Large-Width New Physics at Colliders

A gauge-invariant resummation approach

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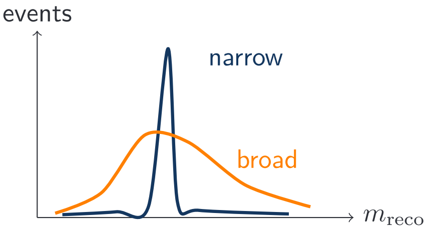
Motivation: broad resonances are not rare in BSM searches

- Many LHC searches are optimized around a **narrow-resonance** intuition.
- But in BSM models, masses and couplings are often scanned independently.
- Large couplings or mass-enhanced interactions can give
$$\frac{\Gamma}{M} \not\ll 1.$$
- Then rates, lineshapes, and kinematics can change qualitatively.

Takeaway: The width is not just a nuisance parameter; it can alter the physics predicted by the event generator and, in turn, the downstream searches.



Narrow-width approximation

$$\frac{1}{(p^2 - M^2)^2 + M^2\Gamma^2} \to \frac{\pi}{M\Gamma}\delta(p^2 - M^2)$$

$$\sigma(pp \to N \to X) \simeq \sigma(pp \to N) \times \text{BR}(N \to X)$$

Benchmark: heavy Majorana neutrino

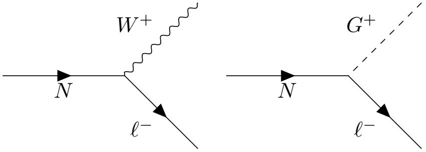
Interactions after electroweak symmetry breaking

$$\mathcal{L} \ni \sum_{\ell} \Big[-\frac{gV^*_{\ell N}}{\sqrt{2}} \bar{N} \not{W}^+ P_L \ell - \frac{gV^*_{\ell N}}{2\cos\theta_W} \bar{N} \not{Z} P_L \nu_\ell - \frac{g m_N V^*_{\ell N}}{\sqrt{2} m_W} \bar{N} \tilde{\Phi}^\dagger L_\ell + \text{h.c.} \Big].$$

Mass-enhanced width by *Goldstone Boson Euqivalence Theorem*

$$\Gamma_N \sim |V_{\ell N}|^2 \left(\frac{m_N}{m_W}\right)^2 m_N$$

- Heavy neutrino is a clean example of large-width BSM dynamics.
- Same issue can appear for broad Z' or W' resonances.
- In high-mass scans, $\Gamma_N \sim m_N$ can be reached.



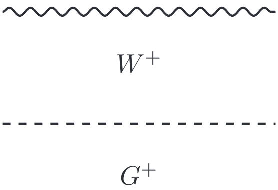
Why the usual Monte-Carlo treatment can fail

For a massive gauge boson, the propagator depends on the gauge parameter ξ:

$$D_W^{\mu\nu}(p) = \frac{i}{p^2 - m^2}\left[-g^{\mu\nu} + \frac{p^\mu p^\nu}{p^2 - \xi m^2}(1-\xi)\right].$$

For the corresponding Goldstone boson, the propagator also depends on ξ:

$$D_G(p) = \frac{i}{p^2 - \xi m^2}.$$



How does the gauge dependence cancel?

In the full amplitude, the unphysical ξ dependence cancels among the gauge-boson propagator, the Goldstone contribution, and the vertex structure. This cancellation is enforced by the Slavnov–Taylor identity,

$$k^\mu \Gamma_\mu = m_i \, i\Gamma_\phi + i\left[S_f^{-1}(\not{p})\, P_L - P_R\, S_i^{-1}(\not{q})\right].$$

This is the non-Abelian analogue of the QED Ward–Takahashi identity,

$$k^\mu \Gamma_\mu = i\left[S^{-1}(\not{p}) - S^{-1}(\not{q})\right].$$

Large width: when does resummation reduce to Breit–Wigner?

Consistently resummed propagator

$$D_{\mathrm{resum}}(p^2) = \frac{i}{p^2 - M_0^2 - \Sigma(p^2)} \xrightarrow{p^2 \simeq M_0^2,\, \Sigma'(M_0^2) \simeq 0} \frac{i}{p^2 - M_0^2 + iM_0\Gamma}$$

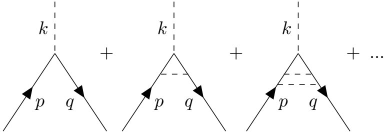
Why the large-width regime is subtle

- For a narrow resonance, the propagator is dominated by the near-pole region.
- Then the momentum dependence of the width can be neglected.
- For a broad resonance, off-shell regions become important, and this approximation can fail.

Consistent resummation: propagator plus vertex

$$D = D_0 + D_0 \Sigma D_0 + D_0 \Sigma D_0 \Sigma D_0 + \cdots$$

$$D(p) = \frac{i}{p^2 - M_0^2 - \Sigma(p^2)}$$



$$\Gamma_\mu = \Gamma_\mu^{(0)} + K \otimes \Gamma_\mu^{(0)} + K \otimes K \otimes \Gamma_\mu^{(0)} + \cdots$$

$$\Gamma_\mu = \Gamma_\mu^{(0)} + K \otimes \Gamma_\mu$$

Gauge consistency is enforced by the Slavnov–Taylor identity:

$$k^\mu \Gamma_\mu = m_i \, i\Gamma_\phi + i \left[S_N^{-1}(\not{p})\, P_L - P_R\, S_f^{-1}(\not{q}) \right] .$$

That said, we can reconstruct the vertex Γ^μ by STI if we know the resummed propagator $S(\not{p})$.

Implementation in MadGraph5

What we changed

- Compute the heavy-neutrino self-energy.
- Renormalize around the complex pole.
- Modify the propagator and vertices at UFO level.
- Generate events in Feynman gauge.

Schemes compared

- Normal Breit-Wigner treatment.
- Complex-mass scheme.
- Fully resummed propagator + STI vertex, with $\Gamma_N \leq m_N$ to maintain perturbative control.

Takeaway: The comparison isolates which phenomenology comes from the large-width treatment itself.

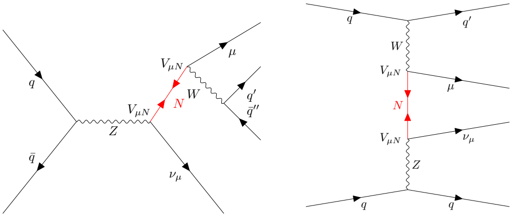
Processes used for the phenomenology study

Simulated final states

$$pp \to \mu \nu_\mu jj, \qquad pp \to \mu\mu jj.$$

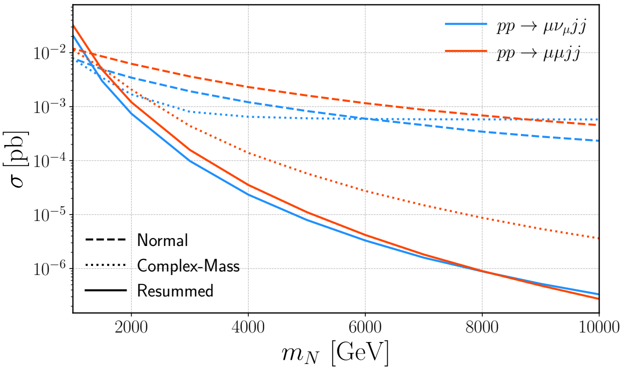
These channels expose both rate effects and kinematic changes between s-channel and VBF-like contributions.

- Representative mass scan: $m_N = 750$–10000 GeV.
- Focus on the large-width region.



Left: resonant-like production. Right: VBF process.

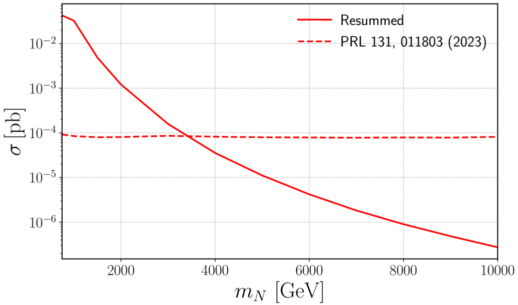
Result I: cross sections can be misestimated



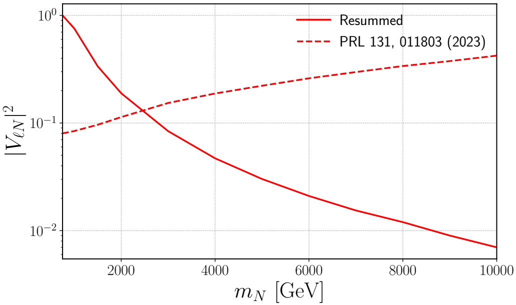
- At smaller widths, the schemes agree reasonably well.
- At high masses, normal and complex-mass treatments can give qualitatively different behavior.
- The resummed scheme suppresses unphysical enhancements and changes the scaling with m_N and $|V_{\ell N}|^2$.

Takeaway: Existing limits based on standard samples may not extrapolate reliably into the broad-width regime.

Result I: cross sections can be misestimated



Cross-section comparison with the CMS VBF same-sign charged-lepton search.

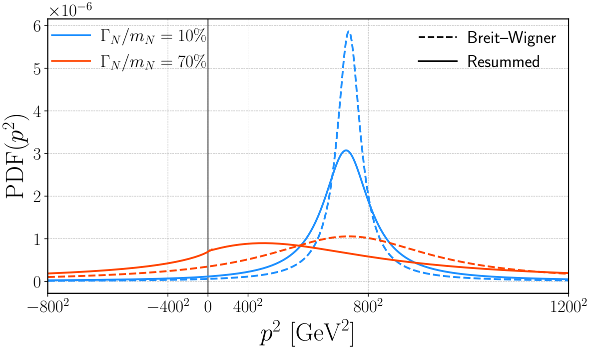


Corresponding constraint in the $(m_N, |V_{\ell N}|^2)$ plane.

Main message

Existing CMS searches already probe the multi-TeV heavy-neutrino region using VBF topology and same-sign dileptons. The resummed treatment can be compared directly with these published limits to quantify how large-width modeling changes the interpretation.

Result II: the lineshape is distorted

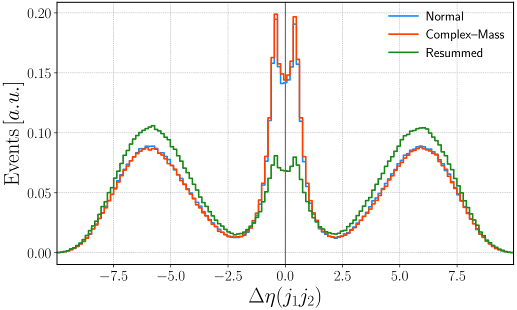


- Benchmark: $m_N = 750$ GeV.
- Resummation shifts and broadens the distribution.
- For large Γ_N/m_N, the space-like region contributes non-negligibly.

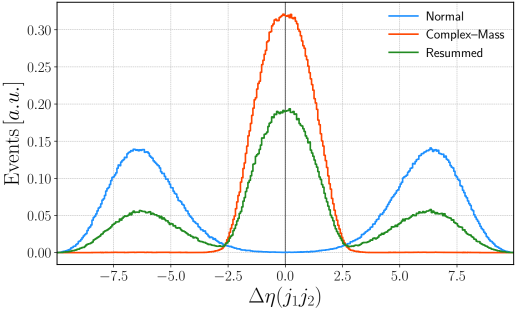
Experimental meaning

A broad signal is a shape-modeling problem, not only a change in total normalization, *e.g.*, interference with SM background.

Result III: event kinematics change



$m_N = 750$ GeV



$m_N = 10$ TeV

Takeaway: At high mass, $\Delta\eta(j_1 j_2)$ distinguishes central s-channel-like behavior from forward VBF-like behavior; the resummed result retains both components.

Main message for phenomenology and searches

What we found

- Large widths can distort rates, lineshapes, and angular correlations.
- Propagator-only width insertion is not enough in this regime.
- STI-implied vertices give a practical gauge-consistent route.

What it implies

- Broad heavy-neutrino limits may need reinterpretation.
- Similar issues can arise for Z' and W' searches.
- MC tools should expose more flexible resummed propagator/vertex structures.

Large-width new physics is not just “wide narrow physics.”

Backup: key formula for the resummed fermion propagator

Propagator structure

$$S(\not{p}) = \frac{i}{\not{p} - m_{\rm R} - \Sigma(\not{p})} = \frac{i}{A\not{p} - Bm_{\rm R}} = \frac{i(A\not{p} + Bm_{\rm R})}{A^2p^2 - B^2m_{\rm R}^2}.$$

STI-guided vertex

$$\Gamma^\mu = \frac{A_N + A_\ell}{2}\gamma^\mu P_L + \frac{A_N - A_\ell}{2}\frac{p^\mu + q^\mu}{p^2 - q^2}(\not{p} + \not{q})P_L.$$

$$\Gamma_\phi = \frac{1}{m_i}(m_{\rm R}B_N \cdot P_L - P_{\rm R} \cdot B_f m_f)$$

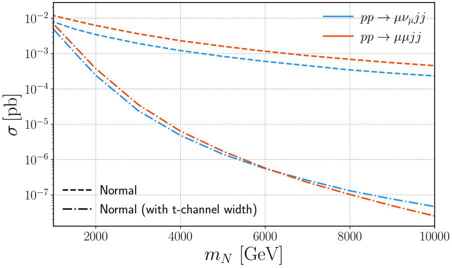
- A corrects the wave-function structure.
- B corrects the mass-related structure.
- Thresholds enter through the imaginary parts of loop functions.

Backup: why the default t-channel treatment matters

MadGraph default behavior

For a heavy-neutrino propagator, the width is kept for time-like momentum but removed for space-like momentum:

$$D(p^2) = \begin{cases} \dfrac{\not{p} + m_N}{p^2 - m_N^2 + i m_N \Gamma_N}, & p^2 \geq 0, \\ \dfrac{\not{p} + m_N}{p^2 - m_N^2}, & p^2 < 0. \end{cases}$$



Turning off/on the width in the t-channel.

Consequence

At large m_N, $\Gamma_N \sim |V_{\ell N}|^2 m_N^3$, so the s-channel is strongly suppressed, while the default t-channel contribution is not width-suppressed in the same way.