Resummation for Physics Beyond the Standard Model [1]

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elusives
neutrinos, dark matter & dark energy physics

IP3

invisiblesPlus

[1] Based on lots of work: See slides for Refs. (*) = IPPP student.

What this talk is about

I would like to...

- motivate the existence of new physics from a neutrino perspective
- breakdown of fixed order (**FO**) perturbation theory in collider predictions
- factorization and exponentiation in mass gauge theories (QED/QCD)
- impact of QCD resummation on BSM searches at colliders

Central Idea: The property of **universality** of gauge interactions implies what works for SM largely works for BSM

- E.g., NLO+NNLL corrections for W_{SM} and a 4 TeV W_{KK} are identical
- Lots will be covered, so please ask questions!
- This is a BSM seminar, not a formal lecture.

Where we are today

The LHC is operating spectacularly! $\sim$60 fb^{-1} at 13 TeV ($\sim 5x$ Tevatron)

- Higgs : Not just a hep-th problem but now also a hep-ex problem.
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After Run I and early Run II (Fall '17), 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 :(

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)

Issue: "Day 1" pheno = simple channels with moderately good signal/bkg, e.g., Drell-Yan process like $q\overline{q'} \to W_R \to Ne^{\pm} \to e^{\pm}e^{\pm} + q\overline{q'}$

In "exotic processes", e.g., VBF and mono-X, contributions from phase space integration ($\int dk^2$) over add'l propagators ($1/k^2$) generates logs:

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

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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, BSM collider pheno looks **qualitatively different**.

Results focus on Seesaw partners (N, W_R) but are applicable/ necessary for other high-mass, colorless systems, e.g., $W^\pm h$, $\tilde{\ell}\tilde{\nu}_\ell$.

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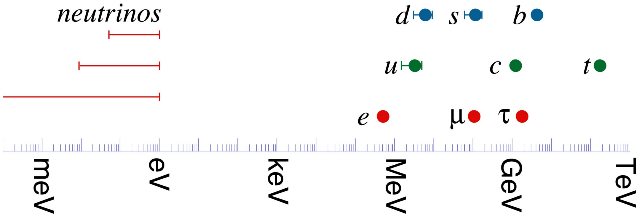
Message: *QCD is a useful and powerful tool for BSM@Colliders*

Motivation for new 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 and **2015**  !)
2. Neutrinos have unusually small mass (**Seesaw Mechanism**?)

Evidence for New Physics from Neutrinos

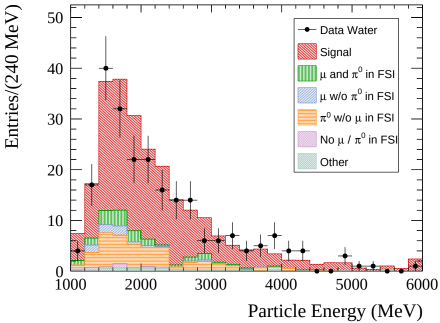
To generate ν masses similar to other SM fermions, we need N_R

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \left(\overline{\nu_L} \quad \overline{\ell_L}\right) \begin{pmatrix} \langle \Phi \rangle + h \\ 0 \end{pmatrix} N_R + H.c. \implies -m_D \overline{\nu_L} N_R + H.c.$$

$m_D = y_\nu \langle \Phi \rangle$, and y_ν is the neutrino's Higgs Yukawa coupling.

Since ${N_R}^i$ do not exist in the SM, massless neutrinos are predicted.

However, we have learned through neutrino oscillations that massless neutrinos is not an accurate description. [T2K ν_e appearance, 1503.08815v3]



Neutrino masses is evidence of physics beyond the SM.

Collider Connection to Neutrino Mass Models

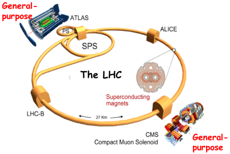
ν mass models predict new partners of all shapes, spins, and color, e.g.,

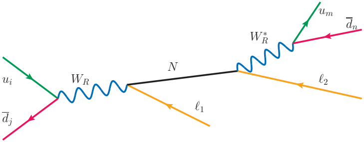
$$N \text{ (Type I)}, \quad T^{0,\pm} \text{ (Type III)}, \quad Z_{B-L}, \quad H_R^{\pm,\pm\pm} \text{ (Type I+II)}$$

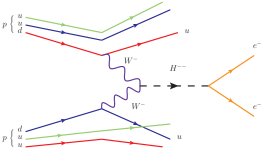
Through gauge couplings and mixing, production in $ee/ep/pp$ collisions[2]

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

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



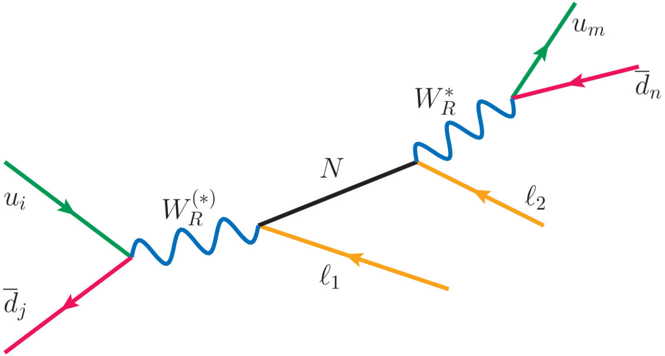




Identification of Seesaw partners is then inferred by their decays to SM particles and the associated final-state kinematics

[2] Review on ν mass models at colliders, Y. Cai, T. Li, T. Han, and **RR** [1711.02180]

Benchmark Scenario: 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:

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

After scalar Δ_R acquires a vev $v_R \gg v_{SM}$: $\hookrightarrow \mathrm{U}(1)_Y$

Higgs field Φ then breaks down the EW group $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \to \mathrm{U}(1)_{EM}$

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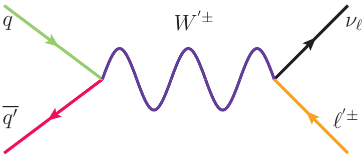
With N_R, all SM fermions can be grouped in $\mathrm{SU}(2)_L$ *and* $\mathrm{SU}(2)_R$ doublets. Dirac masses generated in (mostly) usual way with Φ, i.e., $\Delta\mathcal{L} \ni \overline{Q}_L \Phi Q_R$

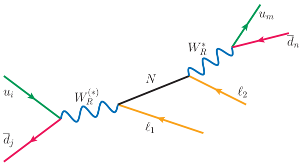
Neutrinos obtain LH (RH) Majorana masses from triplet scalar Δ_L (Δ_R):

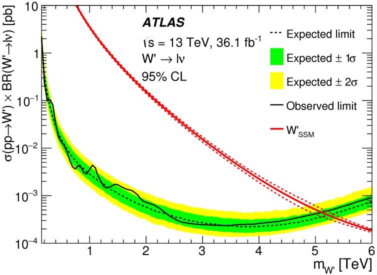
$$m^{\nu}_{\text{light}} = \underbrace{y_L \langle \Delta_L \rangle}_{\text{Type II}} - \underbrace{\left(y_D y_R^{-1} y_D^T \right) \langle \Phi \rangle^2 \langle \Delta_R \rangle^{-1}}_{\text{Type I a la Type II}} \sim \mathcal{O}(0) + \text{symm.-breaking}$$

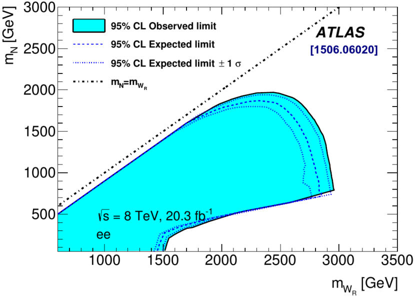
Major pheno: heavy N, W'/Z' ($\approx W_R/Z_R$), and $H_i^{\pm\pm}$, $H_j^{\pm}$, H_k^0

LHC Tests of Left-Right Symmetry









Moriond: very light, long-lived N : $M_{W_R} \gtrsim 5$ TeV [1706.04786]

Question: Can 13 TeV LHC say anything about $M_{W_R} \gtrsim 5$ TeV?

Threshold (or Soft Gluon) Resummation in pQCD[3]

[3] **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.

Hadron colliders like the LHC are ultimately counting experiments

$$\underbrace{N_{W_R}}_{\text{No. of } W_R} = \underbrace{\mathcal{L}}_{\text{Luminosity [barns}^{-1}]} \times \underbrace{\sigma(pp \to W_R + \text{anything})}_{\text{Production cross section [barns]}}$$

[4] Collins, Soper, Sterman ('85,'88,'89); Collins, Foundations of pQCD (2011)

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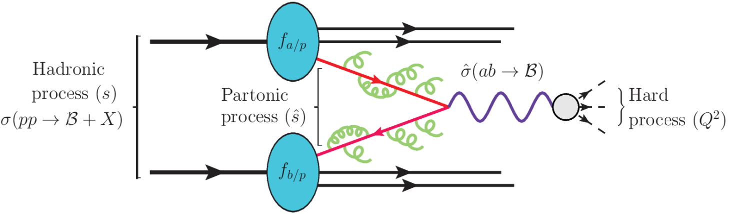
We usually employ the **Collinear Factorization Theorem**[4] (master equation for colliders) to get hadronic scattering rate:

Hadron-level scattering probabilities are the product (convolution) of parton-dist. (PDFs), -emission (Sudakov), and -scattering probab. ($|\mathcal{M}|^2$)

$$d\sigma(pp \to \mathcal{B} + X) = f \otimes f \otimes \Delta \otimes d\hat{\sigma}$$



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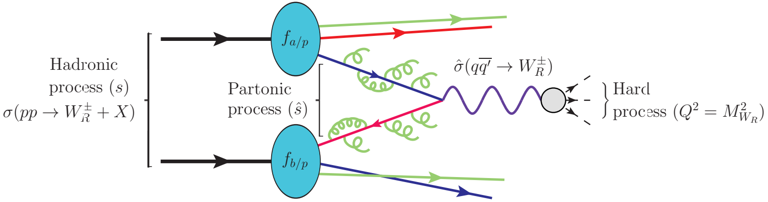

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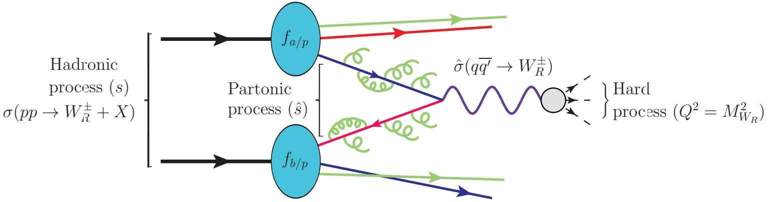

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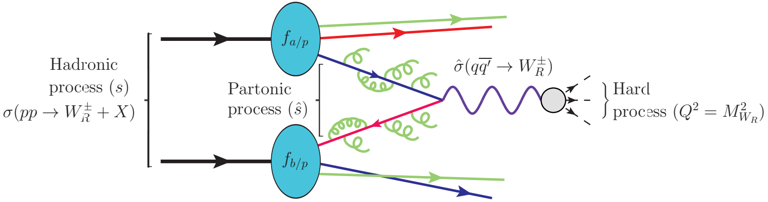

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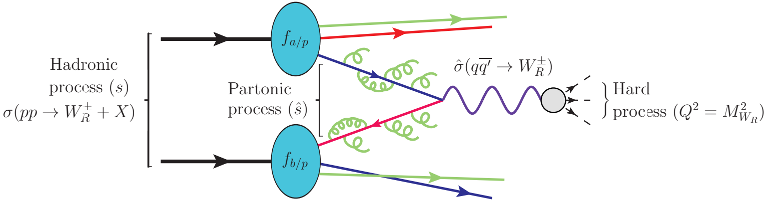

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$$\sigma(q\overline{q'} \to W_R + g) \sim \int d^{4-2\varepsilon} PS_2 \sim \lambda^{\frac{1-2\varepsilon}{2}} \left(1, \frac{Q^2 = M_{W_R}^2}{\hat{s}}, \frac{k_g^2 = 0}{\hat{s}}\right)$$

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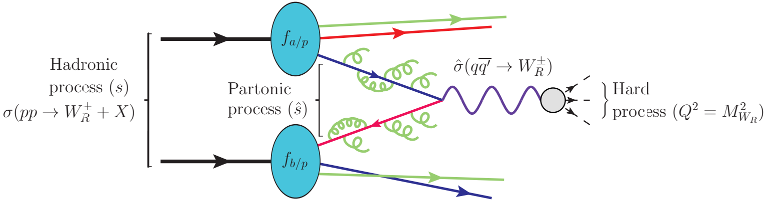

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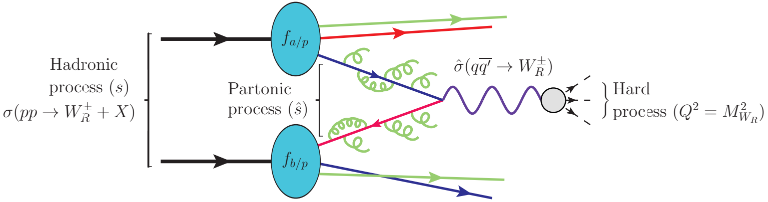

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More logs $\implies \mathcal{O}(\alpha_s^{k+1}) > \mathcal{O}(\alpha_s^k) \implies$ expansion in α_s **not** justified.

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In PT, one (Taylor) expands in powers of coupling constant:

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Stop/truncate at finite/fixed order only if $\mathcal{O}(\alpha_s^{k+1}) < \mathcal{O}(\alpha_s^k)$.

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All is not lost! Kinematics of soft, massless radiation are special:[6]

Soft rad. factorizes → all-orders summation → exponentiation

⇒ All-orders (*re*)summation of $\alpha_s \log(1 - M^2/\hat{s})$

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Factorization, Exponentiation,

and REnormalization Group-Improved Summation[7]

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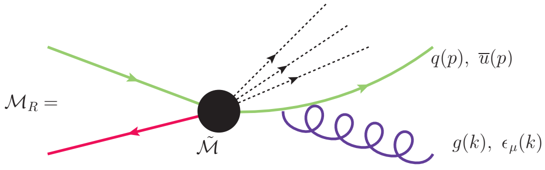
Soft Factorization in Gauge Theories

Factorization in gauge theories is where a radiation amplitude $\mathcal{M}_R$ in certain kinematic limits can be written as the no-radiation amplitude $\mathcal{M}_B$ and a **universal**, i.e., process-independent, piece:



For radiation $q^*(p+k_g) \to q(p) + g(k_g),\ E_g \ll E_q$, the amplitude is

$$\mathcal{M}_R \equiv \overline{u}(p)\epsilon^*_\mu(k)(ig_s T^A)\gamma^\mu \frac{(\not{p}+\not{k}_g)}{(p+k_g)^2} \cdot \tilde{\mathcal{M}} \approx (ig_s T^A)\overline{u}(p)\frac{\epsilon^*_\mu \gamma^\mu \not{p}}{(2p\cdot k_g)} \cdot \tilde{\mathcal{M}}$$

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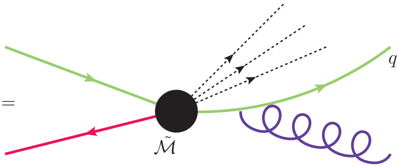

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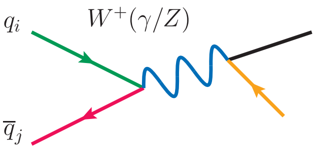
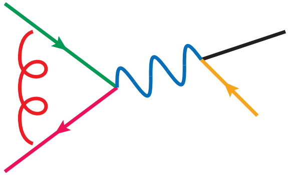
Anti-commute and applying Dirac Eq. gives us

$$\underbrace{\mathcal{M}_R\big|_{\text{Soft}}}_{\text{Soft rad. amp.}} = (ig_s T^A)\ \overline{u}(p) \cdot \frac{(p^\mu \epsilon^*_\mu)}{(p\cdot k_g)} \cdot \tilde{\mathcal{M}} = \underbrace{(ig_s T^A)\frac{p^\mu \epsilon^*_\mu}{(p\cdot k_g)}}_{\text{Process independent}} \cdot \underbrace{\mathcal{M}_B}_{\text{Born amp.}}$$

Factorization of Virtual α_s Corrections to Currents

QCD corrections to colorless currents with massless quarks are special





At one-loop, corrections also **factorize**(!) for *generic* V-A structure:

$$\begin{aligned}
\overline{v}(p_d)\gamma^\mu\left(g_L P_L + g_R P_R\right)u(p_u) &\rightarrow \overline{v}(p_d)\Gamma^\mu(p_u,p_d)u(p_u), \\
\overline{v}(p_d)\Gamma^\mu(p_u,p_d)u(p_u) &= \overline{v}(p_d)\gamma^\mu\left(g_L P_L + g_R P_R\right)u(p_u) \times \mathcal{F} \\
\mathcal{F} &\equiv \frac{\alpha_s(\mu_r^2)}{4\pi} C_F C_\varepsilon(\hat{s})(-1)^\varepsilon \Gamma\left(1+\varepsilon\right)\Gamma\left(1-\varepsilon\right)\left(\frac{-2}{\varepsilon^2} - \frac{3}{\varepsilon} - 8\right) \\
C_\varepsilon(\hat{s}) &= \left(\frac{4\pi\mu_r^2}{\hat{s}}\right)^\varepsilon \frac{\Gamma\left(1-\varepsilon\right)}{\Gamma\left(1-2\varepsilon\right)}, \quad C_F = 4/3.
\end{aligned}$$

$$\sum|\mathcal{M}^{1-Loop}|^2 = \sum|\mathcal{M}^{Born}|^2(1 + 2\Re[\mathcal{F}]) + \mathcal{O}(\alpha_s)$$

Hold for all phase space at 1-loop, and in soft/coll. limit beyond that.

Sketch of Factorization and Exponentiation

Is it possible to study soft/collinear radiation with perturbative QCD? **Yes!** Combine our factorized results:

$$\mathcal{M}_{\mathrm{W_R+1\ soft/collinear\ radiation}} = \left(\underbrace{\text{rad. pole} + \text{loop pole}}_{\text{universal factor}}\right) \times \mathcal{M}^{\mathrm{FO}}_{\mathrm{W_R}}$$

The squaring, averaging, and integrating over $(n+1)$-body phase space

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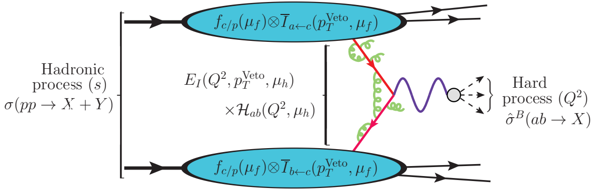
Keeping track of symmetry factors lets us do this for k-emissions:

$$d\sigma_{\mathrm{W_R+k\ soft/collinear}} = \frac{1}{k!}[\mathcal{S}]^k \times \sigma^{\mathrm{FO}}_{\mathrm{W_R}}$$

Summing over ***all*** such emissions gives us a closed result:

$$d\sigma_{\mathrm{W_R+any\ soft/collinear}} = \sum_k \frac{1}{k!}[\mathcal{S}]^k \times \sigma^{\mathrm{FO}}_{\mathrm{DY}} = \exp[\mathcal{S}] \times \sigma^{\mathrm{FO}}_{\mathrm{W_R}}$$



A different perspective[8]: In general, scattering rates have the form

$$\frac{d^3\sigma}{d\xi_1 \ d\xi_2 \ dz \ dPS} = \sum_{i,j=q,g,\ldots} \underbrace{[f_i(\xi_1,\mu) f_j(\xi_2,\mu) + (1 \leftrightarrow 2)]}_{\text{parton flux, } \hat{s}=\xi_1\xi_2 s}$$

$$\underbrace{C(z)}_{\text{soft emissions, } C(z=Q^2/\hat{s})=\delta(1-z)+\mathcal{O}(\alpha_s(\mu))} \times \underbrace{d\hat{\sigma}(ij \to A)}_{\text{hard process, } Q^2}$$

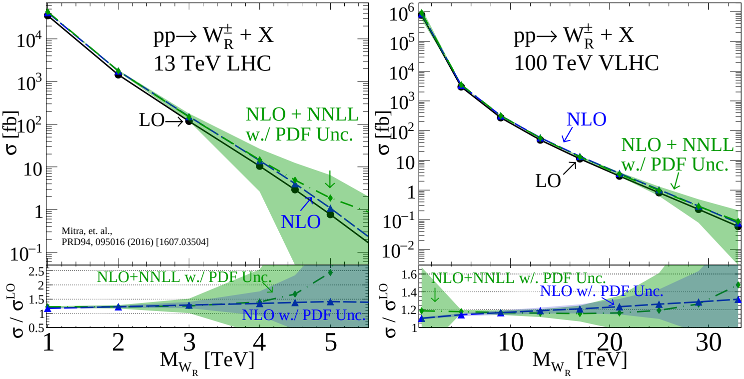
Multi-scale problem: $\sqrt{s}$, $\sqrt{\hat{s}}$, Q, m_A, but also μ (put in by hand).
Nature works independent of us:

$$\frac{d}{d\log\mu} d\sigma = 0 \implies \frac{d}{d\log\mu} C(z,\mu) = f(z,\mu) C(z,\mu)$$

$\implies C(z,\mu) = \exp[\mathcal{S}(\mu,\mu_0)] C(z,\mu_0)$ Each piece follows RG evolution

[8] Contopanagos, Laenen, Sterman ('96); Becher, Neubert etc; Stewart, Tackmann etc

$pp \to W_R^\pm + X$ at NLO+NNLL(Thresh.)[9]



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

[9] Mitra, **RR**, Scott*, Spannowsky [1607.03504]

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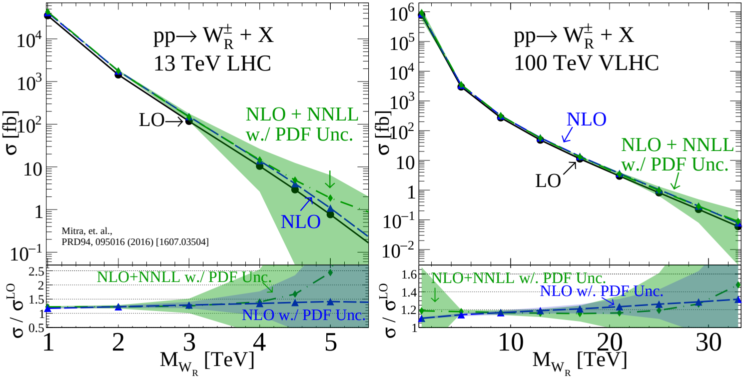

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- $\sigma^{LO}(M_{W_R} = 5\ \mathrm{TeV}) \sim 0.7$ fb $\implies \sigma \times\ (1\ \mathrm{ab}^{-1}) = 700$ events

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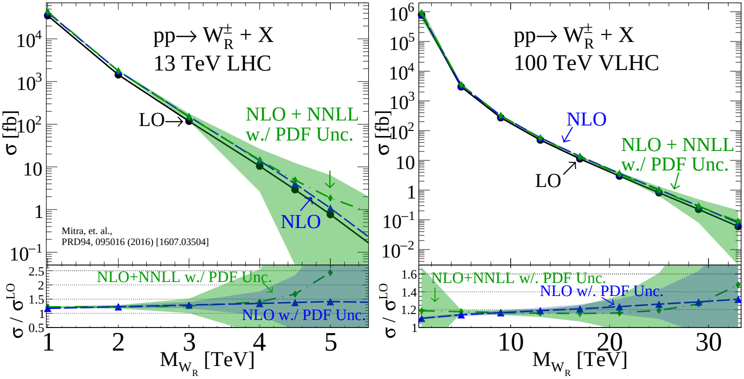

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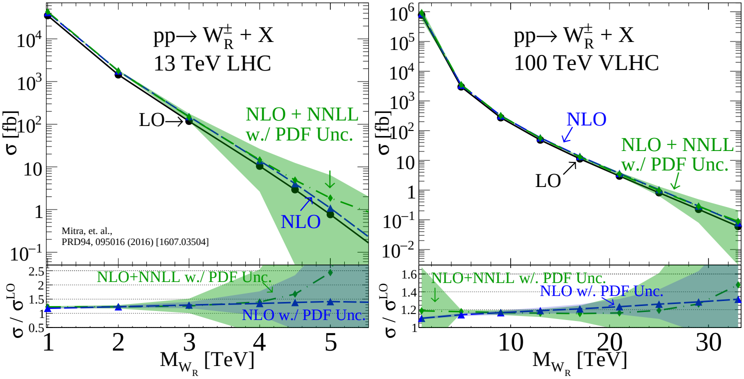

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Assuming $\text{BR} \times \varepsilon \times \mathcal{A} = 2\%$ $\implies$ $N \approx 34$ events ($\sim 6\sigma$ *vs* $\sim 4\sigma$)

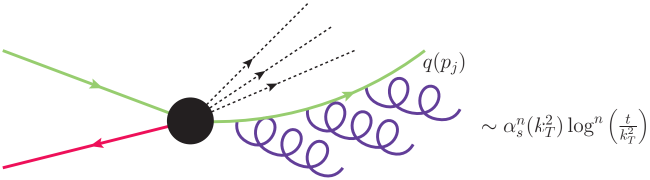
[9]Mitra, **RR**, Scott*, Spannowsky [1607.03504]

Parton Shower Resummation[10]

[10] **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.

Parton Showers

The idea of a parton shower is to capture the emission of soft/collinear (but mostly collinear) emissions in the initial and final state.



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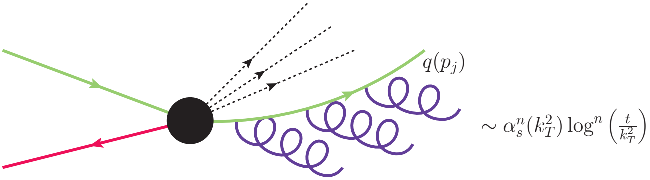

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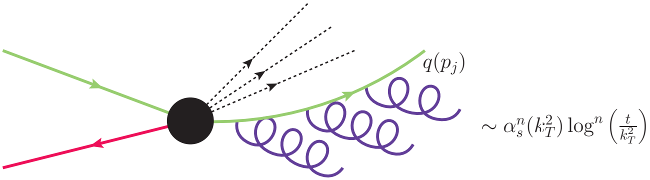

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Using collinear factorization and unitarity, we can build an evolution factor that accounts for all such radiations, up to leading logarithmic accuracy

For virtuality t of internal line, collinear factorization give us:

$$\sigma_{(n+1)} \sim \sigma_n \ \times \ \int dz \ \frac{dt}{t} \ \frac{\alpha_s C_i}{2\pi} P_{ji}(z), \quad z = E_g / E_{\rm parent}$$

The differential splitting probability is then given as

$$d\mathcal{P}_{\rm Split} \sim \frac{\sigma_{(n+1)}}{\sigma_n} = \frac{dt}{t} \ \int dz \ \frac{\alpha_s C_i}{2\pi} P_{ji}(z)$$

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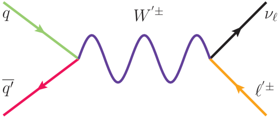
Note: As the leading splitting $\alpha \log(t_1/t_0)$ is exponentiated, i.e., sums to all orders in (couplings×log), this **resummation** is *leading log* accurate

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

BSM @ NLO+PS/LL(q_T)

Major focus of MC community past decade was automation of NLO

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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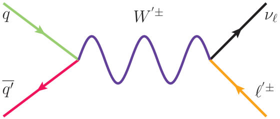
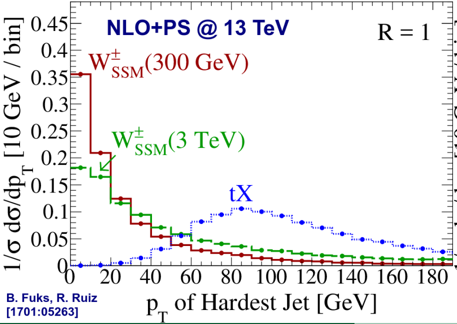
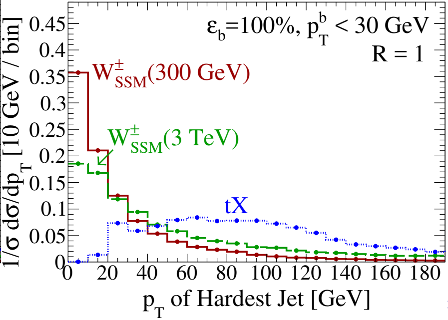


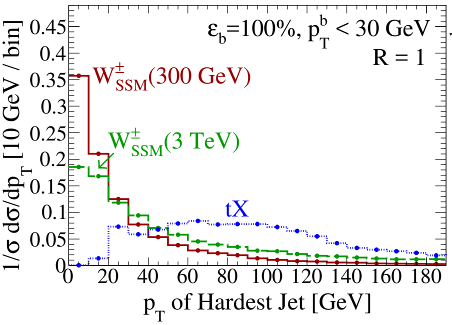
Monte Carlos: modeling jet observables *correctly* **now possible**
- b-jet vetoes do not remove all QCD radiation ($tX = t\bar{t},\ tW,\ tq$)

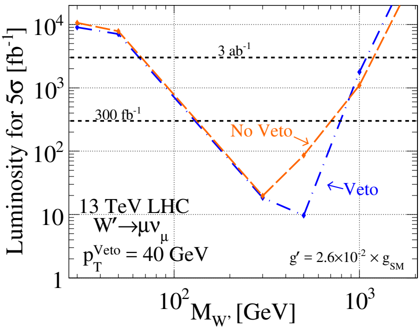




B. Fuks, R. Ruiz
[1701:05263]

BSM @ NLO+PS/LL(q_T)+Veto





Monte Carlos: modeling jet observables as *bkg discriminants* **now possible**

- ***Why?*** QCD/$t\bar{t}$ have different radiation patterns than color-singlets
- E.g., veto $R = 1$ anti-k_T jets with $p_T^j > 40$ GeV eliminates top quarks
- E.g., improve $\tilde{\ell}\tilde{\nu}_\ell$ discovery potential [Tackman, et al, 1603.03052]

NLO+PS in **agreement** w/ NLO+NNLL [Fuks, **RR**, 1701.05263]

- Nontrivial but not total surprise $\implies$ NLO+PS sufficient for discovery

Resummation in Modern Event Generators

NLO+PS and NLO+NNLL(Veto)[11] automated in MG5_amc@NLO

- All one needs NLO-accurate FeynRules input model file

[11]Veto possible for color-singlet processes only. Becher, et al [1412.8408]

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Explosion past two years: [*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	All figures available from the arxiv
W'/Z' model (more details)	R. Ruiz, B. Fuks	arXiv:1701.05263	vPrimeNLO.fr	vPrimeNLO UFO	-

As of Dec 2017, updated regularly

Modern general purpose MC packages are *very* sophisticated

"With great power there must also come - great responsibility"- S. Lee ('62)

[11] Veto possible for color-singlet processes only. Becher, et al [1412.8408]

Threshold (or Soft Gluon) Resummation for Gluon Fusion[12]

[12] **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 (or Soft Gluon) Resummation for Gluon Fusion[12]

Myth that QCD is Unimportant for BSM

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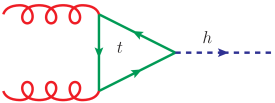
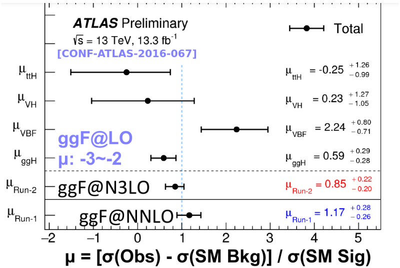
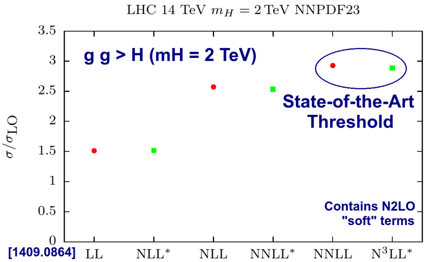
Threshold Resummation for GF

- QCD corrections to $gg \to h_{\rm SM}$ are *large*



- GF@LO is *excluded* by LHC!

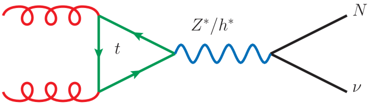




- Corrections also *large* for heavy H^0, A^0.

Resum. captures leading FO corrections.

Bonvini, et al, [1409.0864]



- What about heavy *N* production?

Common Statement: "QCD is unimportant for colorless BSM"

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

These are the assumptions for the Collinear Factorization Thm

$$\sigma(pp \to A + \text{anything}) = \sum_{i,j} f_{i/p} \otimes f_{j/p} \otimes \Delta_{ij} \otimes \hat{\sigma}(ij \to A)$$

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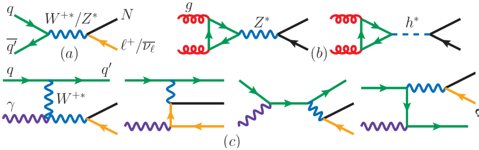
Relaxing these assumptions has consequences:

- For $M_{W'/Z'} \sim \sqrt{s}$, $\sigma_{DY}^{NLO+N^2LL}/\sigma^{LO} \sim 2-2.5$
- For W'/Z' at any M_V, NLO+PS needed for jet-based/exclusive cuts
- In $gg \to H^0/A^0$ for any $m_{H/A}$, $\sigma^{N^3LX}/\sigma^{LO} \sim 2-3$

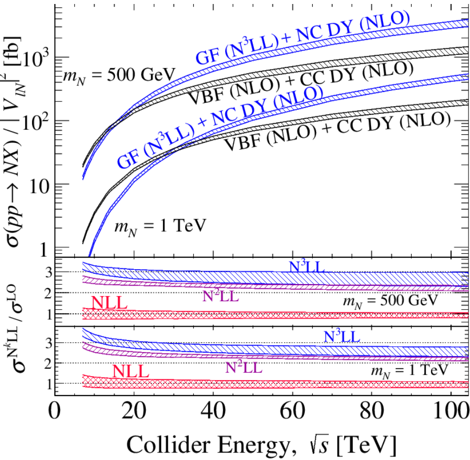
- How about $gg \to h^*/Z^* \to N\nu$?

Threshold Corrections to Heavy N Production[13]



Heavy N from GF is very interesting:

- ggZ^* contribution identical to pseudoscalar (Equiv Thm)
- Large corrections: $\sigma_{GF}^{N^3LL}/\sigma_{GF}^{LO} \sim 2-3$
- Largest channel for $\sqrt{s} \gtrsim 20-30$ TeV



[13] Willenbrock, Dicus ('85); Dicus, Roy ('91); Hessler, et al [1408.0983]; Degrande, Mattelaer, **RR**, Turner(*) [1602.06957]; **RR**, Spannowsky, Waite(*) [1706.02298]

Summary

Over the past decade, a revolution in FO and Resummed calculations!

- New tools + new formalisms $\implies$ new results

Maturity of N^{j}LO/N^{k}LL formalism allows application to BSM

- Automated tools *and* ***instructions*** are publicly available

QCD is a useful/necessary and powerful tool for Seesaws@Colliders

- Threshold resummation $\implies$ $\sigma^{N^K LL}/\sigma^{LO} = 2 \sim 3$
- p_T/veto resummation $\implies$ new dimension for pheno analyses
- IRC-safety $\implies$ more rigorous and robust collider signatures

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.