

Event-Dependent Jet Veto^{es}: A New Prospect for Multilepton, LHC Searches

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Disclaimers

Acknowledgements, Apologies, and Disclaimers

Apologies: the notion of *jet vetoes* in hadronic collisions is nearly as old as *QCD phenomenology* itself

E.g., "Rapidity gaps" Dokshitzer, Khoze, Troyan ('86). Context: AP Splitting Functions ('77), Drell-Yan@NLO ('79)

... but ongoing “renaissance” since LHC Run I (~2010)

- Major effort by **hep-ex**, **(n)pQCD**, and **Monte Carlo** communities
- Despite generous allotment of time (thanks organizers!),
no attempt to review 30+ years of literature

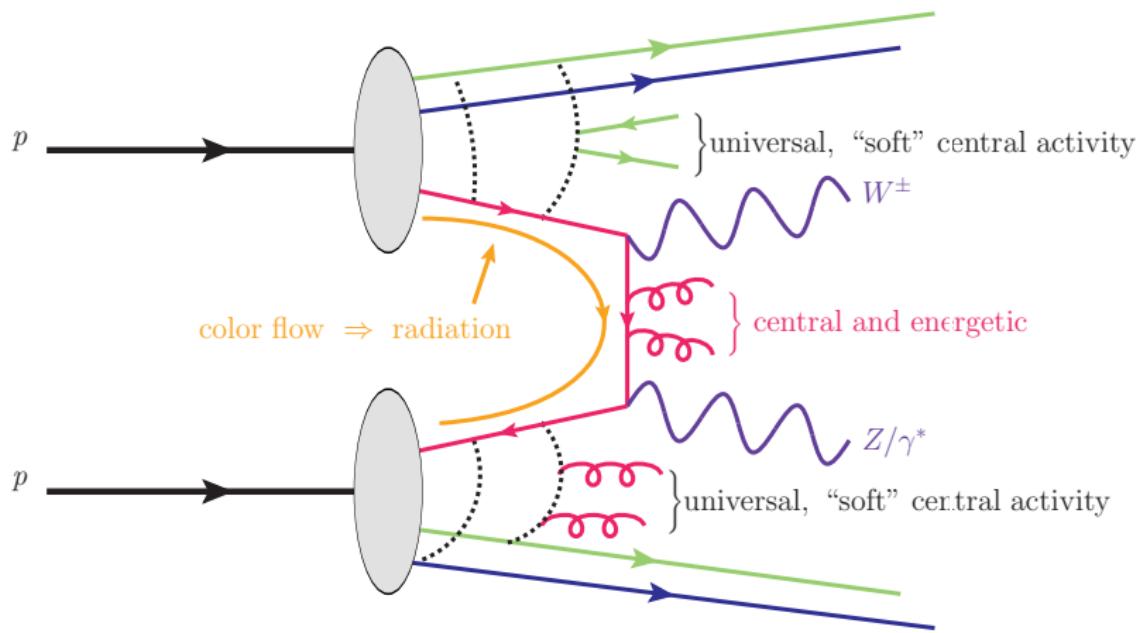
Outline: Instead, focus on “jet veto renaissance”

- ① Why jet vetoes?
- ② Precision **data**! Precision **formalism**! Precision **tools**!
- ③ Jet vetoes for new physics searches
- ④ Outlook for Run III-V and Beyond!

I. Why jet vetoes?

In high-momentum transfer (Q^2) events...

flow of QCD color charges is **everywhere!**

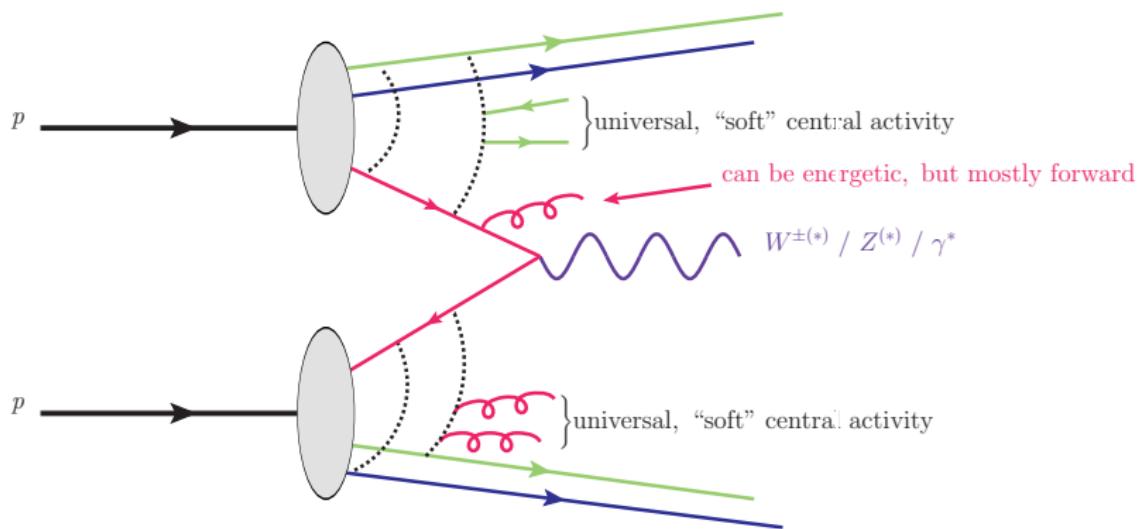


From (classical) electrodynamics, accelerated dipoles \Rightarrow real radiation
- Notably, while radiation existence is universal, emission pattern is not

Ex 1: QCD Radiation in High-Mass Drell-Yan (DY)

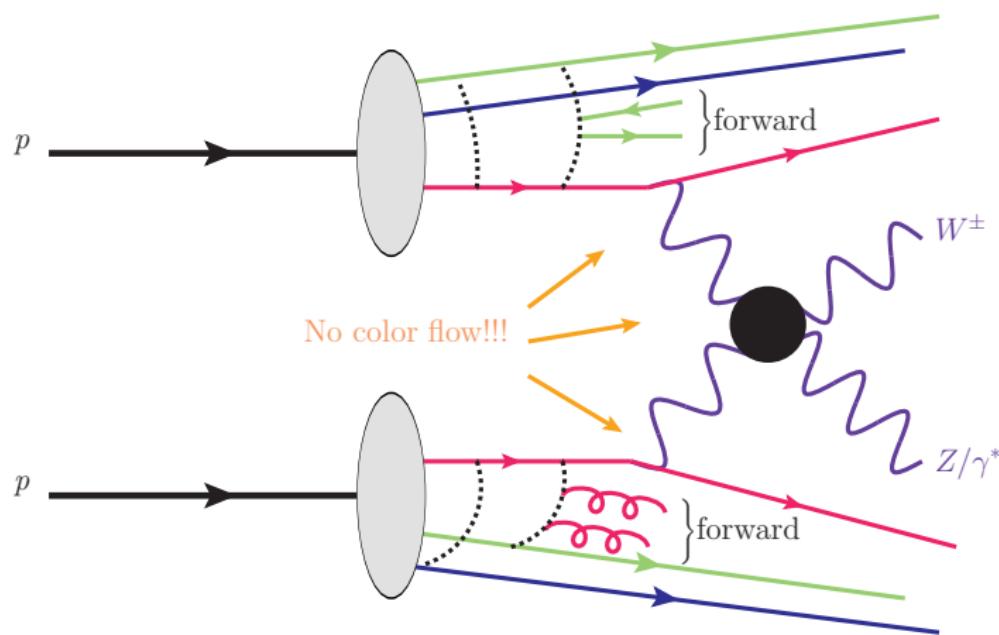
For high-mass Drell-Yan ($q\bar{q}$ -annihilation), QCD radiation can be energetic but mostly forward \implies low p_T^j (compared to $Q = M_{V*}$) :

$$p_T^j \sim M_{V*} \times e^{[-\sqrt{(\beta_0/16\pi) \log(M_{V*}^2/\Lambda_{\text{QCD}}^2)}]} \quad (\text{Sudakov shoulder})$$



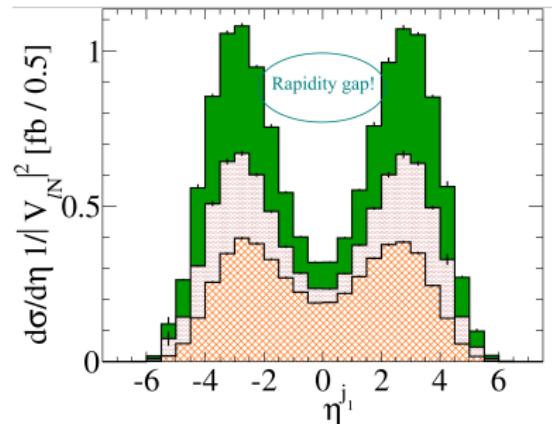
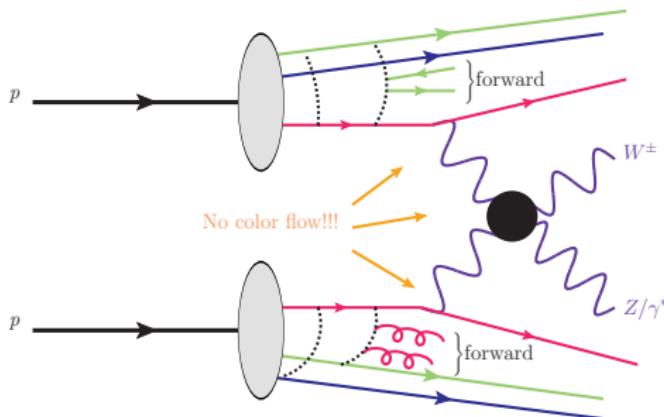
Ex 2: QCD Radiation in EW Boson Scattering/Fusion

In EW Boson Scattering, there is an absence of central color flow



In EW Boson Scattering, there is an absence of central color flow
 \Rightarrow absence of central, high- p_T jets

["Rapidity gaps" Dokshitzer, Khoze, Troyan ('86)]



Basis for Central Jet Veto

[Barger, et al, PRD ('91) + PLB ('95); Bjorken, PRD ('94)]:

- Reject events with any jet satisfying $p_T^j > 25 - 30 \text{ GeV}$, $|\eta^j| < 2 - 3$
 - ▶ After applying meaningful jet PID, equivalent to keeping only 0-jet bin
- Crucial to Higgs and EW physics but not perfect...

II. The Perfect Storm

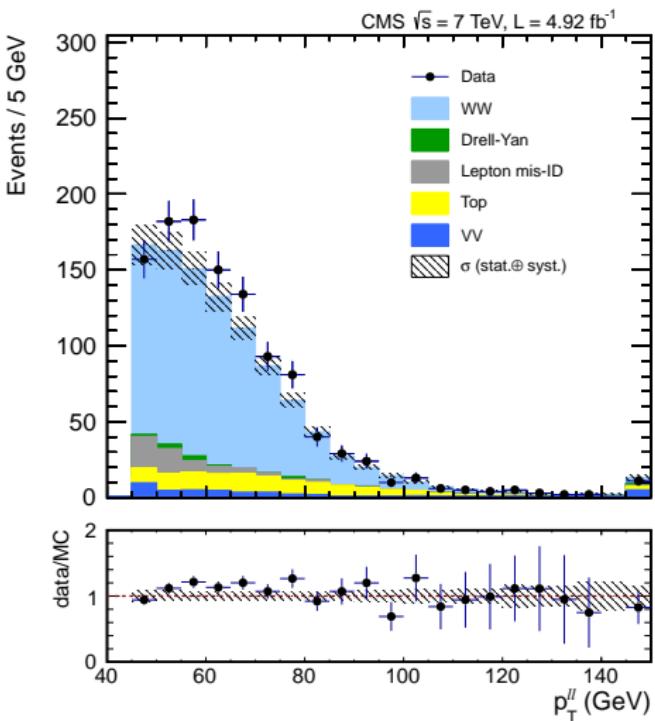
II. The Perfect Storm: Jets in the LHC Era

Diboson Production at the LHC

Diboson production is important for many reasons:

- Precision test of $SU(2)_L \otimes U(1)_Y$
- Theoretically trusted: known to N2LO in QCD and NLO in EW
- Experimentally trusted: background/calibration for Higgs processes

Interesting then that in Run I-II data, ATLAS_[1507.03268] and CMS_[1301.4698] consistently observe $\mathcal{O}(20)\%$ excess of $pp \rightarrow W^+W^-$



The excess was real and beyond *estimated* uncertainties:

SM expectation of $57.3^{+2.3}_{-1.6}$ pb, calculated in Ref. [2] by using MCFM at NLO with the MSTW08 PDF and setting the factorization and renormalization scales to the W mass. Additional processes may increase the production yield in the W^+W^- final state by as much as 5% for the event selection used in this analysis. Higgs boson production would give an additional contribution of about 4% of the cross section given above, based on next-to-next-to-leading-order cross section calculations for the $H \rightarrow W^+W^-$ process [43] under the assumption that the newly discovered resonance [44, 45] is a SM-like Higgs boson with a mass of 125 GeV. Contributions from diffractive production [46], double parton scattering, and QED exclusive production [47] are also considered.

CMS [1306.1126]

The devil was in the details: a jet veto

4 Event selection and background estimates

4.1 W^+W^- production

Events are selected with two oppositely charged electron or muon candidates, both with $p_T > 20$ GeV and with $|\eta| < 2.5$ for the electrons and $|\eta| < 2.4$ for the muons. The τ leptons contribute to the measurement only if they decay to electrons or muons that pass the selection requirements. At the trigger level, events are required to have a pair of electrons or muons where one of the leptons has $p_T > 17$ GeV and the other $p_T > 8$ GeV, or a single electron (muon) with $p_T > 27$ (24) GeV. The trigger efficiency is approximately 98% for both $q\bar{q} \rightarrow W^+W^-$ and $gg \rightarrow W^+W^-$ processes.

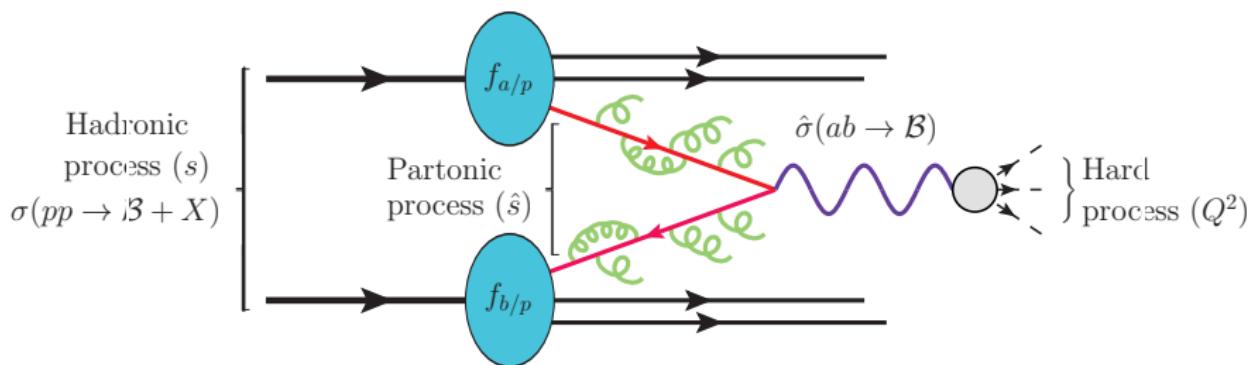
To reduce the background from top-quark decays, events with one or more jets surviving the jet selection criteria and with $p_T > 30$ GeV and $|\eta| < 4.7$ are rejected. The residual top-quark background is further suppressed by 50% after applying the top-quark-tagging techniques.

Jet Veto ϵ s vs Factorization

To get pp scattering rates, employ the **Collinear Factorization Theorem**

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

$$d\sigma(pp \rightarrow WW + X) = \textcolor{blue}{f} \otimes \textcolor{blue}{f} \otimes \Delta \otimes d\hat{\sigma}(WW) + \mathcal{O}(\Lambda_{\text{NP}}^p/Q^{p+2})$$



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

When deriving the CFT, one crucially assumes:

- ① inclusive over all initial- and final-state radiation (veto truncates this)
- ② fixed order predictions have no scale hierarchy $(M_{WW}/p_T^{\text{Veto}} \gg 1)$



The CFT vs Jet Veto

Issue 1: jet vetoes truncate sum over all ISR and FSR

- Okay! modern jet clustering algos. are infrared- and collinear-safe
⇒ no radiation is neglected and clusters are meaningful in pQCD as long as one starts at NLO+PS(LL) for color-singlet processes

Collins, Soper, Sterman ('85), Collins ('11); Stewart, Tackmann and Waalewijn ('10); Becher and Neubert ('12)

- Analysis-quality jets (j_k) are "hard" and "central(ish)" clusters
⇒ $pp \rightarrow WW + 0j$ rate is **inclusive** w.r.t. ultra-soft ($p_T^{j_k} < p_T^{\text{Veto}}$) and ultra-forward ($|\eta^j| > \eta^{\text{cut}}$) hadronic clusters

Stewart, Tackmann and Waalewijn ('10); Becher and Neubert ('12)

In other words:

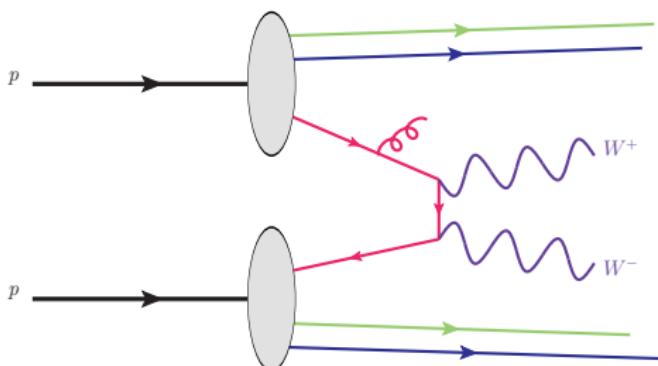
$$\underbrace{\sigma(pp \rightarrow WW + 0j)}_{\text{(secretly inclusive) } 0\text{-jet rate}} = \underbrace{\sigma(pp \rightarrow WW + X)}_{\text{totally inclusive rate}} - \underbrace{\sigma(pp \rightarrow WW + 1j + X)}_{\text{1-jet inclusive rate}}$$

Issue 2: A large $(M_{WW}/p_T^{\text{Veto}})$ ratio \implies breakdown of FO predictions

$$\sigma(WW + 1j + X) \sim \int \frac{dPS_1 \alpha_s}{(p_f - p_g)^2 (p_{f'} - p_g)^2} \sim \int \frac{\alpha_s d \cos \theta dE_g^2}{E_f E_g (1 - \cos \theta') E_{f'} E_g (1 - \cos \theta)}$$

for $\theta \ll 1$, $E_g \ll M_{WW}$ $\int \frac{\alpha_s d\theta^2 dE_g^2}{\theta^2 E_g^2} \sim \alpha_s \log^2(M_{WW}/p_T^{\text{Veto}})^2$ $p_T^{\text{Veto}} \ll M_{WW} \rightarrow \infty$

Large veto hierarchy can drive $\sigma(pp \rightarrow WW + 0j) < 0!$



Solution: (i) use a cutoff (μ_X) to split and regulate log, (ii) regroup, (iii) then RG-evolution equations to resum $\log(\mu_X/p_T^{\text{Veto}})$ terms (see backup!)

Revolution in Jet Veto Resummation

$$d\sigma(X + 0j) = \underbrace{f \otimes f \otimes \Delta}_{\text{LL, NLL, NNLL, etc.}} \otimes \underbrace{d\hat{\sigma}}_{\text{LO, NLO, etc.}} + \underbrace{\text{(matching scheme)}}_{\text{removes dbl counting}}$$

- Jet veto factorization thms

[Stewart, et al ('09); Becher, et al ('12); etc.]

- $pp \rightarrow h/Z + 0j$

[Becher, et al ('12,'13); Banfi, et al ('12); Stewart, et al ('13)]

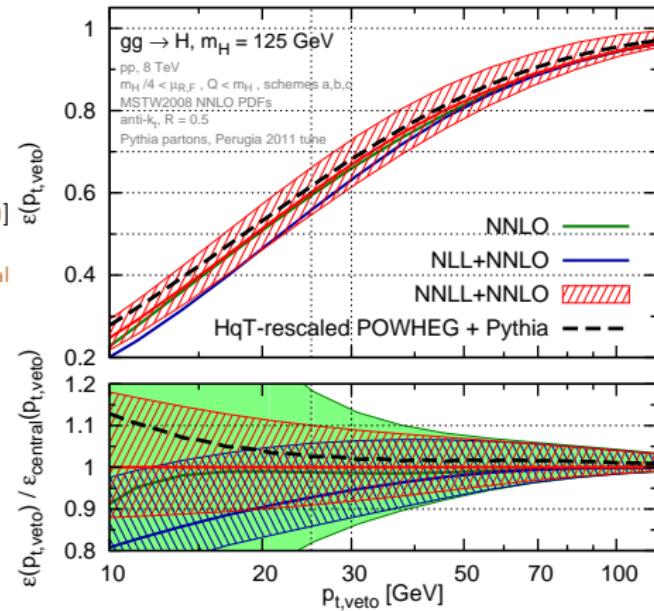
- $pp \rightarrow WW + 0j$ [Meade, et al ('14); Jaiswal, et al ('14); Monni, et al ('14); Becher, et al ('14)]

- Analytic resummation vs (N)NLO vs NLO+PS(LL)

[Monni, et al ('14); Fuk, RR, et al ('17,'18,'19); Pascoli, RR, et al ('18); Jager, et al ('18)]

- Rapidity window-dependence

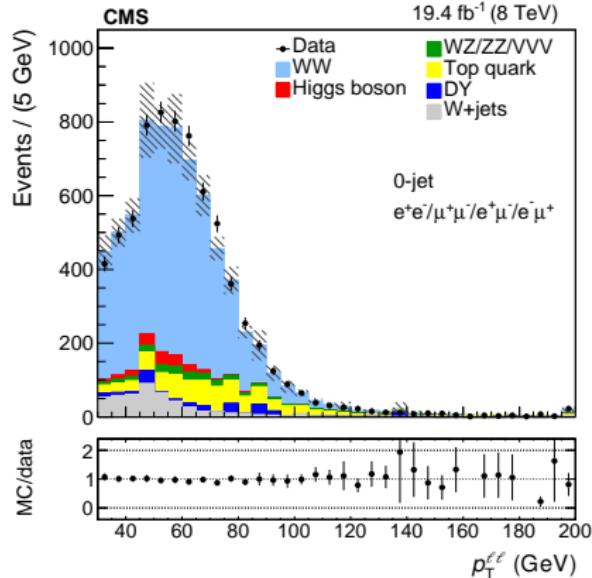
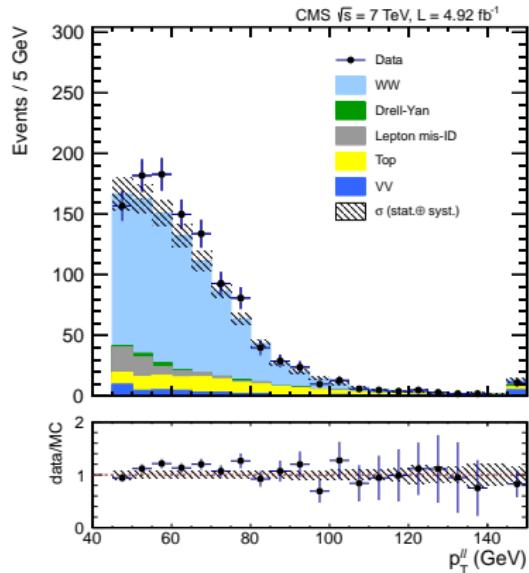
[Gangal, et al ('14,'17); Michel, et al ('18)]



Banfi, et al [1203.5773, 1206.4998]

Standard Model vs Jet Veto

Plotted: p_T of the $(\ell_1^+ \ell_2^-)$ -system in $pp \rightarrow W^+ W^- + 0j \rightarrow \ell_1^+ \ell_2^- \nu \bar{\nu} + 0j$



Summary: Discrepancy resolved by accounting for (resummable) **ultra soft and ultra forward** gluon emission (ditto for ATLAS - See V Lang's talk!)

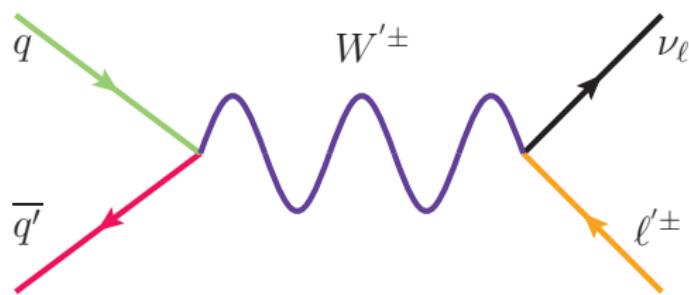
III Jet Veto^{es} vs New Physics Searches

Case for new physics at the LHC is extremely strong¹:

- origin of fermion mass hierarchy
 - ▶ Compact, extra dimensions
⇒ predicts heavy copies of SM particles, e.g., W_{KK} or W_{SSM}
- origin of nonzero neutrino masses
 - ▶ Low-scale Type I Seesaw
⇒ predicts heavy neutrinos (N) and charged lepton flavor violation
 - ▶ Low-scale Type II Seesaw
⇒ predicts scalars with exotic EW quantum numbers $(\Delta^{\pm\pm}, \Delta^\pm, \Delta^0)$ and lepton number violation
- gauge coupling unification + particle nature of dark matter
 - ▶ supersymmetry+ R -parity
⇒ predicts superpartners + DM candidate, e.g., $\tilde{\mu}^\pm \rightarrow \mu^\pm + \tilde{\chi}_1$

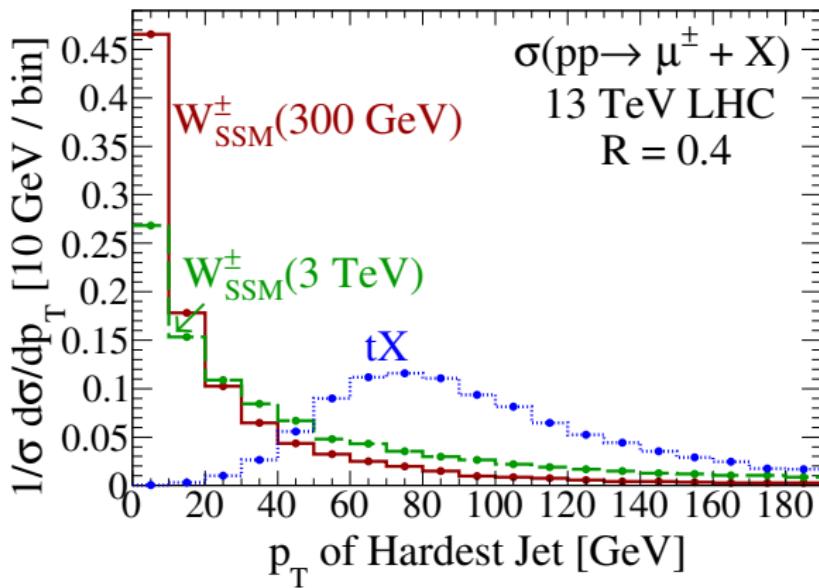
¹ See, for example, TDRs for ATLAS, CMS, and LHCb, or Letters of Intent for Phase II Upgrades

Jet Vetoes vs Searches for $pp \rightarrow W_{KK}$ or $pp \rightarrow W_{SSM}$



Plotted: (Normalized) leading jet p_T distribution at NLO+PS² for

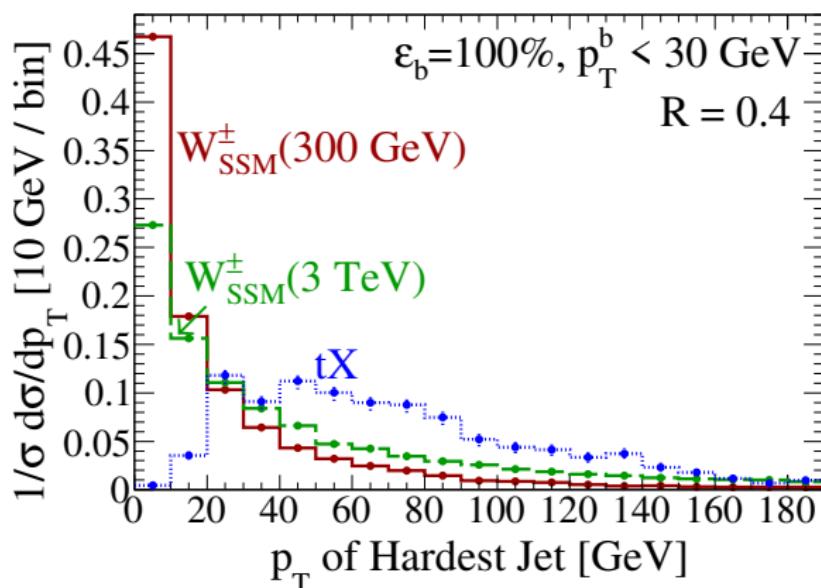
$$pp \rightarrow W'_{\text{SSM}} \rightarrow \mu\nu \quad \text{and} \quad pp \rightarrow t(\bar{t}) \rightarrow \mu X$$



Fuks, RR [1701.05263]

- Clear separation between leading jet p_T in signal and top background
- $p_T^{j_1}$ spectrum lurches rightward for larger $M_{W'}$

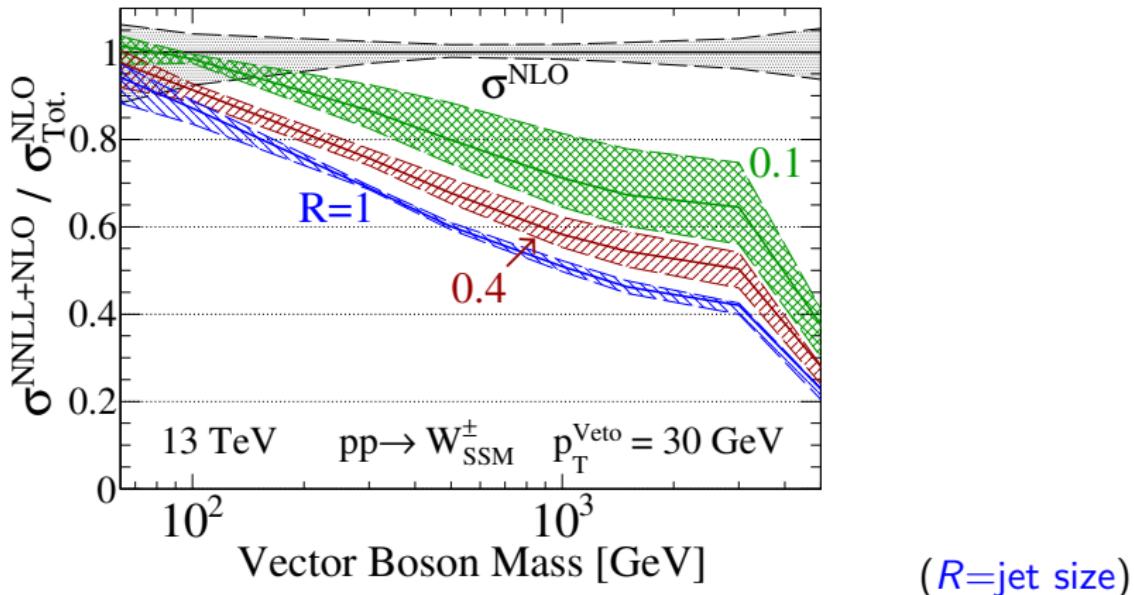
Plotted: (Normalized) leading jet p_T distribution at NLO+PS
+ b -jet veto with perfect tagging efficiency ($\epsilon_b = 100\%$)



Fuks, RR [1701.05263]

- A separation between signal and top background remains
- **Question:** instead of b -jet veto, how about just a generic jet veto?

Plotted: veto efficiency³ $\varepsilon = \sigma^{\text{NLO+NNLL}}(p_T^{\text{Veto}}) / \sigma_{\text{Tot}}^{\text{NLO}}$ for $pp \rightarrow W'_{\text{SSM}}$



- For fixed p_T^{Veto} threshold, signal survival crashes for increasing mass!⁴
- Question:** Is a veto even useful when $p_T^{\text{Veto}} > 30 - 40 \text{ GeV}$?

³ a la automated resummation with mg5amc@nlo+scet by Becher, et al [1412.8408] (more on this later!)

⁴ Ditto for sleptons, Tackmann, et al [1603.03052]; and heavy neutrinos, Pascoli, RR et al [1805.09335, 1812.08750].

What do we want from a jet veto?

- ① High signal acceptance
(Yes, for high p_T^{Veto} thresholds)
- ② High background rejection
(Yes, for low p_T^{Veto} thresholds)
- ③ Low/less sensitivity to missing higher order corrections
(Yes, for p_T^{Veto} thresholds where $p_T^{\text{Veto}} \sim Q$)

Suggestive hint: what is the value of the hard process scale Q ?

- for $pp \rightarrow t\bar{t}$, the hard process scale is $Q \sim m_{t\bar{t}}$, not $Q \sim M_{W'}$
- for $pp \rightarrow W'$, the hard process scale is $Q \sim M_{W'}$, not $Q \sim m_{t\bar{t}}$
- etc.

Reenvisioning Jet Vetoess: Event-Based⁵ Jet Vetoess⁶

⁵aka: "dynamic jet veto," "phase space-dependent jet veto", or "safe jet veto"

⁶Early literature: Bjorken (dynamic rapidity gap) [PRD ('93)]; Denner, et al (regulator trick) [[0906.1656](#)]; Companario, et al ($x = E_T / \sum_k E_T^k$ fraction) [[1410.4840](#)] ; more recent work by DESY+NIKEF+Mainz (rapidity-dependent vetoes)

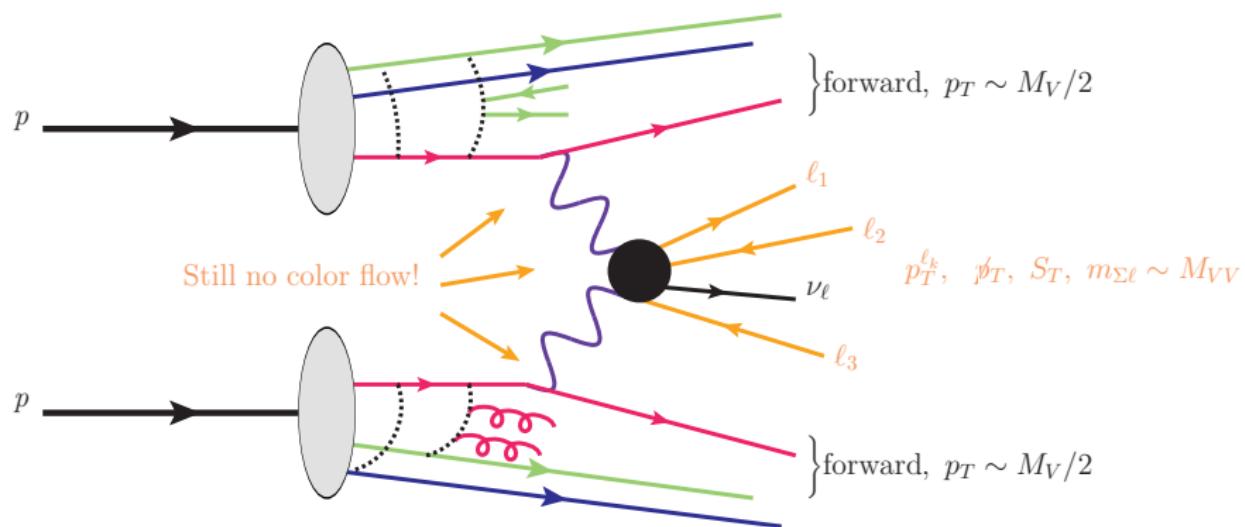
an idea:⁷: on an event-by-event basis,
allow an event's kinematics to set p_T^{Veto}

⁷ Pascoli, RR, Weiland [PLB ('18), 1805.09335]

Leptons in EW Vector Boson Fusion/Scattering

For production of leptons in EW VBF/VBS:

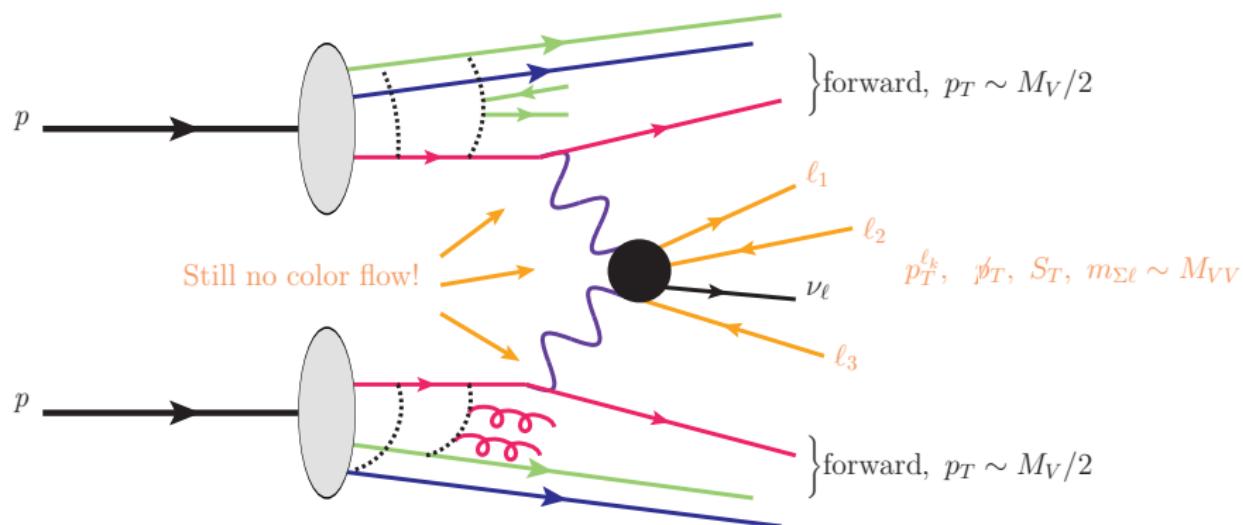
$$p_T^{\ell_k}, S_T \sim M_{VV} \gg p_T^{j_{VBS}} \sim M_V/2$$



Leptons in EW Vector Boson Fusion/Scattering

For production of leptons in EW VBF/VBS:

$$p_T^{\ell_k}, S_T \sim M_{VV} \gg p_T^{j_{VBS}} \sim M_V/2$$

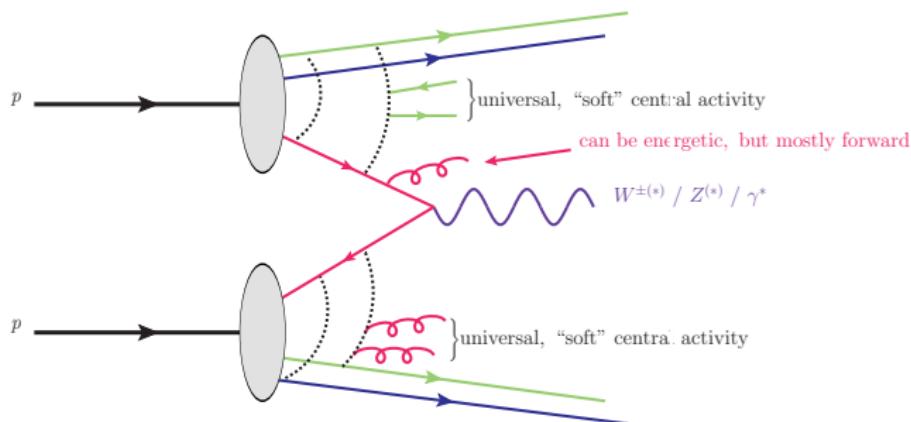


An idea: on event-by-event basis, set $p_T^{\text{Veto}} = p_T^{\ell_1}$

- VBF events pass by construction.
- What about other color-singlet processes, e.g., high-mass Drell-Yan?

Leptons in High-Mass Drell-Yan and Gluon Fusion

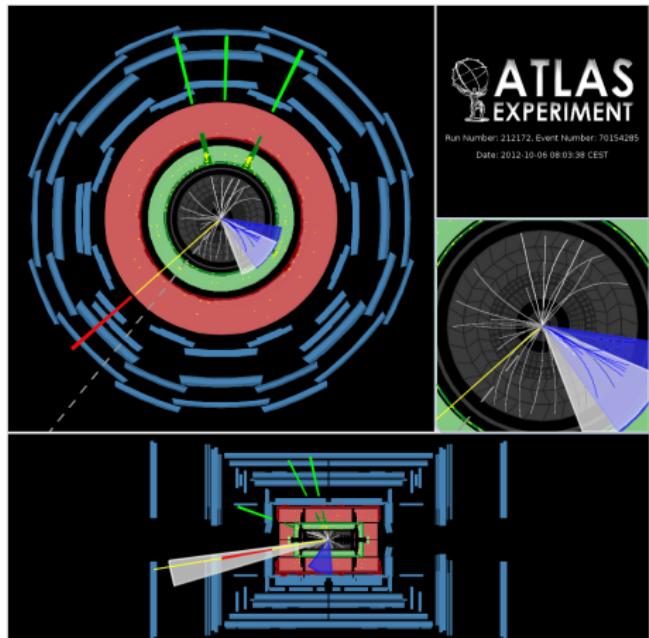
For leptons in high-mass DY: $p_T^{\ell_k}$, $S_T \sim M_{V^*} \gg p_T^j \sim \text{Sudakov shoulder}$



An idea: on event-by-event basis, set $p_T^{\text{Veto}} = p_T^{\ell_1}$

- High-mass, DY- and GF-type processes pass by construction
- Since $(M_{V^*}/p_T^{\text{Veto}}) \sim 1$, jet veto logarithms not inherently large
- What about background processes, e.g., top quarks?

Top Quark Background vs Event-Based Jet Veto



$pp \rightarrow t\bar{t}Z \rightarrow 1\mu + 3e + 2j_b + \cancel{E}_T$
candidate event [1509.05276]

Textbook kinematics:

- $m_{ee} = 93$ GeV
- $\cancel{E}_T = 57$ GeV

Typically,

- $p_T^{e_3} \sim \frac{M_Z}{2} \sim 45$ GeV
- $p_T^{e_1} \sim \frac{m_t}{4} \left(1 + \frac{M_W^2}{m_t^2}\right) \sim 50$ GeV
- $p_T^{b_1} \sim \frac{m_t}{2} \left(1 - \frac{M_W^2}{m_t^2}\right) \sim 60$ GeV

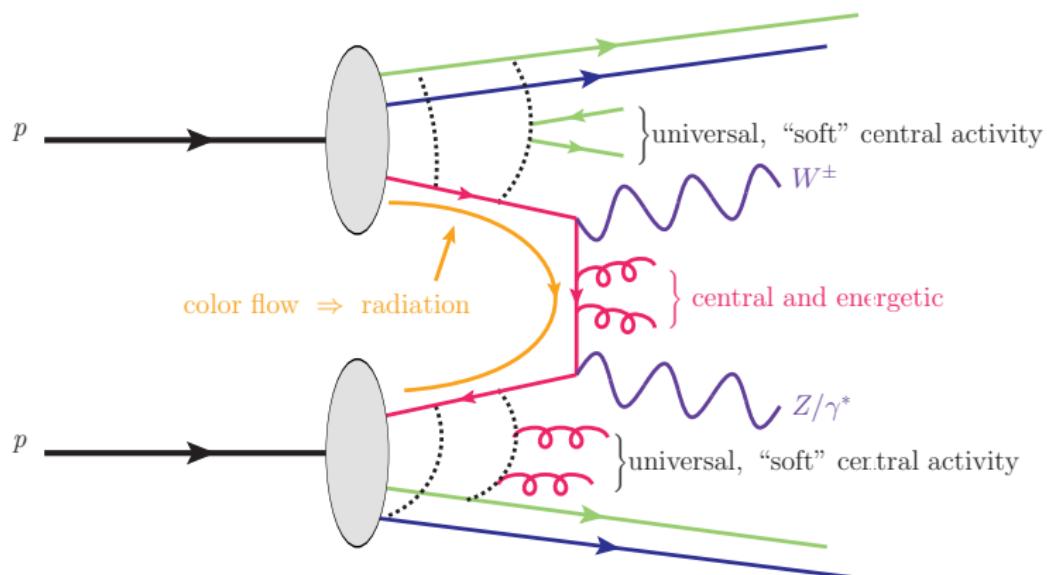
$p_T^{b_1} > p_T^{\ell_k} \implies$ event vetoed!

Setting $p_T^{\text{Veto}} = p_T^{\ell_1}$ can reduce top background **without** b -jet tagging!

Diboson and Triboson Processes

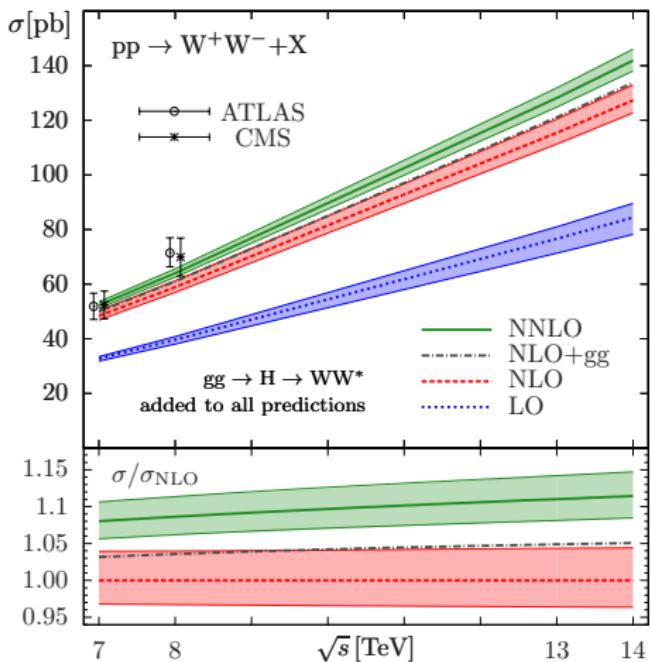
Di- / triboson processes contain large amounts of hadronic activity

- Significant s - and t -channel cancelations for Born-like configurations⁸
- Nontrivial color flow, despite naïve, color-singlet nature



⁸i.e., Radiation zeros (super interesting!) Mikaelian ('78); +Brown, et al ('78-'79); Zhu ('80); Brodsky, et al ('82,'83);

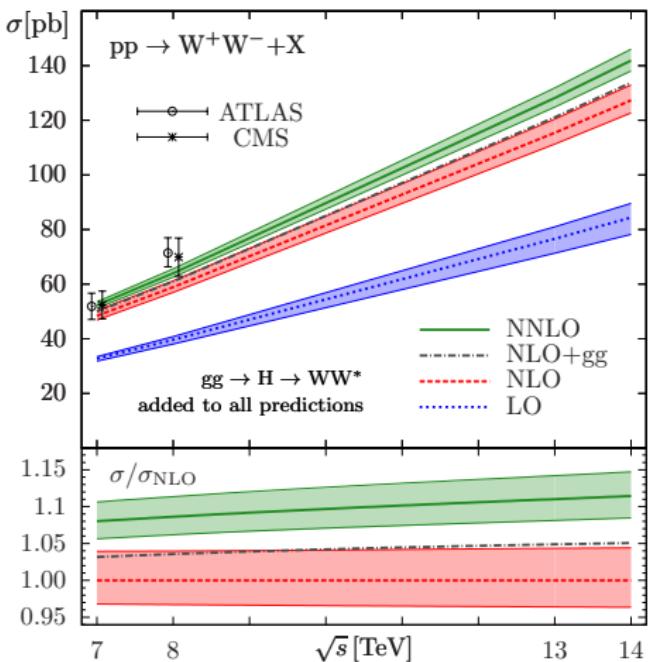
Irreducible Bkgs vs Event-Based Jet Veto



Inclusive diboson production driven by $pp \rightarrow VV'j + X$

- Manifests as large K -factor in $pp \rightarrow W^+W^-$ at NNLO [1408.5243]
- $p_T^\ell \sim \frac{M_V}{2} + \frac{p_T^j}{2n_b}$ ($n_b = \#$ bosons)
⇒ large $p_T^j > p_T^\ell$ tail

Irreducible Bkgs vs Event-Based Jet Veto



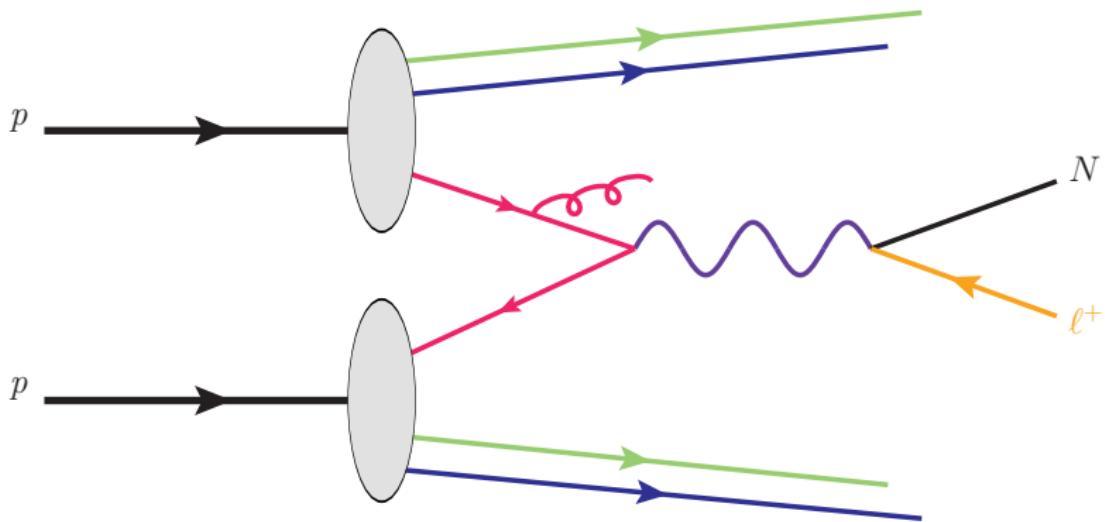
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⇒ large $p_T^j > p_T^\ell$ tail

Jets mistagged/IDed as τ_h/e , i.e., "fake leptons," major irreducible bkg:
- E.g., $pp \rightarrow W^+W^-j$
- Subleading jets more likely to be mis-IDed than leading jet

Setting $p_T^{\text{Veto}} = p_T^{\ell_1}$ can reduce irreducible backgrounds

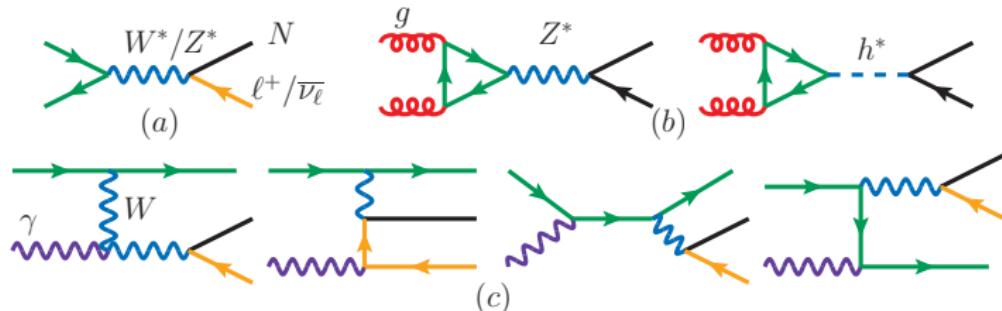
Case Study I: Heavy Neutrinos at the LHC⁹



⁹ Pascoli, RR, Weiland [PLB ('18), 1805.09335], JHEP ('19), 1812.08750]

Heavy N can be produced in a variety of ways in pp collisions

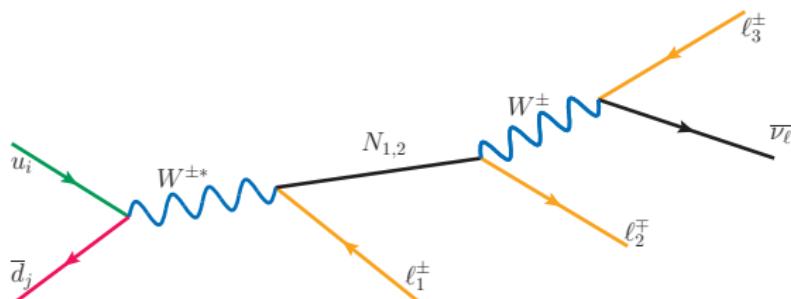
Review on ν mass models at colliders, Y. Cai, T. Li, T. Han, RR [1711.02180]



DY + $W\gamma$ fusion dominant mechanisms for heavy N at LHC

Alva, Han, RR [1411.7305]; Degrande, Mattelaer, RR, Turner [1602.06957]

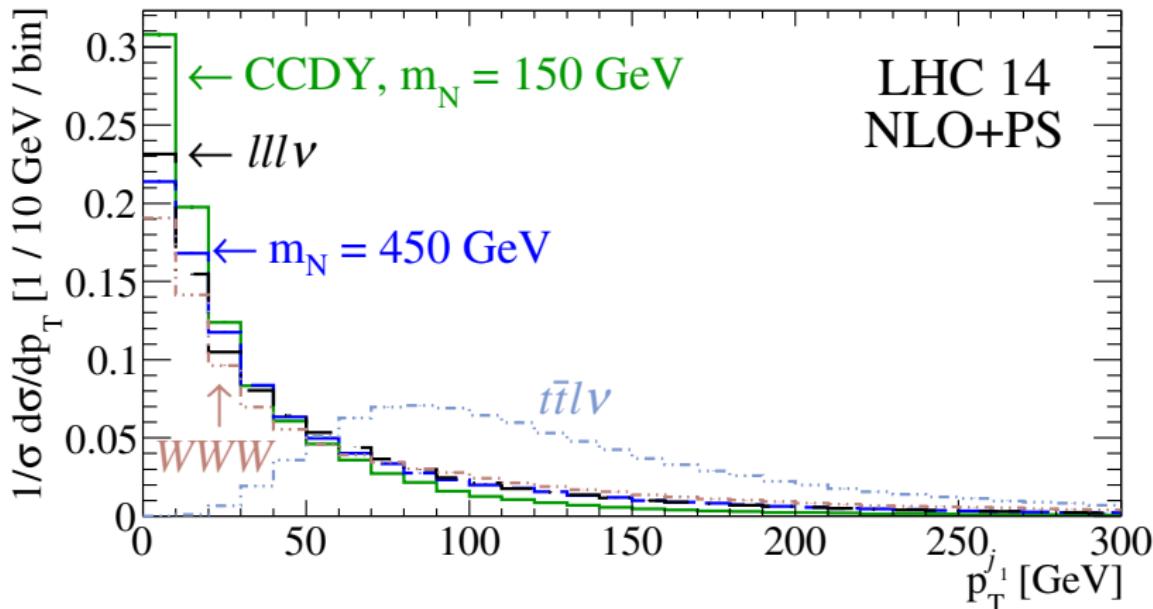
Focus on the final state: $pp \rightarrow 3\ell$



Jet vetoes tries to discriminate jet activity in signal and background.

Consider $pp \rightarrow 3e/\mu + X$ at NLO+PS(LL)+anti- $k_T(R = 1)$

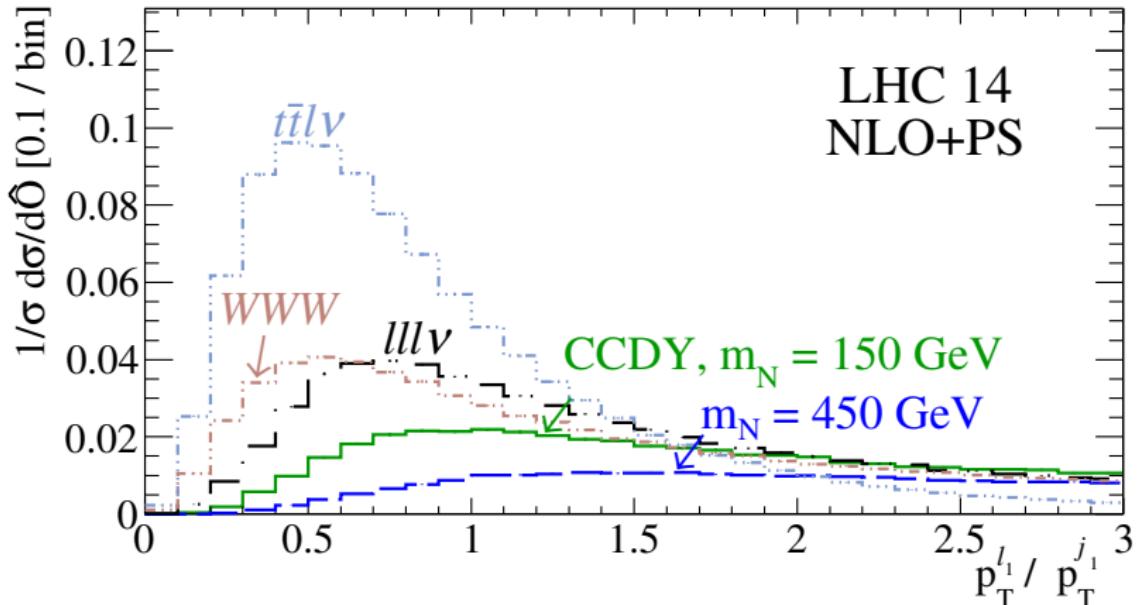
Plotted: $p_T^{j_1}$ for CC DY signal + SM Bkg



Again separation according to Born color structure clear

Event-based jet vetoes discriminate against hadronic and leptonic activities

Plotted: $r_{j_1}^{\ell_1} = p_T^{\ell_1}/p_T^{j_1}$ for CC DY signal + SM Bkg



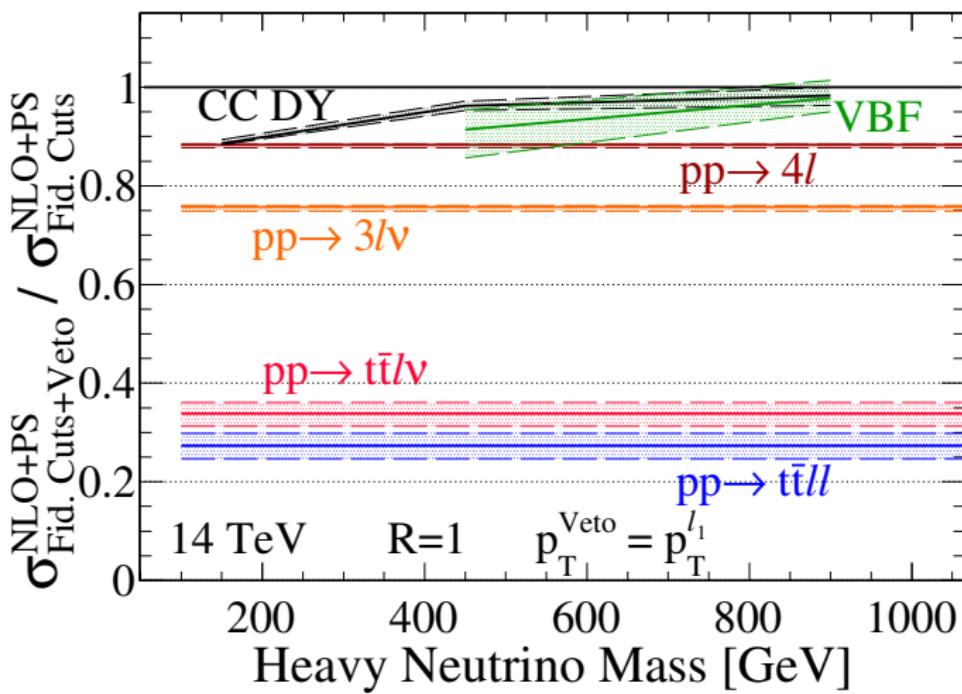
Similar behavior for other ratios, e.g., S_T/H_T , $p_T^{\ell_k}/H_T$

- Not universal, e.g. degenerate mass limit in $\tilde{\mu} \rightarrow \mu \tilde{\chi}^0$ [1901.09937]

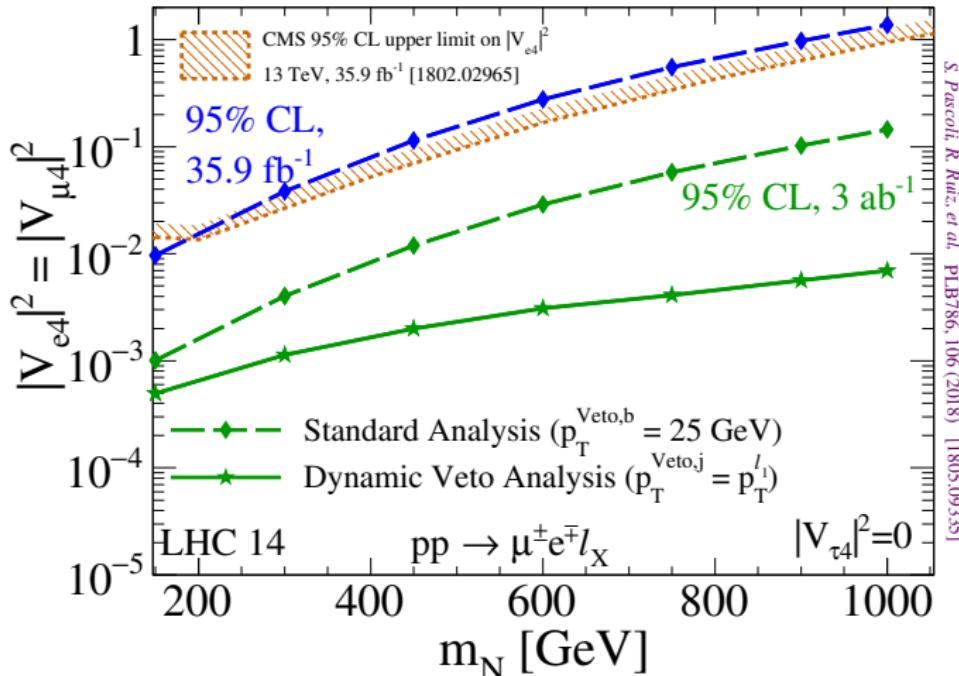
Static jet vetoes \implies poor signal efficiency for high-mass BSM

- Setting $p_T^{\text{Veto}} = p_T^{\ell_1}$ can alleviate this

Plotted: veto efficiency $\varepsilon(p_T^j < p_T^{\text{Veto}}) = \sigma_{\text{Fid. Cuts} + \text{Veto}}^{\text{NLO+PS}} / \sigma_{\text{Fid. Cuts}}^{\text{NLO+PS}}$



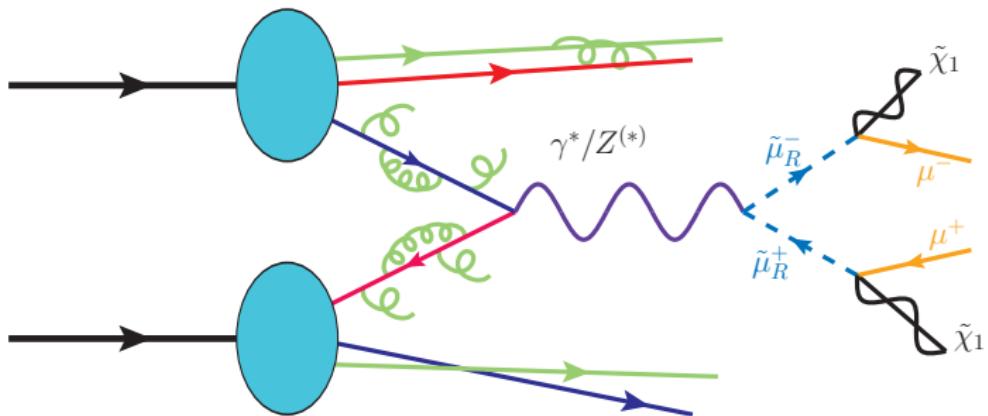
Plot: LHC 14 sensitivity to active-sterile neutrino mixing (coupling²) vs heavy N mass (m_N), in search for $pp \rightarrow \mu^\pm e^\mp l_X + X$ ($l_X = e, \mu, \tau_h$)



Improved sensitivity up to $10 - 11 \times$ with $\mathcal{L} = 3 \text{ ab}^{-1}$.

See also [1812.08750] for various lepton flavor permutations, uncertainty plots, etc

Case Study II: sleptons and generalizing event-based jet veto definitions¹⁰



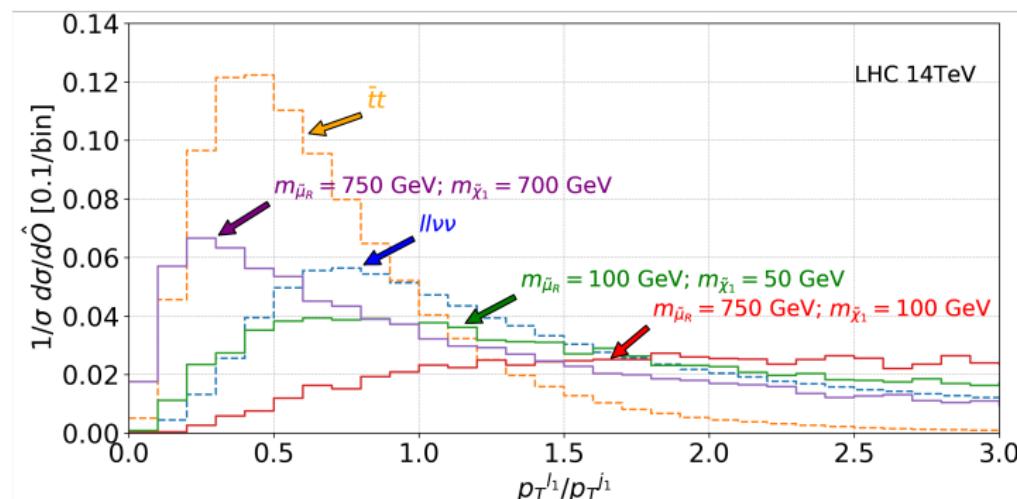
¹⁰ Fuks, Nordstrom, RR, Williamson [1901.09937]

Leptons vs Hadrons Redux

Consider the signature $pp \rightarrow \mu^+ \mu^- + X$ at NLO+PS(LL)

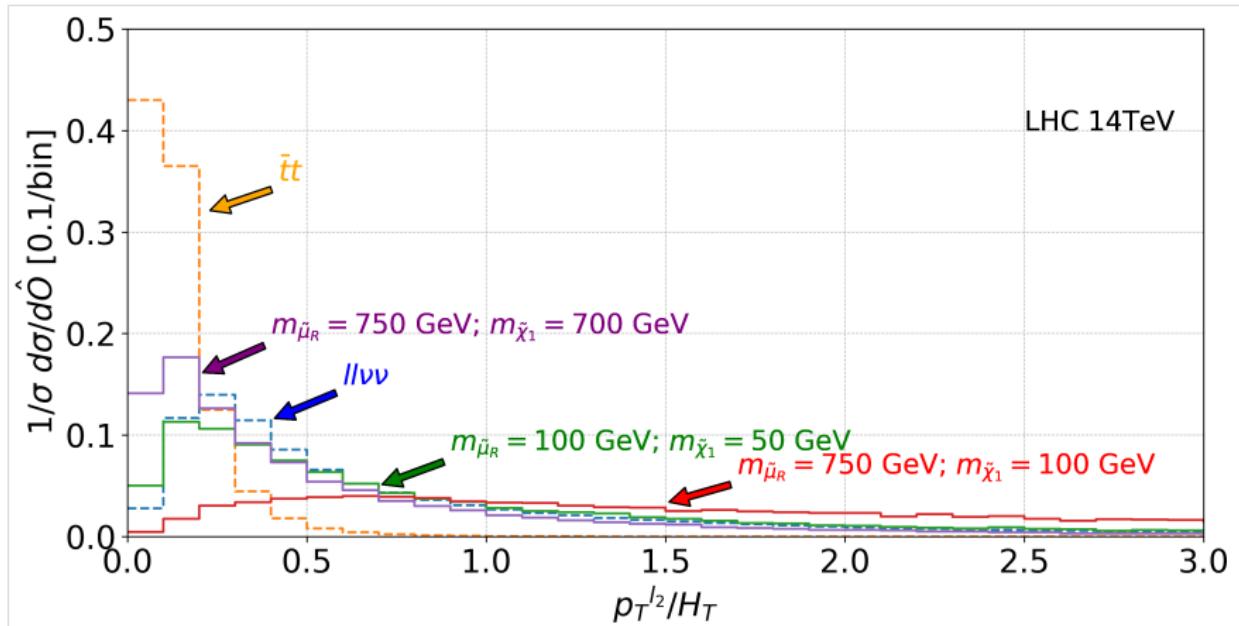
- Generator cuts + $p_T^\ell > 15$ GeV + $|\eta^\ell| < 2.4$ + anti- $k_T(R = 1)$

Plotted: $r_{j_1}^{\ell_1} = p_T^{\ell_1}/p_T^{j_1}$



Poorer S/B separation than heavy neutrino case, esp. for $m_{\tilde{\mu}} \sim m_{\tilde{\chi}}$

Plotted: $r_{H_T}^{\ell_2} = p_T^{\ell_2}/H_T$, $H_T = \sum_{k \in \{clusters\}} E_T^k$



Turns out $p_T^{\text{Veto}} = p_T^{\ell_1}$ is not best ratio :)
 Nevertheless, separation between $t\bar{t}$ from $V^{(*)}V^{(*)}$ is clear :)

Had "fun" looking into uncertainties :)

Cut / Channel	$\sigma(\ell\ell VV) [fb]$			$\sigma(\ell\ell\ell\ell V) [fb]$			$\sigma(t\bar{t}) [fb]$		
	Incl.	Incl.+MPI	FxFx+MPI	Incl.	Incl.+MPI	FxFx+MPI	Incl.	Incl.+MPI	FxFx+MPI
Common Analysis Requirements									
Generator	10 200 ^{+4.1%} _{-4.8%}	10 200 ^{+4.1%} _{-4.8%}	10 300 ^{+4.5%} _{-5.1%}	1600 ^{+5.5%} _{-6.5%}	1600 ^{+5.5%} _{-6.5%}	1680 ^{+5.5%} _{-6.2%}	85 800 ^{+9.2%} _{-10.4%}	85 800 ^{+9.2%} _{-10.4%}	91 000 ^{+11.9%} _{-11.7%}
Dimuon Selection	850 ^{+4.1%} _{-4.8%} (8.4%)	850 ^{+4.5%} _{-5.1%} (8.4%)	840 ^{+4.9%} _{-5.3%} (8.4%)	140 ^{+6.3%} _{-7.0%} (8.7%)	140 ^{+6.3%} _{-6.8%} (8.7%)	140 ^{+6.1%} _{-6.5%} (8.6%)	6400 ^{+12%} _{-12%} (7.5%)	6400 ^{+12%} _{-12%} (7.5%)	6800 ^{+12%} _{-13%} (7.5%)
+ $m_{\ell\ell}$ Requirements	590 ^{+4.2%} _{-4.8%} (69%)	590 ^{+4.5%} _{-5.2%} (69%)	580 ^{+3.3%} _{-3.5%} (69%)	40 ^{+7.0%} _{-7.6%} (28%)	40 ^{+6.9%} _{-7.4%} (28%)	40 ^{+6.3%} _{-6.8%} (29%)	5000 ^{+12%} _{-12%} (77%)	5000 ^{+12%} _{-12%} (78%)	5300 ^{+12%} _{-13%} (78%)
+Minimum M_{T2}	2.9 ^{+6.6%} _{-7.5%} (0.49%)	3.0 ^{+6.6%} _{-8.8%} (0.51%)	2.4 ^{+0.9%} _{-0.2%} (0.42%)	0.74 ^{+0.6%} _{-1.0%} (1.9%)	0.76 ^{+7.2%} _{-7.7%} (1.9%)	0.56 ^{+7.0%} _{-8.2%} (1.4%)	8.8 ^{+13%} _{-15%} (0.18%)	9.2 ^{+13%} _{-12%} (0.18%)	8.6 ^{+12%} _{-25%} (0.16%)
Benchmark Static Jet Veto Analysis Requirements									
+ $p_T^{\ell_1} > 50 \text{ GeV}, p_T^{\ell_2} > 20 \text{ GeV}$	2.7 ^{+9.0%} _{-8.9%} (94%)	2.8 ^{+4.6%} _{-12%} (94%)	2.3 ^{+12%} _{-7.2%} (96%)	0.70 ^{+11%} _{-12%} (95%)	0.71 ^{+7.4%} _{-8.0%} (94%)	0.53 ^{+7.8%} _{-10%} (95%)	7.7 ^{+13%} _{-20%} (87%)	8.3 ^{+15%} _{-13%} (90%)	7.8 ^{+12%} _{-33%} (91%)
+Static Jet Veto	1.5 ^{+13%} _{-11%} (54%)	1.5 ^{+5.6%} _{-17%} (53%)	1.6 ^{+13%} _{-7.8%} (70%)	0.27 ^{+11%} _{-12%} (39%)	0.26 ^{+9.3%} _{-8.0%} (36%)	0.31 ^{+7.8%} _{-13%} (60%)	0.033 ^{+240%} _{-20%} (0.43%)	0.049 ^{+66%} _{-66%} (0.60%)	0.15 ^{+68%} _{-58%} (1.9%)
Dynamic Jet Veto Analysis Requirements									
$p_T^{\text{Veto}} = p_T^{\ell_1}$	2.6 ^{+6.7%} _{-14%} (86%)	2.5 ^{+7.0%} _{-8.8%} (85%)	2.4 ^{+10%} _{-7.4%} (> 99%)	0.58 ^{+11%} _{-9.9%} (77%)	0.58 ^{+11%} _{-10%} (77%)	0.55 ^{+7.3%} _{-8.6%} (99%)	3.8 ^{+12%} _{-13%} (43%)	3.9 ^{+12%} _{-13%} (42%)	4.5 ^{+32%} _{-32%} (57%)
$p_T^{\text{Veto}} = p_T^{\ell_2}$	2.0 ^{+4.4%} _{-8.0%} (67%)	1.9 ^{+7.6%} _{-11%} (68%)	2.2 ^{+11%} _{-8.6%} (91%)	0.41 ^{+15%} _{-13%} (55%)	0.43 ^{+9.1%} _{-8.9%} (57%)	0.50 ^{+7.1%} _{-7.5%} (87%)	0.84 ^{+25%} _{-35%} (9.0%)	0.95 ^{+22%} _{-12%} (10%)	0.98 ^{+57%} _{-17%} (12%)
$p_T^{\text{Veto}} = S_T$	2.8 ^{+6.2%} _{-12%} (94%)	2.7 ^{+8.2%} _{-7.7%} (94%)	2.4 ^{+5.9%} _{-6.7%} (> 99%)	0.68 ^{+8.9%} _{-9.9%} (90%)	0.67 ^{+9.4%} _{-9.5%} (90%)	0.56 ^{+6.9%} _{-9.0%} (> 99%)	5.8 ^{+19%} _{-18%} (62%)	7.1 ^{+13%} _{-26%} (71%)	6.6 ^{+23%} _{-26%} (89%)
$H_T^{\text{Veto}} = p_T^{\ell_1}$	2.2 ^{+7.4%} _{-16%} (73%)	1.9 ^{+10%} _{-7.3%} (67%)	2.2 ^{+9.2%} _{-5.8%} (87%)	0.46 ^{+9.4%} _{-8.7%} (60%)	0.41 ^{+16%} _{-10%} (55%)	0.46 ^{+7.3%} _{-13%} (84%)	0.40 ^{+23%} _{-13%} (4.2%)	0.49 ^{+25%} _{-50%} (4.9%)	0.54 ^{+22%} _{-25%} (7.1%)
$H_T^{\text{Veto}} = p_T^{\ell_2}$	1.5 ^{+4.9%} _{-11%} (51%)	1.2 ^{+5.3%} _{-5.4%} (43%)	1.5 ^{+7.7%} _{-3.3%} (60%)	0.31 ^{+8.3%} _{-8.6%} (41%)	0.25 ^{+8.9%} _{-8.0%} (34%)	0.33 ^{+8.6%} _{-8.9%} (58%)	0.049 ^{+69%} _{-13%} (0.53%)	0.016 ^{+200%} _{-210%} (0.17%)	0.12 ^{+620%} _{-81%} (1.5%)
$H_T^{\text{Veto}} = S_T$	2.5 ^{+4.6%} _{-13%} (84%)	2.4 ^{+6.1%} _{-8.3%} (82%)	2.3 ^{+9.6%} _{-9.7%} (97%)	0.55 ^{+13%} _{-10%} (74%)	0.53 ^{+11%} _{-10%} (71%)	0.54 ^{+7.0%} _{-8.5%} (95%)	1.4 ^{+23%} _{-24%} (16%)	1.1 ^{+44%} _{-15%} (11%)	1.9 ^{+31%} _{-20%} (23%)

Table 2 The cross section [fb] with uncertainties [$^{+/-}\%$] and cut efficiency [%] of the selection cuts in table 1 for the dominant SM backgrounds, when modeled at the inclusive NLO+PS level without MPI (Incl.), with MPI (Incl.+MPI), and FxFx-merging with MPI (FxFx+MPI). Uncertainties are obtained by adding the renormalization and factorization scale envelope with the shower scale envelope and statistical uncertainty in quadrature. At the generator-level, statistical confidence corresponds to 5-10 M events for each sample and shower variation.

As a benchmark, we considered CMS's Run II search

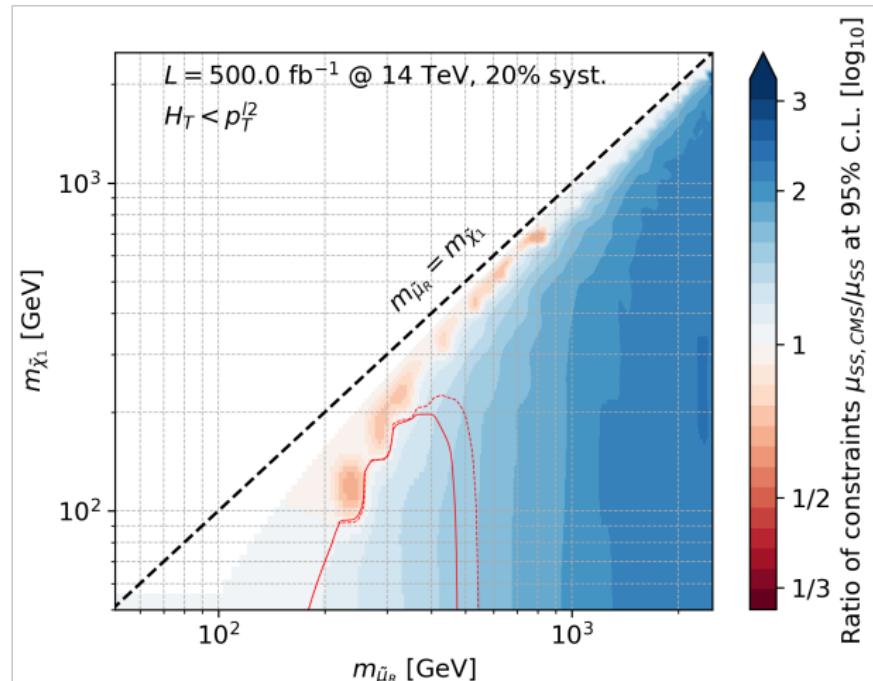
[1806.05264]

- Changes: relaxed leading $p_T^{\ell_1}$ cut and swapped out $p_T^{\text{Veto}} = 25 \text{ GeV}$
- + FxFx1j merging, MPI/UE tuning

Plot: Sensitivity change using $H_T^{\text{Veto}} = p_T^{\ell_2}$ in $(m_{\tilde{\chi}}, m_{\tilde{\mu}})$ -space

darker = improvement

- Improved sensitivity to large mass splitting
- Worse for small mass splitting
- Other ratios show qualitatively opposite behavior [1901.09937]



IV. Outlook

What is next?

- ① Application to other new physics scenarios and possible searches
 - ▶ Explore best ratios for final states and parameter space
 - ▶ Mandate for community to explore and have fun

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- ▶ Machine Learning (this seems appears promising Nordstrom, RR [unpublished])

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③ Improved Monte Carlo Tools

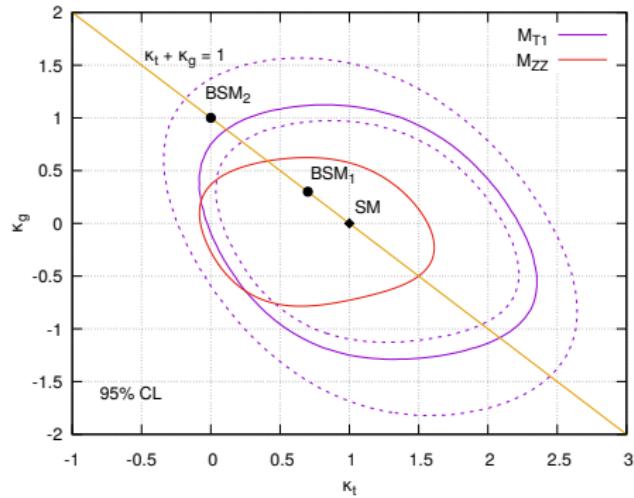
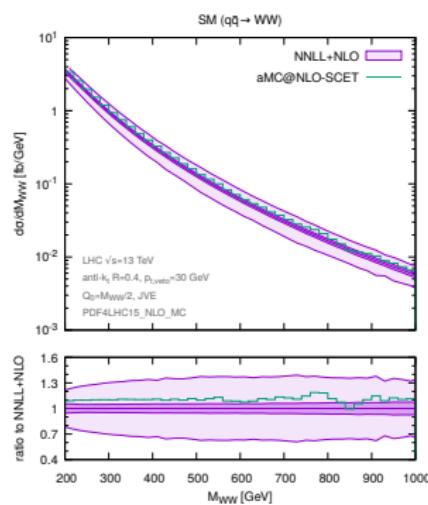
- ▶ Parton showers beyond LL precision (**See Marius' talk!**)
Hoeche, ('17,'17); Dasgupta, et al ('18) ; Monni, Wiesmann, et al ('19)
- ▶ Dedicated tools
- ▶ General-purpose tools

New Monte Carlo Tools: Jet Veto^s for the Masses

Automated Jet Veto Resummation: Dedicated Codes

MCFM-RE: Extension to MCFM with jet veto resummation up to NLO+NNLL(veto) in pQCD

[Arpino, Banfi, Jager, Kauer 1905.06646]



SCETlib: C++ libraries for computing (bulky!) SCET objects

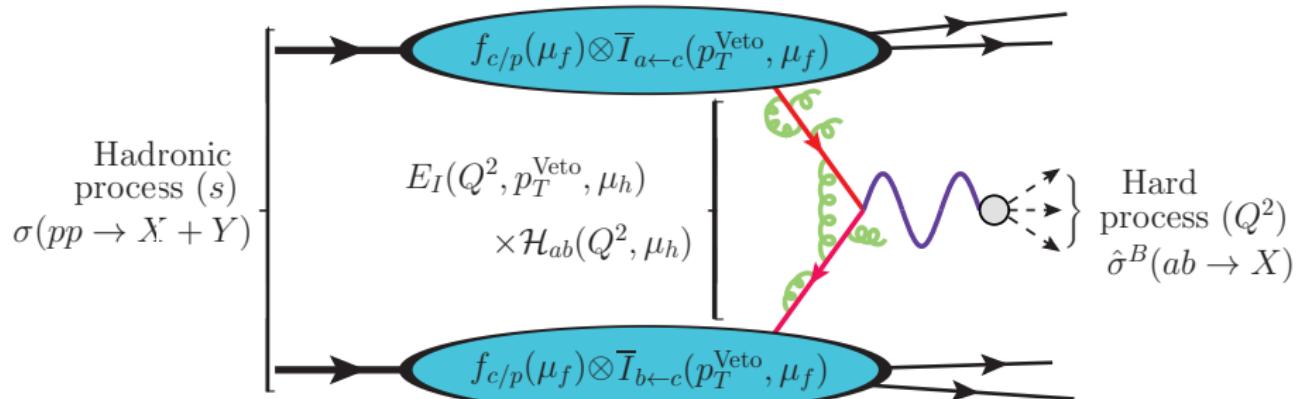
[Ebert, Michel, Tackmann SCETlib]

Automated Jet Veto Resummation: General Purpose

In 2014, MadGraph5_aMC@NLO+SCET framework *quietly* released

Becher, et al [1412.8408]

$$d\sigma(X + 0j) = \mathcal{B} \otimes \mathcal{B} \otimes \underbrace{E}_{\text{NNLL in SCET}} \otimes \underbrace{d\mathcal{H}}_{\text{LO, NLO, etc.}} + \underbrace{\text{(matching scheme)}}_{\text{removes dbl counting}}$$



- Jet veto resummation up to NLO+NNLL(Veto) in **SCET**
- NLO in QCD UFO model files needed

NLOCT and BSM @ NLO in QCD

While automated SM@NLO in QCD available since 2009 [0903.0356; 0910.3130] automation for a generic model took more time

- Need UV and " R_2 " counter terms for vertices

Solution NLOCT protocol for building CT from tree-level \mathcal{L} [Degrande 1406.3030]



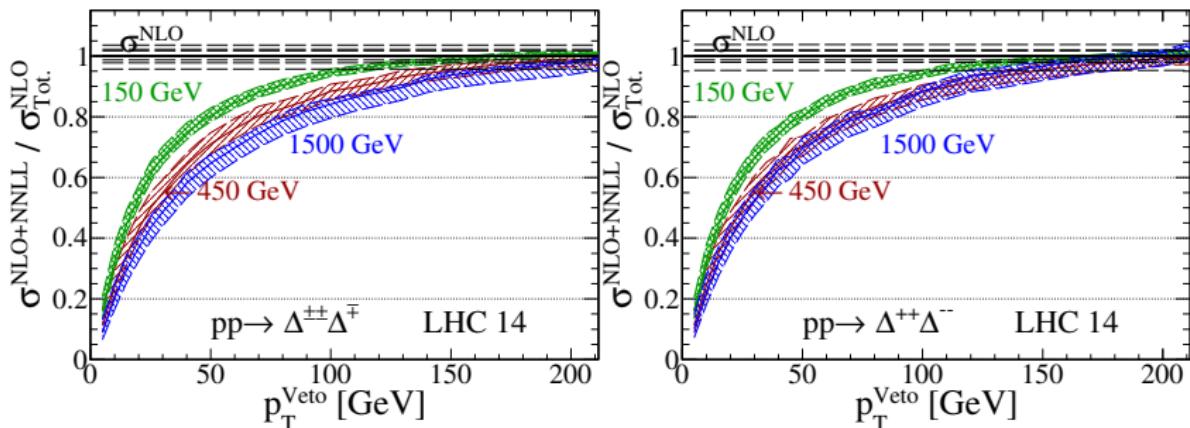
Models files are systematically being written based on need/interest (happy to collaborate)

[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:1610.09985]	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 gluon pair production	B. Fuks	[arXiv:1412.5589]	sgluons.fr	sgluons_ufo.tgz	s gluons_validation.pdf ; s gluons_validation_root.tgz
Pseudoscalar top-phobic resonance (more details)	D.B. Franzosi	[http://arxiv.org/abs/1707.06760]	-	AHtbar NLO UFO	-
Spin-2 (more details)	C. Degrande	[http://arxiv.org/abs/1605.09359]	dm_s_spin2.fr	SMspin2 NLO UFO	-
Stop pair -> t bar + 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	-

Automated Jet Veto Resummation: General Purpose

Type II Seesaw@NLO: (L) $pp \rightarrow \Delta^{\pm\pm}\Delta^{\mp}$ (R) $pp \rightarrow \Delta^{++}\Delta^{--}$



Nemevsek, RR [To Appear Soon]

- Jet veto thresholds of $p_T^{\text{Veto}} = 20 - 40$ GeV do more harm than good
- NLO UFO libraries enable BSM@NLO+PS using favorite generator: HERWIG, MG5aMC, SHERPA

Summary

- ① The science of jet vetoes is very mature
 - ▶ Precision sufficient for both indirect and direct BSM searches
 - ▶ Uncertainties extracted at NLO+PS(LL) may be large but reliable (consistent with higher accuracy results)
 - ▶ High precision resummation necessary if $p_T^{\text{Veto}} \ll Q$
- ② Building jet veto thresholds on event-by-event basis, e.g., $p_T^{\text{Veto}} = S_T$, appears very promising:
 - ▶ New schemes reveals $> 90 - 95\%$ veto acceptance for signal with little-to-no dependence on BSM mass scales [1805.09335, 1901.09937]
 - ▶ Irreducible backgrounds, e.g., $t\bar{t}$ and multi-boson particularly impacted
 - ▶ Setting $p_T^{\text{Veto}} \sim Q \implies$ milder jet veto logs
 \implies less need for high-precision resummation [1812.08750]
- ③ No single veto scheme is optimal for all analyses (have fun, explore!)
 - ▶ Dedicated and general-purpose MC tools are available and in dev.
 - ▶ BSM UFO model files with ingredients for NLO in QCD available feynrules.irmp.ucl.ac.be/wiki/NLOModels



Thank you.

Jet Veto Resummation via SCET

The Factorization Theorem is funny¹¹ since describes physical processes:

$$\underbrace{d\sigma(pp \rightarrow WW + 1j)|_{\text{low-}p_T^j}}_{\frac{d}{d \log \mu}(d\sigma)=0 \leftarrow \text{Independent of IR,UV cutoffs.}} = \color{blue}f \otimes f \otimes \Delta(\frac{\mu_X}{p_T^{\text{Veto}}}) \otimes d\hat{\sigma}|_{\text{low-}p_T^j}$$

soft/fwd. emissions

Working in Mellin space (“probability space”) (and $\mathcal{D} \equiv d/d \log \mu$), scale invariance of physical quantities gives us one big zero!

$$0 = \mathcal{D}(d\sigma) = \mathcal{D}f \times f \times \Delta \times d\hat{\sigma} + f \times \mathcal{D}f \times \Delta \times d\hat{\sigma} \\ + f \times f \times \mathcal{D}\Delta \times d\hat{\sigma} + f \times f \times \Delta \times \mathcal{D}d\hat{\sigma}$$

Appears messy, but $\mathcal{D}f$ is just DGLAP (PDF scale evolution) equation:
(in probability space)

$$\mathcal{D}f = \frac{d}{d \log \mu} f = \underbrace{\Gamma(\alpha_s)}_{\text{anomalous dim.}} f$$

$$\Rightarrow \underbrace{f(\mu_2)}_{\text{Dressed}} = \underbrace{\exp[\int d \log \mu \Gamma(\alpha_s)]}_{\text{LL, NLL, NNLL, etc.}} \underbrace{f(\mu_1)}_{\text{Bare}} \equiv U(\mu_2, \mu_1) f(\mu_1)$$

¹¹ ... in Massless Gauge Theories. Contopanagos, Laenen, Sterman ('96); Becher, Broggio, Ferroglio ('14)

Both Δ and $d\hat{\sigma}$ also obey relations of the form

$$\frac{d}{d \log \mu} X = \Gamma X \implies X(\mu_2) = U(\mu_2, \mu_1)X(\mu_1)$$

Collecting like-terms shows scattering rates have the form:

$$d\sigma(pp \rightarrow WW + 0j) = f(\mu_f) \otimes f(\mu_f) \otimes \underbrace{\Delta(\mu_f, \mu_s, \mu_h)}_{\text{evolution absorbed into Sudakov}} \otimes d\hat{\sigma}(\mu_h)$$

Accuracy of Δ determines accuracy of jet veto resummation

