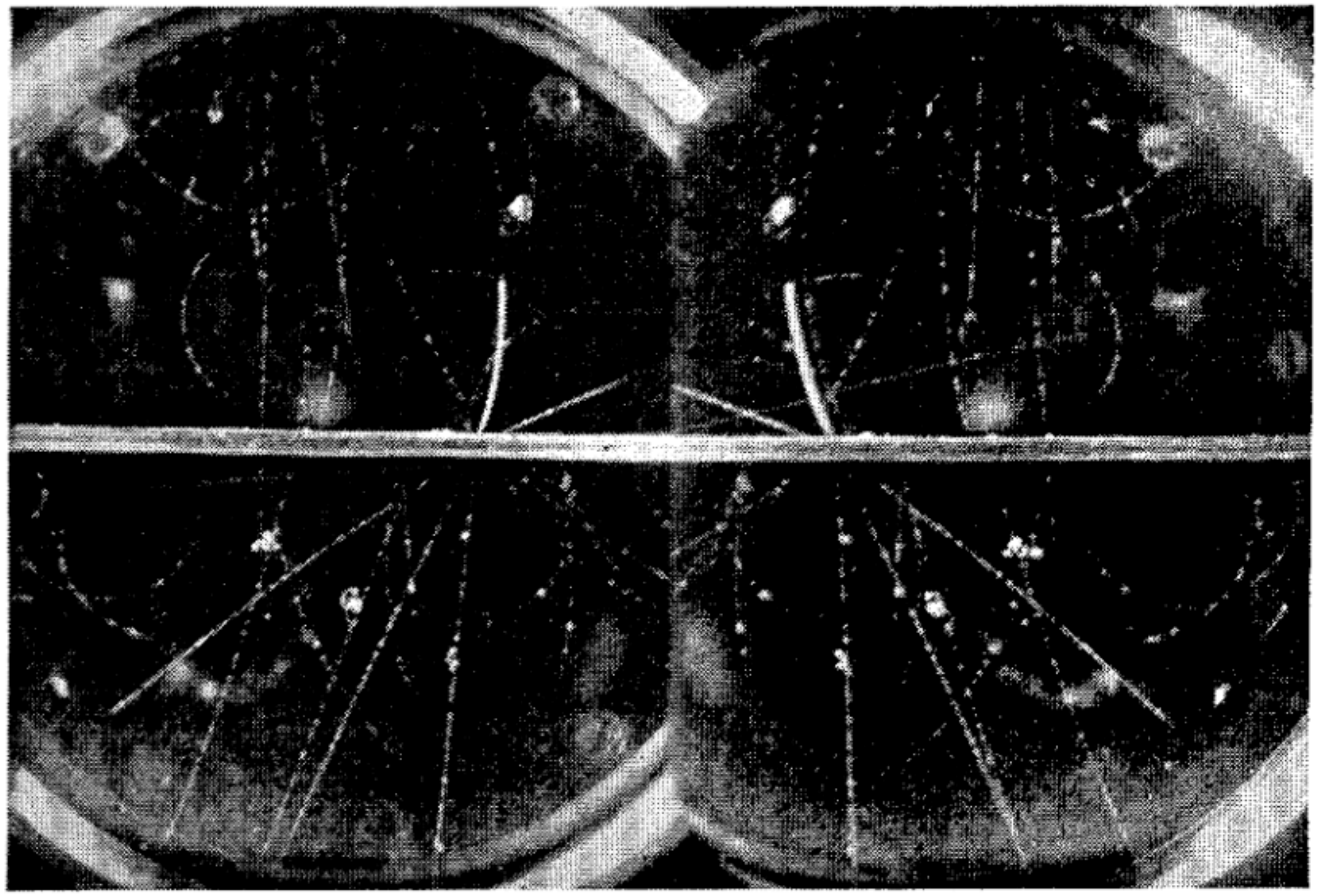
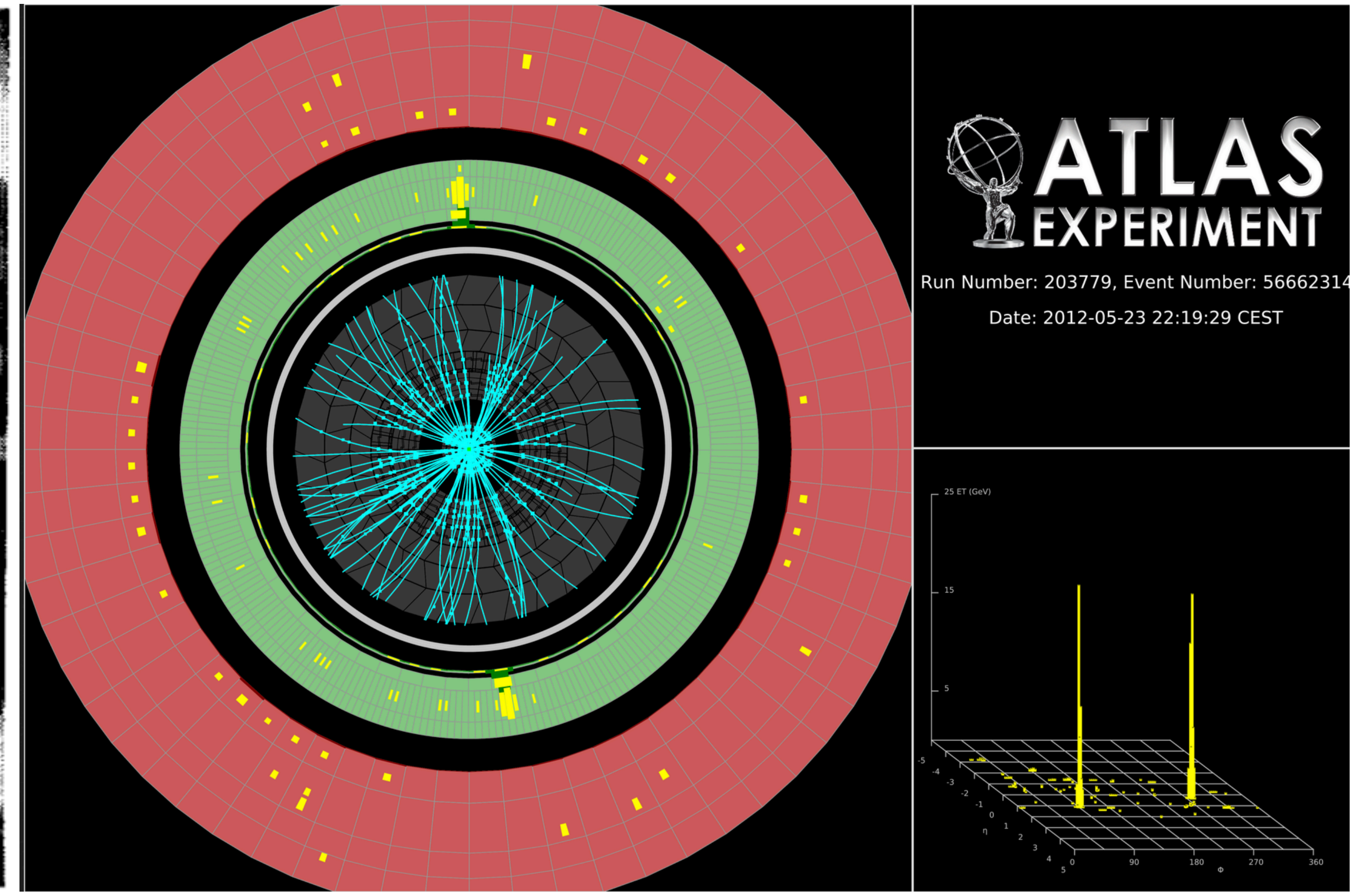


C. D. Anderson, S. H. Neddermeyer, 1936, Physical Review 50 (4): 263–71



ATLAS collaboration, Science Vol. 338 no. 6114 pp. 1576-1582

Searching for the unknown

Other direct searches

Rosa Simoniello (CERN), ICFA23, 01.12.2023

How we look for new physics?

- In all ways!
  - Complementarity between **direct searches,** precision measurements and EFT
  - For direct searches, in case of discovery we can measure the properties of the new particle(s)!
- and everywhere:
  - Broad signature-based program: >600 BSM analyses from ATLAS and CMS exploring different phenomenology, models, kinematics
  - Many reaching and passing the TeV scale
  - Constantly asking if we miss any signature or leaving gaps

Current challenges and limitations

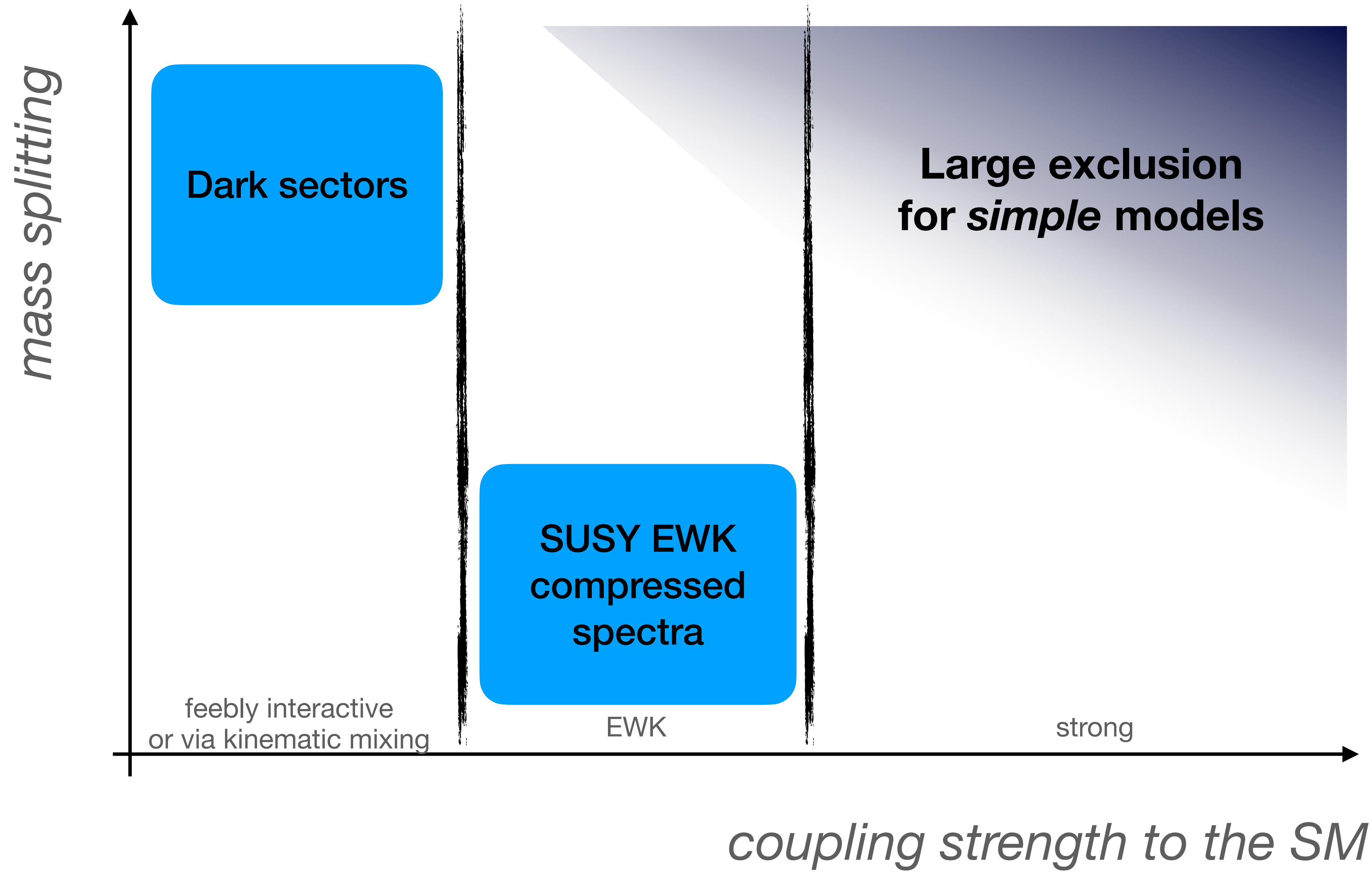
- Difficult phase space:
  - Trigger strategies
  - Reconstruction

→ Need for methodological innovation (already now) and future colliders/detectors

- Extension to longer lifetimes
- Extension to higher energies

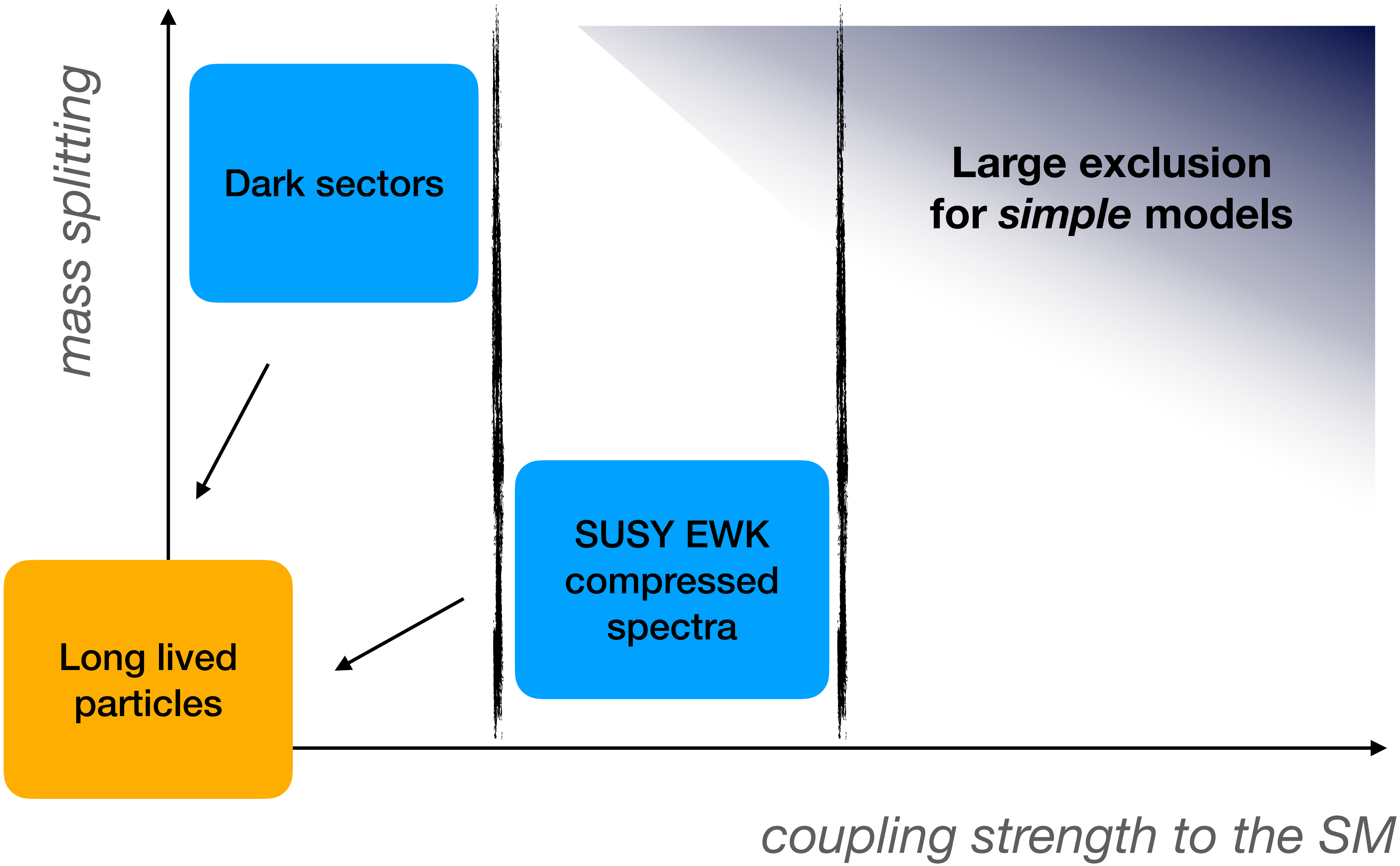
→ Need for future colliders/detectors

Overview of this talk



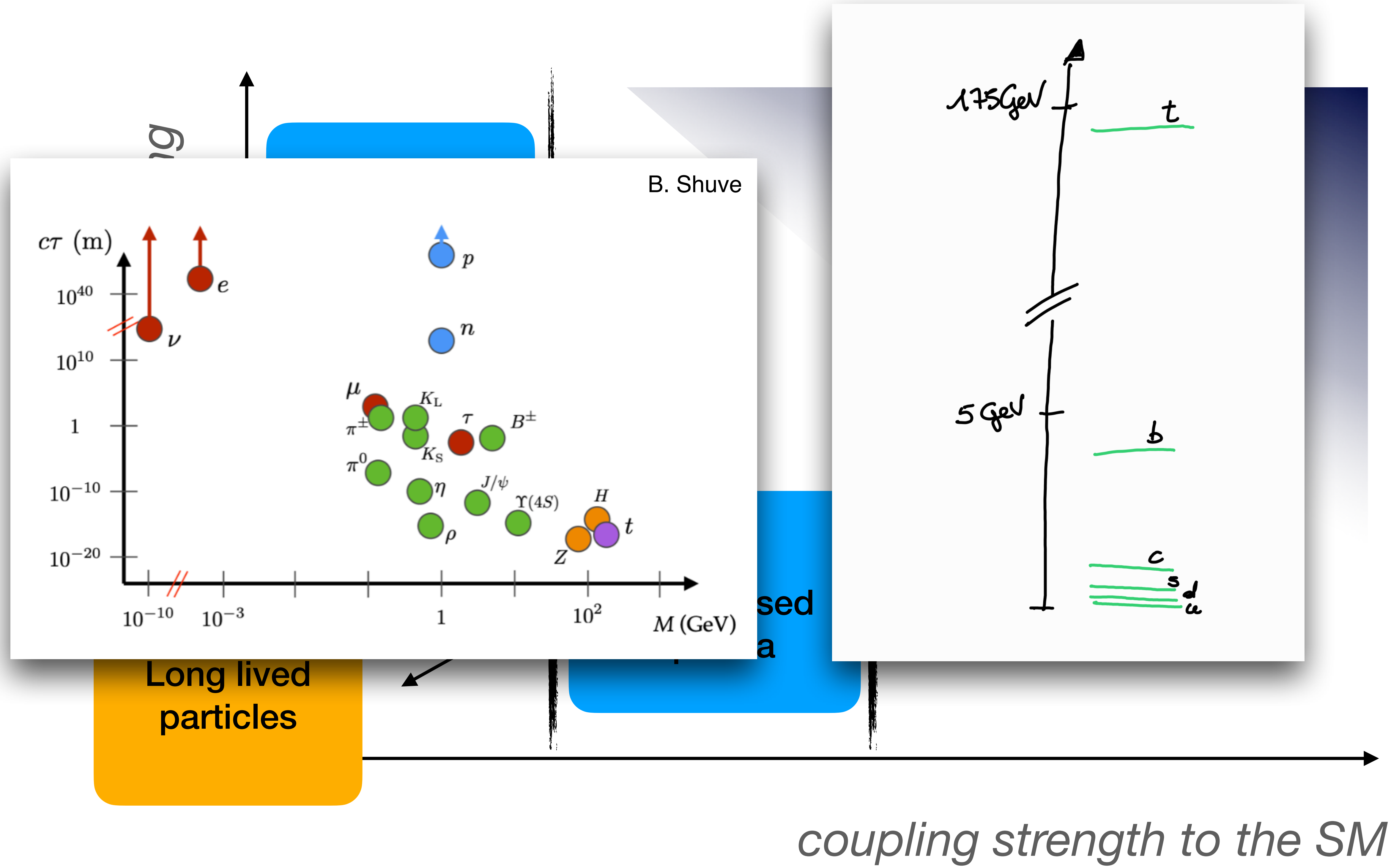
More models/possibilities available! These chosen as benchmarks for this talk

Overview of this talk



Overview of this talk

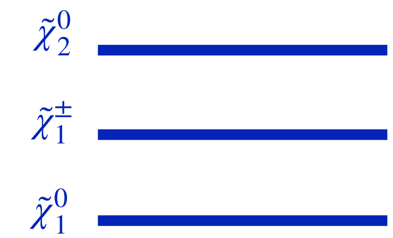
Experimentally challenging but well motivated!

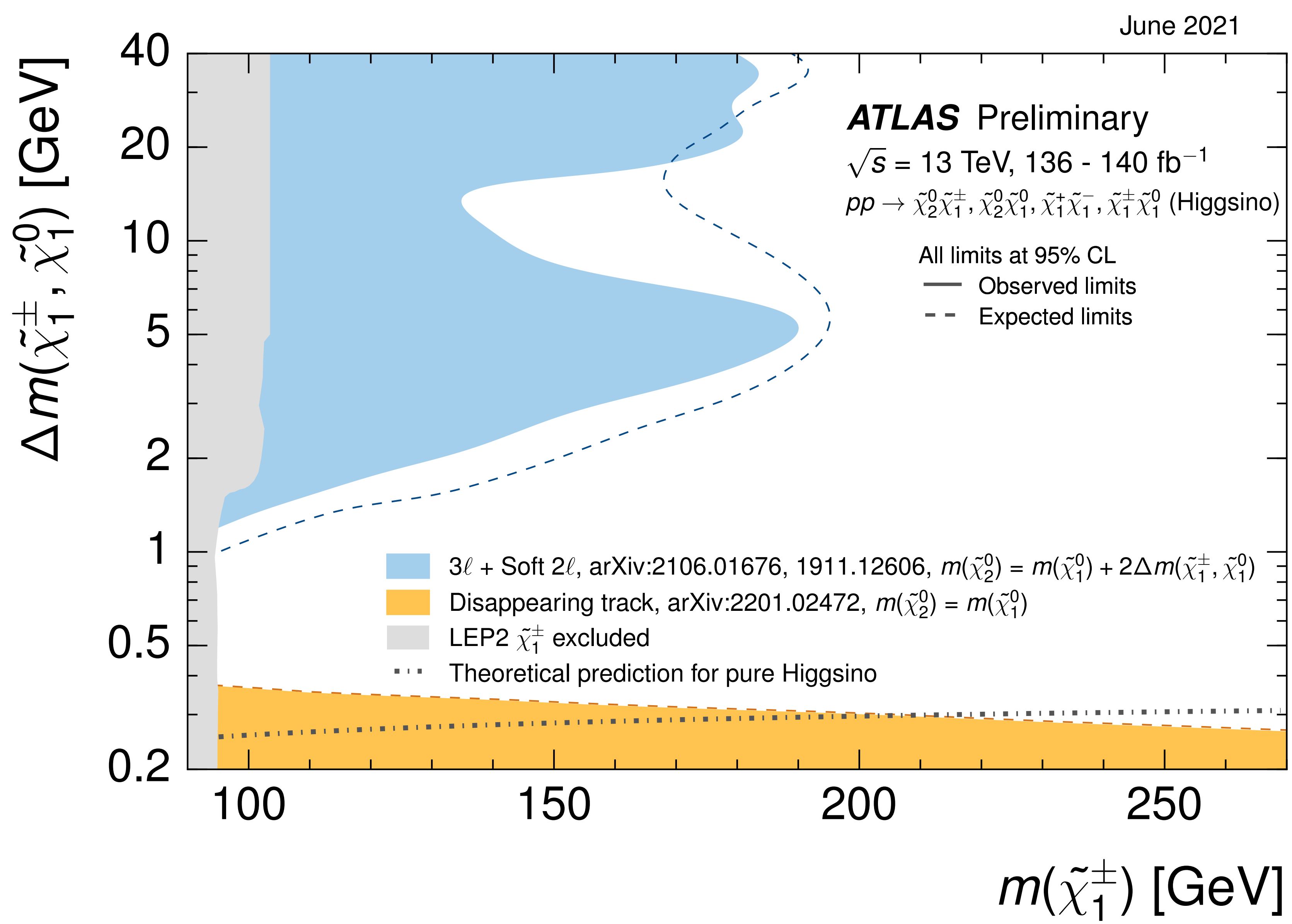


SUSY EWK compressed spectra

EWK SUSY compressed spectra

- Naturalness and DM arguments suggest light Higgsinos
- Higgsinos thermal DM target: 1.1 TeV

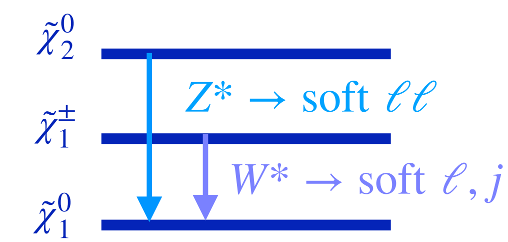


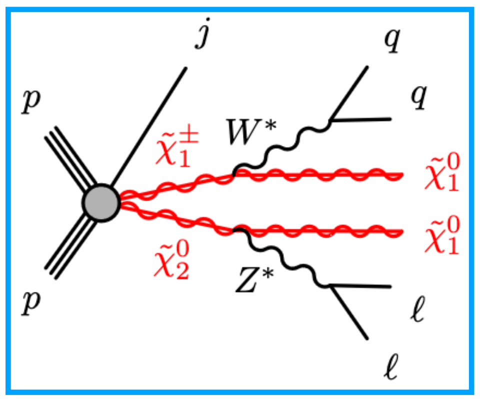


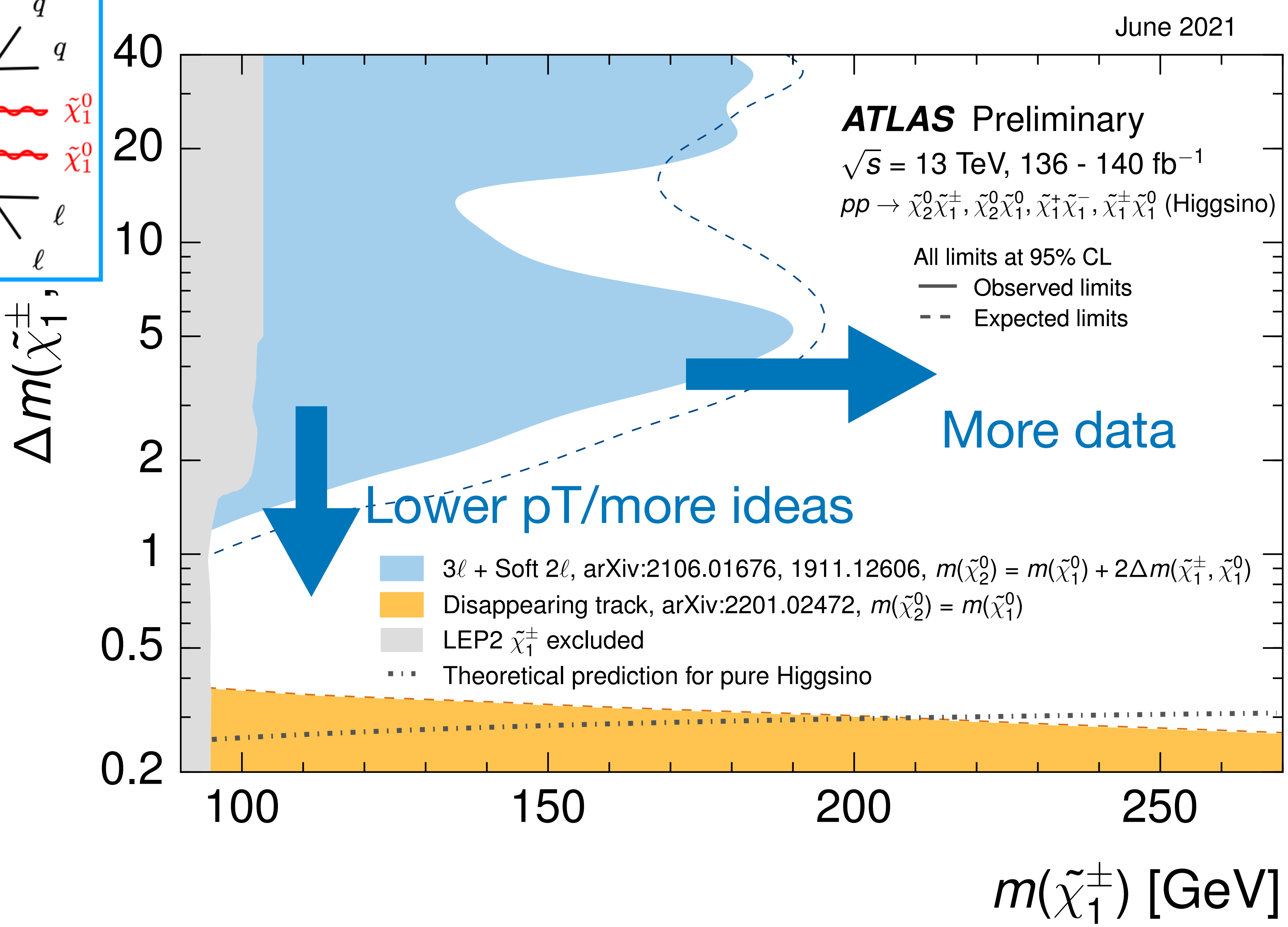
<u>Similar results by CMS</u>, including the small data excess

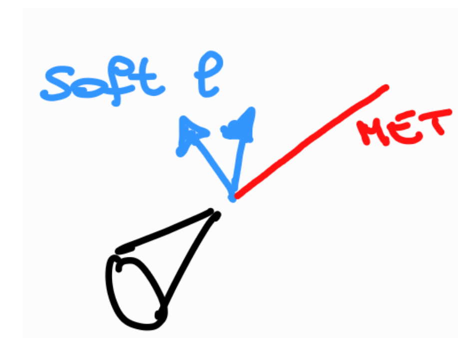
EWK SUSY compressed spectra

- Naturalness and DM arguments suggest light Higgsinos
- Higgsinos thermal DM target: 1.1 TeV
- Signature depends on composition and masses of EWK states









EWK SUSY compressed spectra

- Naturalness and DM arguments suggest light Higgsinos
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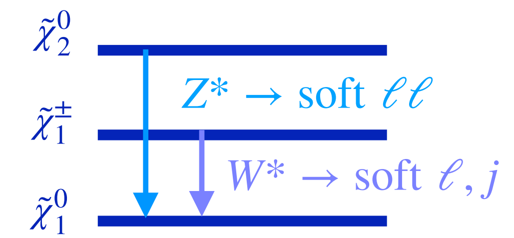
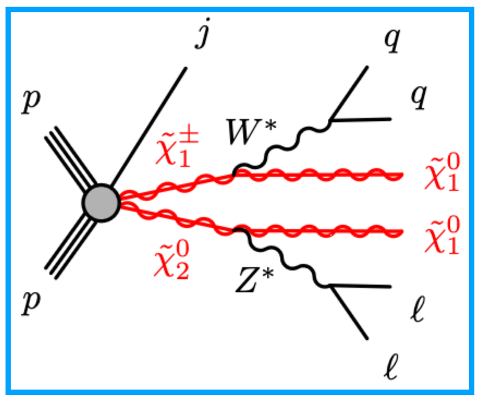
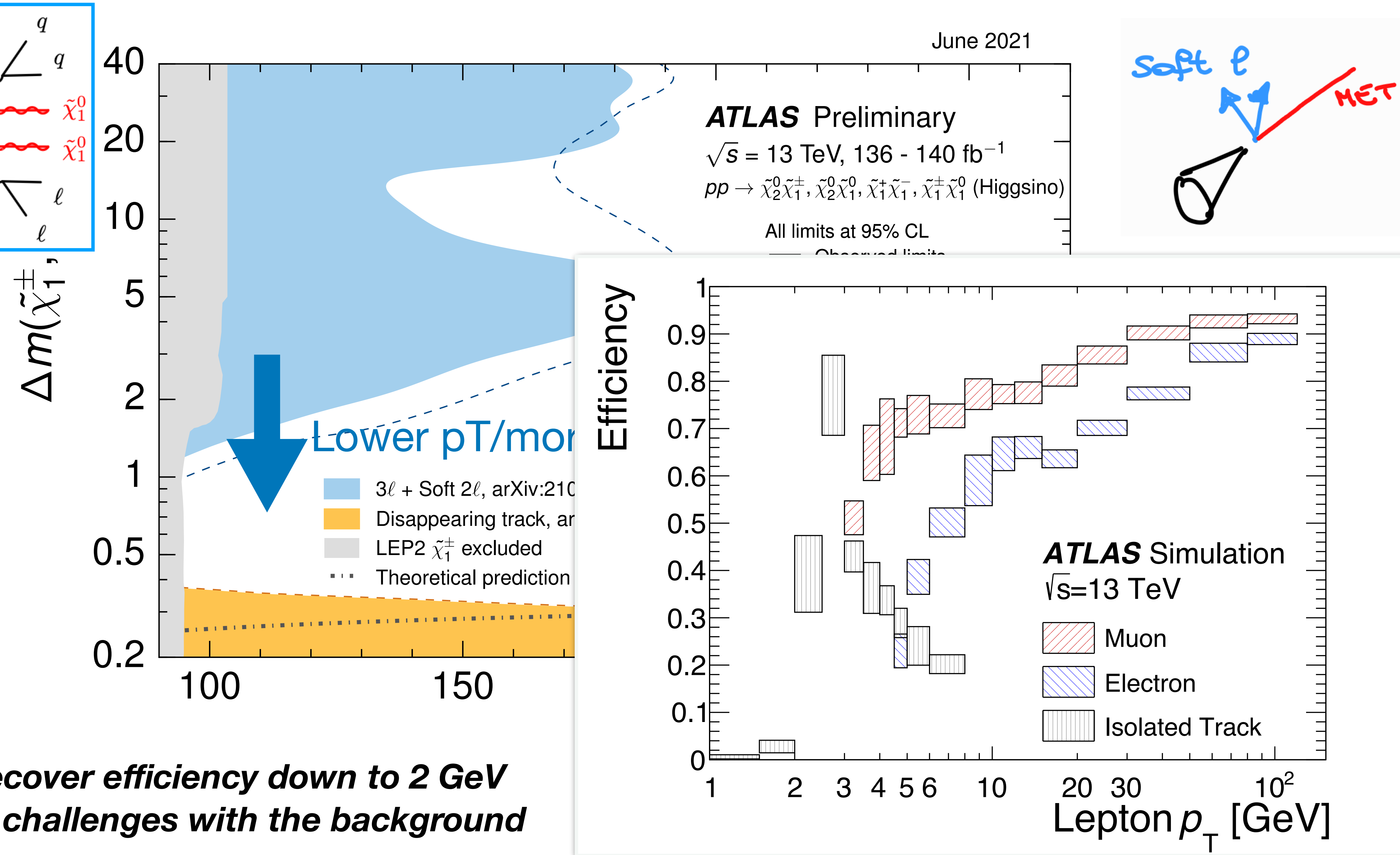


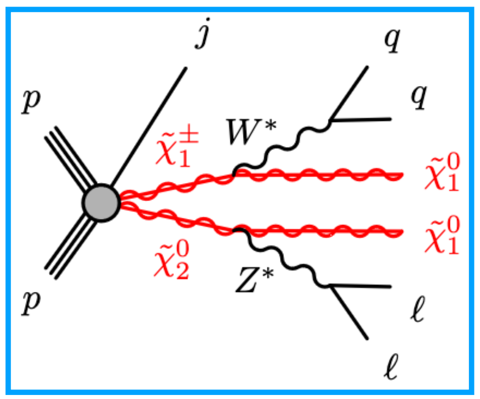


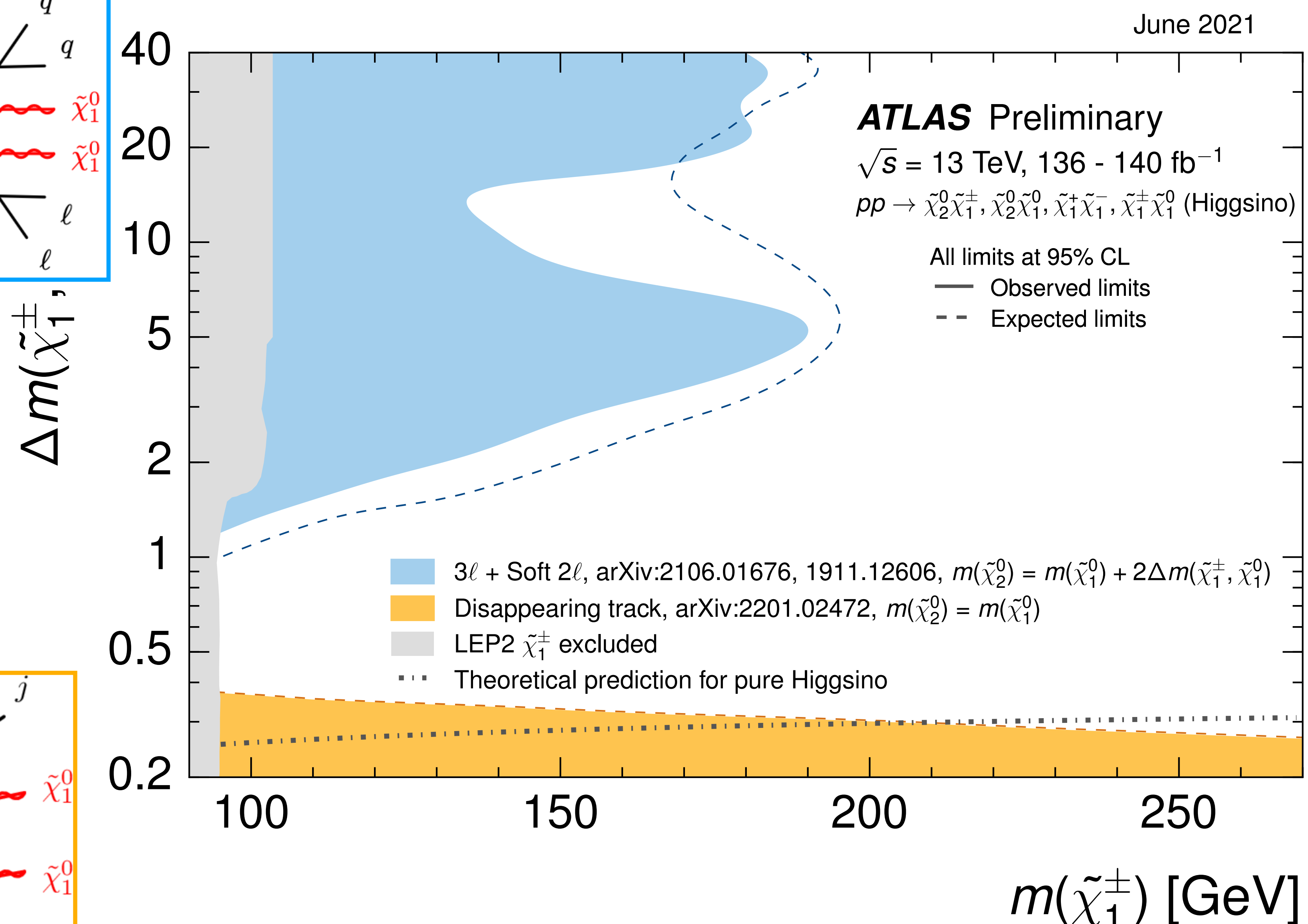


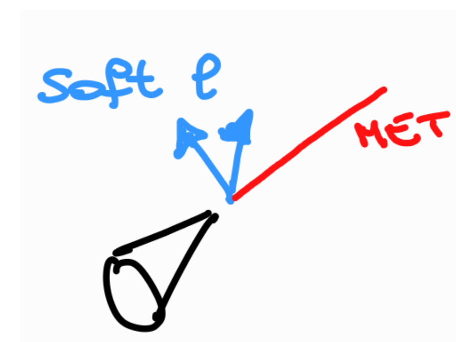
Recover efficiency down to 2 GeV but challenges with the background

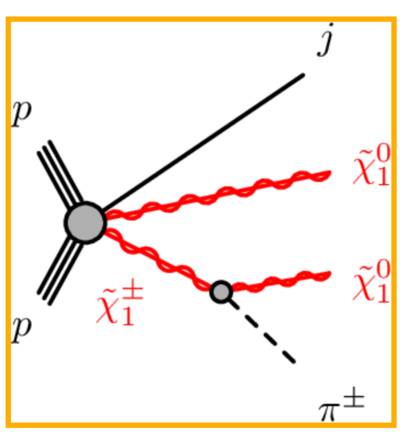
EWK SUSY compressed spectra

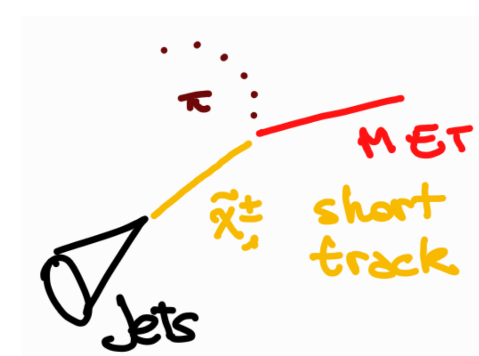
- Naturalness and DM arguments suggest light Higgsinos
- Higgsinos thermal DM target: 1.1 TeV





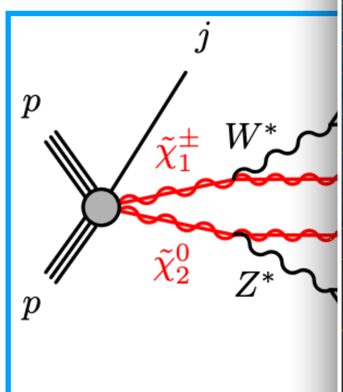


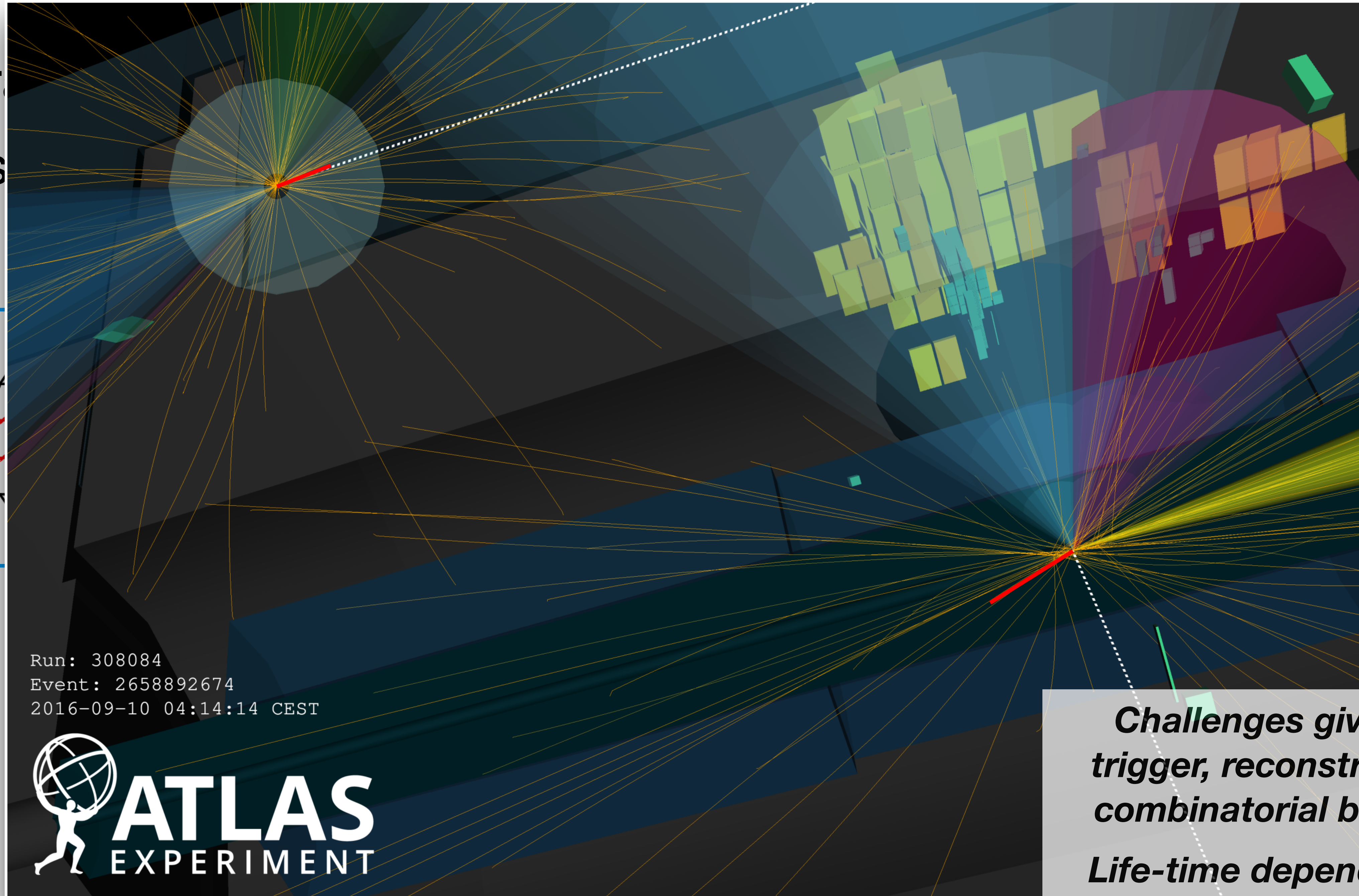


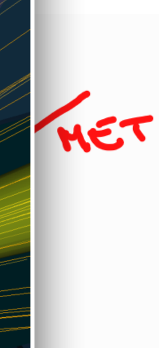


EWK SUSY compressed spectra

- Natur
- Higgs

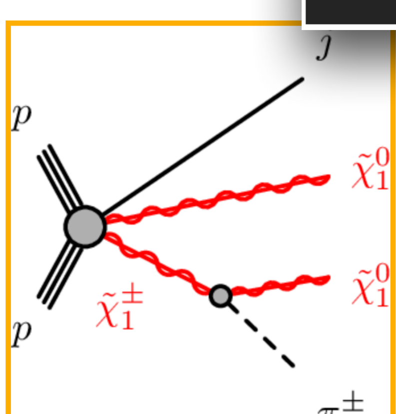


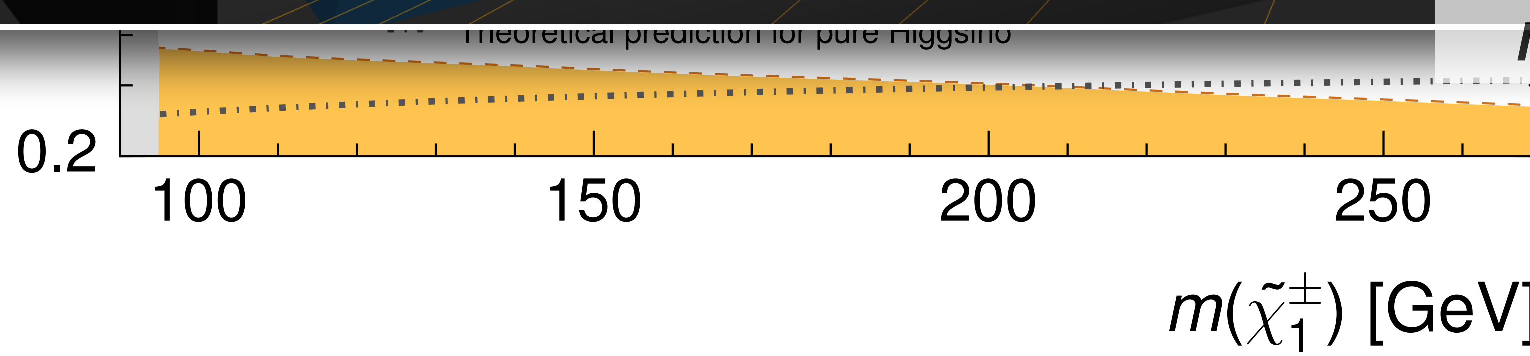


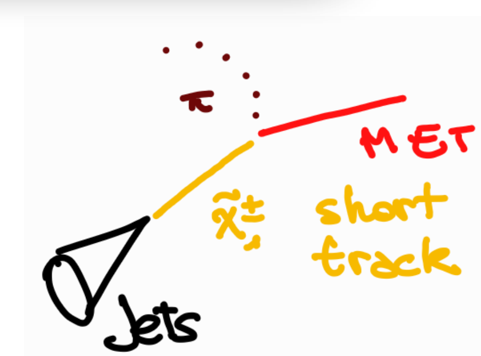


Challenges given by the trigger, reconstruction and combinatorial background

Life-time depends on track length and on <u>tracker geo</u>





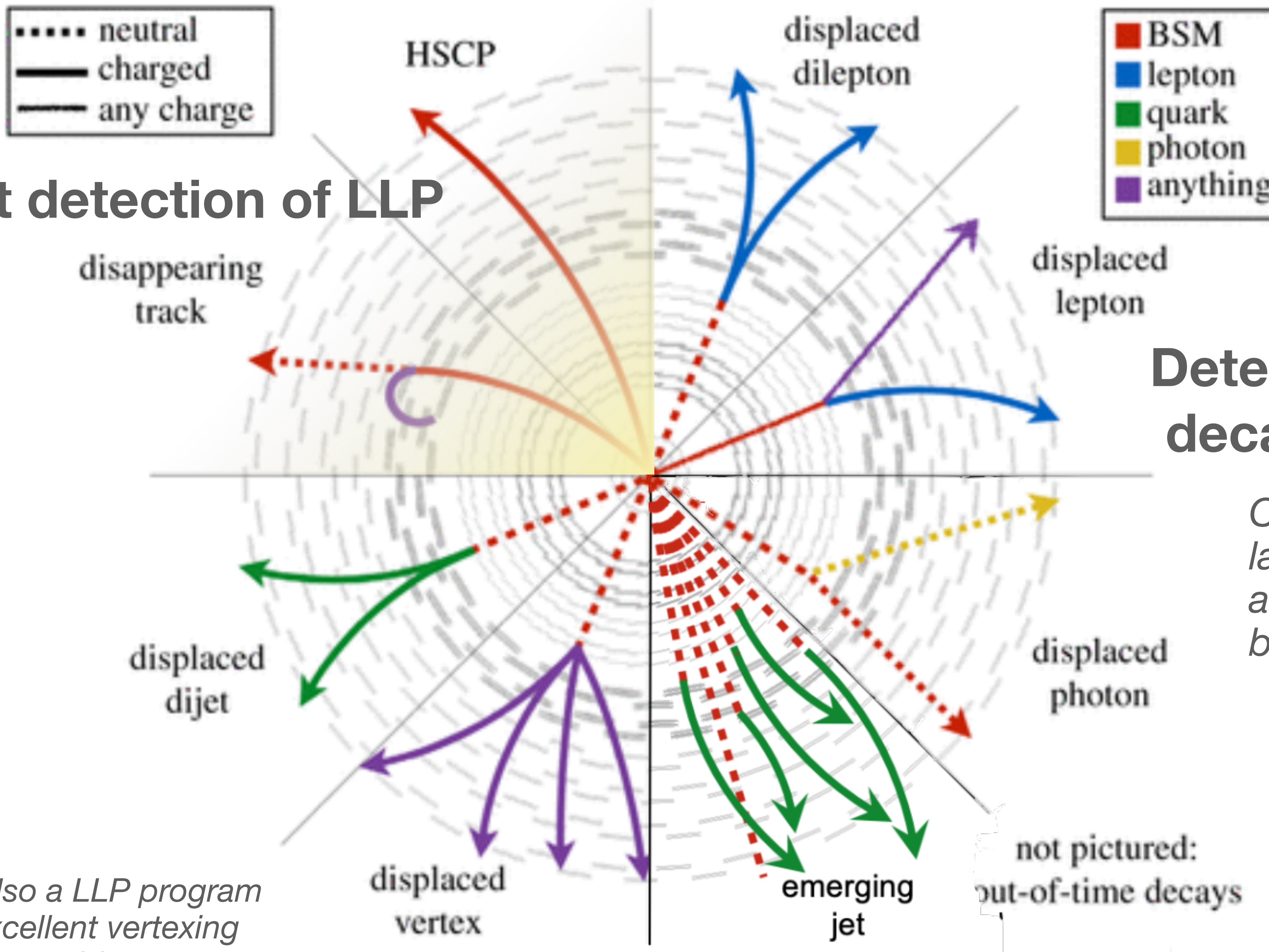


Let's talk more about long-lived particles

LLP signatures

- Different signatures according to different LLP charge and life-time

Direct detection of LLP



Detection of LLP decay products

Challenges due to lack of projectivity and unusual background

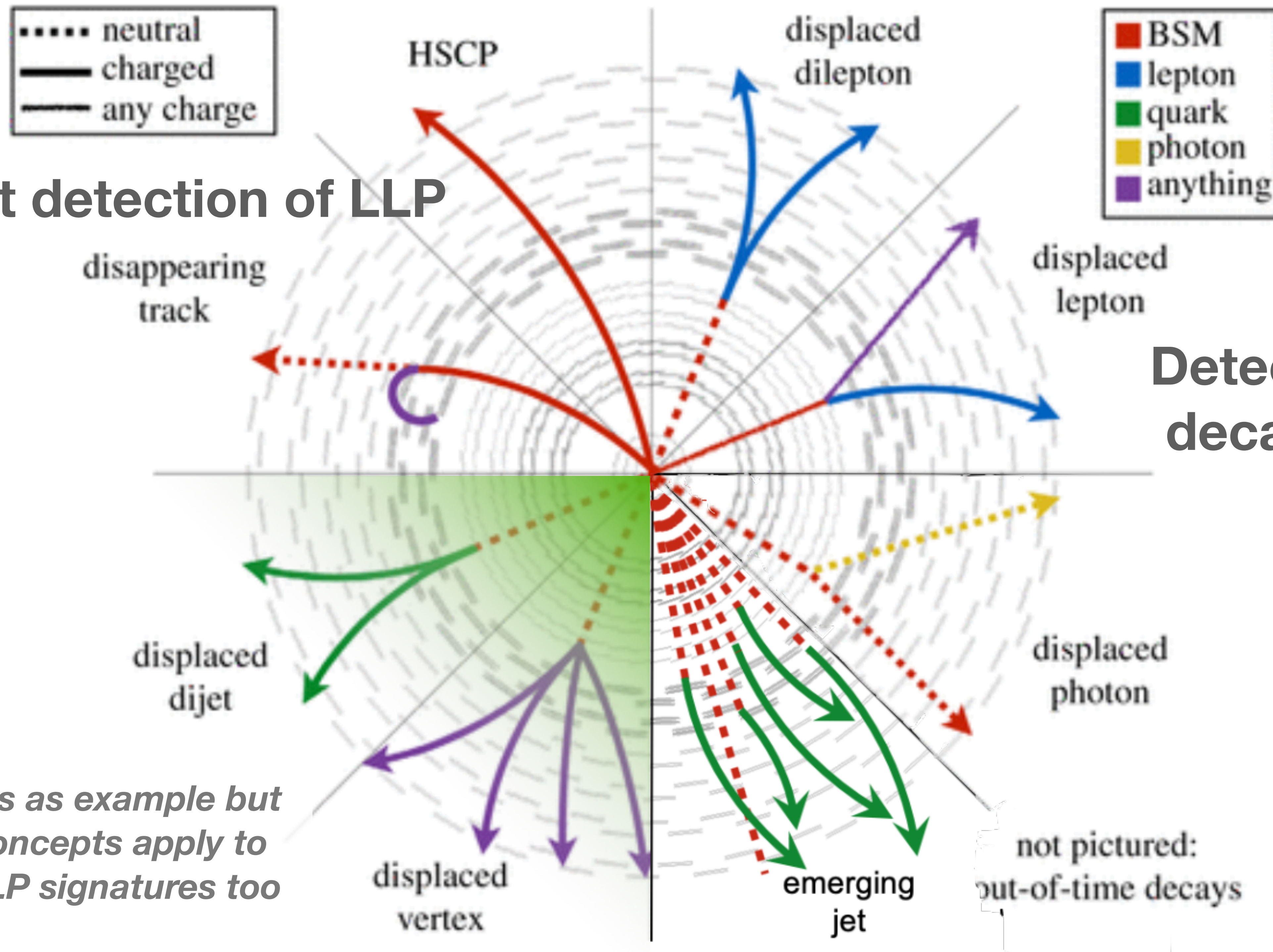
LHCb has also a LLP program based on excellent vertexing performance, probing a more forward region

Sketch by J. Antonelli

LLP signatures

Direct detection of LLP

Detection of LLP decay products

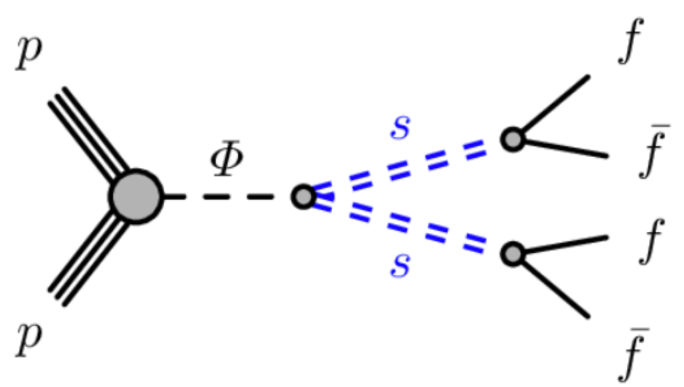


Take this as example but many concepts apply to other LLP signatures too

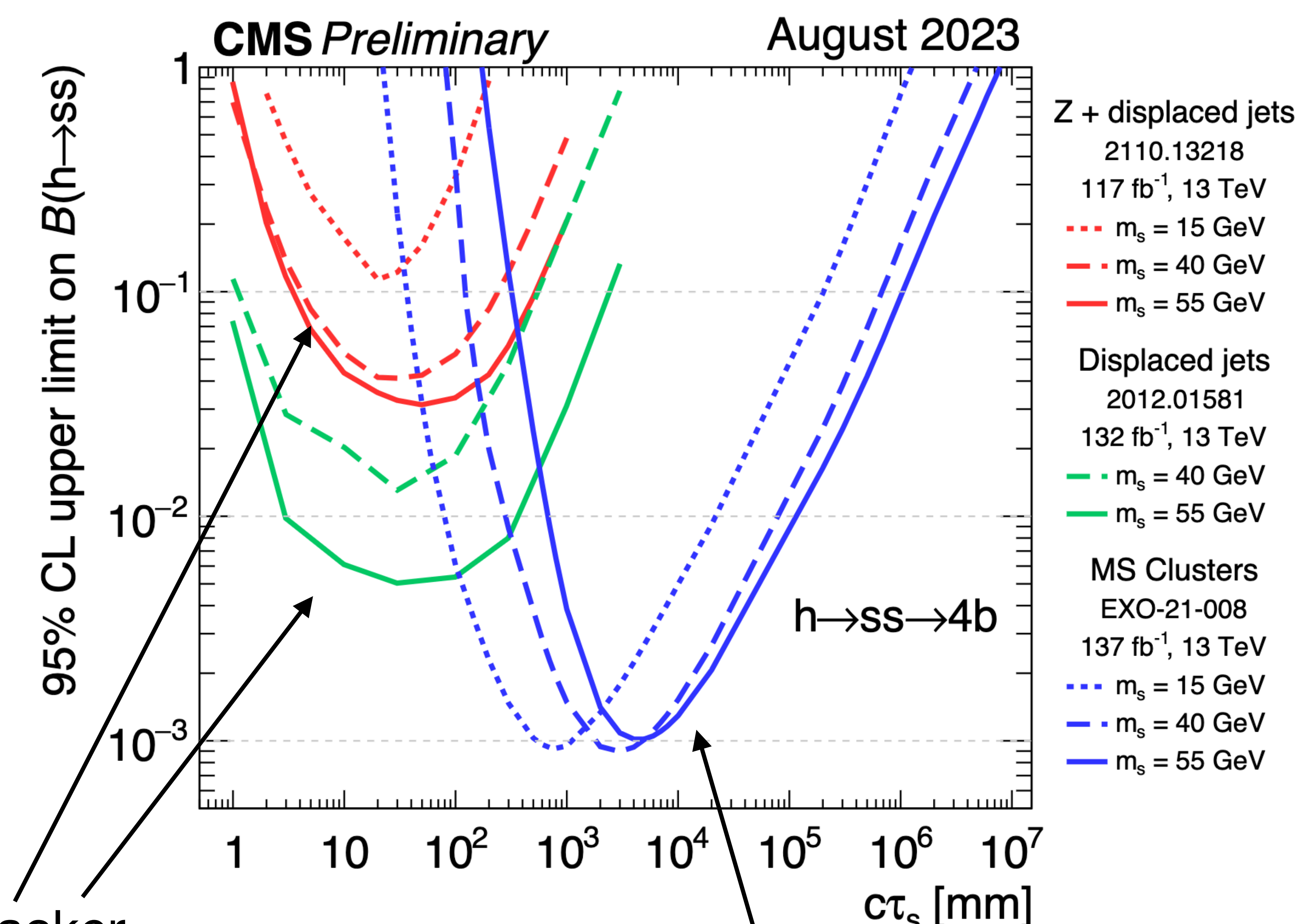
Sketch by J. Antonelli

Dark sectors and LLP

- Dark sectors: full new sector with a DM candidate
- Mediator to interact with SM, often feebly giving LLP
- Upper limit on $c\tau \sim 10^7\mathrm{m}$ from Big Bang nucleosynthesis considerations



Complementary searches looking for LLP decays in various subdetectors



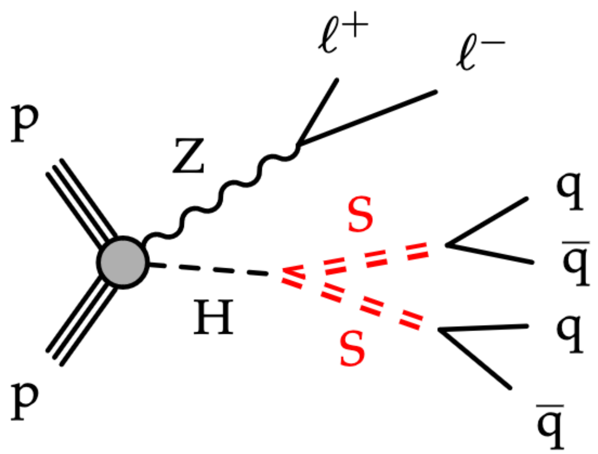
Decay in the tracker

Decay in the muon detector

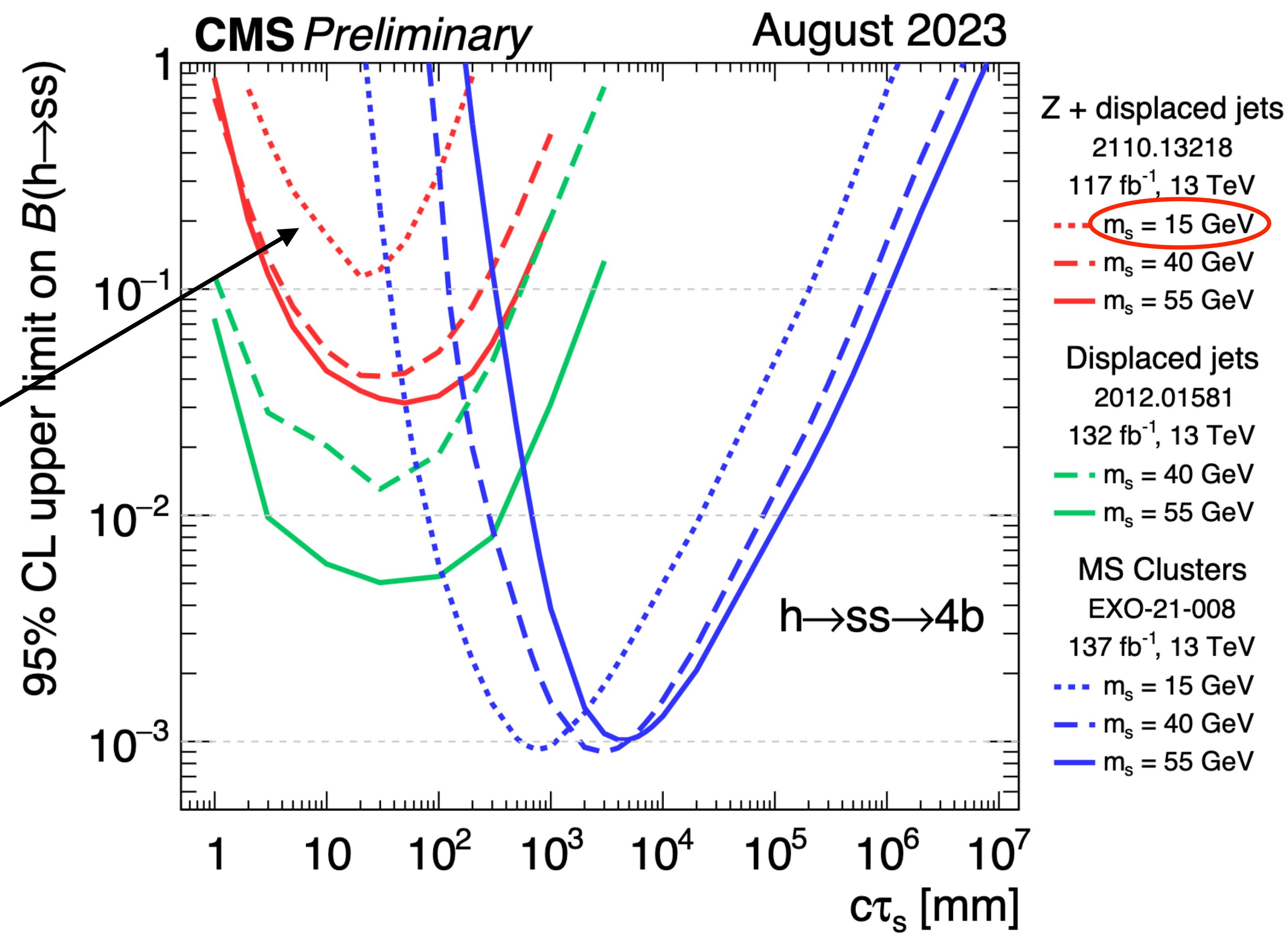
<u>Similar results by ATLAS</u>

Dark sectors and LLP

- Dark sectors: full new sector with a DM candidate
- Mediator to interact with SM, often feebly giving LLP
- Upper limit on $c\tau \sim 10^7\mathrm{m}$ from Big Bang nucleosynthesis considerations

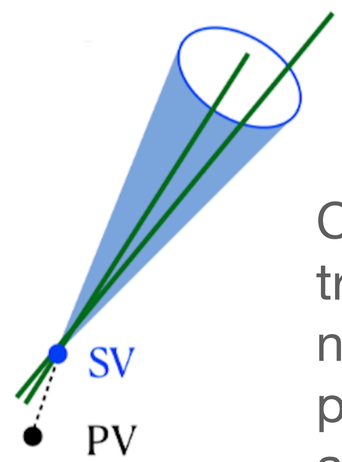


Use of SM objects to
help with trigger
Increase sensitivity for
light LLPs

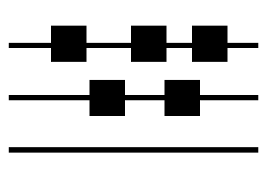


Dark sectors and LLP

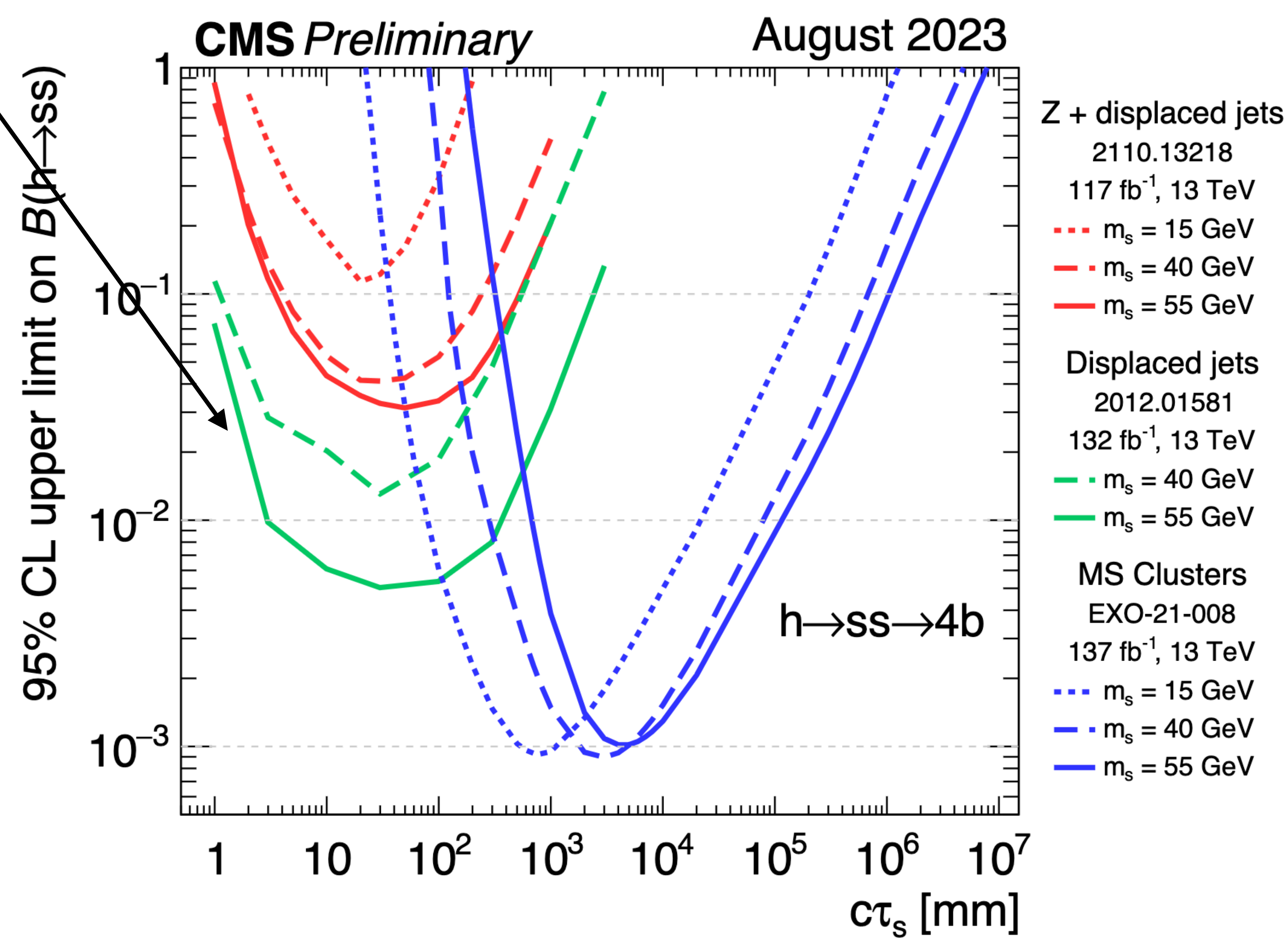
Trigger on displaced objects: successfully explored in Run2, large gains with improved strategies in Run3 for many LLP signatures



CMS: select displaced tracks online and count number of displaced/ prompt tracks associated to a jet



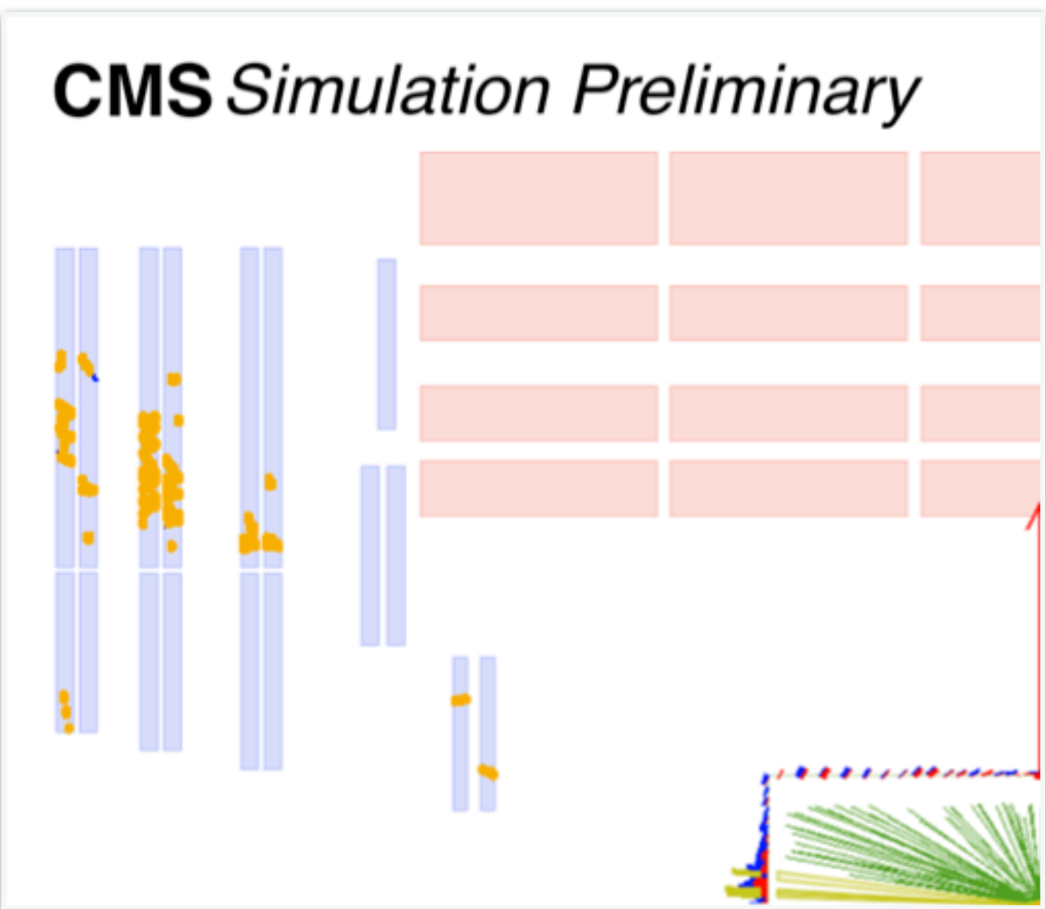
ATLAS: use hits not associated to prompt tracks, exploiting higher multiplicity for outer layers w.r.t. inner layers for triggering displaced vertices

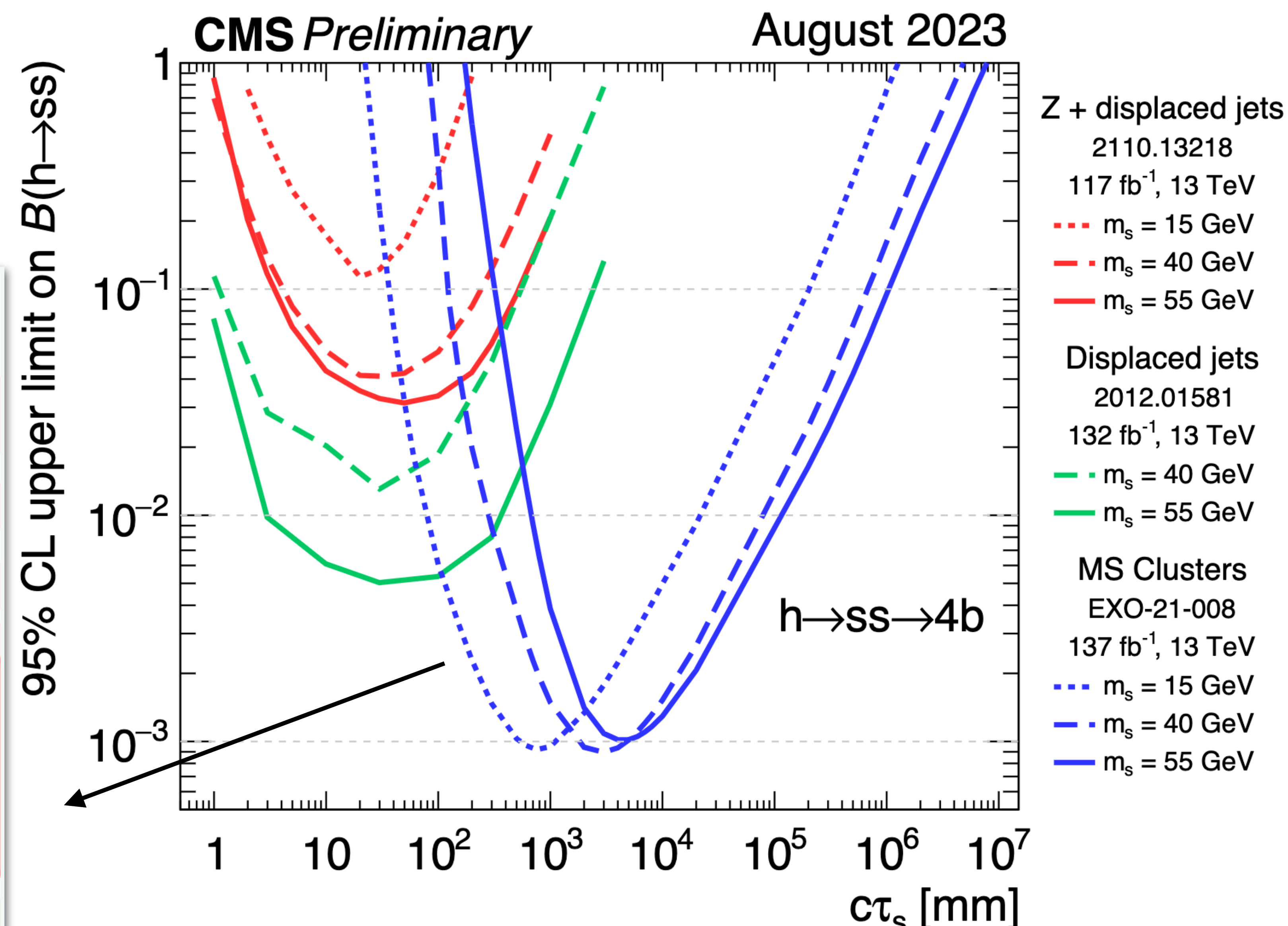


Dedicated triggers can open up phase space + allow for less model dependency

Dark sectors and LLP

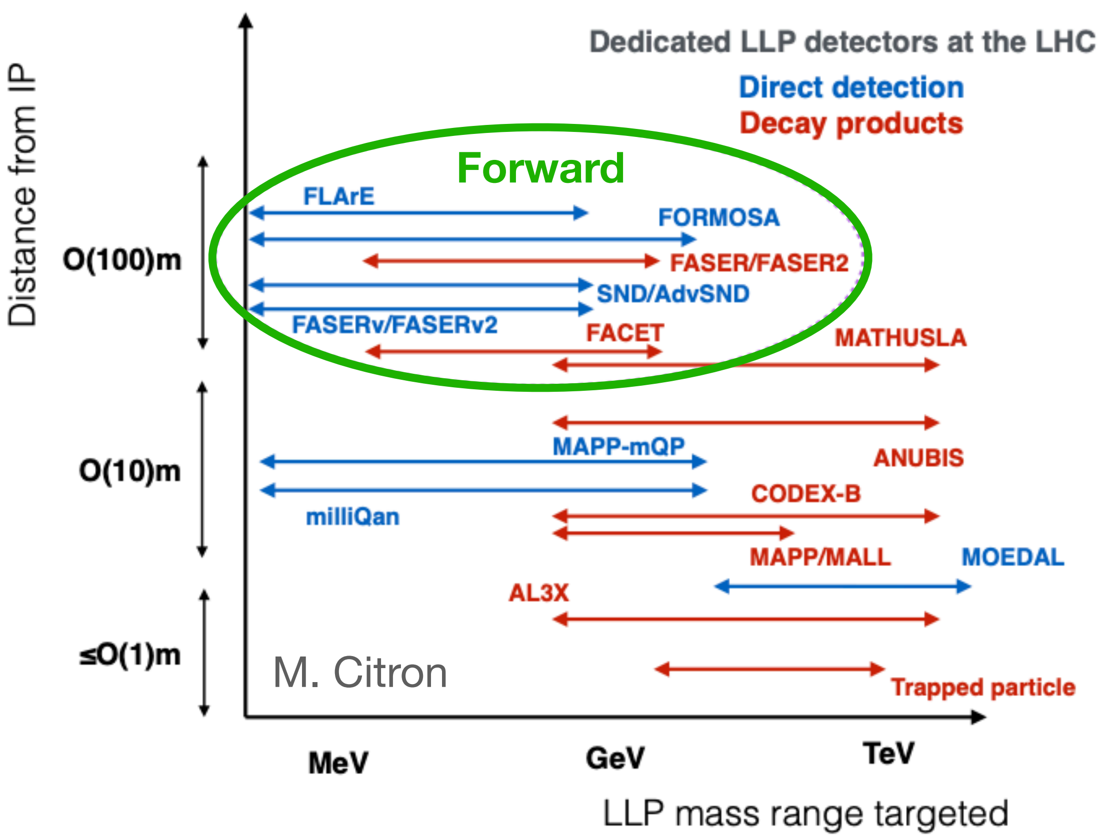
- CMS muon detectors used as sampling calorimeter
- Enough background suppression to allow detection of a single LLP decay —> increase signal acceptance
- Calorimeter showers sensitive to LLP E instead of m

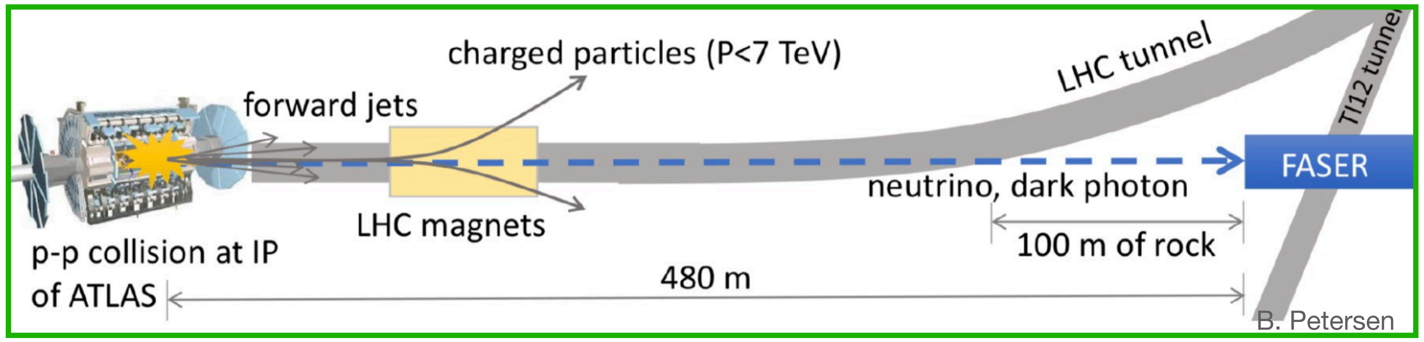


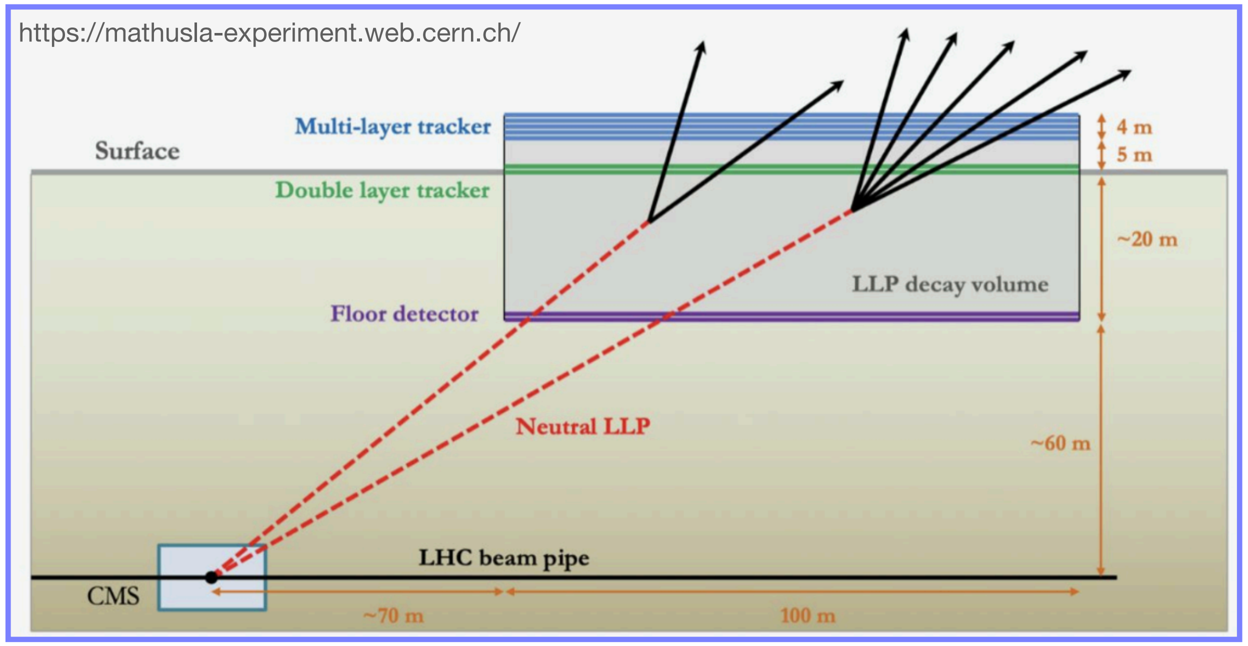


Use of detectors in unconventional way!

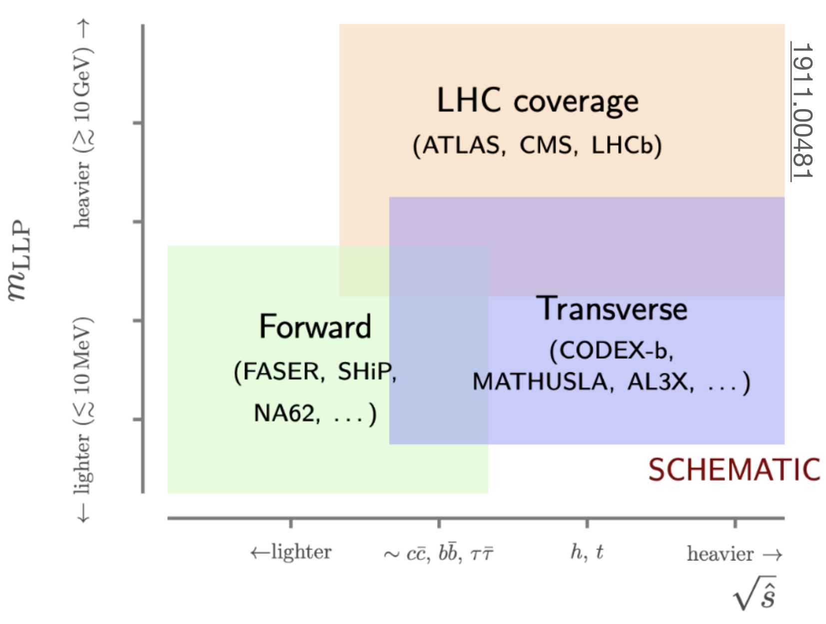
HL-LHC and LLP







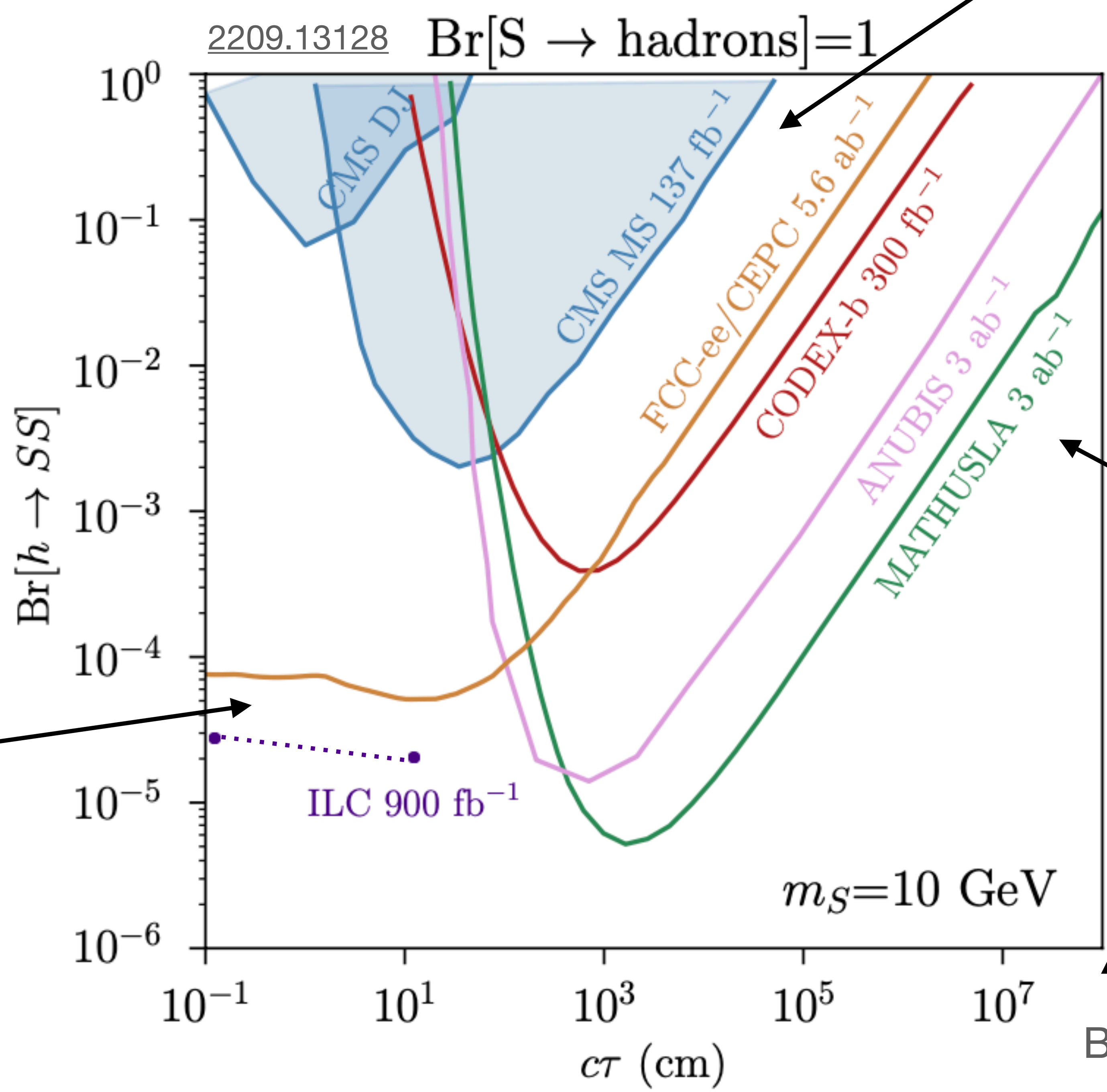
- Large number of proposals for new dedicated LLP detectors covering different scenarios —> maximise the HL-LHC physics program
  - Direct detection: neutrinos and anomalous charge
  - Detection of decay products:
    - Forward: light LLP produced in meson decay in the forward region
      - FASER built, taking data and producing first results!
    - Transverse: neutral LLP decaying to charged particles
- Feebly interactions + no/reduced background searches (thanks to extra shielding) —> profit the best from high luminosity



HL-LHC and LLP

- Going back to the scalar portal example

+ improvements obtained by ATLAS and CMS at the HL-LHC



BBN limit

Extend 3 orders of magnitude in lifetime and BR

Higgs factories lepton colliders*: lower background + easier trigger (or triggerless)

Opportunities also for other light LLPs, e.g. ALPs, long-lived HNL

** Similar results expected for Muon Collider*

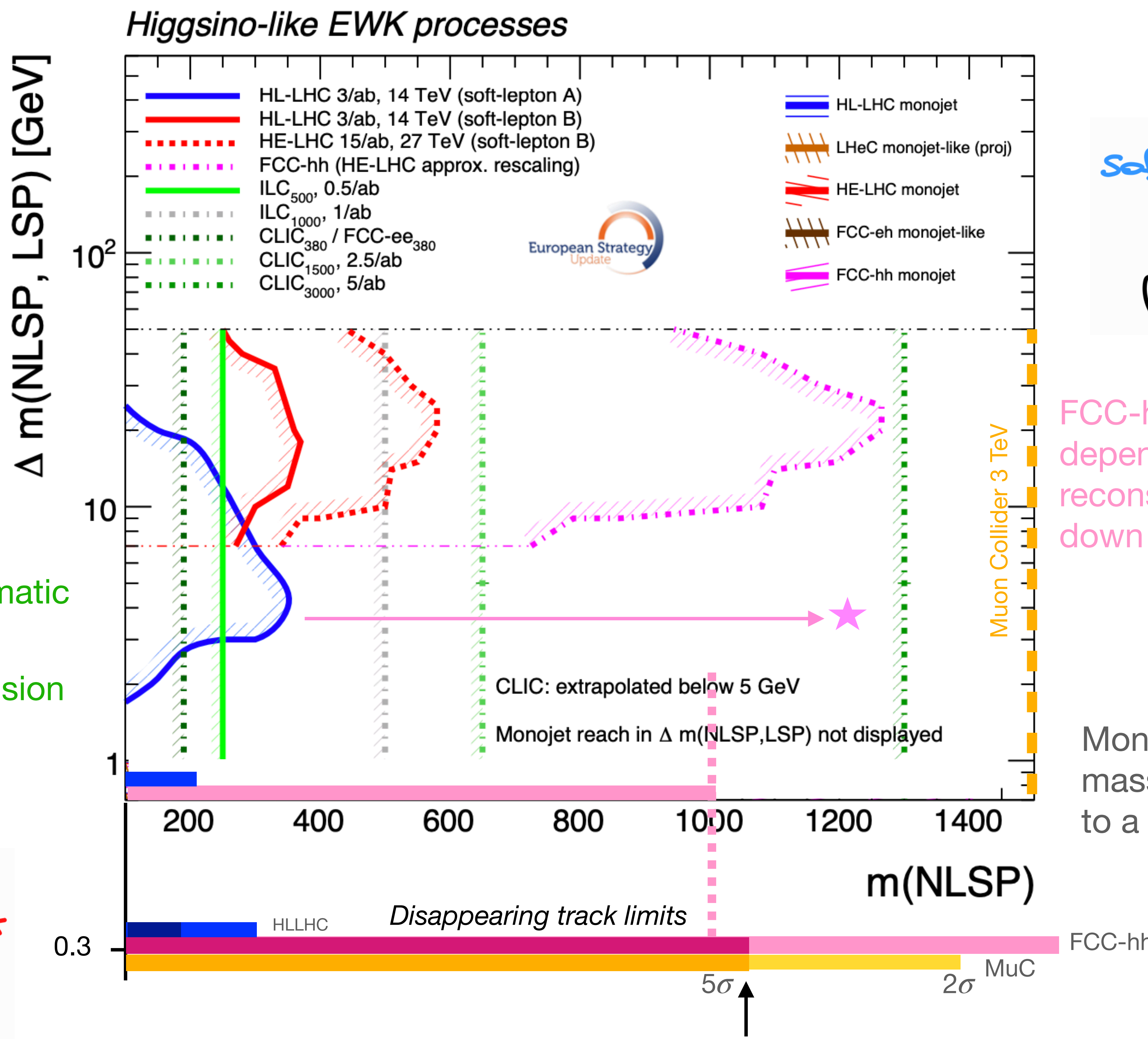
Future opportunities with the main detectors

Looping back to Higgsinos

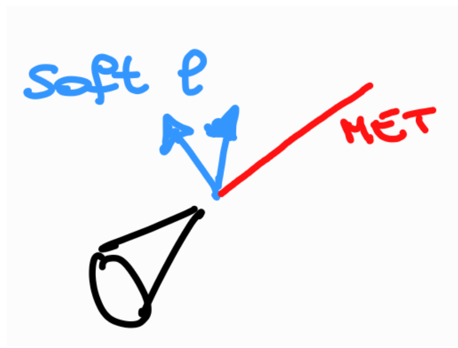
plot from 1910.11775 supplemented with results from 2209.13128

HL-LHC: x20 more data + detector upgrades

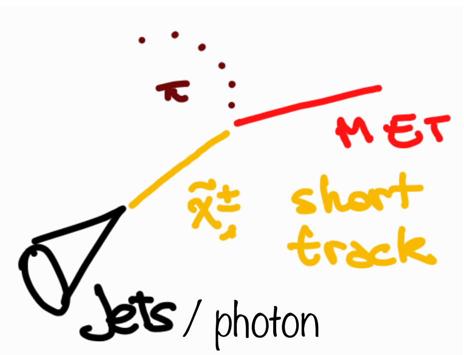
Lepton colliders: sensitivity to kinematic limit $\sqrt{s}/2$ for discovery or exclusion



FCC-hh extrapolation depends on ability to reconstruct leptons down to 5-3 GeV



Monojet sensitivity mass independent up to a few GeV in Dm

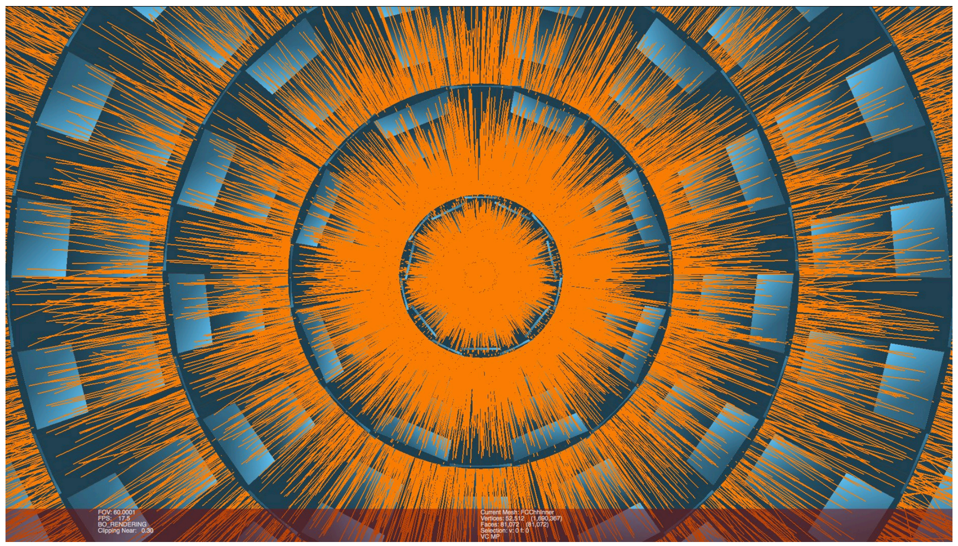


FCC-hh and Muon Collider can reach DM thermal target (1.1 TeV)

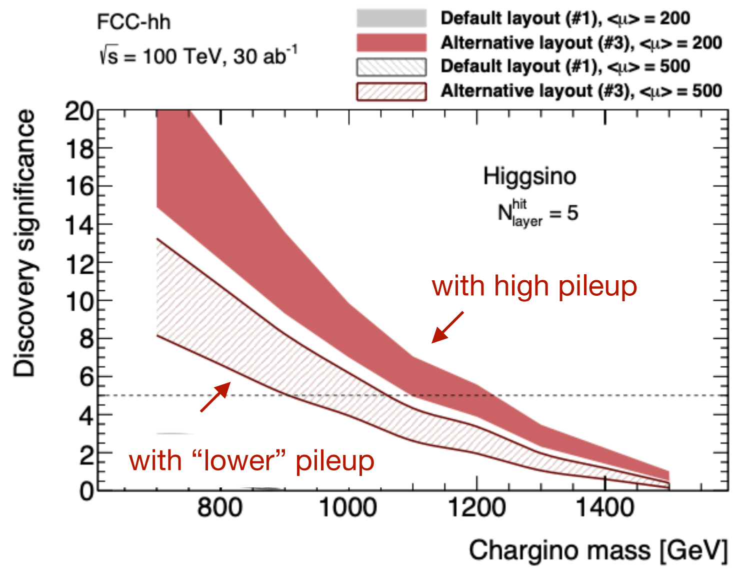
Looping back to Higgsinos

FCC-hh and Muon Collider can reach thermal target, facing some challenges

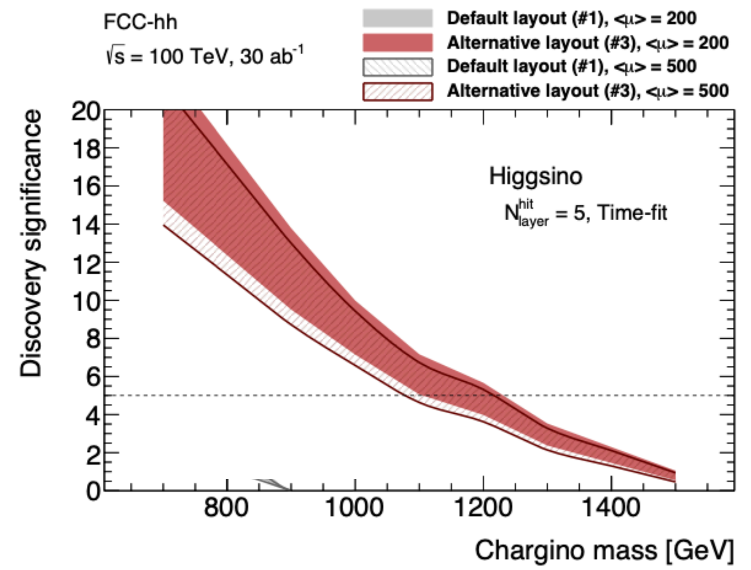
FCC-hh pileup $\langle \mu \rangle = 1000$



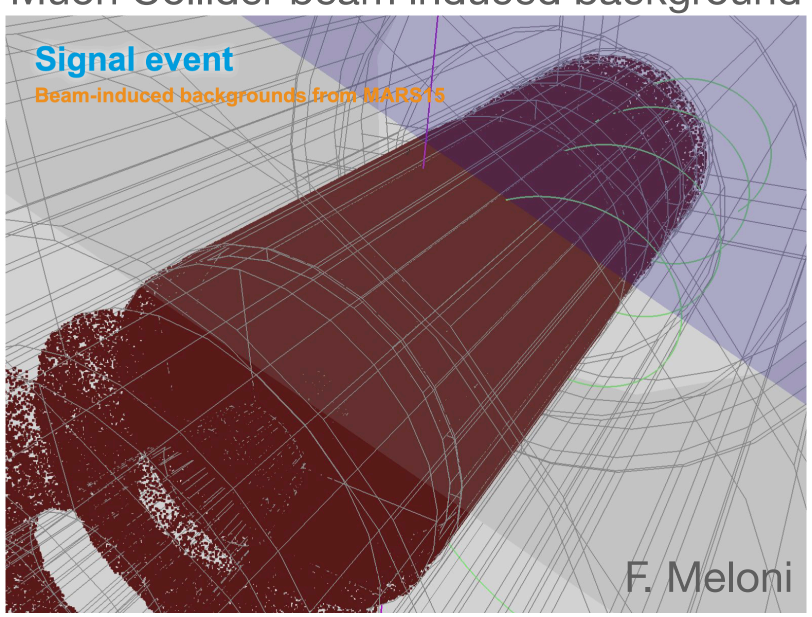
w/o hit timing in track fit

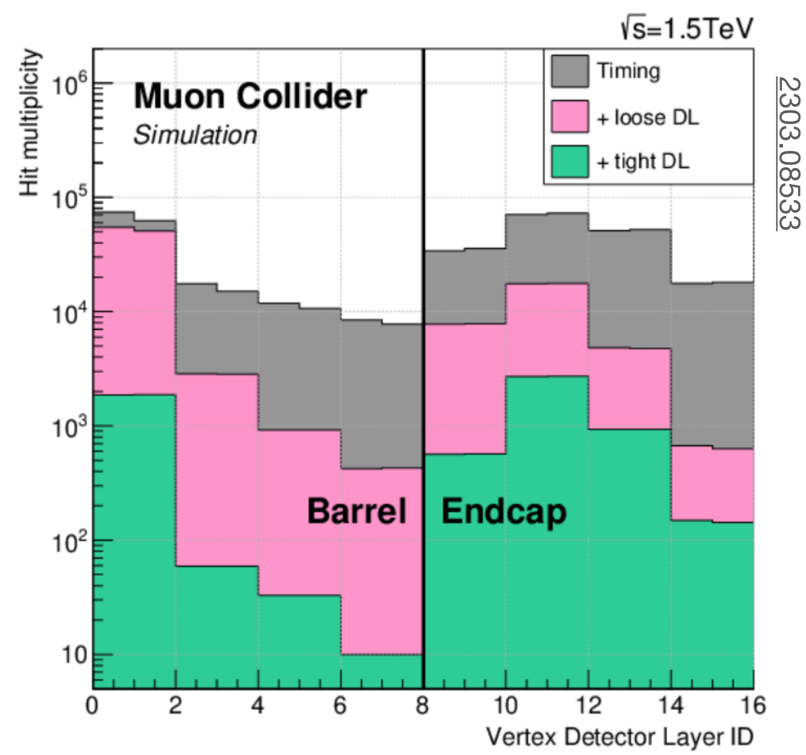


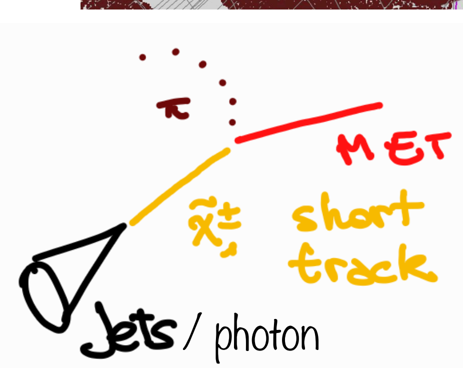
with hit timing in track fit



Muon Collider beam induced background







Detector timing O(10ps) is critical
Sensitivity depends on detector geometry —> input for detector design
Opportunities for reconstructing the pion too

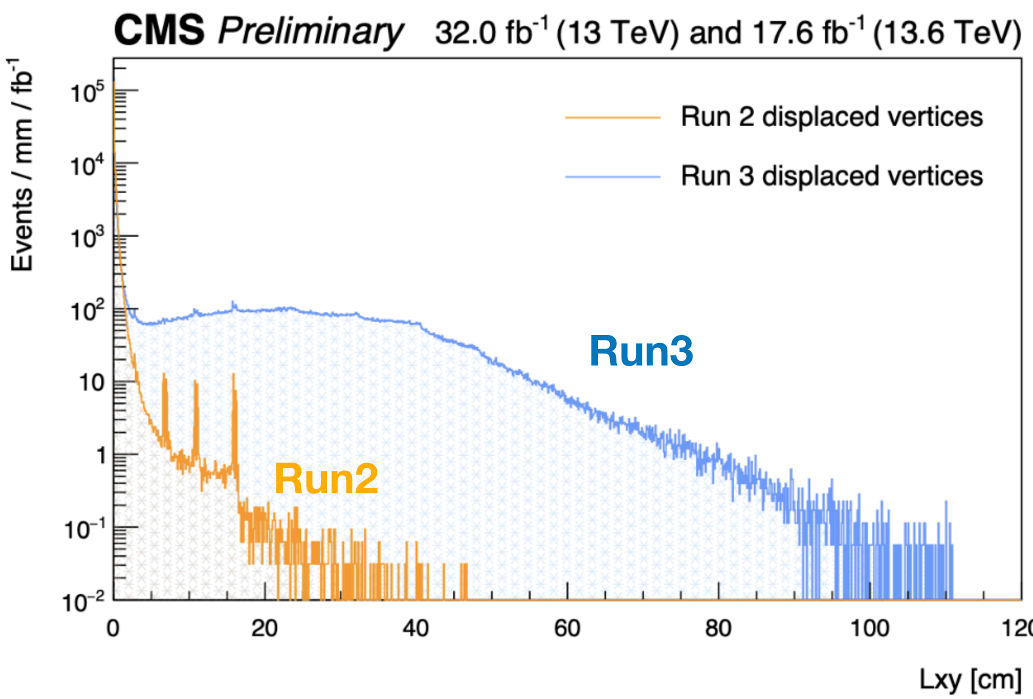
Other interesting opportunities

- Methodological innovation
  - **Real-time analyses, delayed analyses, partial event building (pioneered by LHCb)**
  - Anomaly detection
- Opportunities at future facilities
  - Heavy particles and strong interaction
  - Heavy Neutral Leptons

Ways to by-pass storage or reconstruction trigger limitations

Development on these techniques important for trigger-based colliders (usually more relevant for hadron colliders)

Real time displaced di-muon analysis



Other interesting opportunities

- Methodological innovation
    - Real-time analyses, delayed analyses, partial event building (pioneered by LHCb)
    - **Anomaly detection**
- Opportunities at future facilities
    - Heavy particles and strong interaction
    - Heavy Neutral Leptons

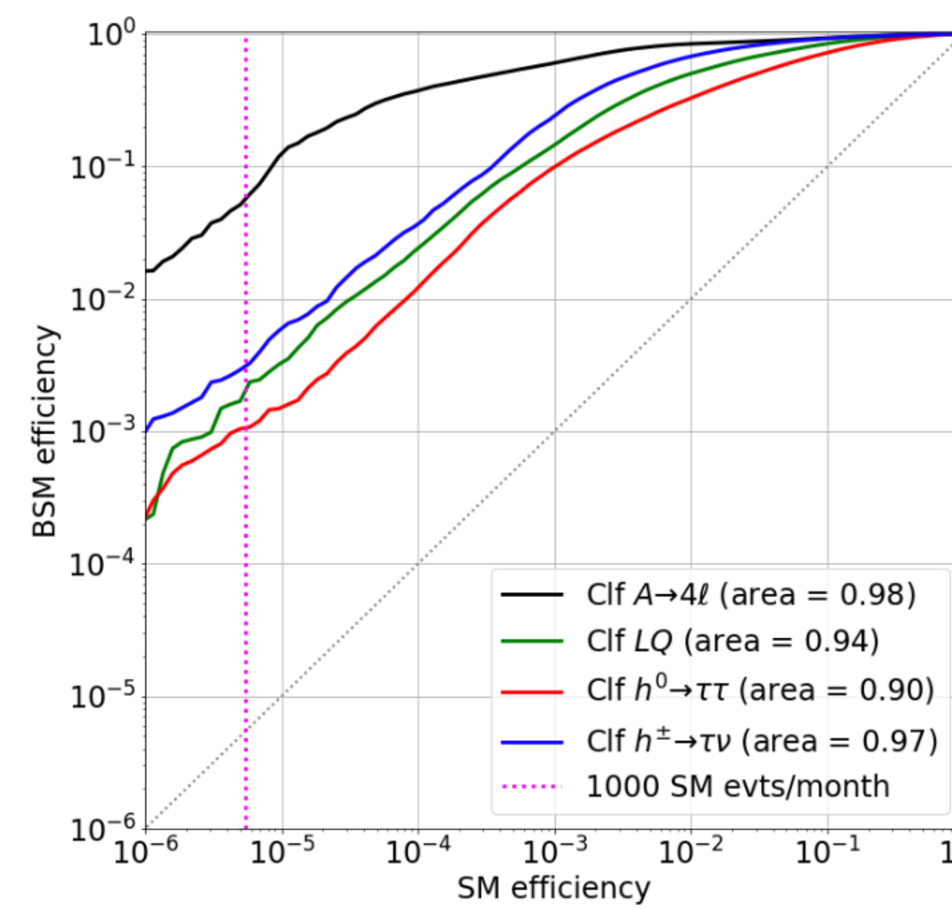
Unsupervised ML started to be used in bump-hunter/resonance searches

Opportunity to be model agnostic

May miss new physics if it is not deemed anomalous (care when defining "anomalous")

Quickly evolving field

Possible usage of anomaly detection in the trigger (our selections start with the trigger!)



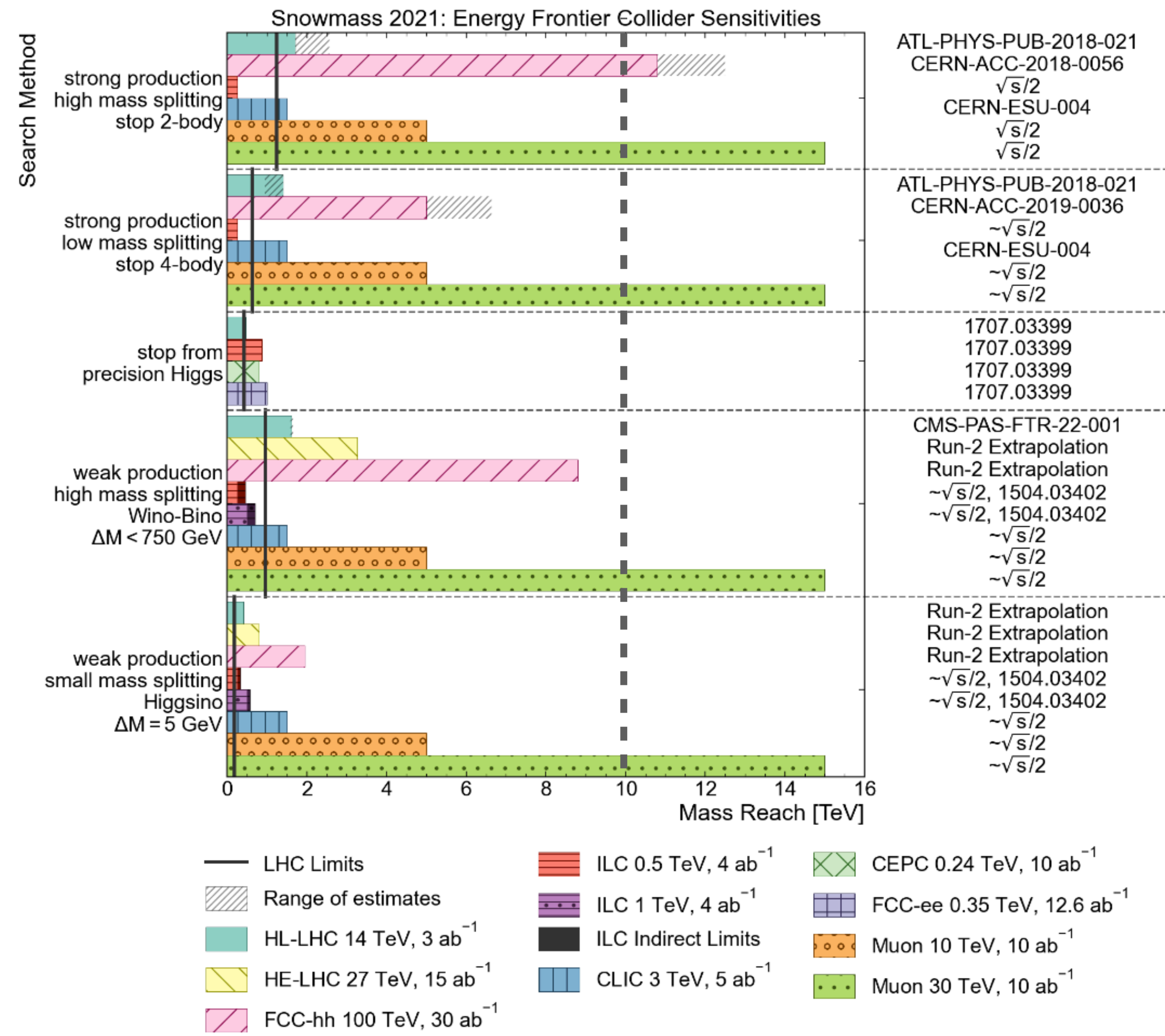
1811.10276

Other interesting opportunities

- Methodological innovation
  - Real-time analyses, delayed analyses, partial event building (pioneered by LHCb)
  - Anomaly detection
- Opportunities at future facilities
  - **Heavy particles and strong interaction**
  - Heavy Neutral Leptons

New physics can simply be to higher scales
Exploration at high masses allows for possible "surprises" not necessarily link to a model

2209.13128



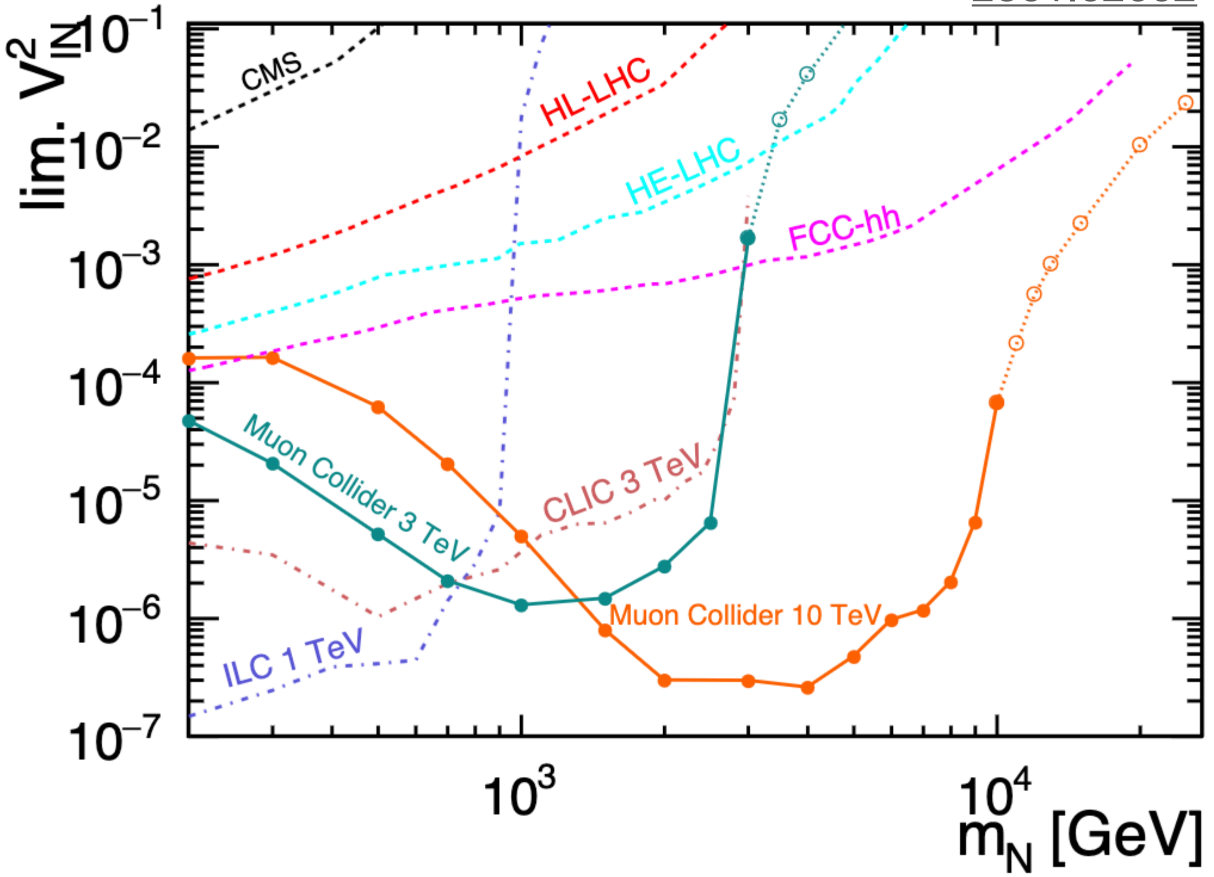
FCC-hh sensitivity up to 10 TeV for heavy particles with strong production

Other interesting opportunities

- Methodological innovation
    - Real-time analyses, delayed analyses, partial event building (pioneered by LHCb)
    - Anomaly detection
- Opportunities at future facilities
    - Heavy particles and strong interaction
    - **Heavy Neutral Leptons**

Heavy Neutral Leptons: extension of SM ν sector that could explain neutrinos masses

2301.02602



multi-TeV lepton collider can extend sensitivity for heavy HNL up to 6 orders of magnitude: higher production cross-section + clean environment

Conclusions

- Great machine and detectors performance + creativity of people brought excellent results beyond expectations
  - We challenged our conceptions of reconstruction, triggering and we used detectors in creative ways
- Future accelerators and detectors have the potential to fill gaps in sensitivity in experimentally challenging regions and to extend our reach to higher energies
- Run3 is still under way and a discovery is still possible!
  - However, there are no guarantees nor in Run3 nor in future

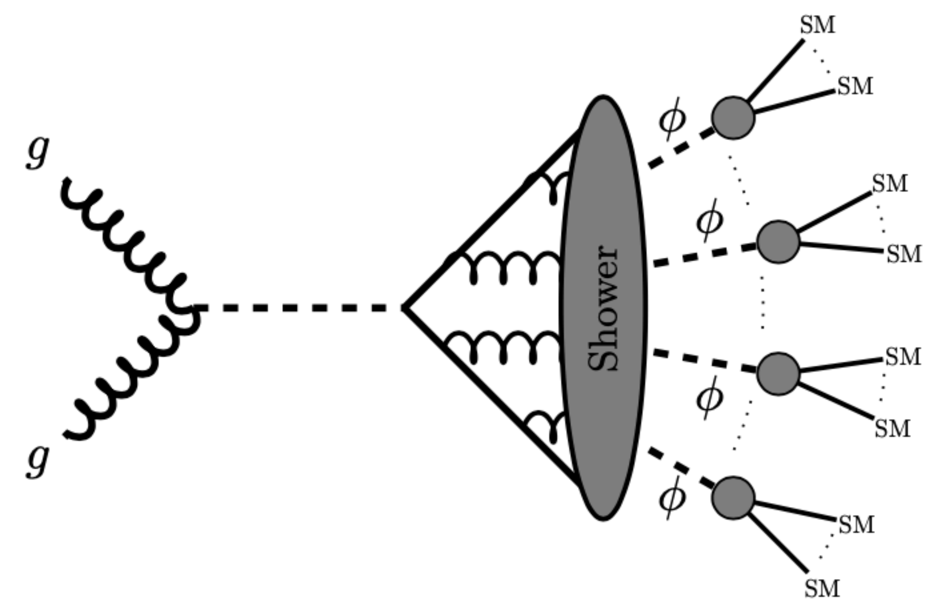
"Our responsibility is to do what we can, learn what we can, improve the solutions, and pass them on."

R. P. Feynman

Back-up

Other interesting opportunities

- Methodological innovation
  - Real-time analyses, delayed analyses, partial event building (pioneered by LHCb)
  - Anomaly detection
- Opportunities at future facilities
  - **Heavy particles and strong interaction**
  - Heavy Neutral Leptons



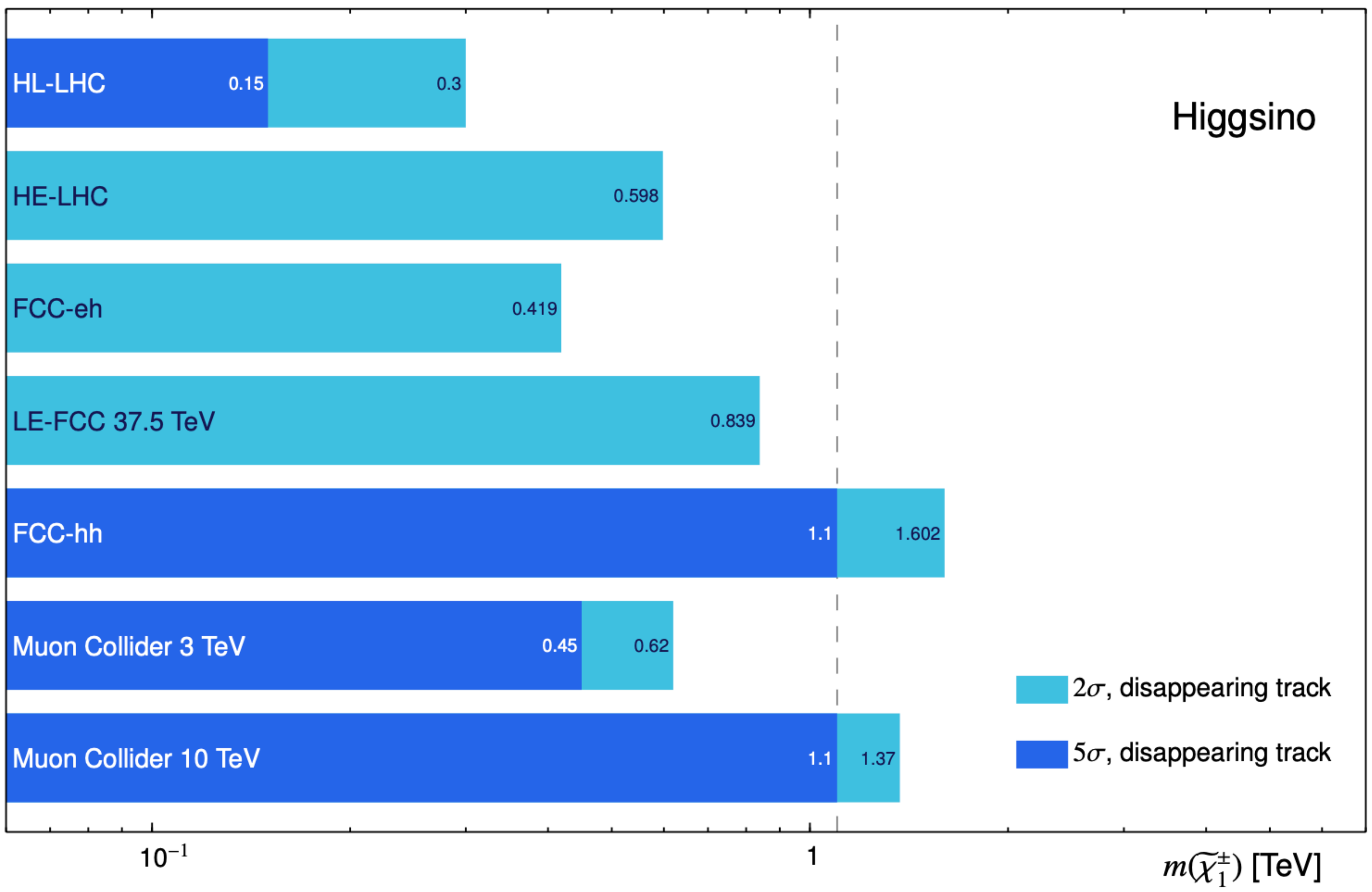
Large phenomenology

Theory and experimental landscape still in development

Dark showers could be searched for only at hadron colliders?

Disappearing track limits

2209.13128

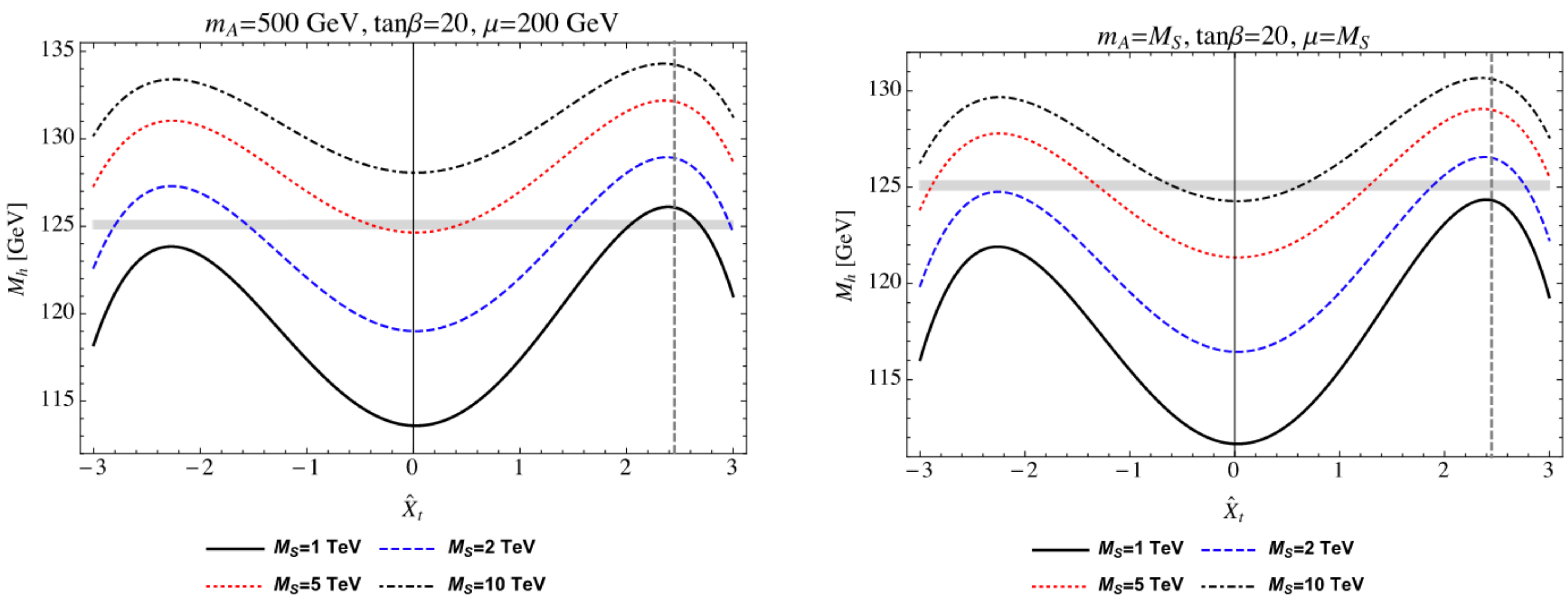


> 1 TeV stop

MSSM Guidance:
Stop Masses above about 1 TeV lead to the right Higgs Masss

P. Draper, G. Lee, C.W.'13, Bagnaschi et al' 14, Vega and Villadoro '14, Bahl et al'17

G. Lee, C.W. arXiv:1508.00576

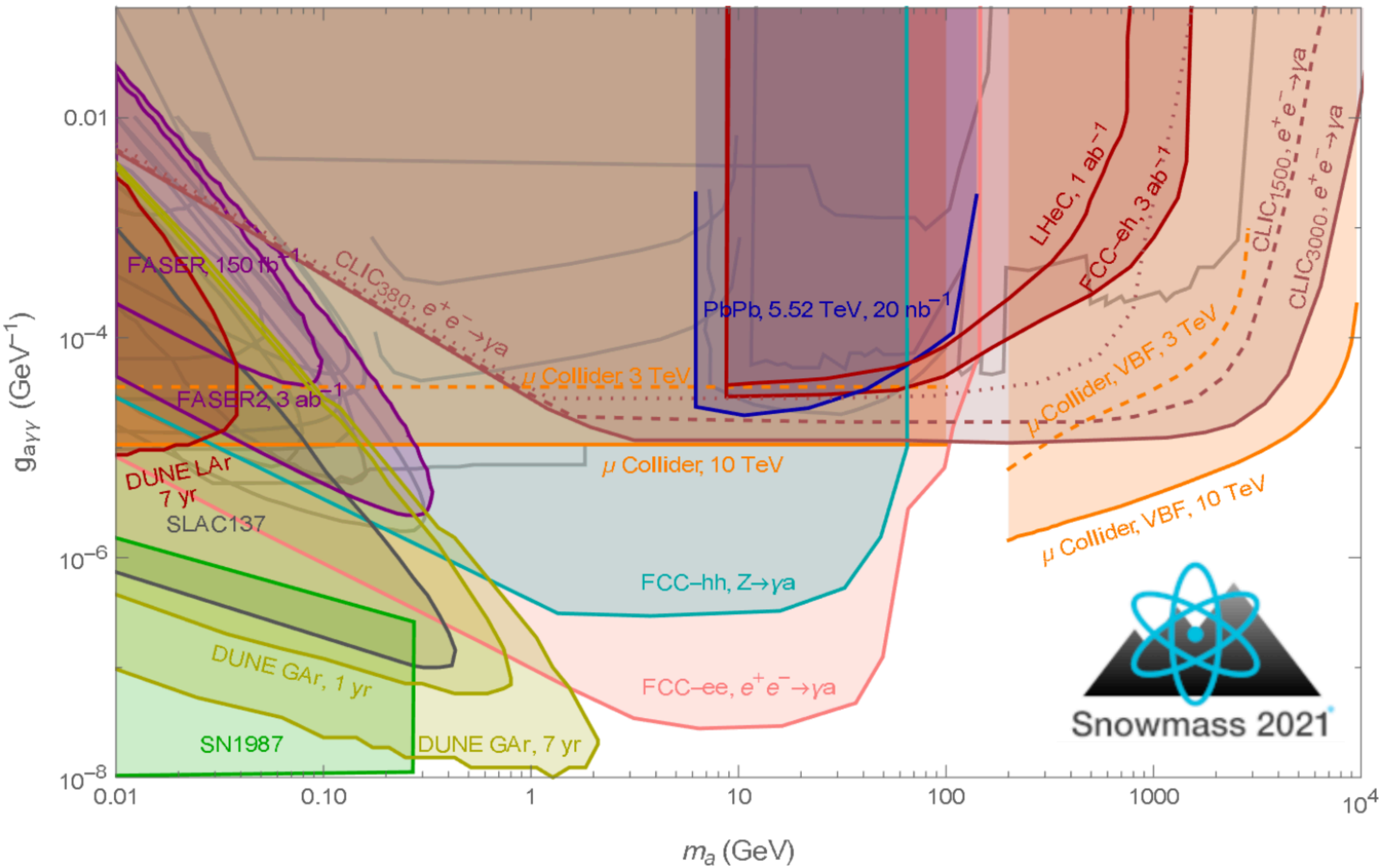


Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

Lighter stops demand large splittings between left- and right-handed stop masses

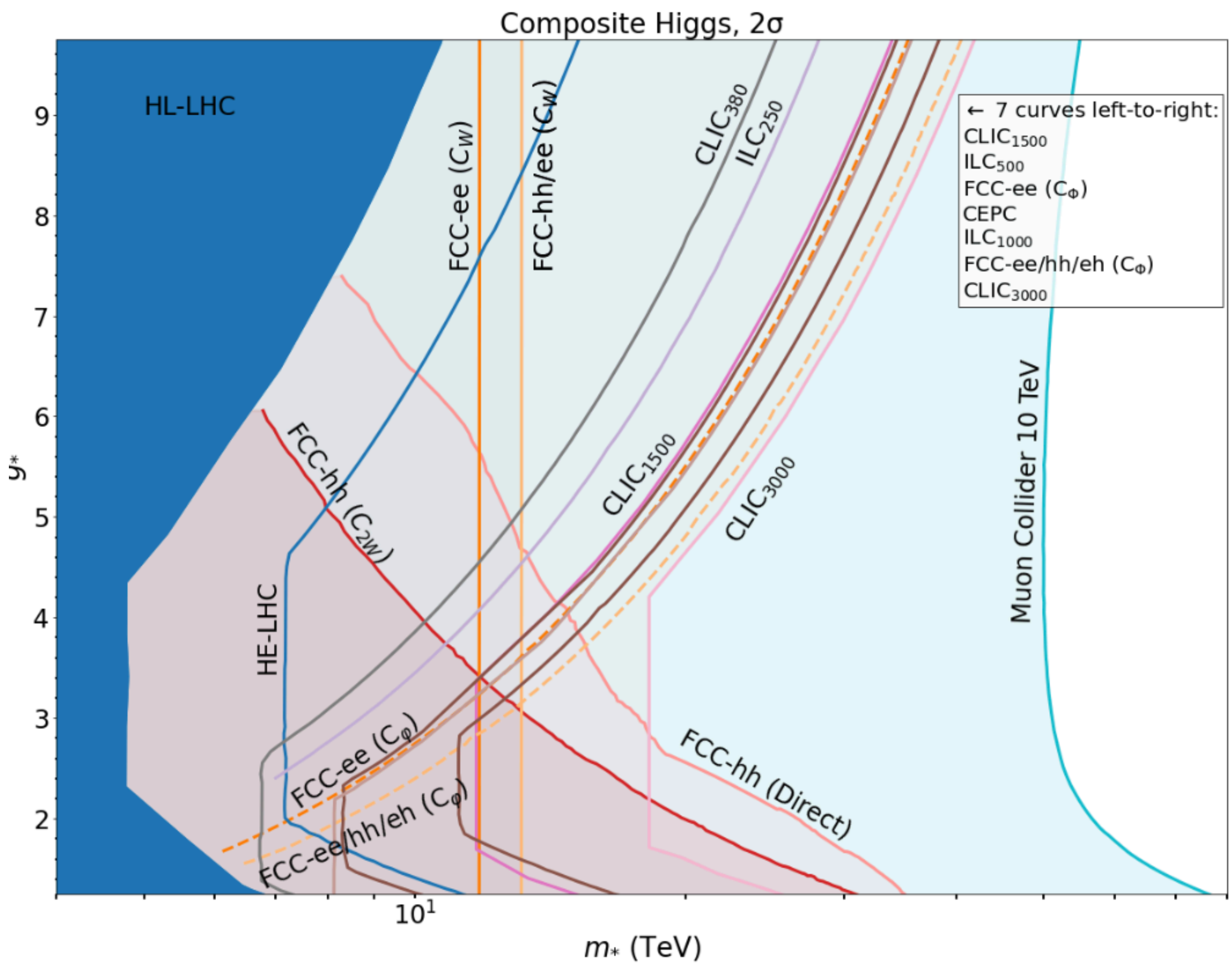
Carlos E.M. Wagner

ALPs

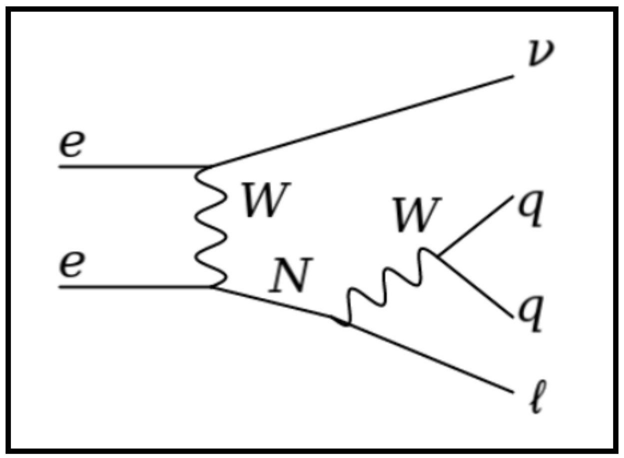


0.01
10^{-4}
10^{-6}
10^{-8}
$g_{a\gamma\gamma}$ (GeV^{-1})
0.01
0.10
1
10
100
1000
10^4
m_a (GeV)
FASER, 150 fb^{-1}
FASER2, 3 ab^{-1}
CLIC$_{380}$, $e^+e^-\to\gamma a$
μ Collider, 3 TeV
μ Collider, 10 TeV
PbPb, 5.52 TeV, 20 nb^{-1}
LHeC, 1 ab-1
FCC-eh, 3 ab-1
CLIC$_{1500}$, $e^+e^-\to\gamma a$
CLIC$_{3000}$, $e^+e^-\to\gamma a$
μ Collider, VBF, 3 TeV
μ Collider, VBF, 10 TeV
DUNE LAr
7 yr
SLAC137
FCC–hh, $Z\to\gamma a$
DUNE GAr, 1 yr
FCC–ee, $e^+e^-\to\gamma a$
SN1987
DUNE GAr, 7 yr
Snowmass 2021

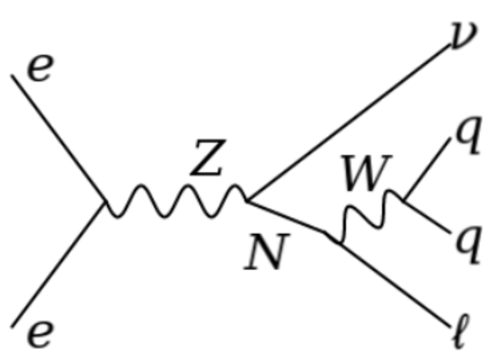
Higgs compositeness



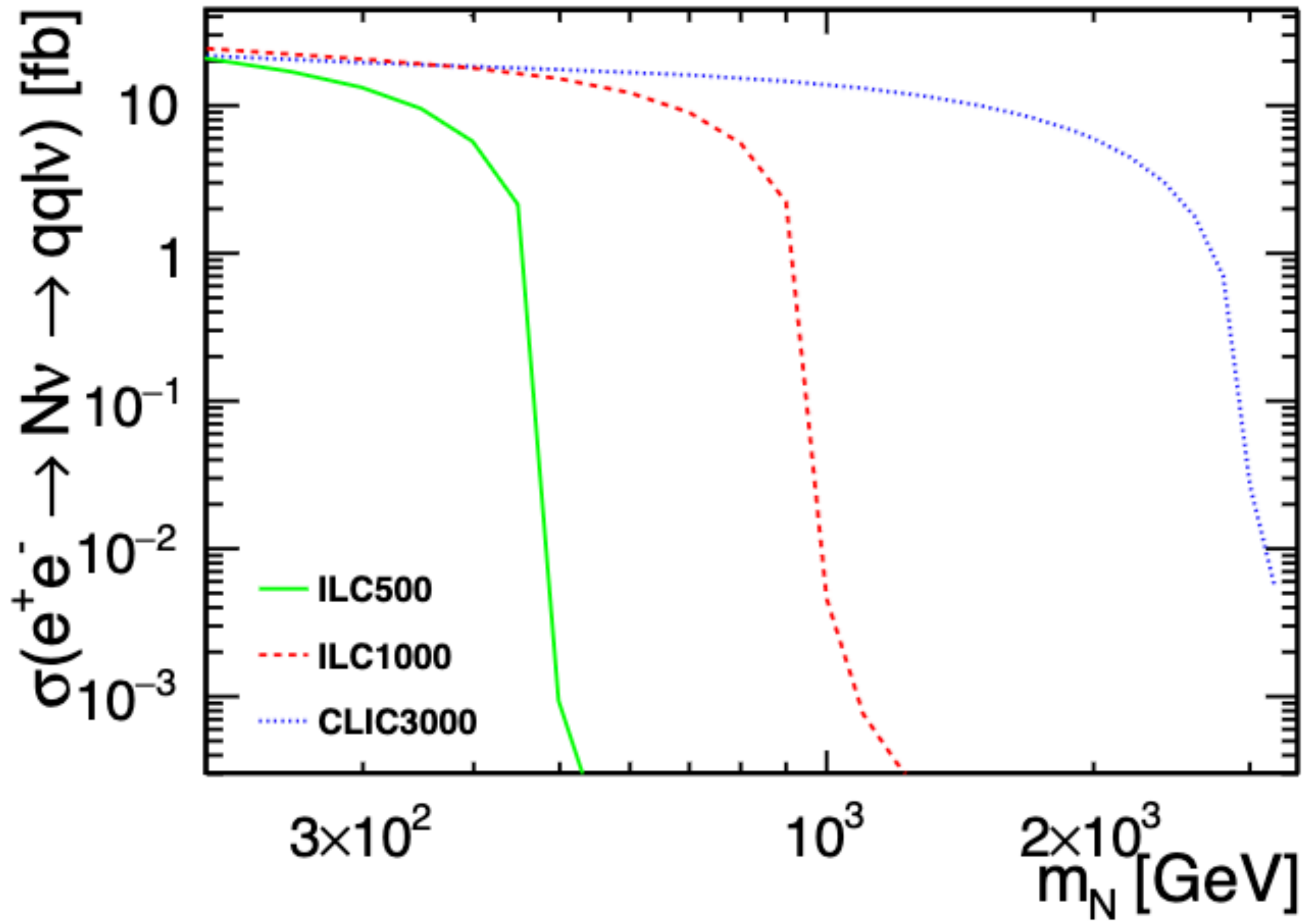
HNL



e
e
W
N
W
ν
q
q
ℓ

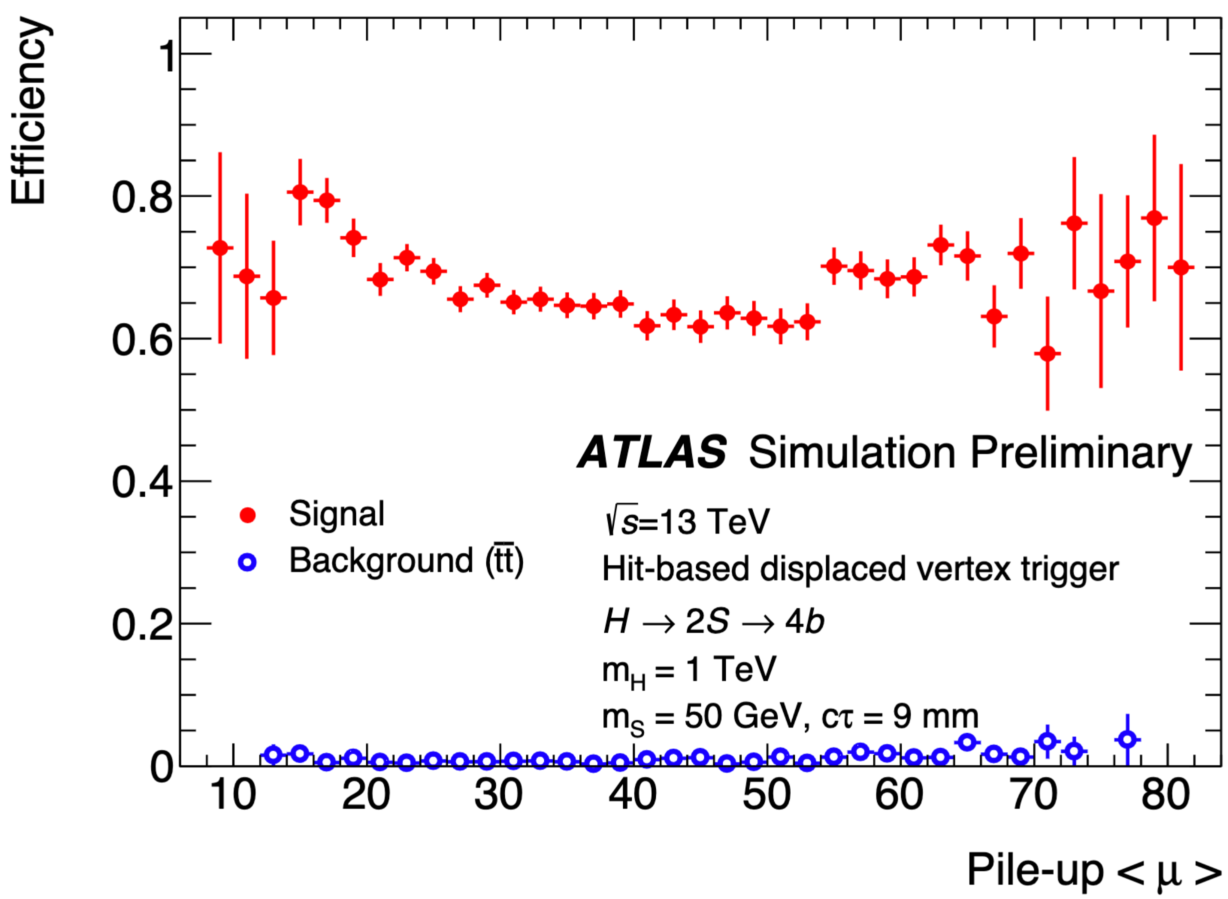


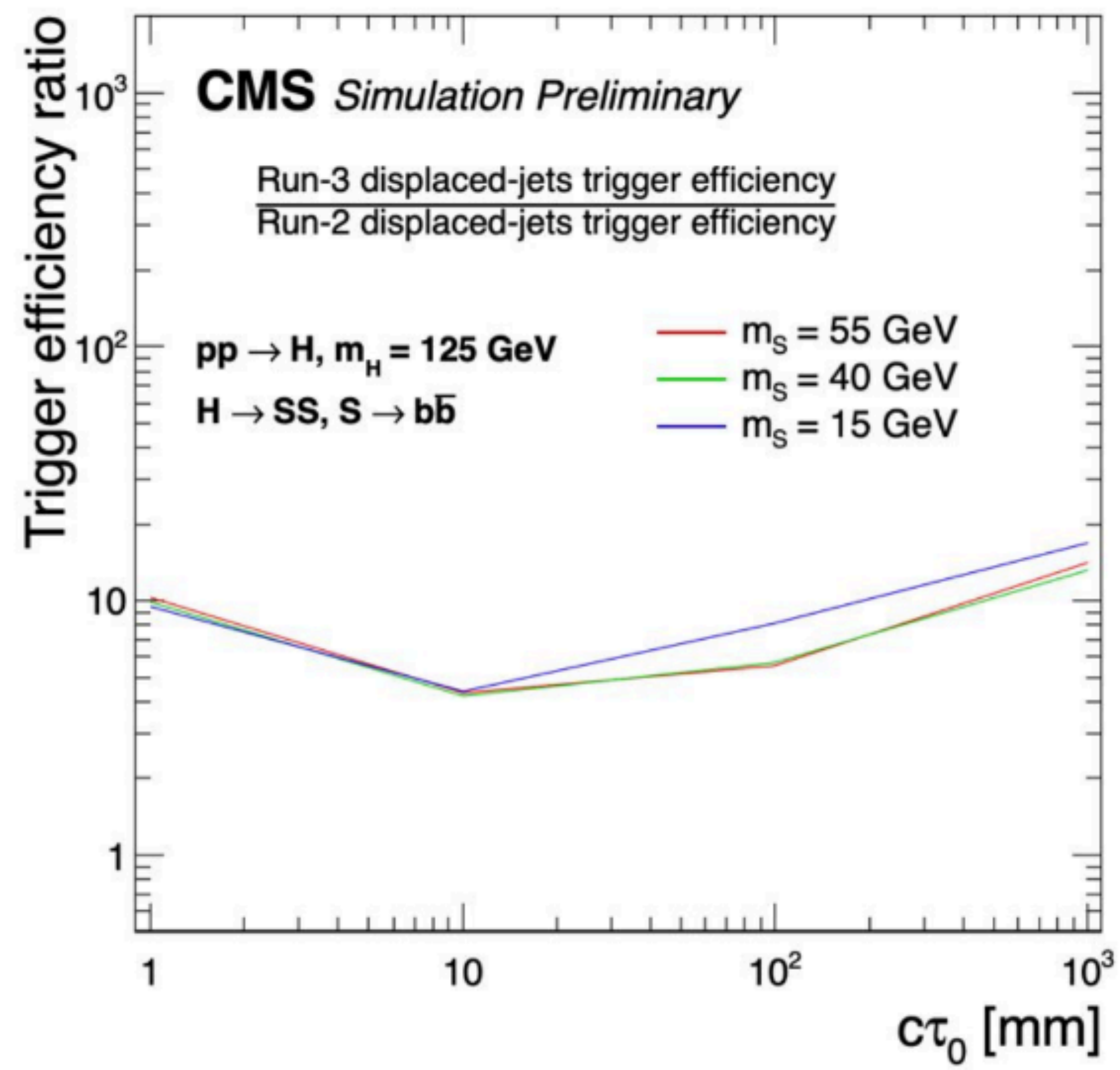
e
e
Z
N
W
ν
q
q
ℓ



σ(e⁺e⁻ → Nν → qqlν) [fb]
10
1
10⁻¹
10⁻²
10⁻³
ILC500
ILC1000
CLIC3000
3×10²
10³
2×10³
m_N [GeV]

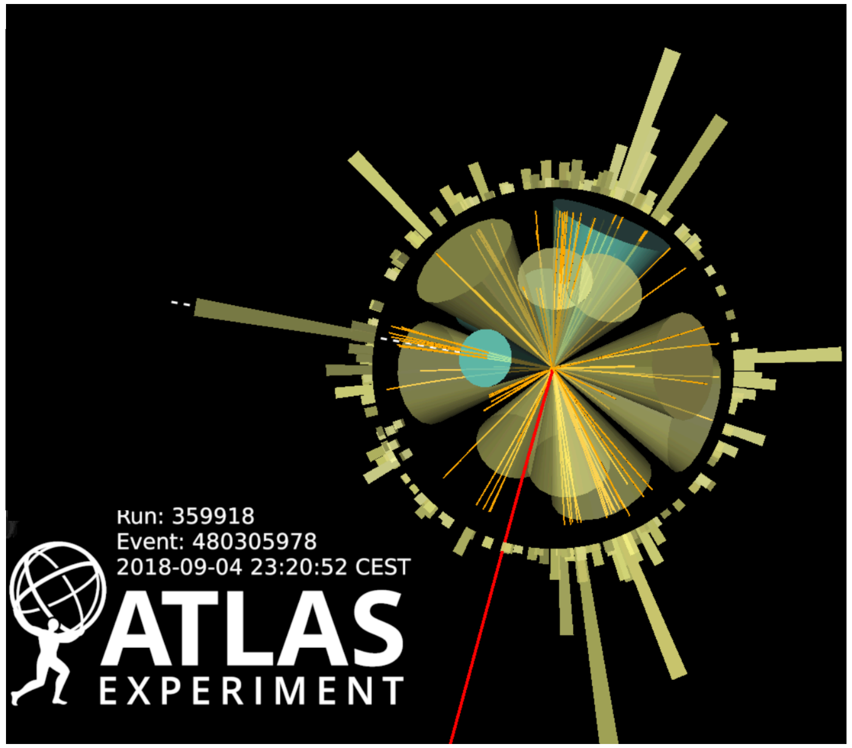
ATLAS and CMS triggers for DV



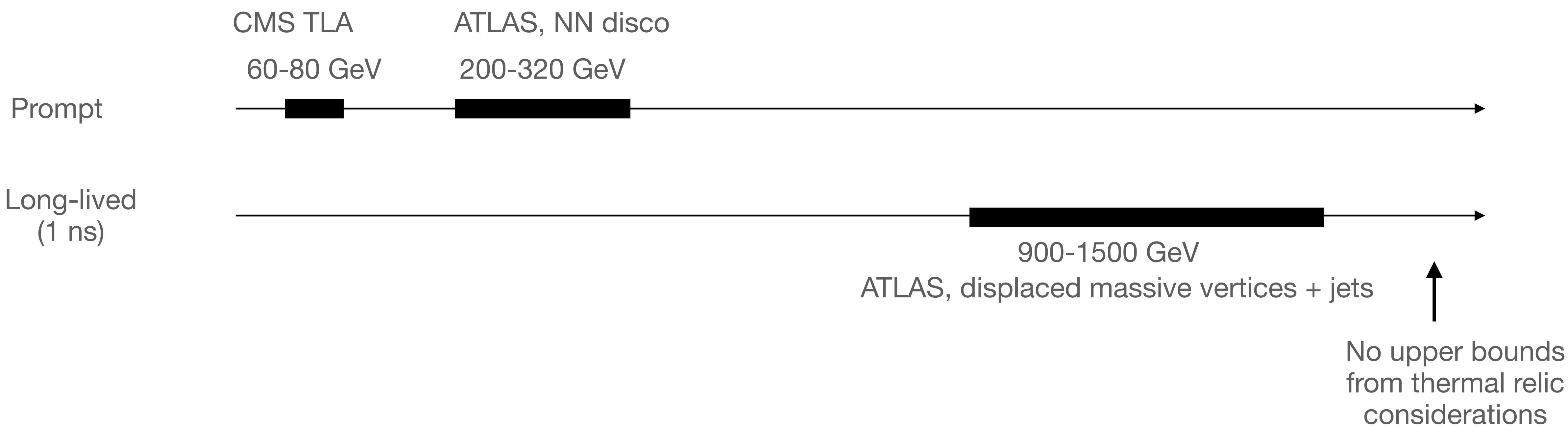


What if there are RPV couplings?

Higgsino with fully hadronic decay couplings

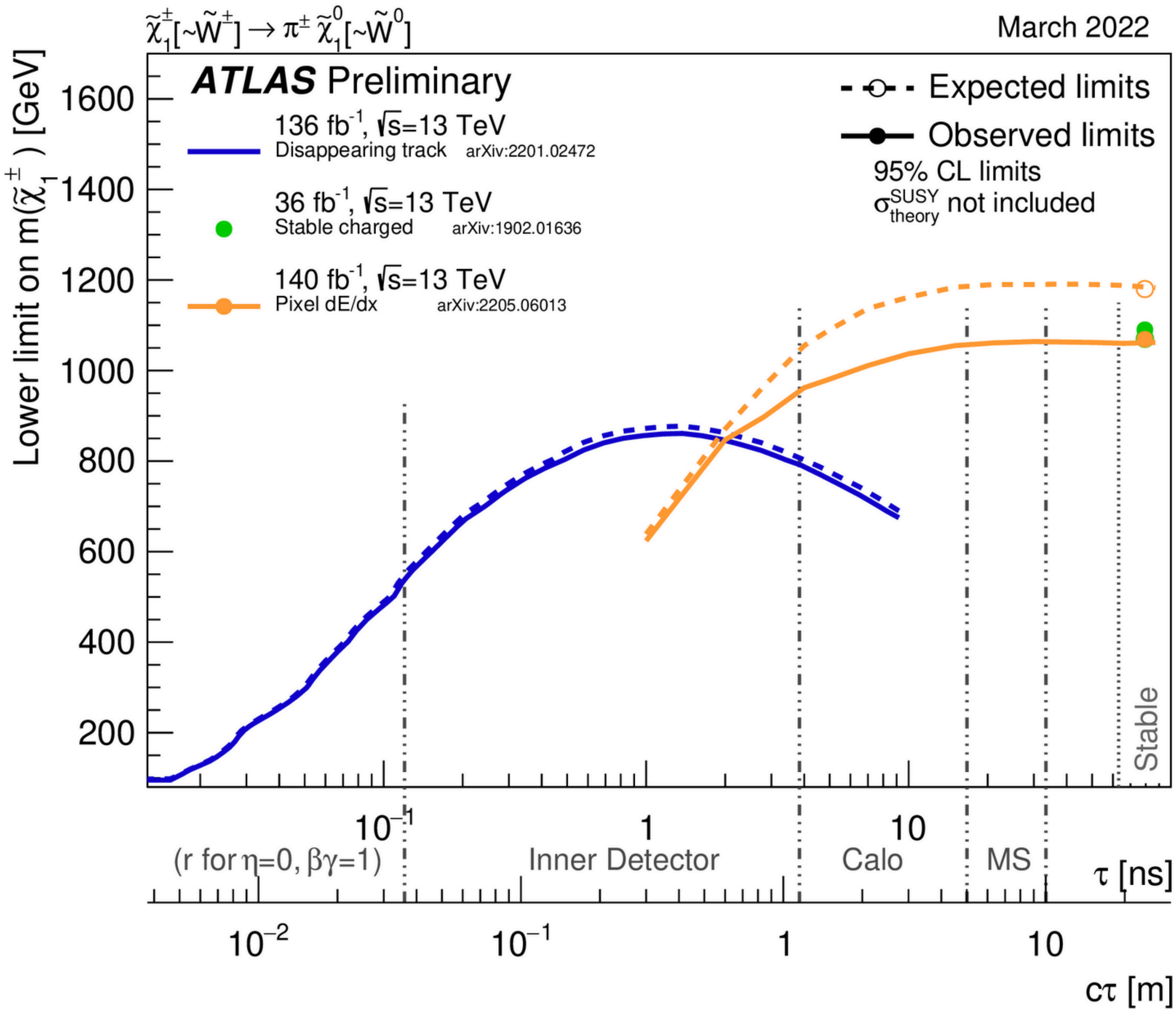


- LSP Higgsino can decay to SM particles
  - Higgsino is no longer DM candidate (there could be other, e.g. axion and axinos, but not the WIMP Higgsino)
  - Cross section stays small
- Hadronic decay particularly challenging for hadron colliders and LEP limits up to $\sqrt{s}/2$ => There is unexplored phase-space
  - Signature with large number of jets
  - LLP signature with displaced jets if RPV couplings get very small

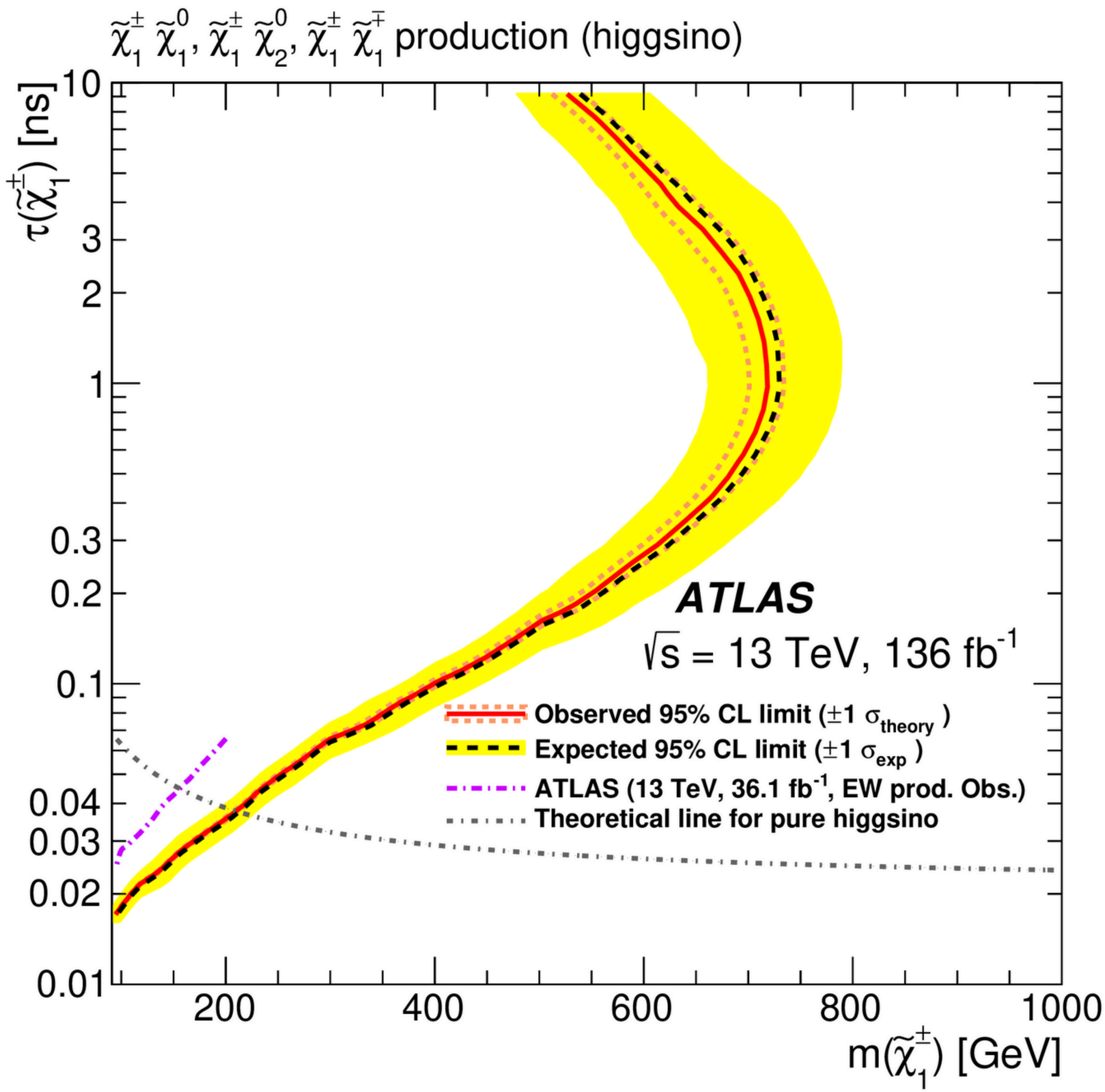


What if it does not decay in the tracker?

Wino

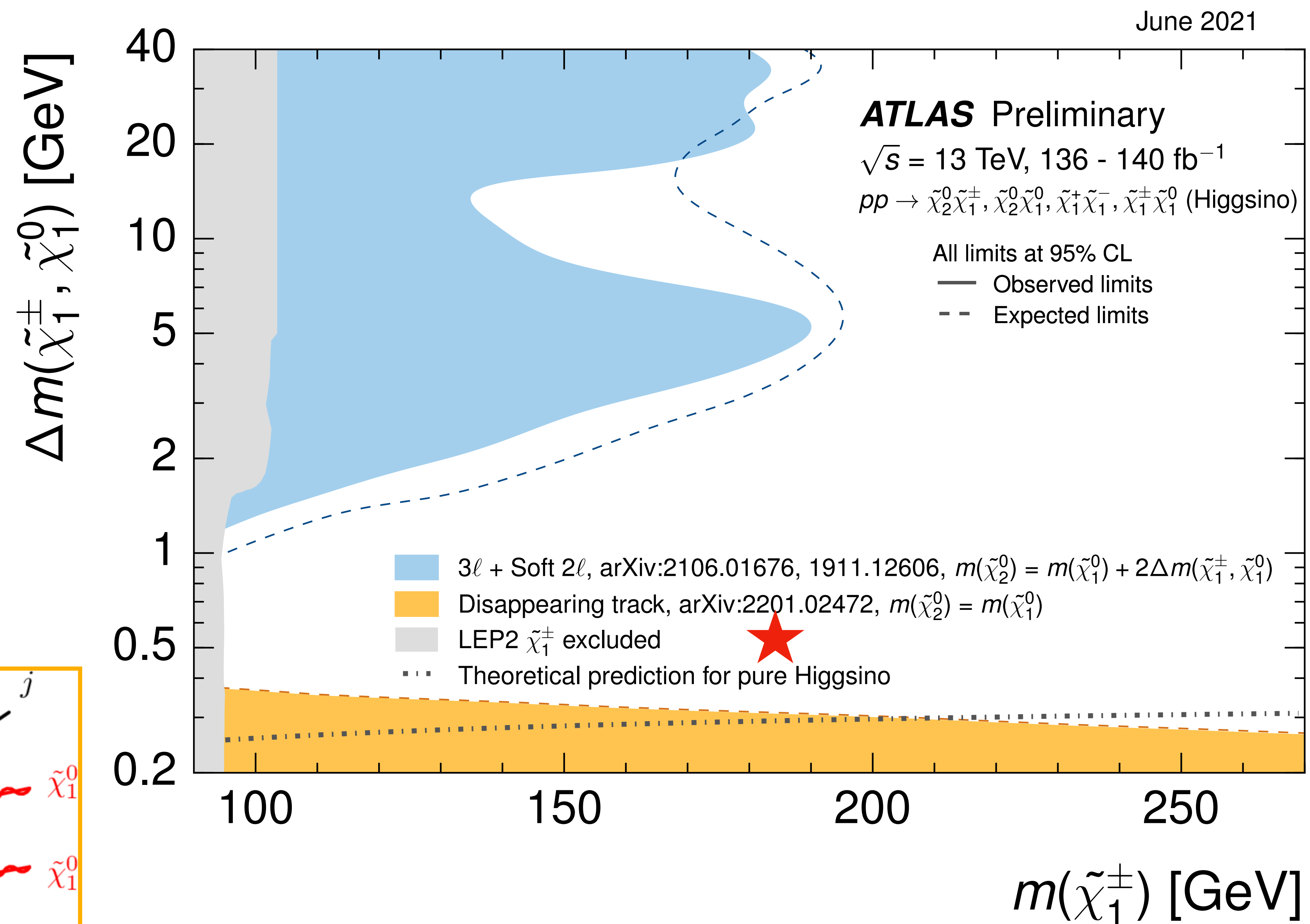


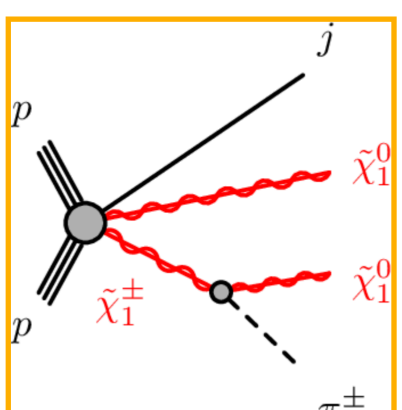
Disappearing track, Higgsino



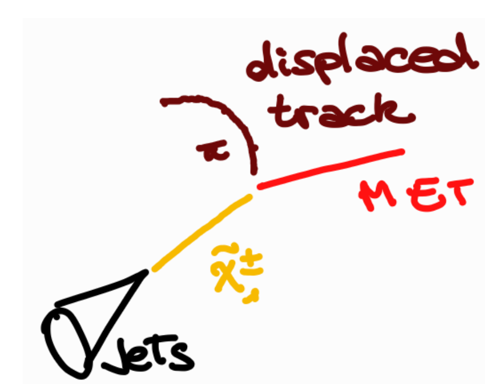
EWK SUSY compressed spectra

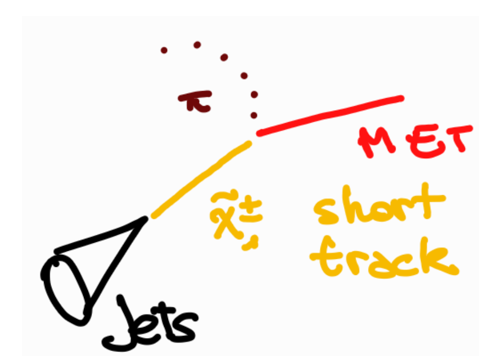
- What about the gap?





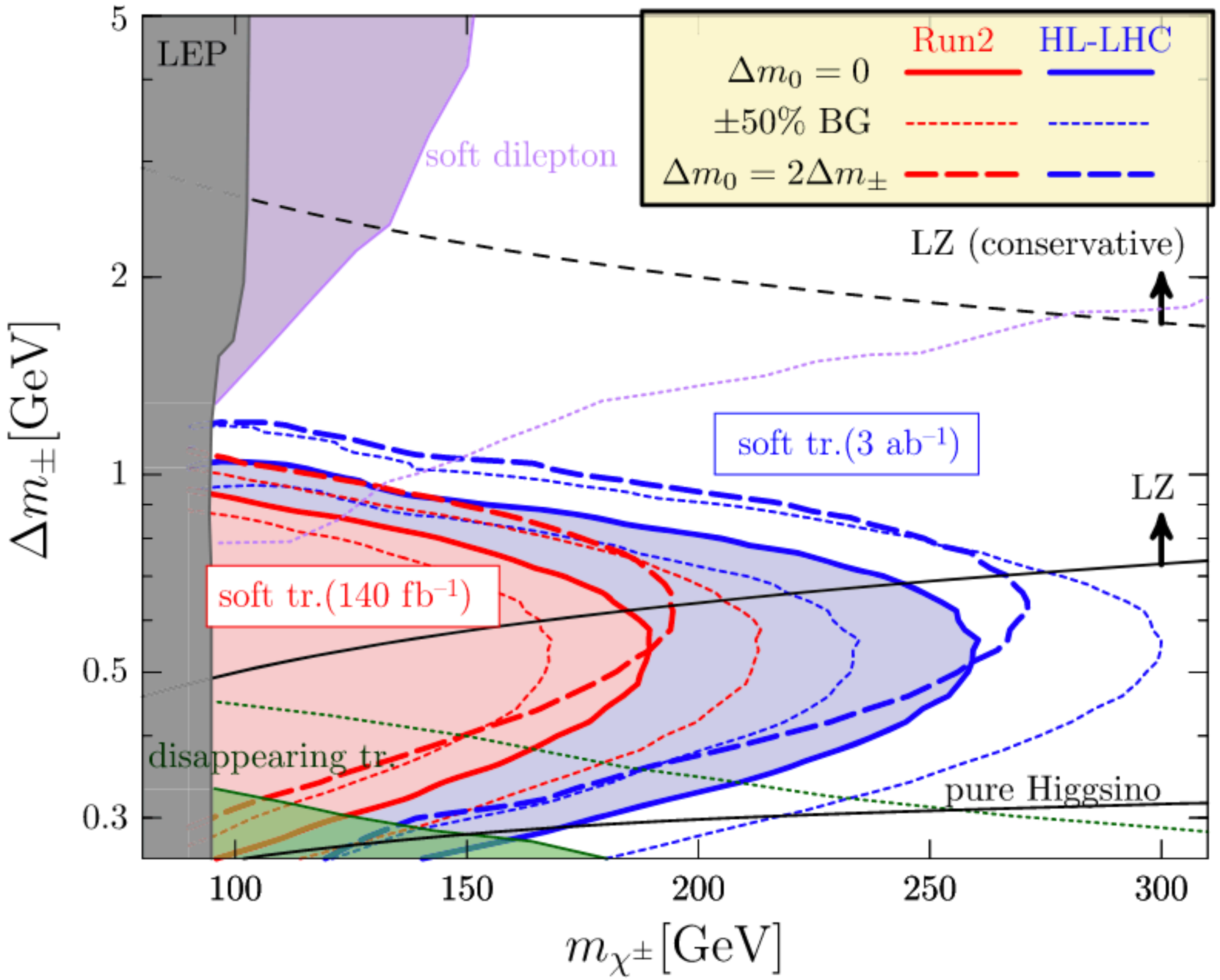
Pion reconstruction





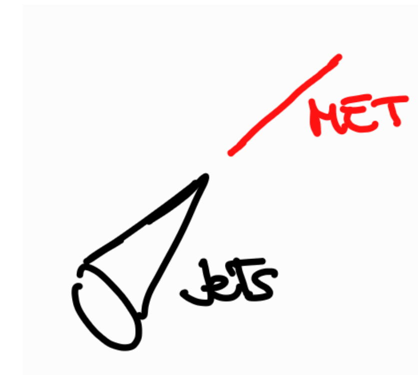
Possibilities for the Higgsino gap

PhysRevLett.124.101801

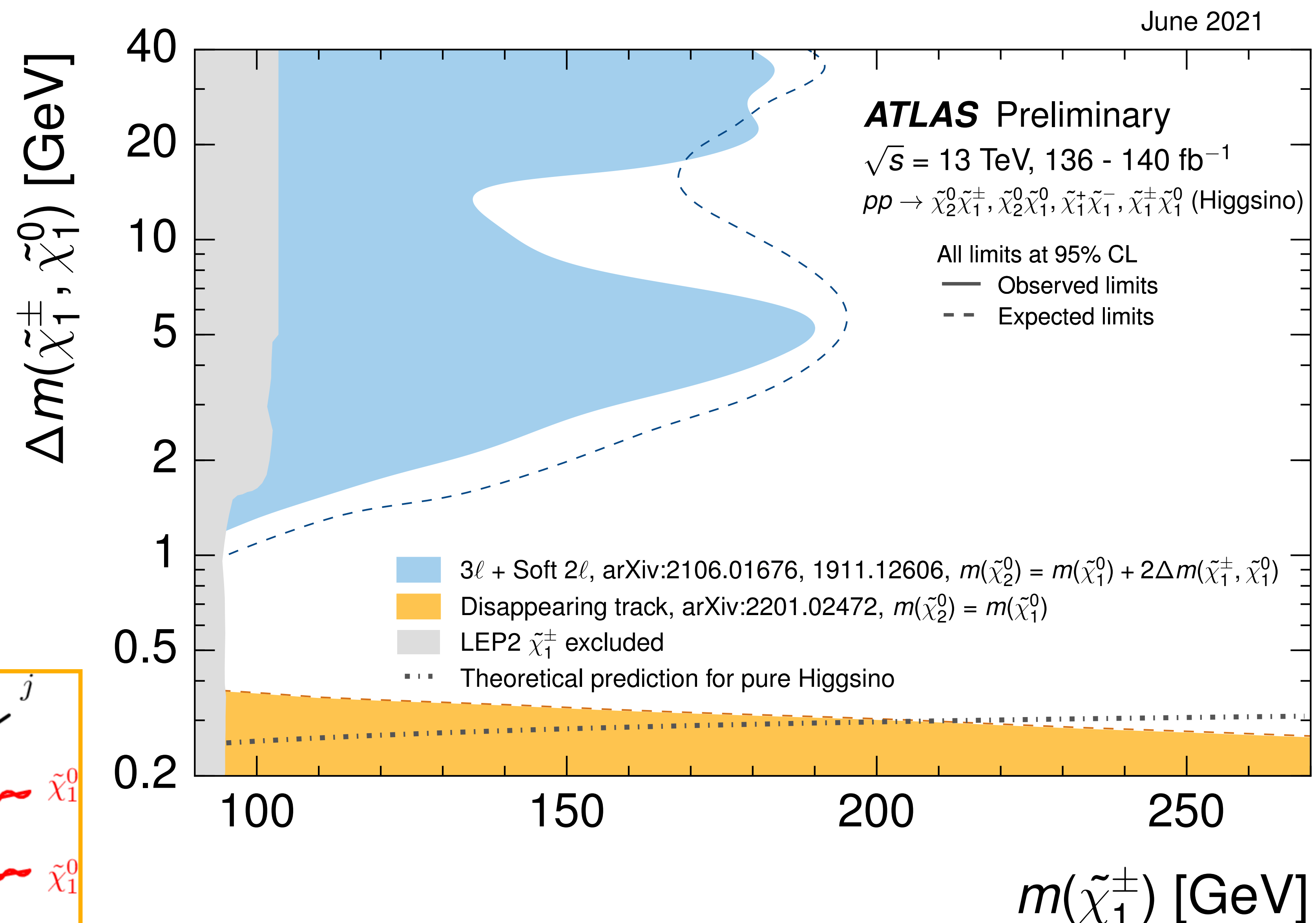


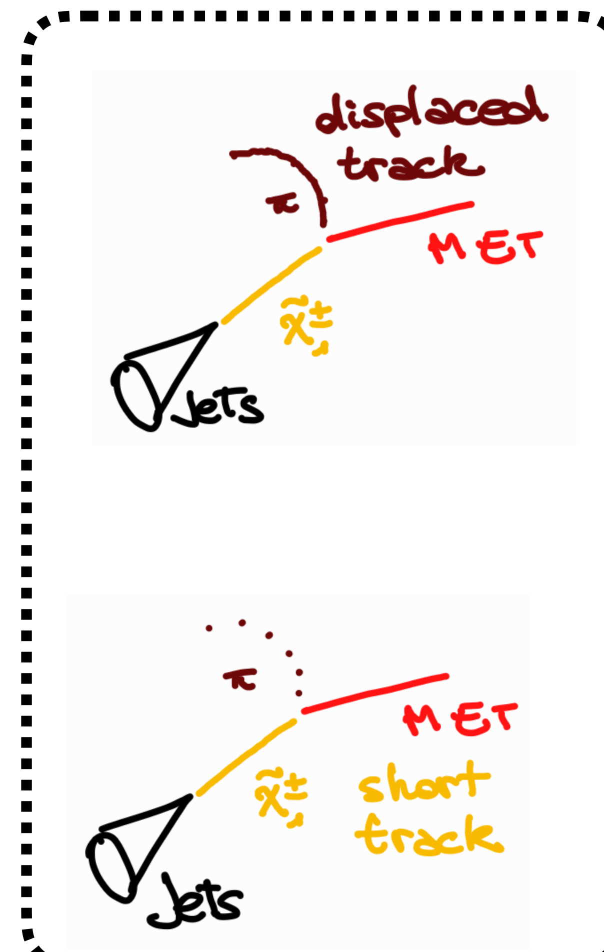
EWK SUSY compressed spectra

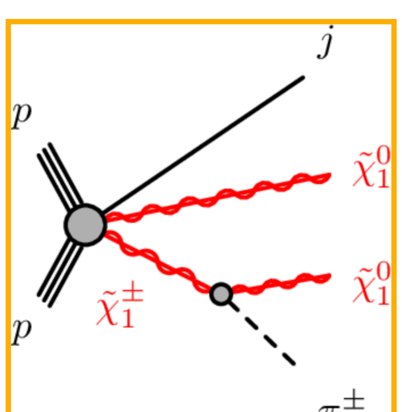
- What about the gap?



If one ignores the track, “monojet” signature (but lower sensitivity)







What drives us?

- Known unknown
  - Big open questions: baryogengesis, nature of dark matter/energy, neutrino masses, weakness of gravitational force, …
  - Guidance from: naturalness and minimal principles
- The big surprises
  - Tensions in current measurements (aka “anomalies”)
  - Uncovered and underexplored signatures and phase-space

$(g-2)_\mu$: 5.1 σ *

R(D*)-R(D): 3.2 σ *

CDF m(W): 7 $\sigma^\dagger$

ANITA: 3.3 $\sigma^\dagger$

* *likely to be reduced by theory updates*

† *not confirmed by other experimental results*

Tensions may stay or go, but important for now and the future, to allow for flexibility for ***reaction*** if something unexpected comes up

EWK SUSY compressed spectra

- Naturalness and DM arguments would suggest a light EWK sector
- Thermal DM targets: 1.1 TeV (Higgsinos), 2.8 TeV (Wino)

Phenomenological MSSM: simplifying assumptions based on experimental constraints and general features of SUSY breaking mechanism
—> opportunity to scan models and see which survive experimental (LHC and external) constraints

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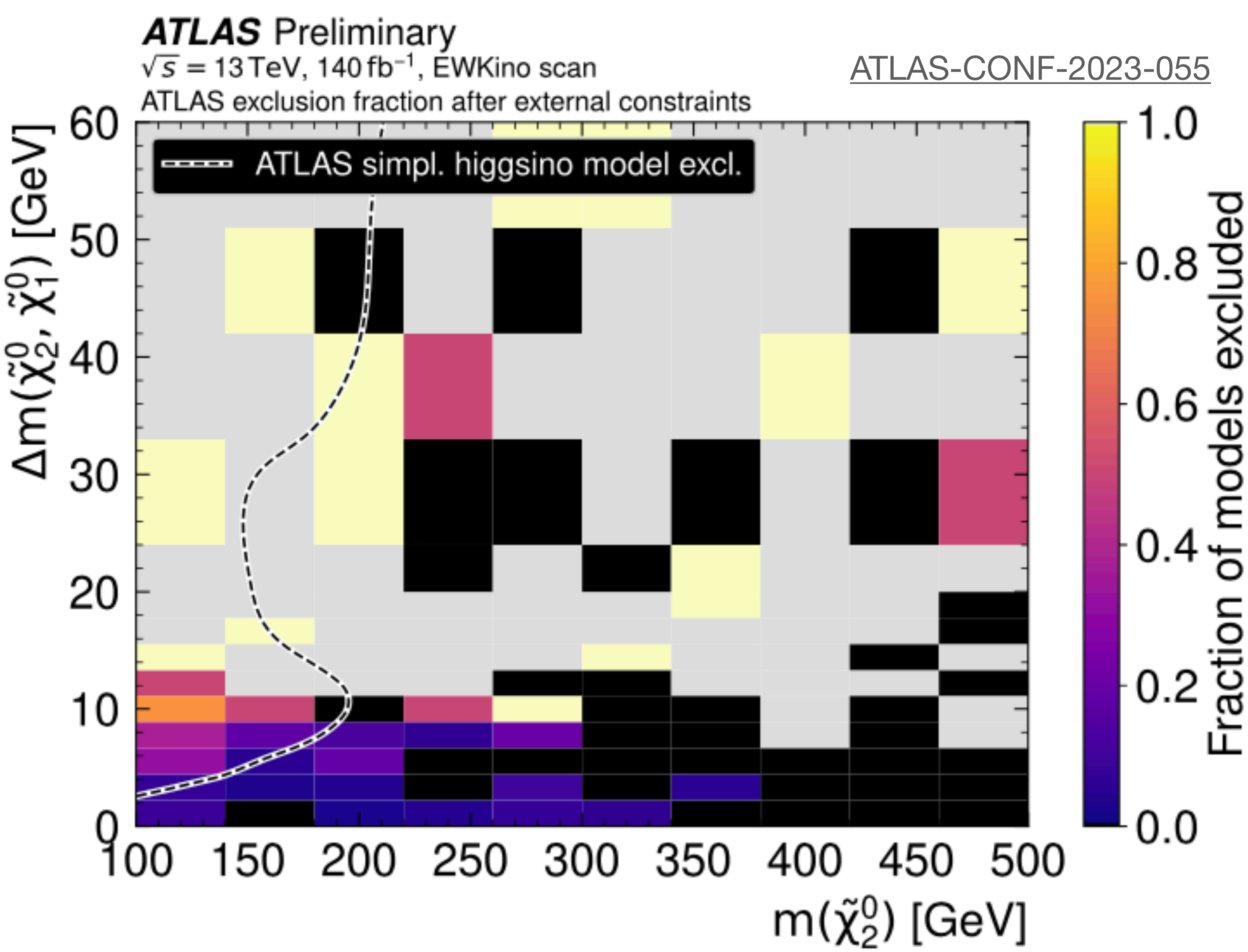
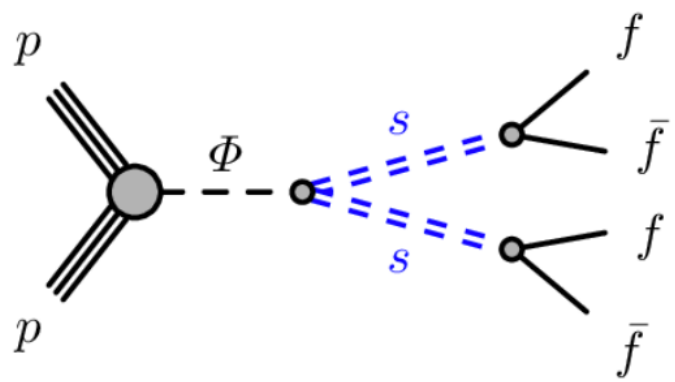
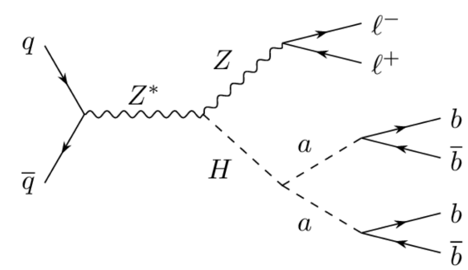
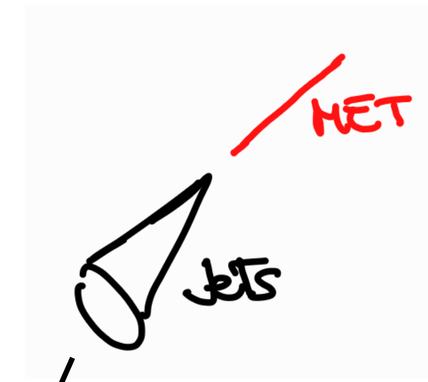


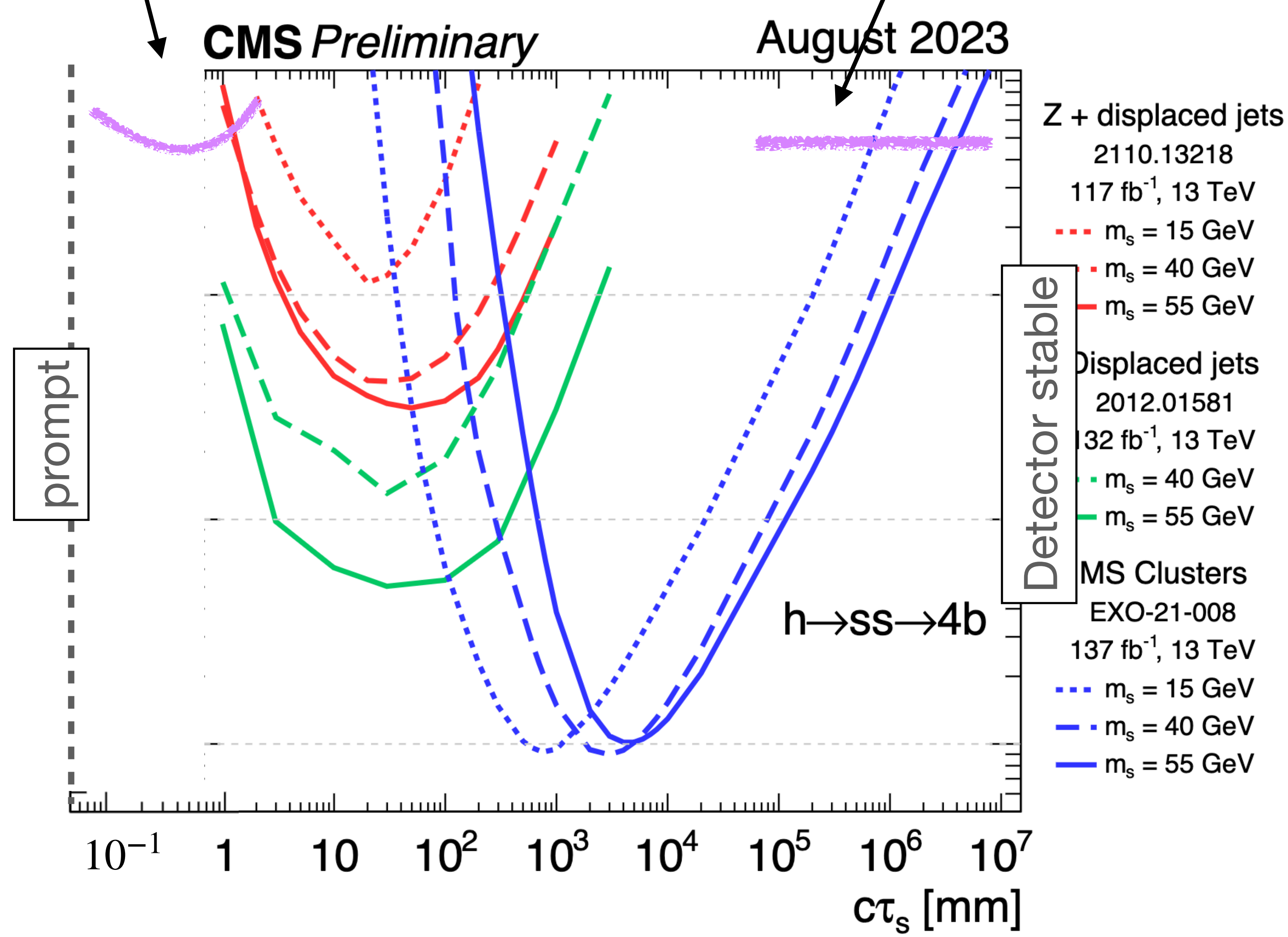
Dark sectors and LLP







Care between the prompt-to-displaced and the displaced-to-stable regimes with analysis reinterpretations



Results taken from ATLAS

Is this the only possibility?

- No, other options still viable!

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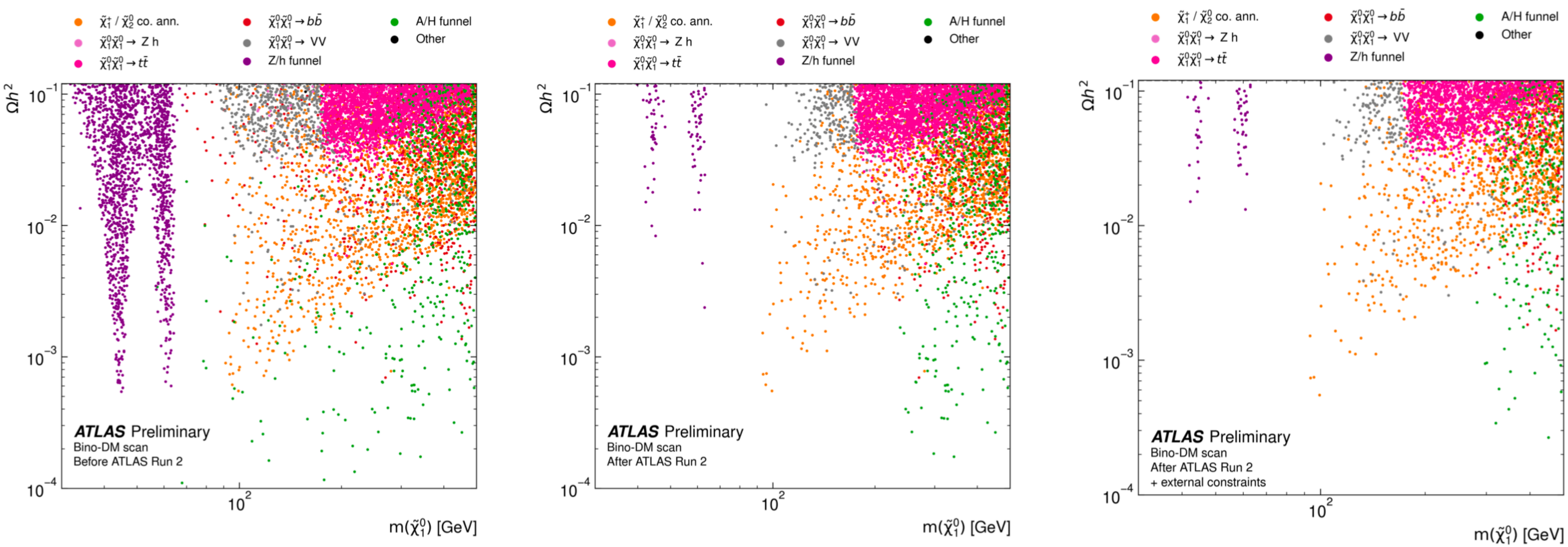


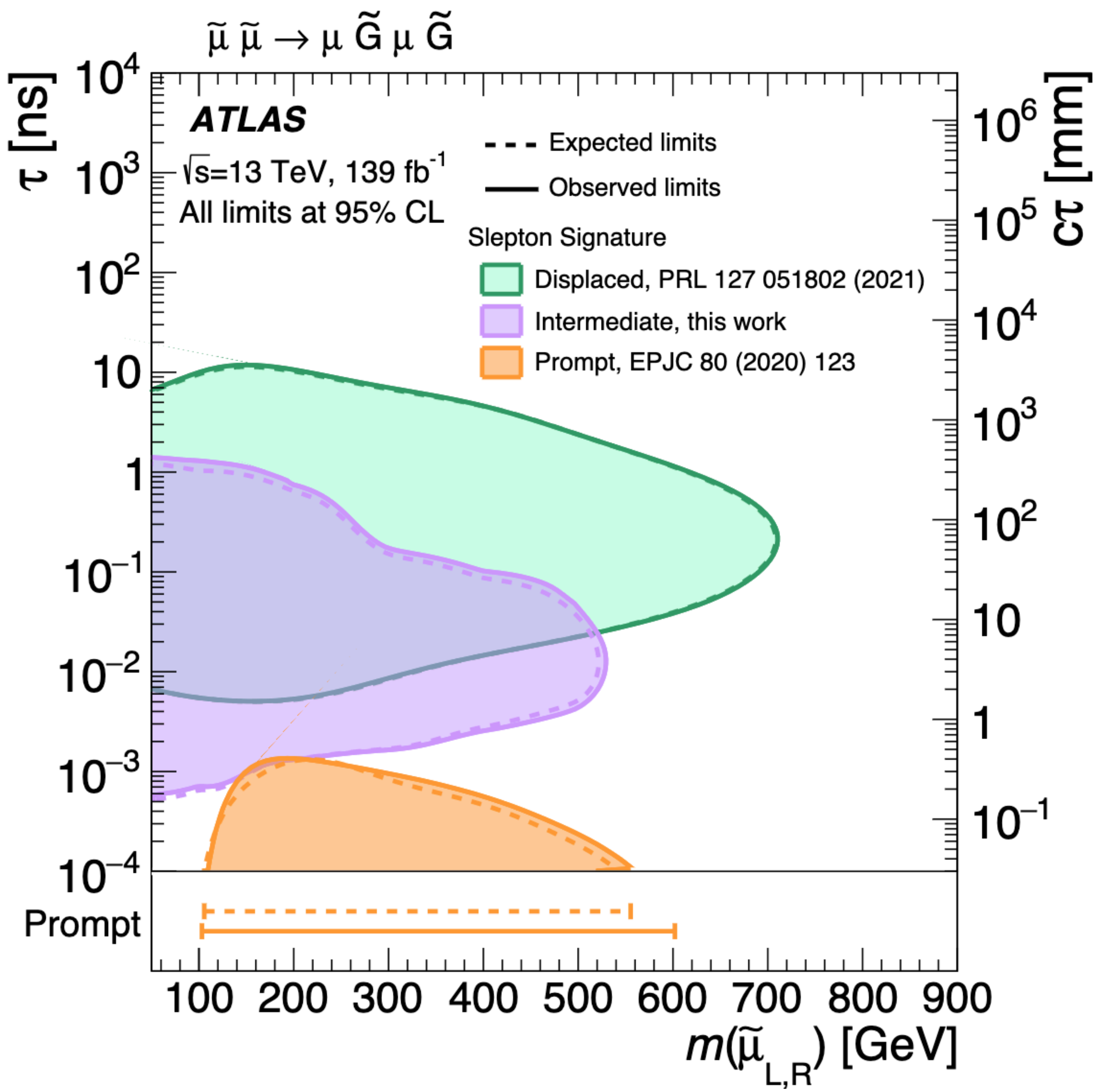
(a) All models

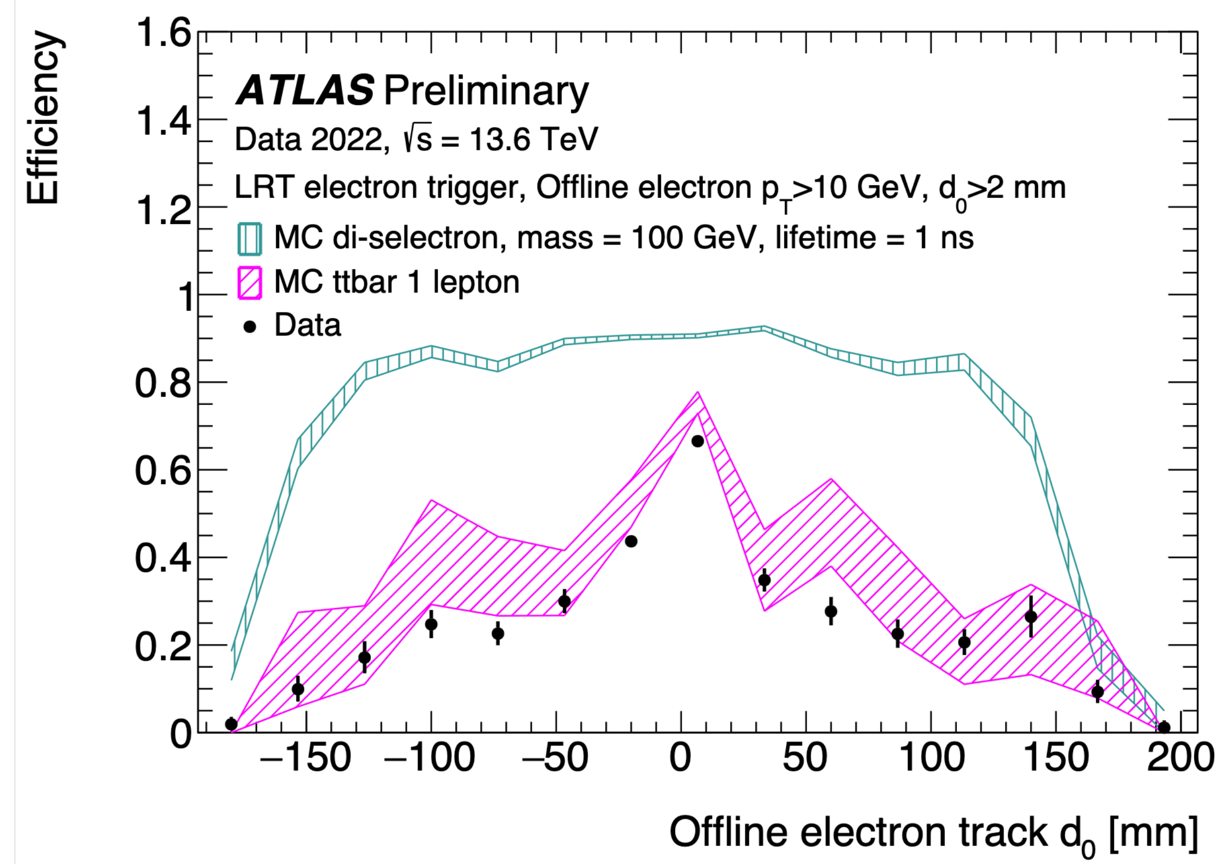
(b) Models not excluded by ATLAS

(d) Models not excluded by ATLAS or external constraints

LLP, sleptons

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2020-09/





Care between the prompt and displaced regime with dedicated analyses and reinterpretations

Dedicated triggers in Run3 can open up sensitivity to unexplored phase space