# Revisiting jet vetoes as handles on new physics

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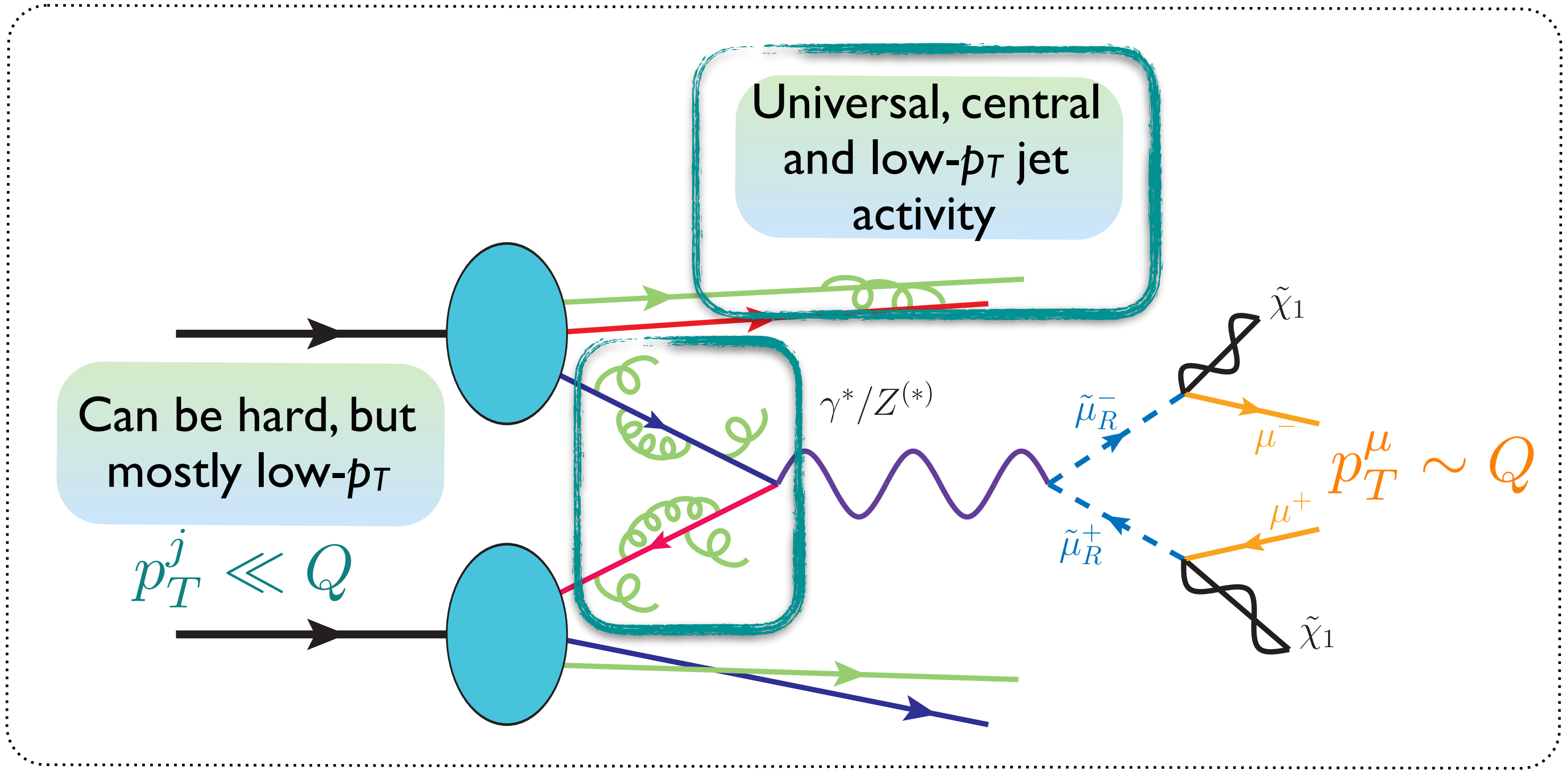
# About jet vetoes

# Jet vetoes for (electroweak) new physics

- Jet vetoes have been applied to a variety of new physics searches
  - Especially for the electroweak production of new particles (e.g. heavy Higgs in VBF) [ Barger *et al.* (PRD'91) ]
  - Most jet activity in the signal is soft (in contrast with the backgrounds)



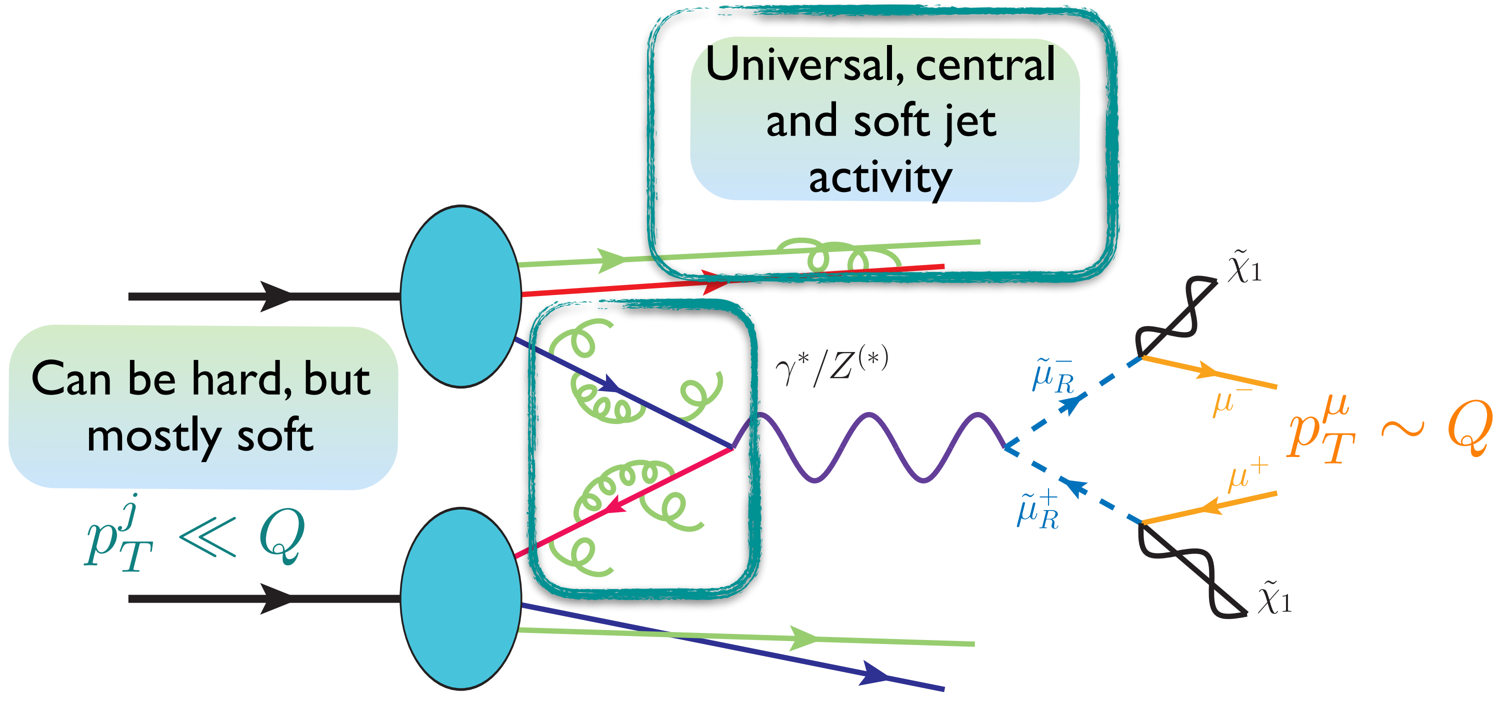

- Example: smuon production in the dimuon (plus missing energy) channel
  - Main background: top-quarks (and diboson)
  - Veto → good background rejection
  - Most analyses rely on static and central jet vetoes
  - Example of CMS-SUS-17-009 (smuon search in the dimuon + MET channel)

Rejection of events featuring any central jet ($|\eta| < 2.4$) with $p_T > 25$ GeV

# Introducing dynamic jet vetoes

✦ The hard scale $Q$ is connected to the event leptonic activity

✤ Idea: vetoing events featuring a large hadronic activity relative to the leptonic one




✤ Properties

★ Increase in the efficiency

★ Top-vetoes without *b*-tags

★ Better sensitivity to lepton mis-identification

★ Efficient rejection of diboson backgrounds

[ Pascoli, Ruiz & Weiland (PLB'18; JHEP'19) ]

✦ Bonus

✤ Less sensitivity to higher-order corrections (veto logarithms smaller)

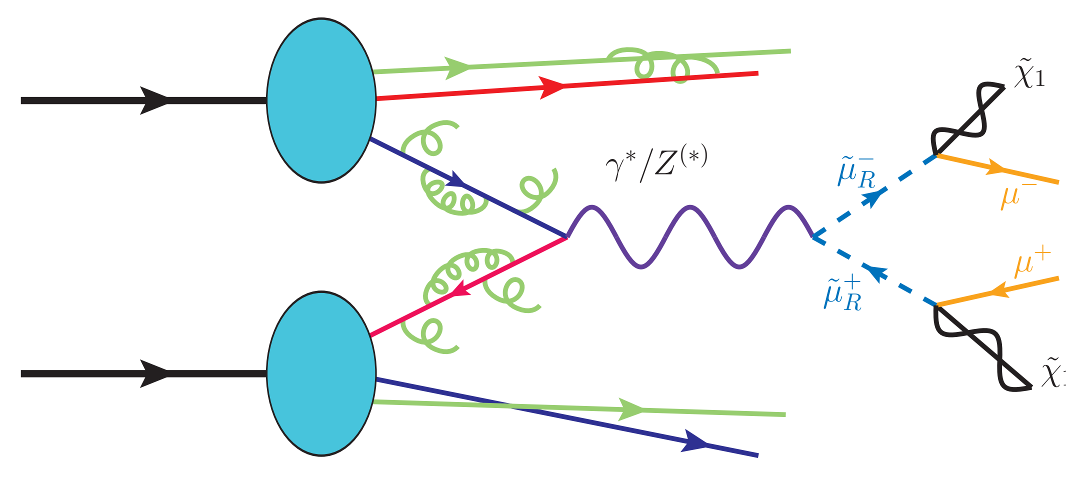
How to properly define hadronic and leptonic activities?
Impact of dynamic vetoes?
Sensitivity of the strategy to QCD modelling?

**Simulation framework**

# Simulated processes and model

## ✦ Processes

- ✤ Signal: smuon pair production
- ✤ Backgrounds
  - ★ Top-antitop (dileptonic)
  - ★ Diboson (2 and 3 leptons)
  - ★ WWW (3 leptons)
- ✤ Other backgrounds found irrelevant
  - ★ Other diboson/triboson processes
  - ★ Drell-Yan
  - ★ Top-antitop plus boson

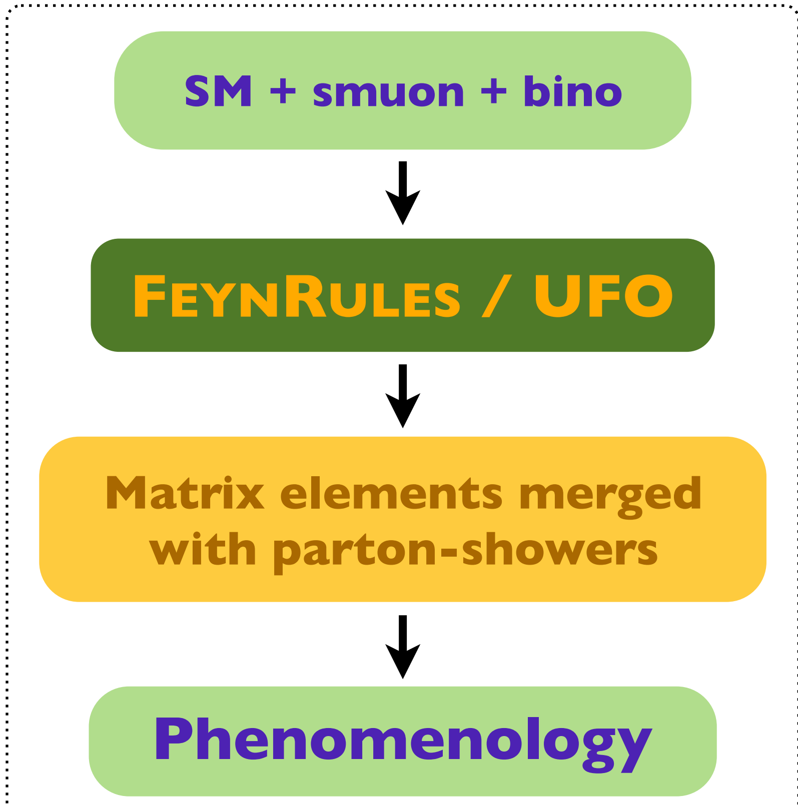



## ✦ New physics model

- ✤ Simplified model
- ✤ SM + muon + bino
- ✤ Lagrangian inspired by the MSSM
  - ★ Kinetic and mass terms
  - ★ SUSY-gauge interactions

$$\mathcal{L} = \left[\partial_\mu \tilde\mu_R^\dagger\right]\left[\partial^\mu \tilde\mu_R\right] + \frac{i}{2}\overline{\tilde\chi_1}\partial\!\!\!/\tilde\chi_1 - m^2_{\tilde\mu_R}\tilde\mu_R^\dagger\tilde\mu_R - \frac{1}{2}m_{\tilde\chi_1}\overline{\tilde\chi_1}\tilde\chi_1$$
$$+ \left[\partial^\mu\tilde\mu_R^\dagger\tilde\mu_R - \tilde\mu_R^\dagger\partial^\mu\tilde\mu_R\right]\left[ieA_\mu - \frac{ies_W}{c_W}Z_\mu\right]$$
$$- \frac{\sqrt{2}e}{c_W}\left[\left(\overline{\tilde\chi_1}P_R\mu\right)\tilde\mu_R^\dagger + \text{H.c.}\right]$$

# Simulations




## ✦ Simulation chain

✤ Model building: from Lagrangian to tools

★ FEYNRULES + NLOCT + FEYNARTS ➢ UFO @ NLO

[ Alloul, Christensen, Degrande, Duhr & BF (CPC'14) ; Degrande (CPC'15); Hahn (CPC'01) ]
[ Degrande, Duhr, BF, Mattelaer & Reither (CPC'12) ]

✤ Matching matrix elements with parton showers

★ Fixed order: NLO (decays: MADSPIN/MADWIDTH)

★ Parton shower matching: PYTHIA 8 (MC@NLO)

★ Merging @ 1 jet (FxFx)

★ Automation within MG5_AMC

[ Artoisenet *et al.* (JHEP'13); Alwall *et al.* (CPC`15); Frixone & Webber (JHEP'02) ]
[ Sjöstrand *et al.* (CPC'15) ; Frederix & Frixone (JHEP'12) ; Alwall *et al.* (JHEP'14) ]

## ✦ Key features

✤ Merging @ 1 jet: better description of the first two QCD emissions

★ 1st jet: LO+LL ⇒ NLO+LL ; 2nd jet: LL ⇒ LO+LL

★ A good jet modelling is crucial for the description of the hadronic activity

✤ Parton shower tuning and multiple particle interactions

★ Monash* tune + colour reconnection + recoil against dipole radiation

★ Underlying event model of PYTHIA 8

[ Skands, Carrazza & Rojo (EPJC'14) ]

★ May impact the hadronic activity

# Event reconstruction

- **Jet clustering with FastJet and MadAnalysis 5**
  - Anti-$k_T$ algorithm, radius parameter $R$=1 [ Cacciari, Salam & Soyez (JHEP'08) ]
  - Ideal $b$-tagging, $\tau_h$-tagging and object identification
- **Analysis**
  - Realistic reconstruction (smearing, mis-identification)
  - Objects
    - ★ Electrons: $p_T$ > 10 GeV, $|\eta|$ < 2.4
    - ★ Muons: $p_T$ > 10 GeV, $|\eta|$ < 2.4
    - ★ Taus: $p_T$ > 20 GeV, $|\eta|$ < 2.4
    - ★ Jets: $p_T$ > 25 GeV, $|\eta|$ < 2.4

Only central objects

[ Cacciari, Salam & Soyez (EPJC'12) ]

[ Conte, BF, Serret (CPC '13); Conte, Dumont, BF, Wymant (EPJC '14); Dumont, BF, Kraml *et al.* (EPJC '15); Conte & BF (IJMPA'18) ]

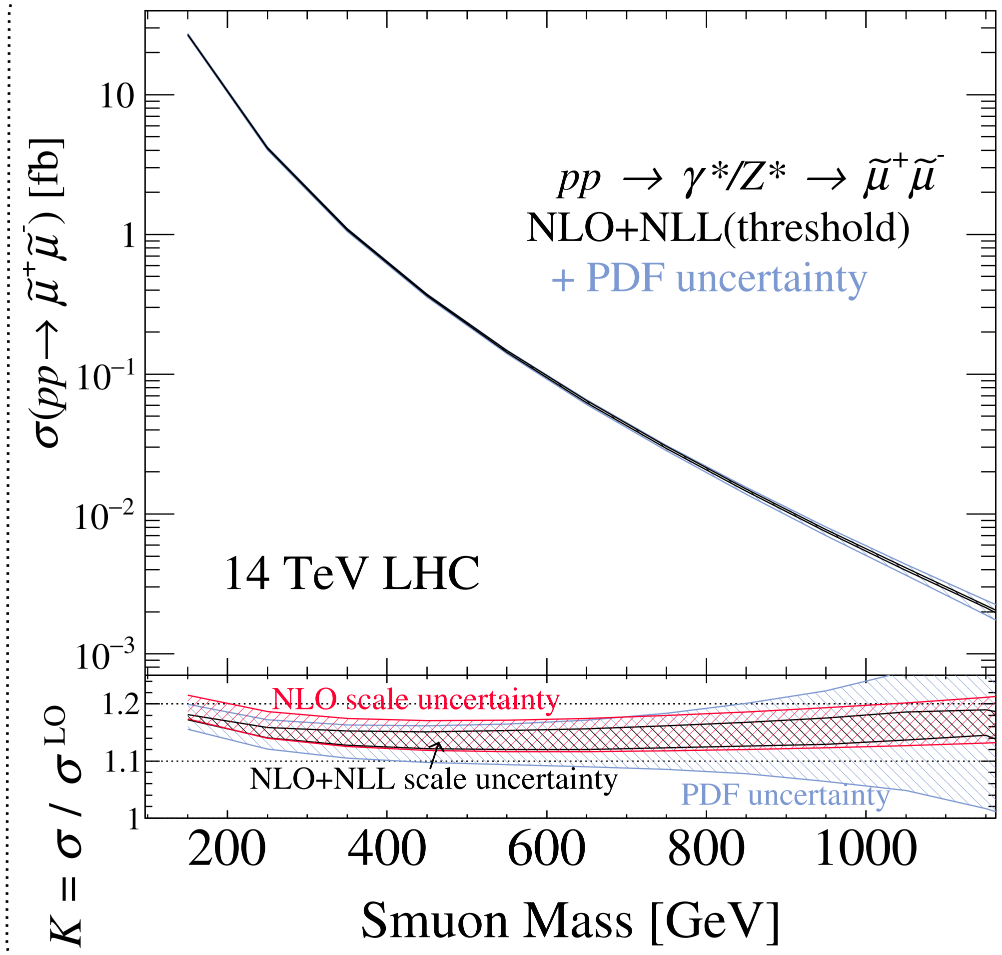
- **Preselection *à la* CMS-SUS-17-009 (2 muons compatible with a smuon signal)**
  - 2 opposite-sign off-Z muons with $M_{\mu\mu}$ > 20 GeV
  - Third lepton veto
  - $M_{T2}$ > 90 GeV
  - $\not{E}_T$ > 100 GeV

CMS includes lepton cuts
→ not here (by default)

# Uncertainties

# Uncertainties on the signal rate

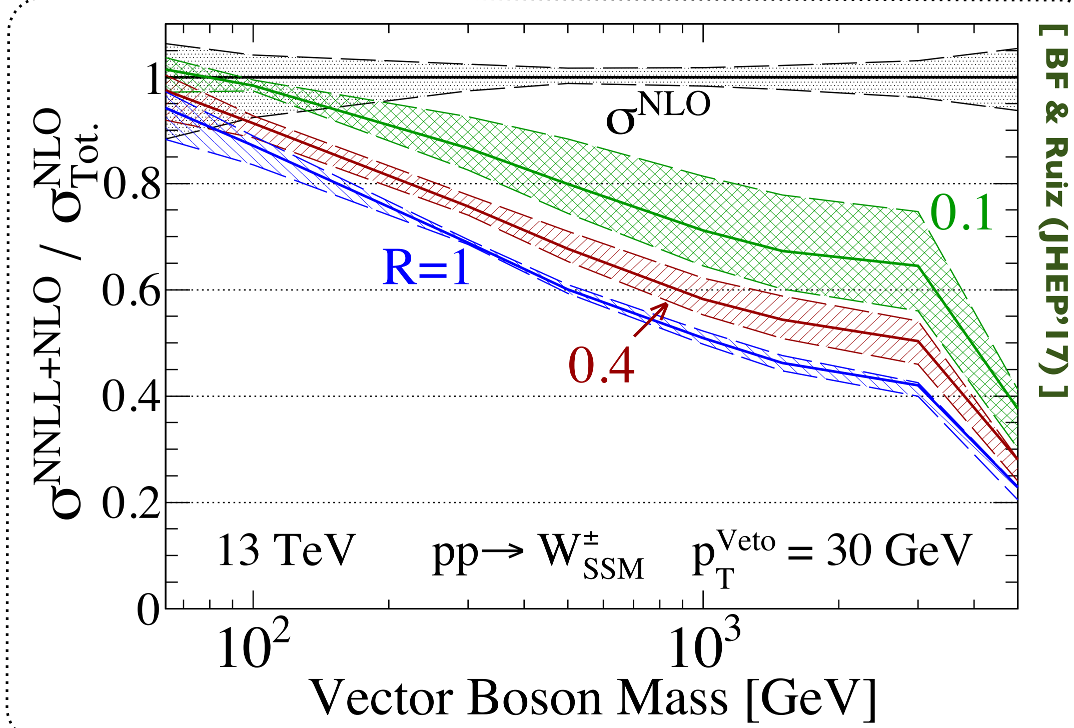
- ✦ Factorisation and renormalisation scale
  - ✤ $\mu_0$: average $M_T$ of the final-state particles
  - ✤ Band: factor of 2 up and down
- ✦ Shower scale
  - ✤ Central scale: min [$\mu_0$, $d^*$]
    ($d^*$ = min. $k_T$ over all QCD splittings)
  - ✤ Band: factor of 2 up and down
- ✦ PDF
  - ✤ Standard prescription (PDF4LHC)
- ✦ Signal rate @ NLO+NLL
  - ✤ $K$-factor of 1.15, pert. uncertainties of 4%
  - ✤ Larger uncertainties at large masses (PDF)




[ BF, Klasen, Lamprea & Rothering (EPJC'13) ]

# Uncertainties and jet vetoes

- **Static veto**
  - Larger *R*-values reduce pert. uncertainties
  - No small-*R* logarithms if *R* is large
  - Fails for heavy new physics




- **Static veto with *R*=1**
  - Perturbative uncertainties minimised
  - But: worsens the non-perturbative ones

[ Dasgupta, Magnea & Salam (JHEP'08) ; Becher *et al.* (EPJC'15) ]
[ BF & Ruiz (JHEP'17) ]

- **NLO+PS predictions (with a veto) yield reliable, more precise estimates**
  - With comparable uncertainties

- **Dynamic veto** [ Pascoli, Ruiz & Weiland (PLB'18) ]
  - Automatic absence of large logarithms (smaller sensitivity to higher orders)
  - NLO+PS (with a veto) ➢ reliable estimate (with comparable uncertainties)
  - New and better strategy for heavy new physics?

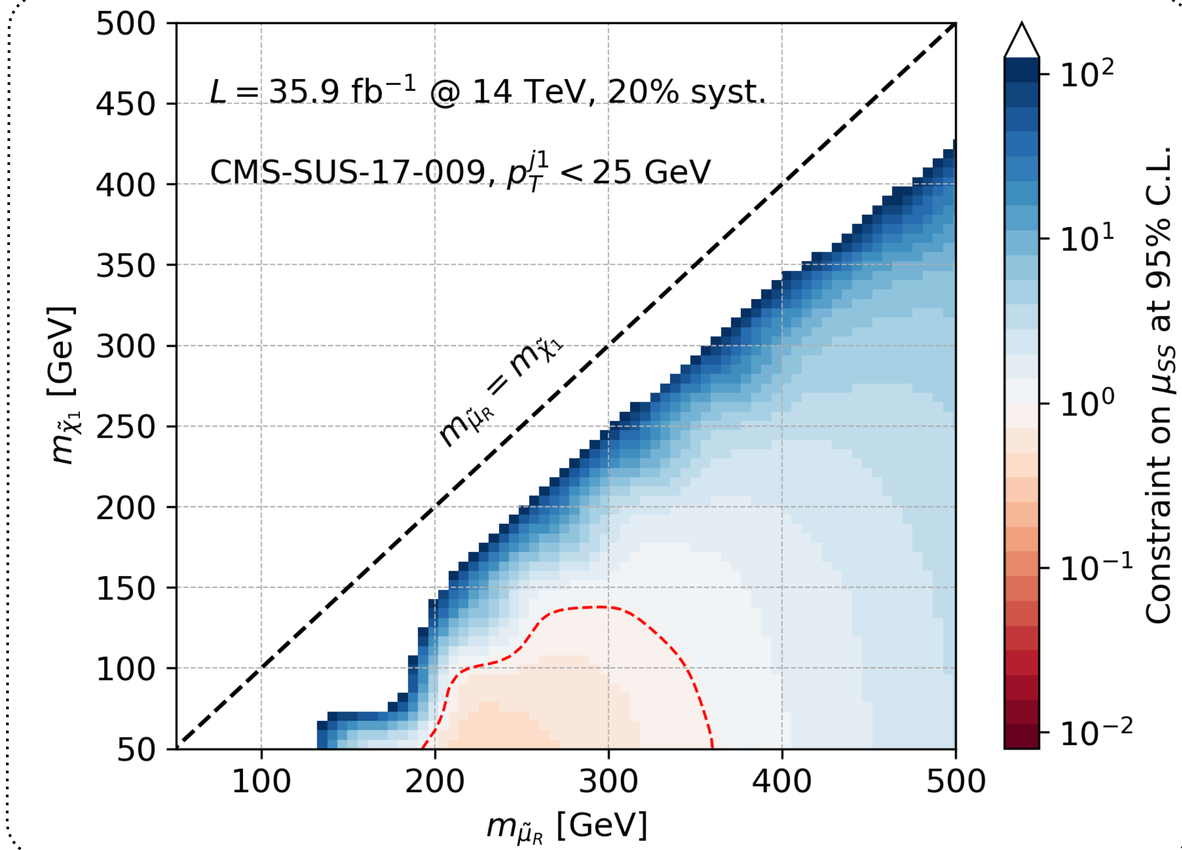
- **Systematics in our study**
  - Impact of FxFx, MPI, *etc.* → 10% − 15% (consistent with Monte Carlo studies)
    [ Chakraborty *et al.* (EPJC'18); Jones & Kuttimalai (JHEP'18) ]
  - 20% of systematics is included (all potential EXP and TH uncertainties)

# Phenomenological analysis

# A reference analysis

## ✦ Selection cuts (mimics the CMS-SUS-17-009 analysis)

- ✤ Preselection cuts
  - ★ 2 OS off-Z muons, $M_{\mu\mu}$ > 20 GeV,
  - ★ 3rd lepton veto
  - ★ $M_{T2}$ > 90 GeV, $\not{E}_T$ > 100 GeV
- ✤ 4 $\not{E}_T$ bins: <150 GeV, in 150−225 GeV, in 225−300 GeV, >300 GeV
- ✤ Static veto
  - ★ Hadronic activity: no jet
  - ★ Leptonic activity: $p_T^{\mu_1} > 50$ GeV, $p_T^{\mu_2} > 20$ GeV




## ✦ Bounds: slightly stronger than CMS

- ✤ Results given as signal strengths (exclusion: $\mu_{SS}$ < 1)
- ✤ Detector simulation from publicly available information
  - ★ Smearing (resolution) and reconstruction efficiencies

  [ CMS: SUS-17-005; SUS-17-009; ]
  [ EXO-15-006; PRF-14-001; JME-10-011 ]
- ✤ Different center-of-mass energy (14 TeV); but same luminosity
- ✤ Background normalization at NLO+PS (missing higher-order contributions)
- ✤ Simplified treatment of the systematics (the best region drives the limits)

[ More information in BF, Nordström, Ruiz & Williamson (2019) ]

# Naive dynamic veto

## ✦ CMS-SUS-17-009: static and central veto

✤ Hadronic activity: no jet

✤ Leptonic activity: $p_T^{\mu_1} > 50\ \mathrm{GeV}, \quad p_T^{\mu_2} > 20\ \mathrm{GeV}$

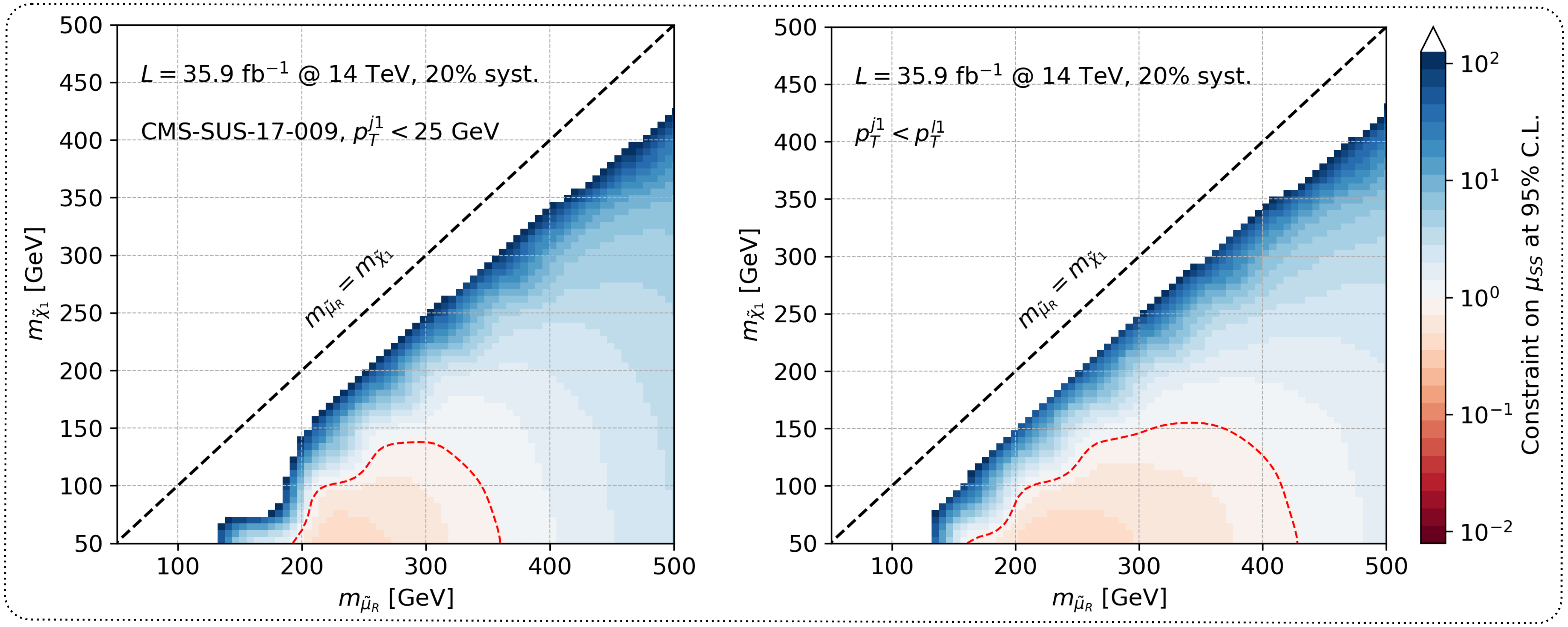
Reference

## ✦ A first naive dynamic jet veto analysis: $p_T(j_1) < p_T(l_1)$

✤ Removal of all lepton cuts (they affect the signal too much)

✤ The leading muon $p_T$ as a measure of the leptonic activity

Improvement of 15%



# Other schemes for dynamic jet vetoes

## ✦ CMS-SUS-17-009: static and central veto

- Hadronic activity: no jet
- Leptonic activity: $p_T^{\mu_1} > 50\ \mathrm{GeV}, \quad p_T^{\mu_2} > 20\ \mathrm{GeV}$

Reference

## ✦ A first naive dynamic jet veto analysis: $p_T(j_1) < p_T(l_1)$

- Removal of all lepton cuts (they affect the signal too much)
- The leading muon $p_T$ as a measure of the leptonic activity

Improvement of 15%

## ✦ Other measures for the leptonic activity

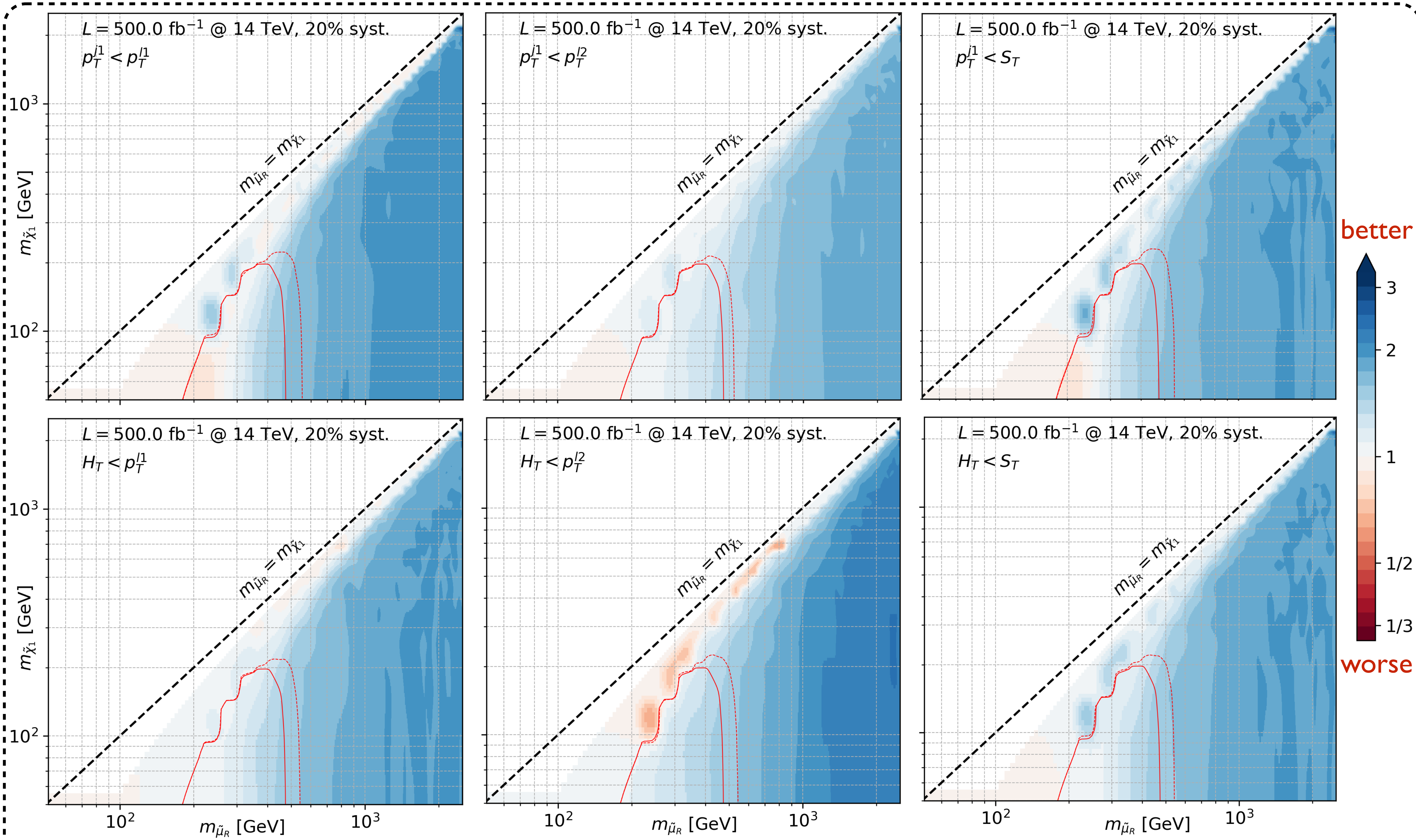
- Removal of all lepton cuts (relatively to the reference analysis)
- The next-to-leading muon $p_T$ as a measure of the leptonic activity
- The $S_T$ variable (sum of the $p_T$ of both muons)

## ✦ Other measure for the hadronic activity

- The (inclusive) $H_T$ variable

Veto events in which
'hadronic activity' > leptonic activity'

# Dynamic jet vetoes: results (I)




$\mu_{SS}$(ref.) / $\mu_{SS}$(new) → Increase in sensitivity (> 1). Different schemes → different parameter space regions

# Dynamic jet vetoes: summary

✦ Dynamic jet vetoes ≡ comparison of leptonic/hadronic activities

- ✤ Increase in sensitivity at the 25−50% level
- ✤ This holds for much of the parameter space

✦ Potential strategy

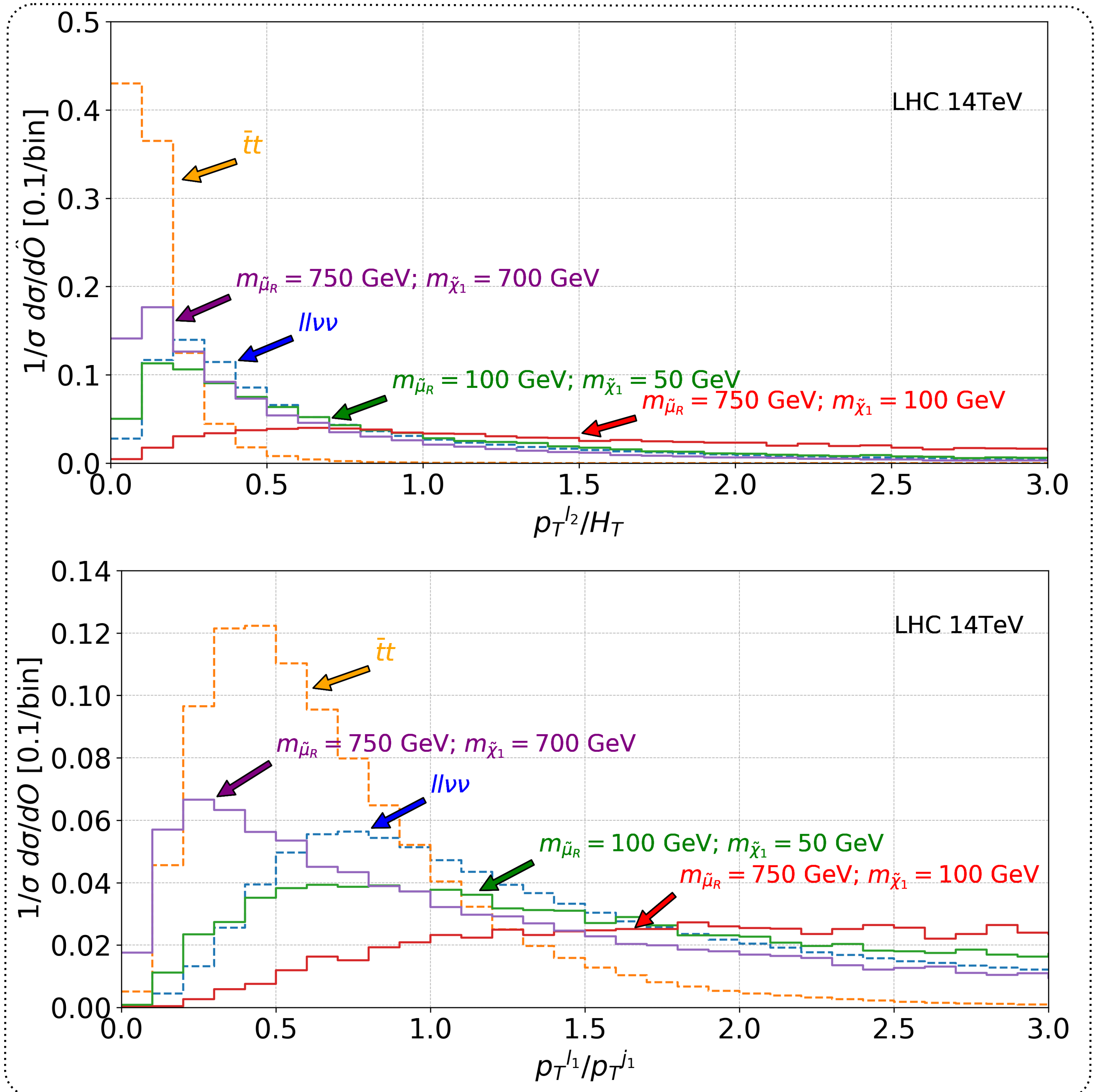
- ✤ Considering several dynamic jet veto schemes
- ✤ Combination of the regions to maximise the gain

✦ Further improvements

- ✤ Different relative behaviours of the leptonic and hadronic activities for S and B
- ✤ Relaxing the jet centrality requirements

# Improvement of the veto criterion

✦ The S and B leptonic and hadronic activities feature different behaviours




- Top background can be killed
- Signal: spectrum dependence
  ≠ analyses targeting ≠ spectra
- Generalising the veto condition
  [most B: at low *r* ]

Veto events in which
'lept. activity' < *r* 'hadr. activity'

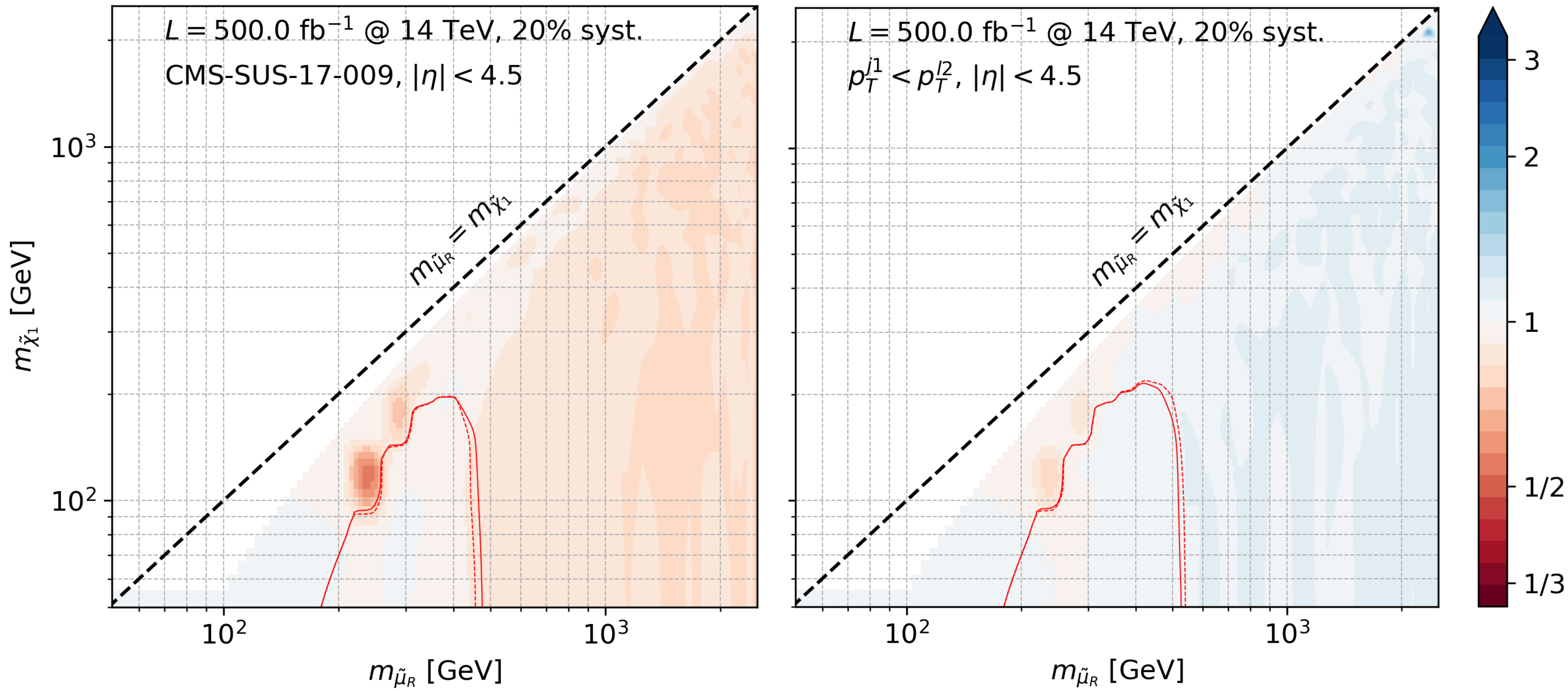
# Centrality requirements

## ✦ Extension of the pseudorapidity window

✤ Jets are allowed to be forward ($|\eta| < 4.5$)

✤ Veto: static (left) or $p_T(j_1) < p_T(\mu_2)$ (right)

Further increase in sensitivity (5 - 20%)
Impossible with static vetoes



# Summary

# Summary

✦ Dynamic jet vetoes ≡ generalized comparison of leptonic/hadronic activities

- On an event by event basis
- Increase in sensitivity at the 25-50 % level
- Smuon example: this holds in much of the parameter space
- Further improvements are possible (centrality, weighting the activities)

✦ Conclusions robust

- Perturbative QCD uncertainties under control
- Underlying events, multiple particle interactions, QCD modelling

✦ Machine-learning based veto?

- Dynamic nature of the proposed analysis

✦ Applications in SM physics?