$ GeV, $\lvert\eta^{j,b}\rvert < 4.5$ $+\Delta R_{jb} > 0.4, \Delta R_{\ell X} > 0.3$ No Decay	2.17×10^9	11.0×10^6	63.8×10^6	44.0×10^6	4.18×10^6	344×10^6	327×10^3
+Decay+ $p_T^{\ell\ \max} > 1$ TeV+ $\not{E}_T < 50$ GeV	218	2.61	0.201	0.660	0.062	184	0.637
+Smearing+$\lvert\eta^\ell\rvert < 2.0$ $+\ p_T^\ell > 35$ GeV + + 2nd $e^\pm$ veto	218	–	–	–	–	57	–
$\not{E}_T < 35$ GeV	85	–	–	–	–	25	–

Signal Discovery Potential

Due to the unusual signal topology, final analysis cuts are pretty simple:

- $p_T^{\ell, j_N} > 1$ TeV, MET<100 GeV, $|m(\ell, j_N) - M_{W_R}| < 200$ GeV
- Analysis efficiency measured my $\mathcal{A} = \sigma^{\text{All Cuts}}/\sigma^{\text{Fid. Kin.}}$

$\sigma(pp \to W_R^{\pm} \to \ell^{\pm} N \to \ell^{\pm} j_N)$ [fb]					
13 TeV LHC					
	(M_{W_R}, m_N) [TeV, GeV]				
Cut	$(3, 30)$	$(3, 150)$	$(3, 300)$	$(4, 400)$	$(5, 500)$
Fiducial+Kinematics +Detector+K-Factor [Eq. (4.13)]	6.87	6.76	6.39	0.69	0.06
MET [Eq. (4.14)]	4.30 (63%)	4.22 (62%)	4.02 (63%)	0.40 (58%)	0.03 (50%)
$m_{\ell j_{\text{Fat}}}$ [Eq. (4.15)]	3.64 (85%)	3.59 (85%)	3.41 (85%)	0.30 (75%)	0.02 (67%)
$\mathcal{A} = \sigma^{\text{Cuts}}/\sigma^{\text{Fid.+Kin.}}$	53%	53%	53%	43%	33%
$\frac{S}{\sqrt{S+B}}$ [$\mathcal{L} = 10$ fb^{-1}]	5.9	5.9	5.7	1.7	0.4
$\frac{S}{\sqrt{S+B}}$ [100 fb^{-1}]	19	19	18	5.4	5.7 [2 ab^{-1}]

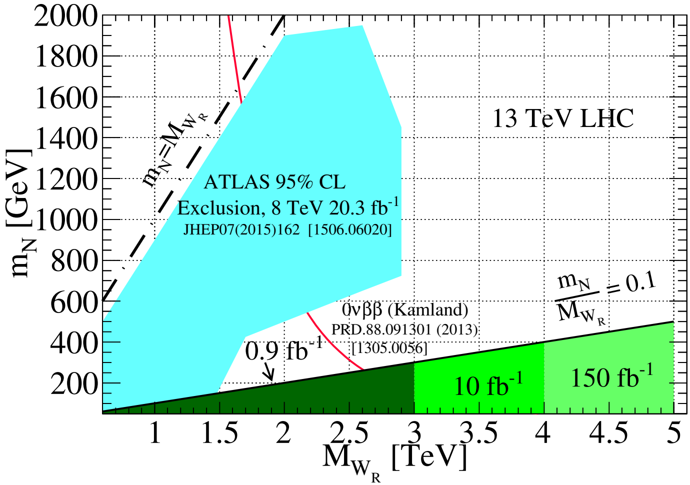
Extrapolate for other masses and set 95% sensitivity if

$$N_{\text{evt}} = \mathcal{L}_{95} \times \sigma^{\text{NLO+NNLL}} \times \text{BR} \times \text{BR} \cdot \epsilon \cdot \mathcal{A} \geq N_{95} = 3$$

Discovery Potential

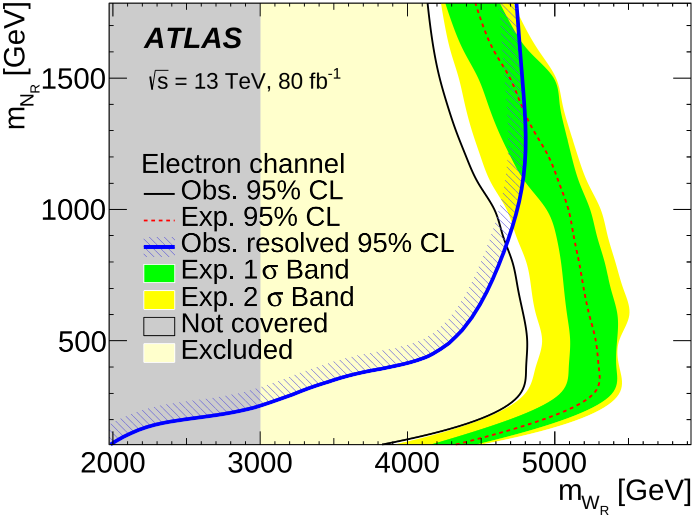
With neutrino jets, we recover lost sensitivity:

- At 13 TeV, $M_{W_R} \approx 3$ (4) [5] TeV discovery after 10 (100) [2000] fb^{-1}



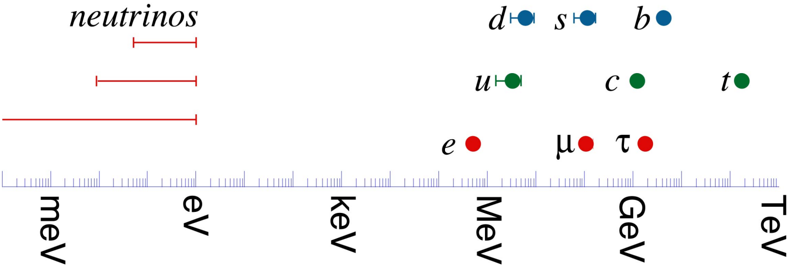
Searches for Neutrino Jets

Sadly, no discovery but new analysis object and lots of territory to explore!



Summary and Outlook

Big Picture



Unambiguous expt evidence that neutrino have nonzero masses

- This is contrary to the Standard Model (SM) of particle physics
- Under general arguments, implies new particles exist

We have covered many topics this week:

- Neutrino masses and neutrino oscillations
- Neutrino mass models and their collider tests
- Jets and searches for neutrino jets

The origin of tiny neutrino masses is a major open question in HEP

- The solution is not obvious but proposals are being tested
- Important since proposals have strong connections to cosmology, dark matter, unification, and more

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- New strategies, new software tools, and new LHC discovery prospects
  - one example: neutrino jets
  - many results applicable to other LHC searches, e.g., dark matter
- Plenty of work for new students and postdocs

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It is an incredibly exciting time for HEP

Until we have discovered and verified the origin of neutrino masses, and an explanation to their smallness, we have much more work to do.

Thank you for your time.