Status of Theory Calculations for Seesaw Collider Searches [1]

Neutrinos@CERN

Richard Ruiz

Institute for Particle Physics Phenomenology,
University of Durham

29 March 2017

elusi**v**es
neutrinos, dark matter & dark energy physics

IP³

in**v**isiblesPlus

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[1] Lots of work with FR/MG/MA/QCD folks & small army of good IPPP students

Where we are today

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

- Higgs 🏅: No longer a hep-th problem. Now also a hep-ex problem.

- ν masses 🏅, mass hierarchy, particle nature of dark matter, origin of EWSB, etc., require more data and thought

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After Run I and early Run II (Moriond), data is clear:

Interaction Strength \ Mass Scale	$\Lambda_{\rm BSM} \lesssim \langle \Phi_{\rm EW} \rangle$	$\Lambda_{\rm BSM} \gg \langle \Phi_{\rm EW} \rangle$
$g_{\rm BSM} \gtrsim g_{\rm SM}$	$\times$	Need more data!
$g_{\rm BSM} \ll g_{\rm SM}$	Need more data!	Cannot probe :(

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Picture first suggested by LEP + Belle I + Tevatron is telling:

- No "low hanging fruit"

hep-ph from 90s-00s designed for "day 1" discoveries, not for extreme regions of BSM parameter space (and hence collider phase space)

"Day 1" pheno = simple channels with moderately good signal/bkg, e.g., Drell-Yan process like $q\overline{q'} \to W_R \to Ne^{\pm} \to e^{\pm}e^{\pm} + q\overline{q'}$.
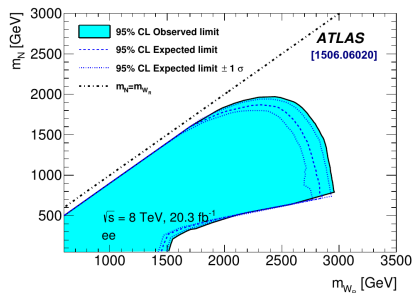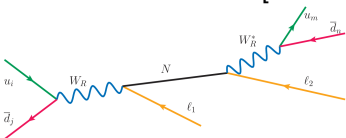
- New studies[2] are revealing holes in sensitivities
- Limitations were known, but necessary tools/formalisms are new

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[2]Seesaw Examples: Maiezza, et al [1503.06834]; Mitra, RR, Scott, Spannowsky [1607.03504]; RR [1703.04669]

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LRSM: For $(m_N/M_{W_R}) \sim (y_N^{\Delta}/g_R) \lesssim 0.1$, $pp \to e^{\pm}e^{\pm} + nj$ searches breaks down due to electron ID failure [1607.030504]
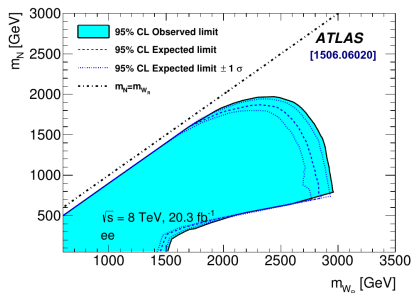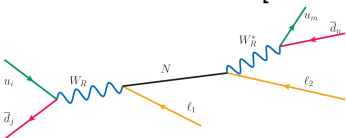

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"Exotic" regions of parameter space imply/require "exotic" topologies, e.g., vector boson fusion, gluon fusion, Lorentz-boosted resonances

- Hard to calculate by hand
- For first time, exotic channels can be computed quickly and *reliably*

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The Monte Carlo Analysis Chain for Collider Experiments
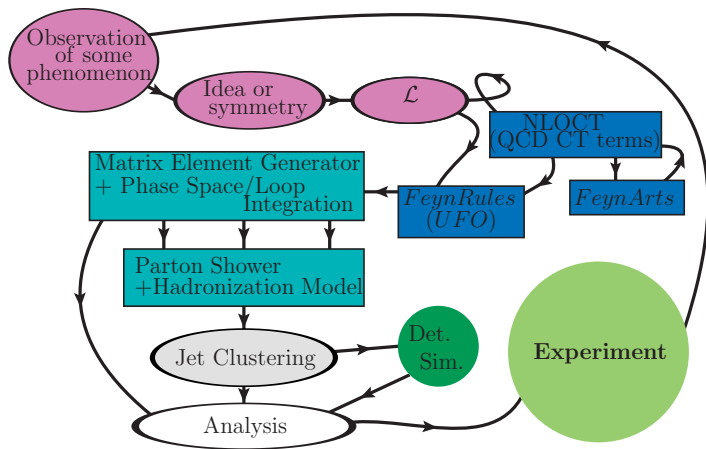
Lots of tools on the market [hepforge.org/projects].
Robust & general purpose: **Herwig**, **MadGraph_aMC@NLO**, **Sherpa**

State of FeynRules NLO Model Library

In '14/'15, approached by hep-ex to search for $W\gamma \to N\ell^{\pm}$
- Discovered then that MC tools did not exist to redo the calculation
- Except: $pp \to W^*_{L/R} \to N\ell^{\pm}$ in ALPGEN/PYTHIA & Type III in FR

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European+Midwest effort! [*feynrules.irmp.ucl.ac.be/wiki/NLOModels*]

| Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	⇨arXiv: 1508.00564 , ⇨arXiv: 1508.05327 , ⇨arXiv: 1509.05785	-	DMsimp_UFO.2.zip	-
Effective LR symmetric model (more details)	R. Ruiz	⇨arXiv:1610.08985	effLRSM.fr	EffLRSM UFO	-
GM (more details)	A. Peterson	⇨arXiv:1512.01243	-	GM_NLO UFO	-
Heavy Neutrino (more details)	R. Ruiz	⇨arXiv:1602.06957	heavyN.fr	HeavyN NLO UFO	-
Higgs characterisation (more details)	K. Mawatari	⇨arXiv:1311.1829 , ⇨arXiv:1407.5089 , ⇨arXiv: 1504.00611	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	⇨arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Spin-2 (more details)	C. Degrande	⇨http://arxiv.org/abs/1605.09359	dm_s_spin2.fr	SMspin2 NLO UFO	-
Stop pair -> t tbar + missing energy	B. Fuks	⇨arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
SUSY-QCD	B. Fuks	⇨arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Two-Higgs-Doublet Model (more details)	C. Degrande	⇨arXiv:1406.3030	-	2HDM_NLO	-
Top FCNC (more details)	C. Zhang	⇨arXiv:1412.5594	TopEFTFCNC.fr	TopFCNC UFO	-
Vector like quarks	B. Fuks	⇨arXiv:1610.04622	VLQ_v3.fr	UFO in the 5FNS, UFO in the 4FNS, event generation scripts	All figures available from the arxiv
W'/Z' model (more details)	R. Ruiz, B. Fuks	⇨arXiv:1701.05263	vPrimeNLO.fr	vPrimeNLO UFO	-

As of 27 March, updated regularly

Modern general purpose MC packages are *very* sophisticated

"With great power there must also come - great responsibility"- B. Parker ('62)

LRSM Ex: $(m_N/M_{W_R}) \sim (y_N^\Delta/g_R) \ll 1$
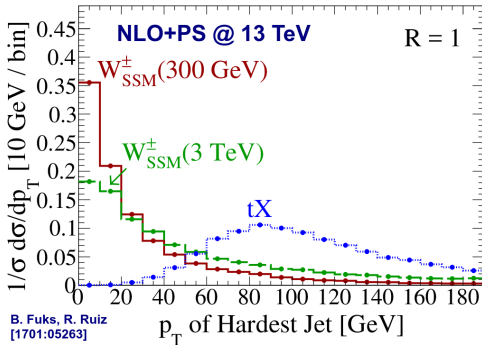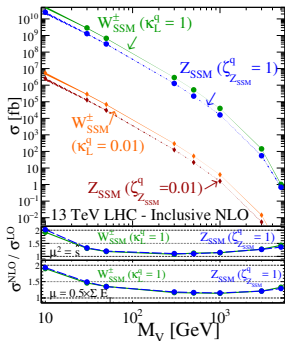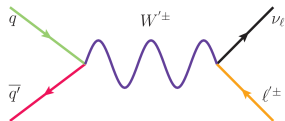- N is light and "long"-lived
- $pp \to W_R \to Ne$ looks like SSM W'
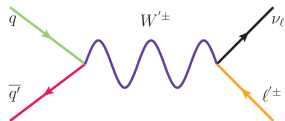
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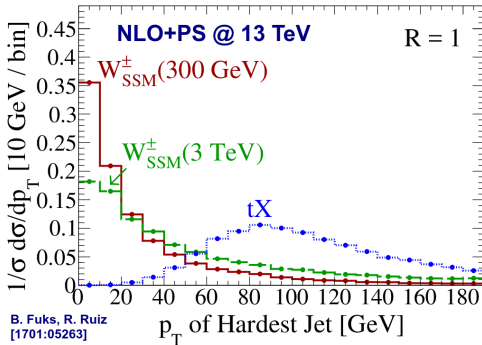**NLO+PS @ 13 TeV**   R = 1

$W_{SSM}^\pm(300 \text{ GeV})$

$W_{SSM}^\pm(3 \text{ TeV})$

tX

B. Fuks, R. Ruiz
[1701:05263]
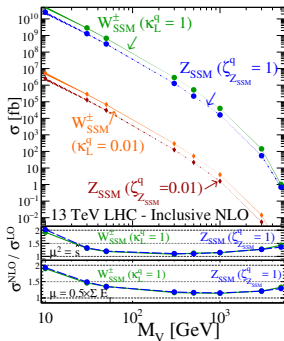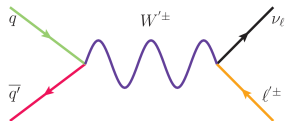
p_T of Hardest Jet [GeV]

For low-mass W', Z', $\sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}} \gg 1.2 - 1.3$

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New BSM Pheno: NLO+PS/LL(k_T) = *lowest order* at which first QCD radiation is *qualitatively* correct / physically meaningful [CSS ('85)]

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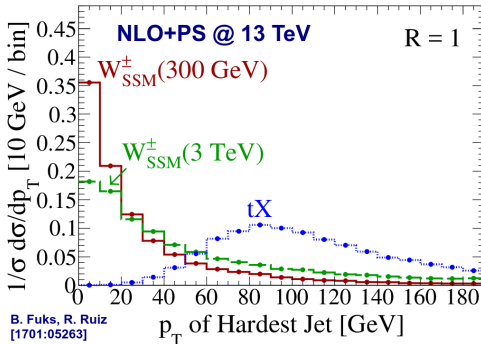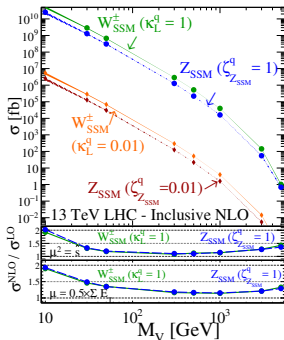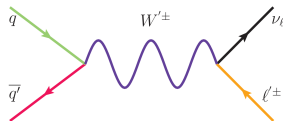For low-mass W', Z', $\sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}} \gg 1.2 - 1.3$

New BSM Pheno: NLO+PS/LL(k_T) = *lowest order* at which first QCD radiation is *qualitatively* correct / physically meaningful [CSS ('85)]
- Selection cuts on jet observables now possible

Outlook: Automated Monte Carlo at NNLO (1 slide)

MC@NNLO for BSM

Is MC@NNLO important for BSM?

- No. Except when MC@NNLO really means MC@NLO

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[3]Dicus, Roy ('91); Hessler, et al [1408.0983]; Degrande, et, al [1602.06957]
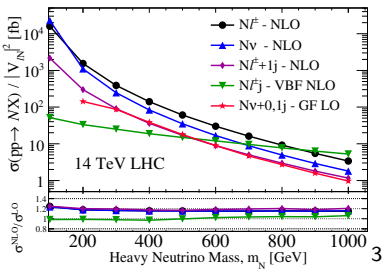
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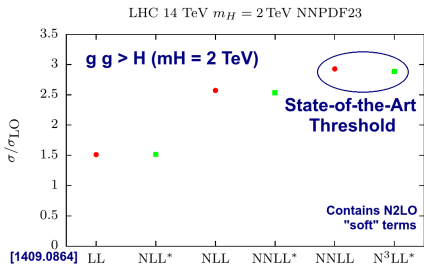
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For loop-induced processes, MC@NLO $\implies$ 1-loop @ LO

- $gg \to H^0$, A^0: QCD corrections are *large*

- Heavy N at 100 TeV: GF@LO > DY@NLO

LHC 14 TeV $m_H = 2$ TeV NNPDF23
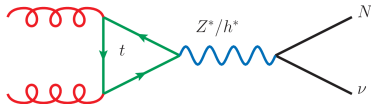
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Part II: Myth of Unimportant QCD Corrections[4]

Common Statement: ''QCD is unimportant for colorless BSM''

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

These are the assumptions for the Collinear Factorization Thm [CSS ('80s)]

$$\sigma(pp \to A + X) = \sum_{i,j} \int d\xi_1 \int d\xi_2 \ [f_i(\xi_1)f_j(\xi_2) + (1 \leftrightarrow 2)]\hat{\sigma}(ij \to A)$$

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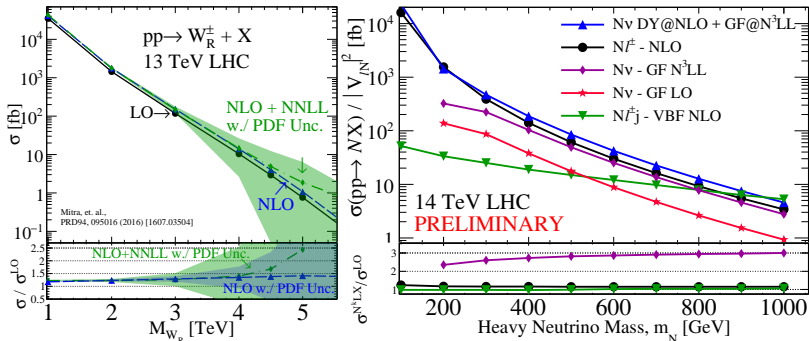
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Relaxing these assumptions has consequences:

- For $M_{W'/Z'} \ll \sqrt{s}$, $\qquad \sigma^{NLO}/\sigma^{LO} \gg 1.2 - 1.3$
- For W'/Z' at any M, NLO+PS needed for jet-based cuts
- In $gg \to H^0/A^0$ for any $m_{H/A}$, $\qquad \sigma^{N^3LX}/\sigma^{LO} \sim 2 - 3$

- How about $M_{W'/Z'} \sim \sqrt{s}$ or $\quad gg \to h^*/Z^* \to N\nu$?

Impact of Threshold Resummation[6]

Threshold resummation is important when

- $(M_{\text{BSM}}/\sqrt{s}) \gtrsim 0.3$ for $q\bar{q}$[5]: $K_{DY}^{NLO+N^2LL} \sim 2 - 2.5$
- gg always: $K_{GF}^{N^3LL} \sim 2 - 3$ (

New: Neutral current production of N largest rate at LHC!

[5]Appell, Sterman, Mackenzie ('88)

[6]Mitra, RR, Scott, Spannowsky [1607.03504]; RR, Spannowsky, Waite [Soon]

Summary

Over the past few years, strong push to modernize Seesaw analyses

- New topologies, new tools, new understanding of colliders themselves
  - ▸ "With great power there must also come - great responsibility"

- QCD is a useful and powerful tool for Seesaws@Colliders
  - ▸ "With great power there must also come - great responsibility"

- Not possible without strong European effort
- To hep-ex/ph folks, tell us your needs!

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

- Pheno studies from '90s-'00s assumed 14 TeV and 100-300 fb^{-1}
- High-Luminosity LHC and Belle II goals: 1-3 ab^{-1} and 50 ab^{-1}
- Premature to claim "nightmare scenario" (SM Higgs + nothing else)