Event-Dependent Jet Vetoes: New prospects for multi-lepton, LHC searches [1]

PSR 2019 - Universität Wien

Richard Ruiz

Center for Cosmology, Particle Physics, and Phenomenology (CP3)
Universite Catholique de Louvain

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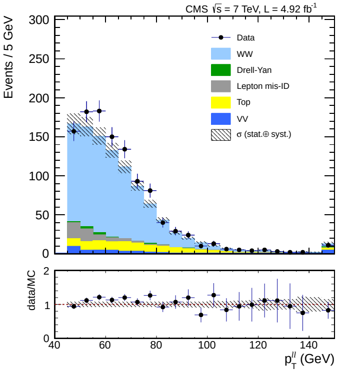
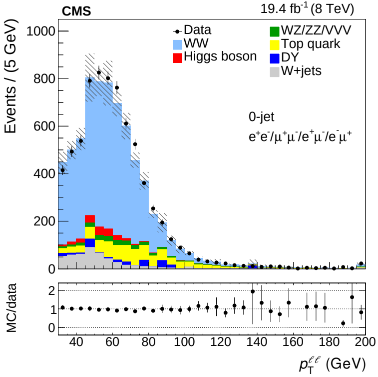
[1] w/ folks from Durham+Pittsburgh and NIKHEF+Paris

Disclaimer

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

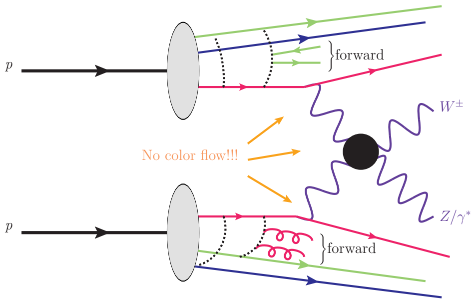


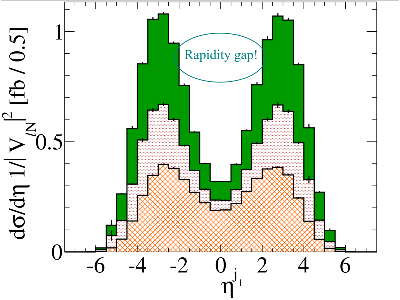


- During Run I, ATLAS and CMS [1306.1126; 1507.03268] consistently disagreed with SM predictions for $pp \to WW + 0j$
- Resolved by accounting for ultra low p_T gluon emission
  - Resolved due to major work by greater PSR community!
  - Too many papers to cite here, but please email if not cited in papers!

(Central) Jet Vetoes

Abscence of central color flow in EW Boson Scattering $\implies$ absence of central, high-p_T jets ("rapidity gap"[2])





Basis for Central Jet Veto[3]:

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

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

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

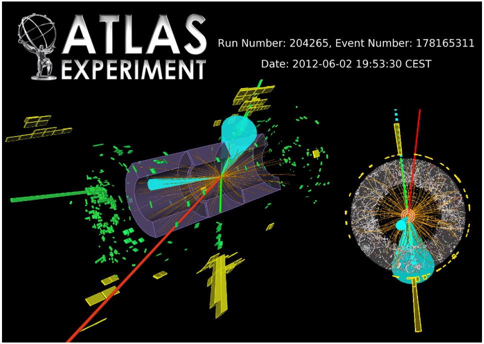
Three Imperfections

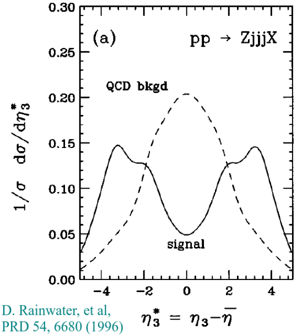
1. Central Vetoes vs Weak Boson Scattering

Rapidity gap $\neq$ 100% jet veto survival rate

- Central region for (VV)-system $\neq$ central region for lab-frame
- Motivation for alternative gap definitions[4], 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)

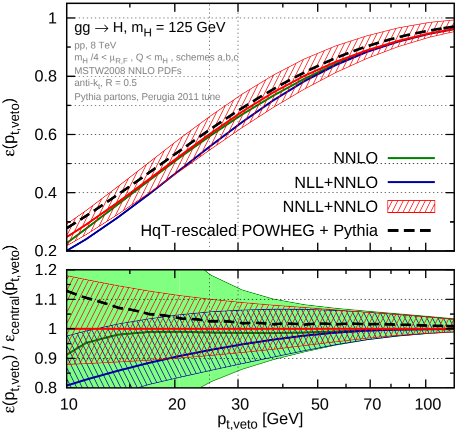
[4]Rainwater, Szalapski, Zeppenfeld, PRD ('96)

2. Tight Vetoes vs Gluon Fusion

For $pp \to h + 0j$, large uncertainty ***despite*** precision

In practice, ATLAS/CMS veto "analysis quality" jets

- = "hard," "central(ish)" clusters
- inclusive to activity that is soft/forward w.r.t. hard process
- restrictive veto predictions are more sensitive to missing higher order soft/forward emissions

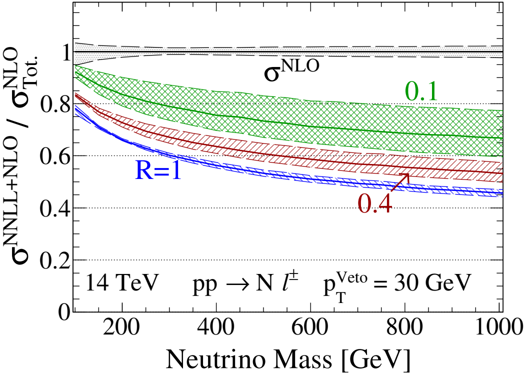


manifests as large logs / scale unc.
e.g., Banfi, et al [1203.5773,1206.4998]

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

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

Plotted: veto efficiency[5] $\varepsilon = \sigma^{\rm NLO+NNLL}(p_T^{\rm Veto}) \ / \ \sigma^{\rm NLO}_{\rm Tot.}$ for $pp \to N\ell$[6]



R=jet size

- Is a veto even useful when $p_T^{\rm Veto} \gg 20-30$ GeV due to top quarks?

[5] a la automated resummation with mg5amc@nlo+scet by Becher, et al [1412.8408]

[6] Pascoli, RR, et al [1805.09335, 1812.08750], but ditto for sleptons, Tackmann, et al, [1603.03052], and SSM W'/Z', Fuks, RR [1701.05263]

What do we want from a jet veto?

Our cake and to eat it too!

1. High signal efficiency
2. High background rejection
3. Low/less sensitivity to missing higher order corrections

Event-Based[7] Jet Vetoes[8]:

Reenvisioning the Jet Veto[9]

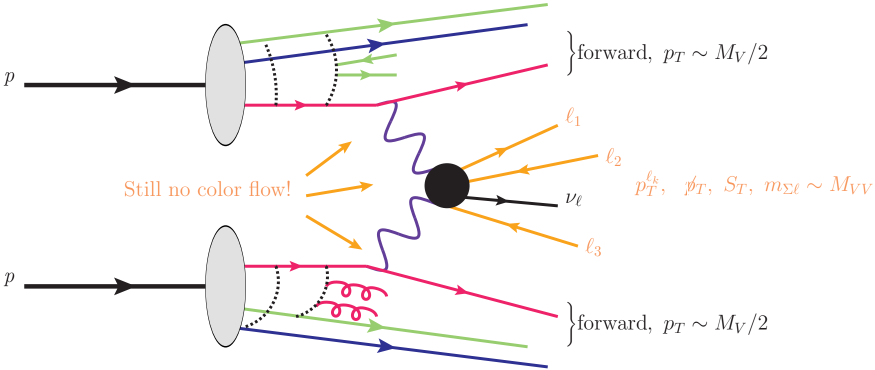
[7] aka: "safe jet veto," "dynamic jet veto," or "phase space-dependent jet veto"

[8] **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)

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

Leptons in Vector Boson Fusion

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



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

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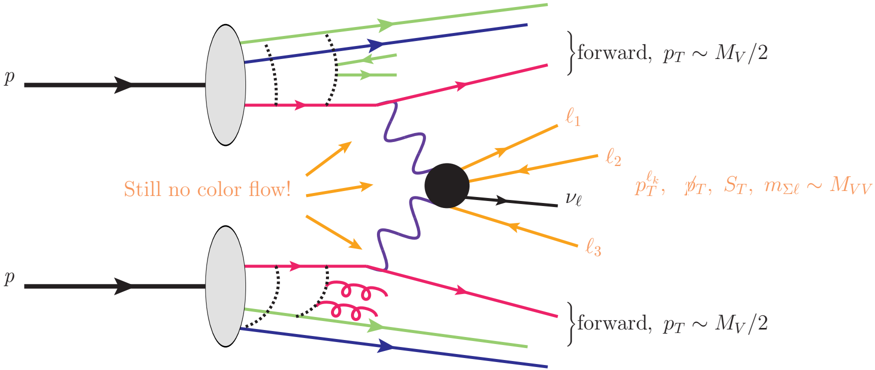


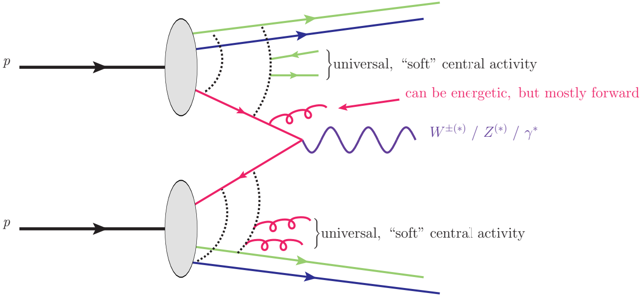
An idea[10]: on event-by-event basis, set $p_T^{\rm Veto} = p_T^{\ell_1}$

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

[10] 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

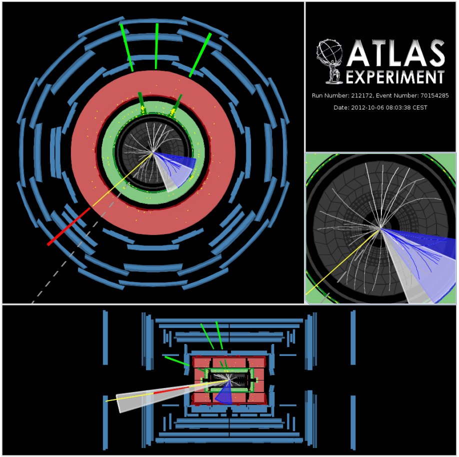
For leptons in high-mass DY: $p_T^{\ell_k},\ S_T\ \sim M_{V^*} \gg p_T^j \sim$ Sudakov shoulder



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 $(M_{V^*}/p_T^{\mathrm{Veto}}) \sim 1$, 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

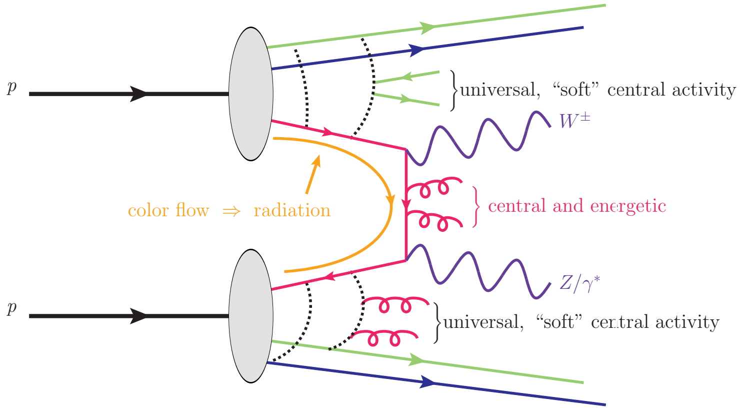
$p_T^{b_1} > p_T^{\ell_k} \implies$ event vetoed!

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

Diboson and Triboson Processes

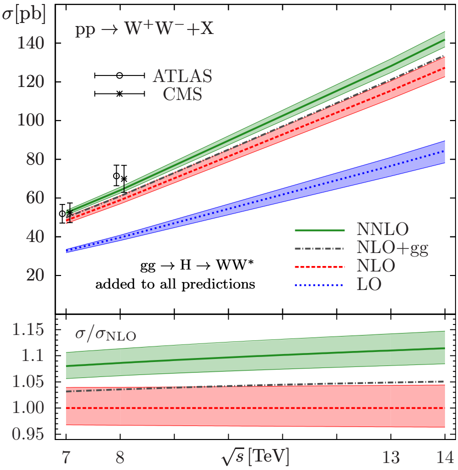
Di- / triboson processes contain large amounts of hadronic activity

- Significant cancelations in Born-like configurations[11]
- Nontrivial color flow, despite naïve, color-singlet nature



[11] 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)

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

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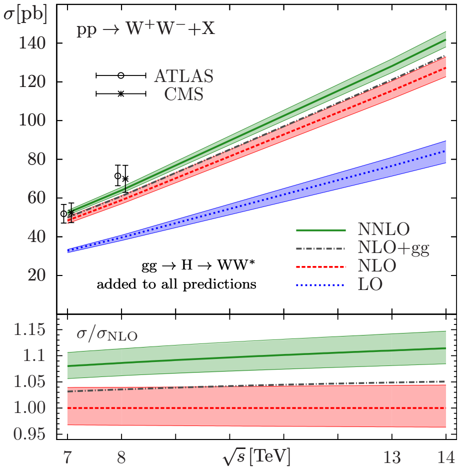

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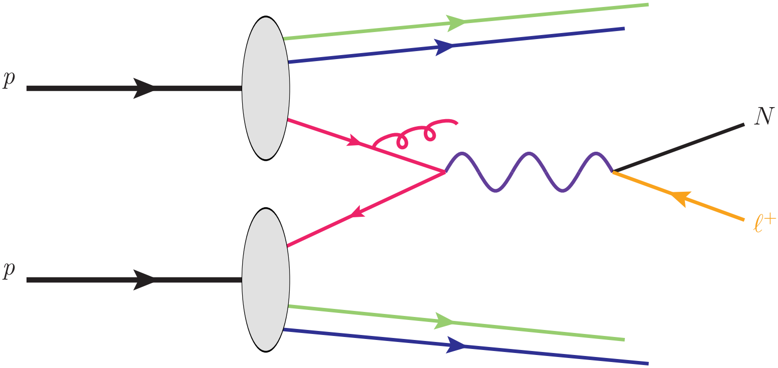
Jets mistagged/IDed as τ_h/e, i.e., "fake leptons," major irreducible bkg:
- E.g., $pp \to W^+W^-j$
- Subleading jets more likely to be mis-IDed than leading jet

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

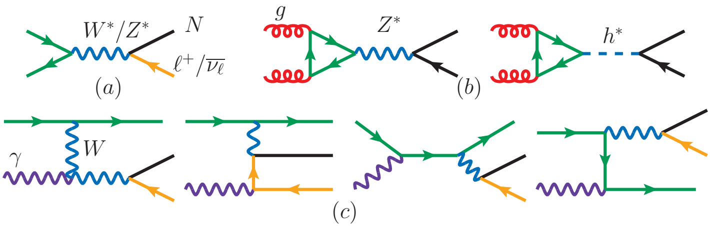
Case Study I:
Heavy Neutrinos at the LHC[12]



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

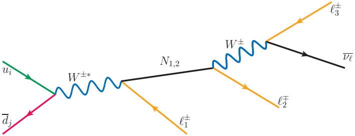
Heavy Neutrinos at Hadron Colliders[14]

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



$W\gamma$ fusion dominant mechanism for TeV-scale heavy neutrinos[13].

- Focus on inclusive 3ℓ final state:



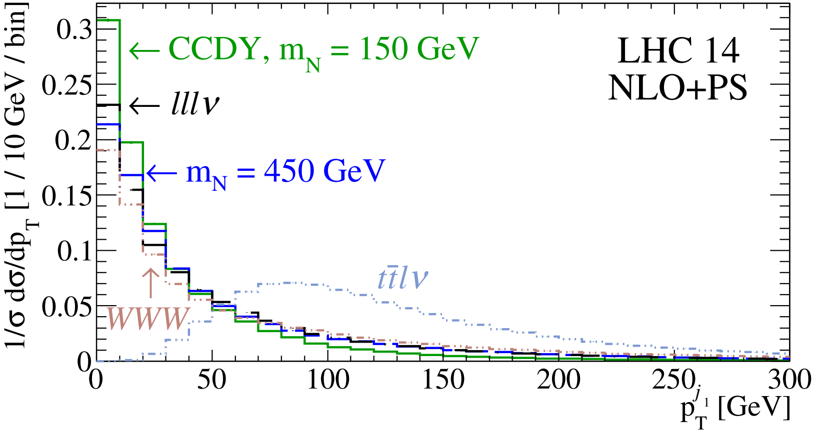
[13] Alva, Han, RR [1411.7305]; Degrande, Mattelaer, RR, Turner [1602.06957]

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

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

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

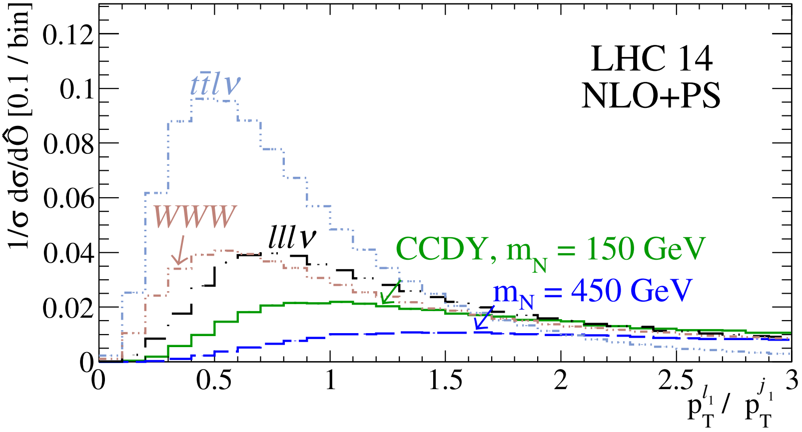
Plotted: $p_T^{j_1}$ for CC DY signal + SM Bkg



Separation according to Born color clear but more overlap for larger m_N

Event-based jet vetoes descriminate 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



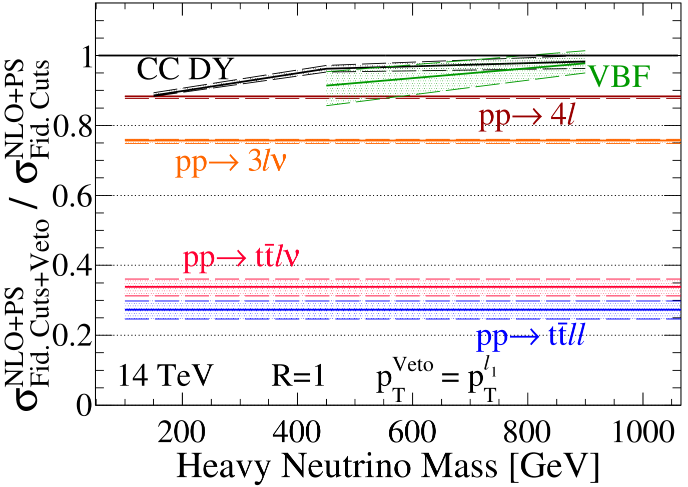
Similar behavior for other ratios, e.g., S_T/H_T, $p_T^{\ell_k}/H_T$

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

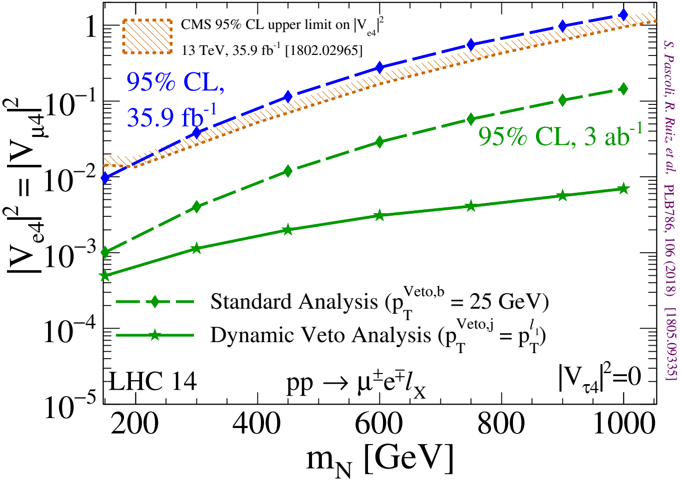
Static jet vetoes $\Longrightarrow$ poor signal efficiency for high-mass BSM

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

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



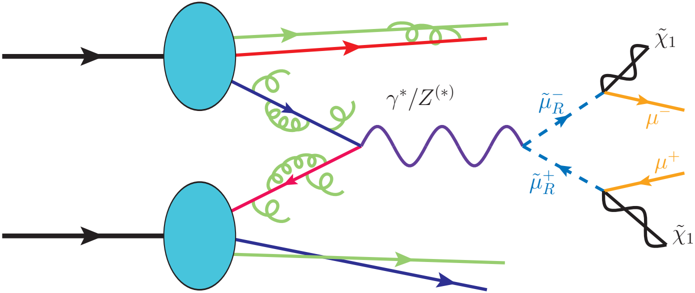
Plot: LHC 14 sensitivity to active-sterile neutrino mixing (coupling^2) vs heavy N mass (m_N), in search for $pp \to \mu^\pm e^\mp \ell_X + X \quad (\ell_X = e, \mu, \tau_h)$[15]



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

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

Case Study II:
sleptons and generalizing event-based jet veto definitions[16]



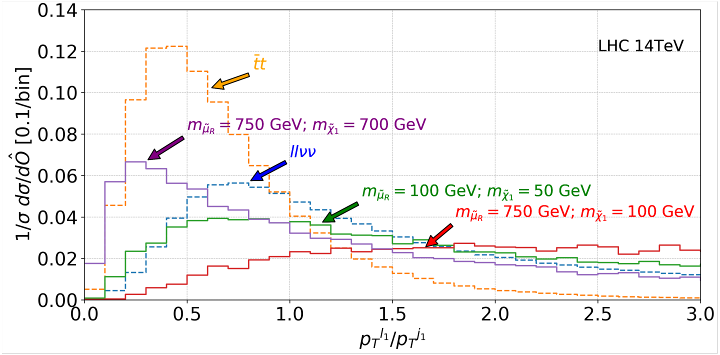
[16] Fuks, Nordstrom, RR, Williamson [1901.09937]

Leptons vs Hadrons Redux

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

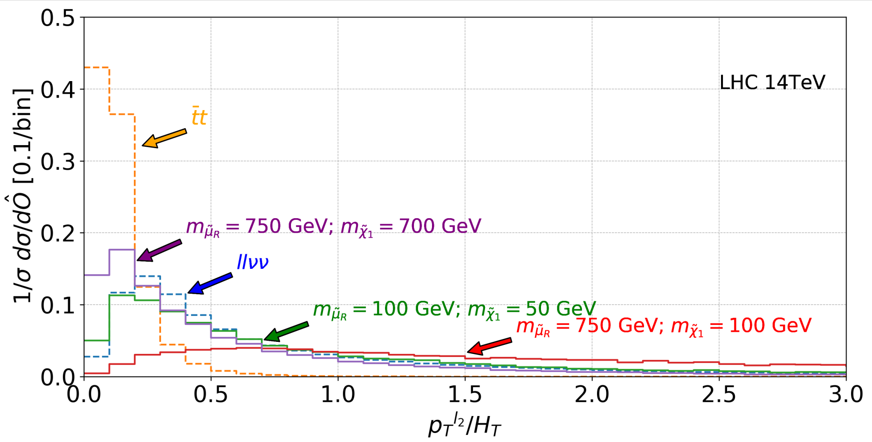
- Generator cuts + $p_T^\ell > 15$ GeV + $|\eta^\ell| < 2.4$ + anti-$k_T(R = 1)$

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 $p_T^{\rm Veto} = p_T^{\ell_1}$ is not best ratio :)

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

As a benchmark, we considered CMS's Run II search [1806.05264]

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

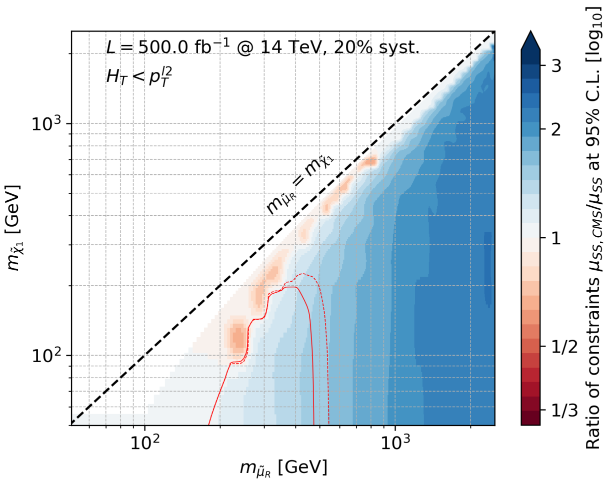
Plot: Sensitivity change using $H_T^{\rm Veto} = p_T^{\ell_2}$ in $(m_{\tilde{\chi}}, m_{\tilde{\mu}})$-space

darker = improvement

- Improved sensitivty to large mass splitting

- Worse for small mass splitting

- Other ratios show qualitatively opposite behavior [1901.09937]



What do we want from a jet veto?

Our cake and to eat it too!

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

1. High signal efficiency ✓
   - New scheme reveals $> 90 - 95\%$ signal acceptance with little-to-no dependence on mass scales [1805.09335]
2. High background rejection ✓
   - Redesigned analysis gives better reduction of background
3. Low/less sensitivity to missing higher order corrections ✓
   - Substantial reduction in QCD theory uncertainty
     $\Longrightarrow$ less need for high-precision resummation [1812.08750]
4. Universality ✗
   - Collider signature and param space dependence [1901.09937]
5. Analytical Control ✗
   - Resummation beyond parton shower-precision less clear

Thank you.

Backup I: The Monte Carlo Campaign

Jet vetoes are nonstandard selection cuts and make MC generation tricky

- **Need**: reliable description of ***leading*** jet at all p_T for signal (color-singlet) and background
- **Need**: "jets" (resummation/parton shower + jet definition) $\Longrightarrow$ cannot apply veto at same time as other cuts
- **Need**: inclusive samples since bkgs include $\ell^\pm$ outside fid. volume

Moto: "We start at NLO"

1. Event Generation: `HeavyN@NLO` UFO [17] + MadGraph5_aMC@NLO
   - Bare-bones, gen-level cuts on leptons + MadSpin for decay
2. Shower: Pythia8.2 (w/ QED shower + recoil + Monash* Tune+had.)
3. Particle-level clustering:[18] MadAnalysis5 + FastJet($R = 1$, anti-k_T)
4. Smearing + fiducial cuts / offline analysis: private ROOT code
5. Only at this point can veto be applied

[17] Degrande, Mattelaer, RR, et al [1602.06957]; same as CMS [1802.02965]
[18] See W'+jet veto analysis, Fuks, RR [1701.05263]