Heavy Type III Seesaw Leptons at NLO in QCD[1]

Phenomenology Symposium 2015

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[1] [arXiv:1505.yyyyy]

The Plan

Today, I would like to talk about...

- motivation for physics beyond the SM from neutrino masses
- motivation for QCD corrections to BSM processes
- Type III Seesaw Mechanism
- Phase space slicing method
- Results

The Standard Model (SM) of Particle Physics

SM: A very successful theory that describes how matter and energy function at small distances.

Consists of spacetime and internal symmetries:

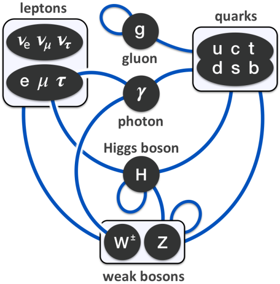
Lorentz, color, weak isospin, weak hypercharge,

and several fields that interact through these conserve currents:

$$L^i, \quad Q^{i\alpha}; \quad {u_R}^{i\alpha}, \quad {d_R}^{i\alpha}, \quad {e_R}^i; \quad \Phi.$$

Impose local invariance ($\partial_\mu \to \partial_\mu + igA_\mu$), break with $\langle \Phi \rangle = v/\sqrt{2}$.

During electroweak (EW) symmetry breaking (EWSB), anything that couples directly to the Higgs field acquires a spontaneously generated mass proportional to this interaction strength.



Note: In SM, ν are massless

Nonzero Neutrino Masses are BSM Physics

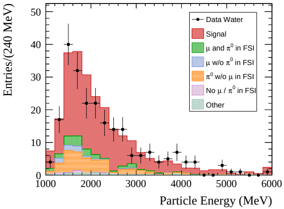
To generate ν masses similar to other SM fermions, we need N_R

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi} N_R + H.c. \implies -m_D \overline{\nu_L} N_R + H.c.$$

$m_D = y_\nu \langle \Phi \rangle$, and y_ν is the neutrino's Higgs Yukawa coupling.

Since ${N_R}^i$ do not exist in the SM, neutrinos must be massless.

On the other hand, we have discovered through neutrino oscillations that massless neutrinos is not an accurate model.
[T2K ν_e appearance, 1503.08815v3]



Neutrino masses are evidence of physics beyond the SM.

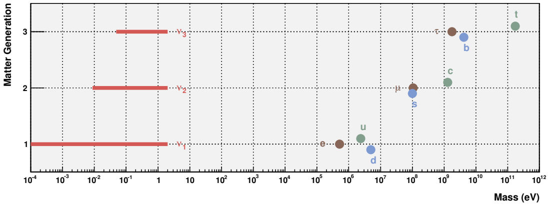
So, neutrinos have masses $\lesssim \mathcal{O}(0.1)$ eV.

Is this a problem?

Maybe.

The SM: a Complete but Unsatisfactory Picture

The SM, via the Higgs Mechanism, predicts *how* elementary fermions obtain mass, i.e., $m_f = y_f \langle \Phi \rangle$, **not** their values.



[1109.5515v2]

Spanning many orders of magnitudes, the relationship of fermion masses is a mystery.

- Neutrinos have unusually small masses.
- Is this due to new physics?

Importance of Being Earnest (or QCD Corrections)

BSM at NLO in QCD precision is becoming standard:

- More accurate **rate** predictions (reduced scale dependence)
- More accurate description of **distribution shapes** (crucial!)

Seesaw mechanisms are a class of models that simultaneously explain the origin of neutrino masses and their smallness compared to other elementary fermions:

- Type I: Heavy Majorana neutrino $N\ell^{\pm}$ estimated at NNLO[2]
- Type II: W' at NLO+NLL[3]
- Type II: $SU(2)_L$ triplet scalars $H^{++}H^{--}$ at NLO[4]
- Type III: $SU(2)_L$ triplet fermion $NE^{\pm}$, $E^{+}E^{-}$ ....
  previously only at LO (**This talk**)

[2] [Alva, et al, 1411.7305]
[3] NLO [Sullivan (2002)], + NLL[Jezo, et al, 1410.4692]
[4] [Muhlleitner, Spira (2003)]

Type III Seesaw Mechanism

Type III Seesaw Mechanism

Introduce SU(2)$_L$ **fermion** triplet (zero hypercharge) with mass m_Σ

$$\Sigma = \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}, \quad \mathcal{L}_\Sigma = \frac{1}{2}\mathrm{Tr}\left[\overline{\Sigma} i \not{D} \Sigma\right] - m_\Sigma \overline{\Sigma^a}\Sigma^a$$

and couple to SM leptons via Higgs Yukawa couplings

$$\mathcal{L}_Y = y_\Sigma \overline{L}\, \Sigma^a \sigma^a (i\sigma^2)\Phi \to \frac{y_\Sigma}{\sqrt{2}}(v+h)\overline{\nu_L}\Sigma^0 + y_\Sigma (v+h)\overline{e_L}\Sigma^-$$

The resulting mass matrix for neutral fermions is

$$\begin{pmatrix} \overline{\nu_L} & \overline{\Sigma^0_L} \end{pmatrix} \begin{pmatrix} 0 & y_\Sigma v/\sqrt{2} \\ y_\Sigma v/\sqrt{2} & m_\Sigma \end{pmatrix} \begin{pmatrix} \nu^c_R \\ \Sigma^0_R \end{pmatrix}$$

Assuming that m_Σ (Majorana mass) $\gg y_\sigma v$ (Dirac mass)

$$m_{\text{light}} \approx -\frac{y_\Sigma^2 v^2}{4 m_\Sigma}, \quad m_{\text{heavy}} \approx -m_\Sigma$$

For $m_{\text{light}} = 0.1$ eV, if $y_\Sigma \sim y_e \approx 3 \cdot 10^{-6}$, then $m_{\text{heavy}} \approx 1.3$ TeV!

Type III Interaction Theory

Combining Σ fields and their conjugates

$$E^- \equiv \begin{pmatrix} \Sigma^- \\ \Sigma^{+c} \end{pmatrix}, \quad N \equiv \begin{pmatrix} \Sigma^0 \\ \Sigma^{0c} \end{pmatrix}.$$

In the Gauge basis (before mixing),

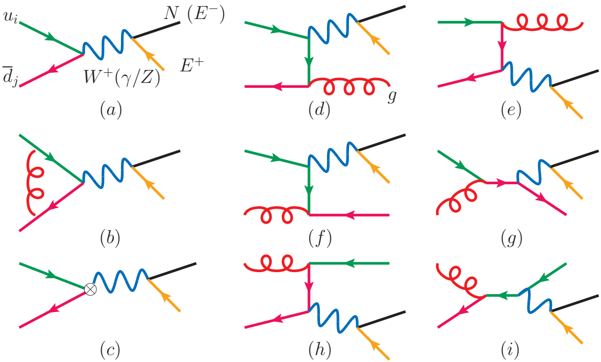
$$\mathcal{L}_\Sigma^{\text{Gauge Basis}} \ni -\overline{E^-}\left(e\gamma^\mu A_\mu + g\cos\theta_W \gamma^\mu Z_\mu\right) E^- \\ - g\overline{E^-}\gamma^\mu W_\mu^- N - g\overline{N}\gamma^\mu W_\mu^+ E^-$$

In the mass basis (after mixing)

$$\mathcal{L}_\Sigma^{\text{Mass Basis}} \ni -\overline{E^-}\left(eY_{EE}\gamma^\mu A_\mu + g\cos\theta_W Y_{EE}\gamma^\mu Z_\mu\right) E^- \\ - gY_{EN}\overline{E^-}\gamma^\mu W_\mu^- N - gY_{EN}\overline{N}\gamma^\mu W_\mu^+ E^-$$

with $Y_{EN},\ Y_{EE} \sim \mathcal{O}(1)$.

We are now in position to compute
$pp \to NE^{\pm}$ and $pp \to E^+E^-$ at NLO in QCD



- (a) Born-level CC and NC Drell-Yan processes
- (b) nonzero virtual correction
- (d-e) $qq \to \overline{L}Lj$, (f-g) $qg \to \overline{L}Lj$, (h-i) $\overline{q}g \to \overline{L}Lj$

Phase Space Slicing (1/2)[5]

Generic procedure for NLO corrections to *n*-body final state:

$$\sigma^{\rm NLO} = \sigma^{\rm 1-loop} + \sigma^{\rm Radiation} \equiv \sigma^{\rm LO} + \underbrace{\sigma^{\rm Virtual} + \sigma^{\rm Radiation}}_{\rm IR\ poles\ cancel}$$

Phase space slicing (**PSS**) is a method for simplifying $\sigma^{\rm NLO}$ calculation by breaking up $\sigma^{\rm Rad}$ into finite and non-finite pieces

- Divide and conquer into more manageable terms
- Non-finite pieces contain collinear and soft poles

PS is *sliced* into soft/hard and collinear/non-collinear regions:

- **Soft** if $E_j < \delta_s \times \hat{s}, \quad \hat{s} = E_{cm}^2$
- **Collinear** if $\hat{t}_{ij}, \hat{s}_{ij} < \delta_c \times \hat{s}$

[5] Harris and Owens [arXiv:hep-ph/0102128]

Phase Space Slicing (2/2)

Radiation process is split into several pieces:

$$\sigma^{\mathrm{Rad}} = \sigma^{H\overline{C}} + \sigma^{S} + \sigma^{SC} + \sigma^{HC}$$

- Hard, non-collinear: $\sigma^{H\overline{C}}$ **finite** in $d = 4$ dimensions
- Soft: $\sigma^{S} \propto \sigma^{B}$ by soft **factorization**
- Soft, collinear: $\sigma^{S\overline{C}} \propto \sigma^{B}$ by soft **factorization**
- Hard, collinear: $\sigma^{HC} \propto \sigma^{B}$ by collinear **factorization**
  Must be **subtracted** since already in definition of PDF

Virtual piece calculated as usual

$$\sigma^{1-\mathrm{loop}} = \sigma^{B} + \sigma^{V} + \mathcal{O}(\alpha_s^{k+2})$$

which we can combine with the divergent terms above:

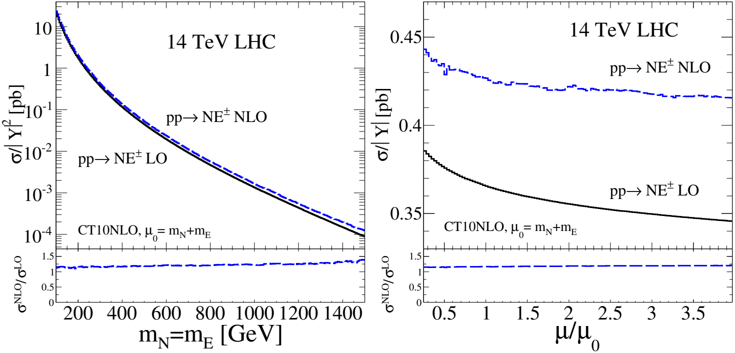
$$\sigma^{B} + \sigma^{V} + \sigma^{S} + \sigma^{SC} = \text{finite (KLN theorem)}$$

NLO calculation is now a sum of n- and $(n+1)$-body final states

$$\sigma^{\mathrm{NLO}} = \underbrace{\sigma^{\mathrm{NLO}}_{\mathrm{n-body}}}_{B+V+S+SC-HC} + \underbrace{\sigma^{\mathrm{NLO}}_{\mathrm{(n+1)-body}}}_{H\overline{C}}$$

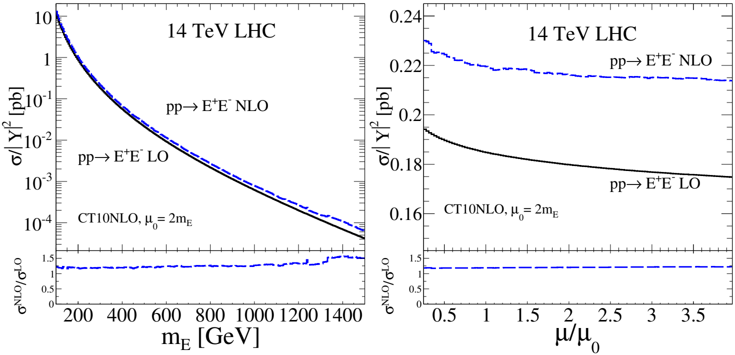
Results

Charge Current



- NLO rate $\approx 1.2 - 1.4\times$ LO rate (normal for DY rates)
- $K^{\text{NLO}} = \sigma^{NLO}/\sigma^{\text{LO}}$ stable under variation of factorization/renormalization scale (μ)

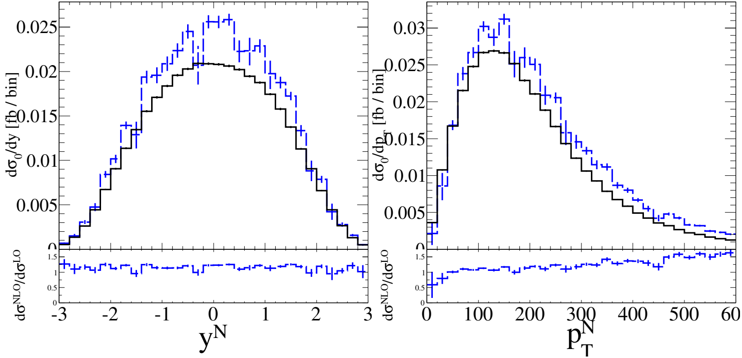
Neutral Current



- Results similar to charge current case
- NLO rate $\approx 1.2 - 1.4\times$ LO rate (normal for DY rates)
- $K^{\mathrm{NLO}} = \sigma^{NLO}/\sigma^{\mathrm{LO}}$ stable under variation of factorization/renormalization scale (μ)

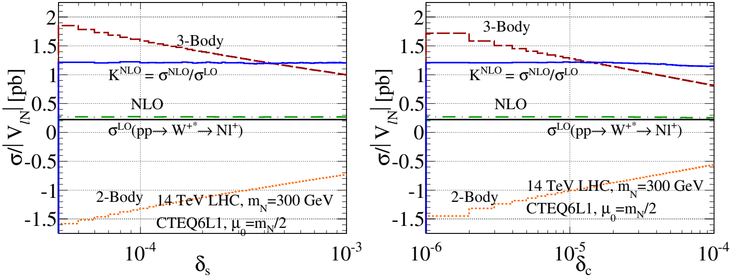
Differential Distributions

New: Distributions fully differential at NLO in QCD.



Shapes changes to $pp \to N\ E^{\pm}\ X$ appear modest.

Sanity Check: Cutoff (In)Dependence



Phase space slicing introduces two cutoff scales:

- Soft (δ_s) and collinear (δ_c) must be small ($\ll 1$) such that factorization is a good approximation
- Summing terms will remove dependence on $\delta_s,\ \delta_c$:

$$\sigma^{2\ Body} + \sigma^{3\ Body} \sim \log \frac{\delta_s \hat{s}}{\hat{s}} + \log \frac{\hat{s}}{\delta_s \hat{s}}$$

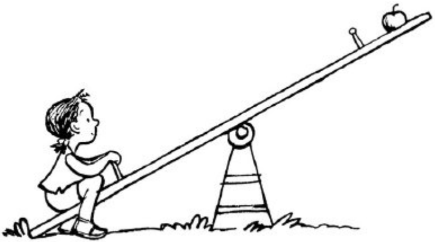
Despite large cancellations, stable under large variations of cutoffs

Summary and Conclusion

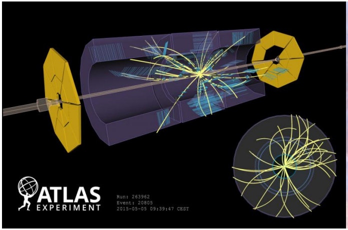
Seesaw mechanisms are a class of models that simultaneously explain the origin of neutrino masses and their smallness compared to other elementary fermions.

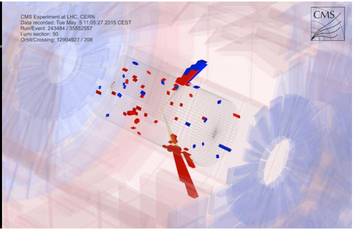
The production of Type III Seesaw leptons (vector-like $\mathrm{SU}(2)_L$ fermions) in *pp* collisions has been calculated at NLO in QCD:

- $K^{\mathrm{NLO}} = \sigma^{NLO}/\sigma^{\mathrm{LO}}$ factors span $1.2 - 1.4$ at 14 TeV LHC
- Factorization/renormalization scale uncertainty is $\mathcal{O}(5\%)$



First Collisions of LHC Run II





Thank you.