2021 TEV Particle Astrophysics Conference

Heavy Dark Matter
@
Colliders

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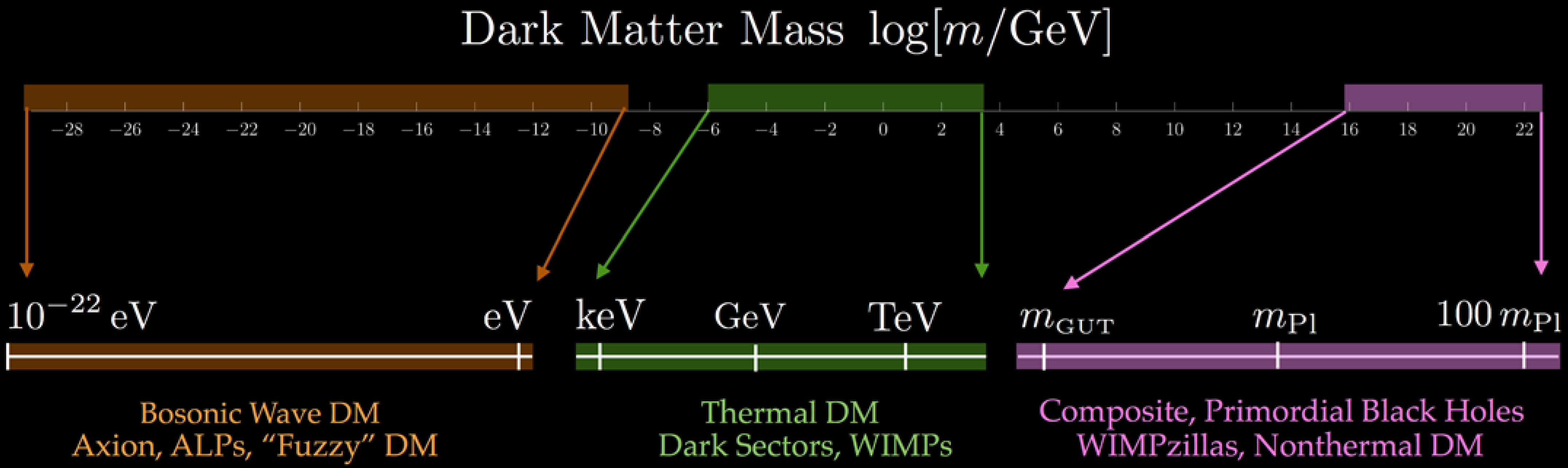
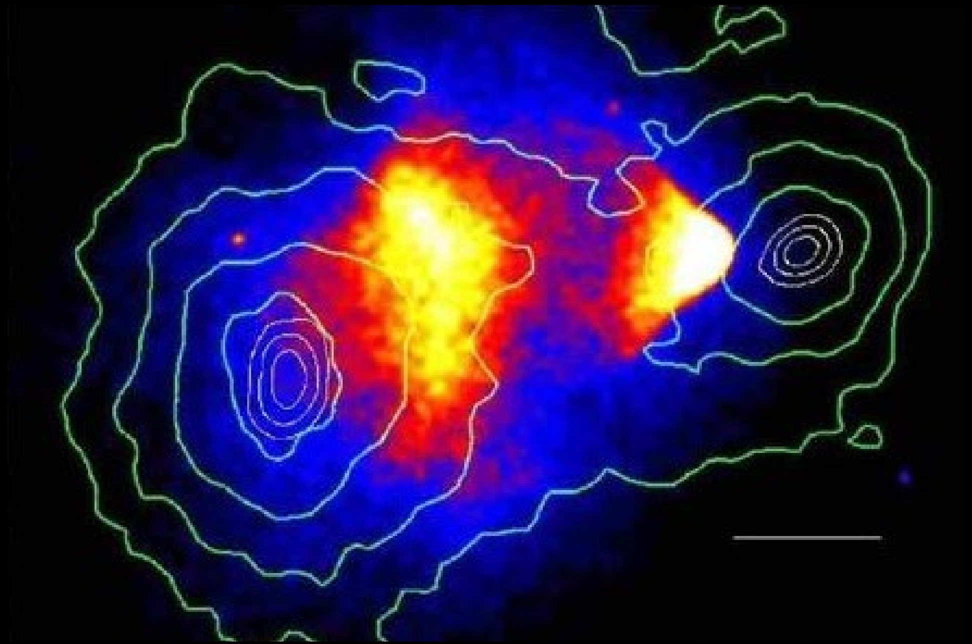
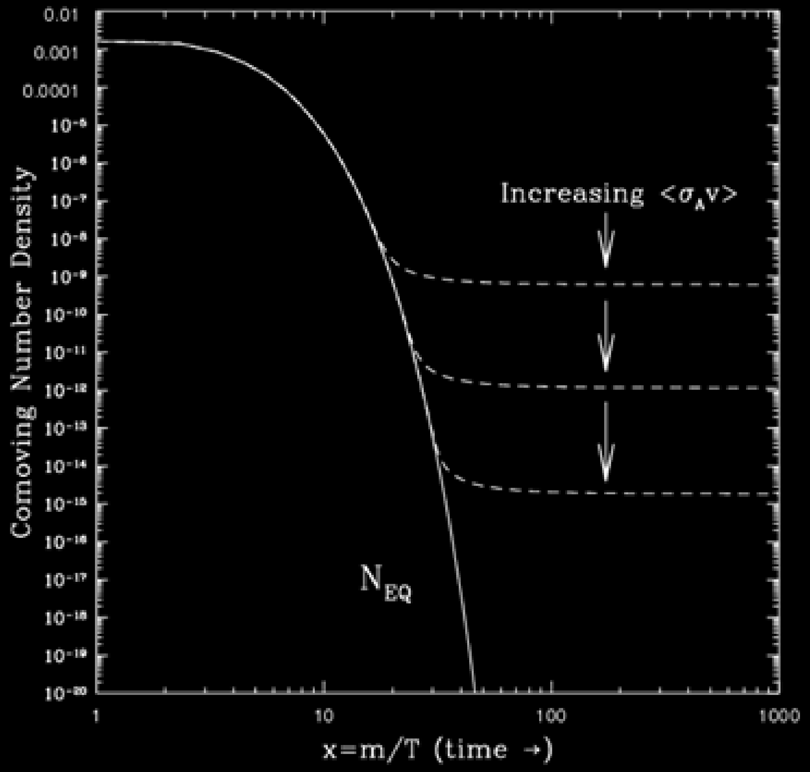
The Quest for Dark Matter



WIMP Dark Matter

Compelling, simple, predictive explanation for thermal, cold dark matter





$$\Omega h^2 \simeq 0.1 \times \left(\frac{2 \times 10^{-26}\mathrm{cm}^3/\mathrm{sec}}{< \sigma_{\mathrm{eff}} v >_{\mathrm{freeze-out}}}\right)$$

$$< \sigma_{\mathrm{eff}} v >_{\chi\bar{\chi}\to VV} \simeq \frac{\pi \alpha_\chi^2}{m_\chi^2}$$

Heavy DM at Colliders

Colliders can (via creative and ambitious efforts)

- Discover
- Test fully this regime
- Reveal their thermal mechanisms
- Check complimentarily and consistently

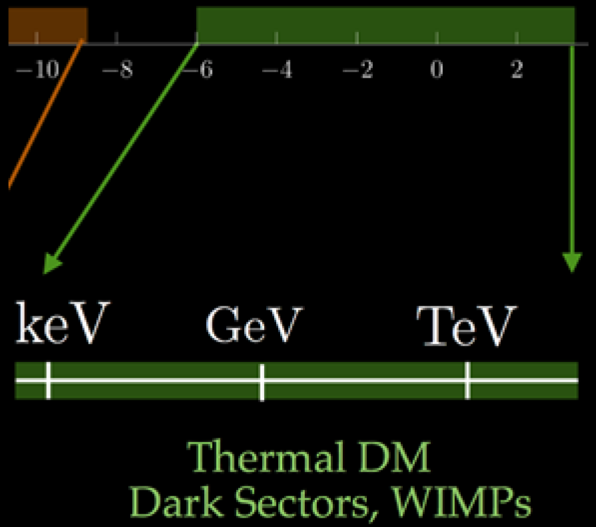
To search for: DM and its friends

WIMP:

Compelling, simple, predictive explanation for thermal, cold dark matter.

Has a scale

Has an upper bound on the scale



Outline

- Basics DM at Colliders
  - Missing Energy
  - Mediators
- Hunting DM's friends
  - Coannihilations
  - Long-Lived Hidden-sector
- Future Colliders
  - Minimal signatures
  - Disappearing Track

The program is extremely rich and active, I can only give you a flavor of the activities via representative examples here in this talk.

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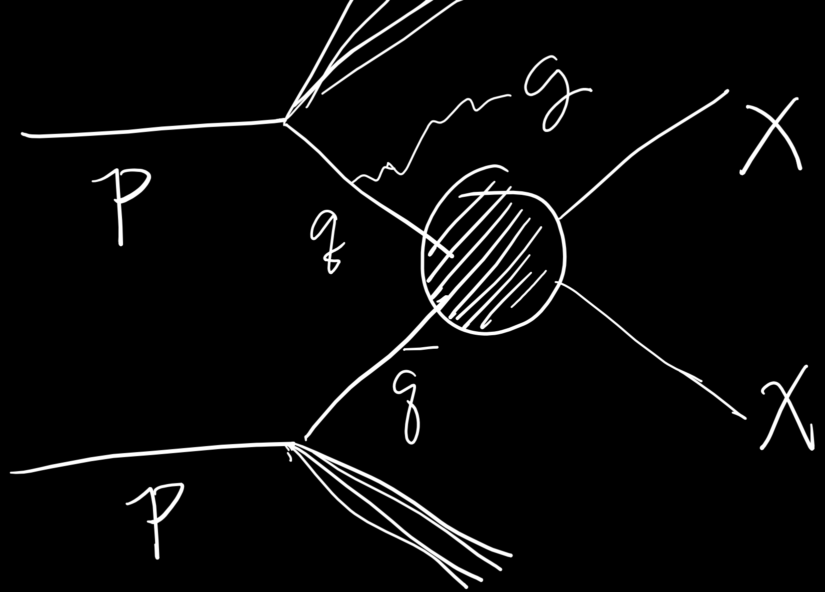
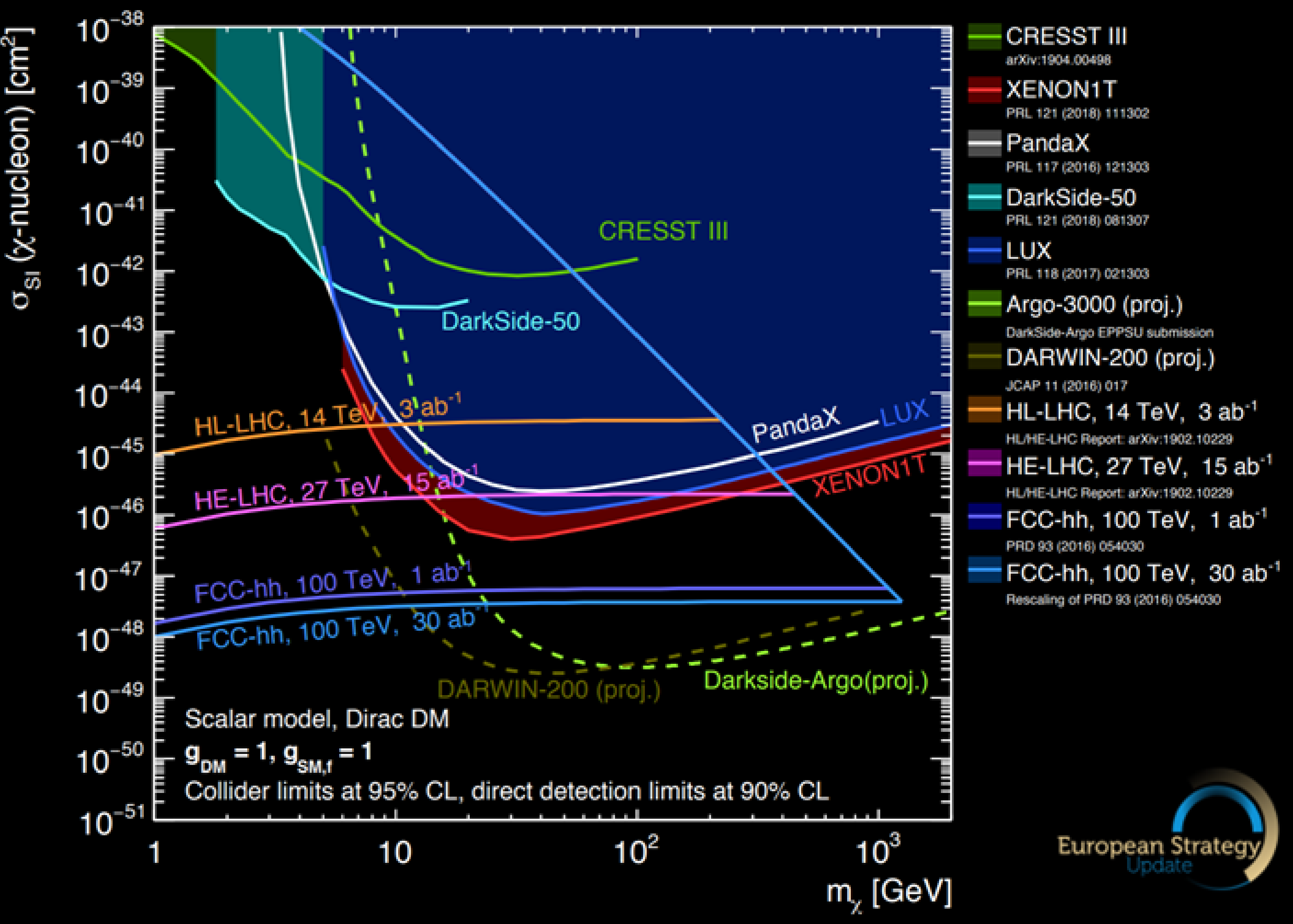
Mono-jet (or generic MET searches)

Many possible operators (mediator types and interaction types) Searching for Missing Transverse Energy is an inclusive strategies

Colliders are to fully cover low mass and below TeV scale

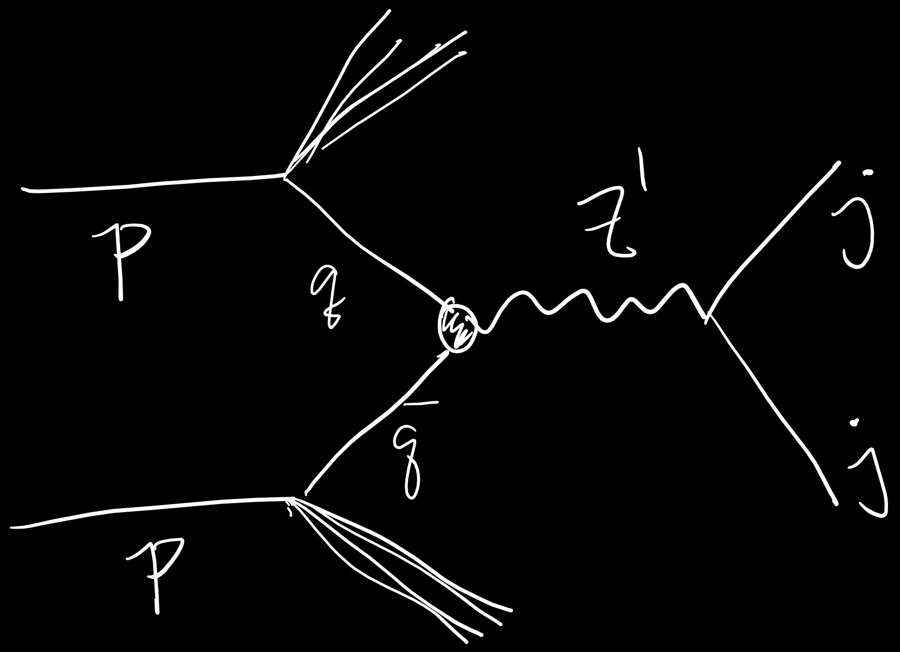


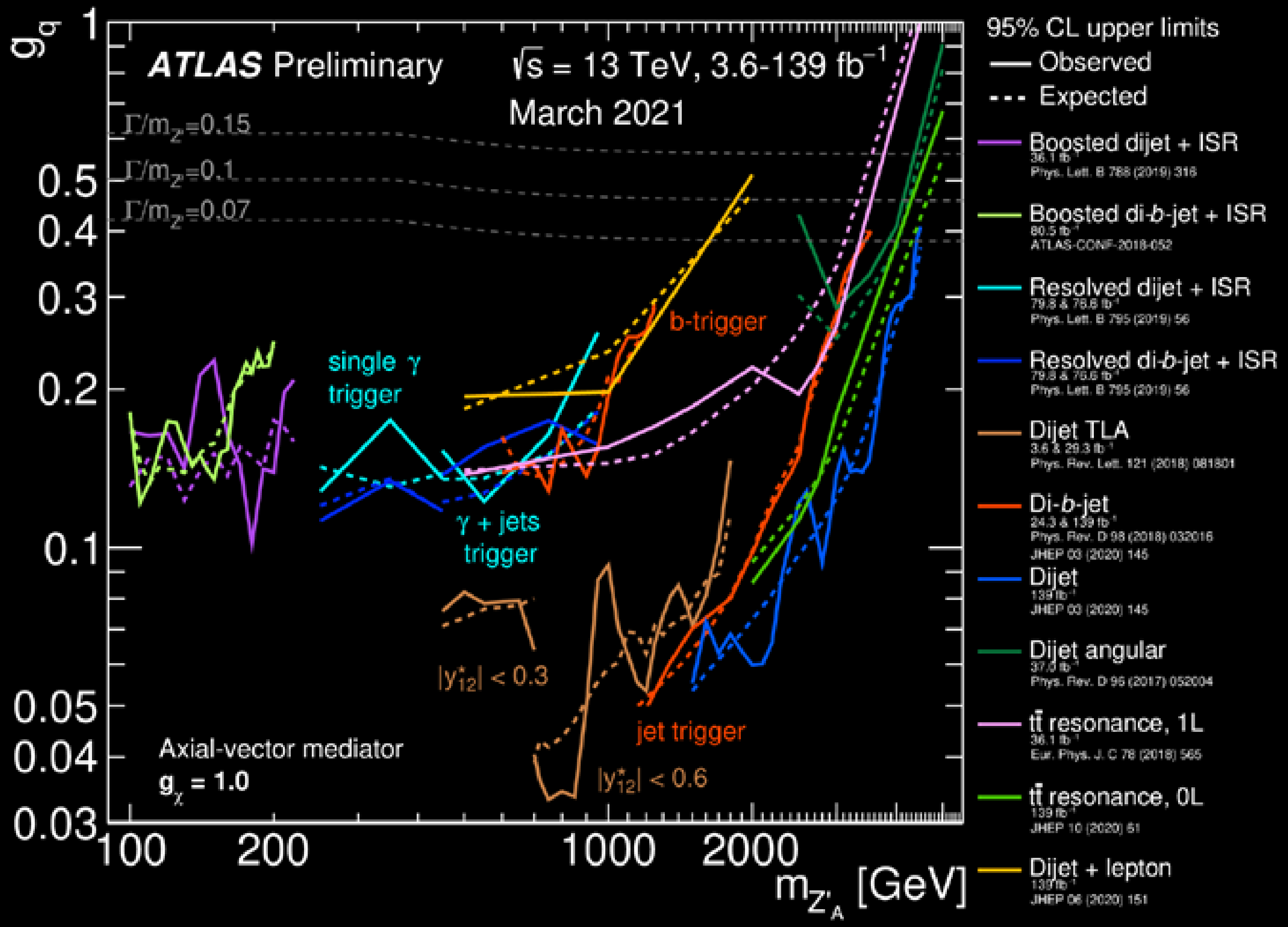


Active Mediator Hunting

Many possible operators (mediator types and interaction types)

Searching for the mediators, e.g., Z', can provide complementary information.





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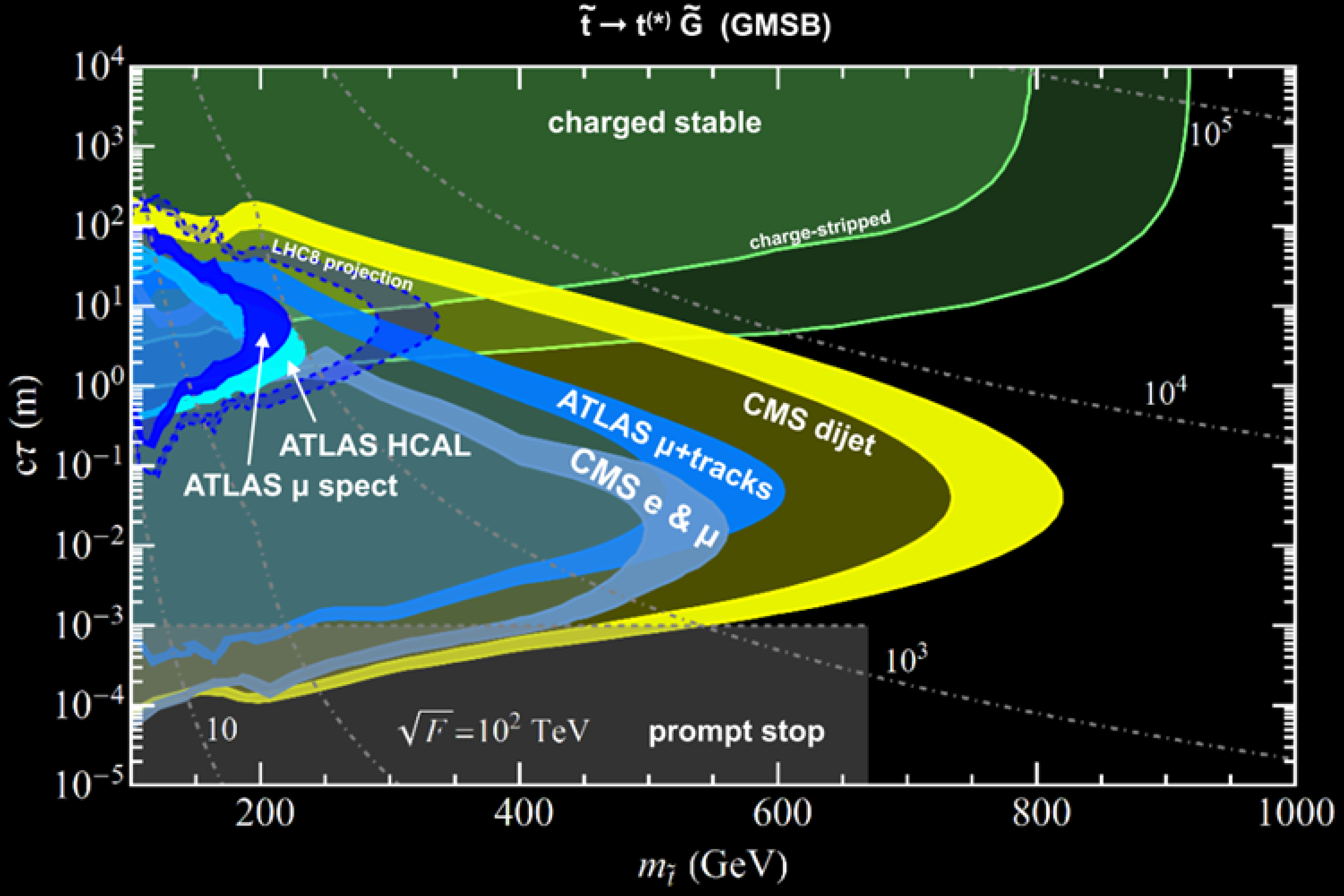
DM’s friends: co-annihilators

- Co-annhilation
  - Dodge direct detection
  - Ensure Thermal Relic
  - Enable co-discovery of DM and New Physics (beyond DM)

Let’s take a SUSY example.

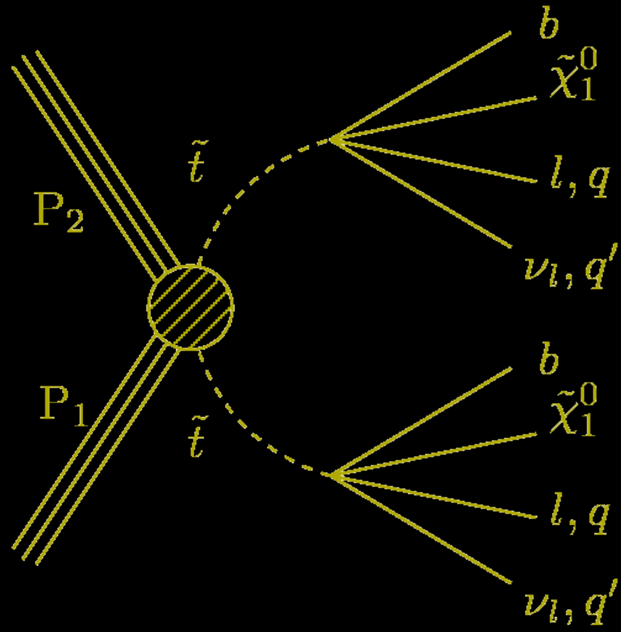
DM Coannihilation and LLP



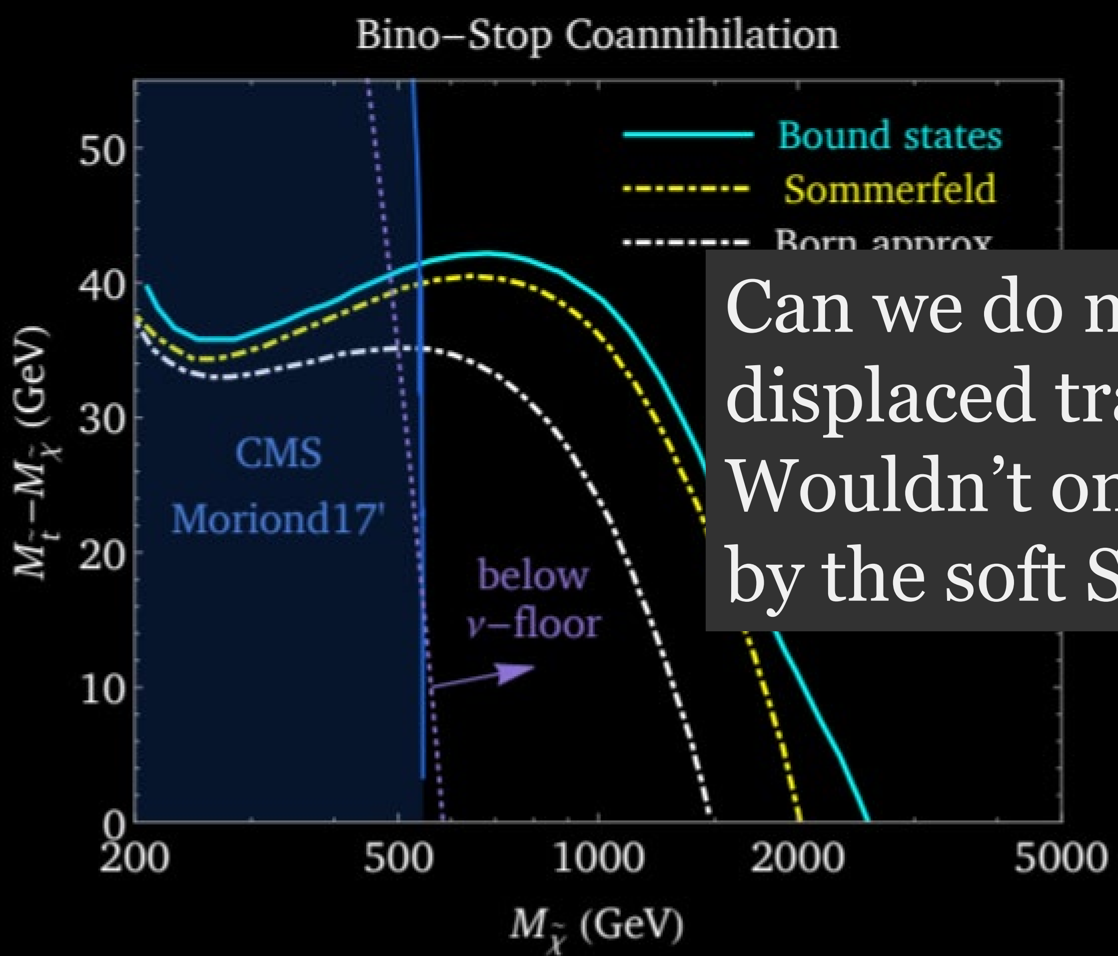
SUSY fully covered, any lifetime?

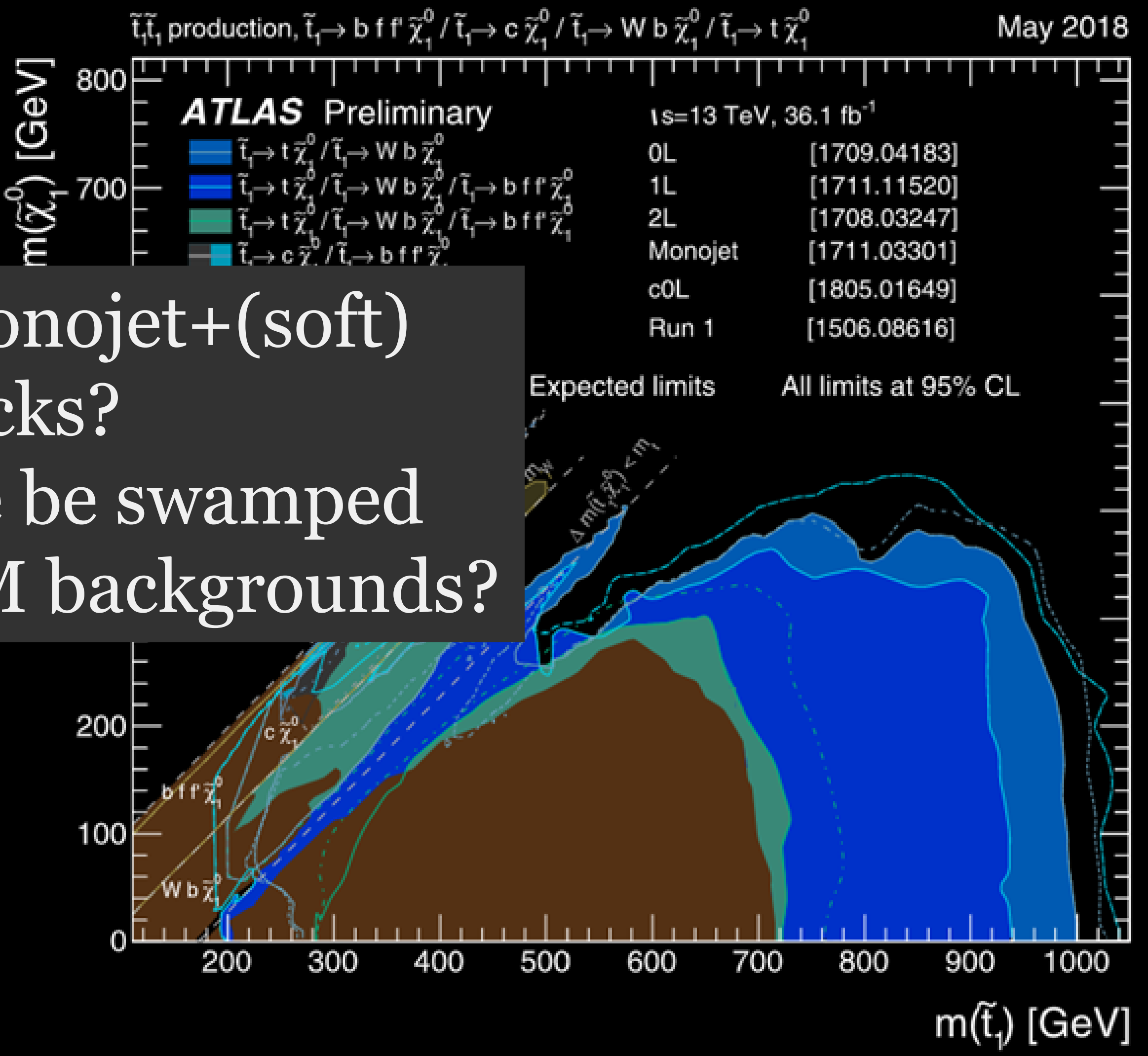
What about (infamous) Compressed SUSY?

Easily long-lived



Coannihilation and LLP





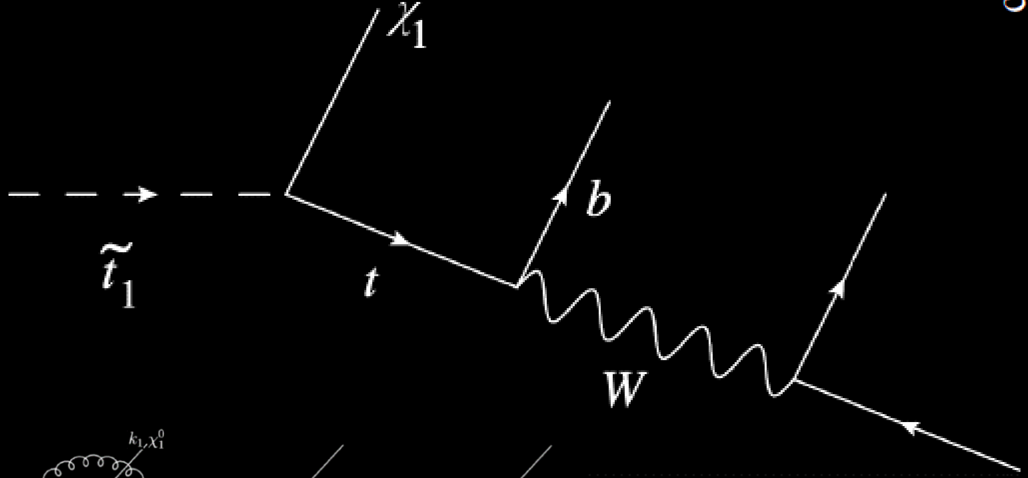
Can we do monojet+(soft) displaced tracks?
Wouldn't one be swamped by the soft SM backgrounds?

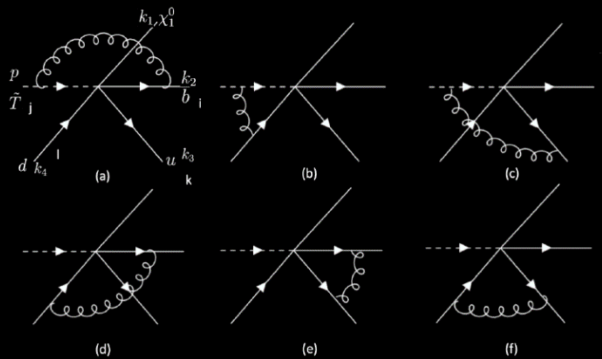
For stau-coannhiliation, the pheno challenges is with soft and prompt tau leptons.
T. Han, ZL, A. Natarajan, 1303.3040

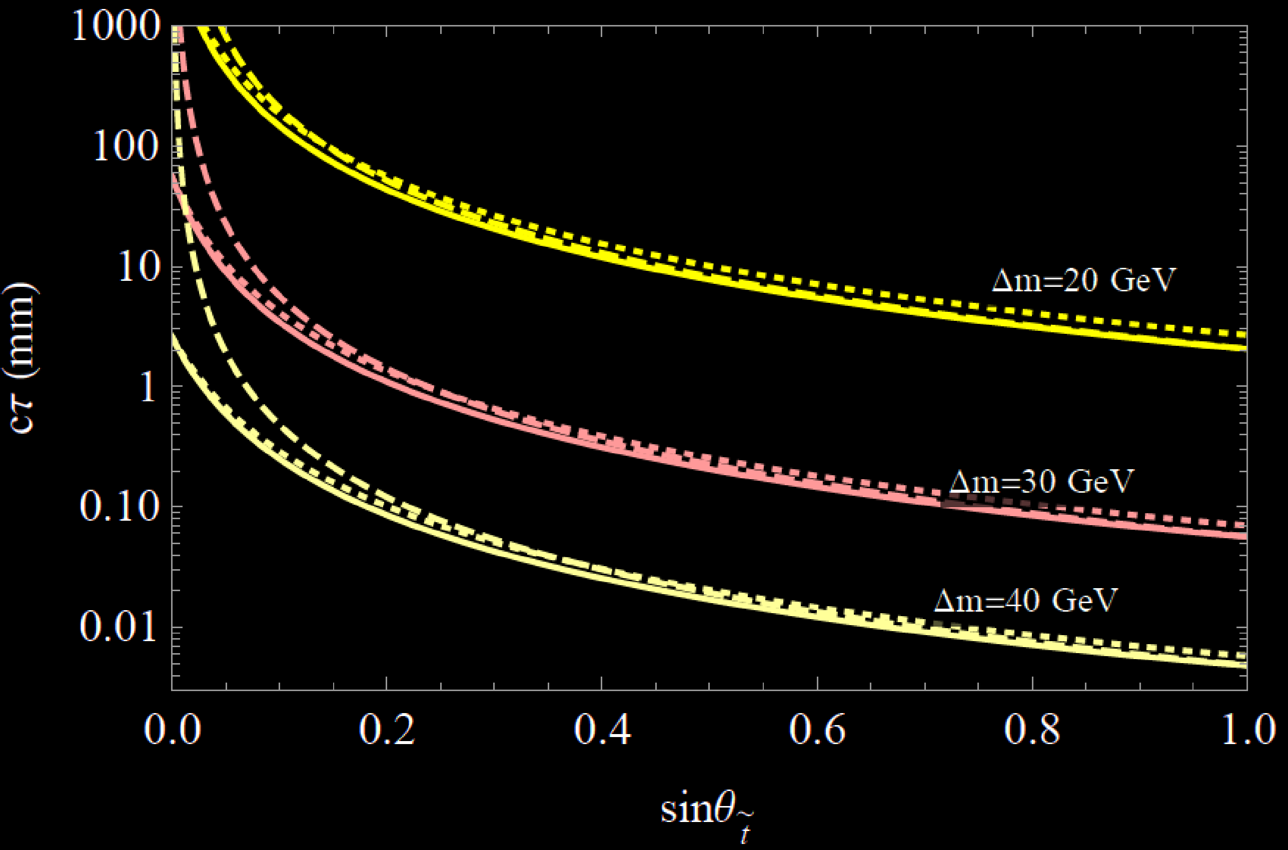
Long-lived compressed stop

$$\Gamma = \frac{g_2^4 g_1^2 \Delta m^8}{20160\pi^5 m_W^4 m_t^2 m_{\tilde{t}}}.$$

$$c\tau \approx 1.4\ \mathrm{mm} \times \left(\frac{20\ \mathrm{GeV}}{\Delta m}\right)^8$$





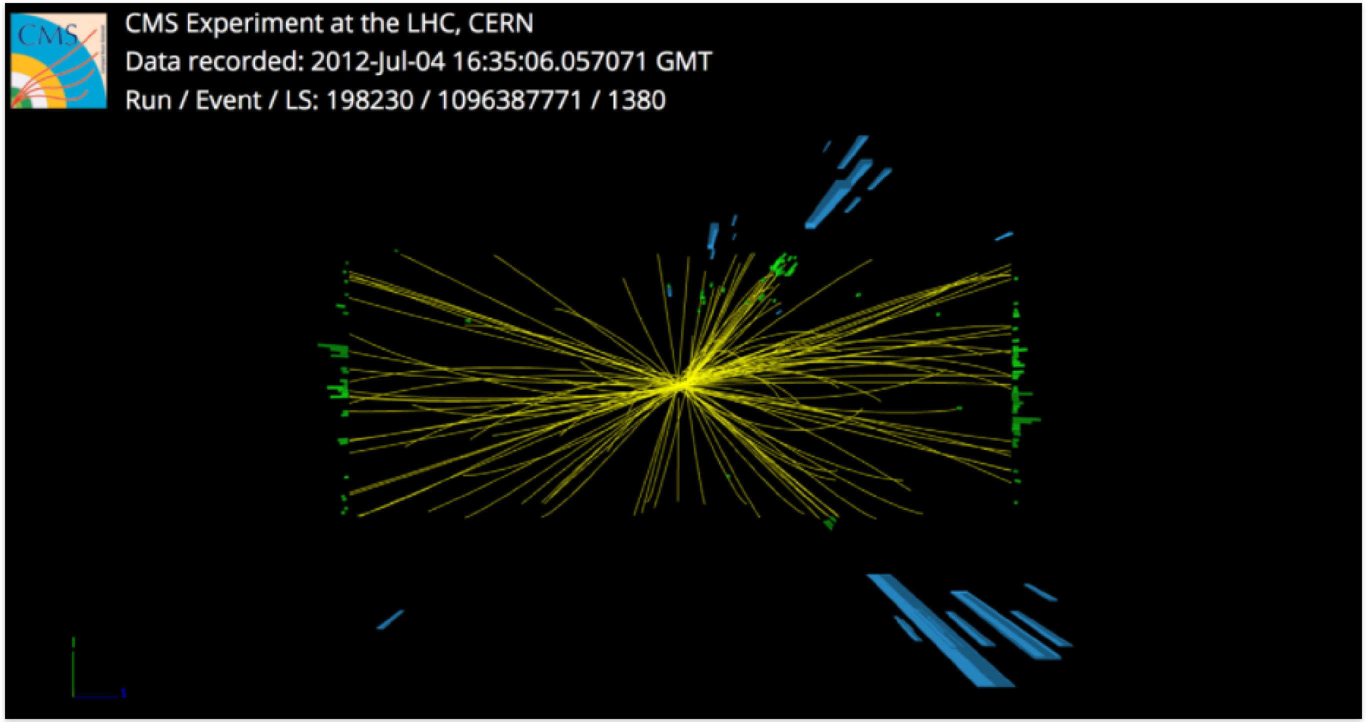


Our Endeavor with Open Data

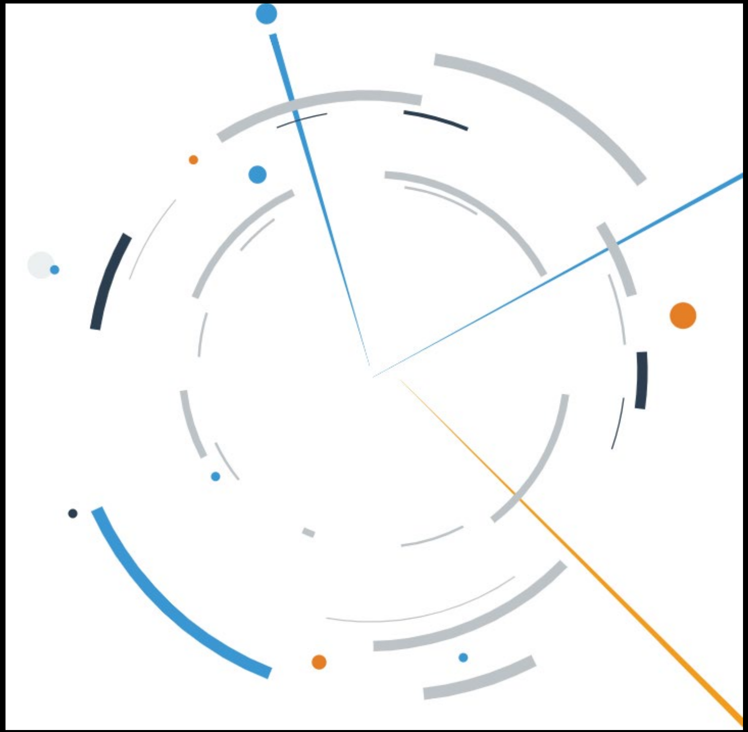
CMS releases more than one petabyte of open data

This release includes datasets that were used to discover the Higgs boson

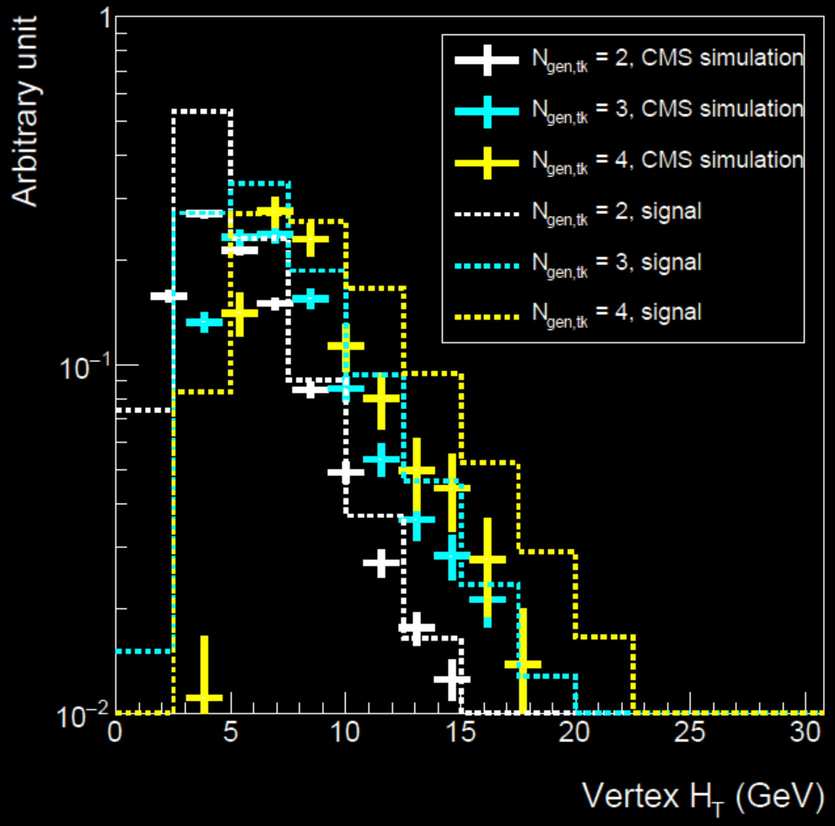
20 DECEMBER, 2017 | By Achintya Rao



A collision event recorded by CMS in 2012 showing a "Higgs candidate", available on the CERN Open Data portal with the latest release of CMS Open Data. (Image: Tom McCauley/CMS/CERN)



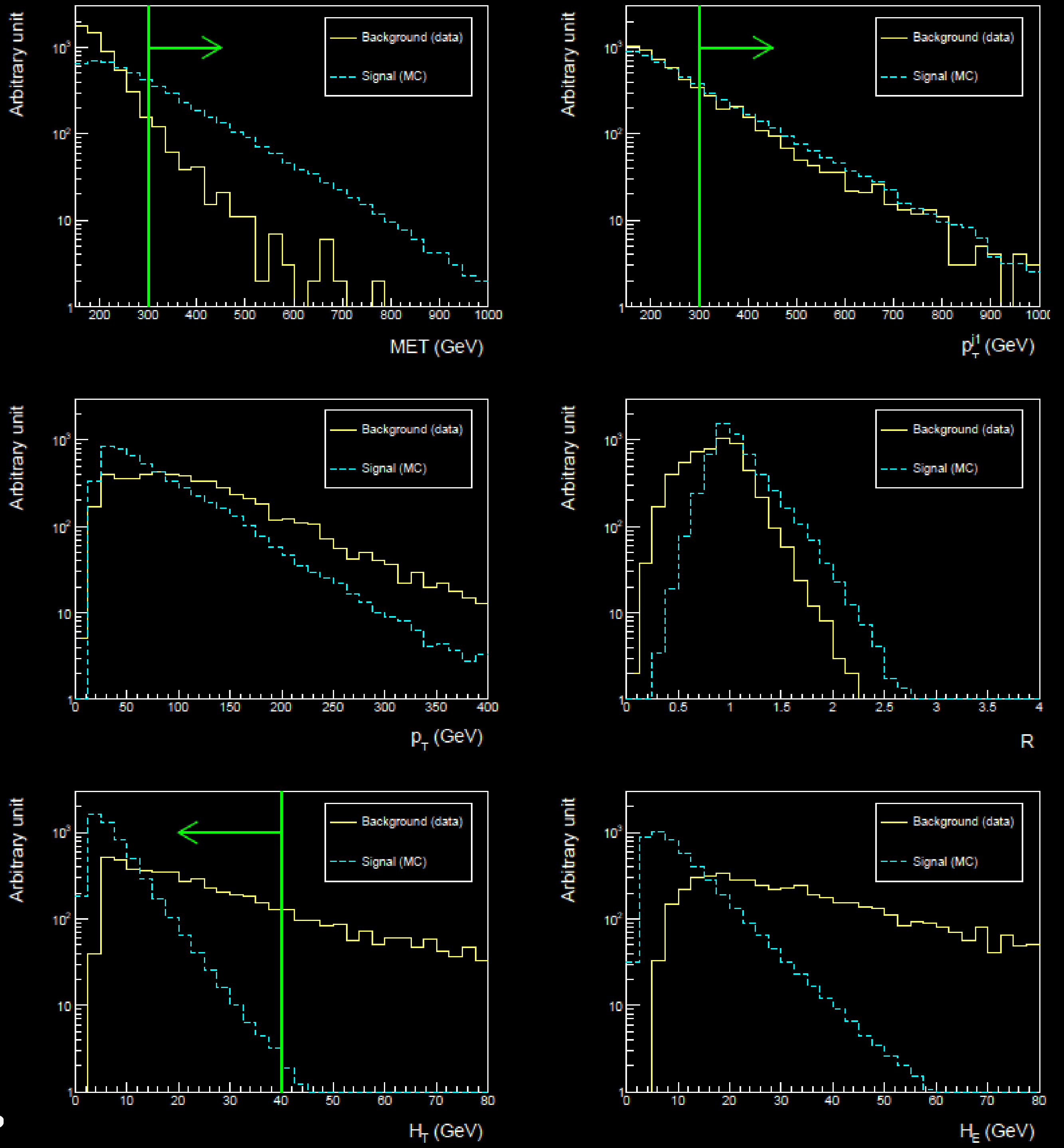
Studying and Validation



Selection	Data	Signal BM
MET primary	4.3×10^7	-
$p_T^{j1} > 150$ GeV, $E_T^{miss} > 150$ GeV	1.4×10^6	830
One displaced vertex ($N_{vtx,tk} \geq 2$)	3.7×10^5	310
One displaced vertex ($N_{vtx,tk} \geq 3$)	4.7×10^4	240
One displaced vertex ($N_{vtx,tk} \geq 4$, default)	5.5×10^3	140
Two displaced vertices	76	9.8
$p_T^{j1} > 300$ GeV, $E_T^{miss} > 300$ GeV	1	3.0
Two displaced vertices with vertex $H_T < 40$	0	3.0

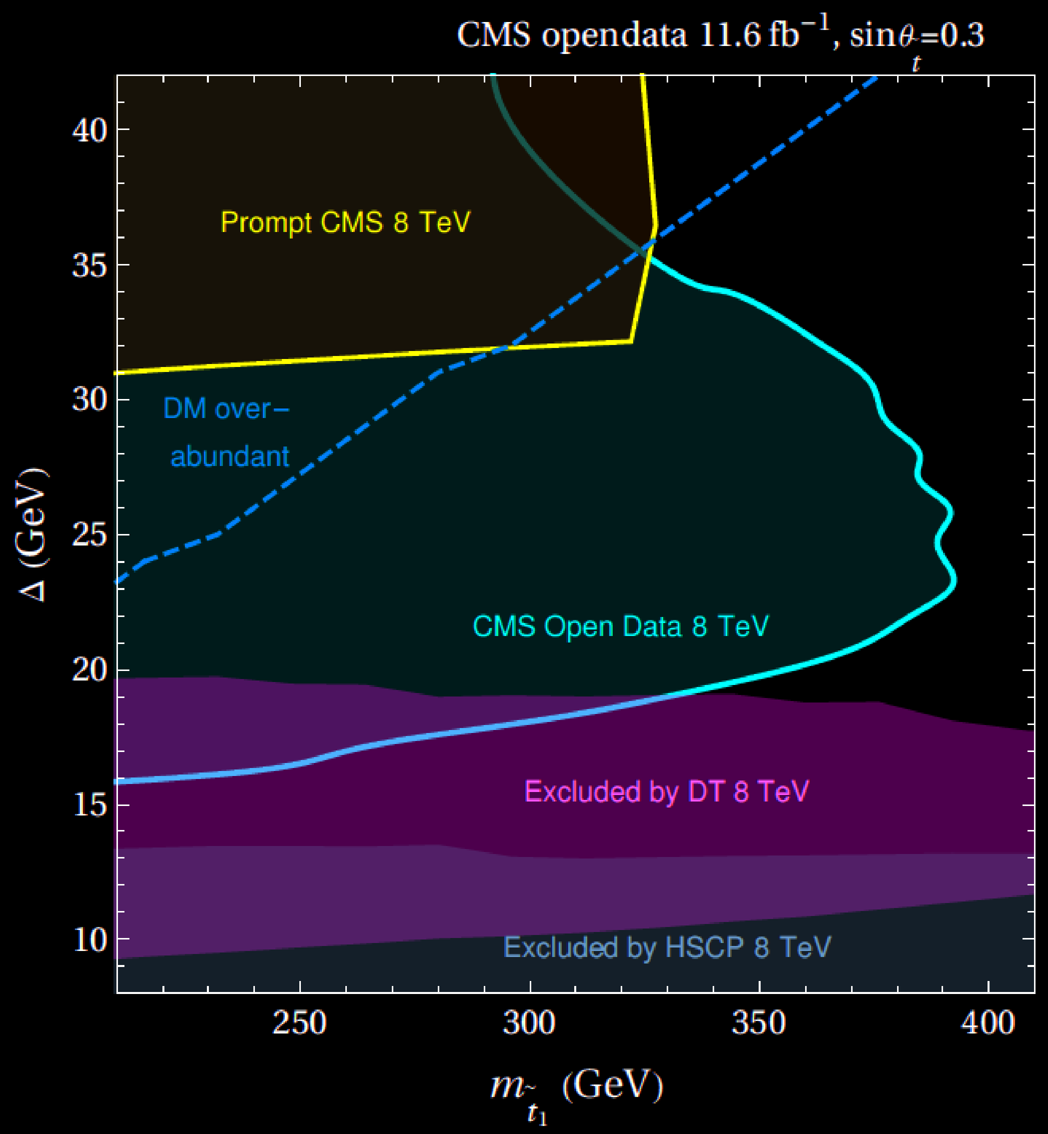
Z

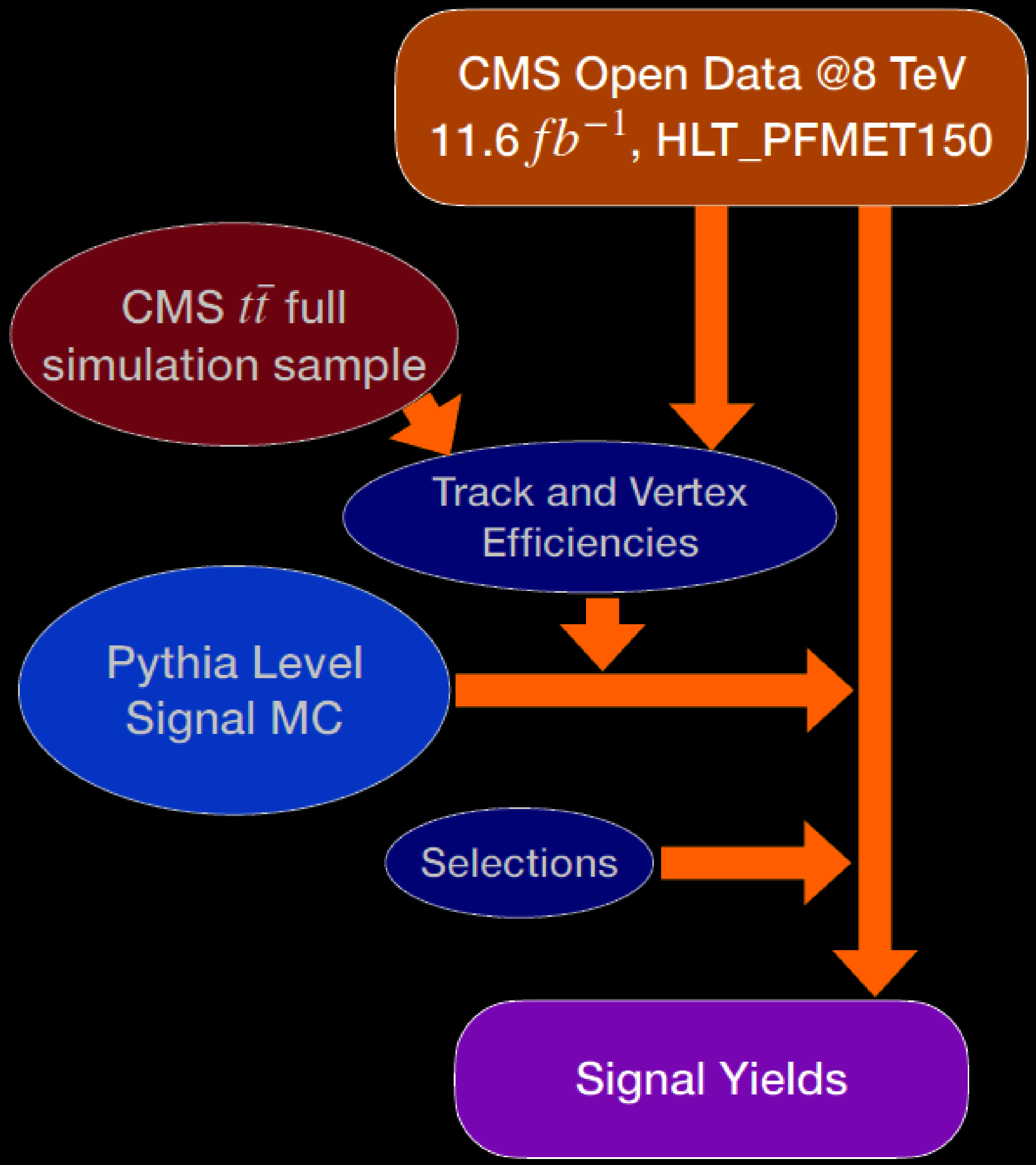
TeVP



New constraints derived!

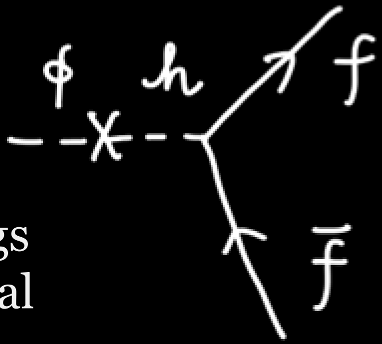
An, Hu, ZL, Yang, 2107.11405



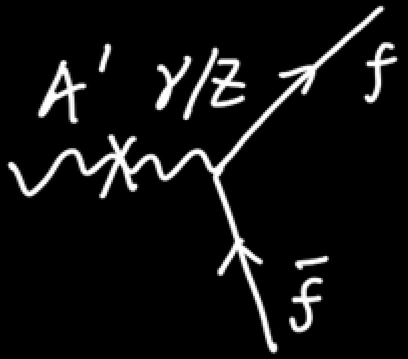


Generalize: search for hidden sector particles

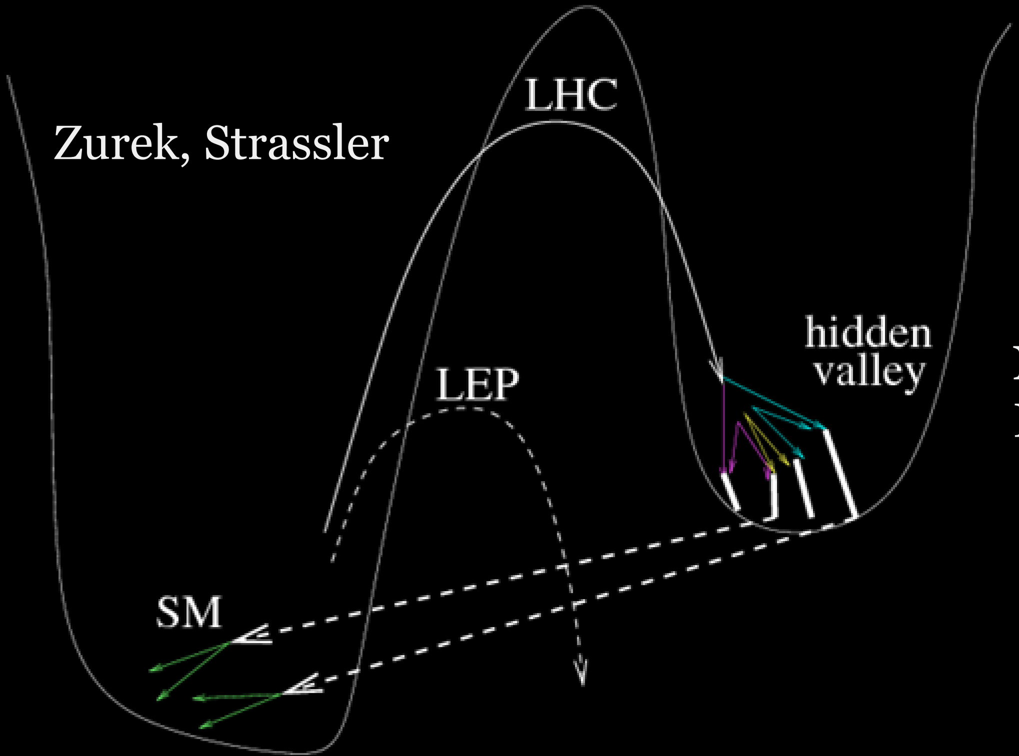
Hidden sector feeble couplings to SM via various portals, suppressed by the smallness of the couplings



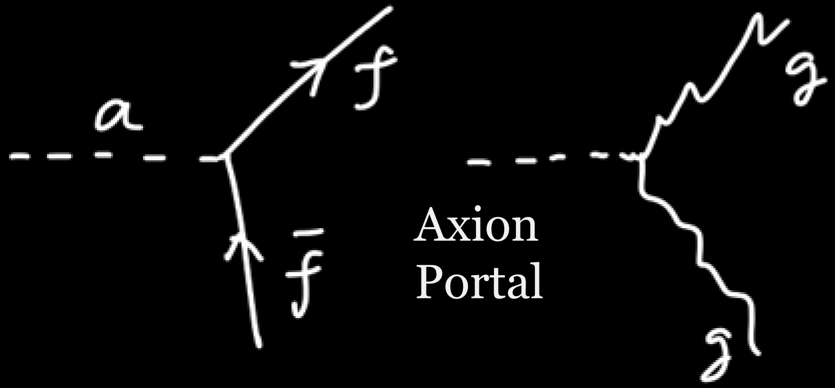
Higgs portal



Dark Photon/Z

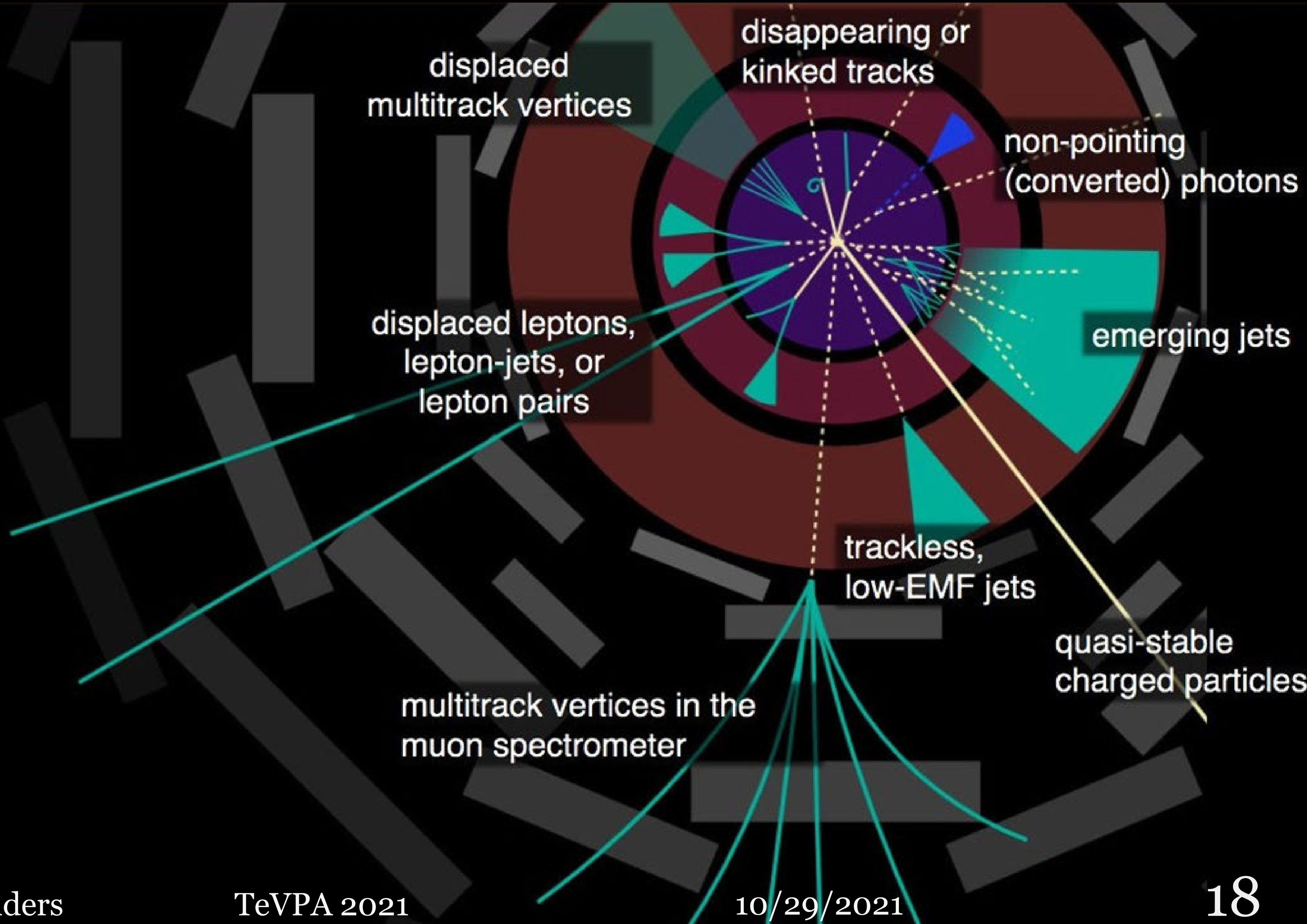


Neutrino Portal



Axion Portal

Generalize: search for hidden sector particles



Generalize: search for hidden sector particles

MATHUSLA
Codex-B
AL3X
Anubis
} Central/Hard LLPs

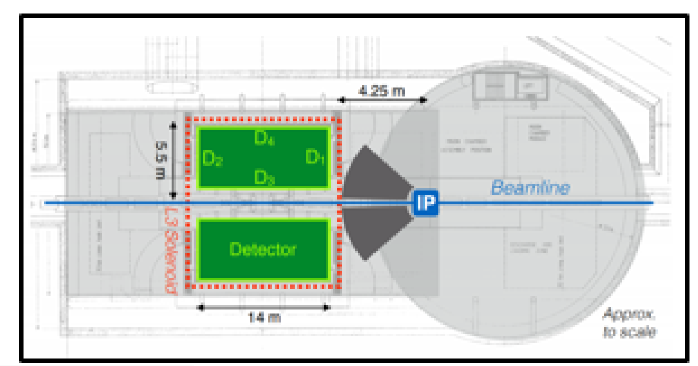
FASER
SHiP
NA62
SeaQuest
} Forward/lighter LLPs

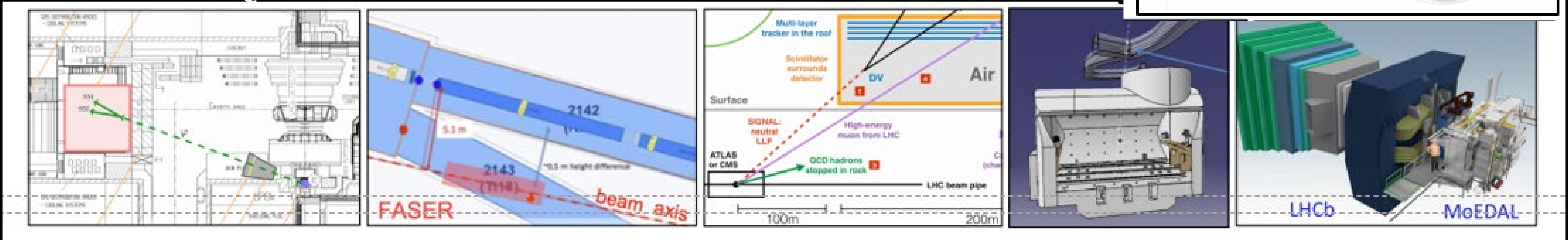
SHiP, NA62, SeaQuest } Beamdump experiments

MoEDAL
MilliQan
} monopole, millicharged particles

} Search for LLPs

The world is planning on conducting new experiments searching for these hidden long-lived particles.





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Our Approach: work on the "nightmare" scenario

Consider the following "Minimal Dark Matter"*:

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

"Nightmare":

- High thermal targets
  - 23 TeV for 7-plet Majarona
- Minimal signatures
  - Only missing energy (details next)

Additional considerations:

- Doublet ☐ "Higgsino"
- Triplet ☐ "Wino"
- Use "epsilon" notation to indicate Dirac case
- Even-plet requires non-zero Y (and additional splitting to suppress direct detection)
- Perturbative Unitarity
- Summonfeld and bound-state effect

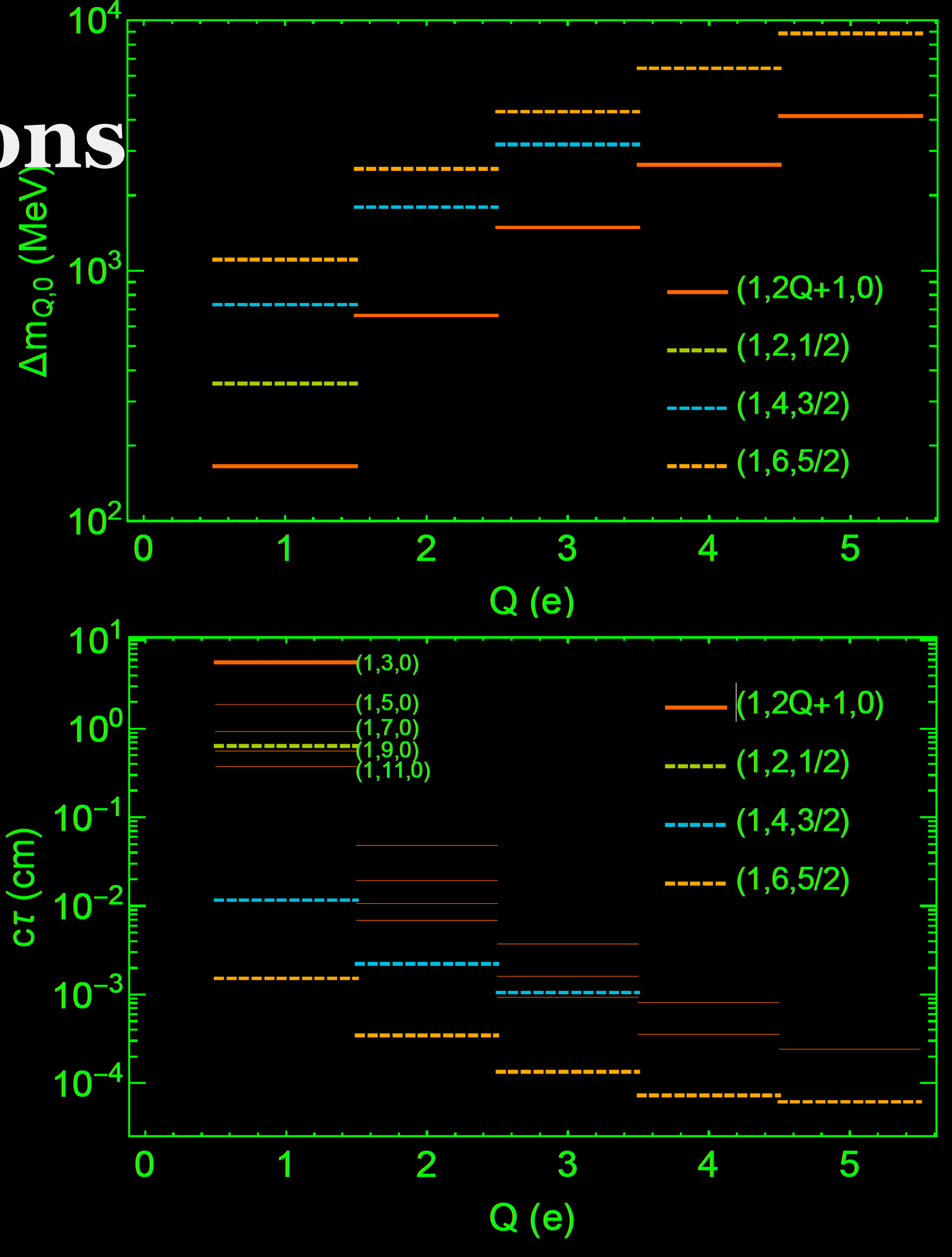
$$< \sigma_{\chi\bar{\chi}\to VV} v > \simeq \frac{g_2^4\, n^4 + 16 Y^4 g_1^4 + 8 g_2^2 g_1^2 Y^2 n^2}{64\pi\, M_\chi^2 g_\chi}$$

Basic Pheno Considerations

"non-trivial" to consider MuC

- Minimal signature
  - Mass splitting O(few hundred MeV)
  - Decay products soft
  - Transition between states fast (<mm for most of the cases)
- Missing ET (at LHC)→Missing Mass (at MuC)

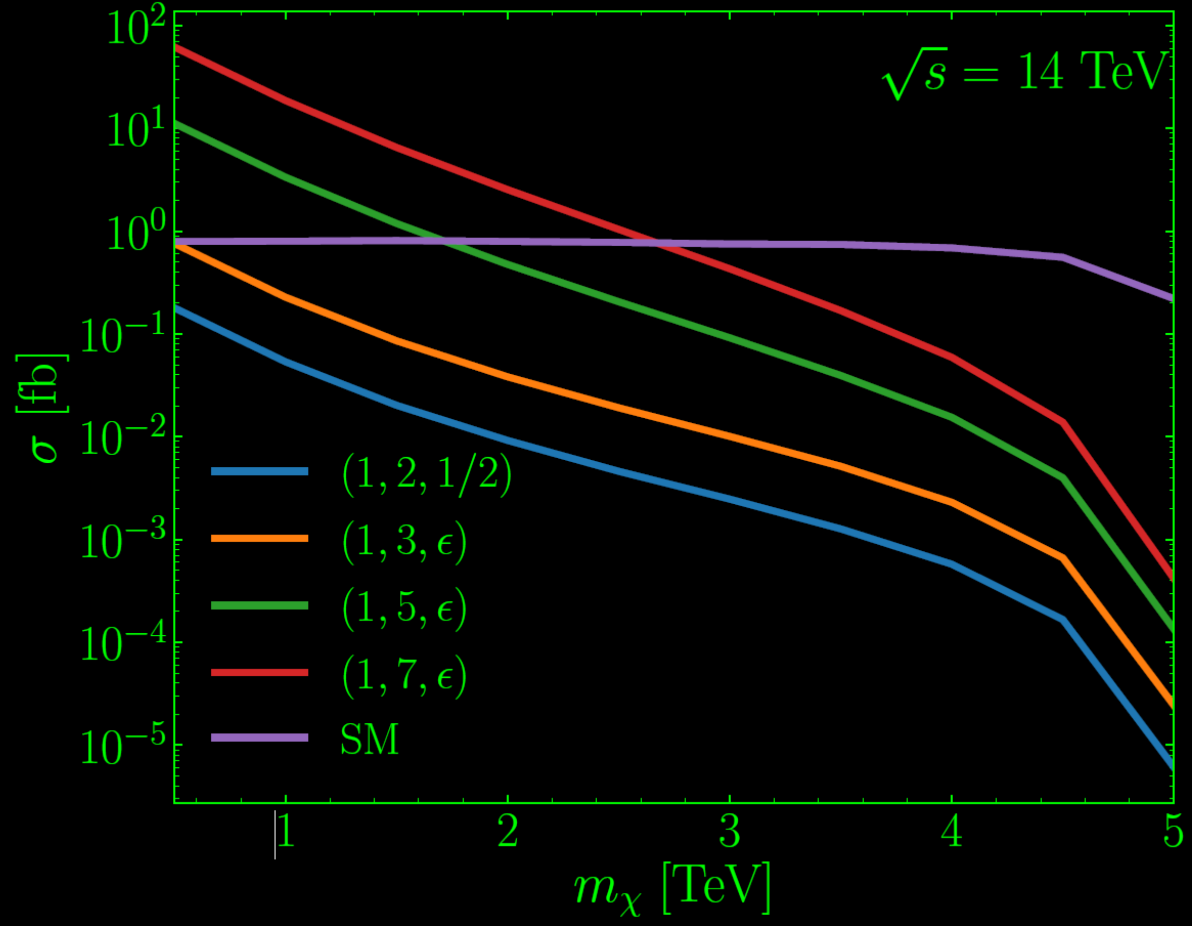
$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$$



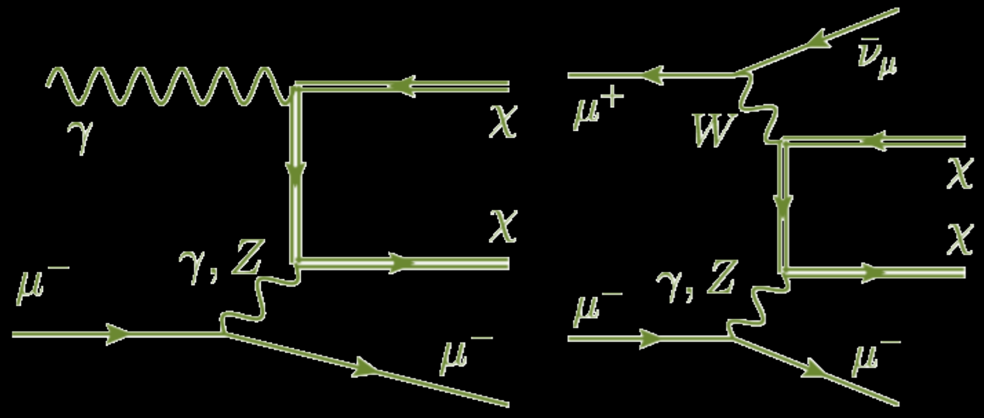
Unique Mono-Muon Channel

Apparent "Charge Violation" channel

(very different from the LHC)



Signature: Energetic mono-muon



Muon pairs □ muon + missing mass

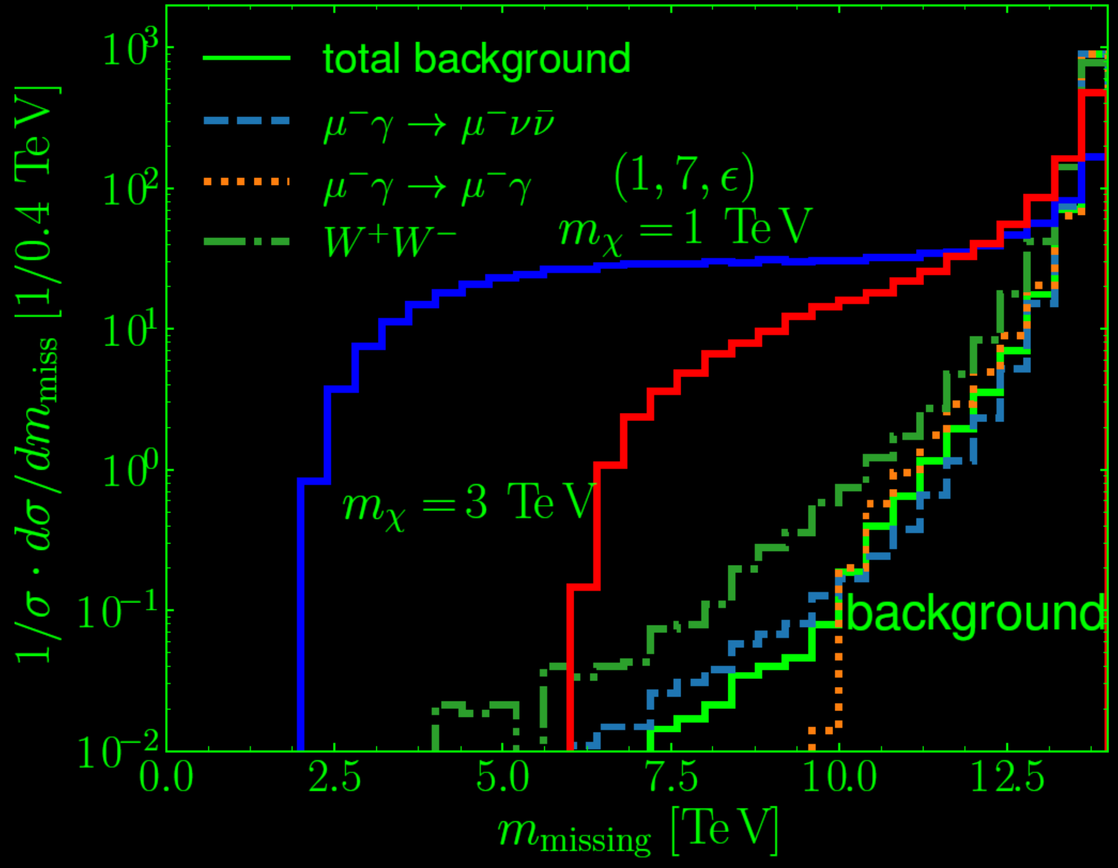
One charge is missed due to the soft (non-reconstructable) decays of the charged states

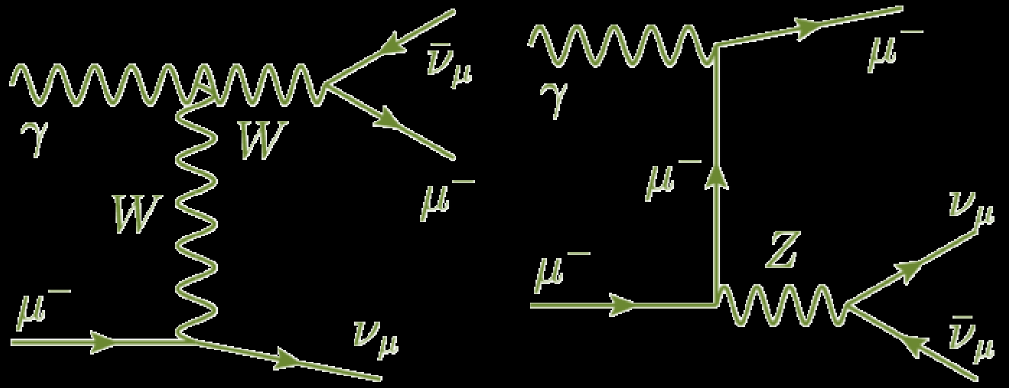
Unique and powerful channel

Unique Mono-Muon Channel

Complex background compositions:

from missing a SM particles via various mechanisms





Collinear emissions, missing final state muons, properly calculated using photon PDF

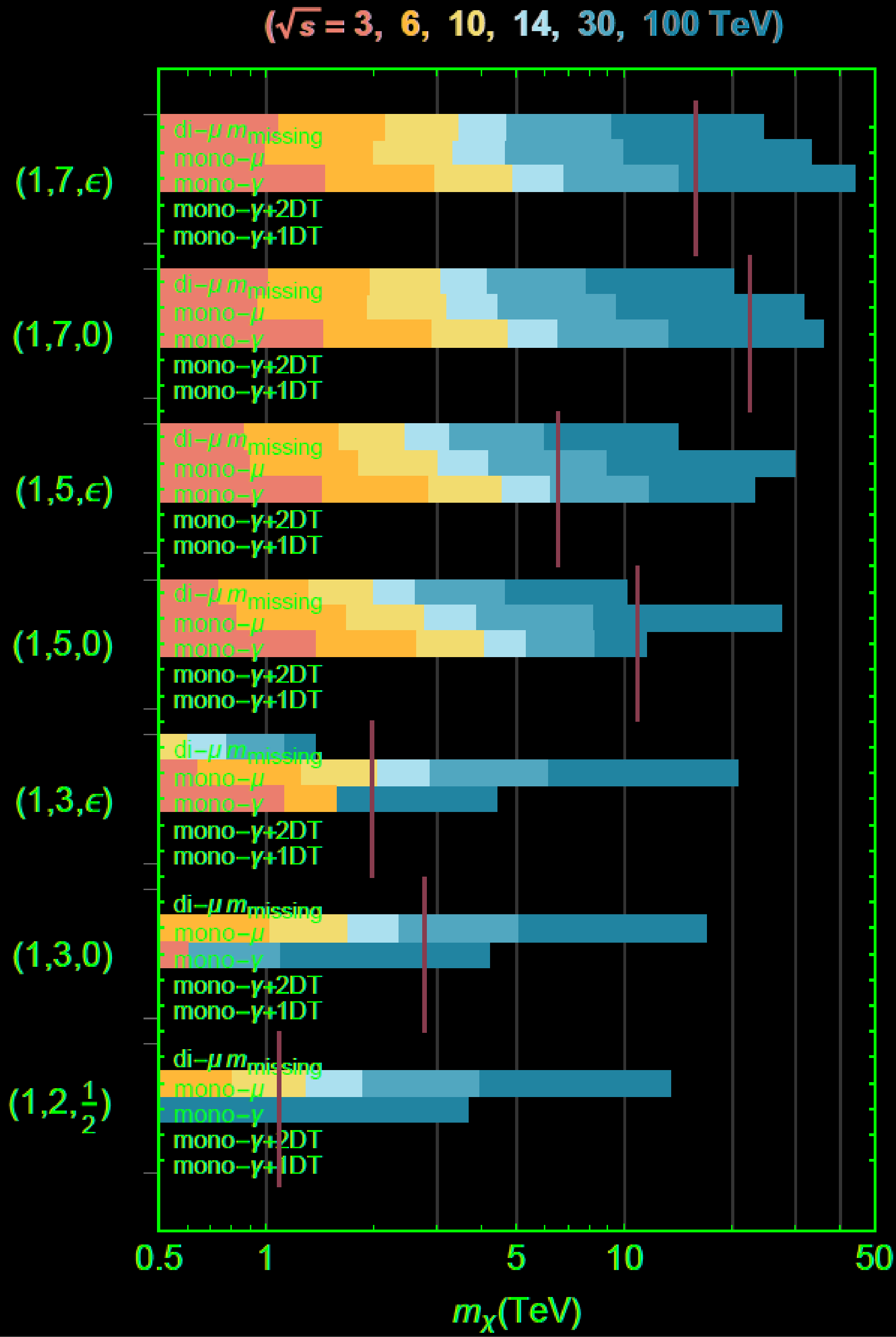
Also includes dominant 2->2 processes with one of them decays forward

$$10^\circ < \theta_{\mu^-} < 90^\circ, \quad 90^\circ < \theta_{\mu^+} < 170^\circ$$

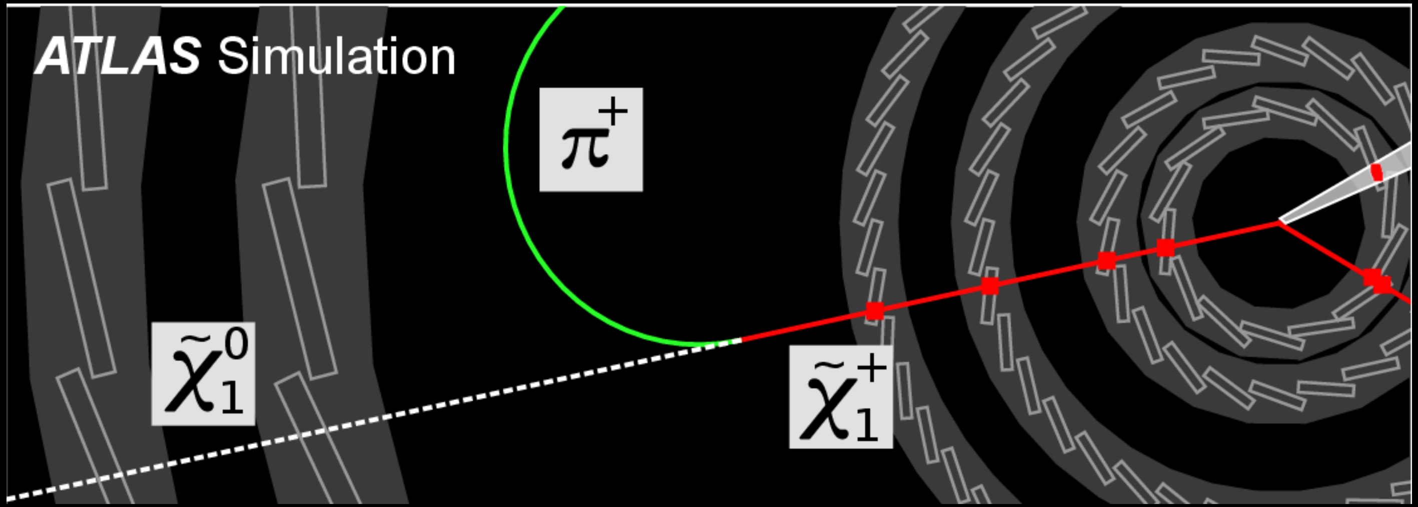
$$E_{\mu^\pm} > 0.71,\ 1.4,\ 2.3,\ 3.2,\ 6.9,\ 22.6 \text{ TeV}, \quad \text{for } \sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30,\ 100 \text{ TeV}$$

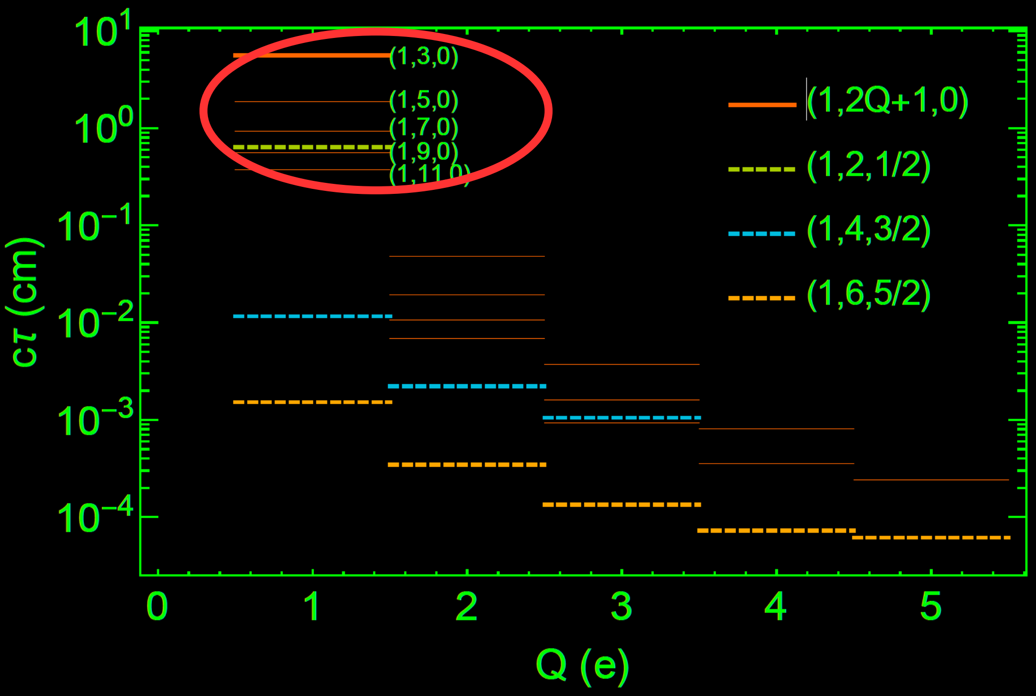
Summary (by channel)

- Mono-photon powerful for high n-]
- Mono-muon uniquely powerful low Higgsinos)
- VBF dimuon large room to improve assumed |\eta mu|<2.5, losing lots

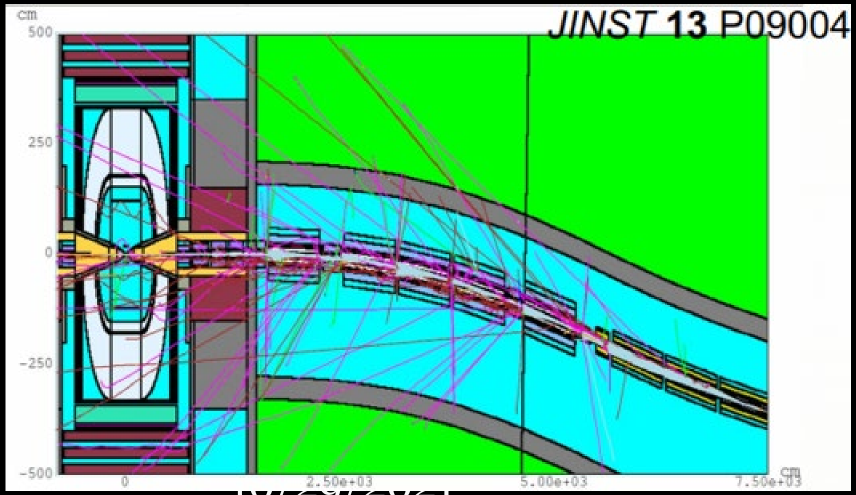


Disappearing Tracks: next to minimal signatures





- Only useful for searches using charge 1 states
- Still, all higher charged states will cascade back to charge 1 states promptly
- Use all the production rates of charged states
- Mono-photon+disappearing tracks
- Beam Induced Background



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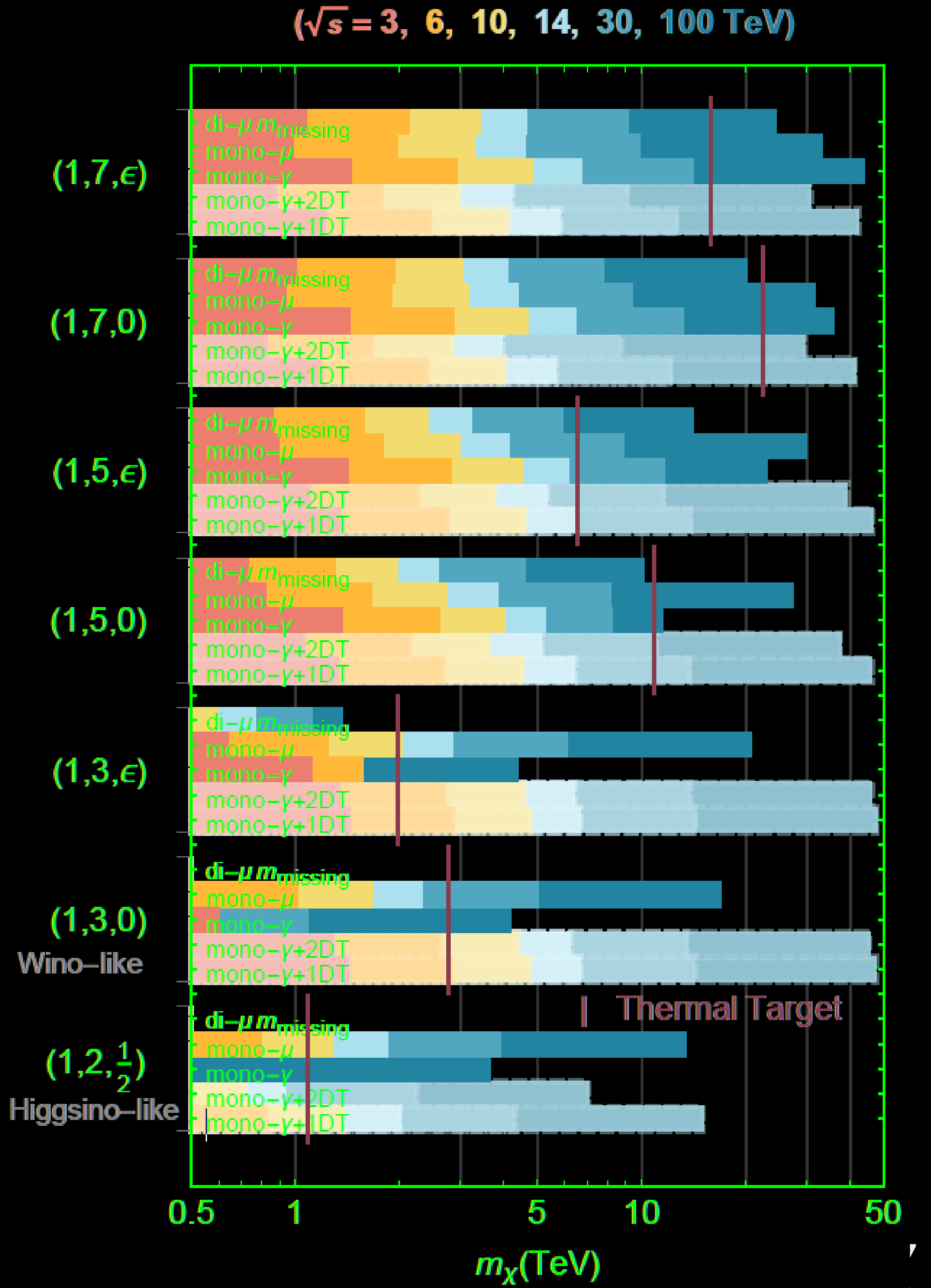
- Disappearing track great potentia kinematic limit)!



See also Capdevilla, Meloni, Simoniello, Zurita, 2102.11292

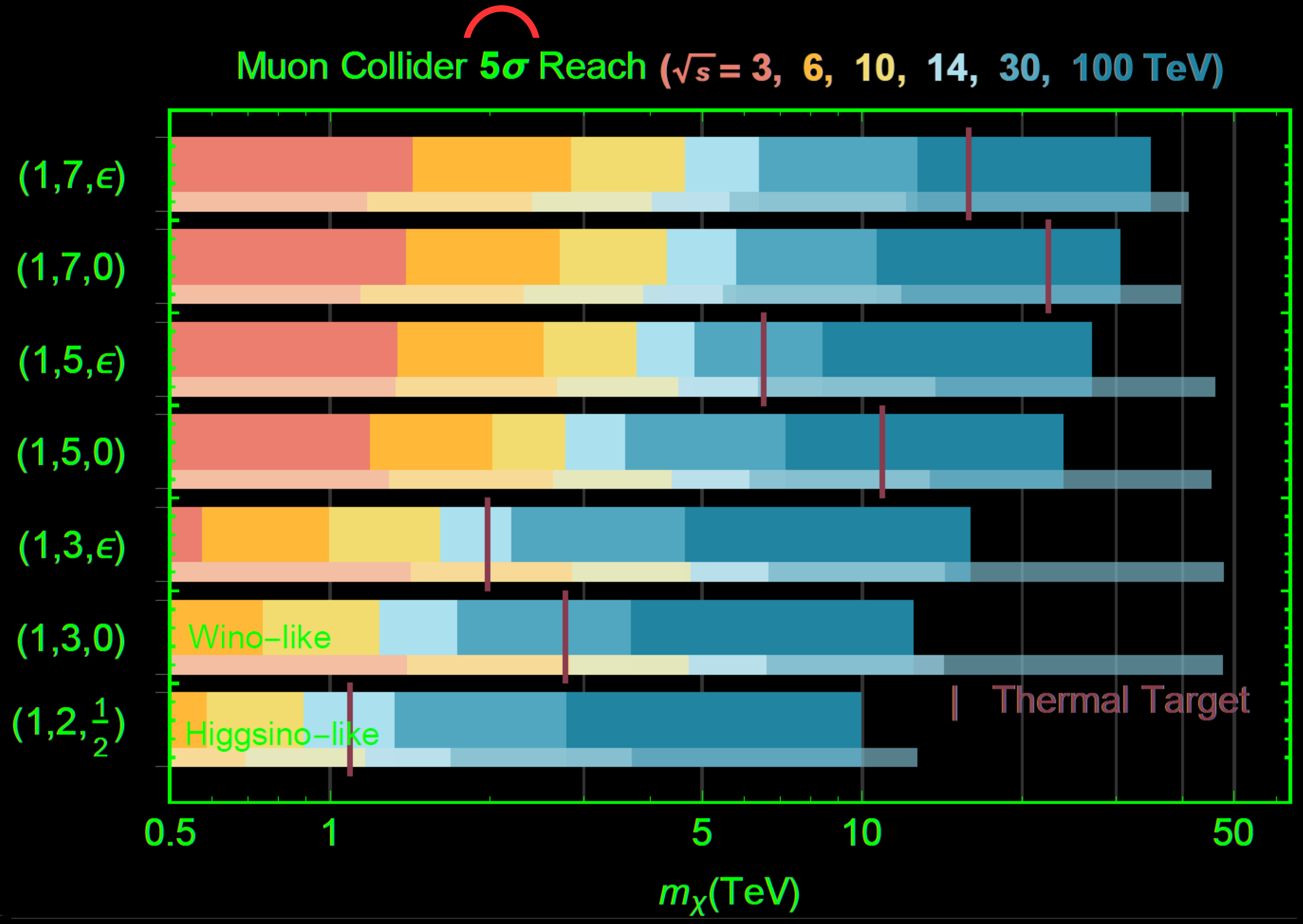
Coverage

We only combine the missing mass searches (mono-muon, mono-photon, VBF dimuon)

High Energy Muon Collider will cover all of them with different run energies.

Electroweak precision probes for these EW multiplets, mainly useful for the high n-plets.

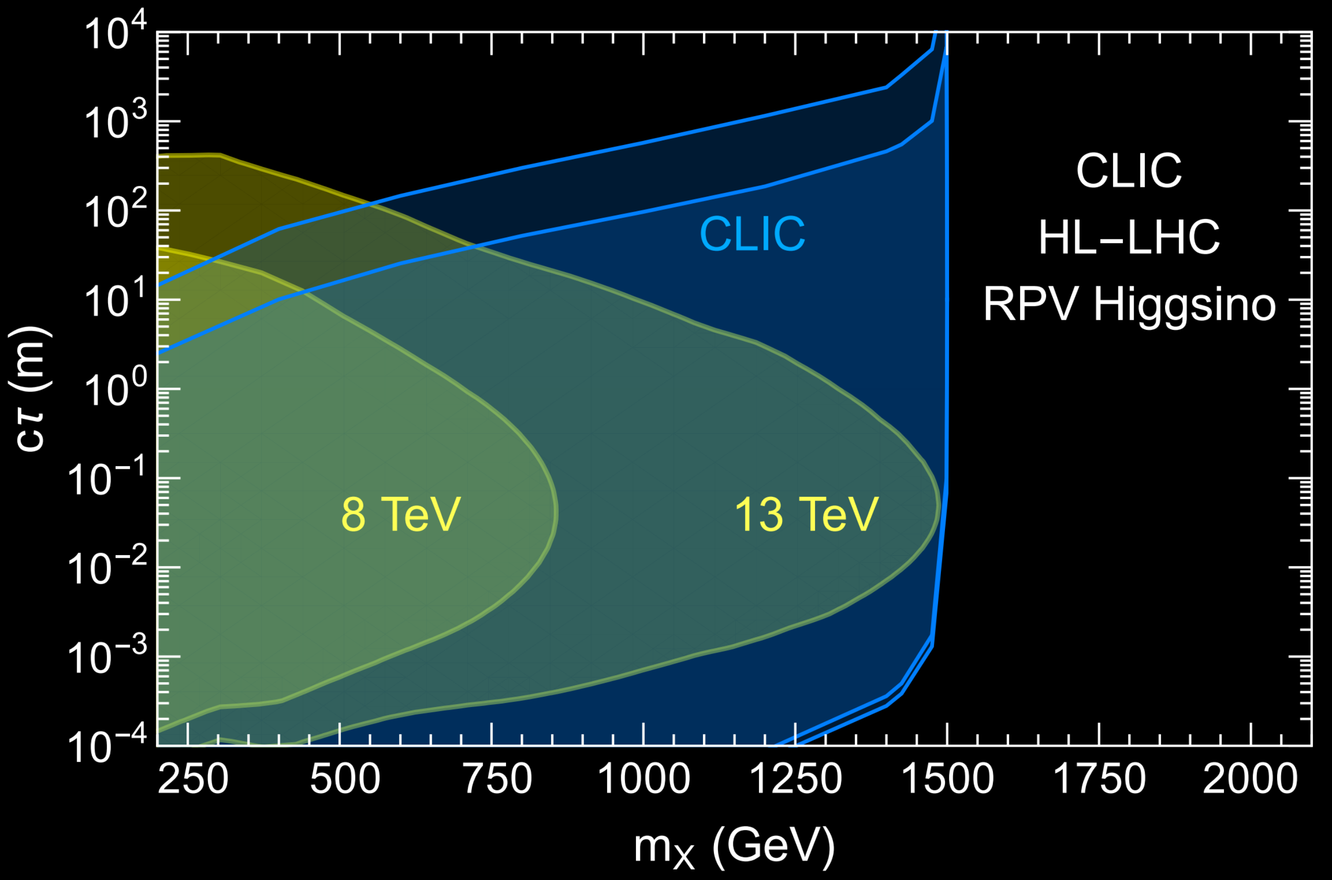
Collider always provides definitive measures for new particles (even if we discover WIMP DM in e.g., DD).



A typical reach for hidden sector

A typical high E lepton collider reach:

- Pair production sensitivity directly to the threshold (so long decays being visible);
- High mass region with low boost can reach long lifetime easily;



Cui, Joglekar, ZL, Shuve, to CLIC physics book, 1812.02093

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- Discover
- Test fully this regime
- Reveal their thermal mechanisms
- Check complimentarily and consistently

To search for: DM and its friends

A Vibrant Program

Thank you!