Disappearing tracks/Mono-Z @ FCC-hh

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Disappearing tracks: R.Mahbubani, P. Schwaller, JZ, [arXiv 1701.vwxyz]

MonoZ: R.Mahbubani, JZ, [arXiv 1702.abcde]

1st FCC Physics Workshop, CERN, 20.01.2017

Outline

- Motivation for TeV Higgsinos (VLF, weak doublet)
- Phenomenology of Bino/Higgsino (doublet/singlet)
- Disappearing tracks @ FCC-hh
- Mono-Z @ FCC-hh
- Conclusions

Choose your side!

- A: If you are a SUSY hardcore fan:
  - The only "uncoverable" spot for MSSM dark matter is "almost pure" Higgsino[*].
  - Relic density: $\mu \leq 1.1$ TeV. Mono-jet covers up to 0.9 TeV, Low, Wang: 1404.0682.
  - Disappearing tracks probe O(10 cm) decay lengths, Cirelli, Sala, Taoso, 1407.7058.
- B: If you loathe SUSY / strongly preference for simplified models / etc…
  - A weak doublet, VL-fermion is a simple BSM model.
  - The "Lifetime Frontier" (D. Curtin, Wed.) also includes O(mm) charged particles.
  - Mono-Z is an overlooked (but well motivated!) signature at the FCC.

Today's menu:

→ Disappearing tracks (customised detector).

→ Mono-Z

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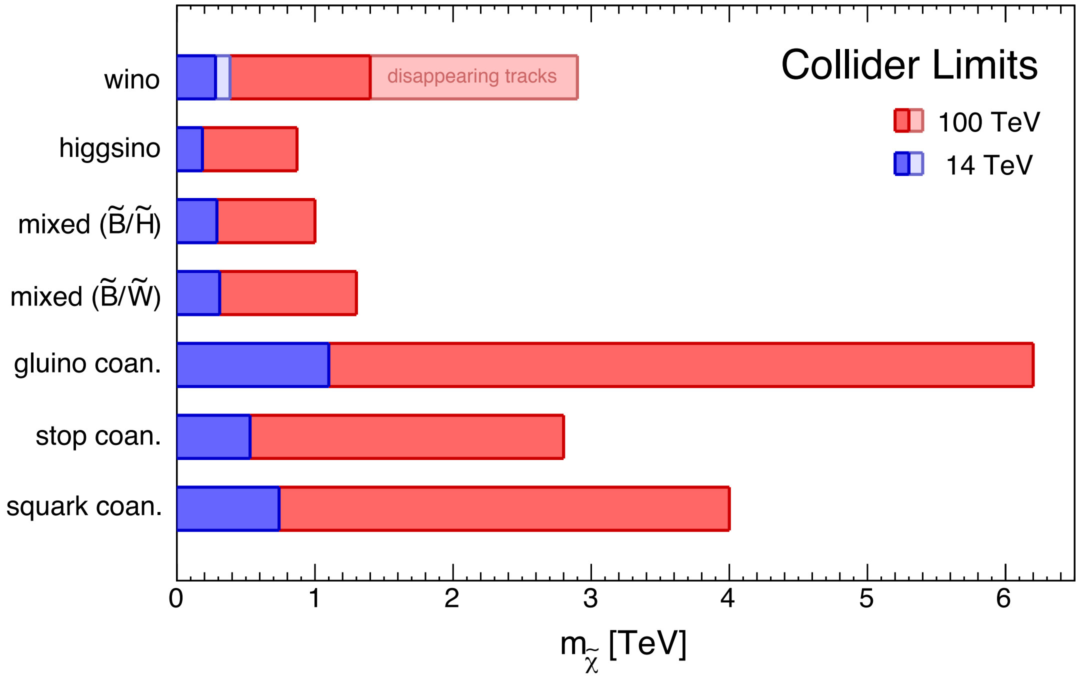
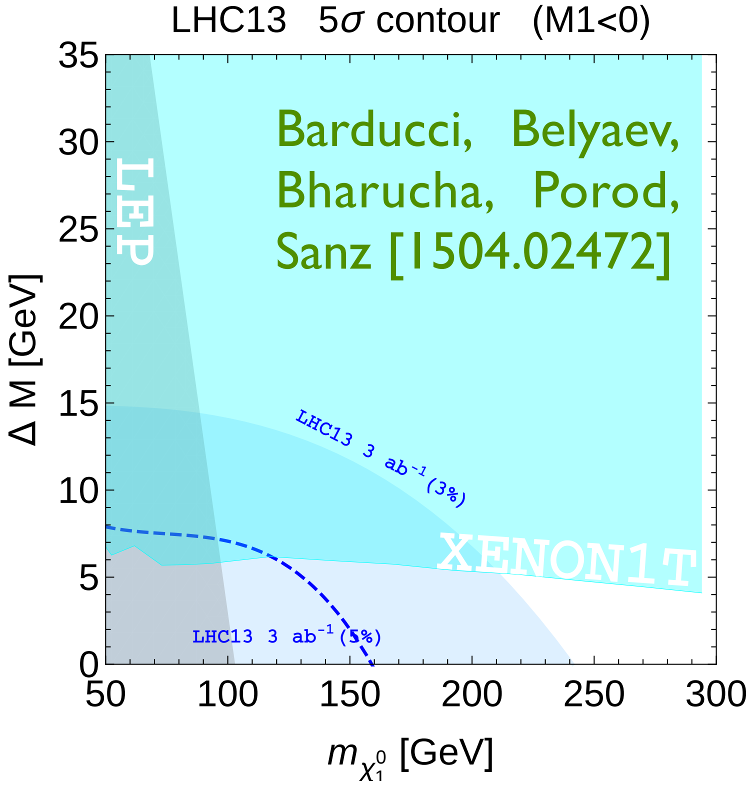
[*] A pure Higgsino, EW doublet, is ruled out, because both neutral states are mass degenerate, and the Z-n1-n2 coupling is actually Z-n1-n1. Z currents with weak couplings are excluded by direct detection experiments (XENON100, LUX, etc). Some additional Bino and/or Wino component is required.

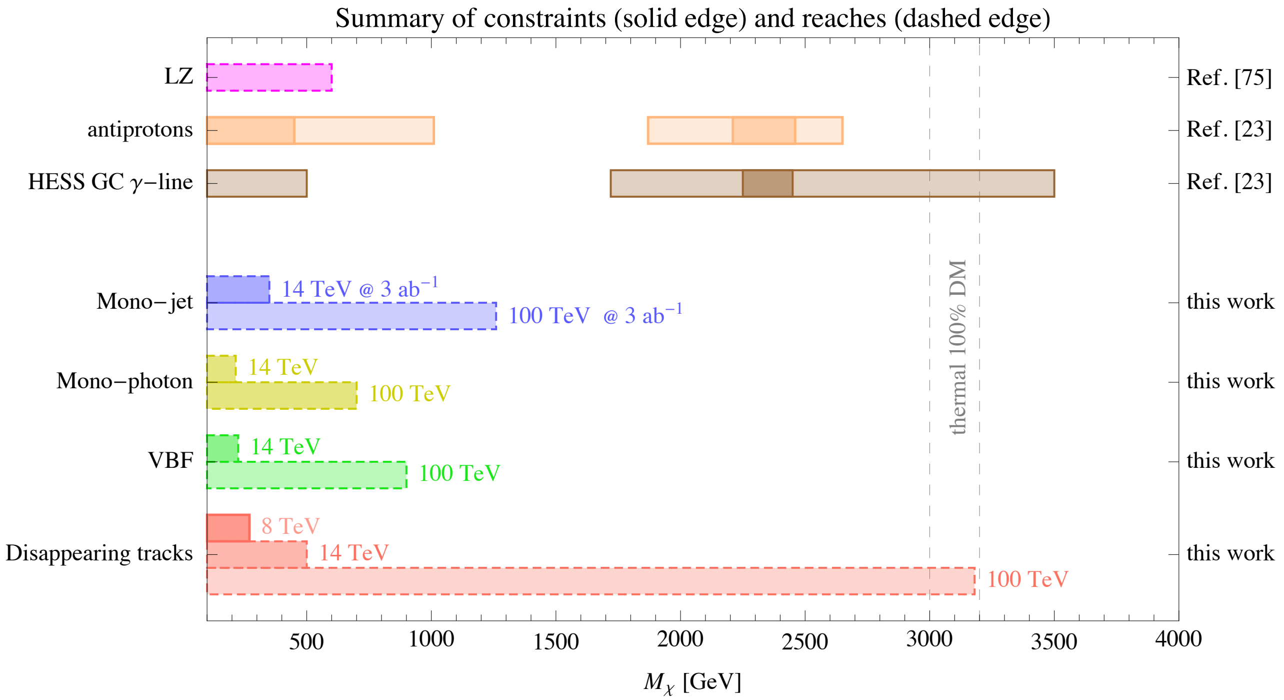
Some recent analyses



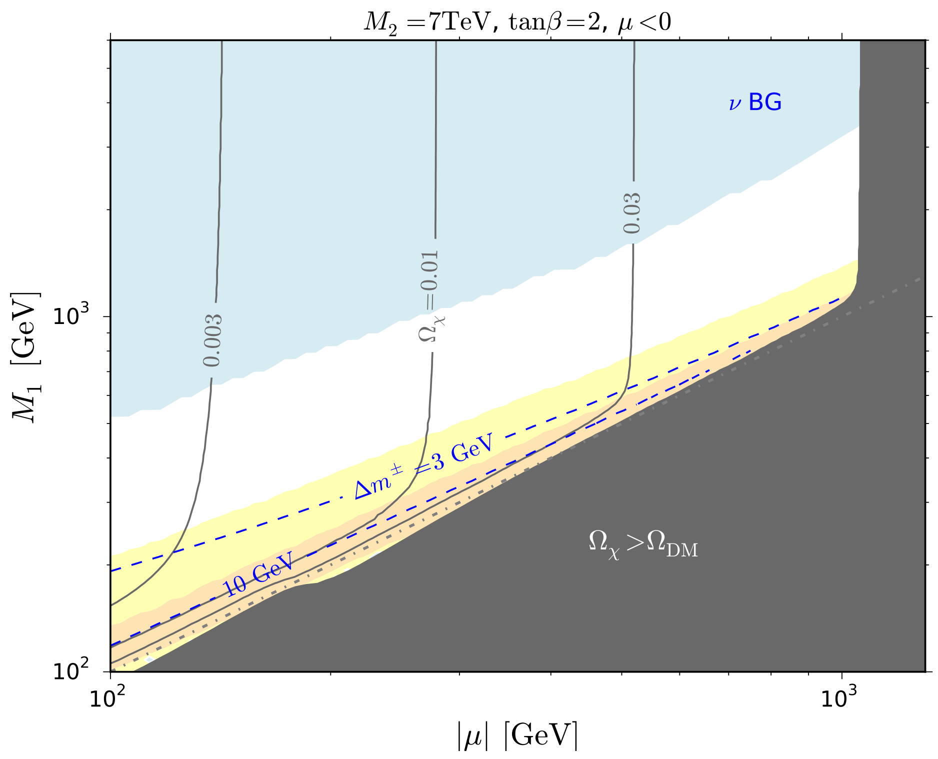
M. Low, L.T.Wang [1404.0682]



Barducci, Belyaev, Bharucha, Porod, Sanz [1504.02472]



Cirelli, Sala, Taoso [1407.7058]



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

See Bryan Ostdiek's talk for latest news!

Higgsino/Bino

(doublet/singlet)

phenomenology

Electroweakino Sector

gauge eigenstates | mass eigenstates

$$\mathcal{M}_\chi^\pm = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta M_W \\ \sqrt{2}\cos\beta M_W & \mu \end{pmatrix} \qquad \tilde{W}^+, \tilde{H_u}^+ \sim \chi_1^+, \chi_2^+$$

→ Charged winos and Higgsinos mix into *charginos* (2).

gauge eigenstates | mass eigenstates

$$\mathcal{M}_\chi^0 = \begin{pmatrix} M_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\ 0 & M_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\ -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\ s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0 \end{pmatrix} \qquad \tilde{H_u}^0, \tilde{H_d}^0, \tilde{B}^0, \tilde{W_3}^0 \sim \chi_1^0, ..., \chi_4^0$$

→ Neutral Wino, neutral Higgsinos and bino mix into *neutralinos* (4).

Too much hassle! Simplify by:

1) decoupling the Wino ($M_2 \to \infty$) → 1 neutral and 1 charged state removed

2) taking a Higgsino/Bino hierarchy ($|\mu| << M_1$) → 1 neutral state removed

Important!

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. →

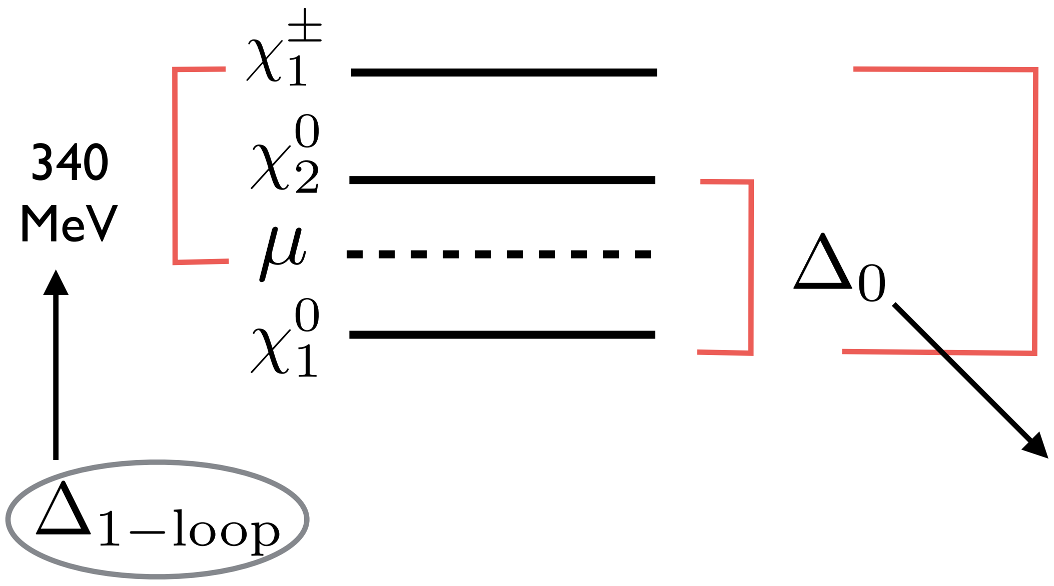
Thomas, Wells, hep-ph/9804359,
Cirelli, Formengo, Strumia, hep-ph/051209

$$\begin{tikzcd} & \tilde{H} \quad 340\ \text{MeV} \\ \Delta_{1-\text{loop}} \arrow[ur] \arrow[dr] & \\ & \tilde{W} \quad 170\ \text{MeV} \end{tikzcd}$$

Simplified Bino/Higgsino (S/D)

$$M = \begin{pmatrix} M_1 & -mc_\beta & ms_\beta \\ -mc_\beta & 0 & \mp\mu \\ ms_\beta & \mp\mu & 0 \end{pmatrix} \qquad m = m_Z s_W \approx 43.8 \text{ GeV}$$

Expanding in μ/M_1



$$\Delta_+ = \Delta_{1-\text{loop}} + \frac{96 \text{ MeV}(1 \mp \text{s}_{2\beta})}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

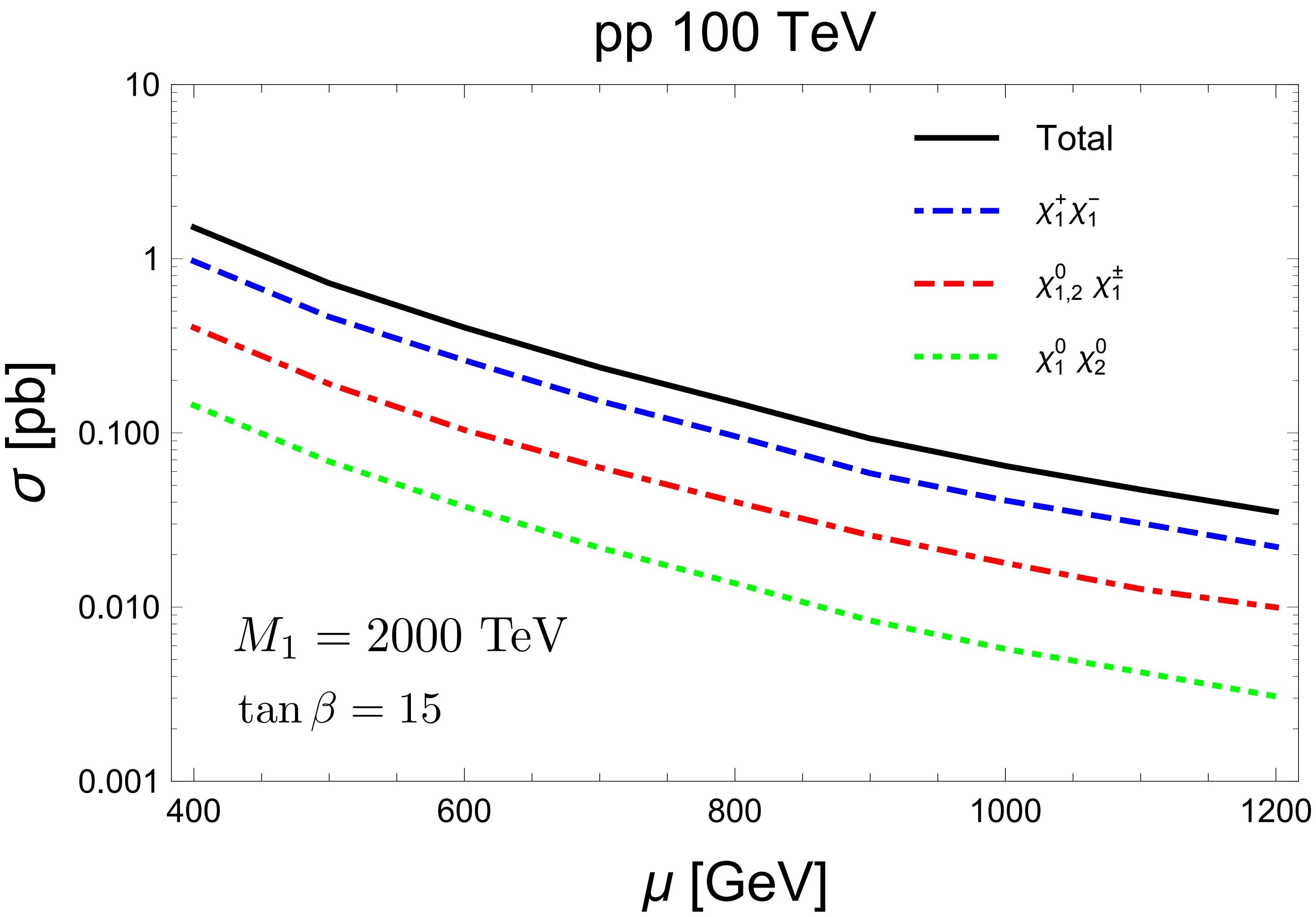
$$\Delta_0 = \frac{192 \text{ MeV}}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

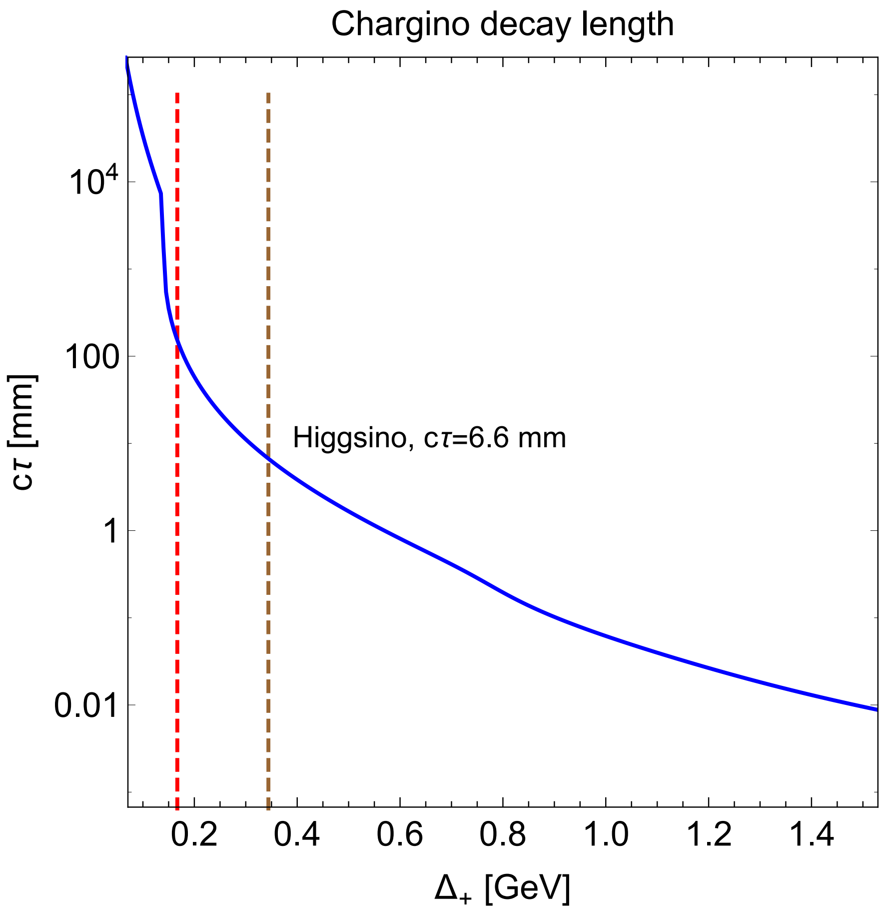
Limiting cases:

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

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

Cross sections and decay lengths





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

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.

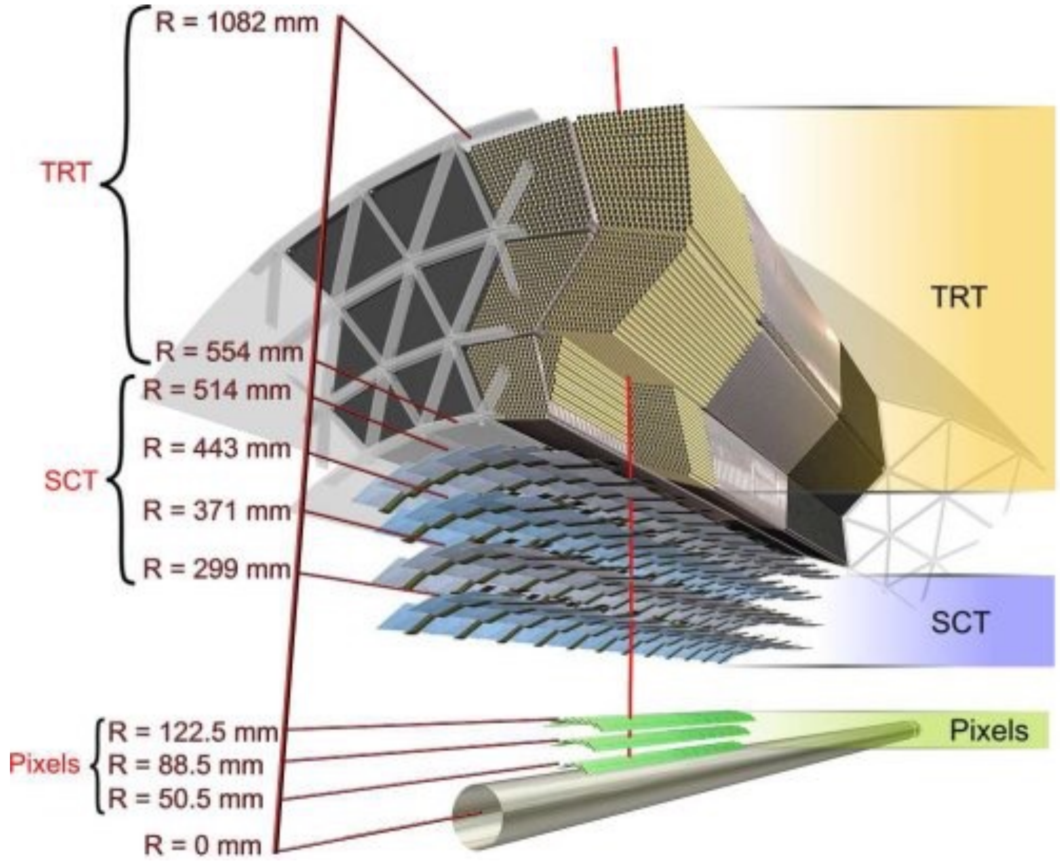
Disappearing tracks

@ FCC-hh

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).
  - ΔΦ(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)

$$d_{min} \approx 30 \text{ cm}$$

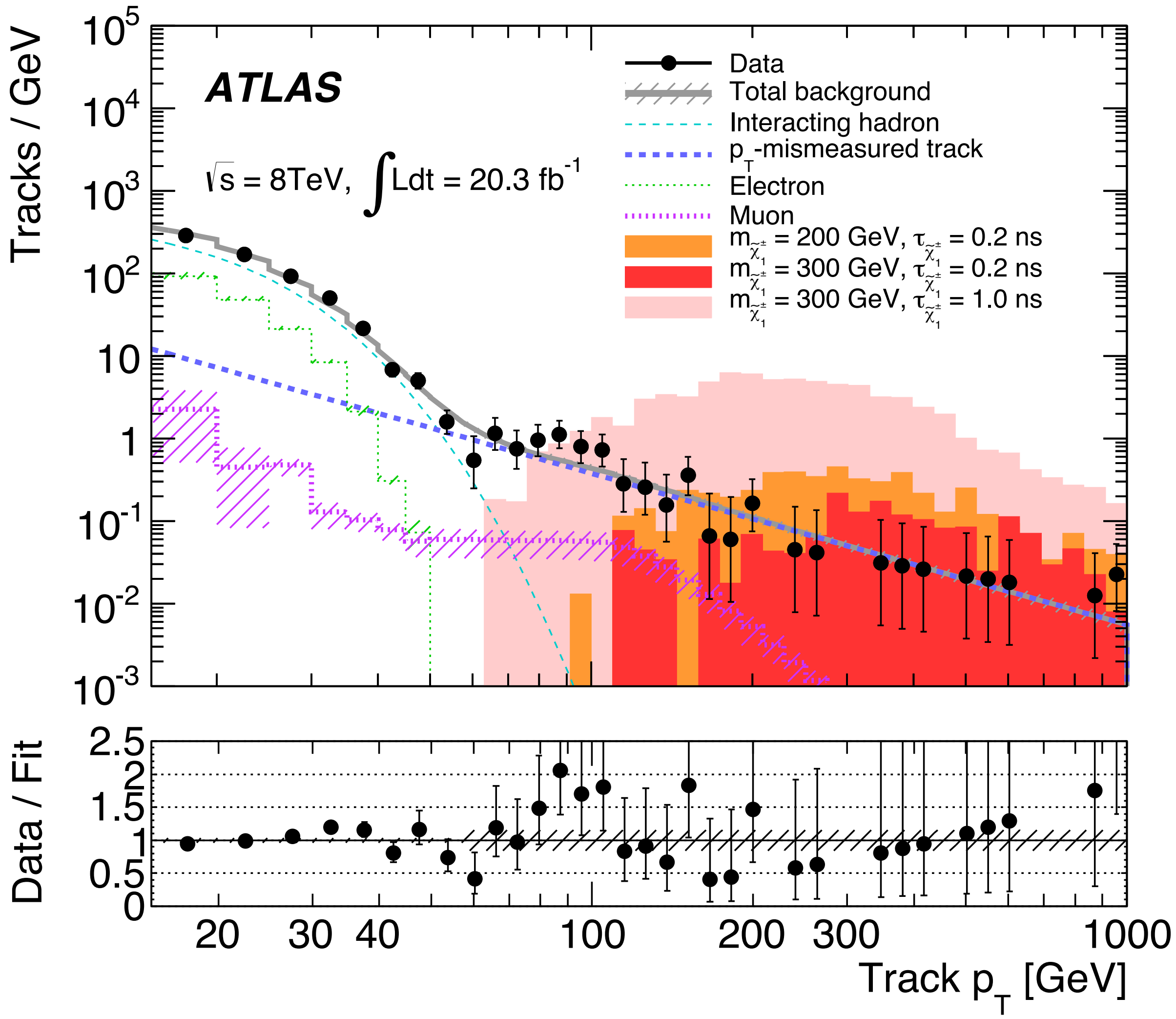
** SM particle leaves (on average) 32 hits in TRT

Don’t forget about backgrounds!

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

    (dominant if pT >100 GeV)

CMS: cuts on E_{calo} < 10 GeV



- Bgds @ 100 TeV (very crudely!!!) estimated by:

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

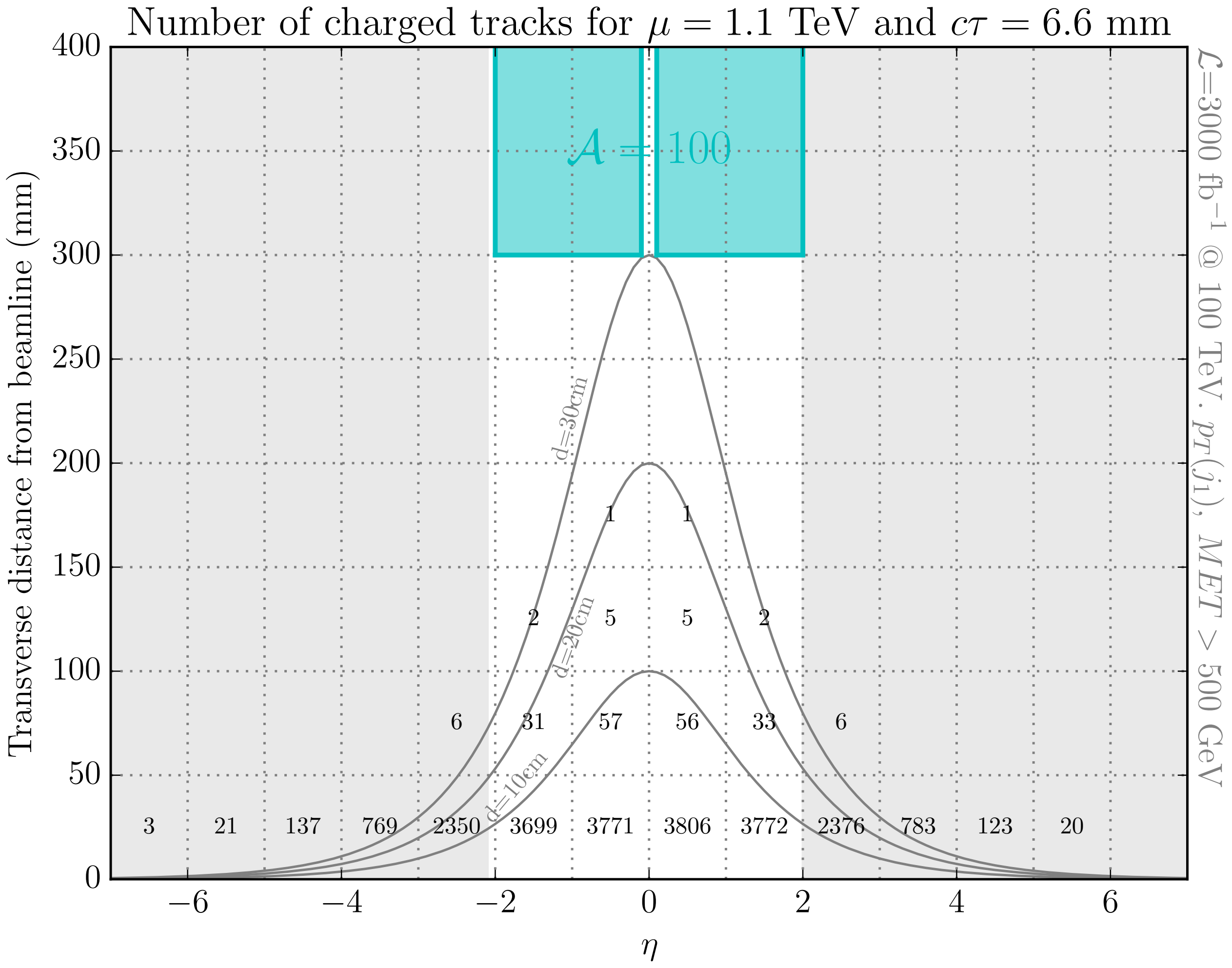
b) Normalize to known process:

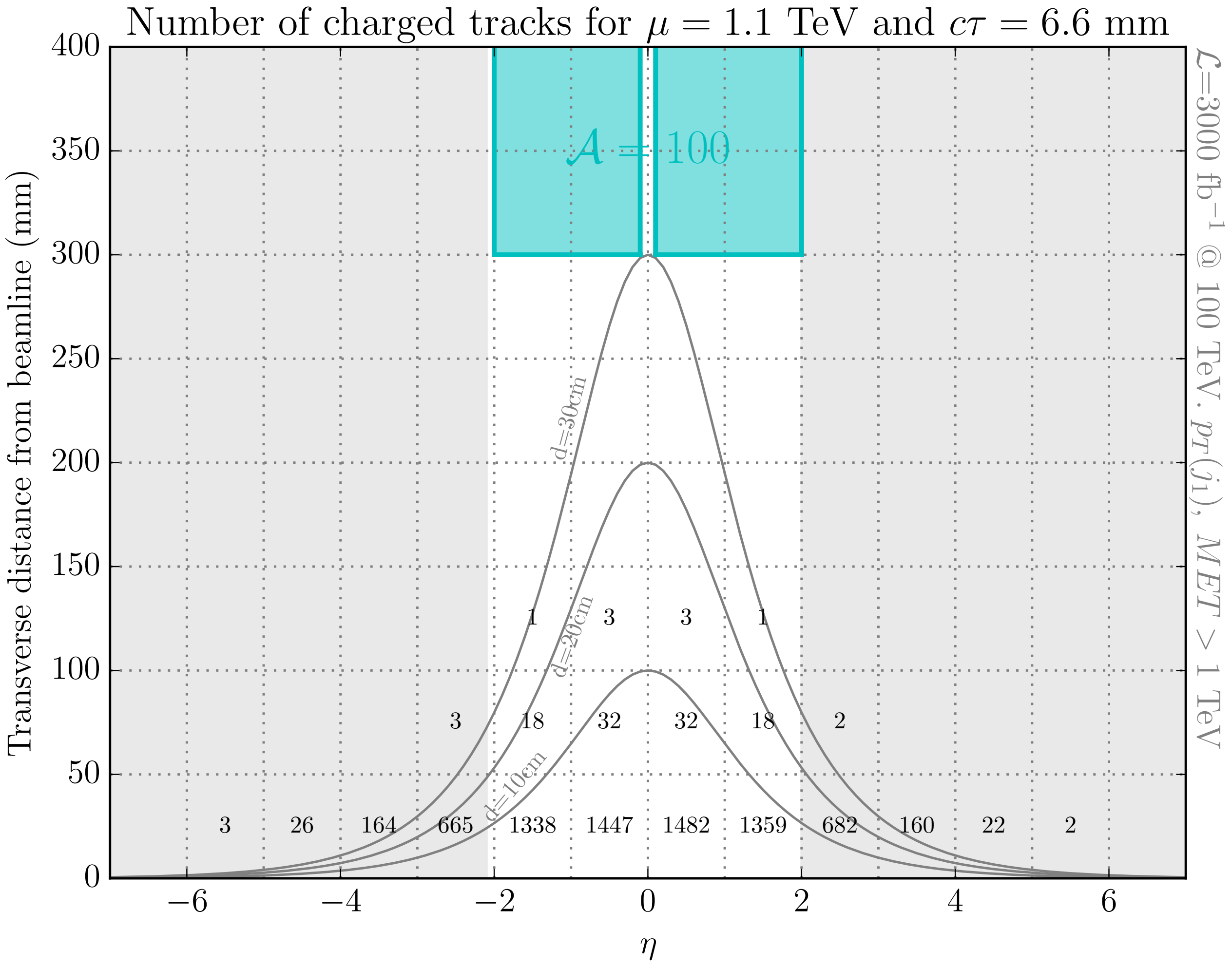
1- Z+jets (used in the literature).

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

Can it be improved?

Charged tracks in r-η

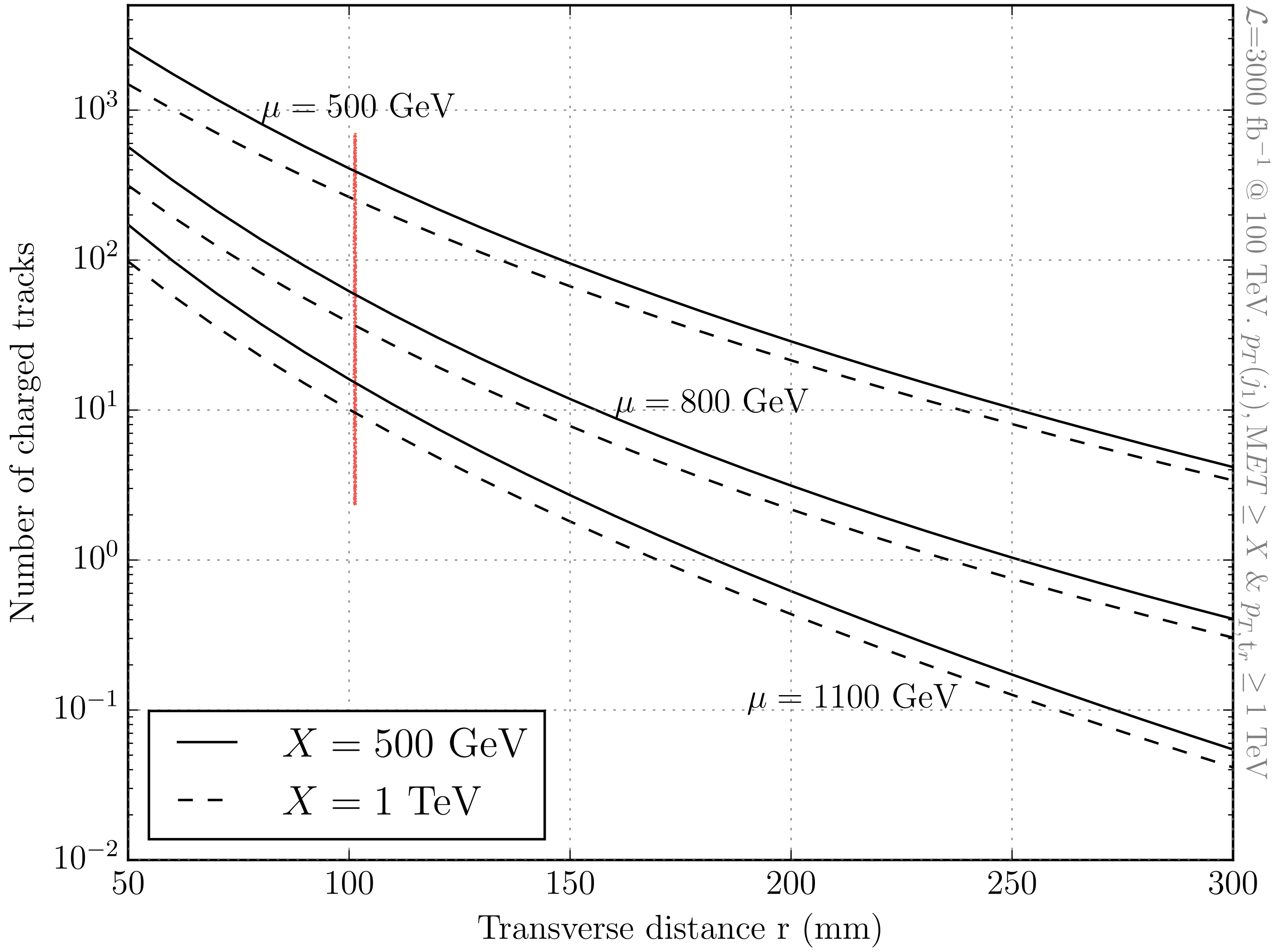


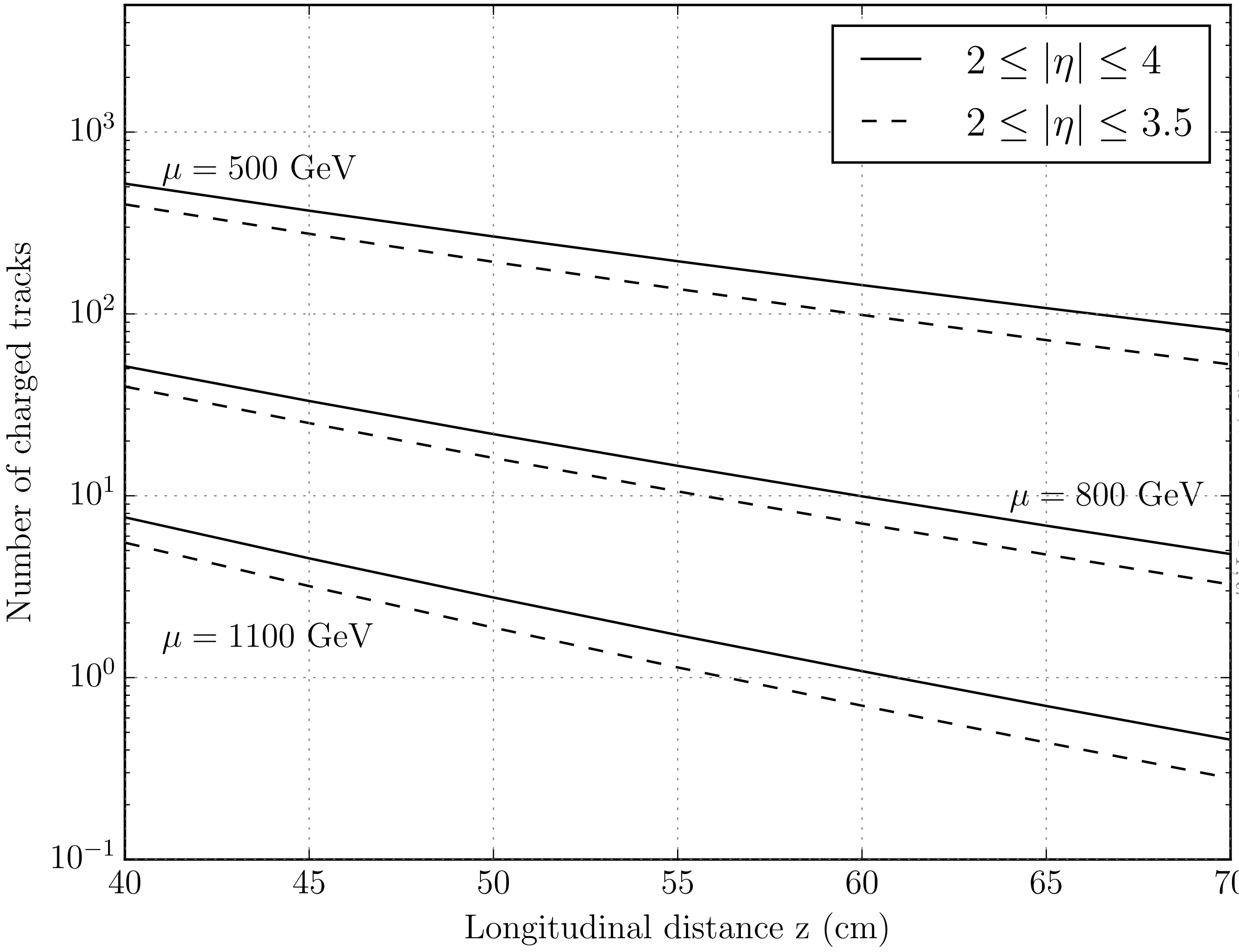


Simplest modification: bring the tracker down!!

How closer to the beam pipe is possible?

Charged tracks in r-z



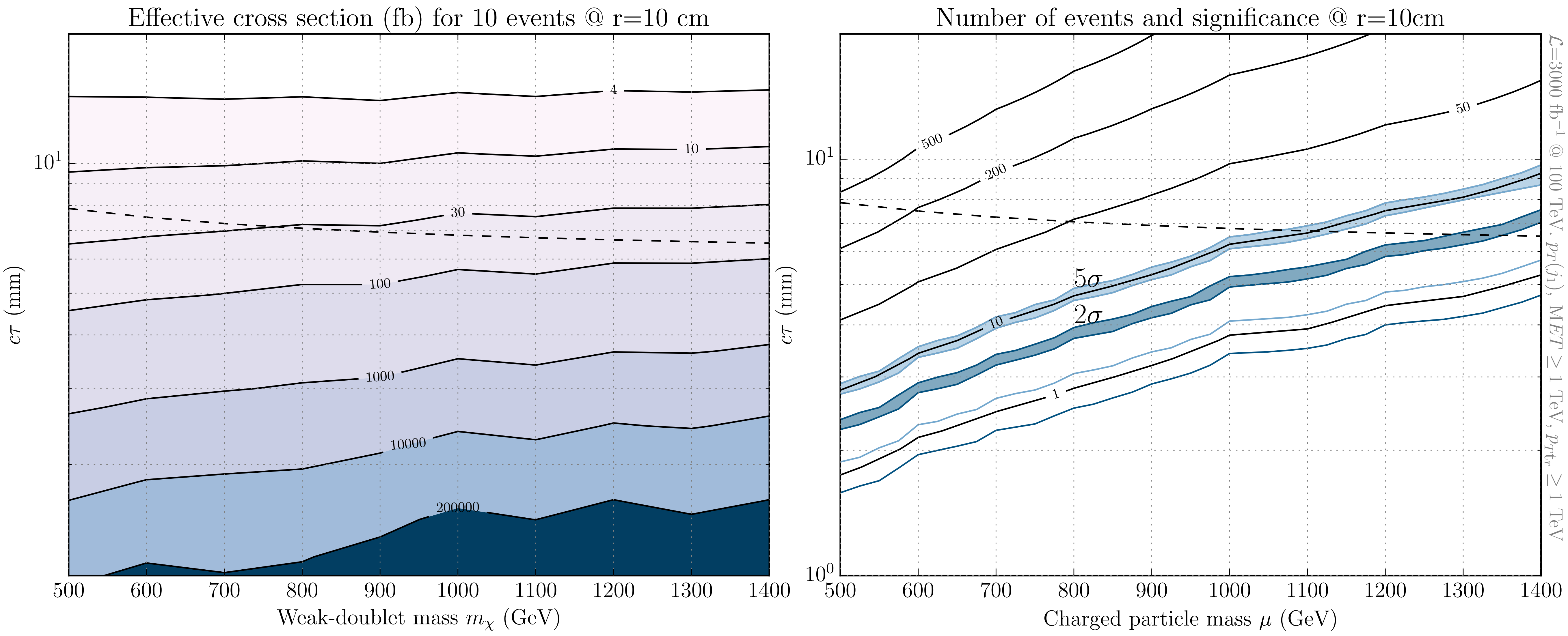


r=10 cm gives 10 events for 1.1 TeV charginos with 1 TeV pT cut.

Forward (η) extension from 3.5 to 4 gives a factor 2 enhancement.

How much more can we extend the η coverage?

Sensitivity (*r*=10cm)

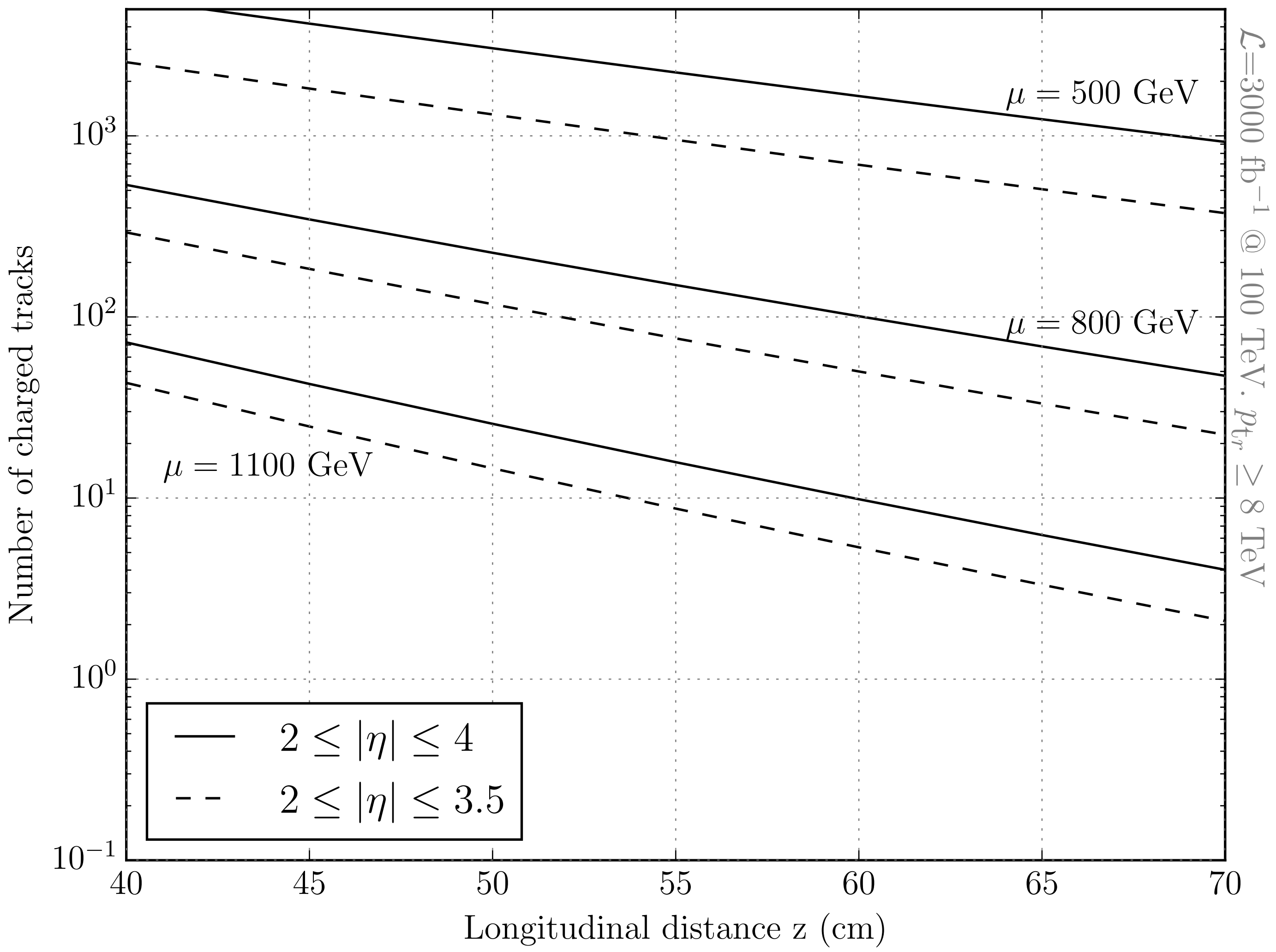


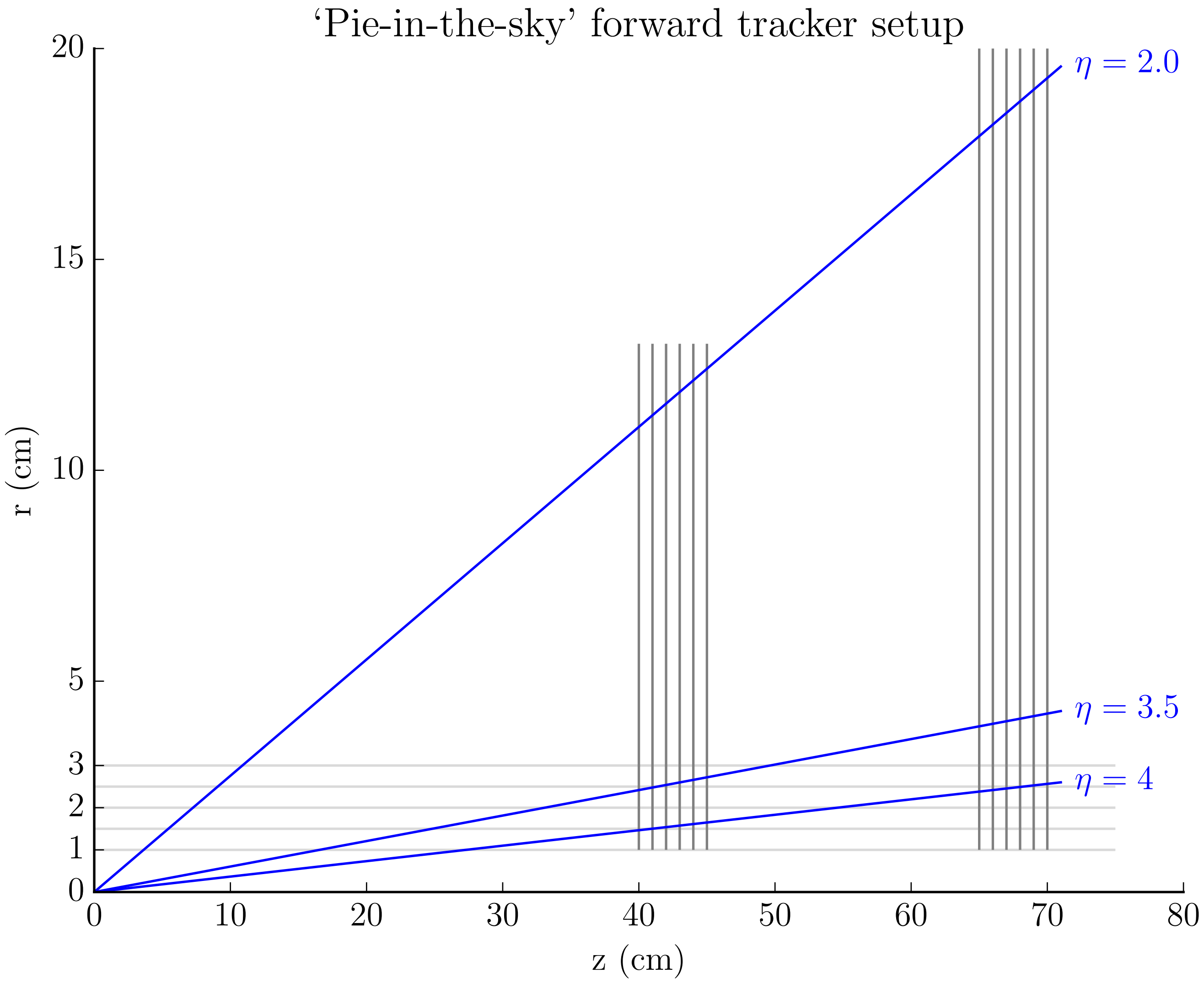
m < 1065 (1286) GeV for discovery (exclusion) for pure Higgsino, 50% systematics.

Scaling with di-jets (gg). If using Z+jets (q-qbar), the reach moves to 1.5 (1.6) TeV.

Pie in the sky

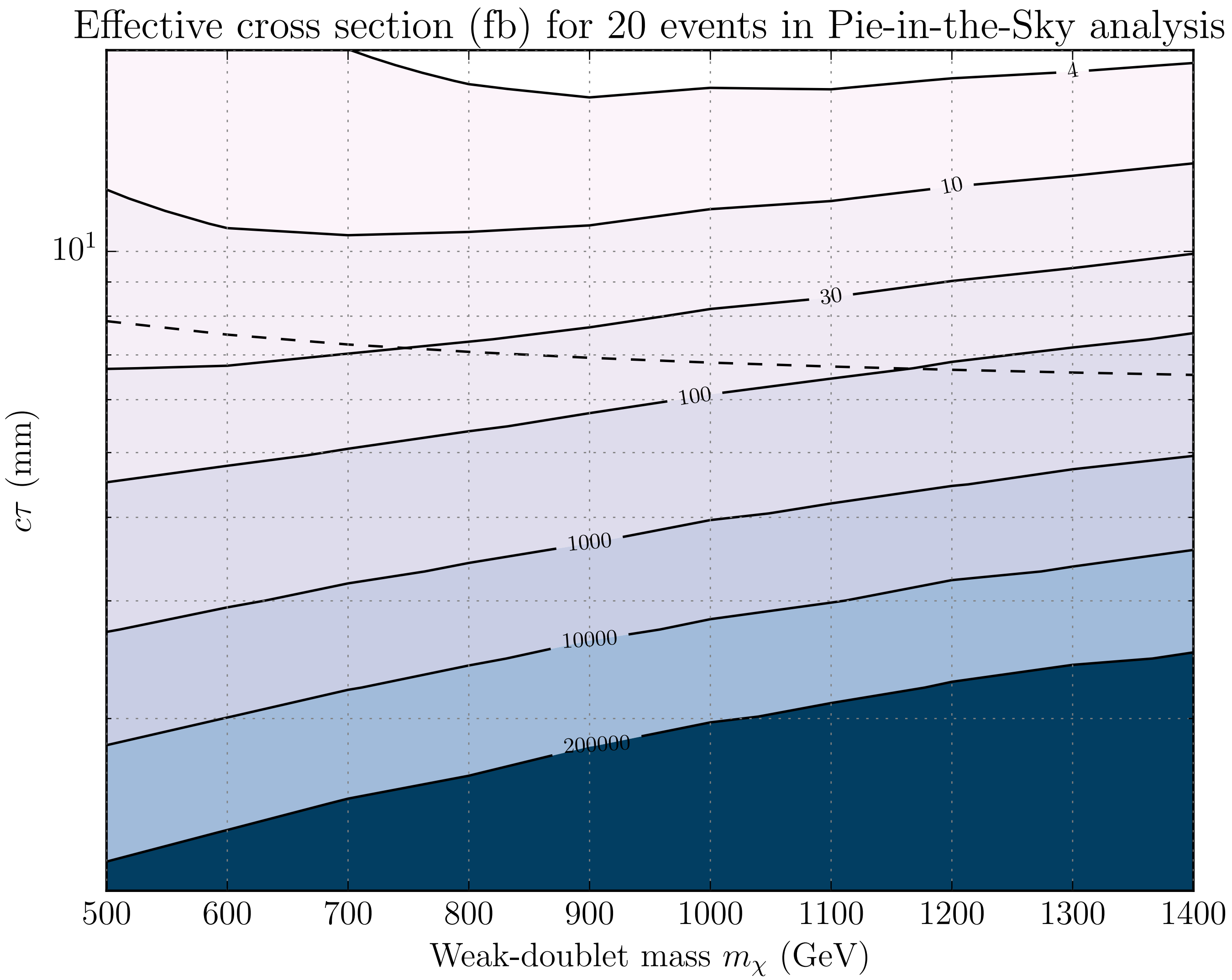
Consider energetic (|p| > 8 TeV) and very forward (3 < η < η$_{max}$) tracks

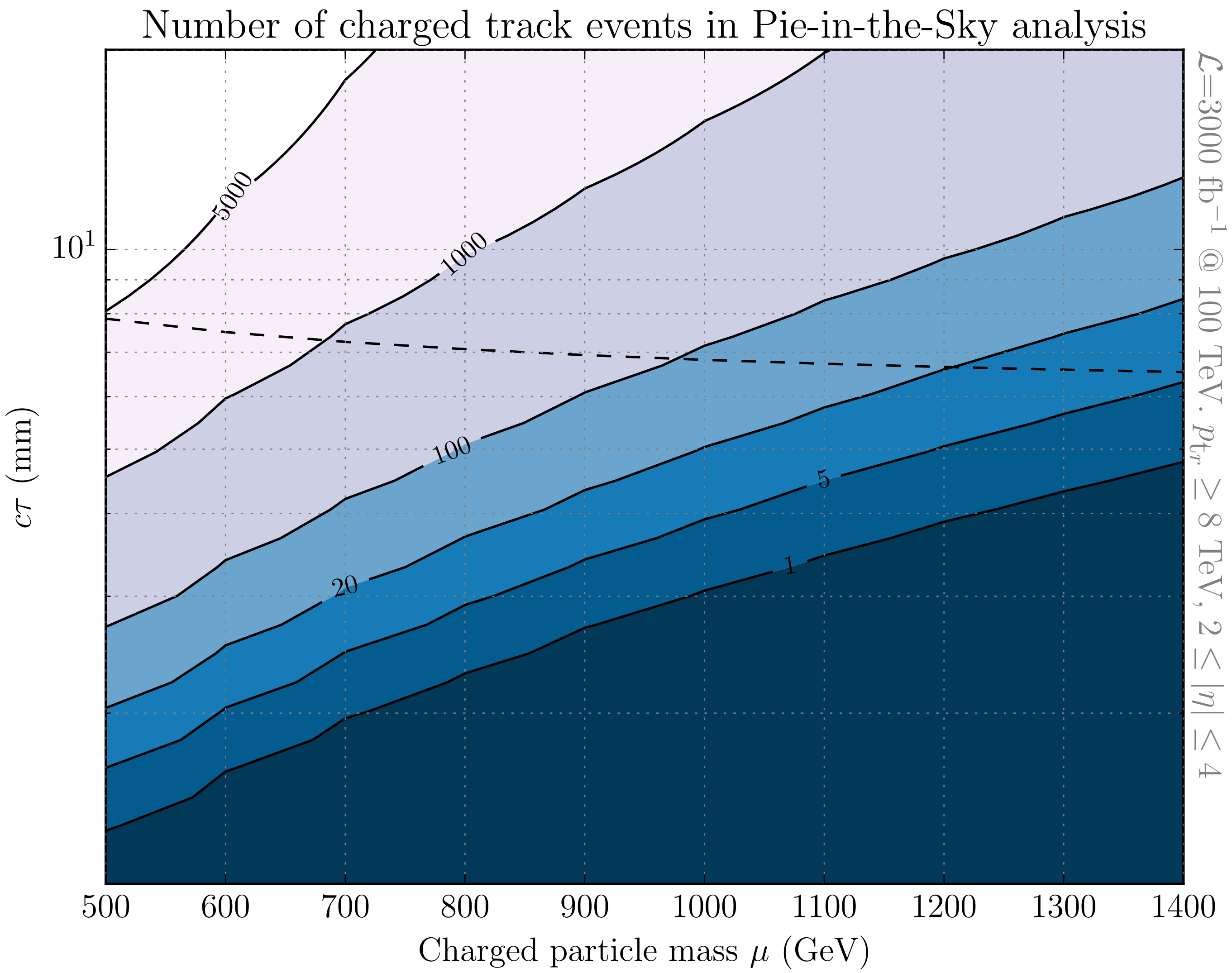




Trigger on this hard, forward track and try to exploit the very forward direction!

Sensitivity (pie in the sky)





Discovery (20) and exclusion (5) for m < 1210 (1420) GeV for pure Higgsino.

About 400 (1600) fb-1 needed to exclude (discover) 1.1 TeV Higgsinos.

Can we estimate forward backgrounds? Is this region morally "background-free"?

Longitudinal boost is ubiquitous! Physics cases benefiting from forward tracker? BYOPC!

Mono-Z analysis

@100 TeV FCC-hh

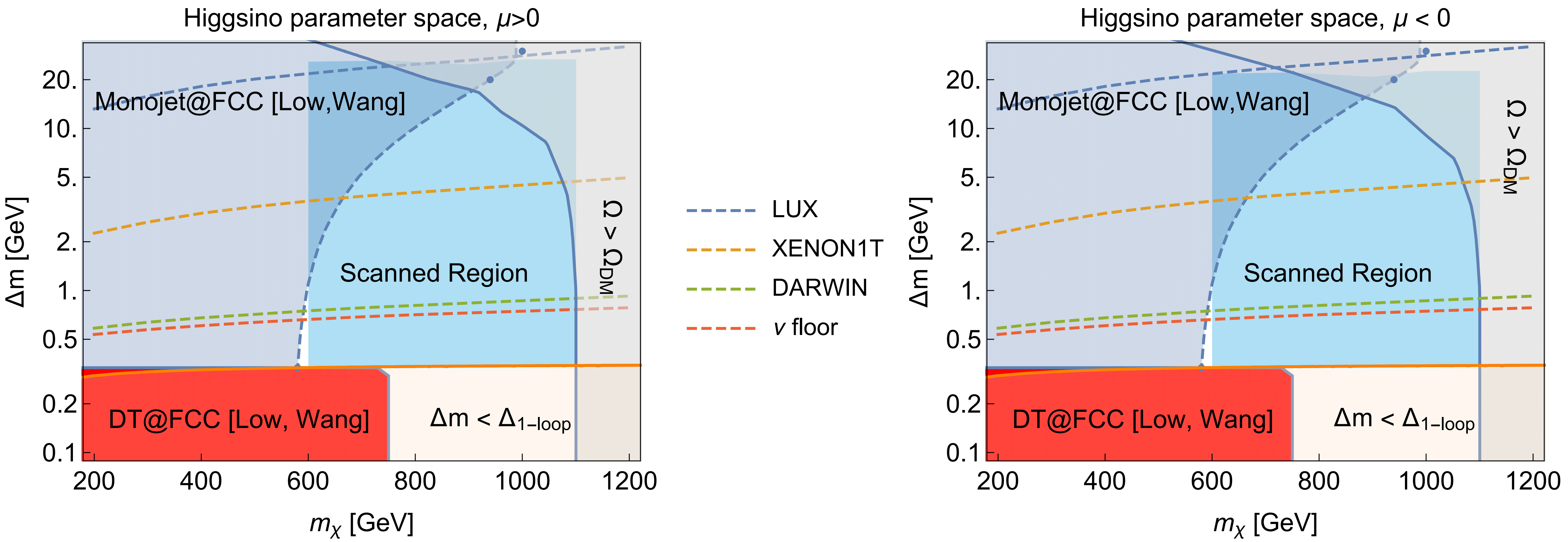
Mono-Z vs mono-jets

At the LHC, LHC, the mono-Z search for EWkinos (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 2-5 GeV.
- LHC 95% C.L bounds give m_χ > 200 GeV.
- FCC monojet bounds: m_χ > 600 GeV for nominal splitting.
- Relic density forces m_χ < 1100 GeV.
- Scanned region: $|\mu|$ = 600, 750, 900, 1000, 1100 ; t_β = 15, M_1 scans Δ_+.

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 tt (matched up to 1 jet).
  - fake $\not{E}_T$: Z ($\rightarrow l^+ l^-$) + jets (similarly ZW,ZZ).
- Parton level cuts: $p_T(l^+, l^-) > 400\ \mathrm{GeV}$ or $H_T, \not{E}_T > 400\ \mathrm{GeV}$.
- Event selection (basic cuts):
  - Tighter cut on $\not{E}_T > 500\ \mathrm{GeV}.$
  - Two OS leptons satisfying $p_T(l) > 50\ \mathrm{GeV}, |m(l^+, l^-) - m_Z| < 15\ \mathrm{GeV}.$
  - 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.

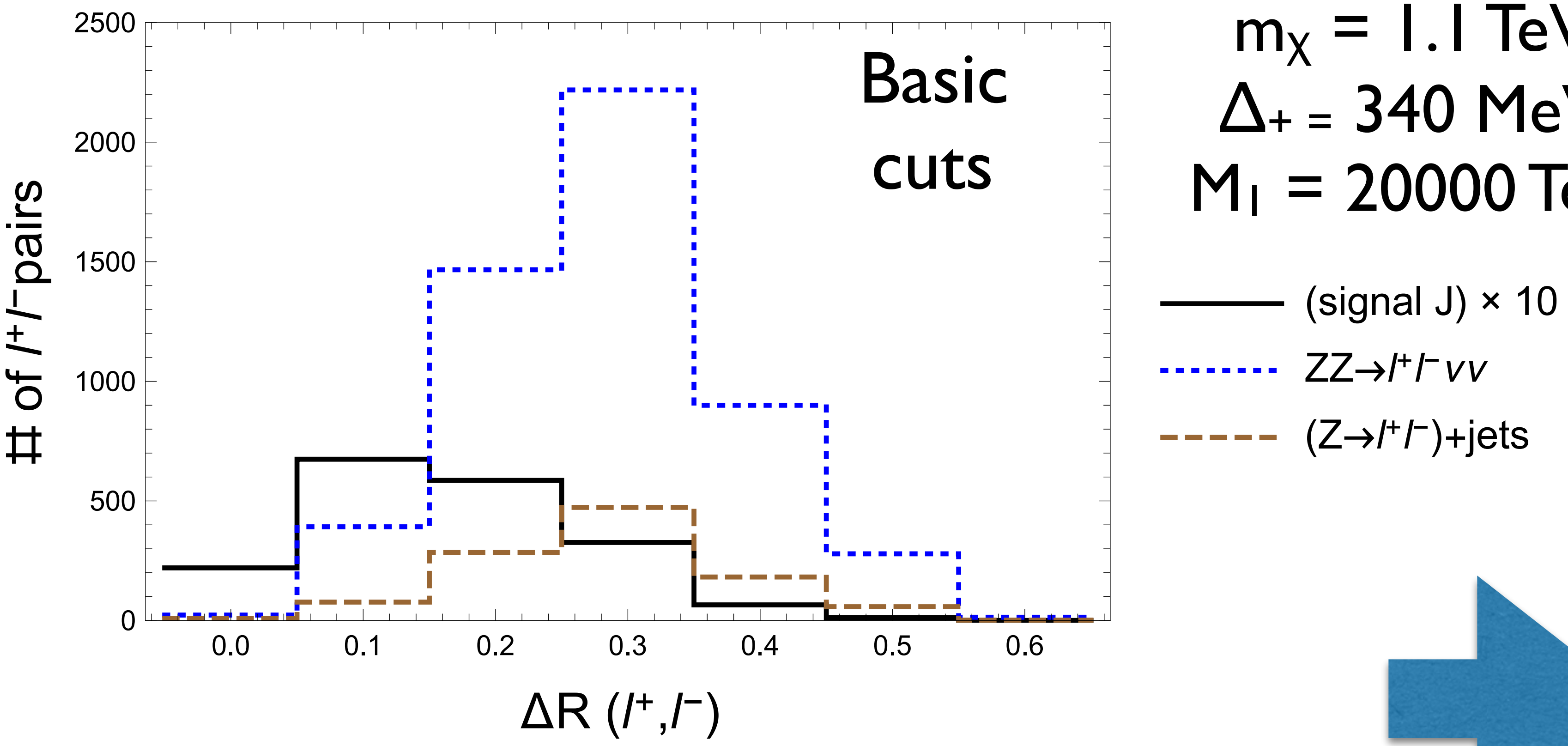
Angular separation

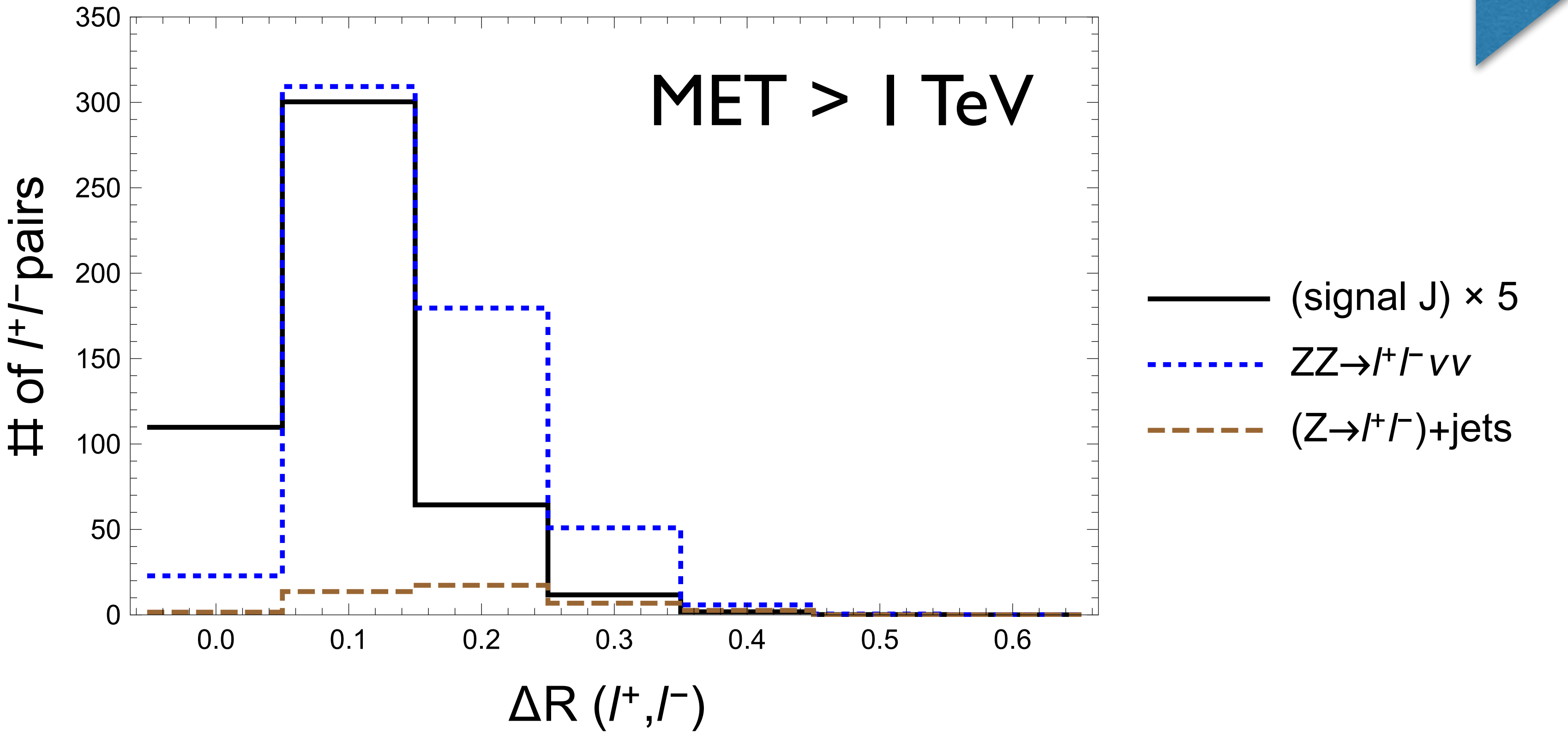
Benchmark J:

m_χ = 1.1 TeV,

Δ_+ = 340 MeV

M_I = 20000 TeV



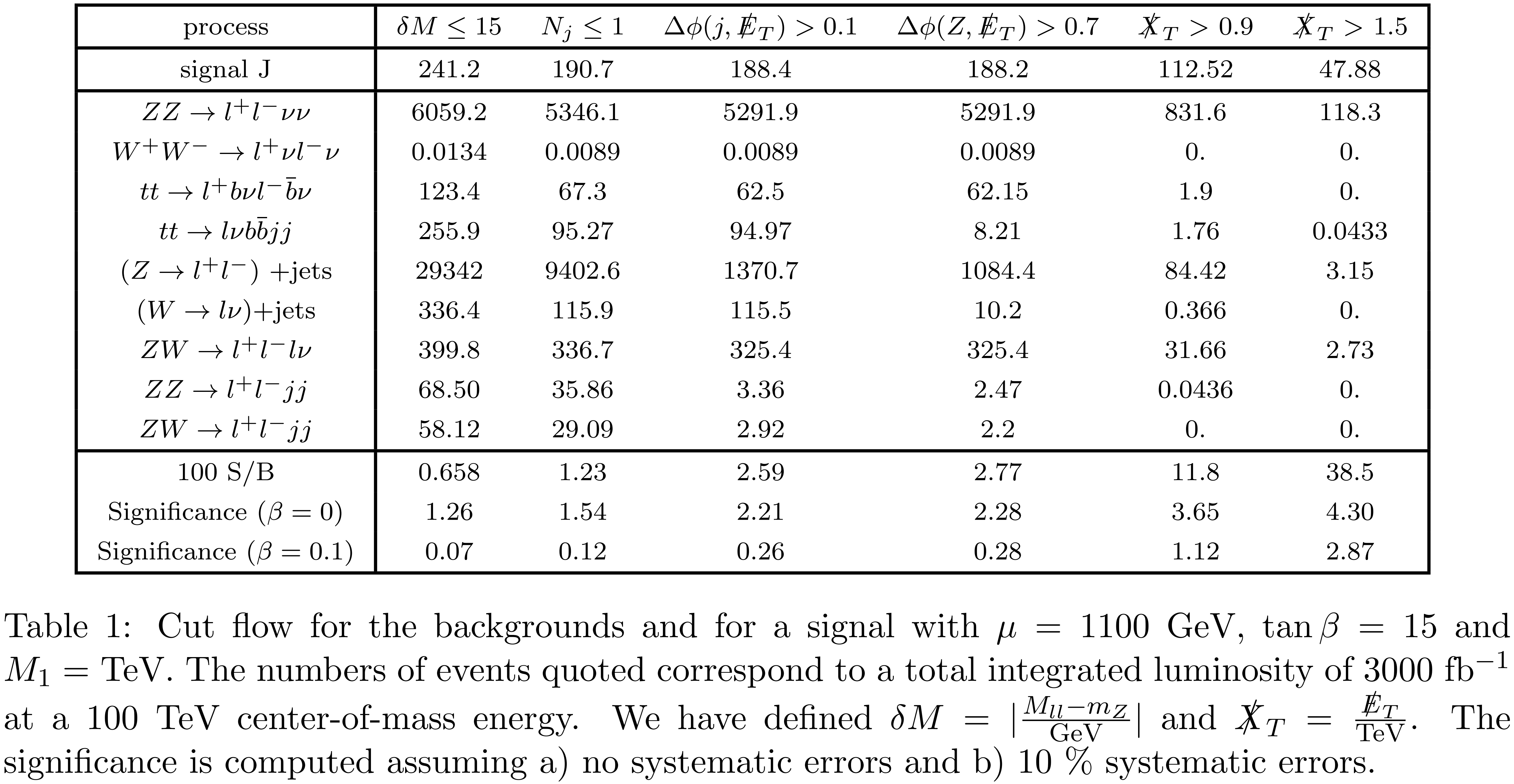


This analysis heavily relies on the capability of tagging a highly boosted, leptonically decaying Z.

Optimisation and cut-flow

Optimal: $\Delta\phi(l^+l^-, \not\!\!E_T) > 0.7,\ \Delta\phi(j_1, \not\!\!E_T) > 0.1+ \not\!\!E_T > 900(+\mathrm{X})$ 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

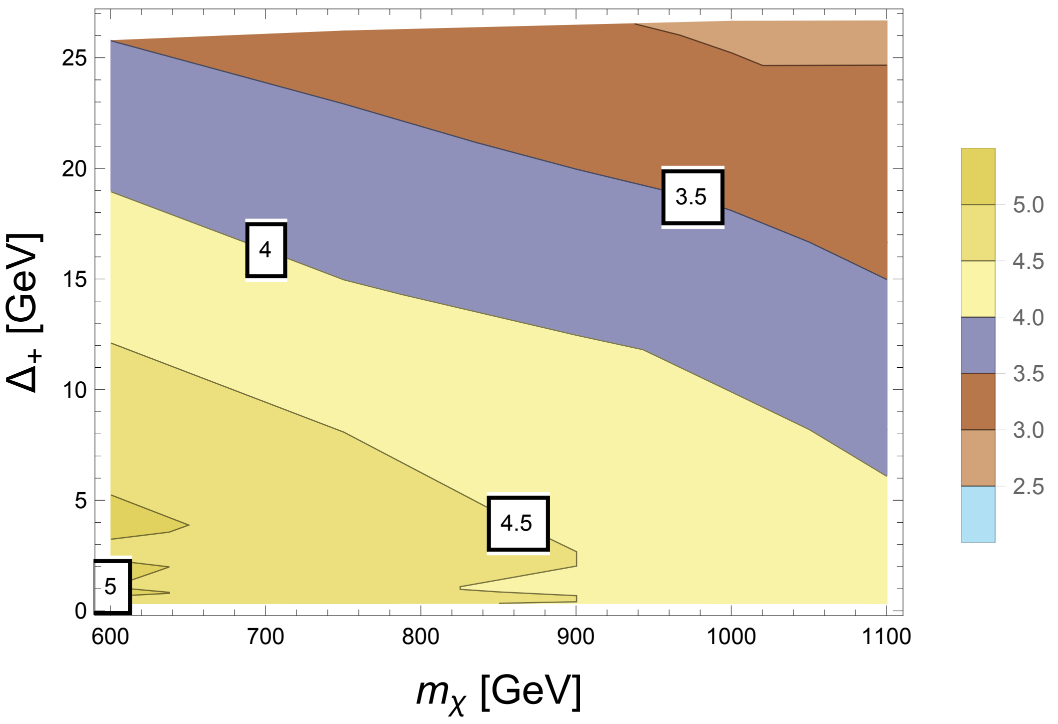
Table 1: Cut flow for the backgrounds and for a signal with $\mu = 1100$ GeV, $\tan\beta = 15$ and $M_1 =$ TeV. The numbers of events quoted correspond to a total integrated luminosity of 3000 fb^{-1} at a 100 TeV center-of-mass energy. We have defined $\delta M = |\frac{M_{ll} - m_Z}{\mathrm{GeV}}|$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

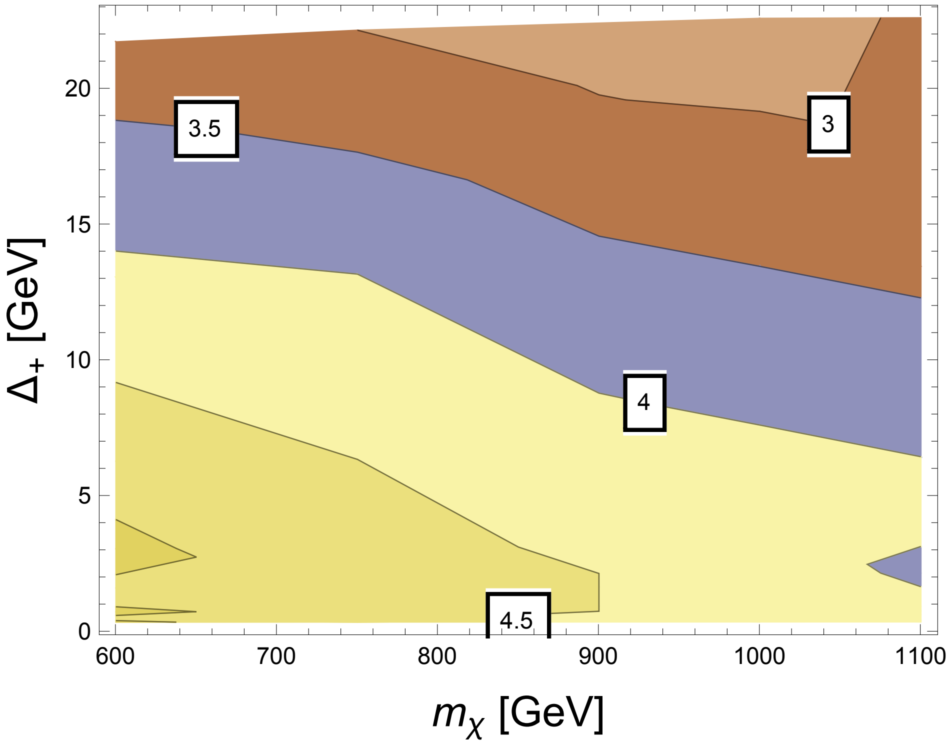
FCC reach

Lumi=3ab^{-1}

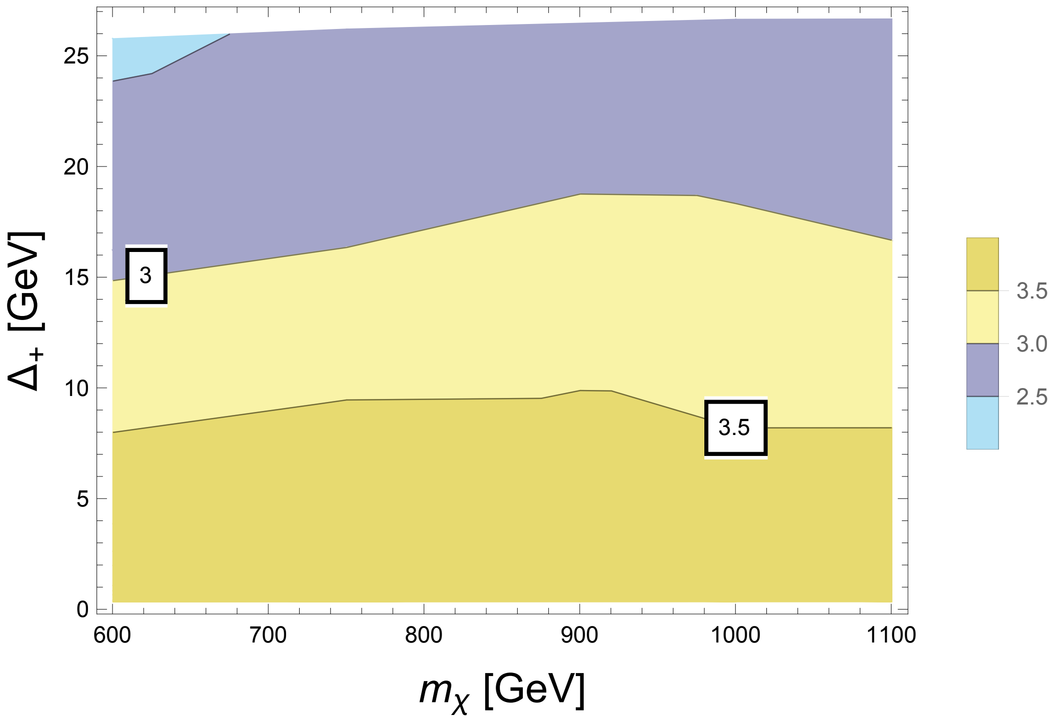
μ > 0 μ < 0

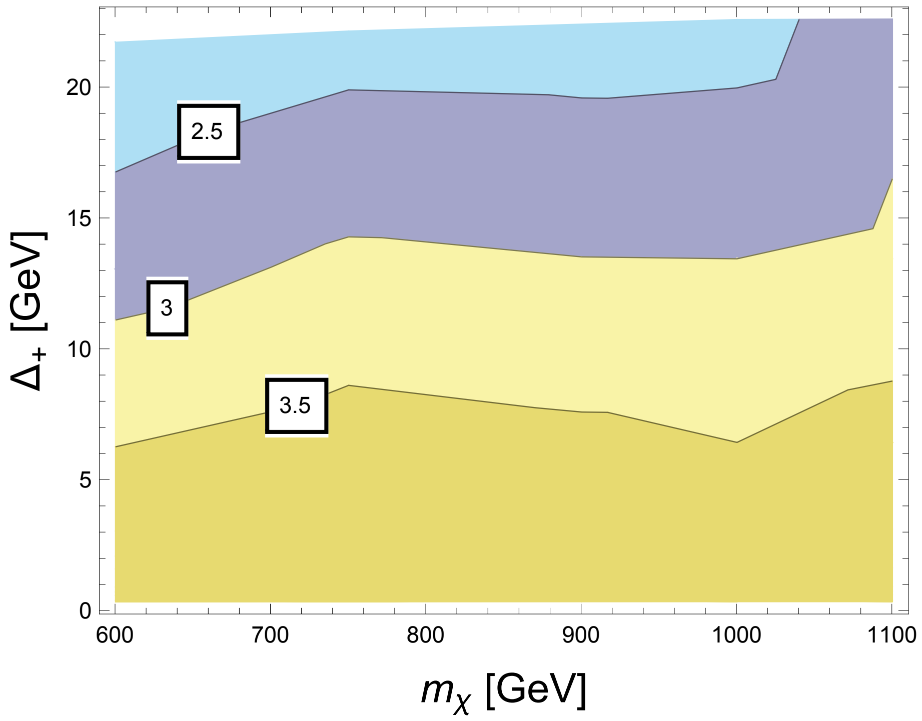
syst=0%





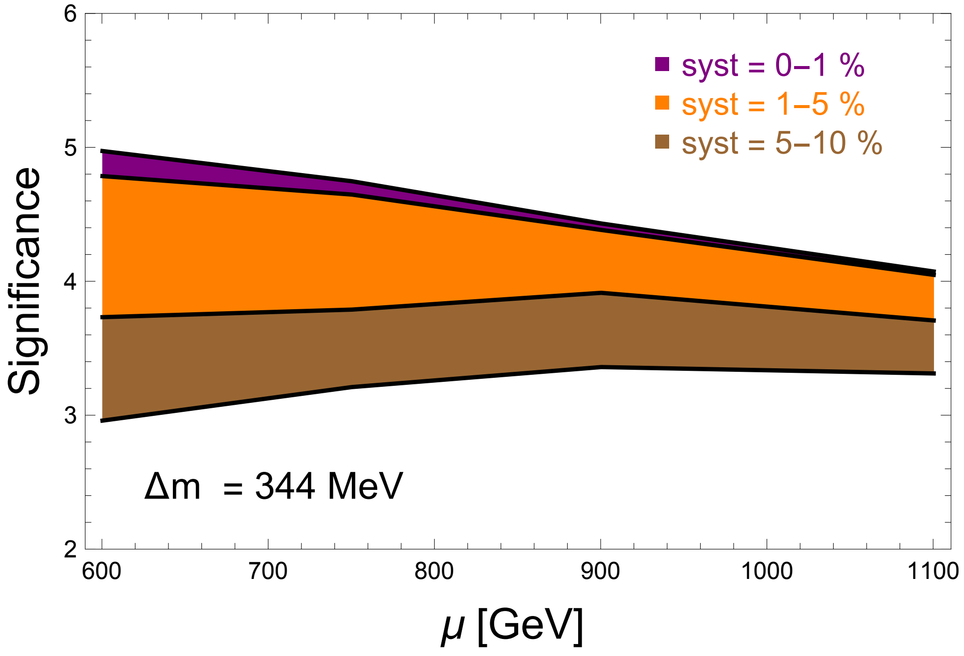
syst=5%

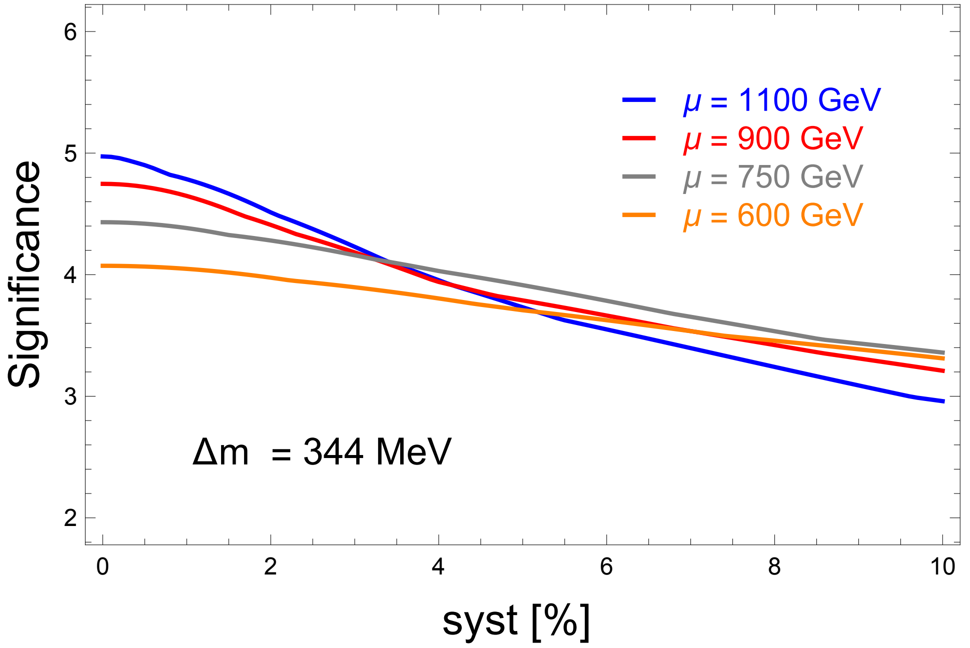




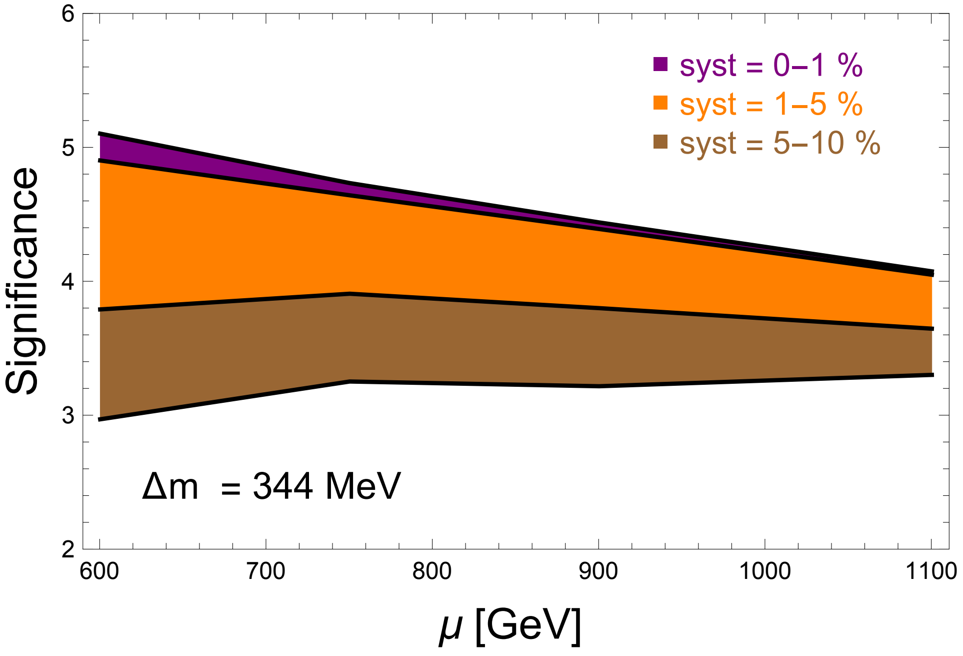
Role of systematics

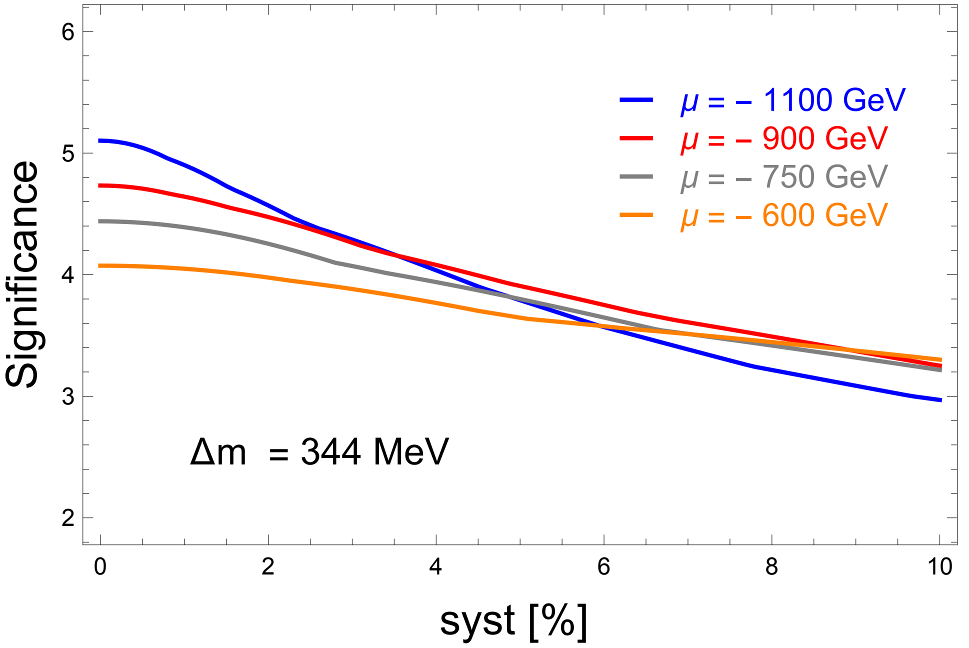
μ > 0



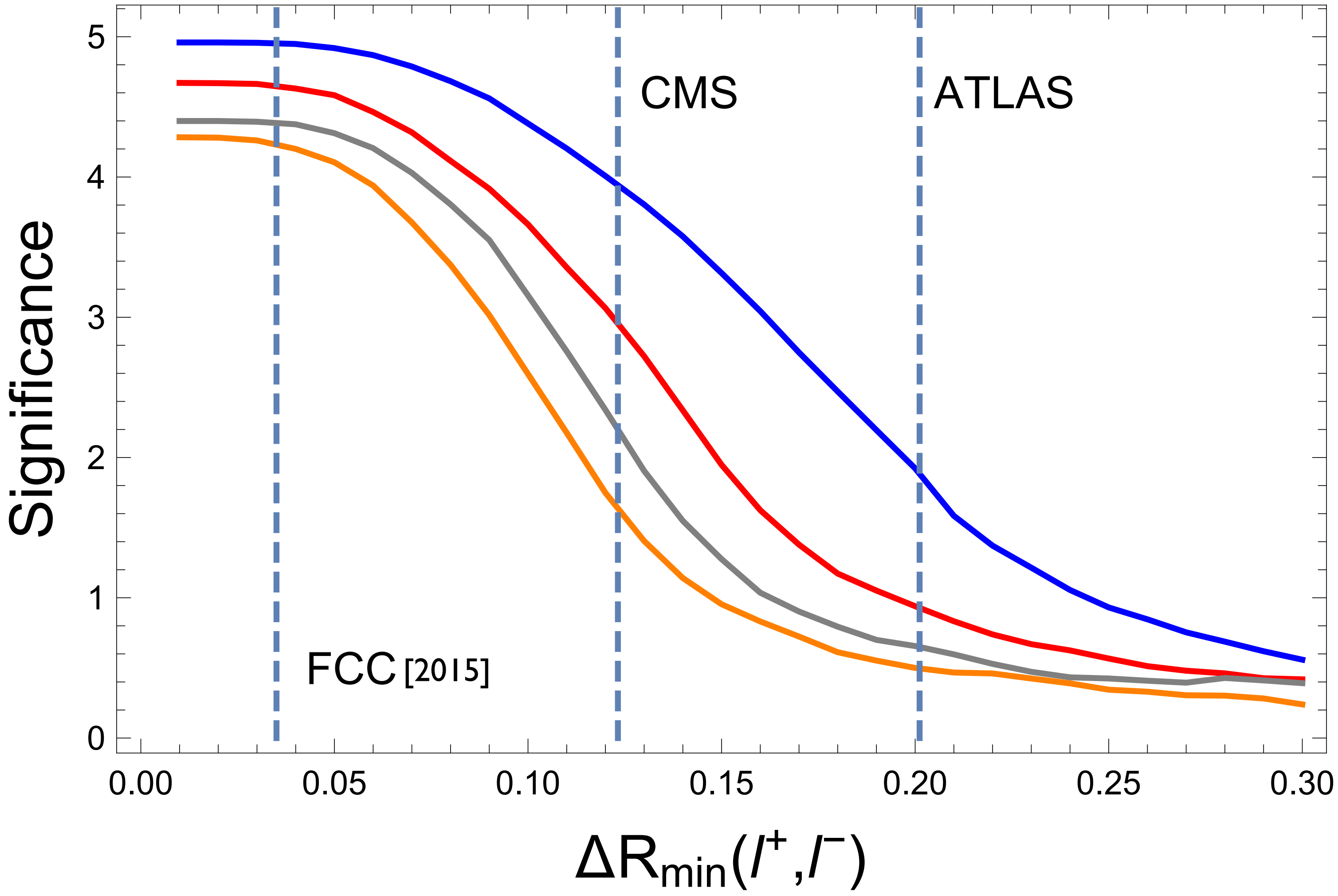


μ < 0





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).

What is a realistically achievable ΔR resolution?

Conclusions

- We have studied the FCC reach for pure Higgsino in disappearing tracks and mono-Z.

- Disappearing tracks:
  - Huge gain if the tracker is brought closer to the beampipe (10 cm covers thermal Higgsinos) or a very forward "endcap" detector is used.
  - Backgrounds are very hard to estimate.
  - Worth exploring new design ideas!

- Mono-Z:
  - Highly boosted Z boson can defeat monojet, excluding TeV masses.
  - "Full coverage" is possible at the 3 (4) σ level with 5% (0%) systematics.
  - ECAL granularity below 0.05 is enough to resolve the di-lepton system. Do we need isolation or can we get leptons directly from tracks?

- Do our proposed tracker serve also to <u>your</u> favourite physics case?

"There presently is no physics case for a 100-TeV hadron collider" F. Zimmerman's talk

1. thermal dark matter!!!
2. …
3. …