Electroweak Searches using Photon Final State Radiation

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New Physics Interpretations at the LHC 2, Argonne

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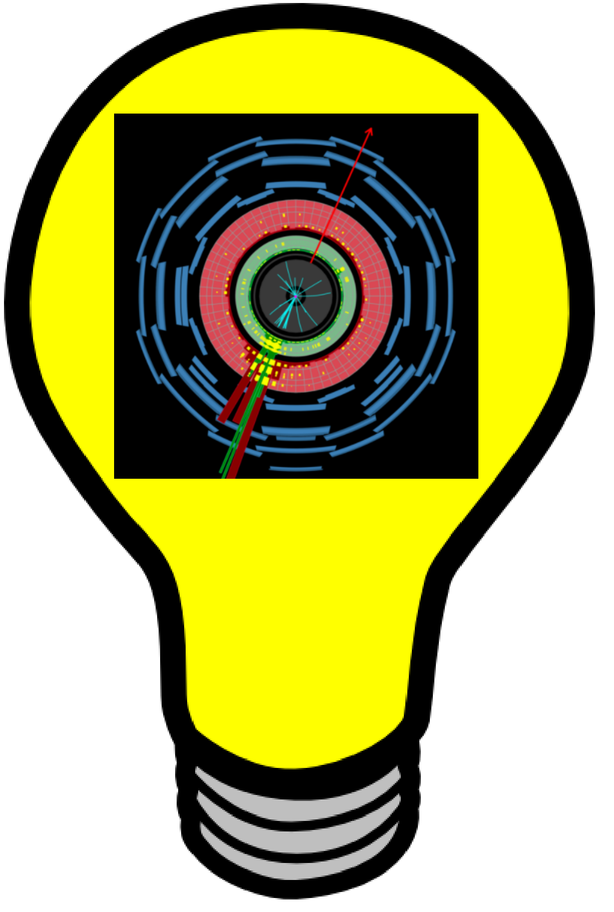
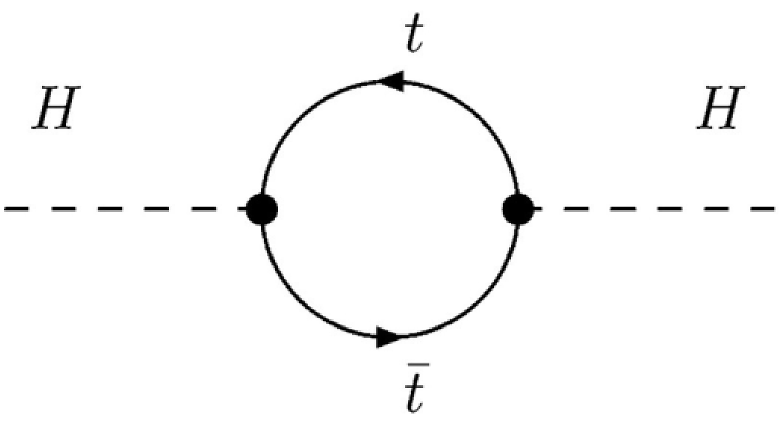
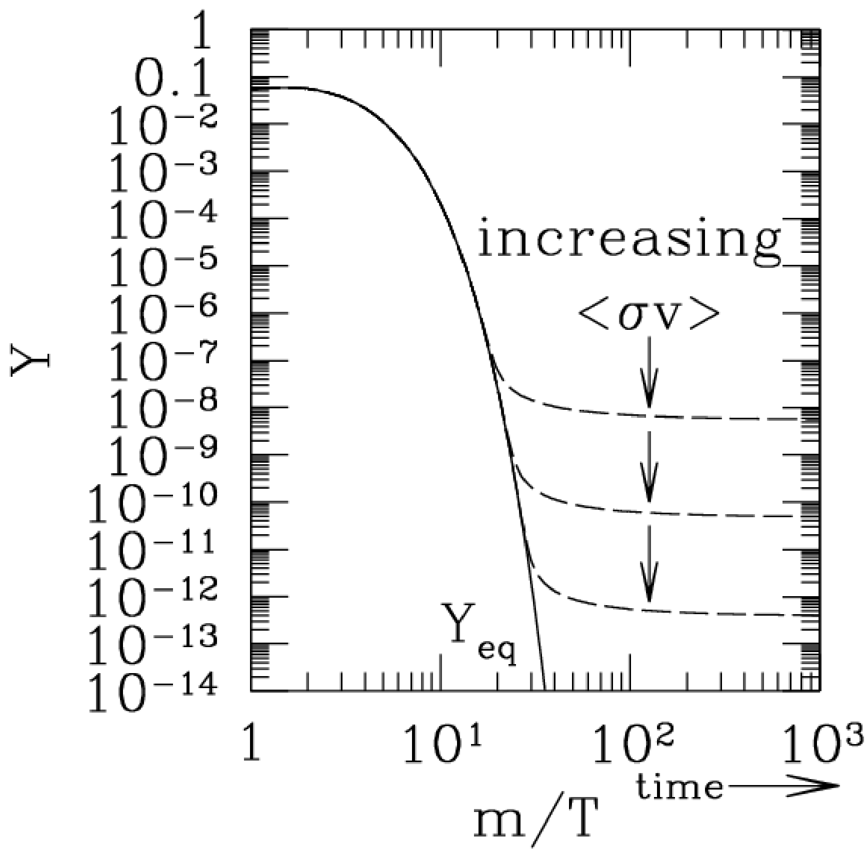


1605.00658, with E. Izaguirre and B. Shuve

Why look for new electroweak states?

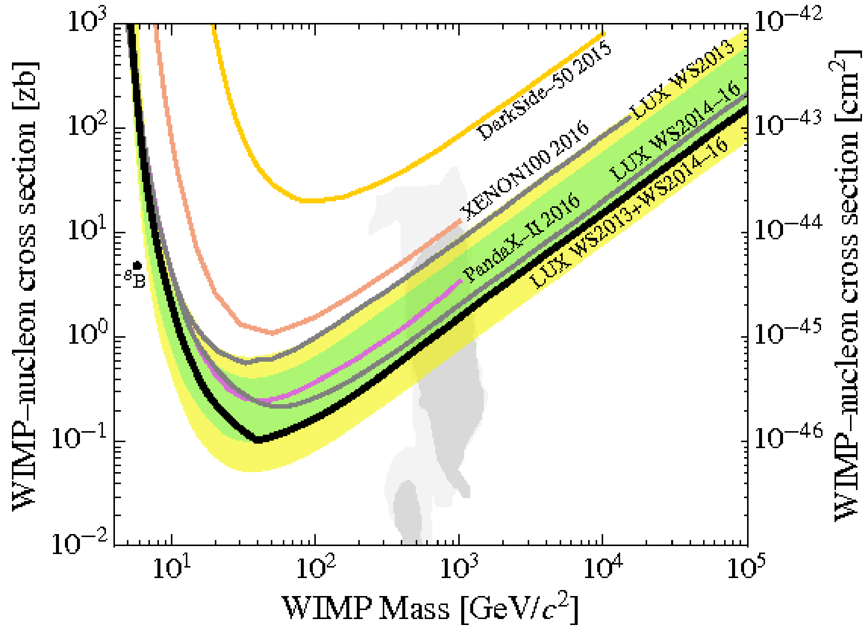
Naturalness, e.g. higgsino mass affects fine-tuning at tree level





WIMP paradigm: a weakly interacting particle near the EW scale approximately reproduces the correct relic density

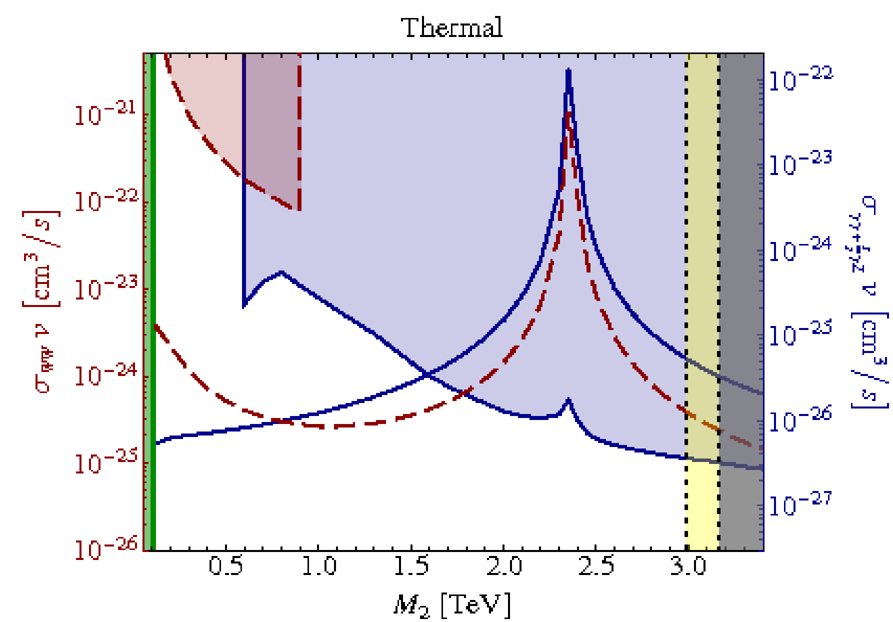
WIMPs



LUX, 1608.07648

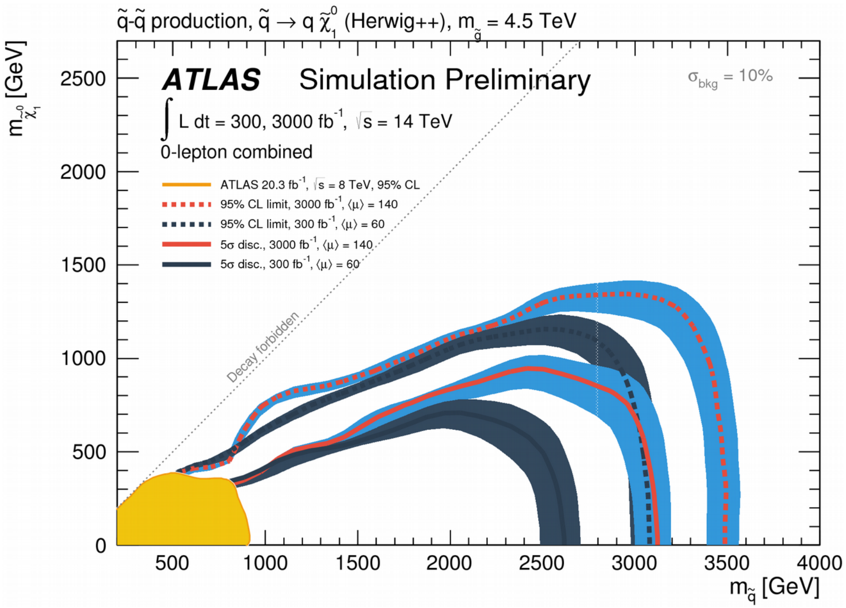
Direct detection already excludes the simplest WIMP, a pure Dirac fermion in an SU(2) doublet

Indirect detection constraints, e.g. SU(2) triplet fermions produce too many γ rays

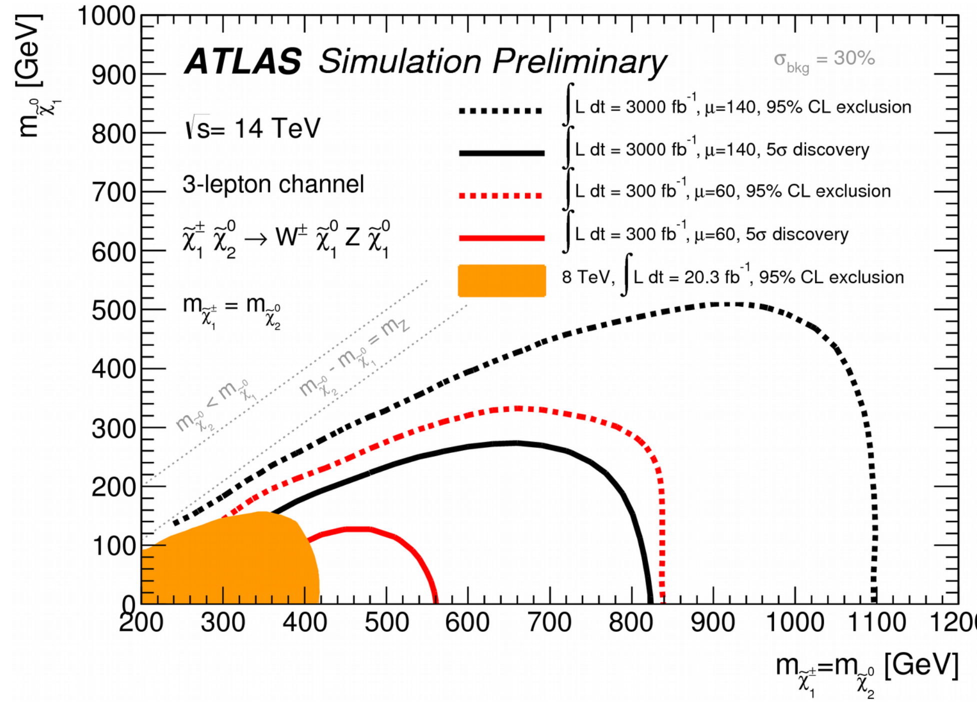


Cohen et al., 1307.4082

Collider searches



Relatively speaking, searches for uncolored new particles will improve more



With increased luminosity, *systematic* rather than statistical uncertainties are limiting factor

New electroweak states and MET

Focus on missing momentum signatures of new EW states

Assumptions:

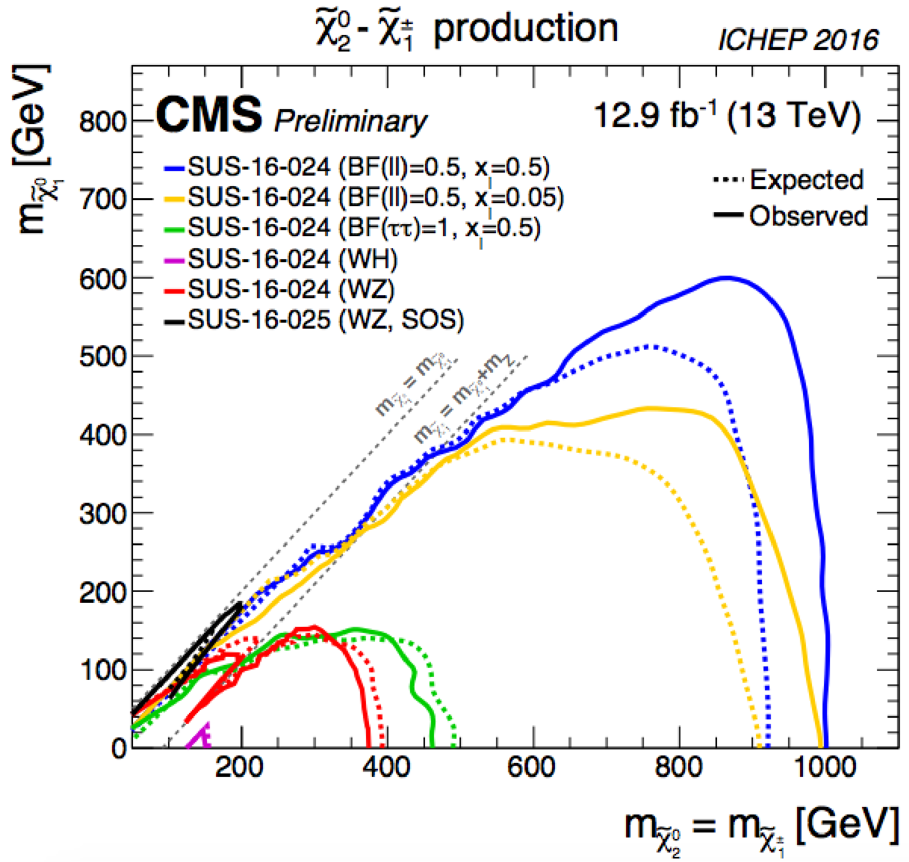
EW multiplet odd under Z_2 symmetry, to avoid decays into SM particles that are covered by other searches

Q = 0 member of multiplet is lightest state, and hence invisible at colliders

New electroweak states and MET

Any non-trivial $SU(2)_L$ multiplet χ contains at least one charged particle

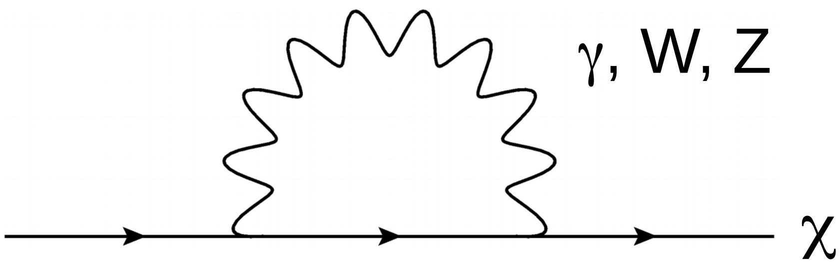
One strategy: produce charged particle and look for decay products plus MET



If charged/neutral splitting is large enough, leptons from χ^+ decay are visible

Mass splitting

Small mass difference from radiative corrections



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

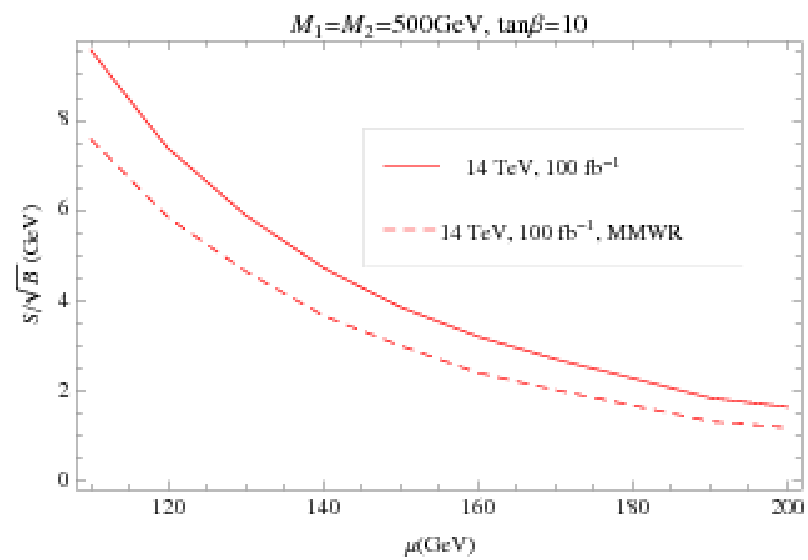
Extra splitting possible from EWSB (scalar: dimension 4)

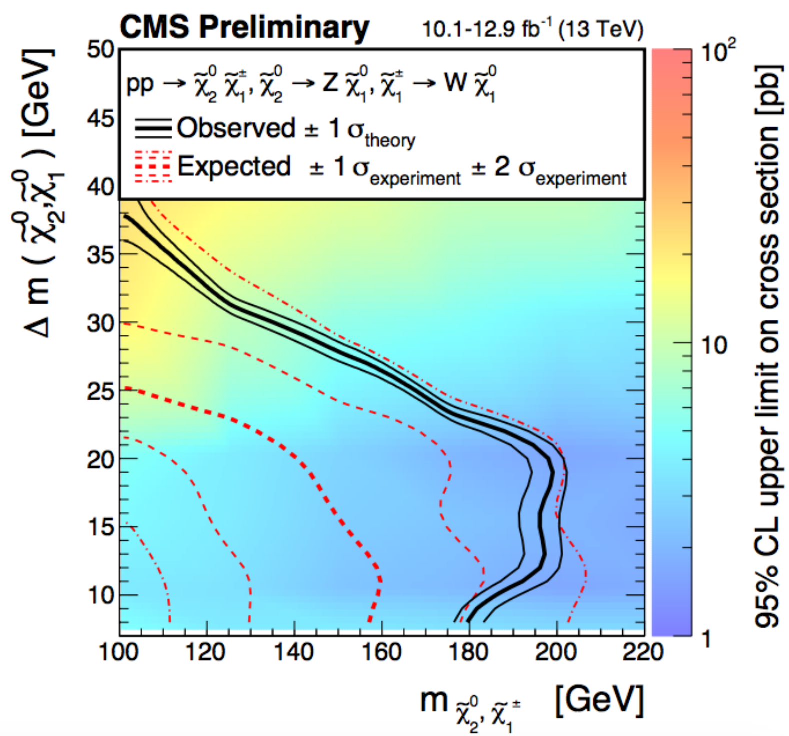
$$\mathcal{L} \supset \frac{i}{\Lambda} (\bar{\chi} \vec{\sigma} \chi) \left(H^\dagger \vec{\sigma} H\right) \to M(\chi^+) - M(\chi^0) \sim \frac{v^4}{\Lambda^2 m_\chi}$$

Signatures: large splitting

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





Multiple states also give leptons from off-shell Z

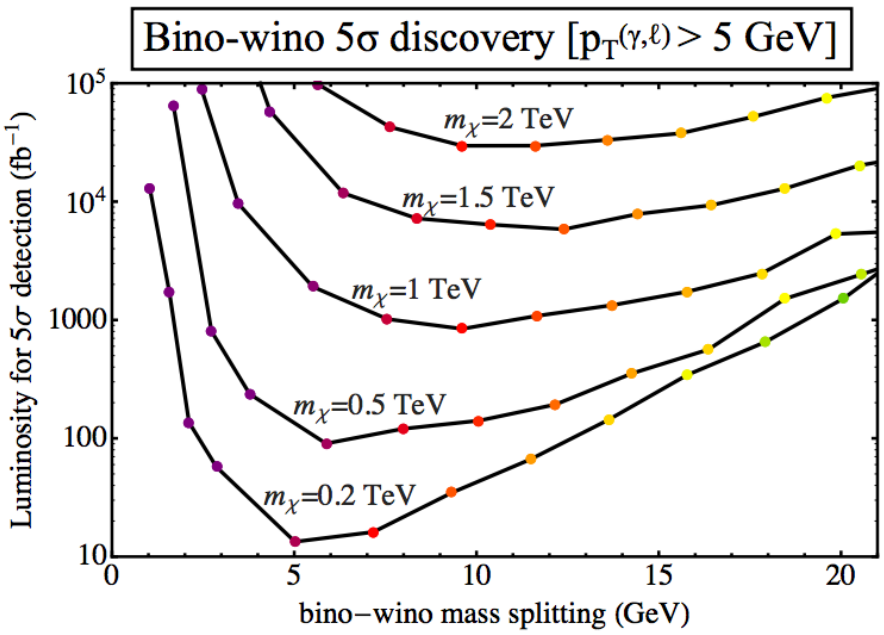
Standard example: gaugino sector of MSSM

Signatures: large splitting

Even lower splittings can again be probed if there are mixings among multiple states

e.g. using photons from neutral → neutral radiative decays

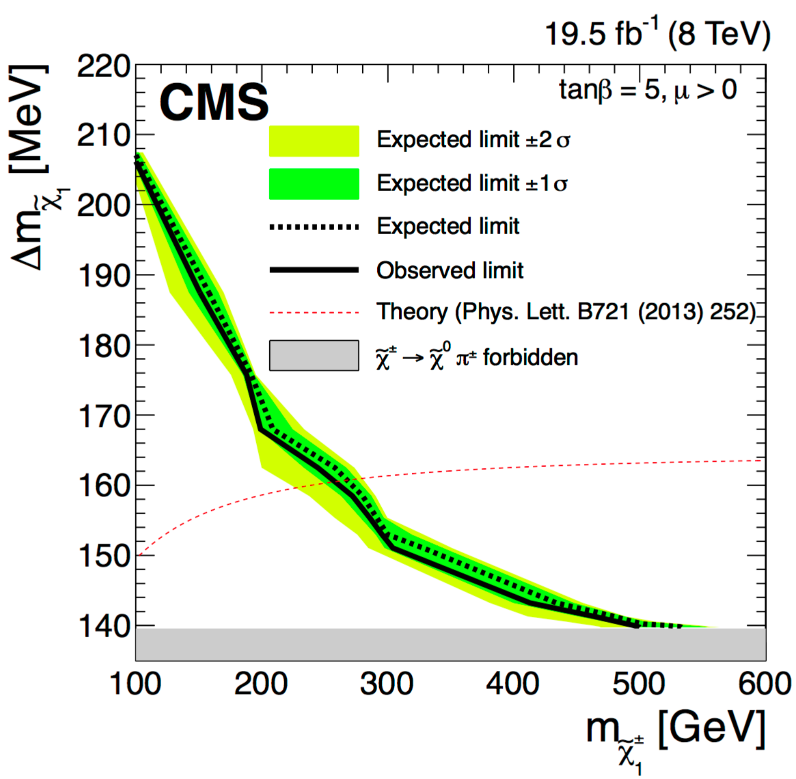
Bramante et al., 1412.4789



With enough energy and luminosity, can get sensitivity to electroweak states that are degenerate down to several GeV

Signatures: small splitting

For mass difference below 200 MeV, $\chi^+ \rightarrow \chi^0 + \pi^+$ gives disappearing tracks



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

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

$$\rightarrow \tau \approx \frac{44\ \mathrm{cm}}{n^2 - 1}$$

Y = 0 *n*-plet

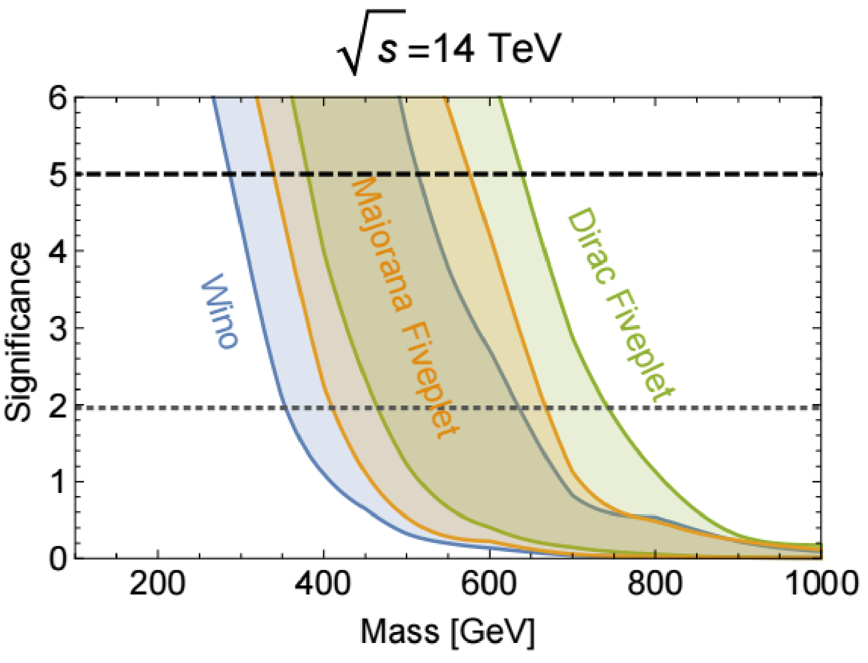
Signatures: small splitting

Radiative splitting for Y = 0 multiplets is ~166 MeV, so disappearing track searches often apply

If χ is Majorana fermion, simplest additional splitting is provided by dimension 7 operator

→ relatively robust limit

Dirac case: dimension 5 operator allowed



Ostdiek, 1506.03445

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

Need to go beyond monojets

Future monojet sensitivity hindered by large V + jet backgrounds

Baer, Mustafayev, Tata 1401.1162; Low and Wang, 1404.0682; Anandakrishnan, Carpenter, Raby 1407.1833; …

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

E_T^{miss} (GeV) $\rightarrow$	>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

Eventual systematic uncertainty limited by control region statistics

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

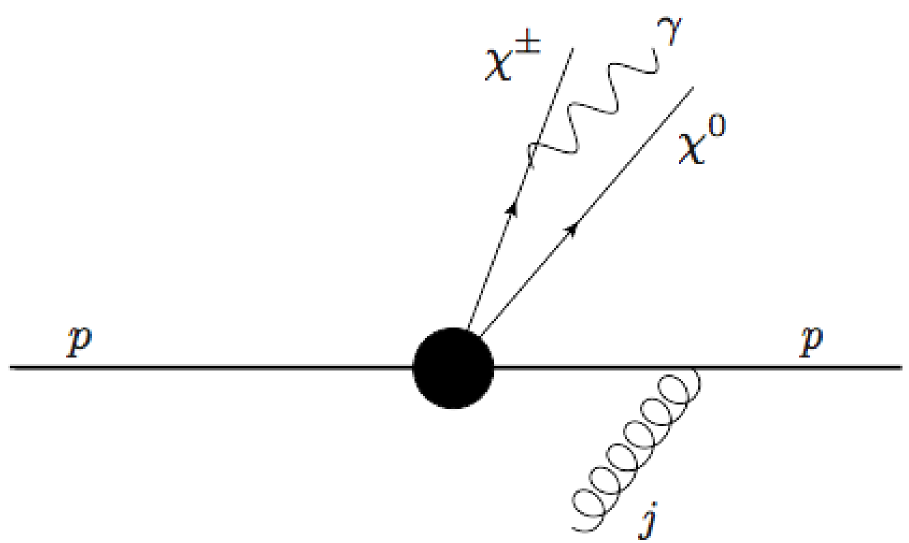
W, Z radiation not as useful for most of the masses considered here, though can be relevant at very high energies

Hook and Katz, 1407.2607

Photon final-state radiation

Take advantage of photon radiation by boosting

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



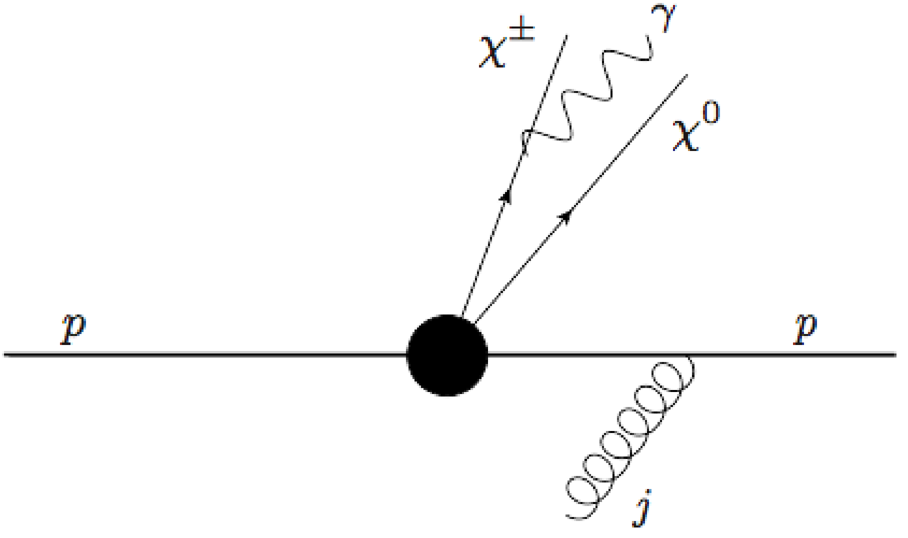
Pay statistical price of α for radiation, but benefit from low backgrounds and extra kinematic handle in γ + j + MET

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

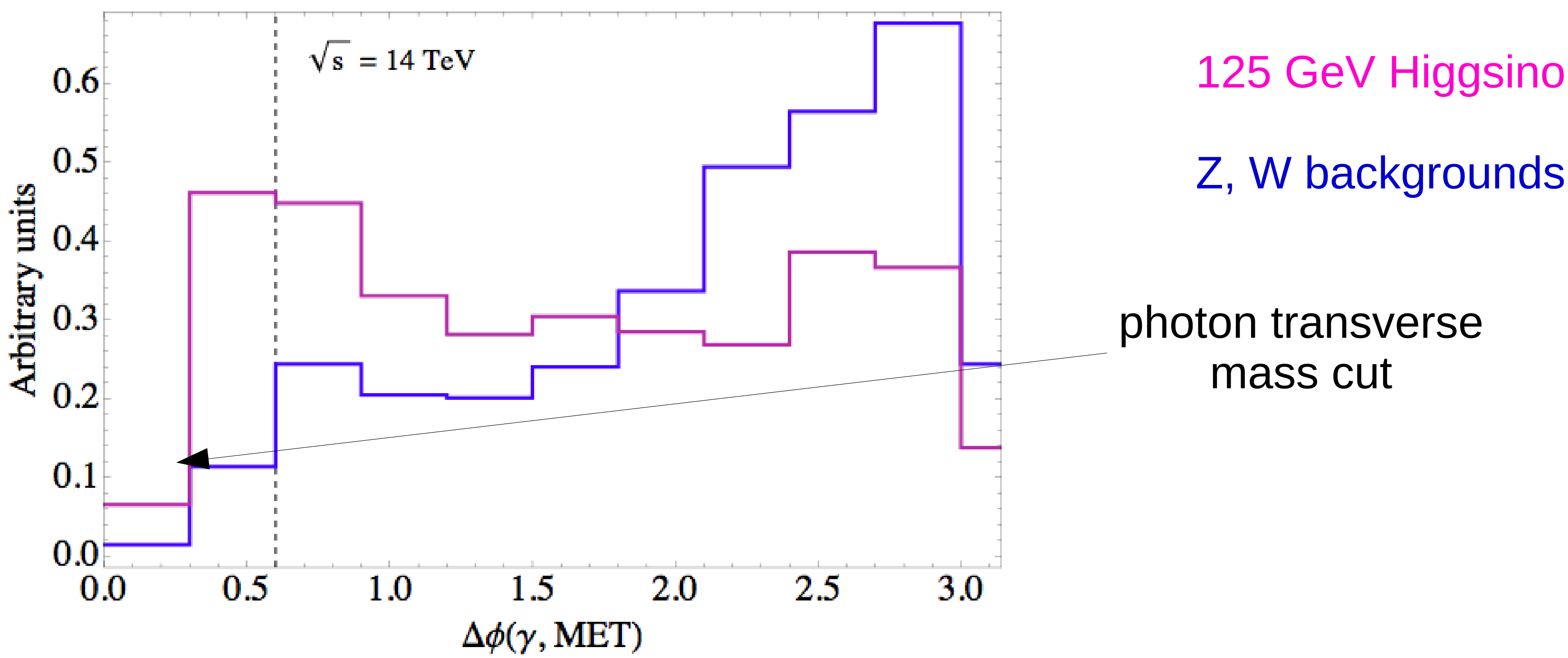


Photon + jet + MET search

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

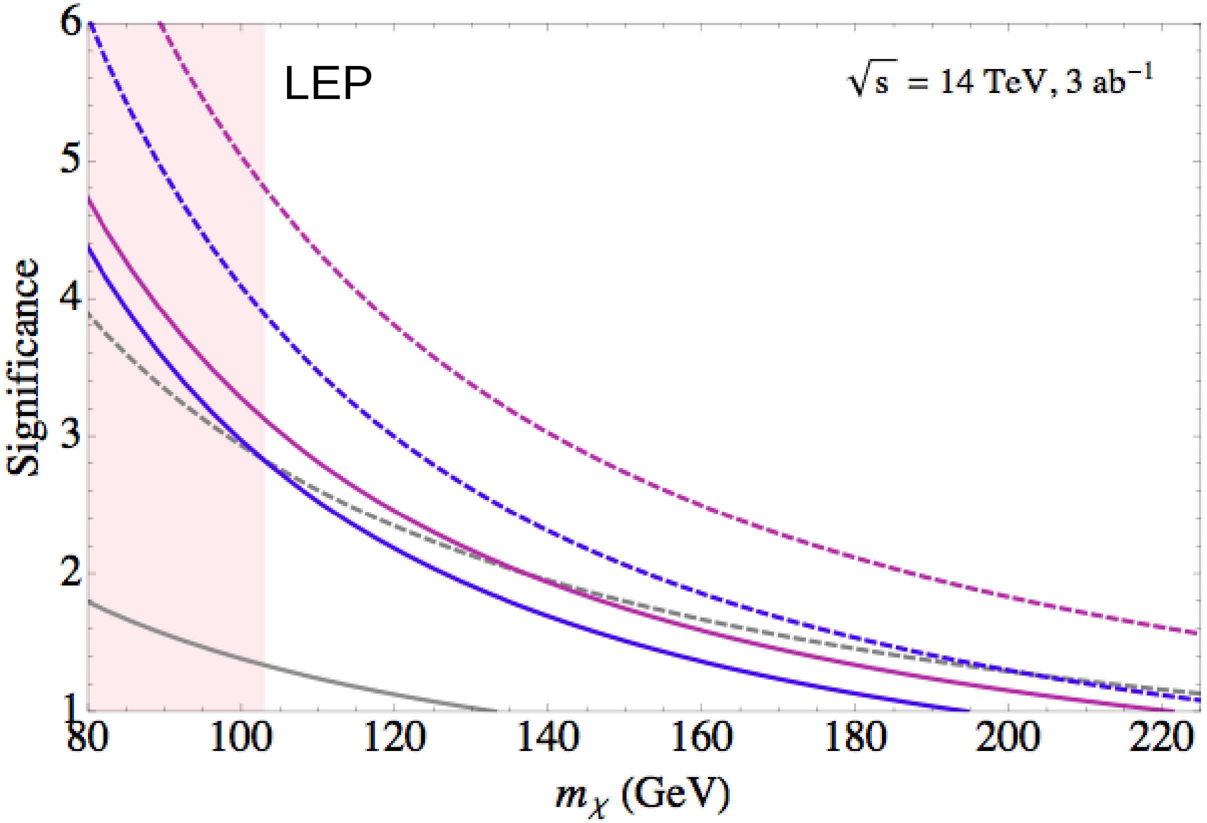
Backgrounds: Z + γ + j, W + γ + j, tops, QCD fakes

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



Results - Higgsino

Adding photon to monojet final state helps, except in the case of low statistics (high mass) with significantly improved systematic uncertainties



Photon + jet + MET

Monojet

Combination

Solid: 5% systematics
Dashed: 2% systematics

Summary

Charged states in an $SU(2)_L$ multiplet may decay invisibly, but still leave photon final state radiation

Can look for photon in events with a hard ISR jet and missing energy, using kinematics to discriminate against backgrounds

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

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 + γ + j from (hard) γ + (soft) γ + j, and W + γ + j from control region with isolated hard leptons $\rightarrow$ expect similar control of systematics

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

Results - Higgsino

Y = ½ doublet (Higgsino):

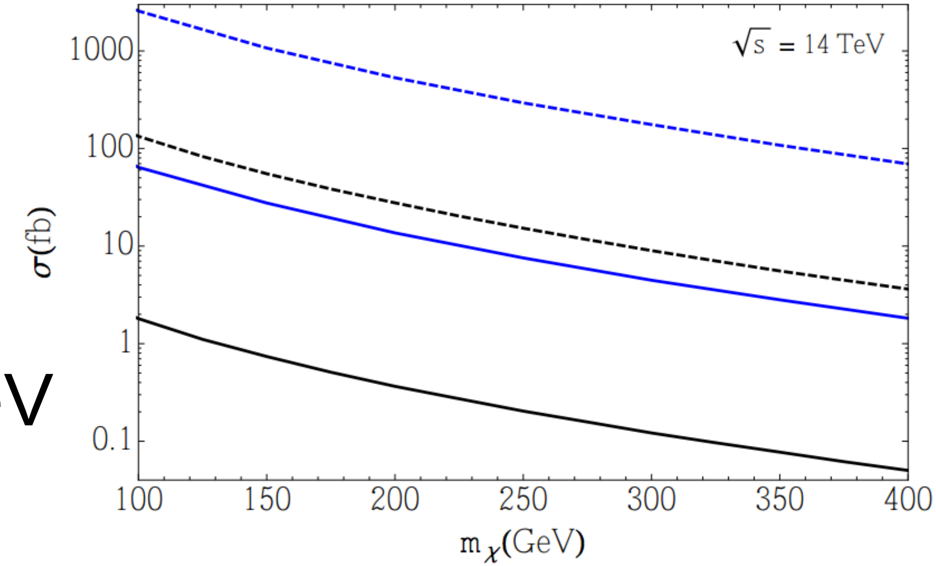
- light in natural SUSY

- thermal dark matter at 1.0 TeV

- radiative splitting between charged and neutral state is 340 MeV

- direct detection through Z exchange In pure Dirac limit, but *very* small splitting eliminates possibility

- indirect detection difficult, even with CTA



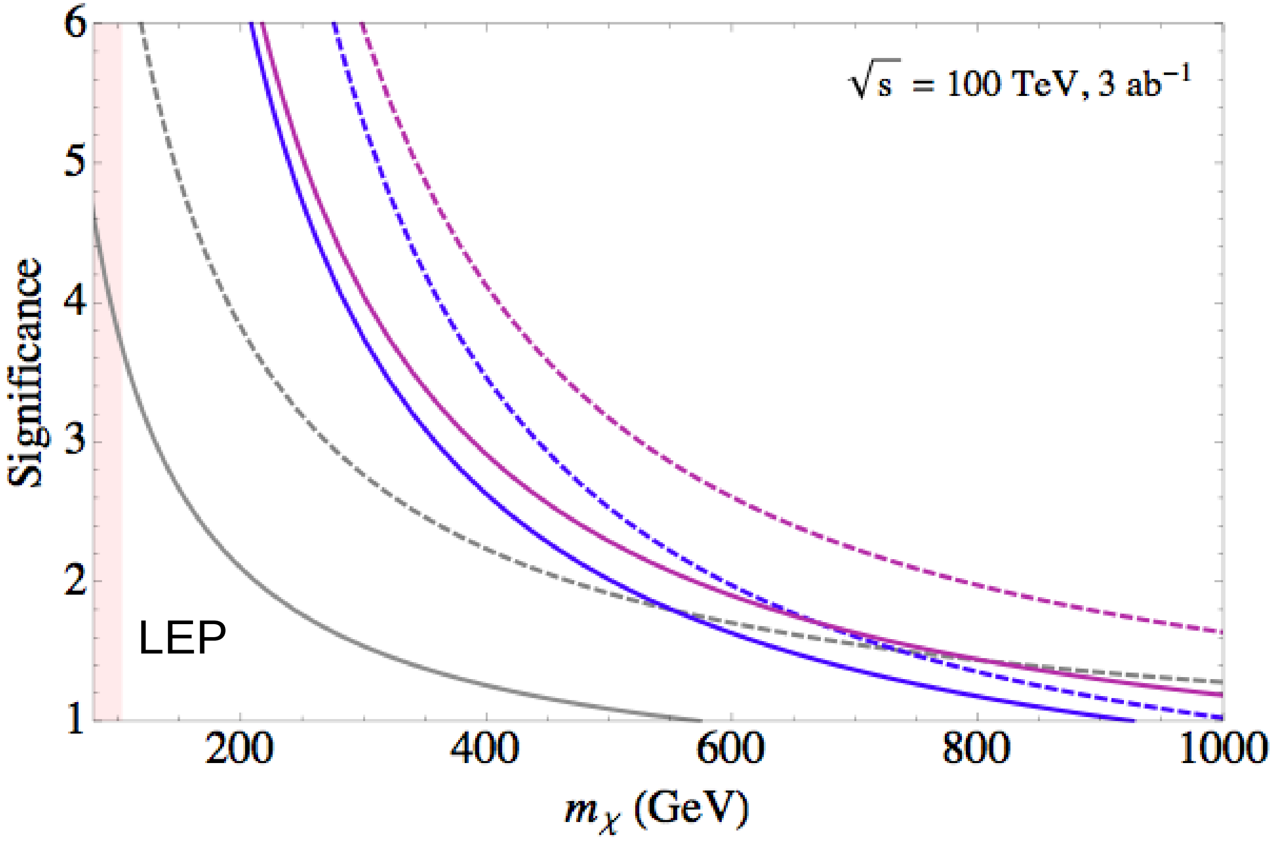
Doublet

Quintuplet

Solid: photon + jet + MET
Dashed: jet + MET

Results - Higgsino

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

Results - Quintuplet

Y = 0 quintuplet:

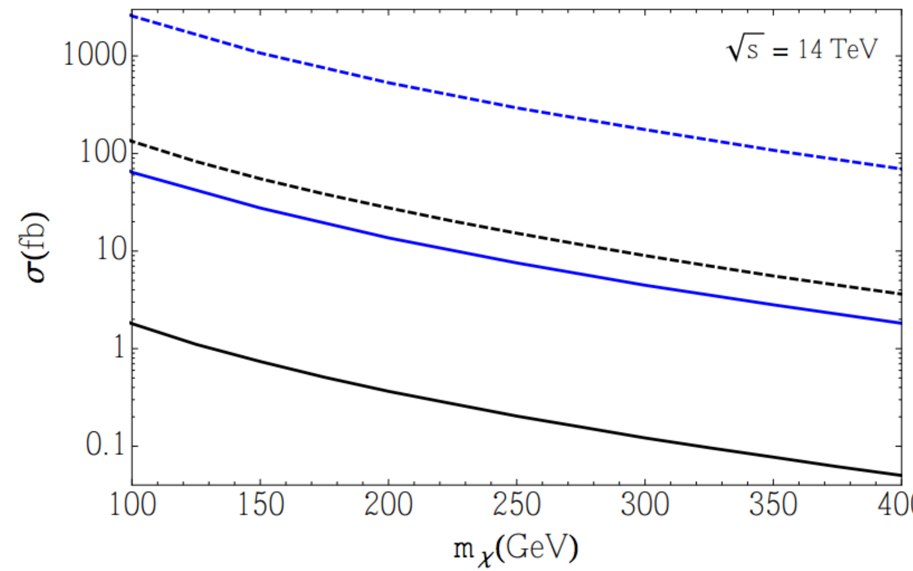
- standard minimal DM candidate

- simplest EW multiplet that cannot decay to SM fields through dimension < 6 operators

- thermal dark matter at 4.4 TeV

- in Dirac case, model-dependent splitting can evade disappearing tracks

- no direct detection



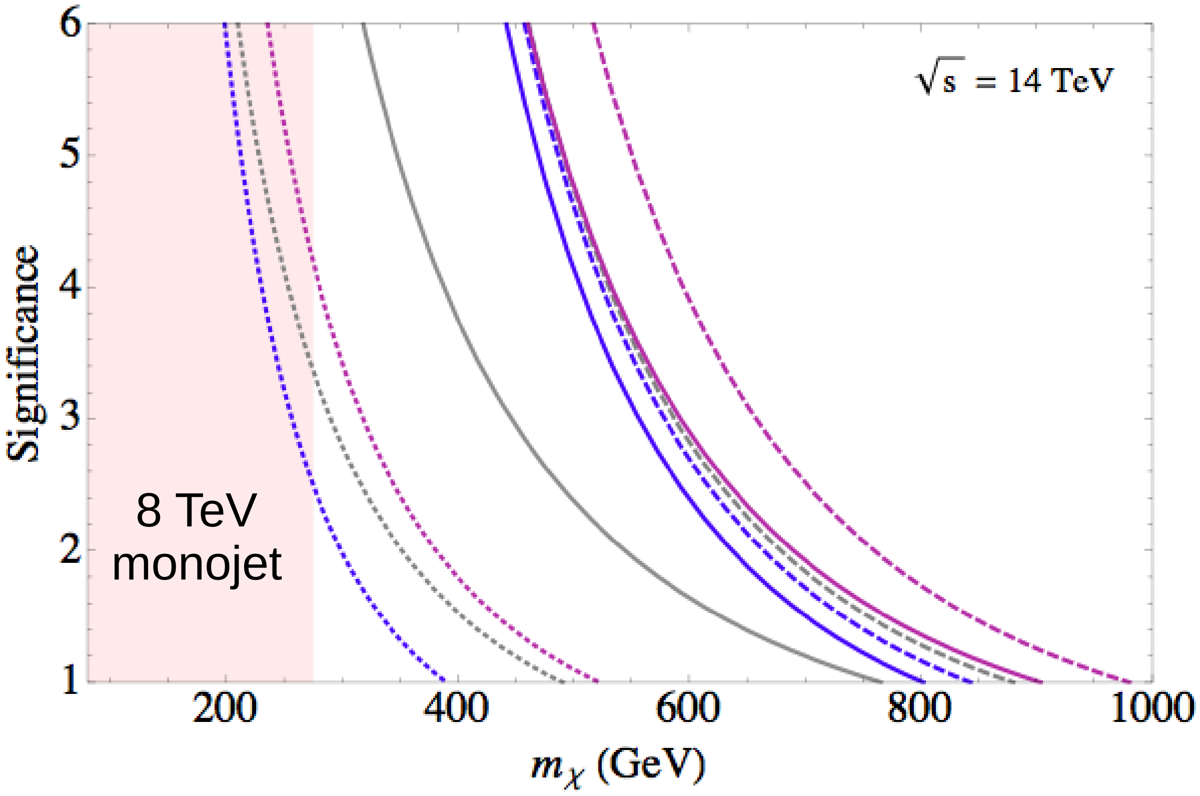
Doubletx

Quintuplet

Solid: photon + jet + MET
Dashed: jet + MET

Results - Quintuplet

With enough luminosity, increased radiation from χ^{++} improves photon + jet + MET analysis to be competitive



Photon + jet + MET

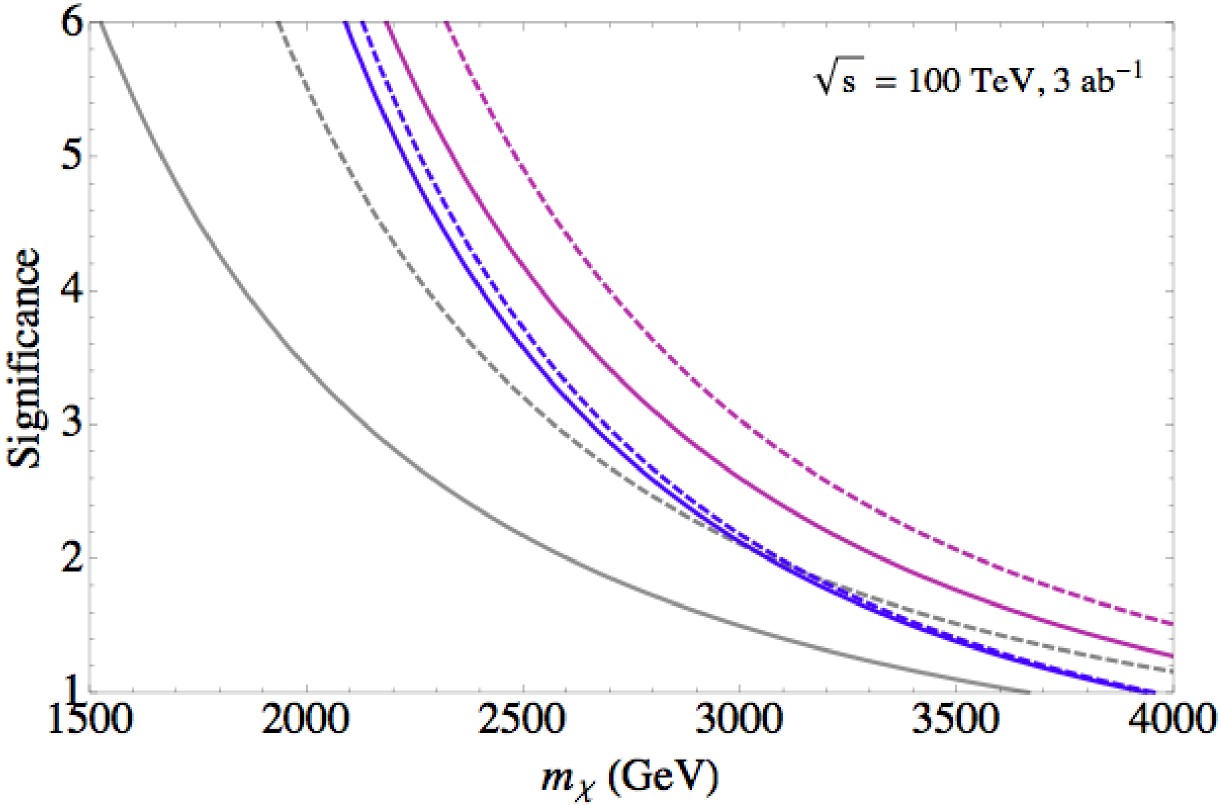
Monojet

Combination

Dotted: 20 fb^{-1}, 5% systematics
Solid: 3 ab^{-1}, 5% systematics
Dashed: 3 ab^{-1}, 2% systematics

Results - Quintuplet

Thermal DM mass not quite reached at 100 TeV, but photon + jet channel still provides useful information



Photon + jet + MET

Monojet

Combination

Solid: 5% systematics
Dashed: 2% systematics