2/9 @ CPPC Sydney

Searching for new EW particles at the 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]

Before physics…

➢ Junichiro Kawamura

'12-'17: Waseda U. (Ph.D)

'17-'18: U. of Tokyo

'18-'18: Keio university

~ Tokyo, Japan

'18-'20: Ohio State University ~ Columbus, USA

'20-'25: IBS-CTPU ~ Daejeon, Korea
(140 km from Seoul)

➢ Research area: BSM pheno.

model building, LHC, DM, neutrino,

flavor violation/hierarchy, cosmology…

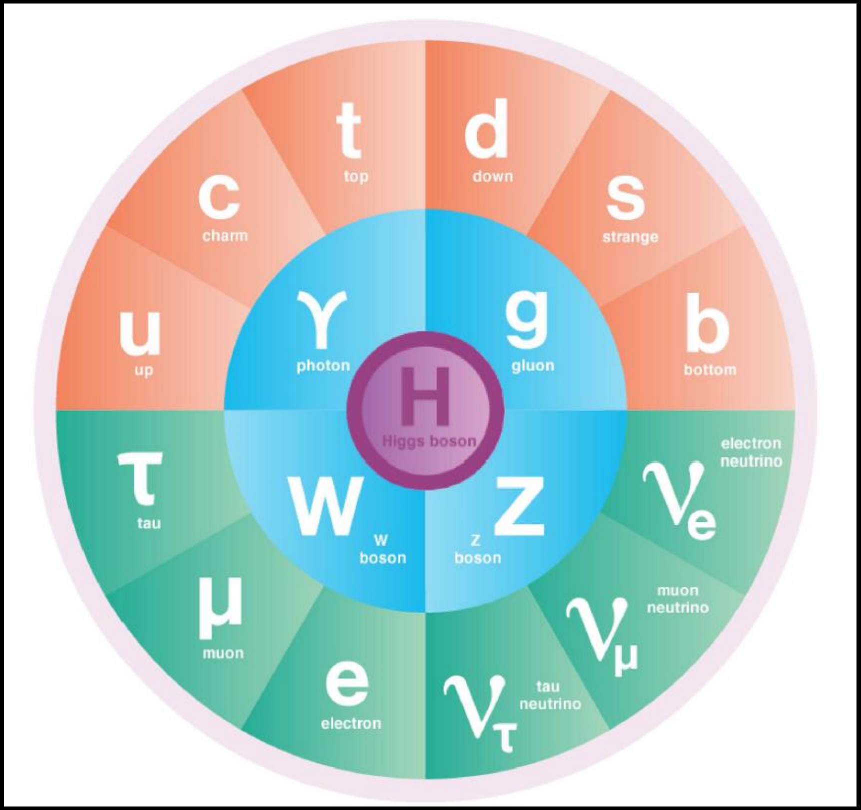
https://upload.wikimedia.org/wikipedia/commons/thumb/e/ed/TaroTokyo20110213-TokyoTower-01min.jpg/200px-TaroTokyo20110213-TokyoTower-01min.jpg

https://www.bizjournals.com/columbus/news/2016/12/05/beer-sales-exceed-1m-in-first-year-at-ohio-stadium.html

Outline

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

Standard Model [SM] $SU(3)_c \times SU(2)_L \times U(1)_Y$ Yang-Mills theory



https://www.symmetrymagazine.org/standard-model/

- 3 gens. of quark/leptons
- All particles are discovered
- Basically consistent with exp.

Is this all ? **No !!**

Problems of SM

- Theoretical problems
  - **Higgs is unstable** under quantum corrections
  - matter contents looks **busy** c.f. hypercharge $Y_Q = \frac{1}{6}, Y_u = \frac{2}{3}, Y_d = -\frac{1}{3}, Y_\ell = -\frac{1}{2}, Y_e = 1$
  - **too many** parameters **with hierarchies**
  - gravity is not **quantized**

... SUSY ?
... composite ?

... GUT ?
... flavor symmetry ?
...string ?

JK S.Raby 2212.00840
Y.Abe, T.Higaki, JK, T.Kobayashi 2301.07439, 2302.11183

- Experimental problems
  - **dark matter** [DM] is missing
  - cannot explain **baryon asymmetry**/**inflation**
  - there may be **anomalies** in precision measurements, e.g. g-2

JK, S.Raby 2109.08605

How to look for new physics ?

there are many ways, but…. **LHC !!**

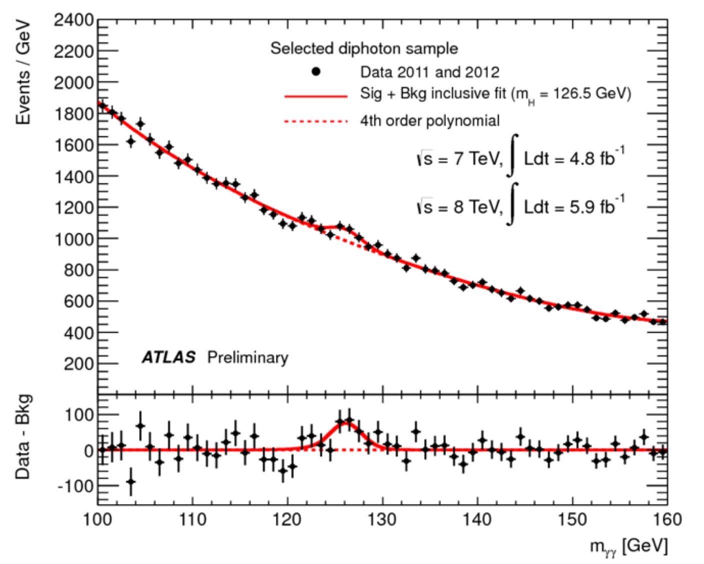
CERN

- Large Hadron Collider

  - pp collision, circular collider
  - highest energy (~13 TeV) collider and **unique TeV collider** in next decade(s)
  - we can **prepare** initial particles ⟷ astrophysics/cosmology
  - **direct probe** for new physics ⟷ precision measurement

Large Hadron Collider [LHC]

- Higgs discovery
  - **125 GeV** resonance discovered
  - **consistent with SM** Higgs
  - **all of the SM particles** are confirmed



- What's next ?
  - "**colored**" particles, e.g. squark/gluino, have been leading targets
  - while **uncolored particles** have not been explored well

I will talk about **EW particles** without **color**

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Vector-like [VL] leptons

- SM fermions
  - are **chiral** under G_{SM}
  - there are **three generations**
  - **top Yukawa** coupling is $\mathcal{O}(1)$

- VL fermions
  - **vector-like** under G_{SM}
  - **masses wo/ Higgs** are allowed
  - **4th gen.** (or more) is possible

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

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

singlet $Y_E = -1$

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

VLL in BSMs

- KSVZ axion(-like particle) / gauge mediated SUSY breaking

Kim '79, Shifman, Vainshtein, Zakharov '80 Dine, Fischler;, Alvarez-Gaume, Claudson, Wise; Nappi, Ovrut, '82

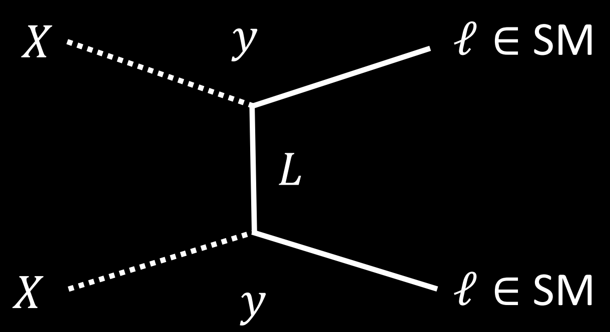
VL-mass term from a singlet X $-\mathcal{L}_{VL} = \lambda\, X\, \overline{\psi}\, \psi$

→

- induce **QCD anomaly** if X has a global $U(1)_{PQ}$ charge
- SUSY breaking in X is **mediated to visible sector**

- Lepton portal DM Y.Bai, J.Berger 1402.6696, S.Chang, R.Edezhath, J.Hutchinson, M.Luty, 1402.7358

Yukawa with DM X and SM lepton $-\mathcal{L}_{VL} = m_L\, \overline{L} L + y\, X\, \overline{L}\, \ell_{SM}$

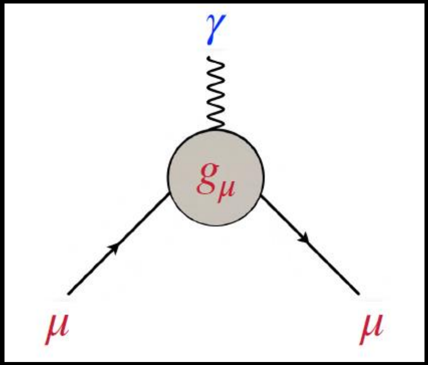


- mediate **DM annihilation**
- can also **explain g-2/B anomaly**

JK, S.Okawa, Y.Omura 2002.12534, 1706.04344

Muon g-2

*Figs. from H.Wittig's slide at Moriond 2023

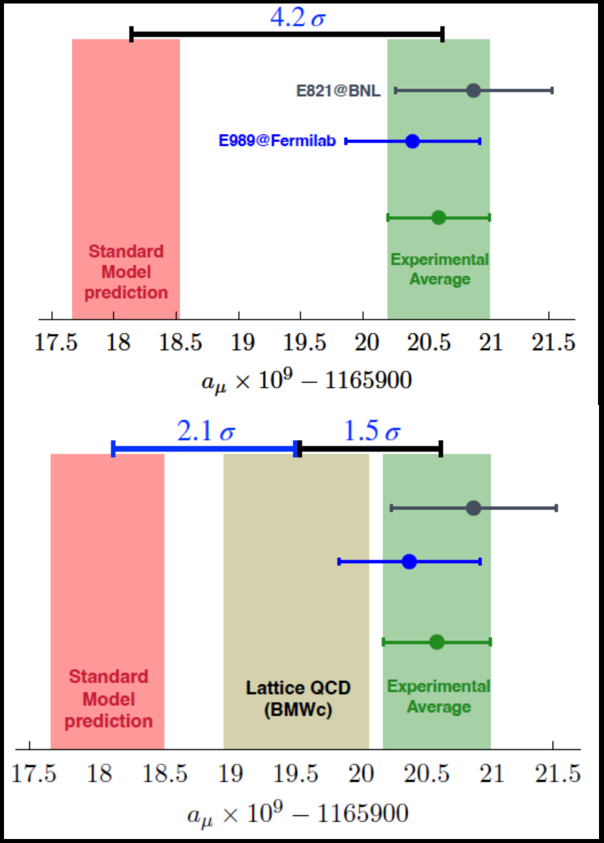


- Muon anomalous magnetic moment g-2

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (25.1 \pm 5.9) \times 10^{-10}$$

'20 muon g-2 initiative

- Current status
  - '21: **Fermilab exp. confirms** old BNL result
  - '21: lattice result (BMW) **relaxes** tension
  - '23: CMD3 result for HVP **relaxes** tension



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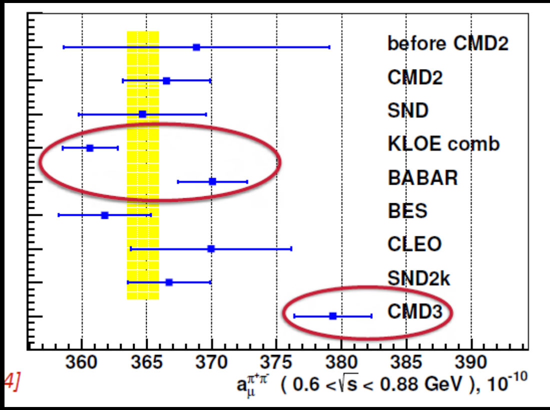
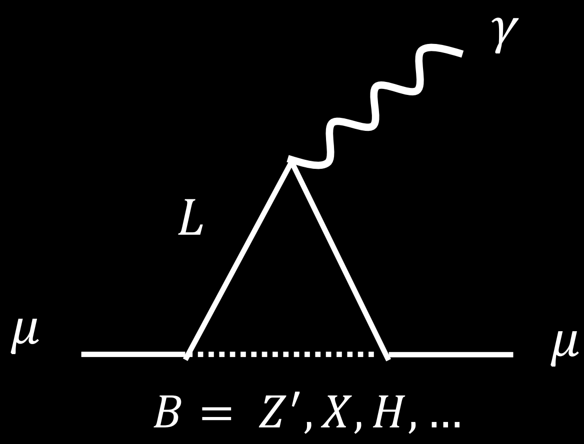


Explanation by VL leptons

2204.07022, JK, S.Okawa, Y.Omura

2205.10480, JK, S.Raby and more ..

- 1-loop corrections to g-2



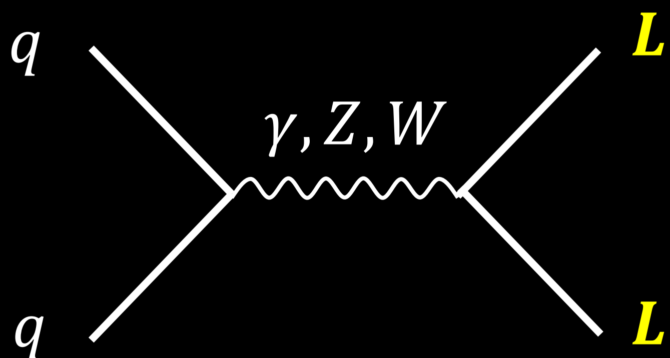
$$\Delta a_\mu \sim \frac{m_\mu\, y_L y_R \boldsymbol{v_H}}{16\pi^2 m_B^2}$$

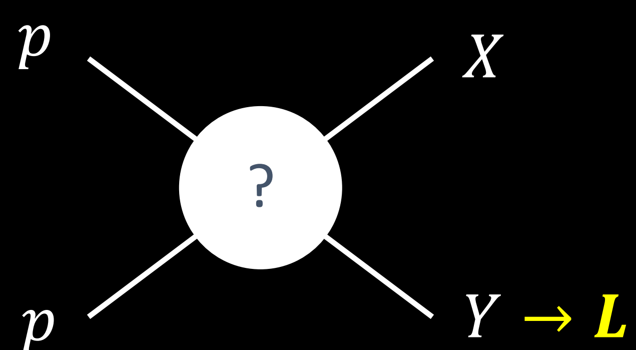
$$\sim 0.1^9 \times \left(\frac{y_L y_R}{0.1^2}\right)\left(\frac{1\ \mathrm{TeV}}{m_B}\right)^2$$

- **boson B** can be **Z' boson**, **DM**, (extra) Higgs and so on
- chiraly **enhanced by Higgs VEV** from doublet/singlet mixing
- **muon g-2** can be explained if VL leptons are lighter than 1.5 TeV

Direct searches at LHC

- Production





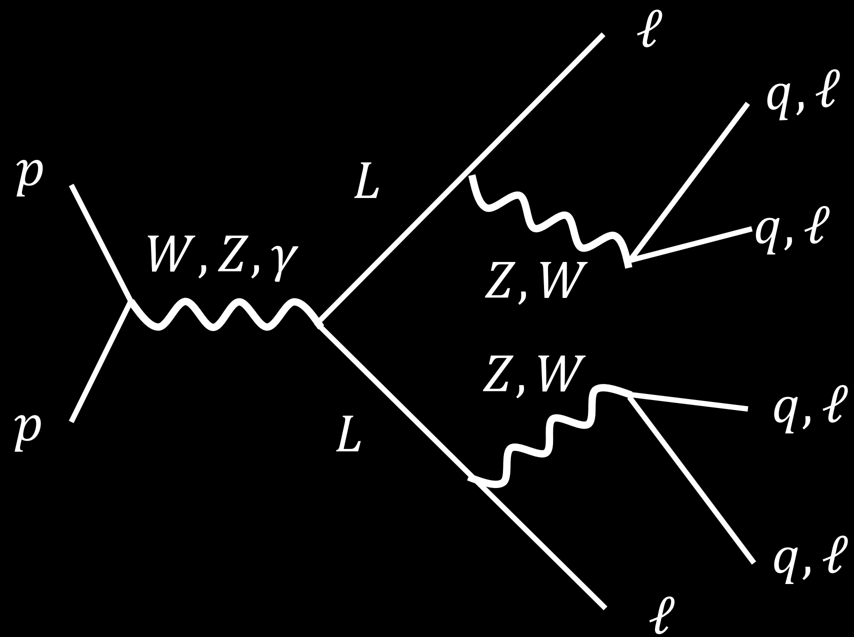
  - **pair production** cross section is determined by gauge number
  - there might be production **from new exotic particle**

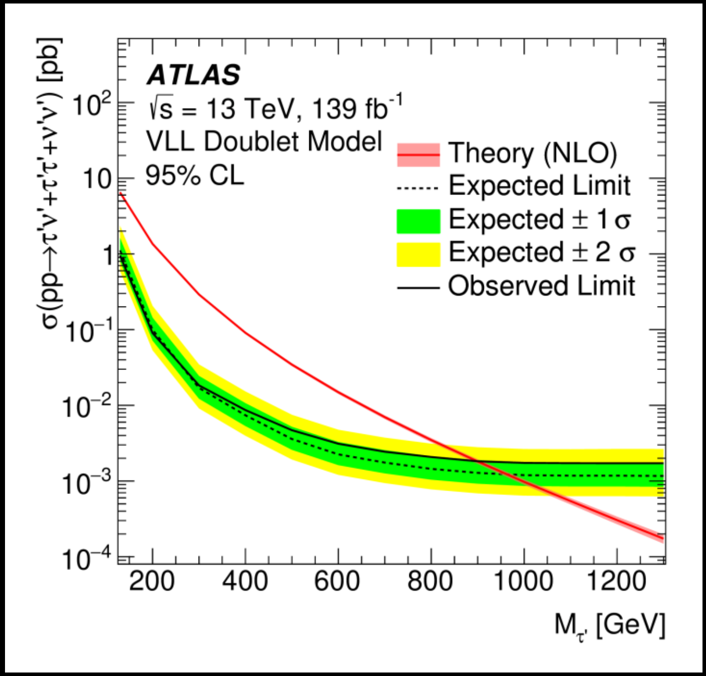
- Decays

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

Decays to SM particles

Without other new particles, signal process is





- the current limit is 900 GeV for $E \to \tau, \nu_\tau + Z, W$
- **no CMS/ATLAS search** at $\sqrt{s} = 13$ TeV for $E \to \boldsymbol{\mu}, \boldsymbol{\nu_\mu} + Z, W$

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 $\nu\, W$.

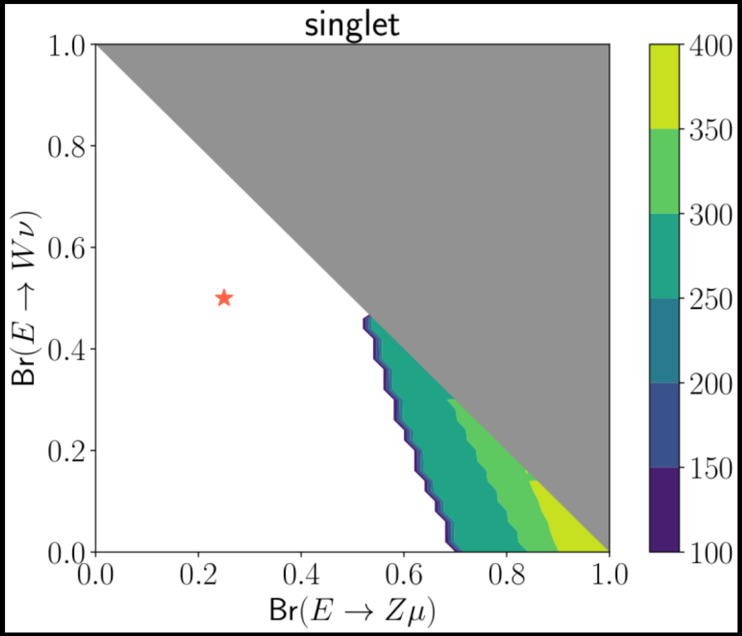
$\epsilon_{bin}^{(P,D)}$: (# pass cut of bin)/(# event generated)

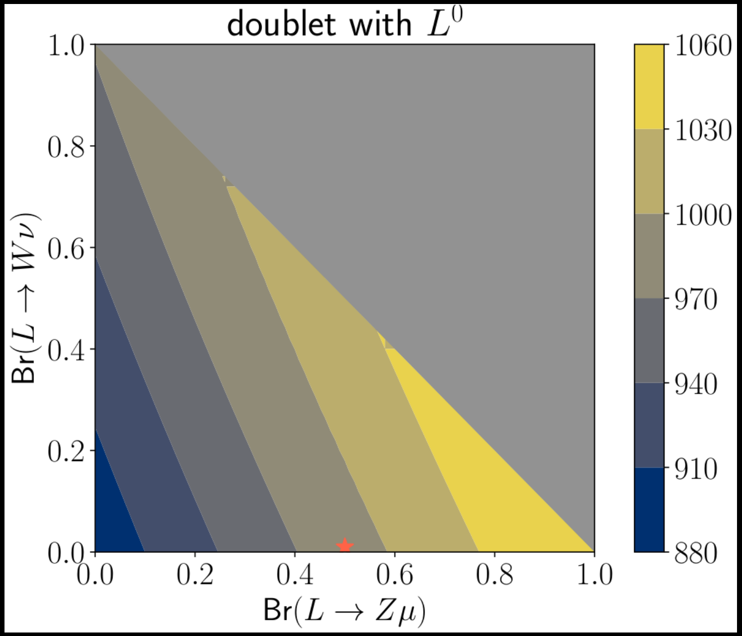
MadGraph5+MadSpin+Pythia8+Delphes

→ get limits by comparing with data/backgrounds

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

➢ Current limits





- **no limit** for singlet VLL with $(Br_Z, Br_W) = (0.25, 0.5)$
- **780 GeV** for doublet VLL with $(Br_Z, Br_W) = (0.5, 0.0)$
- 420 (1050) GeV for singlet (doublet) by **3 ab^{-1} data**

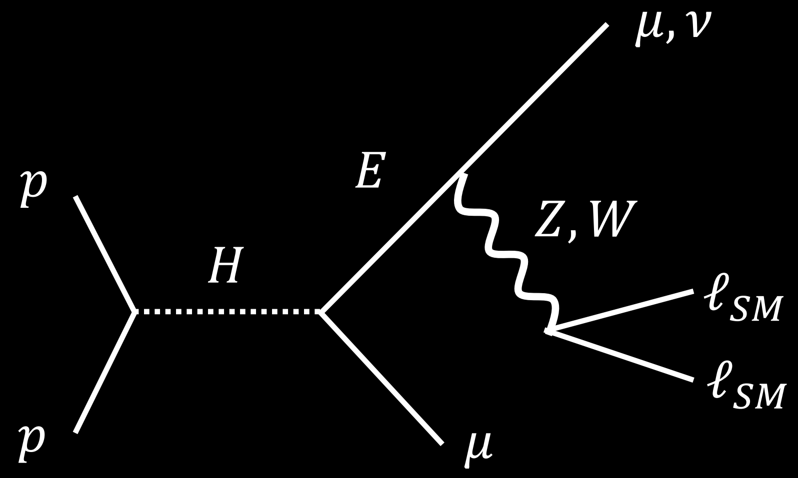
VLL + 2HDM

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

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

- ✓ natural in SUSY models
- ✓ ***tanβ* enhancement** for e.g. muon g-2 and EDM

➢ For $m_{VLL} < m_H < 2m_{VLL}$



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

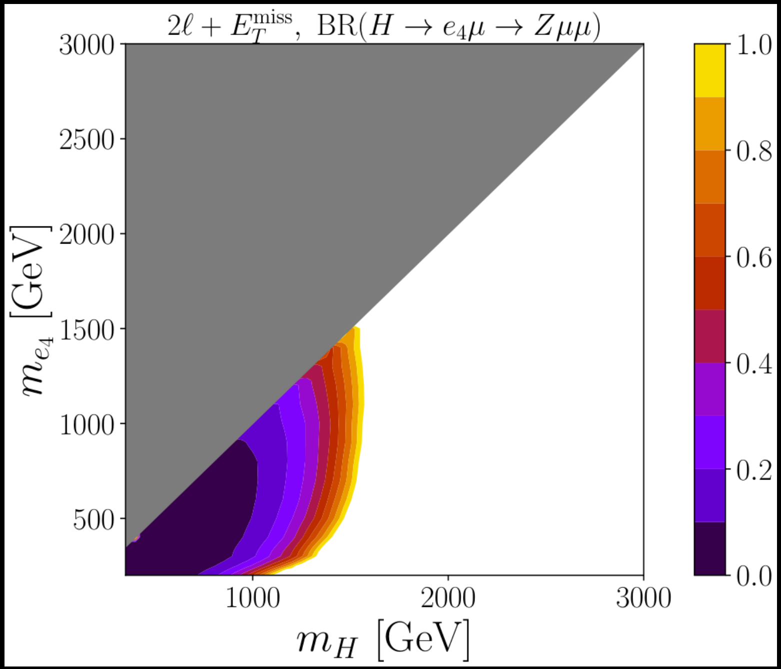
- **single VLL** from Higgs decay
- Higgs production via **bb/gg fusion**
- recast **slepton search** ATLAS-SUSY-2018-32
- recast **general 3/4 lepton search** ATLAS-EXOT-2019-36
- same analysis as previous analysis (but production xsec by SuShi)

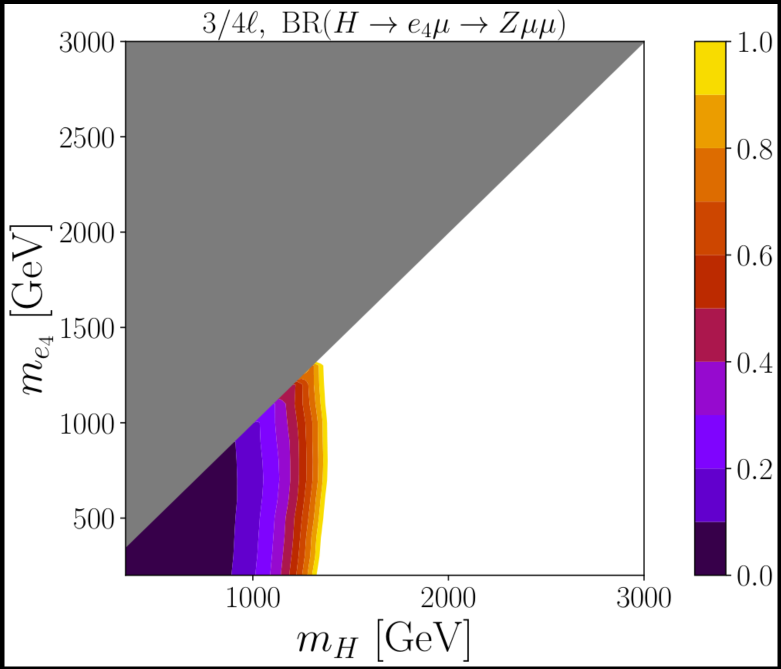
Limits for $H \to \mu\, E\ (\to Z\, \mu)$

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

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

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





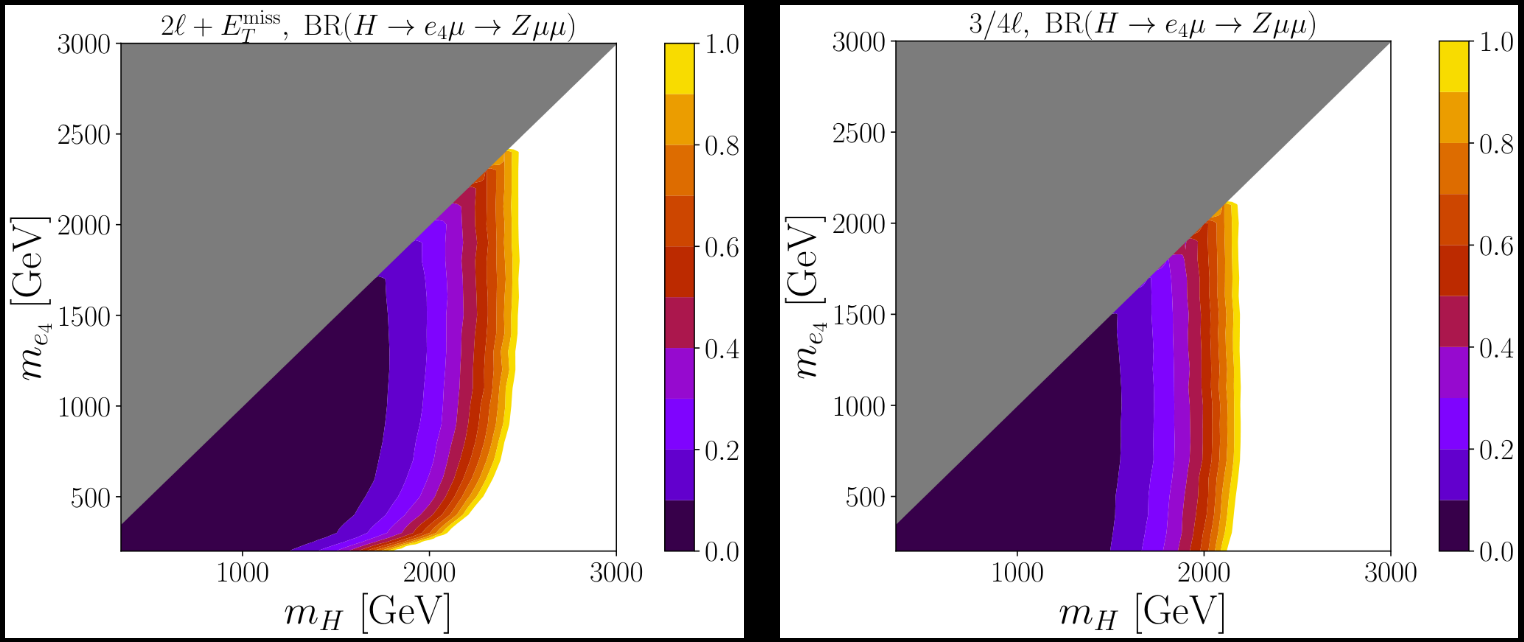
- limit can be larger than **1 TeV by the current data**

Limits for $H \to \mu\, E\, (\to Z\, \mu)$

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

- $\tan\beta = 50$, upper bounds on Br

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



- limit can be larger than **1 TeV by the current data**
- other modes, fully-combined limits at benchmarks are in the paper
- HL-LHC sensitivities are also shown (can reach **~ 3 TeV for Br=1**)

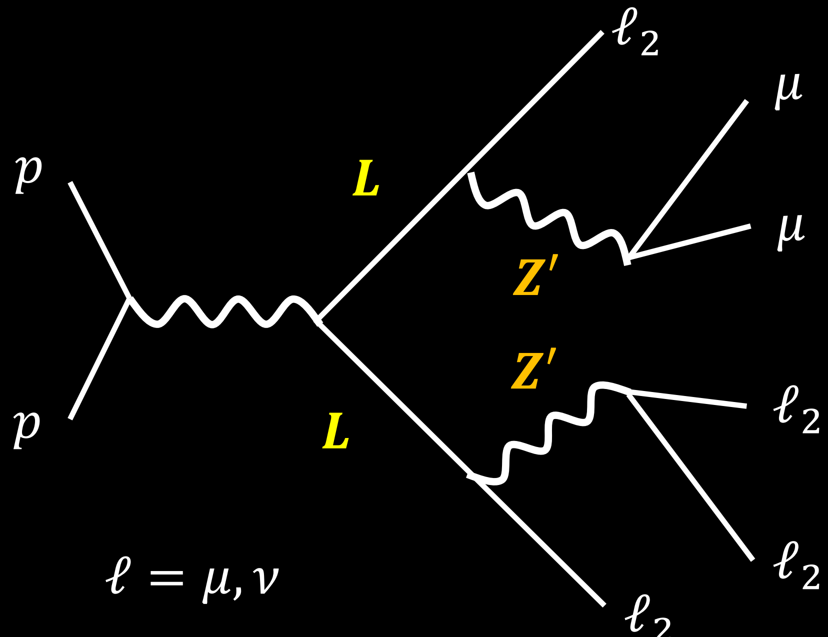
VLL + Z’ JK, S.Raby 2104.04461 [PRD]

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-anomaly**)

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

➢ For $m_{Z'} < m_{VLL}$



$\ell = \mu, \nu$

$\mathrm{L} = E, N$

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

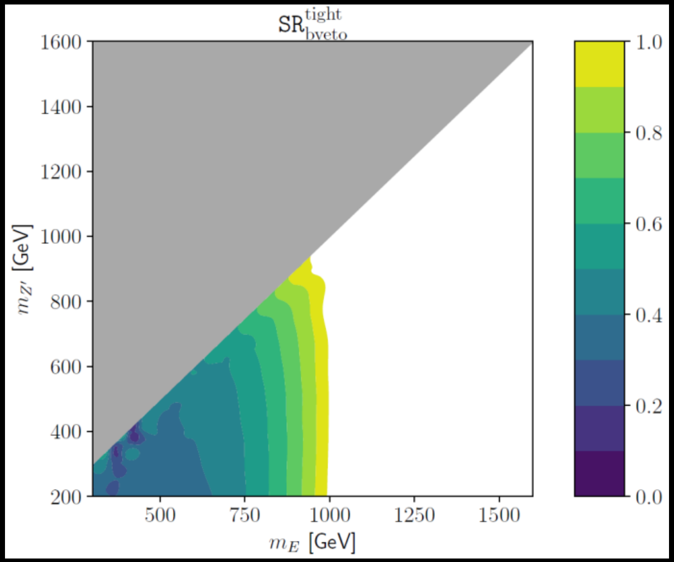
  ATLAS-SUSY-2018-02

- same analysis as previous ones

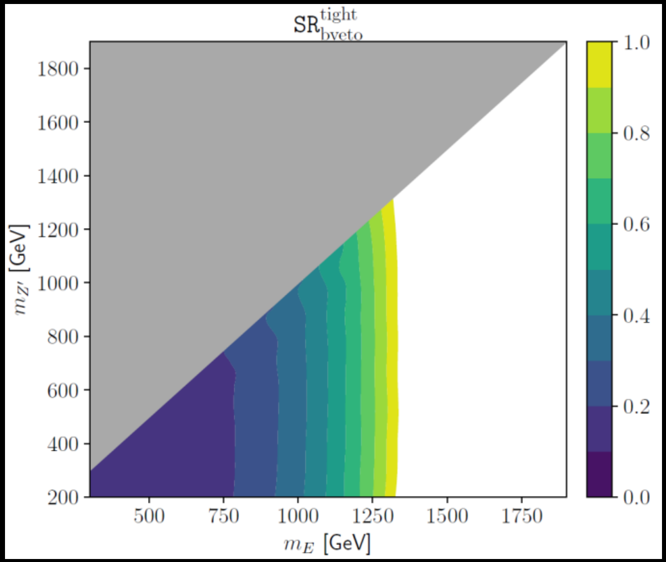
JK, S.Raby 2104.04461 [PRD]

95%C.L. limits on $\mathrm{Br}(E \to Z'\mu)$

- $SU(2)_L$ singlet



- $SU(2)_L$ doublet



Madgraph5+pythia8+Delphes3

- $\mathrm{SR0}^{\mathrm{tight}}_{\mathrm{bveto}}$ gives the strongest bound for $\mathrm{Br}(E \to Z'\mu)$
- limit is **1 (1.3) TeV for $Br(E \to Z'\mu) = 1$ 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
  - obtain **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 TeV even for singlet VLL pair production

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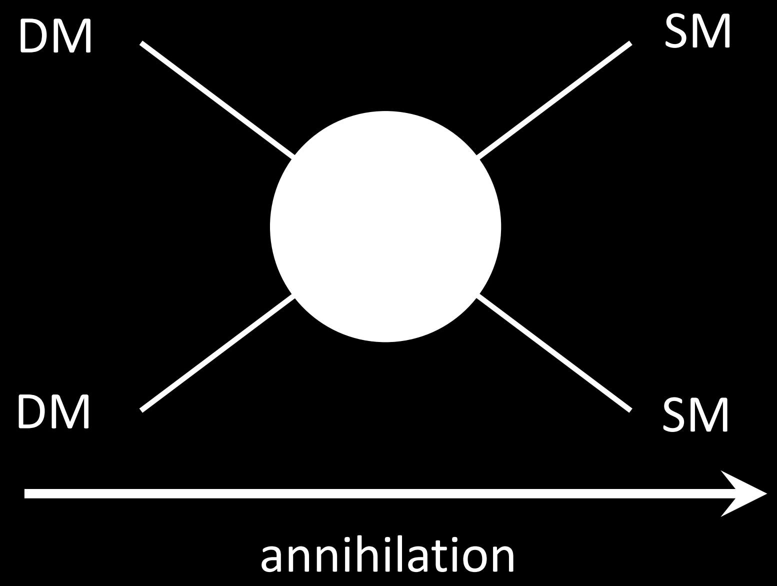
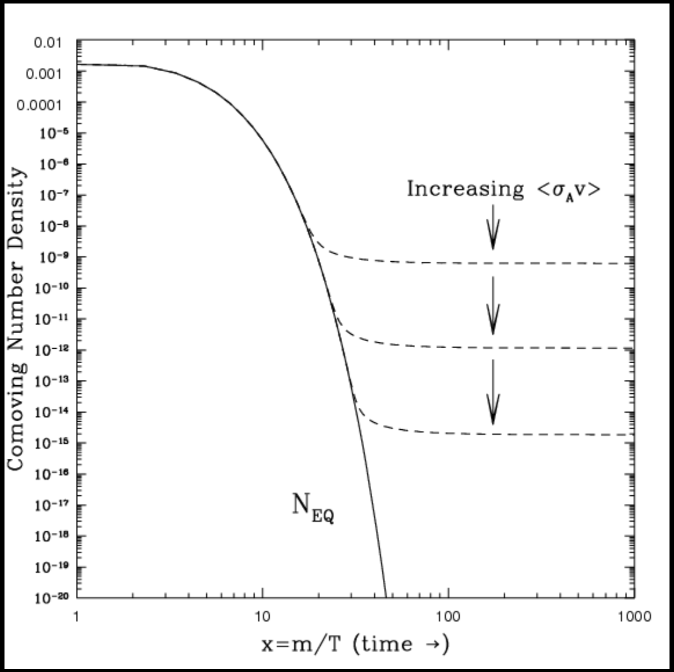
WIMP DM

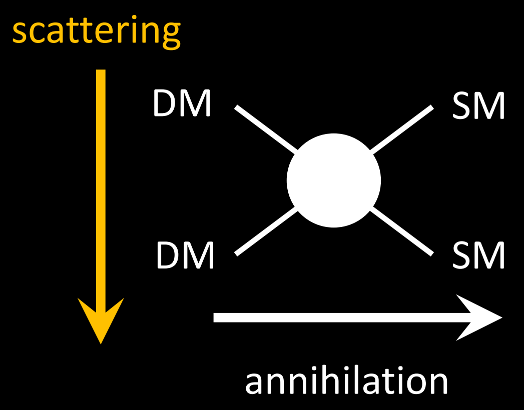




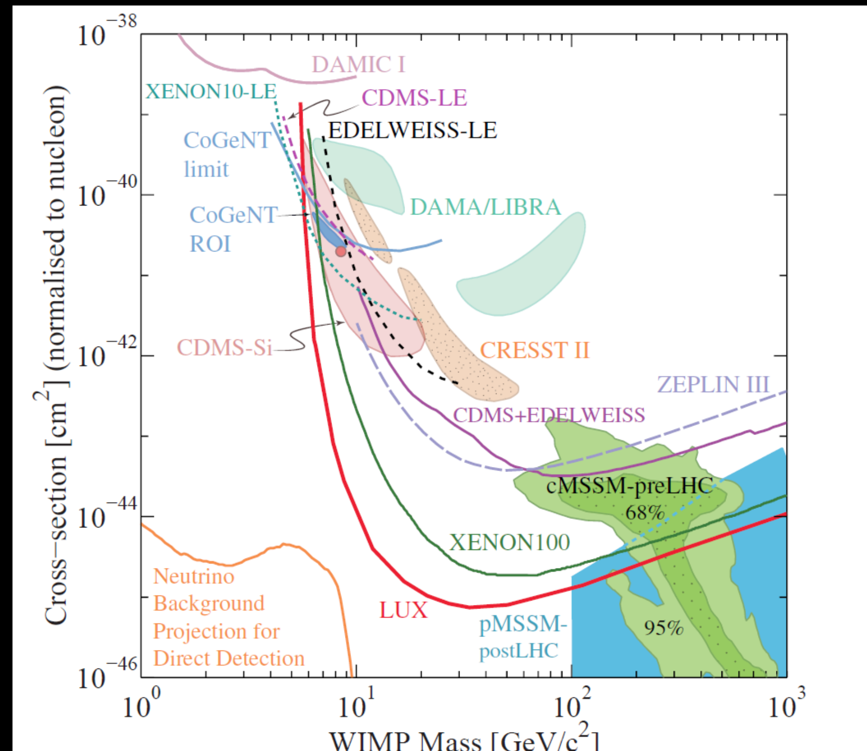
E.W.Kolb, M.S.Turner,
The Early Universe, `89

- DM decouples from thermal bath and **"freeze-out"**
- **Electro-Weak [EW] coupling and mass** can explain relic density
- realized in many BSM models including supersymmetry [SUSY]

Direct detection



$$\sigma_{\mathrm{scat}} \sim \sigma_{\mathrm{ann}}$$

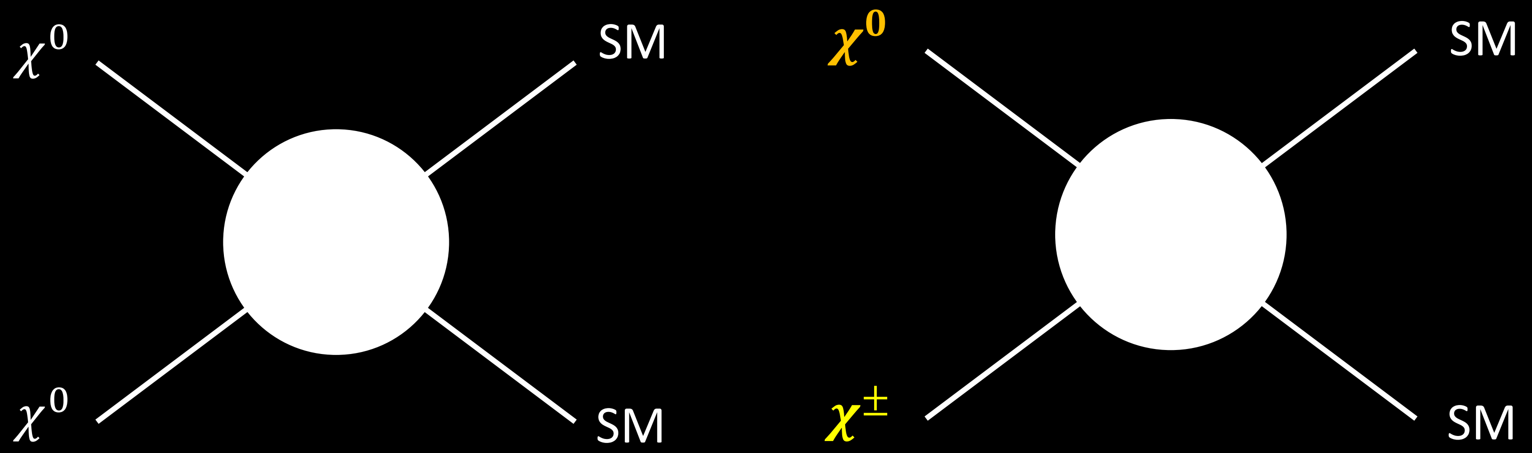


PDG2014

- **null results** in direct detections
- many **interested parameter space has been excluded**

Co-annihilating DM

χ^0: **DM**, $\chi^\pm$: **new particle**



annihilation   co-annihilation

- If $m_{\chi^0} \simeq m_{\chi^\pm}$

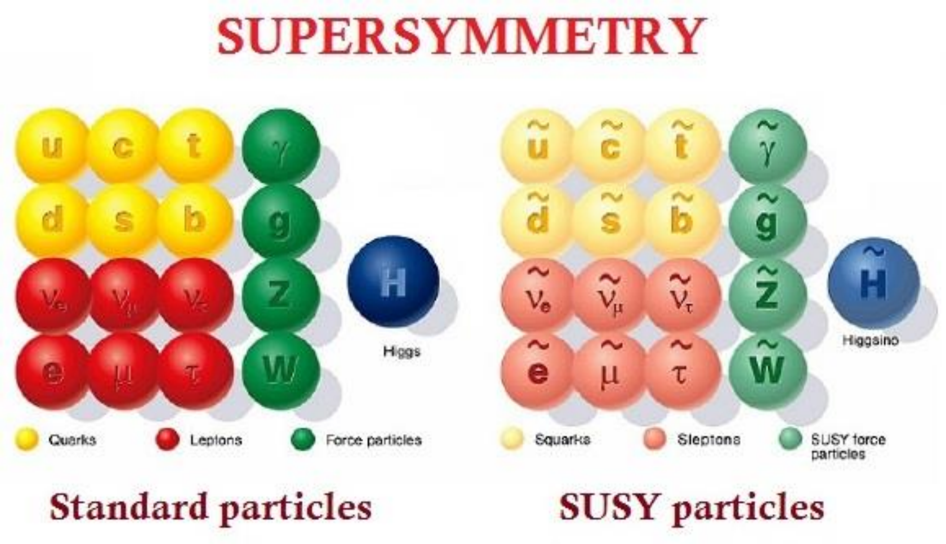
  "**co-annihilation**" $\chi^0\chi^\pm \to \mathrm{SM}^2$ turns on during freeze-out

  → $\boldsymbol{\sigma_{ann}} \gg \boldsymbol{\sigma_{scat}}$ effectively due to co-annihilation

  → **avoid direct detection limits**

Higgsino ...example of co-annihilating DM

- Supersymmetry [SUSY]



- solve hierarchy problem
- GUT/superstring
- Higgs potential
- neutralino DM

*mixture of gaugino/higgsino

- Higgsino
  - **fermionic superpartners of Higgs bosons : $h_{SM}, H, A, H^{\pm}$**
  - there are mass degenerate higgsinos $\tilde{\chi}^0_{1,2}, \tilde{\chi}^{\pm}_1$

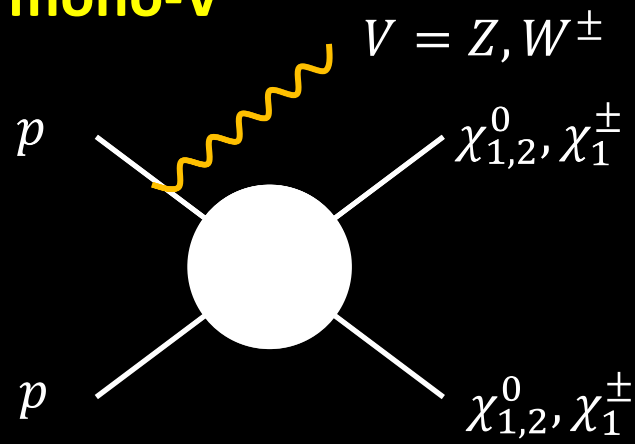
→ co-annihilation DM

mono-Z/W signal

L.Carpenter, H.Gilmer, JK 2110.04185 [PLB]
L.Carpenter, H.Gilmer, JK, T.Murphy 2309.07213 [PRD]

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

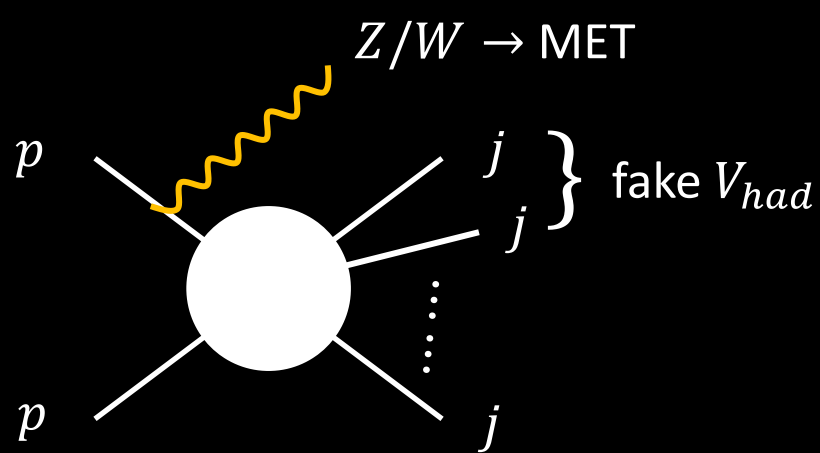
- **mono-V**



✓ **less production** xs. than mono-j

- **much less backgrounds**

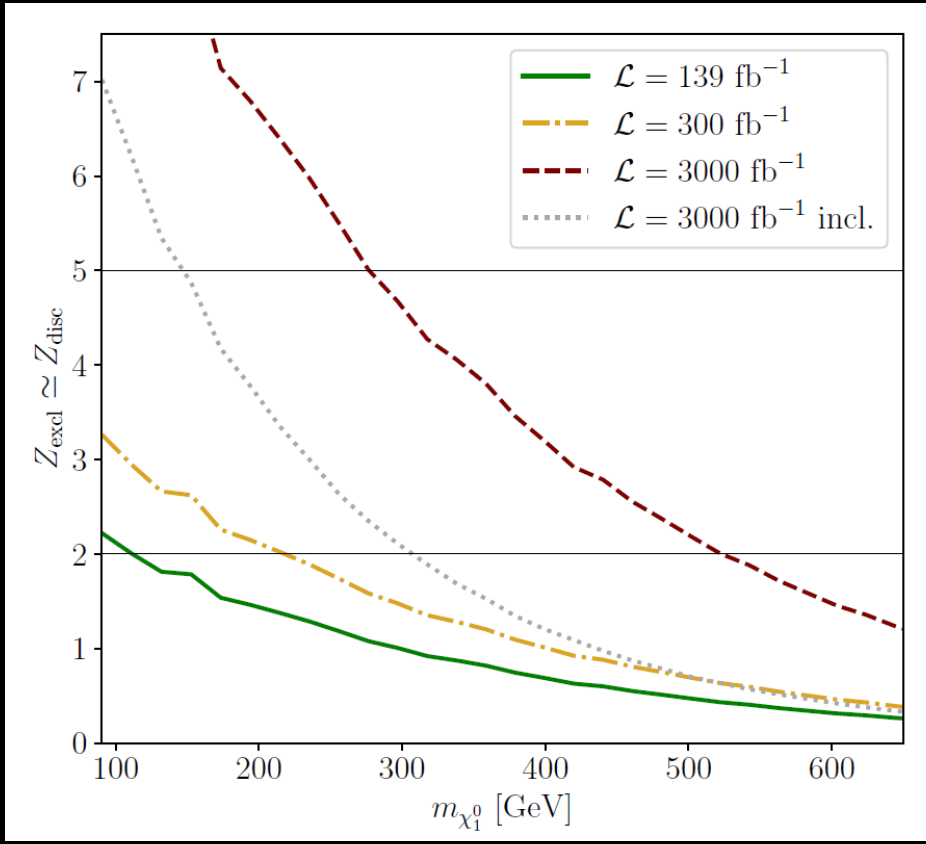
- bkg. discrimination



- **V+jets** is dominant bkg. (≫ diboson)
- V_{had} should be found from jets
- V_{had} **tag from QCD** is important

Results

recast ATLAS analysis w/ 36.1 fb^{-1} data 1807.11471, ATLAS



*** using E_T^{miss}-binned data**

(no correlation)

MadGraph, Pythia, Delphes

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

Summary

mono-V can be an important channel for DM search

- higgsino search
  - **hadronic mono-V signal** is efficient for higgsinos searches
  - can **fill the gap at $\Delta m_{\chi_1^\pm} \sim 1\ GeV$**
  - can test higgsinos up to 520 GeV at HL-LHC

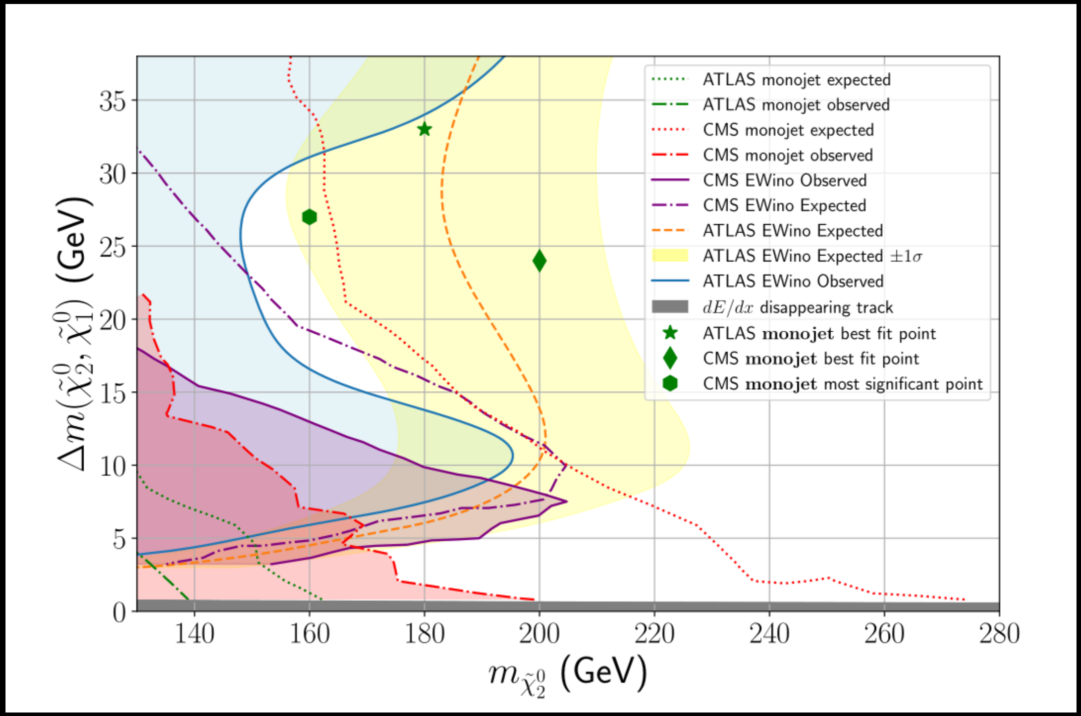
- discussions
  - maybe applicable to **other DM particles**
  - improving **mono-V signal discrimination**

Thank you !!

backups

Excess ??

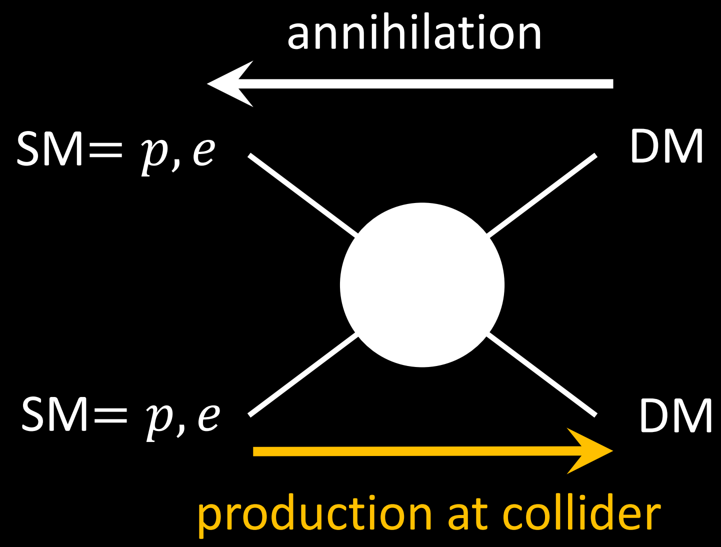
2311.17149, D.Agin, B.Fuks, M.Goodsell, T.Murphy



2106.01676, 2111.06296

- ATLAS & CMS found the $\sim 2\sigma$-level excesses in 1j + soft-leptons channel
- consistent with the **mono-jet** and **mono-V** limits
- **mono-V** could be used for checking the excess

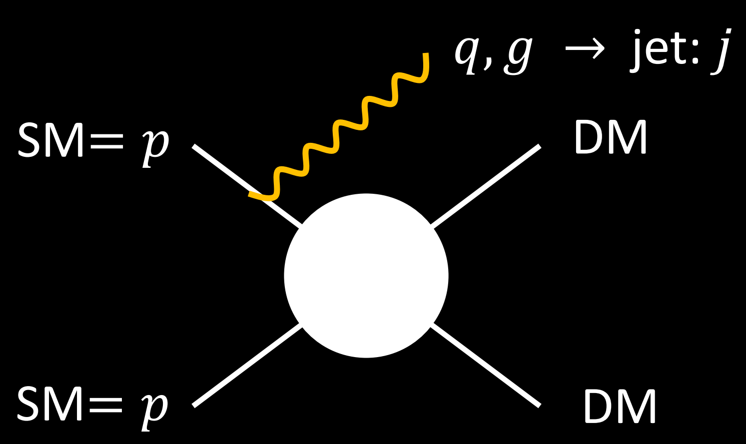
Mono-jet search for DM



- DM may be produced at collider
- However, DM is invisible

➢ mono-jet $1j + E_T^{\text{miss}}$ signal

$E_T^{\text{miss}} \sim |-\vec{p}_T^{\,j}|$



- jet from initial state radiation [ISR]
- suffered from large bkg.
- no limits on Higgsinos at LHC

Higgsino search: higgsino decays

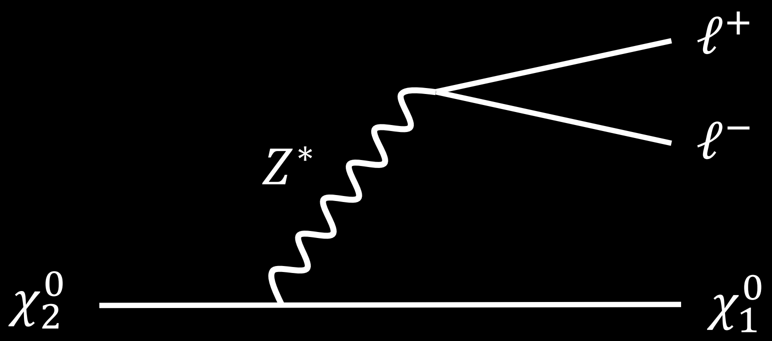
- mass differences of higgsinos

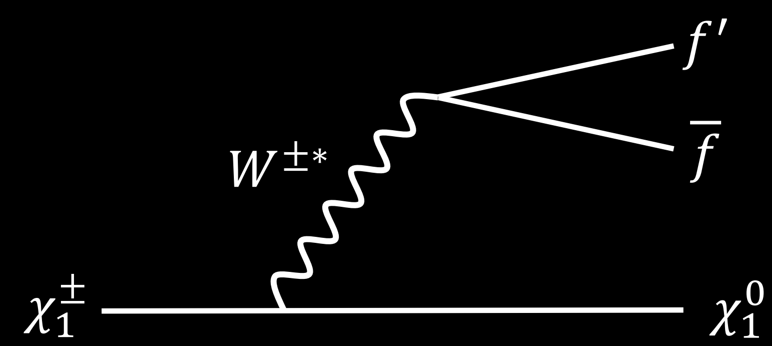
$$\Delta m_{\chi_2^0} \sim 2\Delta m_{\chi_1^\pm} \sim 2.1\ \text{GeV} \times \left(\frac{4\ \text{TeV}}{M_{\text{wino}}}\right)$$

$$\Delta m_{\chi_2^0} := m_{\chi_2^0} - m_{\chi_1^0}$$

$$\Delta m_{\chi_1^\pm} := m_{\chi_1^\pm} - m_{\chi_1^0}$$

- decays of heavier higgsinos: $\chi_2^0, \chi_1^\pm$

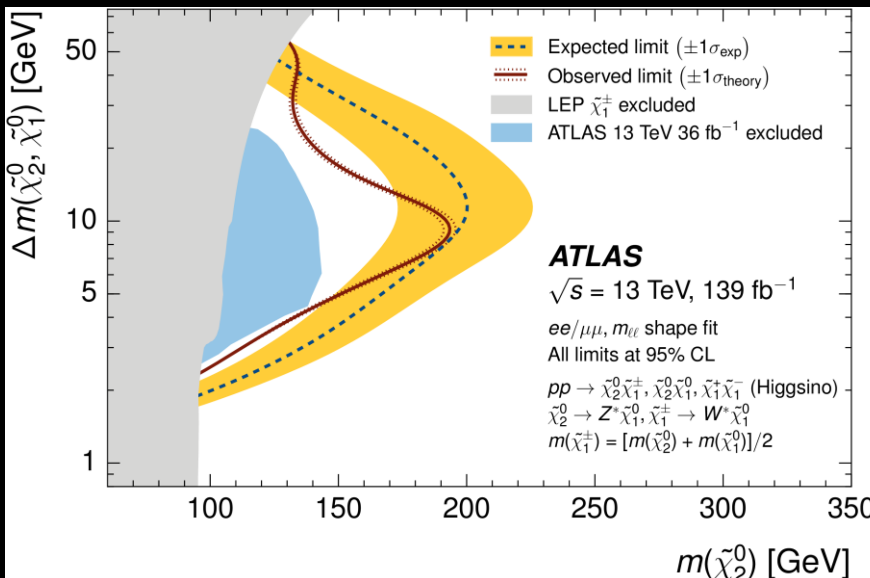




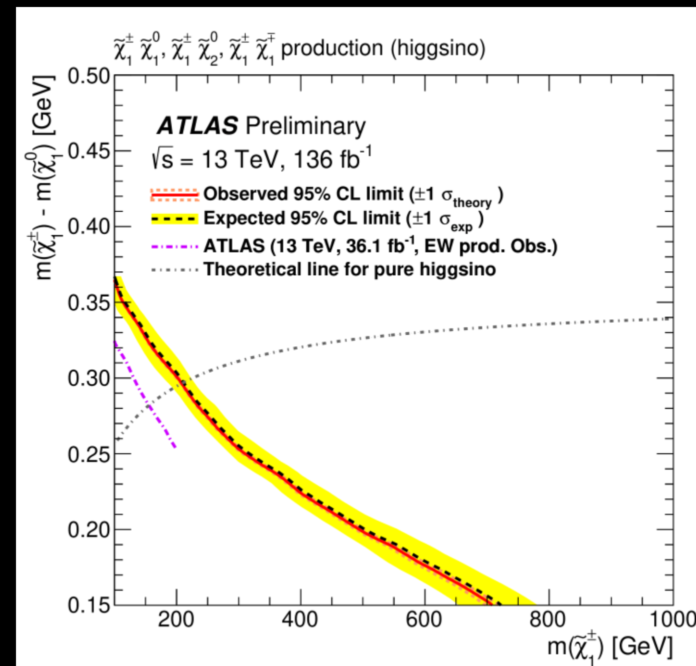
- productions of heavier states are expected
- daughter particles are "soft" due to small mass diff.

Higgsino search: current limits

soft leptons



disappearing track



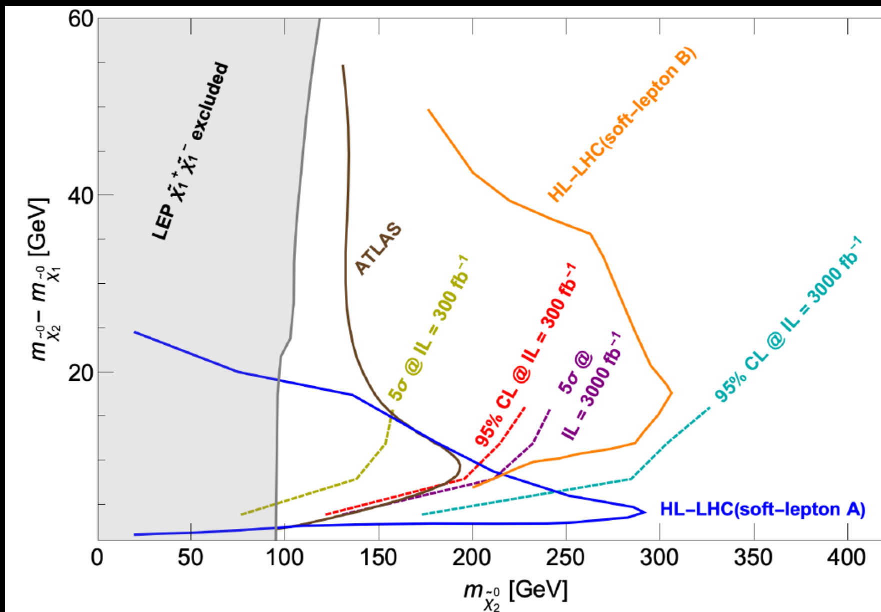
$m_\chi \gtrsim 100$ GeV limits
for $\Delta m_{\chi_1^{\pm}} \sim \Delta m_{\chi_2^0}/2 \gtrsim 1.3$ GeV

for $\Delta m_{\chi_1^{\pm}} \lesssim 0.35$ GeV

- limits are at most 200 GeV
- no limits for $m_\chi \gtrsim 100$ GeV from LHC for $\Delta m_{\chi_1^{\pm}} \sim 1$ GeV

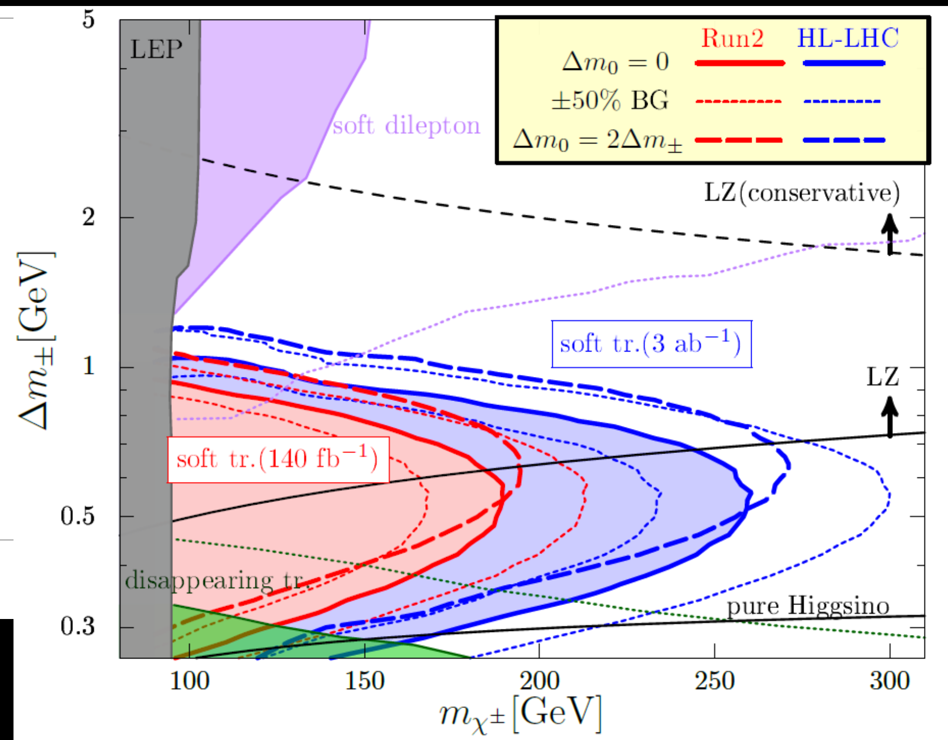
Higgsino search: future limits

soft leptons



2109.14030, Baer, Barger, Sengupta, Tata

soft displaced vertex



1910.08065, Fukuda, Nagata, Oide, Otono, Shirai

- limits are at most about 300 GeV at HL-LHC
- limits are $\sim$ 100 GeV for $\Delta m_{\chi_1^\pm} \sim 1$ GeV, the gap remains

Summary of existing higgsino searches

- generic mono-jet search is not efficient for higgsinos
- soft leptons are available for relatively large mass diffs. $\Delta m_{\chi_1^\pm} \gtrsim 3\ \mathrm{GeV}$
- disappearing tracks are available for very small mass diffs. $\Delta m_{\chi_1^\pm} \lesssim 0.8\ \mathrm{GeV}$
- there is a gap at $\Delta m_{\chi_1^\pm} \sim 1\ \mathrm{GeV}$ corresponding to $M_{\mathrm{wino}} \sim 4\ \mathrm{TeV}$
- known searches basically require ISR jet

Higgsino

- Co-annihilating DM

there are two Higgs doublets in Minimal SUSY SM [MSSM]

→
- two neutral states: χ_1^0, χ_2^0 and two charged states $\chi_1^\pm$
- the lightest state χ_1^0 can be DM
- mass differences are typically less than few GeV

→ co-annihilation DM → ✓ direct detection

- Origin of EW scale

$$m_Z^2 \sim -2|\mu|^2 - 2m_{H_u}^2$$

$m_Z = 91.2\ \mathrm{GeV}$,

μ: Higgsino mass,

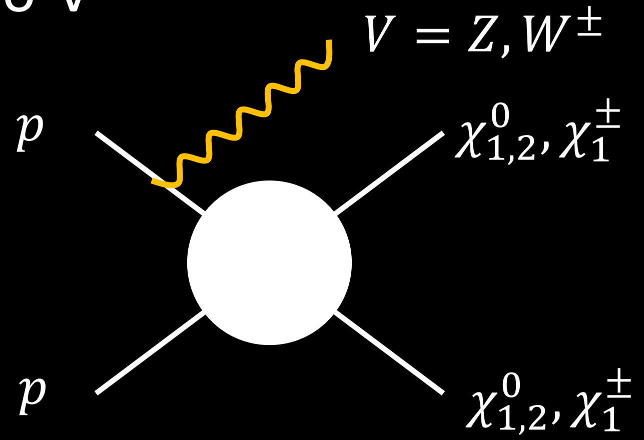
m_{H_u}: Higgs mass term

understanding the origin of EW scale

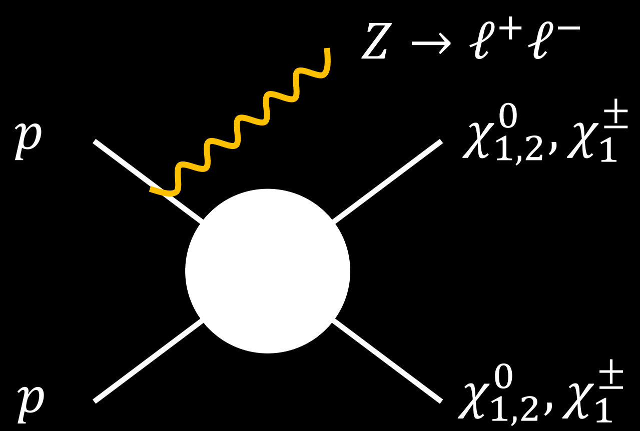
mono-Z/W signal

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

- mono-V



- leptonic mono-Z



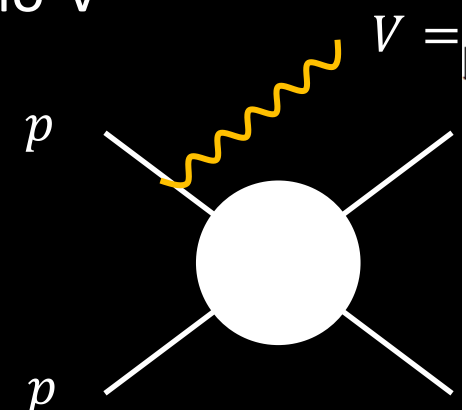
✓ less production cross section

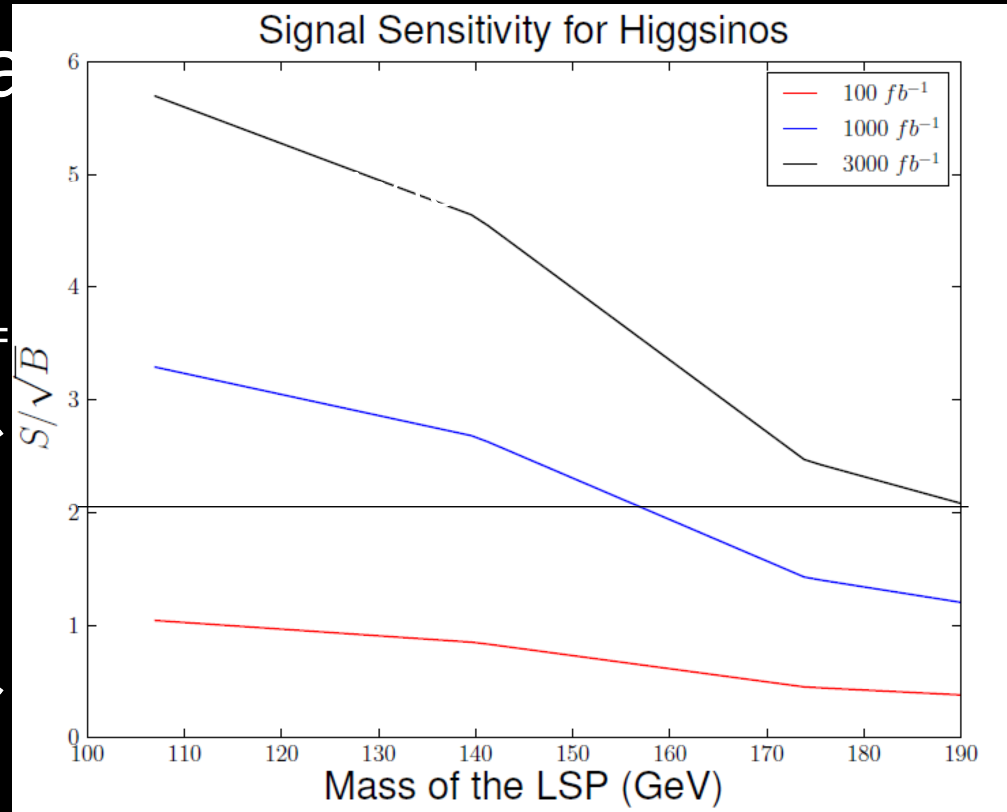
- (much) less backgrounds

mono-Z/W signa

what if we

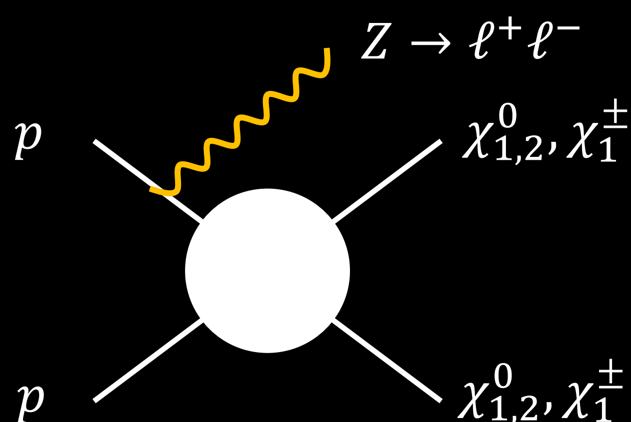
- mono-V





1407.1833, Anandakrichnan, Carpenter, Raby

- leptonic mono-Z

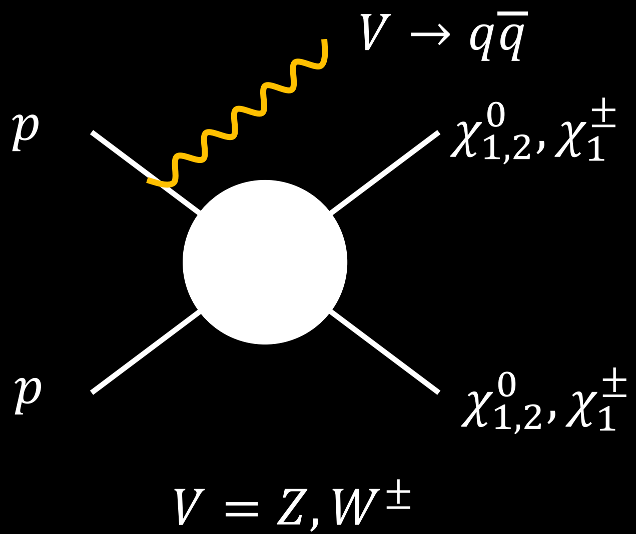


✓ limit is about 190 GeV at HL-LHC

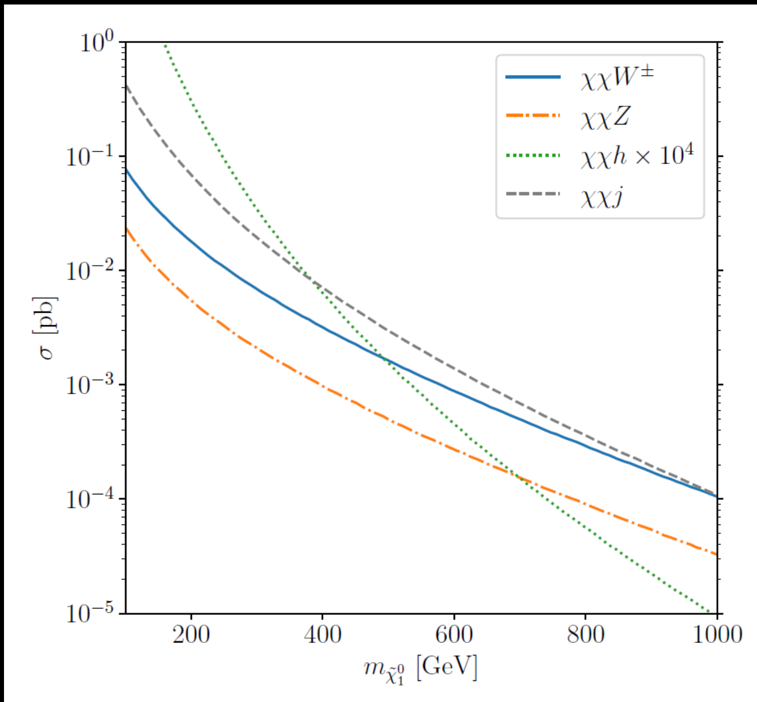
✓ not large production x-section

mono-Z/W signal

➢ hadronic mono-V



production cross section



- W associated production is much larger than prod. with Z
- hadronic BRs $\sim 70\%$ are larger than leptonic BRs $\sim 10\ (30)\%$ for Z (W)

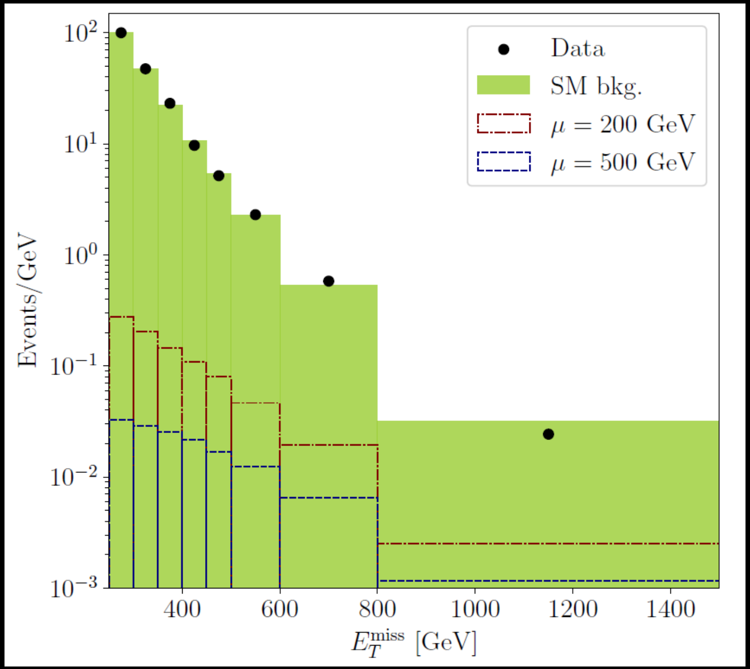
→ significantly large production rate

Analysis

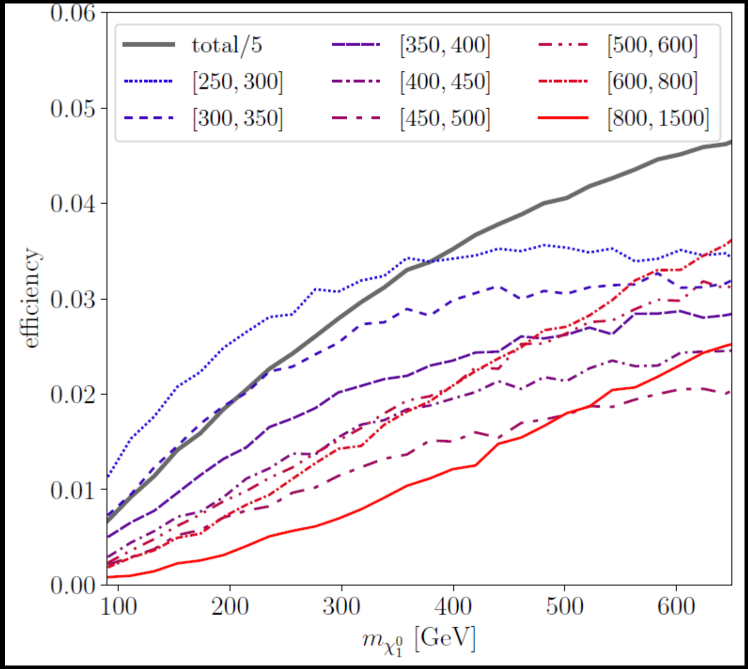
- Recast ATLAS analysis w/ $36.1\ \mathrm{fb}^{-1}$ data 1807.11471, ATLAS
  - one V_{had} jet with $p_T > 250$ GeV and $E_T^{\mathrm{miss}} > 200$ GeV
  - 50% efficiency for V_{had} tagging
  - cuts for multi jet bkg. are applied
  - leptons with $p_T > 7$ GeV are vetoed
- Assumptions
  - all of higgsino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

E_T^{miss} distribution

E_T^{miss} distribution



efficiency =
pass the cuts/# events generated

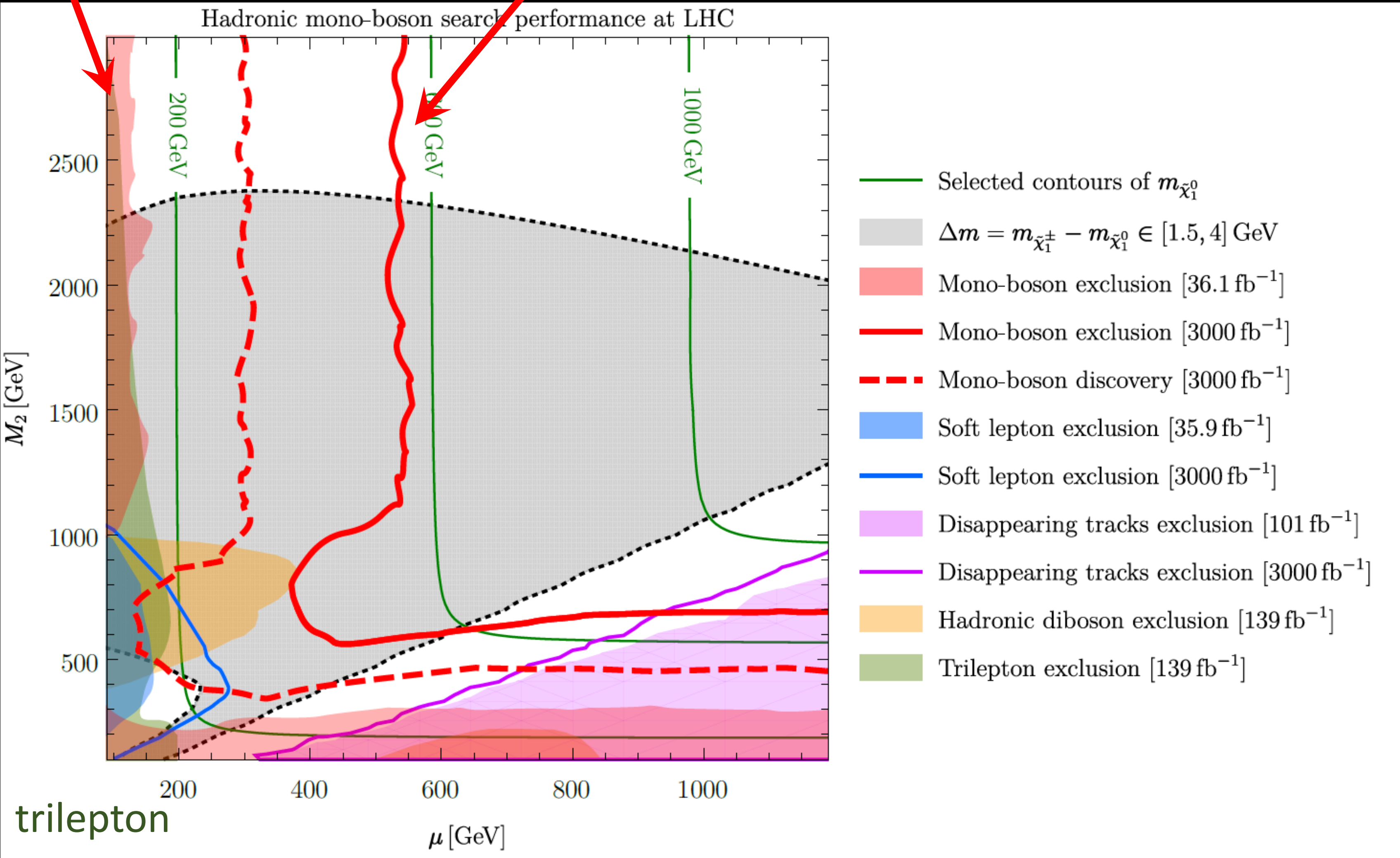


- signals are $\mathcal{O}(0.1 - 1\%)$ of the SM bkg.
- higher E_T^{miss} is expected for heavier masses

Results: μ-M_2 plane

139 fb^{-1} expected

mono-V excl. at HLLHC

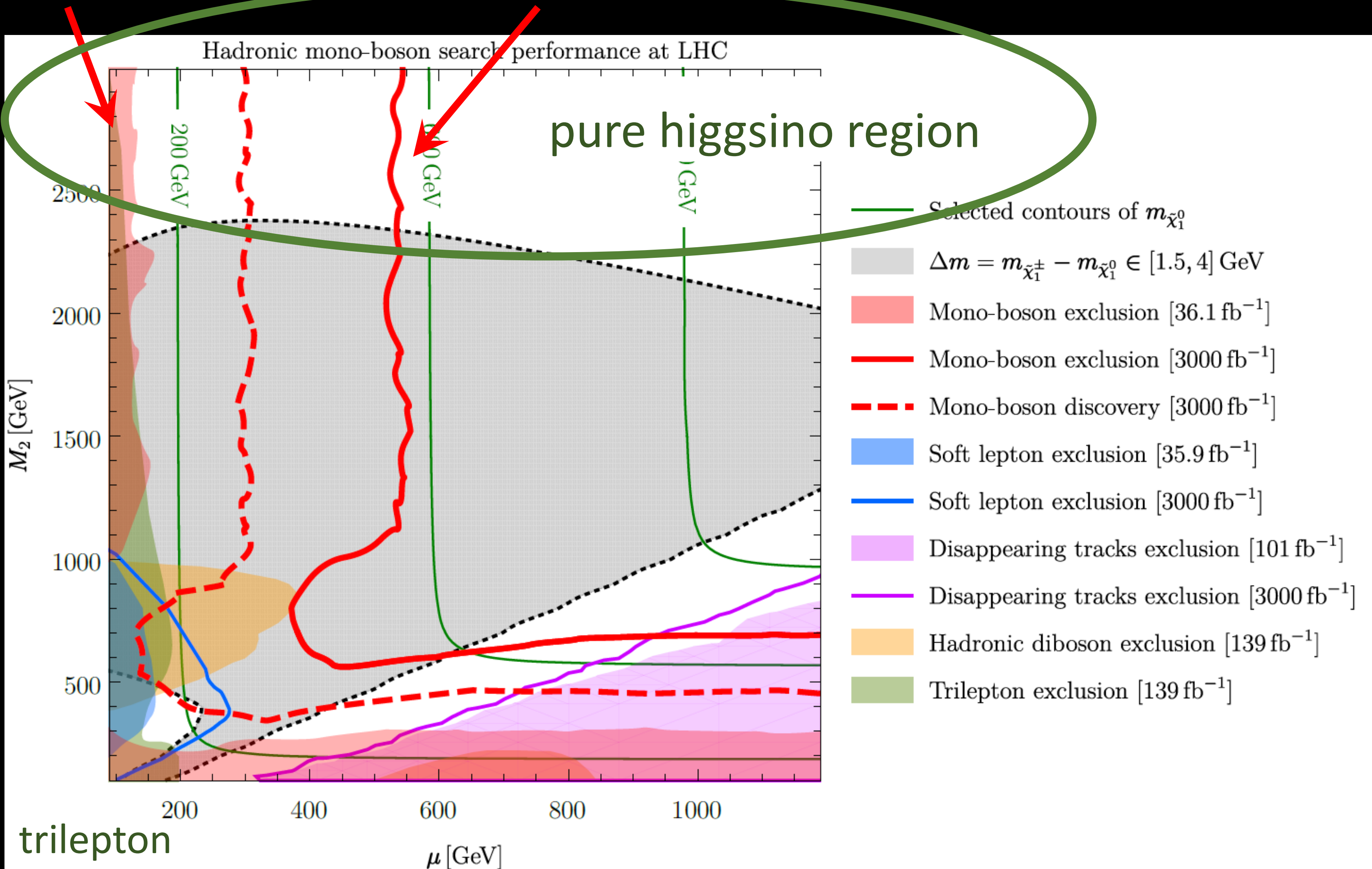


trilepton

Results: μ-M_2 plane

139 fb exp.

mono-V excl. at HLLHC



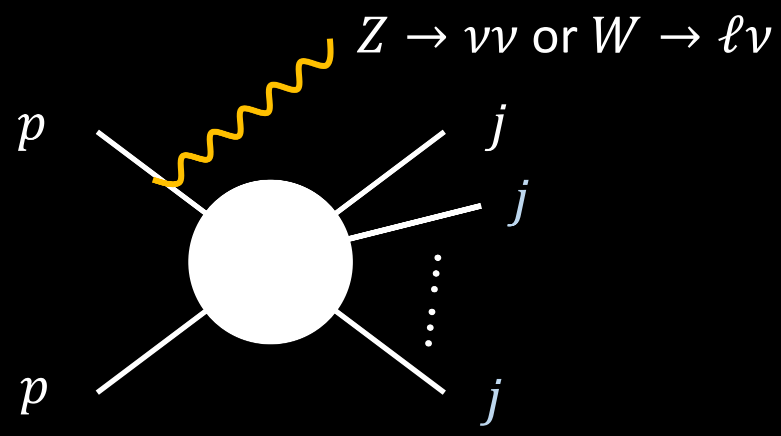
mono-V is most important for pure higgsino region

mono-Z/W signal

are backgrounds small ?

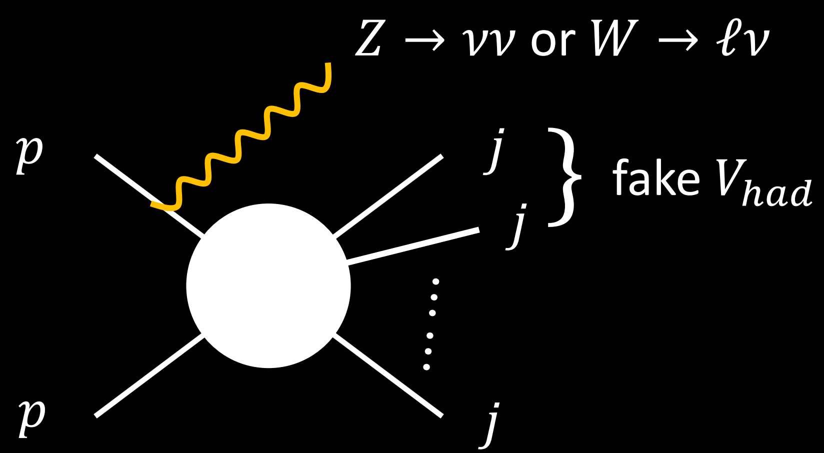
$V = Z, W^{\pm}$

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



- V+jets is dominant bkg.
- topologically same signal

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



- V+jets is dominant bkg. ($\gg$ diboson)
- V_{had} should be found from jets

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

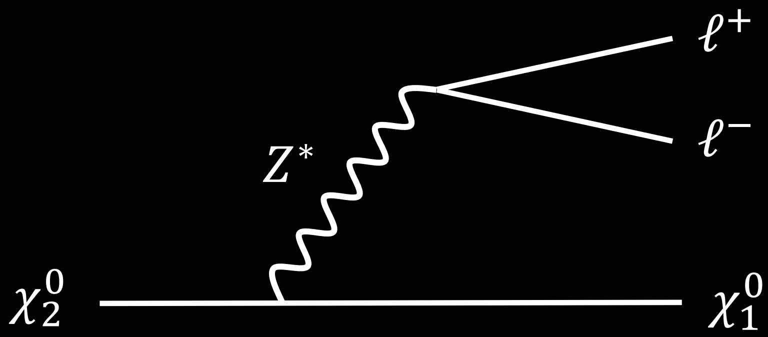
ATLAS-PHYS-PUB-2015-033

→ well discriminate signal/bkg.

Higgsino search: soft leptons

1401.1235 Han, Kribs, Martin Menon

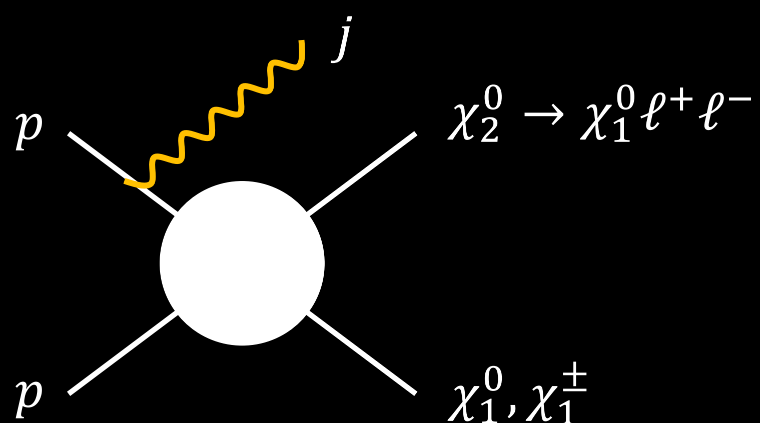
1409.7058, Baer, Mustafayev, Tata



di-leptons are visible

if $\Delta m_{\chi_2^0} \gtrsim 10$ GeV

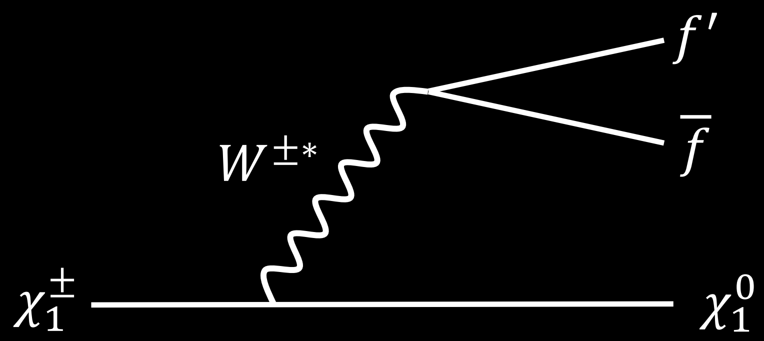
➢ $j + \ell^+\ell^- + E_T^{\text{miss}}$



- productions $pp \to \chi_2^0\chi_1^0, \chi_2^0\chi_1^\pm$
- ISR jet is necessary to trigger
- $m^2_{\ell^+\ell^-} < 10$ GeV cut is effective

Higgsino search: disappearing tracks

0610277 Ibe, Moroi, Yanagida
1703.05327 Mahbubani, Schwaller, Zurita
1703.09675 Fukuda, Nagata, Otono, Shirai

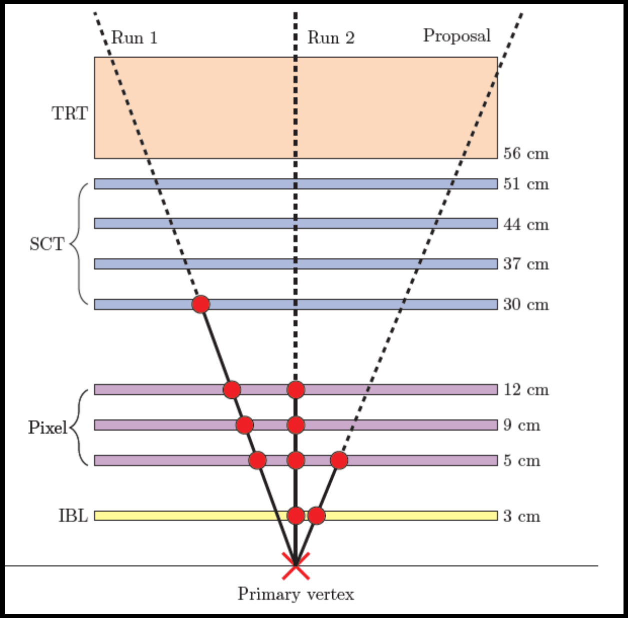


charged state $\chi_1^{\pm}$ is long-lived

if $\Delta m_{\chi_1^{\pm}} \sim \mathcal{O}(100\ \mathrm{MeV})$

➢ disappearing track search

flight length of $\mathcal{O}(\mathrm{cm})$

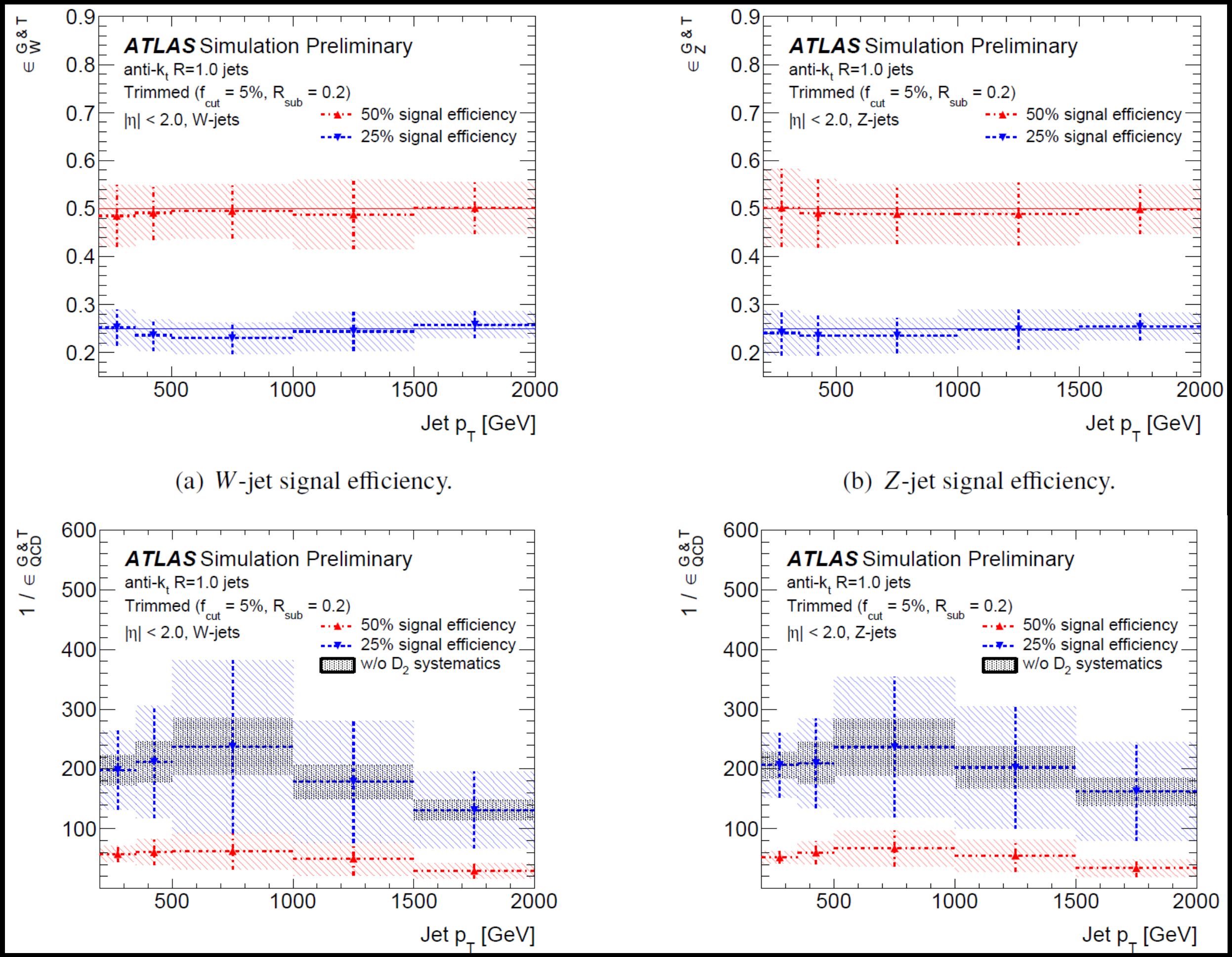


- charged track disappear in detector
- ISR jet is required to trigger

1703.09675, Fukuda, Nagatam Otono, Shirai

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.

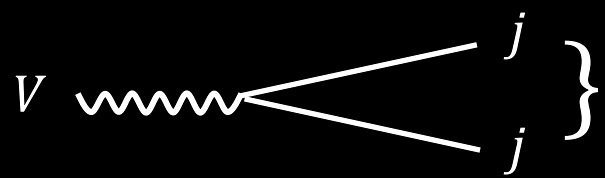
V-tag rate from Z/W

$\sim$ 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

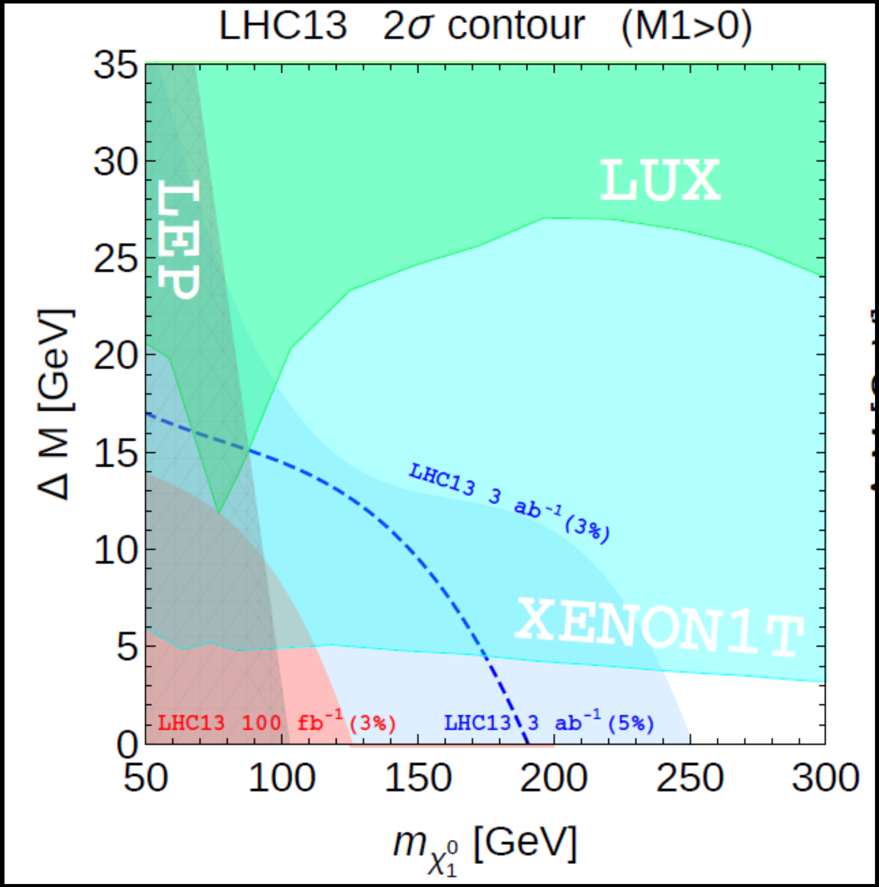
➢ $D_2 = e_3/e_2^3$

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

- 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

mono-jet bounds

1504.02472, Barducci, Belyaev, Bharucha, Porod, Sanz



limits about 250 GeV at HL-LHC

backgrounds

- number of events 1807.11471, ATALS

Process	Merged topology 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

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

Light higgsino from mirage mediation

- mirage = modulus + anomaly mediation K.Choi, T.Kobayashi, et.al, 050829

gaugino masses: $M_a = \frac{F^T}{T+T^*} + \frac{b_a g_0^2}{16\pi^2}\frac{F^C}{C}$ $b_a = (\frac{55}{3}, +1, -3)$

→ ratio M_2/M_3 increases for positive interference at GUT scale

→ $|\mu|^2 \sim -m_{H_u}^2$ decreases through RGE

$$|\mu|^2 \sim -m_{H_u}^2(\mathrm{TeV}) \sim -0.17\, M_2^2 + 0.20 M_2 M_3 + 3.09 M_3^2$$

H.Abe, J.K, H.Otsuka, 1208.5328

- light higgsino scenarios

  - light higgsino together with 125 GeV Higgs is realized

    H.Abe, J.K, 1405.0779, 1405.3754

  - there are more scenarios for light higgsino

    ex) non-universal higgs mass, generalized gauge mediation, ….

Backup

Lepton portal dark matter

Junichiro Kawamura

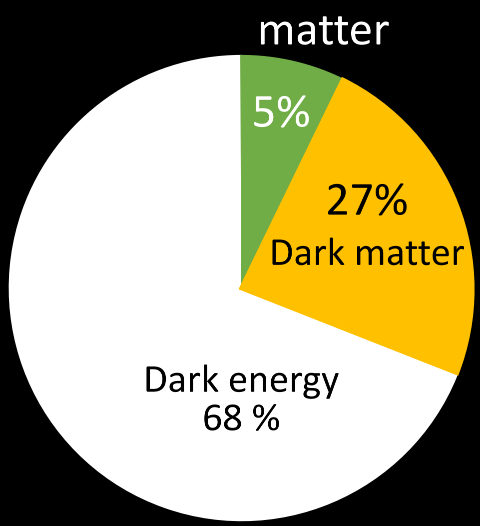
Institute for Basic Science, CTPU

based on [hep-ph]
2002.12534 (JHEP), 2204.07022 (PRD)

in collaboration with
S.Okawa (Barcelona U. → KEK) and Y.Omura (Kindai U.)

Dark Matter [DM]

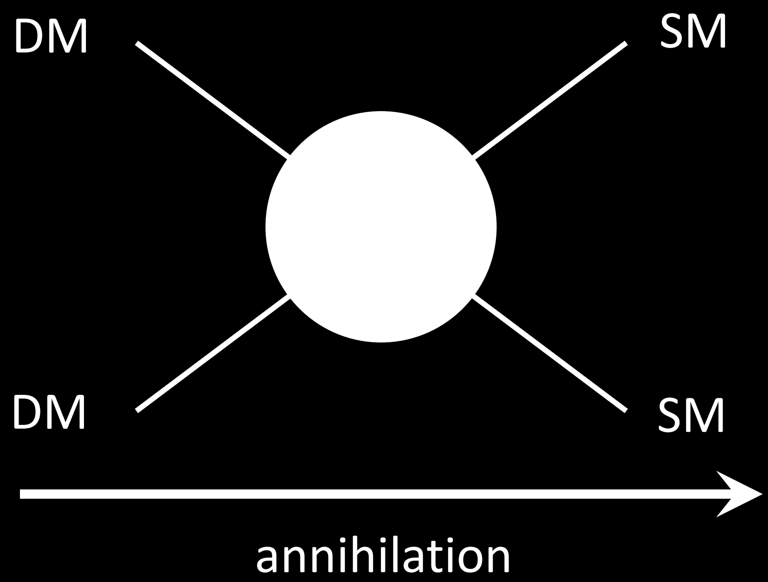
- dark matter
  - dark and cold (particle)
  - 27% of energy of the universe
  - discovered only by gravitational int.

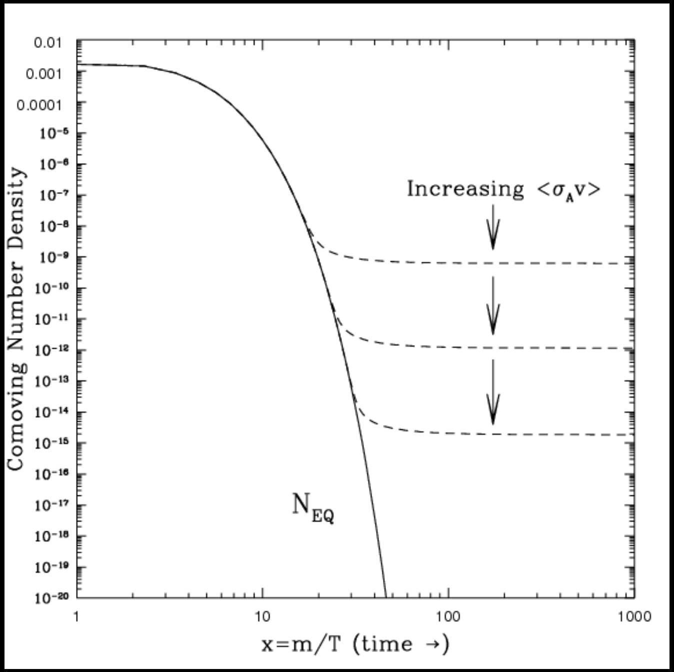


- particle candidates
  - Weakly Interacting Massive Particle [WIMP]
  - axion, ALP
  - SIMP, FIMP, asymmetric, self-interacting, ⋯

WIMP is still an interesting candidate

Freeze-out of WIMP

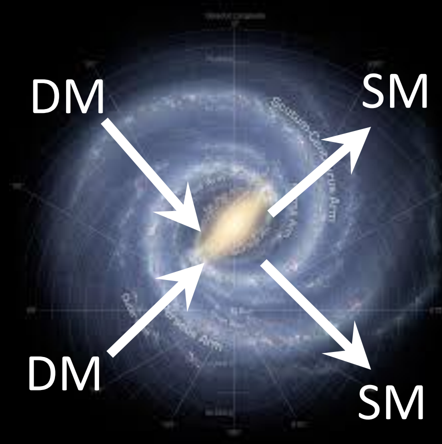




E.W.Kolb, M.S.Turner,
The Early Universe, `89

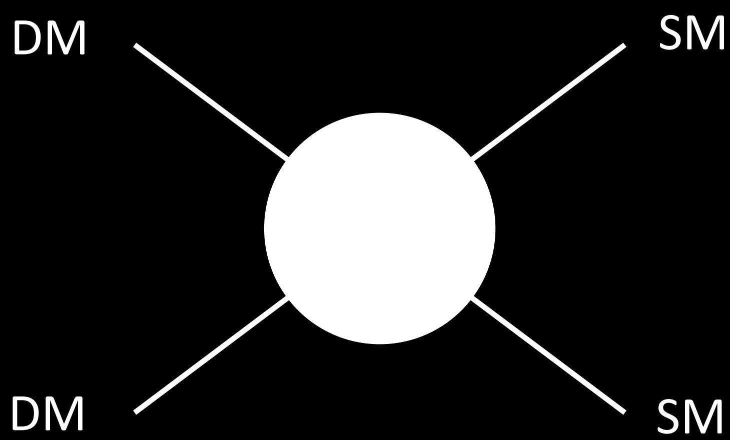
- DM decouples from thermal bath and "freeze-out"
- Electro-Weak [EW] coupling and mass can explain relic density
- WIMP can be in beyond SM e.g. models for muon anomalies

Probes of WIMP

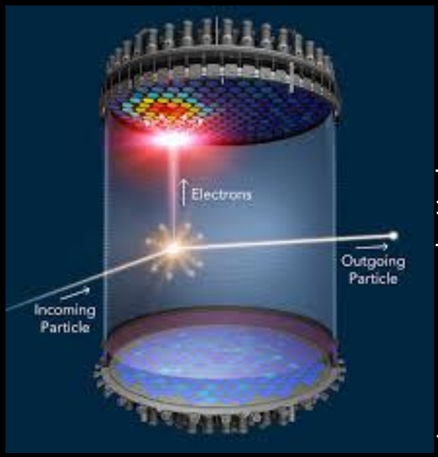


https://solarsystem.nasa.gov/

- annihilation
  - indirect detection
  - annihilation in DM rich env.
  - e.g. Fermi-LAT, CTA, HESS,



- scattering
  - direct detection
  - scattering with nucleus/e
  - e.g. XENON, PANDA, LZ



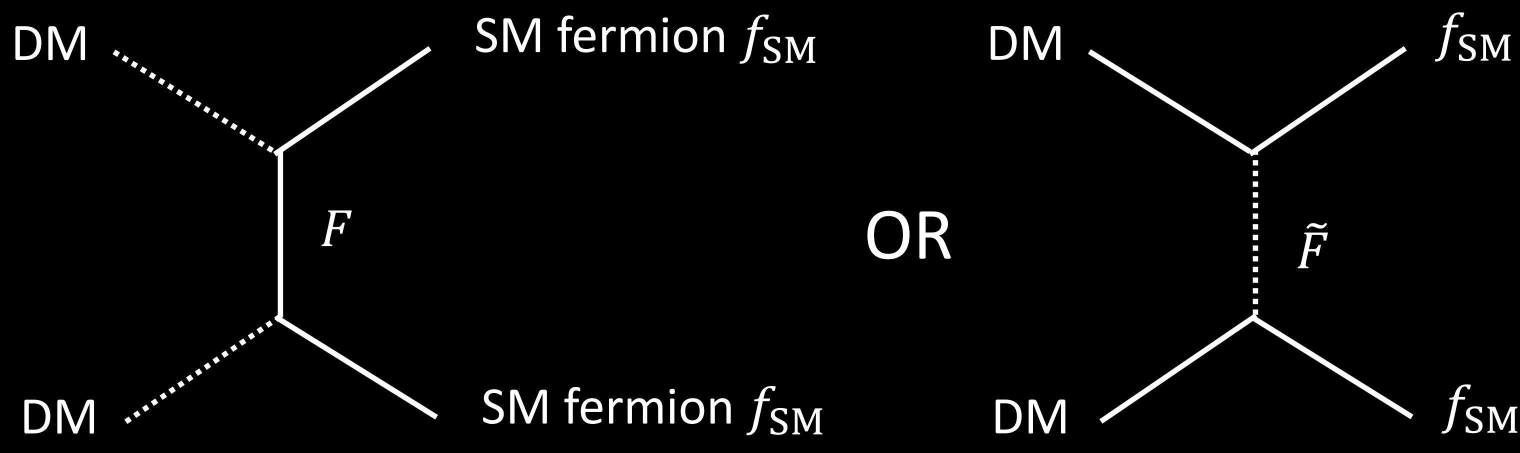
https://kipac.stanford.edu/

- production at collider
  - usually by mono-X searches
  - e.g. LHC, LEP, ILC(?) ⋯

Fermion portal model

1308.0612, 1402.6696 Y.Bai, J.Berger

- SM + EW singlet DM + mediator



- Yukawa coupling, DM and mediator masses are parameter
- co-annihilation of DM and mediator occurs if degenerate
- pure bino + slepton in SUSY is in this class
- We focus on EW singlet DM cf. non-singlet case:

0512090 M.Cirelli, N.Fornengo, A.Strumia (DM)
1804.00009, L.Calibbi, R.Ziegler, J.Zupan (DM+g-2)

Outline

1. Introduction
2. Minimal lepton portal dark matter
3. Relations to recent anomalies
4. Summary

Minimal lepton portal model

- SM + EW singlet DM + 1 mediator (s)lepton

DM is

- 1. scalar / 2. fermion
- a. self-conjugate / b. complex

→

[1a] real scalar
1405.6917, A.Ibarra et.al

[1b] complex scalar
1812.07004, JK, S.Okawa et.al

[2a] Majorana fermion
1403.4634 Garny et.al ,
1401.6457 Kopp et.al

[2b] Dirac fermion
1503.03382 A.Ibarra, S.Wild

mediator is

- 1. fermion / 2. scalar
- i. EW singlet / ii. EW doublet

there are $2 \times 2 \times 2 = 8$ possibilities

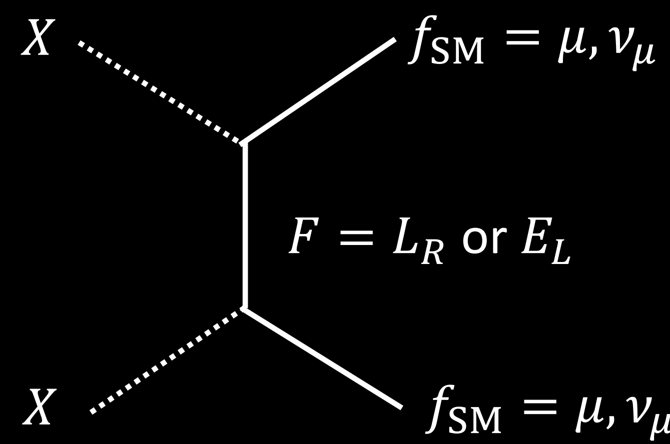
Scalar DM models

- singlet mediator E_L

  $\mathcal{L} \supset m_E \, \overline{E}_L E_R + \lambda_R \overline{E}_L \, X \, \mu_R$

- doublet mediator L_R

  $\mathcal{L} \supset m_L \, \overline{L}_L L_R + \lambda_L \overline{\ell_2} \, X \, L_R \quad \ell_2 = \begin{pmatrix} \mu_L \\ \nu_{\mu_L} \end{pmatrix}$



- fermion mediator should be vector-like
- Yukawa coupling is non-zero only for muon
- Higgs portal is neglected

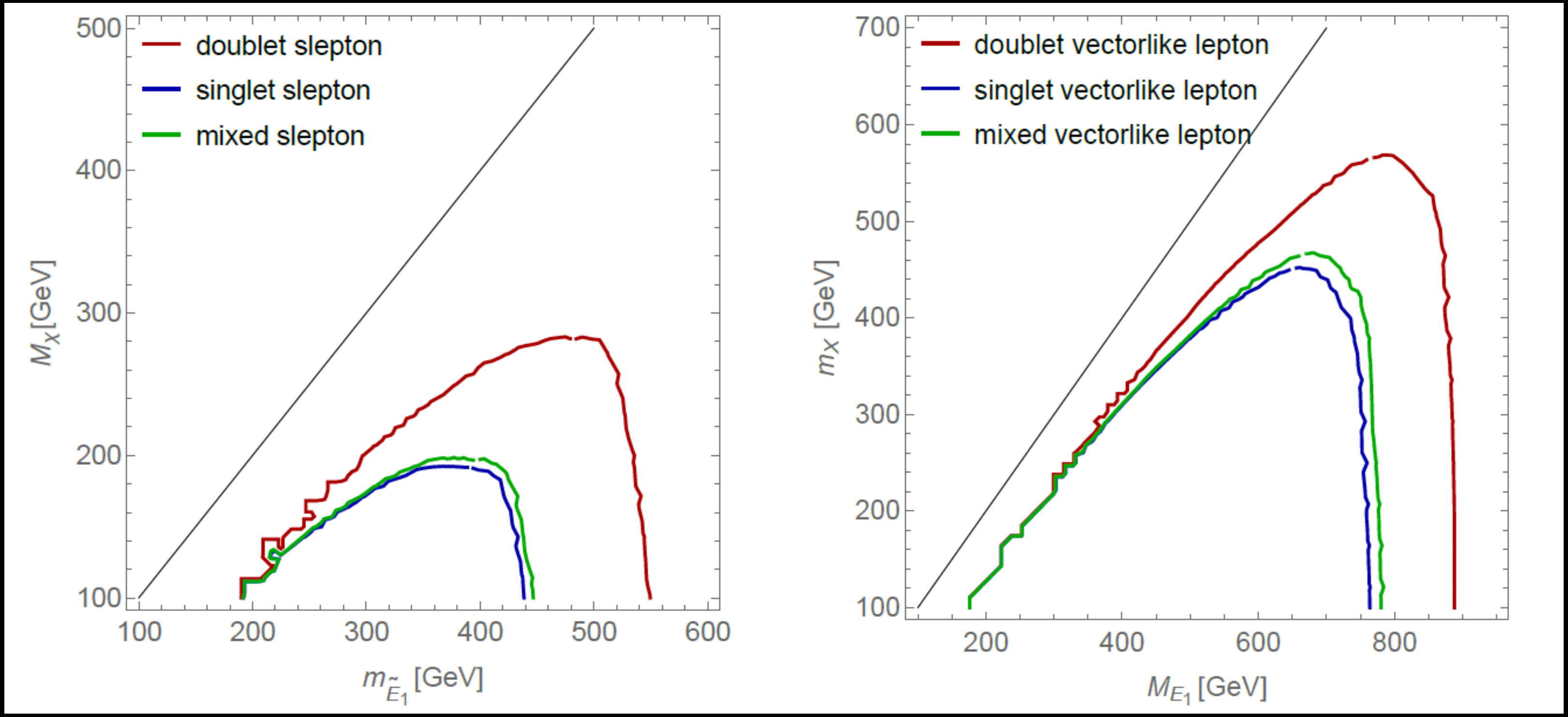
- Fermion DM models
  - mediator is “s”lepton (complex scalar)
  - special case of Majorana DM (= bino) is realized in SUSY

LHC limits

mediator decays to DM and muon

→ $p\,p \to L\,L \to \mu\,\mu + \mathrm{MET}$ is the same as SUSY slepton signal

limit from $139\ \mathrm{fb}^{-1}$ data at ATLAS [1908.08215]

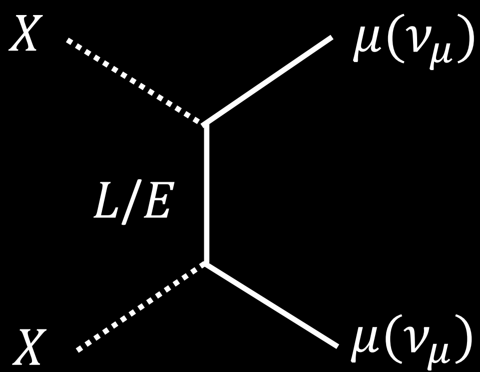


FeynRules, Madgraph5

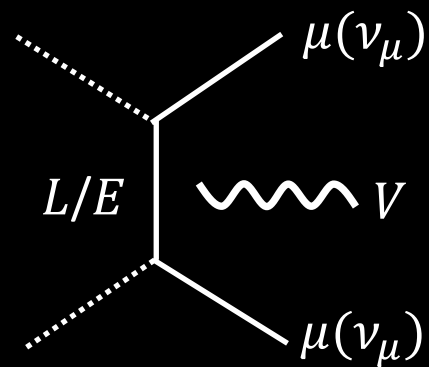
Annihilation

- Processes

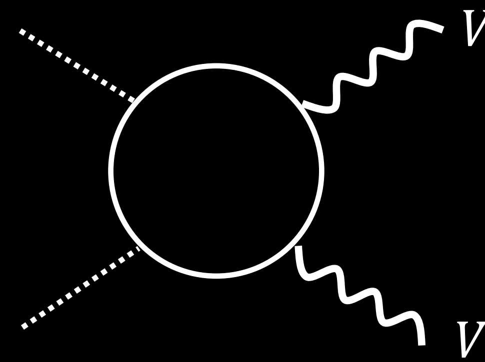
$V, V' = Z, W, \gamma$



$XX^{(\dagger)} \to \mu\mu$



$XX^{(\dagger)} \to \mu\mu + V$



$XX^{(\dagger)} \to VV'$

- 2-2 annihilation

velocity expansion: $\sigma v = a + b\, v^2 + c v^4 + \cdots$ (s-wave, p-wave, d-wave)

$\langle v^2 \rangle \simeq 0.24, \langle v^4 \rangle \simeq 0.1$ at freeze-out

- s-wave is helicity suppressed, i.e. $\propto m_\mu^2/m_X^2$, except Dirac DM
- p-wave is also helicity suppressed for real DM

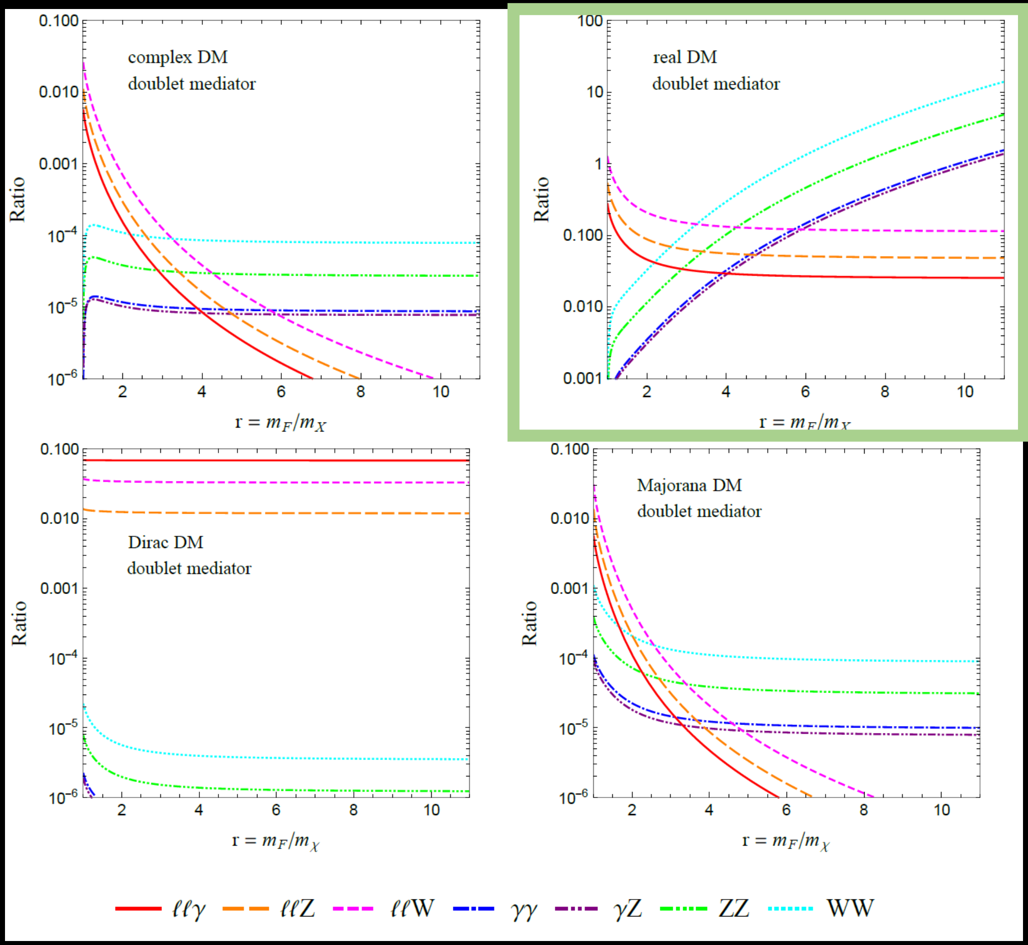
Annihilation

relative importance of higher-order processes

$$\text{Ratio} = \frac{\langle \sigma(XX \to \mu\mu V/VV')v \rangle}{\langle \sigma(XX \to \mu\mu)v \rangle}$$

$$m_X = 500 \text{ GeV}$$

$$r = m_L/m_X$$

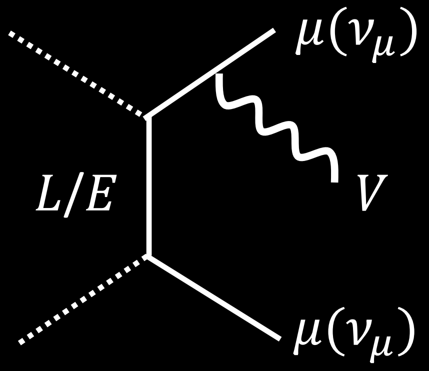


- higher-order processes can be sizable for real DM
- these are less than 0.1 for other cases

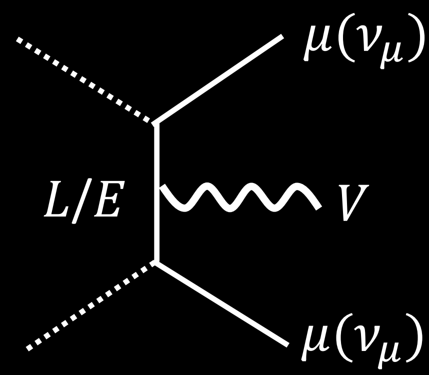
Virtual Internal Bremsstrahlung

e.g. 1203.1312
T.Bringmann, X.Huang et.al

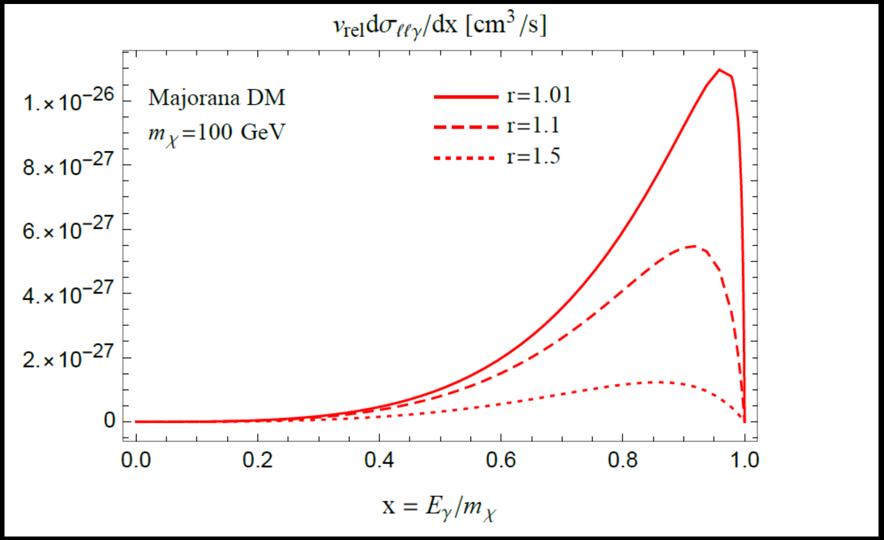
Final State Radiation [FSR]



Virtual Internal Bremsstrahlung [VIB]



- photon spectrum from VIB



$r = m_L/m_X$

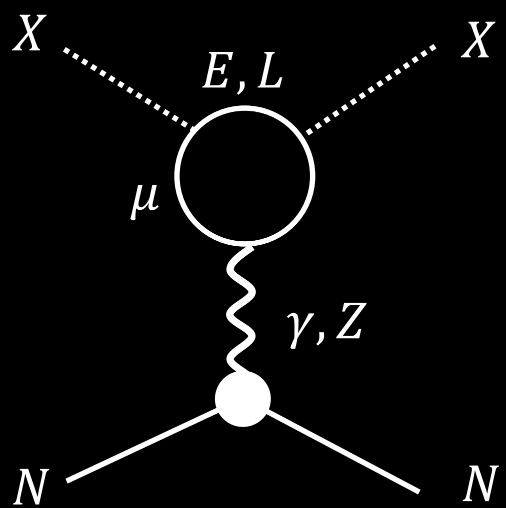
- peak at $E_\gamma \sim m_X$ if $m_L \sim m_X$
- γ from $XX \to \gamma\gamma, Z\gamma$ also has sharp spectral structure

1405.6917
A.Ibarra, T.Toma et.al

Direct detection

tree-level is absent

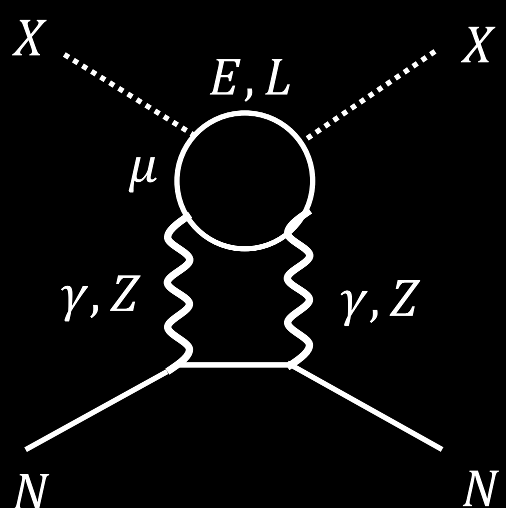
0907.3159, J.Kopp etl.al



- 1-loop penguin

$$\rightarrow \quad \mathcal{L}_{\text{eff}} \supset C\, i \left(X^\dagger \partial_\mu X - \partial_\mu X^\dagger \cdot X \right) \overline{N} \gamma^\mu N$$

  - dominant in complex scalar DM
  - vanishing for real scalar DM

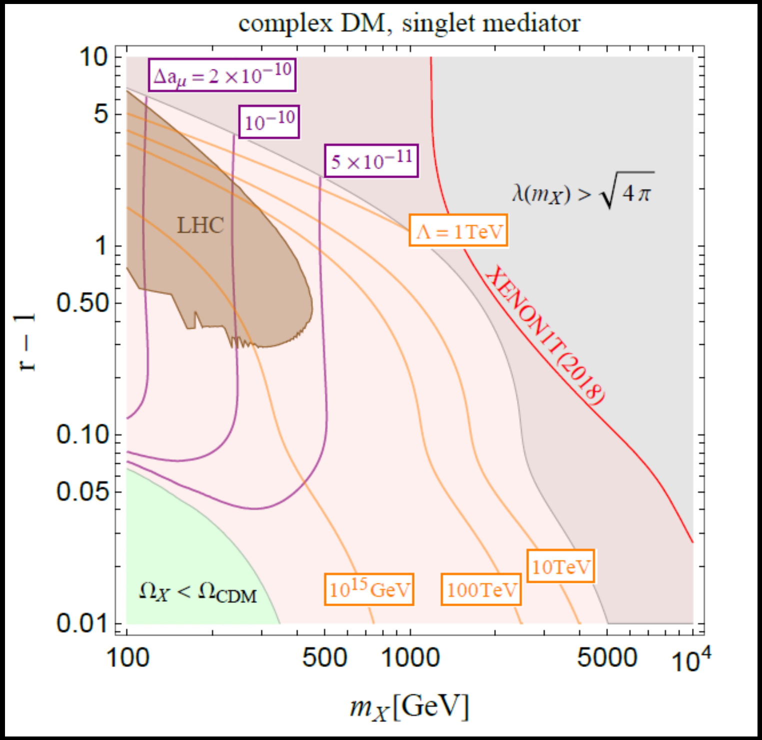


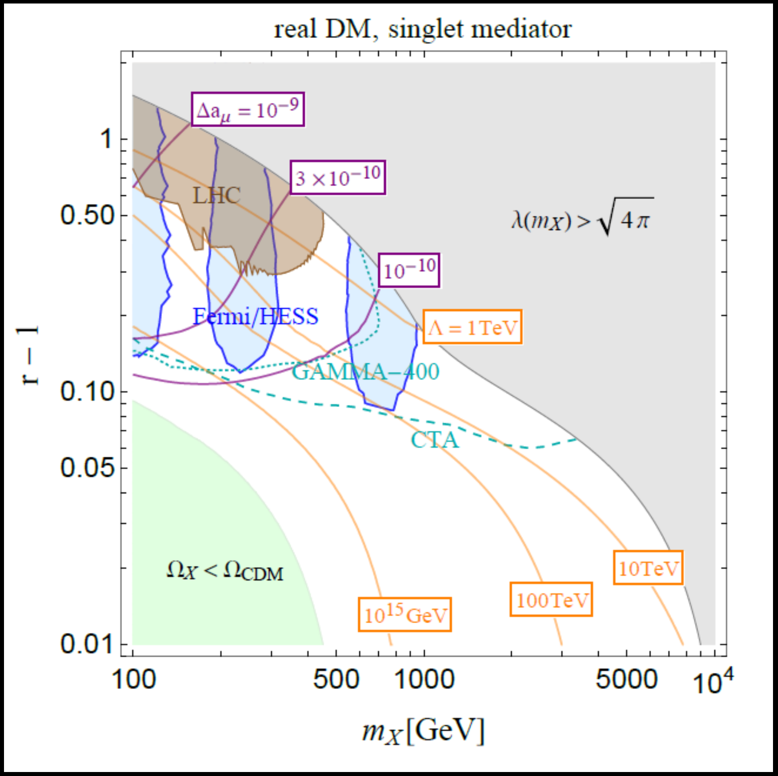
- 2-loop two photon exchange
  - dominant in real scalar DM
  - very much suppressed

Current status of scalar DM

$r = m_E/m_X$

Yukawa is fixed to explain thermal relic density via (co-)annihilation





MicrOmegas

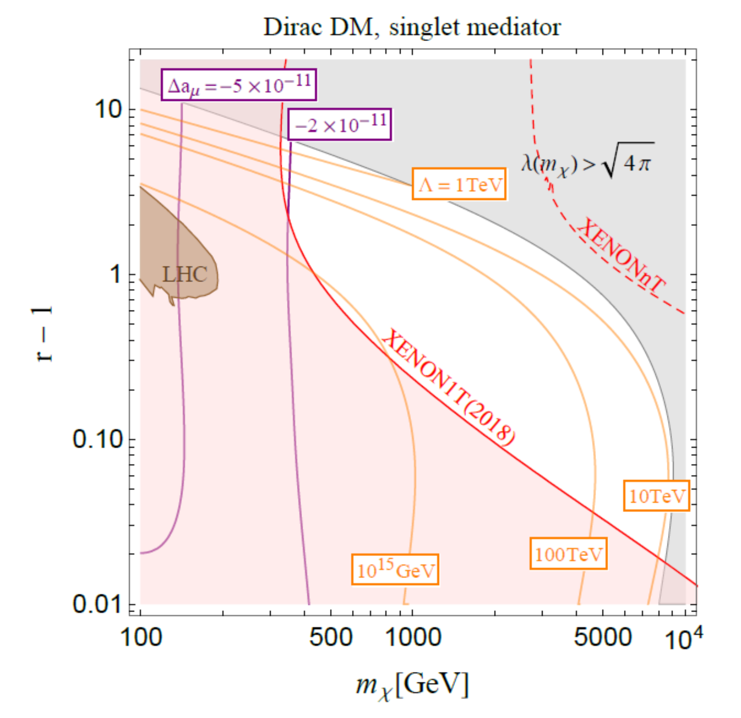
- ✓ excluded by direct detection
- ✓ Δa_μ is too small

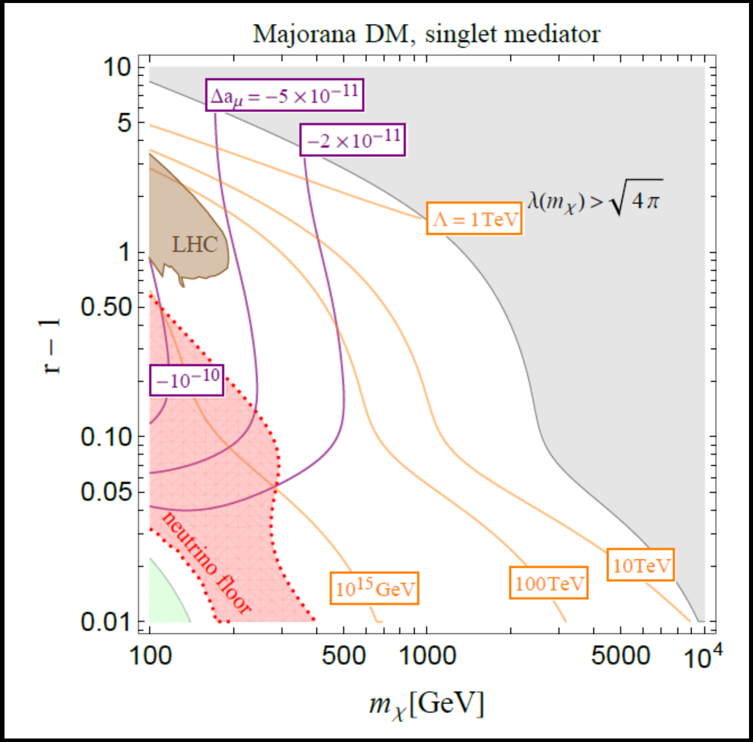
- co-annihilation is needed for abundance
- direct detection bound is absent
- indirect detections give bounds

Current status of fermion DM

$r = m_E/m_X$

Yukawa is fixed to explain thermal relic density via (co-)annihilation





MicrOmegas

✓ XENON excludes wide region

✓ Δa_μ is too small

- p-wave allows larger mass difference
- direct detection bound is absent
- indirect detections give no bound

Summary of minimal models

	real	complex	Majorana	Dirac
relic density $XX \to \mu\mu$	d-wave	p-wave	p-wave	s-wave
direct det. $XN \to XN$	2-loop	1-loop	1-loop v-suppressed	1-loop
indirect det. $\sigma_{\mu\mu\gamma}/\sigma_{\mu\mu}$	$\gtrsim \mathbf{0.1}$	$\lesssim 0.1$	$\lesssim 0.1$	$\lesssim 0.1$

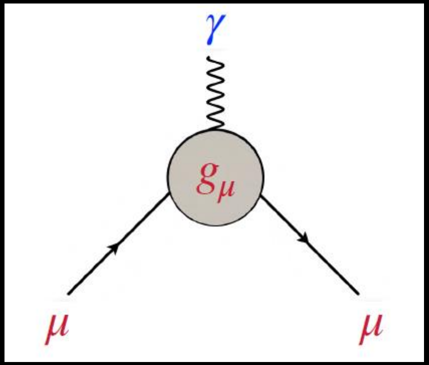
- complex/Dirac DM is strongly constrained by XENON
- real DM is partially constrained by indirect detections due to VIB
- Majorana DM is less constrained
- Analytic formulas are in paper

Outline

1. Introduction
2. Minimal lepton portal dark matter
3. Relations to recent anomalies
4. Summary

Anomalies in EW model ?

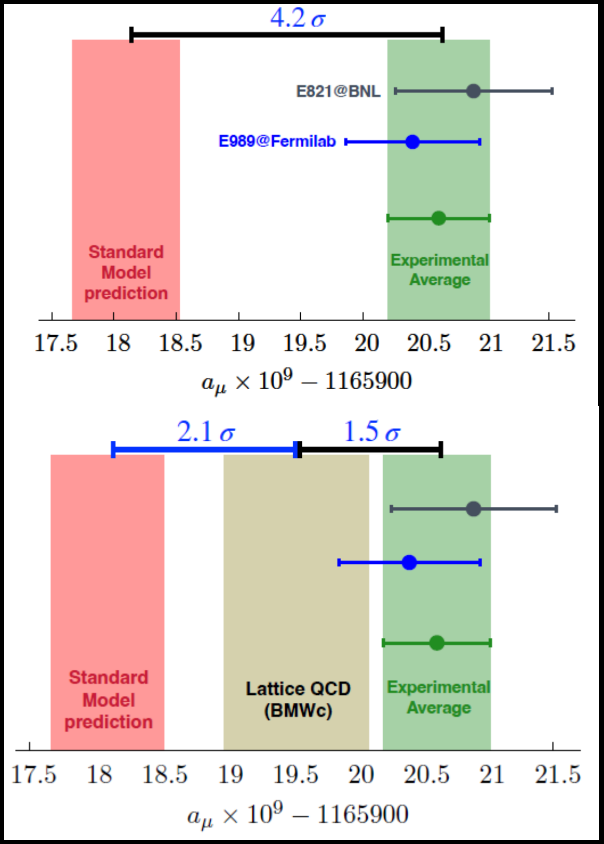
*Figs. from H.Wittig's slide at Moriond 2023



➢ Muon anomalous magnetic moment g-2

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (24.9 \pm 4.8) \times 10^{-10}$$

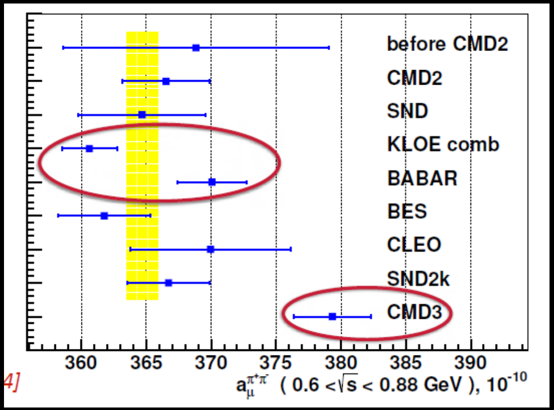
'20 muon g-2 initiative



➢ Current status

- '21: Fermilab exp. confirms old BNL result
- '21: lattice result (BMW) relaxes tension
- '23: CMD3 result for HVP relaxes tension
- '23: Fermilab new result ($\rightarrow 5.1\sigma$?)

???



Anomalies in EW model ?

- W boson mass
  - CDF measurement

    $m_W = 80.4335\ (94)$ GeV

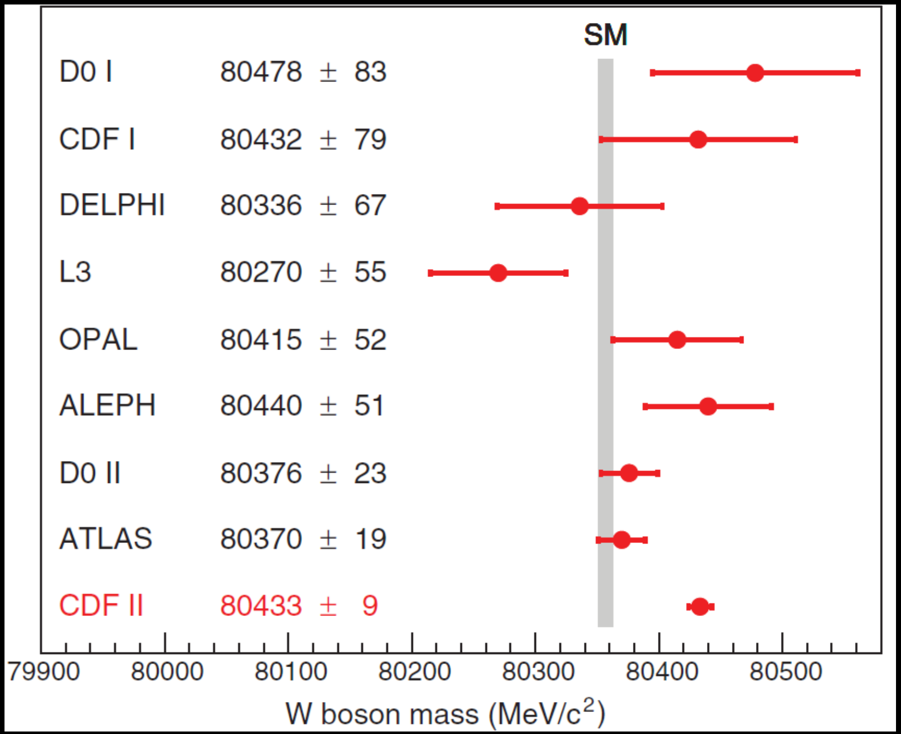
  - PDG average

    $m_W = 80.379\ (12)$ GeV

  - SM value $_{\text{PDG}}$

    $m_W = 80.361\ (6)$ GeV

CDF, Science '22



new value is 7σ larger than the SM expectation

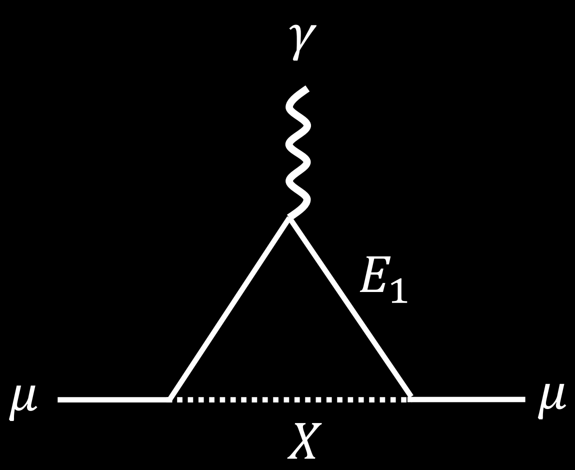
Δa_μ in lepton portal model

- SM + singlet DM + 2 mediator (s)leptons

$$\mathcal{L} \supset \lambda_L \overline{\ell_L}\, X\, L_R + \lambda_R \overline{E}_L X^* \mu_R + \kappa \overline{L}_L H E_R \qquad E'_{L(R)} \in L_{L(R)}$$

$$\rightarrow \begin{pmatrix} E'_R \\ E_R \end{pmatrix} = \begin{pmatrix} c_R & s_R \\ -s_R & c_R \end{pmatrix} \begin{pmatrix} E_{R_1} \\ E_{R_2} \end{pmatrix}, \begin{pmatrix} E'_L \\ E_L \end{pmatrix} = \begin{pmatrix} c_L & s_L \\ -s_L & c_L \end{pmatrix} \begin{pmatrix} E_{L_1} \\ E_{L_2} \end{pmatrix}$$

mixing is induced by Yukawa coupling κ



$$\Delta a_\mu \sim \frac{m_\mu}{16\pi^2 m_X^2} \left[\lambda_L \lambda_R\, c_R s_L m_{E_1} + \mathcal{O}(m_\mu)\right]$$

sizable Δa_μ comes only from mixing

Correlation to DM density

- Annihilation rate

$$\langle \sigma v \rangle \sim \frac{|\lambda_L \lambda_R|^2}{\pi} \left(\frac{c_R s_L m_{E_1}}{m_X^2 + m_{E_1}^2} - \frac{c_L s_R m_{E_2}}{m_X^2 + m_{E_2}^2} \right)^2$$

no suppression by muon mass in the s-wave contribution

- Correlation to Δa_μ

$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ [\mathrm{cm}^3/s]$

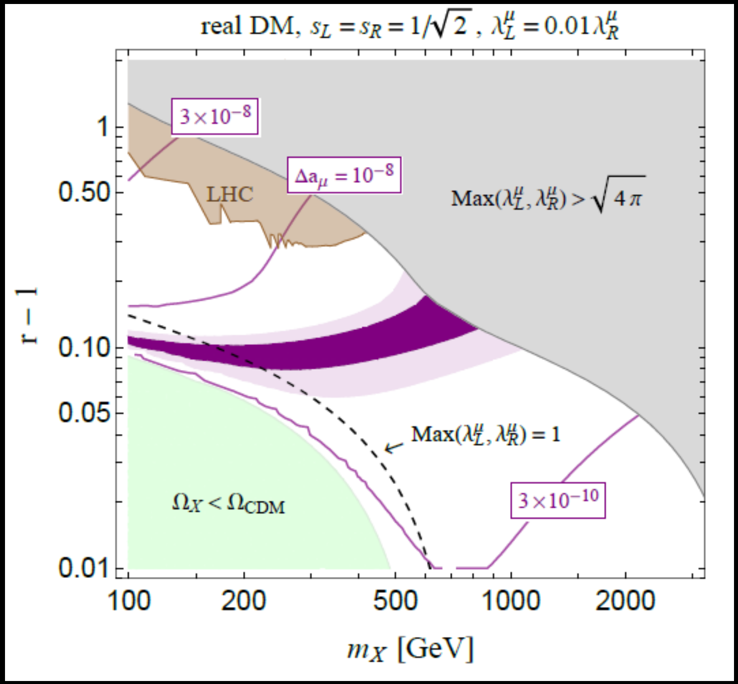
➔ $\Delta a_\mu \sim \frac{m_\mu}{16\pi^2} \sqrt{2\pi \langle \sigma v \rangle} \sim 5 \times 10^{-8}$ is too large for maximal mixing

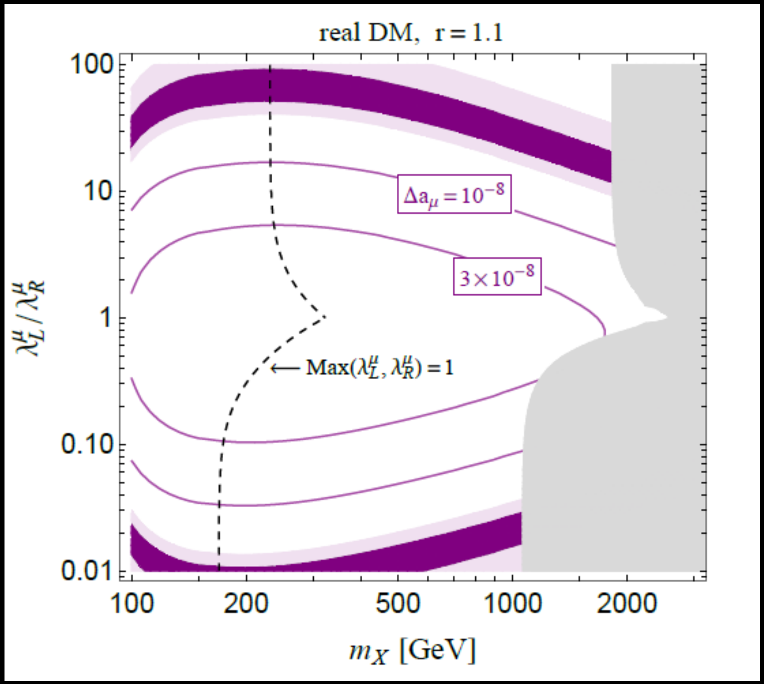
➔ co-annihilation and/or $\lambda_L \ll \lambda_R$ ($\lambda_R \ll \lambda_R$) is/are needed

Result in real DM

$m_{E_2} - m_{E_1} = 100$ GeV
$r = m_{E_1}/m_X$

λ_R is fixed to explain relic density





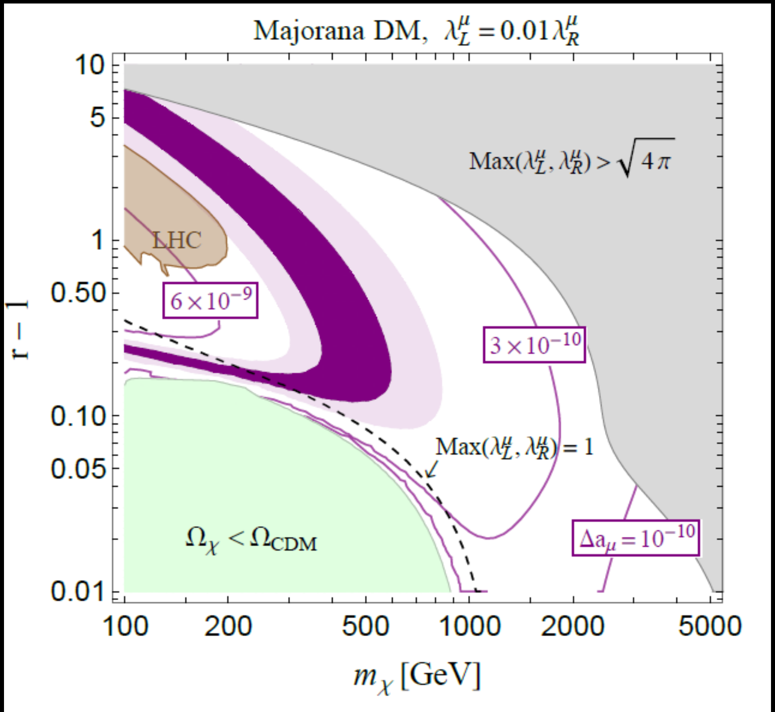
MicrOmegas

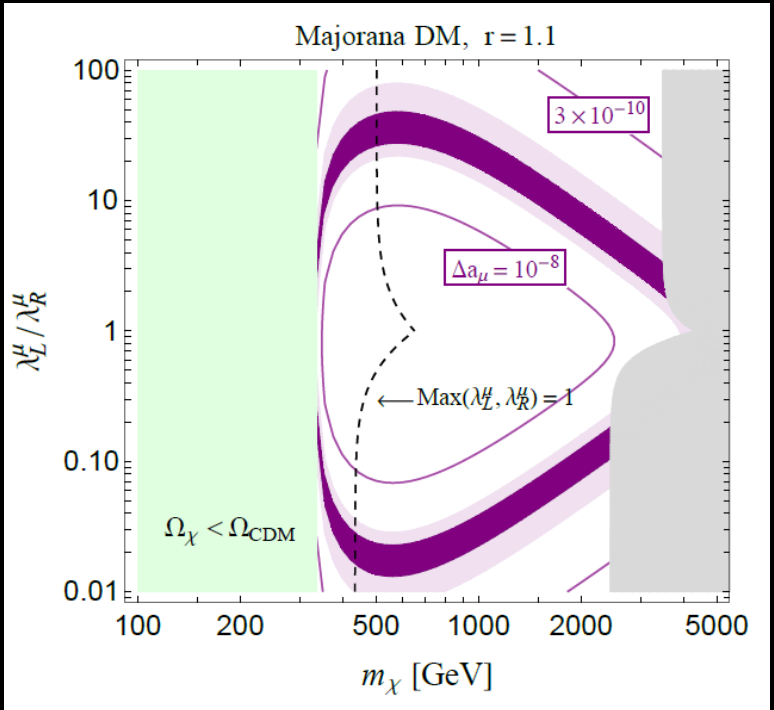
Δa_μ can be explained if $m_{E_1} \sim 1.1 \times m_X$ and $\lambda_L \sim 0.01 \times \lambda_R$

Result in Majorana DM

λ_R is fixed to explain relic density

$m_{E_2} - m_{E_1} = 100$ GeV
$r = m_{E_1}/m_X$

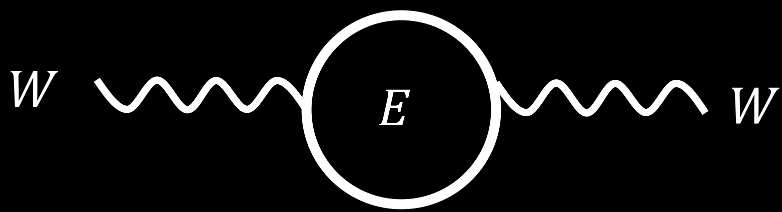




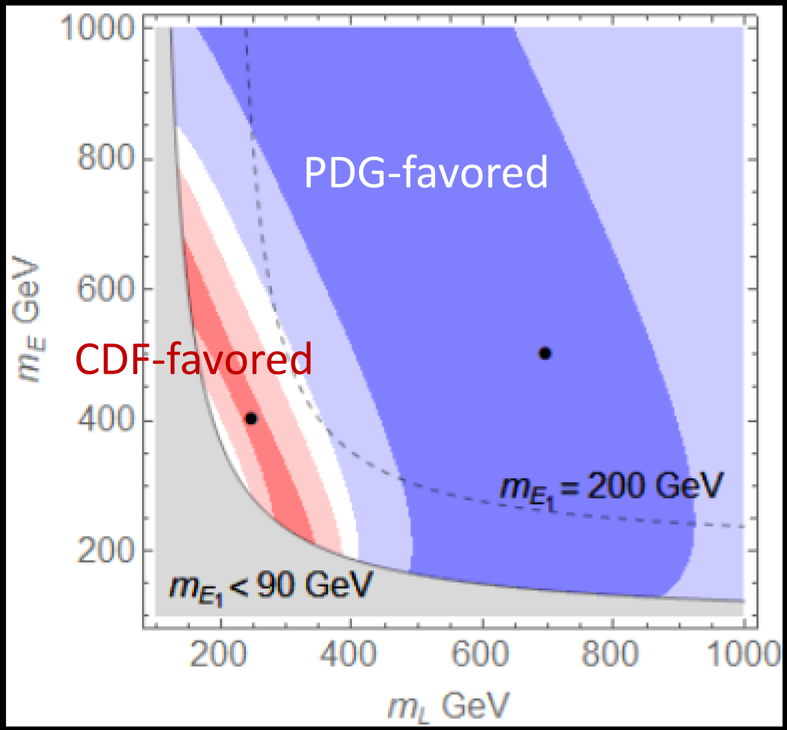
MicrOmegas

- Δa_μ can be explained if $m_{E_1} \sim 1.1 \times m_X$ and $\lambda_L \sim 0.01 \times \lambda_R$
- requirement for degeneracy is relaxed from the real scalar case

W boson mass 2204.07022



- 1-loop corr. from VL-lepton
- chiral enhancement by Higgs VEV



- CDF-value is realized only for VLL lighter than 200 GeV
- only degenerate (co-annihilation) region is allowed by LHC

Conclusion

- Minimal lepton portal DM (DM + 1 mediator)
  - complex and Dirac DM are almost excluded by direct detection
  - real DM may predict peaked signal
  - Majorana DM is toughest to be tested

- Simultaneous explanation with anomalies
  - Δa_μ can be explained in models with both singlet and doublet
  - CDF W-mass can be explained only with VLL lighter than 200 GeV

Thank you !!