Status and prospects of collider searches for dark matter

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HRZZ
Hrvatska zaklada za znanost

Dark matter post naturalness

Strong motivation for physics beyond the standard model.

What do we know about dark matter?

$\Omega_{DM} = 0.25 \times \Omega_{TOT}$ (CMB + supernovae, Planck)

Gravitational interactions dominant at large distances

$\beta \ll 1$ during structure formation (DM simulations)

Small (if any) scattering XS with itself/γ/ν (DM simulations + baryons)

$\tau_{DM} \gg \tau_{universe}$

See Boehm, Nucl.Phys. B 1003 (2024) 116503 and references therein

Dark matter post naturalness

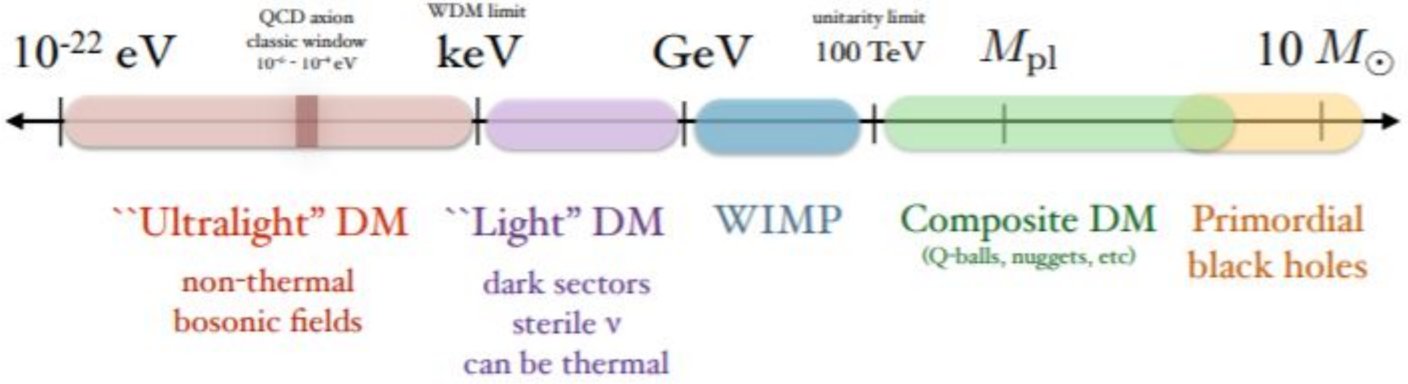


Figure credit: Tongyan Lin arXiv:1904.07915v1

Dark matter post naturalness

Talk by Sebastian

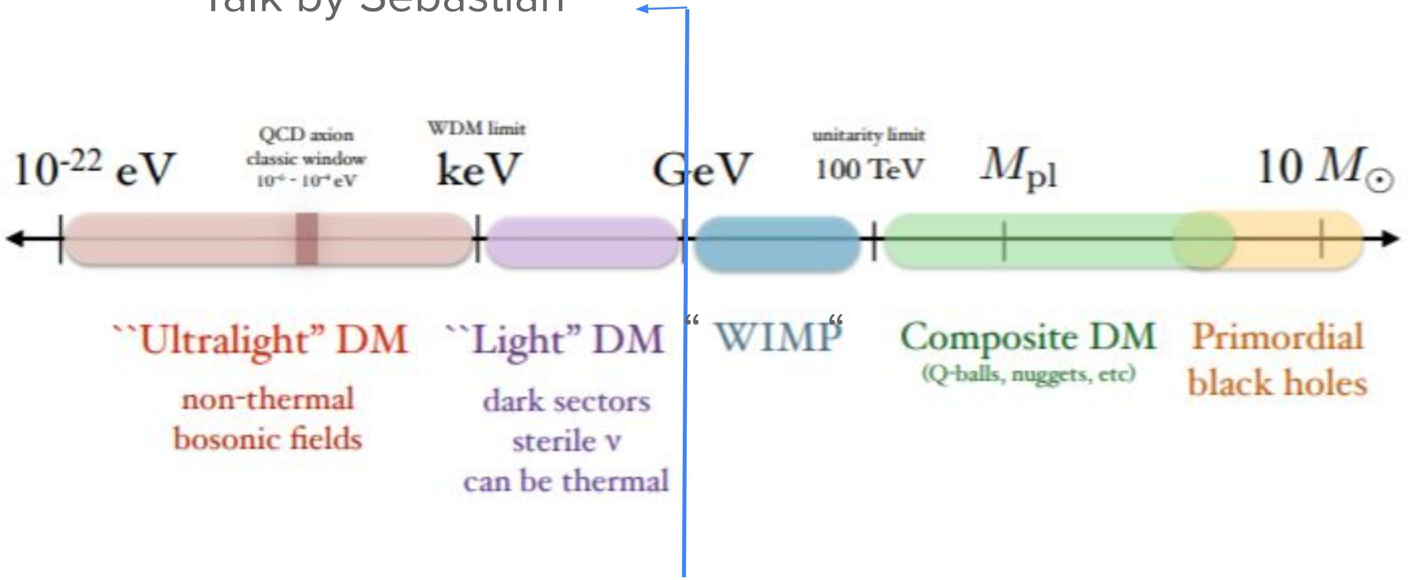
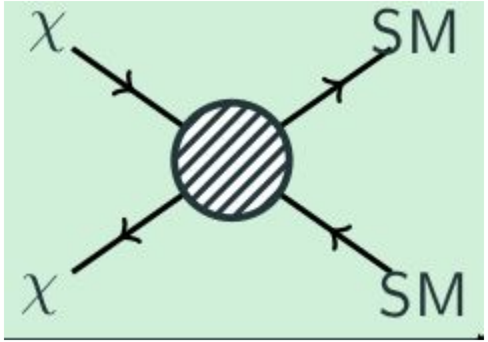


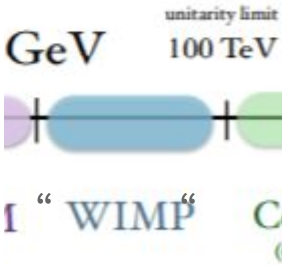
Figure credit: Tongyan Lin arXiv:1904.07915v1

Dark matter at colliders

Sizeable couplings to SM (large enough for DM-SM thermal equilibrium in early universe).



Direct + indirect detection - see Paolo's talk



Also: extended scalar sectors,
Accidental dark matter,
Composite dark matter,

This talk: 'minimal' models of DM - pure electroweak multiplets.

Predictive...

e.g. $$\mathcal{L}_{\rm BSM} = i\bar{\chi}\not{D}\chi - M_\chi\bar{\chi}\chi + \ldots$$ (Dirac fermion)

The original 'wimp miracle' $\sigma \sim \frac{\alpha_2^2}{M_{\rm weak}^2}$

Saturating thermal relic abundance fixes mass

$$\Omega h^2 \approx 0.1 \times \left(\frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle}\right)$$

M_χ =
1.1 TeV (Dirac (1, 2, -½) "higgsino")
2.8 TeV (Majorana (1, 3, 0) "wino")
14 TeV (Majorana (1, 5, 0) "quintuplet" fermion)

Cirelli et. al. hep-ph/0512090

This talk: ‘minimal’ models of DM - pure electroweak multiplets

‘Universal’ constraints:

Sensitive only to gauge charges and # d.o.f. Insensitive to mass splittings

Mono-X

Precision searches

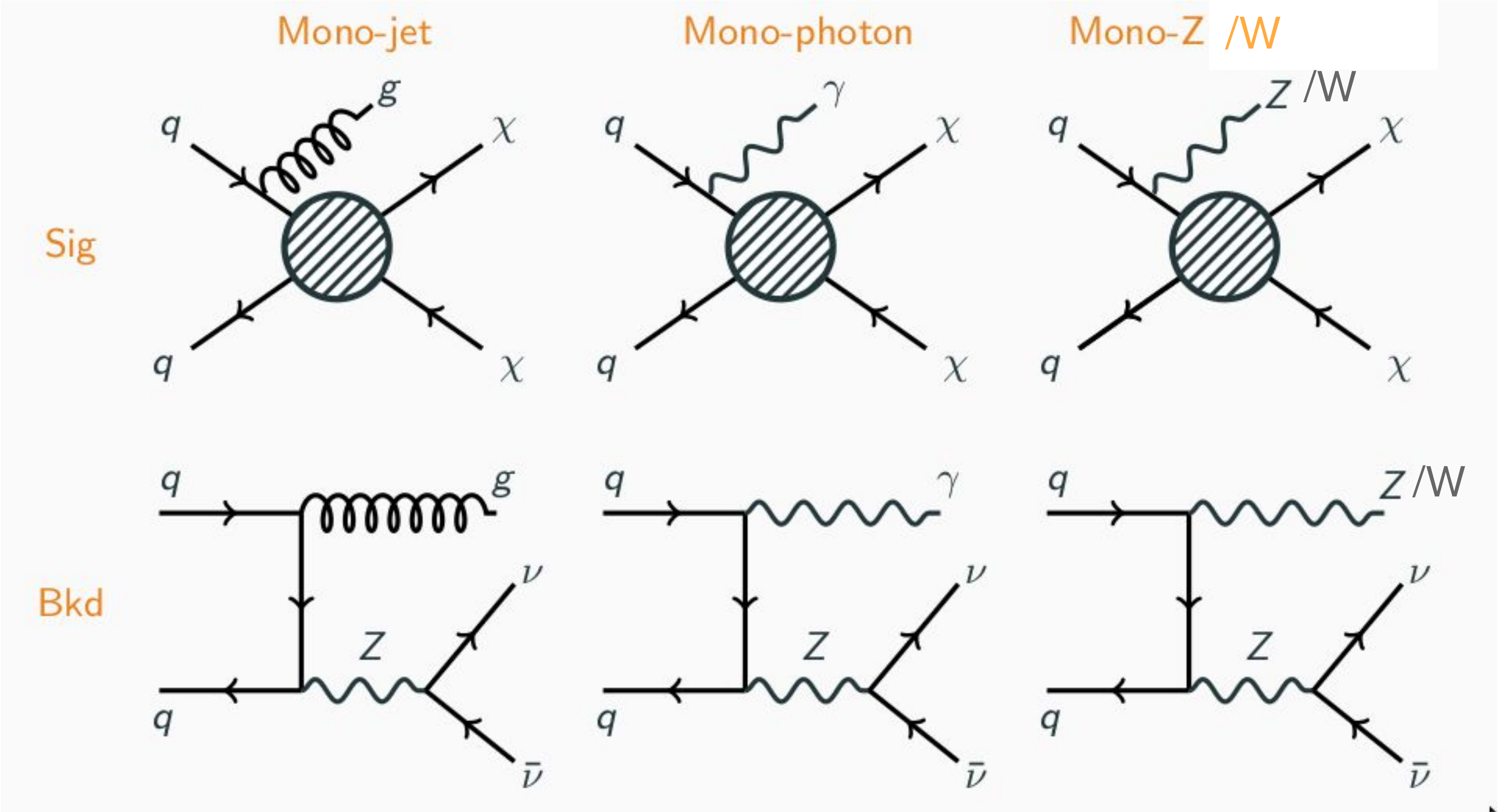
Mass-splitting constraints:

Disappearing charged tracks

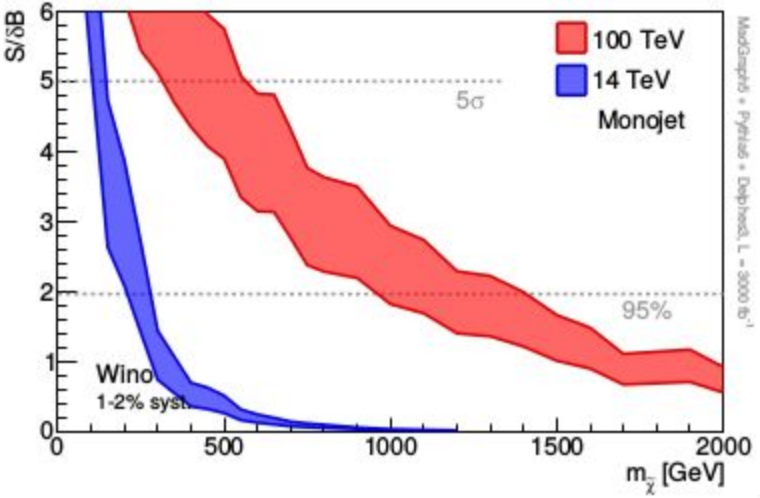
with special focus on “higgsino”

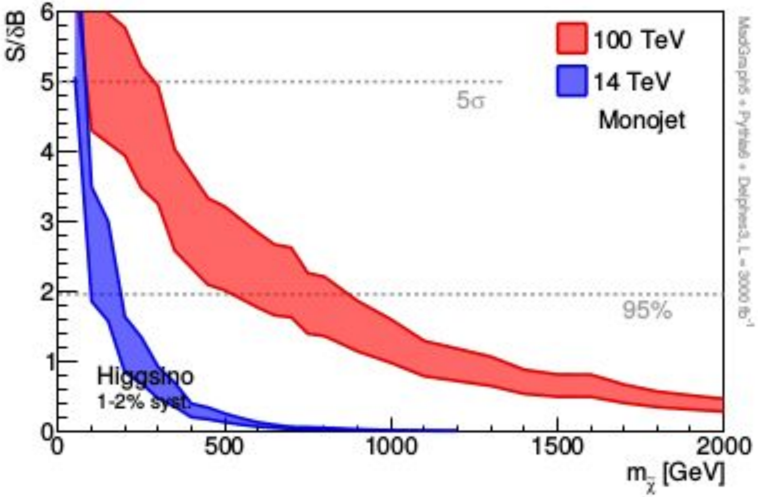
Universal constraints

Mono-X (X+MET) searches



Mono-X at future colliders





Low & Wang arXiv:1404.0682
(see also Cirelli et. al. arXiv:1407.7058)

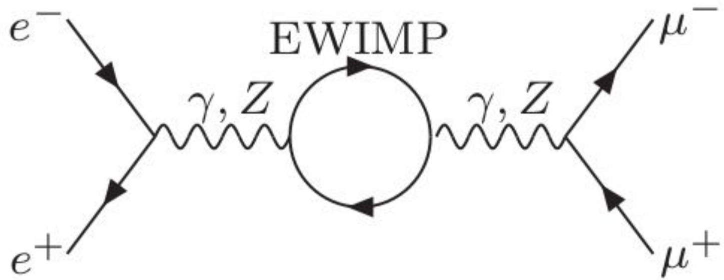
Quintuplet: 95% exclusion for M_χ< 691 GeV for LHC13 and <3.8 TeV for 30 ab^{-1} at FCC-hh (no systematics)

Cao et. al. arXiv:1810.07658

Di Luzio et. al. arXiv:1810.10993
Also: Harigaya et. al. arXiv:1504.03402

Precision searches in Drell-Yan

New EW multiplets give universal corrections to the Drell-Yan processes pp→ℓ⁺ℓ⁻, ℓν (ℓ⁺ℓ⁻→f f̄ at lepton colliders).



Can be sizeable close to pair-production threshold.

Parametrized by gauge boson form factors Π:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{g^2 C^{\text{eff}}_{WW}}{8} W^a_{\mu\nu} \Pi(-D^2/m_\chi^2) W^{a\mu\nu} + \frac{g'^2 C^{\text{eff}}_{BB}}{8} B_{\mu\nu} \Pi(-\partial^2/m_\chi^2) B^{\mu\nu}$$

Precision searches in Drell-Yan

Di Luzio et. al. arXiv:1810.10993

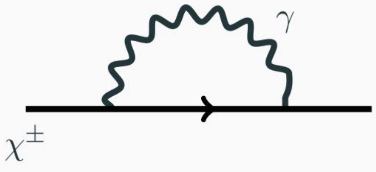
Cut-and-count analysis

χ	Thermal M_χ (TeV)	HL-LHC	HE-LHC	FCC100	CLIC3	Muon14
higgsino	1.1	-	-	-	0.4	0.6
wino	2.8	-	-	0.4	0.6 & [1.0, 2.0]	1.0
quintuplet	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]

95% CLS exclusion for: HL-LHC ($\sqrt{s}$ = 14 TeV, L = 3 ab^{-1}); HE-LHC ($\sqrt{s}$ = 28 TeV, L = 10 ab^{-1}), FCC100 ($\sqrt{s}$ = 100 TeV, L = 20 ab^{-1}), CLIC3 ($\sqrt{s}$ = 3 TeV, L = 4 ab^{-1}), Muon14 ($\sqrt{s}$ = 14 TeV, L = 20 ab^{-1})

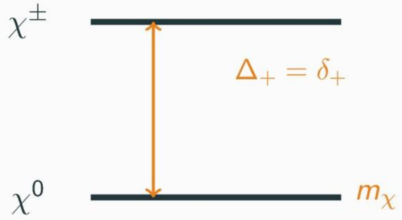
Mass splitting constraints

Mass splitting



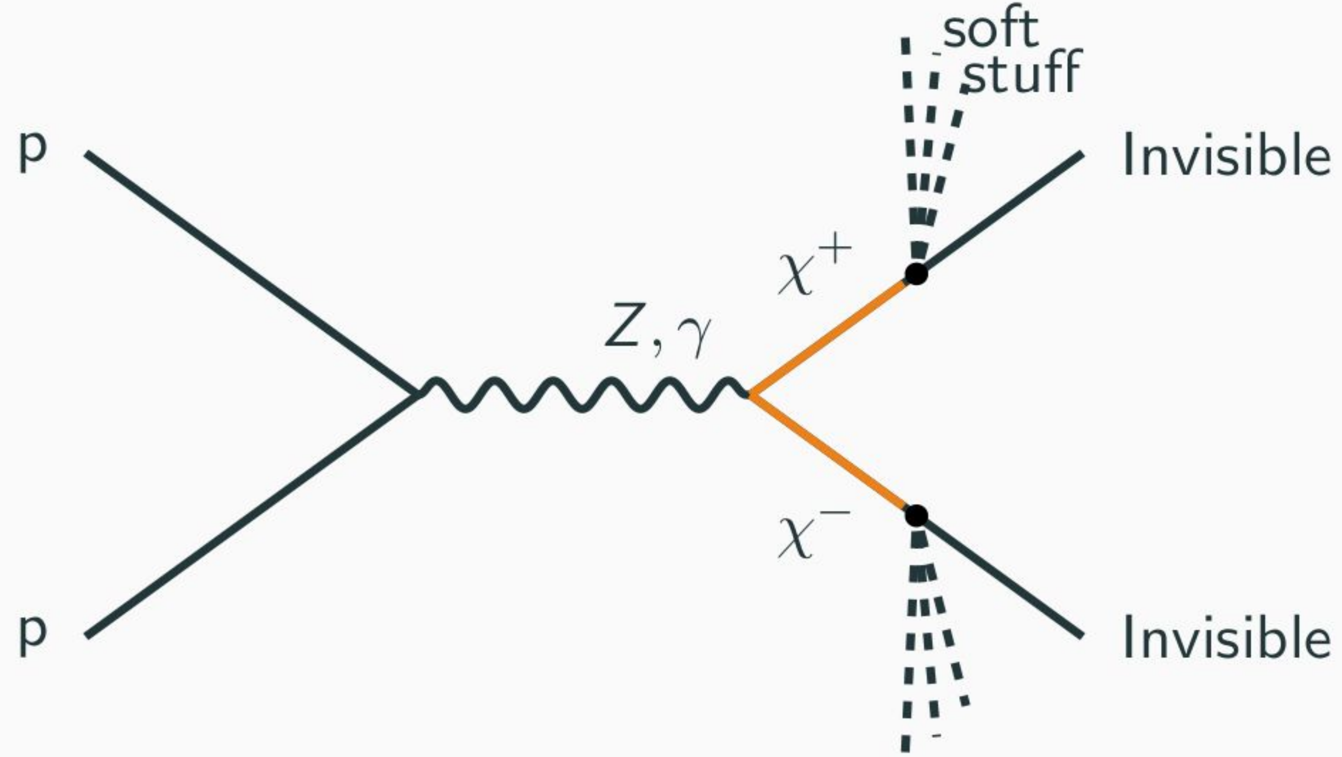
$\delta^{+} \sim \frac{\alpha}{2} m_Z = \mathcal{O}(300\ \text{MeV})$ +UV (higgsino)

O(165 MeV) (wino)



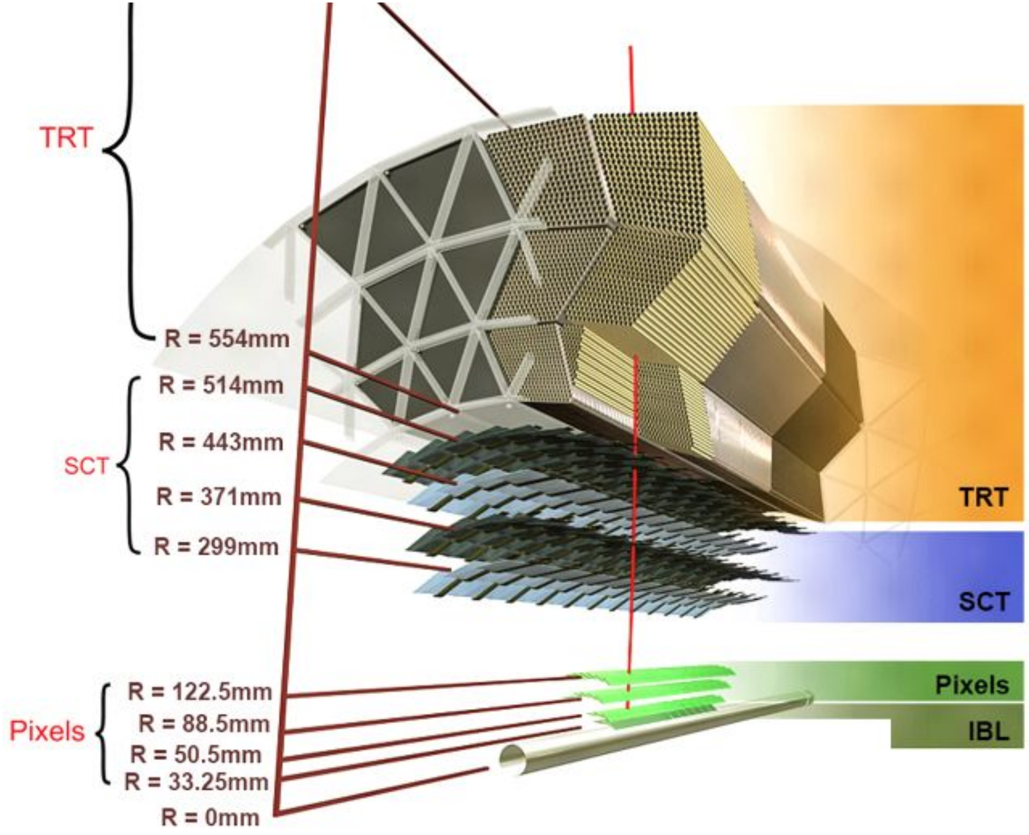
‘Chargino’ cτ = 6.6 mm (higgsino)
6 cm (wino)

‘Disappearing’ track

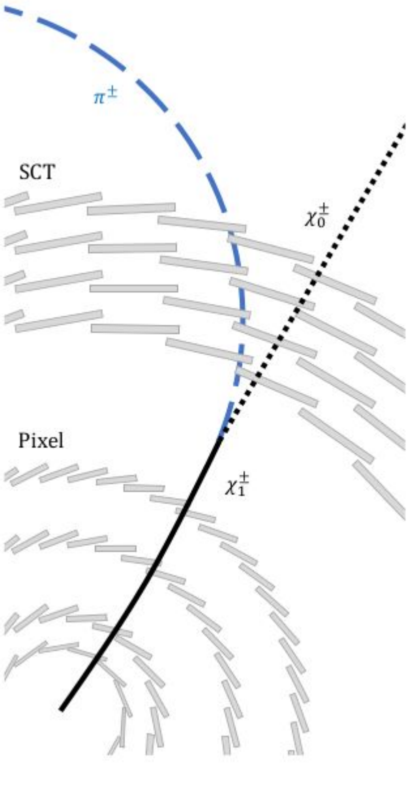


Decay predominantly via soft $\pi^{\pm}$ in inner tracker. Must be boosted to pass selection

'Disappearing' track



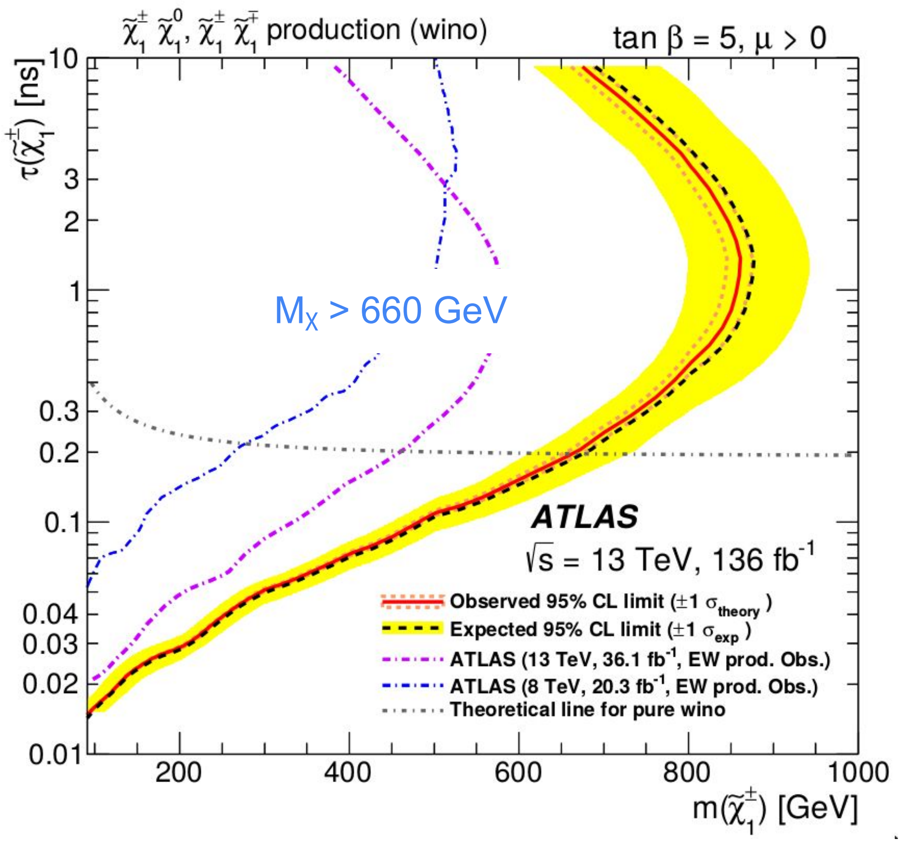
ATLAS (CMS setup similar)

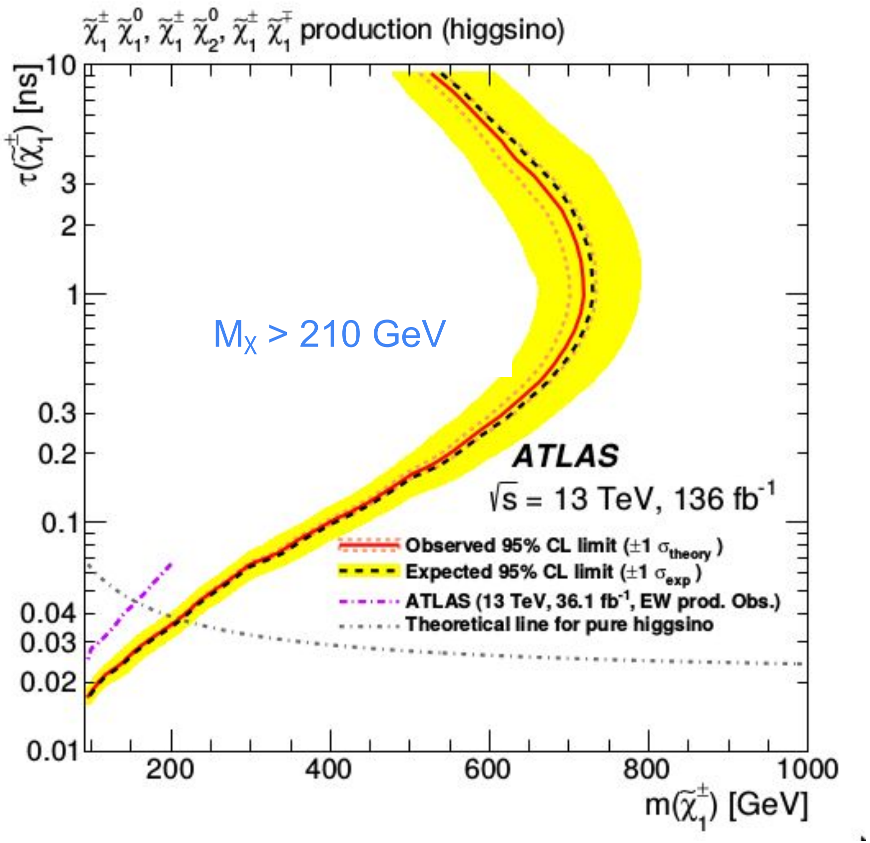


ATLAS require 4 pixel hits

ATLAS results

arXiv:2201.02472





Room for improvement?

Decrease MET cut (MET correlated with vector sum of higgsino p_T, gives loss in efficiency).

Exploit 'free' forward boost.

Decrease # pixel hits for selection.

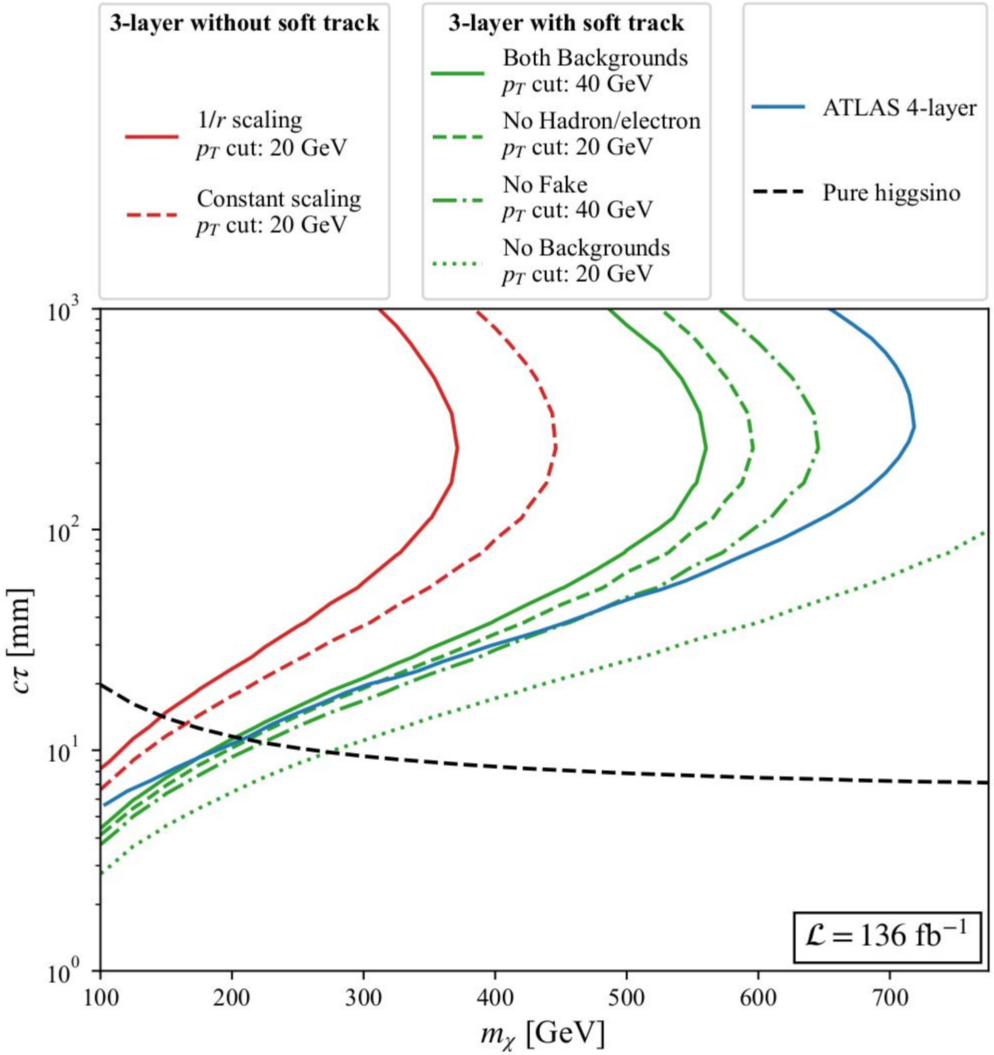
RM, Schwaller, Zurita arXiv:1703.05327

Significant increase in background

Use soft pion?

Results

Hmmm...

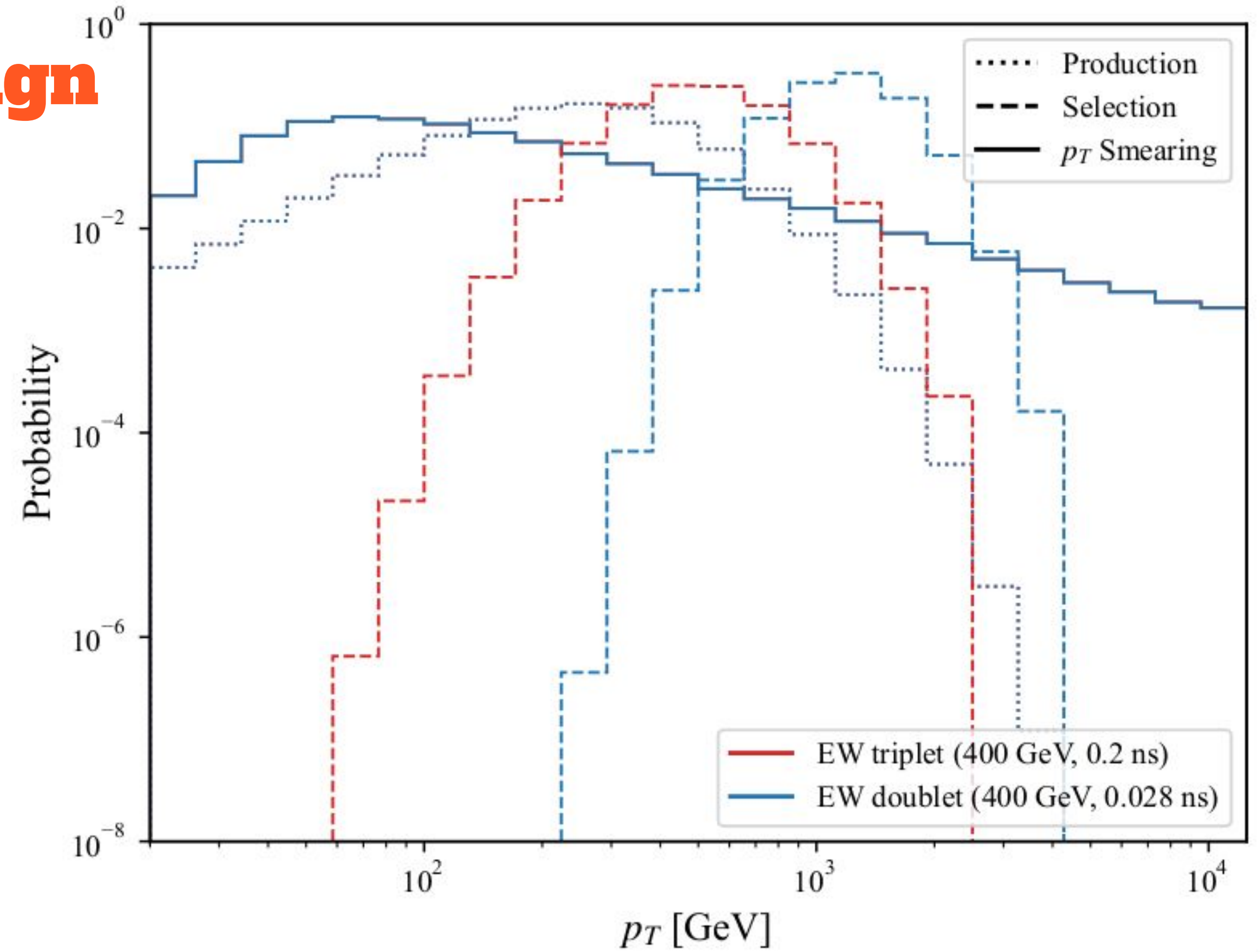


Gignac, RM, Kilic, Youn
arXiv:2211.06949

Smear campaign

Short, high-pT track, resolution is abysmal.

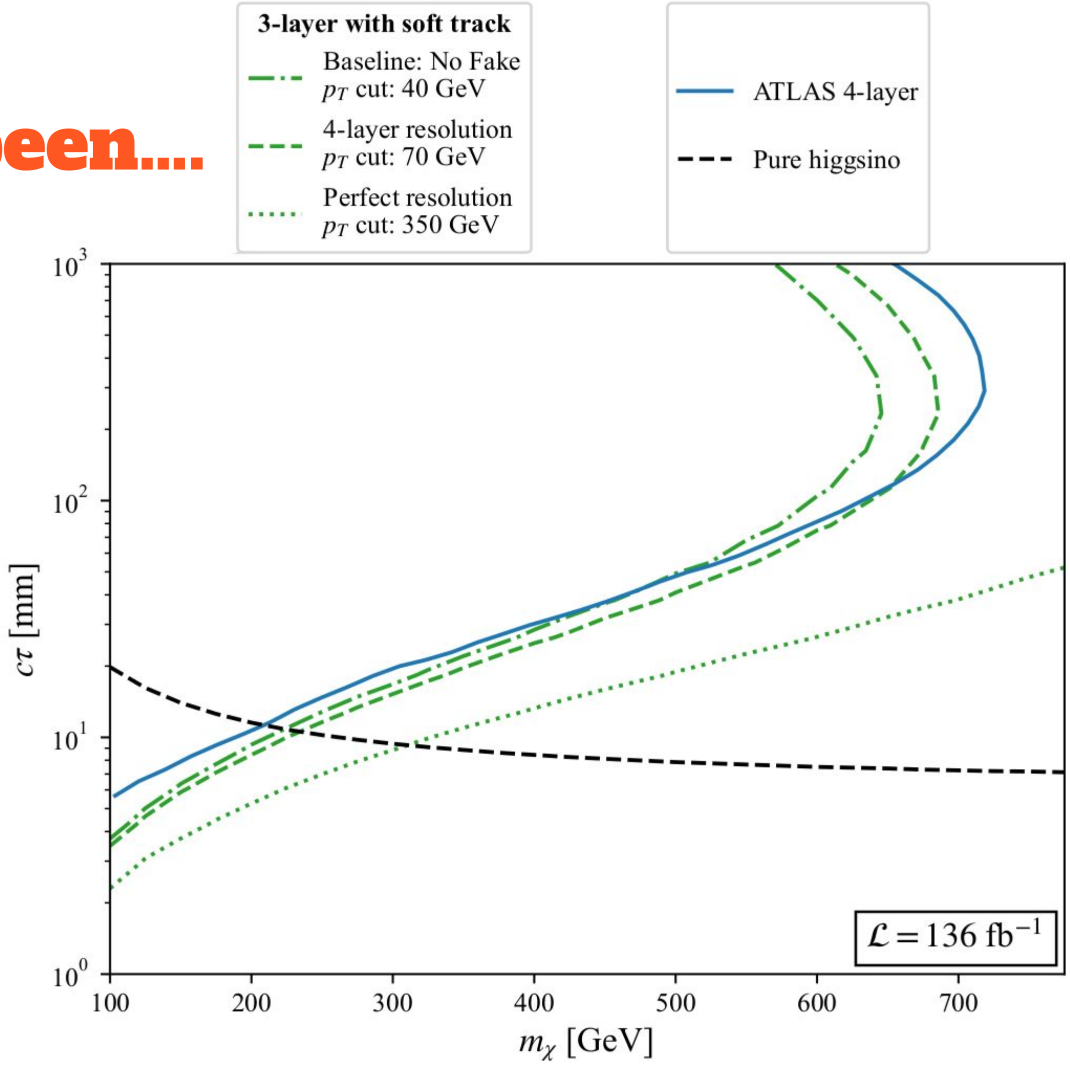
We can't access the smoking gun.



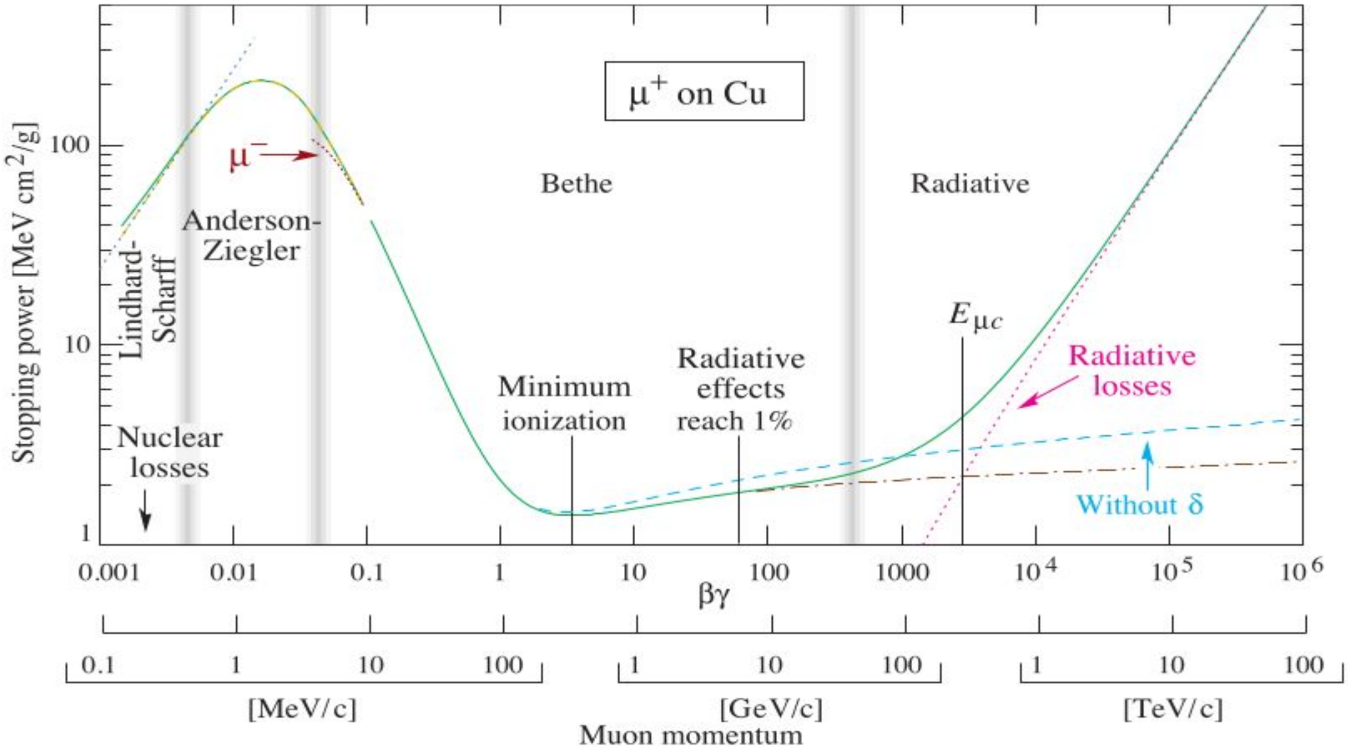
What might have been....

How can we access tracklet p_T information?

dE/dx?



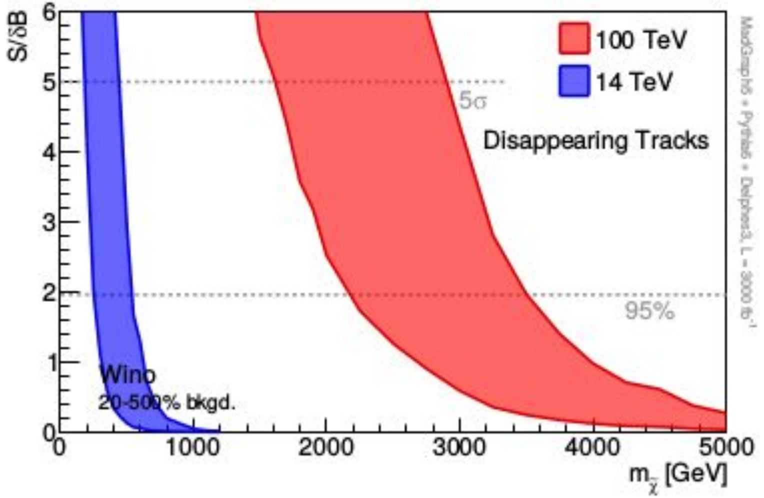
The problems with dE/dx



$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

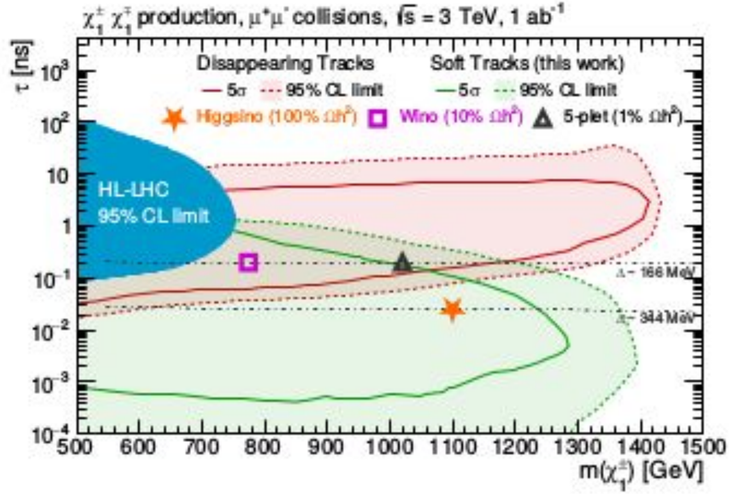
Need independent mass measurement for momentum determination.

Disappearing charged tracks: prospects



Low & Wang arXiv:1404.0682

Exclusion of almost entire thermal window at FCC100



Capdevilla et. al. arXiv:2405.08858

For thermal higgsino need ‘soft tracks’ and Muon3.

A message from our sponsors

"Disambiguating DM with dileptons + MET" - Royal Society collaboration RBI + Southampton, coming soon.

This talk generated
739 kg CO_2eq.

Environmental sustainability in basic research

A perspective from HECAP+

Sustainable HECAP+ Initiative

Accepted for publication in JINST!
Please read,and endorse here: https://sustainable-hecap-plus.github.io/

Summary

Unlike cosmological and astroparticle detectors, colliders can probe subleading components of DM.

Searches for pure EW multiplet DM at colliders:

Status: dim (particularly for higgsino) $M_\chi > 210$ GeV.

Prospects: bright(er)

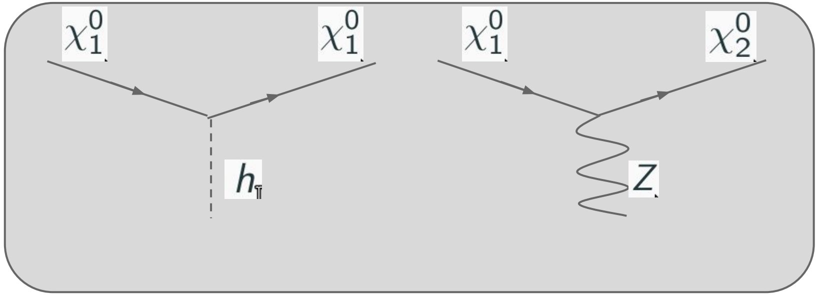
But we need to wait for muon collider (?!)

Unless we can we find a way to exploit smoking gun tracklet p_T.

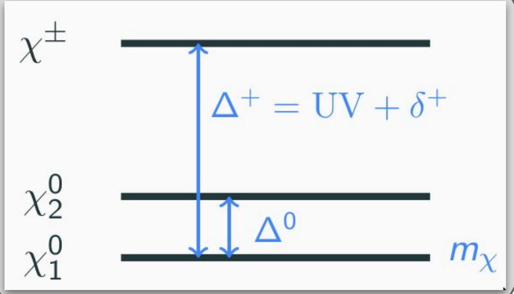
Backup

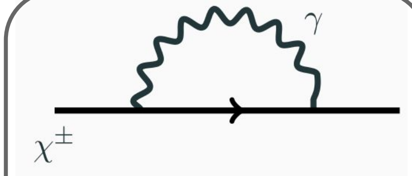
Effective theory for weak doublet fermion

$$\mathcal{L}_{\rm BSM} = i\bar{\chi}\not{D}\chi - \mu\bar{\chi}\chi + \frac{c_+}{\Lambda_{\rm UV}} H^\dagger \frac{\sigma^j}{2} H \, \bar{\chi}\frac{\sigma^j}{2}\chi + \frac{c_0}{\Lambda_{\rm UV}} (\bar{\chi}^c\chi)(H^c H) + \cdots + \cdots$$



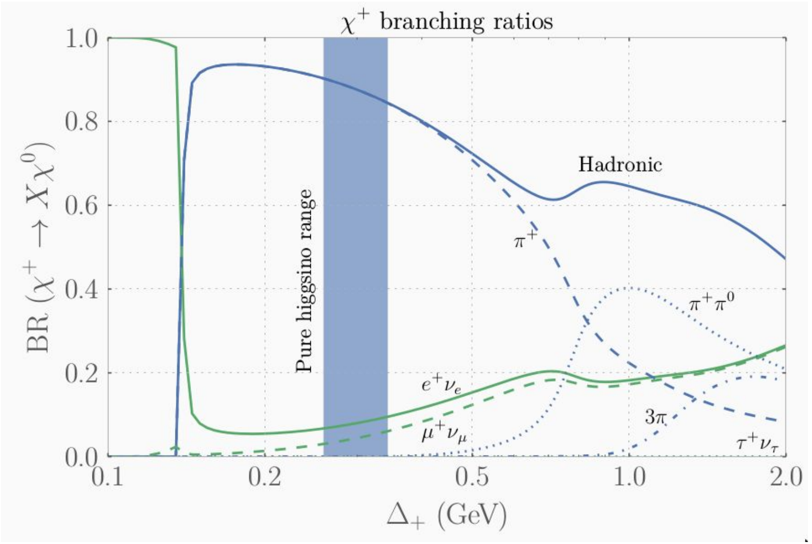
EWSB

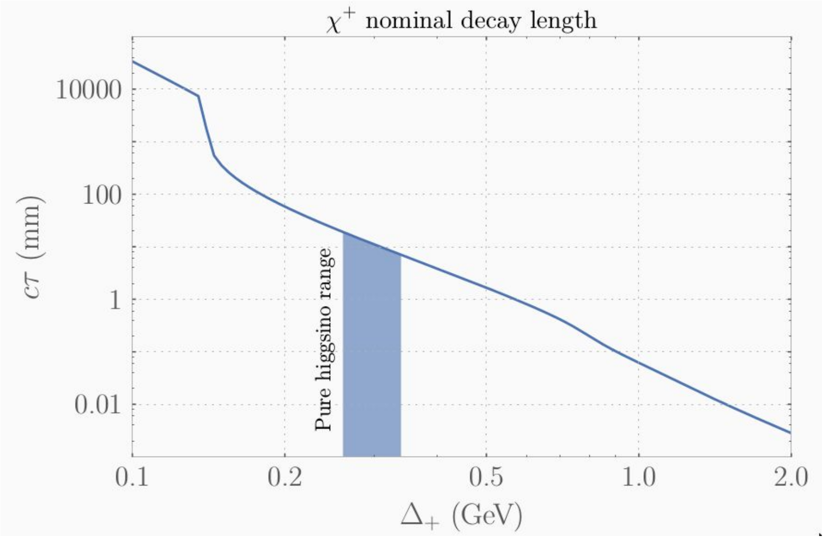




$$\delta^+ \sim \frac{\alpha}{2} m_Z = \mathcal{O}(300\ \text{MeV})$$

Leveraging charged component





$\Gamma_{\pi\chi^0} \propto \Delta_+^3$,

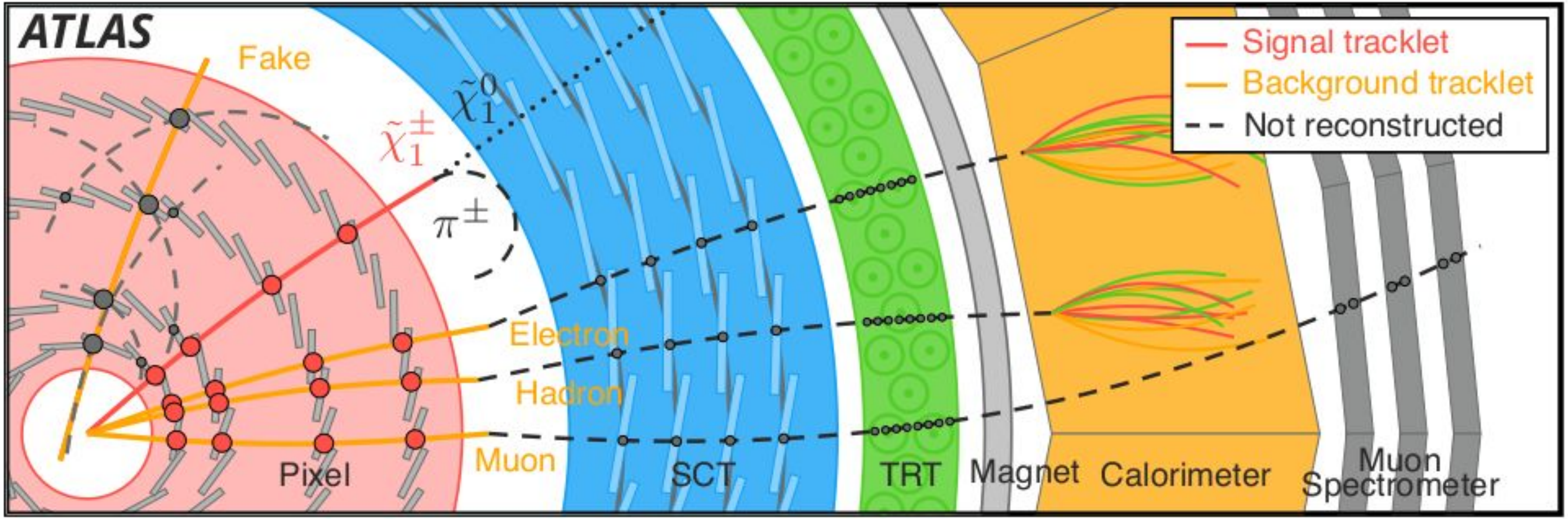
$\Gamma_{\ell\nu\chi^0} \propto \Delta_+^5$

For thermal relic, $c\tau = 6.6\,\mathrm{mm}$

ATLAS analysis

Signal production channel	Electroweak production		Strong production	
$\tau_{\tilde{\chi}_1^\pm}$	0.2 ns	1.0 ns	0.2 ns	1.0 ns
E_T^{miss} trigger	770.8 ± 6.8	775.3 ± 5.2	3177 ± 22	3177 ± 22
Lepton veto	769.4 ± 6.8	774.2 ± 5.2	3165 ± 22	3165 ± 22
$E_T^{miss} > 200$ GeV	394.5 ± 5.2	390.9 ± 4.0	–	–
$E_T^{miss} > 250$ GeV	–	–	1852 ± 17	1852 ± 17
Leading jet $p_T > 100$ GeV	389.7 ± 5.2	384.9 ± 4.0	1848 ± 17	1848 ± 17
Third jet $p_T > 20$ GeV	–	–	1834 ± 17	1834 ± 17
$\Delta\phi_{min}^{jet-E_T^{miss}} > 1.0$	366.7 ± 5.0	362.3 ± 3.9	–	–
$\Delta\phi_{min}^{jet-E_T^{miss}} > 0.4$	–	–	1578 ± 16	1578 ± 16
Pixel tracklet selection ($p_T > 60$ GeV)	8.6 ± 0.6	27.3 ± 0.8	16.0 ± 1.3	105.0 ± 3.3

Backgrounds



EFT vs full EW form factor correction

Di Luzio et. al. arXiv:1810.10993

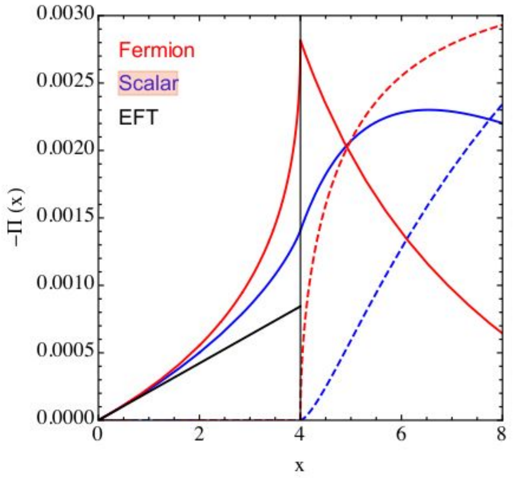
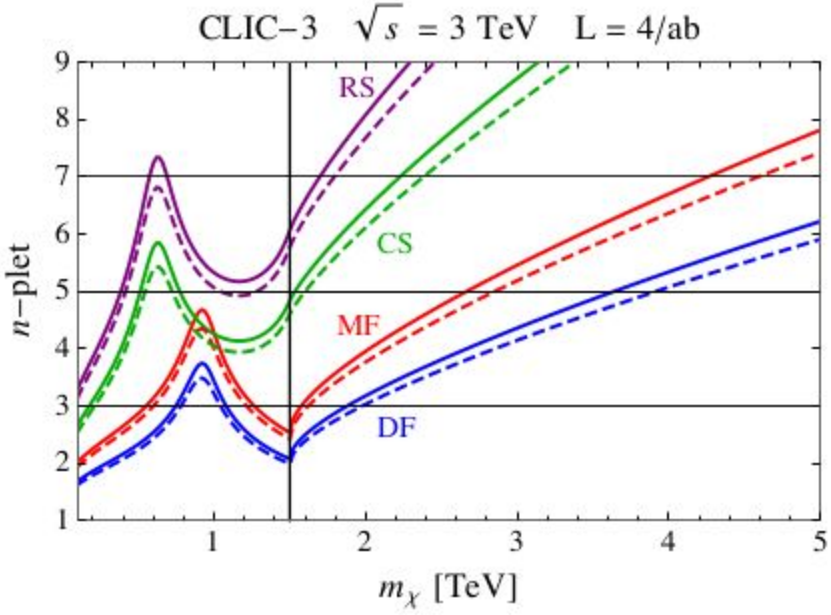
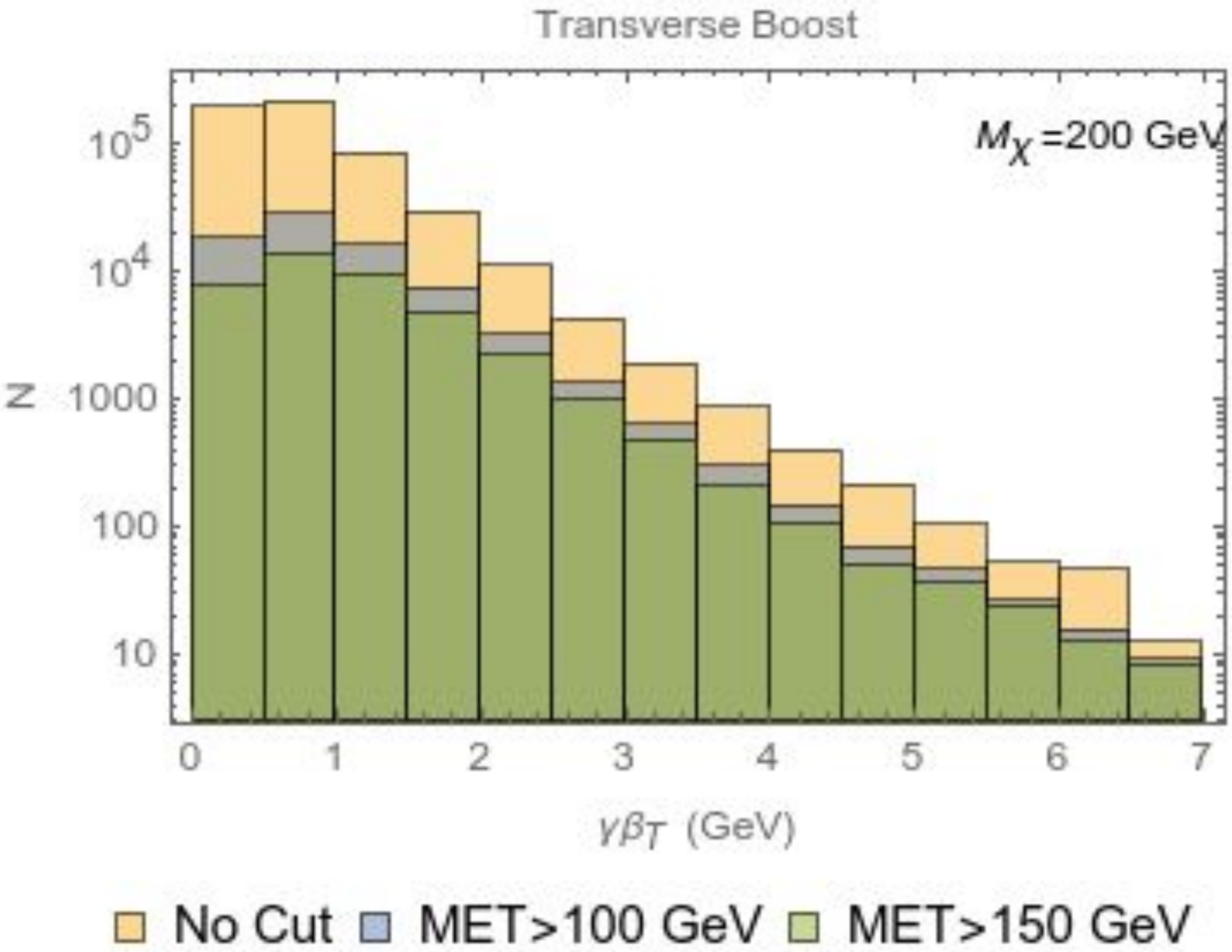


Figure 1. Kinematical dependence of the form factor for fermions (red) and scalars (blue) running in the loop, and in the EFT limit (black). Full and dashed lines denote respectively real and imaginary part of the form factor.





Transverse Boost
M_χ =200 GeV
N
10^5
10^4
1000
100
10
0
1
2
3
4
5
6
7
$\gamma\beta_T$ (GeV)
No Cut
MET>100 GeV
MET>150 GeV

Dark matter (post naturalness)