Search complementarity for supersymmetric dark matter

Ahmed Ismail

University of Pittsburgh

DM@LHC 2017

April 5, 2017

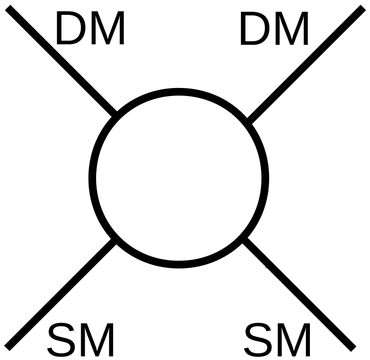
Dark matter in supersymmetry

Naturally arises from R-parity

$$\begin{aligned} W_{\mathrm{RPV}} &= \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k \\ &+ \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k + \mu'_i L_i H_u \end{aligned}$$

Avoid proton decay

$$P_R = (-1)^{3(B-L)+2S}$$



SM particles R-even, sparticles R-odd

Lightest R-odd particle is stable → DM candidate

Neutral superparticles

Neutralino

– canonical DM SUSY target

– in MSSM, mixture of bino/wino/higgsino

– more freedom in extended sectors, e.g. singlino in NMSSM

Sneutrino

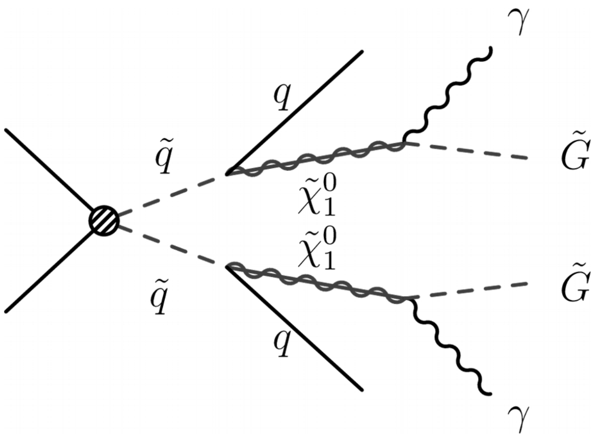
Gravitino

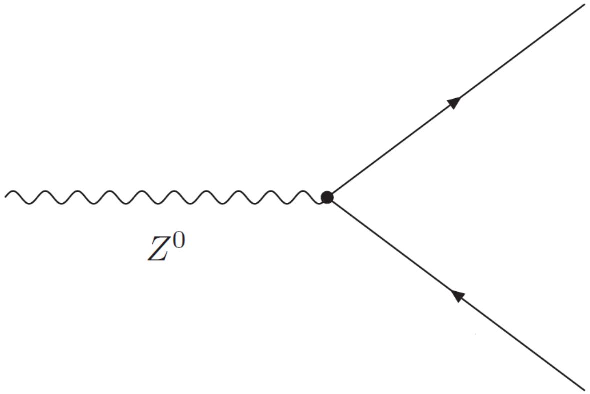
Neutral superparticles

Sneutrino

– conventional sneutrino excluded by SI DD through Z

– RH sneutrino DM can be viable





Gravitino

– thermal production usually too large, but can invoke low reheating temperature

– collider signatures including γ + MET, long-lived particles

The lightest neutralino in the MSSM

Diagonal masses are *inputs* from low-energy perspective through soft SUSY breaking and μ term

Mixing *fixed* by electroweak symmetry breaking

$$M_N = \begin{pmatrix} M_1 & 0 & -g' v_d/\sqrt{2} & g' v_u/\sqrt{2} \\ 0 & M_2 & g v_d/\sqrt{2} & -g v_u/\sqrt{2} \\ -g' v_d/\sqrt{2} & g v_d/\sqrt{2} & 0 & -\mu \\ g' v_u/\sqrt{2} & -g v_u/\sqrt{2} & -\mu & 0 \end{pmatrix}$$

bino	wino	higgsinos
SU(2) singlet Y = 0	SU(2) triplet Y = 0	SU(2) doublets Y = ±½

MSSM neutralino DM possibilities

Thermal WIMP:

– Higgsino at 1 TeV

– Wino at 3 TeV

– Bino-higgsino/wino mixtures

– Bino coannihilations with sfermions

– Resonant annihilation to scalars h, H, A

Non-thermal:

– Higgsinos (winos) lighter than 1 TeV (3 TeV)

– …

...and their mappings onto simplified models

Minimal electroweak

Non-minimal electroweak

Coannihilation

Resonant annihilation

Thermal WIMP:

- Higgsino at 1 TeV
- Wino at 3 TeV
- Bino-higgsino/wino mixtures
- Bino coannihilations with sfermions
- Resonant annihilation to scalars h, H, A

Non-thermal:

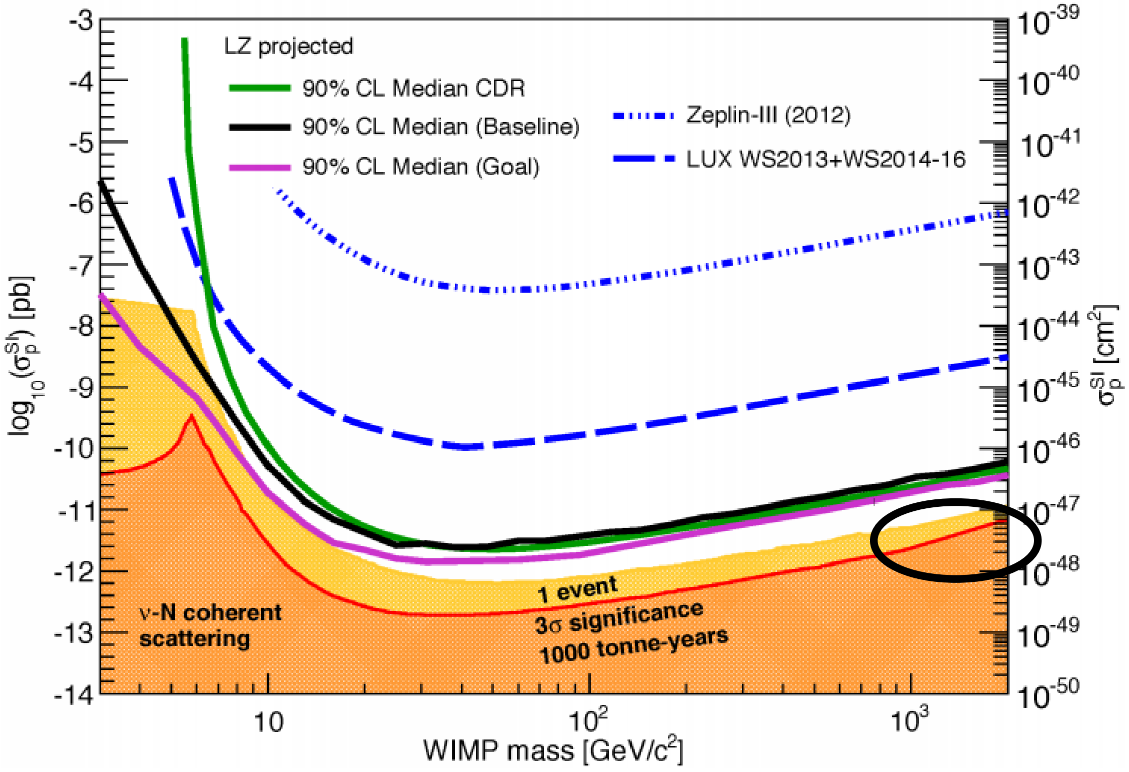
- Higgsinos (winos) lighter than 1 TeV (3 TeV)
- …

Unmixed neutralinos – LHC/direct detection

Pure higgsinos (winos) annihilate to VV, giving right Ωh^2 for masses around 1 TeV (3 TeV) → too heavy for LHC

Spin-independent direct detection ~ 10^{-48} – 10^{-47} cm^2

Hill and Solon 1409.8290



LZ TDR, 1703.09144

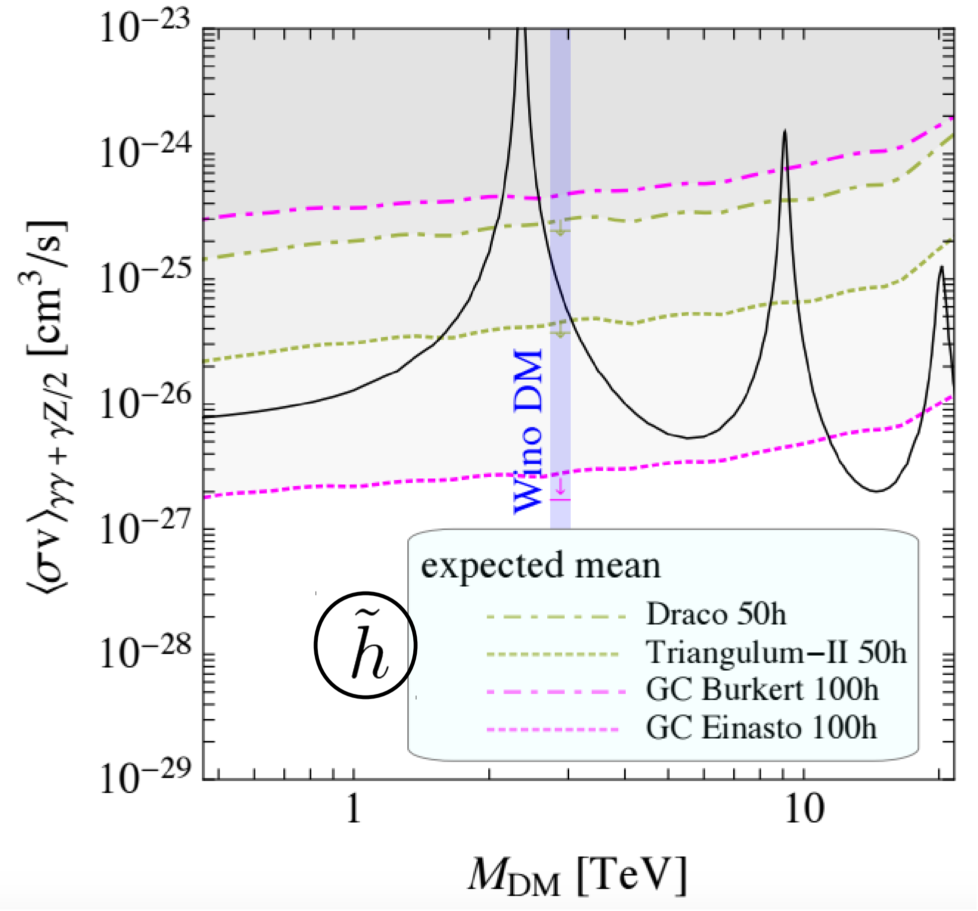
Scattering cross section of same order as neutrino background

Unmixed neutralinos – indirect detection

Loop-induced annihilation to γγ produces a line signal

Thermal wino already excluded by HESS

Cohen et al. 1307.4082, Fan and Reece 1307.4400



Halo profile not important for indirect detection from dwarf spheroidal galaxies, e.g. future CTA bounds

$\tilde{h}$ Thermal higgsinos are still challenging

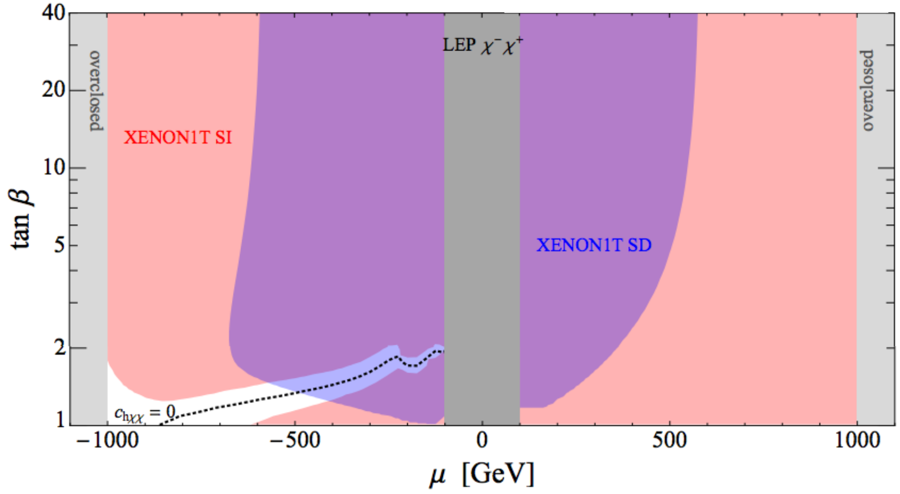
Lefranc et al. 1608.00786

Bino-higgsino and bino-wino mixtures

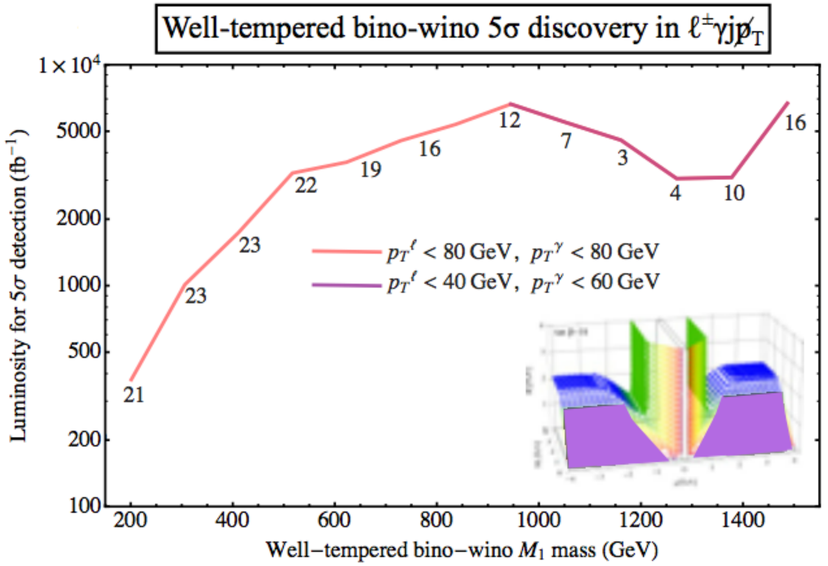
A pure bino can't annihilate, but mixing can achieve the observed relic density for a wide range of masses

Arkani-Hamed, Delgado, Giudice hep-ph/0601041

Higgsino mixing opens up Higgs exchange for DD/ID, while wino mixing is challenging but can be probed at colliders



Cheung et al. 1211.4873

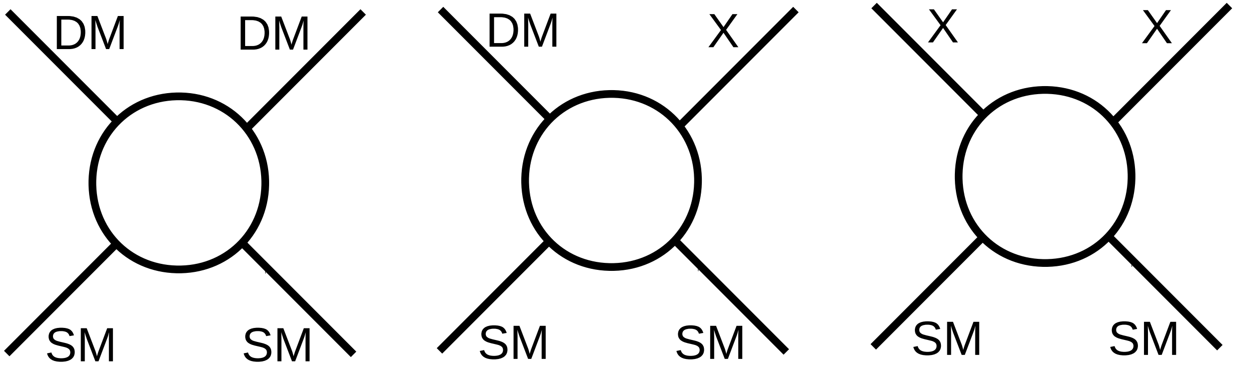


Bramante et al. 1412.4789

Sfermion coannihilations

Increase annihilation cross section for light bino by having sufficiently close sfermion

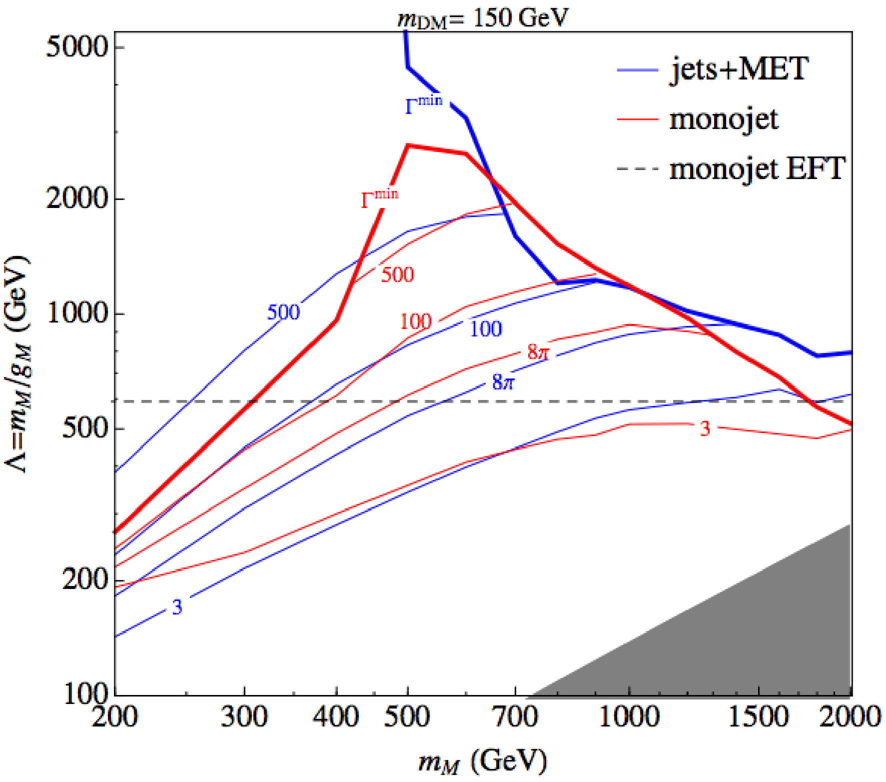
Griest and Seckel 1991



Typically coannihilators need to be within mass ~ T_{FO} of DM to assist in early universe annihilation

Improved signatures from coannihilating partners possible

Sfermion coannihilations



At LHC, monojet and jets + MET searches compete for squark coannihilation

(compare with t-channel mediator simplified model)

Papucci et al. 1402.2285
see also An et al. 1308.0592

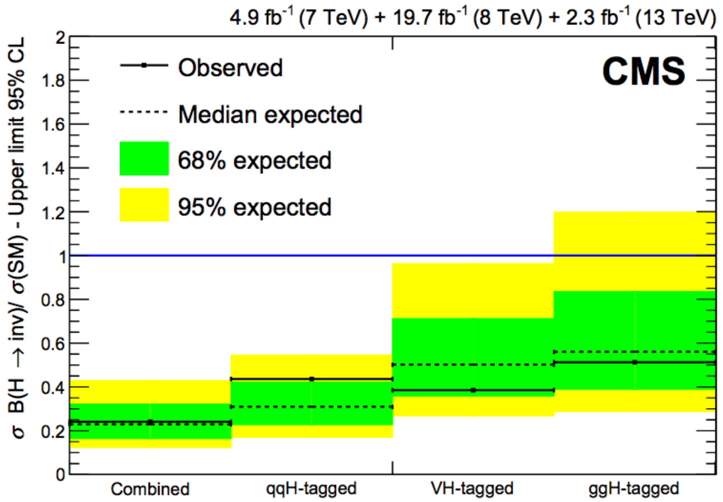
Coannihilation with uncolored sfermions more difficult unless mass difference is extremely small (cf. winos)

Resonant annihilation

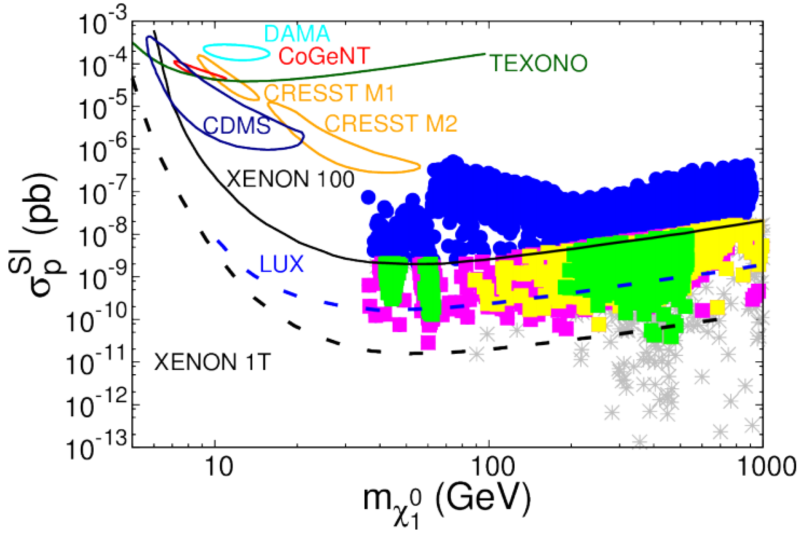
$$m_{DM} \approx \frac{1}{2} m_X$$

X = Z, h, H, A, ...

Annihilation through Z or h is limited by invisible decay searches and direct detection



CMS 1610.09218



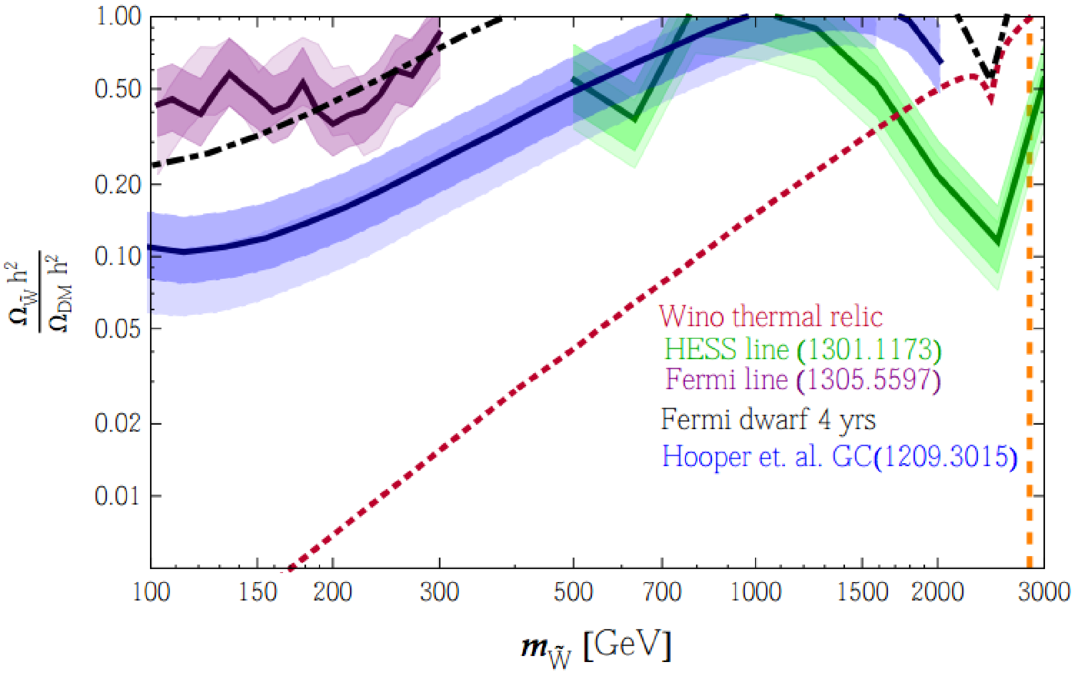
Barring cancellations, probe H and A funnels through direct detection with DM-H/A coupling

Han and Liu 1303.3040

Neutralinos *without* $\Omega_{\text{thermal}} = \Omega_{\text{Planck}}$

Option 1: assume non-thermal production gives right relic density

Option 2: multi-component dark matter, typically with rest of DM interacting only gravitationally

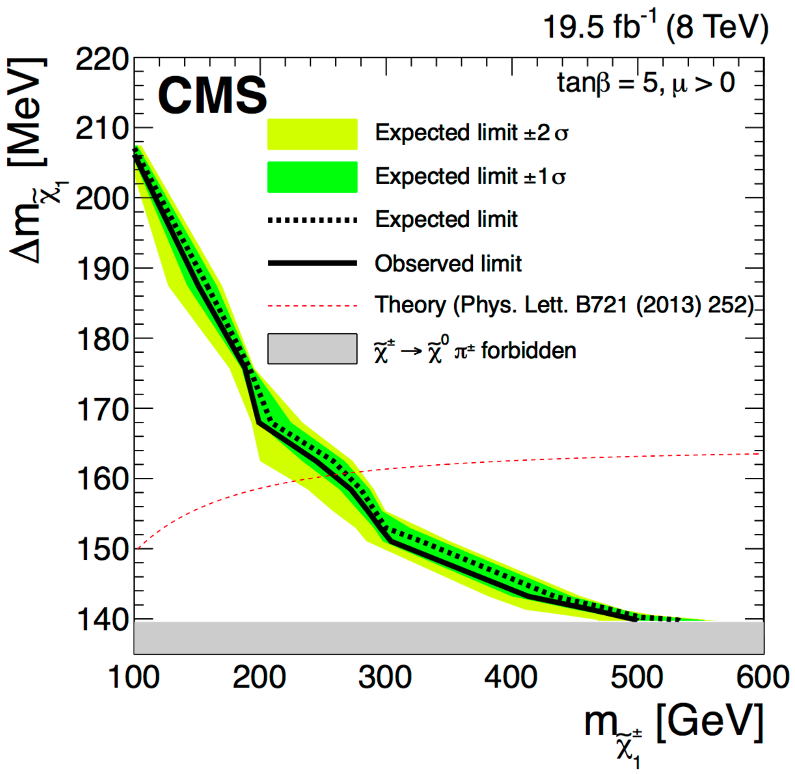


Choice matters for direct detection (ρ) and indirect detection (ρ^2), but not colliders

Fan and Reece 1307.4400
see also Cahill-Rowley et al. 1405.6716

Neutralinos *without* $\Omega_{\text{thermal}} = \Omega_{\text{Planck}}$

Probe light winos at LHC since $\chi^+ \to \chi^0 + \pi^+$ gives disappearing tracks; depends on splitting and mass only



Number of observed events is exponentially sensitive to χ^+ lifetime

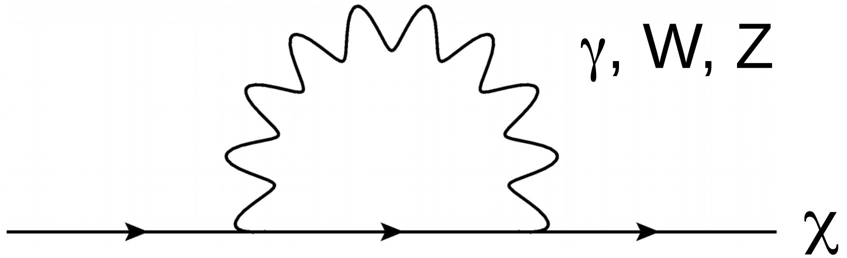
$$\Gamma \propto G_F^2 \Delta M^3 f_\pi^2 \sqrt{1 - \frac{m_\pi^2}{\Delta M^2}}$$

$$\to \tau \approx \frac{44 \text{ cm}}{n^2 - 1}$$

Y = 0 *n*-plet
(wino: n = 3)

Mass splitting in electroweak multiplets

Small mass difference from radiative corrections



$$M(\chi^+) - M(\chi^0) = \left(1 + \frac{2Y}{c_w}\right)\frac{\alpha_2}{2} M_W \left(1 - c_w\right) \approx 166 + 189(2Y)\ \mathrm{MeV}$$

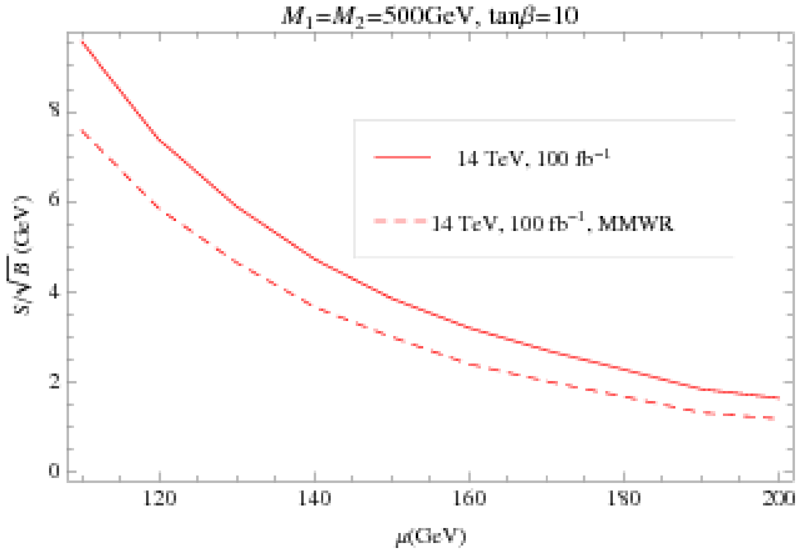
wino: Y = 0
higgsino: Y = ±½

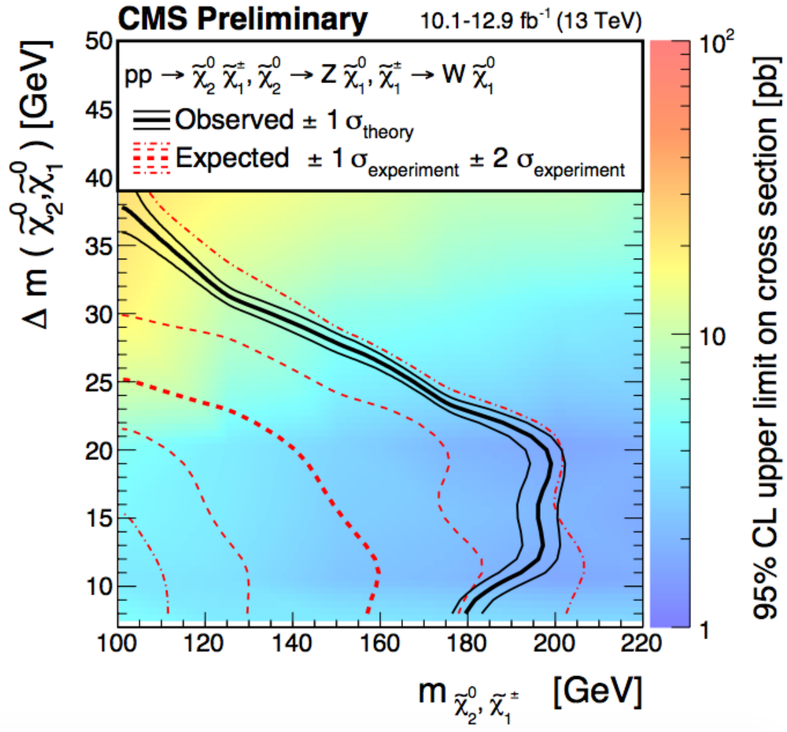
Extra splitting possible from EWSB

$$\mathcal{L} \supset \frac{i}{\Lambda}\left(\bar{\chi}\vec{\sigma}\chi\right)\left(H^\dagger\vec{\sigma}H\right) \to M(\chi^+) - M(\chi^0) \sim \frac{v^4}{\Lambda^2 m_\chi}$$

Collider EWino searches: large splitting

Ability to see SU(2) x U(1) DM at colliders driven by compression between states





For > ~several GeV mass splittings, can still use leptons from $\chi^+ \rightarrow \chi^0 + W^*$

Schwaller and Zurita 1312.7350, Han et al. 1401.1235, Low and Wang 1404.0682

Intermediate splittings?

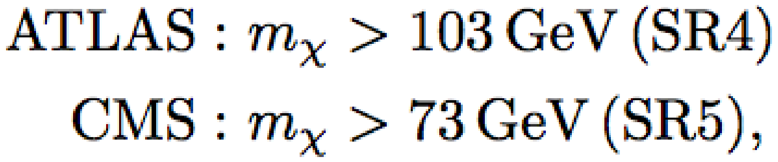
For mass differences between ~0.2-5 GeV, leptons from χ^+ decay are too soft to see in detector

But decay is prompt enough to avoid disappearing tracks!

→ alternative: go back to mono-X searches

canonical example: Higgsinos (doublets)

<u>8 TeV monojet limits</u>



$$\text{ATLAS}: m_\chi > 103\,\text{GeV (SR4)}$$
$$\text{CMS}: m_\chi > 73\,\text{GeV (SR5)},$$

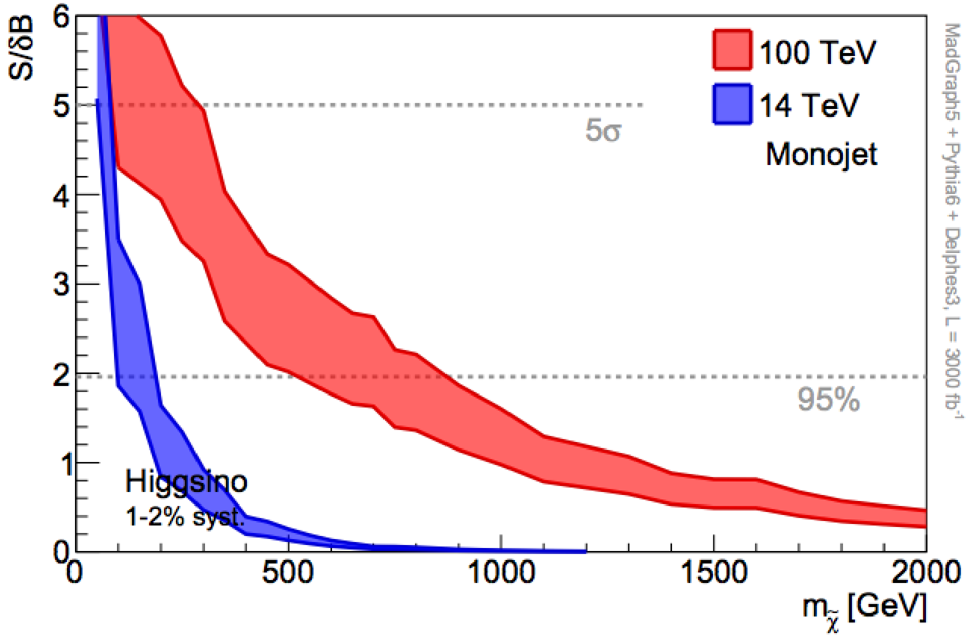
Han et al. 1401.1235

Current limits comparable to LEP

Intermediate splittings?

Future monojet sensitivity hindered by large V + jet backgrounds

Baer et al. 1401.1162, **Low and Wang 1404.0682**, Anandakrishnan et al. 1407.1833 …



Potential for improvement but highly sensitive to systematic error; S/B is small

Photon final-state radiation

Even if χ^+ decays promptly and invisibly, it can still produce electroweak radiation

For massless photon emission, have:

soft divergence – cut off by photon detection threshold

collinear divergence – cut off by χ mass

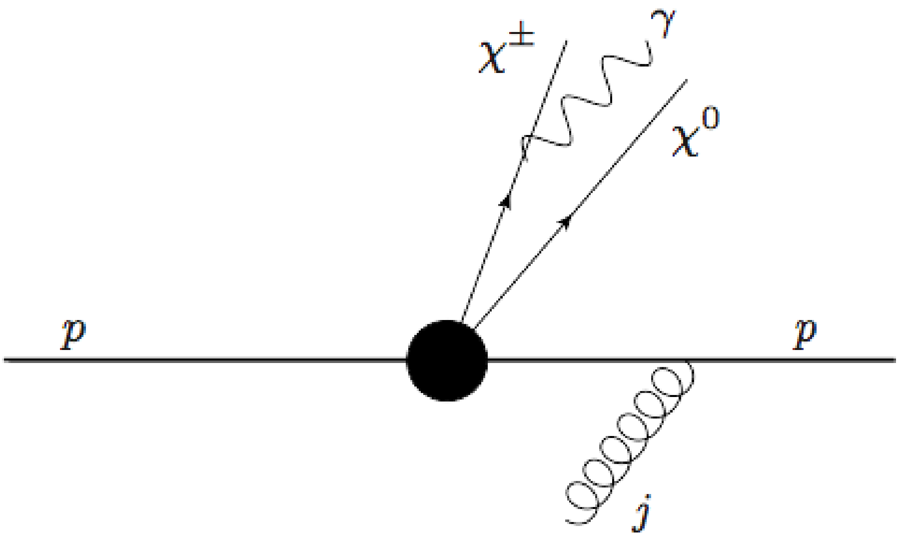
W, Z radiation not as useful for most of the masses considered here, though can be relevant at very high energies

Hook and Katz, 1407.2607

Photon final-state radiation

Take advantage of soft radiation by boosting final state

In monojet events with $p_T(j) > m_\chi$, jet recoils against missing energy + any radiation



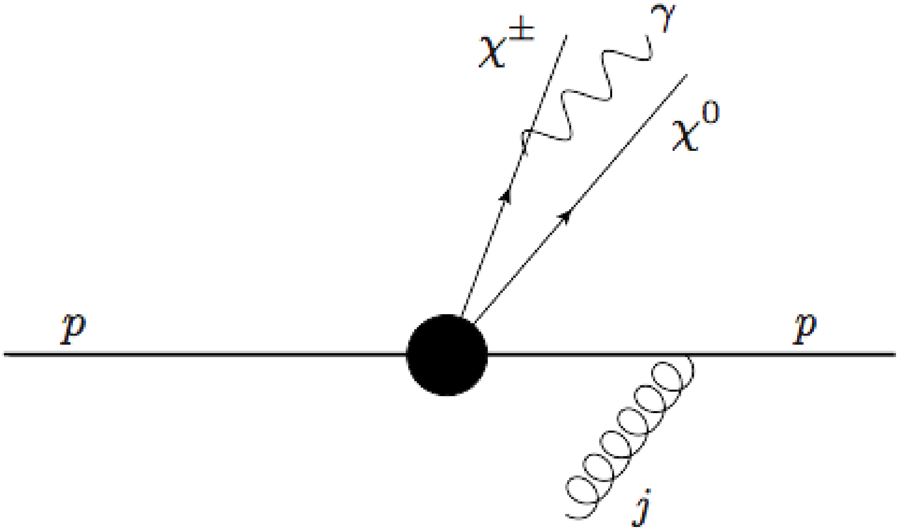
Al, Izaguirre, Shuve 1605.00658

Pay statistical price of α for radiation, but benefit from low backgrounds and extra kinematic handle in γ + j + MET

Photon final-state radiation

By contrast, Z does not radiate photon, so no correlation expected between photon and MET in invisible Z + γ + j background

However, W + jet with photon radiation from missed lepton becomes more important, since it is naturally aligned with the missing energy

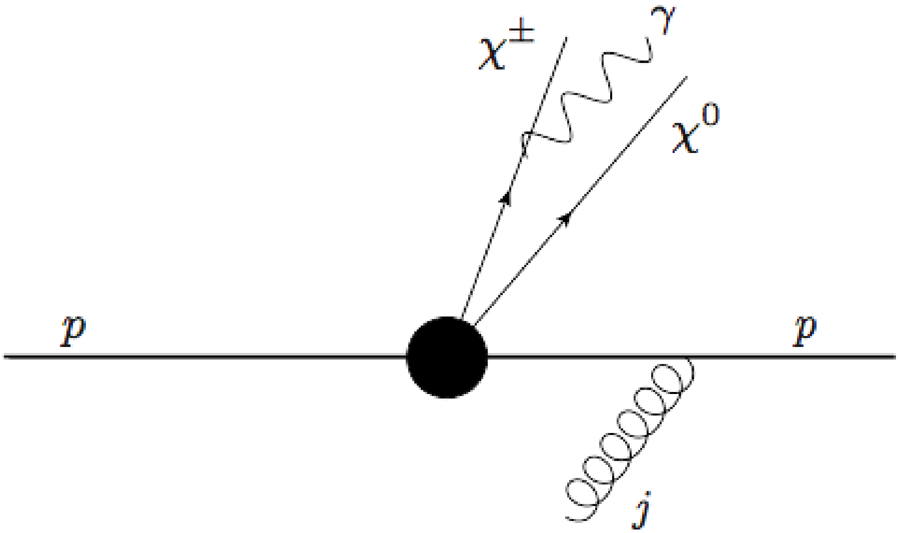


Photon + jet + MET search

Trigger on hard jet and missing energy, then look for soft photon (15 GeV) with small angular separation from MET

Backgrounds: Z + γ + j, W + γ + j, tops, QCD fakes

Require photon $m_T > m_W$, $p_T(j_1)$ / MET > 0.5

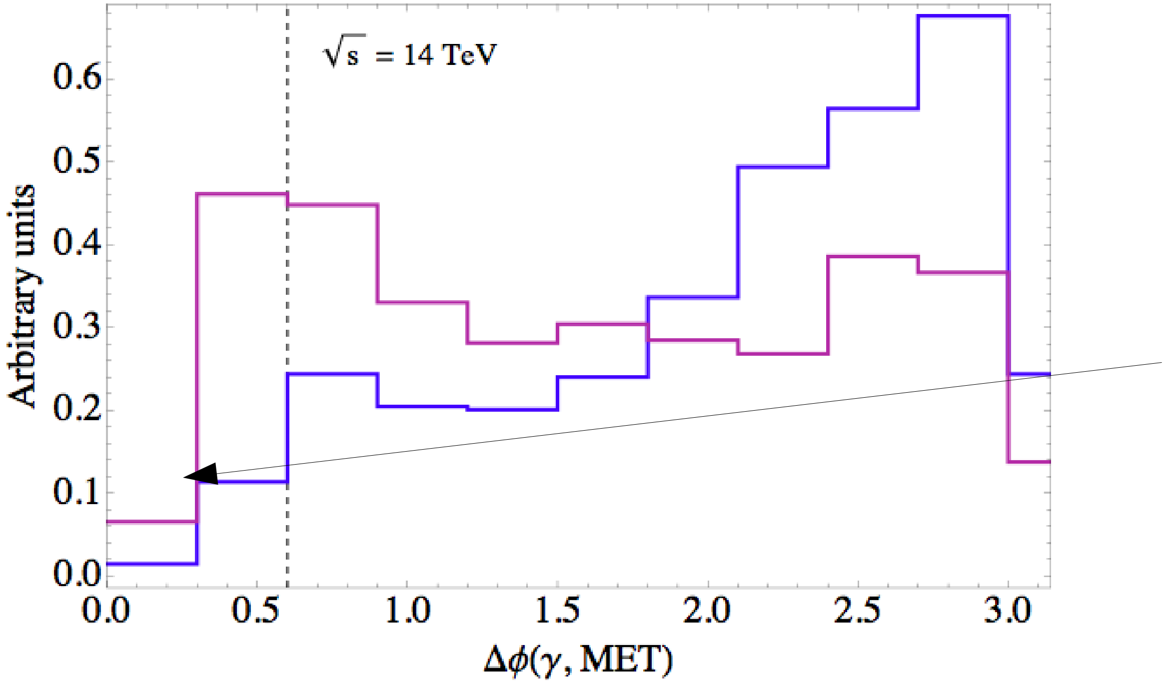


Photon + jet + MET search

Trigger on hard jet and missing energy, then look for soft photon (15 GeV) with small angular separation from MET

Backgrounds: Z + γ + j, W + γ + j, tops, QCD fakes

Optimize further cuts on jet p_T, MET, $\eta(\gamma)$



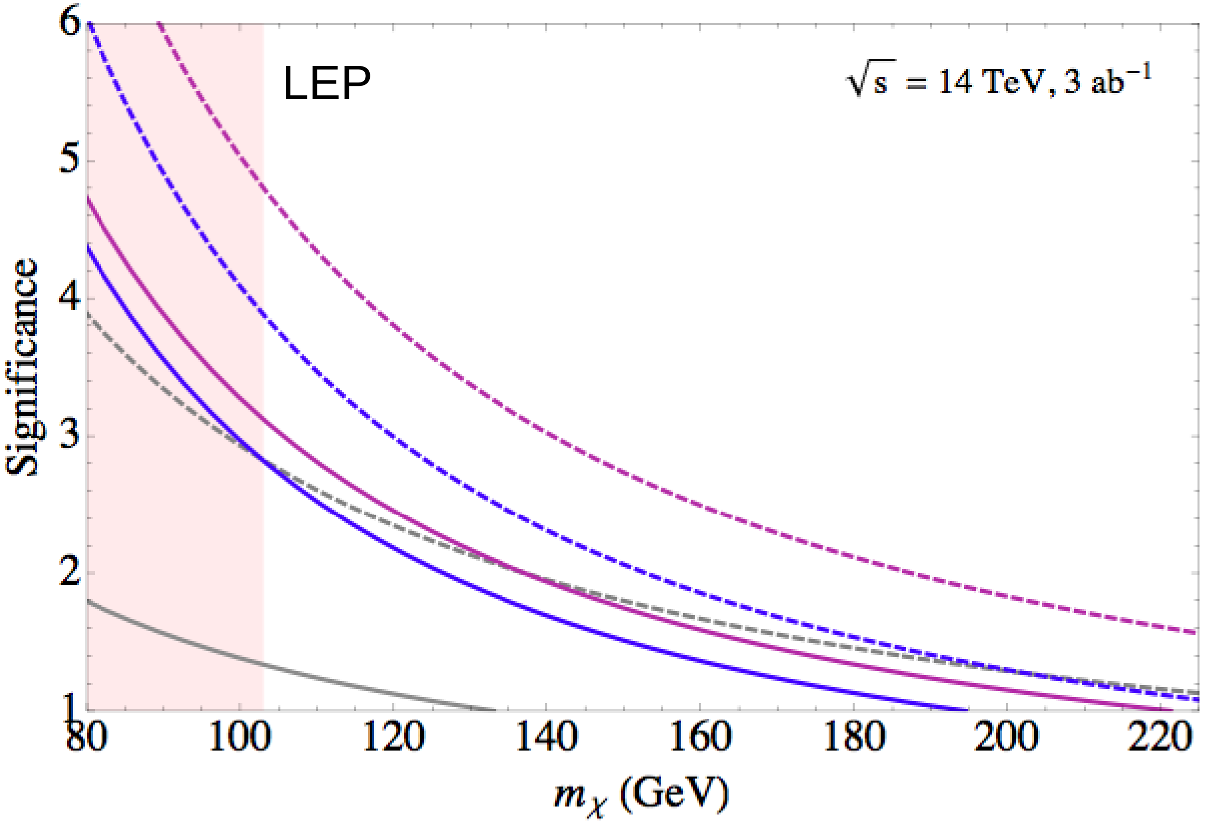
125 GeV Higgsino

Z, W backgrounds

photon transverse
mass cut

Results

For larger systematic uncertainties, photon + jet search improves on LEP limit where monojet is fundamentally limited



Photon + jet + MET

Monojet

Combination

Solid: 5% systematics
Dashed: 2% systematics

Summary

Various DM scenarios in SUSY can be mapped onto simplified models, and are being constrained by combinations of the LHC, direct detection, and indirect detection

Some difficult benchmarks remain, e.g. Higgsinos

Photon + jet can provide equal or better sensitivity than monojets to such states, depending on systematics that will be achievable

Beyond monojets

Eventual sensitivity of monojet analysis limited by systematic uncertainty on extracting backgrounds from control regions

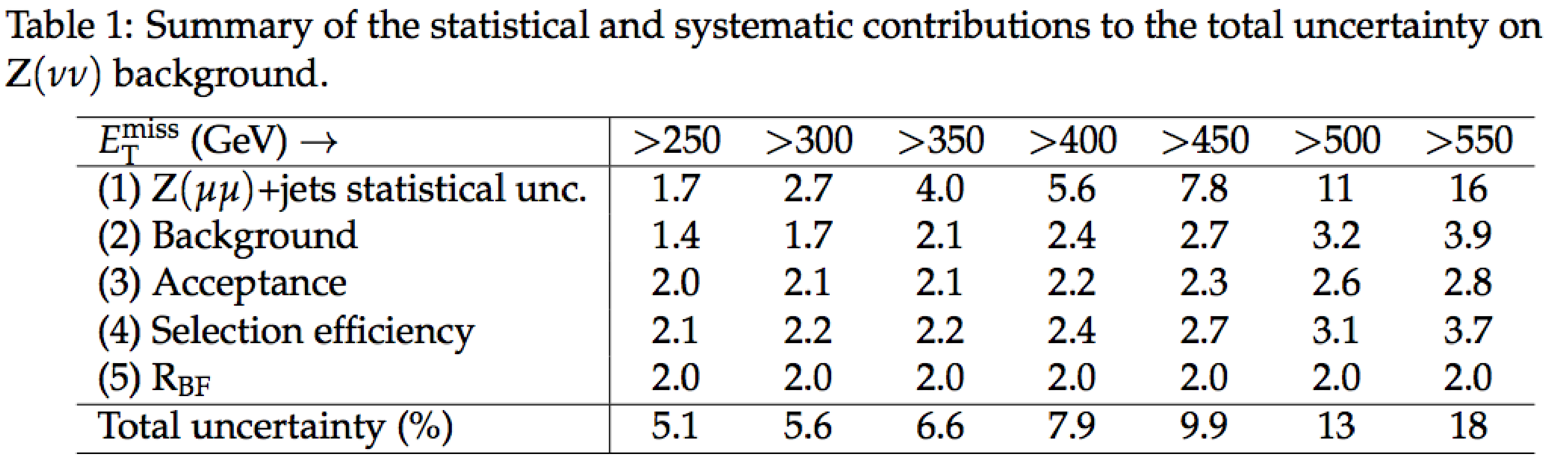


Table 1: Summary of the statistical and systematic contributions to the total uncertainty on the $Z(\nu\nu)$ background.

E_T^{miss} (GeV) →	>250	>300	>350	>400	>450	>500	>550
(1) $Z(\mu\mu)$+jets statistical unc.	1.7	2.7	4.0	5.6	7.8	11	16
(2) Background	1.4	1.7	2.1	2.4	2.7	3.2	3.9
(3) Acceptance	2.0	2.1	2.1	2.2	2.3	2.6	2.8
(4) Selection efficiency	2.1	2.2	2.2	2.4	2.7	3.1	3.7
(5) R_{BF}	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Total uncertainty (%)	5.1	5.6	6.6	7.9	9.9	13	18

CMS 1408.3583

Can afford to use final state with lower statistics instead

Experimental considerations

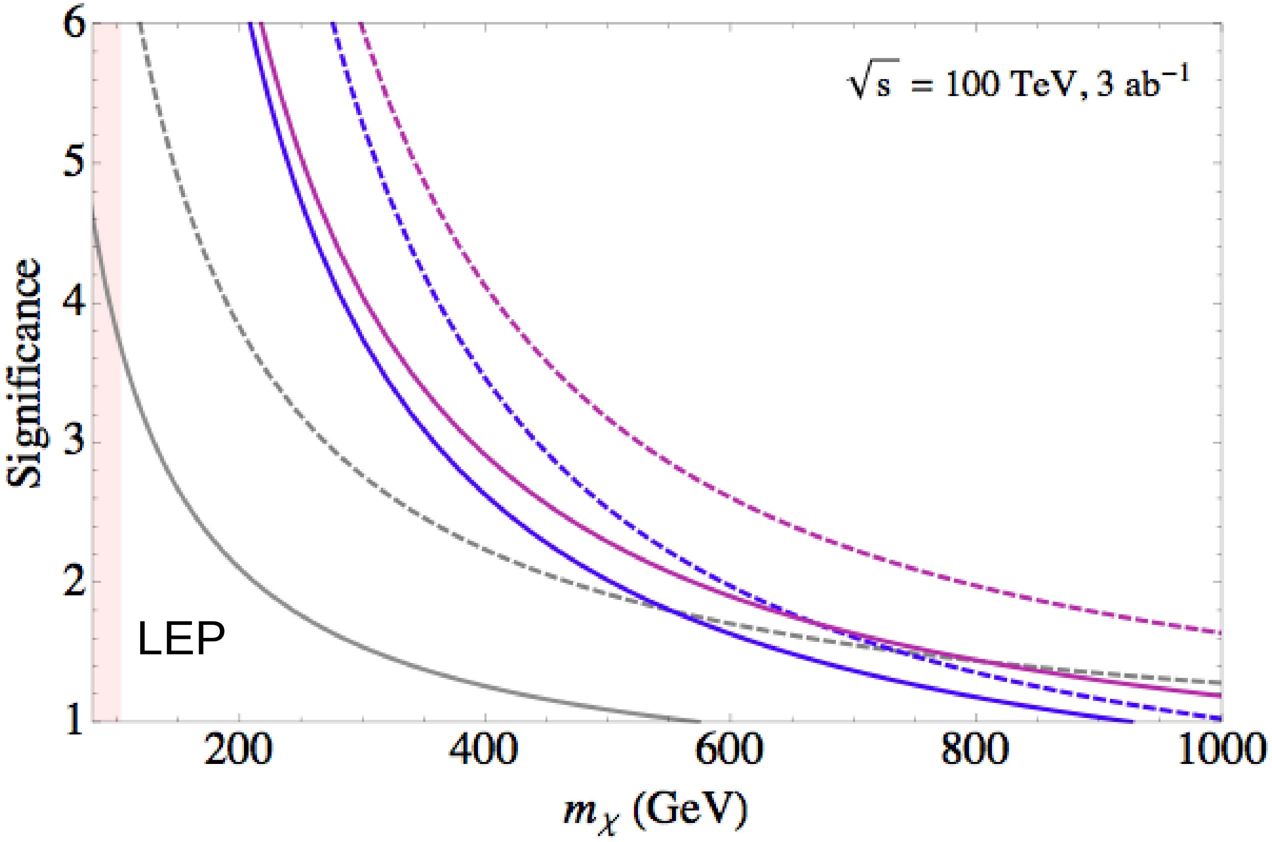
Recoil against hard jet provides alignment but also trigger, enabling acceptance of softer photons

Can estimate main backgrounds from data as for monojet search, e.g. $Z + \gamma + j$ from (hard) γ + (soft) $\gamma + j$, and $W + \gamma + j$ from control region with isolated hard leptons → expect similar control of systematics

Cuts on extra jets, leading jet p_T / MET ratio reduce backgrounds from tops, QCD

Results

At 100 TeV, combining photon + jet with monojet channel can increase exclusion reach from ~ 450 to 750 GeV, with improved systematics



Photon + jet + MET

Monojet

Combination

Solid: 5% systematics
Dashed: 2% systematics