Combined signatures of heavy Higgses and vector-like fermions

Navin McGinnis
Argonne National Lab

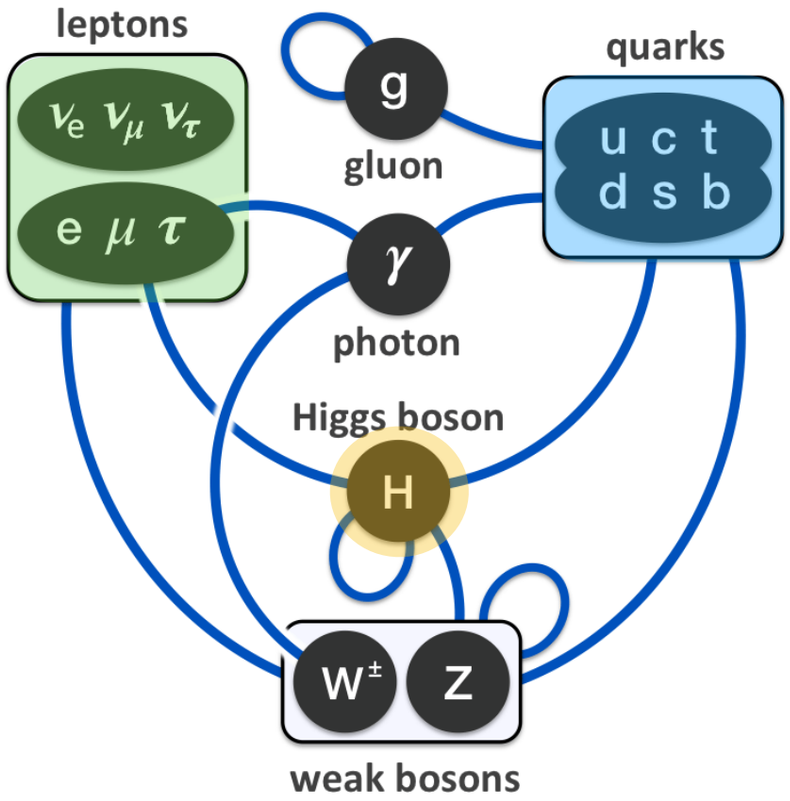
Based on collaboration with Radovan Dermisek, Enrico Lunghi, & Seodong Shin

SNOWMASS EF08: Session on Seesaw and vector-like quarks
Oct. 15, 2020

Argonne NATIONAL LABORATORY

Motivation

Standard Model



What else?

Extended matter sectors

$$Q_{L,R},\ U_{L,R},\ D_{L,R}$$

+

$$L_{L,R},\ E_{L,R},\ N_{L,R}$$

Extended Higgs sectors

$$H,\ A,\ H^{\pm}$$

- No reason for only 3 families
- No reason for 1 Higgs

For me: focus on 2HDM + vector-like fermions

Motivation

Connection to BSM scenarios:

- Composite Higgs
- Supersymmetry
- Z' models
- GUTs
- Etc.

Connection to Pheno:

- $(g-2)_{e,\mu}$
- B-physics
- Cabibbo anomaly
- Etc.

Personal motivation: Understanding of couplings from IR fixed points in MSSM + 1VF: R. Dermisek, NM, arXiv:1812.05240

Direct searches for LHC (typically) focus on production of individual particles

Combined signatures, e.g. cascade decays, presents many new opportunities for searches with many advantages over individual searches

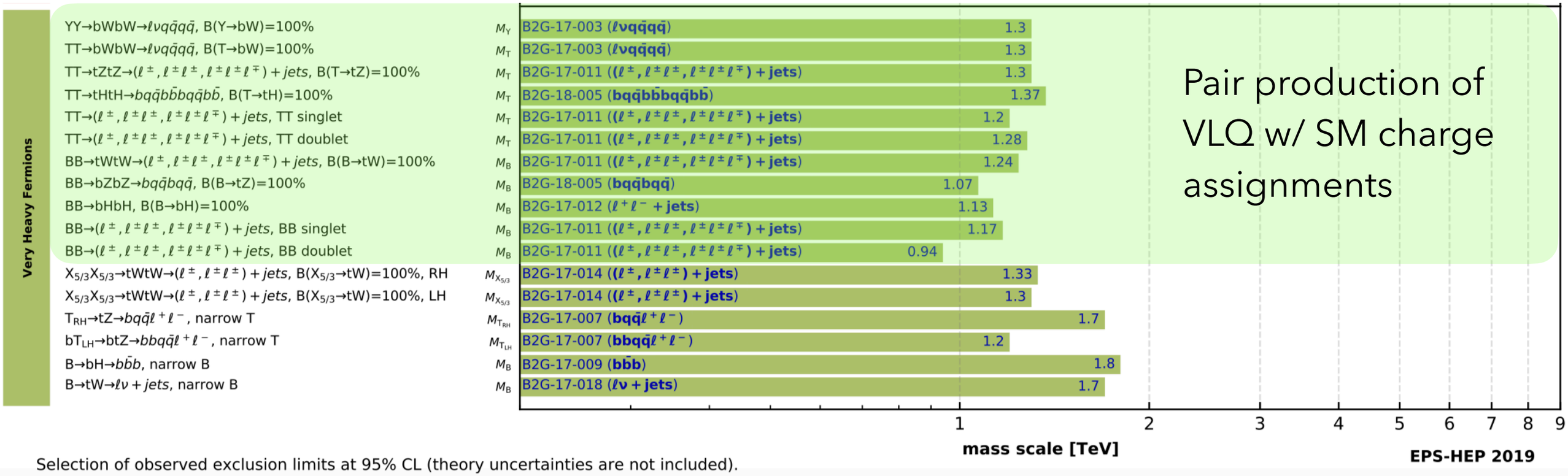
Motivation

Part I: VLQ and heavy Higgses

Part II: VLL and heavy Higgses

VL Quarks + heavy Higgses

CMS Beyond-two-generations (B2G) Public Physics Results



Pair production of VLQ w/ SM charge assignments

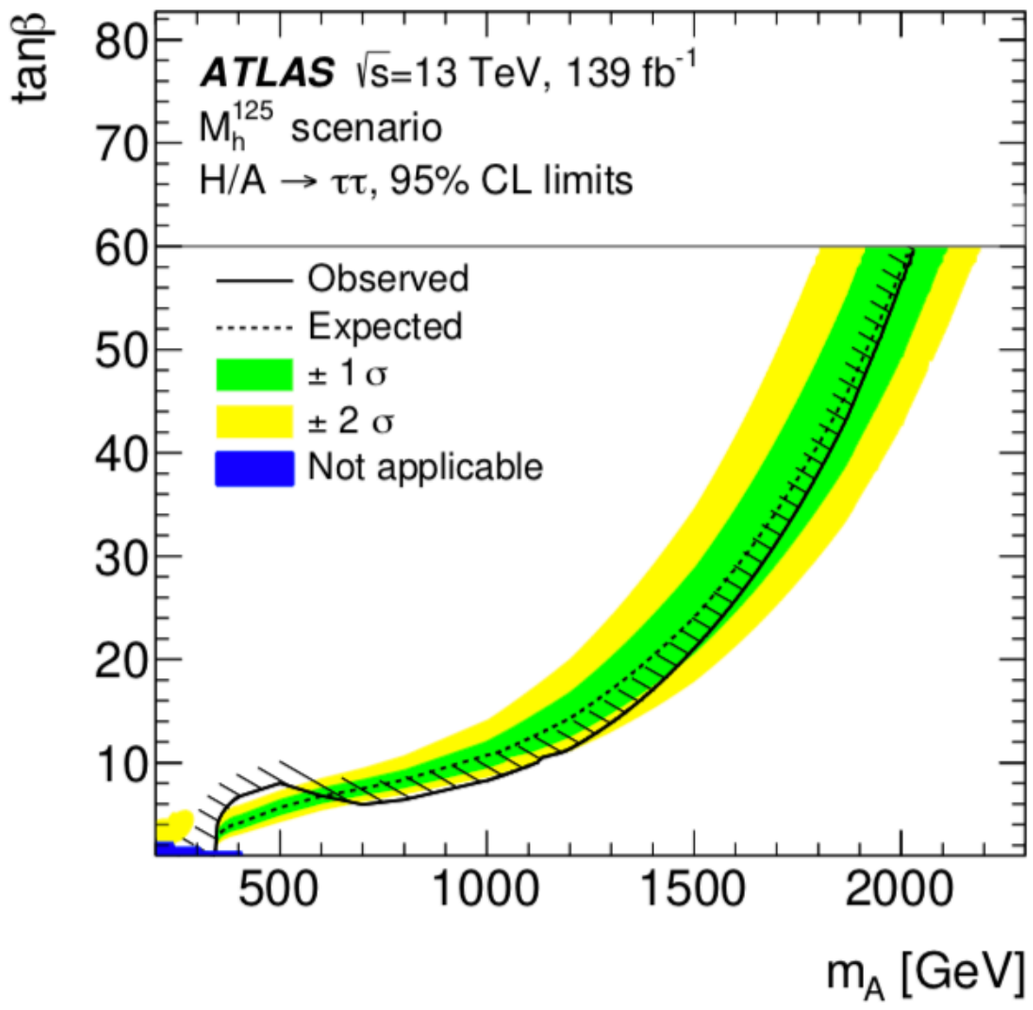
Exclusion of VLQ up to 1.2 ~ 1.4 TeV

IMPORTANT: Assumes 100% BRs to only SM states

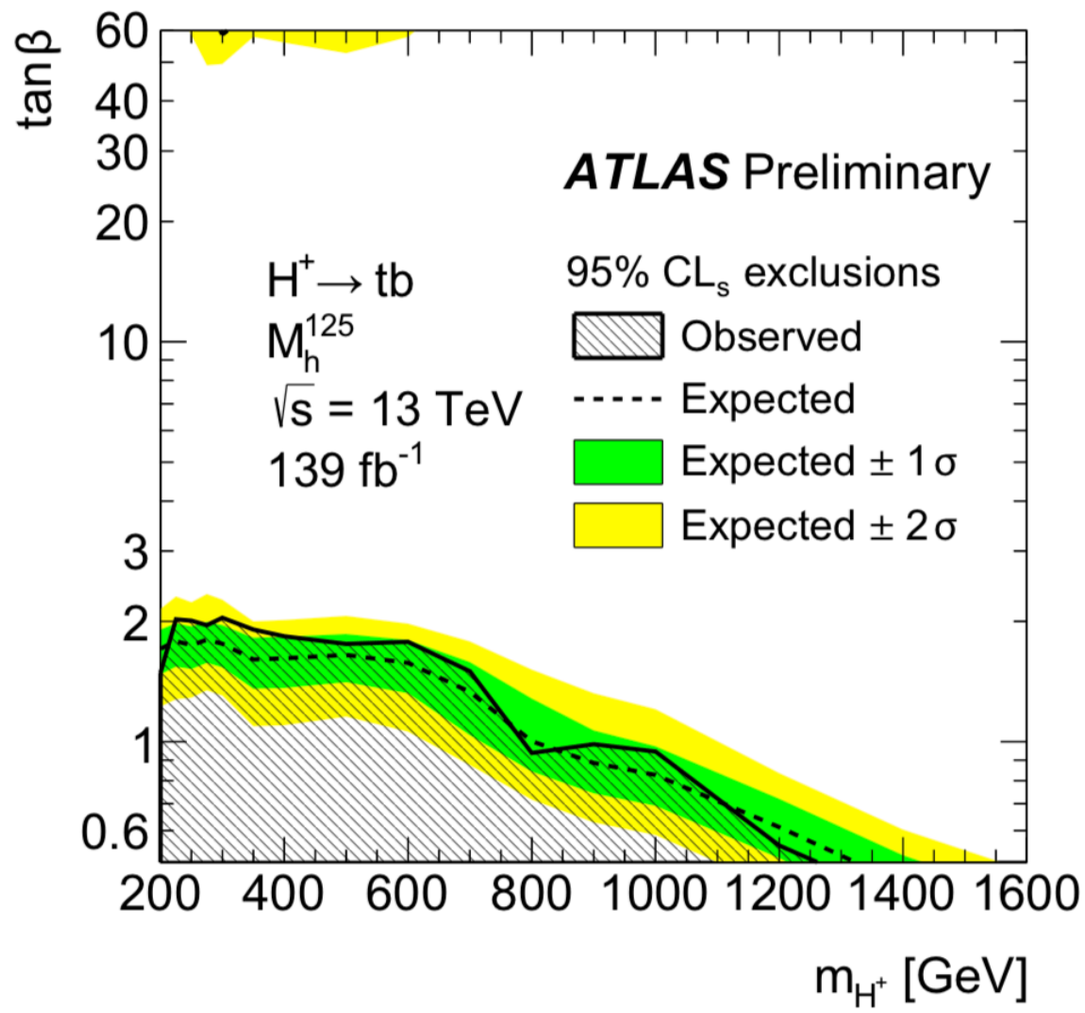
Similar results (and assumptions) from ATLAS: **http://cds.cern.ch/record/2718942?ln=en**

VL Quarks + heavy Higgses

CERN-EP-2020-014

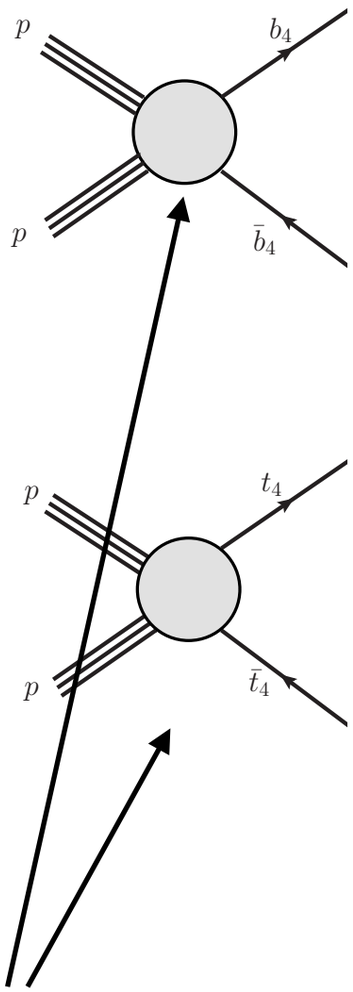


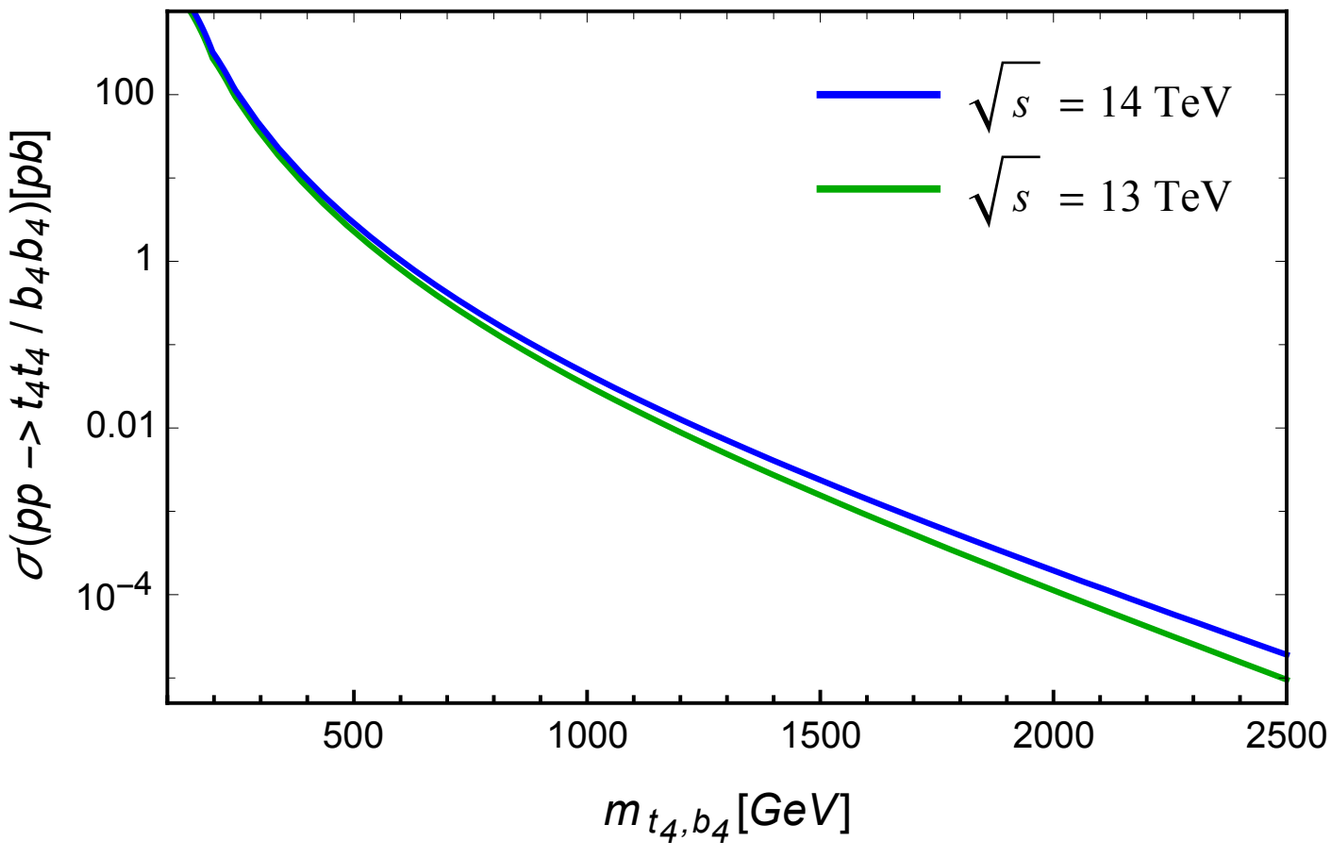
ATLAS-CONF-2020-039



For me: focus on type-II 2HDM scenarios

VL Quarks + heavy Higgses



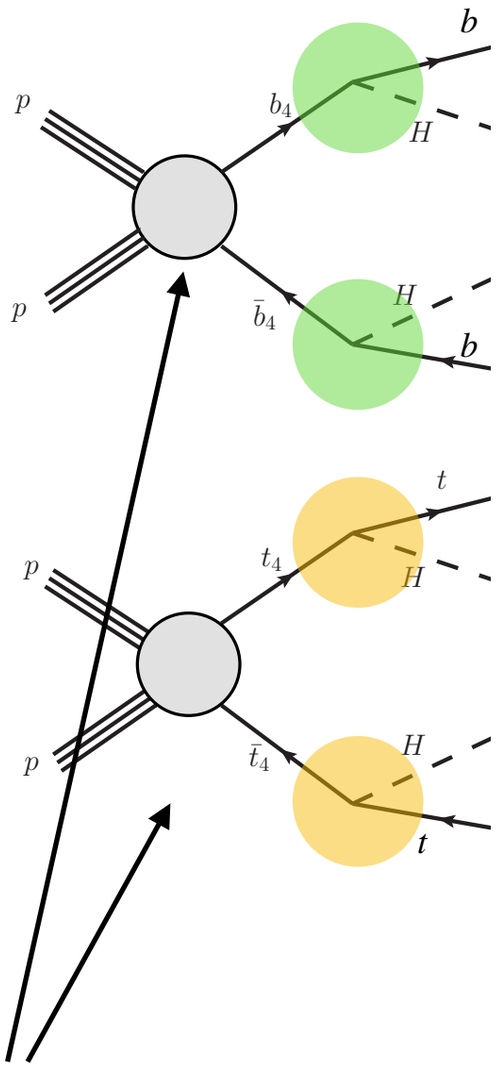


QCD cross section,
model independent,
$\sigma(m_{t4,\, b4} = 1 \text{ TeV}) \simeq 50$ fb

R. Dermisek, E. Lunghi, NM, S. Shin: arXiv:2005.07222

R. Dermisek, E. Lunghi, S. Shin: arXiv:1901.03709

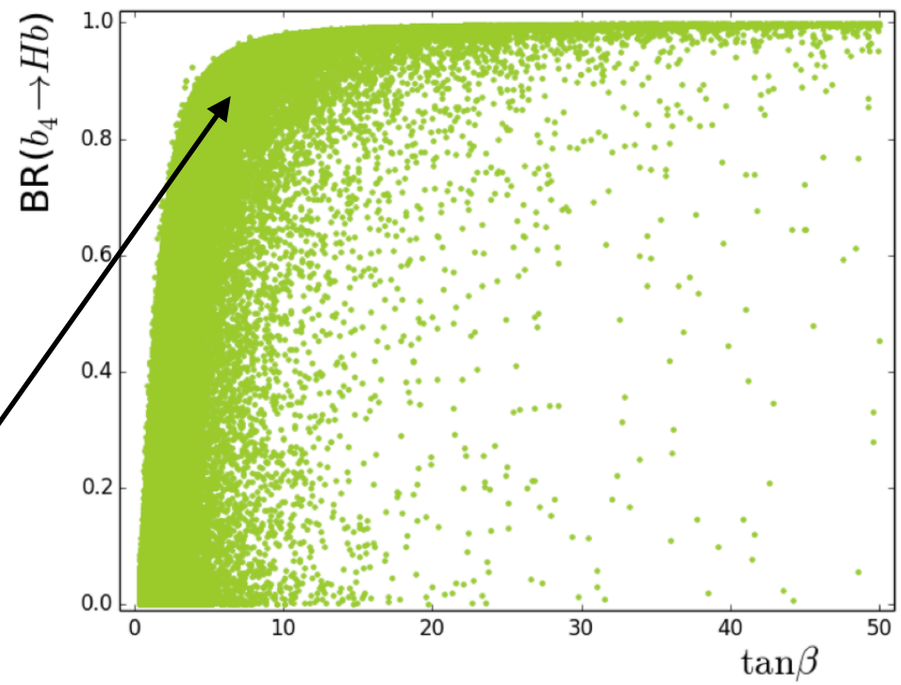
VL Quarks + heavy Higgses

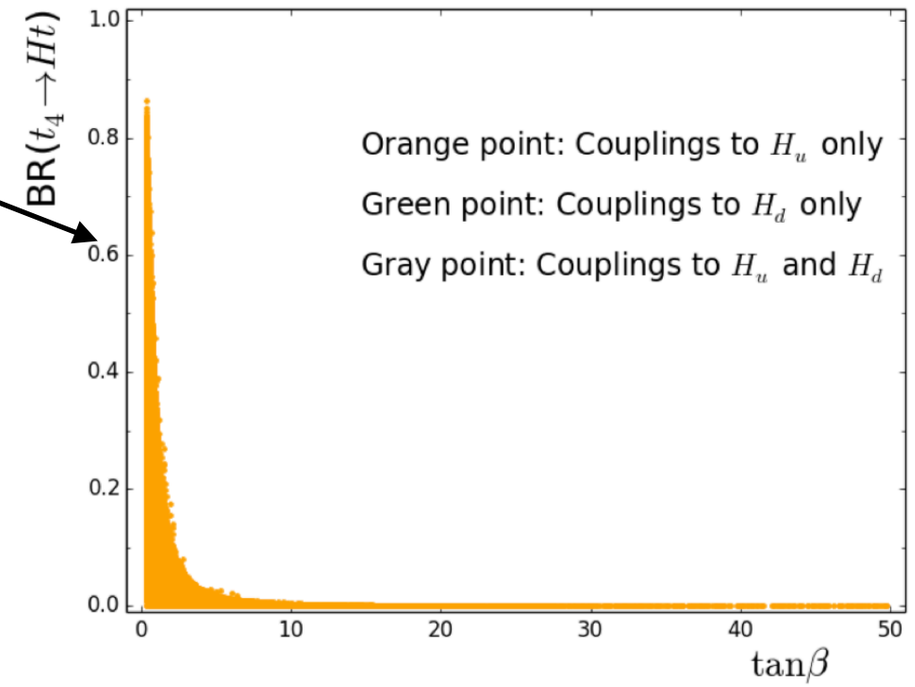


QCD cross section,
model independent,
$\sigma(m_{t4,\, b4} = 1 \text{ TeV}) \simeq 50$ fb

Branching ratios
~100% to
SM + HH

VLQ + 2HDM



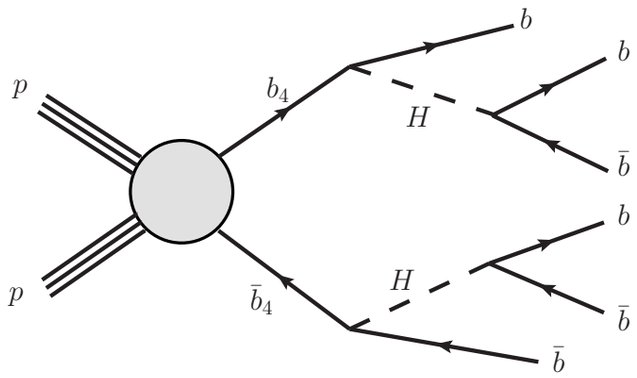


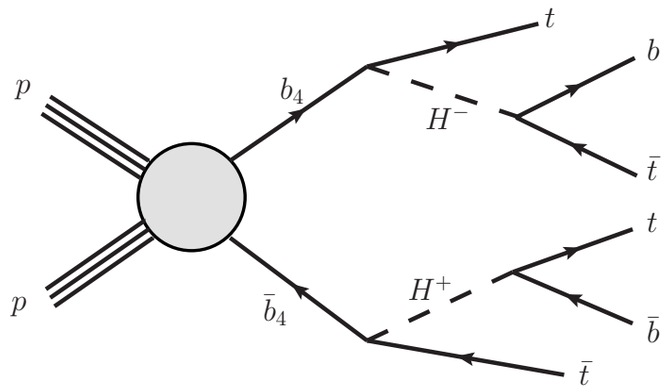
(Assuming couplings as in type-II
2HDM and single heavy Higgs decay channel open)

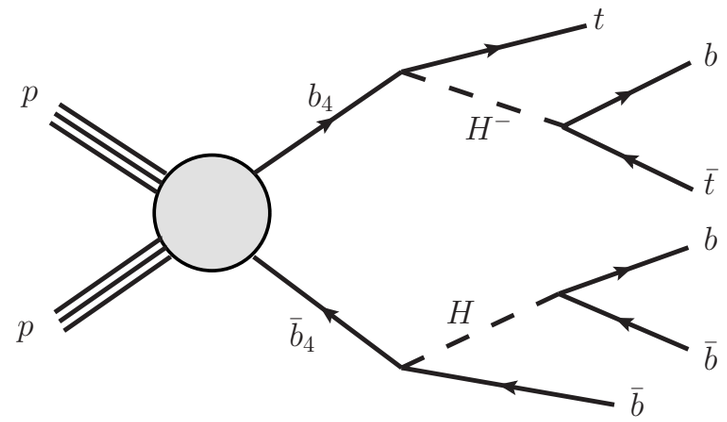
R. Dermisek, E. Lunghi, NM, S. Shin: arXiv:2005.07222

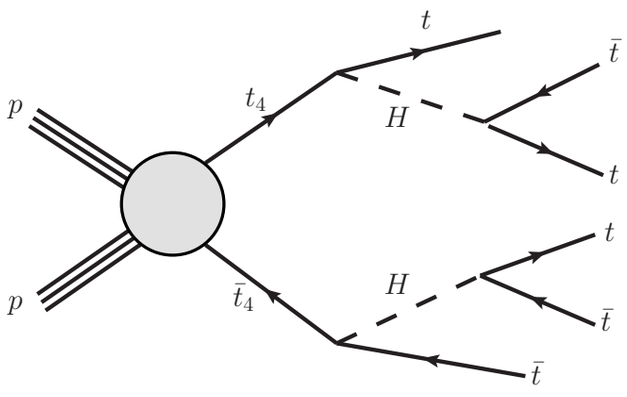
R. Dermisek, E. Lunghi, S. Shin: arXiv:1901.03709

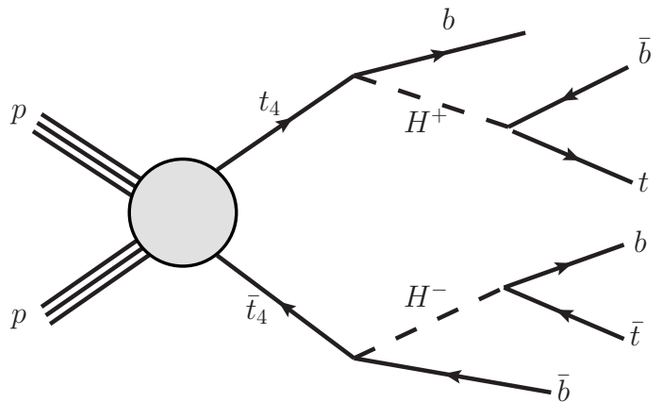
VL Quarks + heavy Higgses

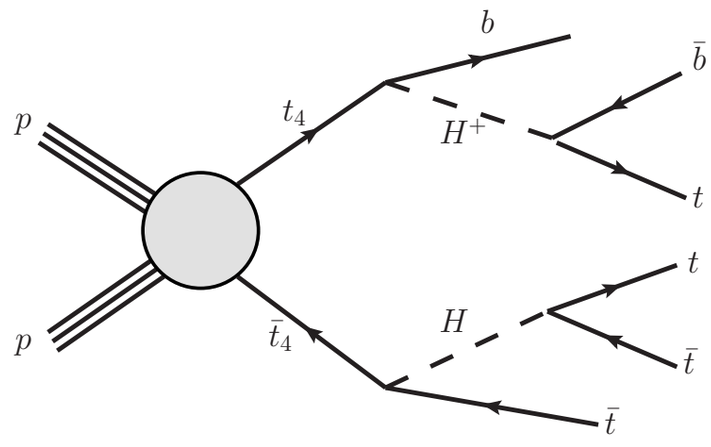












-Including extended Higgs sector, as in 2HDM, opens many possible search channels

-Heavy Higgses produced with QCD size cross sections

-Can simultaneously probe decay patterns of VLQs and heavy Higgs

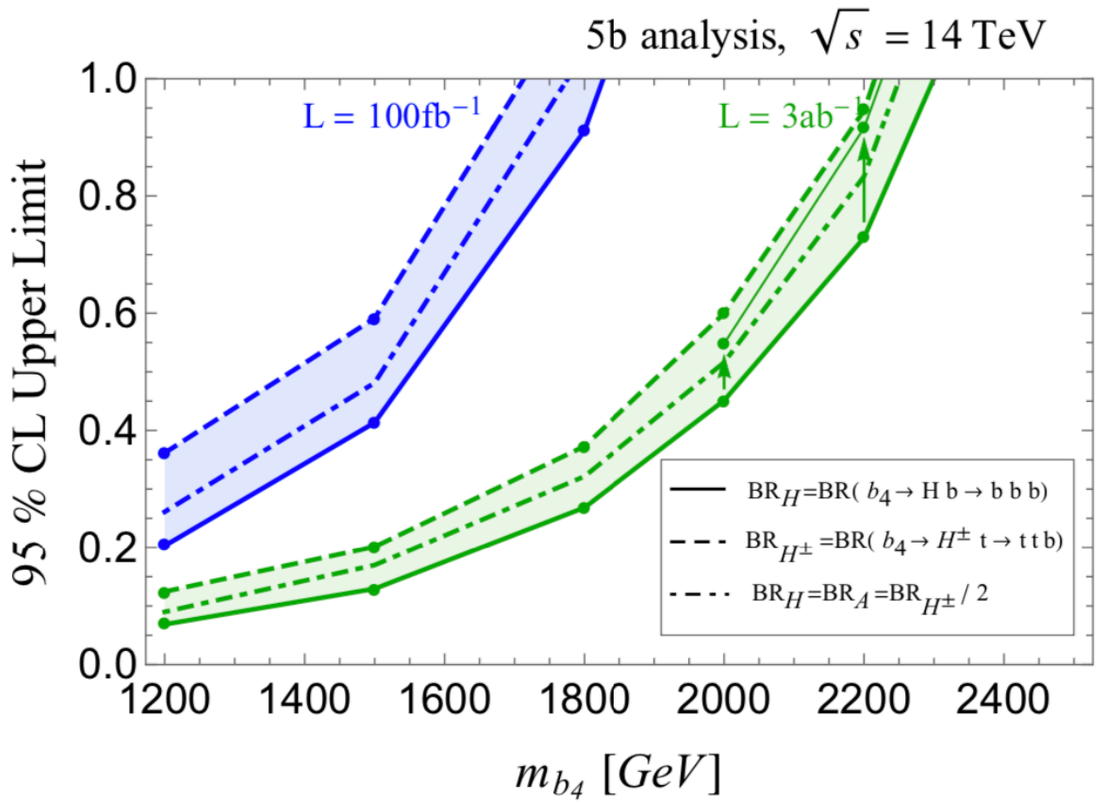
Bottom rich environment common signature!

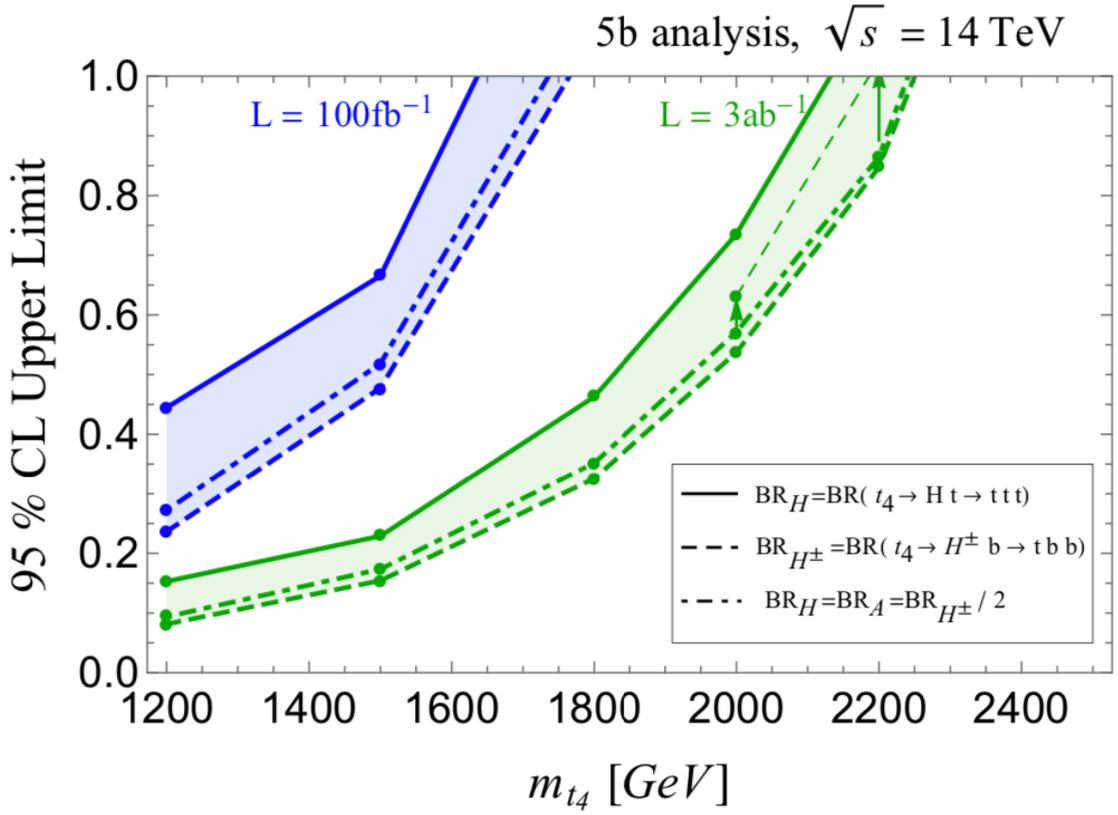
R. Dermisek, E. Lunghi, NM, S. Shin: arXiv:2005.07222

R. Dermisek, E. Lunghi, S. Shin: arXiv:1901.03709

VL Quarks + heavy Higgses

Reach for analysis based on 5 b-tagged jets:





LHC @ 139 fb^{-1} sensitive to heavy Higgses ~ 1.6 TeV

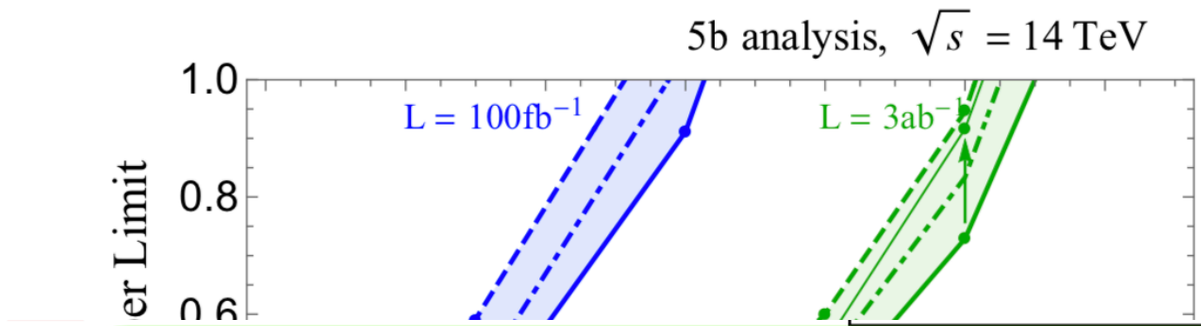
HL-LHC sensitive to heavy Higgses ~ 2 TeV

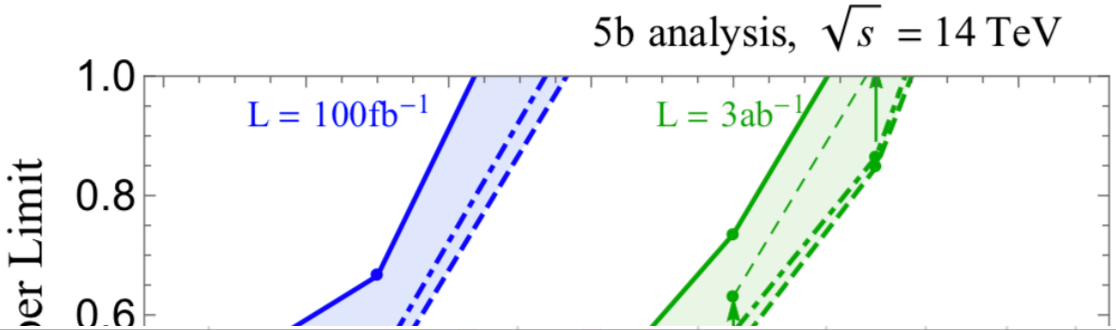
R. Dermisek, E. Lunghi, NM, S. Shin: arXiv:2005.07222

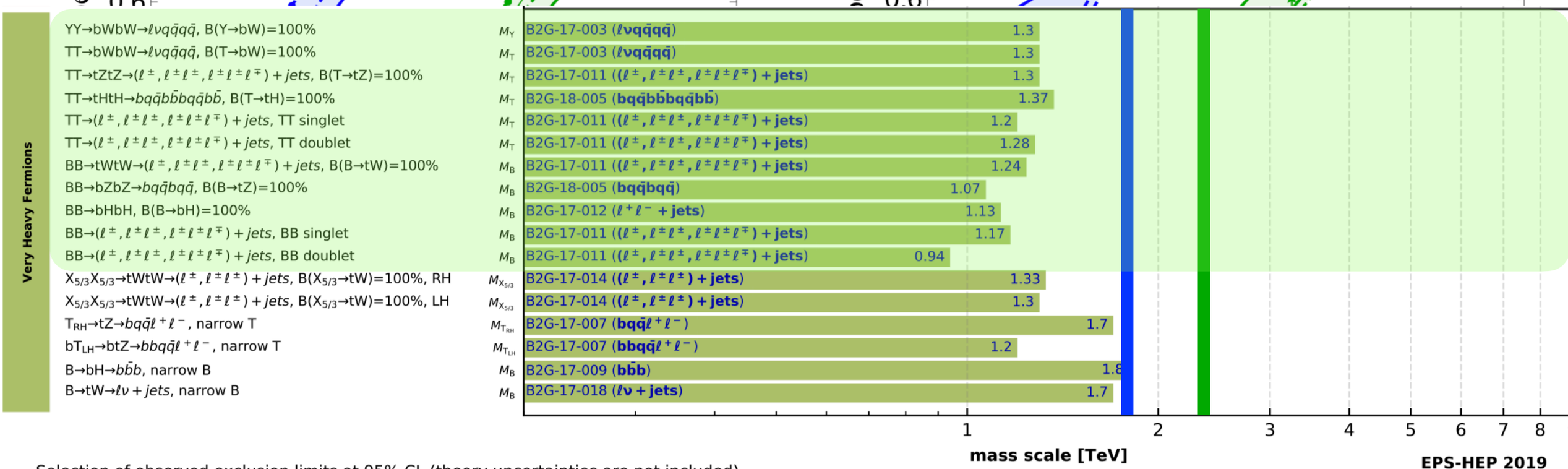
R. Dermisek, E. Lunghi, S. Shin: arXiv:1901.03709

VL Quarks + heavy Higgses

Reach for analysis based on 5 b-tagged jets:







Selection of observed exclusion limits at 95% CL (theory uncertainties are not included).

R. Dermisek, E. Lunghi, NM, S. Shin: arXiv:2005.07222

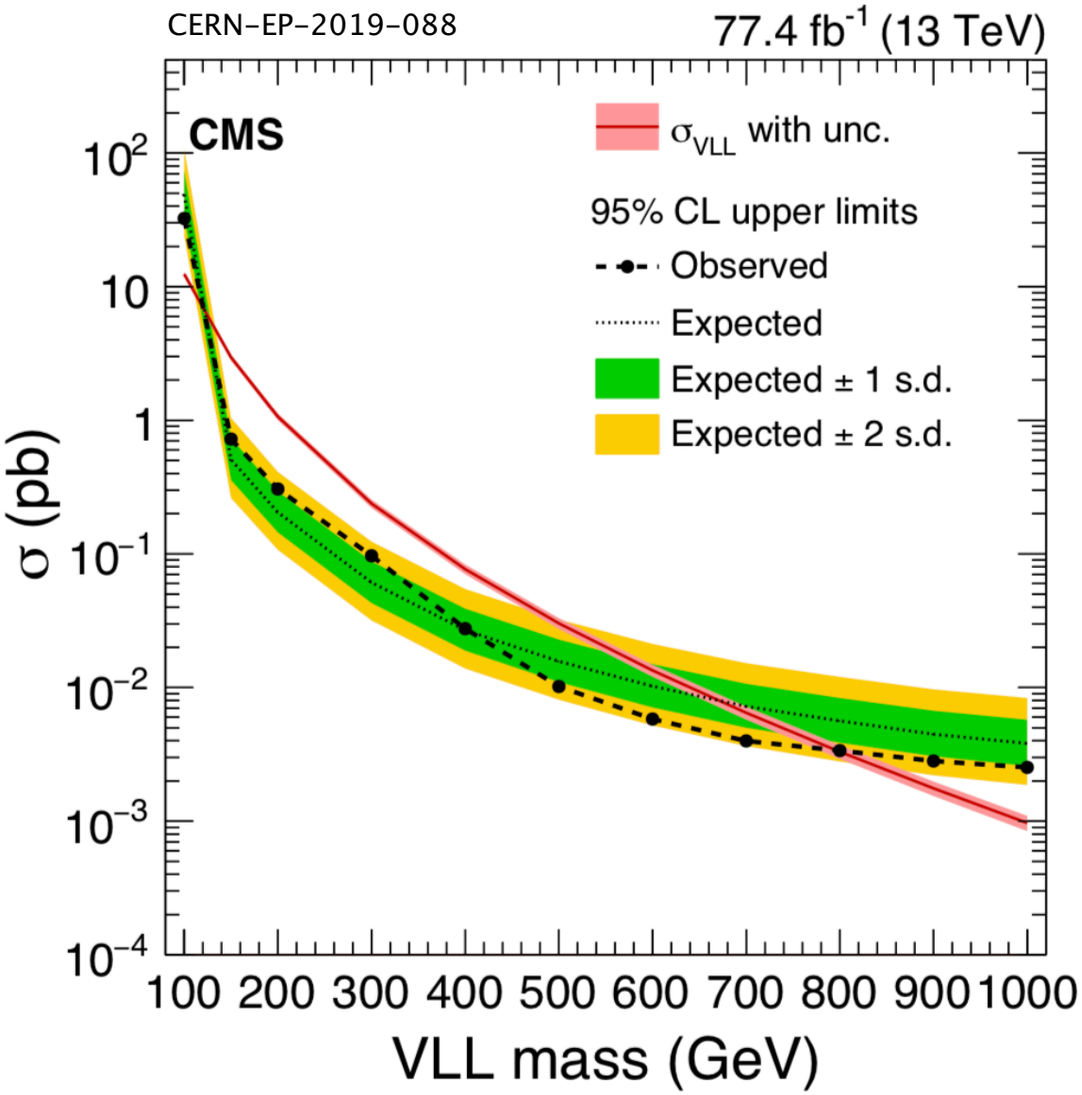
R. Dermisek, E. Lunghi, S. Shin: arXiv:1901.03709

Motivation

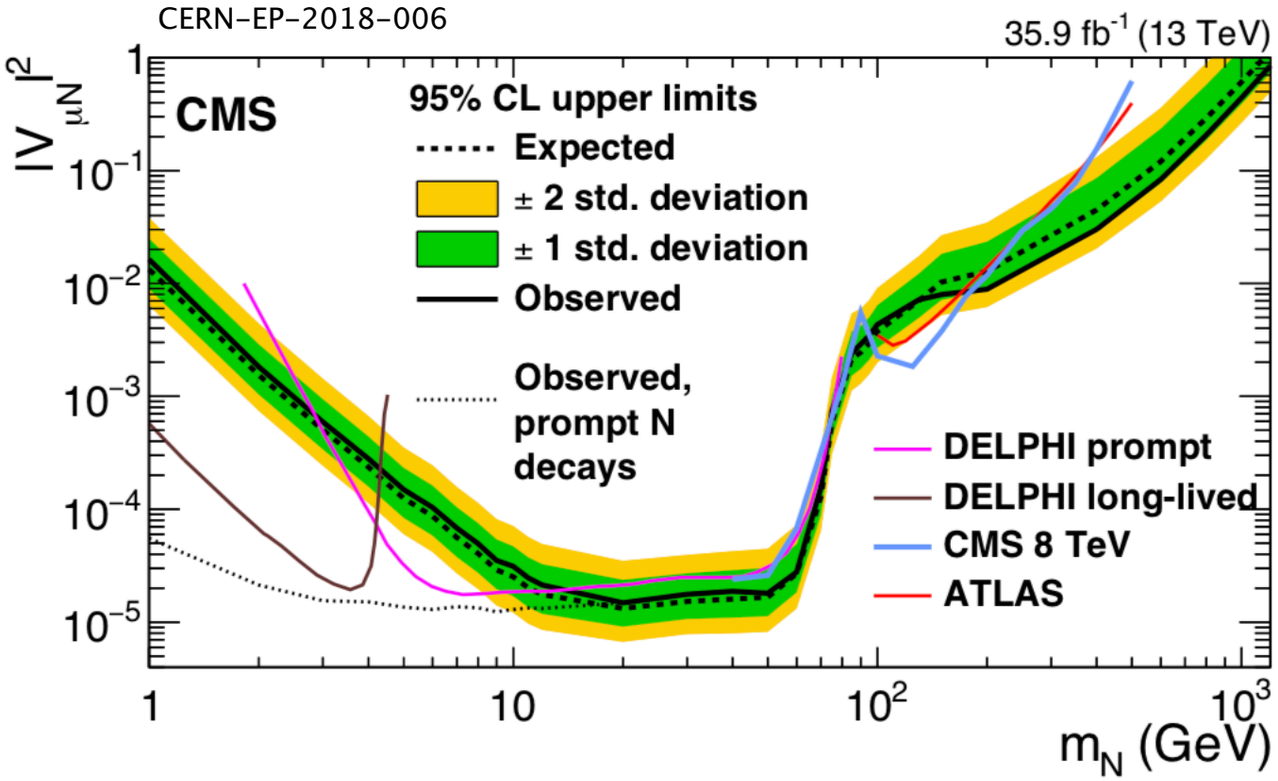
~~Part I: VLQ and heavy Higgses~~

Part II: VLL and heavy Higgses

VL Leptons + heavy Higgses



Assuming charged doublet: $m_{e4} \geqslant 790$ GeV

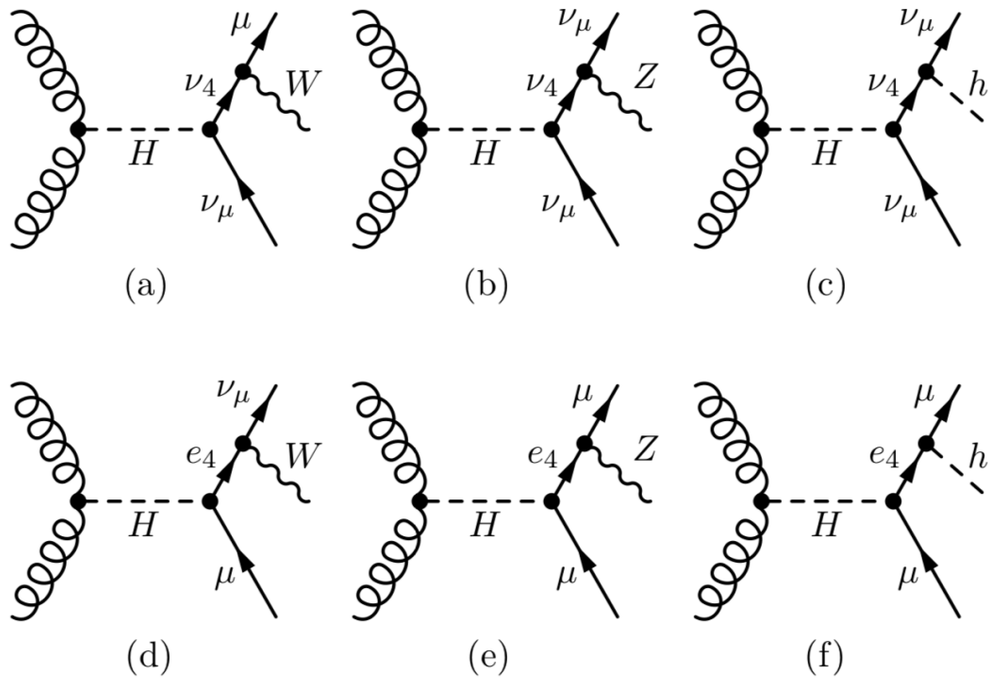


Heavy neutral lepton

$|V_{\mu N}|^2 \simeq 0.01$: $m_N \geqslant 200$ GeV

Again: many assumptions on BR which (likely) do not apply when mixing to other NP states is allowed

VL Leptons + heavy Higgses



Enhanced production rates:

$$\sigma(m_H = 3 \text{ TeV}) \simeq 0.2 \text{ fb}$$

Compared w direct pair production (for charged $SU(2)$ doublet):

$$\sigma(m_L = 2 \text{ TeV}) \simeq 0.4 \text{ ab}$$

R. Dermisek, E. Lunghi, S. Shin: arXiv:1512.07837

R. Dermisek, E. Lunghi, S. Shin: arXiv:1608.00662

R. Dermisek, E. Lunghi, S. Shin: arXiv:1907.07188

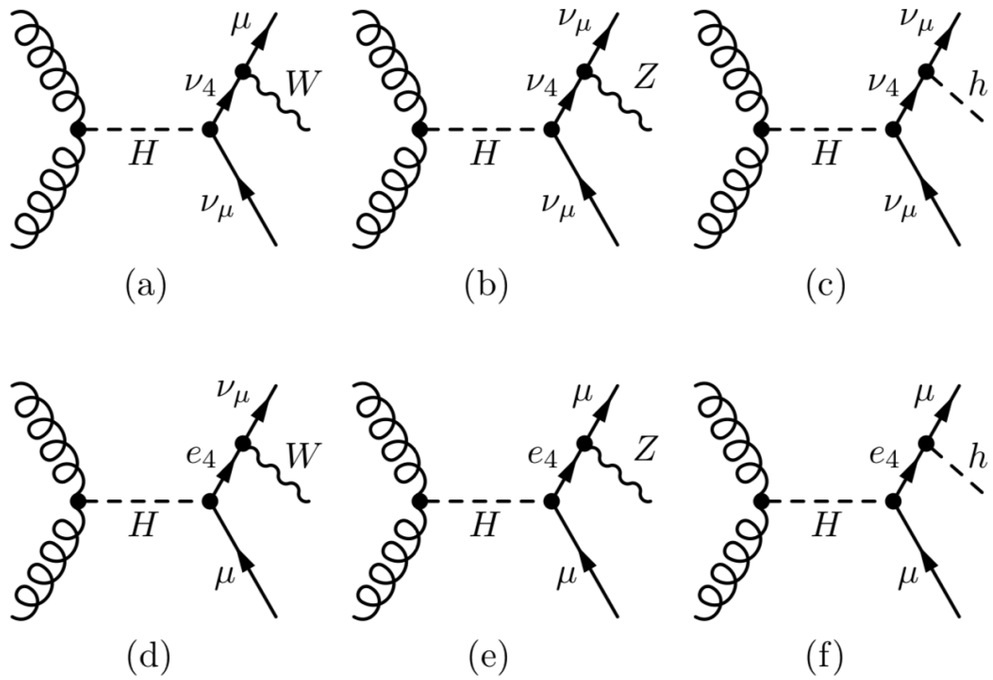
VL Leptons + heavy Higgses

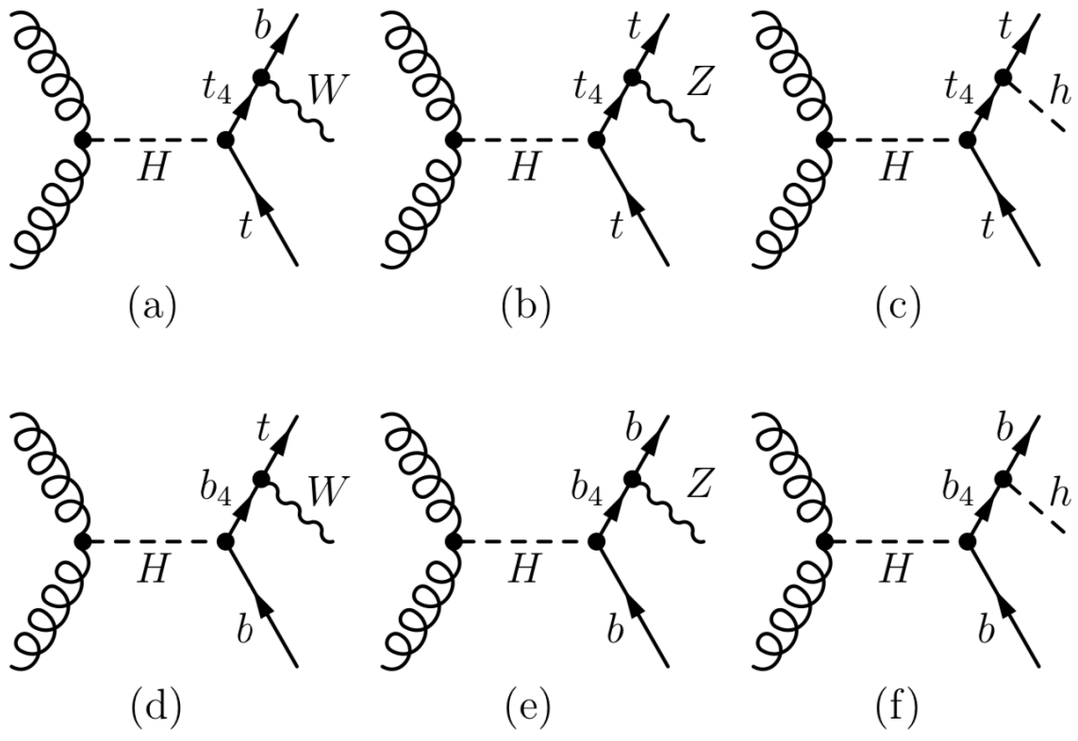
Enhanced production rates:

$$\sigma(m_H = 3 \text{ TeV}) \simeq 0.2 \text{ fb}$$

Compared w direct pair production (for charged $SU(2)$ doublet):

$$\sigma(m_L = 2 \text{ TeV}) \simeq 0.4 \text{ ab}$$





(Similar signatures with e, τ, or quarks)

R. Dermisek, E. Lunghi, S. Shin: arXiv:1512.07837

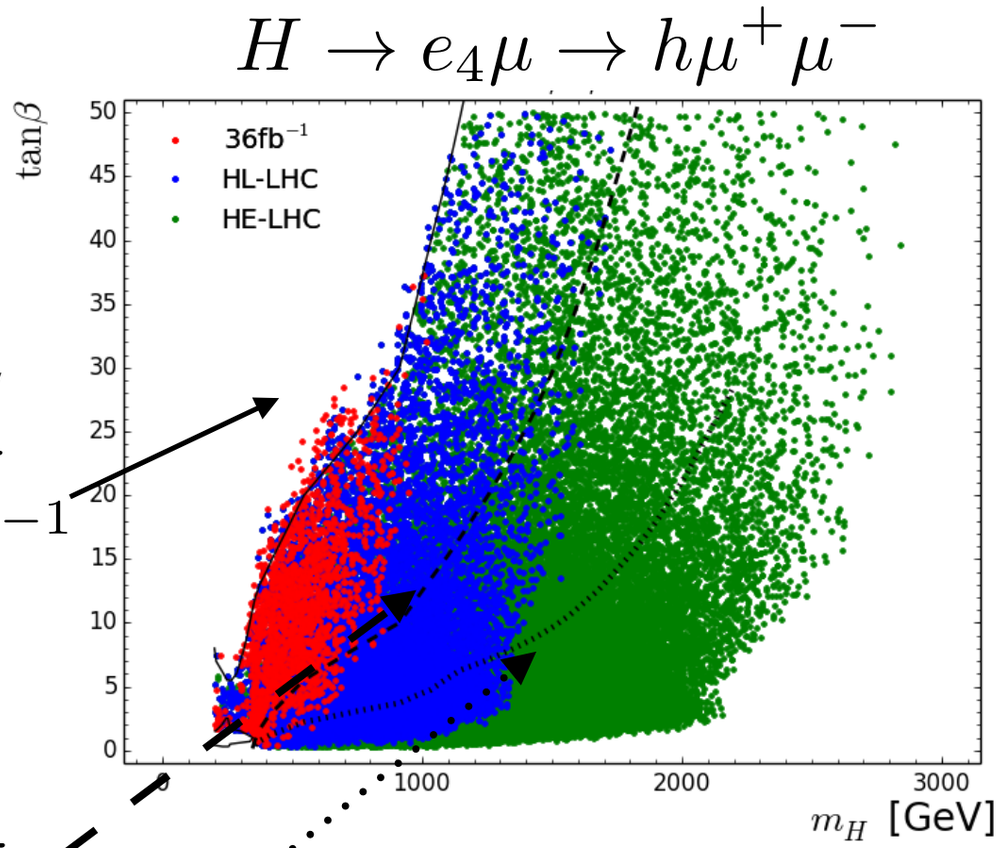
R. Dermisek, E. Lunghi, S. Shin: arXiv:1608.00662

R. Dermisek, E. Lunghi, S. Shin: arXiv:1907.07188

VL Leptons + heavy Higgses

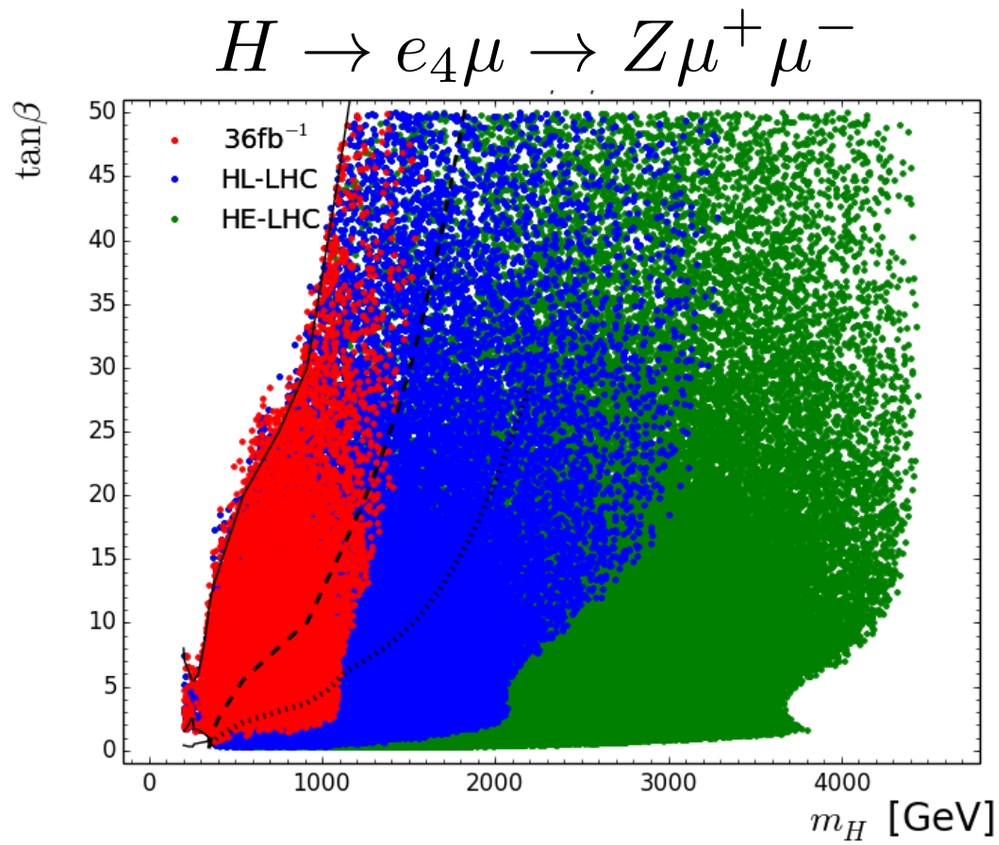
Sensitivity to $H \to h\mu\mu,\ Z\mu\mu$ @ HL-LHC

CERN-LPCC-2018-05



excluded by
$H \to \tau\tau$
with $36\,\mathrm{fb}^{-1}$

projected
$H \to \tau\tau$
at HL-LHC and at HE-LHC

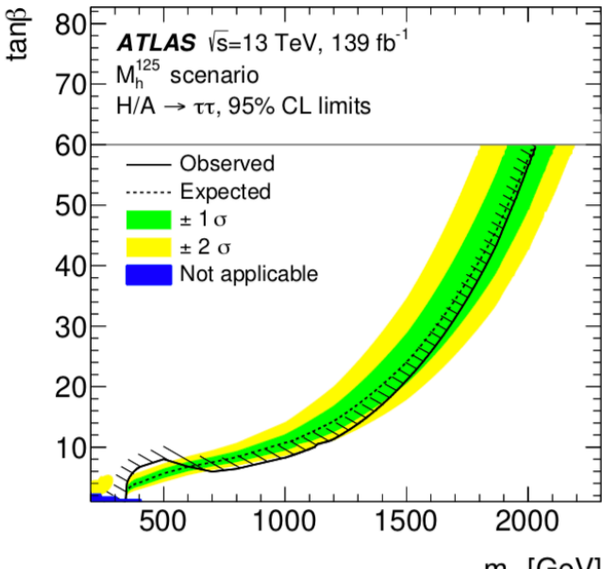


(Scenarios satisfying all relevant limits at 95% CL)

HL(HE)-LHC sensitive to heavy Higgses up to ~3(4.5) TeV

VL Leptons + heavy Higgses

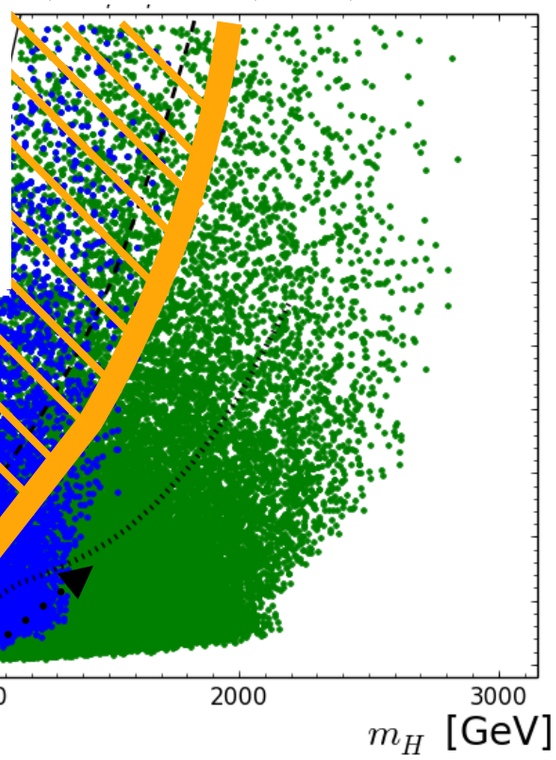
Ser



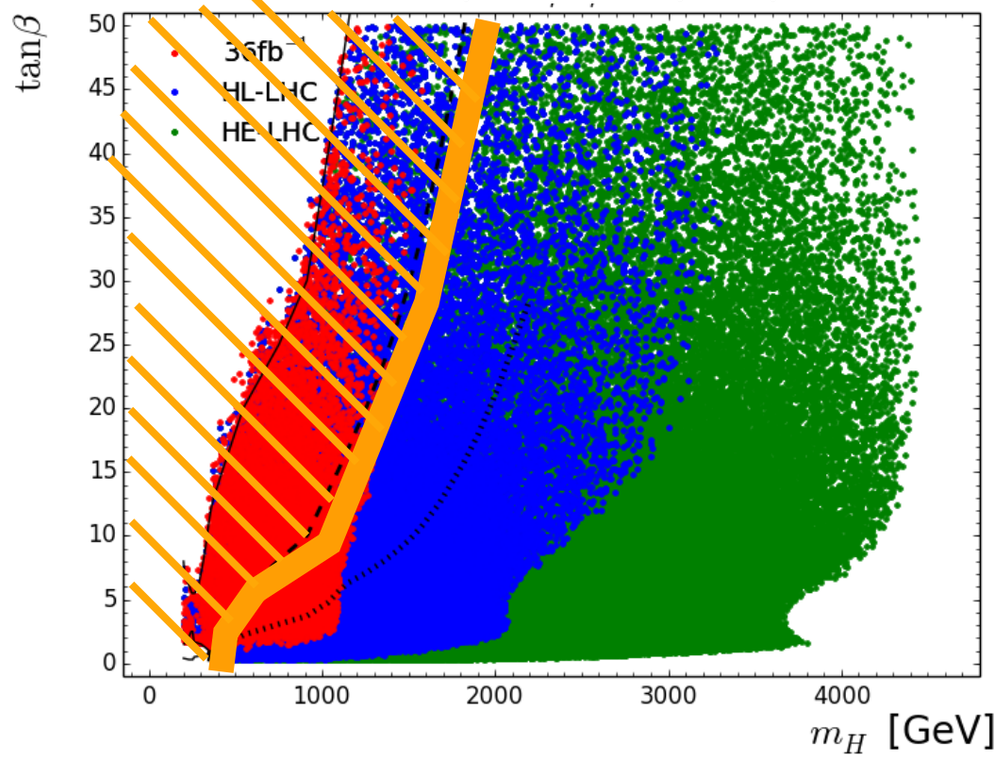
$Z\mu\mu$ @ HL-LHC

CERN-LPCC-2018-05

$_4\mu \to h\mu^+\mu^-$



$H \to e_4\mu \to Z\mu^+\mu^-$



excluded by
$H \to \tau\tau$
with $36\,\mathrm{fb}^{-1}$

projected
$H \to \tau\tau$
at HL-LHC and at HE-LHC

(Scenarios satisfying all relevant limits at 95% CL)

HL(HE)-LHC sensitive to heavy Higgses up to ~3(4.5) TeV

Motivation

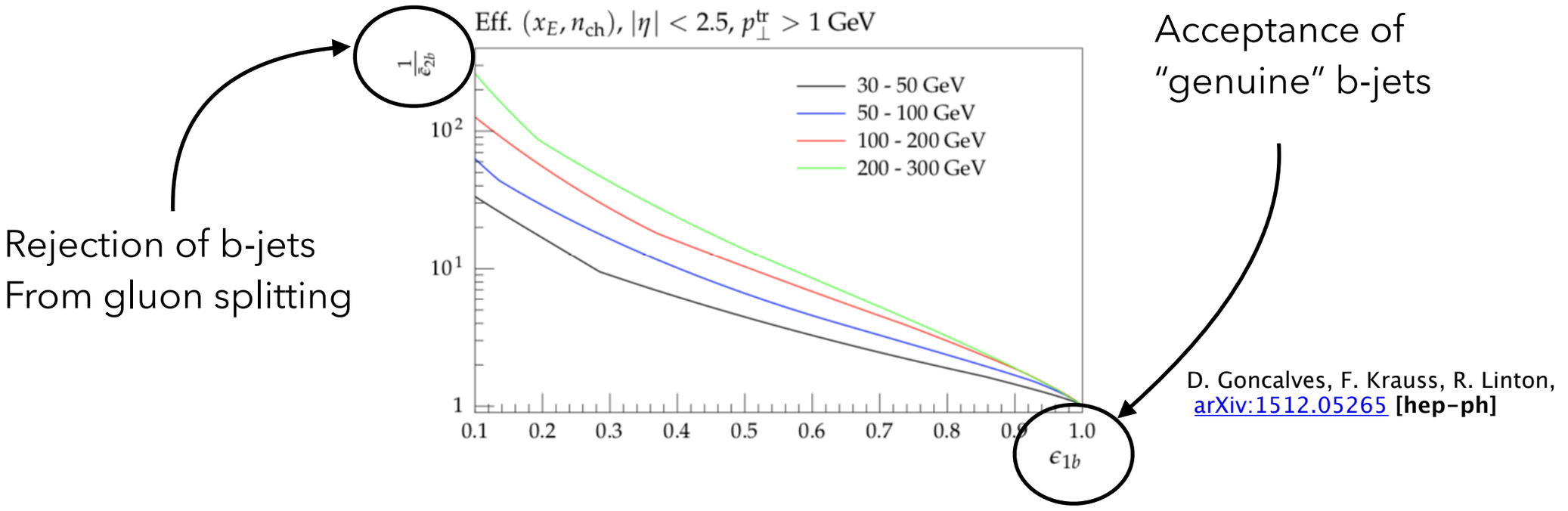
~~Part I: VLQ and heavy Higgses~~

~~Part II: VLL and heavy Higgses~~

Useful inputs going forward:

VLQ analysis with b-tagging:

- bottom rich environment
- Challenging to simulate backgrounds
  - $t \to W + b$ vs. $g \to bb$



Acceptance of
"genuine" b-jets

Rejection of b-jets
From gluon splitting

D. Goncalves, F. Krauss, R. Linton,
arXiv:1512.05265 **[hep-ph]**

- Monte Carlo data for mulit-jet/b may be useful input for many VLQ analyses

Working groups:

- Composite Higgs: some overlap with neutral Higgs decays
- W′, Z′ : some overlap for intermediate boson decay, though rates/couplings different
- Other models benchmarks: VLF with heavy Higgs sector

Conclusions:

- Models with extended Higgs sectors and/or vector-like fermions are among the simplest extensions of the SM

- Pheno can connect to different types of UV completions (under various assumptions)

- Combined signatures of heavy Higgses + VLF offers many opportunities for interesting search strategies

- Some plans:
  - VLQ searches w other Higgs Decays e.g. $t_4 \to H^{\pm} + b \to \tau^{\pm} + \nu_{\tau} + b$
  - Improved b-tagging procedures: kinematics, “2b” jets, etc.
  - Detailed analyses of Higgs cascade decay channels
  - Comments, suggestions, and collaborations welcome!

Thanks!