Left-Right Symmetry: At the Edges of Phase Space and Beyond [1]

Invisibles 17 - U. Zürich

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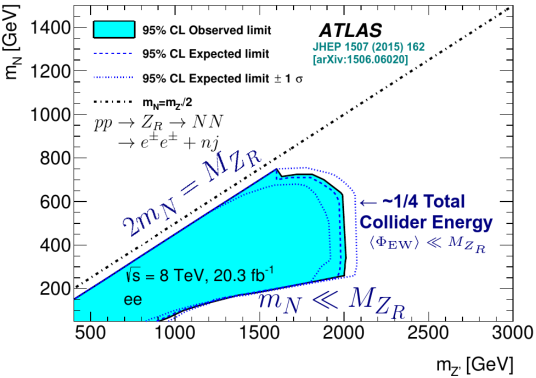
[1] Based on several works and impossible without a small army of good IPPP students

An Emerging Picture of New Physics Physics

The LHC is operating amazingly! $\sim$40 fb^{-1} at 13 TeV ($3 - 4x$ Tevatron)

Plotted: Excluded (m_N, M_{Z_R}) from $pp \to Z_R \to NN$ searches



While no confirmed **BSM** discoveries at colliders, it certainly still possible

- Remaining model space is hierarchical ⇒ extrema of phase space

Left-Right Symmetry...

When hierarchies are present, often a qualitatively different picture emerges. $\Rightarrow$ **Quantitatively**, difficult problems become simpler to solve.

- E.g., Effective Field Theory, Hadronization, Classical Mechanics

Question: Does collider pheno for neutrino mass models (Seesaws) qualitatively change for hierarchical regions of model parameter space?

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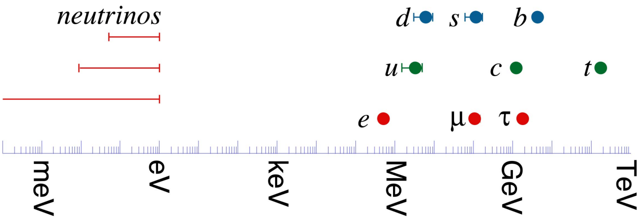
... At the Edges of Phase Space and Beyond:

1. Left-Right Symmetric Model Primer
2. LRSM at the Edges of Phase Space
3. LRSM beyond the Edges of Phase Space
4. Redux I: Edges
5. Redux II: Beyond

Motivation for new physics from ν physics

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?  ?)

Collider Connection to Neutrino Mass Models (1/1)

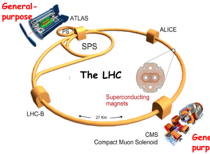
Seesaw models predict new partners of all shapes, spins, and color, e.g.,

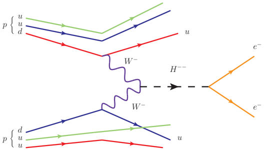
$$N \text{ (Type I)}, \quad T^{0,\pm} \text{ (Type III)}, \quad Z_{B-L}, \quad H_R^{\pm,\pm\pm} \text{ (Type I+II)}$$

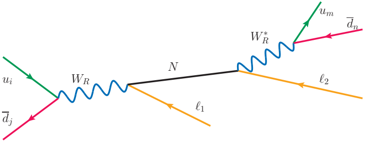
Through gauge couplings and mixing, production in $ee/ep/pp$ collisions

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

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

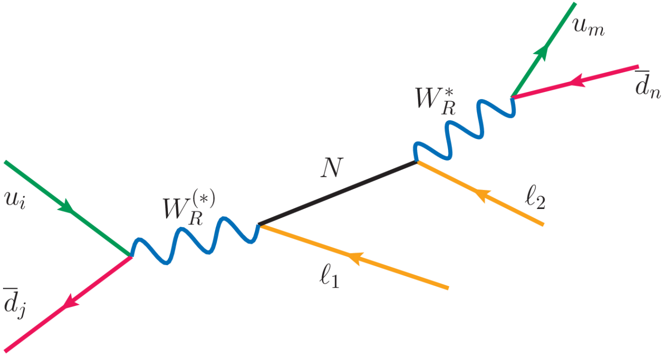






Identification of Seesaw partners is then inferred by their decays to SM particles and the associated final-state kinematics

Left-Right Symmetry at Hadron Colliders



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

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

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With N_R, all SM fermions can be grouped in $\mathrm{SU}(2)_L$ *and* $\mathrm{SU}(2)_R$ doublets. Dirac masses generated in (mostly) usual way with Φ, i.e., $\Delta\mathcal{L} \ni \overline{Q}_L \Phi Q_R$

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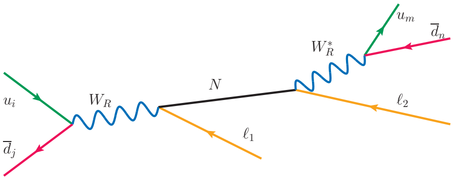
Neutrinos obtain LH (RH) Majorana masses from triplet scalar Δ_L (Δ_R):

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

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

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

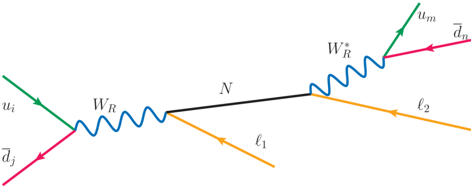
[2] ATLAS [1506.06020; 1512.01530] and CMS [1407.06020; 1512.01224]

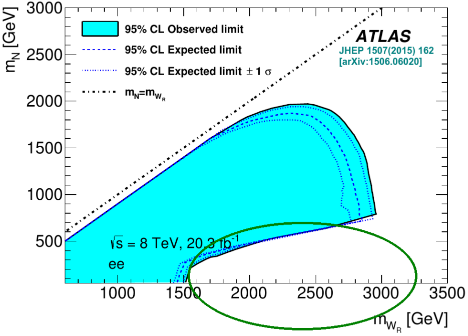
8 TeV LHC Exclusion with $\mathcal{L} \approx 20$ fb^{-1}

LHC expts have performed remarkably!

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

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





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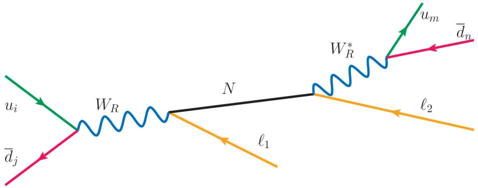
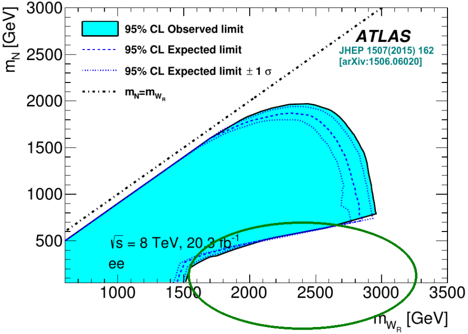


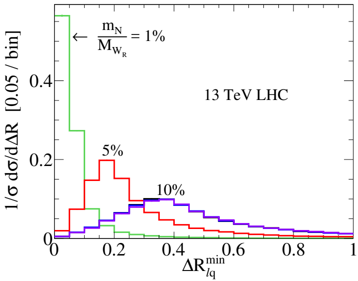


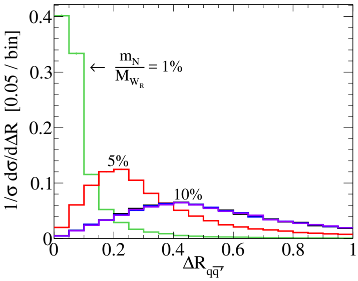
Similar sensitivity to searches for $pp \to Z_R \to NN \to e^{\pm}e^{\pm} + nj + X$

$\implies$ For both W_R and Z_R, loss of sensitivity when $m_N \ll M_V$

(Lets see what is going on.)

Failure of Electron ID in $pp \to W_R \to \ell^\pm N(\to \ell^\pm q\overline{q'})$





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

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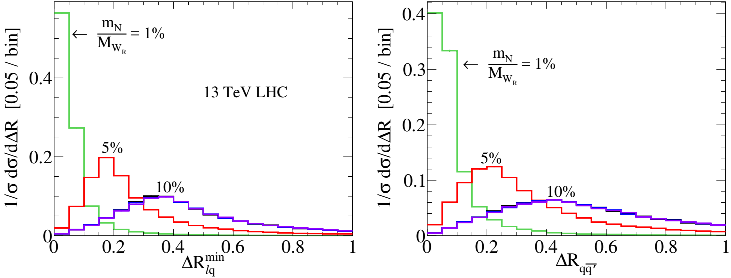

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$$\Rightarrow \Delta R_{ij} \sim \frac{m_N}{\sqrt{E_iE_j}} \sim \frac{4m_N}{M_{W_R}} \Rightarrow \text{For } \left(\frac{m_N}{M_{W_R}}\right) < 0.1, \Delta R^{\text{min}}_{\ell X} = 0.4 \text{ iso. req. fails}$$

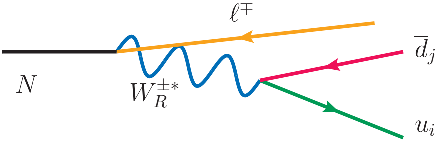
K&S process $pp \to \ell^\pm\ell^\pm jj + X$ contains two same-sign charged leptons
- S/B power comes from high-p_T leptons without accompanying MET

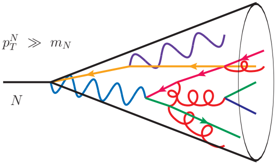
Question: Is it necessary to identify the second lepton or jet multiplicity?

Neutrino Jets[3] (n):

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

(ii) a fat jet originating from a heavy neutrino

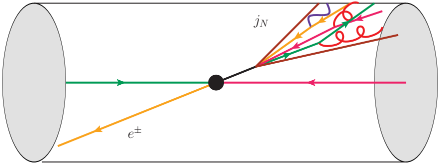




[3] M. Mitra, RR, D.J. Scott, M. Spannowsky, PRD ('16) [1607.03504]; O. Mattelaer, M. Mitra, R. Ruiz [1610.08985]

Neutrino Jets in LRSM

Lets change the scale of our problem: treat $\ell_2^{\pm}$ like any other poorly isolated parton bathed in QCD radiation and cluster via a sequential jet algorithm[4]



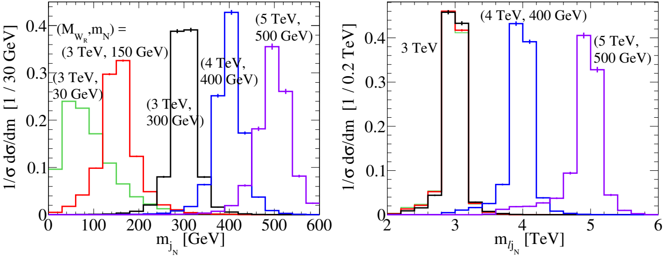
Changing scales *simplifies* the problem, a lot:

For $m_N \ll M_{W_R}$, one has a different collider topology:

$$pp \rightarrow W_R \rightarrow e^{\pm} N \rightarrow e^{\pm} j_{\rm Fat} \text{ (+ no MET!)}$$

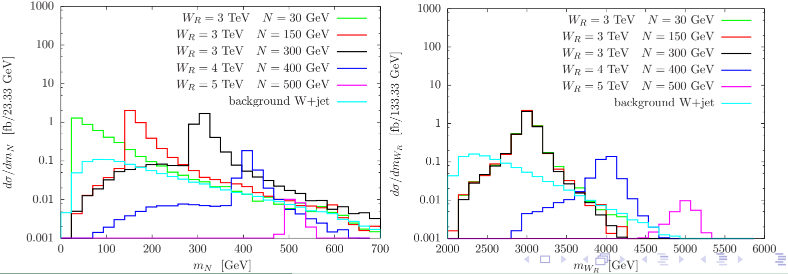
[4]Sequential jet algorithms ≈ definition of collimated, clusters of partons that is meaningful at all orders of perturbation theory

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



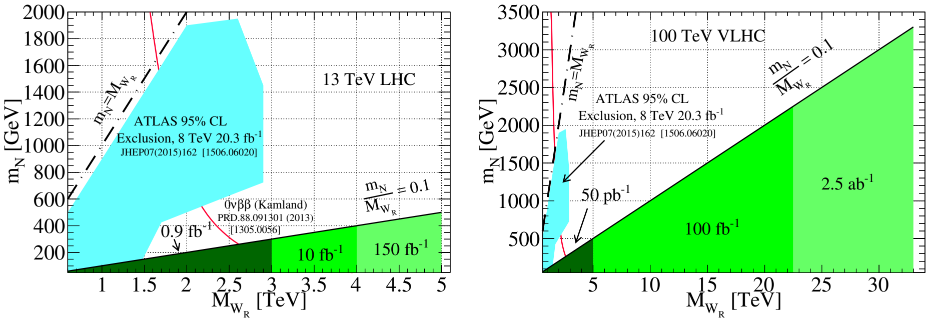
QCD corrections do not change this; oddly, exhibits "ideal" jet behavior

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



Discovery Potential at the Edge of Phase Space

For $m_N/M_{W_R} \leq 0.1$, the region where ATLAS/CMS searches breakdown, neutrino jet searches recovers lost sensitivity



Signature: $pp \to \ell^{\pm} + j_{\rm Fat} + X$ [no MET, $p_T^{\ell,j} \gtrsim 1$ TeV, $M_{\ell j}$ Cut]

- 13 TeV: $M_{W_R} \approx 3$ (4) [5] TeV discovery after 10 (100) [2000] fb^{-1}
- 100 TeV: $M_{W_R} \approx 15$ (30) TeV discovery after 100 fb^{-1} (10 ab^{-1})

Left-Right Symmetry Beyond the Edge of Phase Space:

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A pathological but plausible scenario.

Ignoring UV completions, limits[5] on neutral flavor changing transitions require Δ_R sector to be $\langle \Delta_R \rangle \gtrsim \mathcal{O}(10)$ TeV

What if LR gauge and Yukawa couplings have similar values as in the SM?

- What if $M_{W_R} \sim g_L \langle \Delta_R \rangle \sim 6.5$ TeV and $m_N \sim y^{\tau}_{\rm SM} \langle \Delta_R \rangle \sim 100$ GeV?

[5] Bertonlini, et al [1403.7112, + others]; Zhang, et al. [0704.1662; + others]

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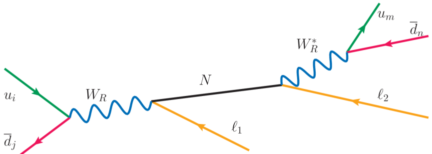
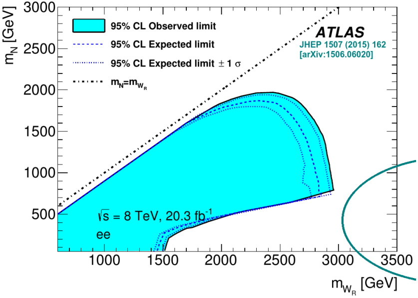
Data may be suggesting EW-scale N but kinematically inaccessible W_R, Z_R





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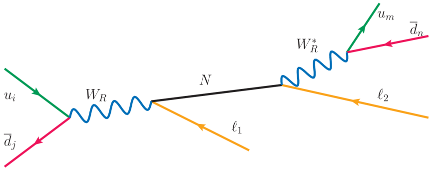

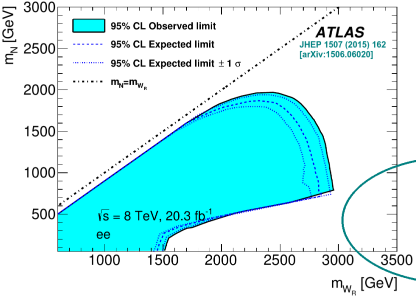

Searches follow Keung & Senjanovic ('83), and assume resonant W_R, N

- Realistically, zero sensitivity to $M_{W_R} > 6 - 7$ TeV due to finite data set
- **Naive Question**: is an on-shell W_R necessary for discovery of N?

[5] Bertonlini, et al [1403.7112, + others]; Zhang, et al. [0704.1662; + others]

Of course $pp \to W_R^* \to N\ell + X$ can occur via an off-shell mediator.

- Simply LR analog of Fermi contact interaction $\mathcal{L} = G_F[\overline{\mathcal{N}}\gamma^\mu\mathcal{P}][\overline{\nu}\gamma_\mu\ell]$

Interestingly, in the limit that $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV,
$pp \to N\ell + X$ production in the LRSM and "Type I" are indistinguishable[6]

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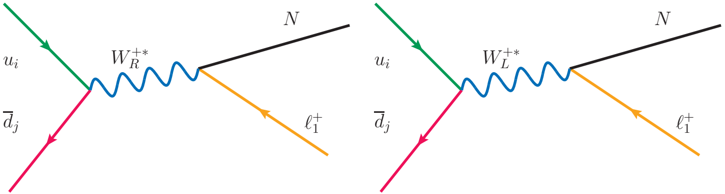

- Occurs near threshold $\sqrt{\hat{s}} \sim m_N$ and same $\ell_1^\pm$ polarization
- Differentiation requires polar and azimuthal polarization measurements of the full $pp \to \ell^\pm\ell^\pm + nj + X$ final state

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L Violation from Beyond the Edges of Phase Space[7]

"Type I" searches and projected sensitivities for can be reinterpreted in the context of LRSM in the limit that $M_{W_R} \sim \sqrt{s} \gg \sqrt{\hat{s}}$

- **Signature**: $pp \to \ell^\pm \ell^\pm + nj + X + p_T^\ell \gtrsim \mathcal{O}(m_N) + \text{no MET}$

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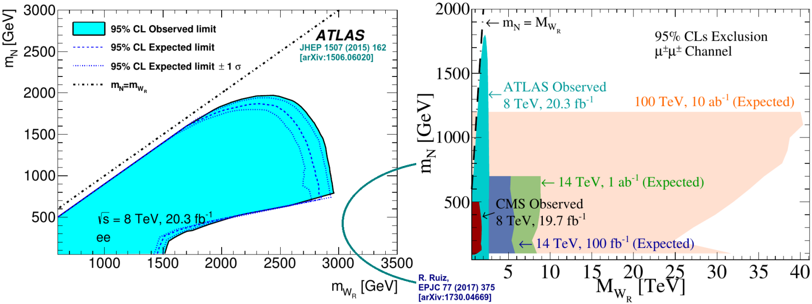

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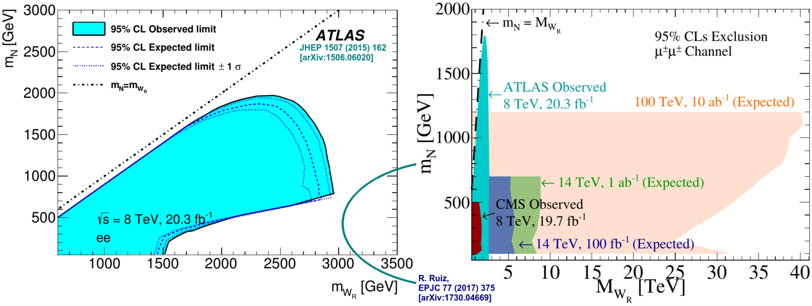

At 14 (100) TeV with $\mathcal{L} = 1$ (10) ab^{-1}, $M_{W_R} \lesssim 9$ (40) TeV can be probed

- Caveat: Numbers can be improved with (a) dedicated analysis (not reinterpretation) and (b) knowledge of 100 TeV detector definition

[7] RR, EPJC ('17) [1703.04669]

Redux I: Back to Edges of the LHC Phase Space

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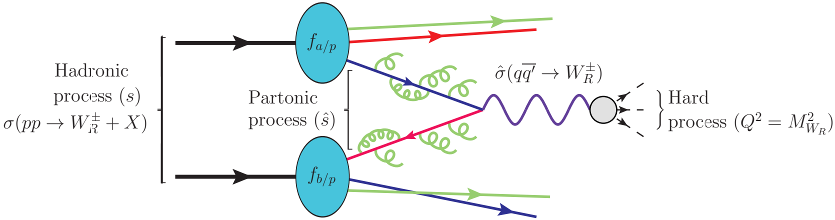
Can you see $M_{W_R} \gtrsim 5$ TeV?

Recall: W_R production is analogous to $W_{\rm SM}$, except $M_{W_R} \gtrsim 3-5$ TeV



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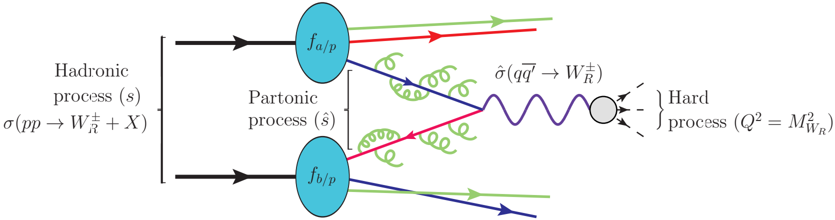

Away from phase space boundaries,

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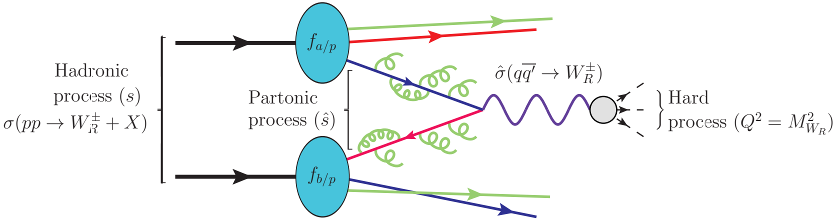

Away from phase space boundaries,QCD corrections are 20-30%.

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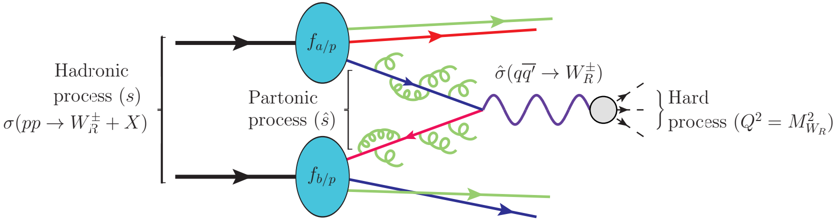
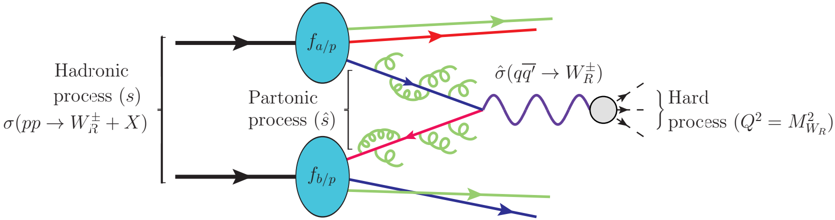


Away from phase space boundaries,QCD corrections are 20-30%.
However, ***near*** boundaries, where $E_g \ll E_q$,

$$\sigma(pp \to W_R + g) \sim \int d^{4-2\varepsilon} PS_2 \sim \lambda^{\frac{1-2\varepsilon}{2}} \left(1, \frac{Q^2 = M_{W_R}^2}{\hat{s}}, \frac{k_g^2 = 0}{\hat{s}}\right)$$

$$= \left(1 - \frac{M_{W_R}^2}{\hat{s}}\right)^{1-2\varepsilon} \sim 2\varepsilon \log\left(1 - \frac{M_{W_R}^2}{\hat{s}}\right)$$

Recall: W_R production is analogous to $W_{\rm SM}$, except $M_{W_R} \gtrsim 3-5$ TeV



Away from phase space boundaries,QCD corrections are 20-30%.
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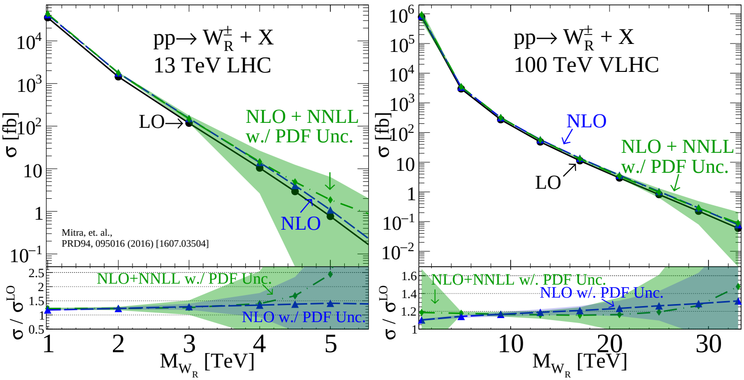
As $M_{W_R}^2 \to s$, logs diverge since $M_{W_R}^2 \to \hat{s} < s$ forces g to be soft.
In this limit, **soft factorization** & **exponentiation** possible!
$\Rightarrow$ All-orders (*re*)summation of $\alpha_s \log(1 - M^2/\hat{s})$

W_R Numerology at the Edge of Collider Phase Space[8]



At 13 TeV, corrections to production rate $> +100\%$ for $M_{W_R} \gtrsim 4.5$ TeV

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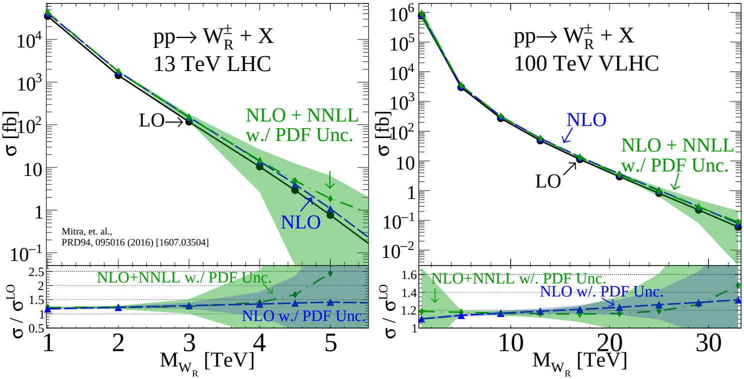

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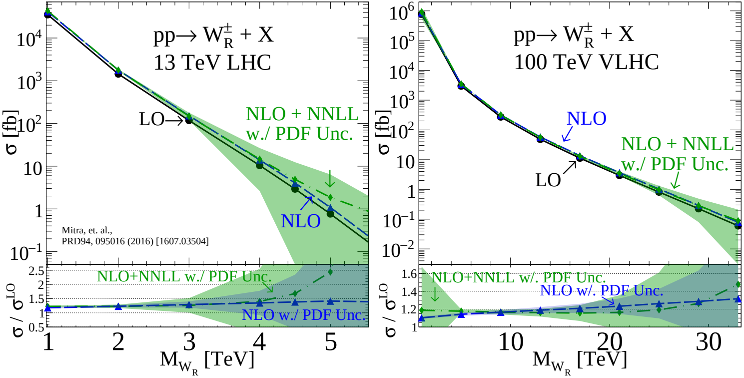

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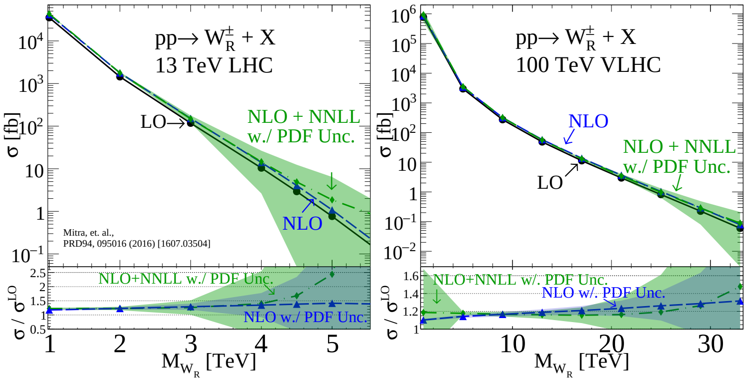

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Assuming $\text{BR} \times \varepsilon \times \mathcal{A} = 2\% \implies N \approx 34$ events ($\sim 6\sigma$ *vs* $\sim 4\sigma$)

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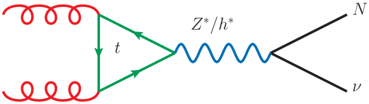
Q: Are high-mass $W_R,\ Z_R$ unique in this respect?

Heavy N at the Edge of Partonic Phase Space[9]

For $gg \to N\nu$, large loops and radiation near "partonic threshold" drives $Q^2 \to \hat{s}$ dynamically
$\Rightarrow$ large increase $(2-3\times)$ in production rate



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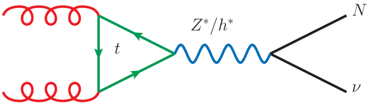

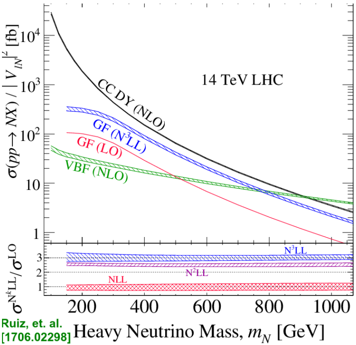

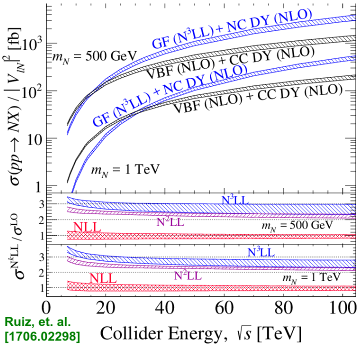

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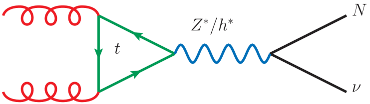

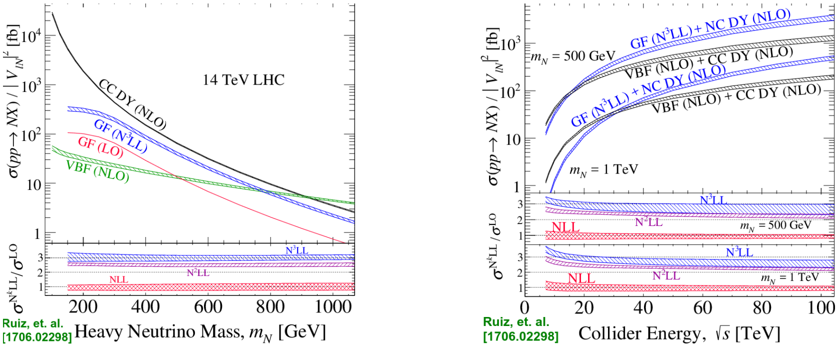

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- At LHC, $\sigma^{\rm GF} \sim \sigma^{\rm DY} \gg \sigma^{\rm VBF} \implies \mathcal{O}(1)$ improvement in sensitivity
- For any (proposed) future pp collider, $\sigma(N\nu) > \sigma(N\ell)$!

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Redux II: Beyond

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An outlook of Left-Right Symmetry beyond LHC Run II

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  - **Need**: pheno analyses for "PS boundary" LRSM parameter space
  - **Need**: "What is the dominant production mode for a sub-TeV N_R?"
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The origin of tiny neutrino masses is still a puzzle and may manifest at collider experiments via the production of LRSM partners, e.g., $W_R^{\pm}$, N.

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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: 1-5 ab^{-1} and 50 ab^{-1}
- Premature to claim "nightmare scenario" (SM Higgs + nothing else)

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Thank you.