Vetoing Tops without B-Tagging [1]
EPS 2019 - Ghent University

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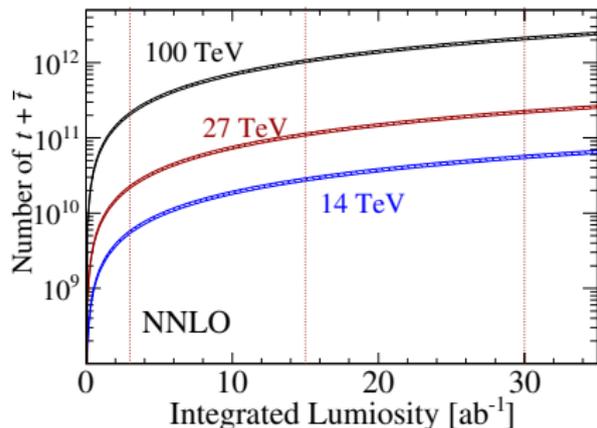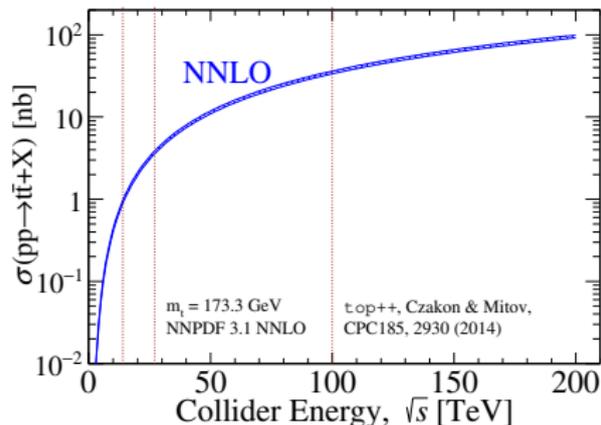Universite Catholique de Louvain

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UCLouvain

Motivation

Inclusive production rate of top quarks at hadron colliders is, well, **big**...

- The LHC generates $L \sim 1 \text{ fb}^{-1}/\text{day} \implies 1\text{M } t\bar{t}$ pairs/day
  - Single- / pair-production background to **all** measurements and searches
- **Subtle bit**: standard tools, i.e., b-tagging, are not perfect
  - $\varepsilon^b \sim 0.7 \implies 10\%$ top pairs survive cull
  - Actually $> 10\%$ since b-tagging requires: $|\eta^j| \lesssim 2.5$, $p_T^j > 25 - 30$ GeV
- **Question**: Can such "irreducible backgrounds" be further reduced?

Revisiting an Old Idea:

(Central) Jet Vetoes

In color-singlet processes, like weak boson scattering:

Abscence of central color flow

$\implies$ absence of central, high-p_T jets ("rapidity gap"[2])
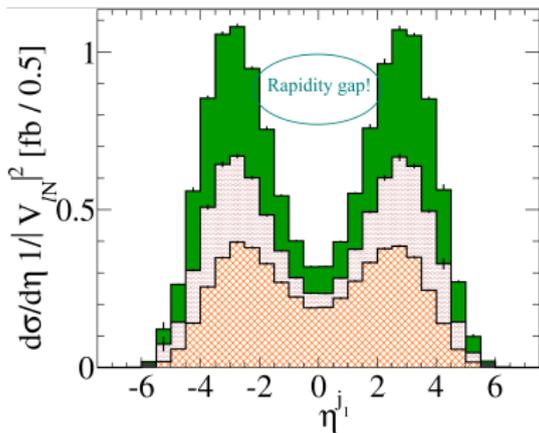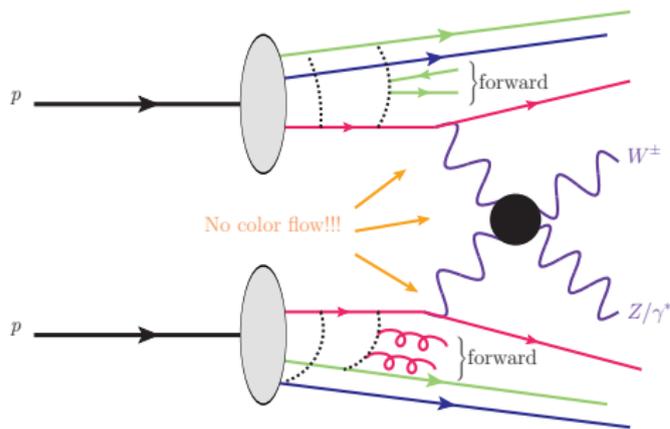
Basis for Central Jet Veto[3]:

- 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)

Limitations of Jet Vetoes

1. Almost uniquely, top are a background **all**[4] measurements + searches
   - heavy quark flavor- / b-vetoing is very good but not perfect

2. Tight/stringent, central jet vetoes can alleviate this, but at cost of sensitivity to missing higher order corrections[5]
   - Substantial pQCD theory uncertainty despite high precision

3. Low signal efficiency for colorless, high-mass BSM[6]
   - At pp colliders, even the most exotic, colorless BSM is accompanied by high-p_T, initial-state radiation

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[4]Literally, just listen to any ATLAS or CMS person about their analysis

[5]E.g., the pQCD/hep-ph literature on jet vetoes on [InSpireHep]

[6]For example: Sleptons by Tackmann, et al, [1603.03052]; SSM W'/Z' by Fuks, **RR** [1701.05263]; and heavy neutrinos by Pascoli, **RR**, et al [1805.09335, 1812.08750]

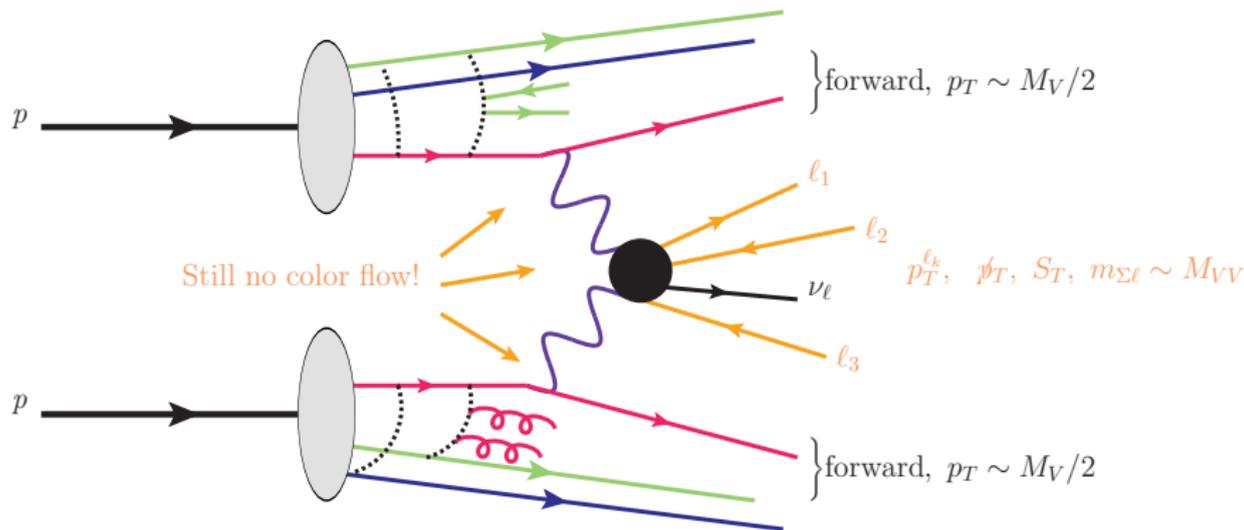**Reenvisioning[7] the Jet Veto:**

Event-Based[8] Jet Vetoes

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[7]Pascoli, **RR**, et al [PLB ('18), 1805.09335]
[8]aka: "safe jet veto," "dynamic jet veto," or "phase space-dependent jet veto"
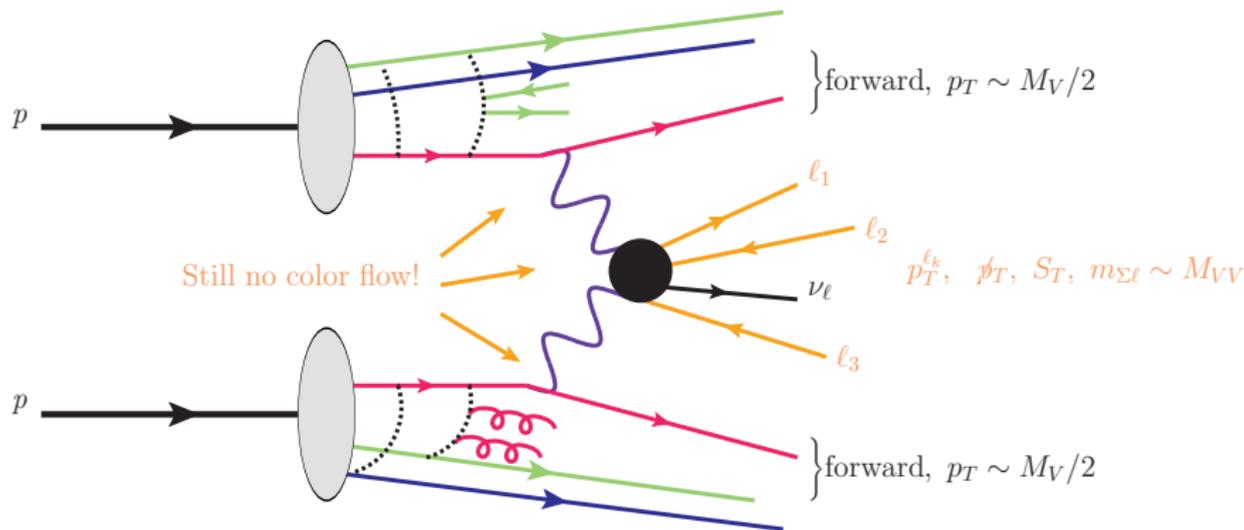
Leptons in Vector Boson Fusion

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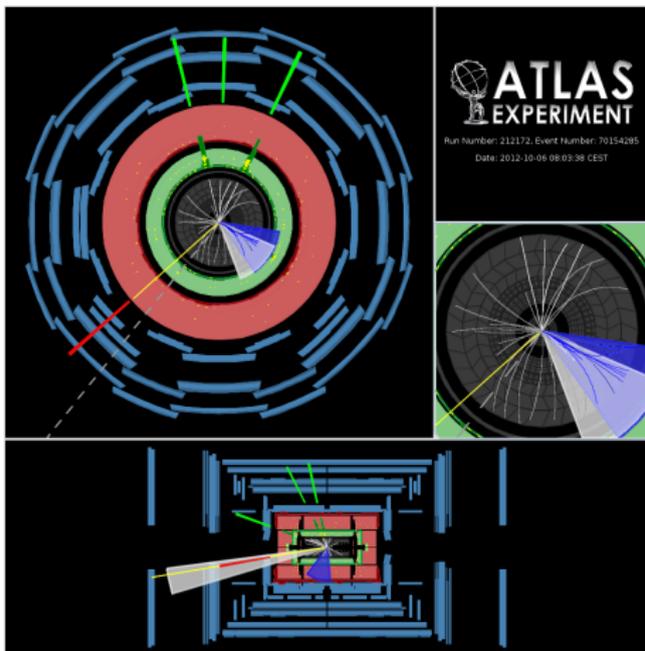
Leptons in Vector Boson Fusion

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

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: $p_T^{\ell_k}$, $S_T \sim M_{V^*} \gg p_T^j \sim$ Sudakov shoulder

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 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
- $p_T^{e_1} \sim \frac{m_t}{4}\left(1 + \frac{M_W^2}{m_t^2}\right) \sim 50$ 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!
- Di-/triboson backgrounds nontrivially impacted, too! [Backup slides]

Case Study I:
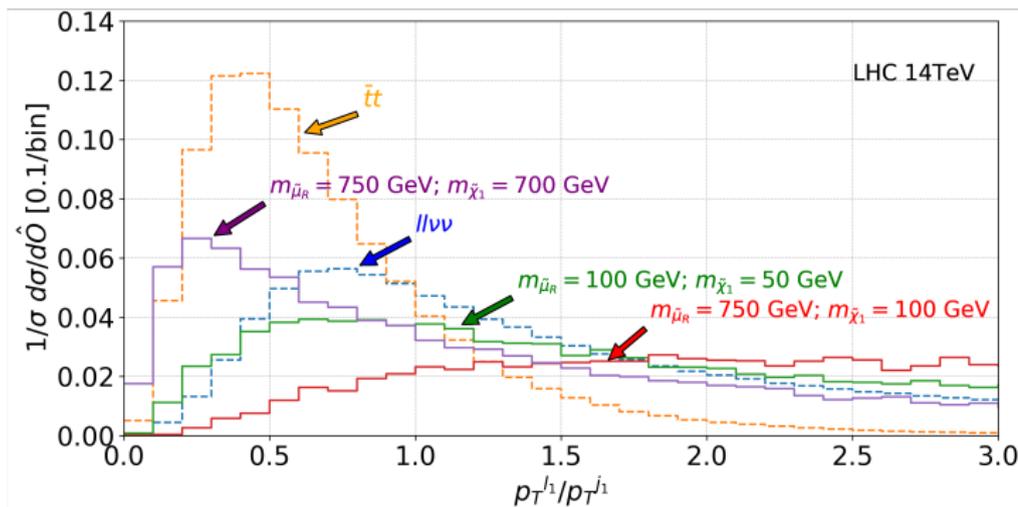### sleptons and generalizing event-based jet veto definitions[9]
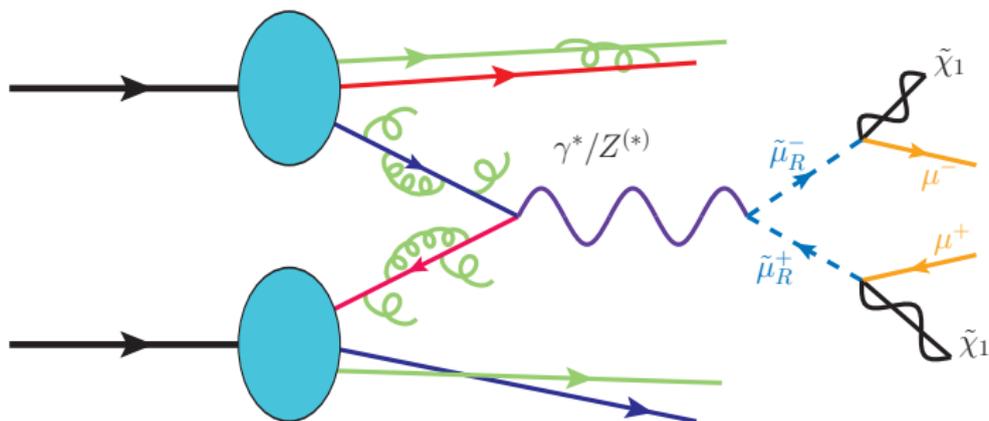
[9]Fuks, Nordstrom, RR, Williamson [1901.09937]

Leptons vs Hadrons

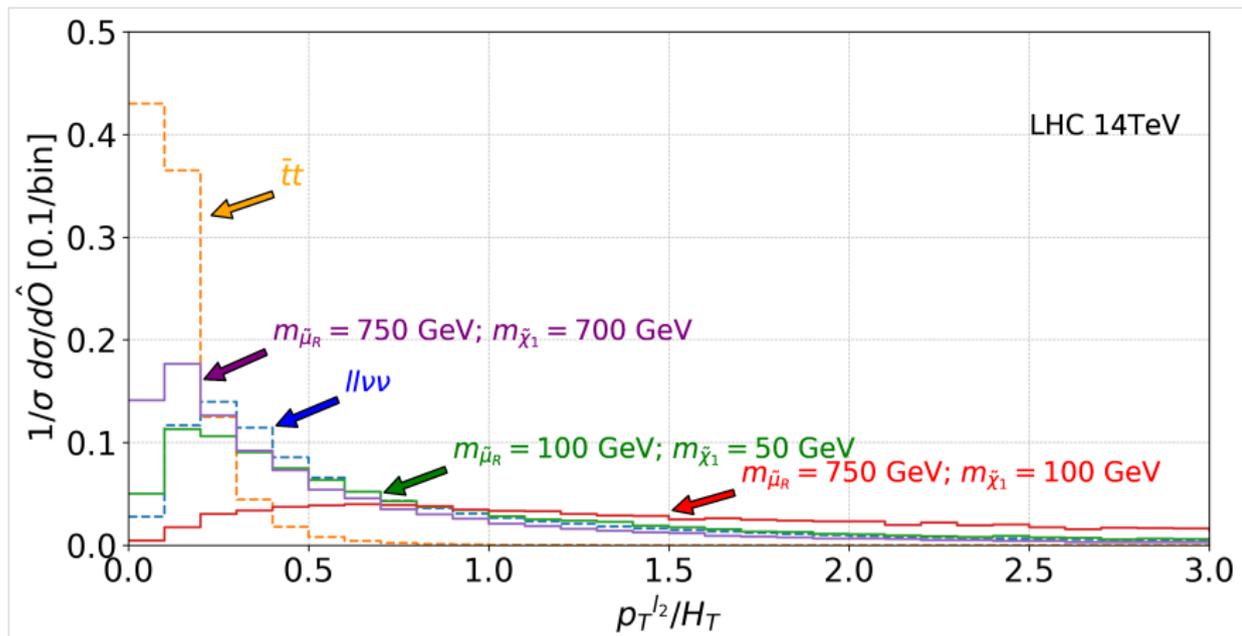Consider the signature $pp \to \mu^+ \mu^- + X$ at NLO+PS(LL)

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

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

Good (poor) S/B separation for $|m_{\tilde{\mu}} - m_{\tilde{\chi}_1^0}|/m_{\tilde{\mu}^0} \gg 0 \; (\sim 0)$

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

Choices of leptonic and hadronic observables is param. space-dependent
Nevertheless, separation between $t\bar{t}$ from $V^{(*)}V^{(*)}$ is clear :)

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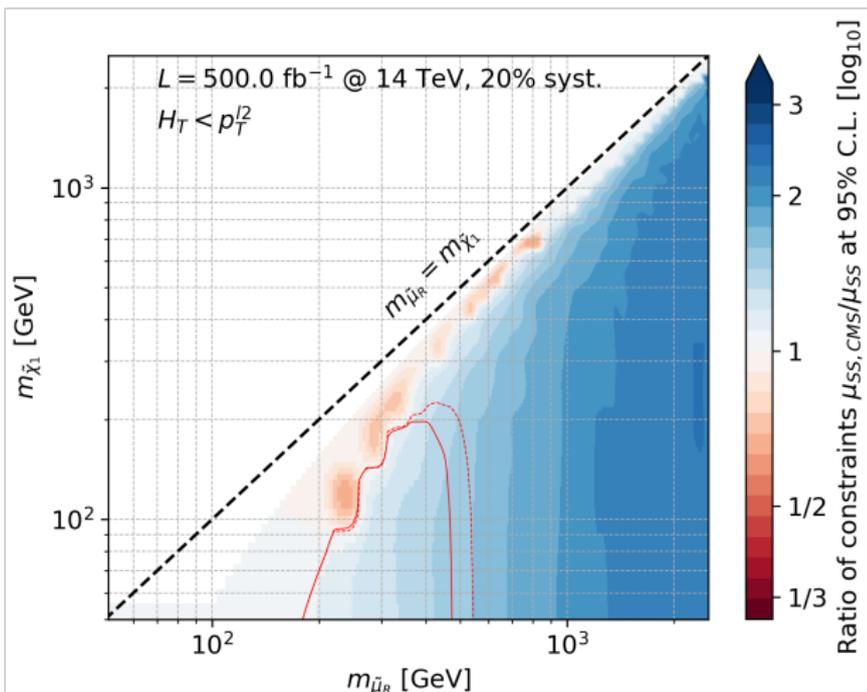- $+$ FxFx1j merging, MPI/UE tuning

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

darker $=$ improvement

- Improved sensitivty for larger mass splittings

- Worse for small mass splitting

- Other ratios show opposite behavior [1901.09937]

Summary, Conclusions, and Outlook

A class of jet vetoes has been investigated for high-mass, multi-ℓ searches, one based on comparing lepton vs hadronic activities, e.g., $p_T^{\mathrm{Veto}} = S_T$
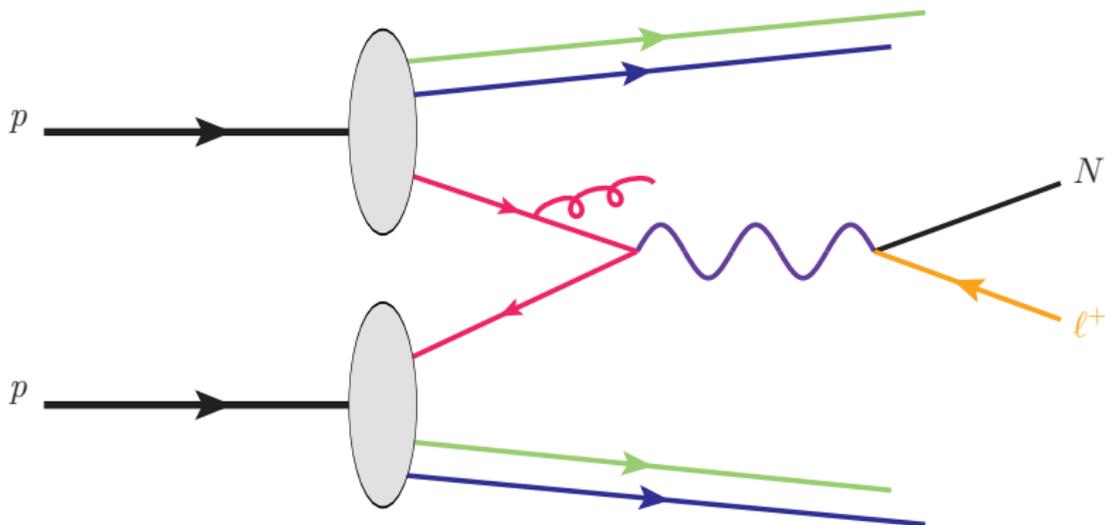
1. High signal efficiency ✓
   - New scheme reveals $> 90 - 95\%$ signal acceptance with little-to-no dependence on mass scales [1805.09335]
2. High background rejection ✓
   - Redesigned analysis gives better reduction of background
3. Low/less sensitivity to missing higher order corrections ✓
   - Substantial reduction in QCD theory uncertainty
     $\implies$ less need for high-precision resummation [1812.08750]
4. Universality ✗
   - Collider signature and param space dependence [1901.09937]
5. Analytic Control ✗
   - Resummation beyond parton shower-precision less clear
6. Broad applicability to BSM looks promising (see backup slides)

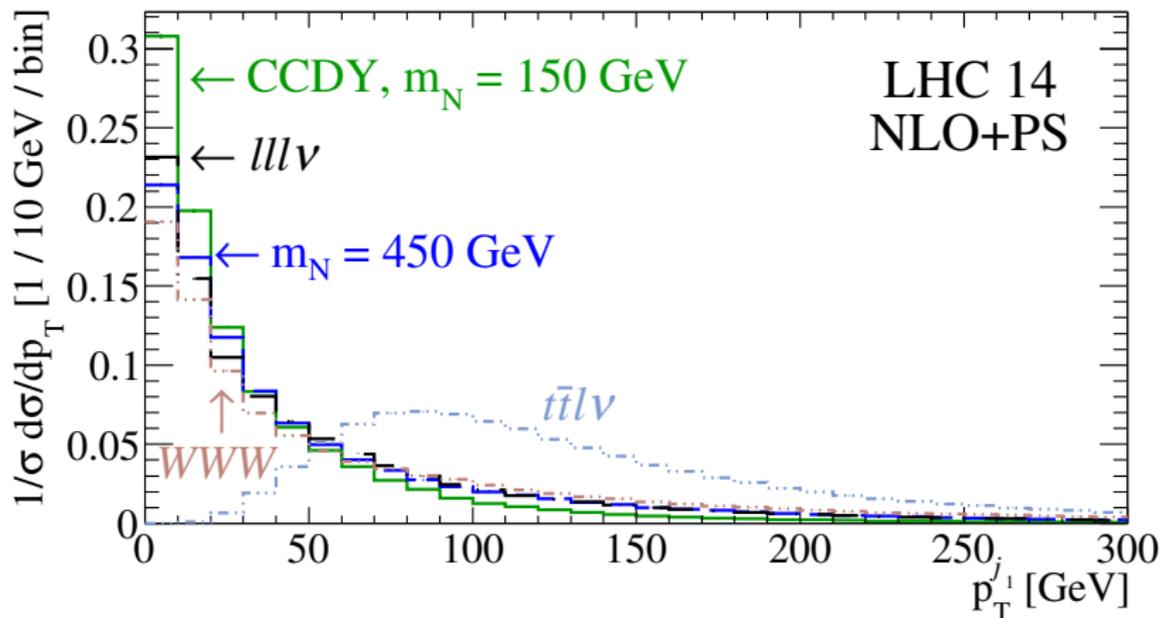**Thank you.**

Case Study II: Heavy Neutrinos at the LHC[10]

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

Consider $pp \to N\ell \to 3e/\mu + X$ at NLO+PS(LL)+anti-$k_T(R=1)$
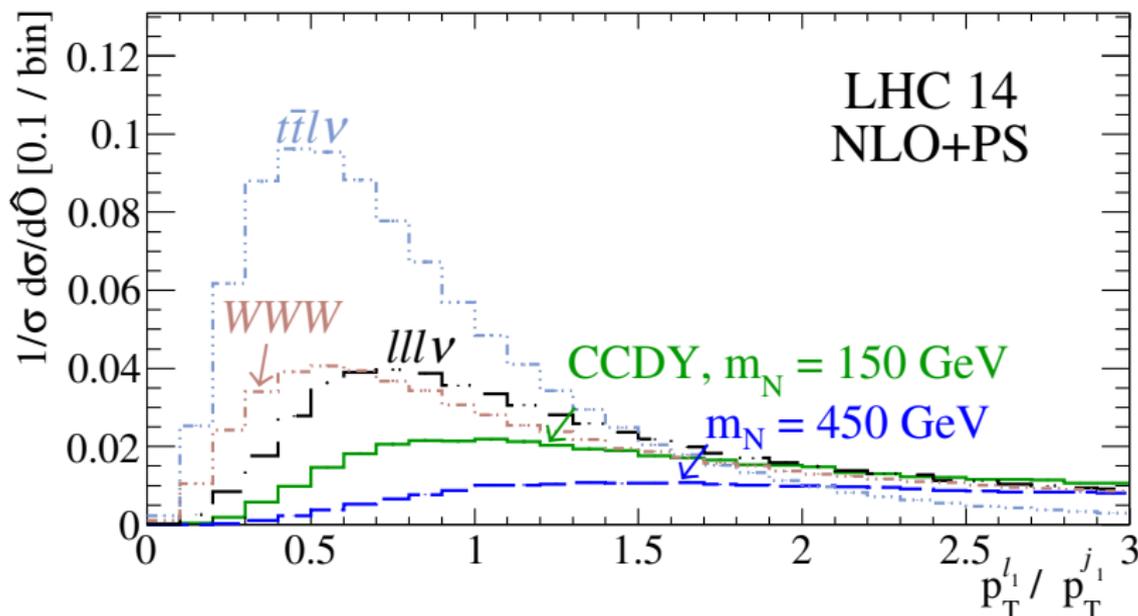
Plotted: $p_T^{j_1}$ for CC DY signal + SM Bkg

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

Event-based jet vetoes descriminate against hadronic and leptonic activities
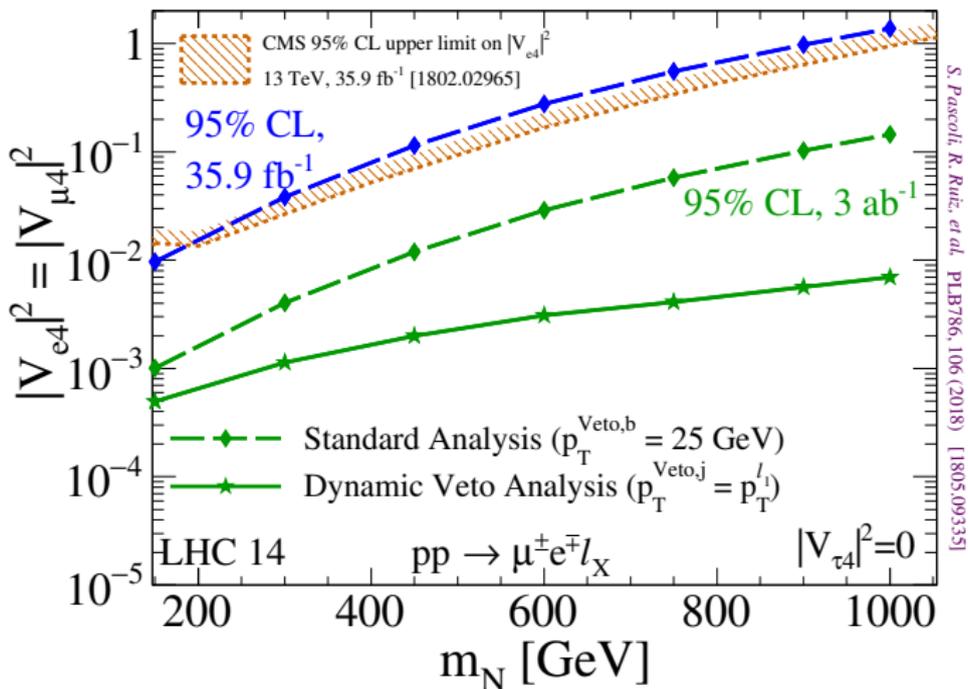
Plotted: $r_{j_1}^{\ell_1} = p_T^{\ell_1}/p_T^{j_1}$ for CC DY signal + SM Bkg

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]

Plot: LHC 14 sensitivity to active-sterile neutrino mixing (coupling^2) vs heavy N mass (m_N), in search for $pp \to \mu^{\pm} e^{\mp} \ell_X + X$ ($\ell_X = e, \mu, \tau_h$)[11]

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

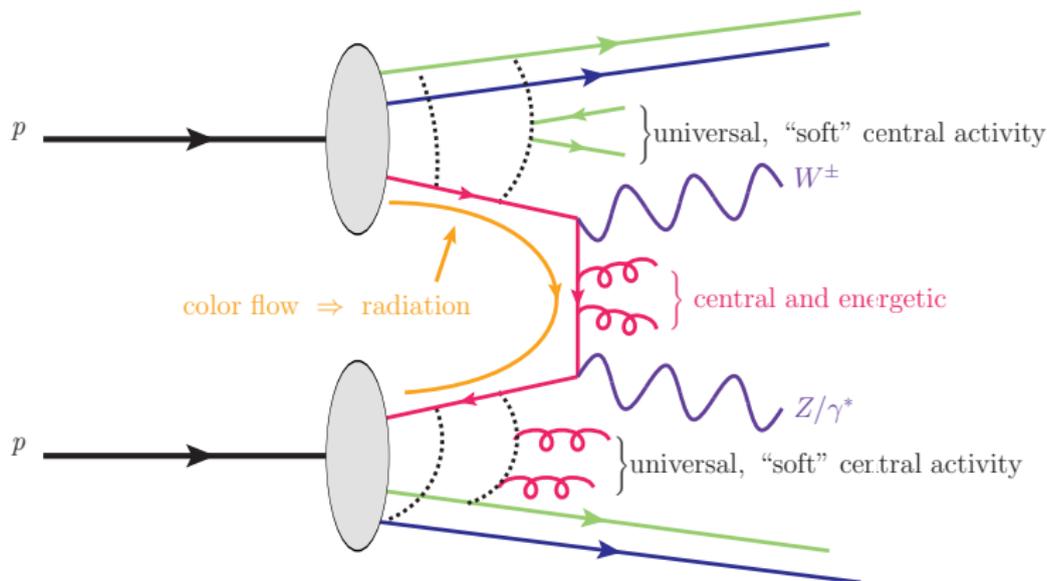[11]See [1812.08750] for various lepton flavor permutations, uncertainty plots, etc

Backup II:

Di- and Tribosons vs Event-Based Jet Vetoes

Diboson and Triboson Processes

Di- / triboson processes contain large amounts of hadronic activity

- Significant cancelations in Born-like configurations[12]
- Nontrivial color flow, despite naïve, color-singlet nature

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[12]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
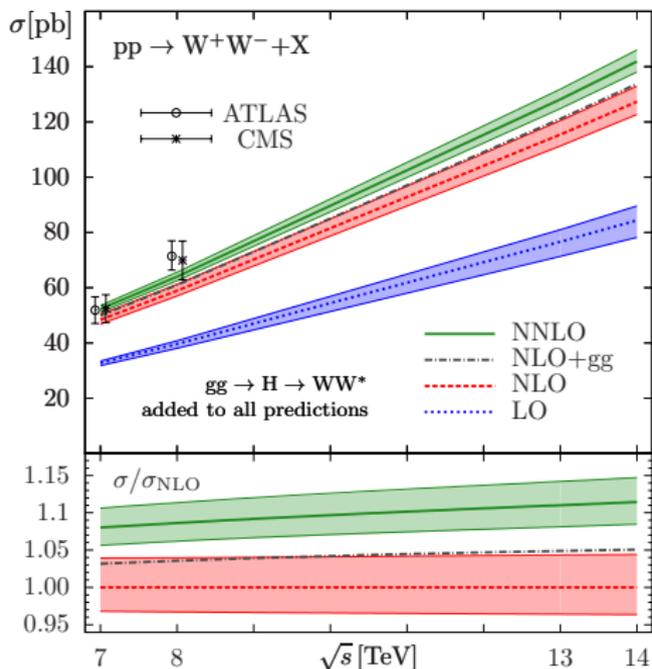
Inclusive diboson production driven by $pp \to VV'j + X$

- 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

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