12/26 @ Osaka University

Taking Aim at Electroweakly Charged Fermions at the HL-LHC

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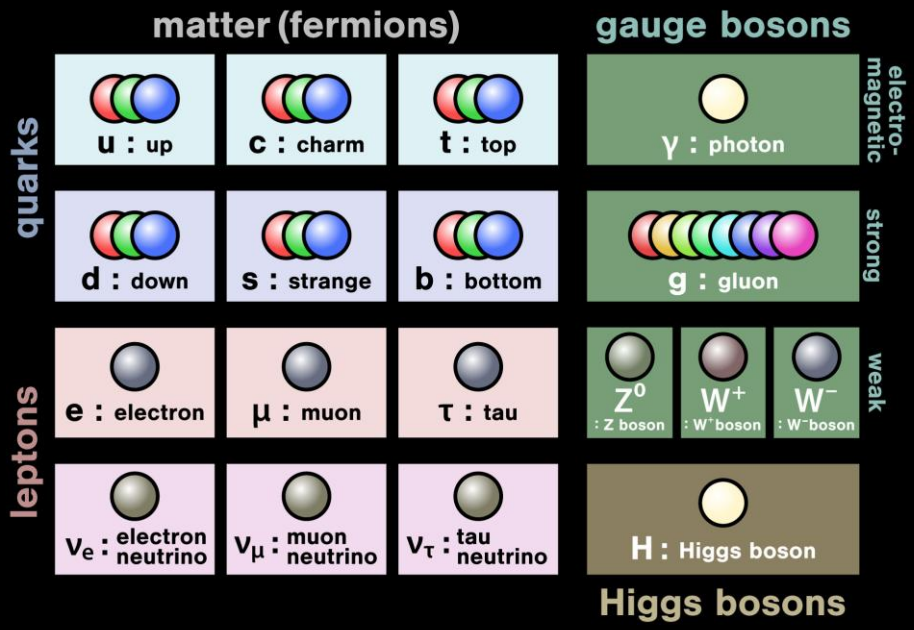
JK, S.Shin 2308.07814 [JHEP]
R.Dermisek, JK, E.Lunchi, N.McGinnis, S.Shin 2204.13272 [JHEP]
JK, S.Raby 2104.04461 [PRD]
L.Carpenter, H.Gilmer, JK 2110.04185 [PLB]
L.Carpenter, H.Gilmer, JK, T.Murphy 2309.07213 [PRD]

EW fermions: basics

In this talk, I focus on exotic electroweak [EW] fermions

➢ What are EW fermions ?

- having **charges under the EW** gauge symmetry, but **no color**
- further, we focus on $SU(2)_L$ **doublet** or **singlet**



+

✓ spin ?

$s = 0, \mathbf{1/2}, 1 \cdots$

✓ charge ?

w./**wo.** color, EW charge ?

✓ mass ?

below/above TeV ?

EW fermions: collider perspective

production cross section is smaller than colored particles

- easily be covered under the QCD backgrounds
- typically, we need (multiple) **leptons**, **missing ET**, or more exotic signals

➢ Collider signals: classification by lepton number L

new EW fermion

$|L| > 0$

- $|L|$ leptons in final states
- e.g. RH neutrino, **VL lepton**….

$|L| = 0$

- no lepton or $\ell\bar{\ell}$ pairs
- **higgsino**, gaugino, minimal DM ….

Outline

1. Introduction
2. Searches for vector-like leptons
3. Searches for higgsino DM
4. Summary

Vector-like [VL] leptons

- SM fermions
  - are **chiral** under G_{SM}
  - masses **via Higgs** VEV
  - up to **3 gens**, since $y_t \sim \mathcal{O}(1)$
- VL fermions
  - **vector-like** under G_{SM}
  - **bare masses** are allowed
  - more than **4th gen.** is possible

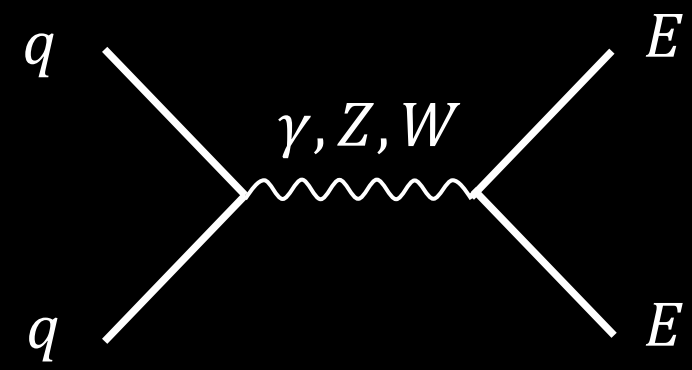
I focus on models with **4th VL leptons** : $(\overline{L}, L)$ and $(\overline{E}, E)$

	$SU(2)_L$-doublet	singlet
	$Y_L = \frac{1}{2}$	$Y_E = -1$

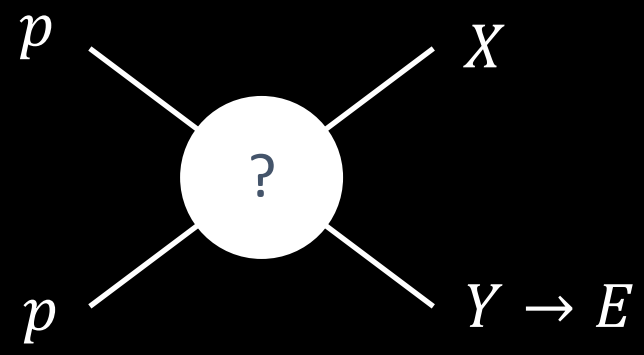
- Why VL leptons ?
  - **ubiquitous** in BSM e.g. KSVZ-like axion, GMSB, composite, DM models…
  - can explain the **recent anomalies** in the experiments

Production and Decays

- Production



pair production



decay from heavier exotic Y

$\sigma \propto \mathrm{Tr}(T_R^a T_R^b)$, given by rep. there may be new bosons, e.g. $Y = H, Z'$

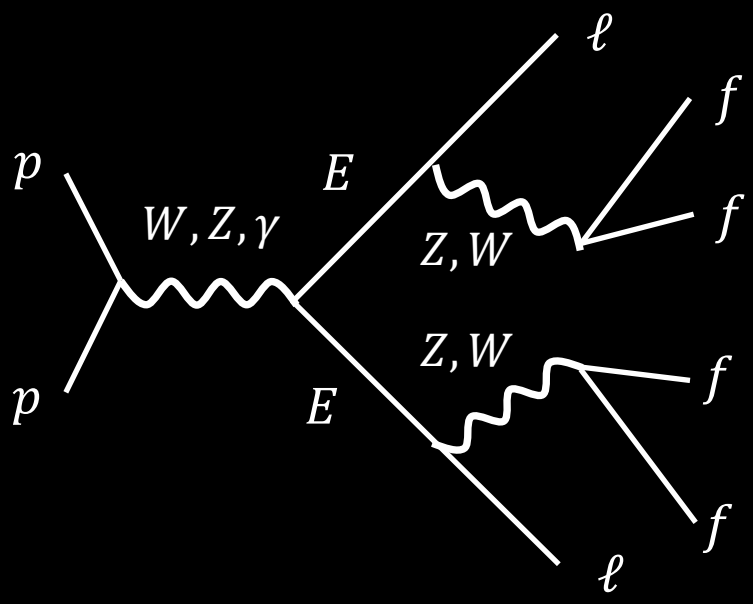
- Decays
  - decay to **SM lepton + SM boson** in minimal case
  - may decay to SM lepton **+ new exotic boson**

Pair production without exotics 2308.07814 [JHEP], JK, S. Shin

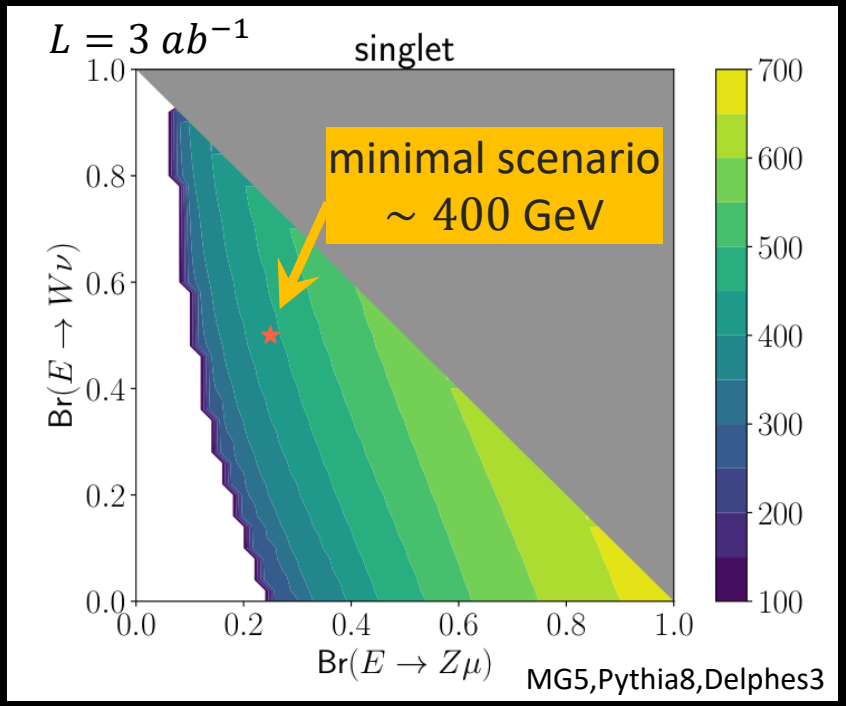
recast **type-III seesaw lepton search** with $\geq 2\ell$

ATLAS 2008.07949, 2202.02039

➢ Signal process



➢ Singlet VLL w. $\ell = \mu$



- our bound is 100-700 GeV depending on $Br(E \to Z\mu)$
- **recent dedicated search** gives 400 GeV with $140 fb^{-1}$ data

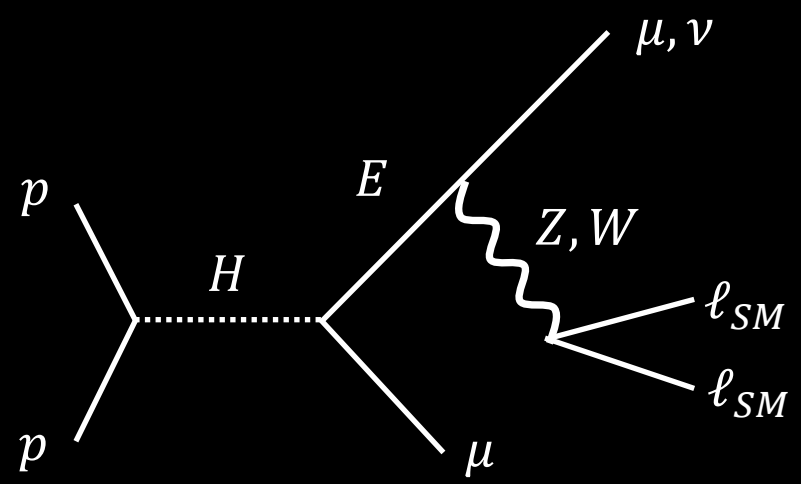
ATLAS 2411.07143

VL Lepton + 2HDM R.Dermisek, JK, E.Lunghi, N.McGinnis, S.Shin, 2204.13272 [JHEP]

what if there are **2 Higgs doublets** ?

- ✓ **natural** in SUSY models
- ✓ $\boldsymbol{tan\beta}$ **enhancement** for e.g. g-2 and EDM

➢ For $m_{VLL} < m_H < 2m_{VLL}$



- **single VLL** from Higgs decay
- Higgs prod. via bb/gg fusion
- recast slepton search ATLAS-SUSY-2018-32
- recast general 3/4 lepton search ATLAS-EXOT-2019-36

$2\ell + E_T^{\text{miss}}$ or $3,4\ell$

Expected limits at HL-LHC

R.Dermisek, JK, E.Lunghi, N.McGinnis, S.Shin, 2204.13272 [JHEP]

- $\tan\beta = 10$, upper bounds on BRs

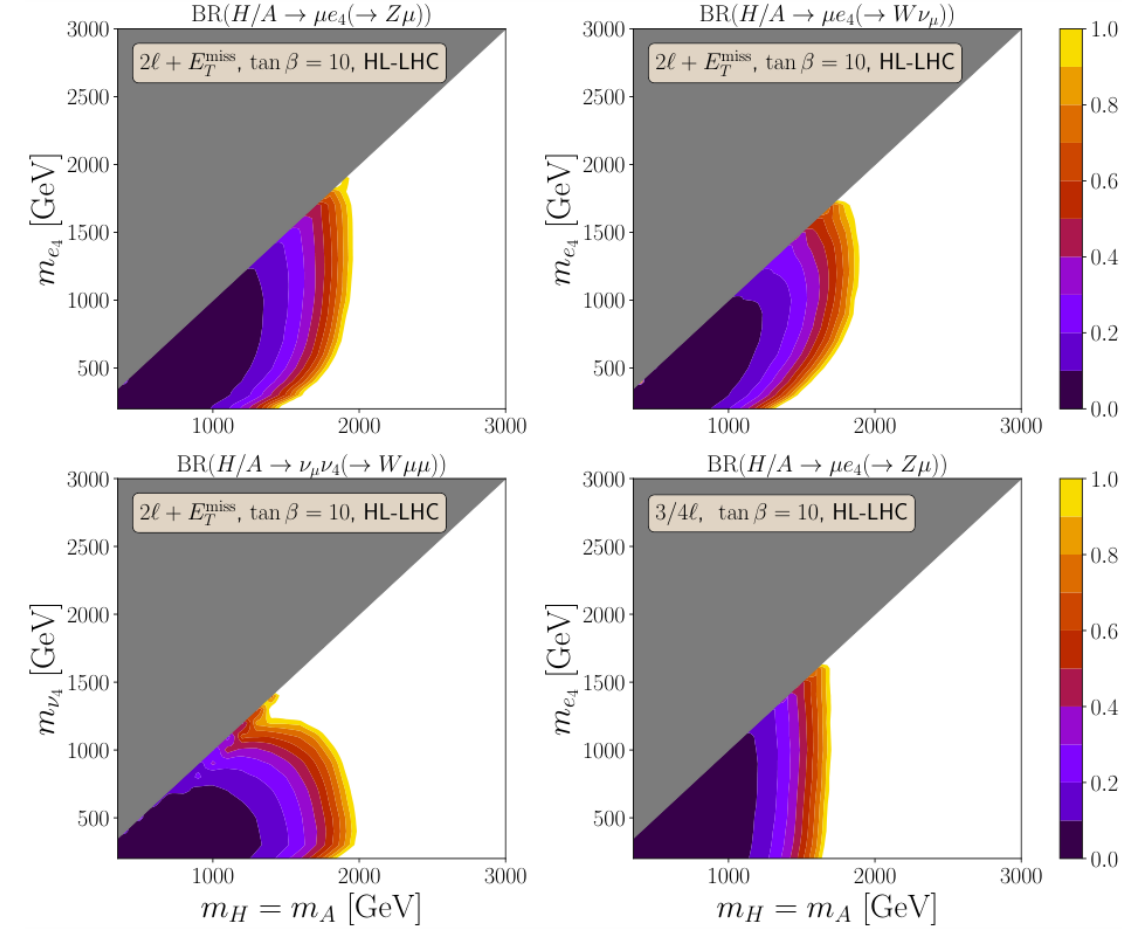
$* e_4 = E$: lightest vector-like lepton

$E \to Z\mu$

$E \to W\nu$

$N \to W\mu$

$E \to Z\mu$



* signals are not combined in these plots

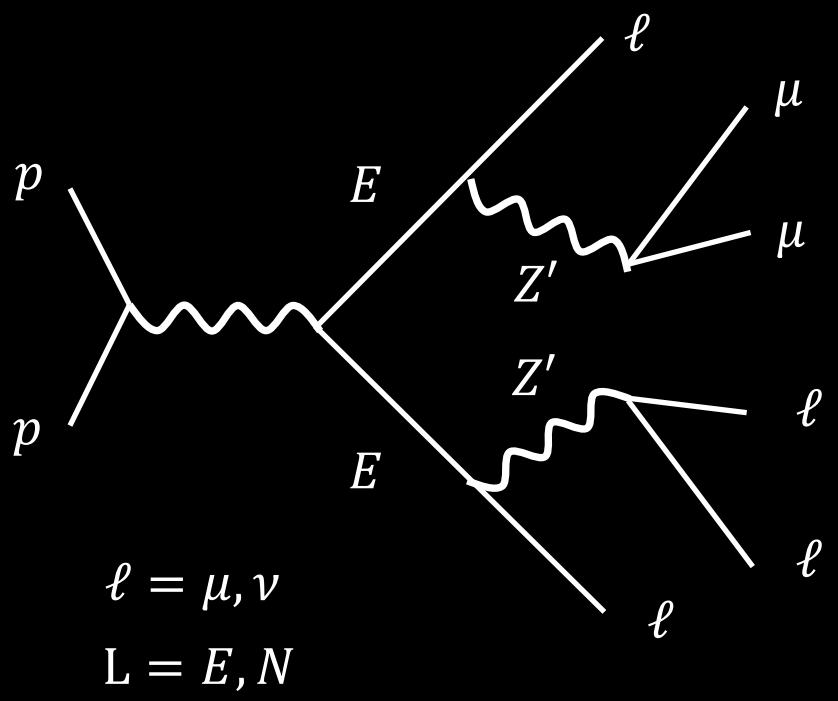
VL Lepton + Z’ JK, S.Raby 2104.04461 [PRD]

A model with VL 4th family charged under U(1)’

- chiral 3 families do not have U(1)’ charge
- can explain muon g-2 and B “anomalies”

JK, S.Raby, A..Trautner
1906.11297. 1911.09127

➢ For $m_{Z'} < m_{VLL}$

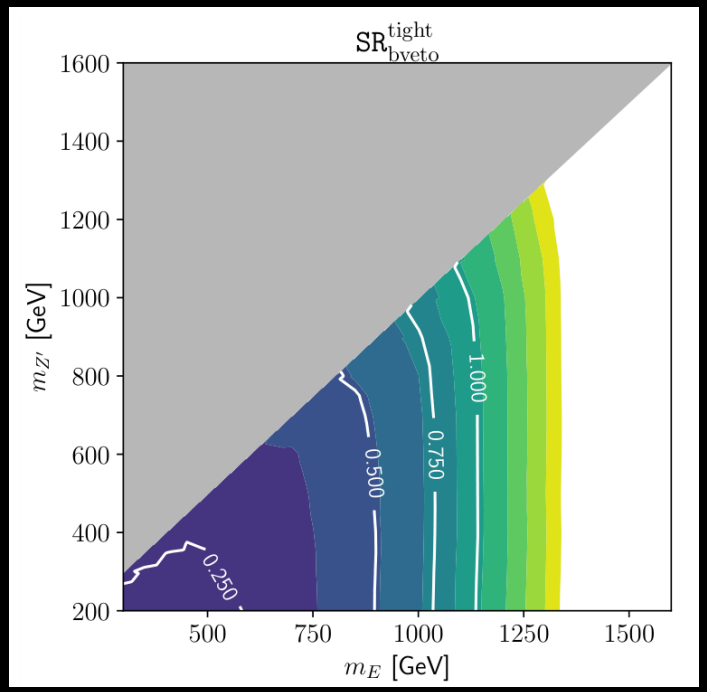


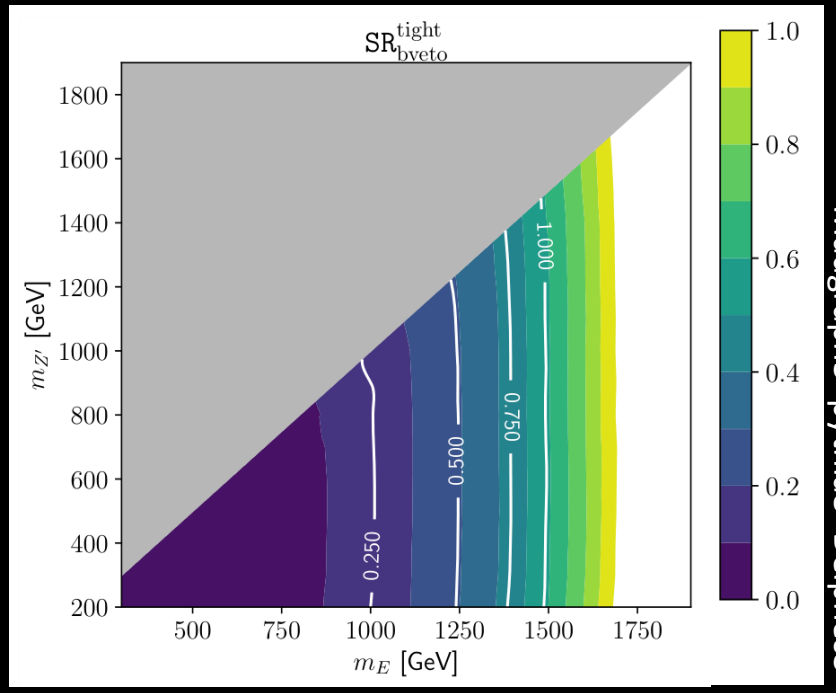
- assume **Z’ is muon-philic**
- $\mathrm{Br}(Z' \to \mu\mu) = 2/3$ motivated by RK
- recast RPV SUSY **4/5 lepton search**

ATLAS-SUSY-2018-02

Future limits on $\mathrm{Br}(E \to Z'\mu)$ JK, S.Raby 2104.04461 [PRD]

- $SU(2)_L$ singlet
- $SU(2)_L$ doublet $\boldsymbol{L = 3\ \mathrm{ab}^{-1}}$





- $\mathrm{SR0}^{\mathrm{tight}}_{\mathrm{bveto}}$ (4 leptons) gives the strongest bound for $\mathrm{Br}(E \to Z'\mu)$
- limit is 1.3 (1.7) TeV for $\mathrm{Br}(E \to Z'\mu) = 1$ for singlet (doublet)
- we also proposed search utilizing there are $m^2_{\mu\mu} \sim m^2_{Z'}$ pairs

Summary of VLL searches

We studied signals involving **muon-philic VLLs**

* other cases will be studied in the future, see e.g. 2203.03852

- VLL pair-production
  - obtained **first limit** using the Run-2 data
  - 780 GeV for doublet, but no limit for singlet
- 2HDM + VLL : $m_{VLL} < m_H < 2m_{VLL}$
  - VLL may appear in **decay of exotic Higgs**
  - cross section is large because of that of the Higgs via gg/bb fusion
- Z' + VLL : $m_{VLL} < m_{Z'}$
  - **high-multiplicity muons signal** is possible
  - limit can be 1.3 TeV even for singlet VLL pair production at HL-LHC

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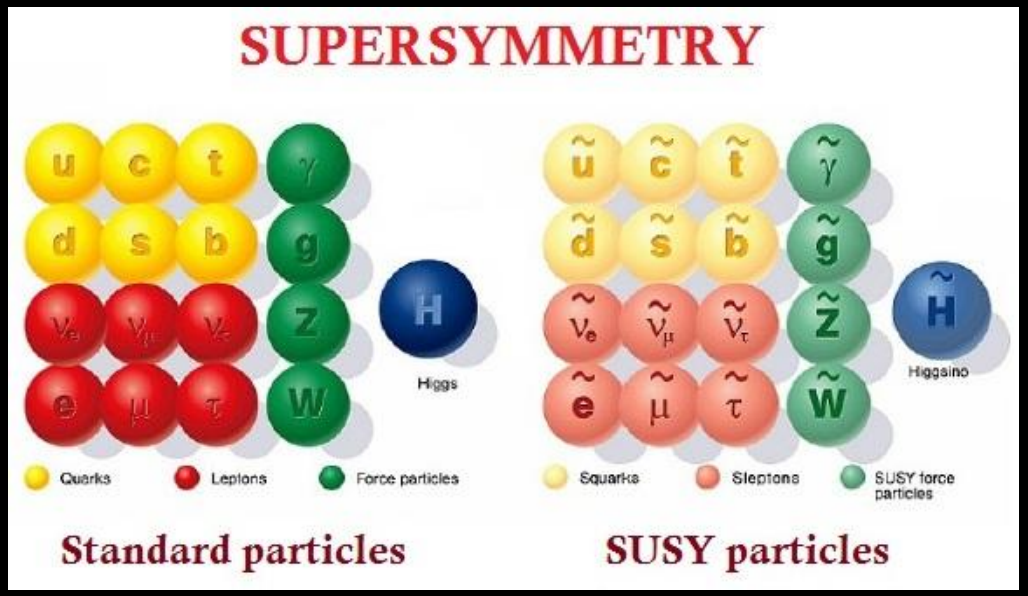
Higgsino

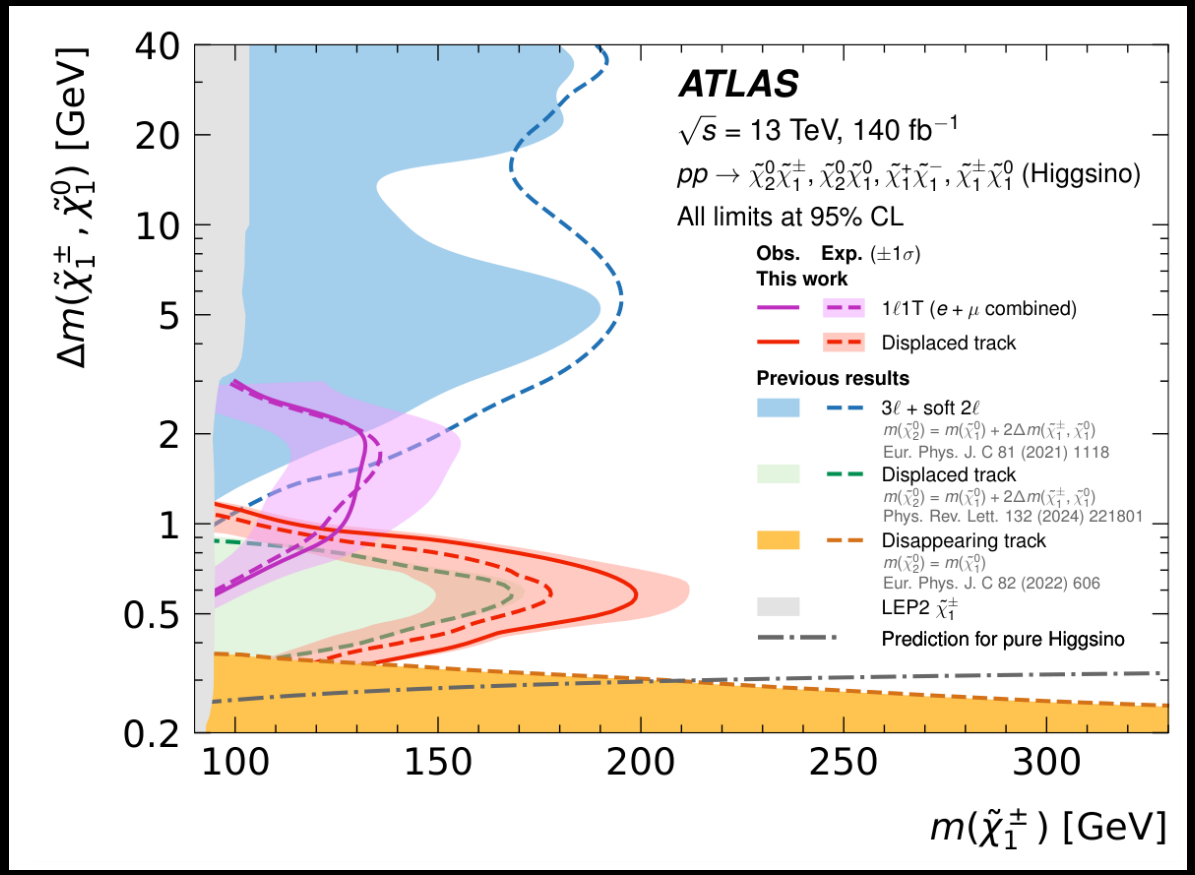
- Supersymmetry



- solve hierarchy problem
- GUT/superstring
- Higgs potential
- neutralino DM
  *mixture of gaugino/higgsino

- Higgsino
  - fermionic superpartners of Higgs bosons; $2_{\pm 1/2}$ under EW
  - since MSSM is 2HDM, there are four states $\tilde{\chi}^0_{1,2}, \tilde{\chi}^{\pm}_1$

Current limits from ATLAS, 2406.01272



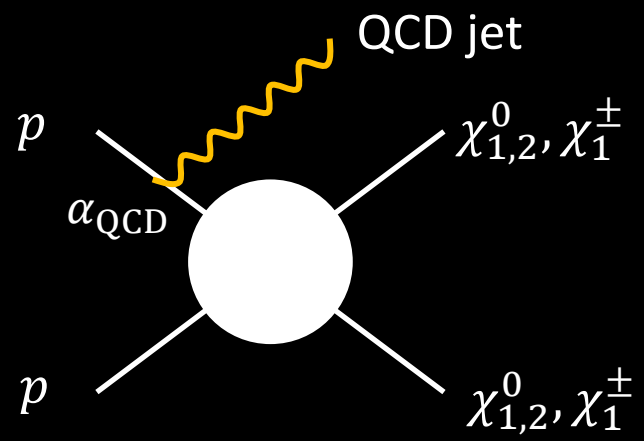
- soft objects via the heavier states $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0$ + soft (long-lived)
- **ISR jet** is required for trigger by large MET

mono-jet and mono-Z/W signal

what if we use Z/W boson instead of jet ?

c.f. $\frac{N_g \alpha_{QCD}}{N_W \alpha_{EW}} \sim 9$

➢ mono-jet

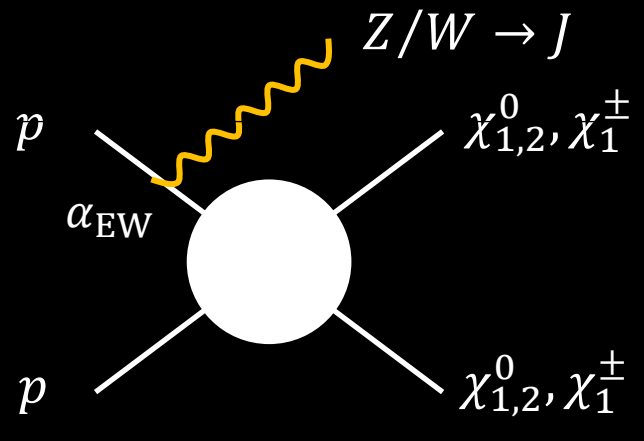


✓ **large** production cross section

× **huge** QCD backgrounds

✓ widely used for DM searches

➢ mono-Z/W



× **smaller** production cross section

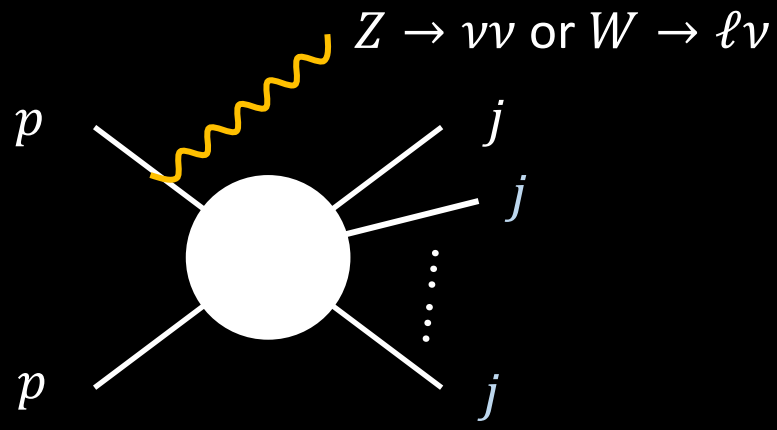
✓ maybe **less** backgrounds

× leptonic decay is too small

1407.1833, L. Carpenter, S, Raby et.al.

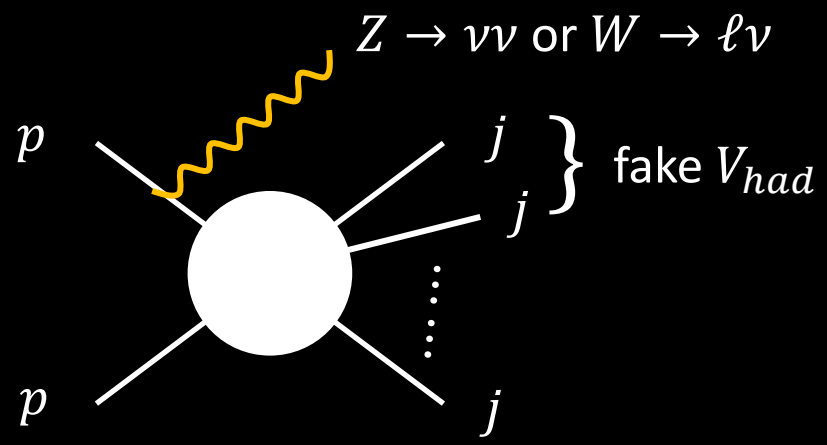
Backgrounds of mono-jet and Z/W

- bkg. for $j + E_T^{\text{miss}}$



- **Z/W+jets** is dominant bkg.
- topologically same signal

- bkg. for $V_{had} + E_T^{\text{miss}}$



- **Z/W+jets** is dominant bkg. (≫ **diboson**)
- V_{had} should be found from jets

V_{had}-tag efficiency $\sim 50\%$ (1.7%) for true W/Z jets (QCD jets)

ATLAS-PHYS-PUB-2015-033

→ **well discriminate** signal and bkg.

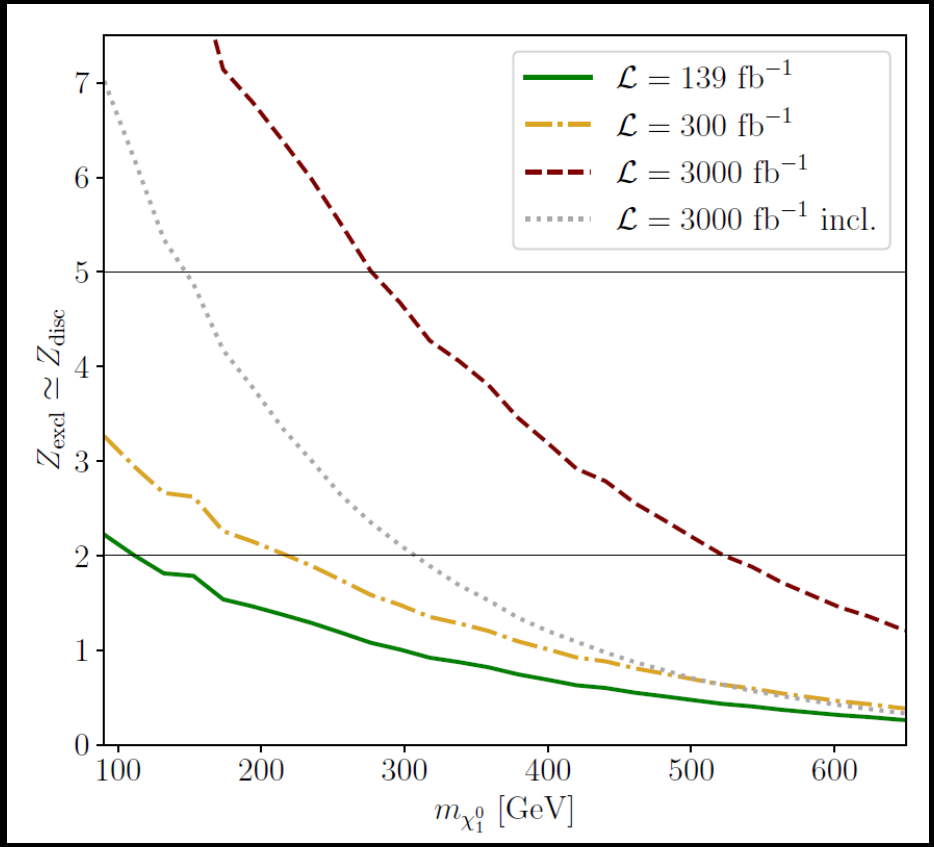
Analysis for mono-Z/W

- Recast ATLAS analysis w/ $36.1\ \mathrm{fb}^{-1}$data 1807.11471, ATLAS
  - **one V_{had} jet** with $p_T > 250$ GeV and $\boldsymbol{E_T^{miss} > 200\ GeV}$
  - **50% efficiency** for V_{had} tagging
  - cuts for multi jet bkg. are applied
  - leptons with $p_T > 7$ GeV are vetoed
- Assumptions
  - all of higgsino states $\chi_{1,2}^0, \chi_1^\pm$ are **invisible** $\longleftrightarrow$ $\Delta m_{\chi_1^\pm} \lesssim 3.5$ GeV
  - large R jet from Z/W is V-tagged with **50% efficienty**
  - events simulated by Madgraph5, pythia8 and Delphes
  - uncertainties only in backgrounds wo. correlations

Results 2106.04238, L. Carpenter, H. Gilmer, **JK**

recast of ATLAS analysis w. $\mathbf{36.1\ fb^{-1}}$ **data**

1807.11471, ATLAS



*using $\boldsymbol{E_T^{miss}}$**-binned data wo. correlation**

*full Run-2 result released

2406.01272, ATLAS

MadGraph, Pythia, Delphes

- even LHC constraints 110 (210) GeV higgsinos at Run-2 (3)
- HL-LHC can probe higgsinos **up to 520 GeV** (!?)

Results: μ-M_2 plane

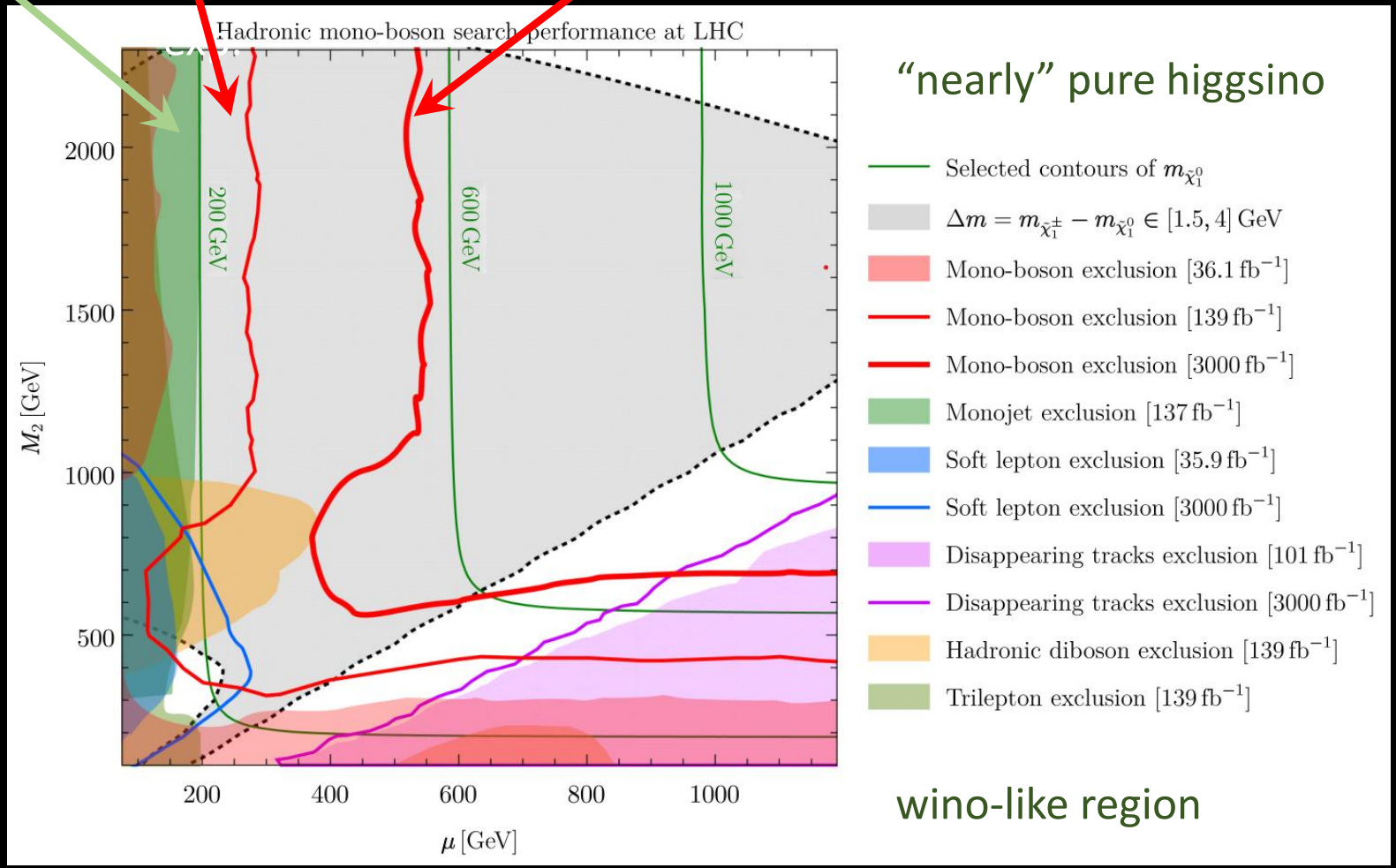
2309.07213, L. Carpenter, H. Gilmer, **JK, T. Murphy**

monojet

139 fb^{-1}

mono-V excl. at HL-LHC

* using MadAnalysis 5



mono-Z/W is the most sensitive for nearly pure higgsino

Summary

- VL lepton searches
  - limits for pair-production has been updated for $\forall\ E \rightarrow e/\mu/\tau + B_{\mathrm{SM}}$
  - 2HDM/Z' + VLL provide varieties of signals, e.g. $\geq 4\ell$ **signals**
- higgsino searches
  - **hadronic mono-Z/W signal** looks efficient for higgsinos searches
  - we would test higgsinos **up to 520 GeV** at HL-LHC
  - further confirmations are desirable
  - mono-V + soft signals and apply mono-Z/W to other DM

Thank you !

backups

Limits for muon-philic VLL JK and S.Shin, 2308.07814 [JHEP]

- Analysis

  we recast two searches for triplet leptons in type-III seesaw

  ATLAS-EXOT-2018-33: 2l + 2j + MET, ATLAS-EXOT-2020-02: 3-4l (+ jets)

  # of signal : $s_{bin} = \mathcal{L} \times \sum_P \sum_D \sigma_P \times Br_D \times \epsilon_{bin}^{(P,D)}$

  $\mathcal{L}$: integrated luminosity ~ 139 fb^{-1}

  σ_P : production cross section NLO using UFO by A.H.Ajjath, B.Fuks, H.S.Shao, Y.Simon

  Br_D: BR of decay $E \to \mu\, Z$ or $\nu\, W$.

  $\epsilon_{bin}^{(P,D)}$: (# pass cut of bin)/(# event generated)

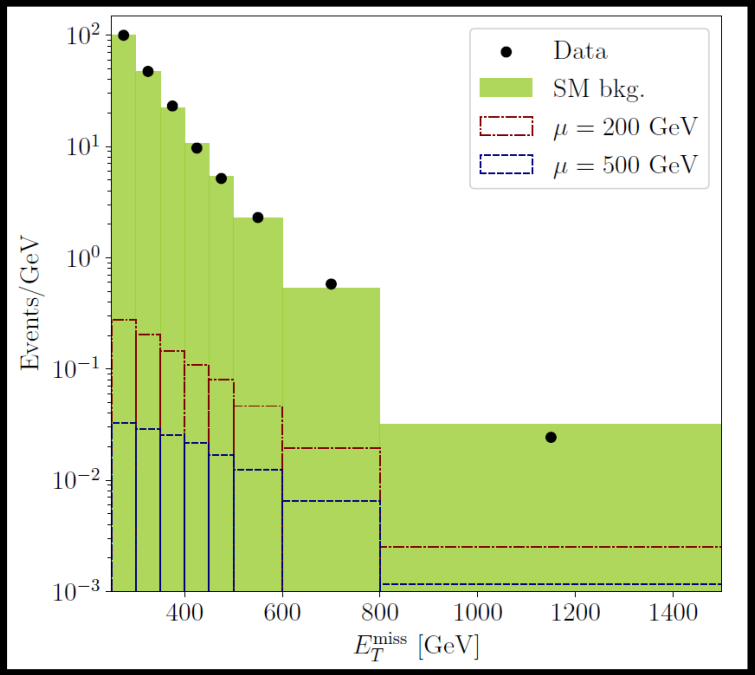
  MadGraph5+MadSpin+Pythia8+Delphes

  → get limits by comparing with data/backgrounds

E_T^{miss} distribution

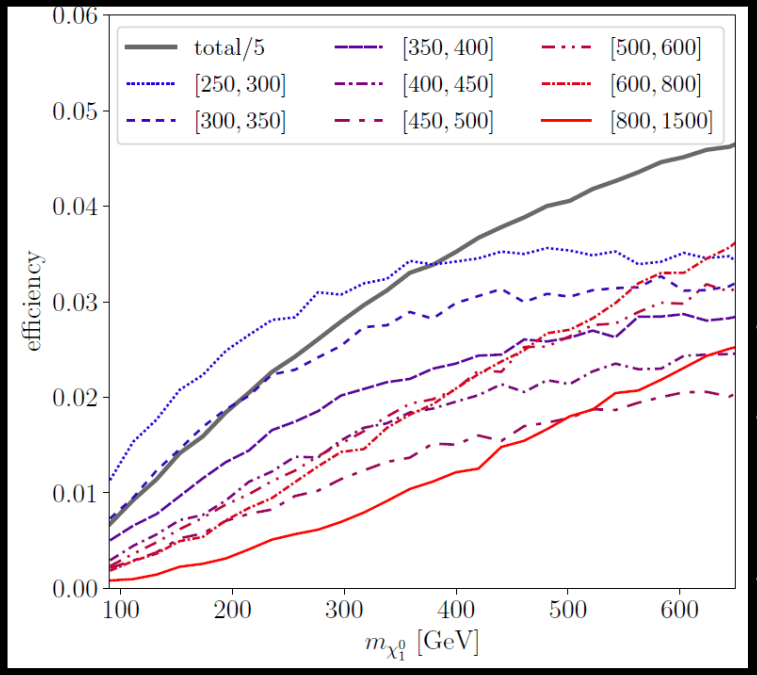
recast of mono-Z/W search by ATLAS, Run-I 1807.11471

E_T^{miss} distribution



efficiency =

pass the cuts/# events generated



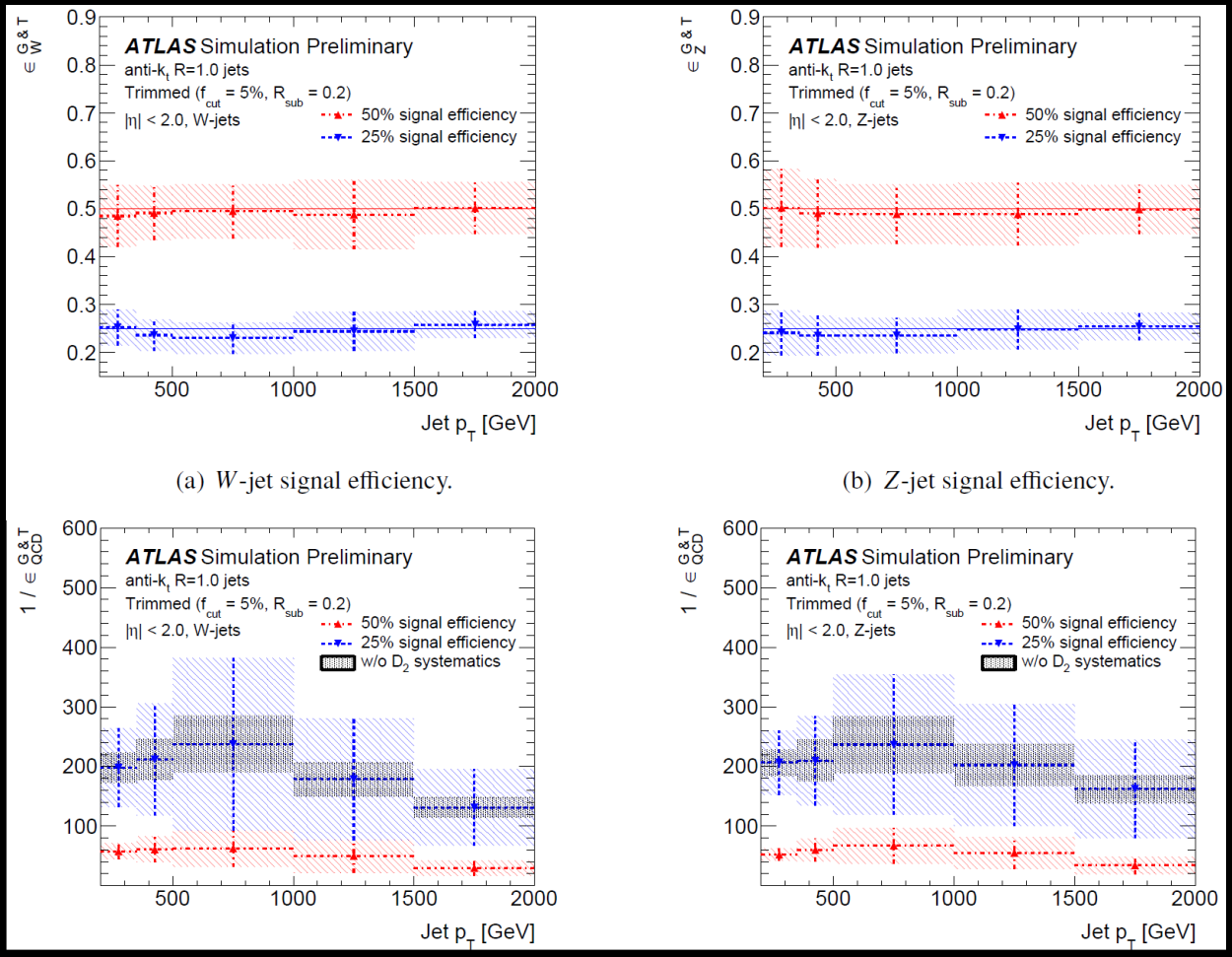
MadGraph, Pythia, Delphes

- signals are $\mathcal{O}(0.1 - 1\%)$ of the SM bkg.
- **higher E_T^{miss}** is expected from **heavier masses**

V_{had} tagging

ATLAS-PHYS-PUB-2015-033

tagging by jet mass $m_J \sim 90$ GeV and D_2



(a) W-jet signal efficiency.

(b) Z-jet signal efficiency.

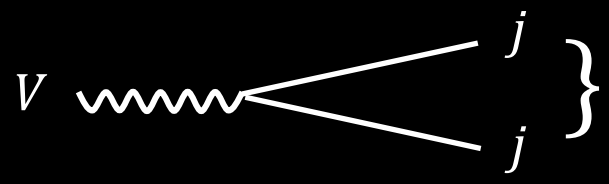
V-tag rate from Z/W

~ 50 % (med.)

V-tag rate from jets

$\sim 60^{-1} \sim 1.7$ % (med.)

V_{had} jet and D_2



large-R (= 1.0) jet: J

mass of large R jet :m_J should be around $m_V \sim 90$ GeV

- $D_2 = e_3/e_2^3$

$$e_2 = \frac{1}{p_{TJ}^2} \sum_{i<j\leq n_j} p_{Ti} p_{Tj} R_{ij} \qquad e_3 = \frac{1}{p_{TJ}^3} \sum_{i<j<k\leq n_j} p_{Ti} p_{Tj} p_{Tk} R_{ij} R_{ik} R_{jk}$$

- e_2, e_3 are smaller when more soft/collinear pair exists
- $e_3 \ll e_2$ is expected for V_{had} since there two hard jets

backgrounds

- number of events 1807.11471, ATALS

			Merged topology		
Process	$0b$-HP	$0b$-LP	$1b$-HP	$1b$-LP	$2b$
Vector-mediator model,					
m_χ =1 GeV, $m_{Z'}$ =200 GeV	814 ± 48	759 ± 45	96 ± 18	99 ± 16	49.5 ± 4.3
m_χ =1 GeV, $m_{Z'}$ =600 GeV	280.9 ± 9.0	268.5 ± 8.8	34.7 ± 3.6	33.8 ± 3.1	15.38 ± 0.84
Invisible Higgs boson decays (m_H = 125 GeV, $\mathcal{B}_{H\to\text{inv.}}$ = 100%)					
VH	408.4 ± 2.1	299.3 ± 2.0	52.06 ± 0.85	44.06 ± 0.82	27.35 ± 0.52
ggH	184 ± 19	837 ± 35	11.7 ± 3.8	111 ± 30	12.3 ± 4.2
VBF	29.1 ± 2.5	96.0 ± 4.6	2.43 ± 0.36	5.83 ± 0.43	0.50 ± 0.07
W+jets	3170 ± 140	10120 ± 380	218 ± 28	890 ± 110	91 ± 12
Z+jets	4750 ± 200	15590 ± 590	475 ± 52	1640 ± 180	186 ± 12
$t\bar{t}$	775 ± 48	937 ± 60	629 ± 27	702 ± 34	50 ± 11
Single top-quark	159 ± 12	197 ± 13	89.7 ± 6.7	125.5 ± 8.7	16.1 ± 1.7
Diboson	770 ± 110	960 ± 140	88 ± 14	115 ± 18	54 ± 10
Multijet	12 ± 35	49 ± 140	3.7 ± 3.3	15 ± 13	9.3 ± 9.4
Total background	9642 ± 87	27850 ± 150	1502 ± 31	3490 ± 52	407 ± 15
Data	9627	27856	1502	3525	414

Statistics

ATLAS, CMS and LHC Higgs Combination Group Collab.
"Procedure for the Higgs boson search combination in Summer 2011"

test statistics

$$q_\mu^n := -2\log\frac{L(n|\mu,\hat{\hat{b}})}{L(n|\hat{\mu},\hat{b})},$$

n_i: # data, s_i: # signal, b_i: # bkg.

$$\lambda_i = s_i\mu + b_i$$

likelihood

$$L(n|\mu,b) := \prod_i^{N_{\rm bin}} \frac{\lambda_i^{n_i}}{n_i!}e^{-\lambda_i} \times \frac{1}{\sqrt{2\pi}\Delta b_i}\exp\left(-\frac{(b_i-b_i^0)^2}{2(\Delta b_i)^2}\right),$$

CLs and significances

$$\mathrm{CL}_s = \frac{1-\Phi\left(\sqrt{q_1^{n_{\rm obs}}}\right)}{\Phi\left(\sqrt{q_1^{b_0}}-\sqrt{q_1^{n_{\rm obs}}}\right)}, \quad Z_{\rm excl} = \sqrt{q_1^{b_0}}, \quad \text{and} \quad Z_{\rm disc} = \sqrt{q_0^{s+b_0}},$$