

# Dynamical Jet Vetoes in VBS <sup>1</sup>

VBSCan 2018 - Krakow

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23 October 2018



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<sup>1</sup>with Silvia Pascoli and Cedric Weiland [1805.09335, 181X.YYYYY]

**Disclaimer: lots of missing references<sup>2</sup>**

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<sup>2</sup>Apologies for omission of many historical references, e.g., Barger, Cahn, Dawson, ..., Zeppenfeld, and everyone in between. Very rich history! 

**A worry<sup>3</sup> about vector boson scattering at higher  $\sqrt{s}$ :**

**Breakdown of standard tools for distinguishing  
vector boson scattering (VBS)**

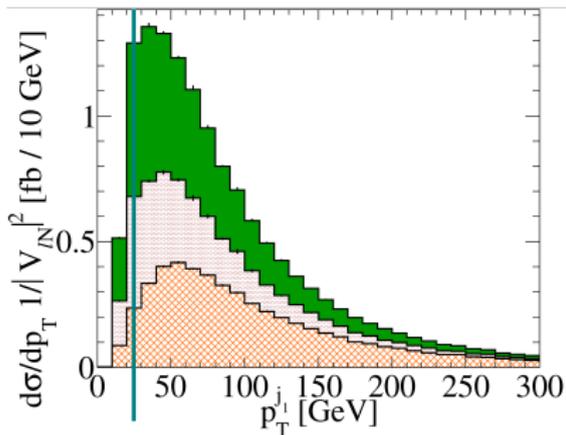
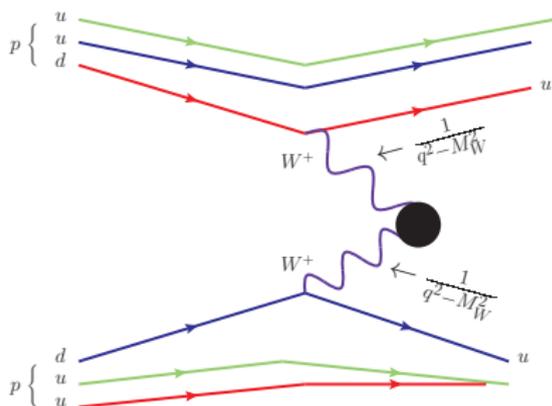
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<sup>3</sup>Alva, Han, RR [[1411.7305](#)]; Degrande, Mattelaer, RR, Turner [[1602.06957](#)]

# Forward Jet Tagging in Weak Boson Scattering

A defining characteristic of  $WW$  scattering is the presence of forward jets

- Massive (colorless)  $t$ -channel bosons  $\implies p_T^{jWBS} \sim M_V/2$



$p_T^{jWBS} \sim 40 - 45$  GeV okay for LHC, where ID thresholds are  $p_T^j \gtrsim 25$  GeV

- At  $\sqrt{s} = 27 - 100$  TeV, higher  $p_T^j$  thresholds will eat into rate

# Forward Jet Tagging in Weak Boson Scattering

$WW$  driven by forward  $W/Z$  emission off valence quarks: high- $|\eta|$  jets

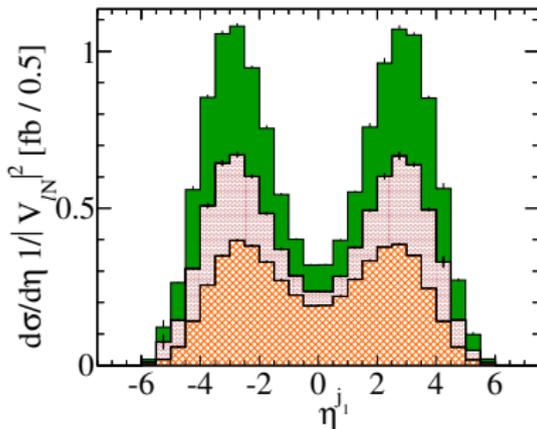
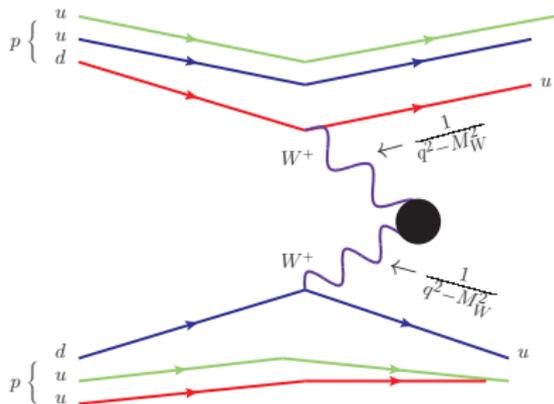
- **LHC Example:**  $u_V(1 \text{ TeV}) \rightarrow W^+(0.5 \text{ TeV}) + d(0.5 \text{ TeV})$  splitting

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$$\implies \eta^d \approx -\log \tan \left( \frac{p_T^d}{2p_z^d} \right) \sim -\log \tan \left( \frac{M_W}{4 \times 500 \text{ GeV}} \right) \gtrsim 3 \ (\sim 4.5^\circ)$$

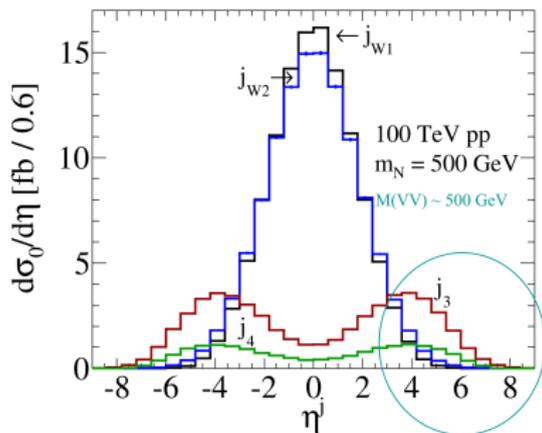
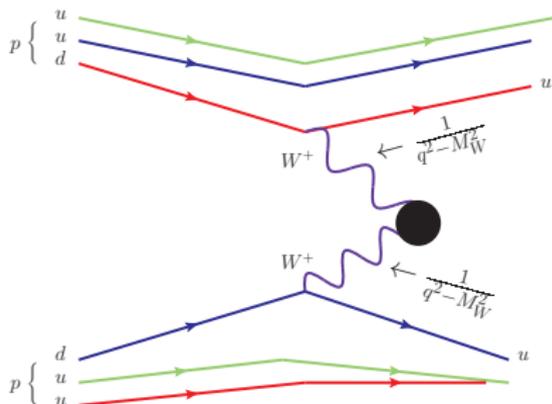


At  $\sqrt{s} = 27 - 100 \text{ TeV}$ ,  $p_z^d$  can grow  $\gtrsim 2 - 20 \times \implies |\eta| \gtrsim 4 - 6$

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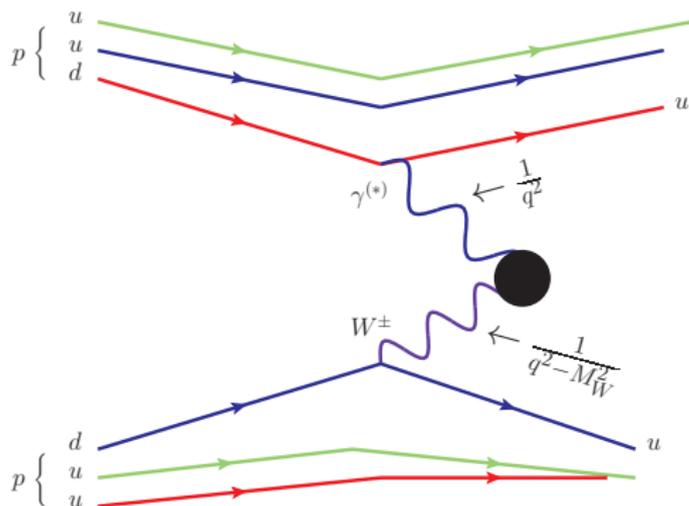
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- Typical VBS jets escaping detector coverage at larger  $\sqrt{s}$

# Forward Jet Tagging in *Electroweak* Boson Scattering

At future colliders,  $WW$  jets may be too “soft” and forward to tag

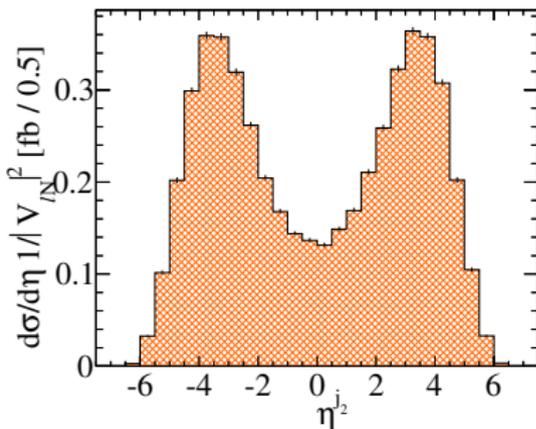
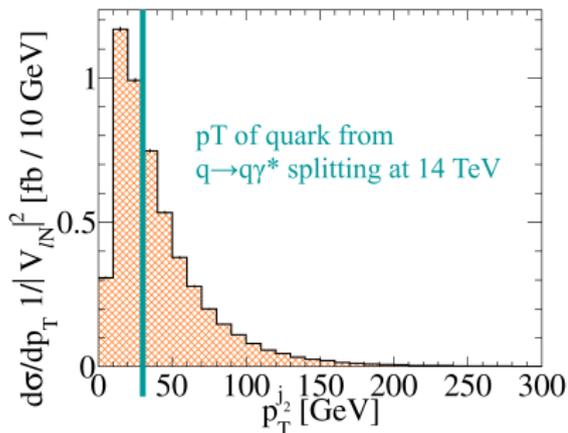
- **Behavior already present at LHC in  $W\gamma^{(*)}$  scattering!**
- Characteristic  $p_T$  and  $|\eta|$  for  $j$  from  $W$  and  $\gamma$  emissions differ:
  - ▶ As  $M_V \rightarrow 0$ , characteristic  $p_T^{jVBS} \rightarrow 0$  and  $|\eta|^{jVBS} \rightarrow \infty$



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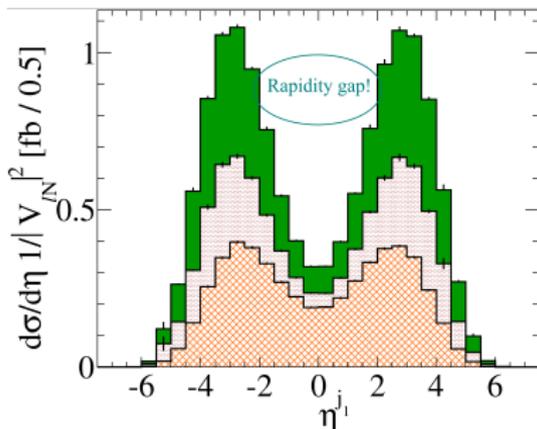
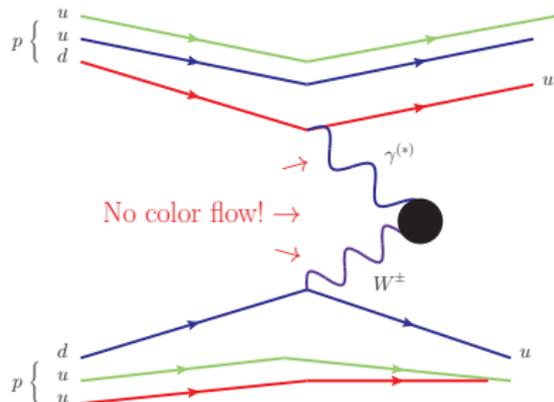
Majority<sup>4</sup>  $W\gamma^{(*)}$  events cannot be (double-)tagged at ATLAS/CMS

<sup>4</sup>**Note:** Analogous to  $q \rightarrow qg$  splitting;  $q_\gamma > 15$  GeV to regulate  $q \rightarrow q\gamma^*$  splitting. Below this, matched to  $\gamma$ -PDF with elastic and inelastic components for inclusive rates.

## “tagging” (E)WBS without tagging

# Rapidity Gaps and Central Jet Vetoes

No color flow  $\implies$  absence of central, high- $p_T$  jets (**rapidity gap**)



## • Basis for central Jet Veto<sup>5</sup>:

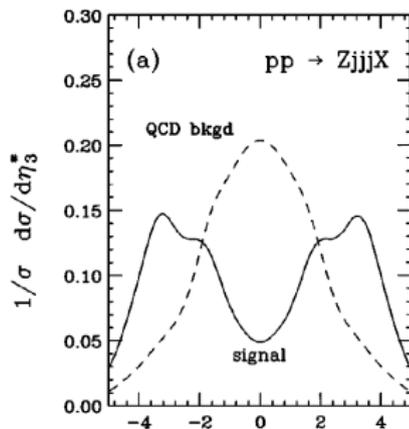
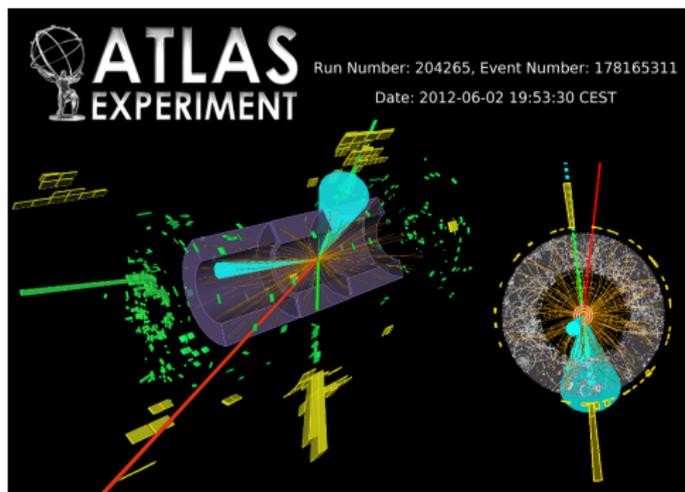
- ▶ Reject events with  $p_T^j > 25 - 30$  GeV and  $|\eta_j^i| < 2 - 3$
- ▶ Crucial to Higgs physics but not perfect...

<sup>5</sup>Barger, Cheung, Han, Zeppenfeld, PRD44, 2701 ('91); PLB346, 106 ('95)

**Issue:** Jets from VBS **not immune** to central jet veto

- Central region for ( $VV$ )-system  $\neq$  central region for lab-frame
- More restrictive veto  $\implies$  smaller QCD backgrounds (and signal<sup>6</sup>...)
  - ▶ Motivates alternative discriminants<sup>7</sup>, 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)

<sup>6</sup>E.g., Sleptons: Tackmann, et al [[1603.03052](#)];  $W'$ : Fuks, RR [[1701.05263](#)]

<sup>7</sup>Rainwater, Szalapski, Zeppenfeld, PRD54, 6680 (1996)

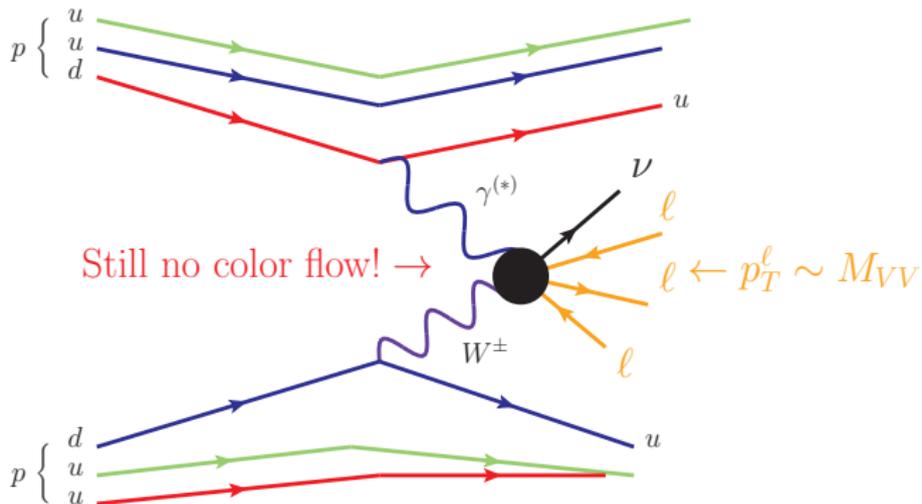
**rethinking the veto entirely<sup>8</sup>**

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<sup>8</sup>Full story a bit more involved: Pascoli, RR, Weiland [1805.09335, 181X.YYYYYY]

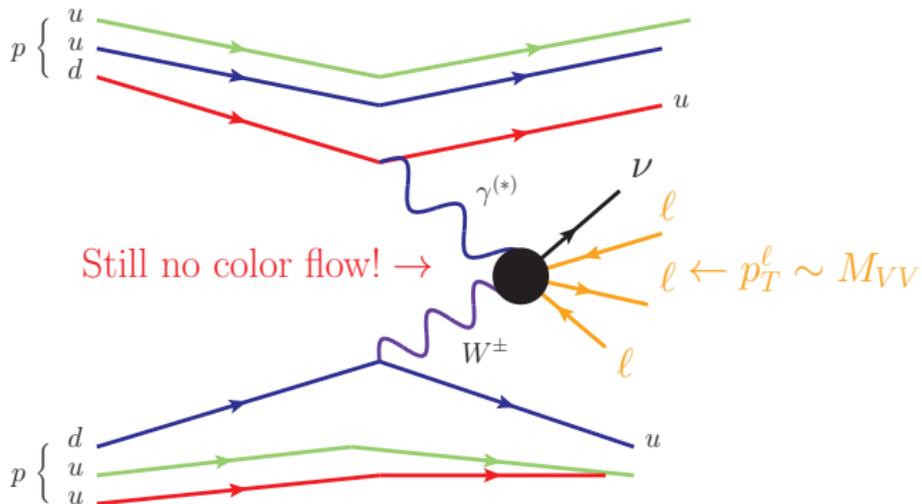
# Dynamical Jet Vetoes in VBS Production of Leptons

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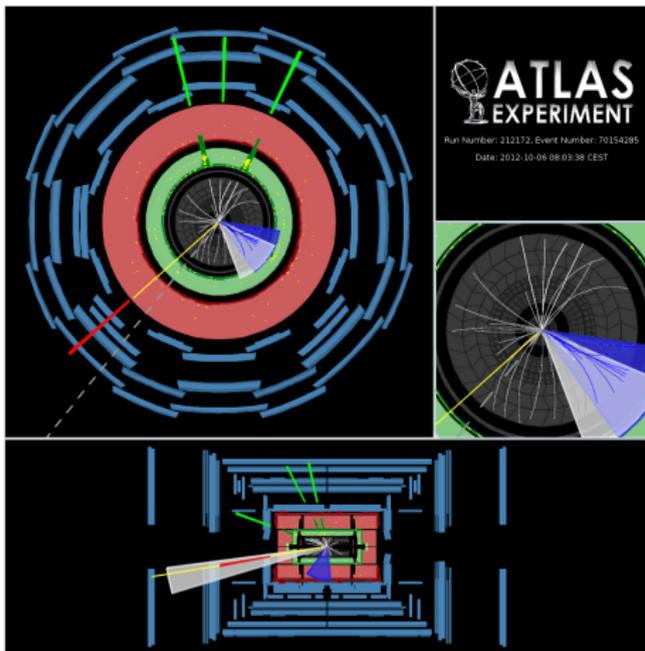
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**Ridiculous idea:** on event-by-event case, set  $p_T^{\text{Veto}} = p_T^{\ell_1}$

- VBS events pass by construction. How about backgrounds?

# Top Quark Background vs Dynamical Jet Vetoes



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

Classic kinematics:

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

Typically,

- $p_T^{e1} \sim \frac{m_t}{4} \left(1 + \frac{M_Z^2}{m_t^2}\right) \sim 50$  GeV
  - $p_T^{e3} \sim \frac{M_Z}{2} \sim 45$  GeV
  - $p_T^{b1} \sim \frac{m_t}{2} \left(1 - \frac{M_Z^2}{m_t^2}\right) \sim 60$  GeV
- $p_T^{b1} > p_T^{\ell1} \implies$  event vetoed!

Setting  $p_T^{\text{Veto}}$  on event-by-event basis to  $p_T^{\ell1}$  can eliminate top quark background **without**  $b$ -jet tagging!

# Jet Vetoes and SM Backgrounds<sup>9</sup>

Associated Top Quark Production:  $pp \rightarrow t\bar{t}l\ell, t\bar{t}l\nu, tqll$

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

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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

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Electroweak Production:  $pp \rightarrow 4\ell, 3\ell\nu, WWW, WWl\bar{l}$

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

<sup>9</sup>Note: by itself, a dynamical jet veto is **not** a “silver bullet” 



Two complementary LHC signal processes ( $\ell_X = e, \mu, \tau_h$ ):

**Signal I:**  $pp \rightarrow \tau_h^+ \tau_h^- \ell_X + \text{MET}$     and    **Signal II:**  $pp \rightarrow \tau_h^\pm e^\mp \ell_X + \text{MET}$

**Plot:** LHC 14 sensitivity to (coupling)<sup>2</sup> vs heavy neutrino mass

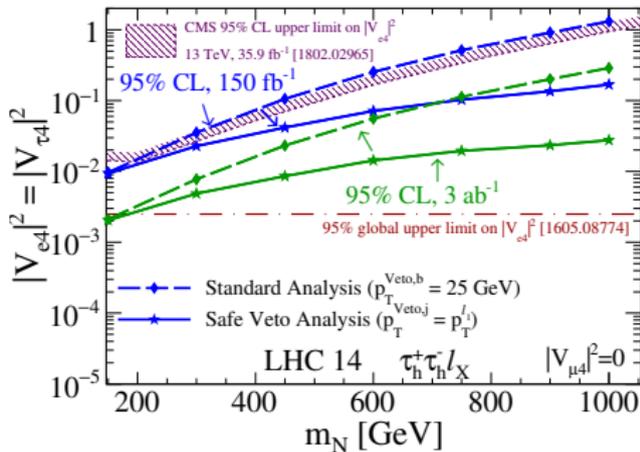
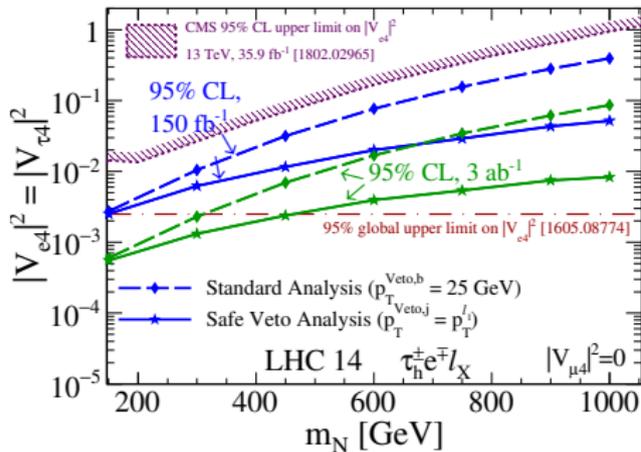
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<sup>11</sup>More aggressive cuts on charged leptons: e.g.,  $p_T^{\ell_1} > 55 \text{ GeV}$ ,  $m_{3\ell} \geq 80 \text{ GeV}$

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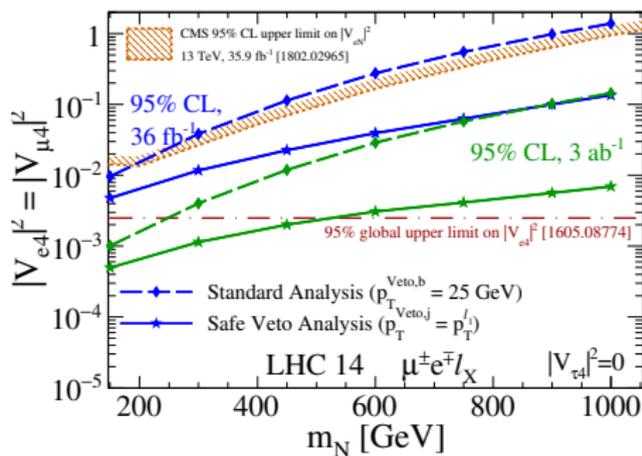
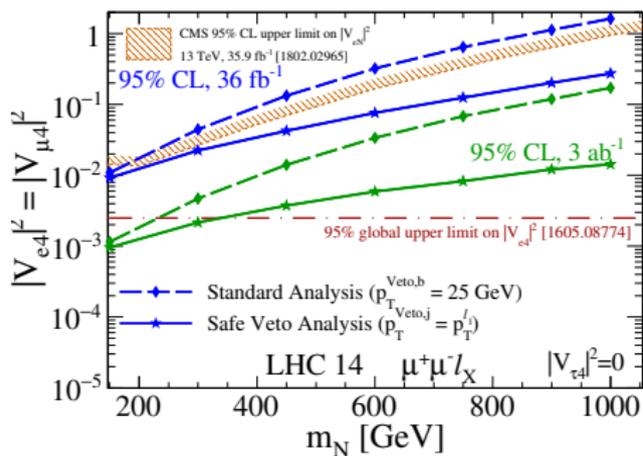
Improved sensitivity up to 10 – 11× with  $\mathcal{L} = 3 \text{ ab}^{-1}$ .

- Dash = standard search<sup>11</sup> with  $b$ -jet veto (13 TeV CMS for  $e/\mu$ )
- Solid = “improved” analysis with special type of jet veto

<sup>11</sup>More aggressive cuts on charged leptons: e.g.,  $p_T^{\ell_1} > 55 \text{ GeV}$ ,  $m_{3\ell} \geq 80 \text{ GeV}$

Two more complementary signal processes with different flavor hypotheses:

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



Again, improved sensitivity  $> 10\times$  with  $\mathcal{L} = 3 \text{ ab}^{-1}$

# Summary

*We have developed a new approach to searches for multi-lepton processes at pp colliders, one based on an unusual jet veto scheme ( $p_T^{\text{Veto}} = p_T^{\ell_1}$ )*

- **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 at NLO+PS(LL) and NLO+NNLL(Veto)  $\implies$  **less need for high-precision resummation**
- Redesigned search analysis with better reduction of background  $\implies$  **Improved LHC sensitivity by up to  $10\times$  over LHC's lifetime**



**Thank you.**



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)  
⇒ cannot apply veto at same time as other cuts
- **Need:** inclusive samples since bkg include  $\ell^\pm$  outside fid. volume

**Moto:** “We start at NLO”

- Event Generation: HeavyN@NLO UFO<sup>12</sup> + MadGraph5\_aMC@NLO
  - ▶ Bare-bones gen-level cuts on leptons + MadSpin for decay
- Shower: Pythia8.2 (w/ QED shower + recoil + Monash\* Tune)
- Particle-level Reco (lhe output)<sup>13</sup>: MadAnalysis5 +  $R = 1$  anti- $k_T$
- Smearing + offline analysis: private ROOT code

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<sup>12</sup>C. Degrande, O. Mattelaer, **RR**, J. Turner [[1602.06957](#)]

Available from FeynRules database: [feynrules.irmp.ucl.ac.be/wiki/HeavyN](http://feynrules.irmp.ucl.ac.be/wiki/HeavyN)

<sup>13</sup>See  $W'$ +jet veto analysis, Fuks, **RR** [[1701.05263](#)]

# Flavor Hypothesis and Signal Definition

As a benchmark flavor mixing scenario we set:

$$|V_{e4}| = |V_{\tau4}| \neq 0 \quad \text{and} \quad |V_{\mu4}| = 0$$

Two complementary<sup>14</sup> signal processes ( $\ell_X = e, \mu, \tau_h$ ):

**Signal I:**  $pp \rightarrow \tau_h^+ \tau_h^- \ell_X + \text{MET}$     and    **Signal II:**  $pp \rightarrow \tau_h^\pm e^\mp \ell_X + \text{MET}$

**Selection Cuts:** Standard ID requirements and  $m_{2\ell,3\ell}$  cuts

**Nonstandard Cuts:**

- Require  $p_T^{j1} < p_T^{\ell1}$  (jet veto) and  $S_T^\ell > 120$  GeV
- Given  $m_N$  hypothesis, cut on closest multi-body transverse mass  $\tilde{M}$

$$\begin{aligned} \tilde{M}_{T,i}^2 &= \left[ \sqrt{p_T^2(\ell^{\text{OS}}) + m_{\ell^{\text{OS}}}^2} + \sqrt{p_T^2(\ell_i^{\text{SS}}, \vec{p}_T) + M_W^2} \right]^2 \\ &- \left[ \vec{p}_T(\ell^{\text{OS}}, \ell_i^{\text{SS}}) + \vec{p}_T \right]^2, \quad i = 1, 2. \end{aligned}$$

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<sup>14</sup>BR( $\tau/W \rightarrow eX$ ) are well-measured  $\implies$  can falsify no-LFV hypothesis if measured

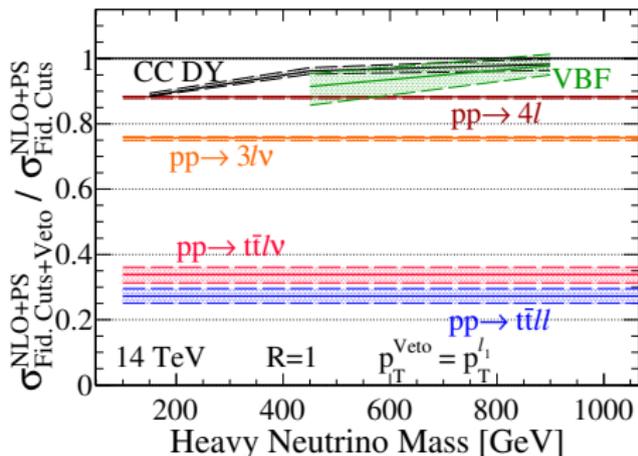
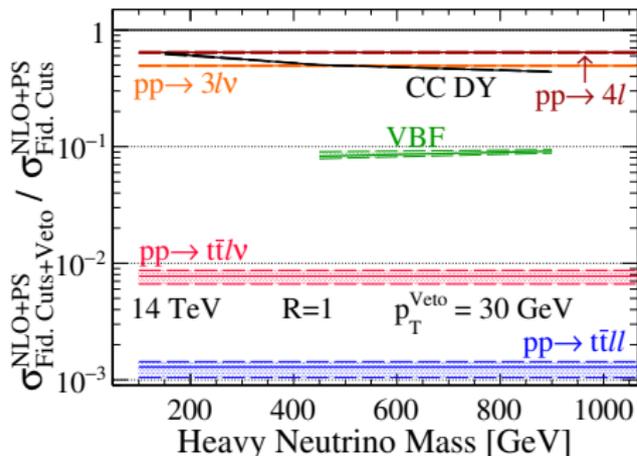
# Veto Efficiency at NLO+PS(LL) **PRELIMINARY**

Signal and background process  $pp \rightarrow 3e/\mu + X$  at NLO+PS(LL)

- Minimal generator-cuts
- $p_T^l > 15$  GeV and  $|\eta| < 2.4$

(L)  $p_T^j < 30$  GeV

(R)  $p_T^j < p_T^l$



With veto on 4th lepton or  $S_T$ , new veto does better than static veto