# MC Techniques for New Physics at NLO and Beyond

## Pheno18 - University of Pittsburgh

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[1] IPPP → CP3, Louvain in Fall '18

# What this talk is about

This talk is ***not***...

- Exhaustive. Unfortunately, lots of omissions.
- A technical lecture on next-to-next-to-...-leading order computations
- Definitely not about modest QCD corrections of $\sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}} \sim 1 - 1.3$

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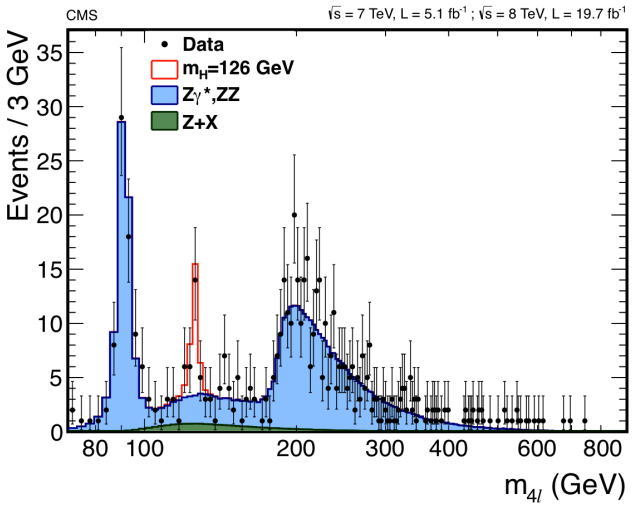
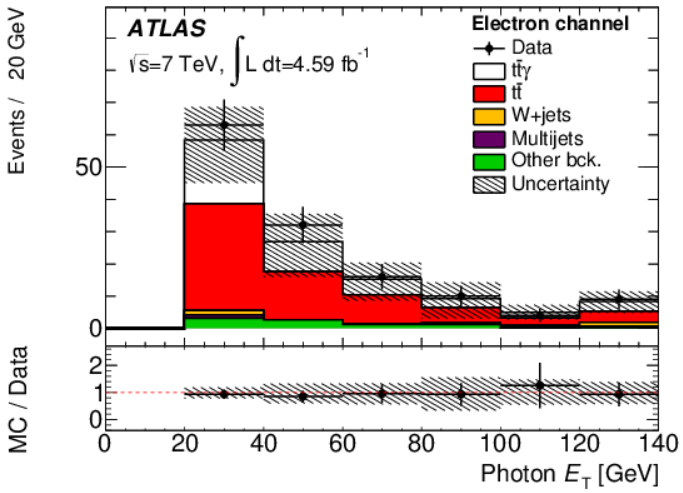
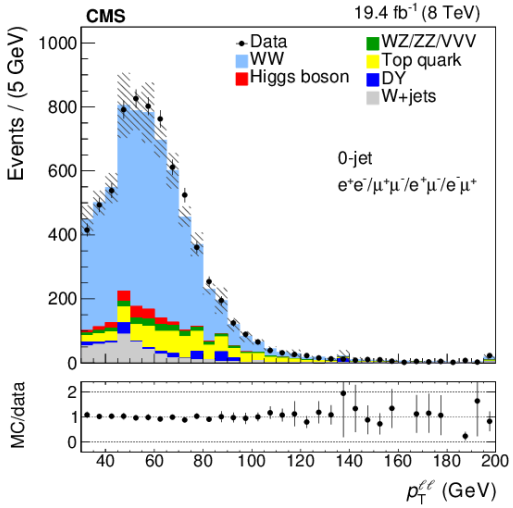
- Propaganda highlighting Europe's role in MC efforts
- Encouragement to hep-ex to continue telling the MC folks your needs

# Importance of pQCD in Monte Carlo (**MC**) Tools




$h \to ZZ^* \to 4\ell$ $\qquad$ $t\bar{t}\gamma$ [1502.00586] $\qquad$ $WW + 0j$ [1507.03268]

- Higgs boson mass, electric charge of top quark, and triple gauge couplings are fundamental quantities in the Standard Model

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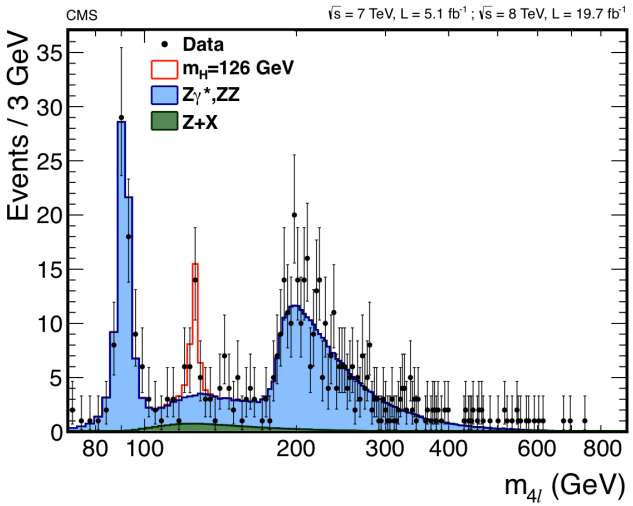
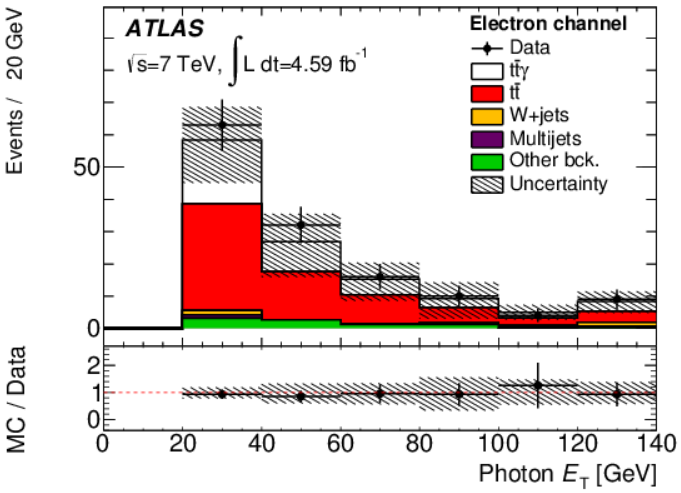
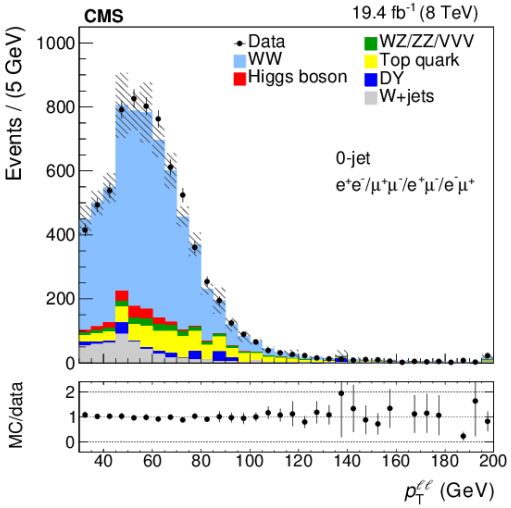



$h \to ZZ^* \to 4\ell$ $\quad$ $t\bar{t}\gamma$ [1502.00586] $\quad$ $WW + 0j$ [1507.03268]

- Higgs boson mass, electric charge of top quark, and triple gauge couplings are fundamental quantities in the Standard Model
- Required MC and both **Fixed Order** (**FO**) / **Resummed** corrections
- Maturity of physics ***and*** technology enables application to BSM
  - Caveat: Utmost care required if $\Lambda_{\mathrm{NewPhysics}} \gg \langle \Phi_{\mathrm{SM}} \rangle$

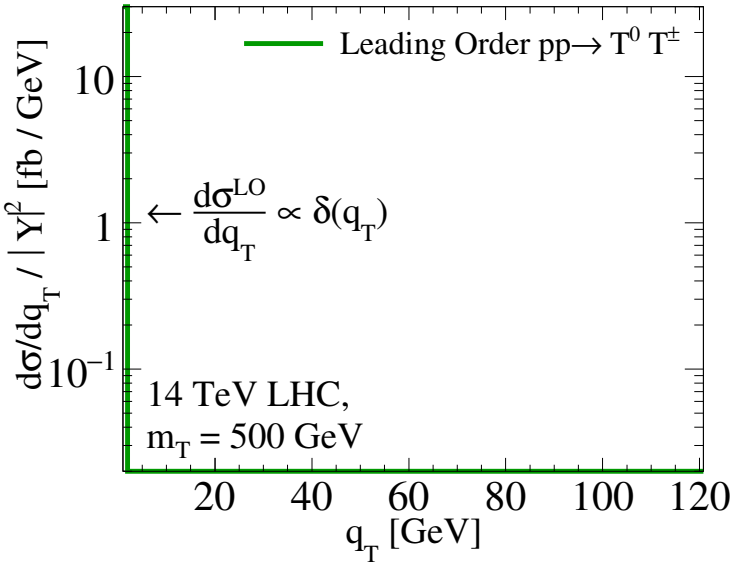
# Precision of Normalization $\neq$ Precision of Distribution

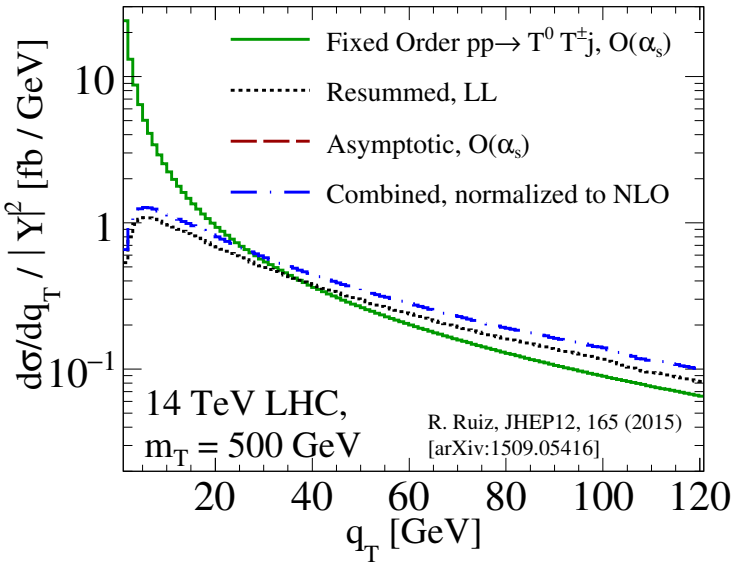
Not all observables $\hat{\mathcal{O}}$ are well-defined (physically meaningful) when total cross section $\sigma$ is known only at Born/leading order (**LO**)

Famous ex: transverse momentum ($q_T$) of $W/Z$ system in $pp \to V + X$

- $q_T = 0$ at Born-level and singular at $\mathcal{O}(\alpha_s)$
- Lowest order $q_T$ physical is when $\sigma$ is known at NLO w/ leading log. (**LL**) resummation (**or +PS**) $\implies$ $d\sigma/dq_T$ is LO+LL accurate

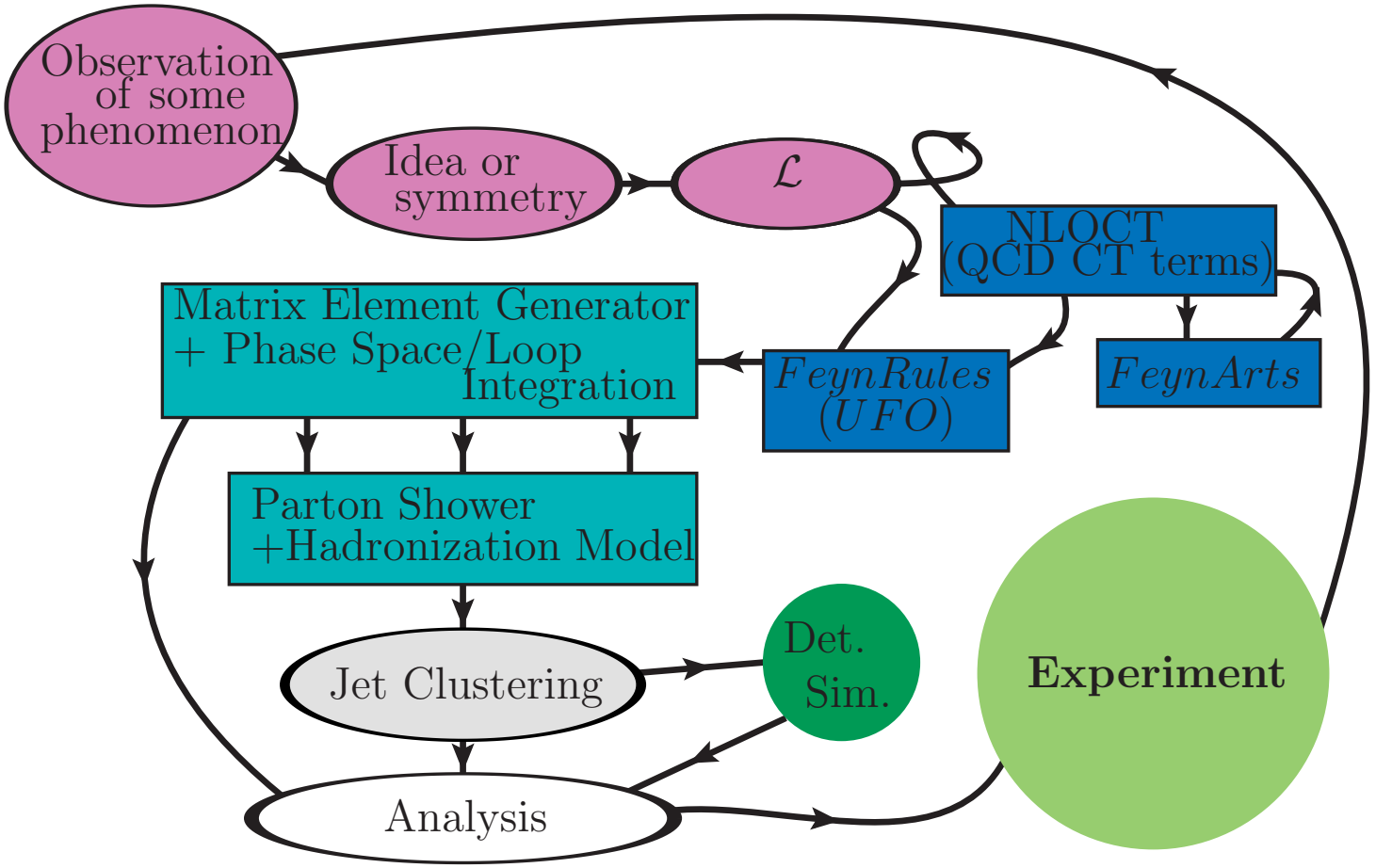
Due to color structure, also true for heavy lepton pairs and dark $\gamma_D/Z'$



## Anatomy of Automated Simulations at Next-to-Leading

# The Monte Carlo Analysis Chain for Collider Experiments

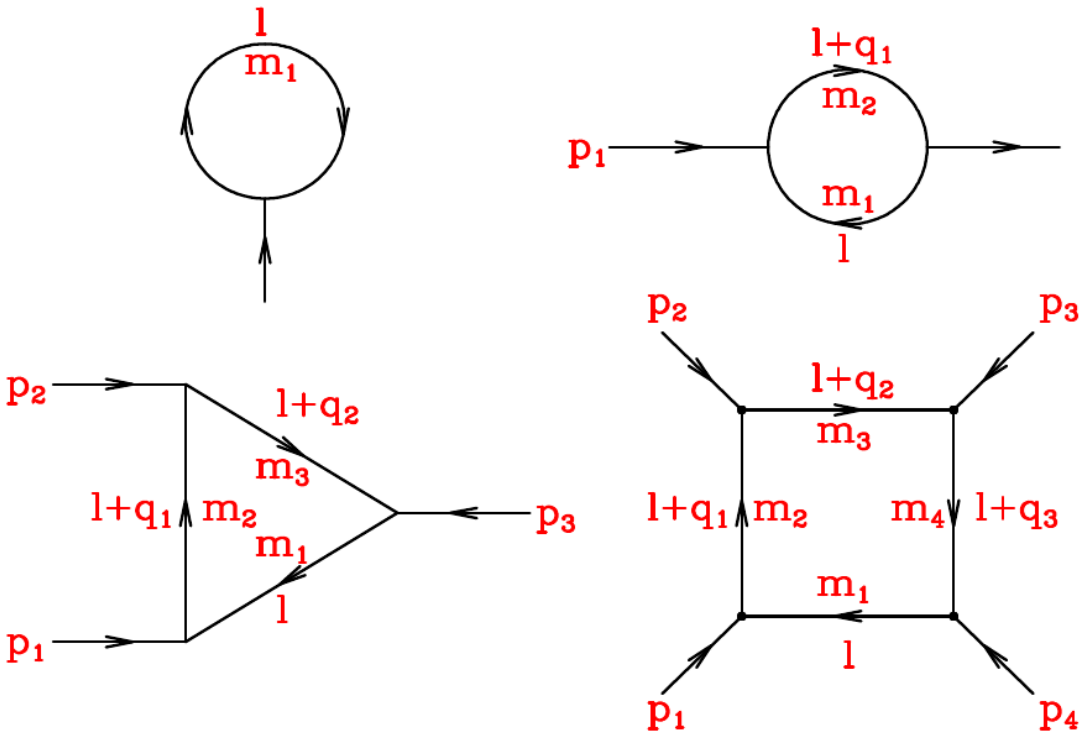



Lots of tools on the market, see hepforge.org/projects.

# Basis of Scalar Loop Integrals (QCDLoop, Collier, etc)

In 2007, Ellis and Zanderighi released a **basis** of scalar integrals from which **any** 1-,2-,3-, or 4-point loop diagram could be built **quickly**. [0712.1851]

It was known by then that $(N > 4)$-point loops could be reduced to combinations of $(N - 1)$-point integrals.




- QCDLoop [0712.1851] returns coefficients of $1/\epsilon^2,\ 1/\epsilon^1,\ 1/\epsilon^0$
- Recent developments, e.g., Collier [1604.06792], focus on speed, complexity, and *interfacing* with event generators

No known basis for two-loop diagrams [See Anastasiou's Talk]

- Progress from MSU (von Manteuffel), Louvain (Duhr), etc

# Fast Scalar Loop *Integrand* Reduction

**Goal**: Decompose a **complicated** loop into sum of **simple**, **fast** loops

In 2006-7, OPP showed that the **integrand** of *any* 1-,2-,3-, or 4-point scalar loop integral could be evaluated numerically and efficiently.

For an $m$-point loop $\mathcal{I}$ with propagators $\overline{D}_i$, one can write

$$\mathcal{I} = \int d^d\overline{q}\; A(q), \quad \text{where}$$

$$A(q) = \frac{N(q)}{\overline{D}_0\overline{D}_1\cdots\overline{D}_{m-1}},$$

$$\begin{aligned} N(q) \;=\; & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0i_1i_2i_3) + \tilde{d}(q;i_0i_1i_2i_3)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i \\ + & \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0i_1i_2) + \tilde{c}(q;i_0i_1i_2)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i \\ + & \sum_{i_0<i_1}^{m-1} \left[b(i_0i_1) + \tilde{b}(q;i_0i_1)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i \\ + & \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q;i_0)\right] \prod_{i\neq i_0}^{m-1} D_i \\ + & \tilde{P}(q) \prod_{i}^{m-1} D_i\,. \end{aligned}$$

**Also called rational terms, R**

Implementations include:
CutTools, Ninja, Collier, etc.

There remains a process-dependent, model-dependent but **finite** contribution (**rational term**) that can be derived from Feynman rules

# NLOCT: Process-Dependent Rational Terms [1406.3030]

While the $R$ terms for the SM (EW+QCD) were known since 2009 [0903.0356; 0910.3130], automation for a generic model took more time.

**Solution**: NLOCT libraries for FeynRules [Degrande, 1406.3030]

$$\mathcal{L}_{\text{Renormalizable}} \to \text{FeynRules} \to \underbrace{\text{FeynArts}}_{\text{construct loops}} \xrightarrow{\text{collect } R_2} \text{FeynRules} \to \text{UFO}$$

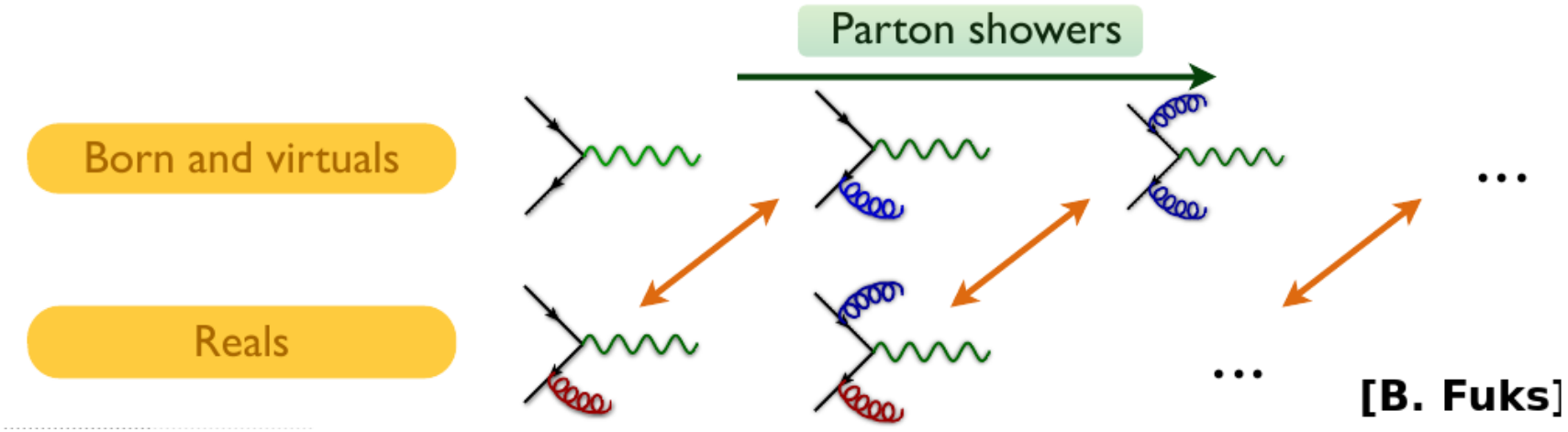
**Models files are systematically being written based on need/interest (happy to collaborate)** [*feynrules.irmp.ucl.ac.be/wiki/NLOModels*]

| 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 | - |
| Dark Matter Gauge invariant simplified model (scalar s-channel mediator) (more details) | G. Busoni | arXiv:1612.03475 , arXiv: 1710.10764 , | - | - | - |
| 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 |
| Pseudoscalar top-philic resonance (more details) | D.B. Franzosi | http://arxiv.org/abs/1707.06760 | - | AHttbar NLO UFO | - |
| 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 Model (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, coupling calculator in the LO conventions | All figures available from the arxiv |
| W'/Z' model (more details) | R. Ruiz, B. Fuks | arXiv:1701.05263 | vPrimeNLO.fr | vPrimeNLO UFO | - |

# MC@NLO

Impetus for "loop revolution" came from another breakthrough: removing phase space **double counting** between matrix element and parton showers

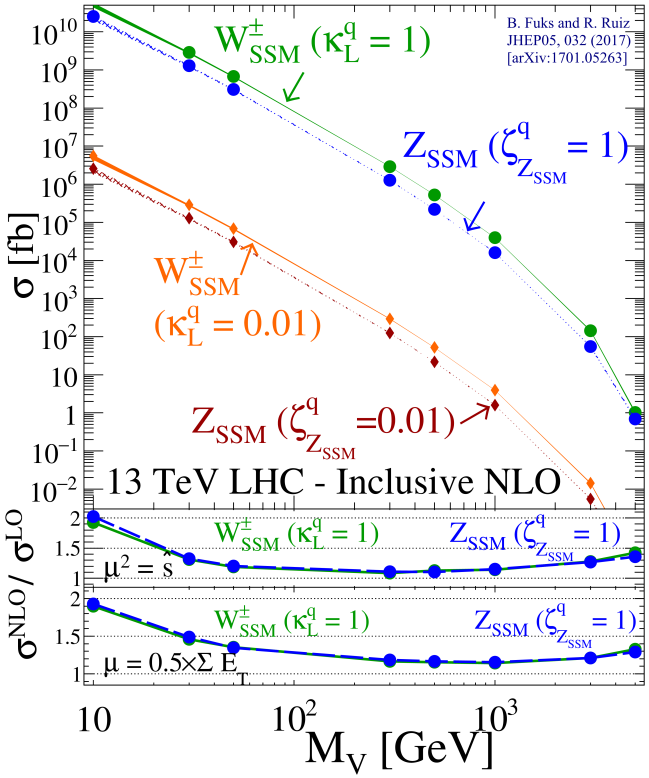
- A parton showers capture soft/collinear emissions off initial and final state legs. Unsuppressed since $\sigma \sim \alpha_s(k_T^2)\log(Q^2/k_T^2),\ k_T^2 \ll Q^2$

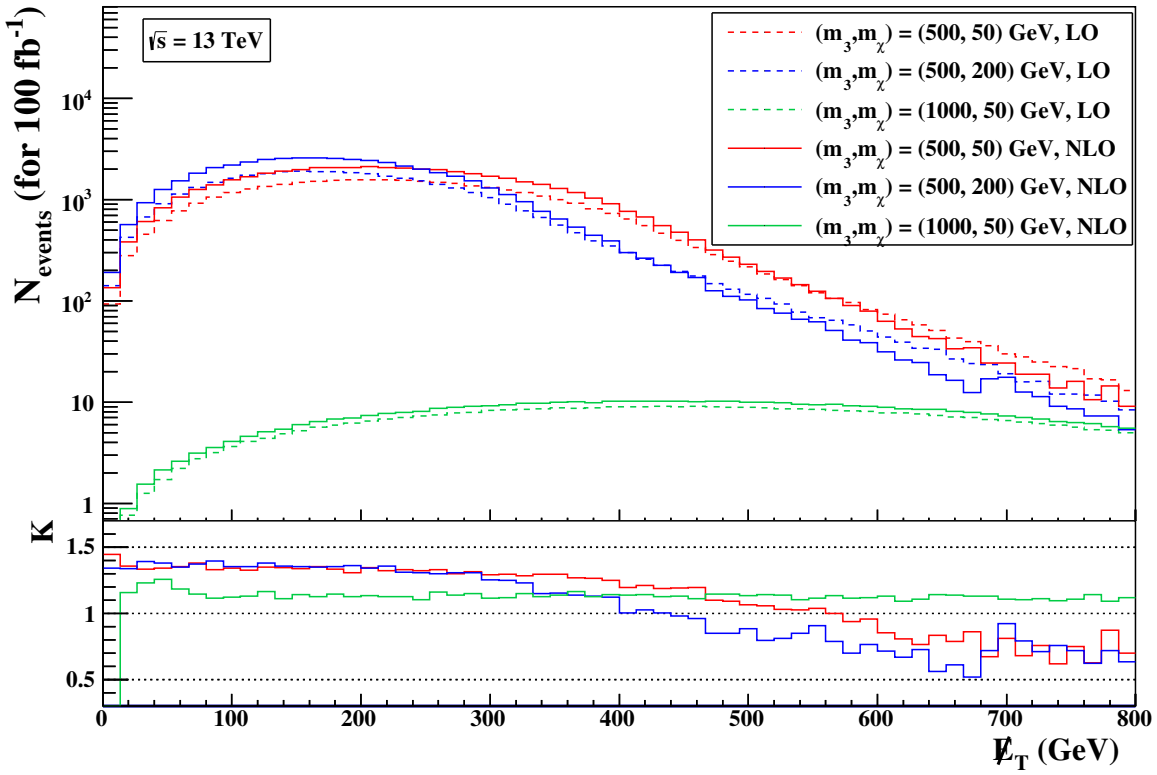



**Solution**: MC@NLO [Frixione, Webber, hep-ph/0204244]. Essentially,

- If collinear/soft, it came from the **PS**. If wide-angle/hard, then **ME**
- PS and ME describe these regions well, respectively.

With a little work, patience, and time, automated inclusive NLO and fully differential NLO+PS results for BSM are now possible




- For low-mass $W'/Z'$, $\sigma^{\rm NLO}/\sigma^{\rm LO} \gg 1.2 - 1.3$, contrary to lore. Important for dark $\gamma_D/Z'_D$ searches. [B. Fuks and **RR**, 1701.05263]

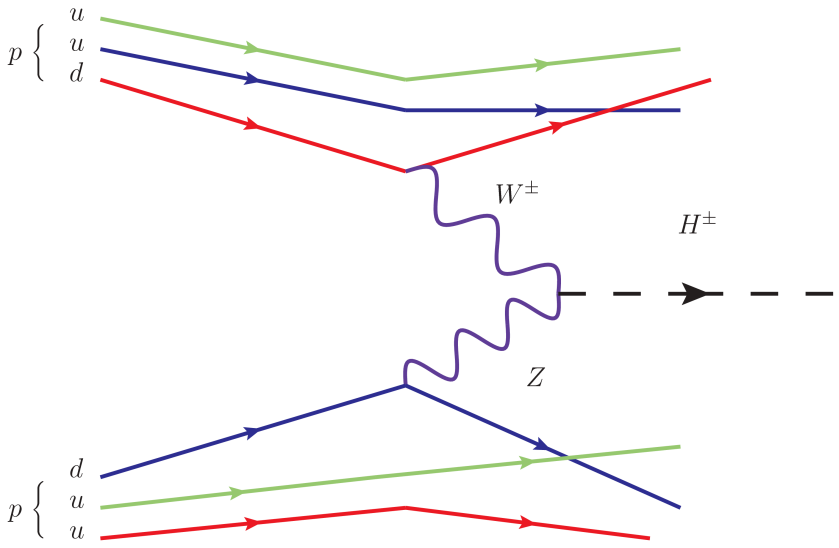
- For $\tilde{t}\bar{\tilde{t}} \to t\bar{t}$+MET, ***shape*** changes are large [Fuks, et al.,1412.5589]

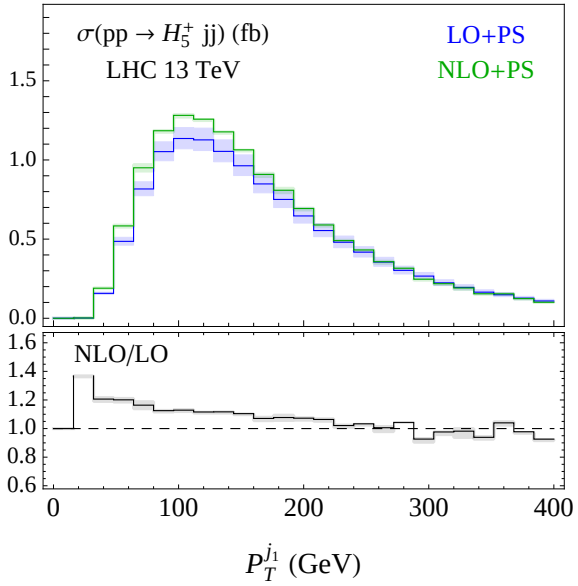
# Georgi-Machacek (Higgs Triplet) [1512.01243]

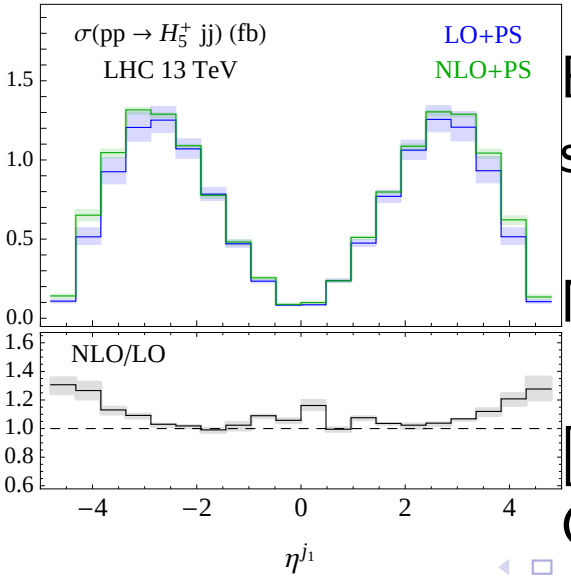
GM model predicts new, exotic higgs $H^0$, $H^{\pm}$, $H^{\pm\pm}$ that couple to EW bosons

For total rate, QCD corrections to VBF known to be small, $\sigma^{NLO}/\sigma^{LO} \sim 1$ [Han, Valencia, Willenbrock, ('92)]

Not true differentially or with cuts



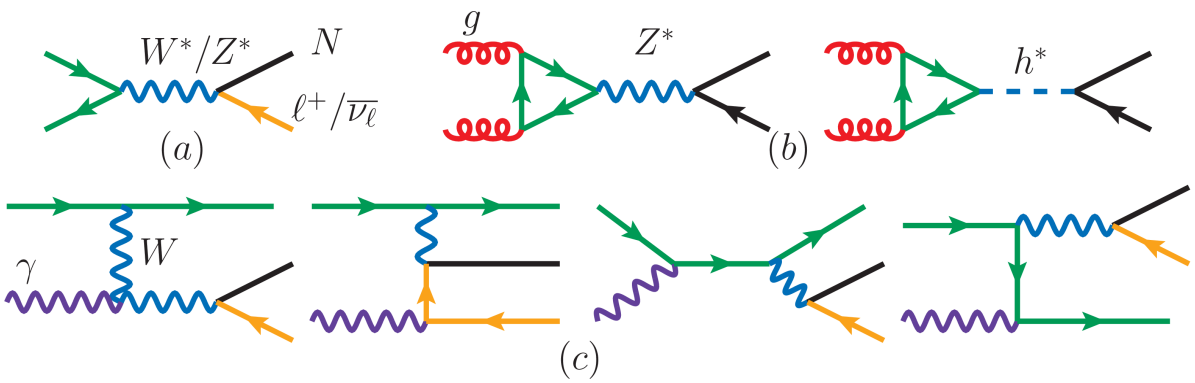

Basic jet kinematics shifts $+10 - +40\%$

Normalization $+10\%$

[More on GM at CW Chiang's talk]

# Heavy Neutrinos [1602.06957]

During '12-'15, series of papers on heavy $N$ at colliders had conflicting claims and $\sigma$ predictions




**Problem (hindsight):** ill-defined collider signatures violated pert. thry.

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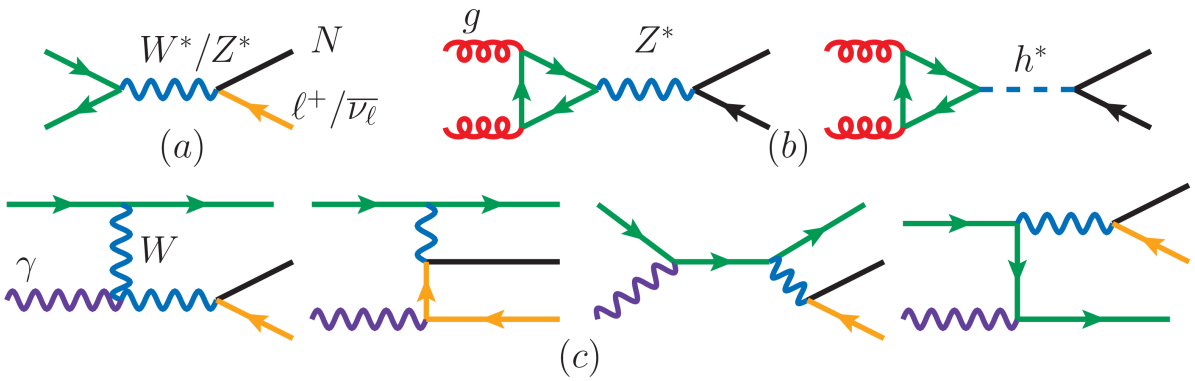
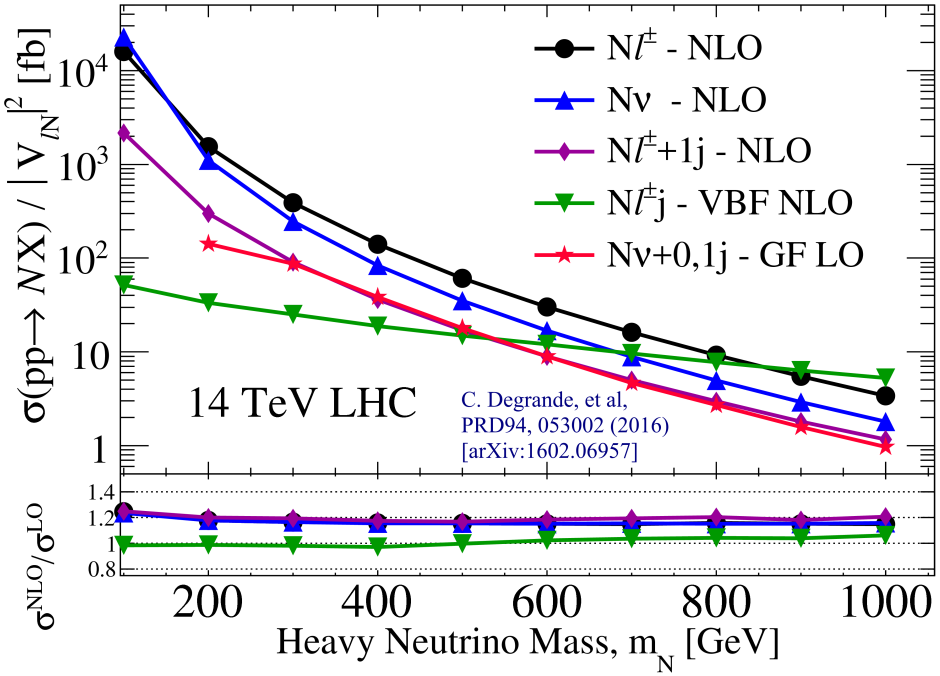



**Problem (hindsight):** ill-defined collider signatures violated pert. thry.

**Solution:**

- Invert perturbativity requirements to enforce stability FO predictions
- **photon PDF** matching for VBF
- Missing $Z^*$ **channel** in GF

See Cai, Han, Li, **RR** [1711.02180]




Stable QCD corrections $\Longrightarrow$ new signatures under perturbative control

# Top-philic Dark Matter [1605.09242]

The LHC is the only operational collider that can produce top quarks.
$\Longrightarrow$ Natural testing ground for top-philic dark matter

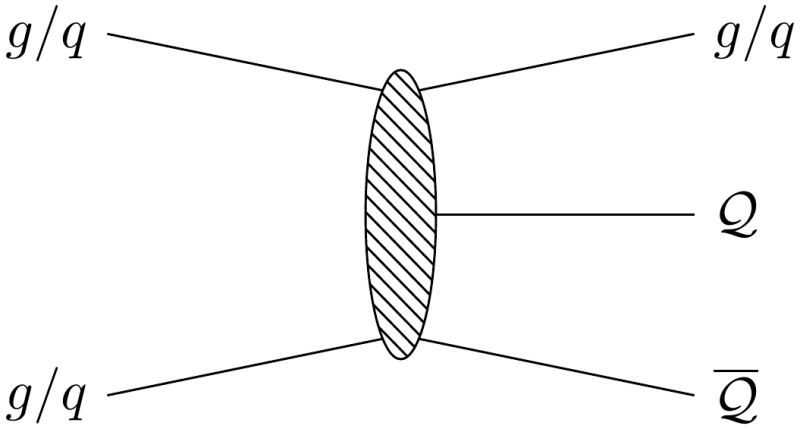
Impact of **scale uncertainty** often **ignored** on setting limits on BSM rates

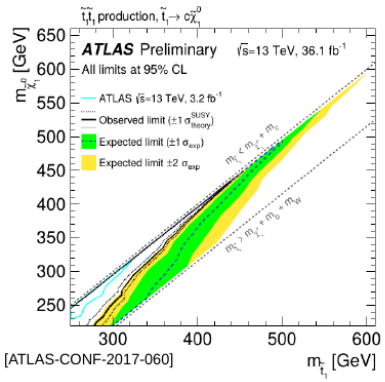
- **Take away**: In BSM searches, LO QCD theory uncertainty large, ignored, and weakens limits. (Let NLO be your **friend**!)

| | $(m_Y, m_X)$ | $\sigma_{\rm LO}$ [pb] | $\mathrm{CL}_{\rm LO}$ [%] | $\sigma_{\rm NLO}$ [pb] | $\mathrm{CL}_{\rm NLO}$ [%] |
|---|---|---|---|---|---|
| I | (150, 25) GeV | $0.658^{+34.9\%}_{-24.0\%}$ | $98.7^{+0.8\%}_{-13.0\%}$ | $0.773^{+6.1\%}_{-10.1\%}$ | $95.0^{+2.7\%}_{-0.4\%}$ |
| II | (40, 30) GeV | $0.776^{+34.2\%}_{-24.1\%}$ | $74.7^{+19.7\%}_{-17.7\%}$ | $0.926^{+5.7\%}_{-10.4\%}$ | $84.2^{+0.4\%}_{-14.4\%}$ |
| III | (240, 100) GeV | $0.187^{+37.1\%}_{-24.4\%}$ | $91.6^{+6.4\%}_{-18.1\%}$ | $0.216^{+6.7\%}_{-11.4\%}$ | $86.5^{+8.6\%}_{-5.5\%}$ |

# NEW Monojet Uncertainties [1806.Friday?]

Monojets are incredibly powerful! Great for $pp \to \mathcal{Q}\overline{\mathcal{Q}} + j$
with $\mathcal{Q} \to$Dark Matter + jets and $(m_{\mathcal{Q}} - m_{DM}) \ll m_{\mathcal{Q}}$

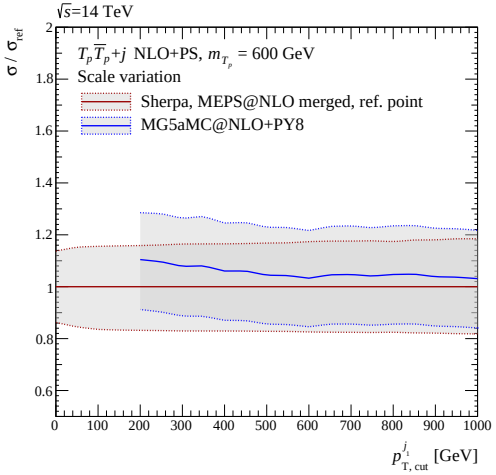


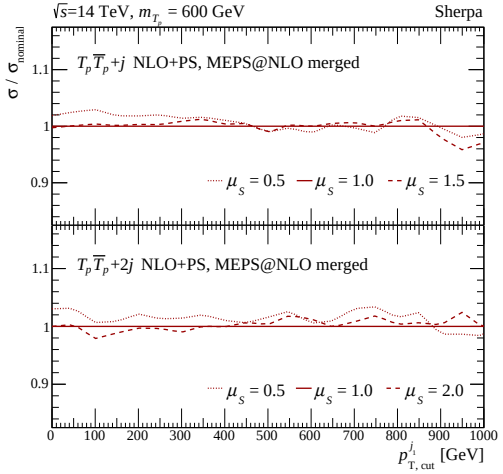




| IM | $E_{T\text{miss}}$ [GeV] | predicted # of events | stat error | error |
|---|---|---|---|---|
| 1 | > 250 | 245900 ± 5800 | 0.2 % | 2.3 % |
| 2 | > 300 | 138000 ± 3400 | 0.3 % | 2.5 % |
| 3 | > 350 | 73000 ± 1900 | 0.4 % | 2.6 % |
| 4 | > 400 | 39900 ± 1000 | 0.5 % | 2.5 % |
| 5 | > 500 | 12720 ± 340 | 0.9 % | 2.6 % |
| 6 | > 600 | 4680 ± 160 | 1.5 % | 3.4 % |
| 7 | > 700 | 2017 ± 90 | 2.2 % | 4.4 % |
| 8 | > 800 | 908 ± 55 | 3.3 % | 6.1 % |
| 9 | > 900 | 464 ± 34 | 4.6 % | 7.3 % |
| 10 | > 1000 | 238 ± 23 | 6.4 % | 9.7 % |

Amit Chakraborty - KEK (Dec 11, 2017)

- Exhaustive look into QCD theory unc., which is large when summed



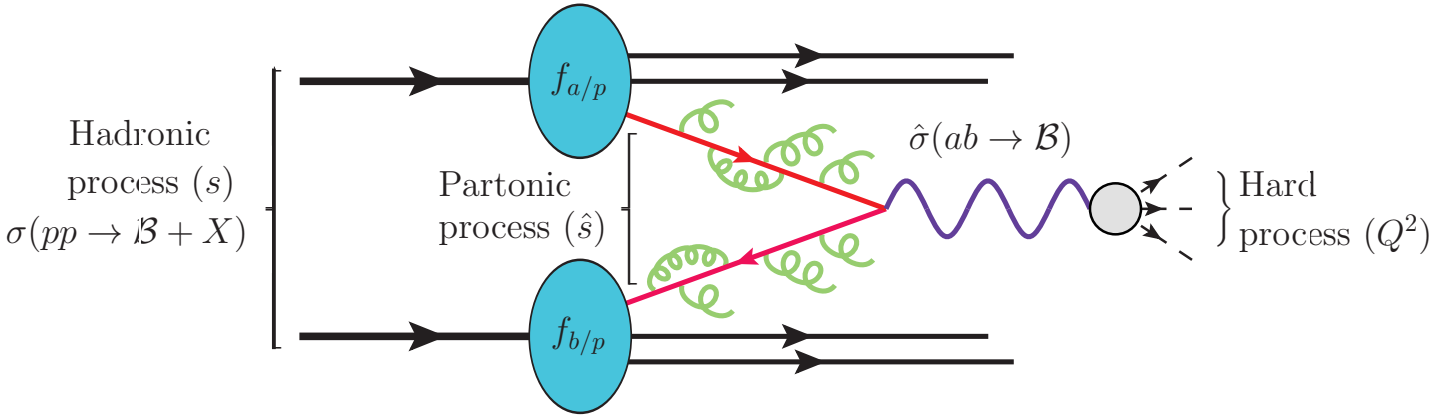




A Chakraborty, S Kuttimalai, HS Lim, MM Nojiri, **RR**

There is hope with friends!
[More Friday(?)]

# Automated Jet Veto Resummation (1/2)

1. Unstable logarithms of the form $\alpha_s(p_T^{\rm Veto})\log(p_T^{\rm Veto}/M_{\mathcal{B}})$ appear. Resummable since still inclusive w.r.t. ultra-soft and -collinear rad.
2. Cancellations when summing over *all* radiations do not occur... [Eg., 1507.01652]. This is more serious...




**Soln:** Non-trivially, observe that residual terms have the form [1205.3806, 1412.8408, +others]:

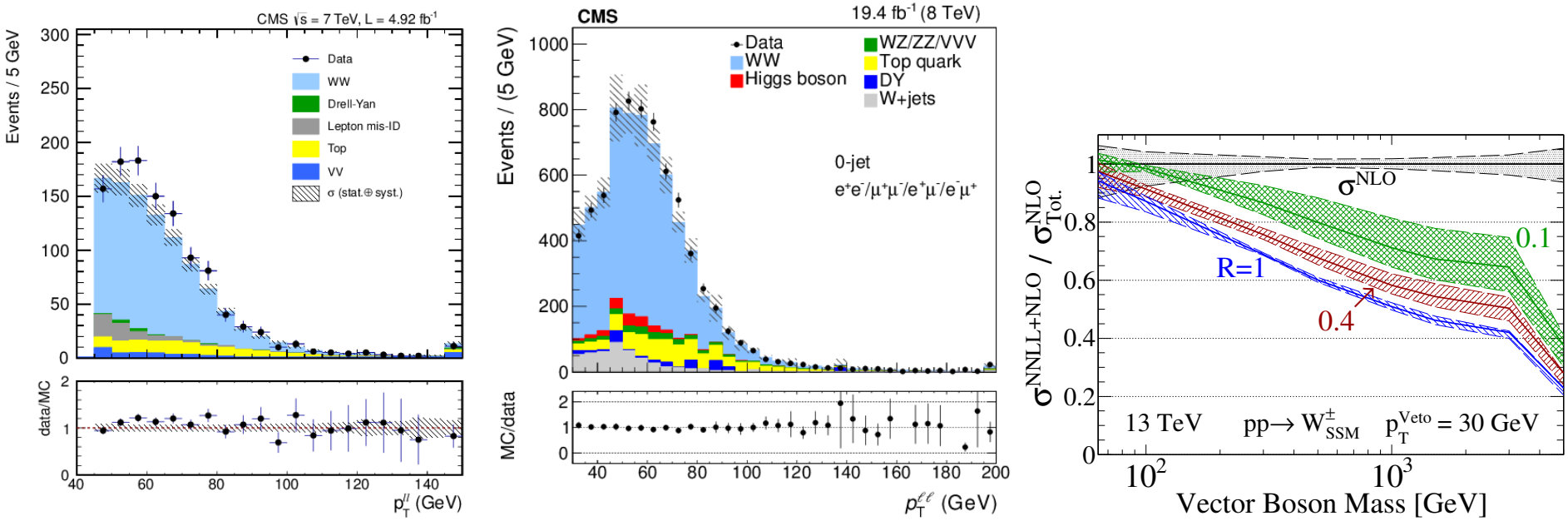
$$\left(\frac{M_{WW}}{p_T^{\rm Veto}}\right)^k \text{ and } \frac{\Lambda_{\rm QCD}}{p_T^{\rm Veto}}\log\left(\frac{M_{WW}}{p_T^{\rm Veto}}\right).$$

If $p_T^{\rm Veto}$ is in the "Goldilocks" region, such terms are numerically small:

$$\Lambda_{\rm QCD} \sim \mathcal{O}(1)\ \text{GeV} \ll p_T^{\rm Veto} \sim 20-40\ \text{GeV} \ll M_{WW}$$

# Automated Jet Veto Resummation (2/2)

Jet veto physics very deep, but also rigorous and ***experimentally tested***.




Computational framework ***quietly*** released in mg5amc@nlo [1412.8408]

- Jet veto resummation up to NLO+NNLL(Veto) in SCET
- BSM@NLO model file **needed**, but available from FeynRules
- Broadly improves color-singlet BSM searches [Fuks,**RR**, 1701.05263]

# Outlook

## NEW: Next-to-Leading Order in Electroweak Theory (1 slide)

# NEW: Automated NLO Electroweak Corrections

A major new mile stone has been reached in the past year:

- Sherpa: *Automation of NLO QCD and EW corrections with Sherpa and Recola* [1704.05783]
- MadGraph5_aMC@NLO: *The automation of next-to-leading order electroweak calculations* [1804.10017]

NLO = loop-induced at LO + real radiation (cures large Sudakov logs!)

| Process | Syntax | Cross section (in pb) LO | Cross section (in pb) NLO | Correction (in %) |
|---|---|---|---|---|
| $pp \to e^+\nu_e$ | `p p > e+ ve QCD=0 QED=2 [QED]` | $5.2498 \pm 0.0005 \cdot 10^3$ | $5.2113 \pm 0.0006 \cdot 10^3$ | $-0.73 \pm 0.01$ |
| $pp \to e^+\nu_e j$ | `p p > e+ ve j QCD=1 QED=2 [QED]` | $9.1468 \pm 0.0012 \cdot 10^2$ | $9.0449 \pm 0.0014 \cdot 10^2$ | $-1.11 \pm 0.02$ |
| $pp \to e^+\nu_e jj$ | `p p > e+ ve j j QCD=2 QED=2 [QED]` | $3.1562 \pm 0.0003 \cdot 10^2$ | $3.0985 \pm 0.0005 \cdot 10^2$ | $-1.83 \pm 0.02$ |
| $pp \to e^+e^-$ | `p p > e+ e- QCD=0 QED=2 [QED]` | $7.5367 \pm 0.0008 \cdot 10^2$ | $7.4997 \pm 0.0010 \cdot 10^2$ | $-0.49 \pm 0.02$ |
| $pp \to e^+e^-j$ | `p p > e+ e- j QCD=1 QED=2 [QED]` | $1.5059 \pm 0.0001 \cdot 10^2$ | $1.4909 \pm 0.0002 \cdot 10^2$ | $-1.00 \pm 0.02$ |
| $pp \to e^+e^-jj$ | `p p > e+ e- j j QCD=2 QED=2 [QED]` | $5.1424 \pm 0.0004 \cdot 10^1$ | $5.0410 \pm 0.0007 \cdot 10^1$ | $-1.97 \pm 0.02$ |
| $pp \to e^+e^-\mu^+\mu^-$ | `p p > e+ e- mu+ mu- QCD=0 QED=4 [QED]` | $1.2750 \pm 0.0000 \cdot 10^{-2}$ | $1.2083 \pm 0.0001 \cdot 10^{-2}$ | $-5.23 \pm 0.01$ |
| $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$ | `p p > e+ ve mu- vm~ QCD=0 QED=4 [QED]` | $5.1144 \pm 0.0007 \cdot 10^{-1}$ | $5.3019 \pm 0.0009 \cdot 10^{-1}$ | $+3.67 \pm 0.02$ |
| $pp \to He^+\nu_e$ | `p p > h e+ ve QCD=0 QED=3 [QED]` | $6.7643 \pm 0.0001 \cdot 10^{-2}$ | $6.4914 \pm 0.0012 \cdot 10^{-2}$ | $-4.03 \pm 0.02$ |
| $pp \to He^+e^-$ | `p p > h e+ e- QCD=0 QED=3 [QED]` | $1.4554 \pm 0.0001 \cdot 10^{-2}$ | $1.3700 \pm 0.0002 \cdot 10^{-2}$ | $-5.87 \pm 0.02$ |
| $pp \to Hjj$ | `p p > h j j QCD=0 QED=3 [QED]` | $2.8268 \pm 0.0002 \cdot 10^0$ | $2.7075 \pm 0.0003 \cdot 10^0$ | $-4.22 \pm 0.01$ |
| $pp \to W^+W^-W^+$ | `p p > w+ w- w+ QCD=0 QED=3 [QED]` | $8.2874 \pm 0.0004 \cdot 10^{-2}$ | $8.8017 \pm 0.0012 \cdot 10^{-2}$ | $+6.21 \pm 0.02$ |
| $pp \to ZZW^+$ | `p p > z z w+ QCD=0 QED=3 [QED]` | $1.9874 \pm 0.0001 \cdot 10^{-2}$ | $2.0189 \pm 0.0003 \cdot 10^{-2}$ | $+1.58 \pm 0.02$ |
| $pp \to ZZZ$ | `p p > z z z QCD=0 QED=3 [QED]` | $1.0761 \pm 0.0001 \cdot 10^{-2}$ | $0.9741 \pm 0.0001 \cdot 10^{-2}$ | $-9.47 \pm 0.02$ |
| $pp \to HZZ$ | `p p > h z z QCD=0 QED=3 [QED]` | $2.1005 \pm 0.0003 \cdot 10^{-3}$ | $1.9155 \pm 0.0003 \cdot 10^{-3}$ | $-8.81 \pm 0.02$ |
| $pp \to HZW^+$ | `p p > h z w+ QCD=0 QED=3 [QED]` | $2.4408 \pm 0.0000 \cdot 10^{-3}$ | $2.4809 \pm 0.0005 \cdot 10^{-3}$ | $+1.64 \pm 0.02$ |
| $pp \to HHW^+$ | `p p > h h w+ QCD=0 QED=3 [QED]` | $2.7827 \pm 0.0001 \cdot 10^{-4}$ | $2.4259 \pm 0.0027 \cdot 10^{-4}$ | $-12.82 \pm 0.10$ |
| $pp \to HHZ$ | `p p > h h z QCD=0 QED=3 [QED]` | $2.6914 \pm 0.0003 \cdot 10^{-4}$ | $2.3926 \pm 0.0003 \cdot 10^{-4}$ | $-11.10 \pm 0.02$ |
| $pp \to t\bar{t}W^+$ | `p p > t t~ w+ QCD=2 QED=1 [QED]` | $2.4119 \pm 0.0003 \cdot 10^{-1}$ | $2.3025 \pm 0.0003 \cdot 10^{-1}$ | $-4.54 \pm 0.02$ |
| $pp \to t\bar{t}Z$ | `p p > t t~ z QCD=2 QED=1 [QED]` | $5.0456 \pm 0.0006 \cdot 10^{-1}$ | $5.0033 \pm 0.0007 \cdot 10^{-1}$ | $-0.84 \pm 0.02$ |
| $pp \to t\bar{t}H$ | `p p > t t~ h QCD=2 QED=1 [QED]` | $3.4480 \pm 0.0004 \cdot 10^{-1}$ | $3.5102 \pm 0.0005 \cdot 10^{-1}$ | $+1.81 \pm 0.02$ |
| $pp \to t\bar{t}j$ | `p p > t t j QCD=3 QED=0 [QED]` | $3.0277 \pm 0.0003 \cdot 10^2$ | $2.9683 \pm 0.0004 \cdot 10^2$ | $-1.96 \pm 0.02$ |
| $pp \to jjj$ | `p p > j j j QCD=3 QED=0 [QED]` | $7.9639 \pm 0.0010 \cdot 10^6$ | $7.9472 \pm 0.0011 \cdot 10^6$ | $-0.21 \pm 0.02$ |
| $pp \to tj$ | `p p > t j QCD=0 QED=2 [QED]` | $1.0613 \pm 0.0001 \cdot 10^2$ | $1.0539 \pm 0.0001 \cdot 10^2$ | $-0.70 \pm 0.02$ |

**Table 2**: Processes considered in sect. 6.2. The second column reports the MG5_aMC syntax used to generate them. The third and fourth columns display the fully-inclusive results for the quantities defined in eq. (6.12). The fifth column shows the results for the fractional correction defined in eq. (6.14). All uncertainties are due to MC integration errors.

[1804.10017]

## Automated Monte Carlo at NNLO (1 slide)

# NNLO Monte Carlos for BSM

When achieved, will MC@NNLO be important for BSM?

- Not for discovery, except when "NNLO" really means "NLO"
- **Remember**: "NLO Monte Carlos" is a technology paradigm

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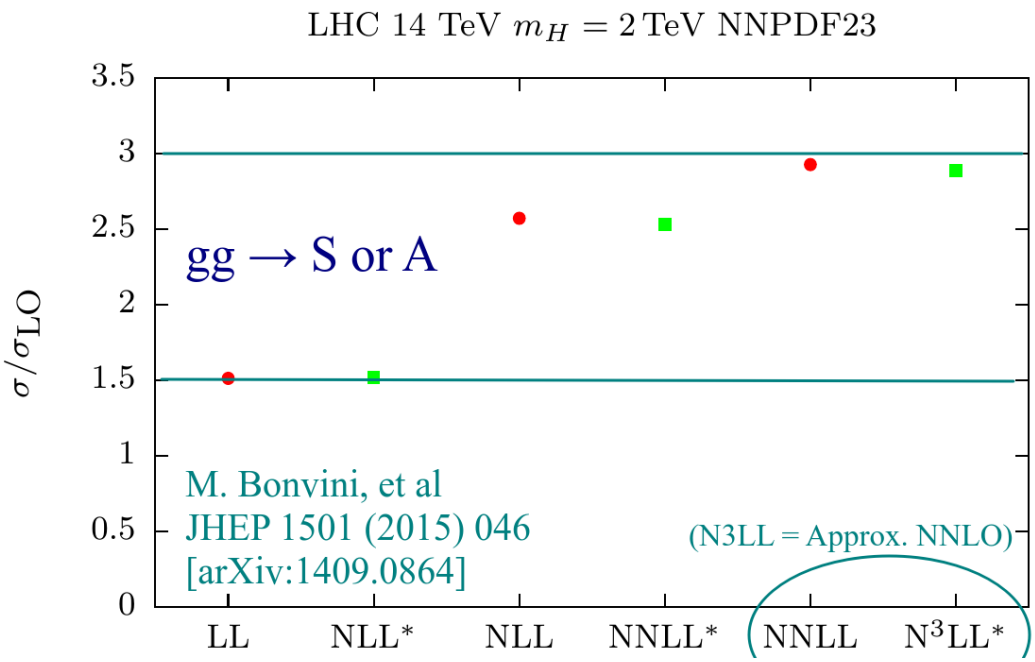
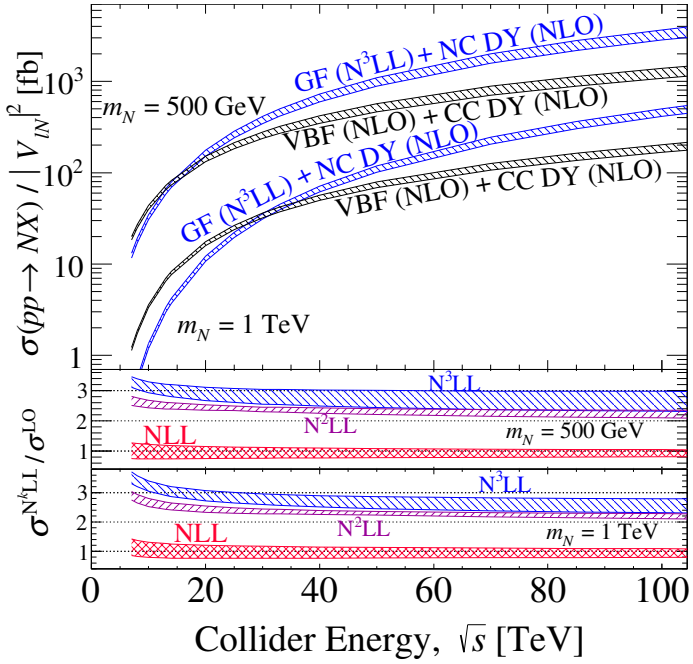
For loop-induced processes, MC@NLO $\implies$ 1-loop @ LO

- $gg \to S^0,\ A^0$: QCD corrections are ***large*** $(\sigma/\sigma^{\rm LO} \sim 2-3)$
- Heavy $N$ production at $\sqrt{s} > 25$ TeV dominated by GF [**RR**, Spannowsky, Waite, 1706.02298]



## One more thing

**SURPRISE**

# Summary

Over the past decade, an evolution in QCD and Monte Carlo technology!

- New tools + new formalisms $\Longrightarrow$ new sensitivity at $pp$ colliders
- Automation of SM and BSM@NLO in **QCD** and **EW**
- Automation of some types of resummation (+PS, Veto, pipeline)

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Last words: "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: 3-5 ab$^{-1}$ and 50 ab$^{-1}$
- Premature to claim "nightmare scenario" (SM Higgs + nothing else)

**Thank you.**