Monte Carlo for New Physics at NLO and Beyond

Terascale@Paris

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- Exhaustive. Unfortunately, lots of omissions.
- A technical lecture on next-to-next-to-...-leading order computations

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- A qualitative discussion on why perturbative QCD corrections are in fact important for new physics searches at colliders

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

What Data Tells Us

The LHC is operating spectacularly!

- Higgs  : No longer a hep-th problem. Now also a hep-ex problem.
- mass hierarchy, little hierarchy, particle nature of dark matter, origin of EWSB, etc., are issues that require more data and thought

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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!

- For $\Lambda_{\rm BSM} \lesssim \langle \Phi_{\rm EW} \rangle$ and $g_{\rm BSM} \ll g_{\rm SM}$, $\mathcal{O}(\alpha_s)$ corrections known to be large due to huge PDF enhancement at low-x
- Corrections for $\Lambda_{\rm BSM} \gg \langle \Phi_{\rm EW} \rangle$ is more subtle

Situation: It appears we may be entering a regime at LHC13 where

$$\Lambda_{BSM} \gg \langle \Phi_{EW} \rangle \gg \Lambda_{QCD}$$

At LEP, Tevatron, and LHC7/8, we were largely exploring a regime where

$$\langle \Phi_{EW} \rangle \gtrsim \Lambda_{BSM} > \Lambda_{QCD}$$

Problem: Terms from radiative processes, e.g., VBF & $+nj$, that scale as

$$\sigma(pp \to X) \sim \log \Lambda_{BSM}/\langle \Phi_{EW} \rangle \text{ and } \sim \log \Lambda_{BSM}/\Lambda_{QCD}$$

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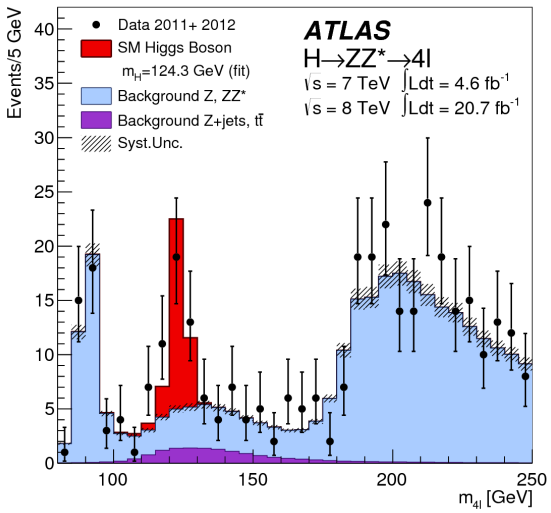
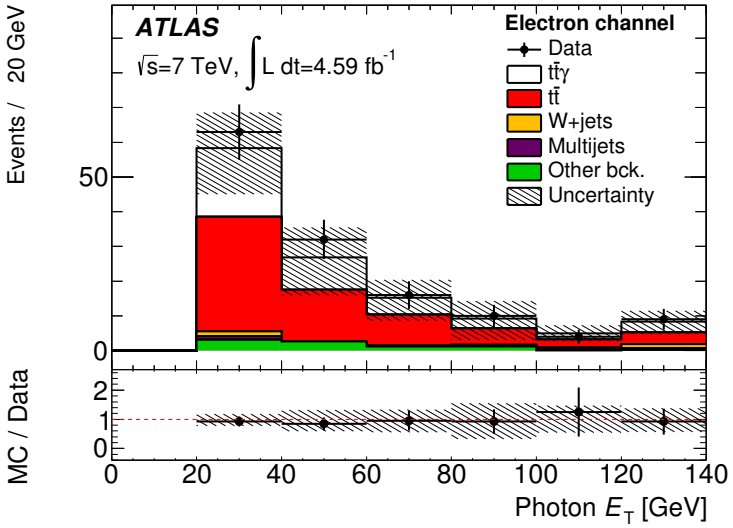
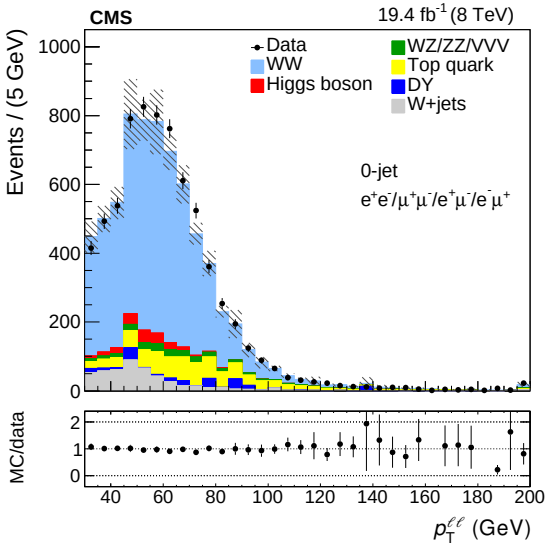
Solution: These are issues long-understood by the pQCD community: exploit soft/collinear factorization, resummation, and IRC-safety.
From this perspective, physics at colliders looks **qualitatively different**.

The Importance of Monte Carlo and pQCD







$h \to ZZ^* \to 4\ell$ $\quad$ $t\bar{t}\gamma$ [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

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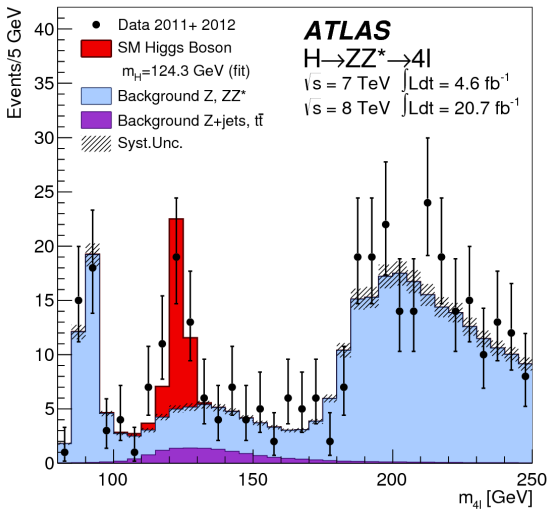

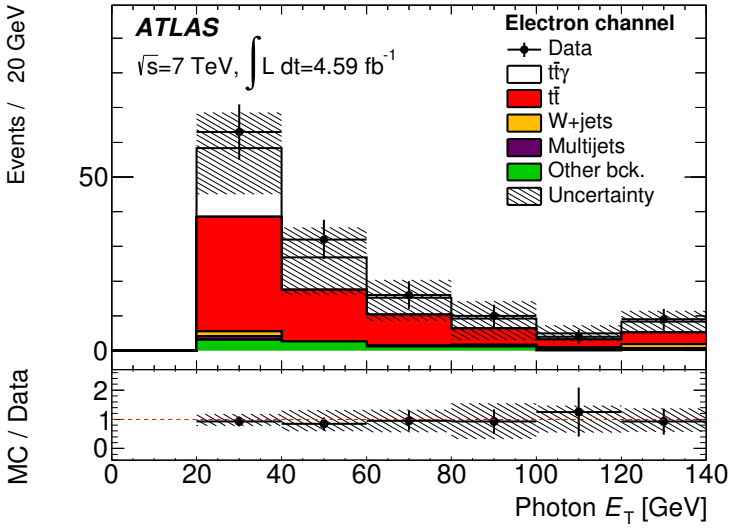

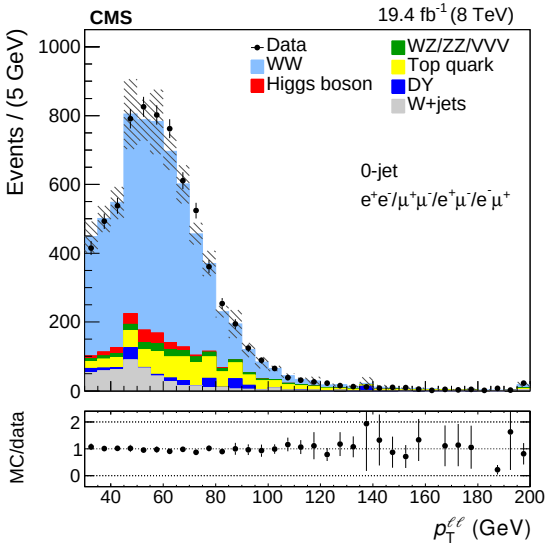

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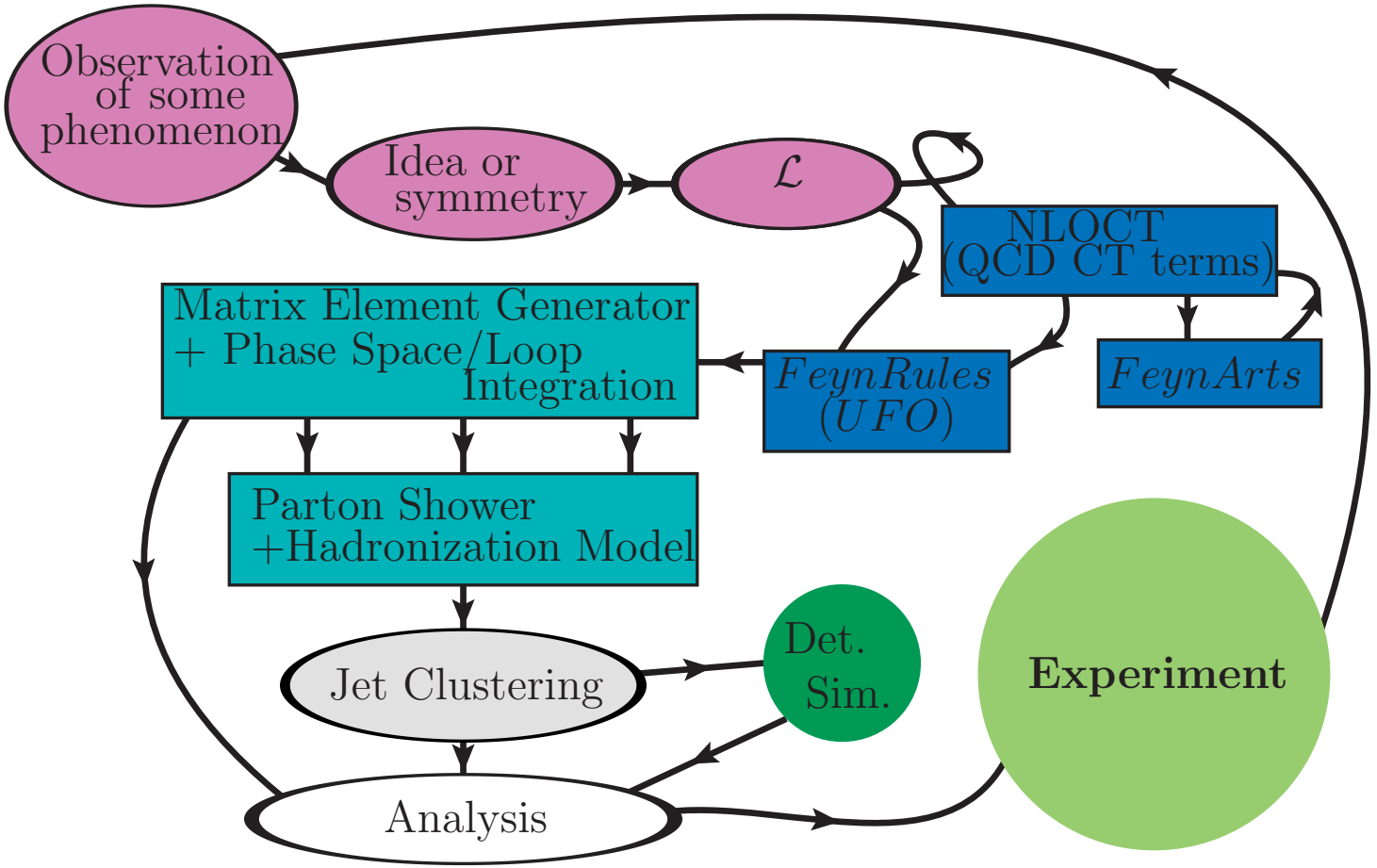
- Higgs boson mass, electric charge of top quark, and triple gauge couplings are fundamental quantities in the Standard Model
- Required MC and both **Fixed Order** (**FO**) / **Resummed** corrections
- Maturity of physics ***and*** technology easily allows application to BSM

Anatomy of MC@NLO

The Monte Carlo Analysis Chain for Collider Experiments

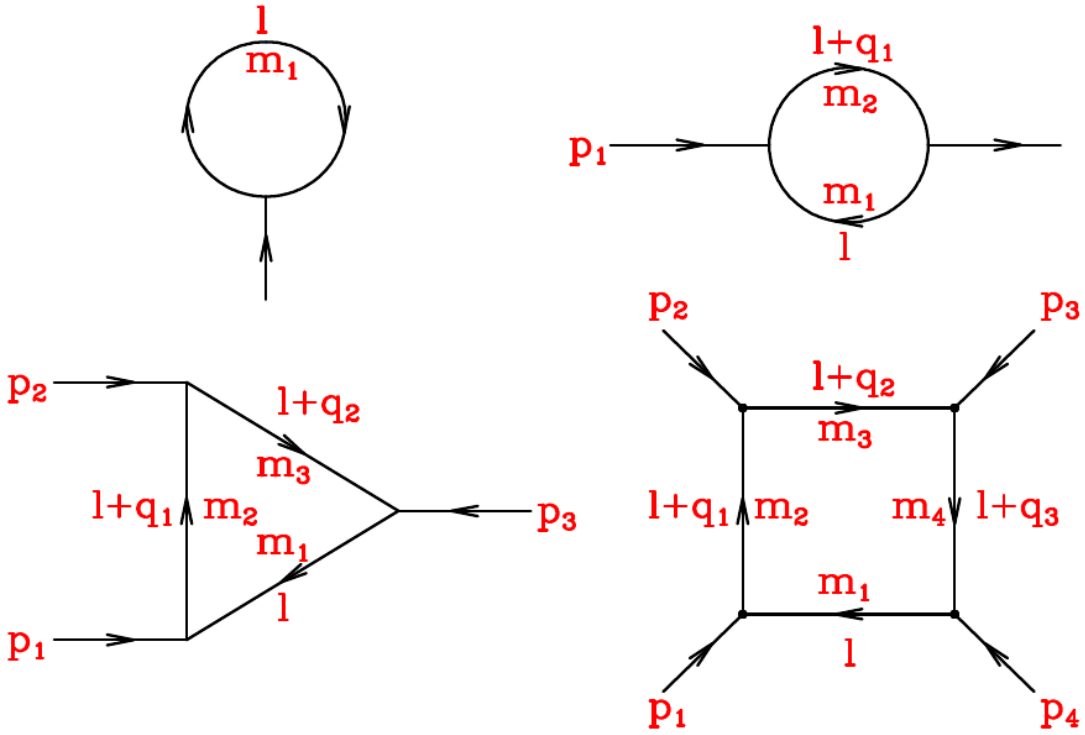


Lots of tools on the market [hepforge.org/projects].

Basis of Scalar Loop Integrals (QCDLoop)

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

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



QCDLoop returns coefficients of $1/\epsilon^2,\ 1/\epsilon^1,\ 1/\epsilon^0$ [qcdloop.fnal.gov]

No such known basis (yet?) for two-loop diagrams.

Fast Scalar Loop Integ*rand* Reduction

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 function with propagators $\overline{D}_i$, one can write

$$I = \int d^d\overline{q}\ A(q),$$

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

where $N(q)$ is $\rightarrow$

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

Also called rational terms, R

CutTools, Collier, Ninja,...

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

Process-Dependent Terms (NLOCT)

While the R terms for the SM (EW+QCD) were made available in [0903.0356; 0910.3130], automation for a generic model took more time.

Solution: NLOCT libraries for FeynRules [Degrande, 1406.3030]

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

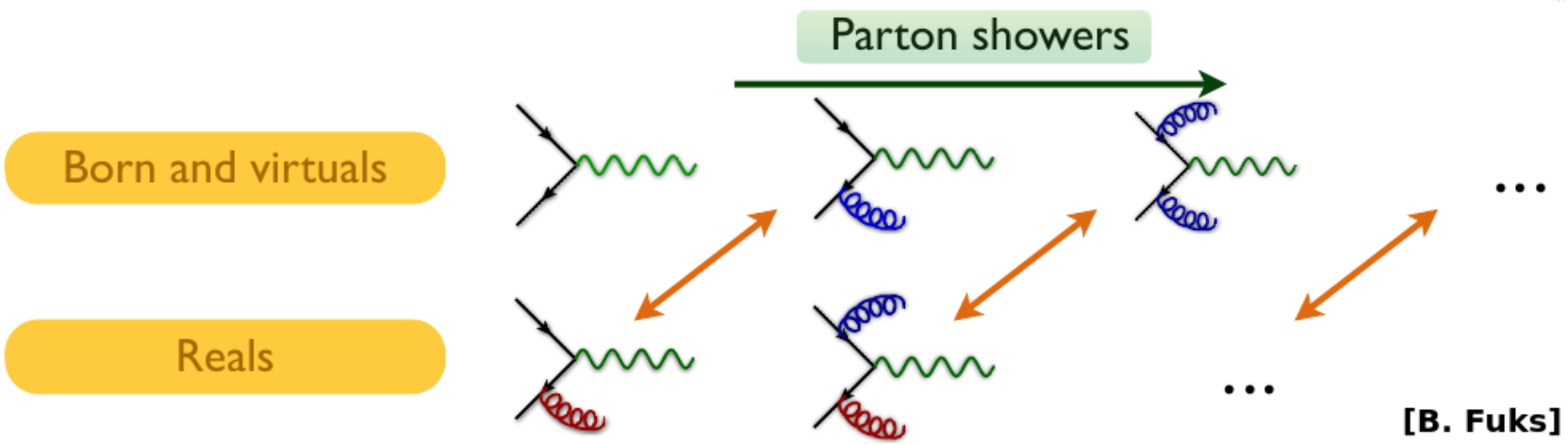
Strong European effort! [*feynrules.irmp.ucl.ac.be/wiki/NLOModels*]

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	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
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
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	All figures available from the arxiv
Effective LR symmetric model (more details)	R. Riuz	arXiv:1610.08985	effLRSM.fr	EffLRSM UFO	-

MC@NLO

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

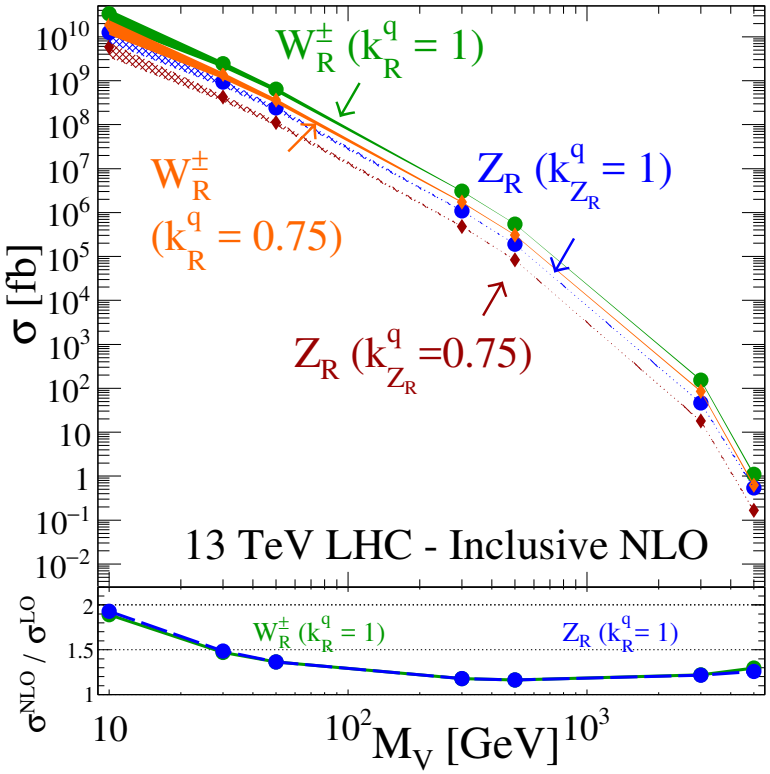
- A parton showers capture soft/collinear emissions from initial and final state. Unsuppressed since $\sigma \sim \alpha_s(k_T^2)\log(Q^2/k_T^2)$

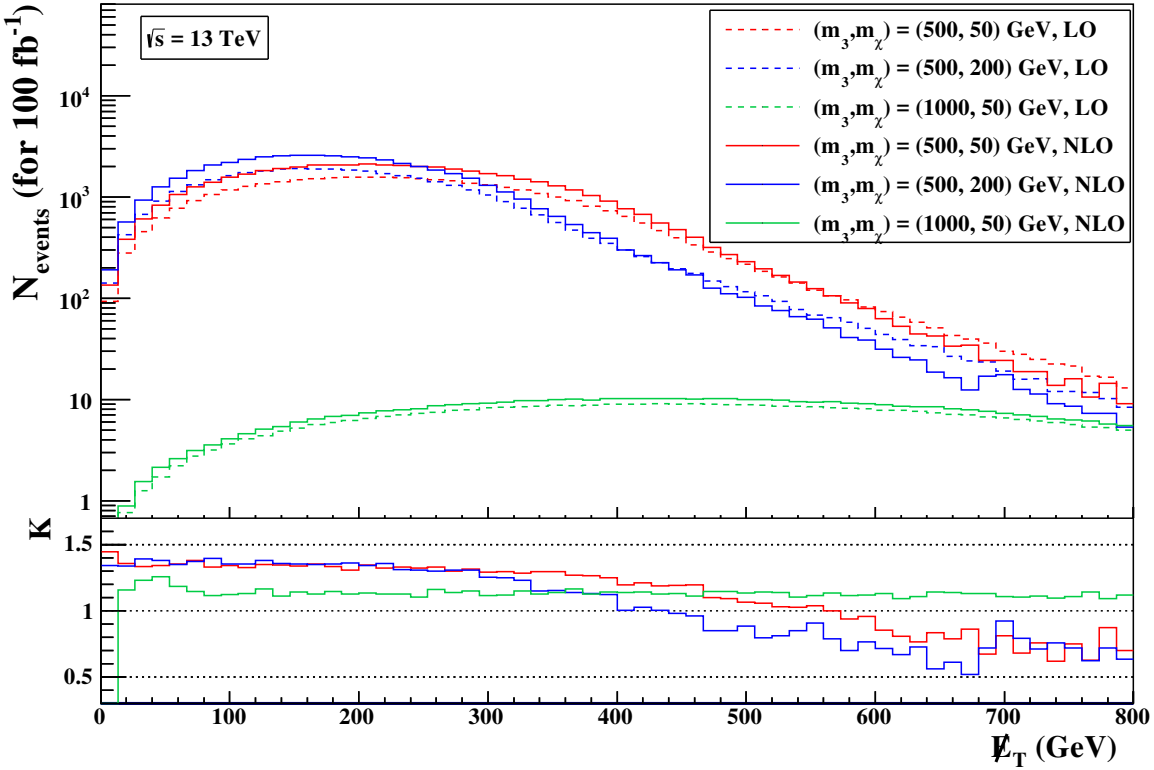


Solution: MC@NLO [Frixione, Webber, hep-ph/0204244]. Essentially,

- 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 possible





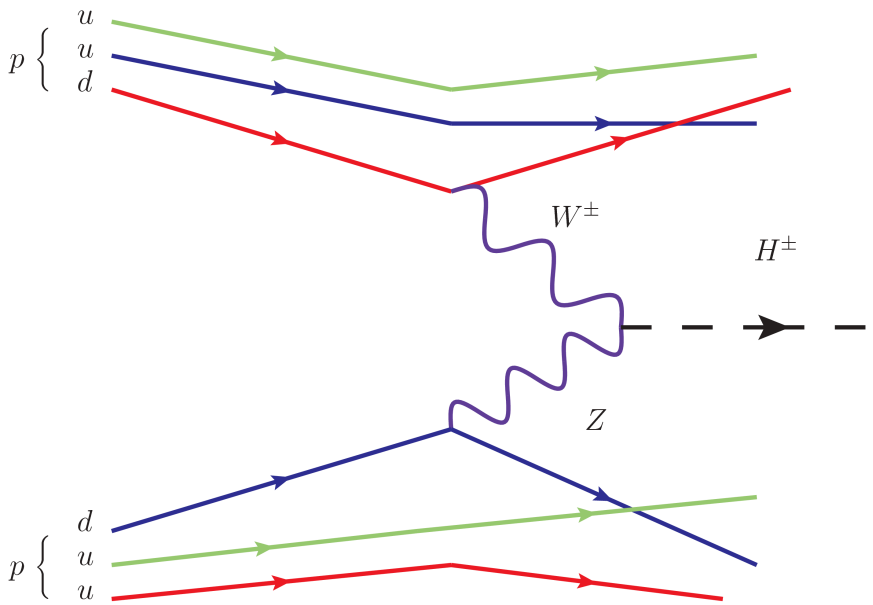
- For low-mass W', Z', we see $\sigma^{\rm NLO}/\sigma^{\rm LO} \gg 1.2 - 1.3$, contrary to lore. Important for dark photon/Z'_D searches. [1607.03504]
- For $\tilde{t}\bar{\tilde{t}} \to t\bar{t}$+MET, *shape* changes are large [1412.5589]

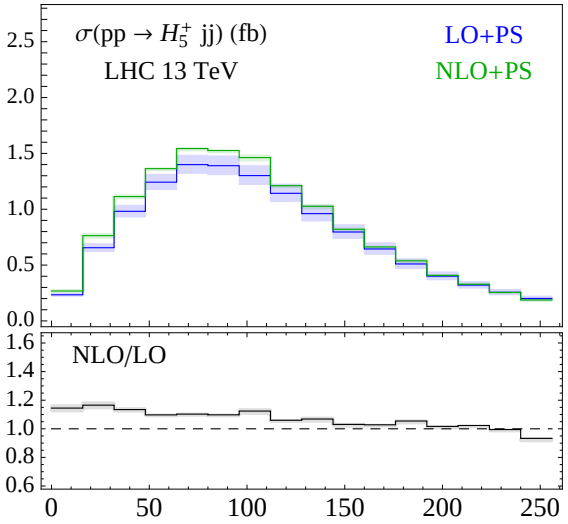
Georgi-Machacek (Higgs Triplet) [1512.01243]

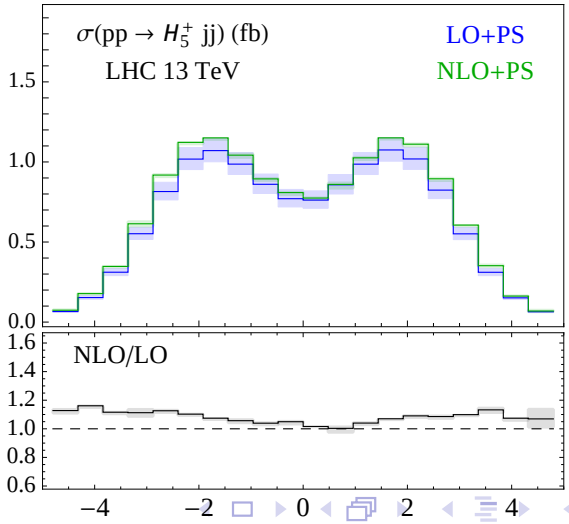
GM model predicts new, exotic higgs H^0, $H^{\pm}$, $H^{\pm\pm}$ that couple to EW bosons

For total rate, QCD corrections to VBF known to be small [Han, et al]

Not true differentially or with cuts: Higgs kinematics shift $\pm 20\%$

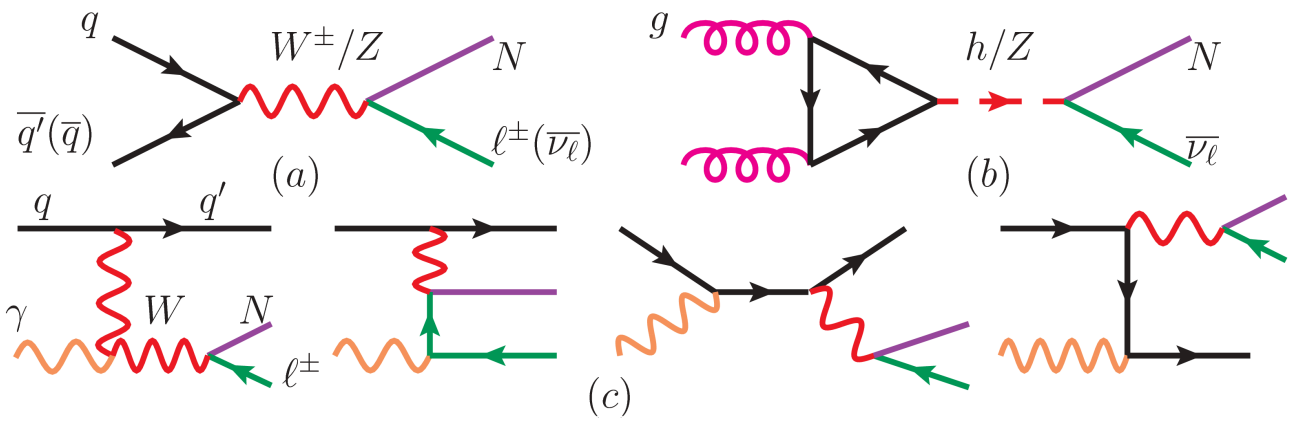






Heavy Neutrinos [1602.06957]

During '12-'15, series of papers on heavy N at colliders had conflicting predictions and conclusions



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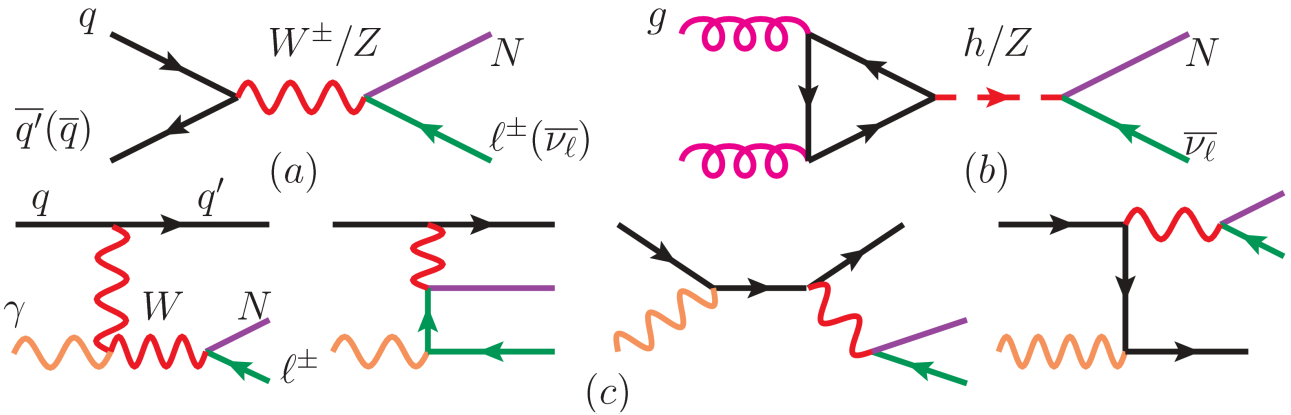
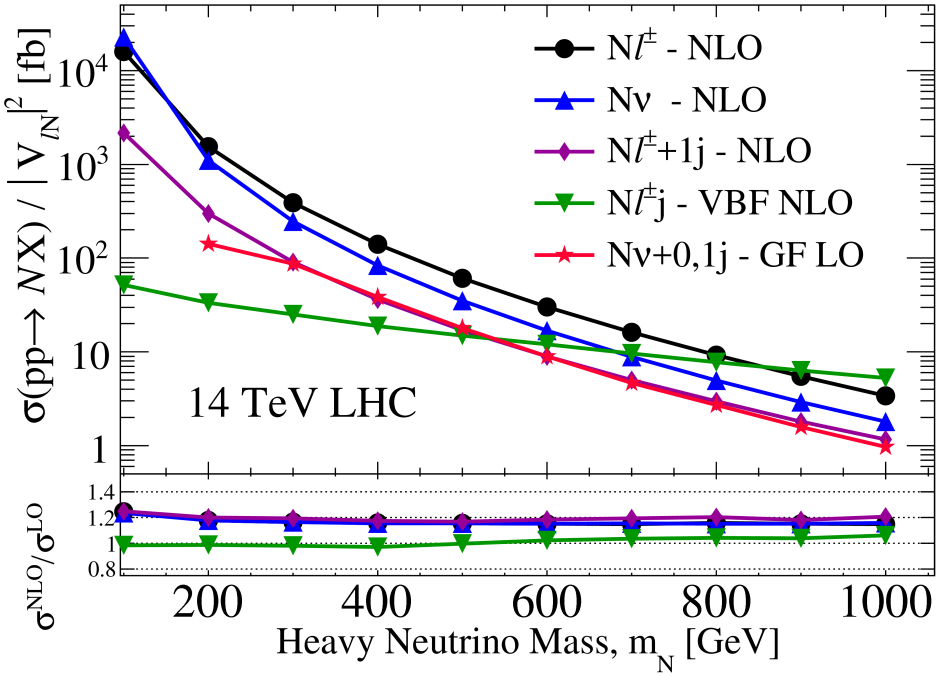


Problem: several studies used ill-defined collider signatures.

Solution:
- Invert perturbativity requirements for validity of FO calculations
- photon PDF matching for VBF
- Missing Z^* channel in GF

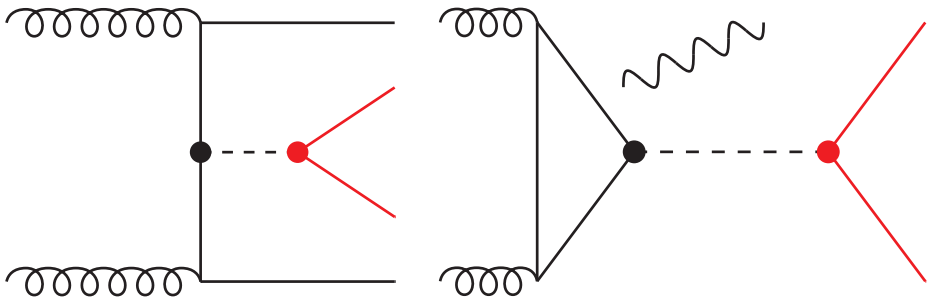
Broadly applicable to colorless BSM since does not rely on nature of N



Top-philic Dark Matter [1605.09242]

The LHC is the only operational collider that can produce top quarks

- Natural testing ground for top-philic dark matter



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

	(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	$0.187^{+37.1\%}_{-24.4\%}$	$91.6^{+6.4\%}_{-18.1\%}$	$0.216^{+6.7\%}_{-11.4\%}$	$86.5^{+8.6\%}_{-5.5\%}$

Outlook

Automated Monte Carlo at NNLO (1 slide)

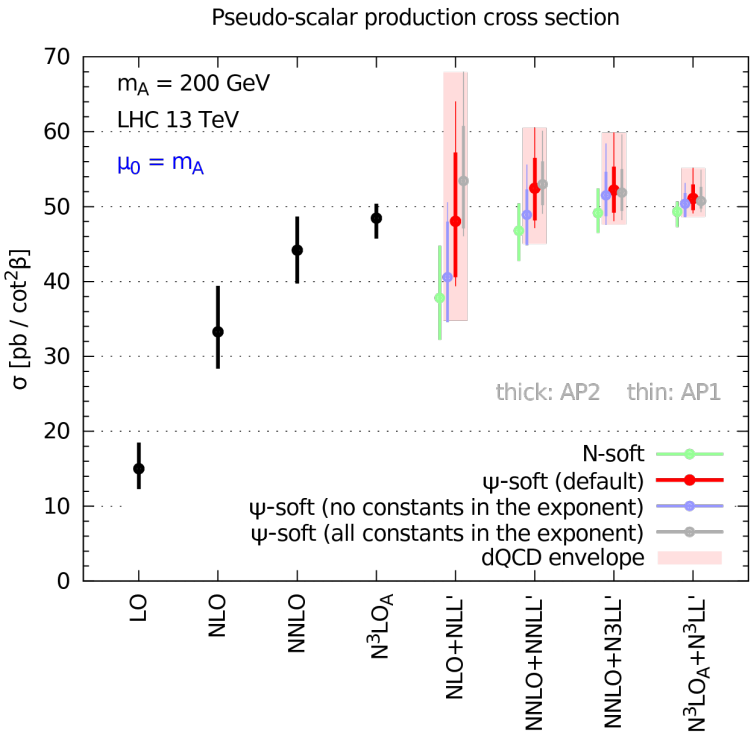
MC@NNLO for BSM

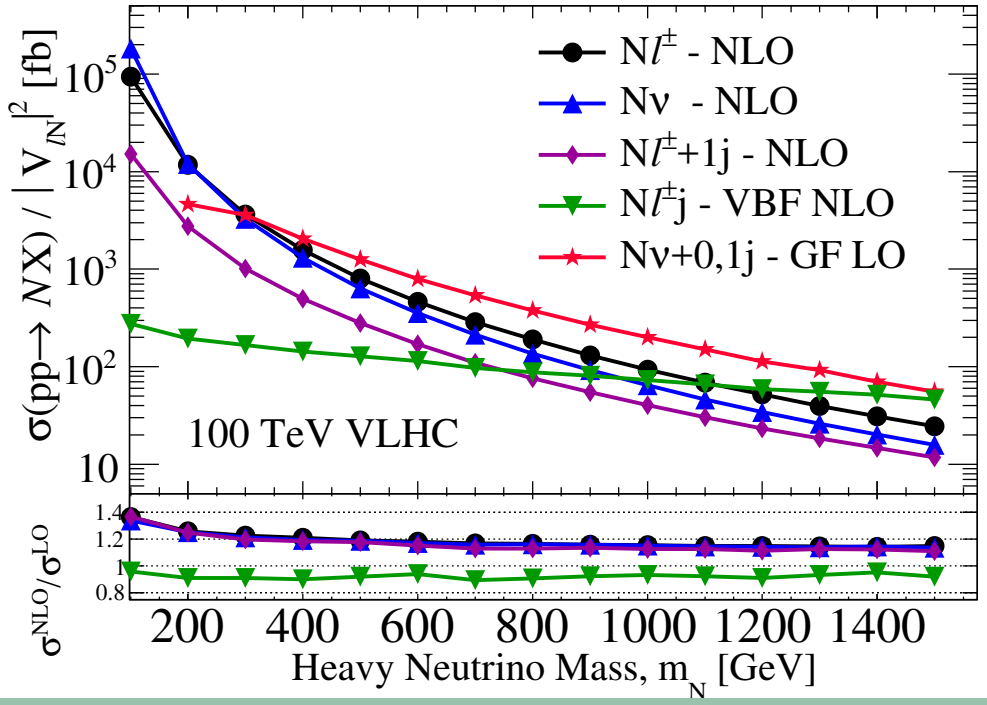
Is MC@NNLO important for BSM?

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

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

- $gg \to S^0,\ A^0$: QCD corrections are ***large***
- Heavy lepton production at 100 TeV: GF@LO $>$ DY@NLO



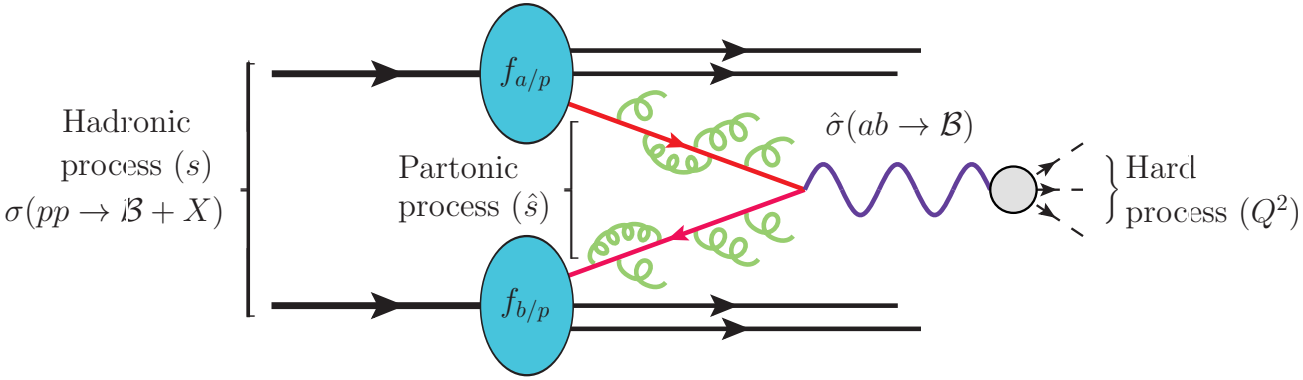


Automated Resummation[1]

[1] **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.

Threshold and Recoil Resummation

Inclusive W' production is identical to $W_{\rm SM}$, except $M_{W'} \gtrsim 3-4$ TeV.



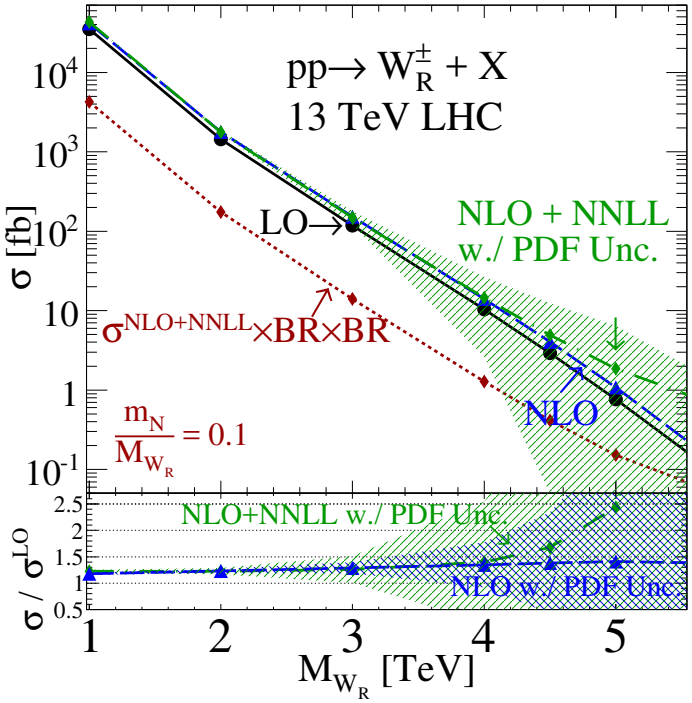
Away from phase space boundaries, QCD corrections for DY-systems are 20-40%. However, radiations generate logs

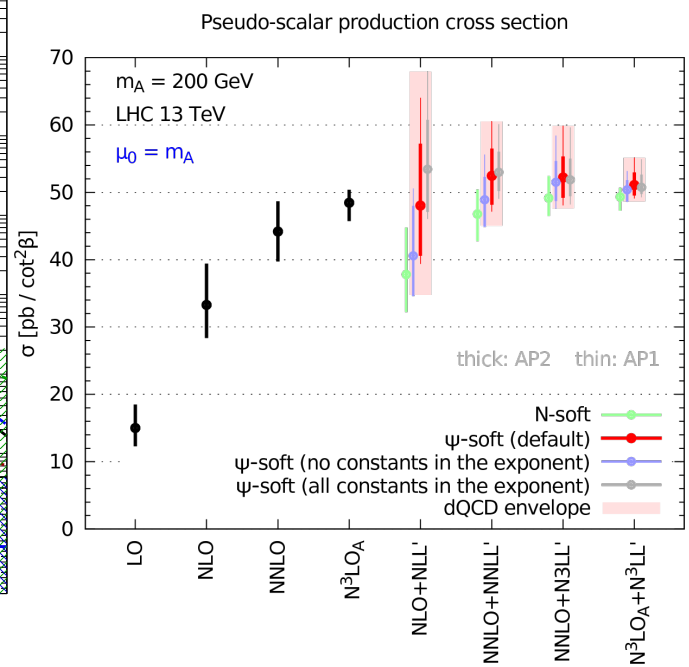
$$\sigma(pp \to W' + g) \sim \int d^{4-2\varepsilon} PS_2 \sim \lambda^{\frac{1-2\varepsilon}{2}} \left(1, \frac{Q^2 = M_{W'}^2}{\hat{s}}, \frac{k_g^2 = 0}{\hat{s}}\right)$$
$$= \left(1 - \frac{M_{W'}^2}{\hat{s}}\right)^{1-2\varepsilon} \sim 2\varepsilon \log\left(1 - \frac{M_{W'}^2}{\hat{s}}\right),$$

As $M_{W'}^2 \to s$, logs explode since $M_{W'}^2 \to \hat{s} < s$ forces ***threshold*** radiation g to be soft.

In this limit, **soft factorization** is justified and logs can be **resummed**!

Numerical Impact of Threshold Resummation





Threshold resummation is important when

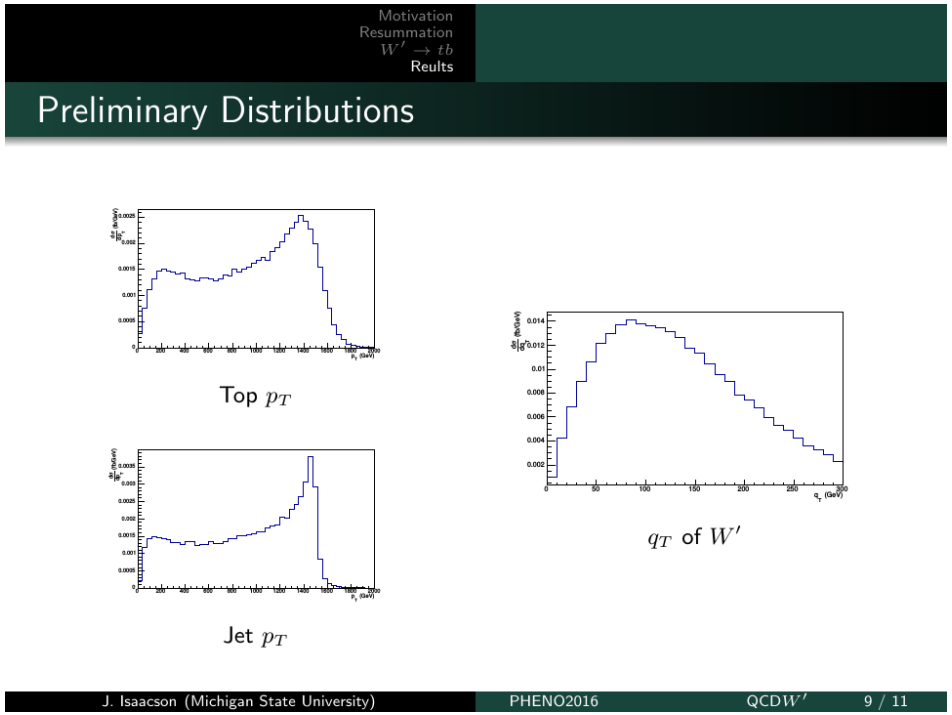
$$(M_{\rm BSM}/\sqrt{s}) \gtrsim 0.3 \text{ for } q\bar{q} \text{ or } (M_{\rm BSM}/\sqrt{s}) \ll 1 \text{ for } gg$$

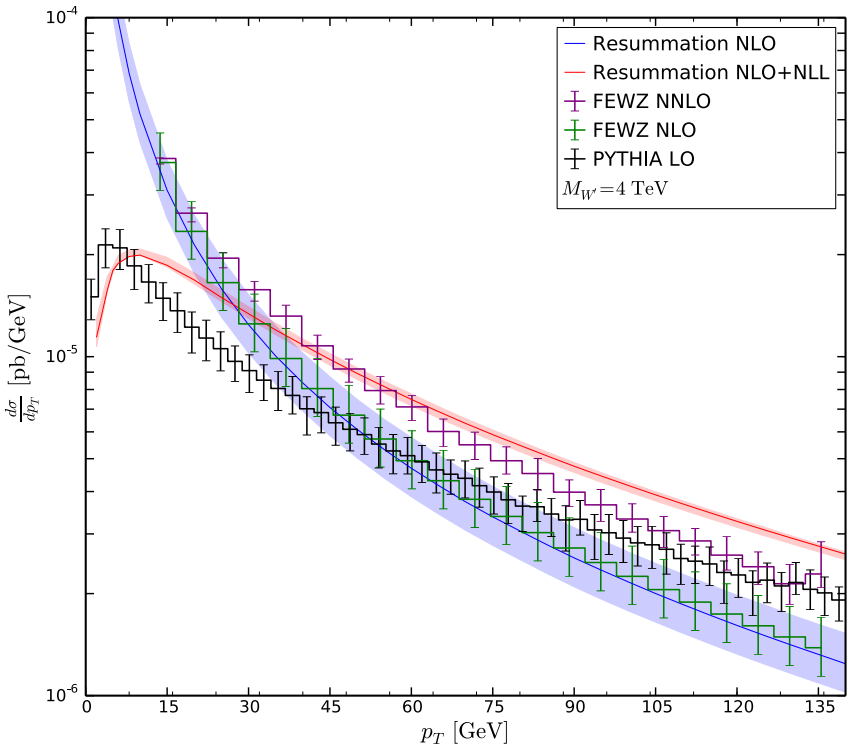
- Electroweak superpartners (Resummino) [*www.resummino.org*]
- Drell-Yan (ReDY) [*www.ge.infn.it/ ∼ bonvini/redy/*]
- GF to (pseudo)scalar (TROLL) [*www.ge.infn.it/ ∼ bonvini/troll/*]

CSS (or recoil or p_T)-Resummation

"Threshold gluons" have sizable impact on kinematics

3-4 TeV W' can be "kicked" such that $p_T^{W'} \sim 100$ GeV.
At LO, $p_T^{W'} = 0$





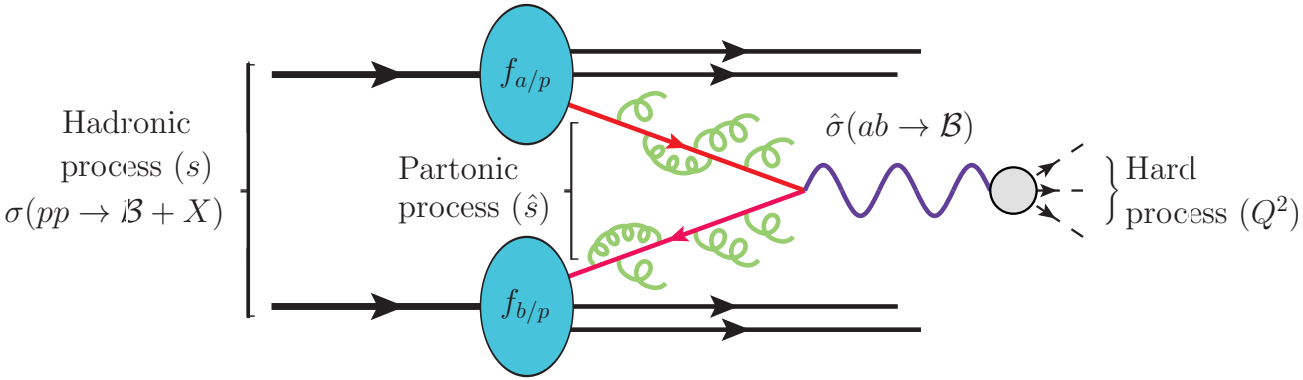
$p_T^{W'}$ shifts impact decay particle kinematics, e.g., in $pp \to W' \to tb$

Changes in detection efficiency investigated with ResBos II

Jet Veto Resummation

When a Jet Veto is Applied to $pp \to W^+W^- + X$

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



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

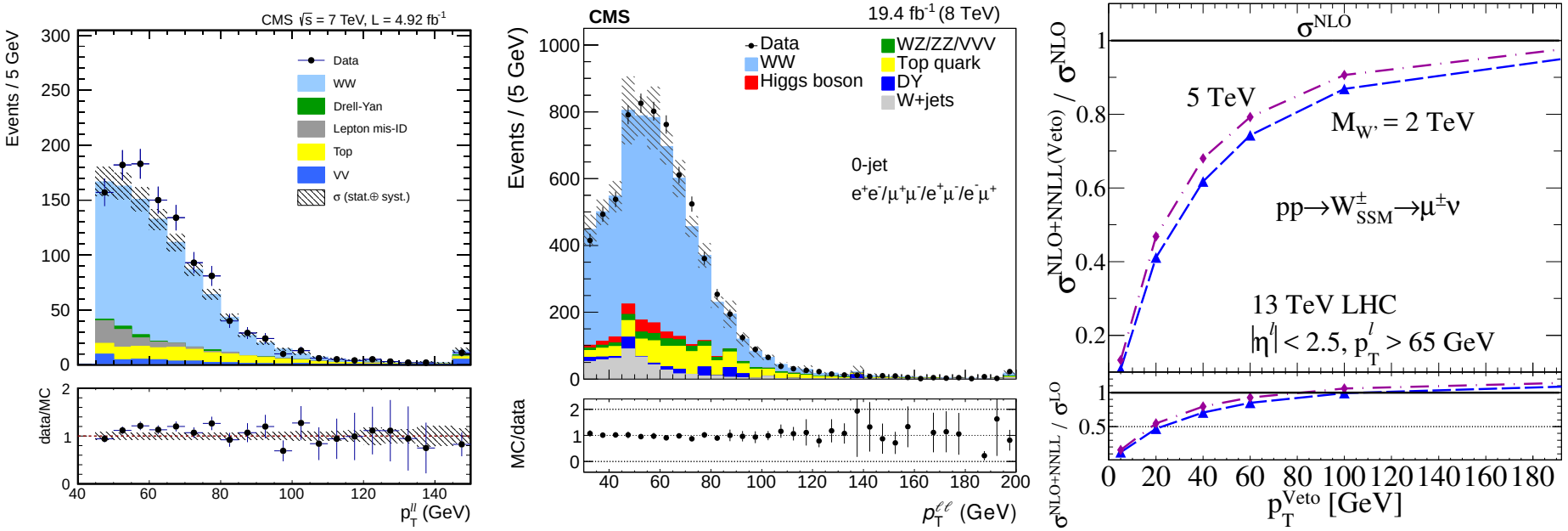
$$\left(\frac{M_{WW}}{p_T^{\rm Veto}}\right)^k \text{ and } \frac{\Lambda_{\rm QCD}}{p_T^{\rm Veto}}\log\left(\frac{M_{WW}}{p_T^{\rm Veto}}\right).$$

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

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



Computational framework quietly released in MG5aMC@NLO [1412.8408].

- Requires BSM@NLO model file, but these are available from FeynRules
- Broadly improves color-singlet BSM searches [Fuks,**RR**, (**soon**)]

Summary

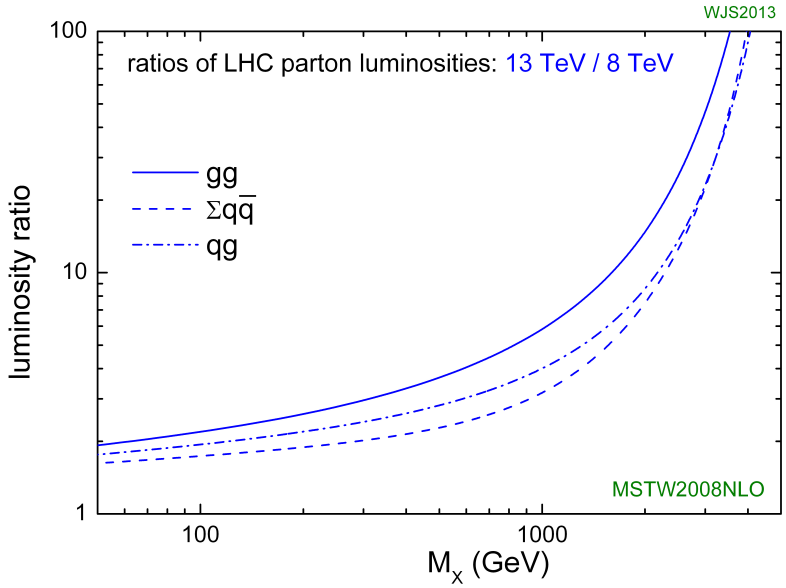
Over the past several years, a very strong push to modernize BSM analyses

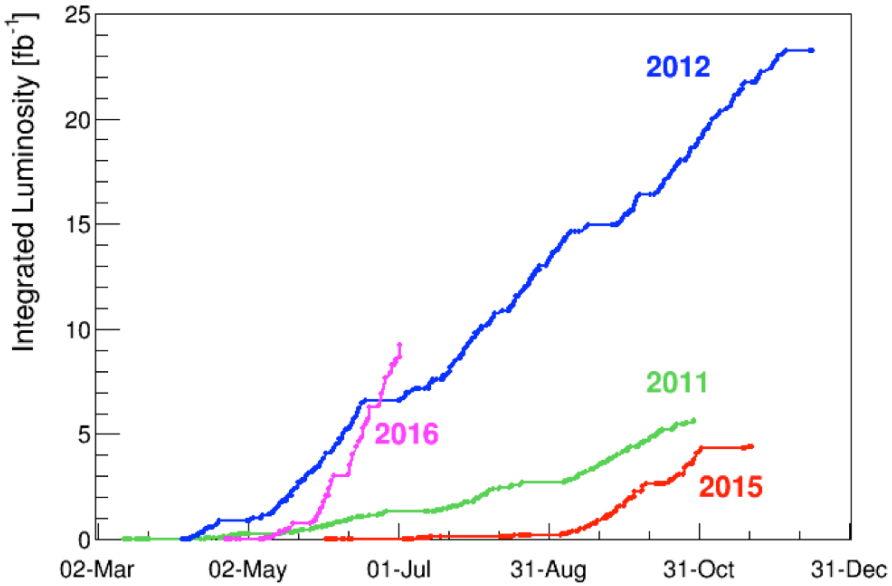
- Less about "+20% rate improvements", more about consistent modeling of color flow in hadronic collisions
- Data suggests we model spaces where QCD corrections are large
  - Okay since SM N3LO and N3LL also suggest perturbative stability
- Changes to kinematics at NLO and beyond have substantial impact on phenomenology
- Not possible without collective European efforts

Last words:

Until 2015, LHC operations were a fraction of designed potential

- 7/8 TeV luminosity (flux) of colliding partons $\ll$ 13/14 TeV lumi
- Pheno studies from '90s-'00s assumed 14 TeV and 100-300 fb^{-1}





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

Thank you.