Dynamic Jet Vetoes for Multi-lepton VBS(F) Searches [1]

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[1] w/ folks from Durham+Pittsburgh and NIKHEF+Paris

Big Picture and Driving Motivation

(brief and very biased)

Nonzero Neutrino Masses

Nonzero neutrino masses implies new degrees of freedom exist [Ma'98]:

$m_\nu \neq 0 + \text{LH currents}$

LH Majorana Mass : $m_\nu^L \overline{\nu_L} \nu_L^c$ and/or Dirac Mass : $m_\nu^D \overline{\nu_L} N_R$

$m_\nu^L = y\langle\Delta\rangle$ or strong dynamics

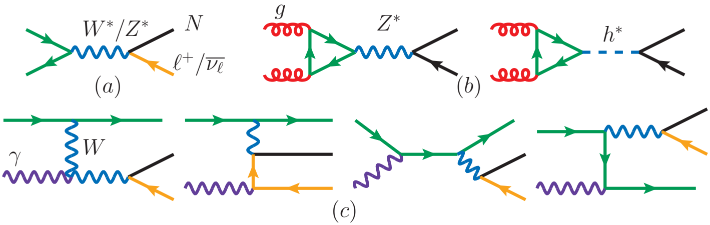
$m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$

$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\implies$ **new particles!**

- New particles might be charged under new or old gauge symm., e.g., N_R may have $U(1)_{B-L}$ charge and Δ_L is scalar $SU(2)_L$ triplet
- Particles must couple to h, L sector, often inducing LNV/cLFV!

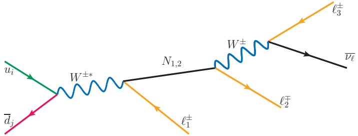
Heavy Neutrinos in Hadron Collisions[3]

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



$W\gamma$ fusion dominant mechanism for TeV-scale heavy neutrinos[2].

- Focus on inclusive 3ℓ final state:



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

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

Big Picture: Collider searches for LNV (same-sign ℓ + no met) / cLFV (opposite-flavor ℓ) are very sensitive since forbidden in SM.

Dominant backgrounds after typical selection criteria:
- jets mis-ID as leptons, leptons outside ID-threshold, etc.

Since 2012-13 ($WW + 0j$ saga), new ideas for jet vetoes[4] in Exotica, SUSY, etc., searches have appeared, with some remarkable ($> 10\times$) sensitivity improvement

[4] Notably work from Bern, DESY, Durham, NIKHEF, Louvain, MIT, Paris, + others

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Reenvisioning Jet Vetoes in BSM Searches :

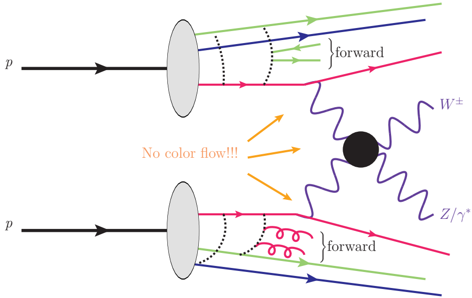
1. Problems with (central) jet vetoes in searches for colorless BSM
2. Resolution with some neat consequences
3. Outlook

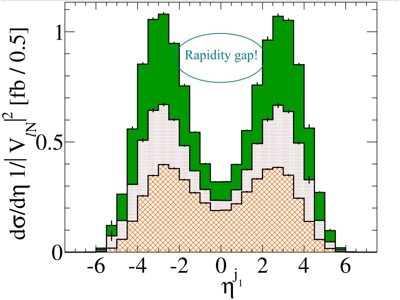
[4] Notably work from Bern, DESY, Durham, NIKHEF, Louvain, MIT, Paris, + others

(Central) Jet Vetoes

Abscence of central color flow in VBS

$\Longrightarrow$ absence of central, high-p_T jets ("rapidity gap"[5])





Basis for Central Jet Veto[6]:

- Reject events with any jet satisfying $p_T^j > 25 - 30$ GeV, $|\eta^j| < 2 - 3$
- Crucial to Higgs physics but not perfect...

[5] Dokshitzer, Khoze, Troyan ('86)

[6] Barger, et al, PRD44, 2701 ('91) + PLB346, 106 ('95); Bjorken ('94)

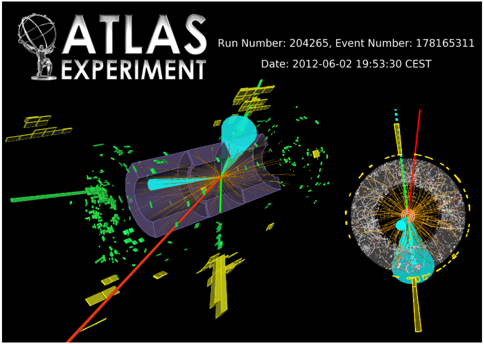
Three Imperfections

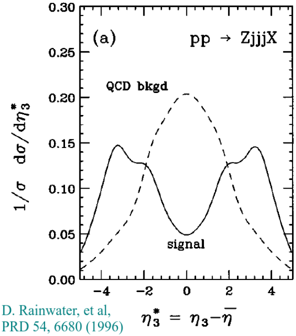
1. Central Vetoes vs Weak Boson Scattering

Despite rapidity gap, VBS **not immune** to central jet veto

- Central region for (VV)-system $\neq$ central region for lab-frame
- Motivation for alternative gap definitions[7], e.g., $\eta^* = \eta^{j_3} - \left(\frac{\eta^{j_1}+\eta^{j_2}}{2}\right)$

Example: 2012 VBF$\rightarrow h \rightarrow \tau_{had}\ \tau_{\mu}$ candidate with 1 very **central** j^{VBS}!





D. Rainwater, et al,
PRD 54, 6680 (1996)

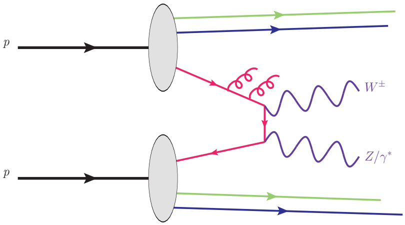
[7] Rainwater, Szalapski, Zeppenfeld, PRD54, 6680 (1996)

2. Static Vetoes vs $pp \to WW + 0j$

Difficulty with $pp \to WW + 0j$ is more technical, but more widespread:

- Analysis-quality jets (j_k) are "hard" and "central(ish)"
- $\implies$ $pp \to WW + 0j$ is inclusive with respect to $p_T^{j_k} < p_T^{\rm Veto}$

$$\sigma(WW + 0j) = \sigma(pp \to WW + X) - \sigma(pp \to WW + 1j + X)$$



Sensitivity to higher-order $\mathcal{O}(\alpha_s^k)$ terms grows if $p_T^{\rm Veto}$ too restrictive:

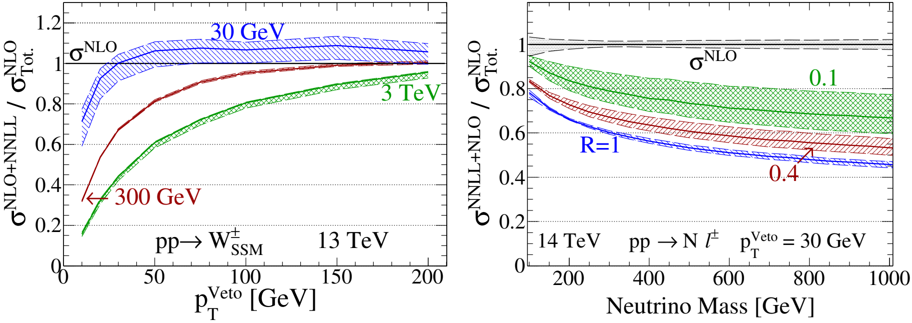
$$\sigma(WW + 1j + X) \sim \int \frac{dPS_1 \ \alpha_s}{(p_f + p_g)^2 (p_{f'} + p_g)^2} \sim \int \frac{\alpha_s \ \ d\cos\theta \ \ dE_g^2}{E_f E_g (1 - \cos\theta') \ \ E_{f'} E_g (1 - \cos\theta)}$$

$$\sim \int \frac{\alpha_s \ \ d\theta^2 \ \ dE_g^2}{\theta^2 \ \ E_g^2} \sim \alpha_s \log^2 (M_{WW}/p_T^{\rm Veto})^2 \to \infty, \text{ if } (M_{WW}/p_T^{\rm Veto}) \to 0$$

2.5 Static Vetoes vs Mass[8]

Plotted: veto efficiency $\varepsilon(p_T^j < p_T^{\rm Veto}) = \sigma^{\rm NLO+NNLL} \;/\; \sigma^{\rm NLO}$ for

(L) SSM $pp \to W'$ ($M_{W'} = 30 - 3000$ GeV) (R) $pp \to N\ell$



- Significant dependence on hard scale / mass scale
- Utility of jet veto unclear when $p_T^{\rm Veto} \gtrsim 60 - 70$ GeV due to top quarks

[8] w/ Fuks [1701.05263] and w/ Pascoli, et al [1805.09335, 1812.08750]

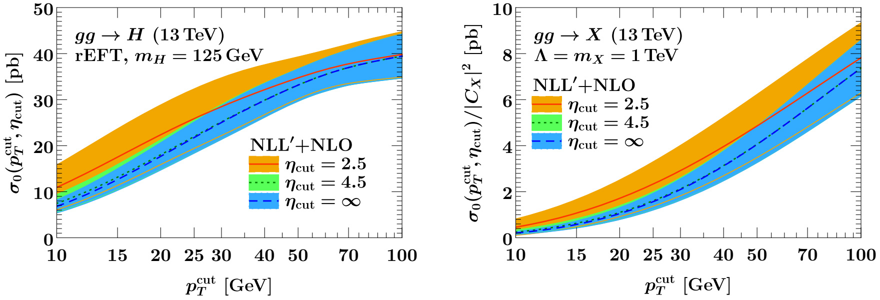
3. Central Vetoes vs Higgs+0j

Often, jet vetoes are restricted to $|\eta^j| < \eta^{\text{cut}}$, where $\eta^{\text{cut}} \approx 2.4$

- smaller η^{cut} $\implies$ less sensitivity pile up
- $\implies$ larger sensitivity to higher-order $\mathcal{O}(\alpha_s^k)$ terms

Until recently[9], analytic calculations implicitly assumed $\eta^{\text{cut}} \to \infty$

- For $pp \to H + 0j$, slight change in σ, but big change to uncertainty



[9] very nice study by Michel, Pietrulewicz, and Tackmann [1810.12911]

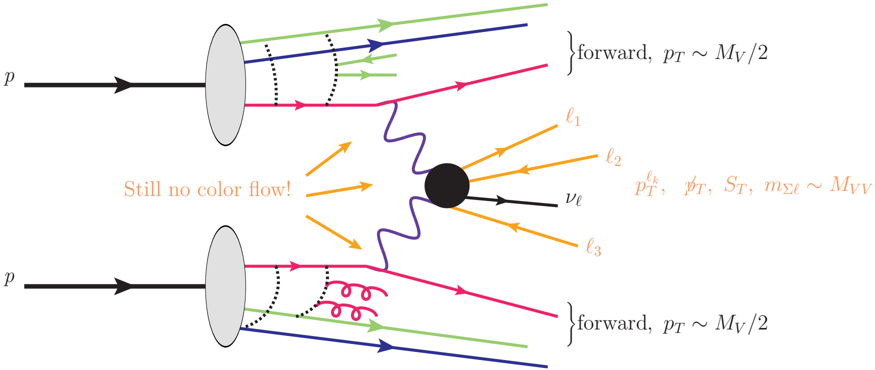
Dynamic Jet Vetoes[10]:

Reenvisioning the Jet Veto

[10] w/ Pascoli, et al [1805.09335]

Leptons in Vector Boson Scattering

For production of leptons in VBS: $p_T^{\ell_k},\ S_T\ \sim M_{VV} \gg p_T^{j_{VBS}} \sim M_V/2$



[11] Inspired by CMS using the ratio $r_j^\ell = (p_T^\ell / p_T^j)$ for lepton isolation [1701.06940]

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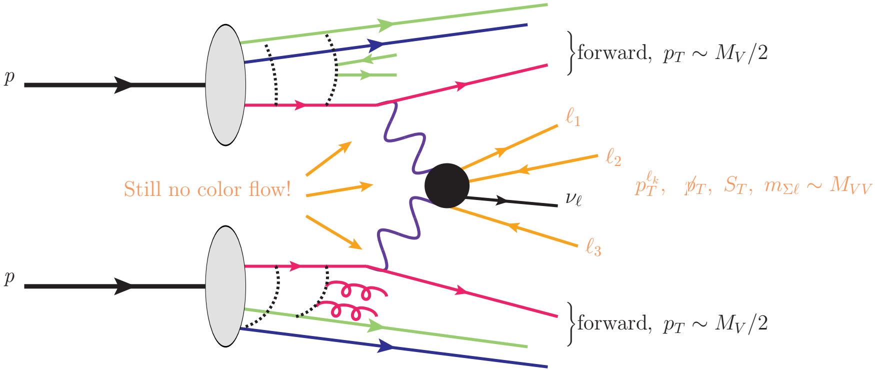


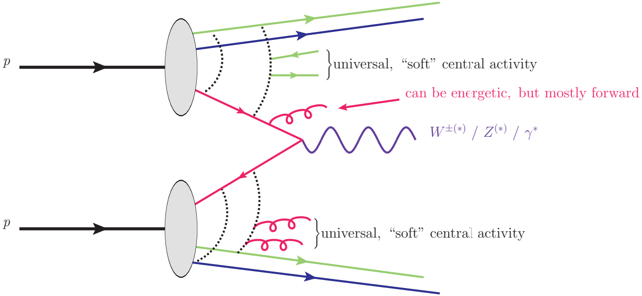
An idea[11]: on event-by-event basis, set $p_T^{\rm Veto} = p_T^{\ell_1}$

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

[11] Inspired by CMS using the ratio $r_j^\ell = (p_T^\ell / p_T^j)$ for lepton isolation [1701.06940]

Leptons in High-Mass Drell-Yan and Gluon Fusion

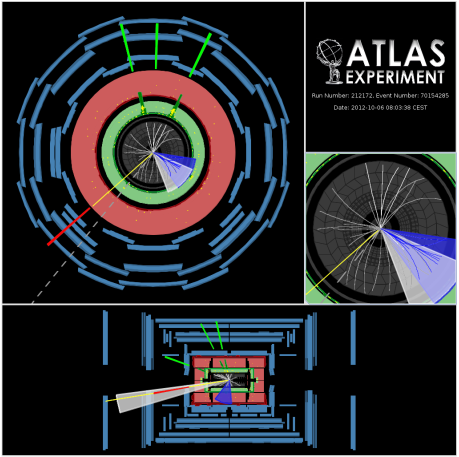
For production of leptons in DY: $p_T^{\ell_k},\ S_T\ \sim Q \gg p_T^j \sim$ Sudakov shoulder



On event-by-event basis, set $p_T^{\mathrm{Veto}} = p_T^{\ell_1}$

- High-mass, DY- and GF-type processes pass by construction
- Since $(Q/p_T^{\mathrm{Veto}}) \sim 1$, higher-order jet veto logarithms negligible
- What about other background processes, e.g., top quarks?

Top Quark Background vs Dynamical Jet Vetoes



$pp \to t\bar{t}Z \to 1\mu + 3e + 2j_b + \not{E}_T$ candidate event [1509.05276]

Classic kinematics:

- $m_{ee} = 93$ GeV
- $\not{E}_T = 57$ GeV

Typically,

- $p_T^{e_1} \sim \frac{m_t}{4}(1 + \frac{M_W^2}{m_t^2}) \sim 50$ GeV
- $p_T^{e_3} \sim \frac{M_Z}{2} \sim 45$ 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 eliminate top background ***without*** *b*-jet tagging!

Jet Vetoes and SM Backgrounds

Associated Top Quark Production: $pp \to t\bar{t}\ell\ell,\ t\bar{t}\ell\nu,\ tq\ell\ell$

- Typical p_T of lepton from top: $p_T^\ell \sim \frac{m_t}{4}(1 + \frac{M_W^2}{m_t^2}) \sim 50$ GeV
- Typical p_T of b from top: $p_T^b \sim \frac{m_t}{2}(1 - \frac{M_W^2}{m_t^2}) \sim 65$ GeV
- $p_T^\ell < p_T^b \implies$ top events vetoed without need of b-tagging

Fake Leptons:

- Low-p_T jet (in $t\bar{t}$ events) identified as $e^\pm$ or $\tau^\pm$
- Low-p_T charged $\ell^\pm$ from weak decays of hadrons (in $t\bar{t}$ events)
- Color conservation $\implies$ second jet with comparable p_T likely exist

Electroweak Production[12]: $pp \to 4\ell,\ 3\ell\nu, WWW,\ WW\ell\ell$

- Jet veto $\implies$ EW bosons at rest since no recoil
- Typical $S_T \equiv \sum_\ell |\vec{p}_T^{\,\ell}|$ for $3W$ or WZ: $S_T \sim \frac{3M_V}{2} \sim 120 - 130$ GeV

[12] **Note:** by itself, a dynamic jet veto is **not** a "silver bullet"

Proof of Concept I:

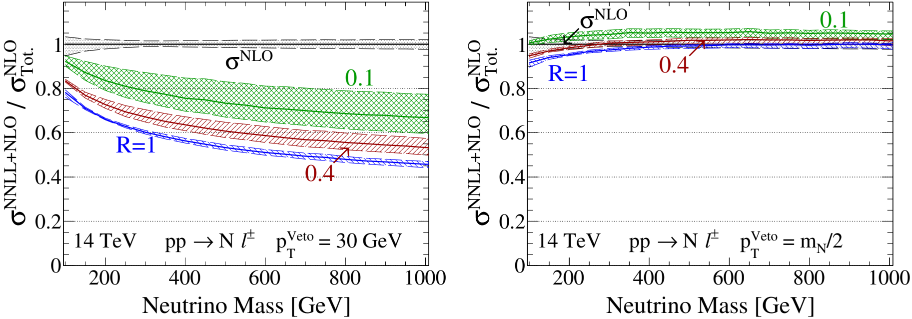
LHC Searches for Heavy Sterile Neutrinos[13]

[13] w/ Pascoli, etc, 8pg letter [1805.09335], 99pg analysis [1812.08750]

Static Vetoes vs Dynamic Vetoes vs Mass

Plotted: veto efficiency $\varepsilon(p_T^j < p_T^{\text{Veto}}) = \sigma^{\text{NLO+NNLL}} \ / \ \sigma^{\text{NLO}}$

for $pp \to N\ell$ with (L) $p_T^{\text{Veto}} = 30$ GeV (R) $p_T^{\text{Veto}} = \frac{m_N}{2} \sim p_T^{\ell 1}$



- Sensitivity to higher order α_s^k reduced since veto logarithms scale as $\alpha_s \log^2(m_N/p_T^{\text{Veto}})^2 \sim \alpha_s \log^2(4) \sim \frac{4}{10} \ll 1$
- veto dependence on mass scale jet radius largely vanish

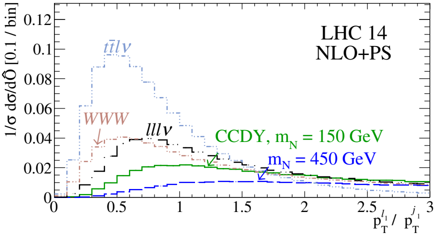
Leptons vs Hadrons I

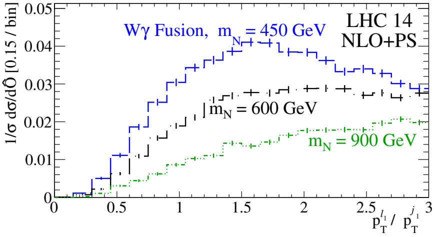
The proposed jet veto scheme descriminates leading j activity against leading ℓ activity. Is this even sensible?

Consider the collider signature $pp \to 3e/\mu + X$ at NLO+PS(LL)

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

Plotted: $r_{j_1}^{\ell_1} = p_T^{\ell_1}/p_T^{j_1}$ for (L) DY signal + SM Bkg and (R) $W\gamma$ fusion





Separation between SM and BSM is clear

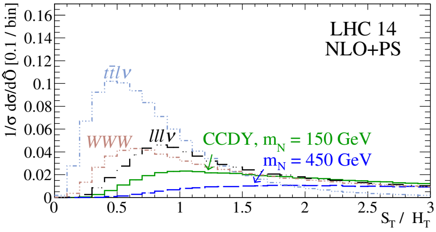
- Fine, but what about other measures of lep. and had. activity?

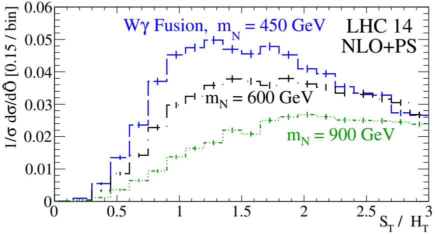
Leptons vs Hadrons II

Leading p_T measures local activity. Global measures include

$$\text{Leptons:} \quad S_T^{\text{Excl.}} = \sum_{k=1}^{3} |\vec{p}_T^{\,\ell_k}|, \quad \text{where } p_T^{\ell_k} > p_T^{\ell_{k+1}}$$
$$\text{Hadrons:} \quad H_T^{\text{Incl.}} \approx \sum_{k\in\{\text{clusters}\}} |\vec{p}_T^{\,j_k}|, \quad \text{for } |\eta^{j_k}| < 4.5$$

Plotted: $r_{H_T}^{S_T} = S_T^{\text{Excl.}}/H_T^{\text{Incl.}}$ for (L) DY signal + SM Bkg and (R) $W\gamma$





Similar behavior to $r_{j_1}^{\ell_1}$, but we will come back to this (or see [1901.09937])

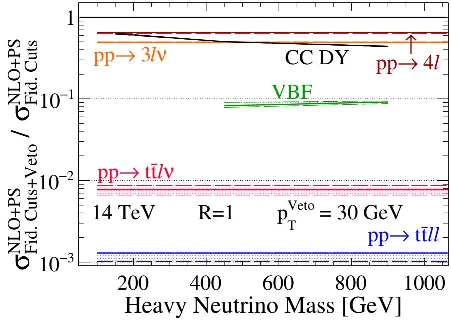
Leptons vs Hadrons III

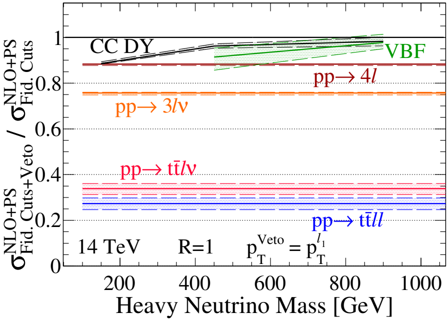
Static jet vetoes $\implies$ poor signal efficiency for high-mass BSM

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

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

for (L) Veto if $p_T^j > 30$ GeV (R) Veto if $p_T^j > p_T^{\ell_1}$



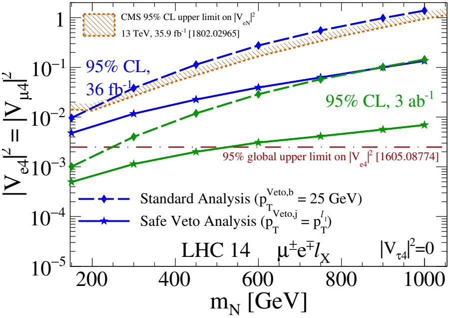


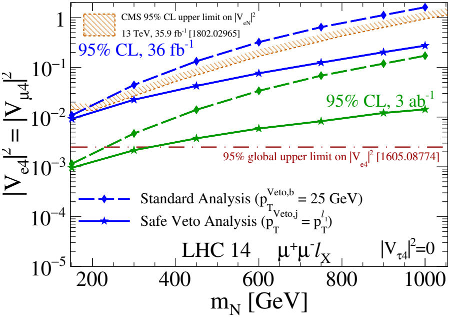
Background grows, too, but with additional lepton cuts, dynamic $\gg$ static

Discovery Prospects

Signal I: $pp \to \mu^{\pm} e^{\mp} \ell_X$+MET and **Signal II:** $pp \to \mu^{+} \mu^{-} \ell_X$+MET

Plot: LHC 14 sensitivity to (coupling)^2 vs heavy neutrino mass





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

- Dash = standard search[14] with b-jet veto (13 TeV CMS for e/μ)
- Solid = "improved" analysis with special type of jet veto

[14] More aggressive cuts on individual leptons: e.g., $p_T^{\ell_1} > 55$ GeV, $m_{3\ell} > 80$ GeV

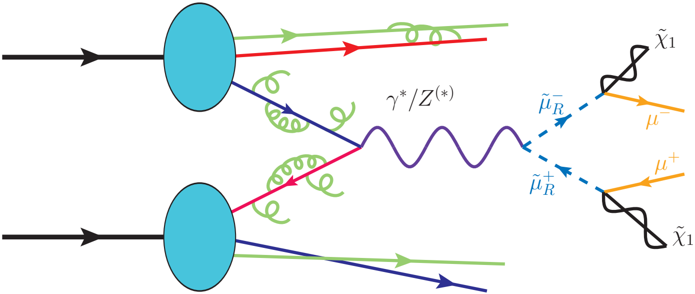
Generalizing Dynamic Jet Vetoes:

Sleptons vs Hadrons[15]

[15] w/ Fuks, Nordstrom, & Williamson [1901.09937]

Sleptons without Hadrons

Clear from heavy neutrino study that a dynamic jet veto can improve slepton searches



Decided to have fun and explore alternative measures of hadronic vs leptonic activities
- Generalizing definition of a dynamic jet veto

Leptons vs Hadrons IV

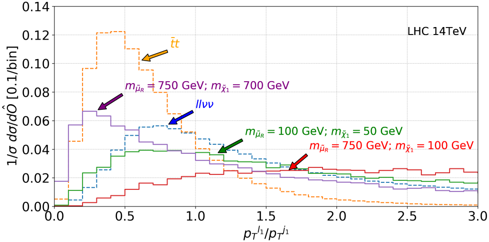
Consider the signature $pp \to \mu^+\mu^- + X$ at NLO+PS(LL)

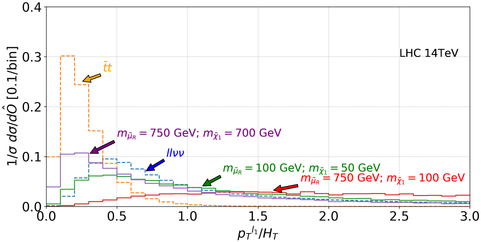
- Generator cuts $+ \; p_T^\ell > 15$ GeV $+ \; |\eta^\ell| < 2.4$ + anti-$k_T(R = 1)$

- (top) $r_{j_1}^{\ell_1} = p_T^{\ell_1} / p_T^{j_1}$

- (bottom) $r_{H_T}^{\ell_1} = p_T^{\ell_1} / H_T$

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



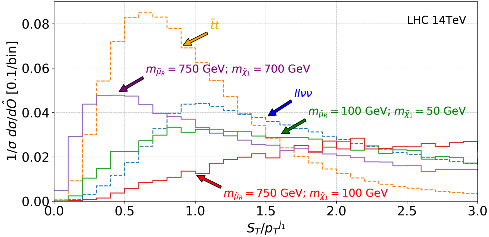


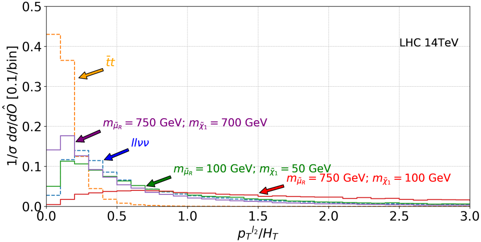
Leptons vs Hadrons V

Some choices were rubbish (top), others were fantastic (bottom)

- (top) $r_{j_1}^{S_T} = S_T / p_T^{j_1}$
- (bottom) $r_{H_T}^{\ell_2} = p_T^{\ell_2} / H_T$

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





Improved Discovery Prospects

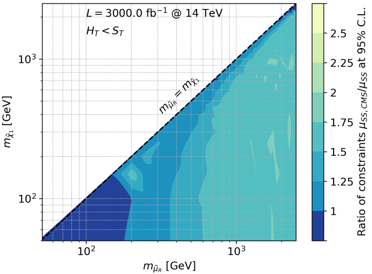
As a benchmark analysis, we considered CMS's Run II search, which uses $p_T^{\text{Veto}} = 25$ GeV for $|\eta^j| < 2.4$ [1806.05264]

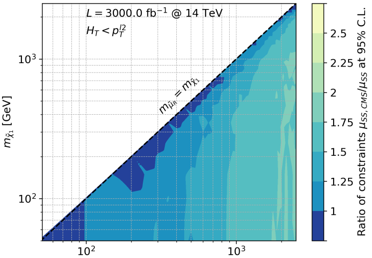
No attempt to optimize cuts:
- Relaxed $p_T^{\ell_k}$ cuts
- swapped static veto for dynamic

Improvement was clear (lighter $\implies$ improvement)

- (top) $H_T^{\text{Veto}} = S_T$
- (bottom) $H_T^{\text{Veto}} = p_T^{\ell_2}$

Using H_T and $p_T^{\ell_k}$ give better improvement





Summary and Next Steps

A class of jet vetoes has been developed for high-mass, multi-ℓ searches, one based on comparing lepton vs hadronic activities, e.g., $H_T^{\mathrm{Veto}} = p_T^{\ell_1}$

- New scheme reveals $> 90 - 95\%$ signal acceptance with little-to-no dependence on mass scales (contrary to previous schemes)
- Substantial reduction in QCD theory uncertainty
  $\Longrightarrow$ less need for high-precision resummation
- Redesigned search analysis gives better reduction of background

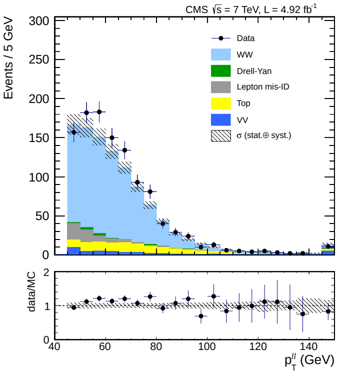
Application to new physics searches appears very promising:

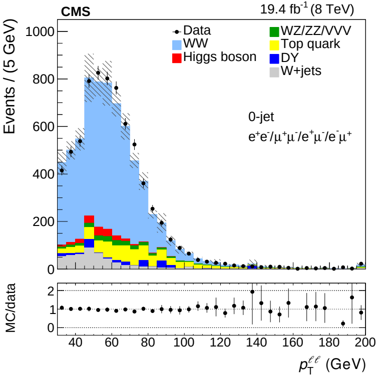
- Sterile neutrinos: improved sensitivity $\sim 10 - 11\times$
- Sleptons: setting p_T^{Veto}, $H_T^{\mathrm{Veto}} = p_T^{\ell_k}, S_T$ reveal generic improvement
- **To Do:**Check impact of MPI and add'l uncertainties
- **To Do:**Rapidity dependencies?

Thank you.

Backup I: Jet Vetoes in LHC Collisions

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





- During Run I, ATLAS and CMS [1306.1126; 1507.03268] consistently disagreed with SM predictions for $pp \to WW + 0j$
- Did not "go away" with more data, was not statistical
- Resolved by noting little suppression of ultra-low p_T QCD radiation
  - Add appropriate terms $\Longrightarrow$ excellent theory control over jet vetoes!