Theory Overview:
Long-Lived Particles

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Why Long-Lived BSM Particles? Supersymmetry

- R-Parity-Violating, small B/L-violating couplings

$$c\tau_{RPV} \sim 1\ \mathrm{m} \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)\left(\frac{10^{-8}}{\lambda_{RPV}}\right)^2$$

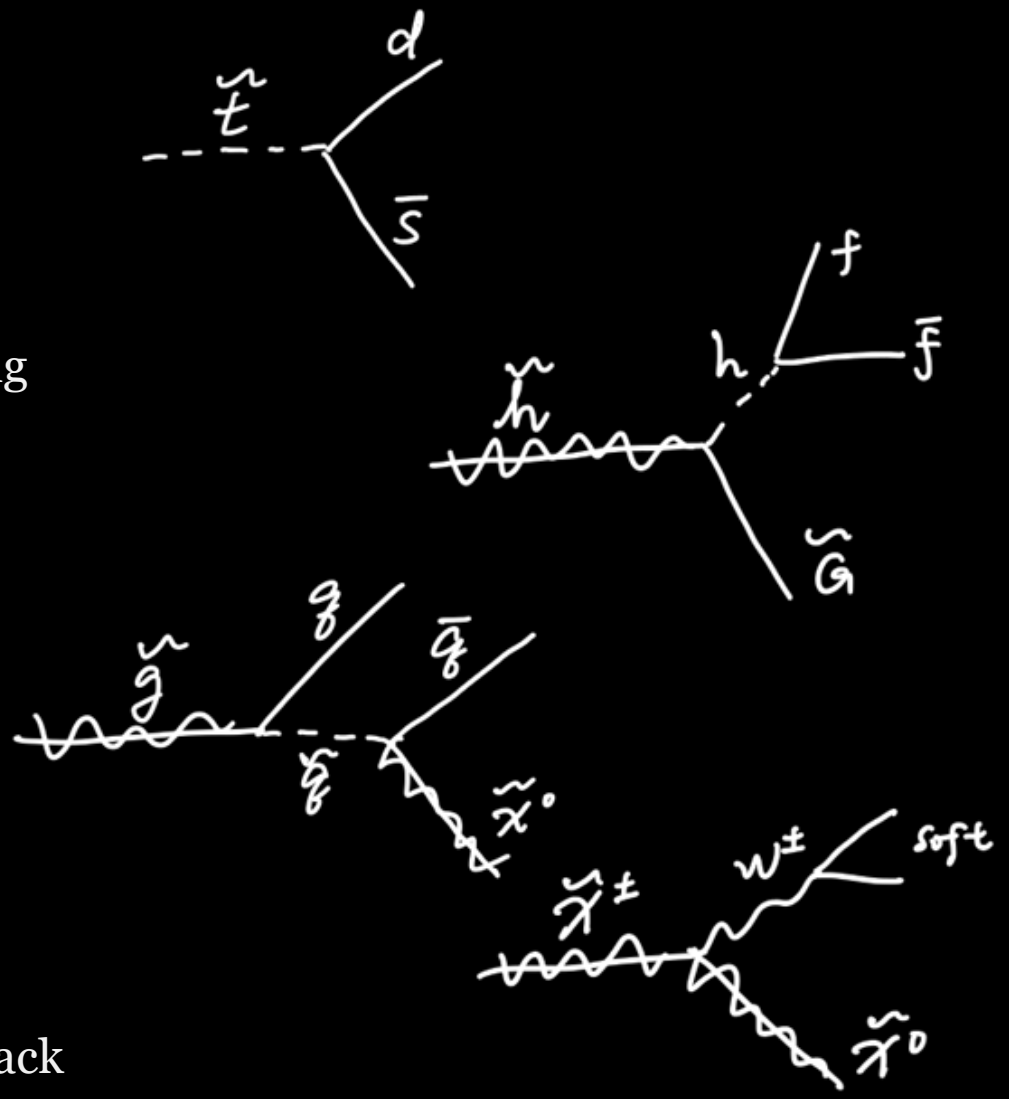
- Gauge mediation—suppressed couplings via SUSY breaking scale

$$c\tau_{\mathrm{GMSB}} \sim 10\ \mathrm{m} \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^5 \left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4$$

- Mini-split spectrum—suppressed couplings through "decoupled" heavy particles

$$c\tau_{\mathrm{milli-split}} \sim 1\ \mathrm{mm} \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^4$$

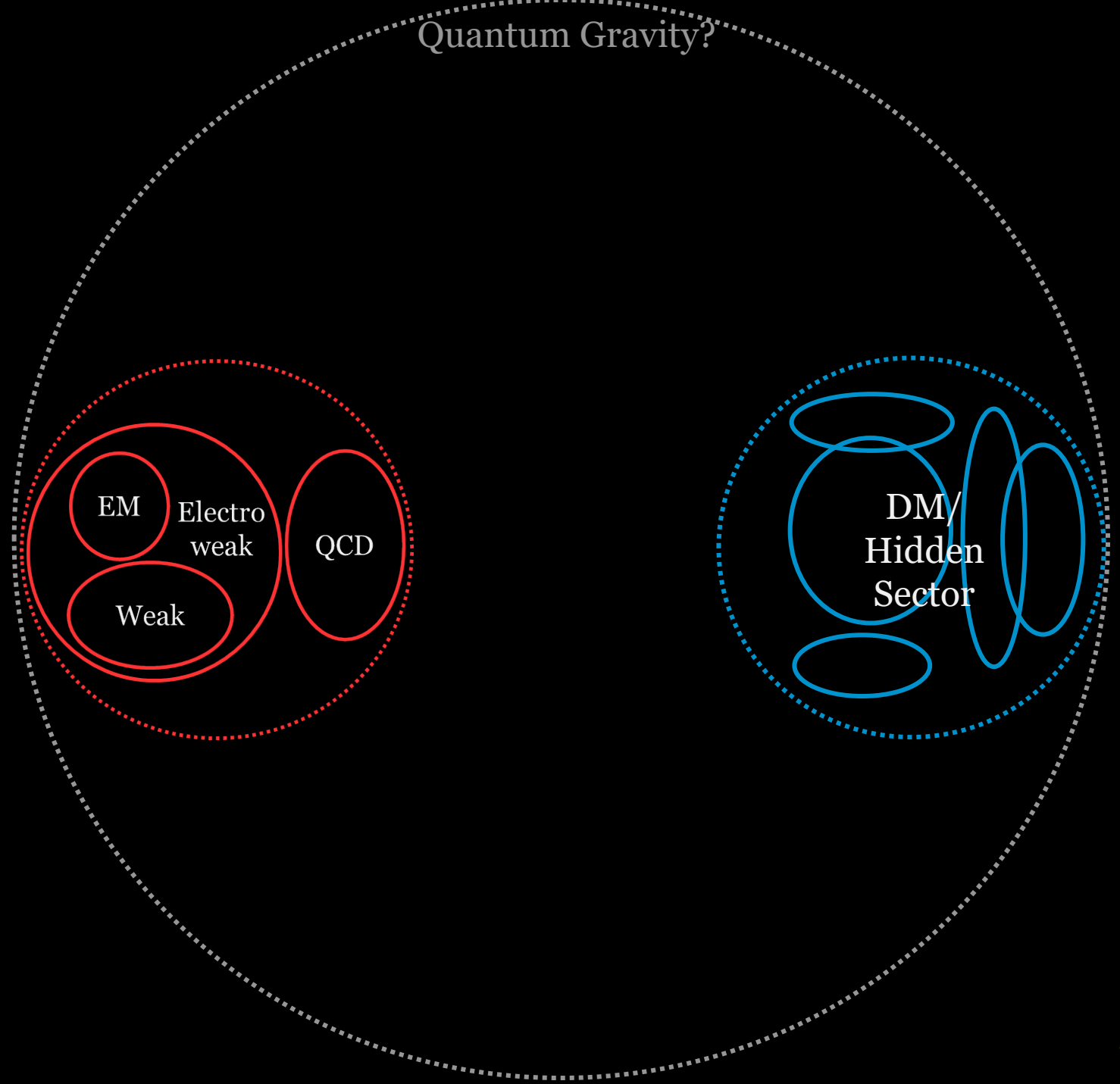
- Pure Wino/Higgsino–nearly degenerated, disappearing track



Why hidden sector?

Generic DM physics can invoke hidden sectors:

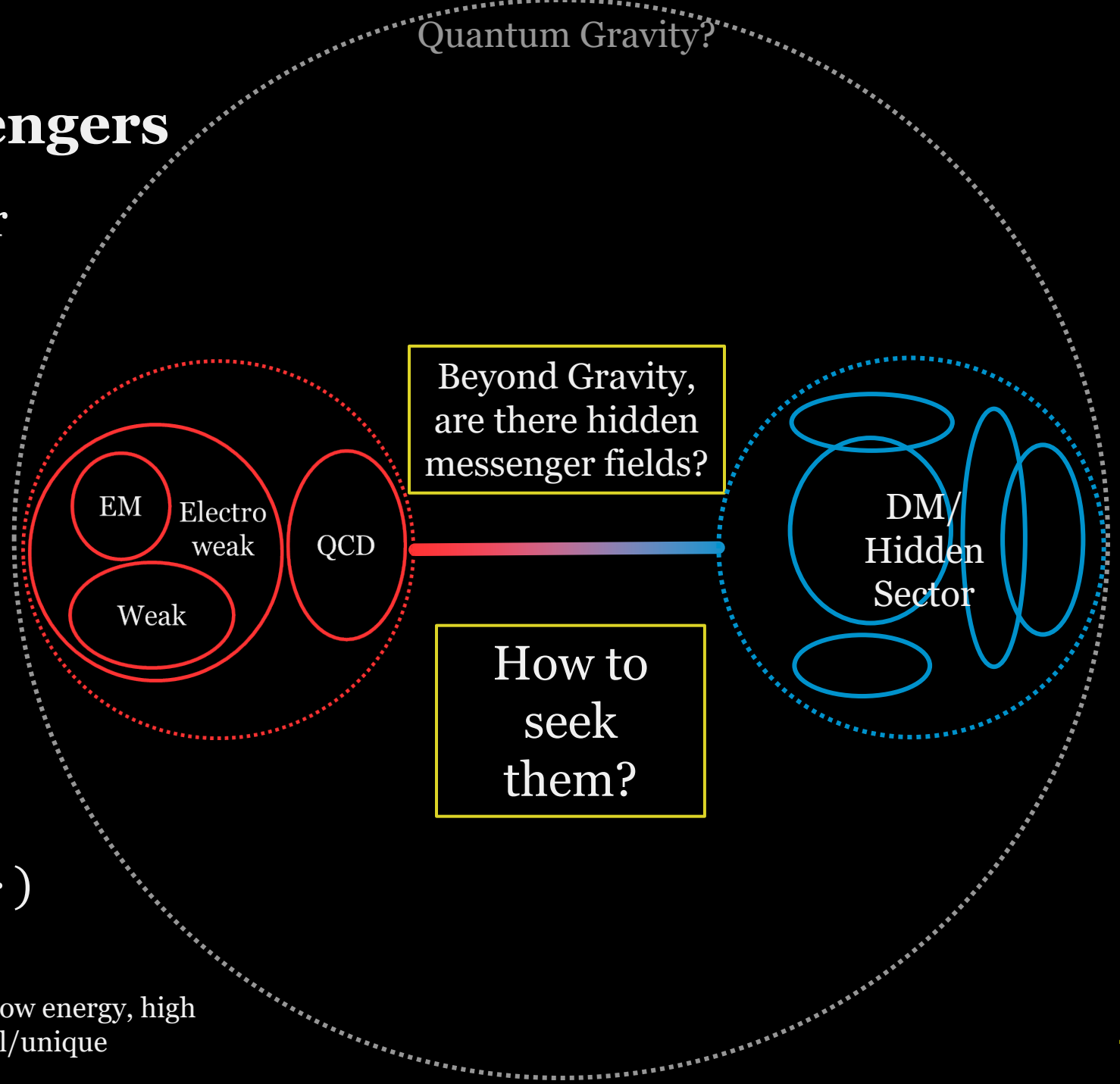
- Rich interaction structure
- Rich mass spectrum
- Can be unified with us at a higher scale



Hidden Sector Messengers

Categorization of messenger fields*:

- Scalar messenger s
  - $\epsilon\Lambda(H^+H)s$
  - $\epsilon(H^+H)(s^+s)$
- Vector messenger A'_μ
  - $\epsilon F^{\mu\nu}F'_{\mu\nu}$
  - $\epsilon\, J^\mu_{SM}A'_\mu$
- Neutrino messenger N
  - $\epsilon(LH)N$
- Axion messenger a
  - $\frac{a}{f_a}\left(\frac{\alpha_3}{8\pi}G\tilde{G}+\frac{\alpha_2}{8\pi}W\tilde{W}+\cdots\right)$



*This also form the basis for many discussions of low energy, high intensity experiments. Collider will provide crucial/unique complementary information in the GeV realm.

Heavy Axion

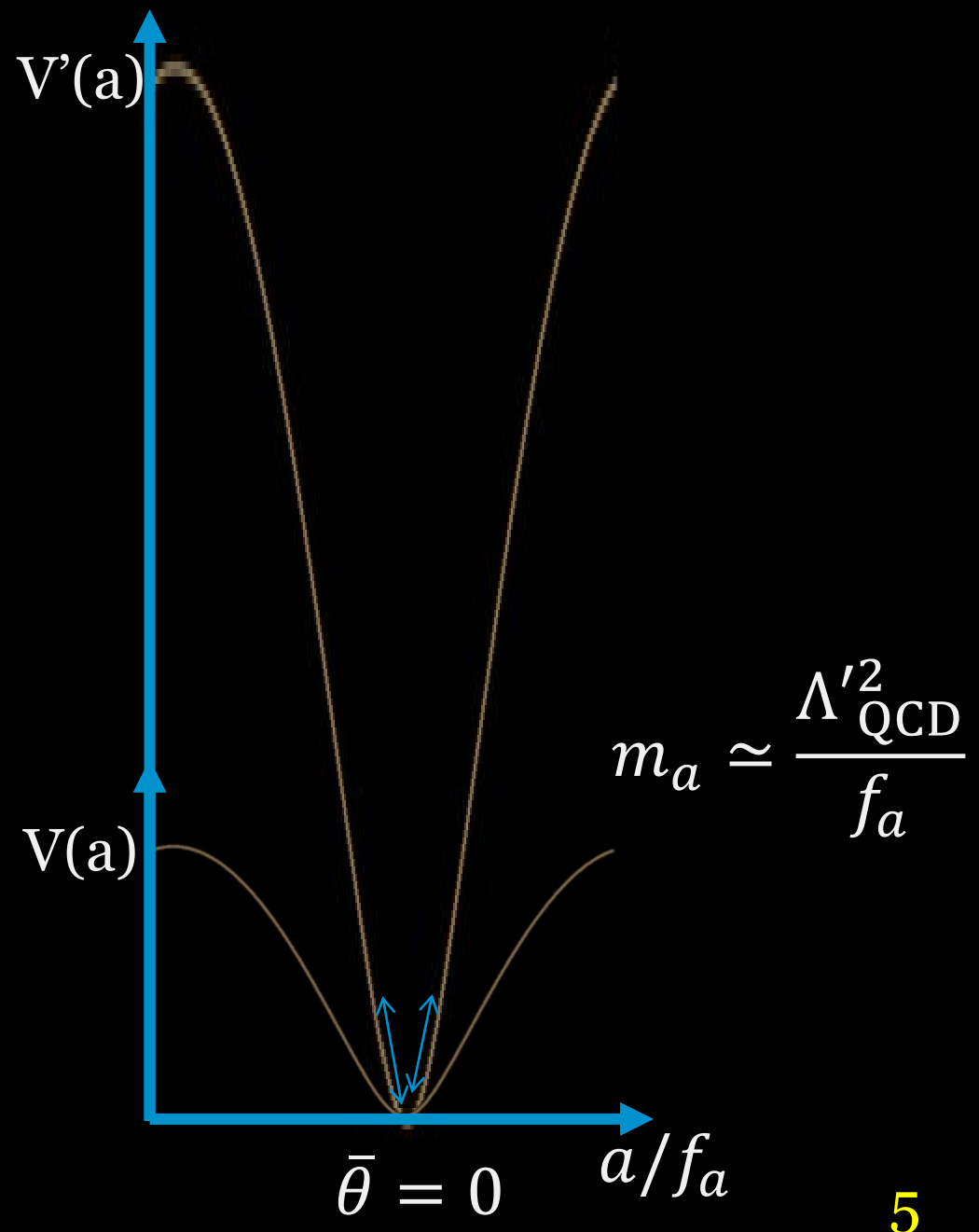
Mass of the axion is a robust prediction

$$V^{QCD}(a) \simeq -f_\pi^2 m_\pi^2 \cos(\theta + \frac{a}{f_a})$$

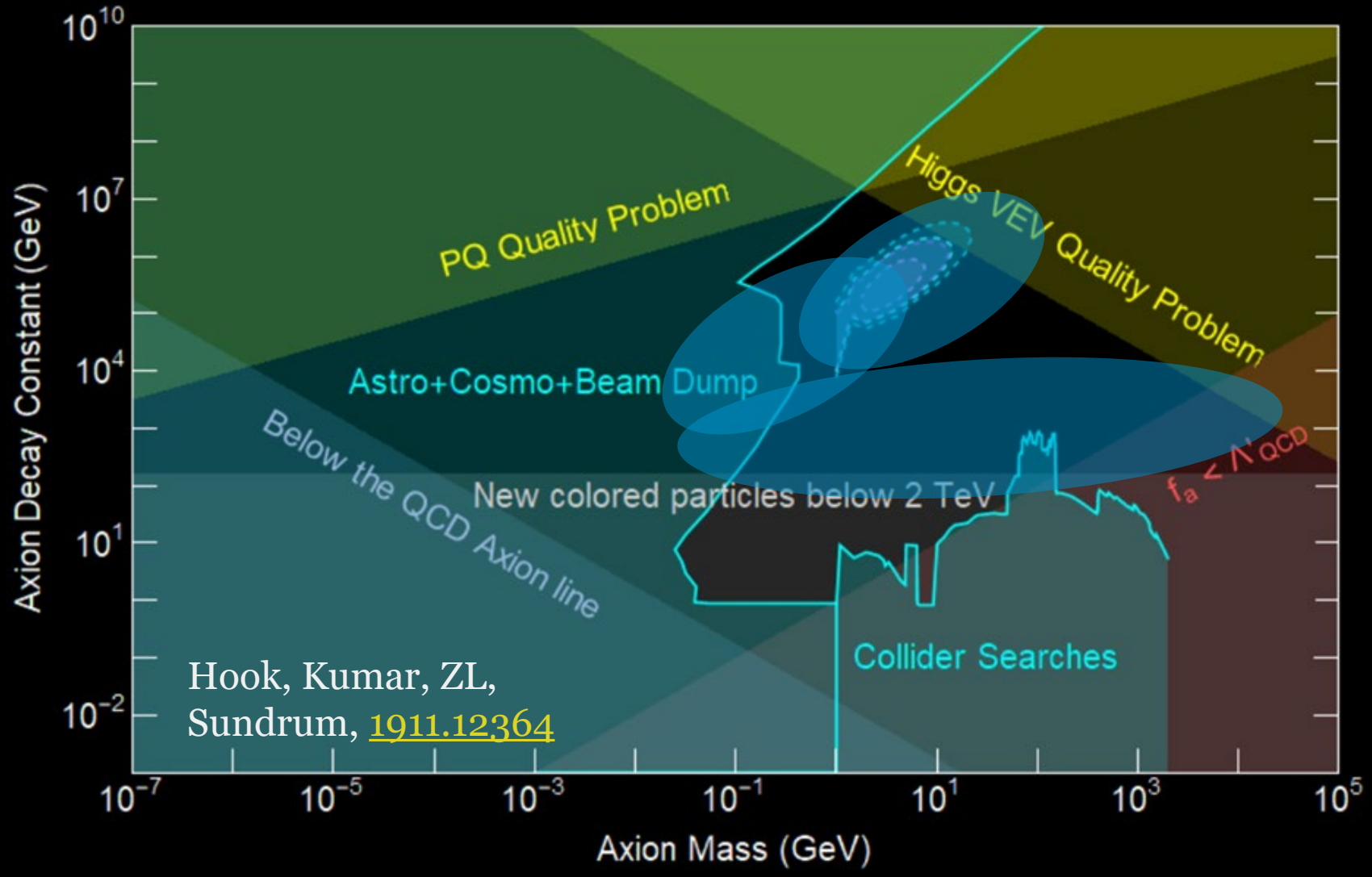
New contributions to the potential and the mass in general will not be aligned with the QCD potential

$$V(a) = V^{QCD} + \frac{f_a^n}{\Lambda^{n-4}} \cos(\theta' + \frac{a}{f_a})$$

Rubakov, 97'
Hook, 14'
Dimopoulos, Hook, Huang, Marques-Tavares, 16'
Gherghetta, Nagata, Shifman, 16'
Argarwal, Howe, 17'
Argarwal, Howe, 17'
Hook, Kumar, ZL, Sundrum, 19'
Csaki, Ruhdorfer, Shirman, 19'
Gherghetta, Khoze, Pomarol, Shirman, 20'



Heavy Axion: challenge & opportunity



Hook, Kumar, ZL, Sundrum, 1911.12364

Challenge: light, rarely produced, hadronic states;

Big open windows for well-motivated heavy Axions

Opens a new direction of singly produced long-lived particles.

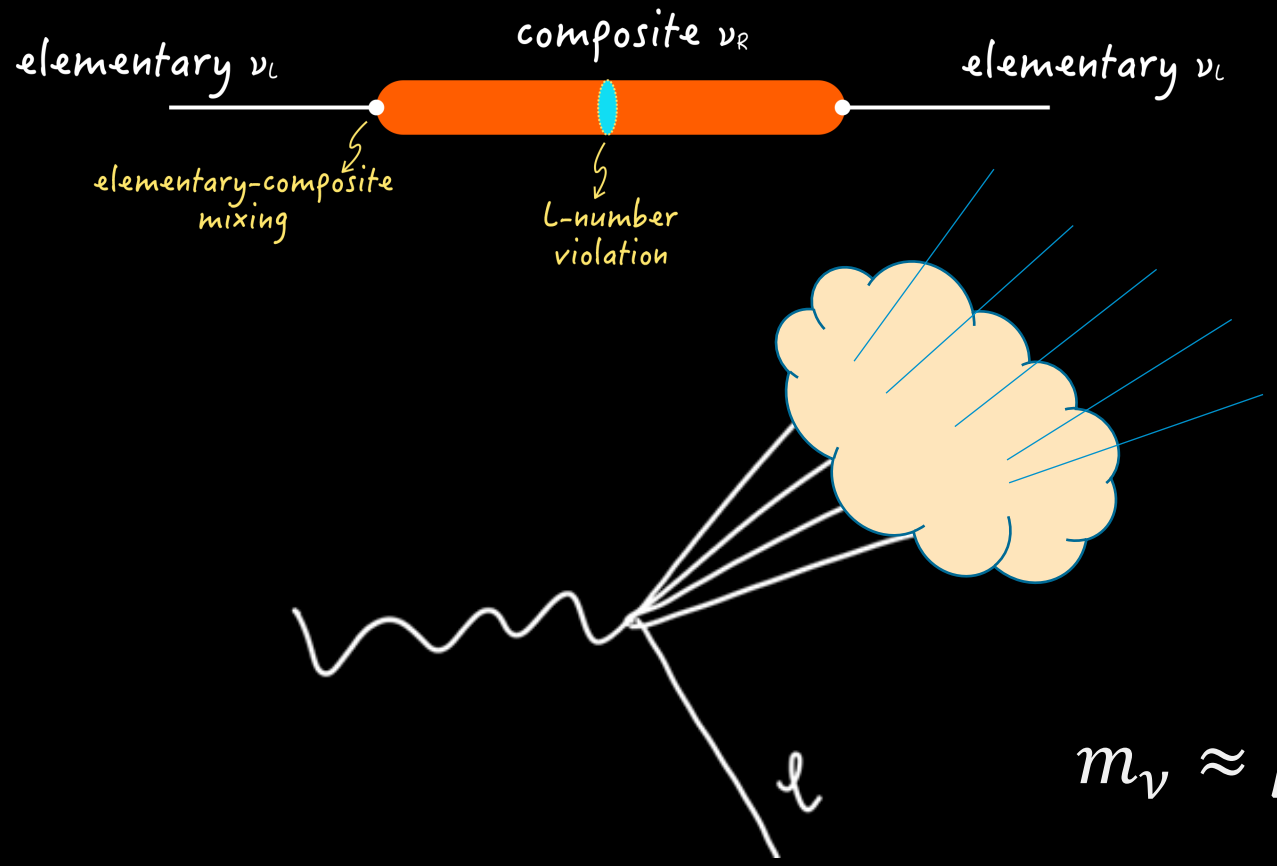
A lot more to explore.

$$\frac{\alpha_s}{8\pi}\left(\theta + \frac{a}{f_a}\right)\tilde{G}G + \cdots$$

Displaced Track Tigger (crucial):
Gershtein, *1705.04321*; Gershtein, Knapen, *1907.00007*

For general HNL LLP pheno, see e.g.,
Liu, ZL, Wang, Wang, 1904.01020
Drews, Hajer, 1903.06100
Cottin, Helo, Hirsch, Silva, 1902.05673
...

Composite Neutrino



A shower of Sterile Neutrinos...

w Chacko, Dev, Sanket, in progress

Inverse Seesaw , Mohapatra, Valle, 86'

General CFT:

$$L_{UV} \supset L_{CFT} + \frac{\hat{\lambda}}{M^{\Delta-3/2}}\bar{L}\tilde{H}O_N + \frac{\hat{\mu}}{M^{\Delta_{2N}-4}}O_{2N}$$

CFT generates

CFT deformation generates

$$L_{IR} \ni -m_N\bar{N}N - (\lambda\bar{L}\tilde{H}N_R + \mu N_L^2 + h.c.)$$

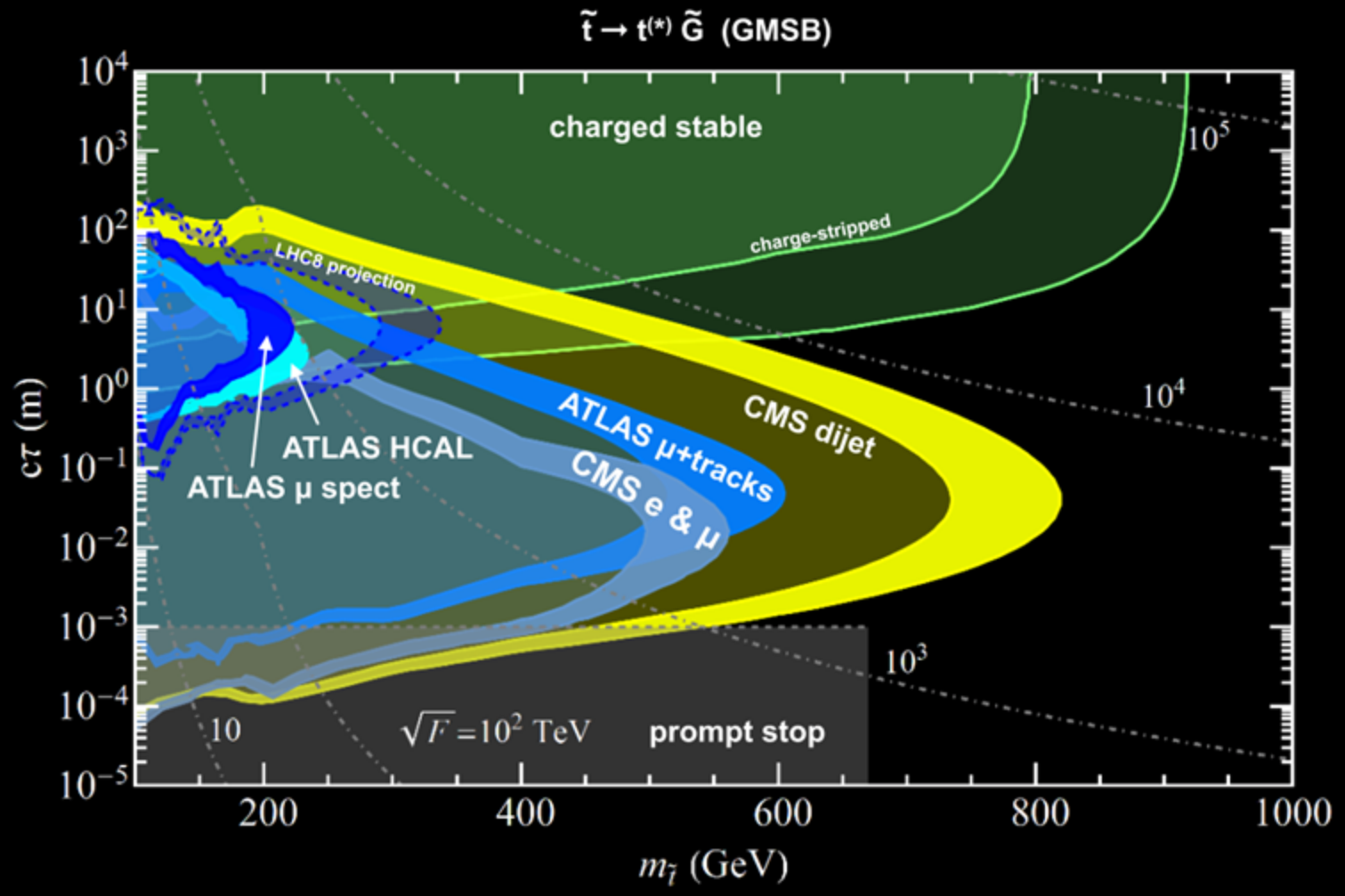
$$m_\nu \approx \mu\left(\frac{\lambda v_{EW}}{M_N}\right)^2$$

$$\Lambda \quad C_\lambda\hat{\lambda}\left(\frac{\Lambda}{M}\right)^{\Delta-\frac{3}{2}} \quad C_\mu\hat{\mu}\left(\frac{\Lambda}{M}\right)^{\Delta_{2N}-4}$$

Arkani-Hamed, Grossman, hep-ph/9806223, Okui, hep-ph/0405083, Grossman, Tsai, 0811.0871, Grossman, Robinson, 1009.2781, McDonald 1010.2659, Robinson, Tsai, 1205.0569, 1404.7118...
Chacko, Fox, ZL, Harnik, to appear

8 TeV result by ZL, B. Tweedie, 1503.05923

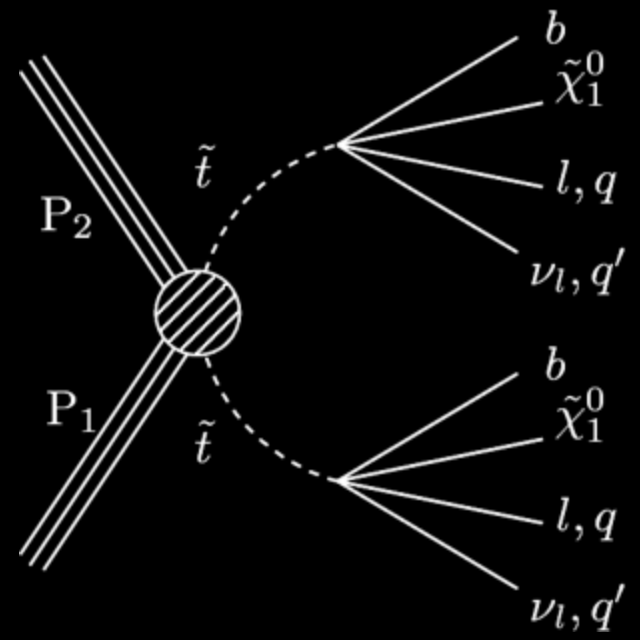
DM Coannihilation and LLP



SUSY fully covered, any lifetime?

(infamous)
Compressed SUSY

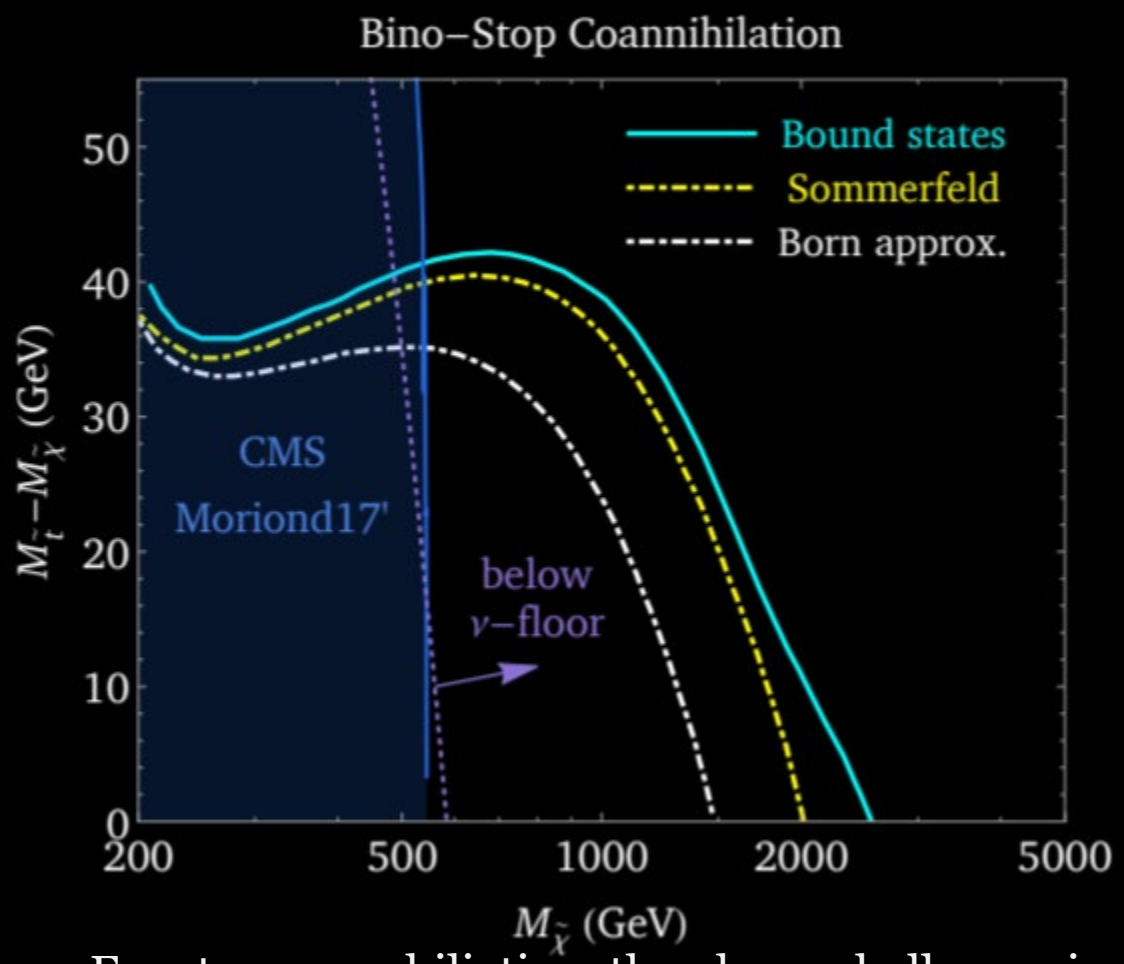
Easily long-lived

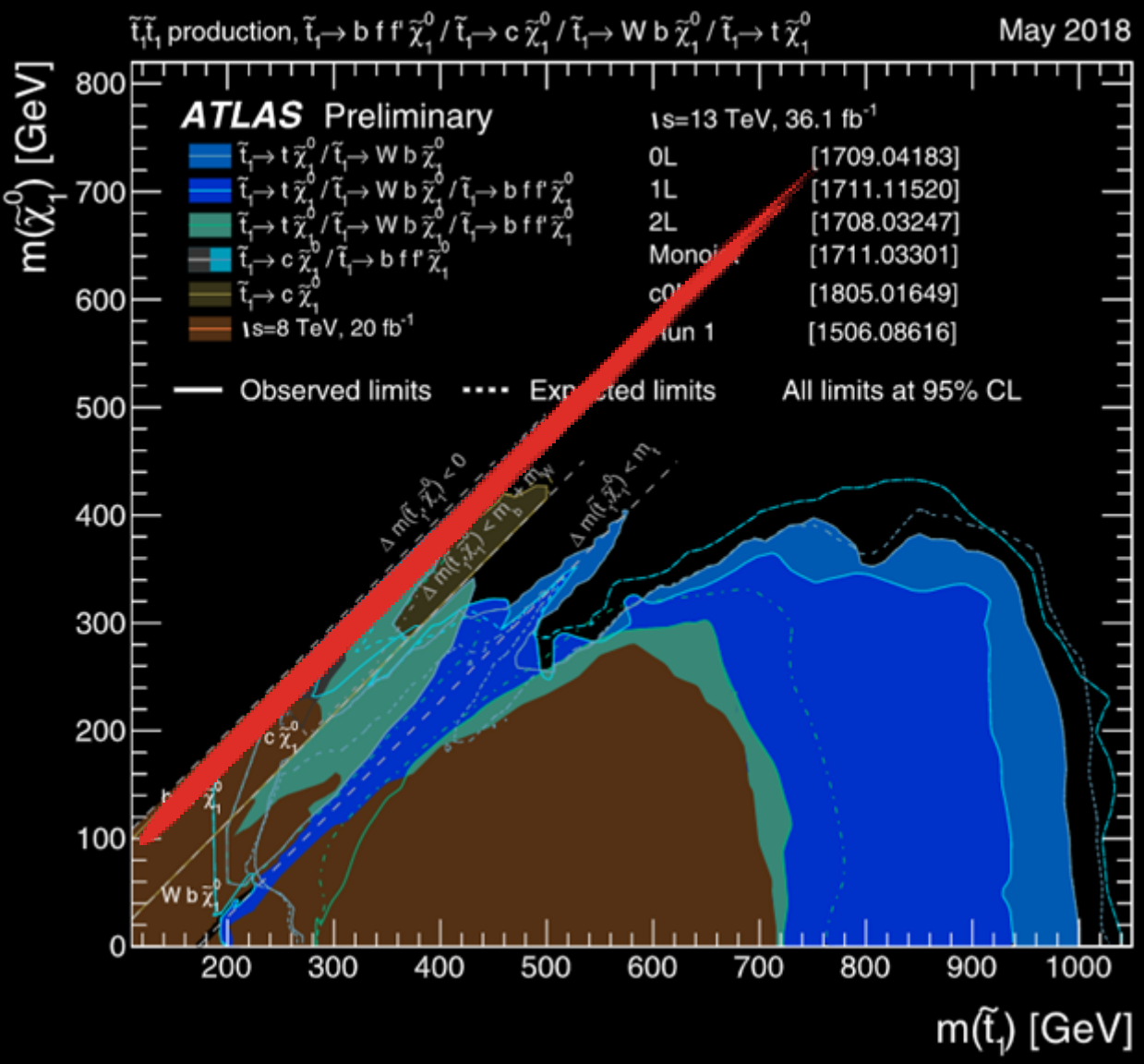


T. Han, ZL, A. Natarajan, 1303.3040 Keung, Low, Zhang 1703.02977 on DM relic

Mono-jet + (soft) displaced tracks
Work in progress with H. An et al.

Coannihilation and LLP





For stau coannhiliation, the pheno challenges is with soft and prompt tau leptons.

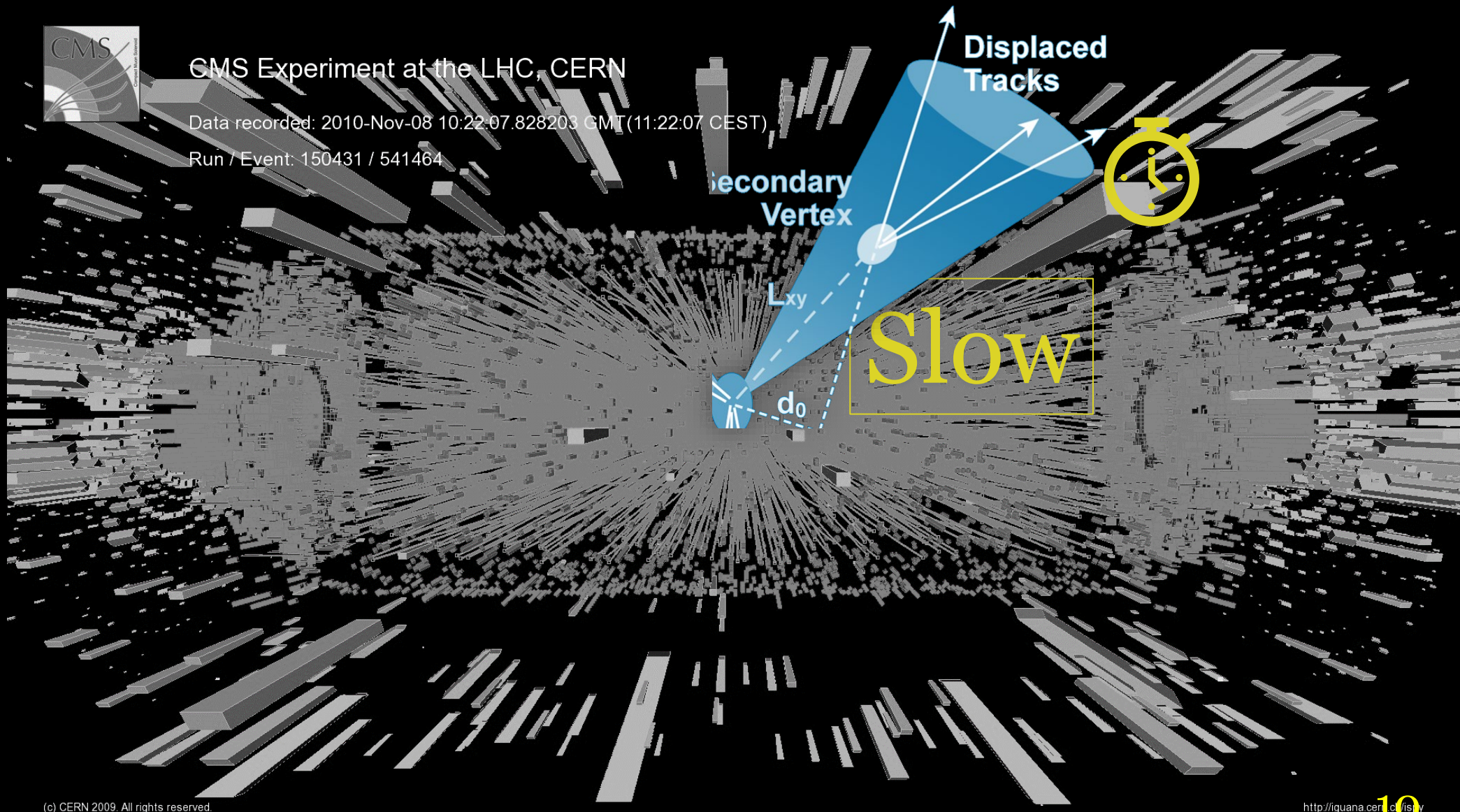
Monojet+(soft) displaced tracks will cover this well motivated region, making direct DM and coannihilator discovery

Long-Lived Particles (LLPs) opportunity

☹trigger
☹reconstruction
☹non-standard background

Delay is a universal feature of Long-Lived Particles*

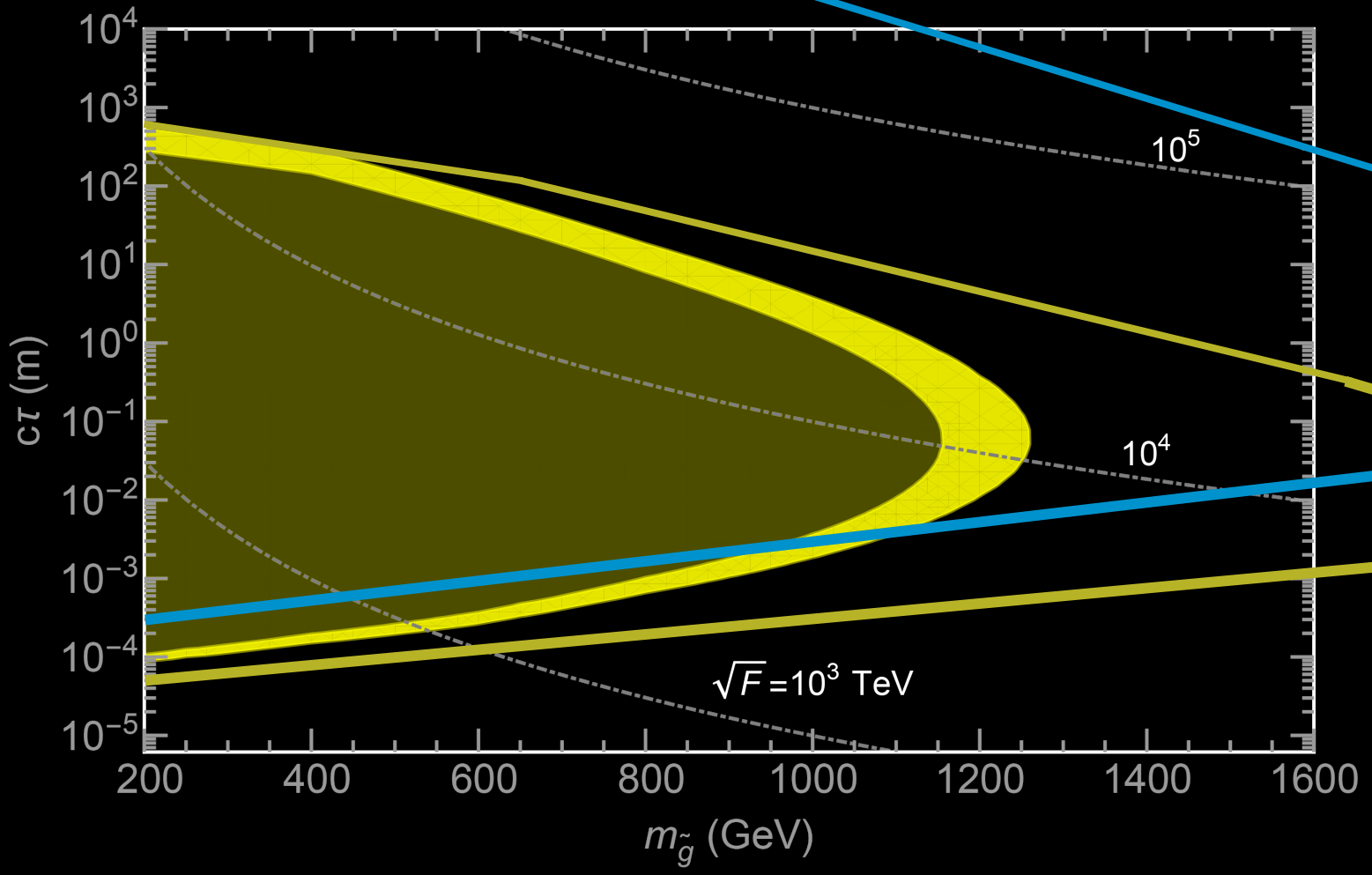
Liu, ZL, Wang, 1805.05957

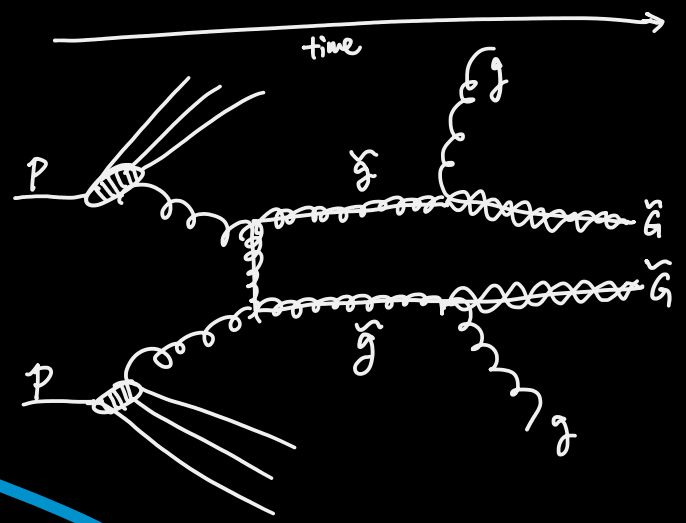


*except for those hyper-boosted $\gamma \geq 7$

For a LLP community review: 1903.04497

Late comers will be spotted easily





Delayed Jet analysis carried out by CMS

Displaced jet at 13 TeV

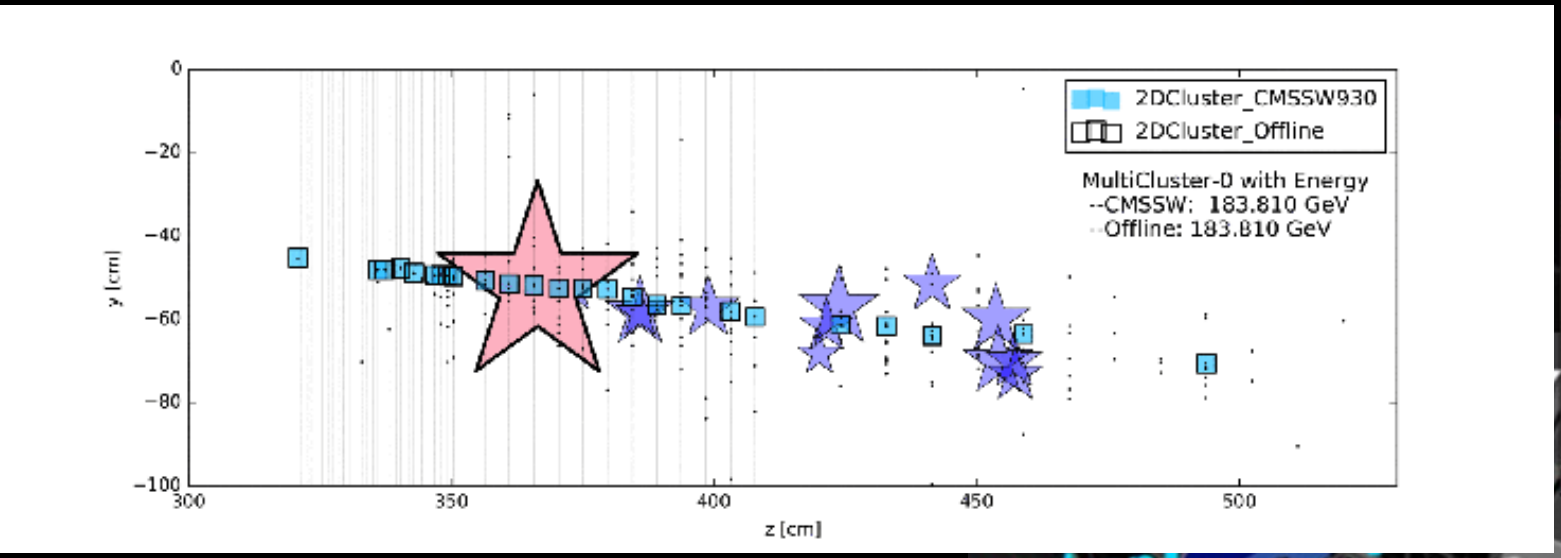
More to come:
CMS MTD upgrade
ATLAS HGTD upgrade
Ecal, Muon system, Hcal, timing information to be used

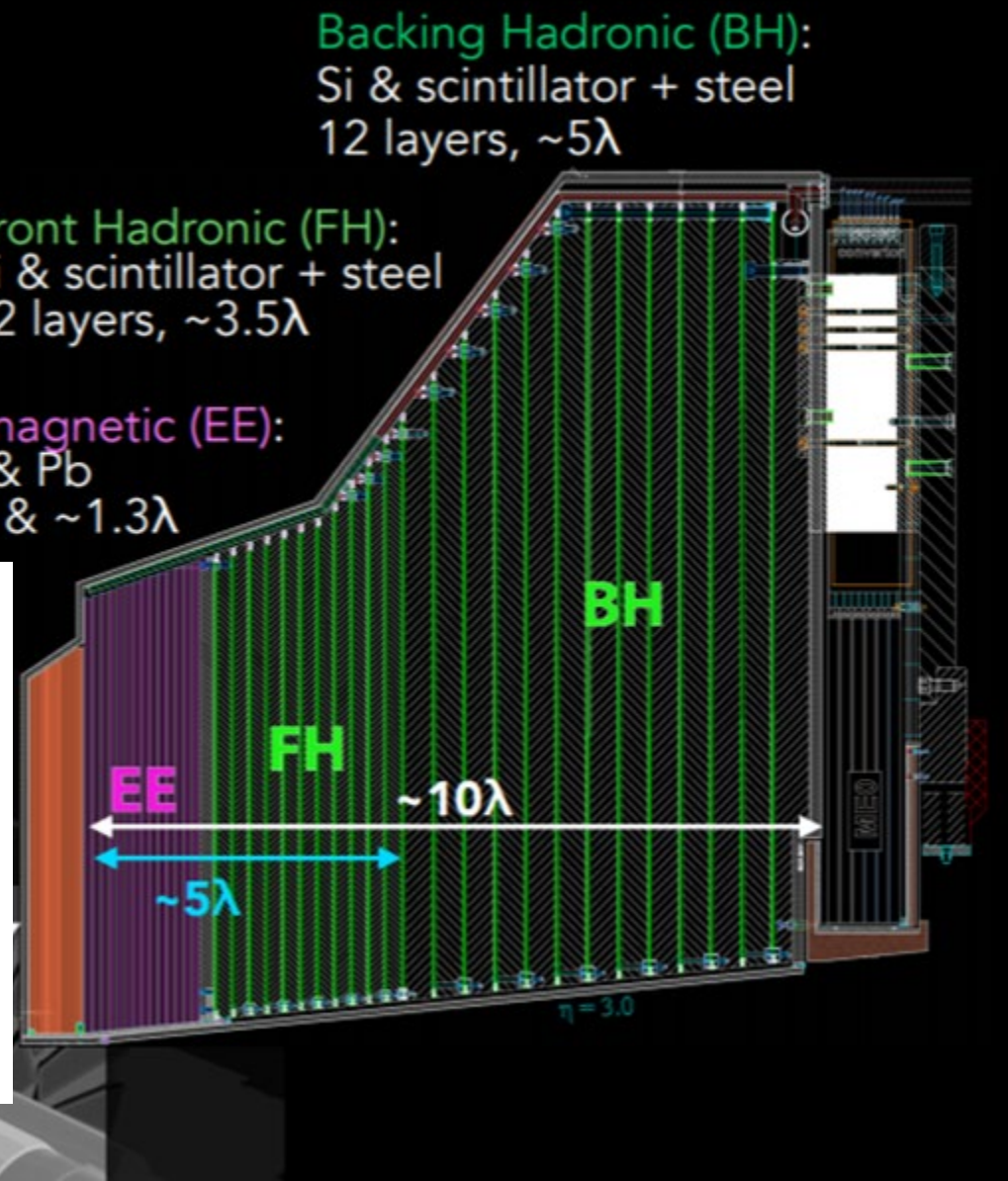
Liu, ZL, Wang, 1805.05957
8 TeV results, ZL, Tweedie, 1503.05923

More ideas: High granularity detectors

HL upgrade:
Directional resolution milli-radian,
Temporal resolution 30 ps (for pT > 30 GeV):

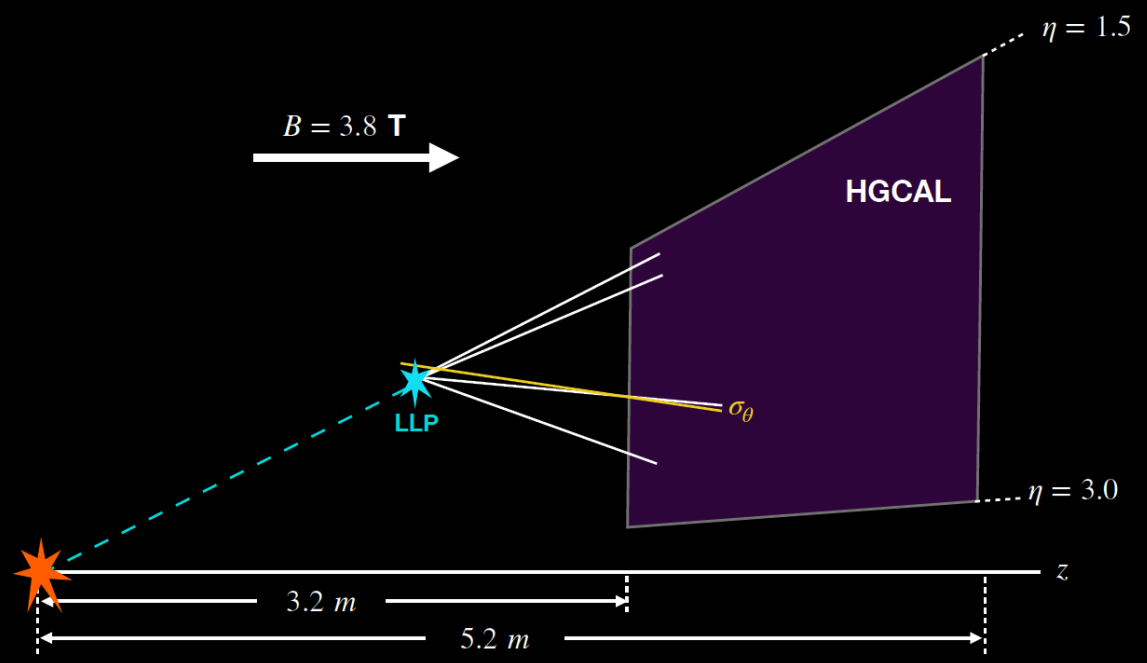
Allowing jet & shower substructure reconstruction:
Infor passed to low level triggers
Perfect for LLPs

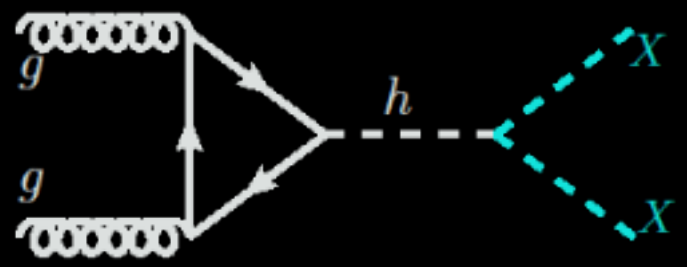


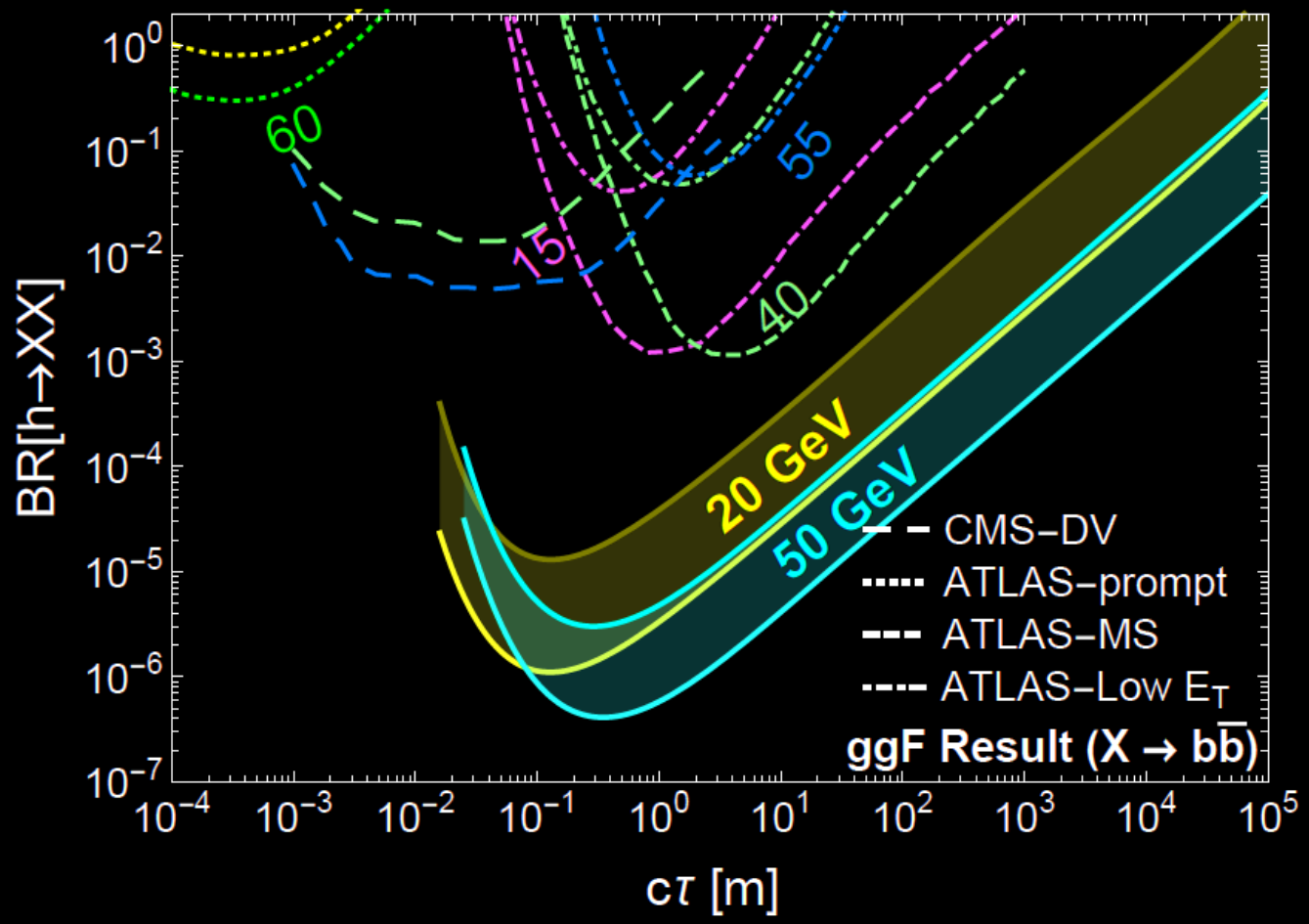


https://galleryziheng.wordpress.com/2018/03/08/cms-hgcal-event-display/

HGCAL potential







Liu, ZL, Wang, Wang, 2005.10836

For HGCAL non-pointing photon w ML, see Alimena, Iiyama, Kieseler 2004.10744

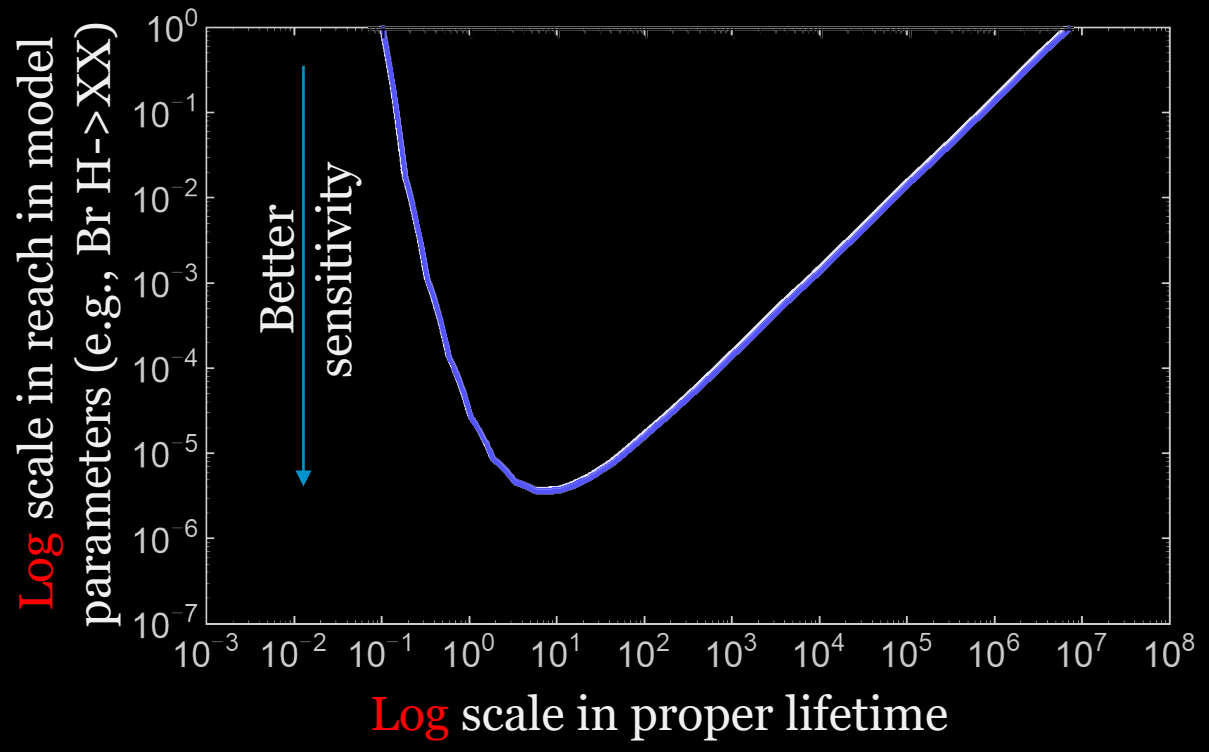
Please join the community activities:
Snowmass 2021, EF09 on LLPs: https://snowmass21.org/energy/bsm_general
LHC-LLP-WG: https://lpcc.web.cern.ch/lhc-llp-wg
LLP community: https://longlivedparticles.web.cern.ch/

Summary

- Theory & Experimental landscape
  - Large class of motivated models for LLPs, mainly classified into SUSY and Hidden sector dynamics
- Challenges and Opportunities
  - Exciting LHC program ahead
  - High Quality Axion (low mass hadronic LLP)
  - HNL shower (semi-leptonic LLP shower)
  - DM & Coannihilation (soft visible energy LLP)
  - Timing in all subdetectors (new dimensions of information greatly boost LLP program, trigger & analysis level)
  - Highly Granularity (new dimensions of information greatly boost LLP program, trigger & analysis level)
  - More Trigger ideas (Bhattacherjee, Mukherjee, Solanki, 2003.03943; Dildick et al, talk link; more at the recent CERN LLP workshop)

Thank you!

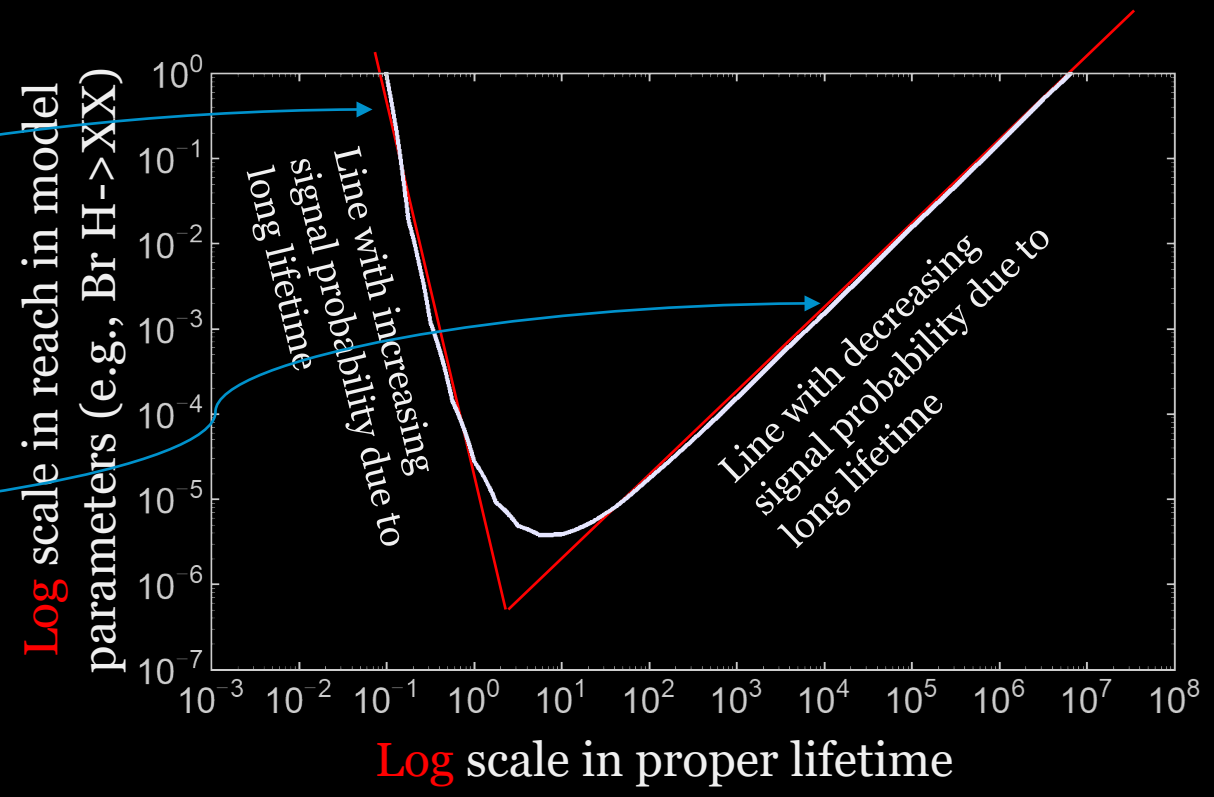
LLP coverage: basics



LLP coverage: basics

Geometrical acceptance P_{in}

$$d = c\tau\gamma\beta$$

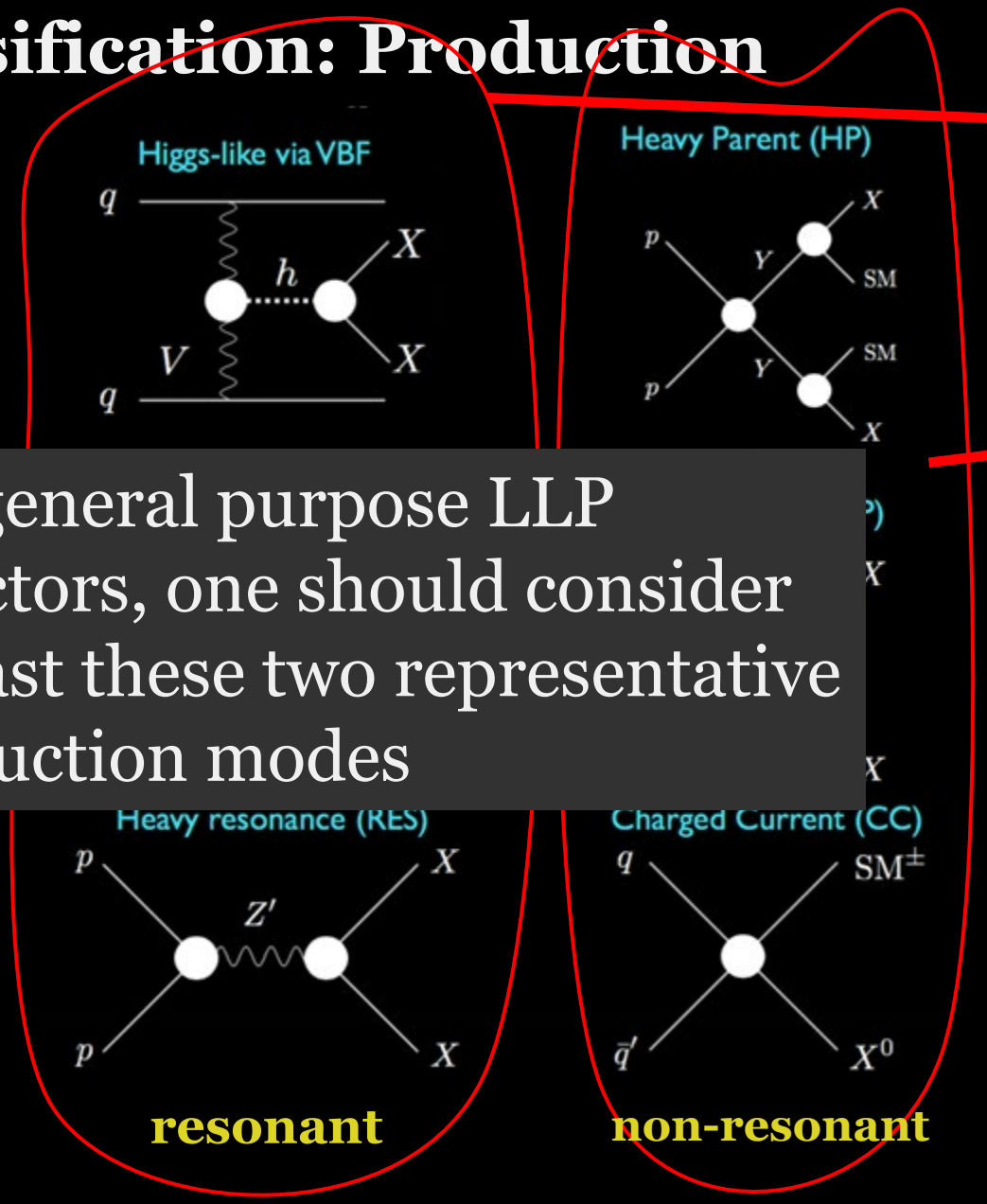


- For short lifetime: the closer the better;
- For long lifetime: the larger decay volume the better (CMS/ATLAS is 5-10 m)
- For any lifetime: angular coverage the large the better (CMS/ATLAS is 4pi)

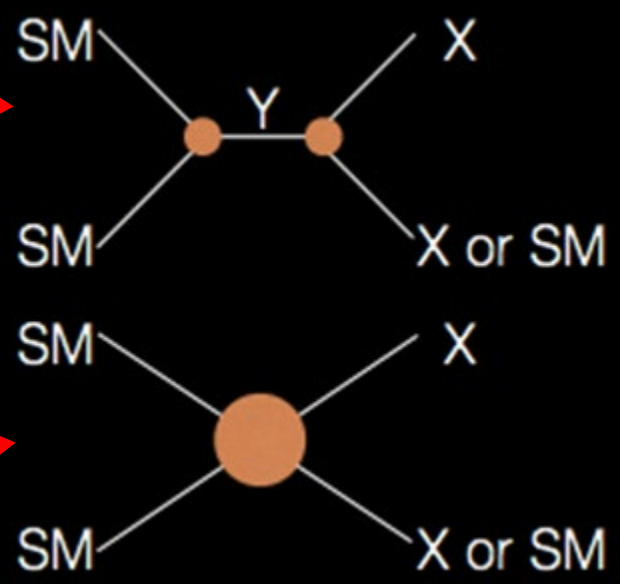
But the **challenges** are in the **triggers** and **background suppression**

LLP community report 1903.04497
also see Review by Lee, Ohm, Soffer, Yu 1810.12602

Classification: Production

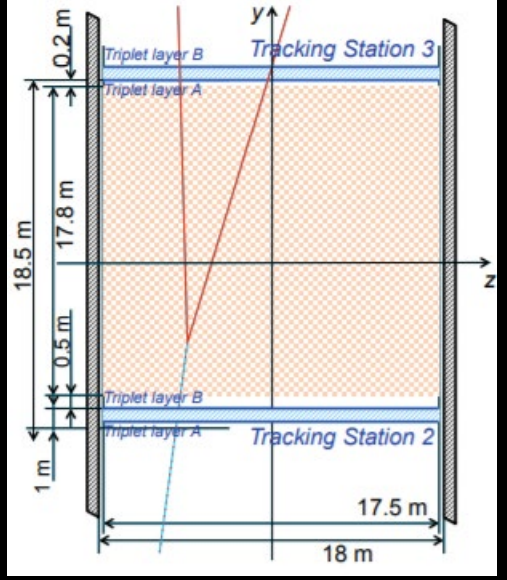


For general purpose LLP detectors, one should consider at least these two representative production modes



- Factorize production and decay;
- Production affects kinematics of LLP and trigger consideration (except for LLP triggers, which are rare currently);
- Decay affects search strategy in picking up the LLPs, convoluting with lab frame geometries;

Forward Spectrometer



Expanding the LHC program

- MATHUSLA
- Codex-B
- AL3X
- ANUBIS

} Central/Hard LLPs

- FASER
- SHiP
- NA62
- SeaQuest
- …

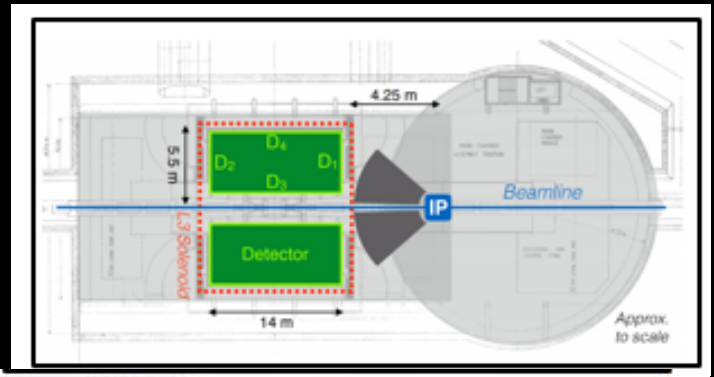
} Forward/lighter LLPs

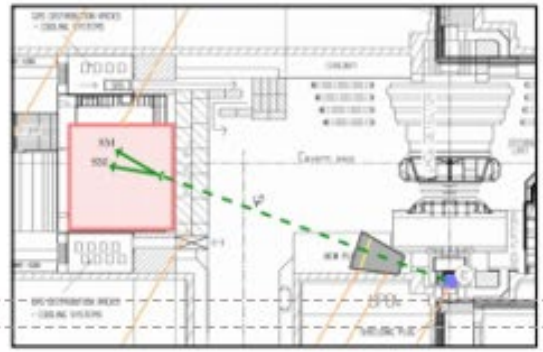
} Beamdump experiments

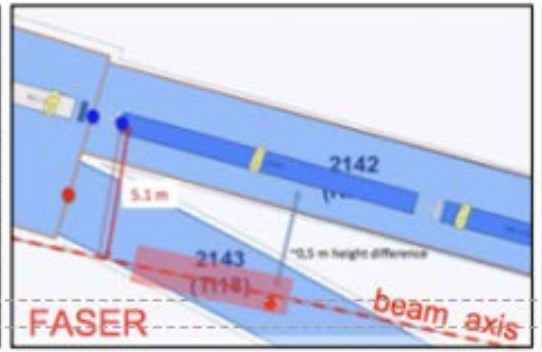
- MoEDAL
- MilliQan

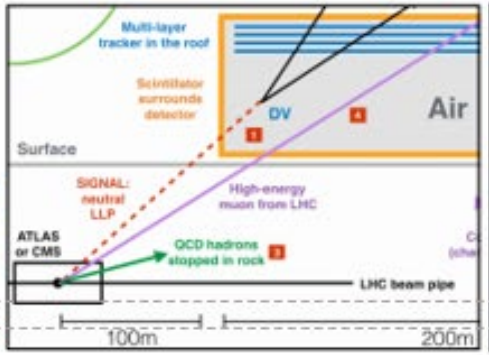
} monopole
millicharged particles

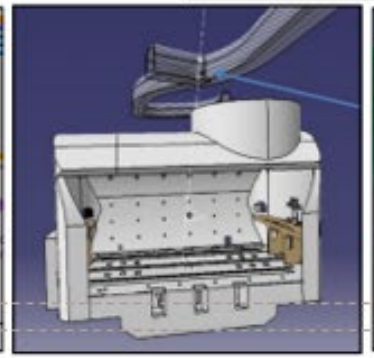
} Search for LLPs

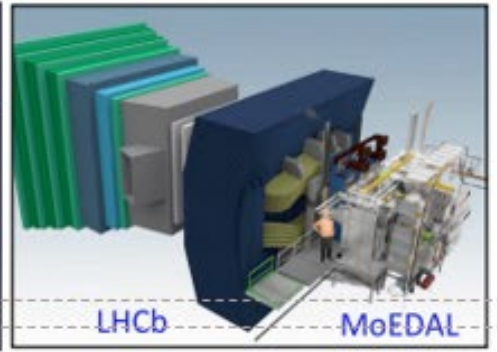




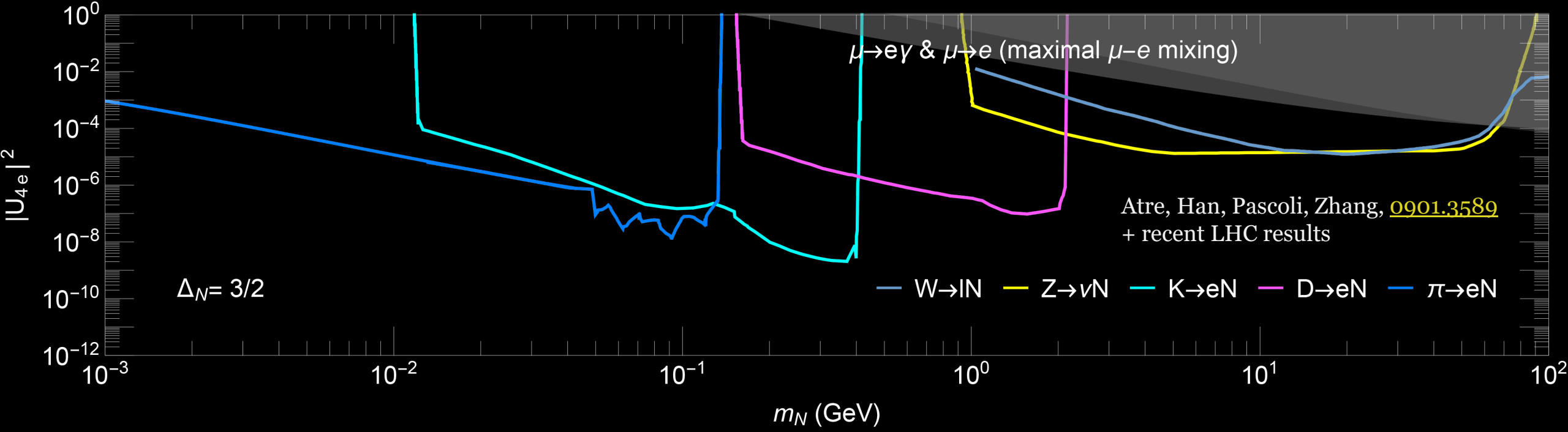




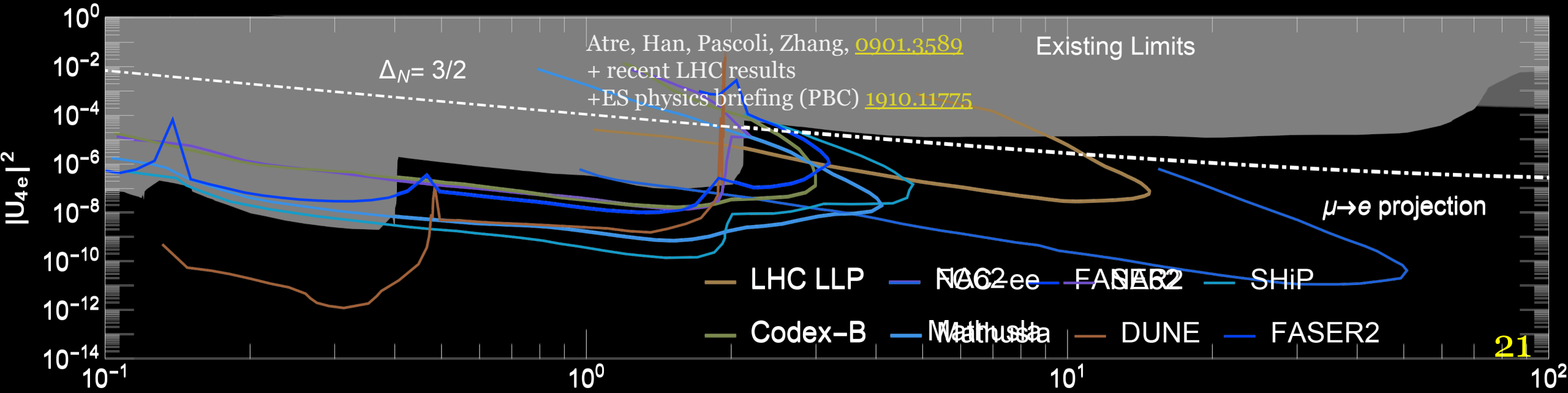




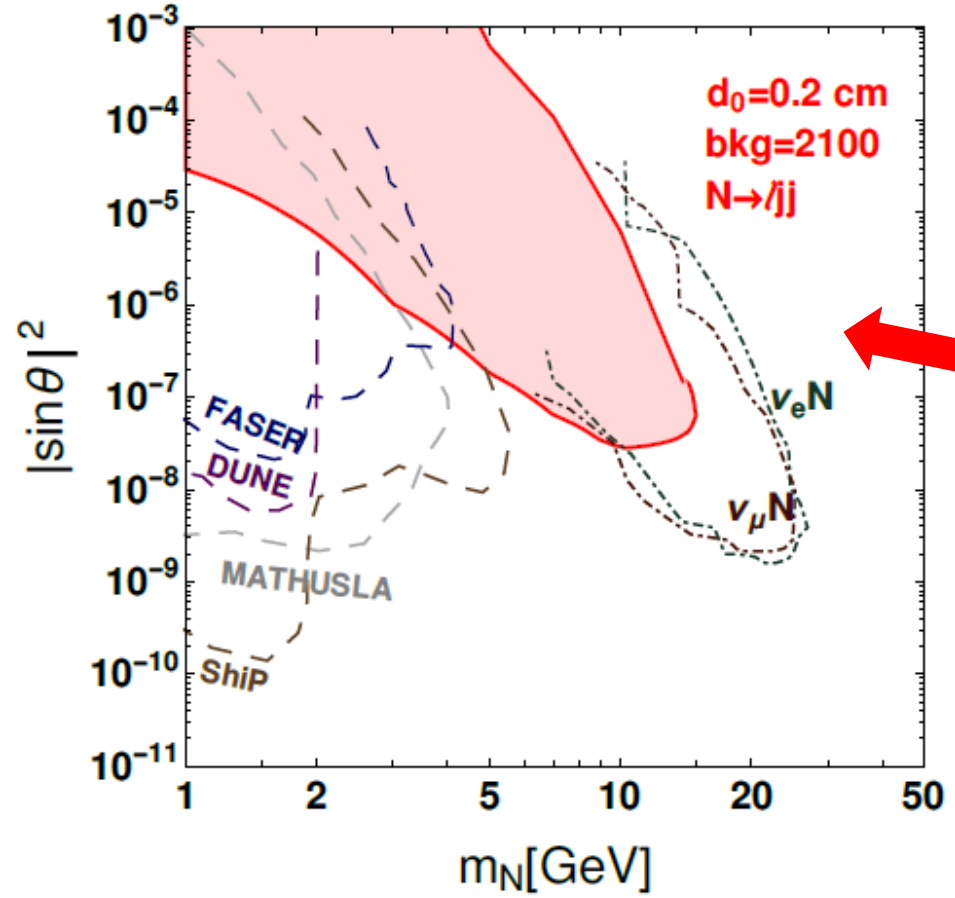
Backup

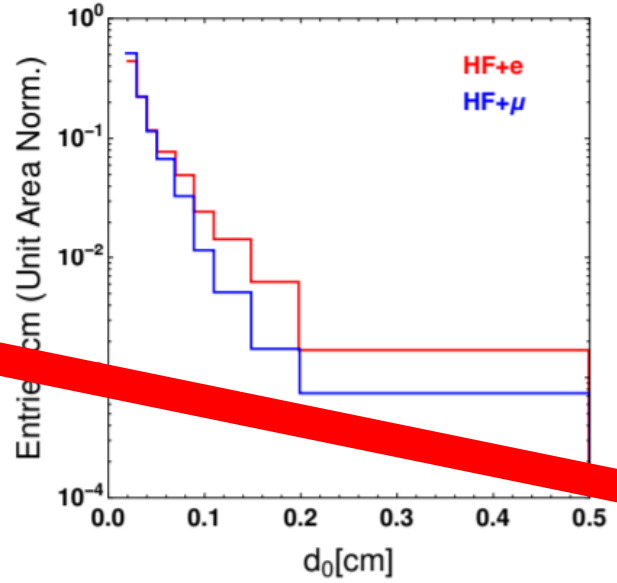


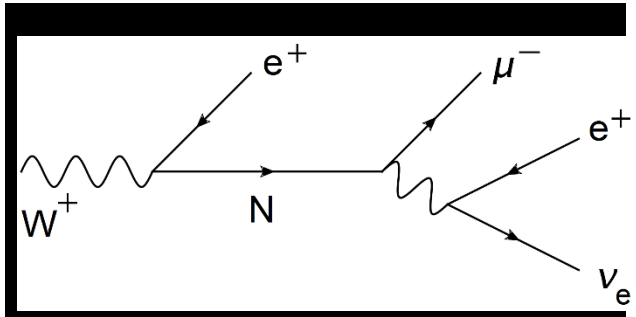
For instance, for Sterile Neutrinos

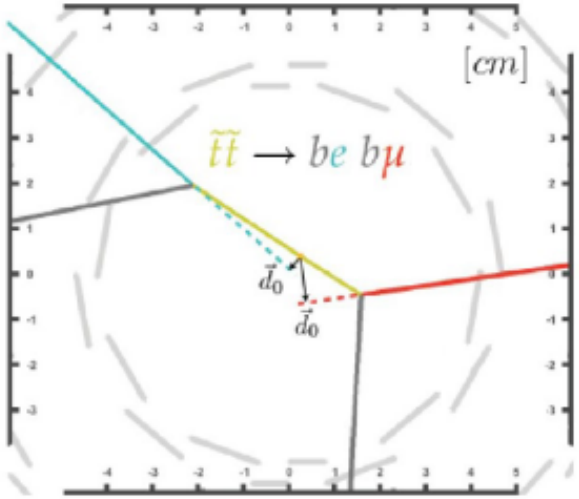


More ideas: displaced lepton



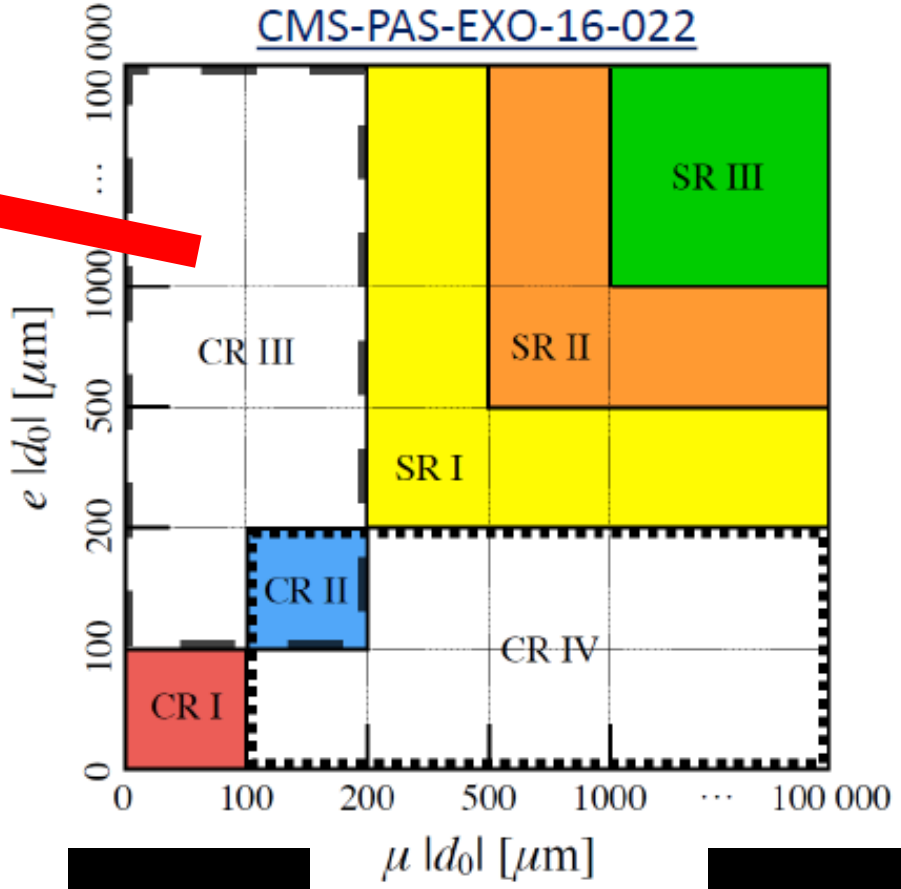






← Single displaced leptons not from the same vertex; focused on e-mu state

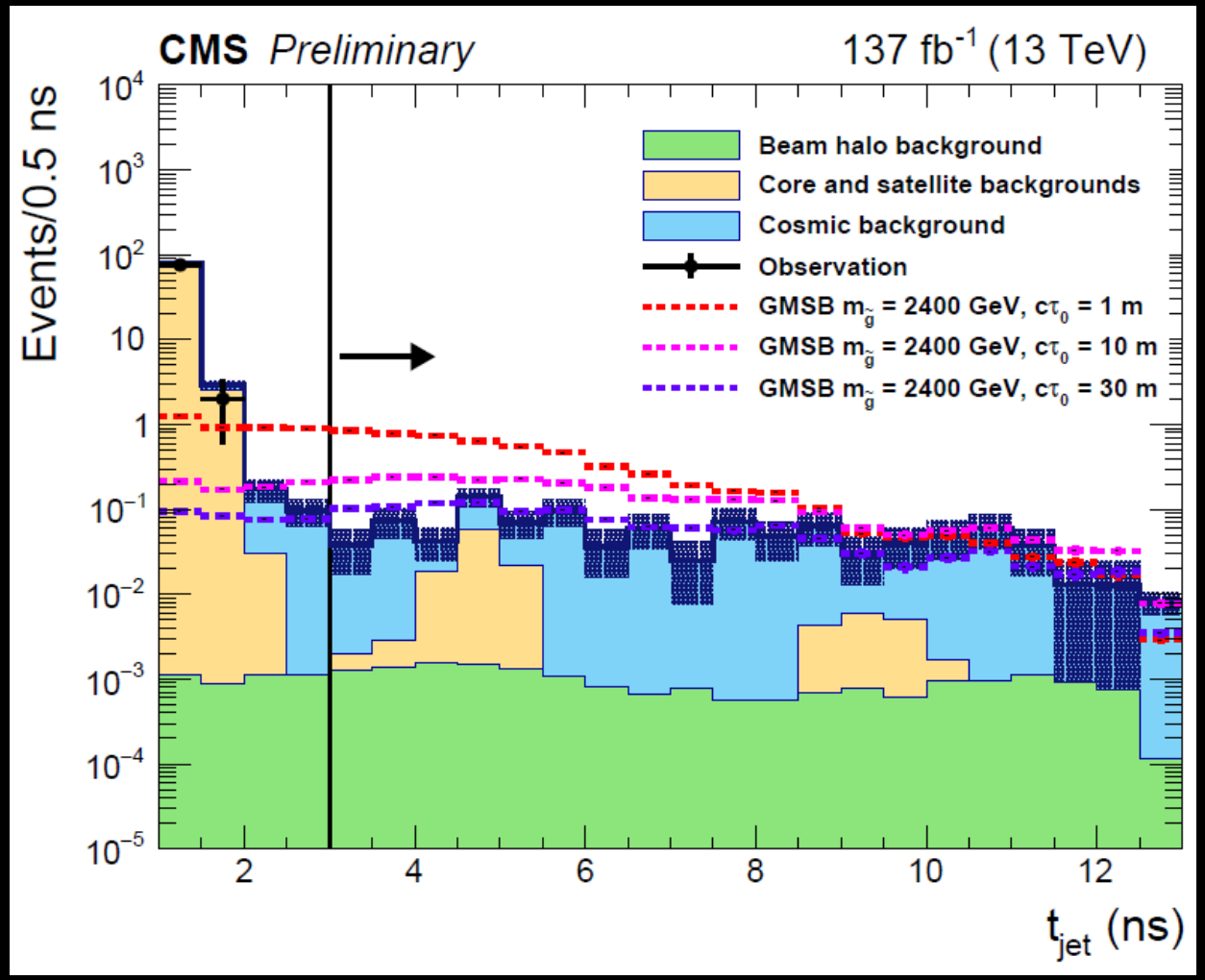
CMS-PAS-EXO-16-022



Digging hard and use the control region studies to propose new searches on sterile neutrinos.

ZL, J. Liu, L.-T. Wang, X. Wang, 1904.01020

New searches and new insights!



Background	Prediction
Beam halo	$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)
Core and satellite bunches	$0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst)
Cosmics	$1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst)

Beam halo small
Core and satellite bunches small but one shall try to improve by precision timing
Cosmics small (for this analysis, no need to do cosmic veto yet but there are many ways) and scale with time but not luminosity

Lot of theory & experimental activities:

- L1 trigger under development
- Delays in all subdetectors under development
- Pheno studies on mass reconstruction
- Pheno studies on jet substructure
- Pheno studies on delayed dark photons
- …