Event-dependent jet vetoes: a new prospect for multilepton searches [1]

DIS 2021, SUNY Stony Brook, Zoom Campus

Richard Ruiz

Institute of Nuclear Physics – Polish Academy of Science (IFJ PAN)

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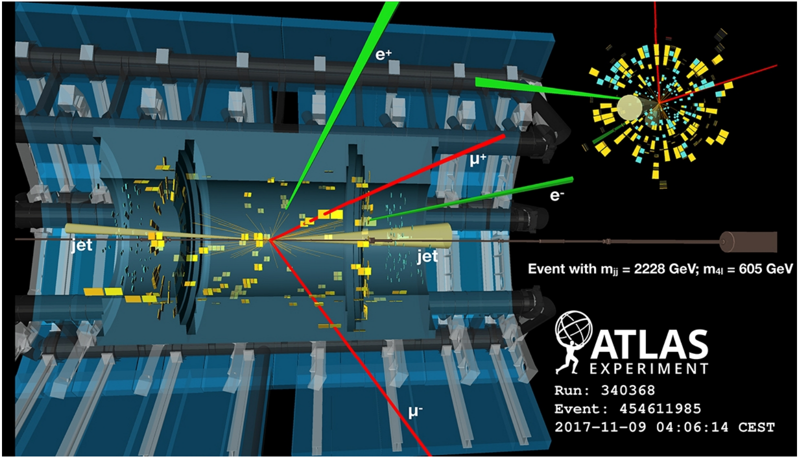
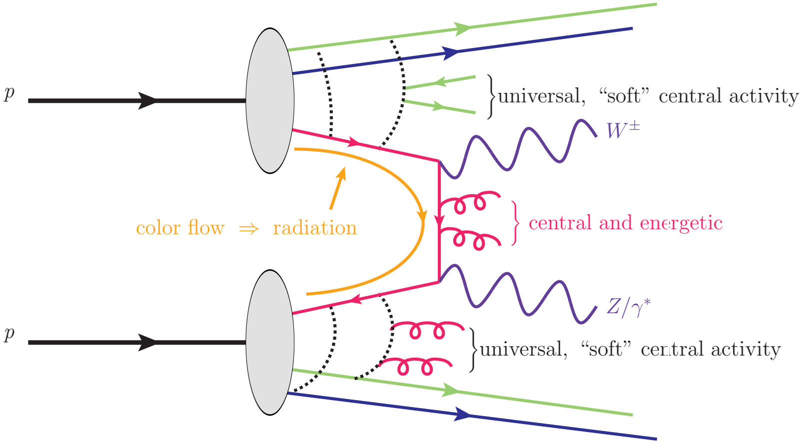
[1] Pascoli, RR, Weiland [PLB ('18), 1805.09335], JHEP ('19), [1812.08750]; w/ Fuks, et al PRD ('19) [1901.09937]

What do high-p_T LHC collisions look like?



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

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

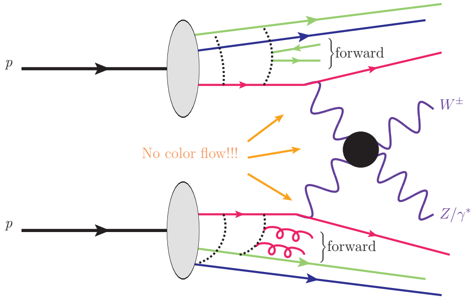


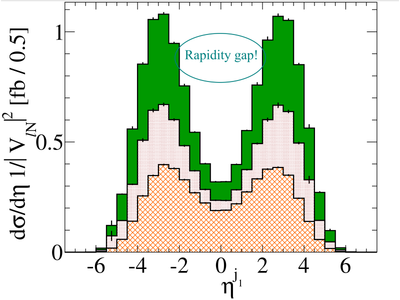
From (classical) electrodynamics, accelerated dipoles $\Longrightarrow$ real radiation

- **Notably,** while radiation existence is universal, emission pattern is not

In color-singlet processes, there is an abscence of central color flow

$\Longrightarrow$ 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 $p_T^j > 25 - 30$ GeV, $|\eta^j| < 2 - 3$
  - After applying meaningful jet PID, equivalent to keeping only 0-jet bin
- CJVs are crucial to precision Higgs and EW studies
  - Discrepancies between SM and Run I data inspired an entire community

Revolution in Jet Veto Resummation

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

- Jet veto factorization thms

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

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

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

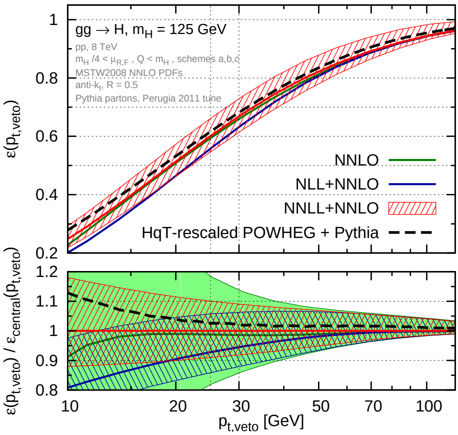
- $pp \to WW + 0j$ [Meade, et al ('14); Jaiswal, et al ('14); Monni, et al ('14); Becher, et al ('14)]

- 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

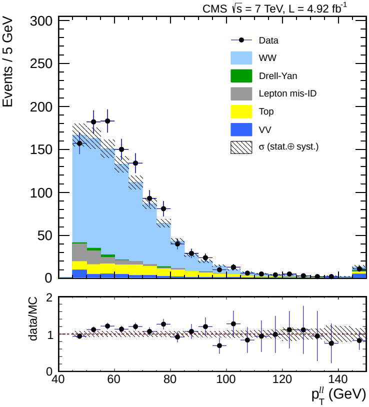
  [Gangal, et al ('14,'17); Michel, et al ('18)]

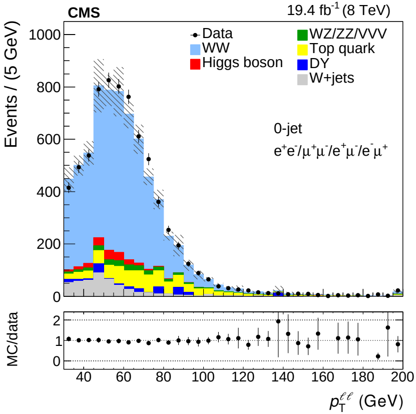


Banfi, et al [1203.5773,1206.4998]

Standard Model vs Jet Vetoes

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

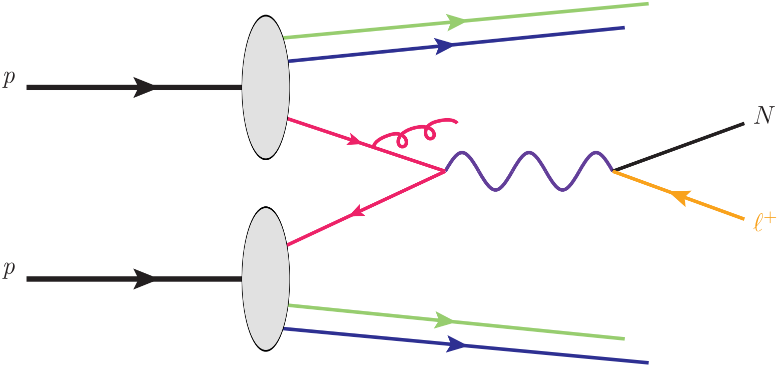




Summary: Past discrepancies resolved by accounting for (resumming) ultra soft and ultra forward gluon emission

jet vetoes in searches for new physics

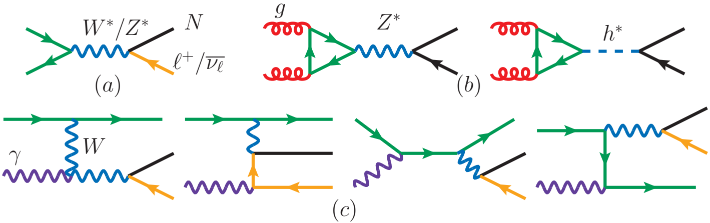
Case Study:
Heavy Neutrinos at the LHC[2]



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

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

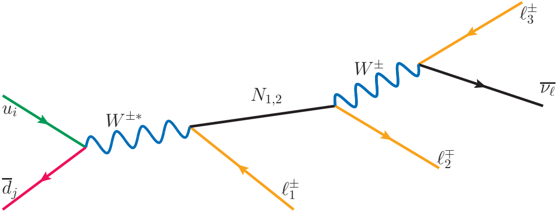
Review on ν mass models at colliders, Y. Cai, T. Li, T. Han, RR [1711.02180]



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

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

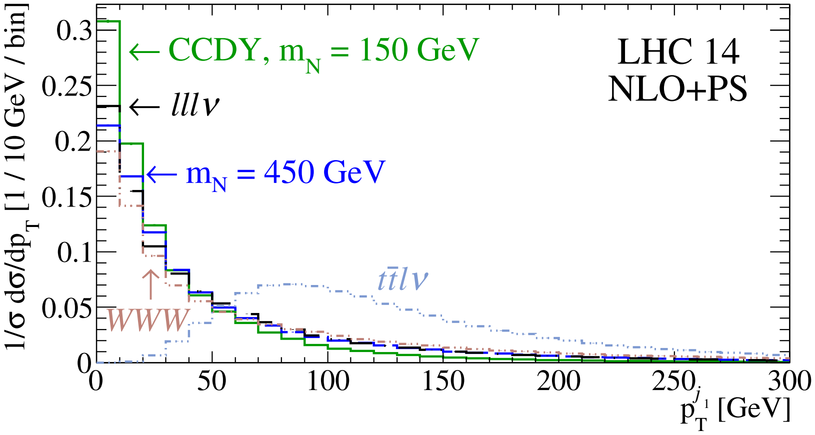
Focus on the final state: $pp \to 3\ell$



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

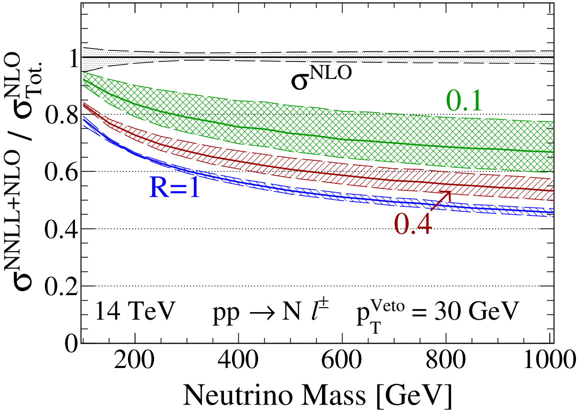
Consider $pp \to 3e/\mu + X$ at NLO+PS(LL)+anti-$k_T(R = 1)$

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



Separation according to Born color structure clear

Plotted: veto efficiency[3] $\varepsilon = \sigma^{\rm NLO+NNLL}(p_T^{\rm Veto}) \ / \ \sigma^{\rm NLO}_{\rm Tot.}$ for $pp \to W'_{\rm SSM}$



(R=jet size)

- For fixed $p_T^{\rm Veto}$ threshold, signal survival crashes for increasing mass![4]
- **Question:** Is a veto even useful when $p_T^{\rm Veto} > 30 - 40$ 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 W'/Z', Fuks, RR [1701.05263]

Reenvisioning Jet Vetoes:

Event-Based[5] Jet Vetoes[6]

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

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

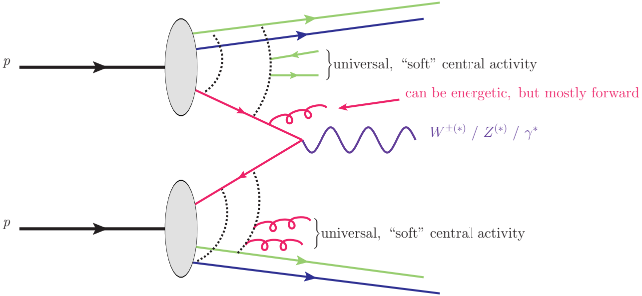
an idea:[7]: **on an event-by-event basis,**

allow an event's kinematics to set $p_T^{\rm Veto}$

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

Leptons in High-Mass Drell-Yan and VBS

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



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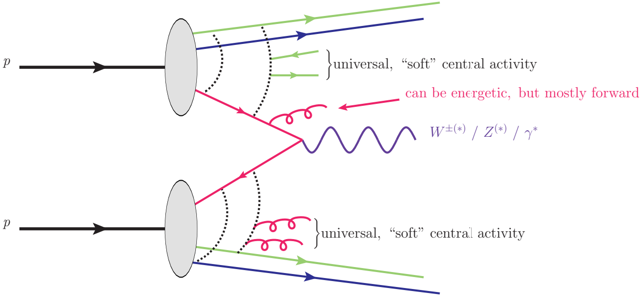
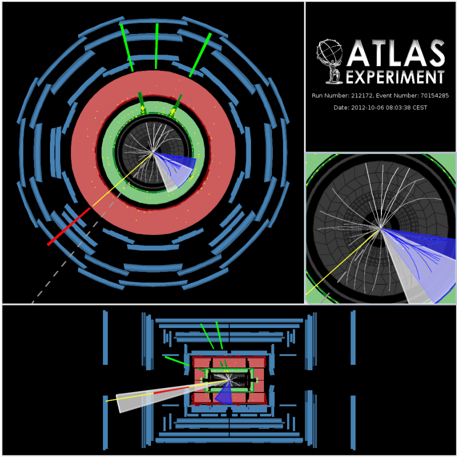


An idea: on event-by-event basis, set $p_T^{\text{Veto}} = p_T^{\ell_1}$

- High-mass, DY- and VBS-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 Vetoes



$pp \to t\bar{t}Z \to 1\mu + 3e + 2j_b + \not{E}_T$
candidate event [1509.05276]
Textbook kinematics:
- $m_{ee} = 93$ GeV
- $\not{E}_T = 57$ GeV

Typically,

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

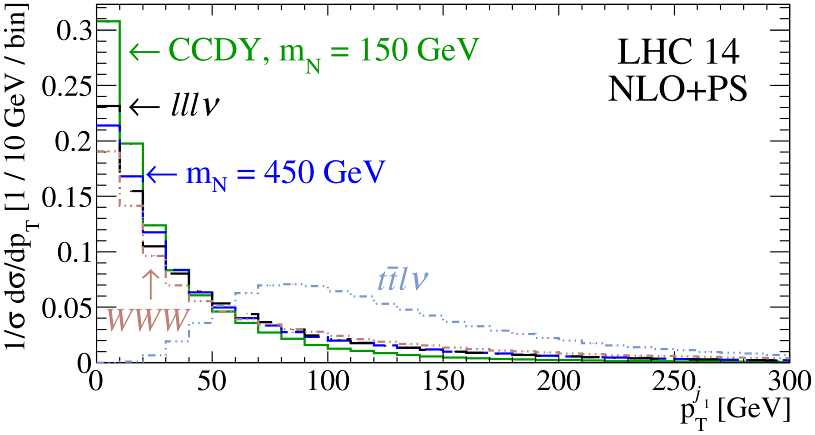
$p_T^{b_1} > p_T^{\ell_k} \implies$ event vetoed!

Setting $p_T^{\rm Veto} = p_T^{\ell_1}$ can **reduce** top background ***without*** b-jet tagging!
- Diboson and triboson backgrounds also reduced! (see backup)

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

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

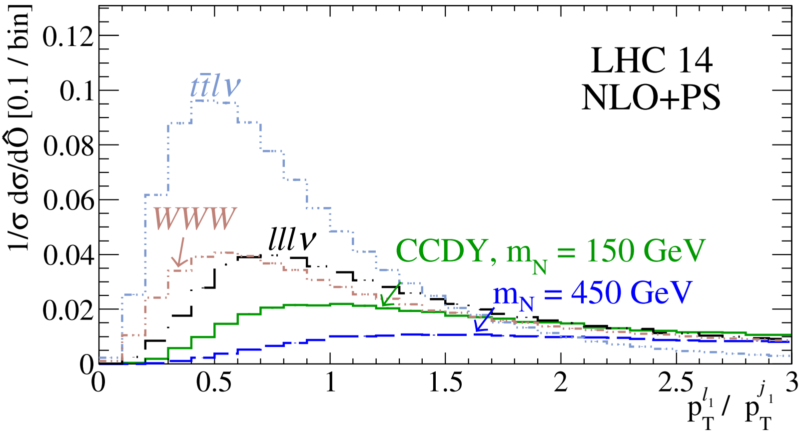
Plotted: $p_T^{j_1}$ for CC DY signal + SM Bkg



Separation according to Born color structure clear

Event-based jet vetoes descriminate against hadronic and leptonic activities

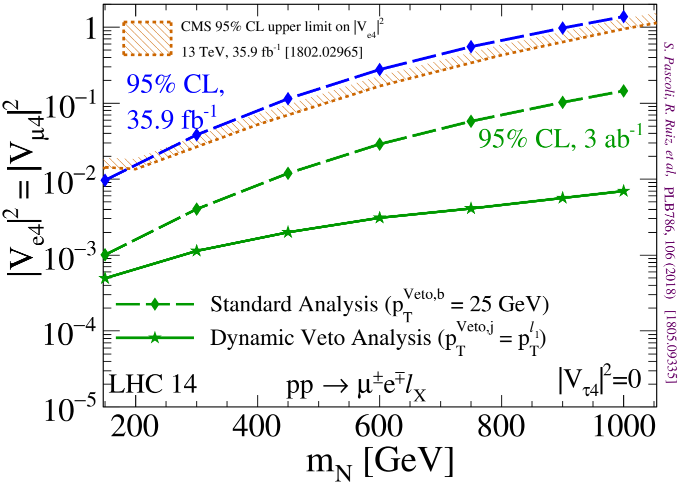
Plotted: $r^{\ell_1}_{j_1} = p^{\ell_1}_T / p^{j_1}_T$ for CC DY signal + SM Bkg



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

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

Plot: LHC 14 sensitivity to active-sterile neutrino mixing (coupling^2) vs heavy N mass (m_N), in search for $pp \to \mu^\pm e^\mp \ell_X + X \quad (\ell_X = e, \mu, \tau_h)$



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

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

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 $p_T^{\mathrm{Veto}} \ll Q$

2. Building jet veto thresholds on event-by-event basis, e.g., $p_T^{\mathrm{Veto}} = S_T$, 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 $p_T^{\mathrm{Veto}} \sim Q \implies$ milder jet veto logs $\implies$ less need for high-precision resummation [1812.08750]

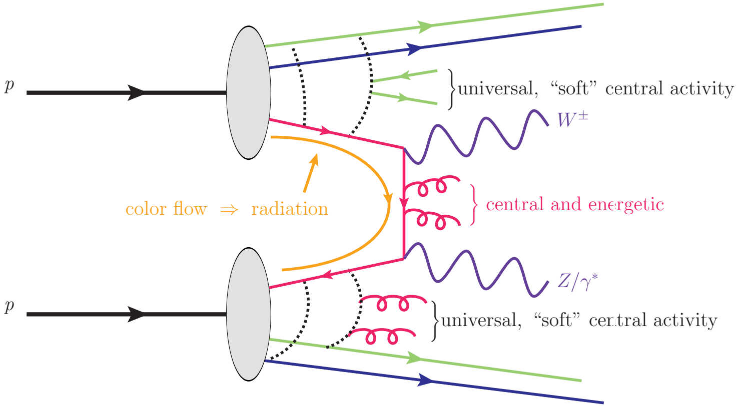
3. No single veto scheme is optimal for all analyses (have fun, explore!)
   - Dedicated and general-purpose MC tools are available and in dev.
   - BSM UFO model files with ingredients for NLO in QCD available feynrules.irmp.ucl.ac.be/wiki/NLOModels

Thank you.

Diboson and Triboson Processes

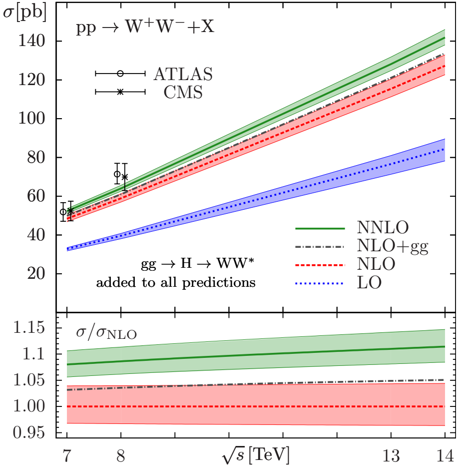
Di- / triboson processes contain large amounts of hadronic activity

- Significant s- and t-channel cancelations for Born-like configurations[8]
- Nontrivial color flow, despite naïve, color-singlet nature



[8] i.e., Radiation zeros (super interesting!) Mikaelian ('78); +Brown, et al ('78-'79); Zhu ('80); Brodsky, et al ('82,'83); Baur, Han, Ohnemus [PRL ('94), hep-ph/9403248]

Irreducible Bkgs vs Event-Based Jet Vetoes



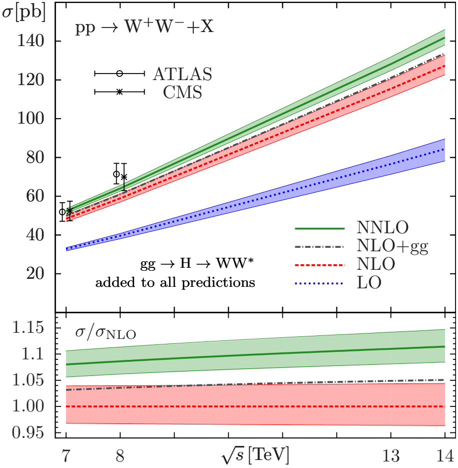
Inclusive diboson production driven by $pp \to VV'j + X$

- Manifests as large K-factor in $pp \to W^+W^-$ at NNLO [1408.5243]

- $p_T^\ell \sim \frac{M_V}{2} + \frac{p_T^j}{2n_b}$ ($n_b = \#$ bosons)

$\Longrightarrow$ large $p_T^j > p_T^\ell$ tail

Irreducible Bkgs vs Event-Based Jet Vetoes



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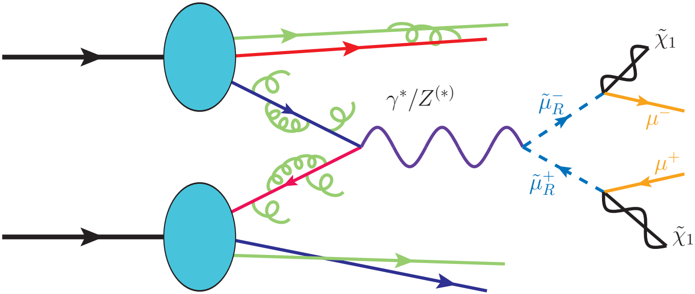
$\implies$ large $p_T^j > p_T^\ell$ tail

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

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

Case Study II:
sleptons and generalizing event-based jet veto definitions[9]



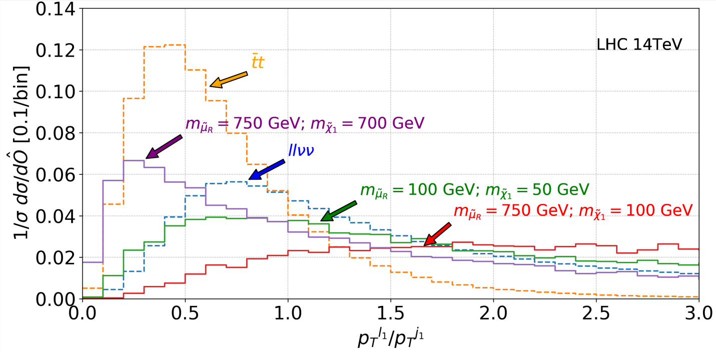
[9] Fuks, Nordstrom, RR, Williamson [1901.09937]

Leptons vs Hadrons Redux

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

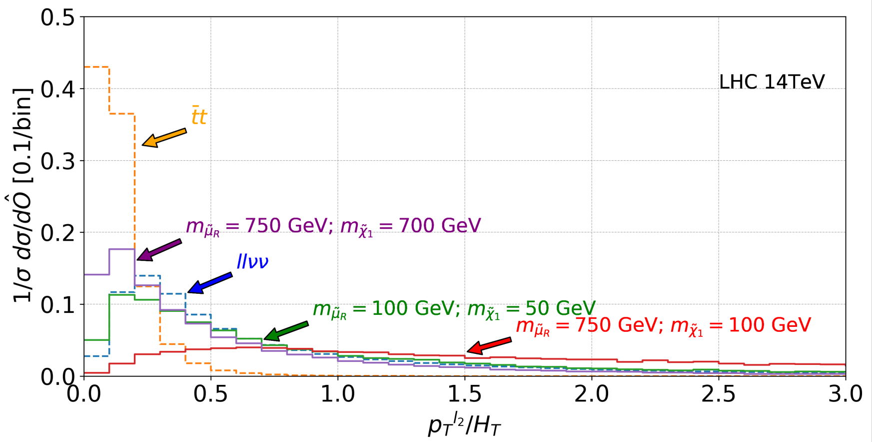
- Generator cuts + $p_T^\ell > 15$ GeV + $|\eta^\ell| < 2.4$ + anti-$k_T(R=1)$

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: $r^{\ell_2}_{H_T} = p^{\ell_2}_T / H_T, \quad H_T = \sum_{k\in\{clusters\}} E^k_T$



Turns out $p_T^{\mathrm{Veto}} = p_T^{\ell_1}$ is not best ratio :)

Nevertheless, separation between $t\bar{t}$ from $V^{(*)}V^{(*)}$ is clear :)

Had "fun" looking into uncertainties :)

Cut / Channel	$\sigma(\ell\ell\nu\nu)$ [fb] Incl.	$\sigma(\ell\ell\nu\nu)$ [fb] Incl.+MPI	$\sigma(\ell\ell\nu\nu)$ [fb] FxFx+MPI	$\sigma(\ell\ell\ell\nu)$ [fb] Incl.	$\sigma(\ell\ell\ell\nu)$ [fb] Incl.+MPI	$\sigma(\ell\ell\ell\nu)$ [fb] FxFx+MPI	$\sigma(t\bar{t})$ [fb] Incl.	$\sigma(t\bar{t})$ [fb] Incl.+MPI	$\sigma(t\bar{t})$ [fb] 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%)	$580^{+5.3\%}_{-5.5\%}$ (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%)	$3.0^{+4.6\%}_{-8.8\%}$ (0.51%)	$2.4^{+9.0\%}_{-6.2\%}$ (0.42%)	$0.74^{+9.6\%}_{-10\%}$ (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									
$+p_T^{\ell_1} > 50$ GeV, $p_T^{\ell_2} > 20$ 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									
$p_T^{\rm Veto} = p_T^{\ell_1}$	$2.6^{+6.7\%}_{-14\%}$ (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%)
$p_T^{\rm Veto} = p_T^{\ell_2}$	$2.0^{+4.4\%}_{-8.0\%}$ (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%)
$p_T^{\rm Veto} = S_T$	$2.8^{+6.2\%}_{-12\%}$ (94%)	$2.7^{+8.2\%}_{-7.7\%}$ (94%)	$2.4^{+8.9\%}_{-6.7\%}$ (> 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%)
$H_T^{\rm Veto} = p_T^{\ell_1}$	$2.2^{+7.4\%}_{-16\%}$ (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%)
$H_T^{\rm Veto} = p_T^{\ell_2}$	$1.5^{+4.9\%}_{-11\%}$ (51%)	$1.2^{+5.3\%}_{-5.4\%}$ (43%)	$1.5^{+7.7\%}_{-7.3\%}$ (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%)	$0.12^{+62\%}_{-81\%}$ (1.5%)
$H_T^{\rm Veto} = S_T$	$2.5^{+4.6\%}_{-13\%}$ (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 $p_T^{\text{Veto}} = 25$ 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 sensitivty to large mass splitting

- Worse for small mass splitting

- Other ratios show qualitatively opposite behavior [1901.09937]