Title: Particle Physics Seminar

Speakers: Zhen Liu

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Perimeter Institute HEP Seminar

LHC Opportunities in Long-Lived Signatures

Zhen Liu
University of Maryland
Dec.2nd, 2019

Outline

- Long-lived particles at the LHC: overview
- Opportunities:
  - High Quality Axion
  - Heavy Neutral Lepton
  - DM & Coannihilation
  - Opportunity in Timing and HGCal

What is LLP?

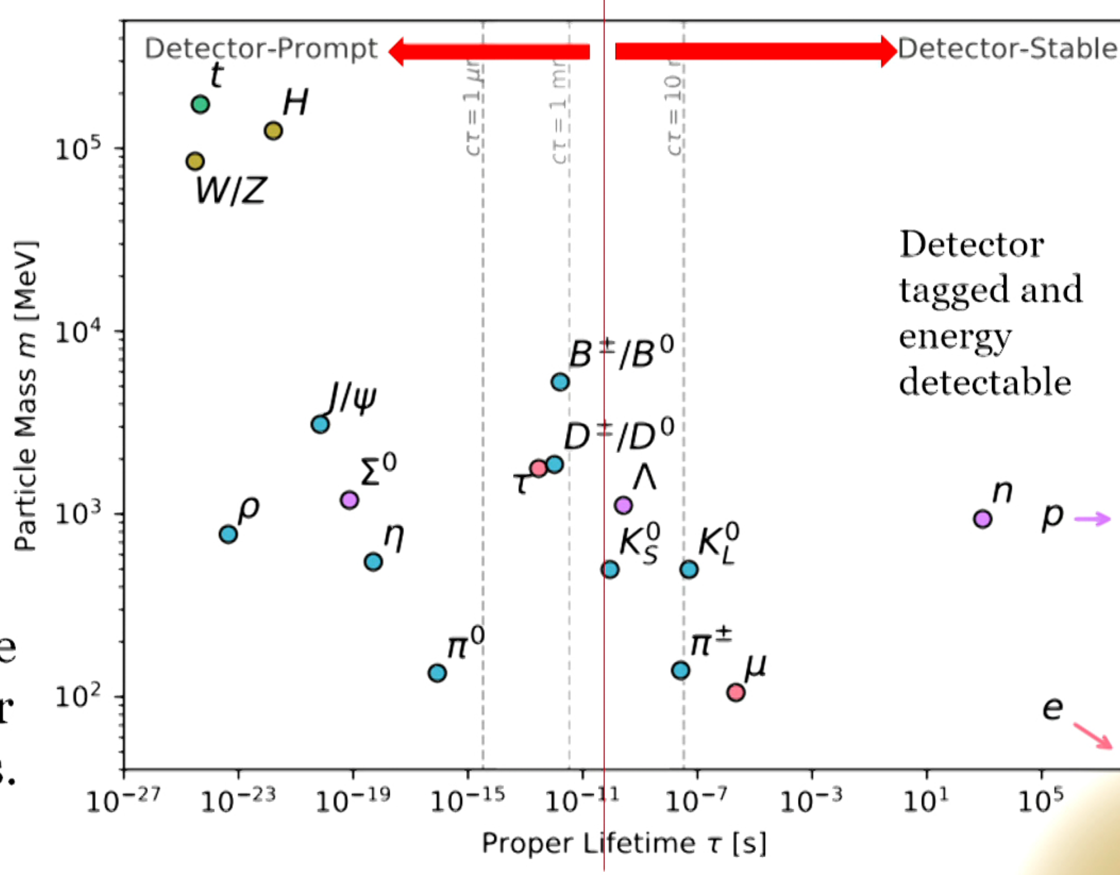
Long-lived particles in the standard model:

- approximate symmetries;
- kinematic suppressions;

For BSM particles:

- Prompt particles being actively probed;
- Detector Stable particles are probed as missing energy or EM charged stable particles.

First pixel layer (first layer of detector)



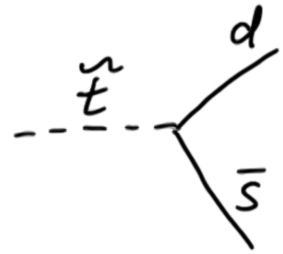
Detector tagged and energy detectable

Fig. credit: L. Lee @ ATLAS

Why Long-Lived BSM Particles? Supersymmetry

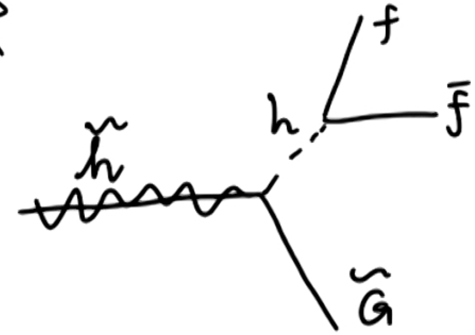
- R-Parity-Violating, small B/L-violating couplings

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



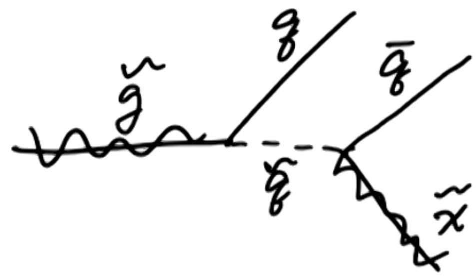
- Gauge mediation—suppressed couplings via SUSY breaking scale

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



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

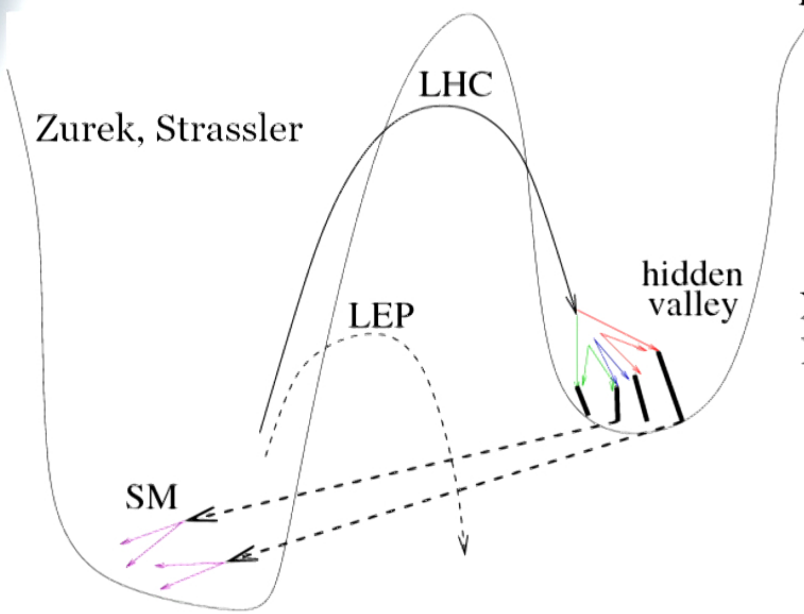
$$c\tau_{\text{milli-split}} \sim 1\text{ mm}\left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5\left(\frac{m_{\tilde{q}}}{\text{PeV}}\right)^4$$

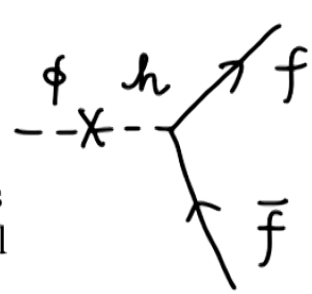


- Pure Wino/Higgsino–nearly degenerated, disappearing track

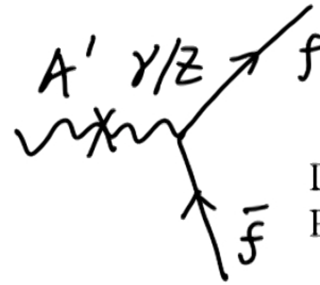
Why Long-Lived BSM Particles? Hidden Valley

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

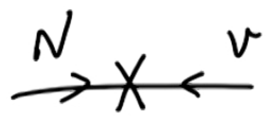




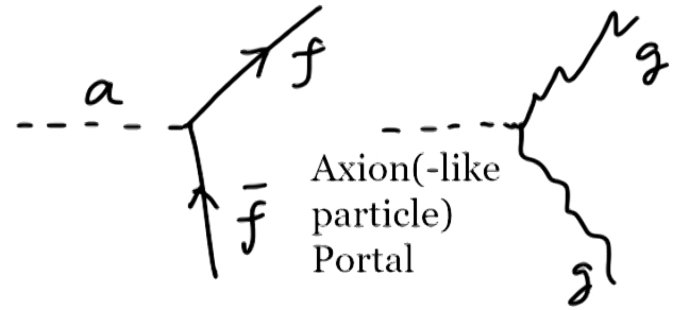
Higgs portal



Dark Photon/Z



Neutrino Portal



Axion(-like particle) Portal

LLP: A rich program

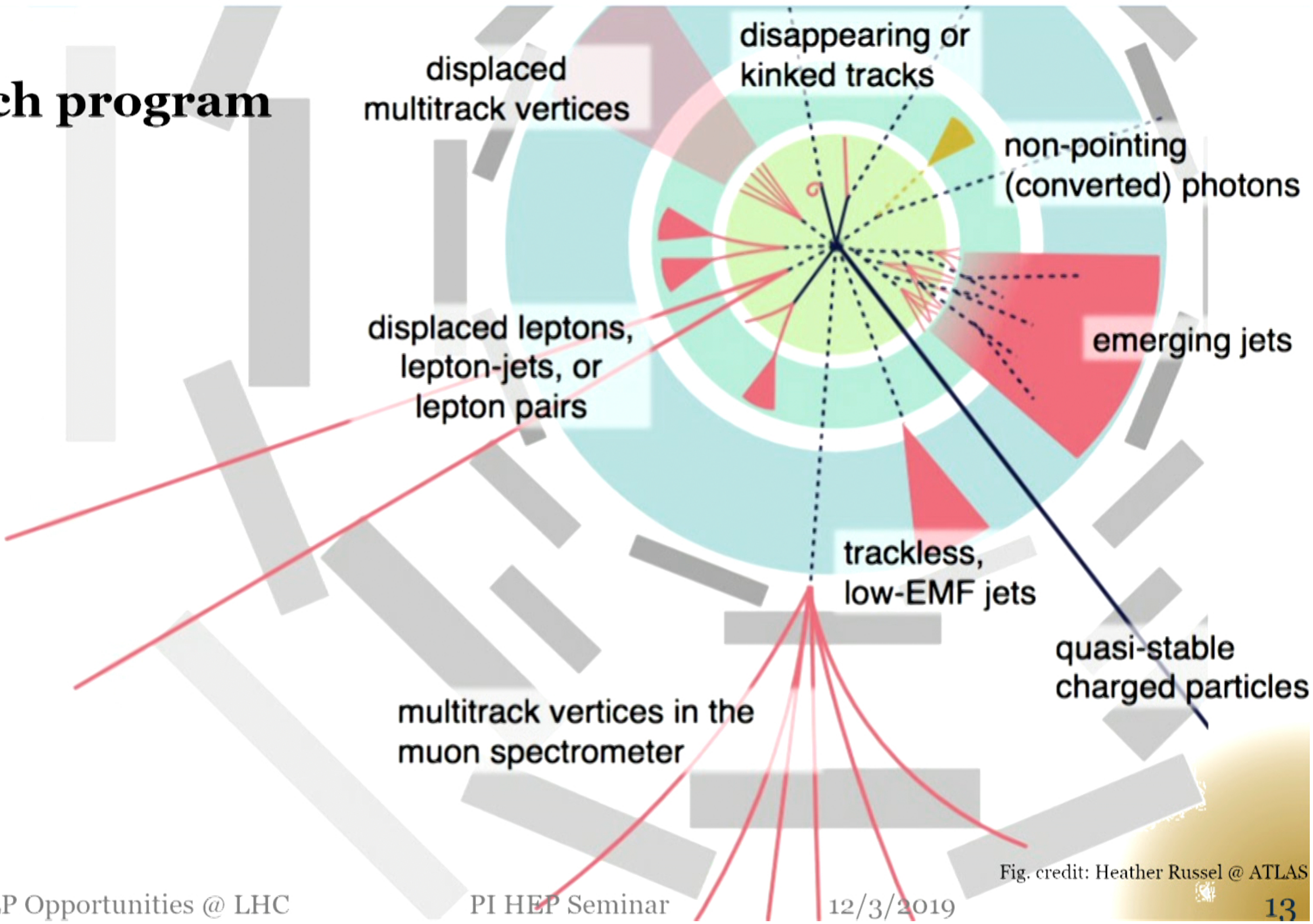


Fig. credit: Heather Russel @ ATLAS

But, a new experimental challenge.

LHC detectors designed for prompt signals. For LLPs:

☹trigger
☹reconstruction
☺standard model background
☹non-standard background

Huge uncharted well-motivated territories to explore!

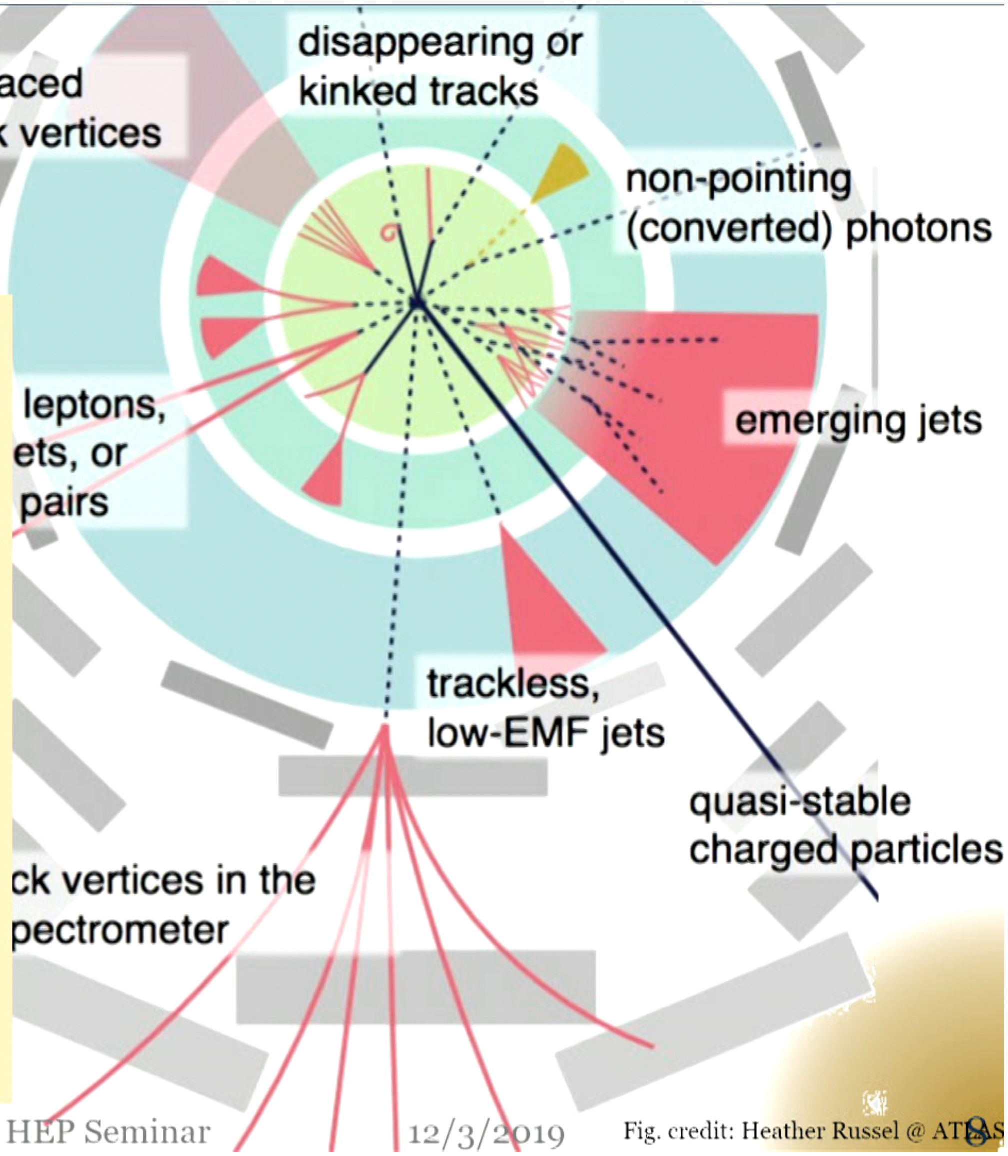


Fig. credit: Heather Russel @ ATLAS

A veritable Renaissance of Long-Lived Particles

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

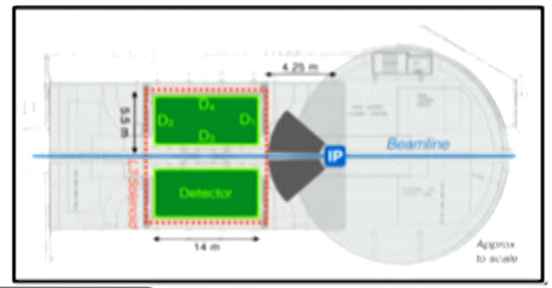
MATHUSLA
Codex-B
AL3X
} Central/Hard LLPs

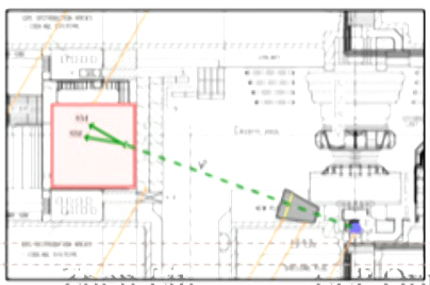
FASER
SHiP
NA62
SeaQuest
} Forward/lighter LLPs

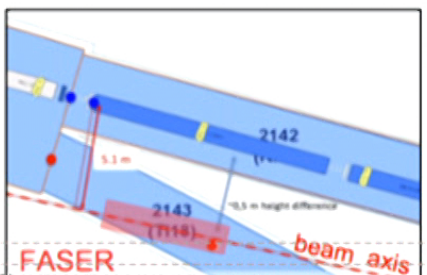
SHiP, NA62, SeaQuest } Beamdump experiments

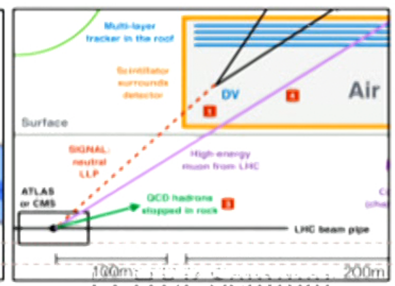
MoEDAL
MilliQan
} monopole, millicharged particles

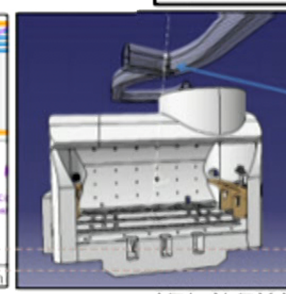
Central/Hard LLPs, Forward/lighter LLPs, Beamdump experiments, monopole, millicharged particles } Search for LLPs

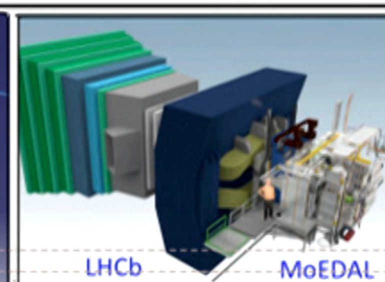












Outline

- Long-lived particles at the LHC: overview
- Opportunities:
  - High Quality Axion   Hook, Kumar, Liu, Sundrum, 1911.12364
  - Heavy Neutral Lepton
  - DM & Coannihilation
  - Opportunity in Timing and HGCal

Strong CP puzzle

$$L \supset \frac{\alpha_s}{8\pi}\theta\tilde{G}G + y_u\bar{Q}_L\tilde{H}u_R + y_d\bar{Q}_L H d_R$$

$$\bar{\theta} \equiv \theta + \mathrm{ArgDet}[Y_u Y_d] \leq 10^{-10}$$

While $\mathrm{ArgDet}[Y_u Y_d]$ anticipated around $\delta_{CKM} \sim O(1)$

Strong CP puzzle of QCD

Four simple solutions

1. ~~Universe is Left-Right symmetric~~ Weak interactions
2. ~~Universe is Time reversal invariant~~ Kaon oscillations
3. ~~Massless up quark~~ Lattice
4. Axions

Peccei, Quinn, 77'

Strong CP puzzle

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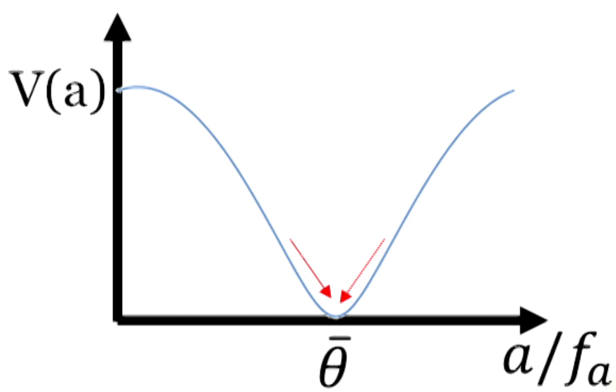
Strong CP puzzle of QCD

Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

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



Peccei, Quinn, 77'

The Quality Problem

The axion fakes a dynamical angle.
How good of an imposter is it?

Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

$$V \approx -(100\,\mathrm{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right) + \Lambda^4_{\mathrm{contamination}} \cos\left(\theta' - \frac{a}{f_a}\right)$$

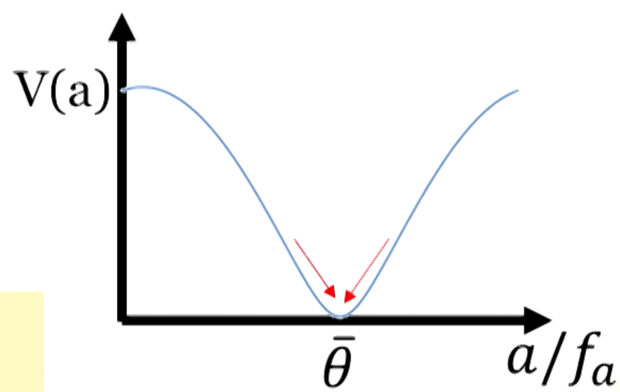
$$\frac{\alpha_s}{8\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G$$

$$\Lambda_{\mathrm{contamination}} < 0.1\,\mathrm{MeV}$$

There are also many other scales :
GUT, Inflation, Gravity, Dark matter

$$V = \frac{\Phi^{14}}{M_{pl}^{10}} \qquad \Phi \equiv e^{i\frac{a}{f_a}}$$

Leading order gravity suppressed operators must be suppressed by 10 powers of the Planck scale!



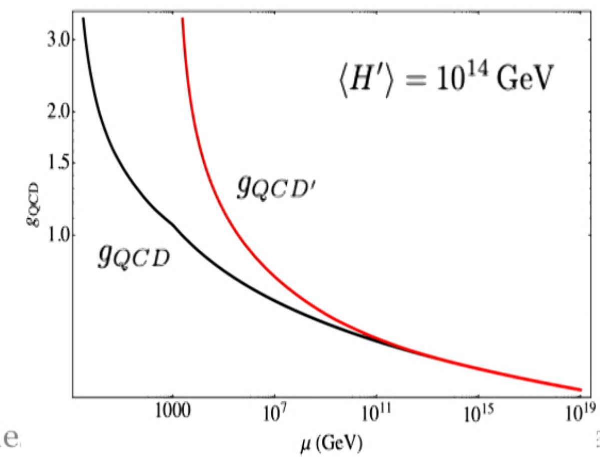
The Quality Problem and reinforced Axion potential

Mirror QCD + Weak with Z2 symmetry,
one axion couples to both and solve both
strong CP puzzles dynamically.

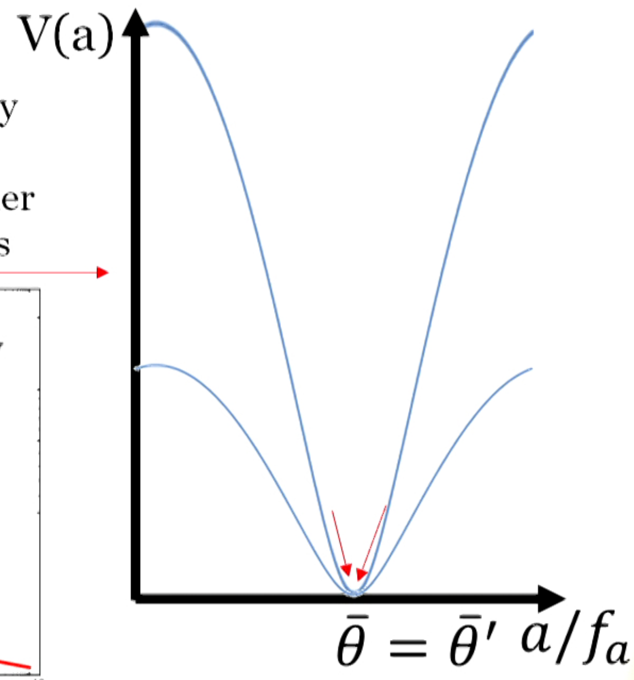
$$m_a \simeq \frac{\Lambda_{\rm QCD}^2}{f_a}$$

Instead, through soft Z2 breaking by giving Mirror Higgs large VEV
➔massive fermions decouples earlier
➔mirror QCD run fast and confines

$$m_a \simeq \frac{\sqrt{\Lambda_{\rm QCD}^4 + \Lambda_{\rm QCD'}^4}}{f_a}$$



Reinforced Axion Potential



The Quality Problem and reinforced Axion potential

Makes the Quality problem better

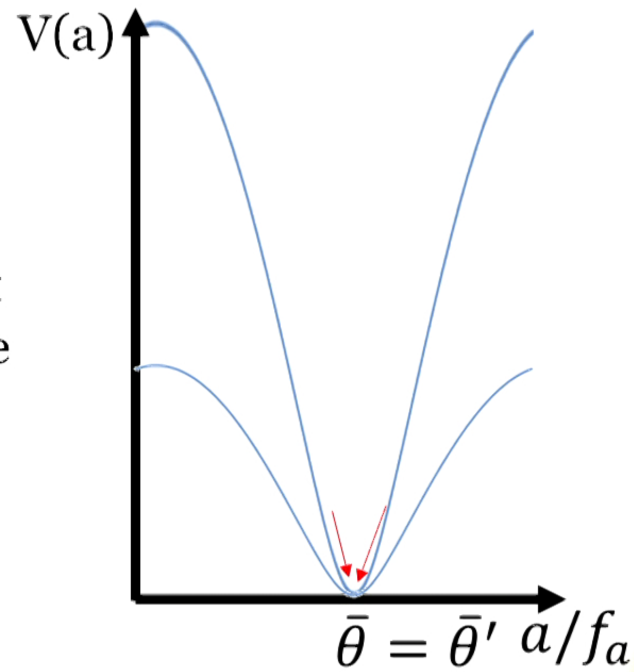
$$V \approx -(100\,\mathrm{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right) - (10^8\,\mathrm{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right)$$

$$+\Lambda^4_{\mathrm{contamination}} \cos\left(\theta' - \frac{a}{f_a}\right)$$

$$\Lambda_{\mathrm{contamination}} < 10^5\,\mathrm{MeV}$$

If the Higgs mass were the only thing different between the two copies, the neutron angles are still the same!
Flavor structure of the SM ensures that any change occurs at 7-loops and beyond
Not true for a generic theory!

Reinforced Axion Potential



The Quality Problem and reinforced Axion potential

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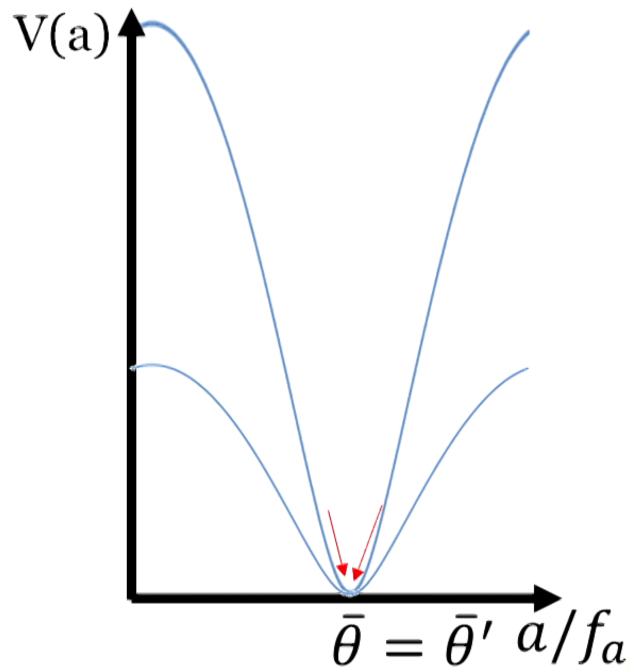
Reinforced Axion Potential



But generates a new quality problem:

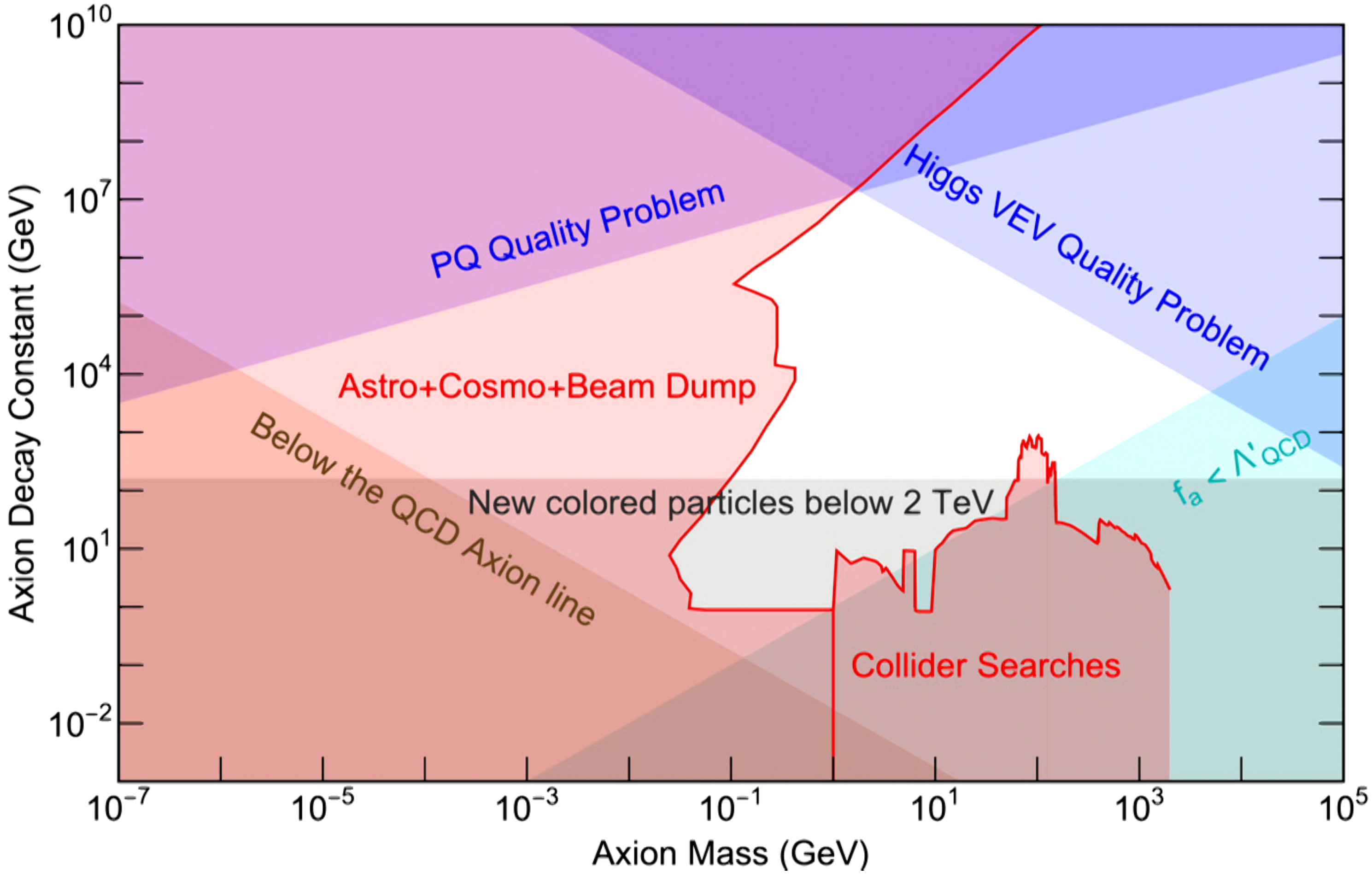
$$\frac{g^2}{32\pi^2}\left(\frac{HH^\dagger}{M_{pl}^2} G\tilde G + \frac{H'H'^\dagger}{M_{pl}^2} G'\tilde G'\right)$$

$$H' \lesssim 10^{14}\,\mathrm{GeV}$$

16

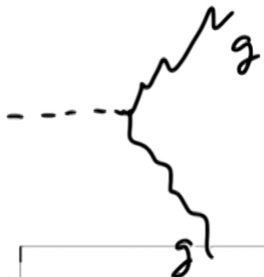
$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Preferred parameter space

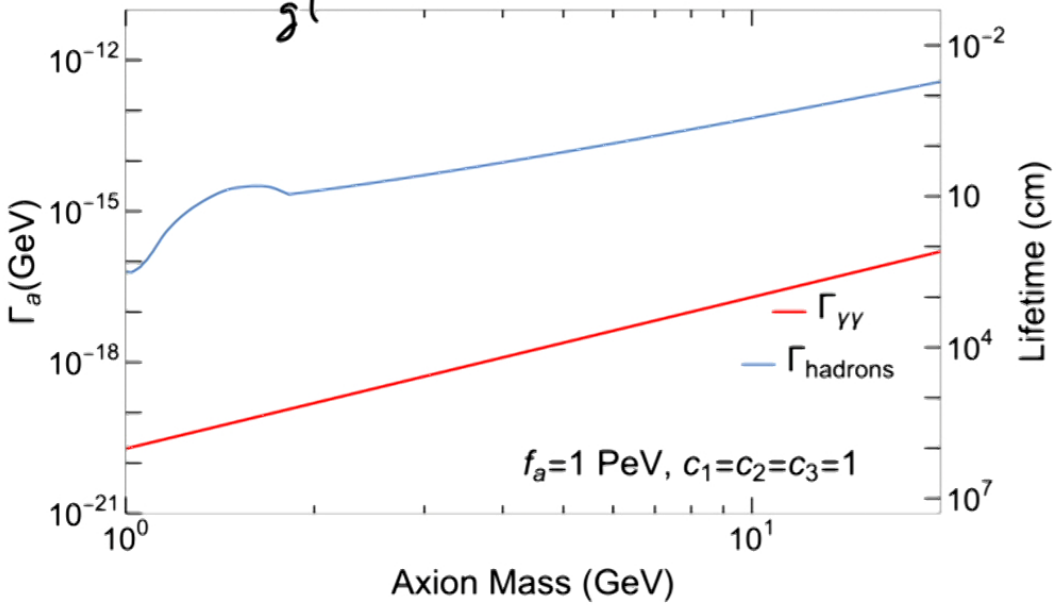


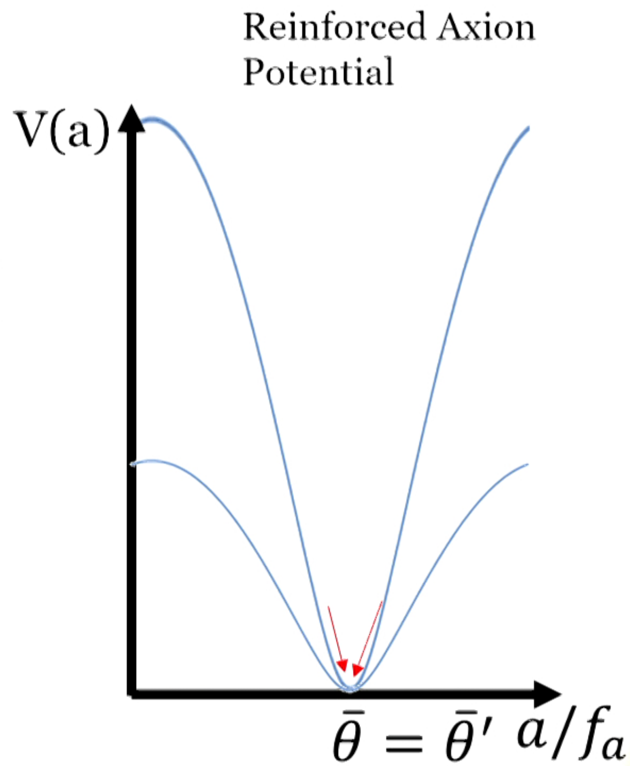
Zhen Liu

Long-lived Axions



$$\frac{\alpha_s}{4\pi}\left(\theta+\frac{a}{f_a}\right)\tilde{G}G+\frac{\alpha}{4\pi}\frac{\boldsymbol{a}}{f_a^{\gamma\gamma}}\widetilde{\boldsymbol{F}}\boldsymbol{F}$$





$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Preferred parameter space

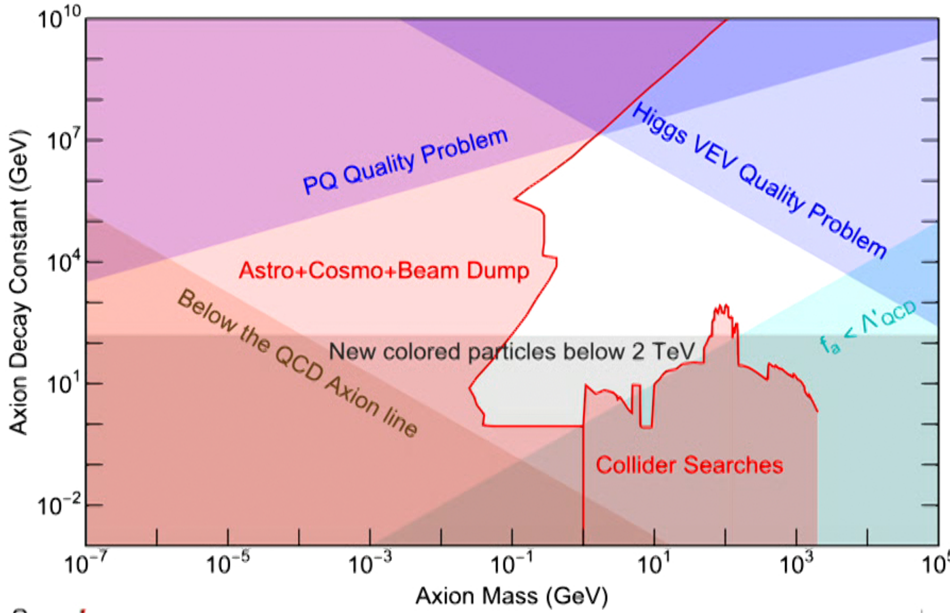
$\tilde{G}G$ the defining coupling for strong CP

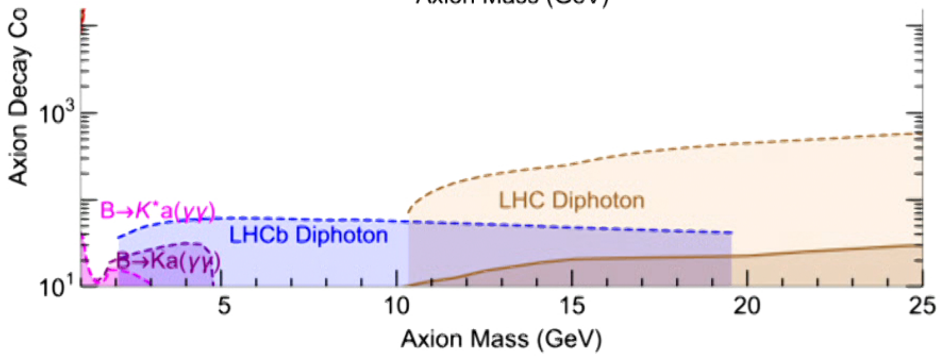
Constraints and studies in the GeV scale realm very minimal.

The existing studies focus on photonic, Higgs decays and leptonic couplings.

Hadronic mode buried under QCD background

$$\frac{\alpha_s}{4\pi}\left(\theta + \frac{a}{f_a}\right)\tilde{G}G + \frac{\alpha}{4\pi}\frac{\boldsymbol{a}}{f_a^{\gamma\gamma}}\tilde{\boldsymbol{F}}\boldsymbol{F}$$

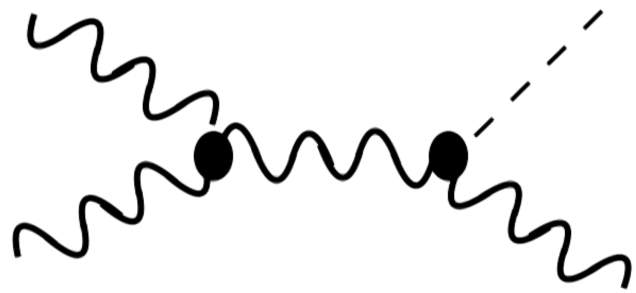




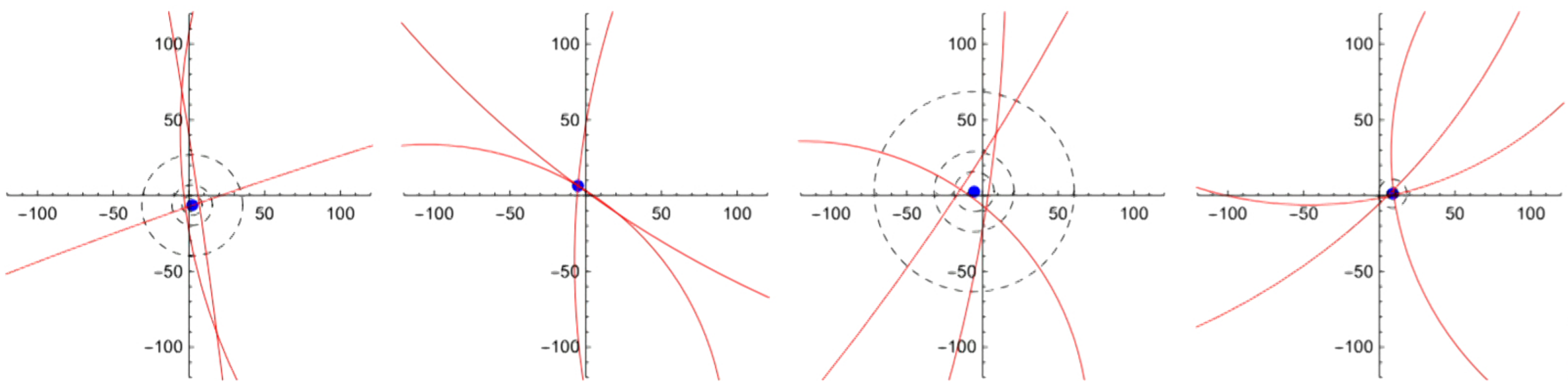
Y. Gershtein, 1705.04321, CMS-PAS-FTR-18-018

Displaced track trigger: crucial ingredient

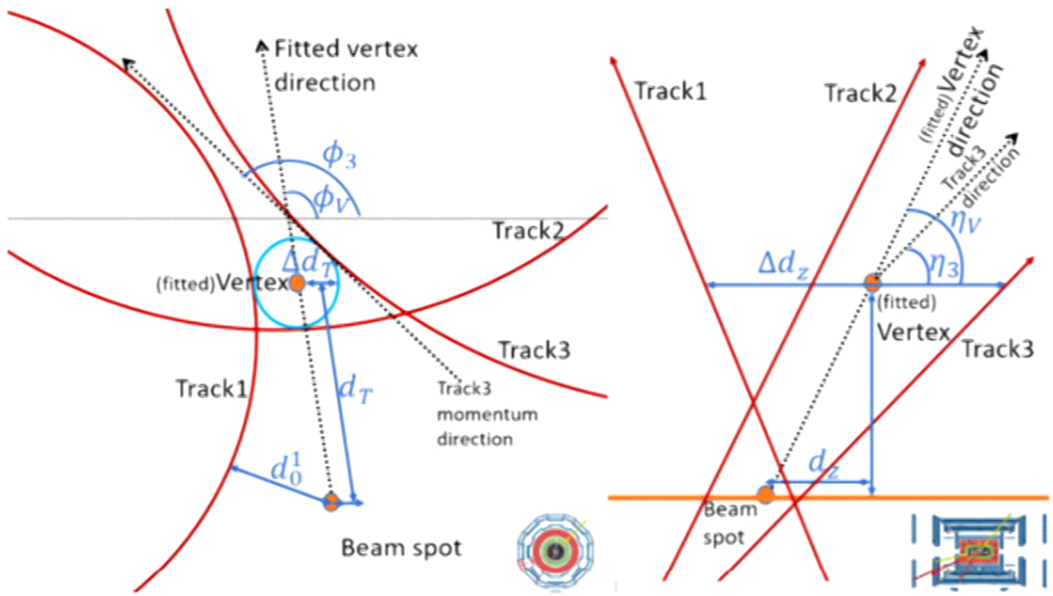
- At least three tracks (within an L1 jet) with $p_T > 2$ GeV;
- Amongst the above tracks, at least three of them have the transverse impact parameter $d_0 > 1$ mm;
- The pseudo-rapidity of the tracks to be $|\eta| < 2.4$;
- The signal decay location in the transverse plane, $d_T < 35$ cm to have enough hits in the tracker outer layers;
- The H_T of the event to be greater than 100 GeV.[2]



Long-lived signals are produced and decayed through a same vertex



Analysis: 2D-4D vertexing selection



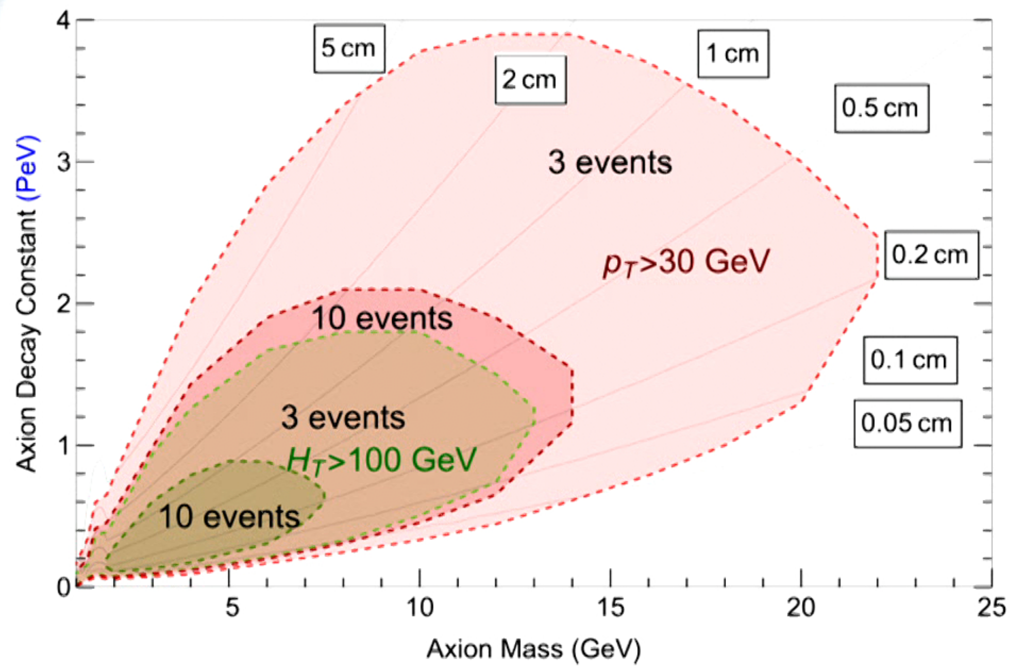
Background: 10^12 to begin with (post triggering);
2D-4D vertexing reduces it to 10^3
Track/jet information matching between different subdetectors can further reduce it to <1

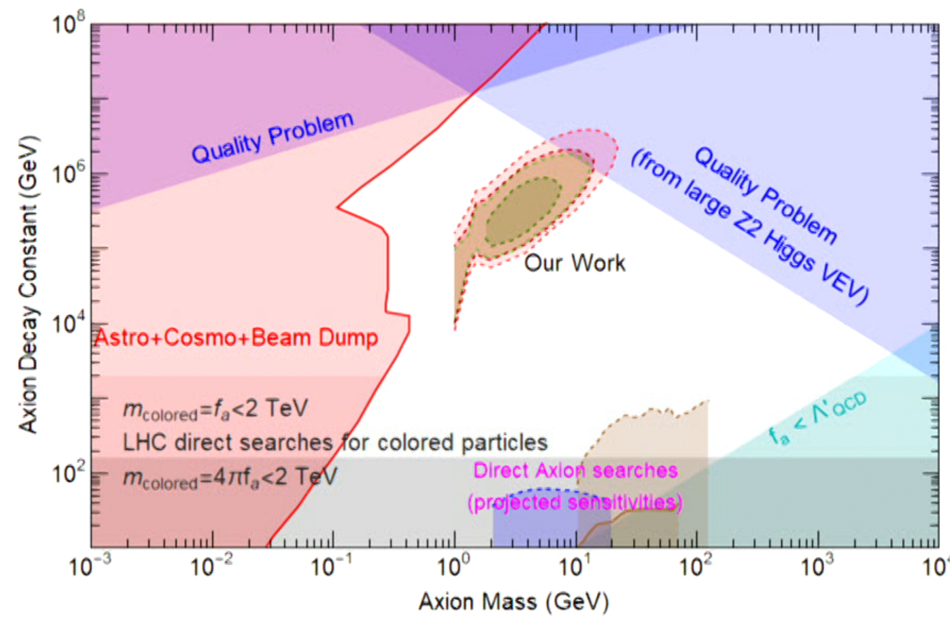
1. The 2D common vertex has a minimal distance to the interaction point of 0.5 cm and maximal distance of 35 cm, 0.5 cm $< d_T <$ 35 cm;
2. The 2D tracks fit a common vertex with standard deviation $\Delta d_T < 1$ cm;
3. The 2D common vertex is sufficiently displaced away from the interaction point, $d_T/\Delta d_T > 5$;
4. The corresponding 4D vertex has a standard deviation in z direction $\Delta d_z < 5$ cm;
5. The corresponding 4D vertex has a z-direction location $d_z < 20$ cm;
6. The corresponding 4D vertex has a standard deviation in time $\Delta d_t < 500$ ps;
7. The corresponding 4D vertex has a time $d_t <$ 1000 ps;
8. The tracks are within 0.4 in pseudorapidity of the reconstructed displaced jet direction $|\eta_i - \eta_V| < 0.4$ for all the three tracks;
9. The tracks are within 0.4 in azimuthal angle of the reconstructed displaced jet direction $|\phi_i - \phi_V| < 0.4$ for all the three tracks;

A displaced track trigger enables searches for axions

Unique singly produced LLPs making the LHC main detectors the major place to look for them:

Long lifetime = low production rate





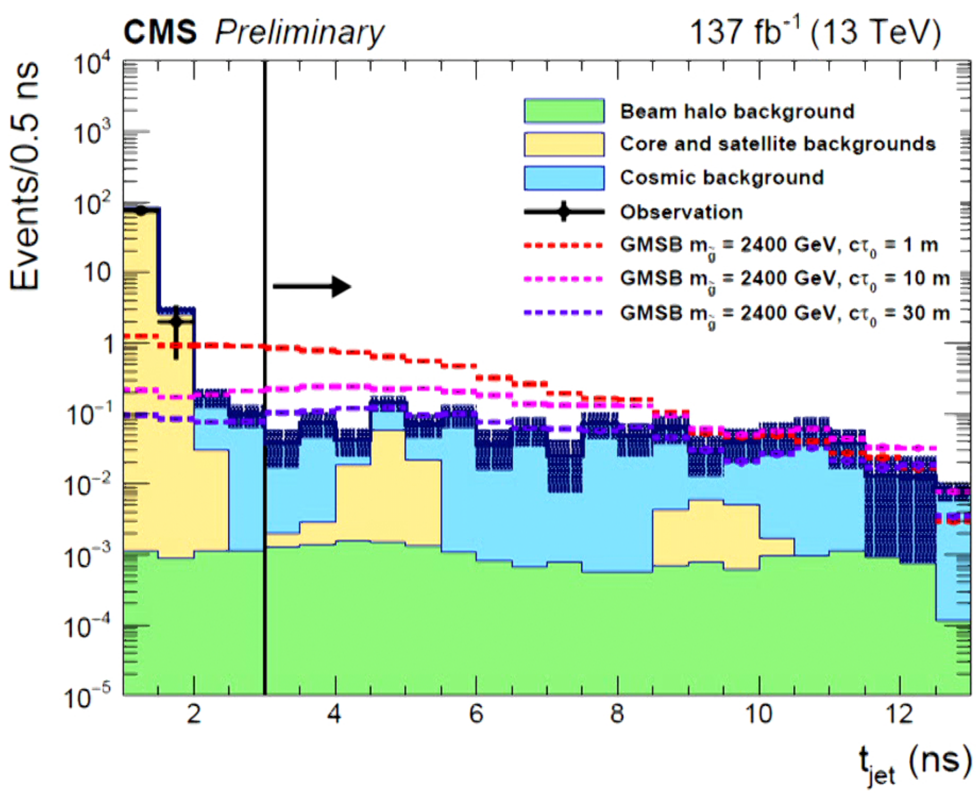
We employ a 2D-4D vertexing selection for displaced jet to veto the fake track background, demonstrating the plausibility of this search.

Outline

- Theory Overview & Community Efforts
- Theory Opportunities:
  - High quality QCD Axion
  - Heavy Neutral Lepton
  - DM & Coannihilation
  - Opportunity in Timing and HGCal

J. Liu, ZL, LT Wang, 1805.05957
J. Liu, ZL, LT Wang, XP Wang, in progress

New searches and new insights!



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

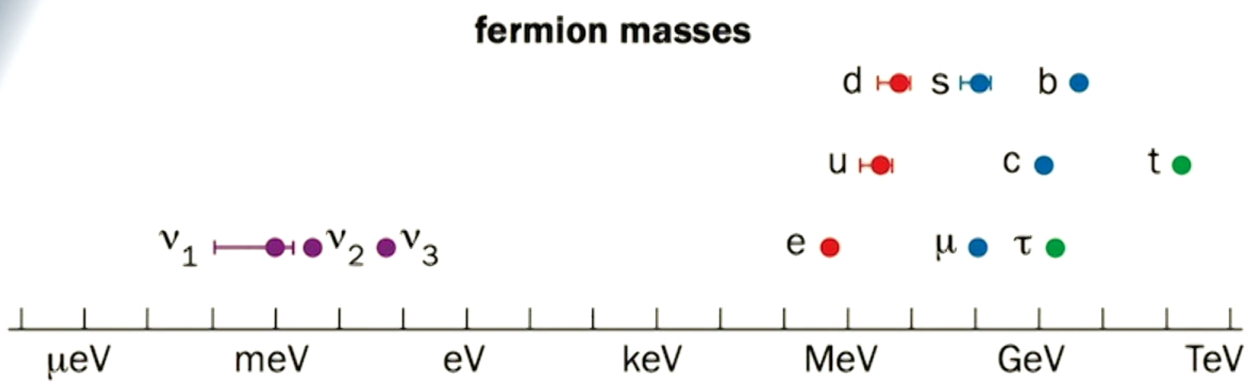
Beam halo small
Core and satellite bunches small but one shall try to improve by precision timing
Cosmics small (for this analysis, no need to do cosmic veto yet but there are many ways) and scale with time but not luminosity

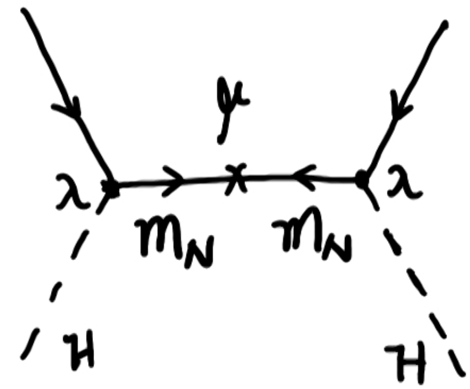
Lot of theory & experimental activities:

- 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
- …

Inverse Seesaw , Mohapatra, Valle, 86'

Neutrino Mass Puzzle also leads to LLPs





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

$$M = \begin{pmatrix} 0 & \lambda v_{EW} & 0 \\ \lambda v_{EW} & 0 & m_N \\ 0 & m_N & \mu \end{pmatrix}$$

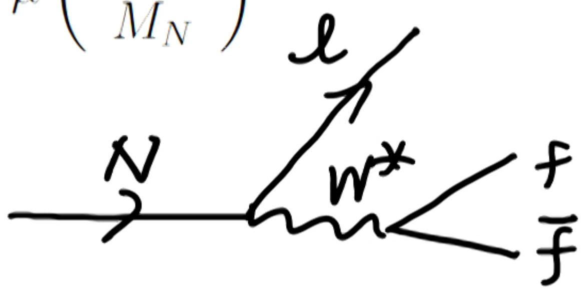
In the $\mu \to 0$ limit, one Dirac Neutrino and one massless Wyle Fermion

➔ $\mu \neq 0$, lightest eigenstate

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

Neutrino Mass Puzzle also leads to LLPs

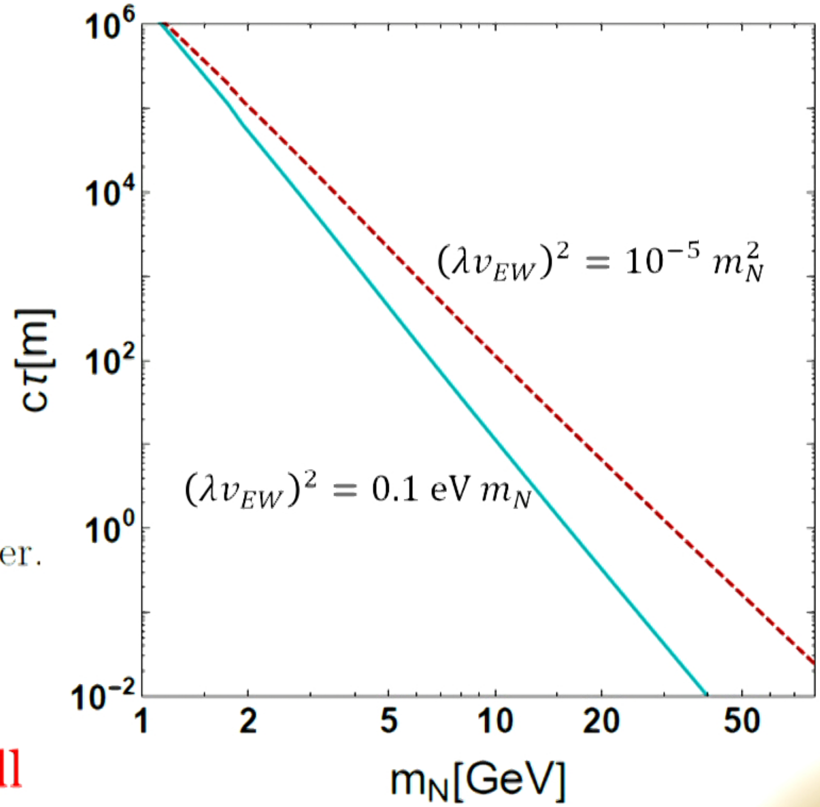
$$m_\nu \approx \mu \left(\frac{\lambda v_{\rm EW}}{M_N}\right)^2$$



Right-handed neutrino N is long-lived:

$$c\tau \simeq 7\times 10^3 \times \left(\frac{\rm GeV}{m_N}\right)^5 \left(\frac{0.01{\rm eV}}{m_\nu}\right)\left(\frac{\mu}{\rm MeV}\right) \text{ meter.}$$

But where do these small parameters come from?



… and it's well-motivated.

Toy example:

$$L_{UV} \supset L_{QCD'} + \frac{LHu'd'd'}{M^3} + \frac{(u_c'd_c'd_c')^2}{M^5}$$

$(u'd'd')$ confines to Neutron$'$= N

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

$$m_N \sim \Lambda_{\mathrm{QCD'}}$$

$$\lambda \sim \left(\frac{\Lambda_{\mathrm{QCD'}}}{M}\right)^3$$

$$\mu \sim \Lambda_{\mathrm{QCD'}} \left(\frac{\Lambda_{\mathrm{QCD'}}}{M}\right)^5$$

Chacko, Fox, Liu, Harnik, in progress

Summary

- Theory & Experimental landscape
- Large class of motivated models for LLPs, mainly classified into SUSY and Hidden Valleys
- Opportunities/Challenges
  - LHC main detectors have great potential for LLPs
  - High Quality Axion (low mass hadronic LLP)
  - Heavy Neutral Lepton (low mass semi-leptonic LLP)
  - DM & Coannihilation (soft visible energy LLP)
  - Timing and HGCal (new dimensions of information greatly boost LLP program)

Thank you!