Closing the window for compressed electroweakinos at a 100 TeV collider

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R.Mahbubani, P. Schwaller, JZ, [arXiv 1703.05327]
R.Mahbubani, JZ, [arXiv 1705.xxyzz]

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Outline

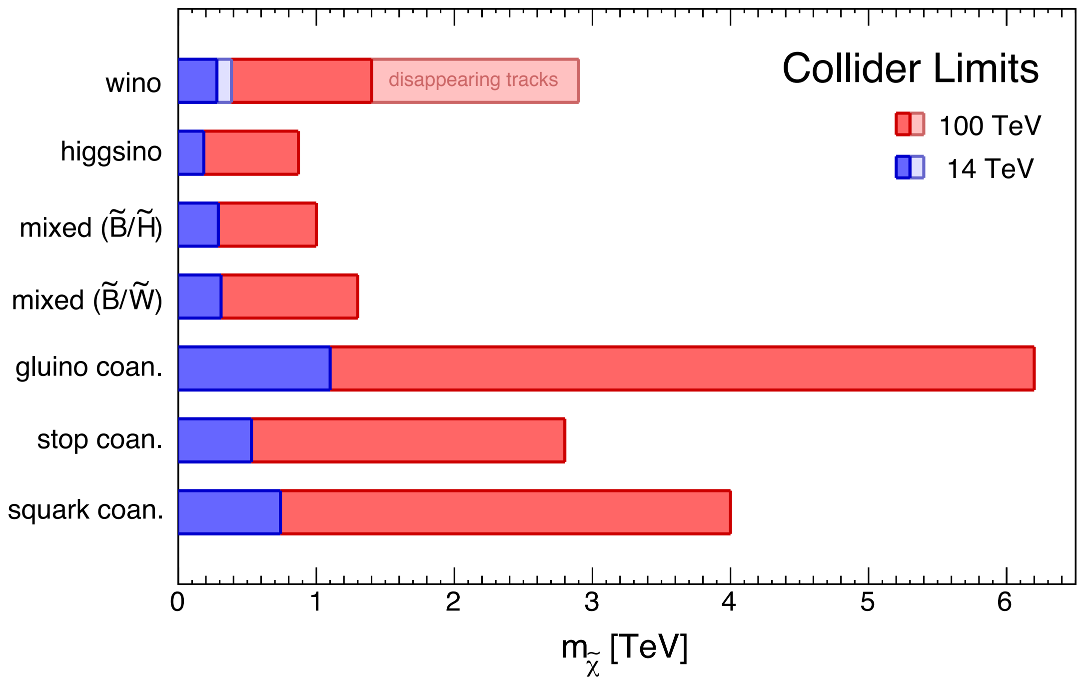
- Why TeV Higgsinos? (VLF, weak doublet)
- Phenomenology of Bino/Higgsino (singlet/doublet)
- Disappearing tracks @ FCC-hh, HL-LHC
- Mono-Z @ FCC-hh
- Conclusions

TeV Higgsinos: MSSM's last stand

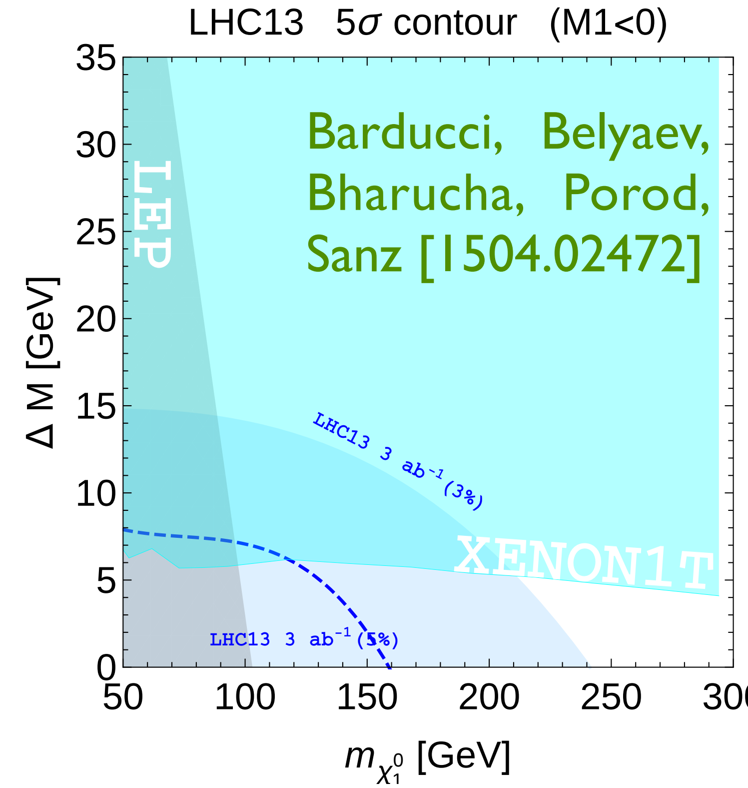
- The neutralino is the MSSM DM candidate, made out of Bino, Wino and Higgsino.
- Relic density sets "pure" masses: $\tilde{B}$ (100 GeV), $\tilde{W}$ (2.7 TeV) and $\tilde{H}$ (1.1 TeV).
- All pure cases and mixtures (wino/Higgsino, bino/Wino, etc) well studied in the literature.
- Only "uncoverable" spot is an "almost pure"* Higgsino, mass ~1.1 TeV:
  - DM search @ LHC(FCC): mono-jet. Reaches 200 (900) GeV (Low, Wang:1404.0682).
  - Disappearing tracks: Reach limited due to Higgsino lifetime.
- This talk:
  - a) disappearing tracks with a customised detector (FCC, HL-LHC).
  - b) mono-Z study with highly boosted di-lepton final states (FCC).

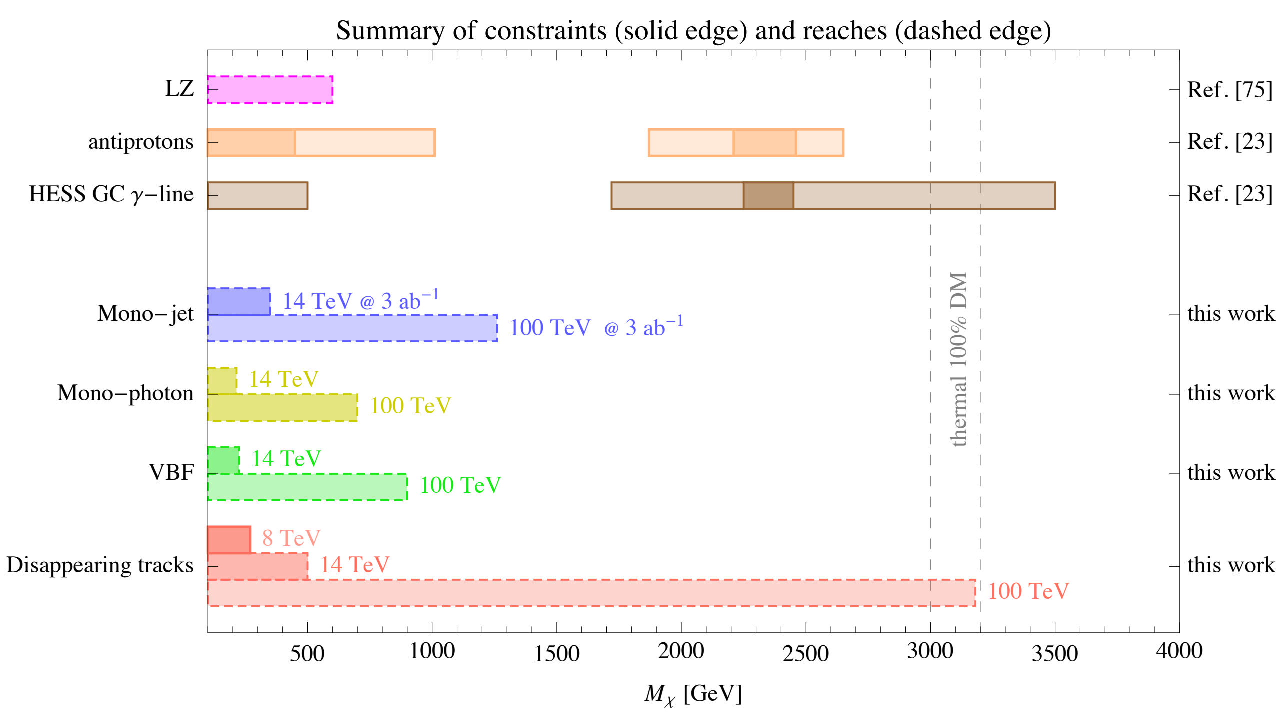
* A pure Higgsino, EW doublet, is ruled out, because both neutral states are mass degenerate, and the Z-n1-n2 coupling is actually Z-n1-n1. Z currents with weak couplings are excluded by direct detection experiments (XENON100, LUX, etc). Some additional Bino and/or Wino component is required.

A sample of pheno studies

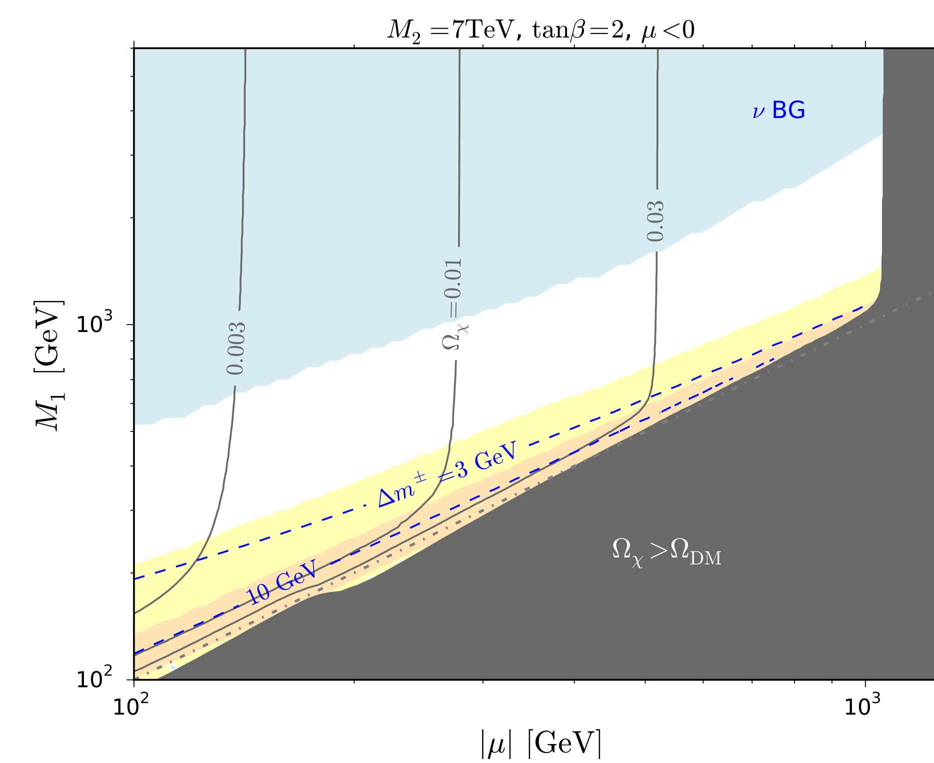


M. Low, L.T.Wang [1404.0682]





Cirelli, Sala, Taoso [1407.7058]



Badziak, Delgado, Olechowski, Pokorski, Sakurai [1506.07177]

Higgsino/Bino

(doublet/singlet)

phenomenology

Bino/Higgsino setup

Thomas, Wells, hep-ph/9804359,
Cirelli, Formengo, Strumia, hep-ph/051209

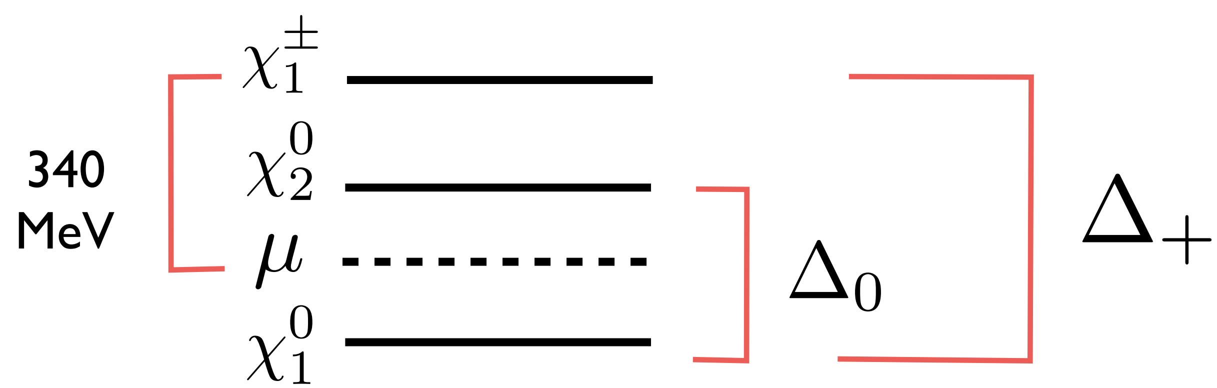
Since EW symmetry is broken, in an EW multiplet neutral components correct their masses due to Z-loops, charged components also have W, γ-loops.

→ $\Delta_{1-\mathrm{loop}}$: $\tilde{H}$ $340\ \mathrm{MeV}$, $\tilde{W}$ $170\ \mathrm{MeV}$

Expanding in $\mu/M_1, m/M_1$

$$M = \begin{pmatrix} M_1 & -mc_\beta & ms_\beta \\ -mc_\beta & 0 & \mp\mu \\ ms_\beta & \mp\mu & 0 \end{pmatrix}$$

$$m = m_Z s_W \approx 43.8\ \mathrm{GeV}$$



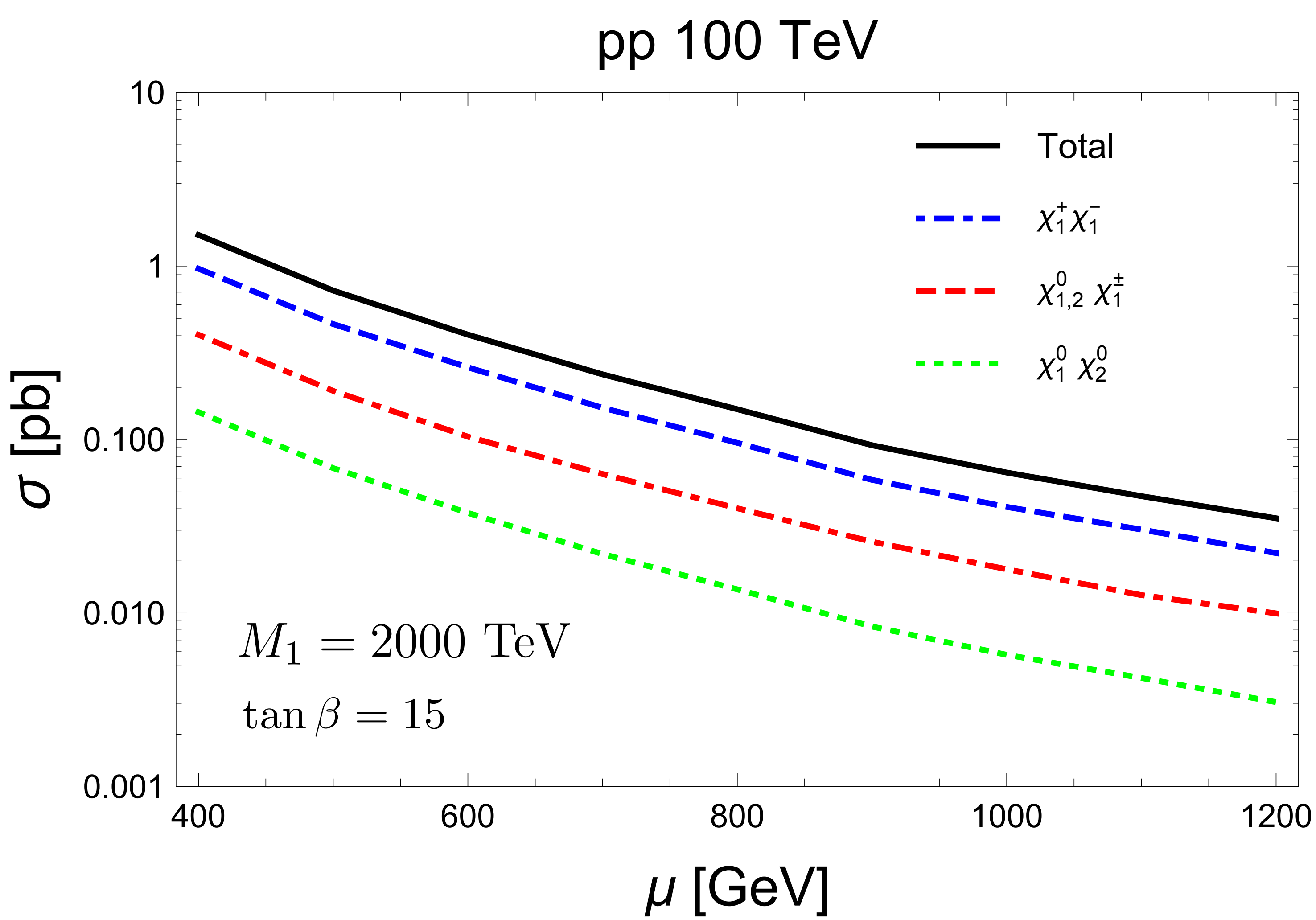
$$\Delta_0 = \frac{192\ \mathrm{MeV}}{(M_1/10\ \mathrm{TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right) \qquad \Delta_+ = \Delta_{1-\mathrm{loop}} + \frac{96\ \mathrm{MeV}(1 \mp s_{2\beta})}{(M_1/10\ \mathrm{TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

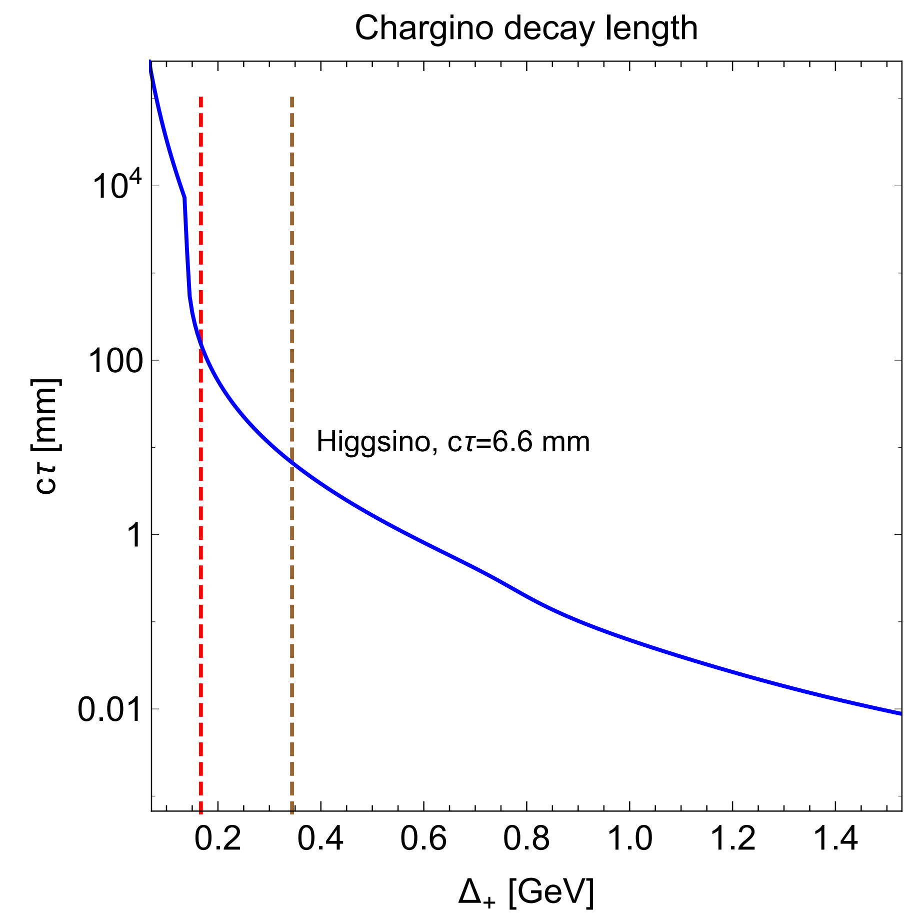
<u>Limiting cases:</u>

1. $\Delta_0 \geq \Delta_+$: decay open only to first neutralino $\longrightarrow$ for $M_1 \lesssim 3|\mu|$.
2. $\Delta_0 = 0\,,\ \Delta_+ = 340\ \mathrm{MeV}$: decays to both, lifetime reduced by half.

Δ_0 < 100 KeV gives inelastic scattering @ DD → M_1 < 20 PeV.

Cross sections and decay lengths





$$\sigma(1.1\ \text{TeV})[\text{fb}] = 47.23\ (39.05)\ \ \text{NLO (LO)}\,.$$

PROSPINO Beenakker, Klasen, Krämer, Plehn, Spira, Zerwas, hep-ph/9906298

Decays formulae (mostly) from

Chen, Drees, Gunion: hep-ph/951230, 9607421, 9902302.

$$\Delta_+ = 340\ \text{MeV} \quad \Rightarrow \quad \text{BR}\ (\chi_1^\pm \to \pi^\pm \chi_0^{(1)}) \sim 97\%\,.$$

Higgsino lifetime too short!!! $\Delta_+/2$ leads to O(20) enhancement.

Disappearing tracks

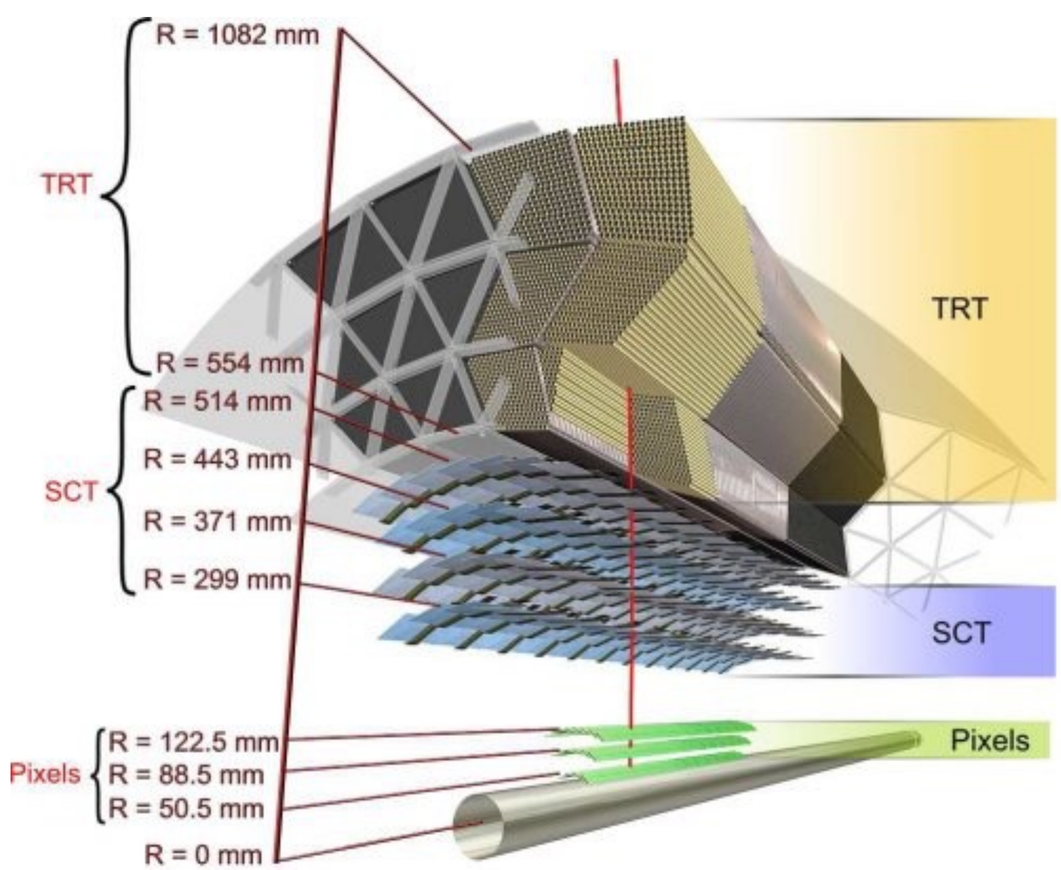
@ FCC-hh / HL-LHC

R.Mahbubani, P. Schwaller, JZ, [arXiv 1703.05327, JHEP soon]

Disappearing tracks @ LHC

ATLAS: CERN-PH-EP-2013-155 [CMS: CERN-PH-EP-2013-037]

- Charged particle (track) decays into neutral + SM (unreconstructed): disappeared!!!
- Event selection requires:
  - 1 “good quality”* (isolated, well reconstructed) track with large pT.
  - large missing transverse energy (MET > O(100 GeV)).
  - 1 hard jet, pT > 100 GeV (from initial state radiation, to trigger the event).
  - $\Delta\Phi$(jet,MET) > 1.0 (0.5) @ ATLAS (CMS) : kills mismeasured QCD multijets.



* Quality track

- At least 3 hits in pixel detectors.
- At least 2 hits in the SCT.
- Less than 5 hits in the TRT**
- pT > 15 GeV, 0.1 < |η| < 1.9 (hard and central)

$d_{min} \approx 30$ cm

ATLAS-CONF-2017-017: new pixel layer (r=3.33cm)

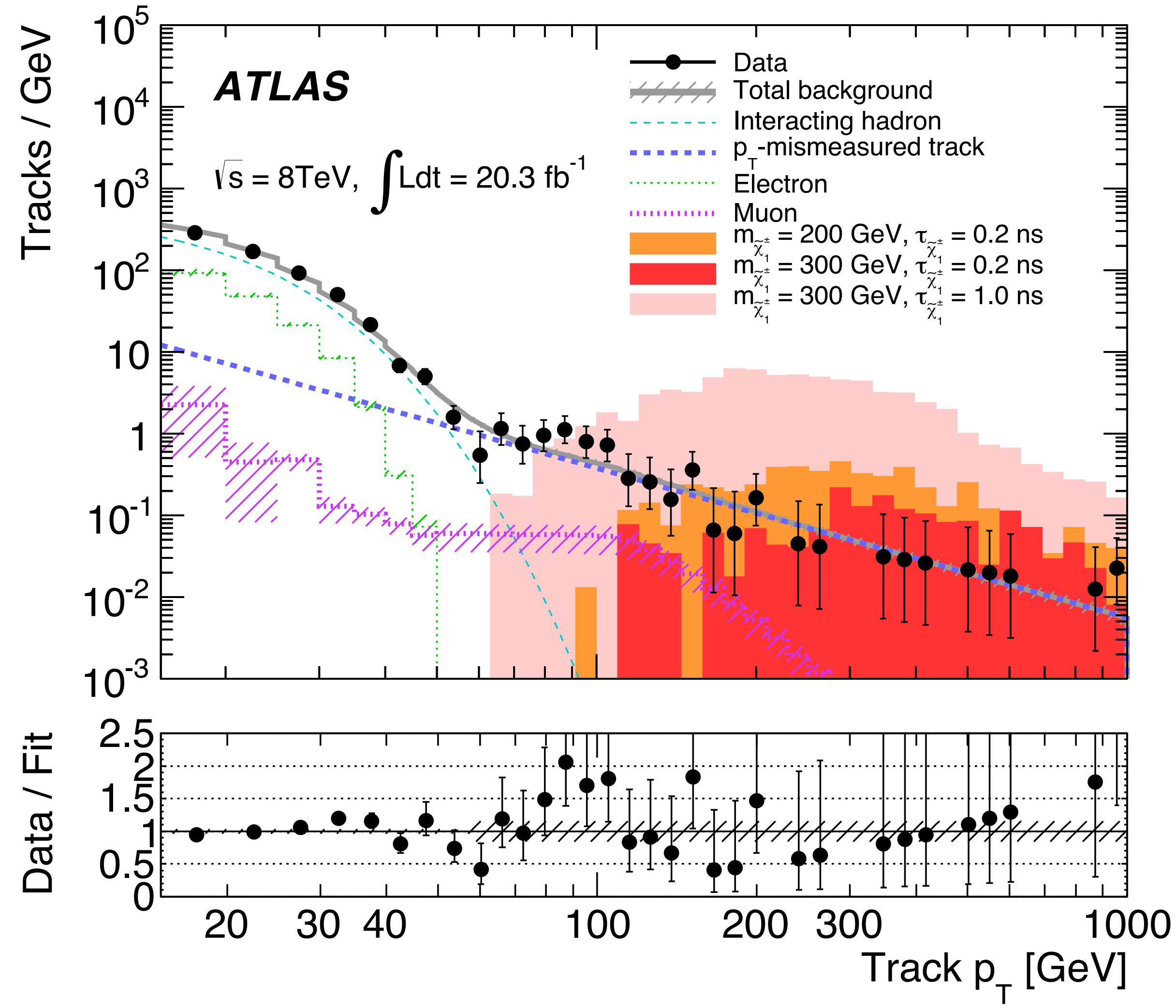
** SM particle leaves (on average) 32 hits in TRT

Don’t forget about backgrounds!

- <u>Background sources:</u>
  - Interacting hadron-tracks
  - Lepton tracks
  - pT-mismeasured tracks

    (dominant if pT >100 GeV)

CMS: cuts on E_{calo} < 10 GeV



- Bgds @ 100 TeV estimated by:

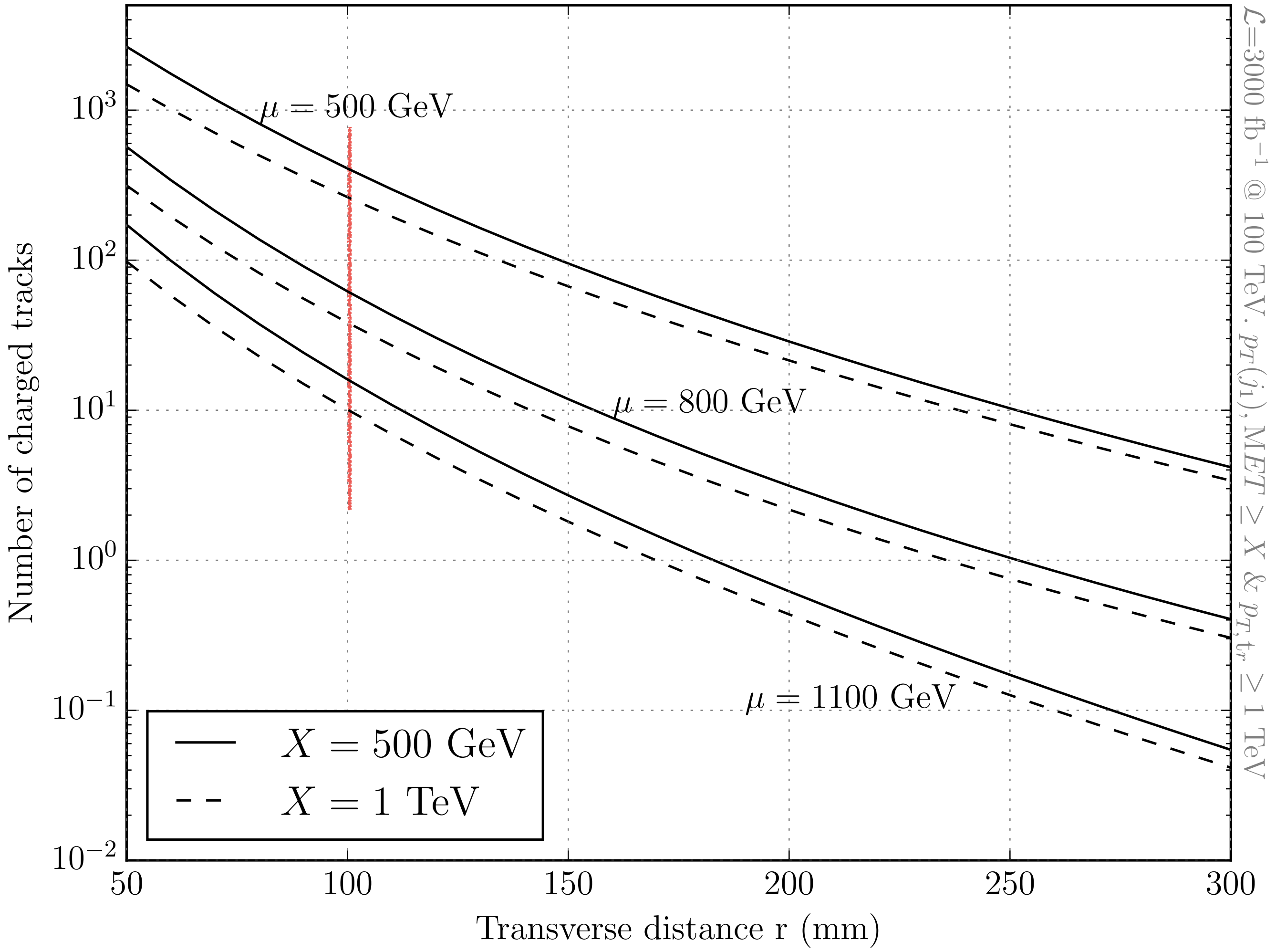
a) Taking distribution shape $(pT)^{-a}$ from LHC data (a = 1.78 ± 0.05).

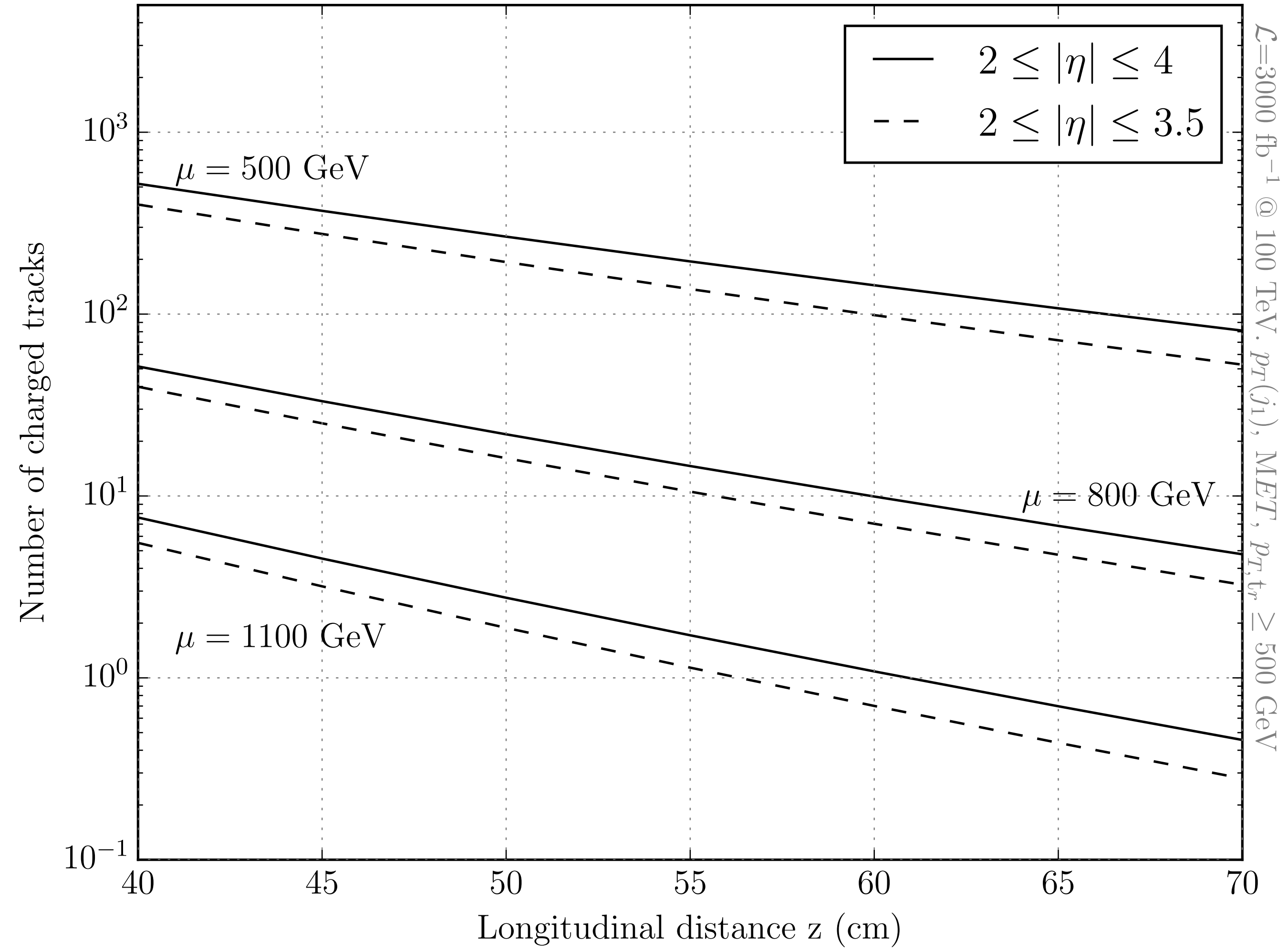
b) Normalize to known process:

1- Z+jets (used in Low, Wang: 1404.0682, Cirelli, Sala, Taoso, 1407.7058).

2- multi-jets (better description of processes with “a high density of silicon hits, hadronic interactions and scattering”).

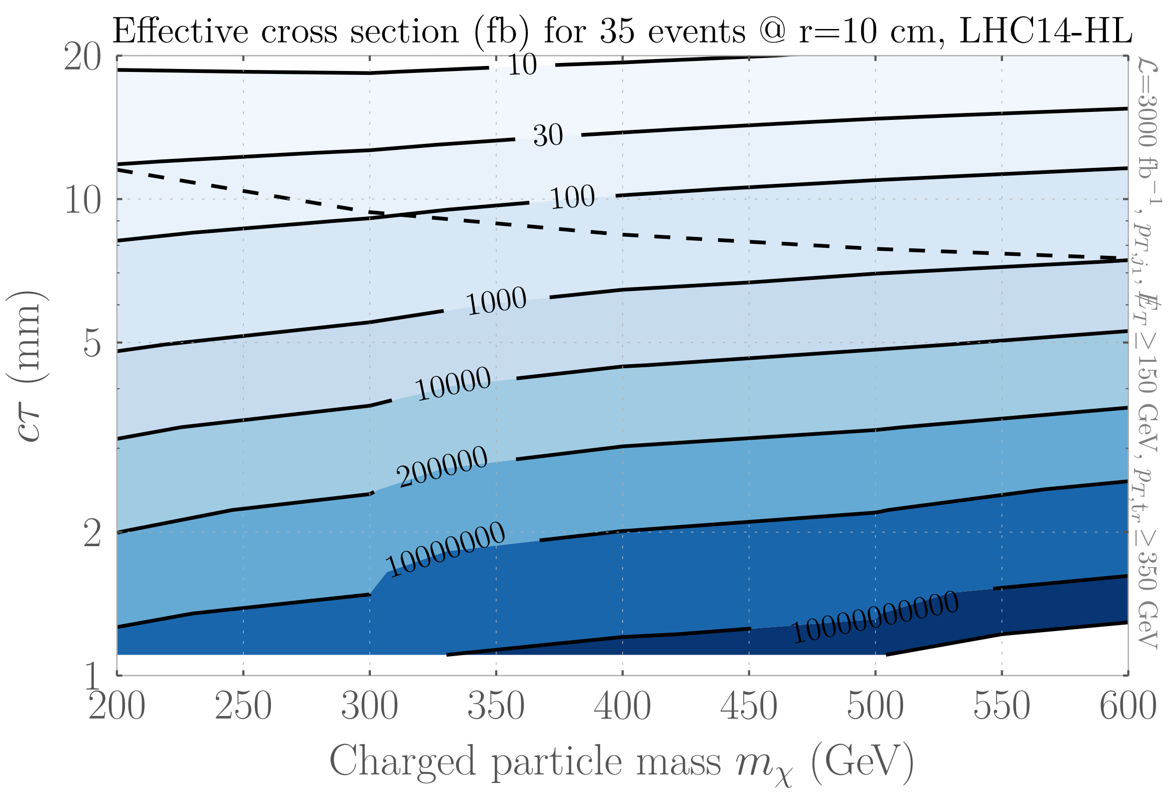
Charged tracks in r-z

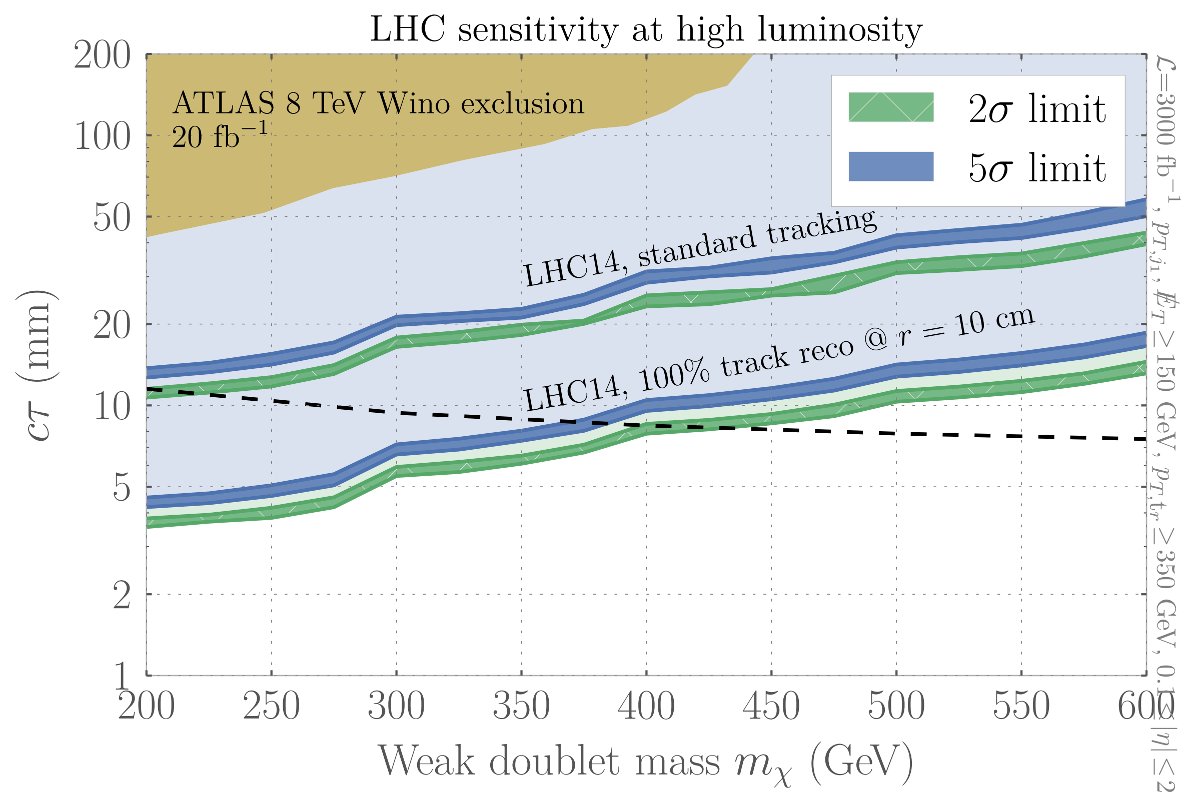




- r=10 cm gives 10 events for 1.1 TeV charginos with 1 TeV pT cut.
- Forward (η) extension from 3.5 to 4 gives a factor 2 enhancement.

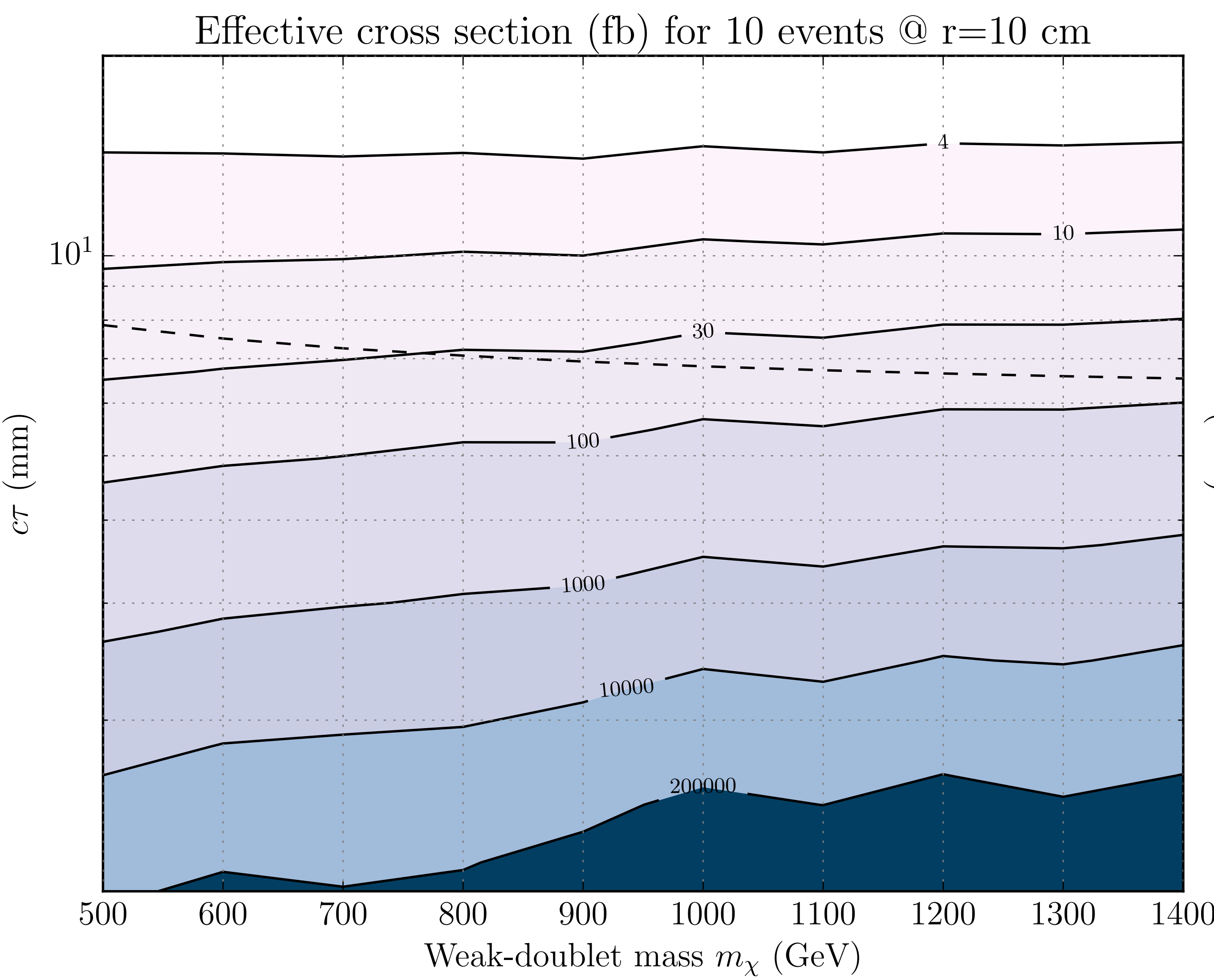
HL-LHC results

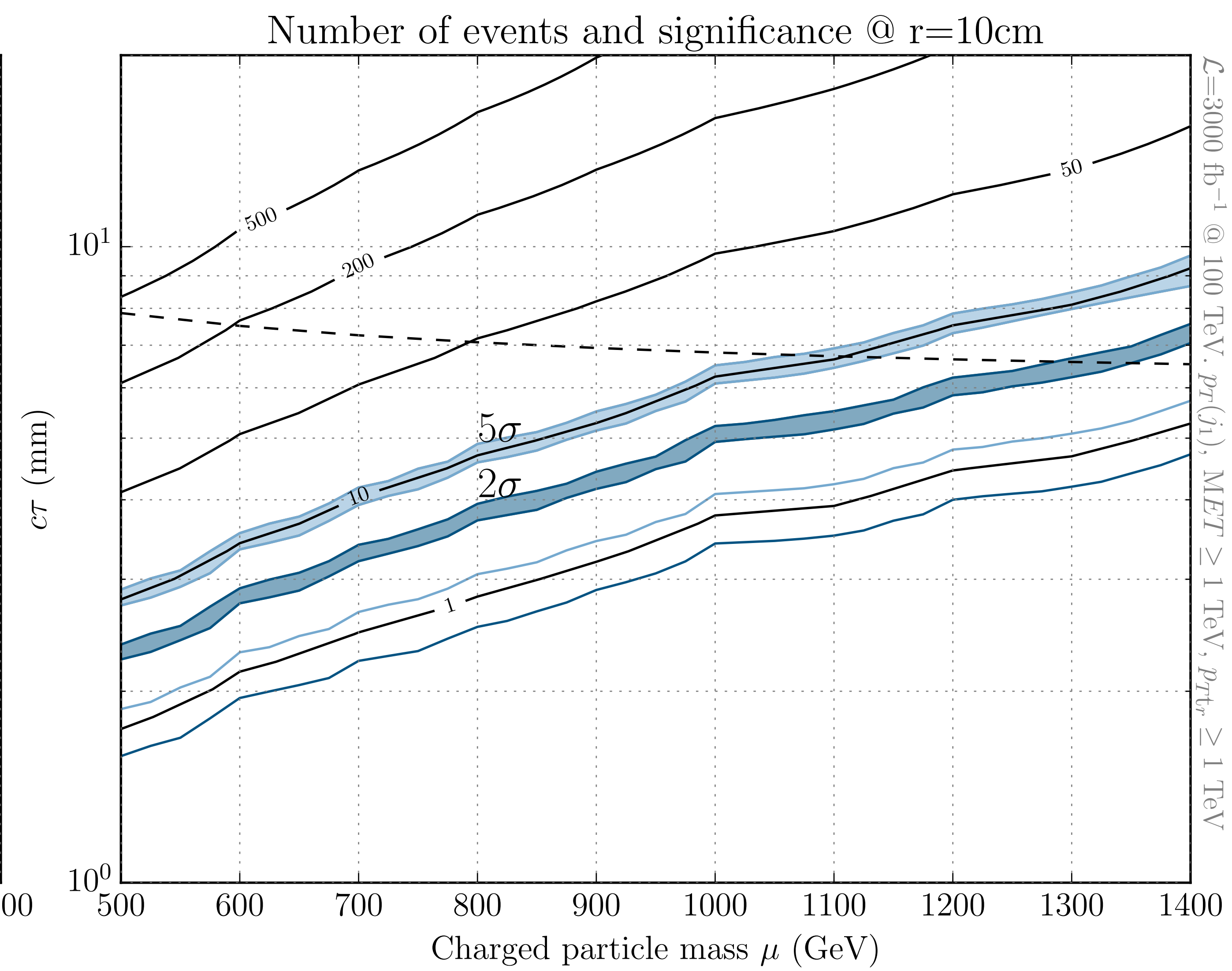




- Discovery (5σ) with 35 events: 50% systematics, bgd extrapolation with Z+jets and multi-jet XS.
- "Effective charged particle XS" = $N_{charged}$ / Lumi allows for straightforward re-interpretation!
- Reducing the track distance from 30 to 10 cm moves the LHC Higgsino reach to 370 GeV. Beats the LHC reach in mono-jet, mono-photon of 200 -250 GeV [see e.g Schwaller, JZ 1312.7350, Barducci, Belyaev, Bharucha, Porod, Sanz, 1504.02472, Ismail, Izaguirre, Shuve, 1605.00658, …].

FCC results (*r*=10cm)





- m_χ < 1070 (1290) GeV for discovery (exclusion) for pure Higgsino, 50% systematics.
- Scaling with di-jets (gg). If using Z+jets (q-qbar), the reach moves to 1.5 (1.6) TeV.

Mono-Z analysis
@100 TeV FCC-hh

R.Mahbubani, JZ, [very soon!]

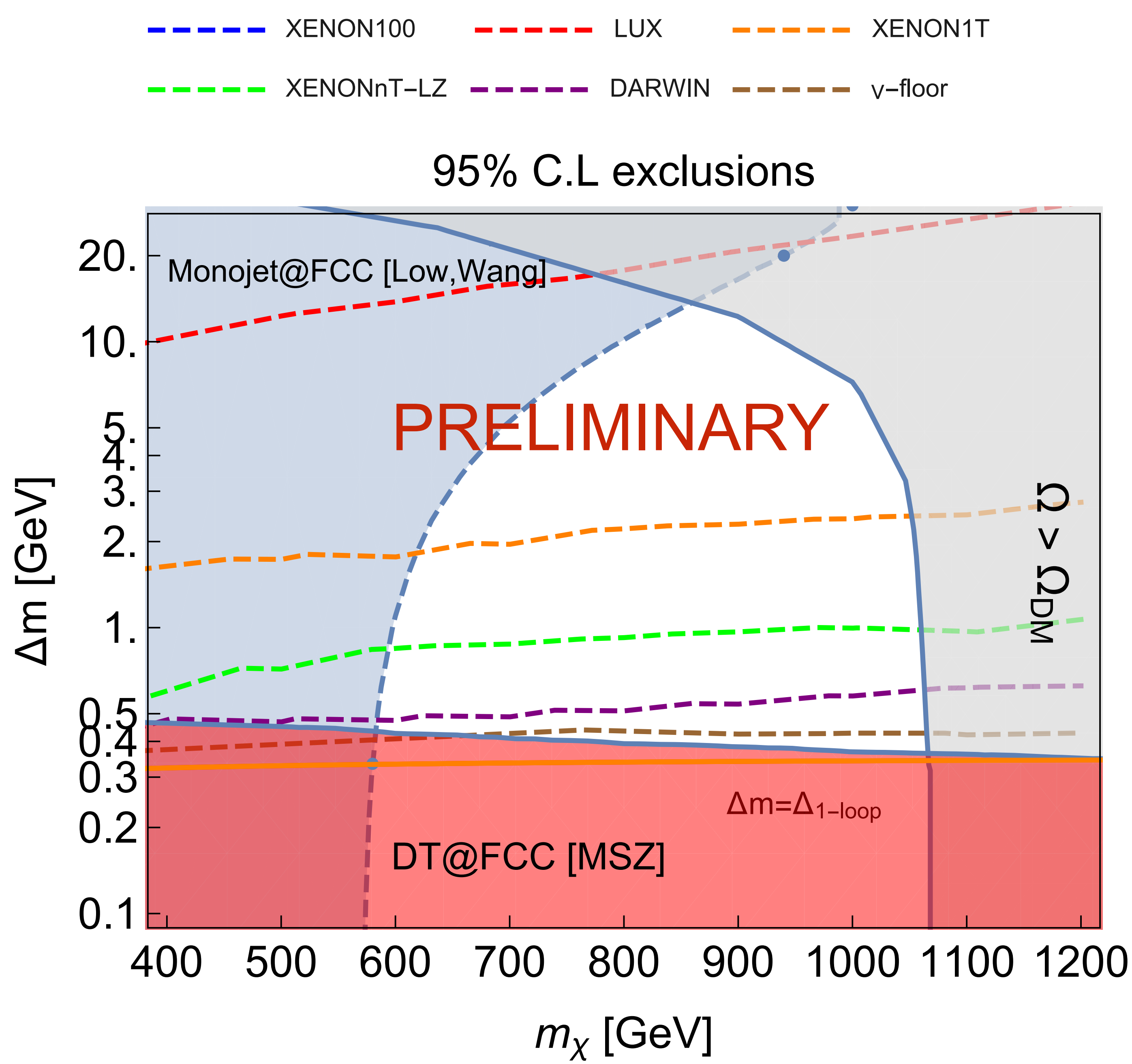
Mono-Z vs mono-jets

At the LHC, the mono-Z search for EWkinos (e.g: Anandakrishnan, Carpenter, Raby, 1407.1833) is much less sensitive than mono-jets, mono-jets plus soft-leptons (Schwaller, JZ, 1312.7350; Low, Wang, 1404.0682; Barducci, Belyaev, Bharucha, Porod, Sanz 1504.02472; Badziak, Delgado, Olechowski, Pokorski, Sakurai 1506.07177…).

Potential advantages for mono-Z at FCC:

- Soft leptons might not be viable (depend on pT thresholds).
- Weak coupling stronger at FCC energies.
- Weak effects in PDFs are important (Rojo, 1605.08302)
- EW Sudakovs can have a large impact (Becher, Garcia i Tormo, 1305.4202 1509.01961).
- Very different systematics (crucial to estimate the sensitivity).

The parameter space



- Xenon 1-T forces splittings below 2-3 GeV.
- FCC monojet bounds: m_χ > 600 GeV for nominal splitting.
- Relic density forces m_χ < 1100 GeV.

Analysis pipeline

- MEs: MG4 and FR+MG5. PS: Pythia 6 (same results with Pythia 8).
  Detector Simulation: Delphes with customised FCC [2015] card (loose ID, larger η)
- Backgrounds:
  - irreducible: $ZZ, WW \longrightarrow l^+ l^- \nu \nu$ + fully leptonic $t\bar{t}$.
  - fake/lost leptons: W+jets, semi leptonic $t\bar{t}$ (matched up to 1 jet).
  - fake $\not{E}_T$: Z ($\rightarrow l^+ l^-$) + jets (similarly ZW,ZZ).
- Parton level cuts: $p_T(l^+, l^-) > 400$ GeV or $H_T, \not{E}_T > 400$ GeV.
- Event selection (basic cuts):
  - Tighter cut on $\not{E}_T > 500$ GeV.
  - Two OS leptons satisfying $p_T(l) > 50$ GeV, $|m(l^+, l^-) - m_Z| < 15$ GeV.
  - Jets: Allow up to one additional hard jet (pT > 50 GeV), veto-b-jets.
  - Ignore any hard jet within $\Delta R < 0.5$ from the leptons.

Optimisation and cut-flow

Optimal: $\Delta\phi(l^+l^-, \not{E}_T) > 0.7,\ \Delta\phi(j_1, \not{E}_T) > 0.1 + \not{E}_T > 900(+X)$ GeV.

X value chosen for the 0% systematics case

process	$\delta M \leq 15$	$N_j \leq 1$	$\Delta\phi(j, \not{E}_T) > 0.1$	$\Delta\phi(Z, \not{E}_T) > 0.7$	$\not{X}_T > 0.9$	$\not{X}_T > 1.5$
signal J	241.2	190.7	188.4	188.2	112.52	47.88
$ZZ \to l^+l^-\nu\nu$	6059.2	5346.1	5291.9	5291.9	831.6	118.3
$W^+W^- \to l^+\nu l^-\nu$	0.0134	0.0089	0.0089	0.0089	0.	0.
$tt \to l^+b\nu l^-\bar{b}\nu$	123.4	67.3	62.5	62.15	1.9	0.
$tt \to l\nu b\bar{b}jj$	255.9	95.27	94.97	8.21	1.76	0.0433
$(Z \to l^+l^-)$ +jets	29342	9402.6	1370.7	1084.4	84.42	3.15
$(W \to l\nu)$+jets	336.4	115.9	115.5	10.2	0.366	0.
$ZW \to l^+l^-l\nu$	399.8	336.7	325.4	325.4	31.66	2.73
$ZZ \to l^+l^-jj$	68.50	35.86	3.36	2.47	0.0436	0.
$ZW \to l^+l^-jj$	58.12	29.09	2.92	2.2	0.	0.
100 S/B	0.658	1.23	2.59	2.77	11.8	38.5
Significance ($\beta = 0$)	1.26	1.54	2.21	2.28	3.65	4.30
Significance ($\beta = 0.1$)	0.07	0.12	0.26	0.28	1.12	2.87

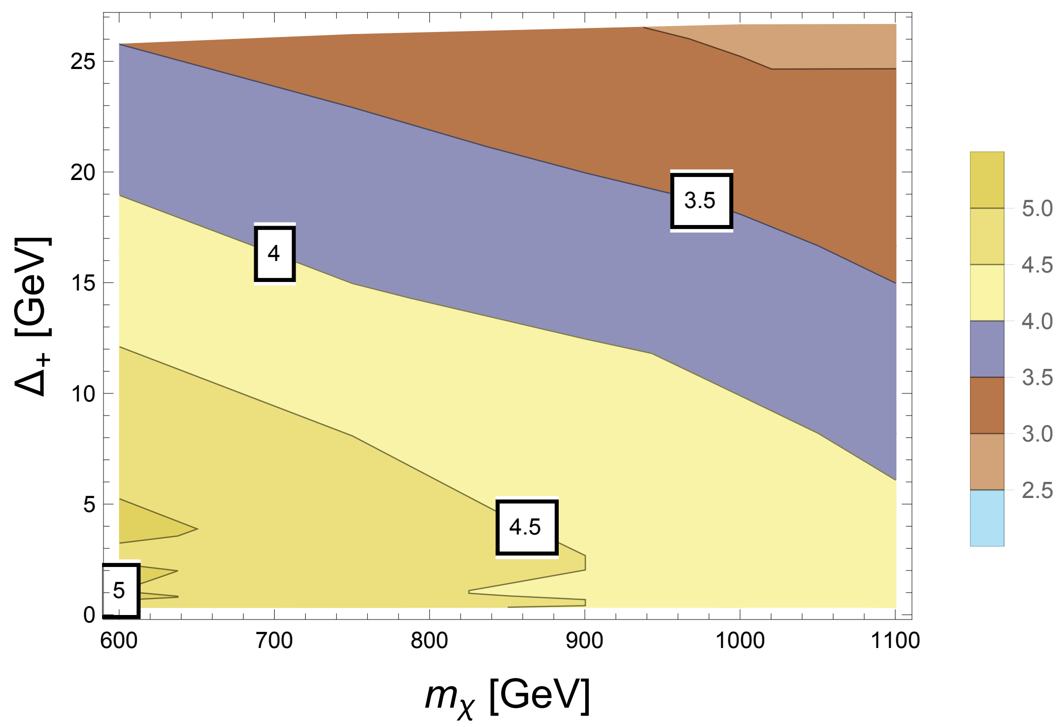
Table 1: Cut flow for the backgrounds and for a signal with $\mu = 1100$ GeV, $\tan\beta = 15$ and $M_1 =$ TeV. The numbers of events quoted correspond to a total integrated luminosity of 3000 fb^{-1} at a 100 TeV center-of-mass energy. We have defined $\delta M = |\frac{M_{ll} - m_Z}{\text{GeV}}|$ and $\not{X}_T = \frac{\not{E}_T}{\text{TeV}}$. The significance is computed assuming a) no systematic errors and b) 10 % systematic errors.

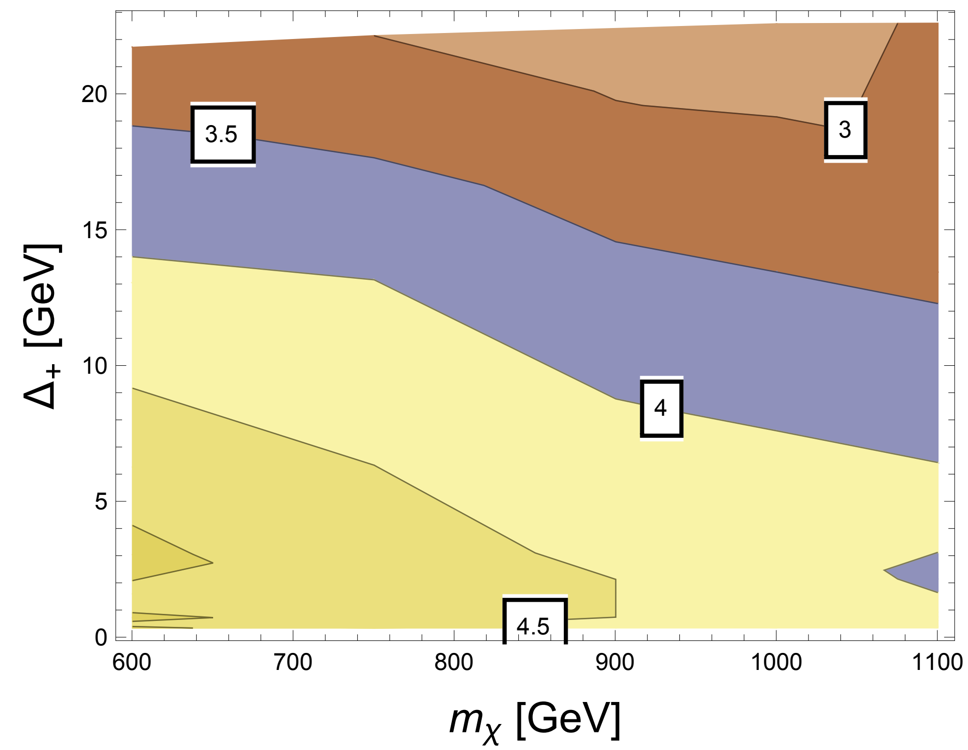
FCC reach

Lumi=3ab^{-1}

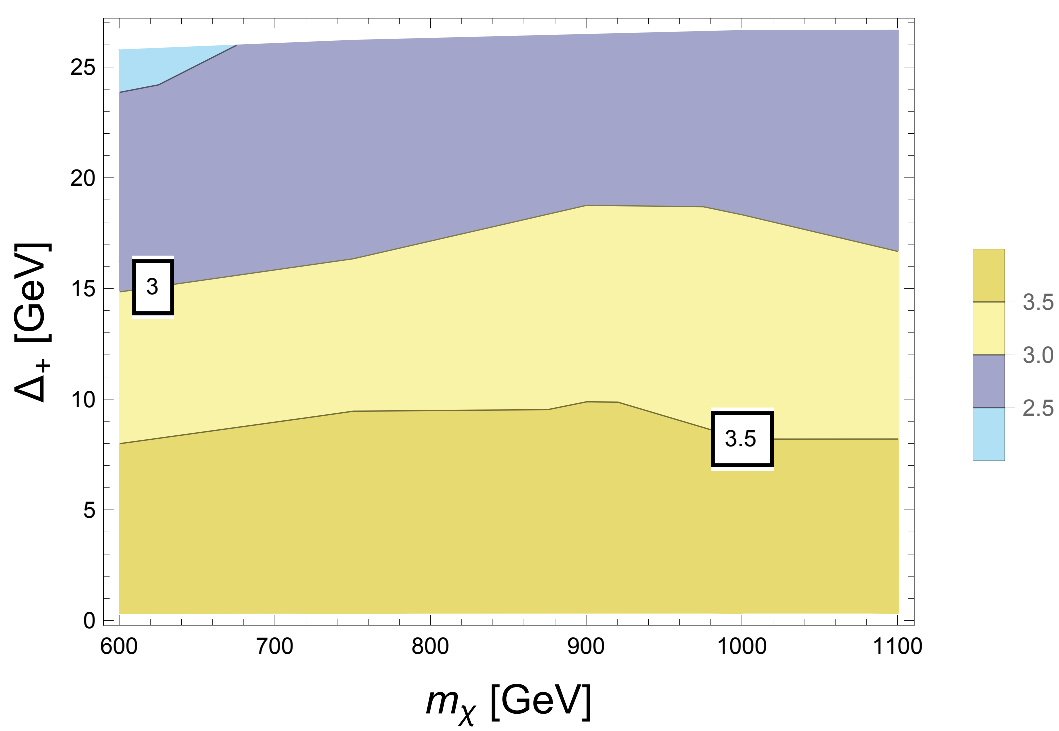
μ > 0 | μ < 0

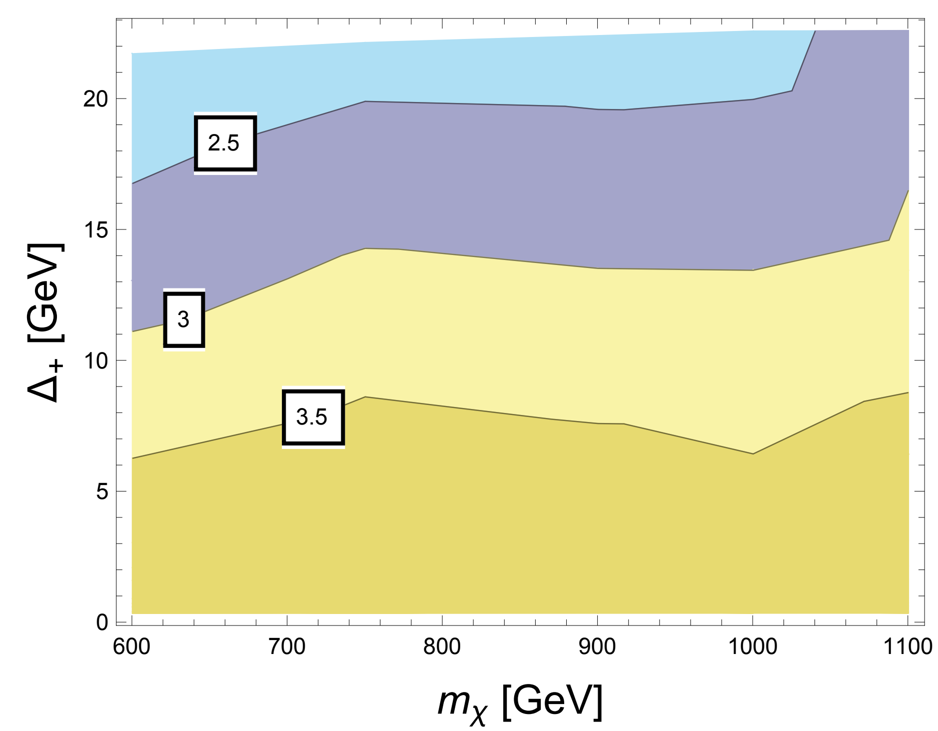
syst=0%





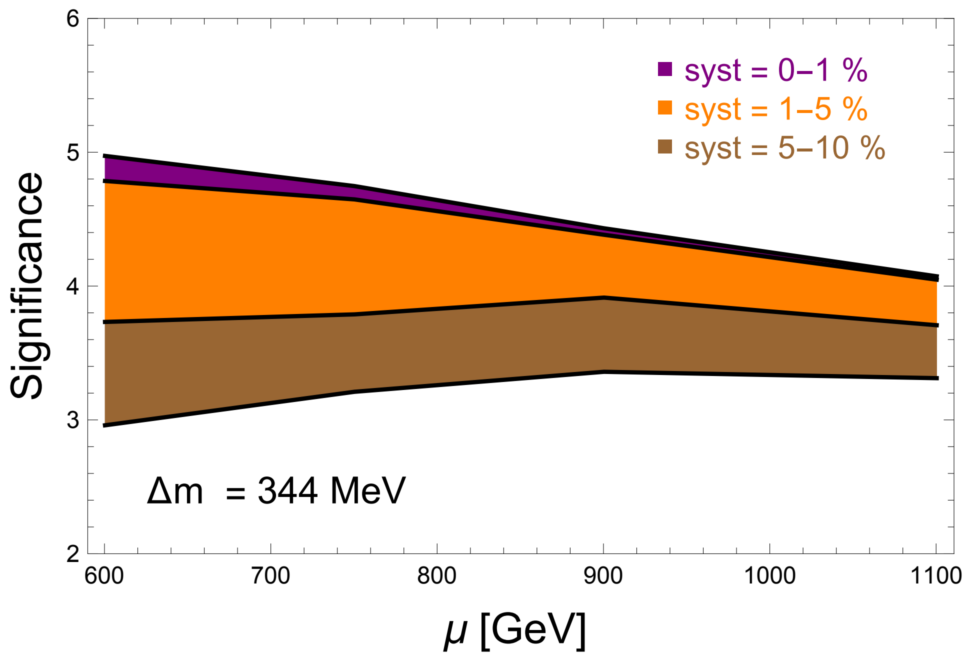
syst=5%

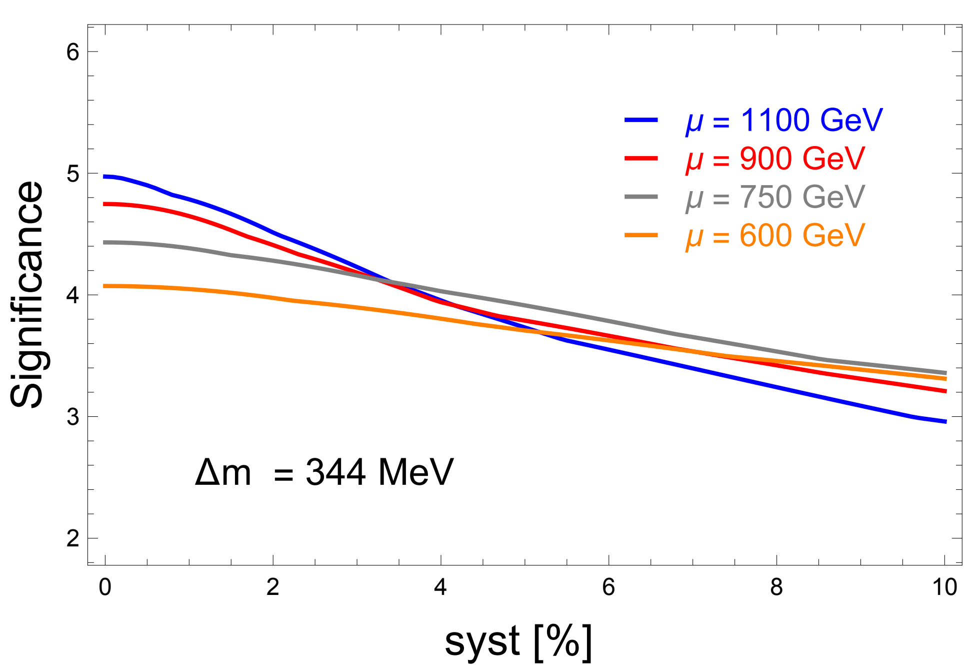




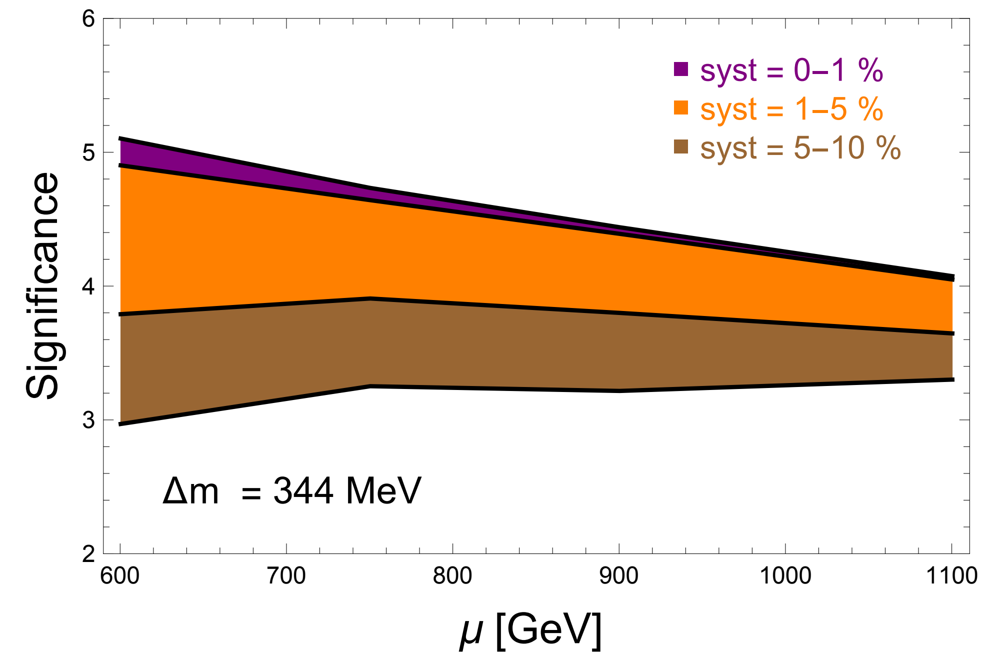
Role of systematics

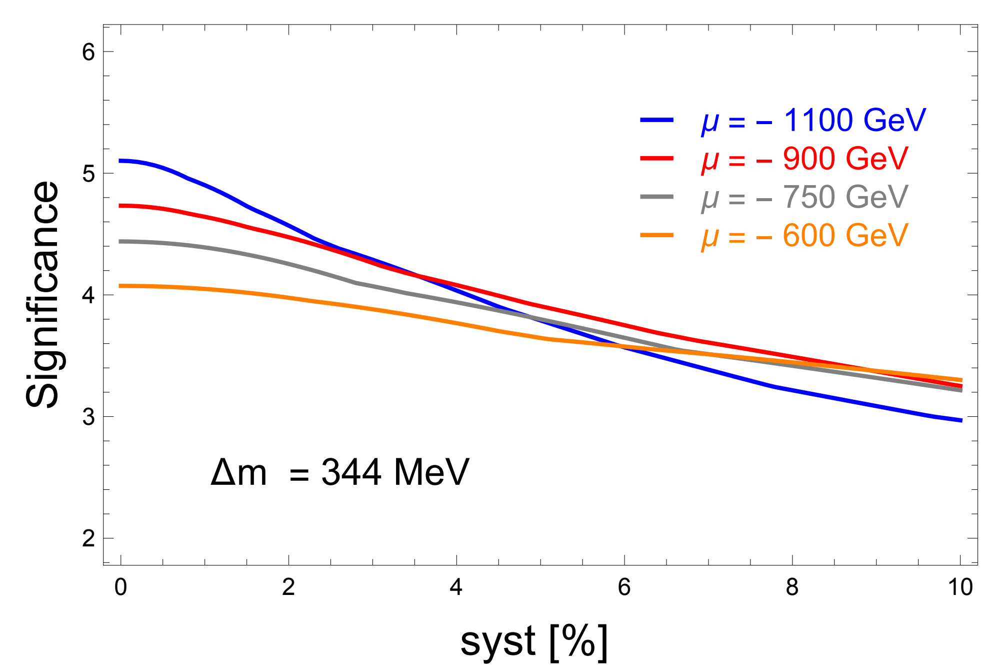
$\mu > 0$



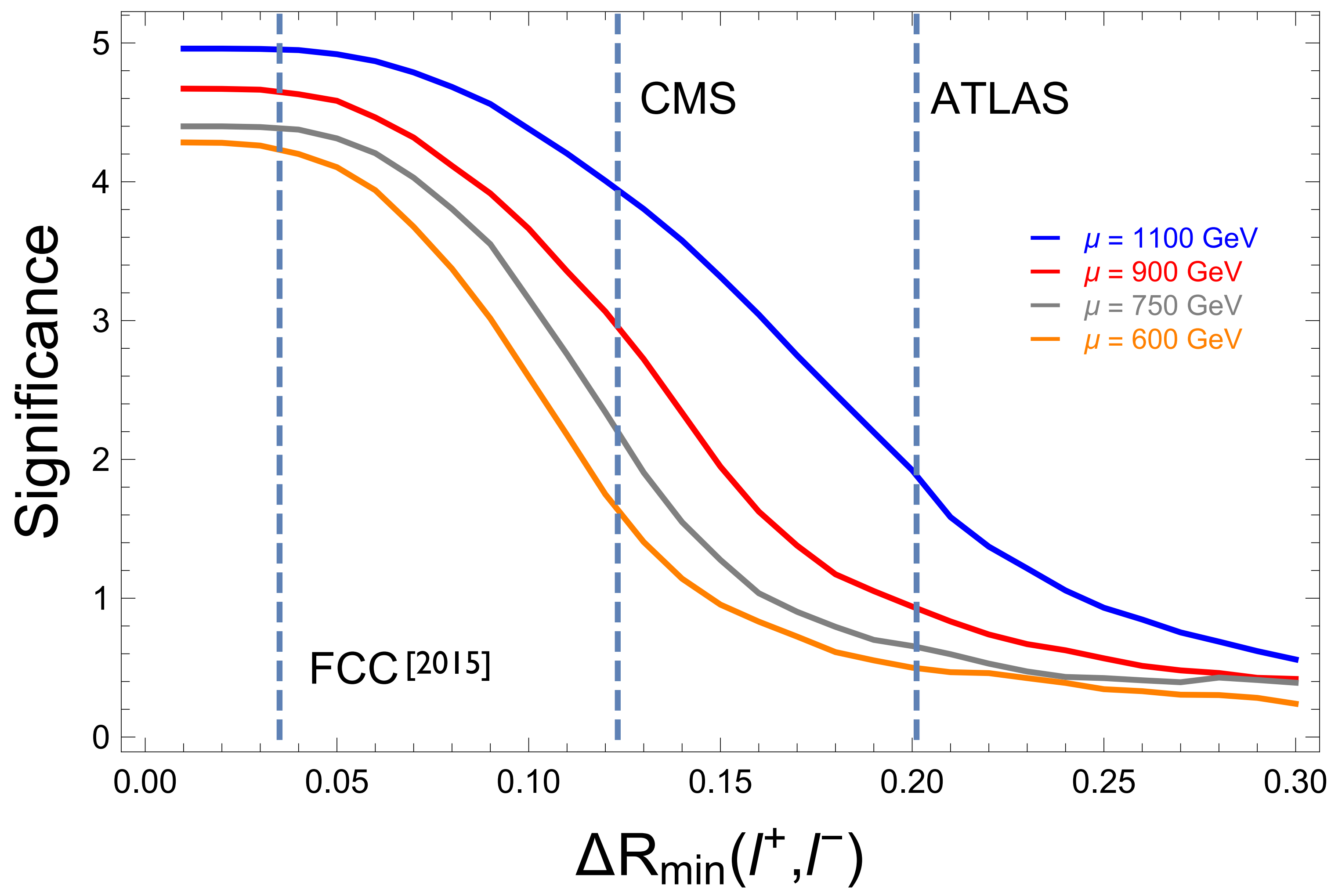


$\mu < 0$





Di-lepton resolution



DELPHES FCC card used has 0.035 resolution in ΔR (η=0.025,φ=π/128).

For CMS, ΔR=0.123 (η=0.087,φ=π/36), ATLAS ΔR=0.201 (η=0.1,φ=π/18).

Conclusions

- Compressed spectra is "natural": O(GeV) splittings among components of the same EW-multiplet. Favored by (lack of signal in) direct detection experiments.

- Discussed two strategies @ FCC: (a) disappearing tracks and (b) mono-Z.

  - (a) 100 TeV detectors yet to be designed: historical chance to write the TDR. Hard to estimate the significance, yet O(10) signal events in "almost background-free" environment for 1.1 TeV Higgsinos.

  - (b) With 3000 fb^{-1}, 5% (0%) systematics one achieves 3.7 (4.3) σ for 1.1 TeV, and "full" coverage of parameter space at the 3 (4) σ level.

- Worth taking time to think what the FCC/next collider (not LHC-100!!!) can do for your favourite physics scenario. What would <u>you</u> need???

"***There presently is no physics case for a 100-TeV hadron collider***"
R. Brinkmann, M. Wing, DESY, 2016

1. thermal dark matter!!!
2. …
3. …