PPP2022@Kyoto University

モノ電弱ボソンシグナルを用いたLHC実験における暗黒物質探索

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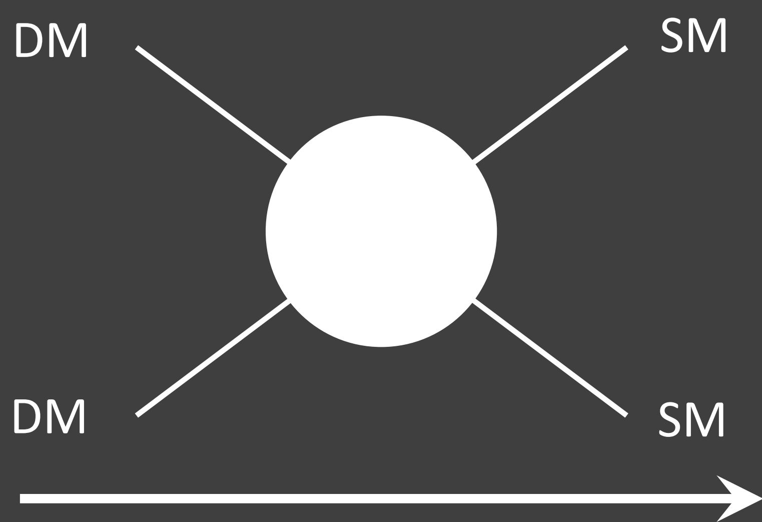
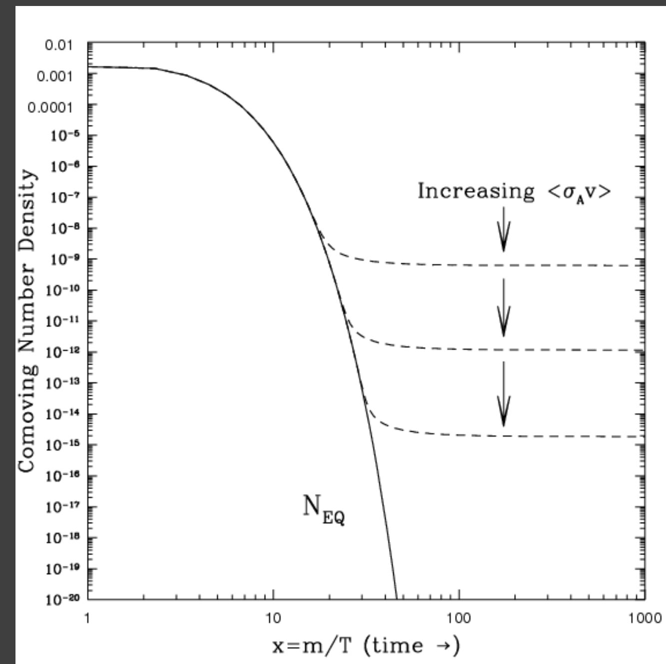
in collaboration with

L.Carpenter and H.Gilmer [Ohio State U.]

WIMP DM

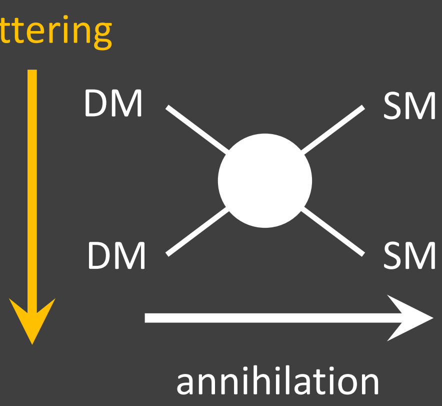




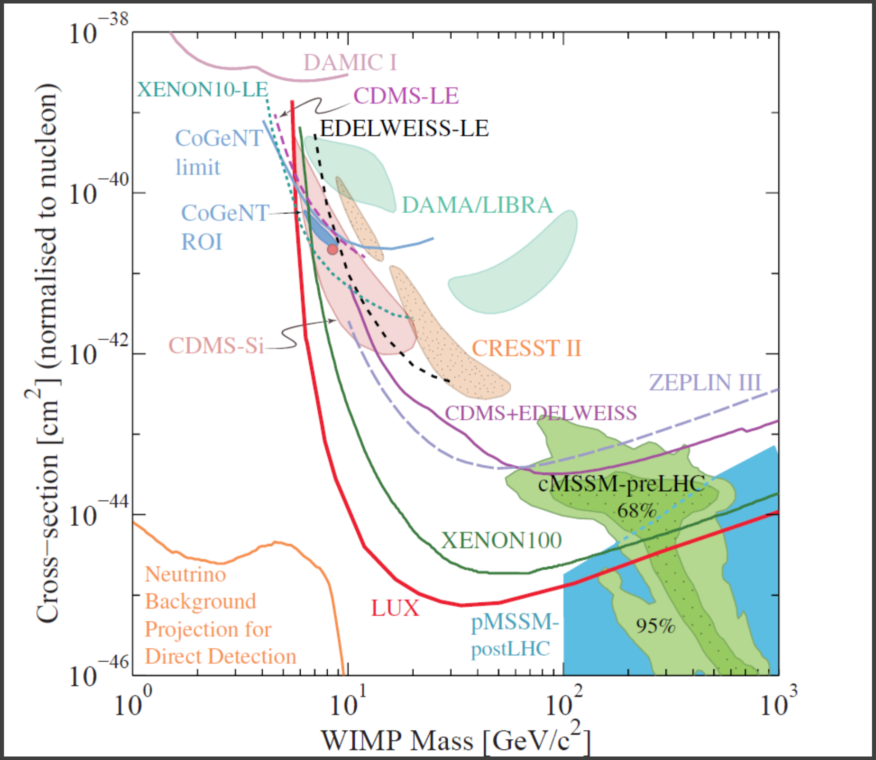
E.W.Kolb, M.S.Turner,
The Early Universe, `89

- 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



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

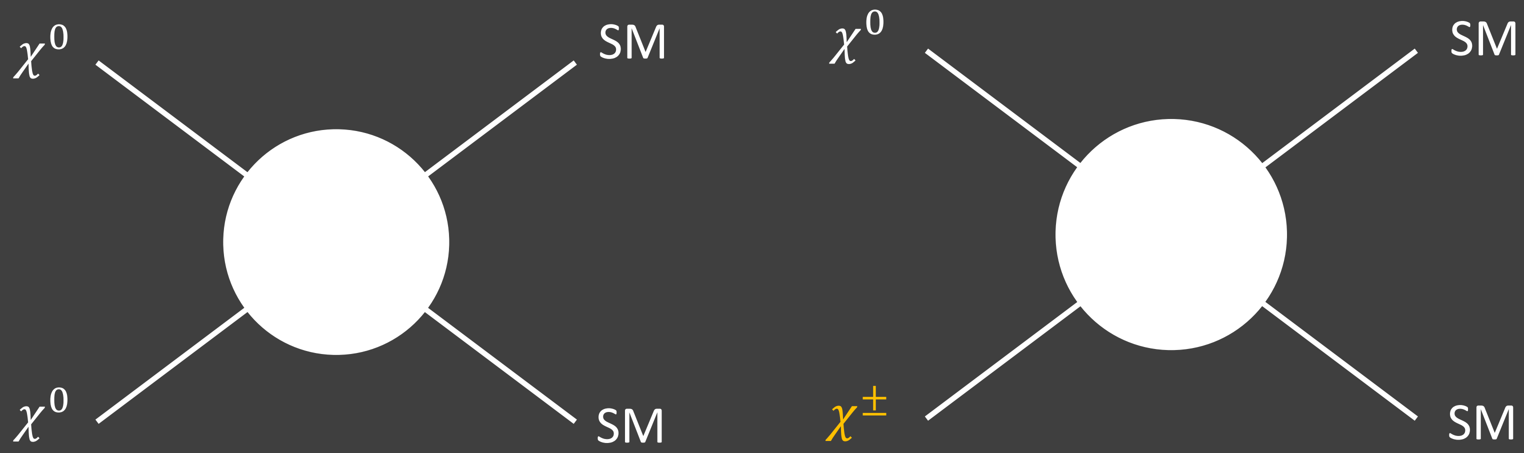


PDG2014

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

Co-annihilating DM

χ^0: DM, $\chi^\pm$: new particle



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

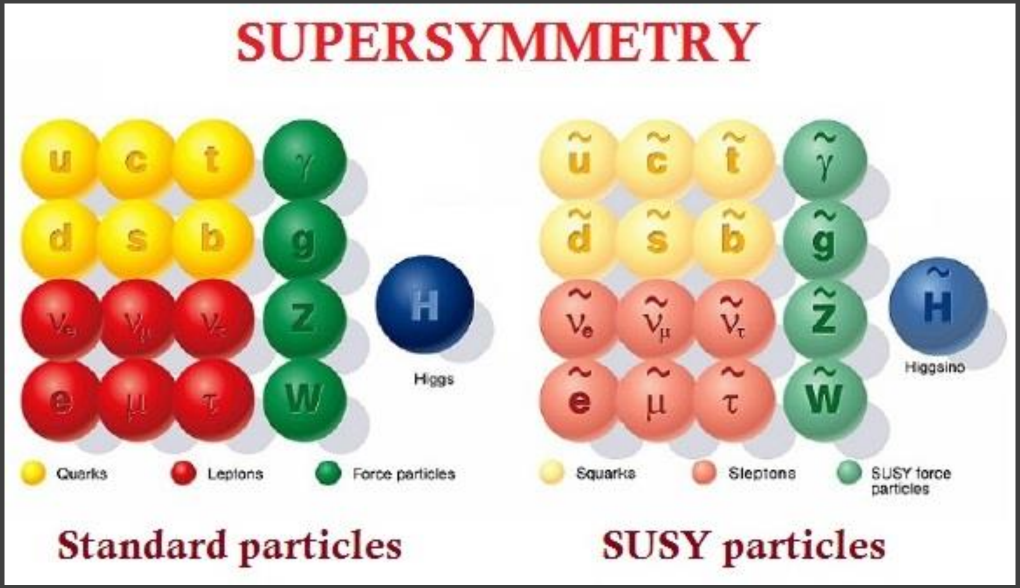
  "co-annihilation" $\chi^0\chi^\pm \to \mathrm{SM}^2$ turns on during freeze-out

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

  → avoid direct detection limits

Higgsino

- Supersymmetry [SUSY]



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

  *mixture of gaugino/higgsino

- Higgsino
  - fermionic superpartners of Higgs bosons
  - neutral component is a part of neutralino DM

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,

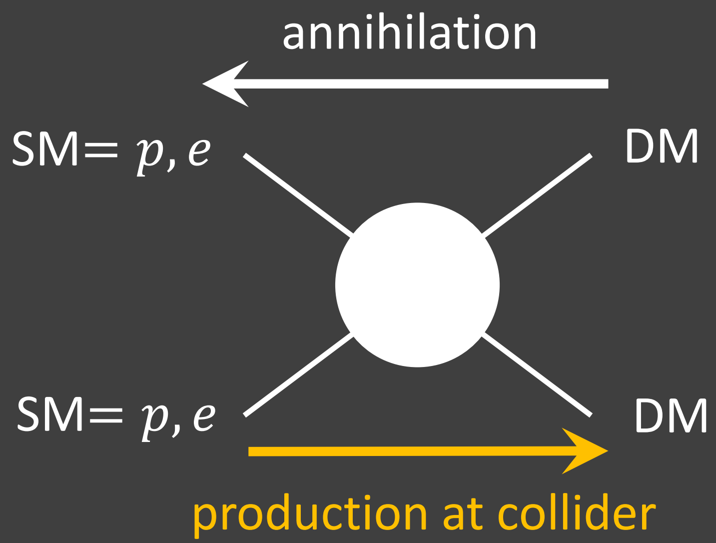
m_{H_u}: Higgs mass term

understanding the origin of EW scale !

Outline

1. Introduction
2. Higgsino searches at LHC
3. Mono-Z/W signal
4. Summary

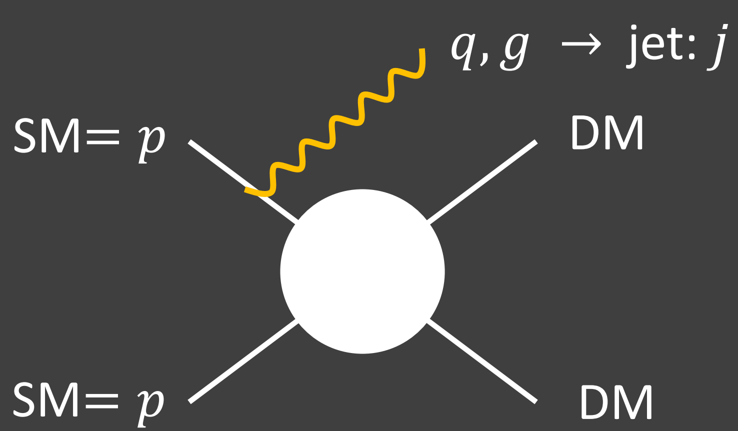
Mono-jet search for DM



- 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

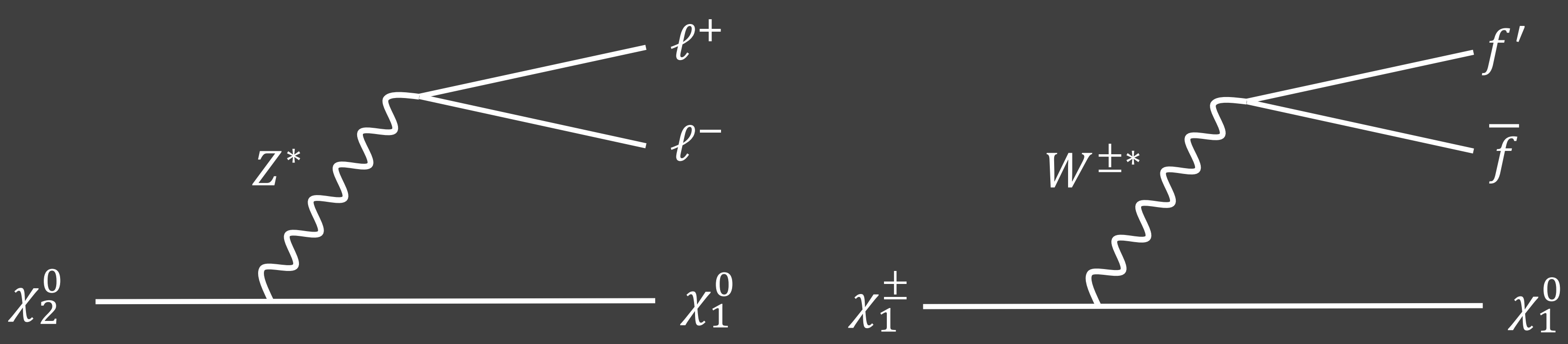
- mass differences of higgsinos

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

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

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

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

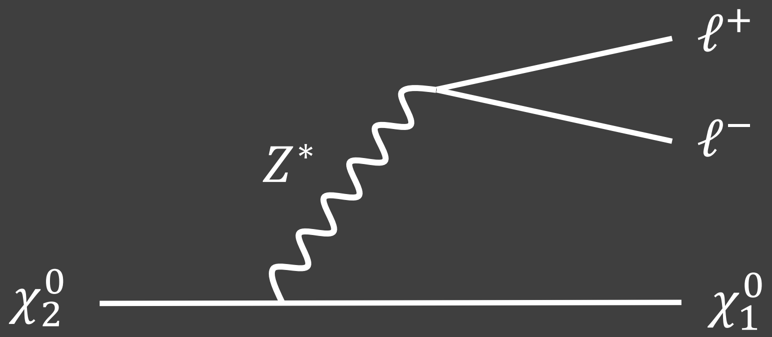


- productions of heavier states are expected
- daughter particles are "soft" due to small mass diff.

Higgsino search: soft leptons

1401.1235 Han, Kribs, Martin Menon

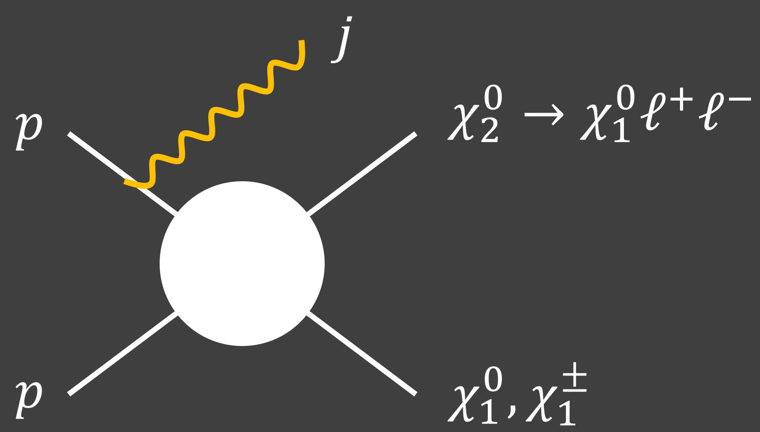
1409.7058, Baer, Mustafayev, Tata



di-leptons are visible

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

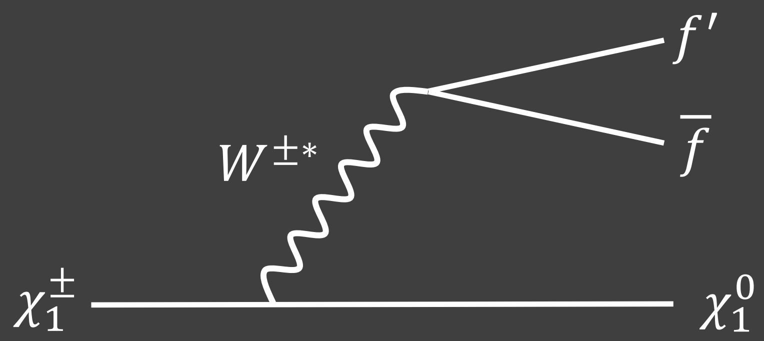
- $j + \ell^+\ell^- + E_T^{\rm miss}$



- 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

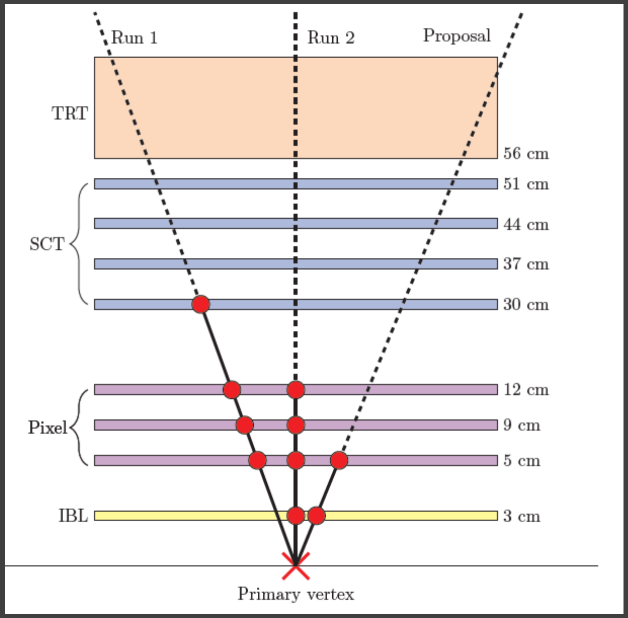


charged state $\chi_1^{\pm}$ is long-lived

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

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

➢ disappearing track search

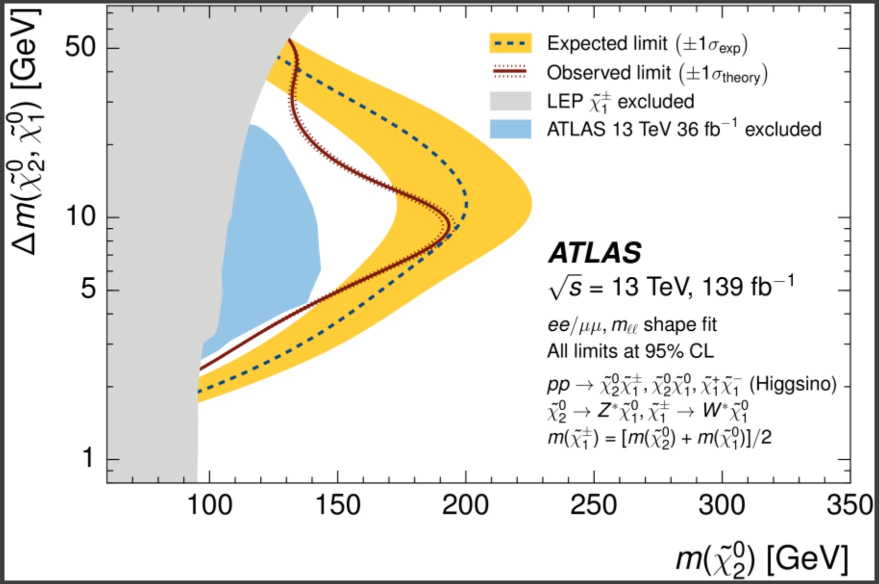


1703.09675, Fukuda, Nagatam Otono, Shirai

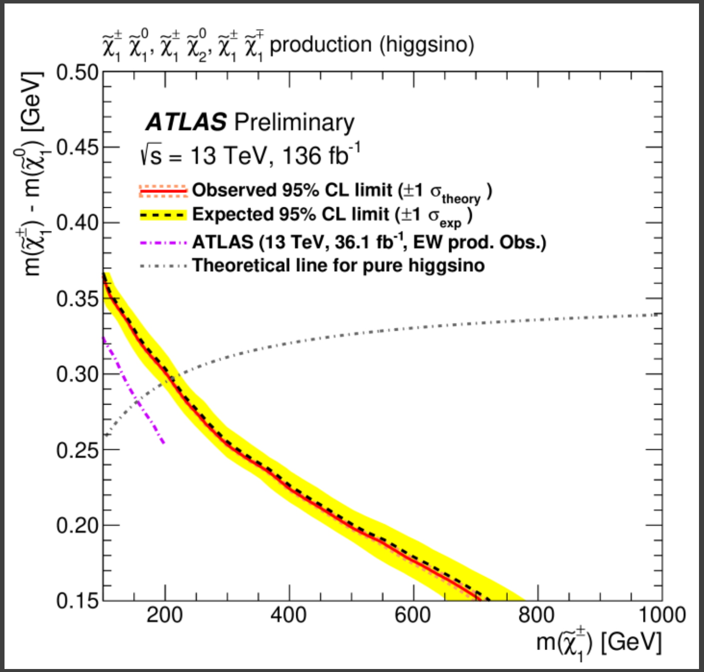
- charged track disappear in detector
- ISR jet is required to trigger

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

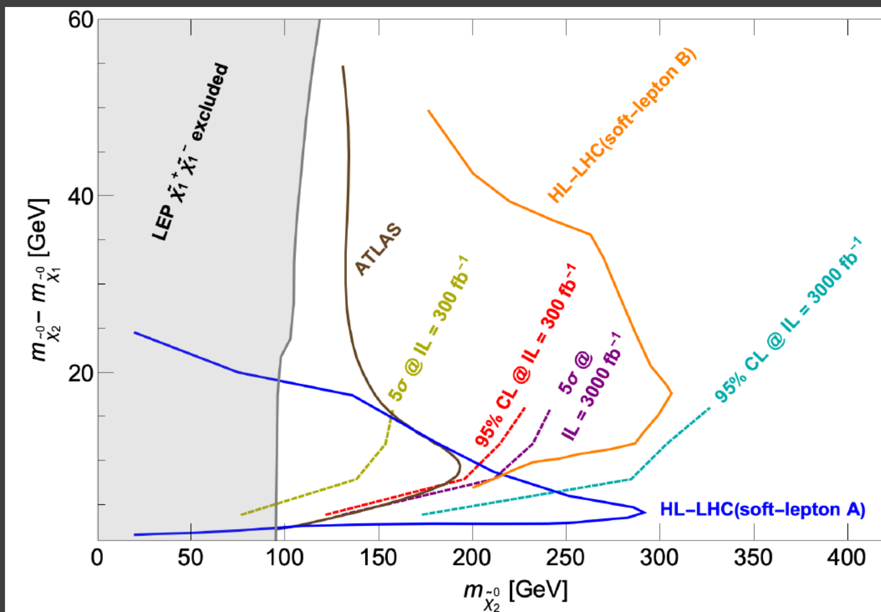
for $\Delta m_{\chi_1^\pm} \lesssim 0.35$ GeV

- 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

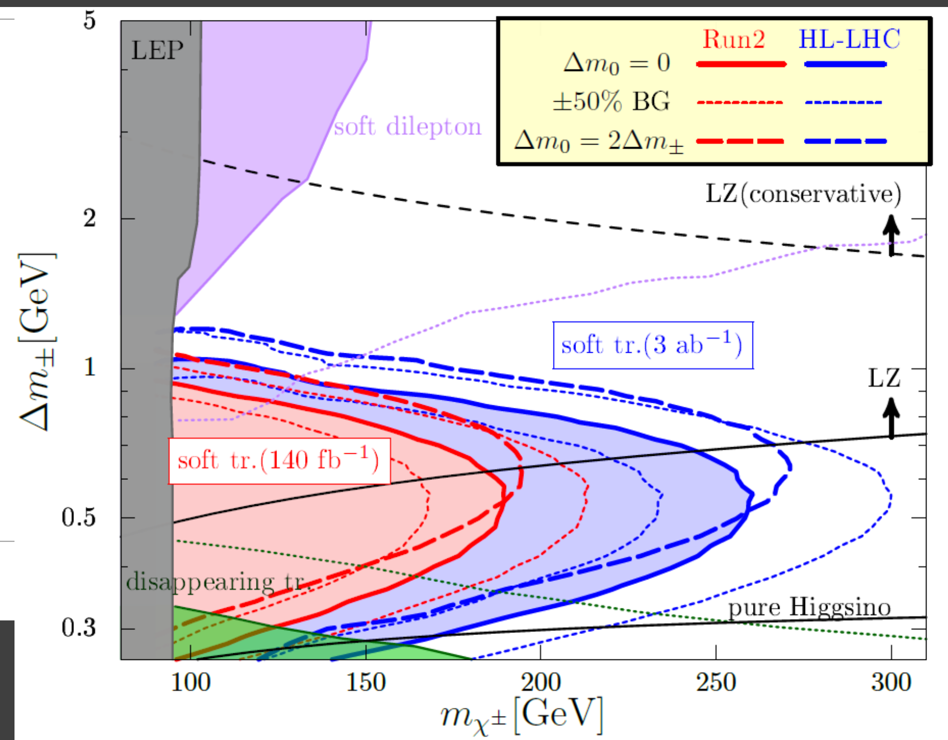
Higgsino search: future limits

soft leptons

(soft) disappearing track



2109.14030, Baer, Barger, Sengupta, Tata



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

- 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 to trigger

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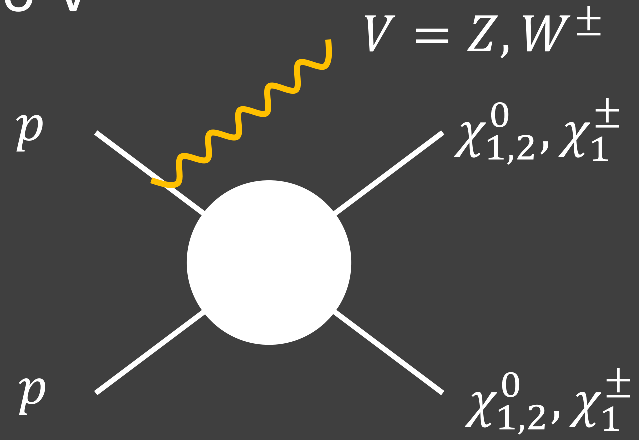
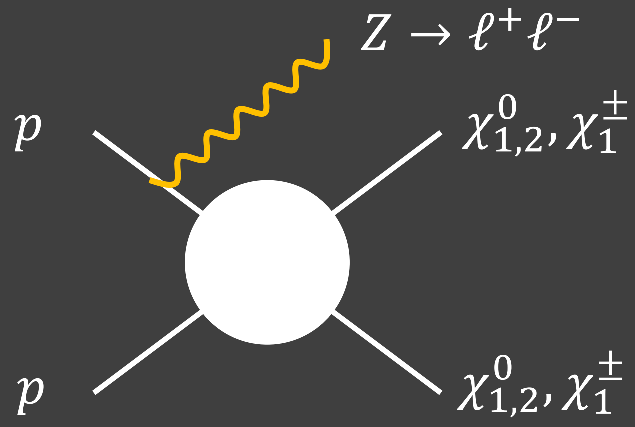
mono-Z/W signal

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

- mono-V



- leptonic mono-Z



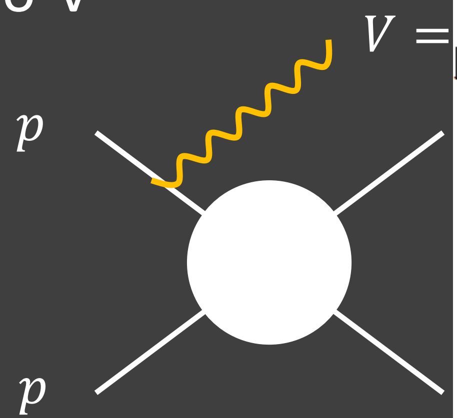
✓ less production cross section

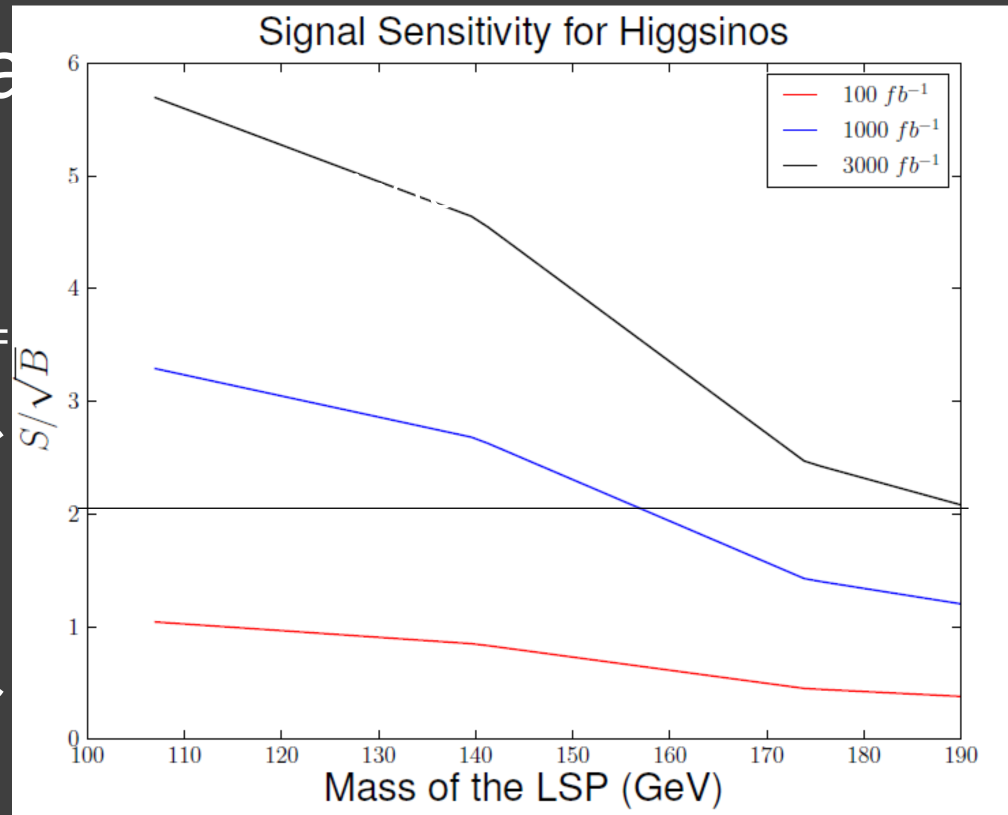
● (much) less backgrounds

mono-Z/W signa

what if we

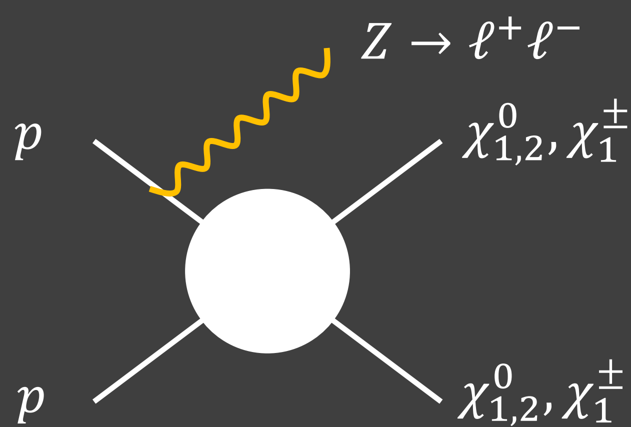
- mono-V





1407.1833, Anandakrichnan, Carpenter, Raby

- leptonic mono-Z

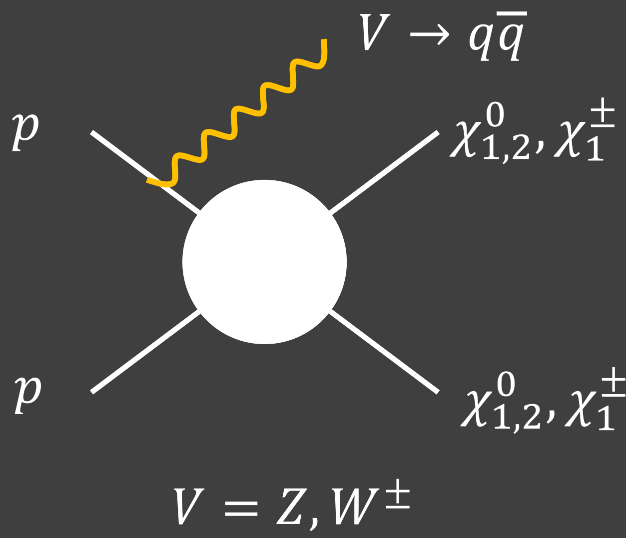


✓ limit is about 190 GeV at HL-LHC

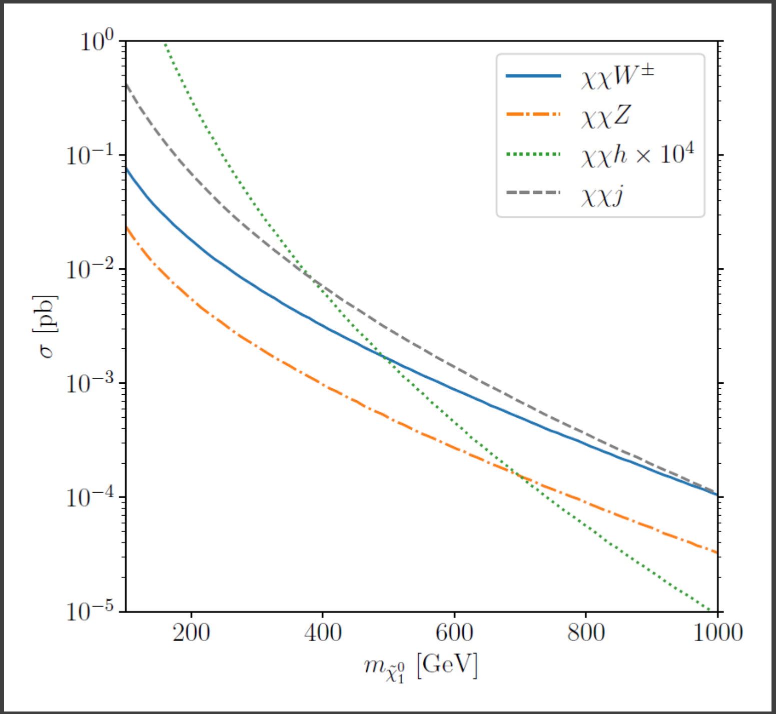
✓ not large production x-section

mono-Z/W signal

- hadronic mono-V



production cross section



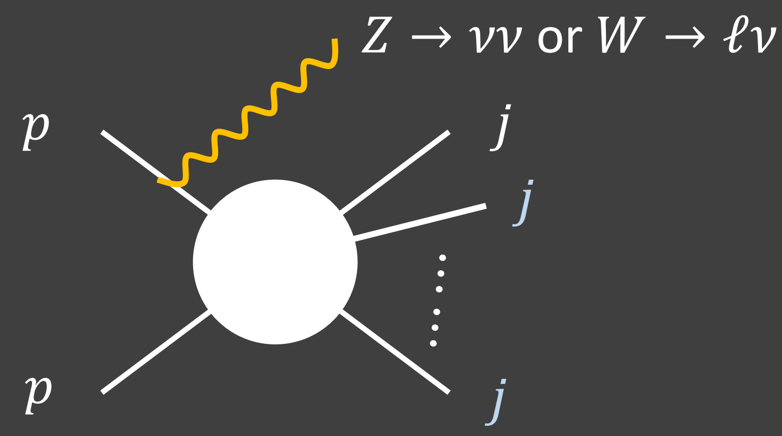
- W associated production is much larger than prod. with Z
- hadronic BRs $\sim 70\%$ are larger than leptonic BRs $\sim 10\ (30)\%$ for Z (W)

→ significantly large production rate

mono-Z/W signal

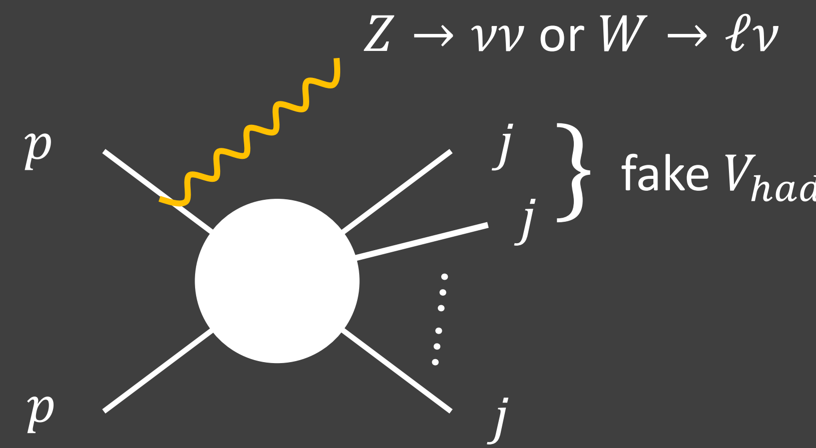
are backgrounds small ? $V = Z, W^{\pm}$

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



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

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



- 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

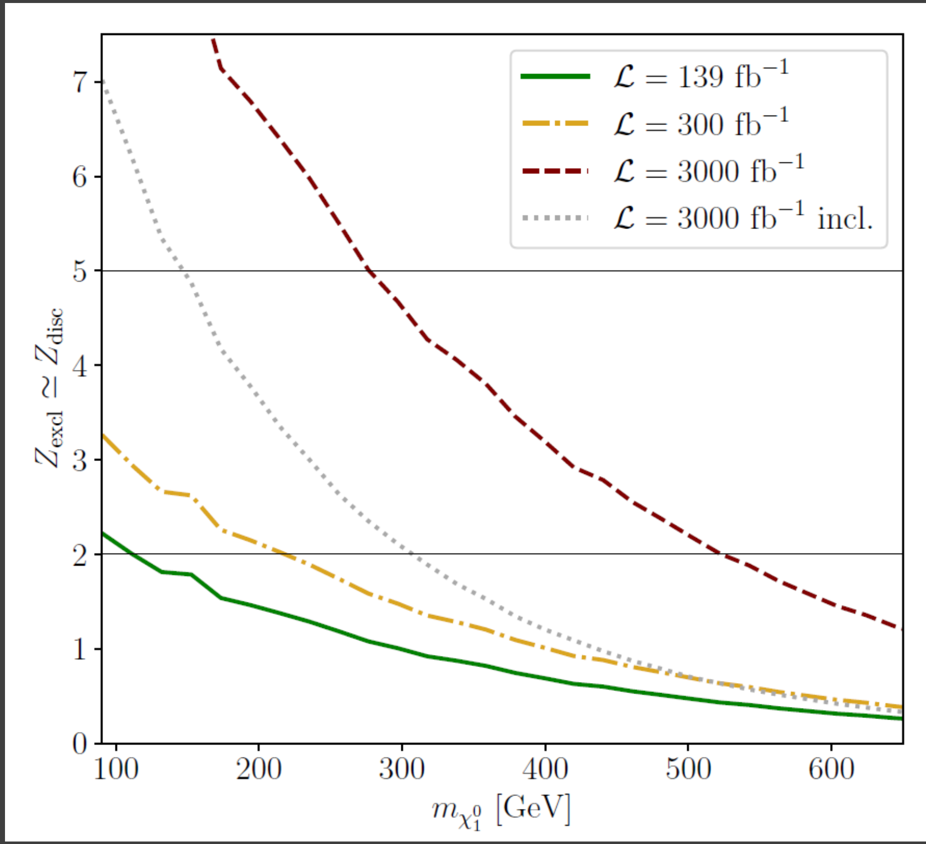
→ well discriminate signal/bkg.

Analysis

- Recast ATLAS analysis w/ $36.1\ \mathrm{fb}^{-1}$data 1807.11471, ATLAS
  - one V_{had} jet with $p_T > 250\ \mathrm{GeV}$ and $E_T^{\mathrm{miss}} > 200\ \mathrm{GeV}$
  - 50% efficiency for V_{had} tagging
  - cuts for multi jet bkg. are applied
  - leptons with $p_T > 7\ \mathrm{GeV}$ are vetoed

- Assumptions
  - all of higgsino states $\chi_{1,2}^0, \chi_1^\pm$ are invisible $\Leftrightarrow$ $\Delta m_{\chi_1^\pm} \lesssim 3.5\ \mathrm{GeV}$
  - 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

Results

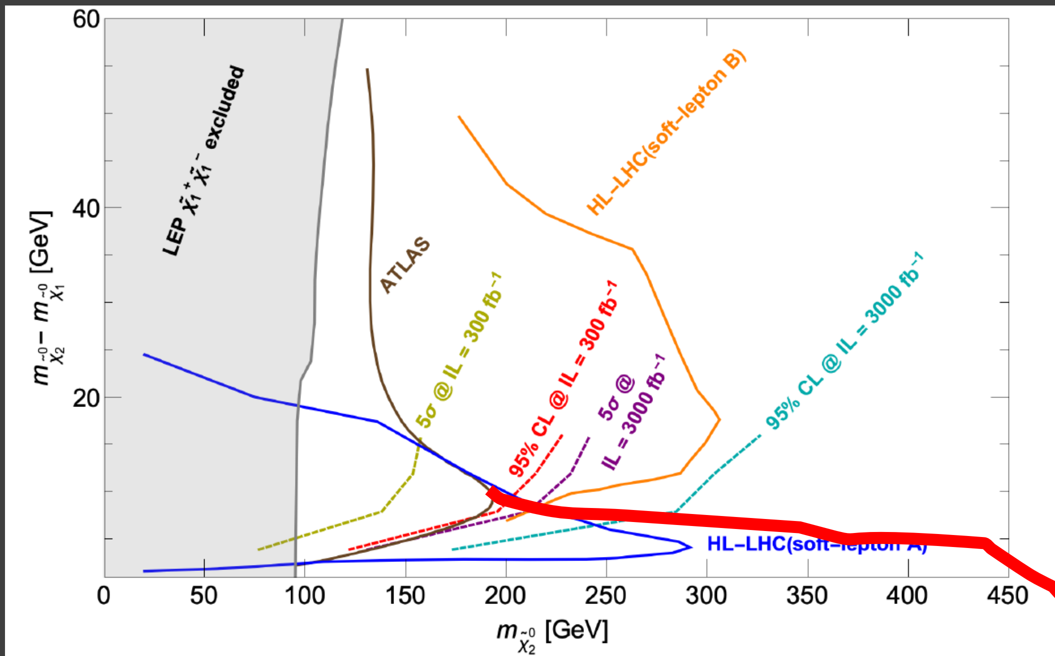


* using E_T^{miss}-binned data

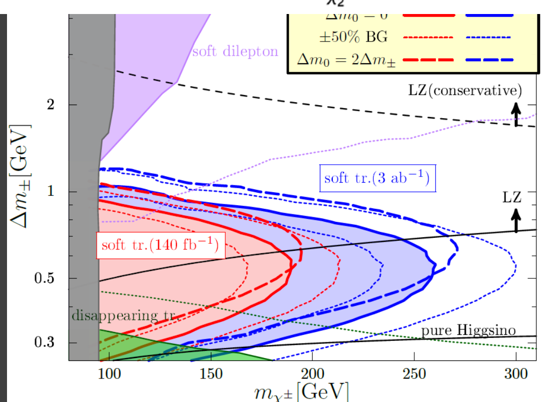
- even LHC constraints 110 (210) GeV higgsinos at Run-2 (3)
- HL-LHC can probe higgsinos up to 520 GeV

Results: comparison

j + soft leptons



our bound at HL-LHC



$\Delta m_{\chi_1^\pm} \sim 1$ GeV

520 GeV

j + soft disappearing tracks

Summary

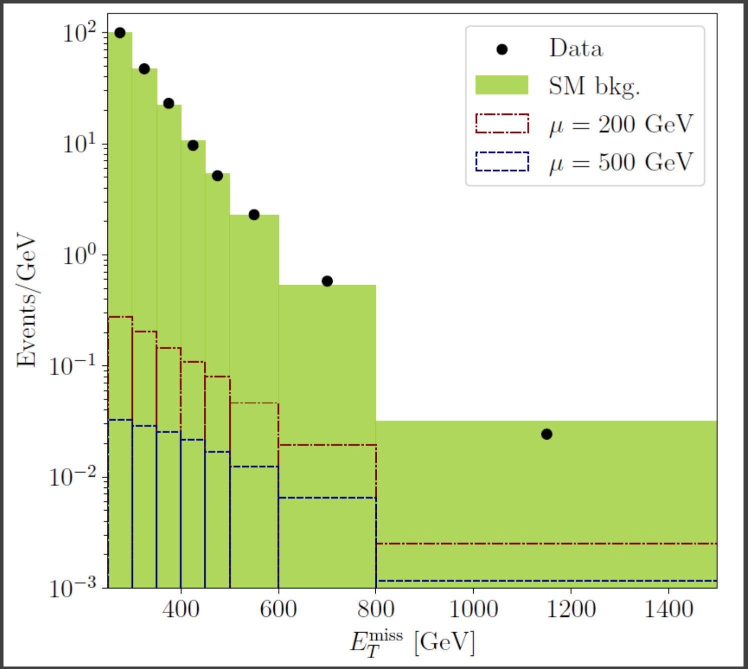
- higgsino search
  - hadronic mono-V signal is efficient for higgsinos searches
  - can fill the gap at $\Delta m_{\chi_1^\pm} \sim 1\ \mathrm{GeV}$
  - can test higgsinos up to 520 GeV at HL-LHC
- discussions
  - V + soft leptons/disappearing tracks may work
  - may be applicable to other co-annihilating DM

Thank you !

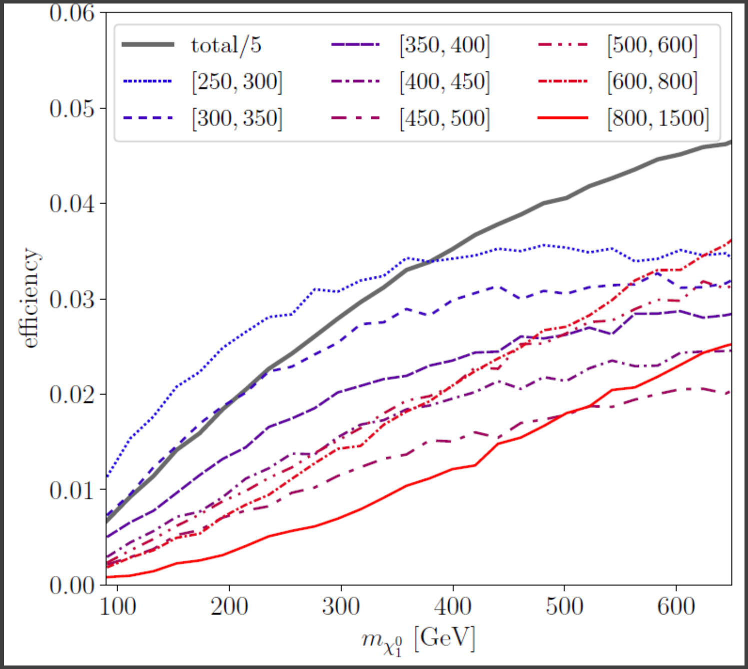
backups

E_T^{miss} distribution

E_T^{miss} distribution



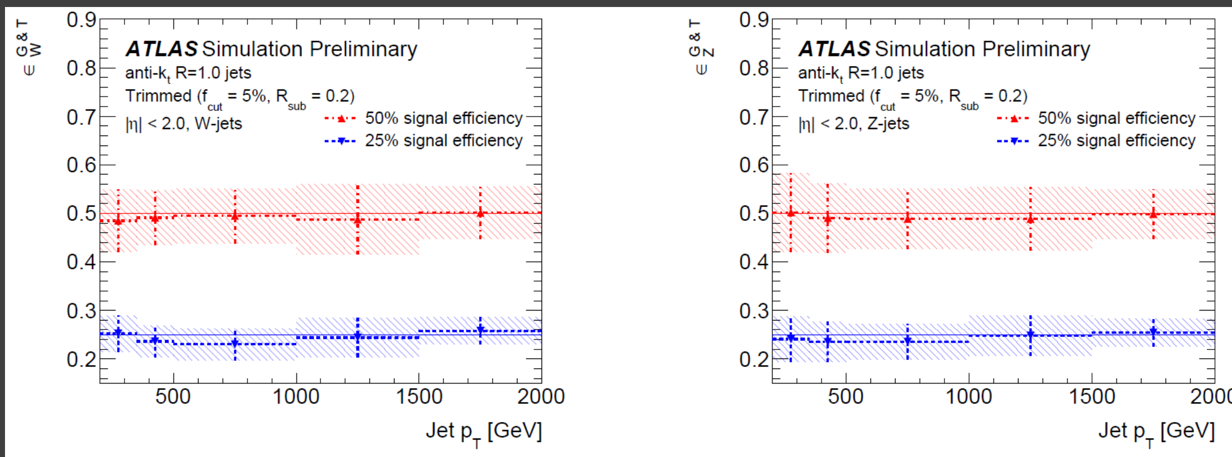
efficiency = # pass the cuts/# events generated



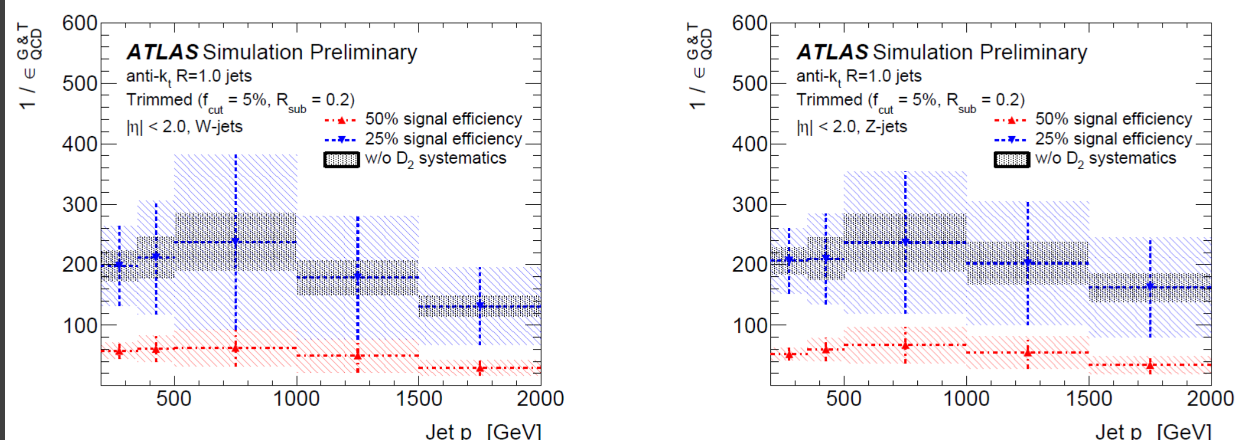
- signals are $\mathcal{O}(0.1 - 1\%)$ of the SM bkg.
- higher E_T^{miss} is expected for heavier masses

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.



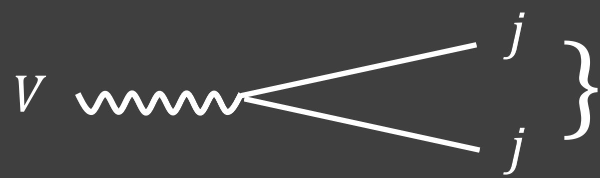
V-tag rate from Z/W

~ 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

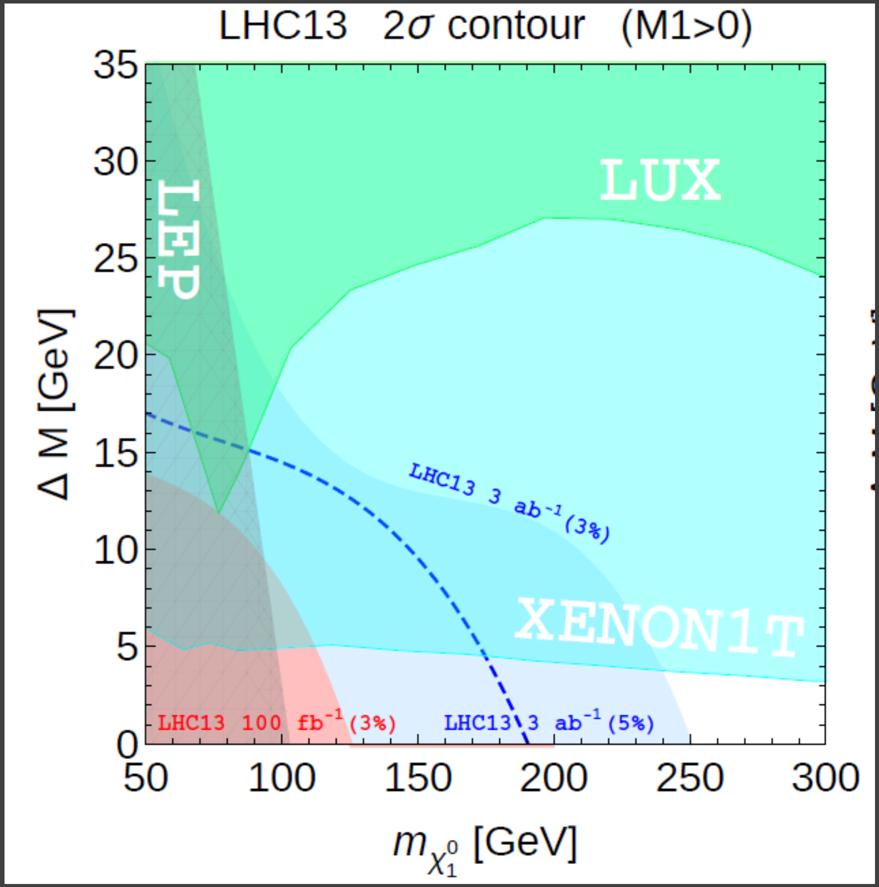
➢ $D_2 = e_3/e_2^3$

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

- 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

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