Closing the window on neutralino dark matter with a 100 TeV hadron collider

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R.Mahbubani, P. Schwaller, JZ, [arXiv 1609.abcde]

Effective Field Theories for Collider Physics, Flavor Phenomena and Electroweak Symmetry Breaking, Eltville am Rhein, 13.09.2016

Outline

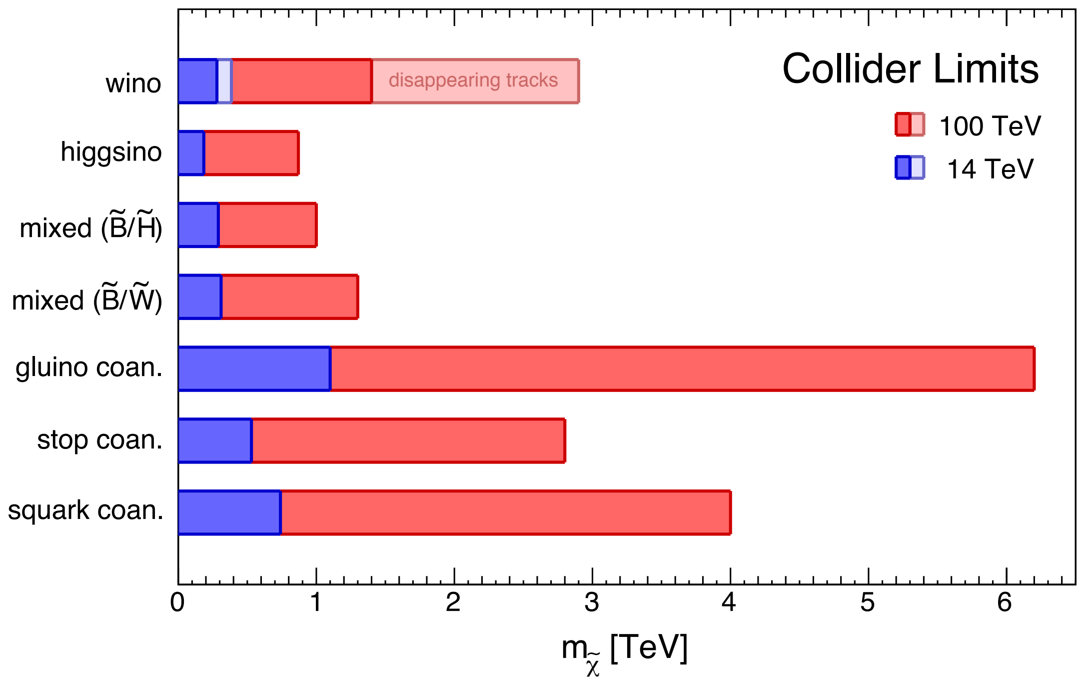
- Motivation
- Phenomenology of Bino/Higgsino DM
- FCC searches
- Conclusions

TeV Higgsinos: MSSM’s last stand

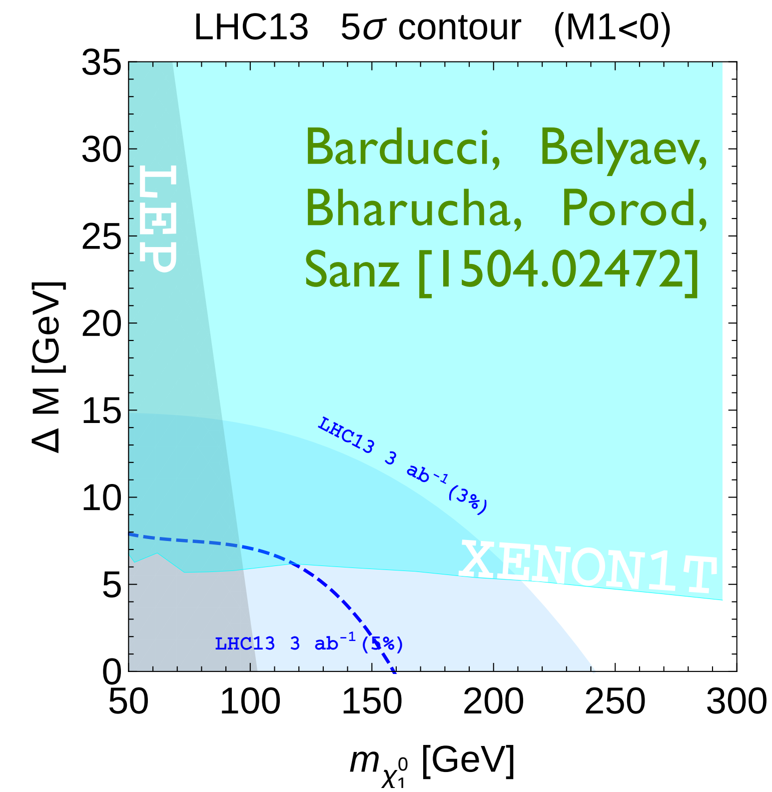
- The neutralino is the MSSM DM candidate, made out of Bino, Wino and Higgsino.
- Relic density sets mass for pure: $\tilde{B}$(100 GeV), $\tilde{W}$(2.7 TeV) and $\tilde{H}$(1.1 TeV).
- All pure cases and mixtures (wino/Higgsino, bino/Wino, etc) well studied in the literature.
- Only “uncoverable” spot 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: Alternative to monojets. Reach limited due to Higgsino lifetime.
- This talk:
    - a) disappearing tracks at FCC with a customised tracker for 1.1 TeV Higgsino
    - b) mono-Z study with highly boosted di-lepton final states (beats mono-jet!)

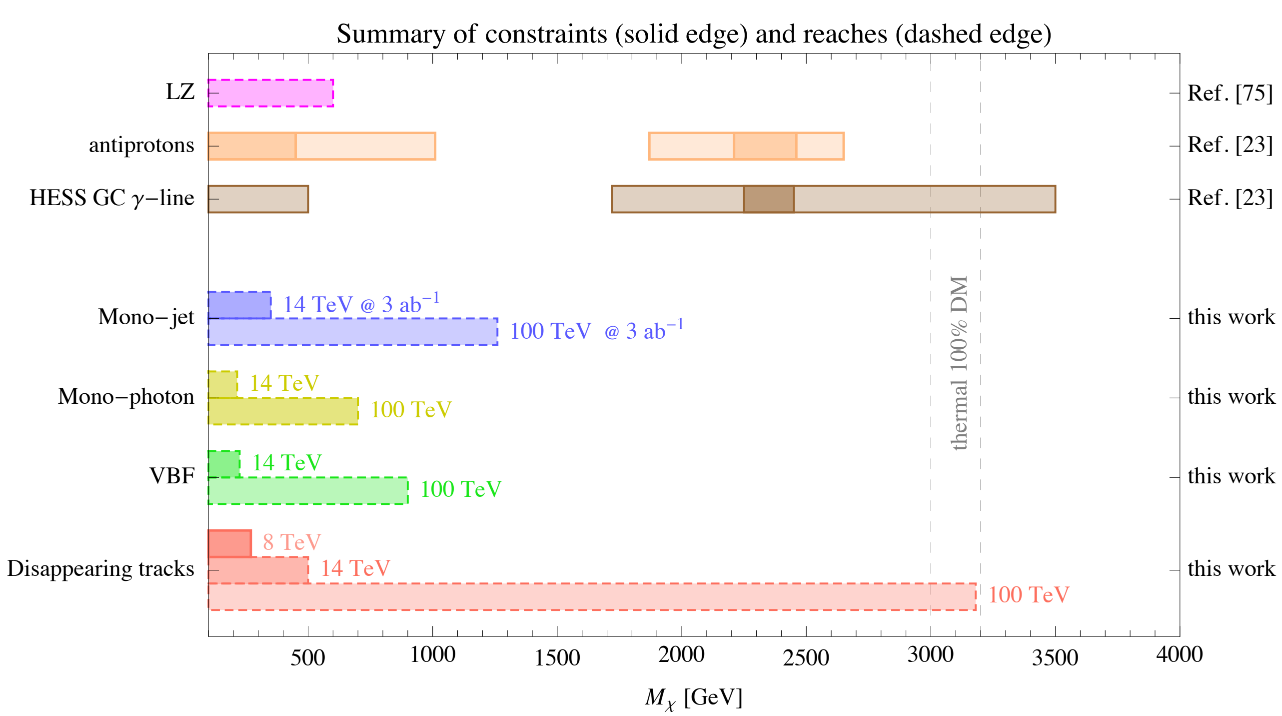
* A pure Higgsino, EW doublet, is ruled out, because both neutral states are mass degenerate, and the Z-n1-n2 coupling is actually Z-n1-n1. Z currents with weak couplings are excluded by direct detection experiments (XENON100, LUX, etc). Some additional Bino and/or Wino component is required.

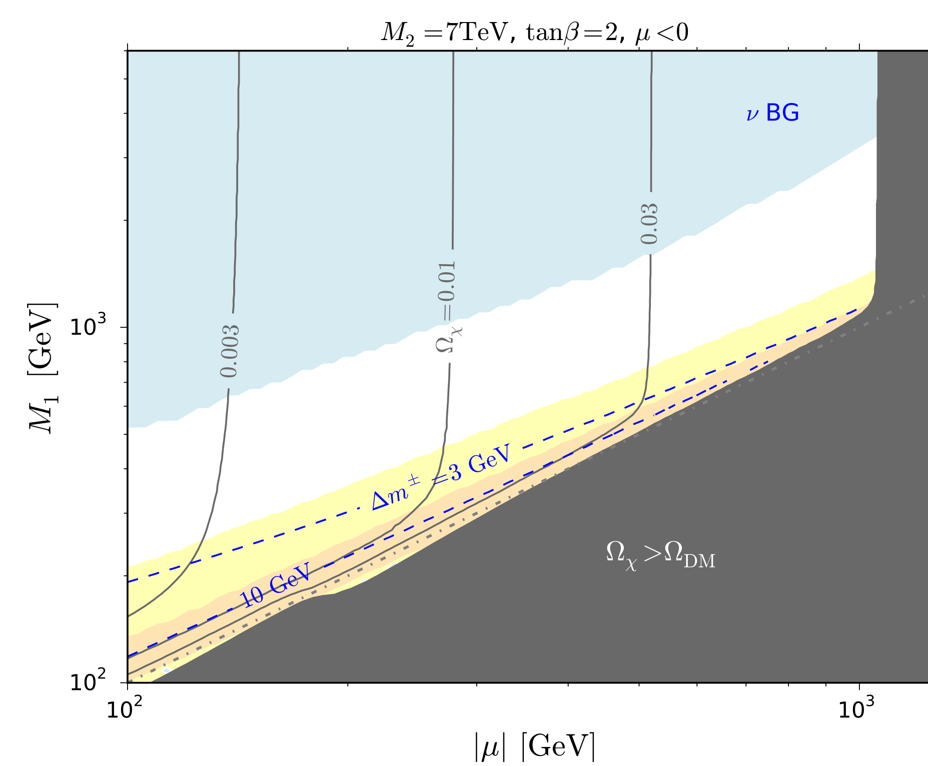
Recent Analyses



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







Cirelli, Sala, Taoso [1407.7058]

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

Higgsino/Bino

dark matter:

phenomenology

Electroweakino Sector

$$\mathcal{M}_\chi^\pm = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta M_W \\ \sqrt{2}\cos\beta M_W & \mu \end{pmatrix}$$

gauge eigenstates — mass eigenstates

$$\tilde{W}^+, \tilde{H_u}^+ \sim \chi_1^+, \chi_2^+$$

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

$$\mathcal{M}_\chi^0 = \begin{pmatrix} M_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\ 0 & M_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\ -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\ s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0 \end{pmatrix}$$

gauge eigenstates — mass eigenstates

$$\tilde{H_u}^0, \tilde{H_d}^0, \tilde{B}^0, \tilde{W_3}^0 \sim \chi_1^0, ..., \chi_4^0$$

→ 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

<u>Important!</u>

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.

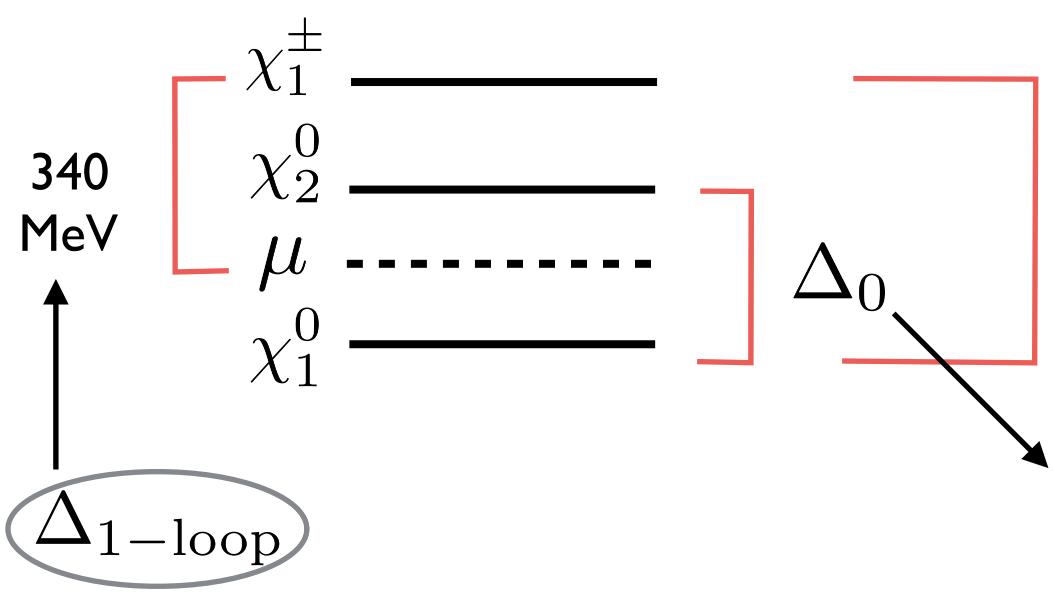
Thomas, Wells, hep-ph/9804359,
Cirelli, Formengo, Strumia, hep-ph/051209

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

Simplified Bino/Higgsino

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

Expanding in μ/M_1



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

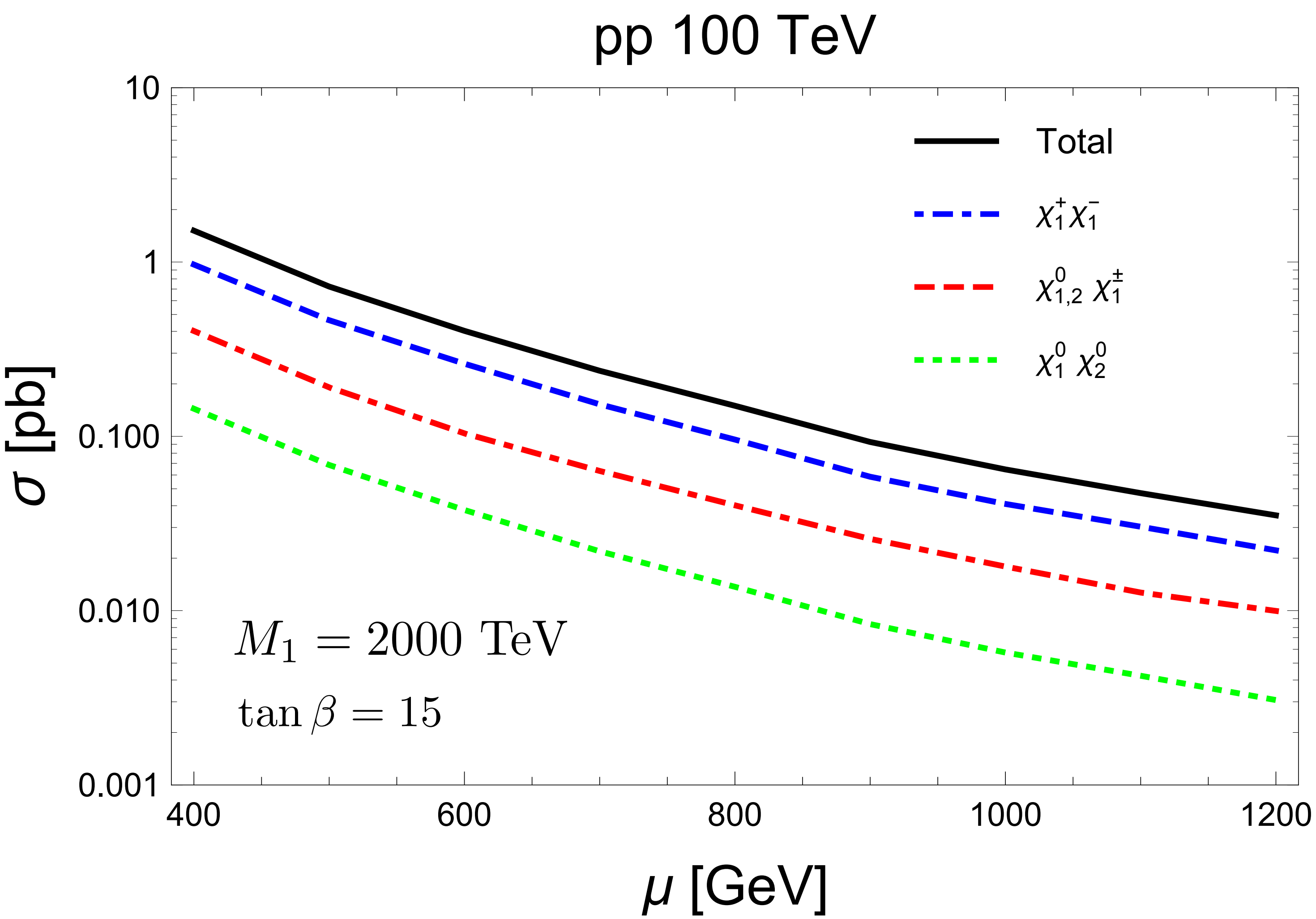
$$\Delta_0 = \frac{192 \text{ MeV}}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

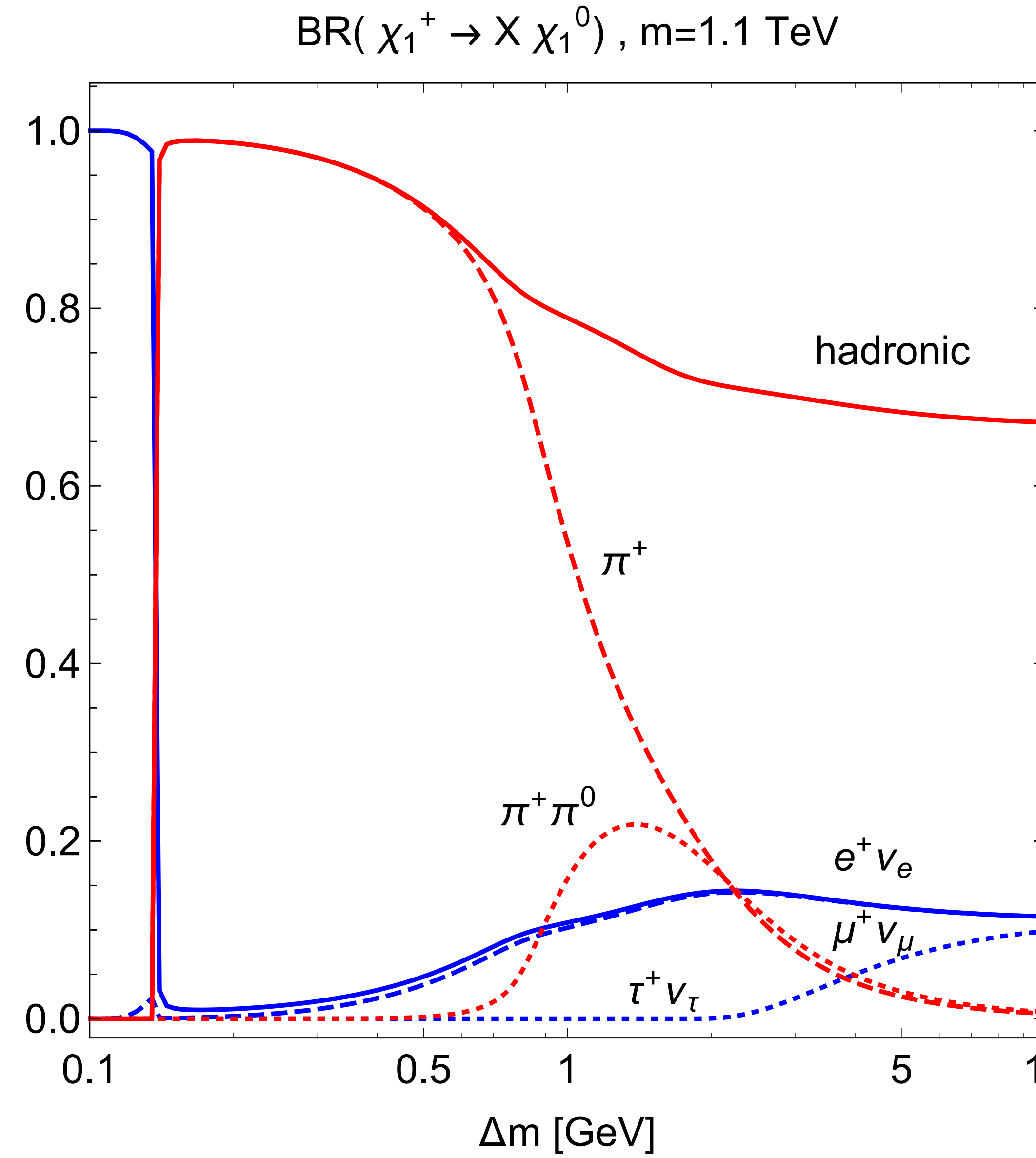
Limiting cases:

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.

XS and branching ratios





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

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

Decays formulae (mostly) from
Chen, Drees, Gunion: hep-ph/951230, 9607421, 9902302.

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

$$\Gamma(\chi_1^\pm \to \pi^\pm \chi_0^{(1)}) \sim (\Delta_+)^{-3} \;\Rightarrow\; \tau_{\tilde{W}} \sim 8\,\tau_{\tilde{H}}$$

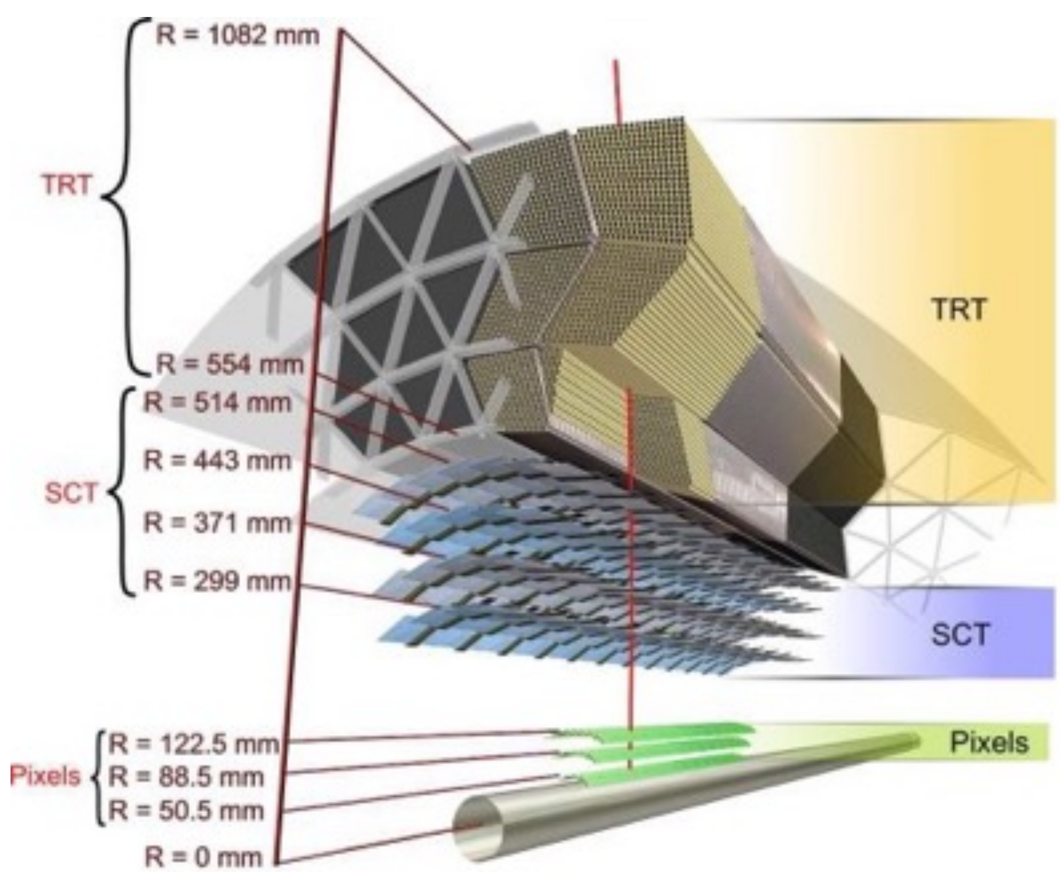
Higgsino lifetime too short!

Disappearing tracks @100 TeV 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.



* “Reinheits 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)

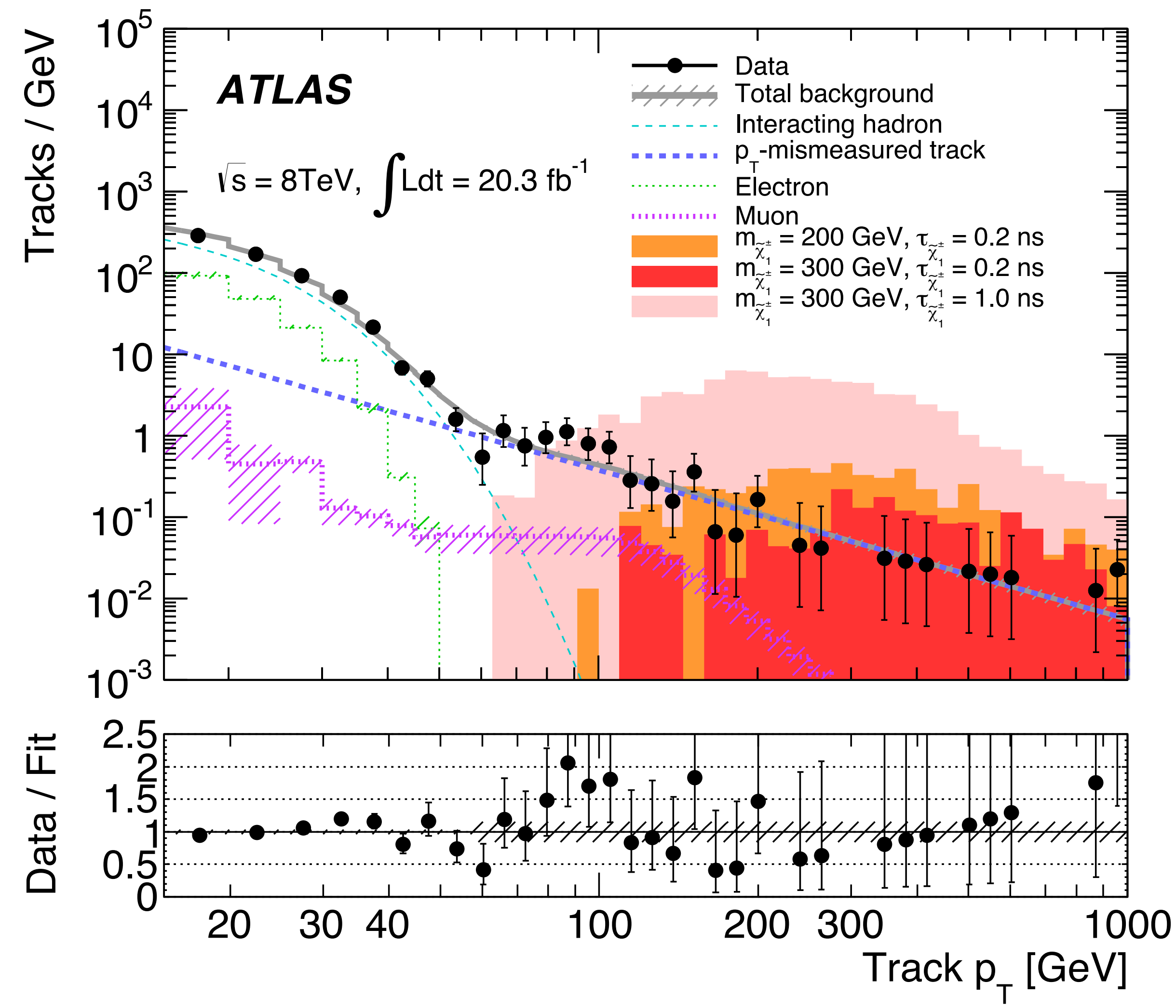
$d_{min} \approx 30\ \mathrm{cm}$

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

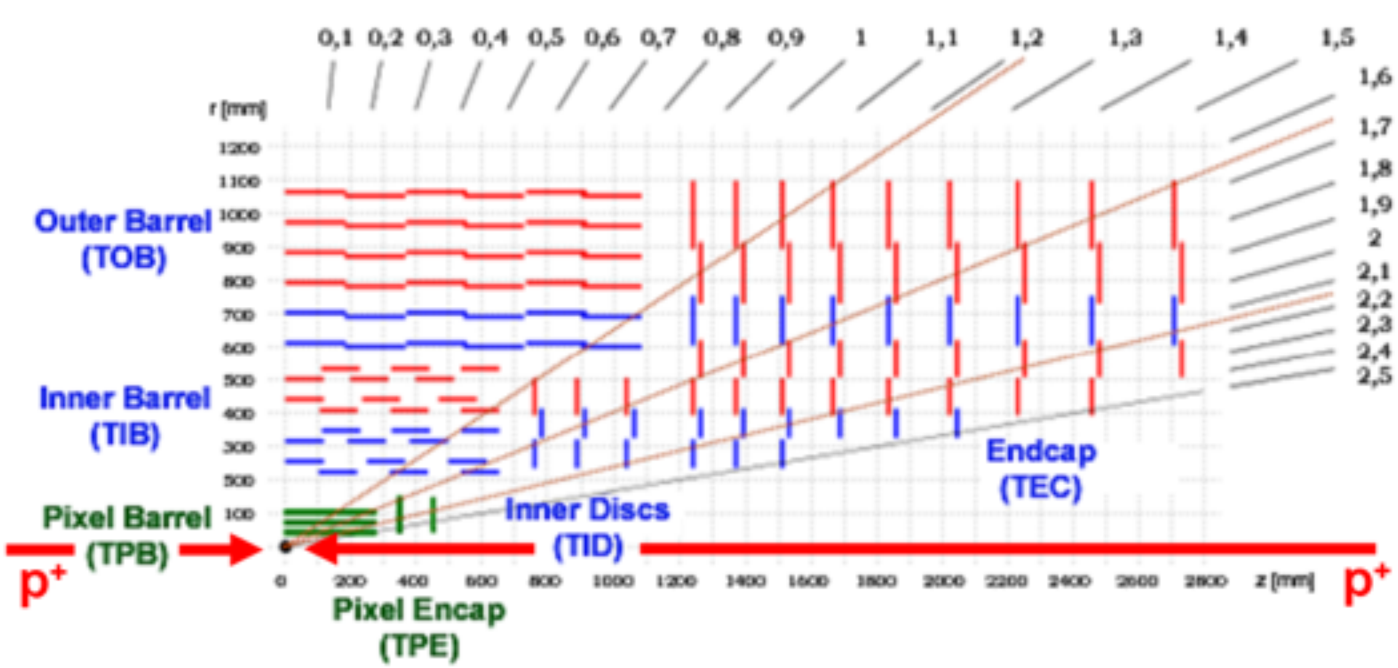
Don't forget about backgrounds!

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

    (dominant if pT >100 GeV)

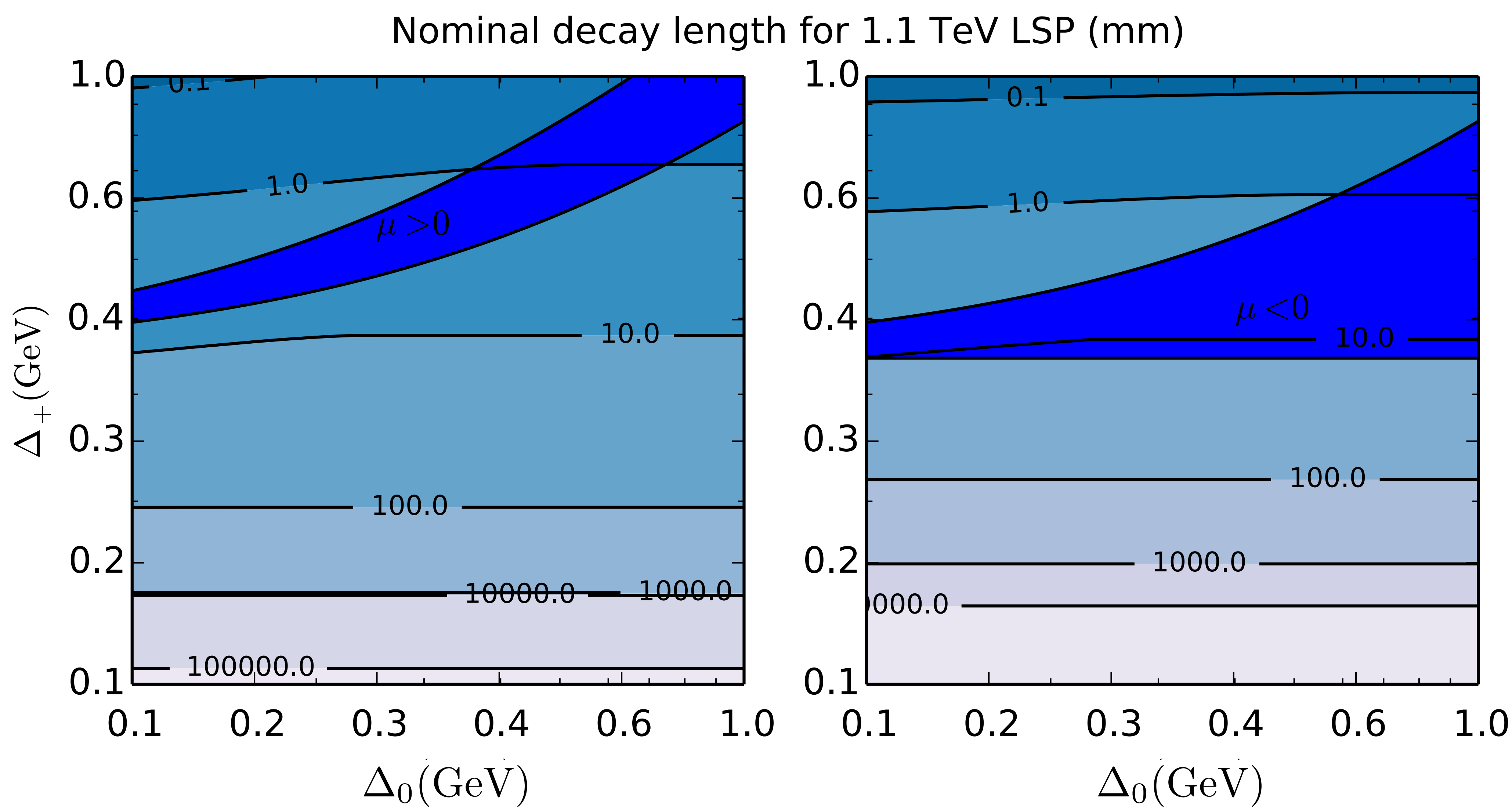


CMS: cuts on E_{calo} < 10 GeV



Same principle, but…
too messy tracker!!!

Decay lengths and parameter space



- Lifetimes ~ 1 mm, larger values (up to 10 mm) reachable for $\mu < 0$.

But

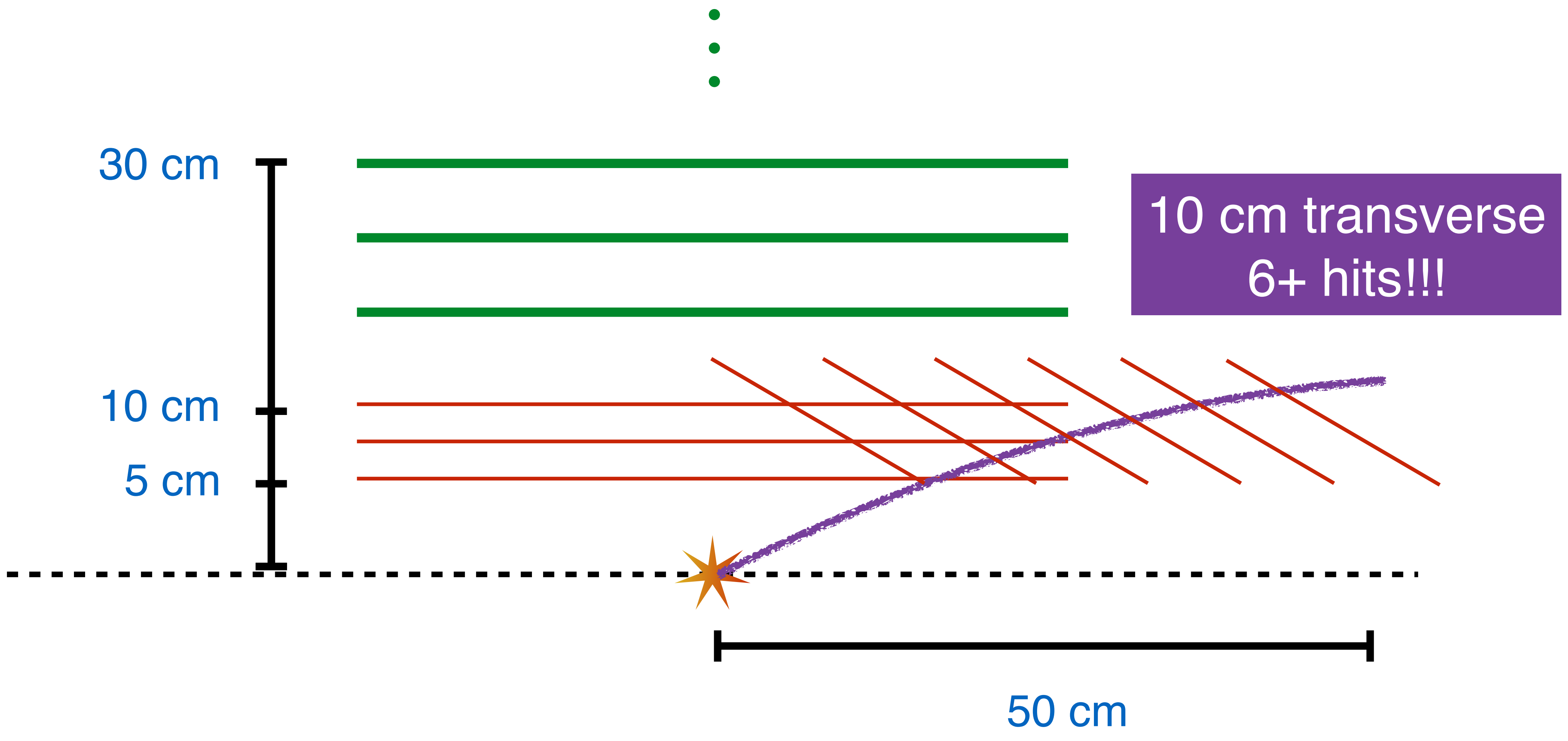
1- Lorentz boost $d = (c\tau)\gamma\beta$

2- Poisson process $P(d > d_0) = exp(-m_{\chi^\pm} d_0 \Gamma / |\vec{p}|)$

A tale of two tails

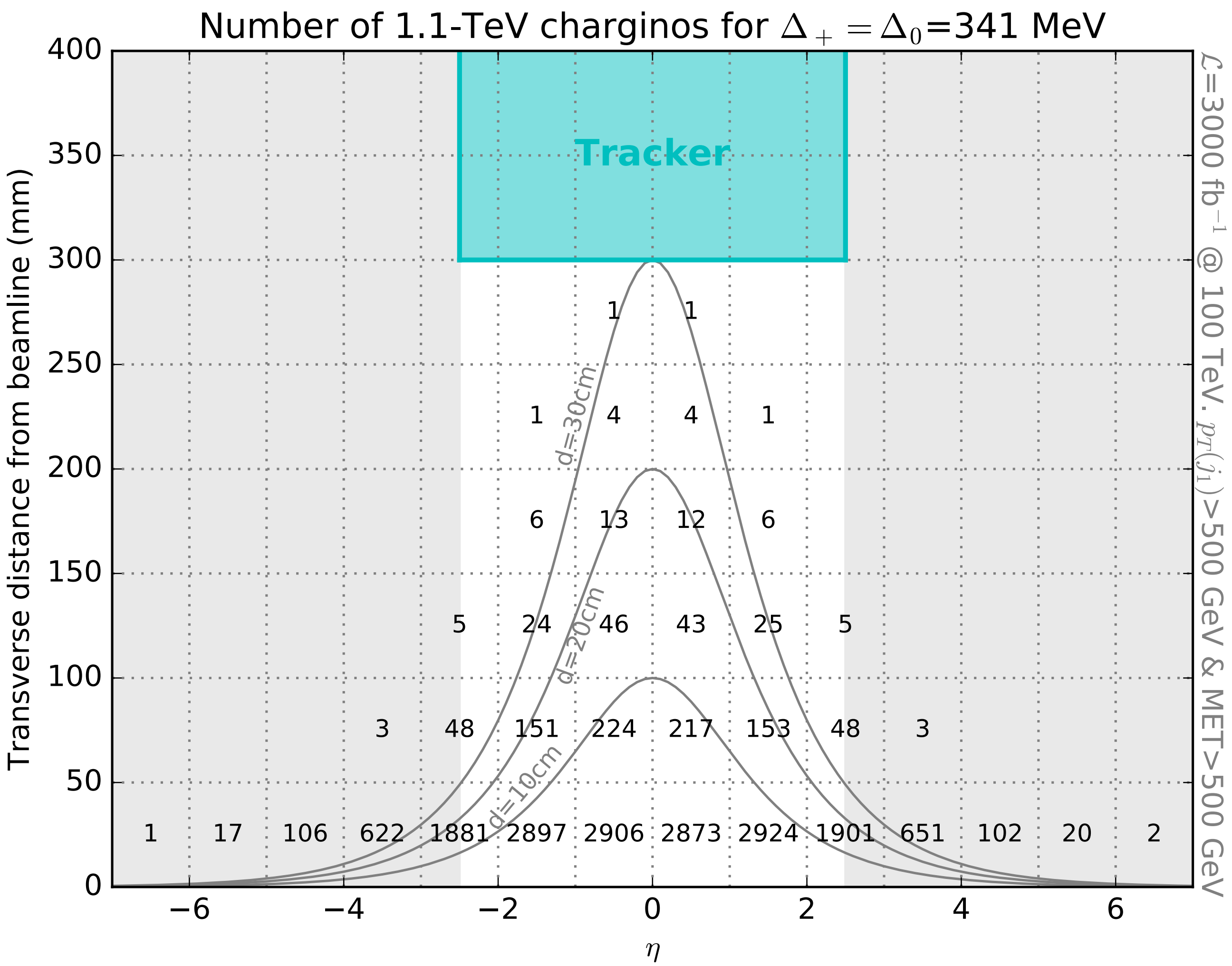
Moreover… who designed the LHC trackers??? why d_{min}= 30 cm???

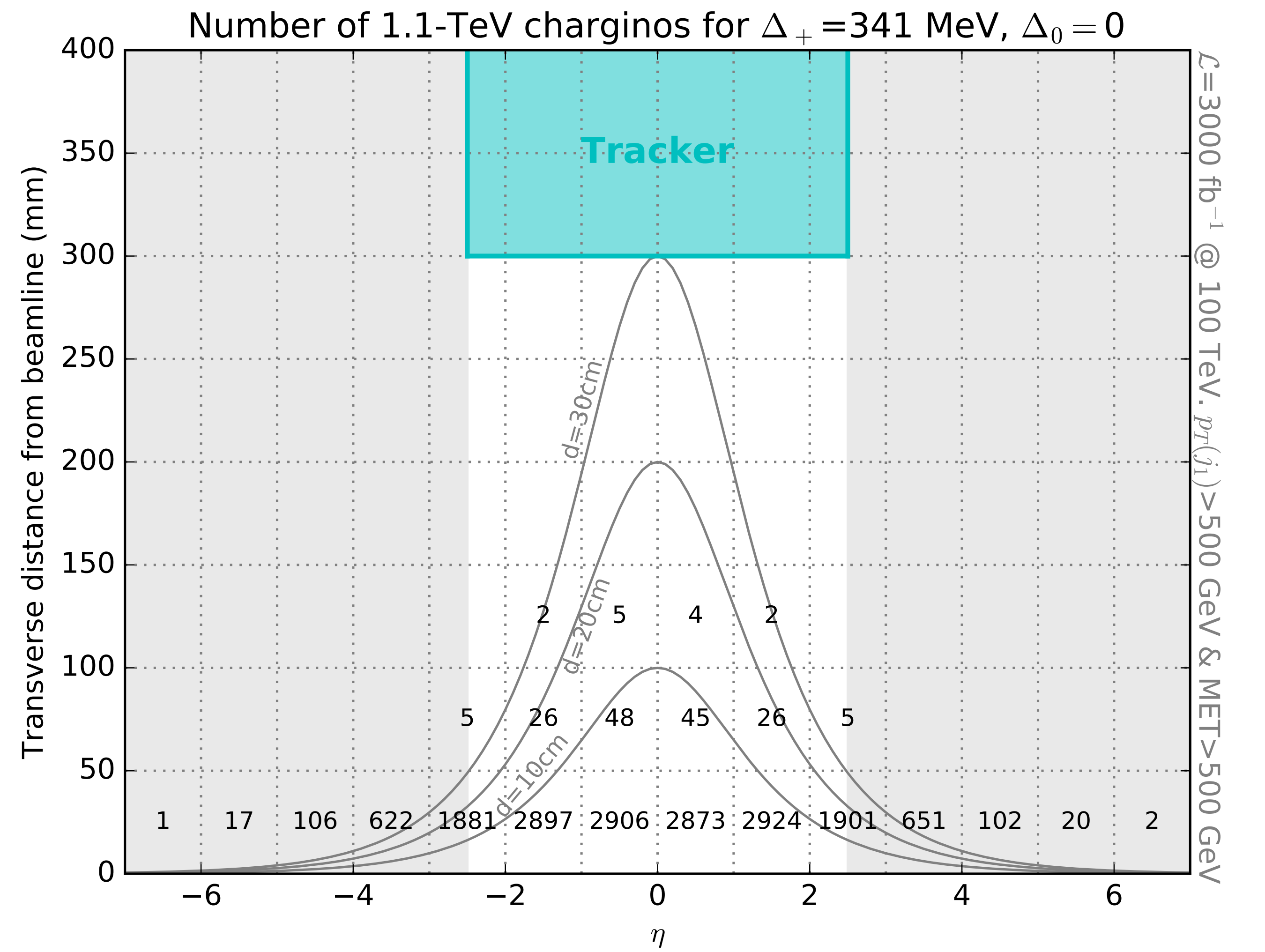
Detector proposal



Tracker design

A: "Squeezing" current geometry

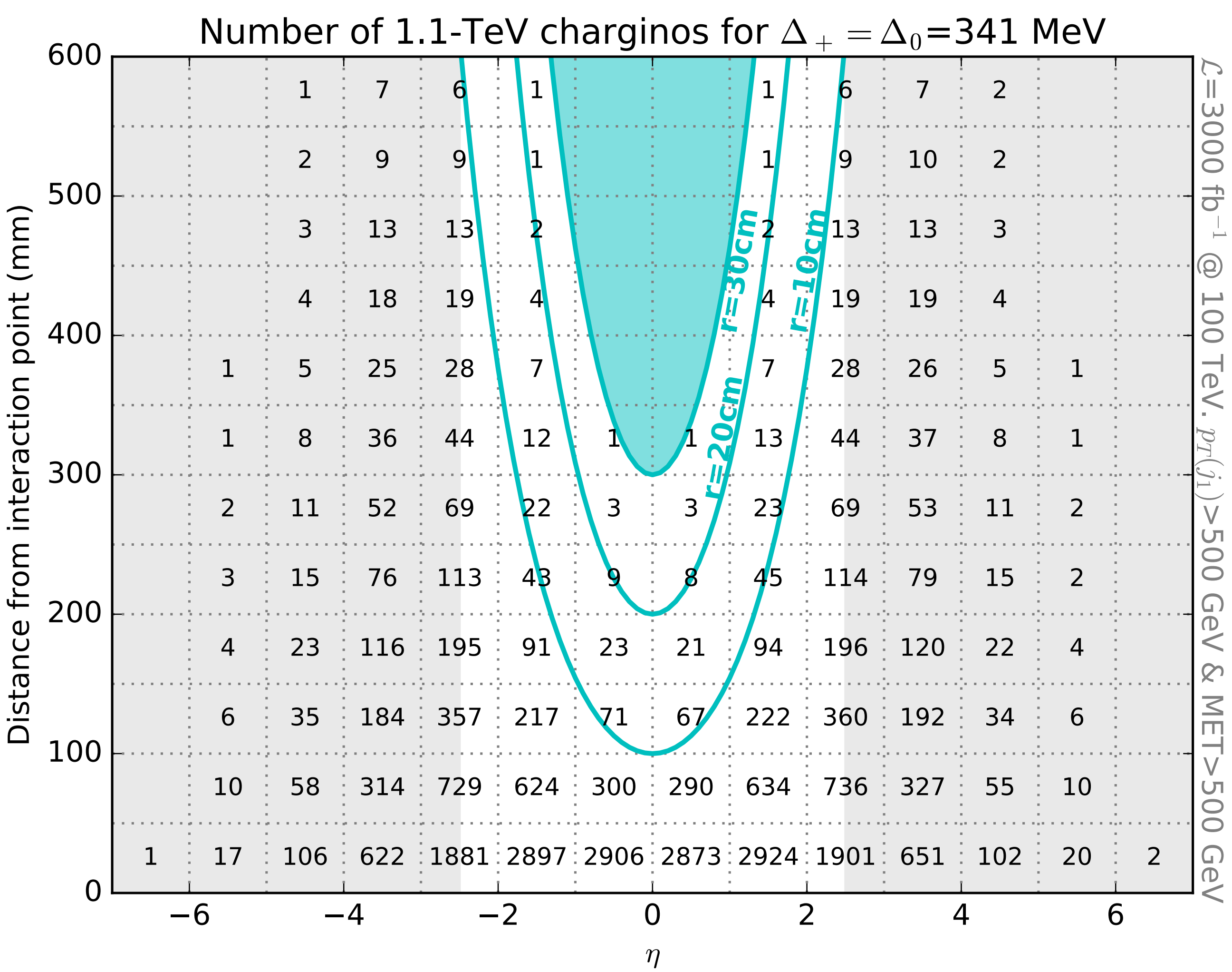


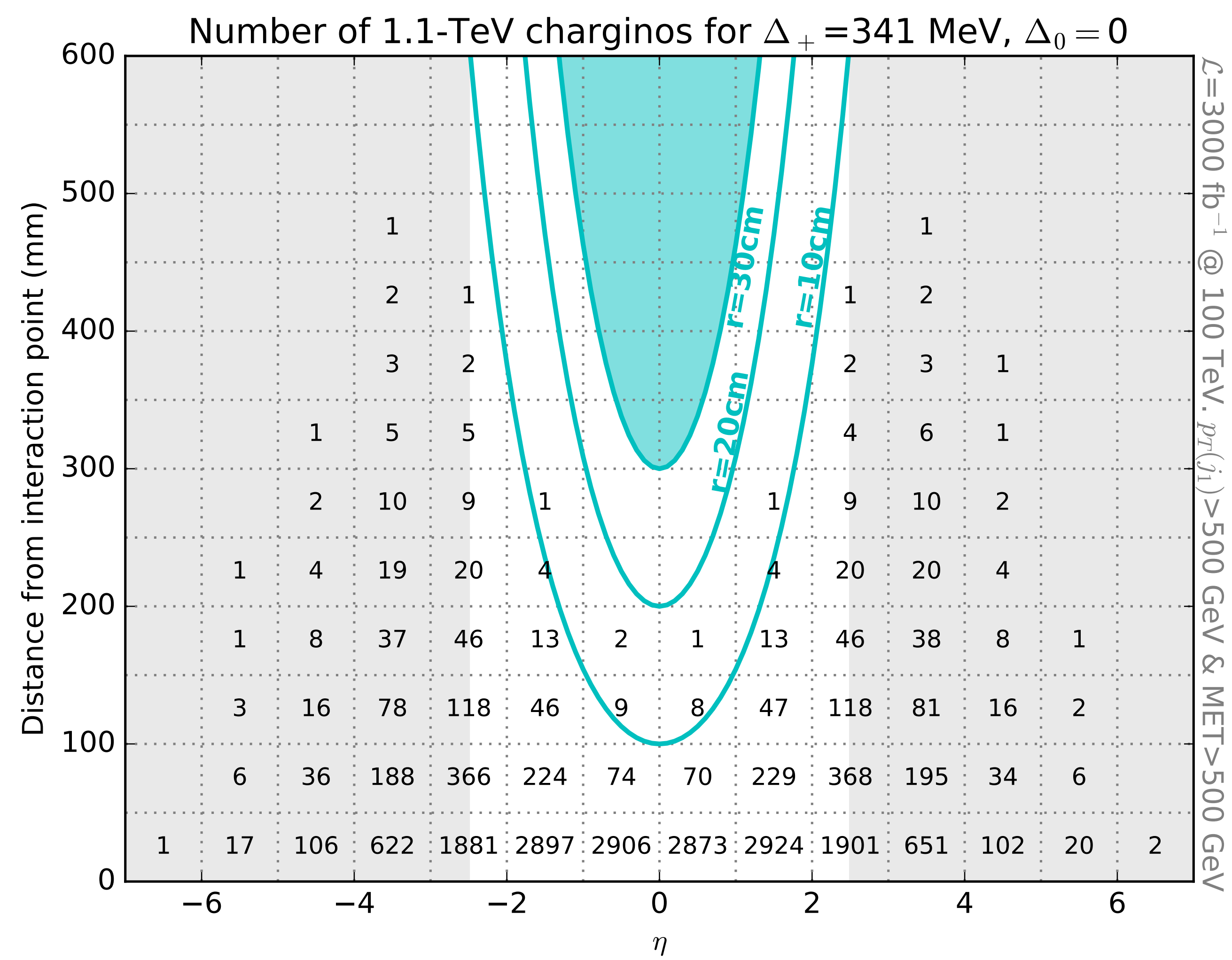


PRELIMINARY

Tracker design

B: Spherical Tracker

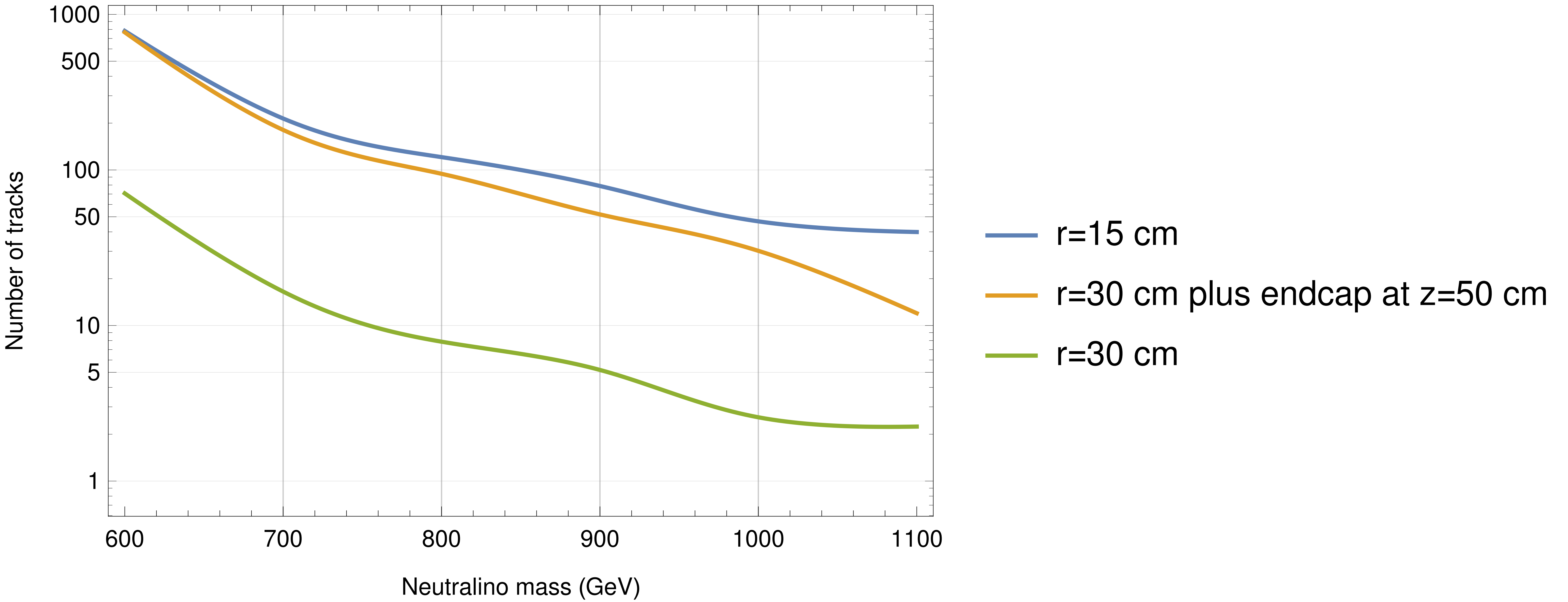




PRELIMINARY

Tracker design

C: Forward ("end-cap") tracker (very original!)



PRELIMINARY

Mono-Z analysis

@100 TeV FCC-hh

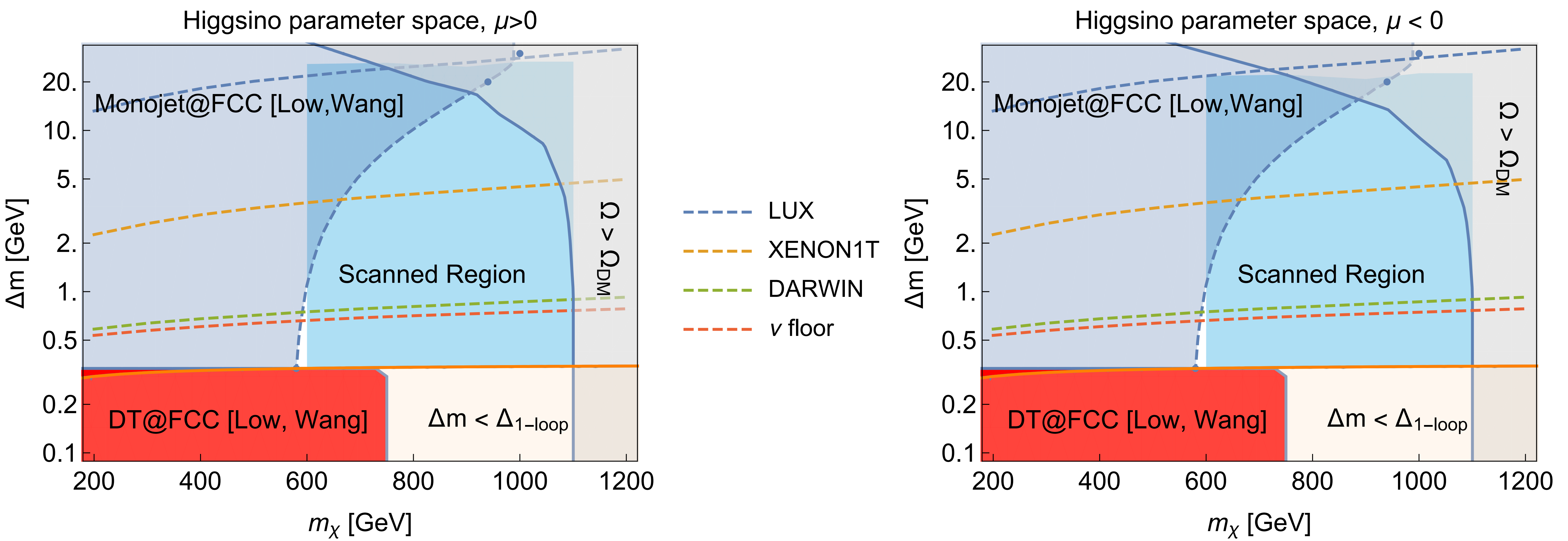
Mono-Z vs mono-jets

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: |μ| = 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 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: $p_T(l^+, l^-) > 400 \text{ GeV}$ or $H_T, \not{E}_T > 400 \text{ GeV}$.
- Event selection (basic cuts):
  - Tighter cut on > $\not{E}_T > 500 \text{ GeV}$.
  - Two OS leptons satisfying $p_T(l) > 50 \text{ GeV}, |m(l^+, l^-) - m_Z| < 15 \text{ GeV}$.
  - Jets: Allow up to one additional hard jet (pT > 50 GeV), veto-b-jets.
  - Ignore any hard jet within ΔR < 0.5 from the leptons.

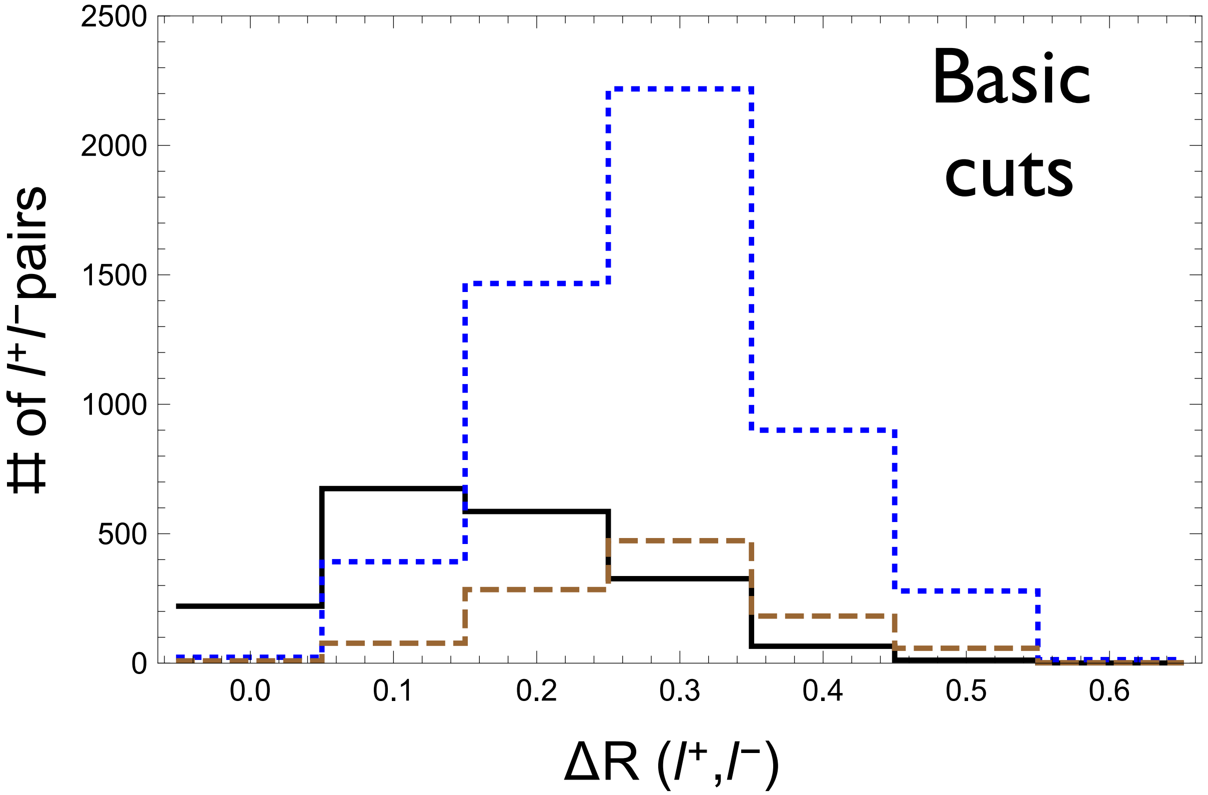
Angular separation

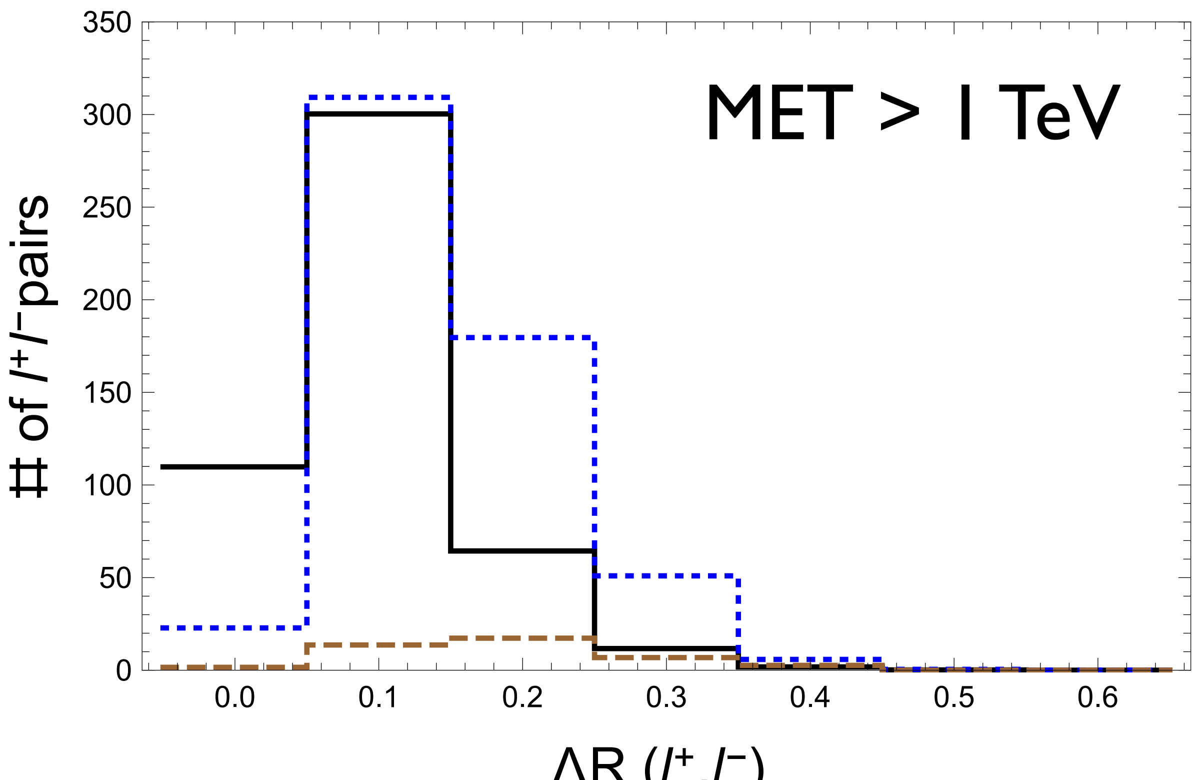
<u>Benchmark J:</u>

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

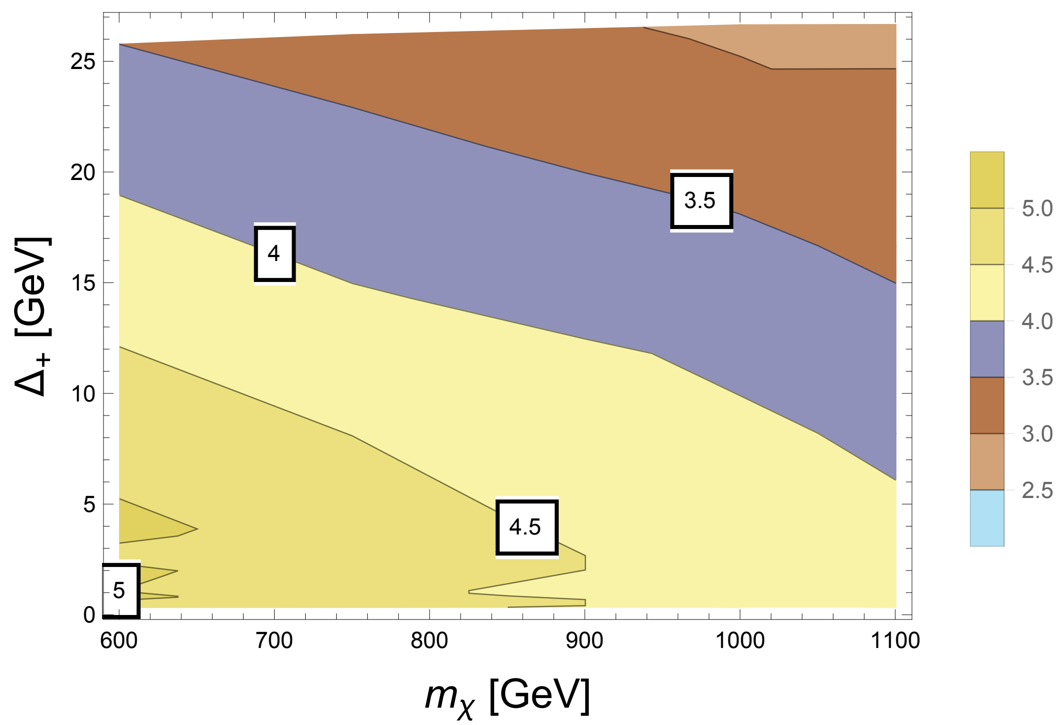
Table 1: Cut flow for the backgrounds and for a signal with $\mu = 1100$ GeV, $\tan\beta = 15$ and $M_1 =$ TeV. The numbers of events quoted correspond to a total integrated luminosity of 3000 fb^{-1} at a 100 TeV center-of-mass energy. We have defined $\delta M = |\frac{M_{ll} - m_Z}{\mathrm{GeV}}|$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

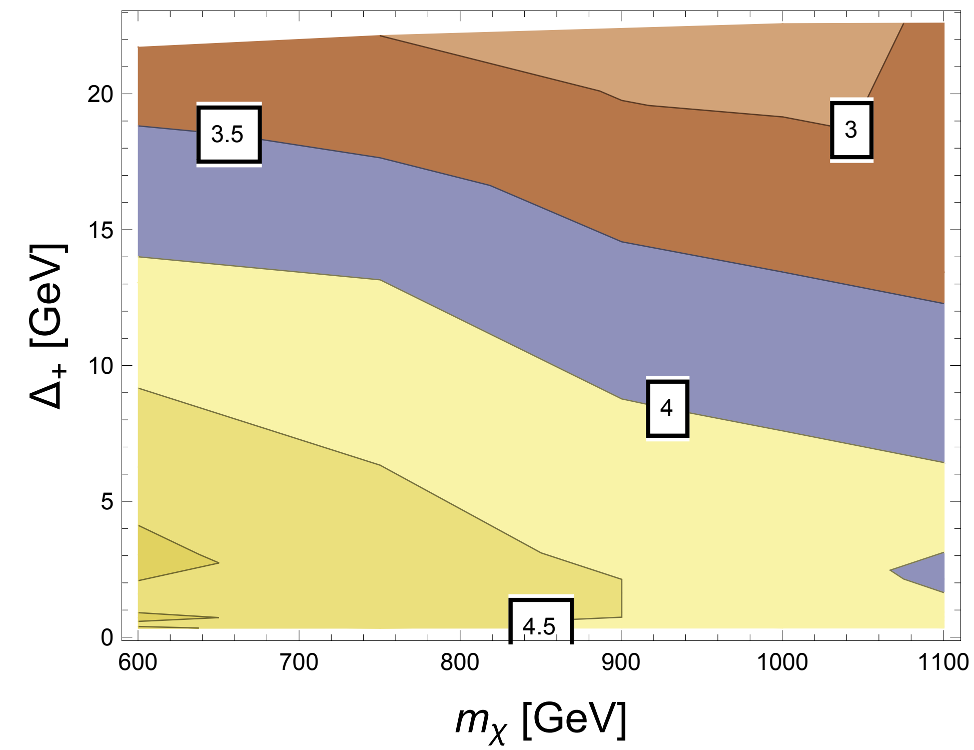
FCC reach

Lumi=3ab^{-1}

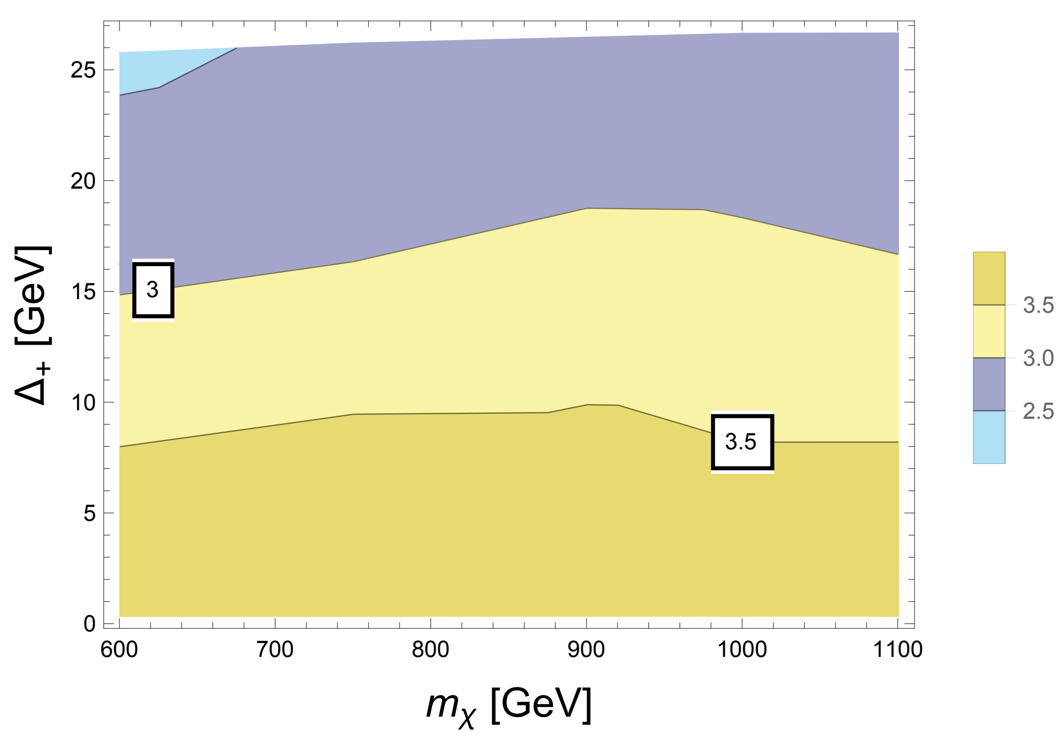
μ > 0 | μ < 0

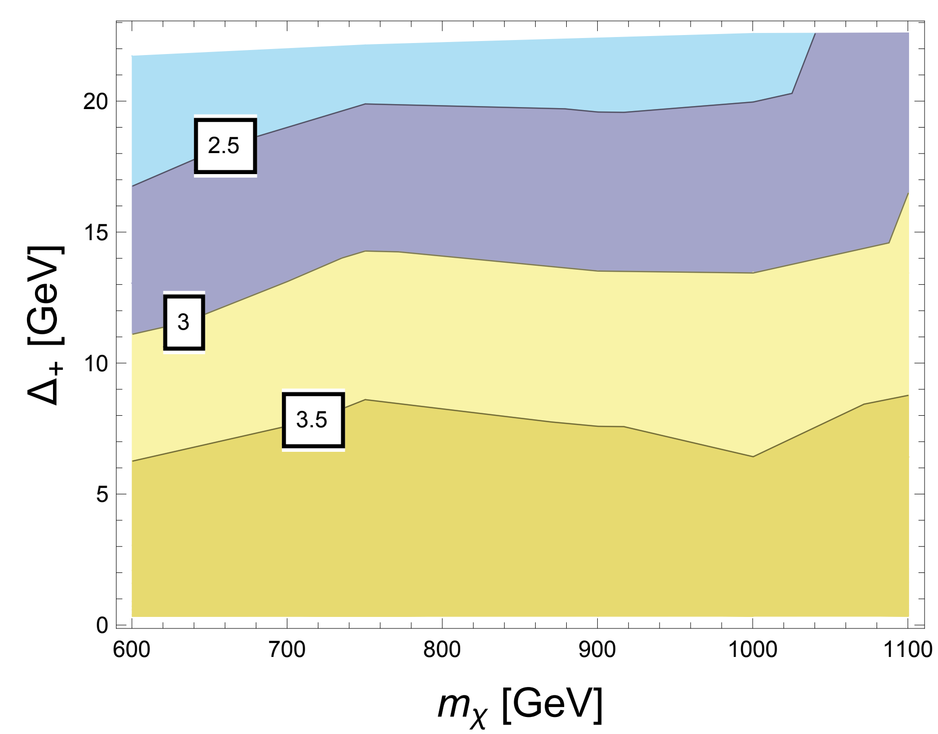
syst=0%





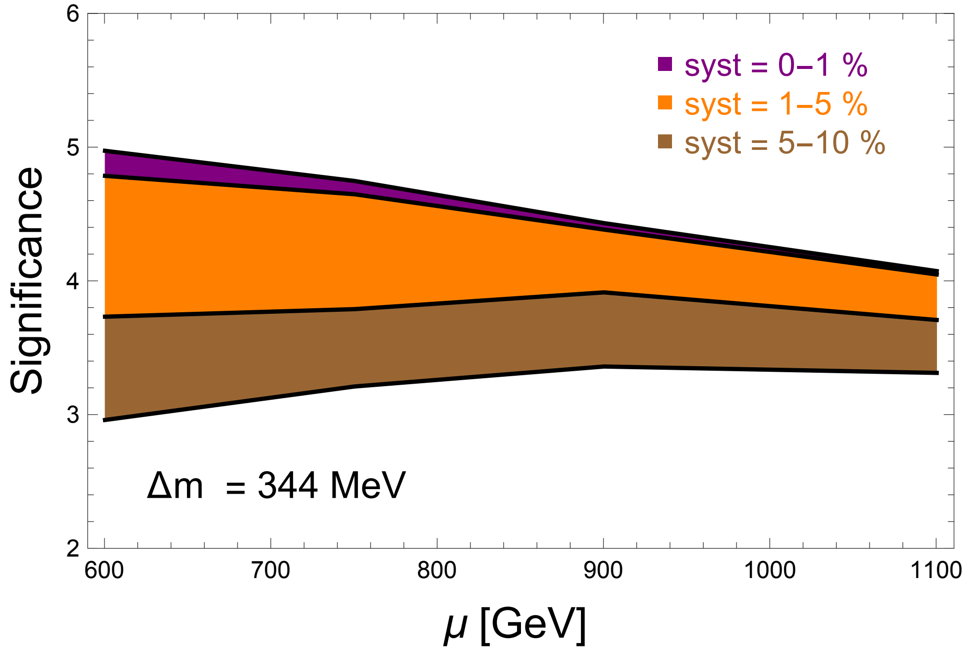
syst=5%

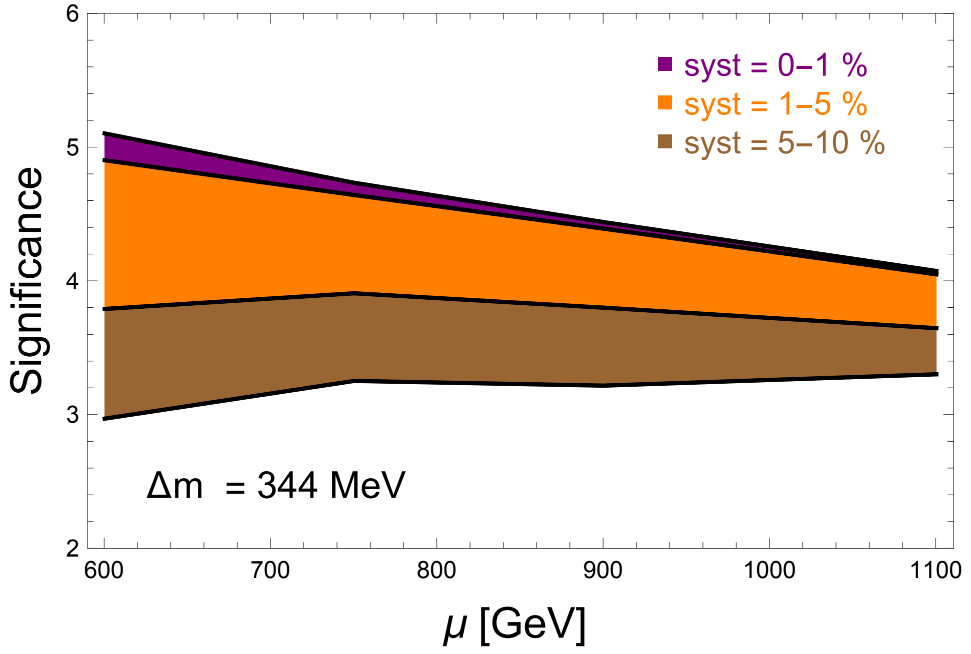


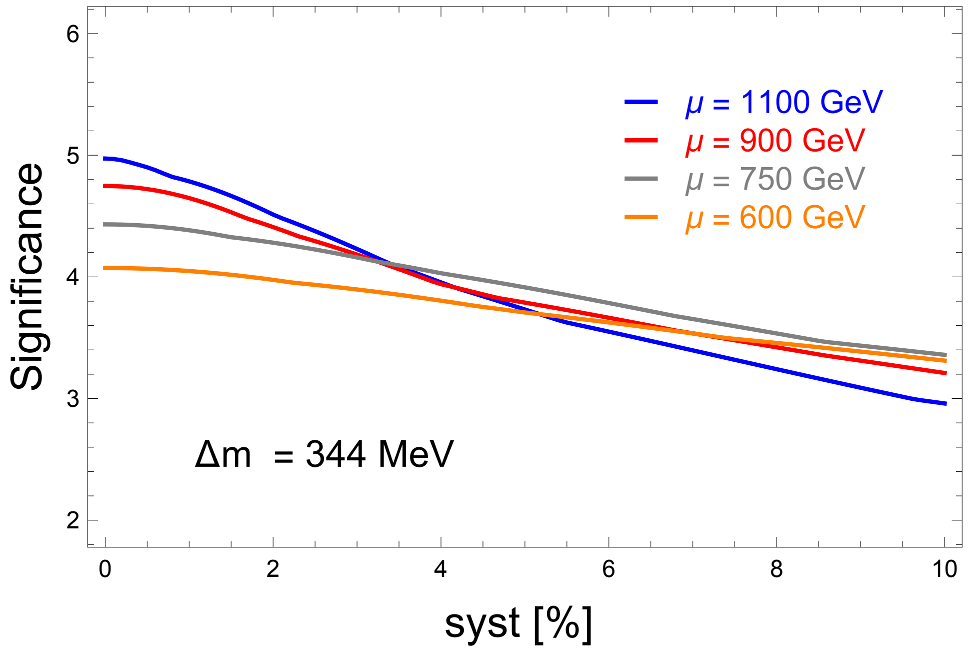


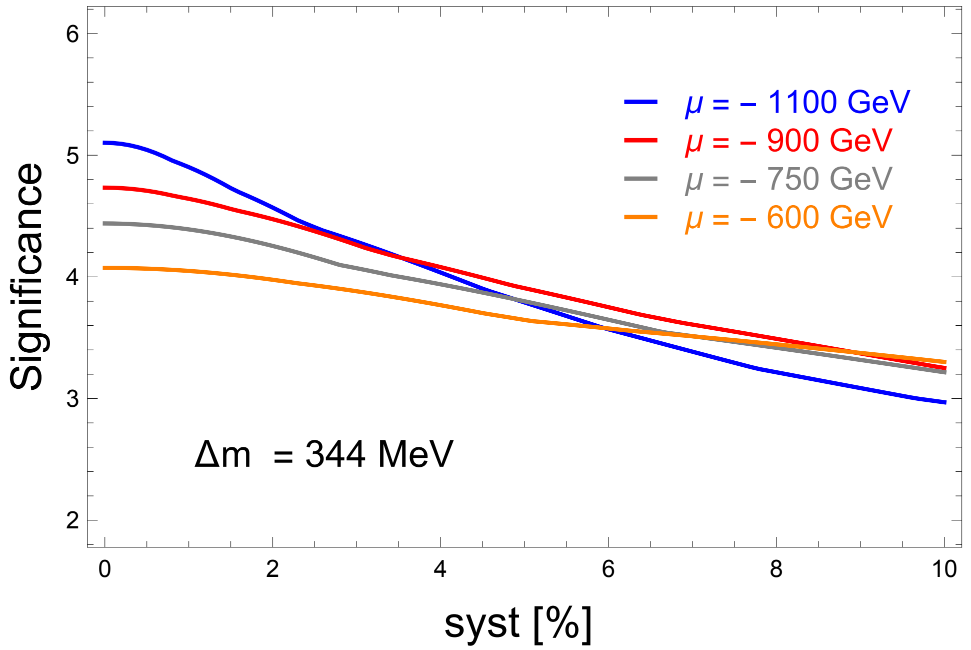
Role of systematics

μ > 0 μ < 0









Conclusions (1)

- SUSY is tightly constrained, but still room for surprises/discoveries.

- "Leave no stones unturned" approach: full coverage of parameter space.

- 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.

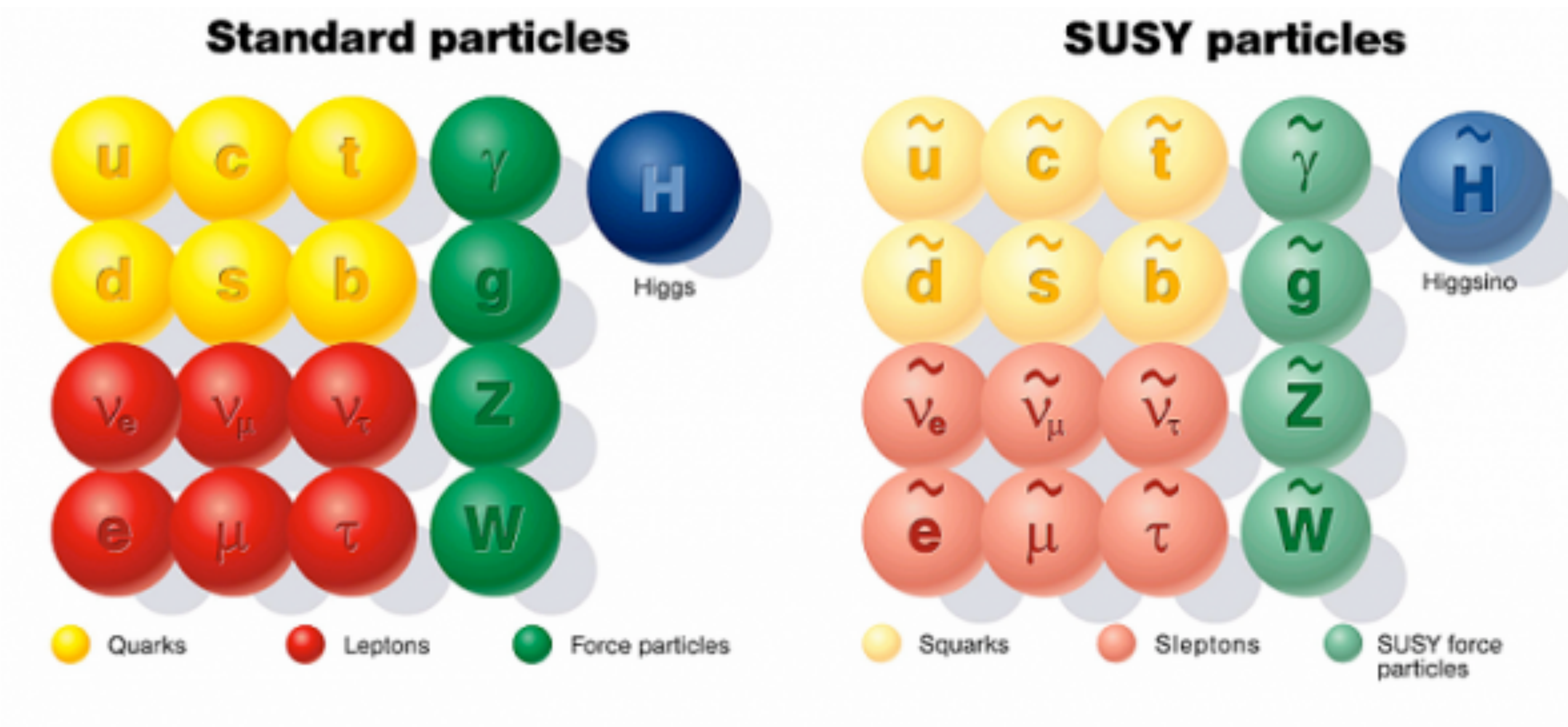
  - (a) 100 TeV detectors yet to be designed: historical chance to write the TDR. Hard to estimate the significance, yet O(10) signal events in "almost background-free" environment for 1.1 TeV Higgsinos.

  - (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???

Outlook (II)

Supersymmetry is out there!!!



"Phenomenological studies are right or wrong based on if they can be reproduced by real experimentalists and real detectors or not."

arXiv: 0910.4182