

# Colorful Production of Heavy Neutrinos at Hadron Colliders <sup>1</sup>

Phenomenology Symposium 2017

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 **elusives**  
neutrinos, dark matter & dark energy physics



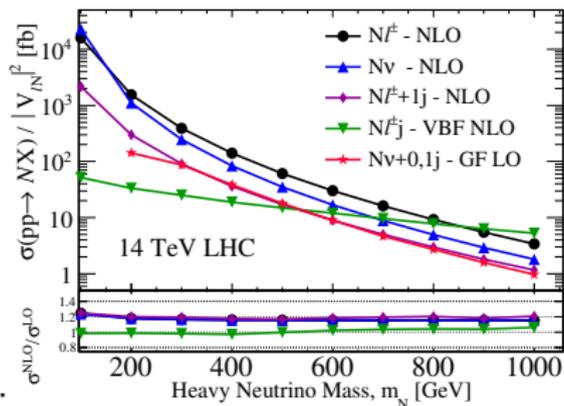
 **invisiblesPlus**

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<sup>1</sup>with M. Spannowsky, P. Waite [1705.soon]. NOT a talk on jet veto resummation 

# The Plan for Today

- Motivation for beyond the SM physics from neutrino masses



- This plot<sup>2</sup> has been updated:

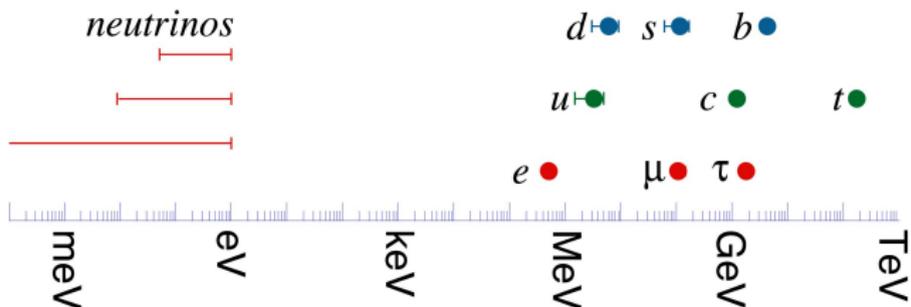
First comparison of **all** leading  $N$  production modes with infrared/collinear (IRC)-safe collider definitions (stable under pert. correction)

- Corrections to  $gg \rightarrow N\nu_\ell$  has qualitatively changed this plot
- Summarize and Conclude

<sup>2</sup>Degrande, Mattelaer, RR, Turner, [1602.06957]; UFO available from FeynRules site

# Our Motivation

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



Spanning many orders of magnitudes, the relationship of fermion masses is still a mystery. Two observations:

- 1 Neutrinos have mass (BSM physics! 🏆)
- 2 Neutrinos have unusually small mass (new physics? 🏆?)

# Seesaw Mechanisms: Pathways to Naturally Small $m_\nu$

**Seesaw Mechanisms:** Class of Standard Model extensions that explain the origin of  $m_\nu$  and how  $m_\nu \ll m_e, m_{\text{top}}$ . Involve introduction of new SM multiplets, e.g.,  $N_R$ ,  $\Delta_L$ , and possibly gauge interactions, e.g.,  $SU(2)_L$ .

- Minimal extensions codified in [Ma'98]: Types I, II, and III

In heavy neutrino extensions (Type I, Inverse/Linear, LRSM), heavy gauge-singlet neutrinos mix with SM neutrinos:

$$\underbrace{|\nu_\ell\rangle}_{\text{chiral/gauge basis}} = \underbrace{\sum_{m=1}^3 U_{\ell m} |\nu_m\rangle + \sum_{m'=1}^n V_{\ell m'} |N_{m'}\rangle}_{\text{mass basis}}$$

Ignoring  $L$  violation, heavy  $N$  Feynman rules are simple and universal:

$$W\ell\nu_\ell \rightarrow W\ell N_{m'} \quad : \quad \frac{-ig}{\sqrt{s}} \gamma^\mu P_L \rightarrow \frac{-ig}{\sqrt{s}} \gamma^\mu P_L V_{\ell N_{m'}}^*$$

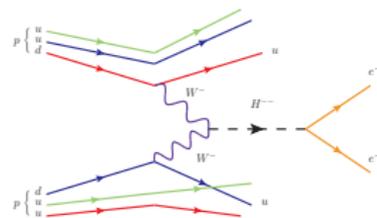
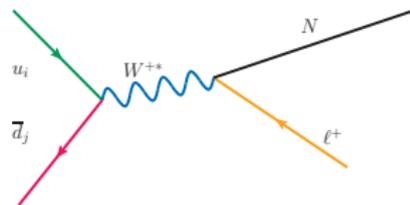
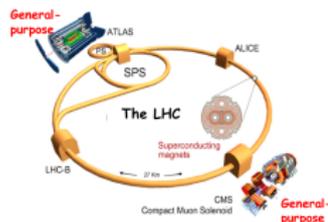
# Collider Connection to Seesaw Models

Through SM interactions and mixing, TeV-scale Seesaw models *predict* production of Seesaw partners, e.g.,  $N_R$ ,  $Z_{B-L}$ , in  $ee/ep/pp$  collisions<sup>3</sup>

$$DY : q\bar{q} \rightarrow \gamma^*/Z^* \rightarrow T^+T^- \quad \text{and} \quad q\bar{q}' \rightarrow W^{\pm*} \rightarrow \ell^{\pm}N \quad \text{or} \quad T^{\pm}T^0$$

$$VBF : W^{\pm}W^{\pm} \rightarrow H^{\pm\pm}$$

$$GF : gg \rightarrow h^*/Z^* \rightarrow N\nu\ell$$



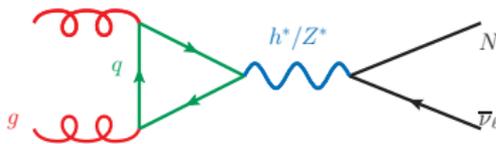
- If heavy states are kinematically accessible at a given collider energy
- Sizable interactions strength (coupling might be suppressed by mixing)

Then direct, on-shell production of Seesaw particles at colliders is possible

<sup>3</sup>Many processes cataloged in [[hep-ph/9311257](https://arxiv.org/abs/hep-ph/9311257)] and compared in [[1602.06957](https://arxiv.org/abs/1602.06957)]

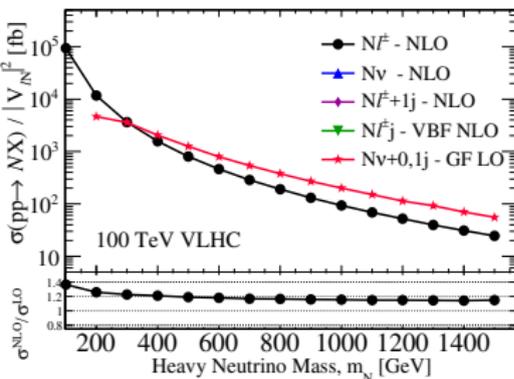
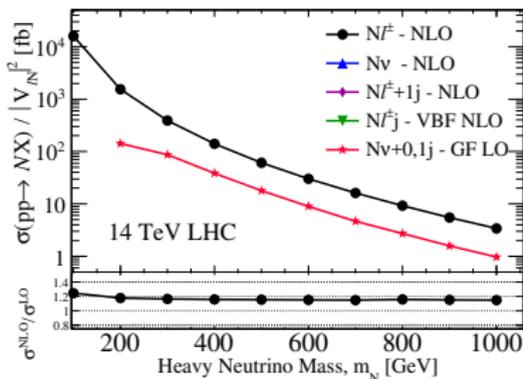
**The posh channel.**

# Gluon Fusion



**GF** is anomalous (loop-induced) at LO<sup>4</sup>

- Top loop  $\implies$  heavy fermion scattering [Appelquist, Chanowitz, ('87)]
- Automated two-loop technology does not exist (yet), so "only" GF@LO



At 100 TeV, GF is bigger than DY!

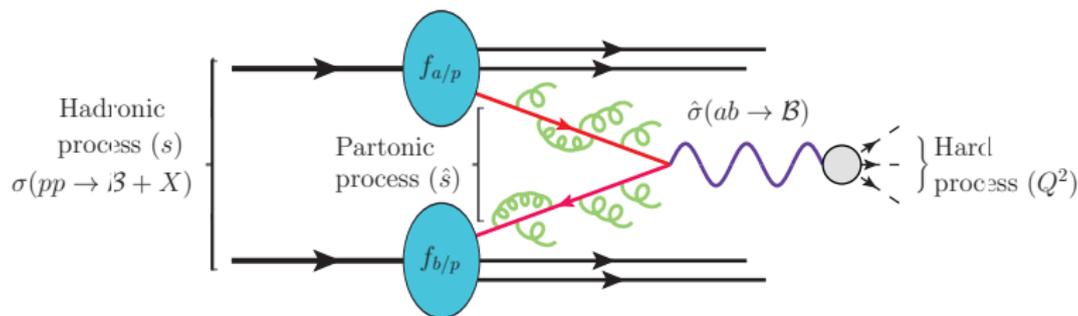
<sup>4</sup>Z\* contribution: Dicus, Roy (PRD '91); h\* contribution: Munich team [1408.0983]; FeynRules + differential (+matching/merging with +1j): IPPP team [1602.06957]

## Threshold (or Soft Gluon) Resummation<sup>5</sup>

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<sup>5</sup>**Non-experts:** Roughly speaking, resummation is a procedure for collecting most (or next-to-most or next-to-next-...) divergent radiation terms at each order of perturbation theory to obtain a finite result. Useful since FO results breakdown near poles. > ≡ ≡ ↶ ↷ ↻

# Resonances near Threshold: when $Q^2 \equiv (p_N + p_\nu)^2 \sim \hat{s}$



Near phase space boundaries,  $g$  radiation is divergent. For  $E_g \ll E_{N\nu_\ell}$ ,

$$\begin{aligned} \sigma(pp \rightarrow N\nu_\ell + g) &\sim \int d^{4-2\epsilon} PS_2 \sim \lambda^{\frac{1-2\epsilon}{2}} \left(1, \frac{Q^2}{\hat{s}}, \frac{k_g^2=0}{\hat{s}}\right) \\ &= \left(1 - \frac{Q^2}{\hat{s}}\right)^{1-2\epsilon} \sim 2\epsilon \log\left(1 - \frac{Q^2}{\hat{s}}\right), \end{aligned}$$

As  $Q^2 \rightarrow \hat{s}$ , logs diverge since  $g$  near **threshold** forced to be soft. In this limit,  $\sigma^{\text{FO}}$  not reliable, but **soft factorization & resummation** possible!

## Threshold (or Soft Gluon) Resummation for Gluon Fusion<sup>6</sup>

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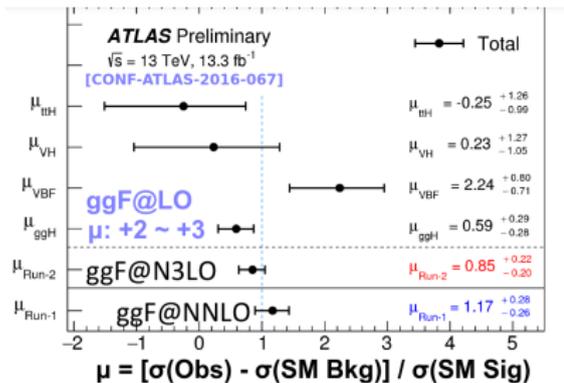
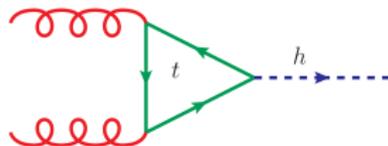
Myth that QCD is Unimportant for Colorless BSM

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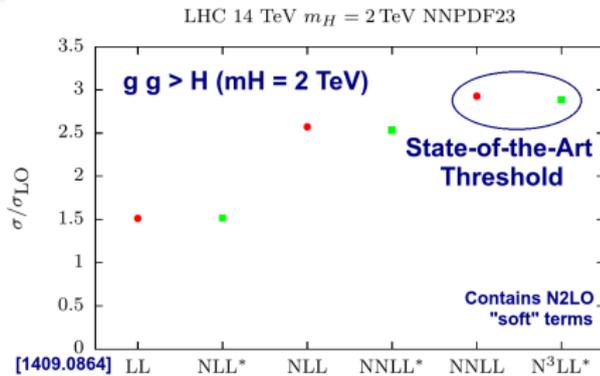
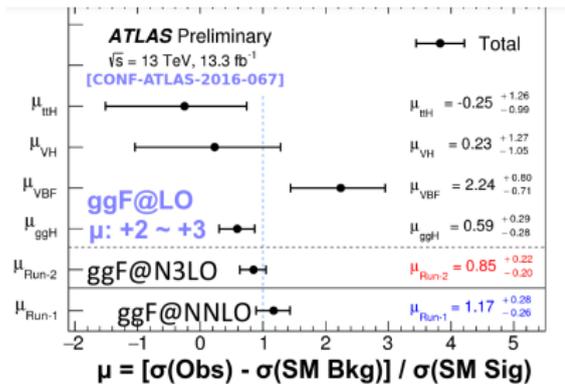
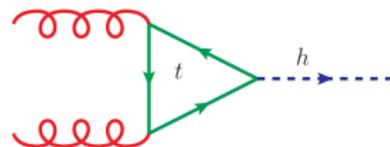
# Threshold Resummation for GF

- QCD corrections to  $gg \rightarrow h_{\text{SM}}$  are *large*
- GF@LO is *excluded* by LHC!

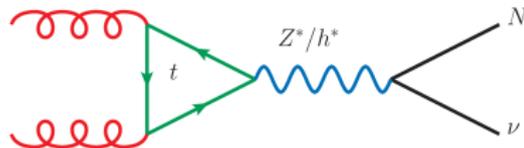


# Threshold Resummation for GF

- QCD corrections to  $gg \rightarrow h_{\text{SM}}$  are *large*
- GF@LO is *excluded* by LHC!



- Corrections also *large* for heavy  $H^0$ ,  $A^0$ .
- Resum. captures leading FO corrections.
- Bonvini, et al, [1409.0864]



- What about heavy  $N$  production?

Common Statement: “QCD is unimportant for colorless BSM”

More correct: “**Away from phase space boundaries**, **totally inclusive** fixed order QCD corrections are  $\sim +20 - 40\%$  for colorless  $s$ -channel BSM processes **initiated by quarks** for non-hierarchical scale choices”

These are the assumptions for the **Collinear Factorization Theorem**<sup>7</sup>

$$\sigma(pp \rightarrow A + \text{anything}) = \sum_{i,j} f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}(ij \rightarrow A)$$

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<sup>7</sup>Collins, Soper, Sterman ('85,'88,'89); Collins, Foundations of pQCD (2011)

<sup>8</sup>Mitra, Scott, RR, Spannowsky [1607.03504]

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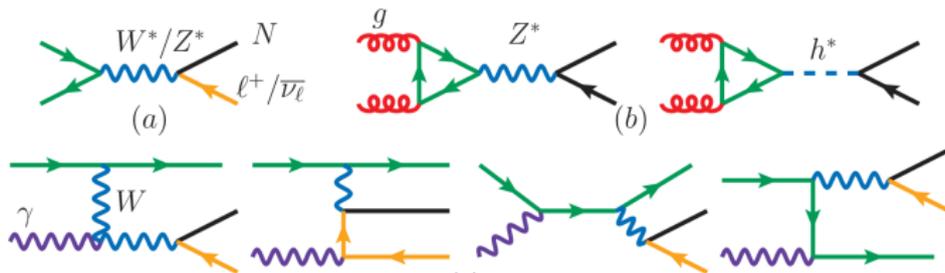
Relaxing these assumptions has consequences:

- For  $M_{W'/Z'} \sim \sqrt{s}$ ,  $\sigma_{DY}^{NLO+N^2LL} / \sigma^{LO} \sim 2 - 2.5$ <sup>8</sup>
- In  $gg \rightarrow H^0/A^0$  for any  $m_{H/A}$ ,  $\sigma^{N^3LX} / \sigma^{LO} \sim 2 - 3$
- How about  $gg \rightarrow h^*/Z^* \rightarrow N\nu$ ?
  - ▶ Recycling  $K$ -factors for  $gg \rightarrow H/A$  not justified.

<sup>7</sup>Collins, Soper, Sterman ('85,'88,'89); Collins, Foundations of pQCD (2011)

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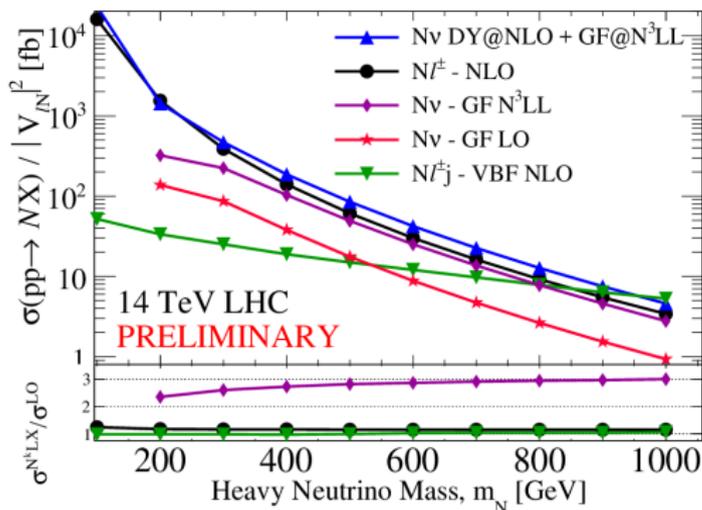
# RG-Improved Heavy $N$ Production at Hadron Colliders<sup>9</sup>



$$\sigma_{GF}^{N^3LL} / \sigma_{GF}^{LO} \sim 2 - 3$$

GF formally  $\mathcal{O}(\alpha_s^2)$  correction to neutral current DY, so should be summed coherently

Neutral current production of  $N$  is the largest rate at LHC  
[Preliminary]



<sup>9</sup>RR. Spannowsky, Waite [Very Soon]

# Summary

The origin of tiny neutrino masses is still a puzzle and may manifest at **collider experiments** via the production of Seesaw partners, e.g.,  $W_R^\pm$ ,  $N$ .

Over the past decade, a revolution in collider tools and formalism!

- Data indicate QCD corrections are large for gluon-induced states
- Maturity of  $N^k LX$  formalism allows application to BSM
- *QCD is a useful and powerful tool for Seesaws@Colliders*

**Remember:** “The LHC is planned to run over the next 20 years, with several stops scheduled for upgrades and maintenance work.” [press.cern]

- High-Luminosity LHC and Belle II goals:  $1\text{-}3 \text{ ab}^{-1}$  and  $50 \text{ ab}^{-1}$
- Premature to claim “nightmare scenario” (SM Higgs + nothing else)

The image features a large, light blue oval logo with a wavy line extending from its left and right sides. Inside the oval, the letters 'IP' are written in a large, serif font, and the number '3' is written in a smaller, sans-serif font to the right. The text 'Thank you.' is centered over the 'IP' in a black, sans-serif font.

**Thank you.**

# Sketch of Factorization and Exponentiation

Is it possible to study soft/collinear radiation with perturbative QCD? **Yes**  
In soft/collinear limits, radiation and loops factorize:

$$\mathcal{M}_{n+1 \text{ soft/collinear radiation}} = \underbrace{\left( \text{rad. pole} + \text{loop pole} \right)}_{\text{finite and universal}} \times \mathcal{M}_{n\text{-body}}^{\text{FO}}$$

The squaring, averaging, and integrating over  $(n+1)$ -body phase space

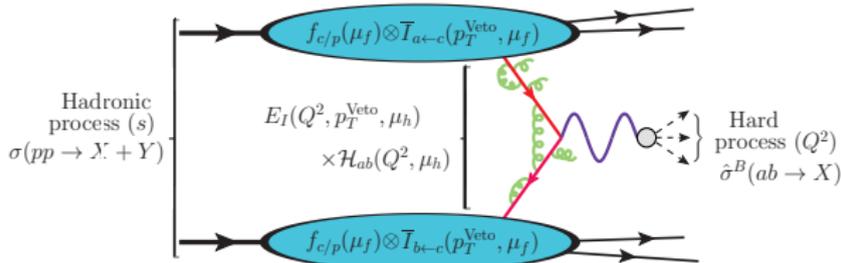
$$d\hat{\sigma}_{n+1} = \underbrace{\int dPS_1 \cdot (\text{finite})}_{\text{universal piece, } \equiv \mathcal{S}} \Big|_{\text{soft/collinear}} \times d\hat{\sigma}_{n\text{-body}}^{\text{FO}}$$

Keeping track of symmetry factors lets us do this for  $k$ -emissions:

$$d\hat{\sigma}_{n+k \text{ soft/collinear}} = \frac{1}{k!} [\mathcal{S}]^k \times d\hat{\sigma}_{n\text{-body}}^{\text{FO}}$$

Summing over **all** such emissions gives us a closed result:

$$d\hat{\sigma}_{n+\text{any soft/collinear}} = \exp[\mathcal{S}] \times d\hat{\sigma}_{n\text{-body}}^{\text{FO}}$$



A different perspective<sup>10</sup>: In general, scattering rates have the form

$$\frac{d^3\sigma}{d\xi_1 d\xi_2 dz dPS} = \sum_{i,j=q,g,\dots} \underbrace{[f_i(\xi_1, \mu) f_j(\xi_2, \mu) + (1 \leftrightarrow 2)]}_{\text{parton flux, } \hat{s} = \xi_1 \xi_2 s} \times \underbrace{C(z)}_{\text{soft emissions, } C(z=Q^2/\hat{s}) = \delta(1-z) + \mathcal{O}(\alpha_s(\mu))} \times \underbrace{d\hat{\sigma}(ij \rightarrow B)}_{\text{hard process, } Q^2 = z\hat{s}}$$

Multi-scale problem:  $\sqrt{s}$ ,  $\sqrt{\hat{s}}$ ,  $\mu_f$ ,  $Q$ ,  $M_B$ , but also  $\mu_r$  (put in by hand).  
Nature works independent of us:

$$\frac{d}{d \log \mu} d\sigma = 0 \implies \frac{d}{d \log \mu} C(z, \mu) = f(z, \mu) C(z, \mu) \\ \implies C(z, \mu) = \exp[S(\mu, \mu_0)] C(z, \mu_0) \quad \text{Each piece follows RG evolution}$$

<sup>10</sup>Contopanagos, Laenen, Sterman ('96); Becher, Neubert etc.; Stewart, Tackmann etc.