# New Physics Opportunities @ HL-LHC and Beyond

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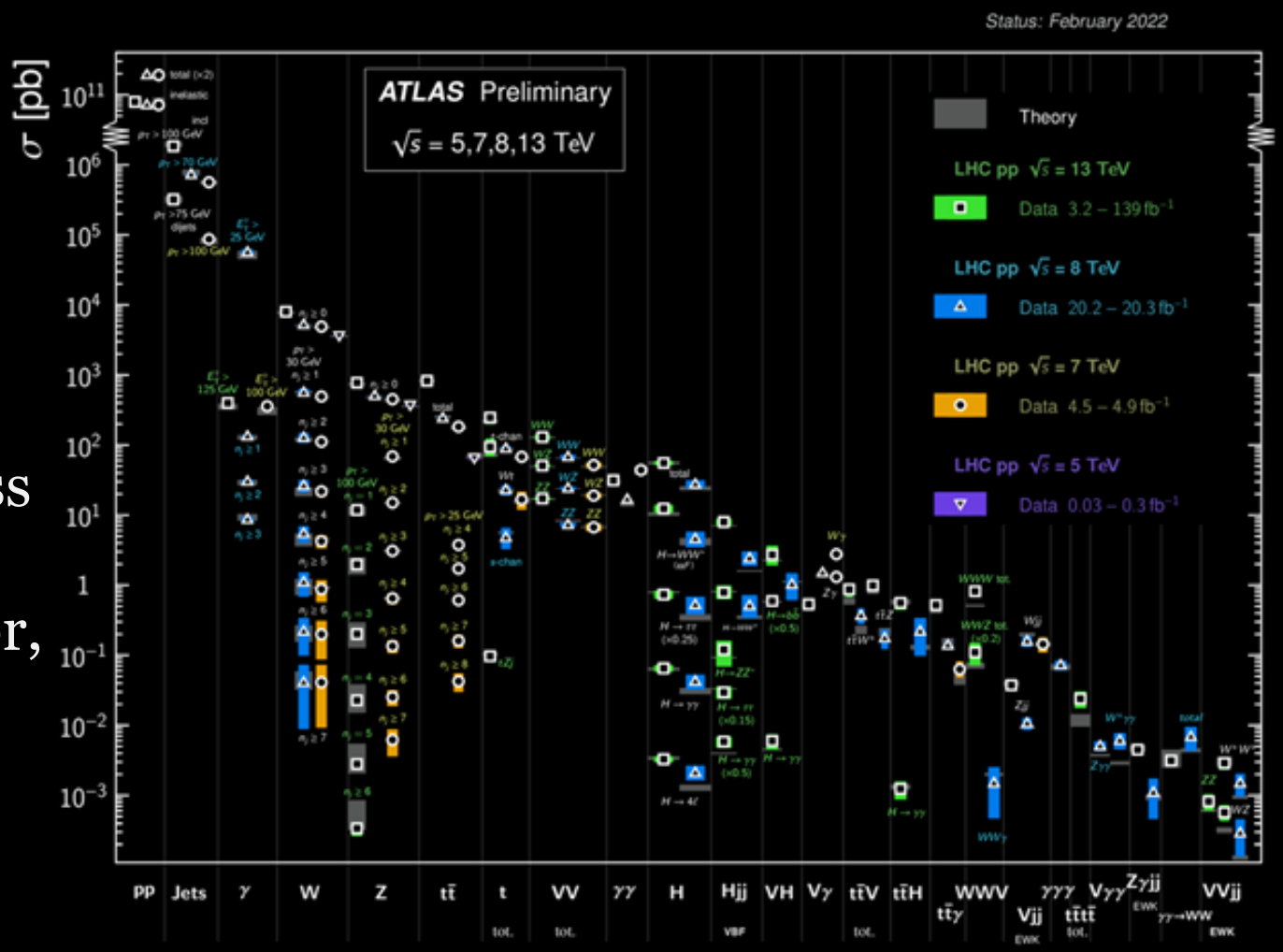
# New Adventures

LHC's successes

- Higgs Discovery
- Precision measurements
- Direct searches on
  - Simplified models
  - SUSY
  - Extra Dim/Compositeness
  - …

+new upgrades in Energy, Detector, Trigger, Analysis methods



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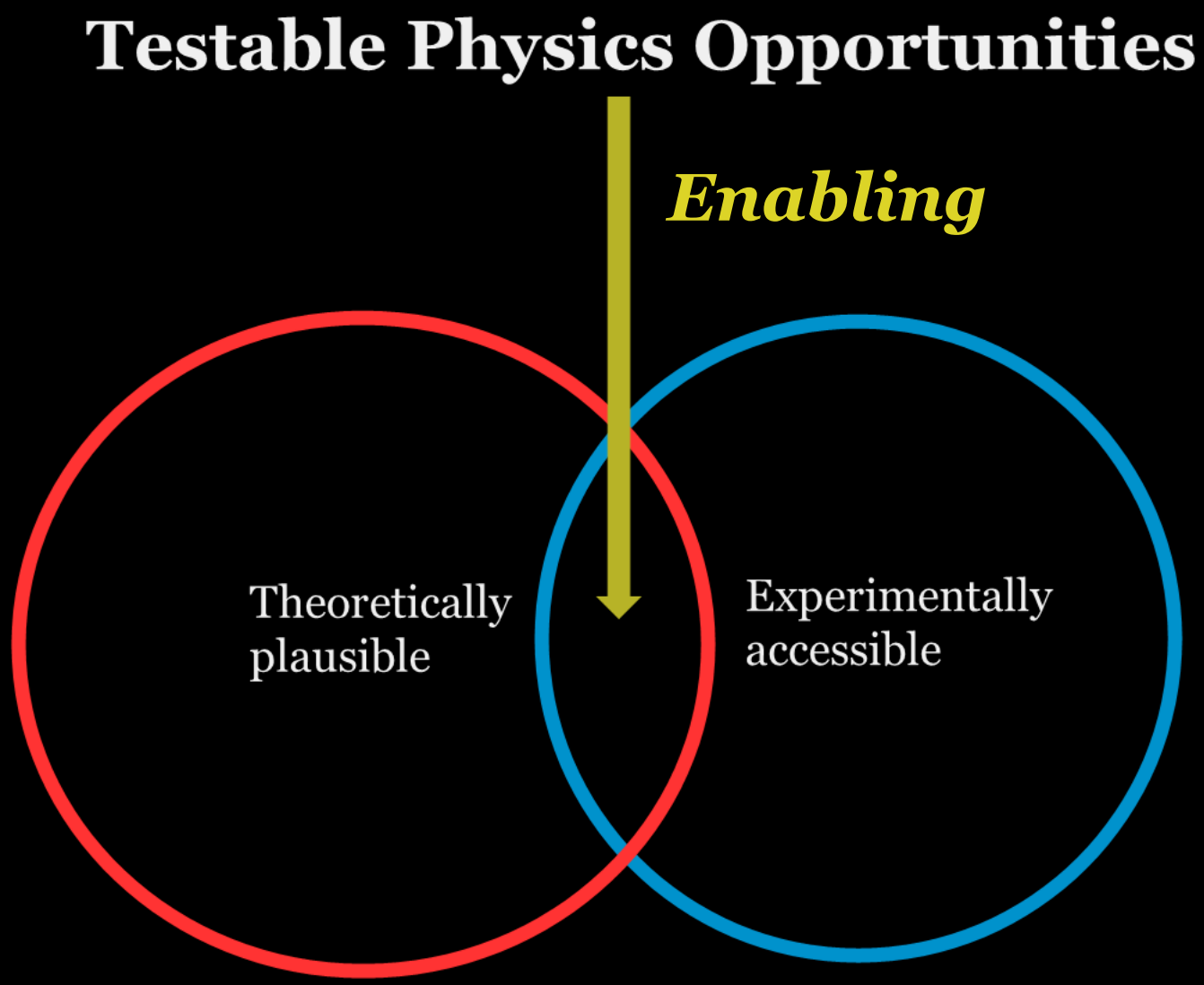
Drove a paradigm shift

- (we become) humble (about how and where new physics would show up)
- more adventurous

# Adventure into the Unknown

We are working hard to achieve breakthroughs in the understanding of Nature; from:

- Theory
- Experimental Evidence




From the Theory side, the amplitude program, Ads/CFT, generalized symmetries, dynamical origin of hierarchy problems, etc., provides new angles and hopefully lead to new insights.

# Characters of our new adventure

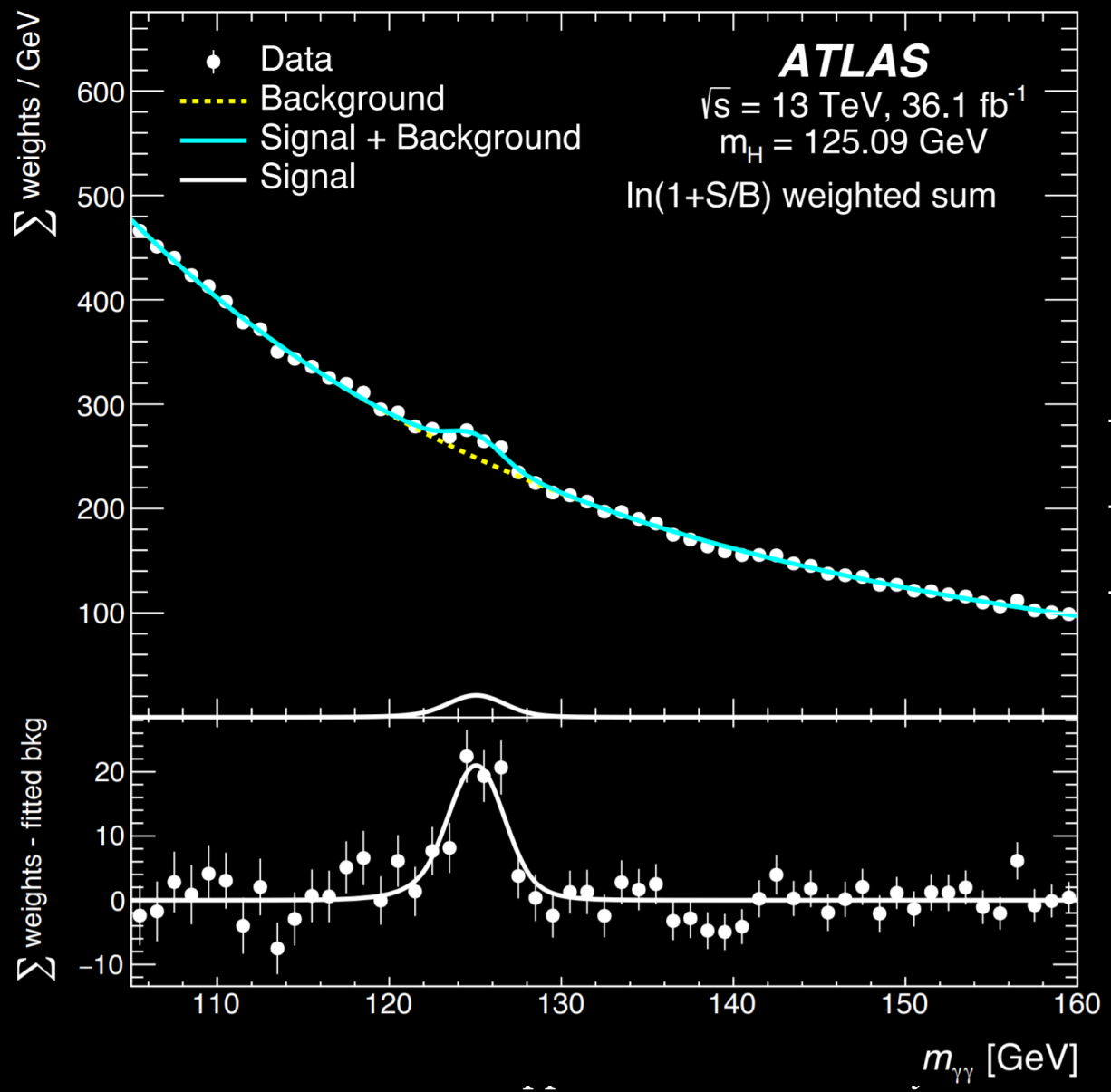
- Deep
- Broad
- Open

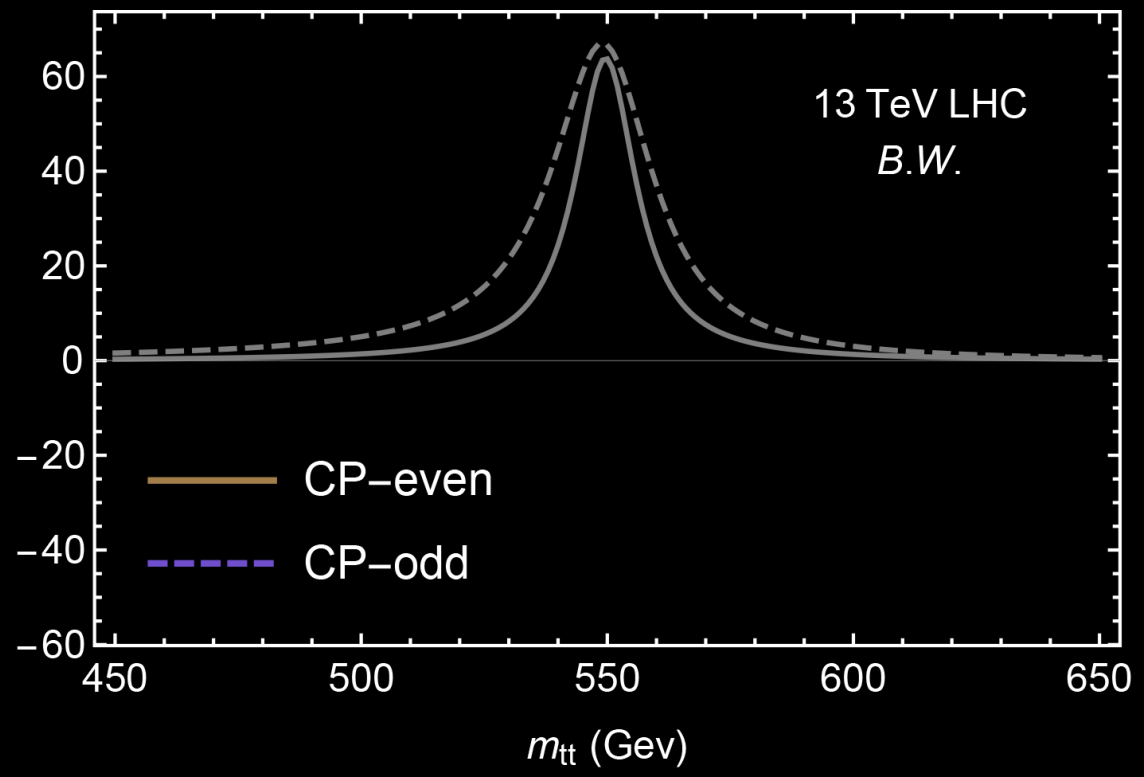
The opportunity space is huge. Here I will highlight a few examples.

## Characters of the adventure

- Deep
  - Beyond the classical level
  - +beyond
- Broad
  - Long-Lived Particles
  - +beyond
- Open
  - Open to non-traditional targets

# Beyond classical (recent $\phi \to t\bar{t}$ search)



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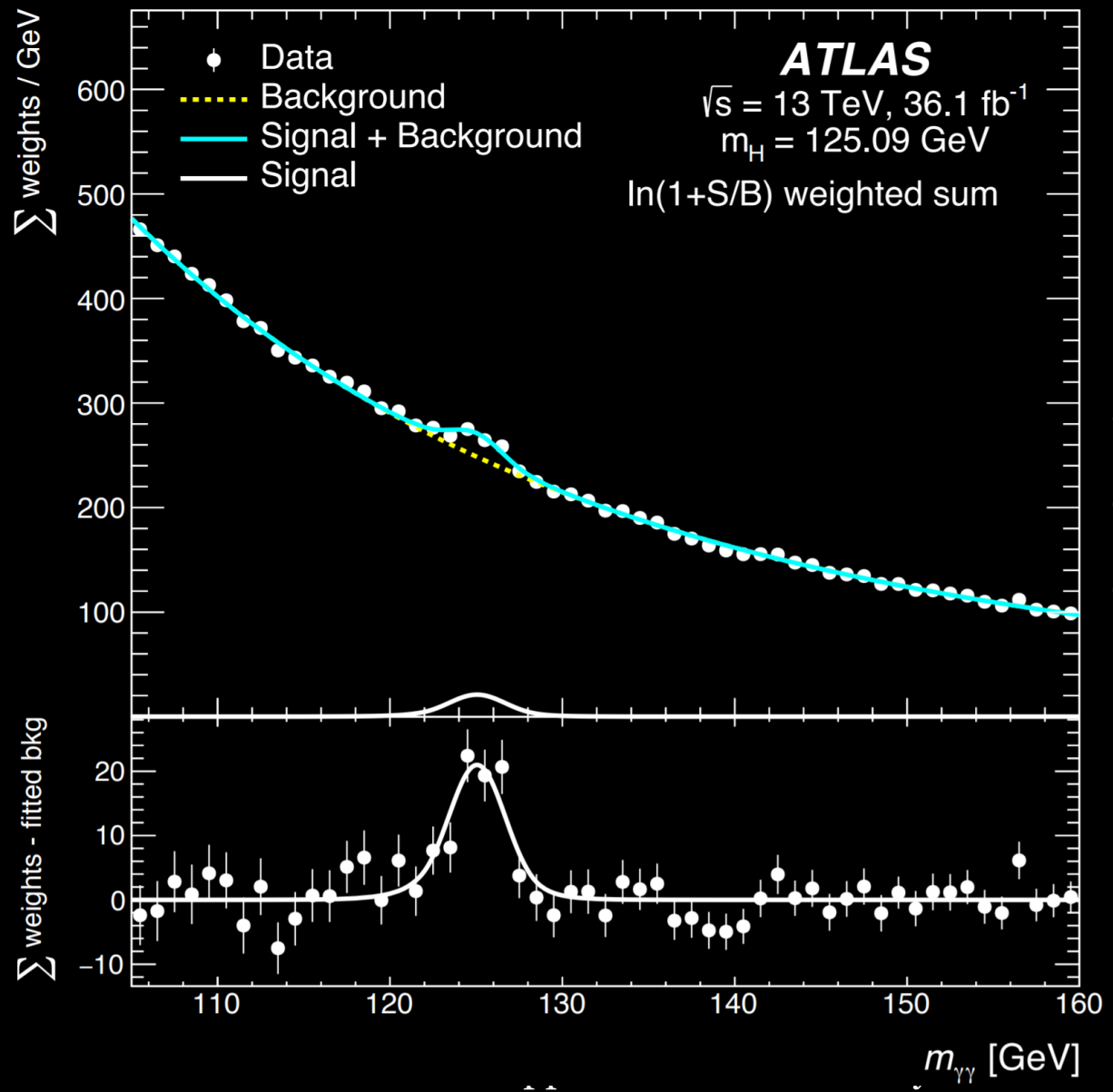


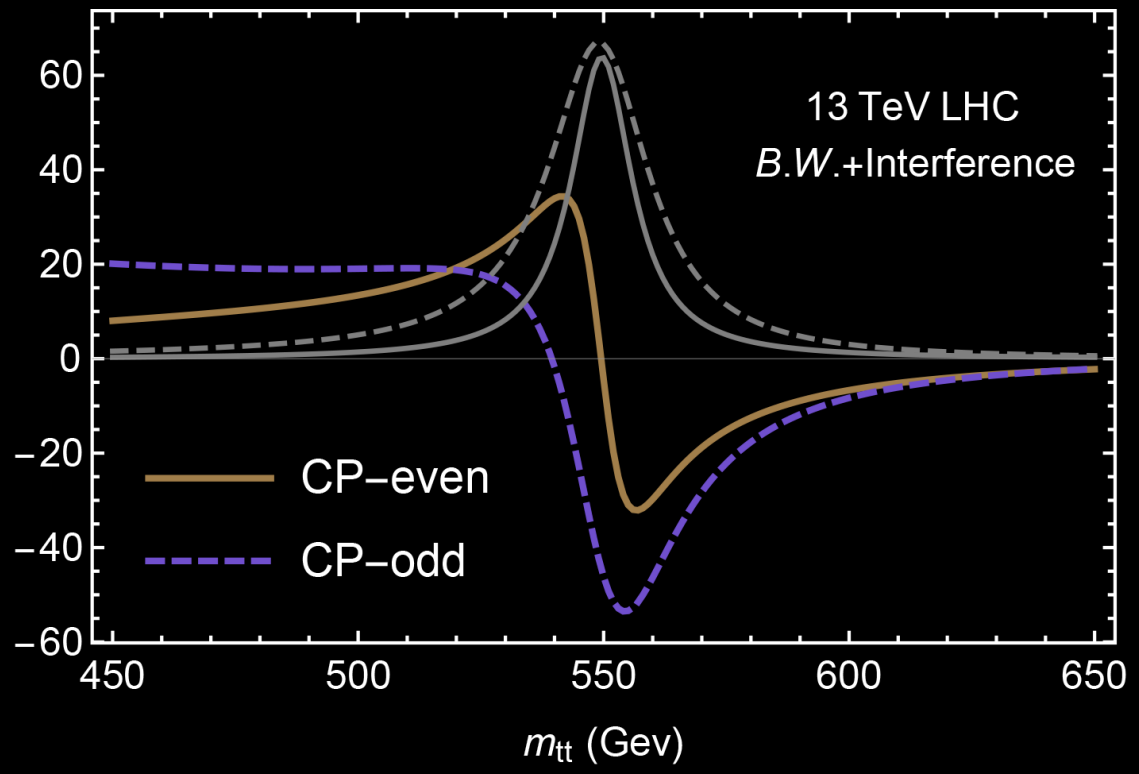

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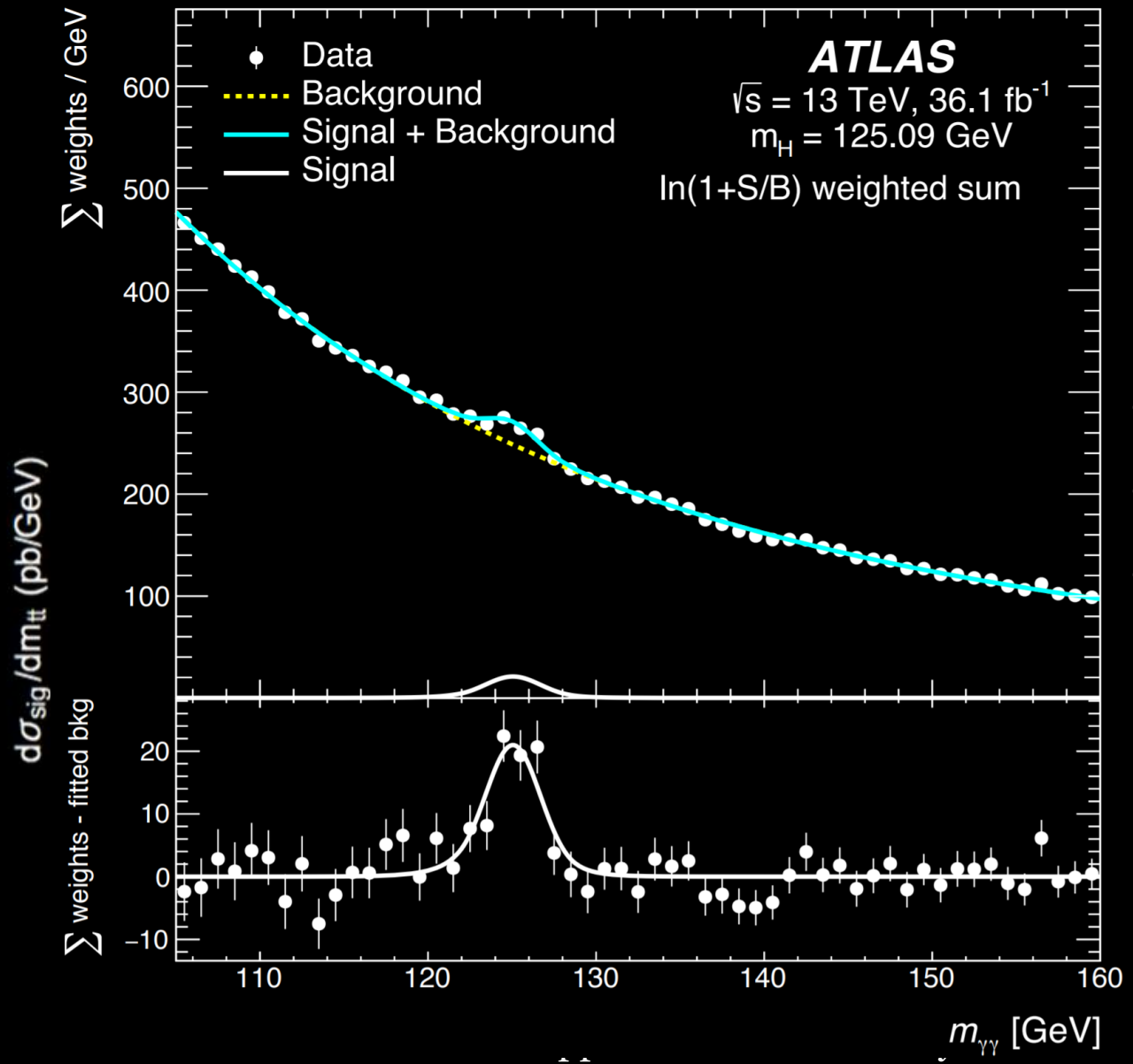
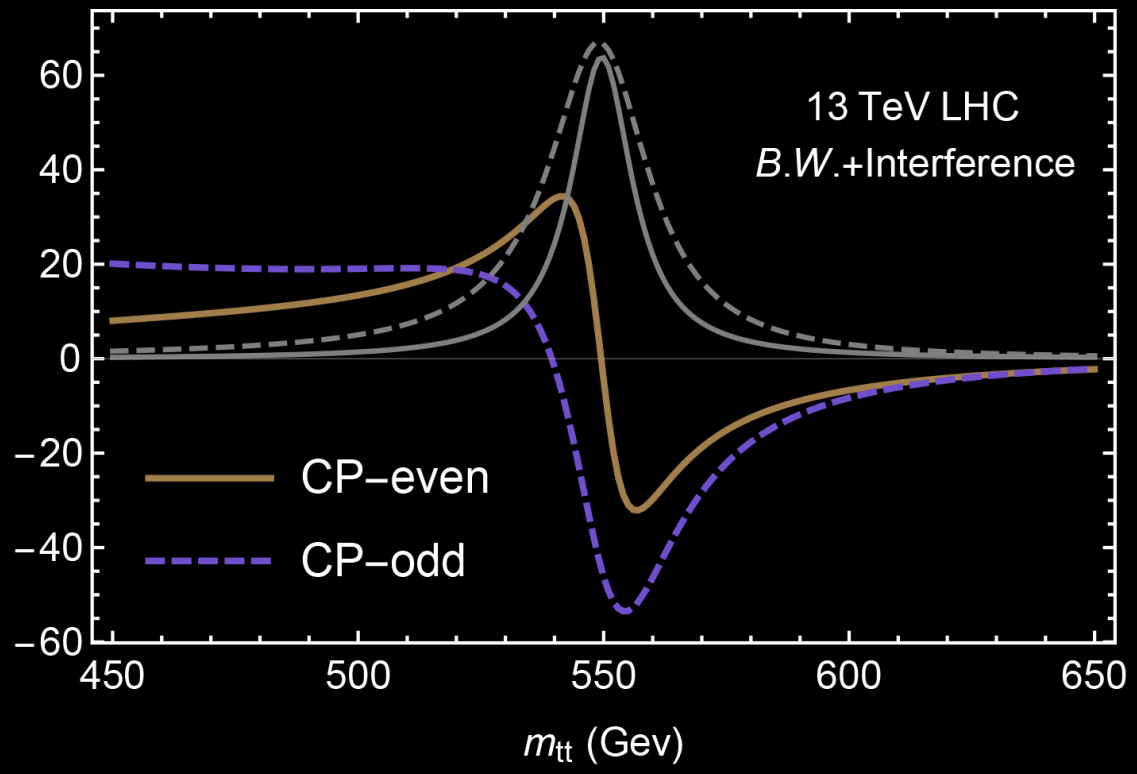
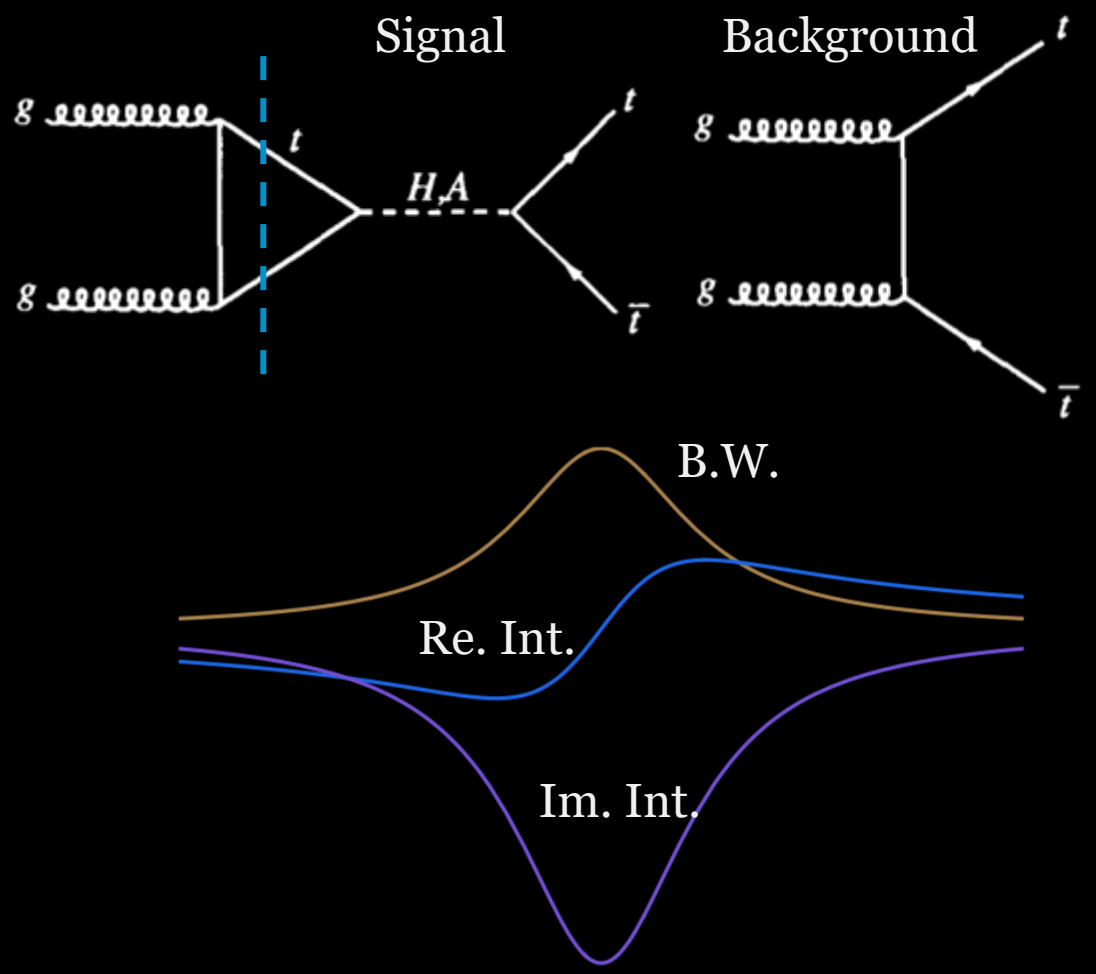
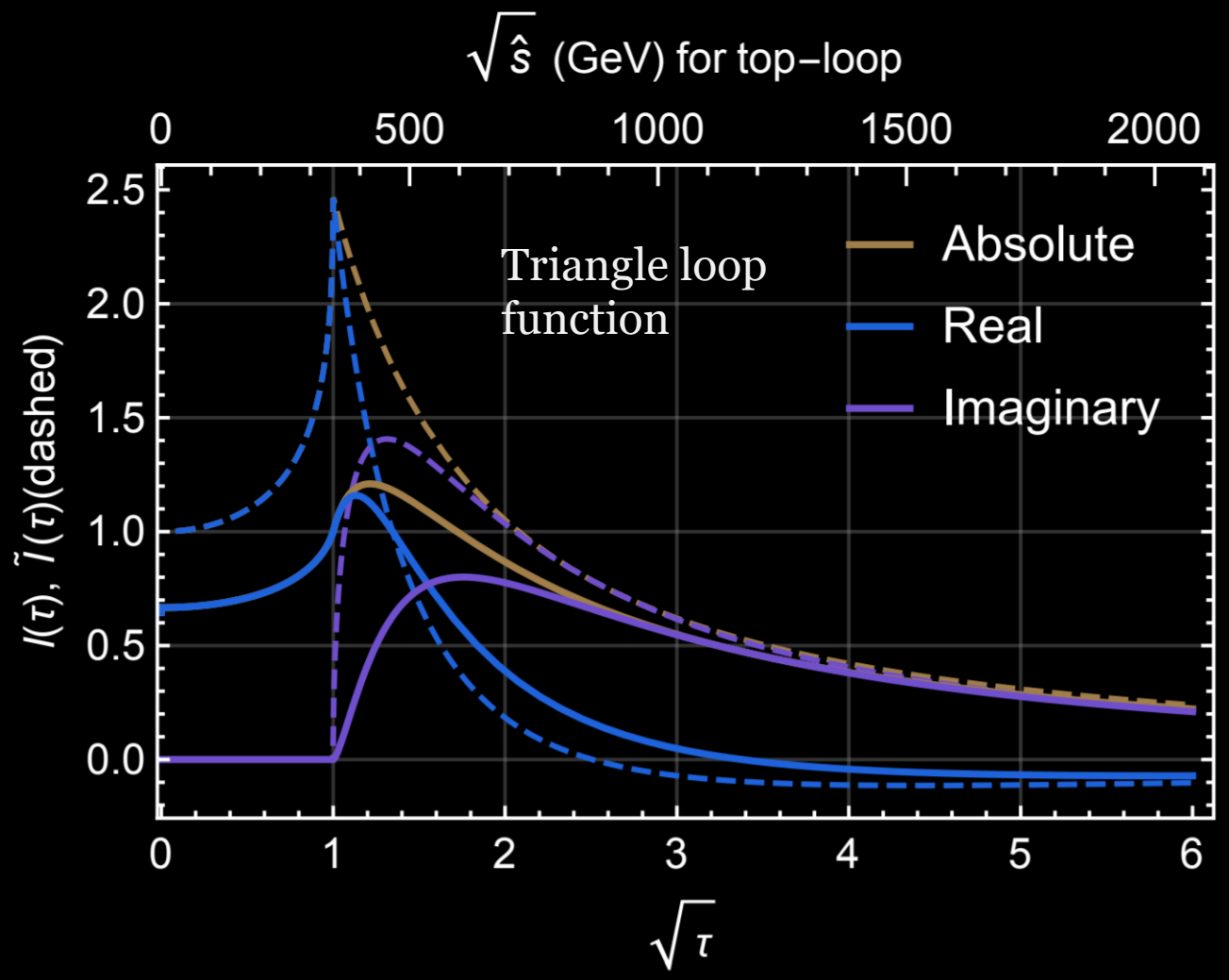



D. Dicus, A. Stange, S. Willenbrock, hep-ph/9404359, Focusing on ttbar @LHC, M. Carena, ZL, arXiv:1608.07282
Other channels and effects, including ttH, tH (see in N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang arXiv:1504.04630 and J. Hajer, Y.-Y. Li, T. Liu J. Shiu arXiv:1504.07617, S. Gori, I.-W. Kim, N. Shah, K. Zurek arXiv:1602.02782 , N. Craig, J. Hajer, Y. Li, T. Liu, H. Zhang, arXiv:1605.08744, B. Hespel, F. Maltoni, E. Vryonidou arXiv:1606.04149, W.S. Hou, M. Kohda, T. Modak 1710.07260, 1906.09703), H+jet, charged Higgs searches,

# Unfamiliar look of heavy Scalars



# Interferences onsite

- Not factorizable into signal and background calculation, Pole-behavior matters (not standard EFT friendly);
- Gain new information about width and strong & weak phase;
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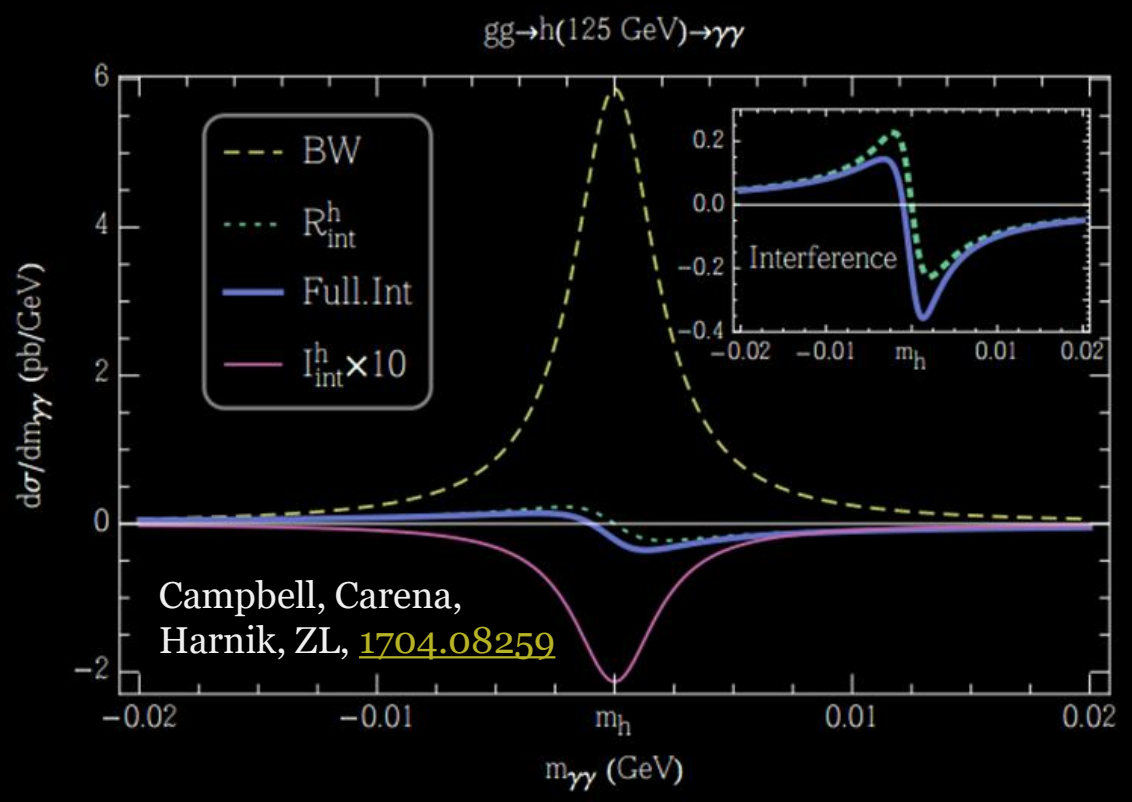


Dixon, Siu, hep-ph/0302233; Cjeri, Coradeschi, de Florian, Fidanza, 1706.07331; Maltoni, Mandal, Zhao, 1812.08703; Chen, Heinrich, Jahn, Jones, Kerner, Schlenk, Yokoya 1911.09314; Bargiela, Buccioni, Caola, Devoto, Manteuffel, Tancredi, 2212.06287; Fiore, Williams, 2306.03956; Also (real-part interference): Dixon, Li, 1305.3854…

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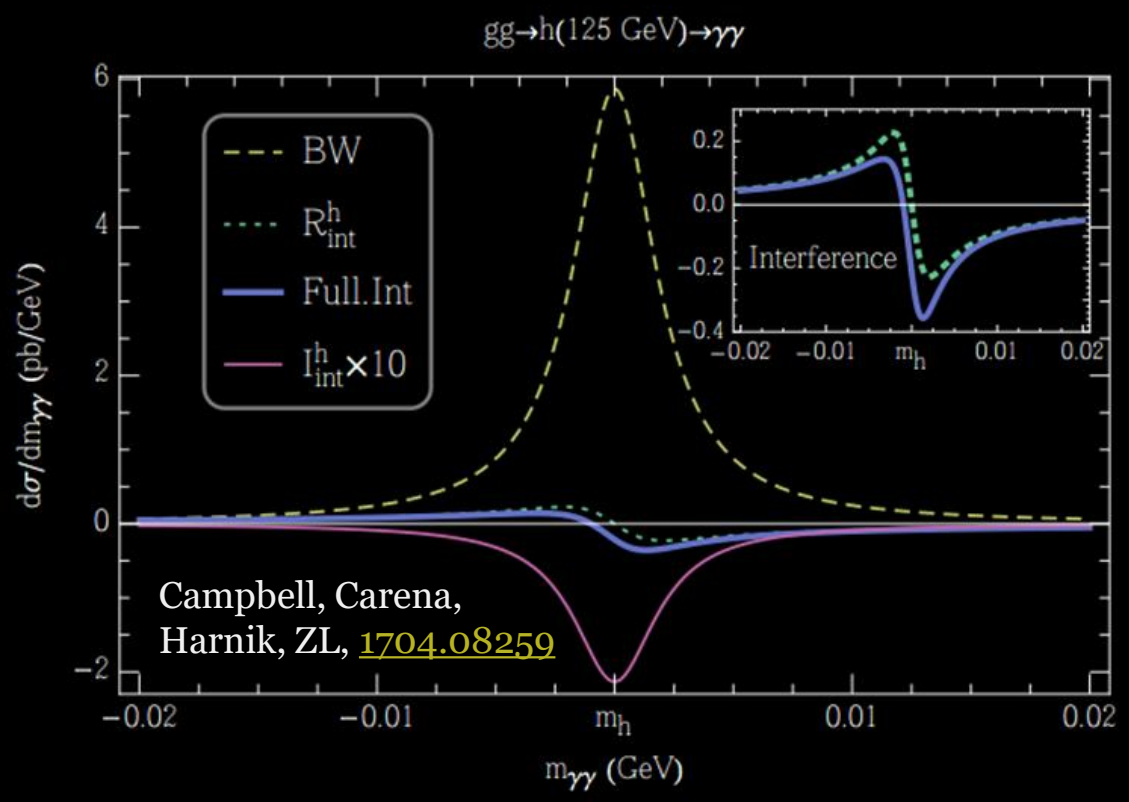


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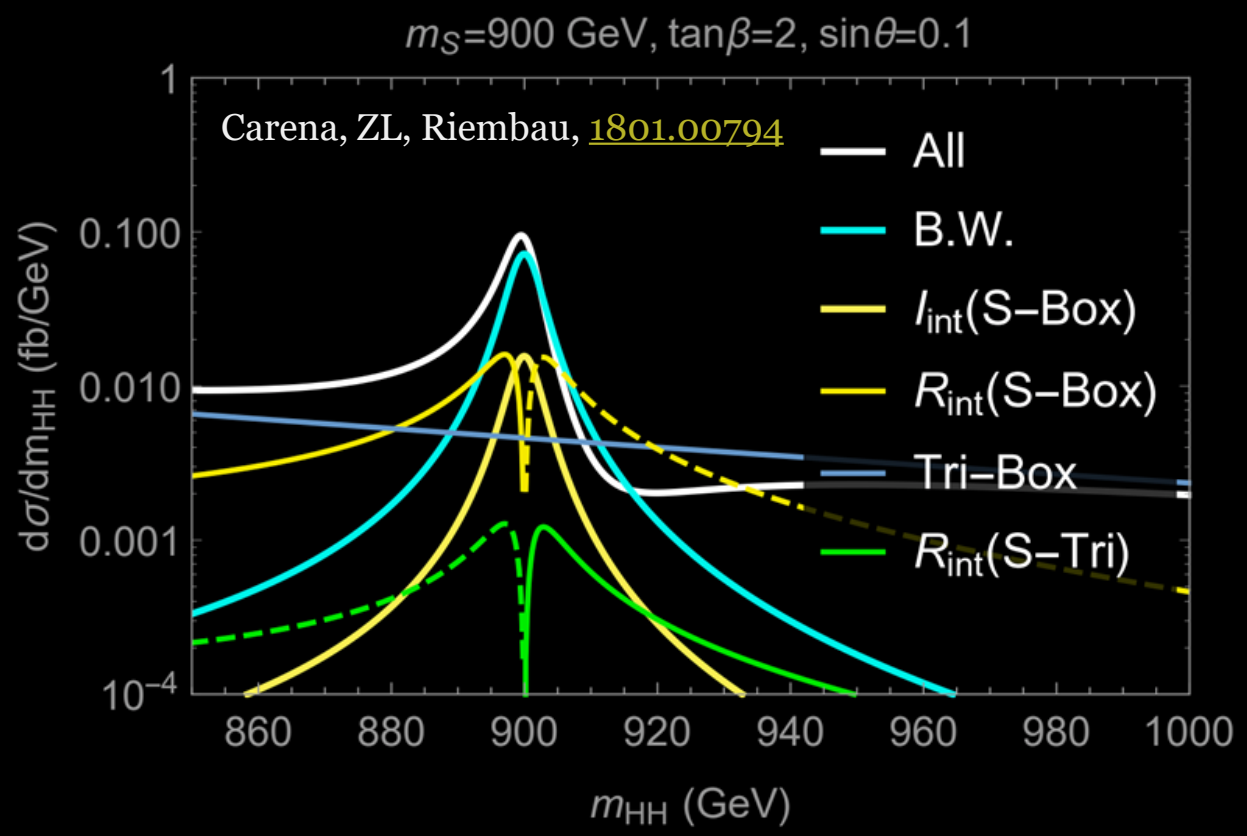
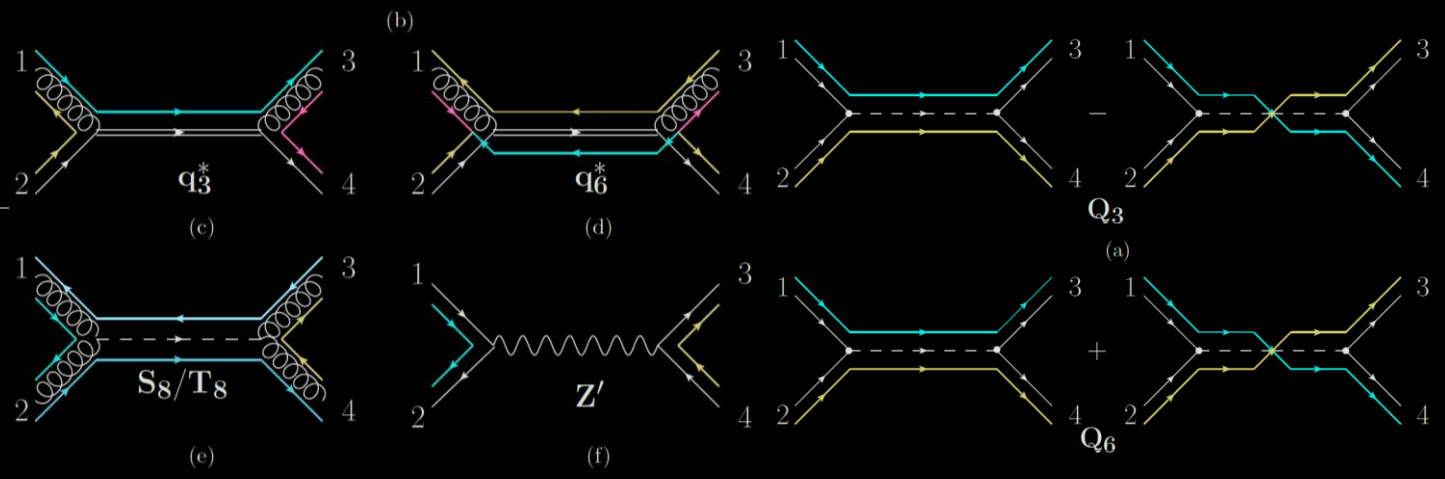



HH whitepaper, 1910.00012
Kauer, Lind, Maierhoefer, Song, 1905.03296
Other channels: Jung, Sung, Yoon, 1510.03450, 1601.00006, (dijets) Martin, 1606.03026, Bhattipirolu, Martin, 2004.06181…

# Color Antenna Pattern




Han, Lewis, Liu, ZL, Wang, 2306.00079

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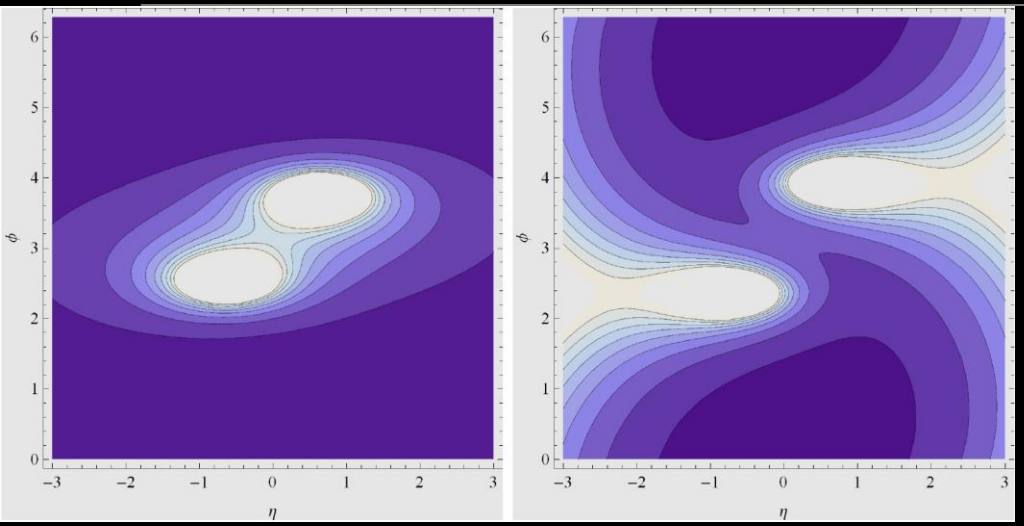


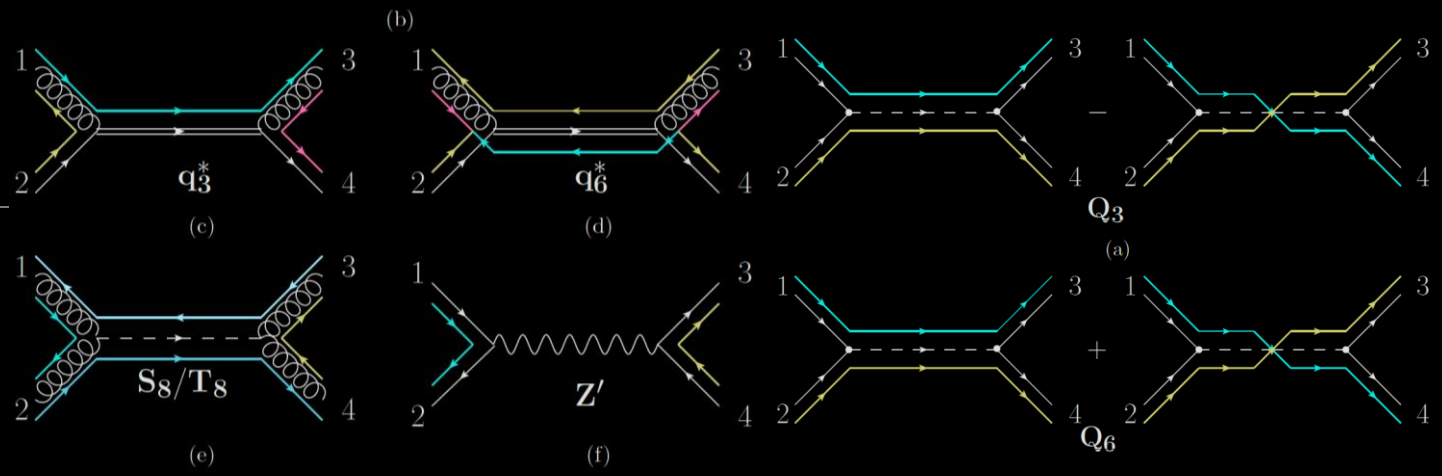


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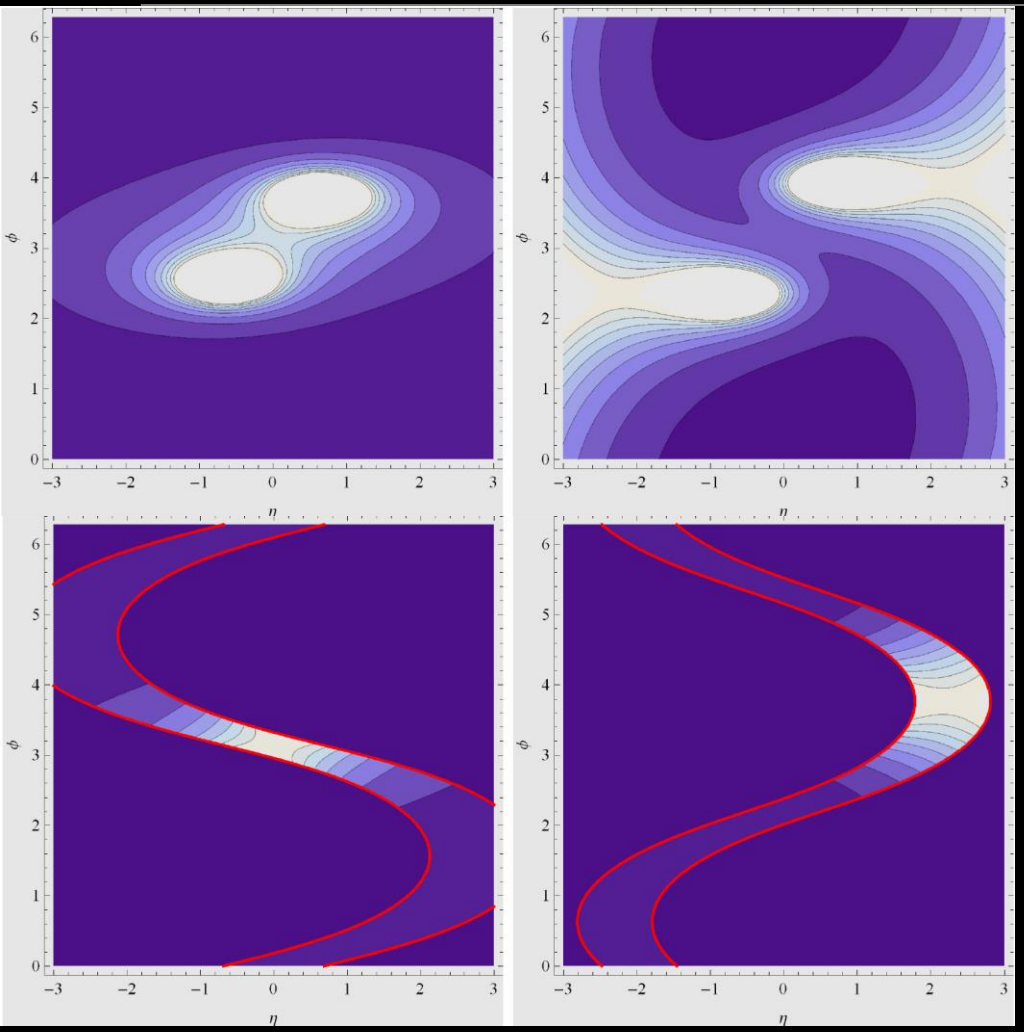


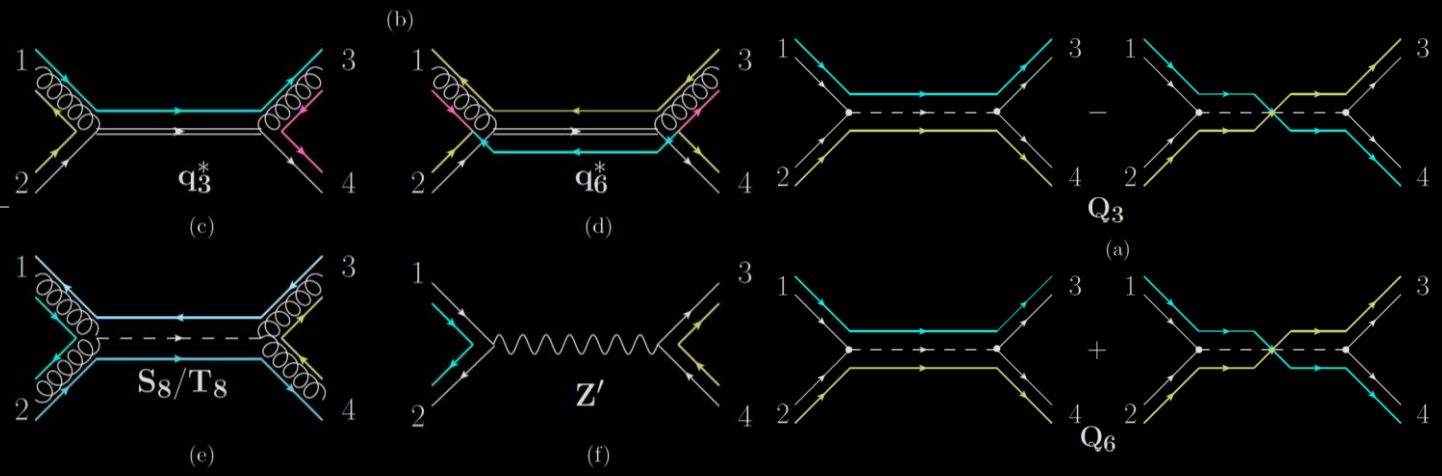


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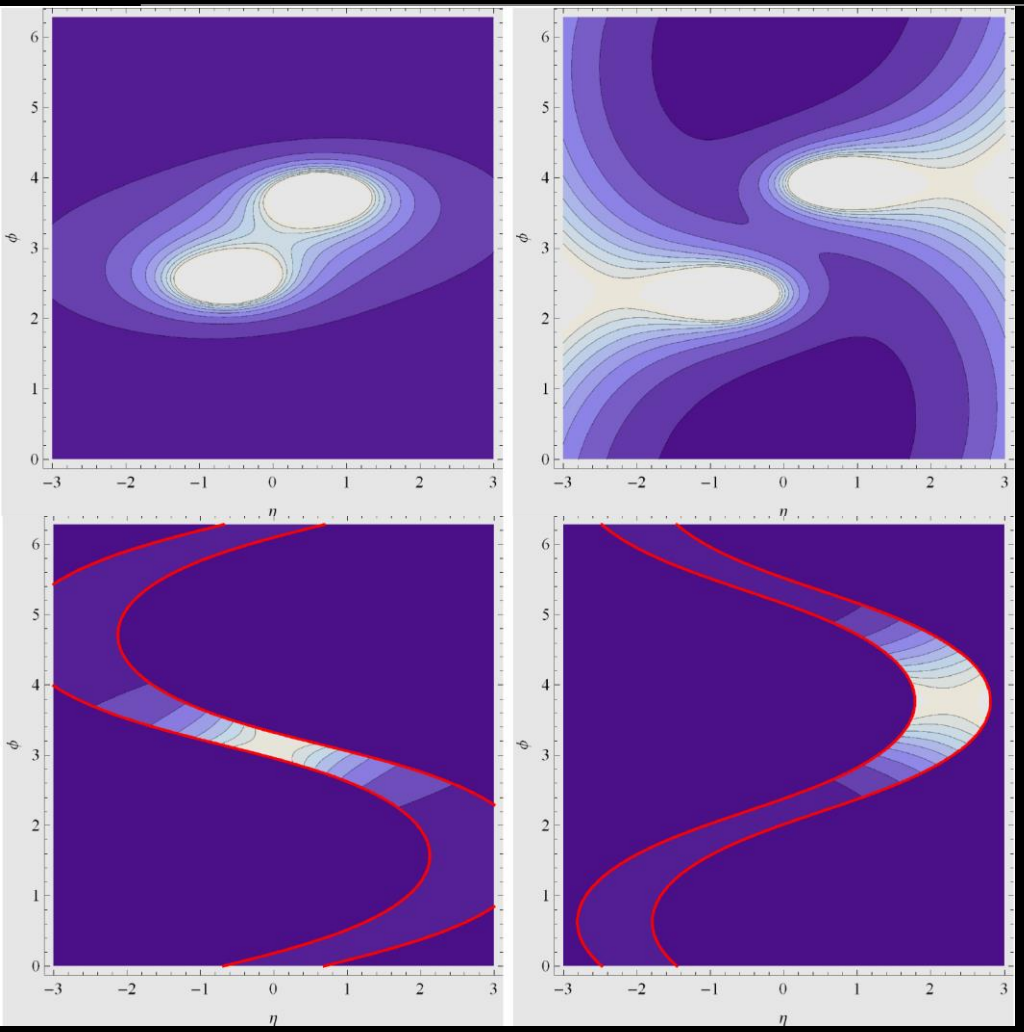

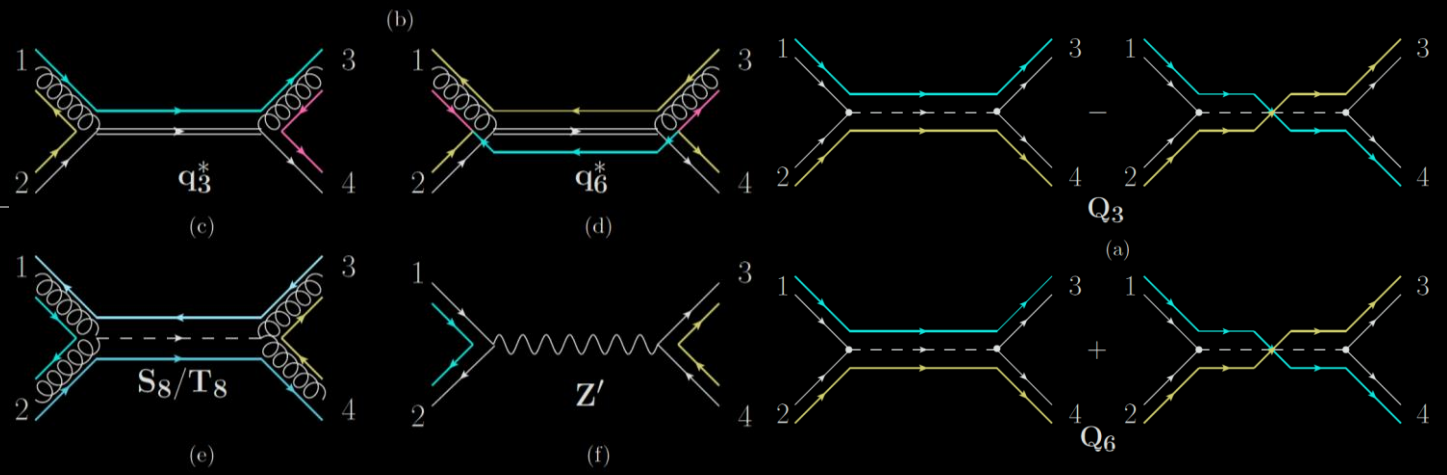


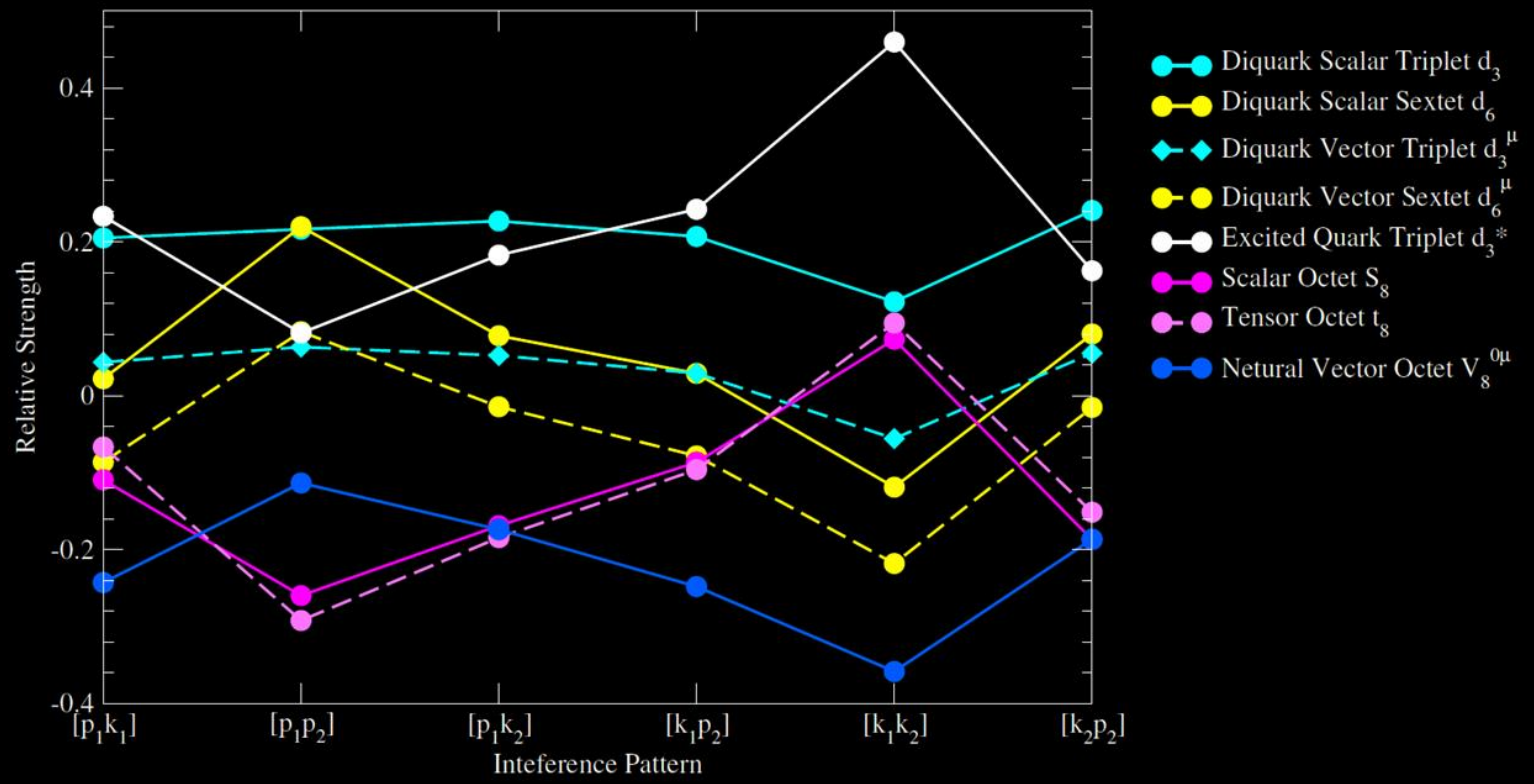


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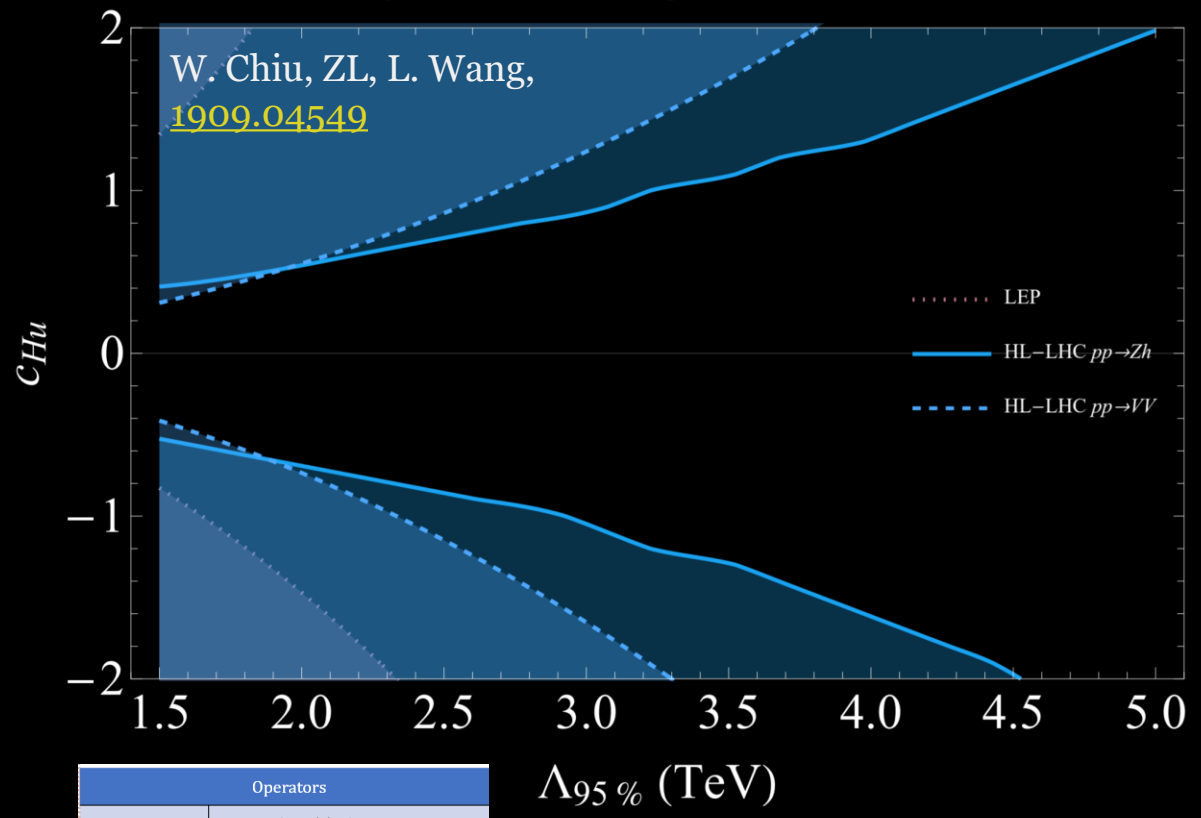
# Differential & Precision

Energy help with precision beyond LEP

Projected Existing Collider Reach




| Operators | |
|---|---|
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R. Franceschini et at, 1712.01310, C. Grojean et al, 1810.05149 & S. Banerjee et al, 1807.01796, F. Bishara et al, 2004.06122, 2011.13941, Panico, Ricci, Wulzer, 2103.10532, Bellafronte, Dawson, Paolo, 2304.00029+....

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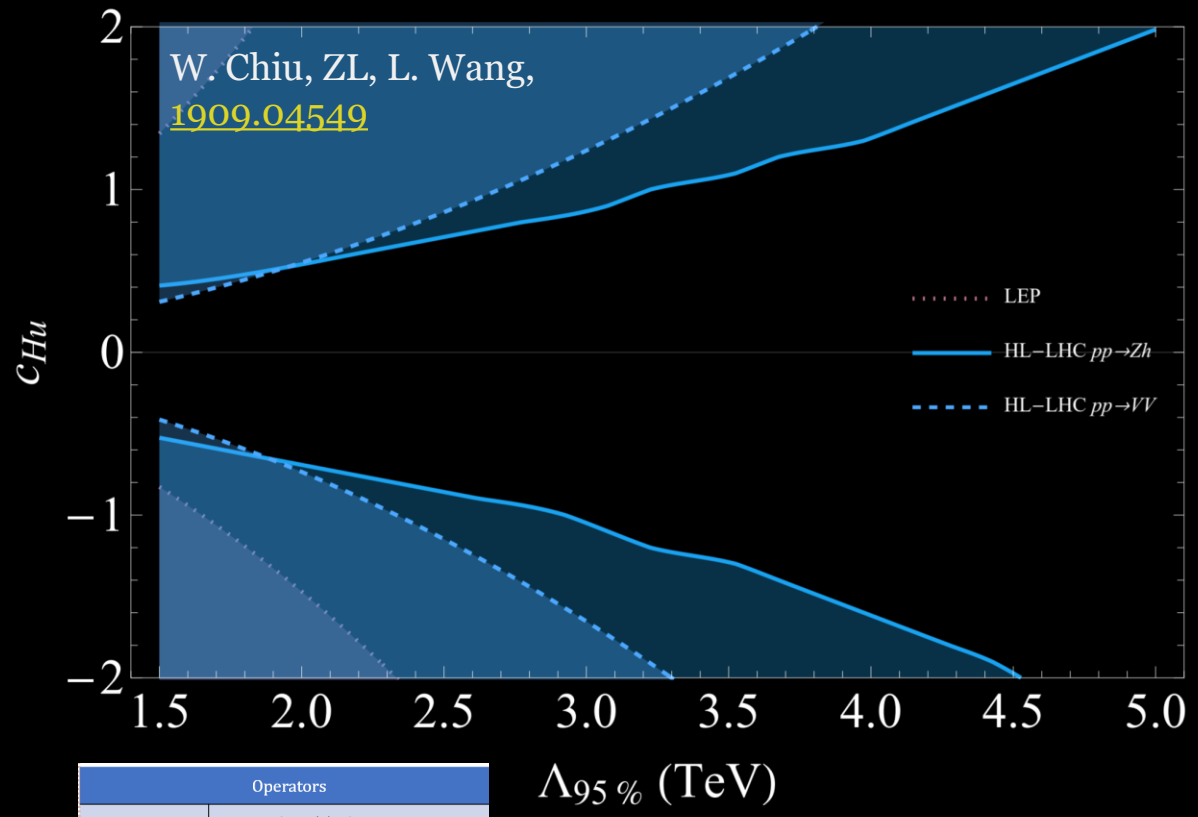


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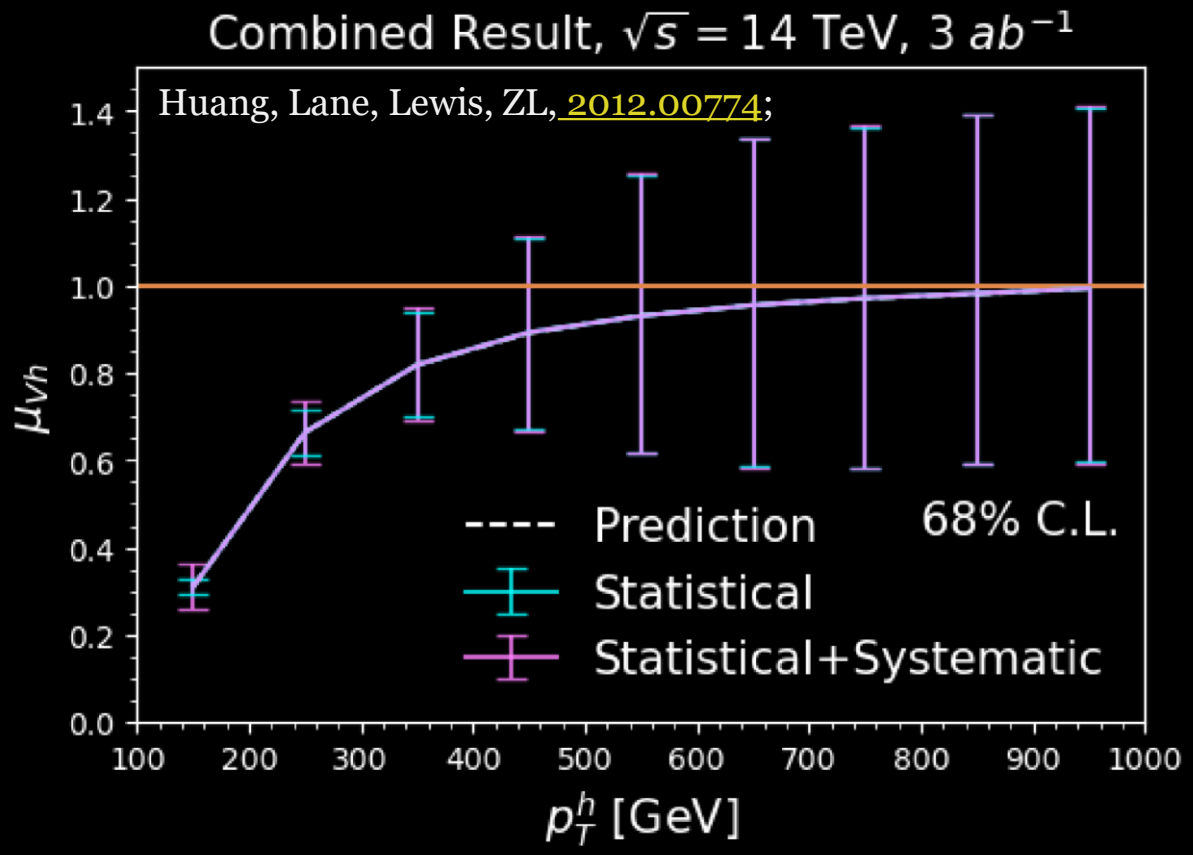
Seeing Goldstone Equivalence

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## Characters of the adventure

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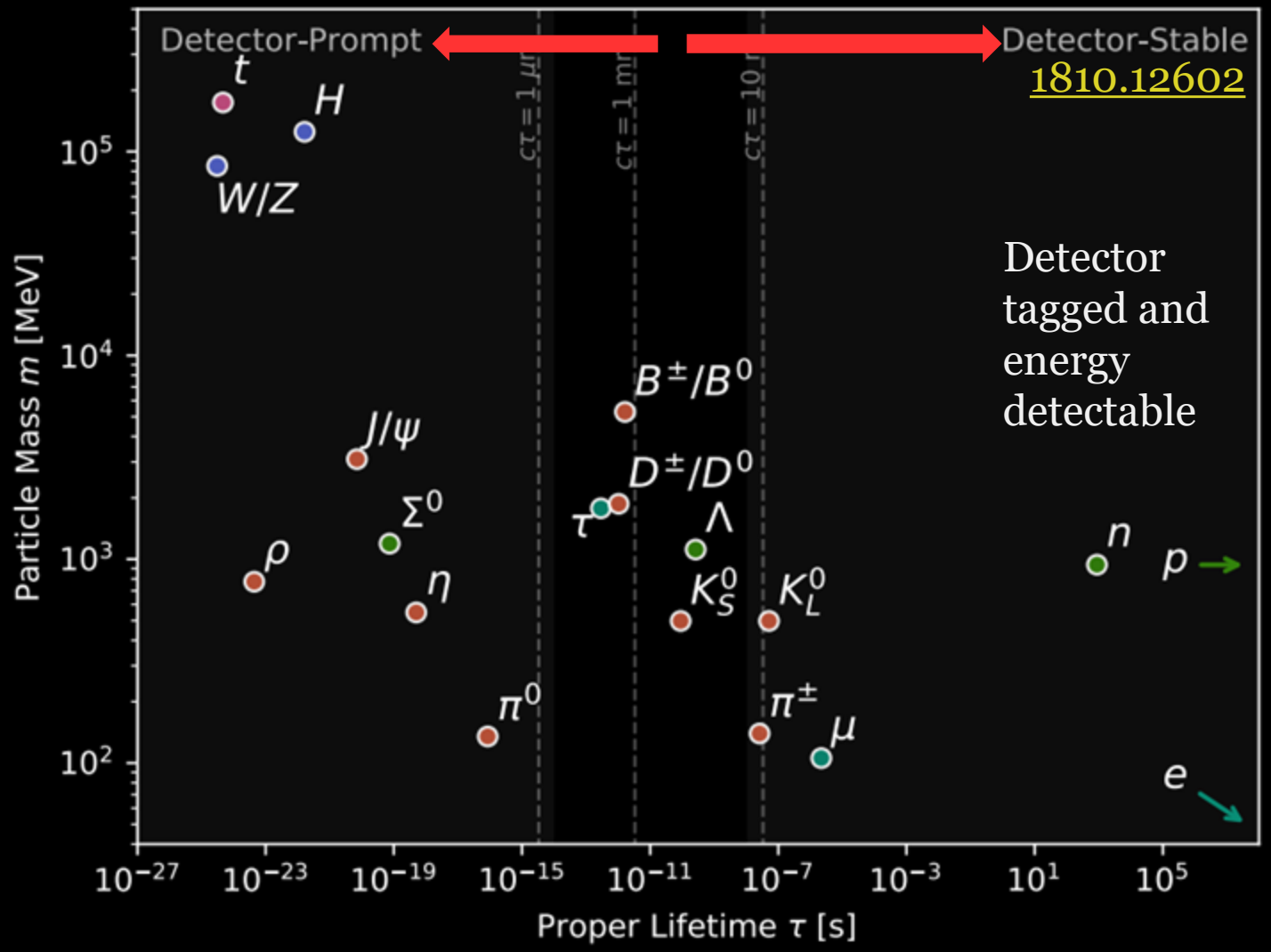
# What is LLP & Why searching for them?

Long-lived particles in the standard model:

- approximate symmetries;
- kinematic suppressions;



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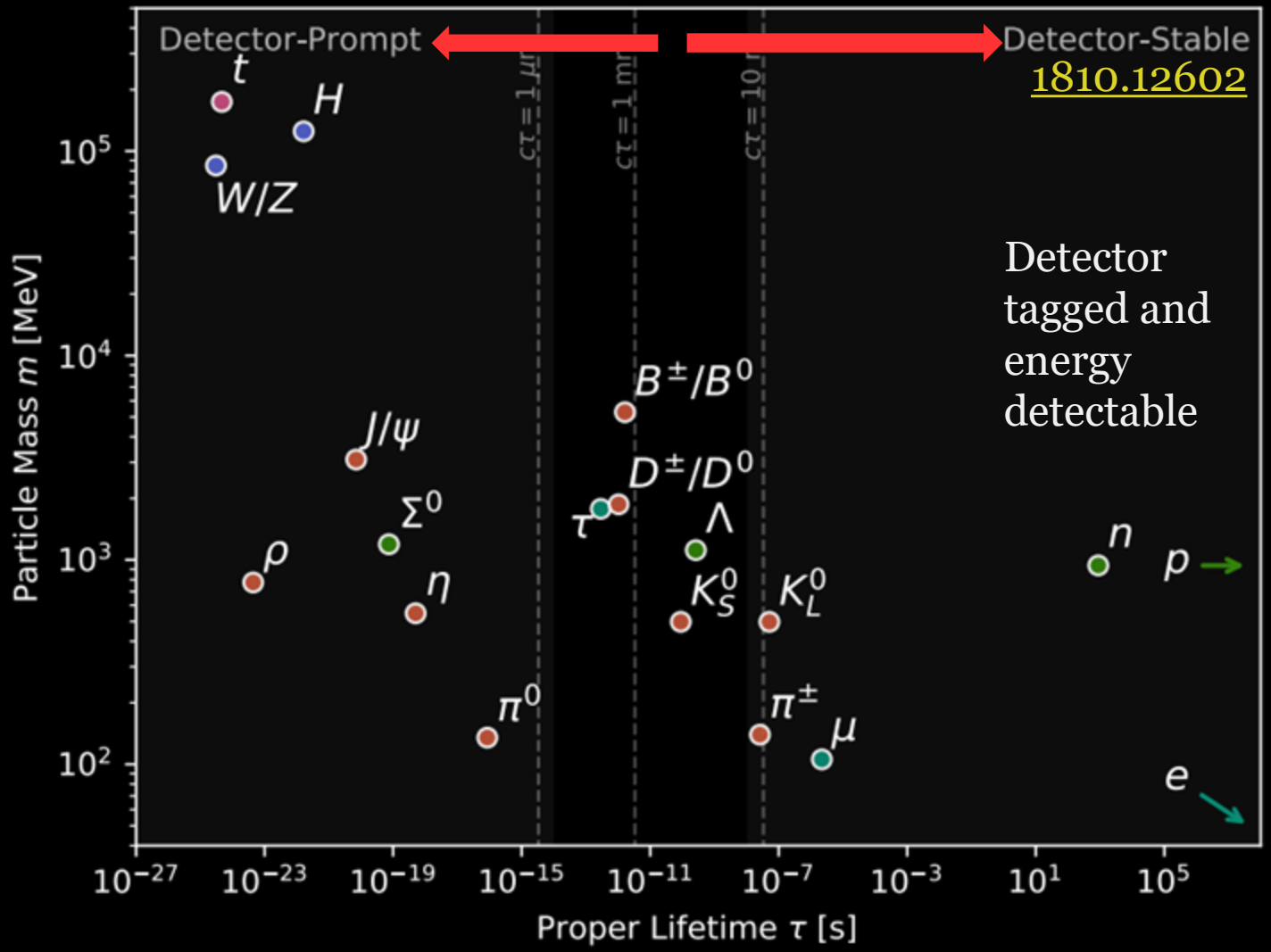
For BSM particles:

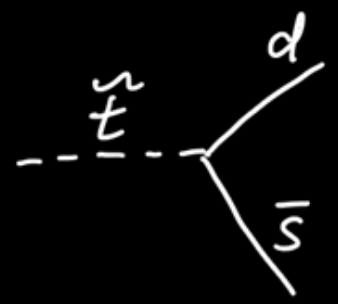
- Prompt particles being actively probed;
- Many scenarios give raise to long-lived signatures;



# SUSY as a Strawman (more towards heavy LLPs)

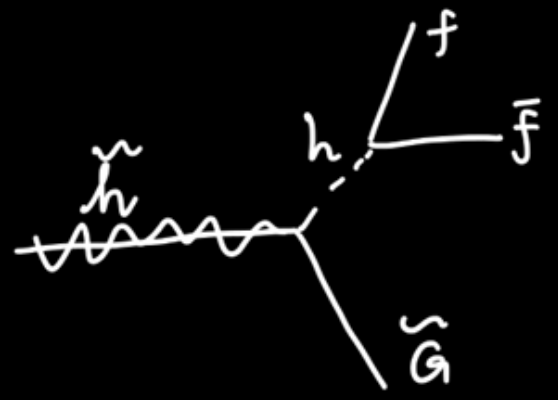
- R-Parity-Violating, small B/L-violating couplings

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



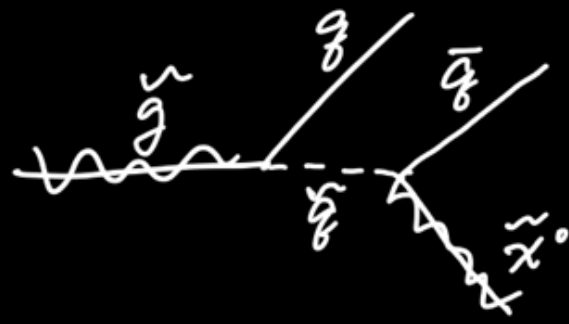

- Gauge mediation—suppressed couplings via SUSY breaking scale

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




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

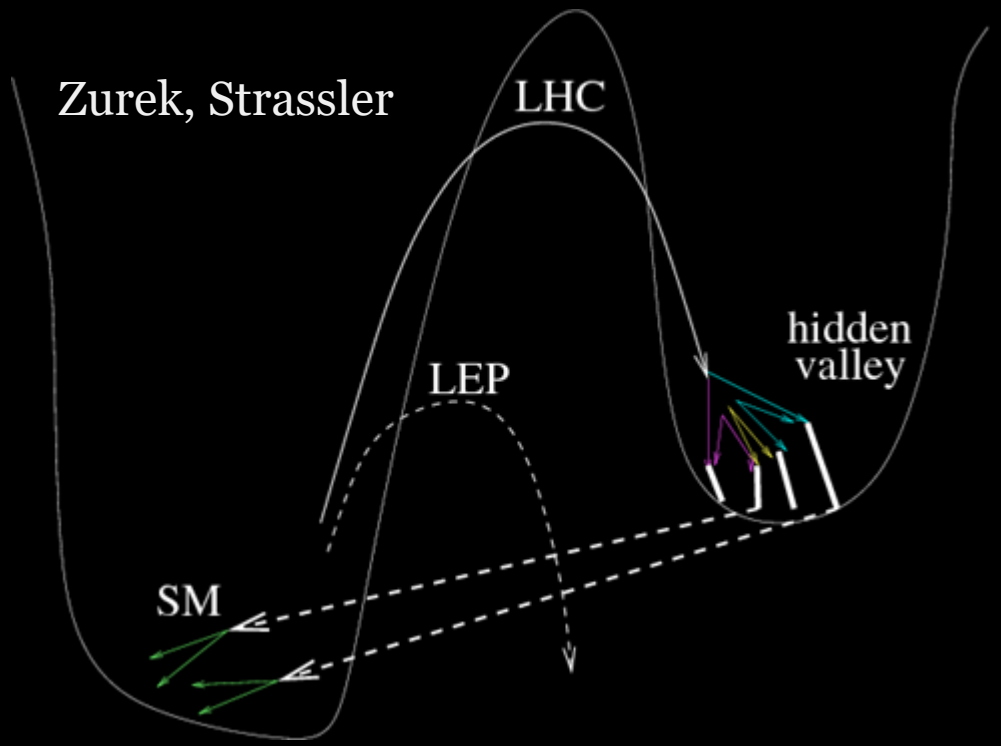
$$c\tau_{\mathrm{milli-split}} \sim 1\ \mathrm{mm} \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^4$$

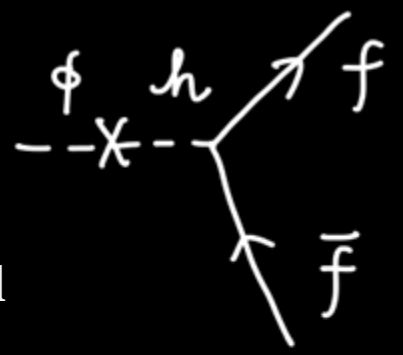



- Pure Wino/Higgsino–nearly degenerated, disappearing track

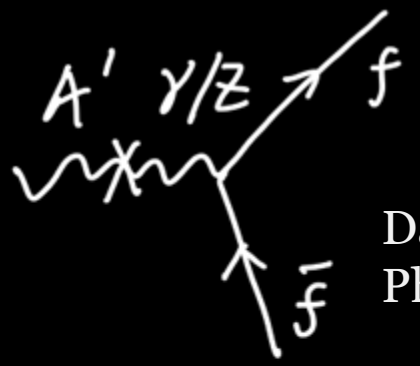
# Hidden Sectors (more towards light LLPs)

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



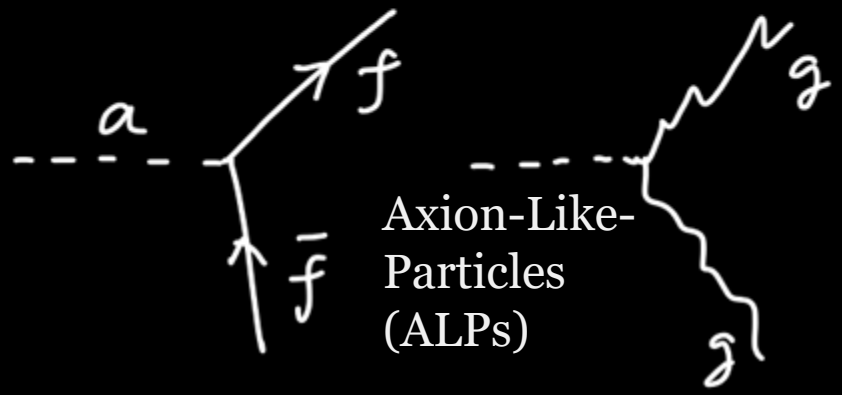




Higgs portal



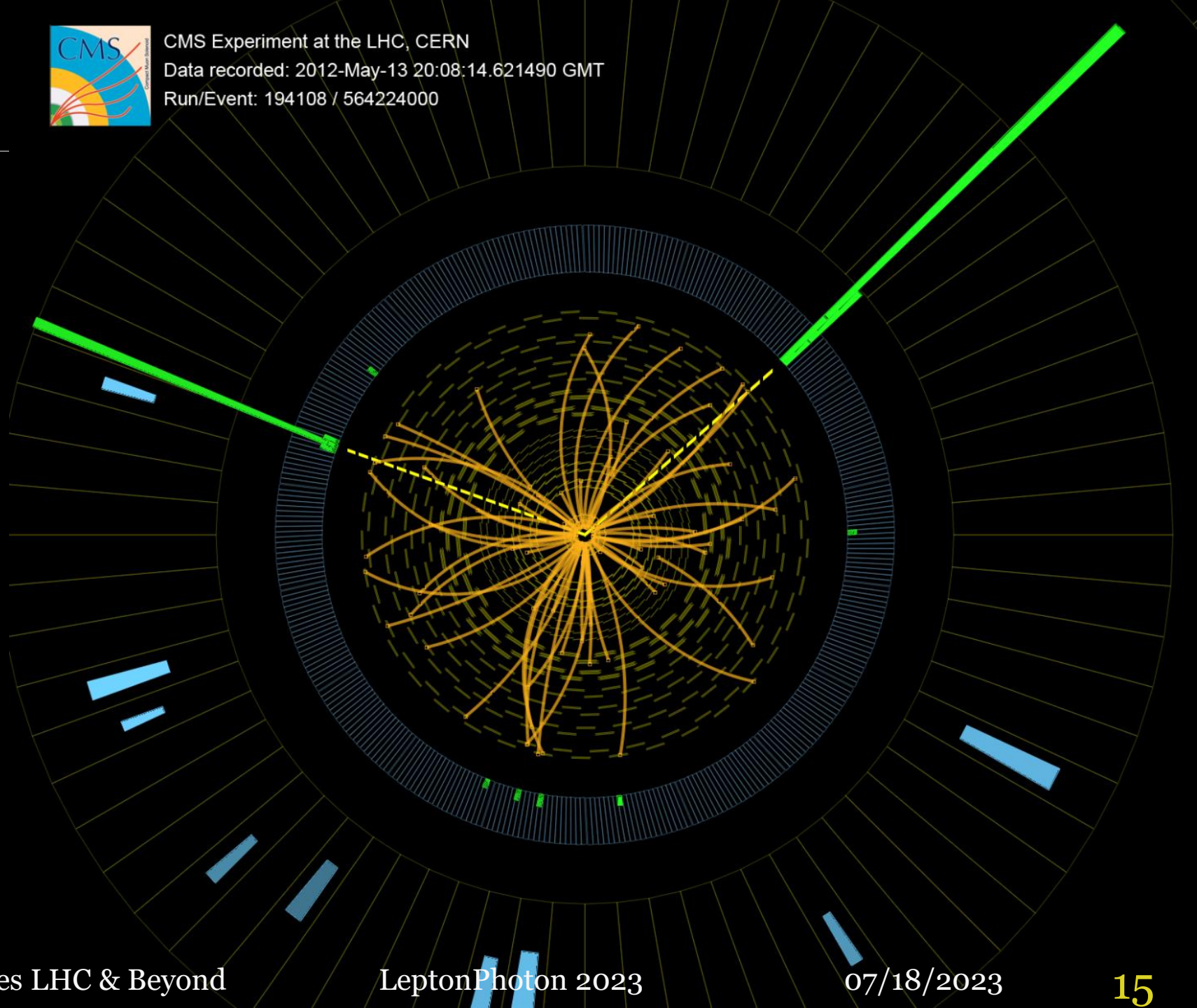

Dark Photon

Heavy Neutral Leptons (HNLs)




Axion-Like-Particles (ALPs)

Fantastic four or Amazing five (plus millicharged)


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

# But, an experimental challenge.

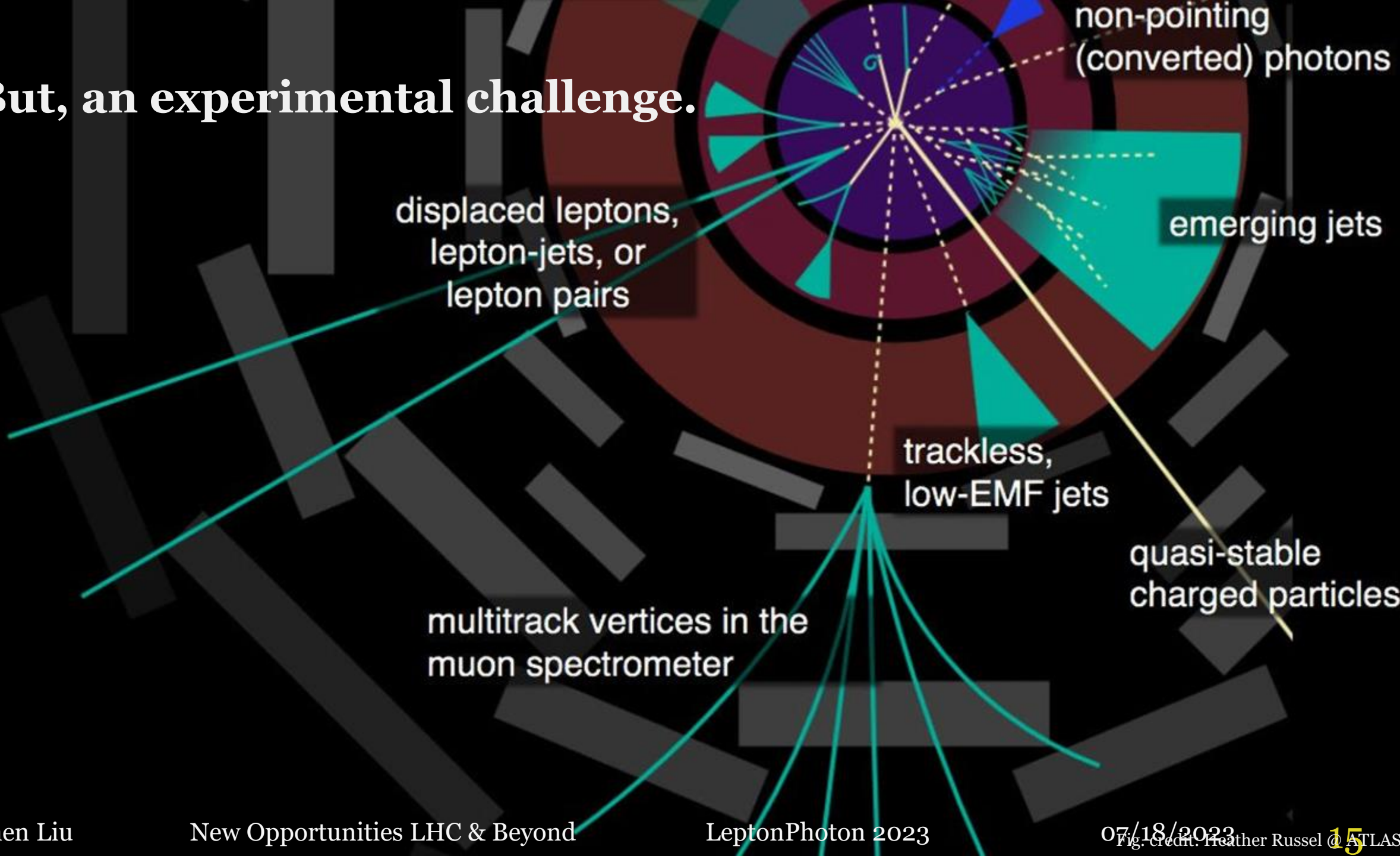



Fig. credit: Heather Russel @ ATLAS

# But, an experimental challenge.

LHC lessons:

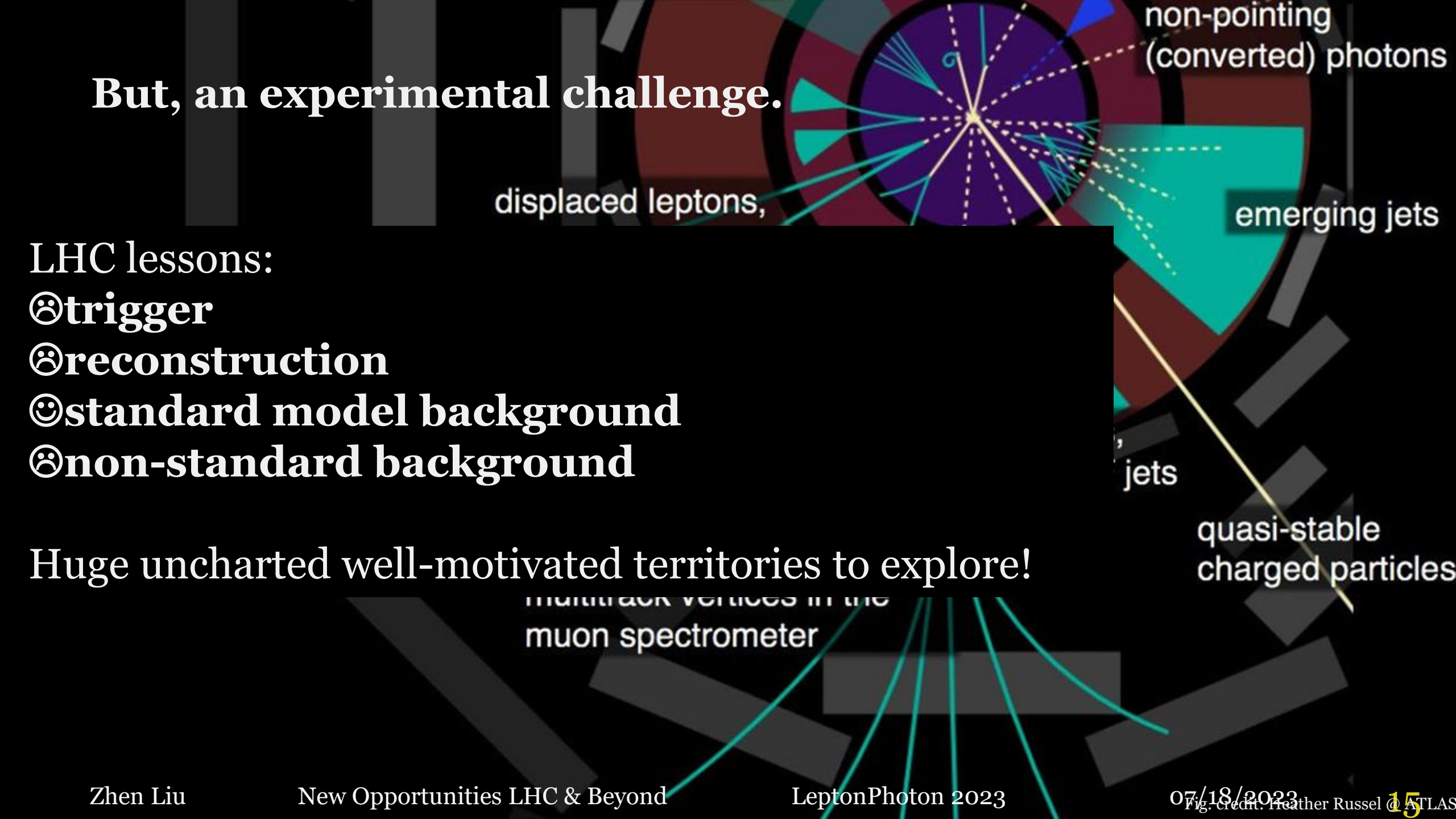
**☹trigger**

**☹reconstruction**

**☺standard model background**

**☹non-standard background**

Huge uncharted well-motivated territories to explore!

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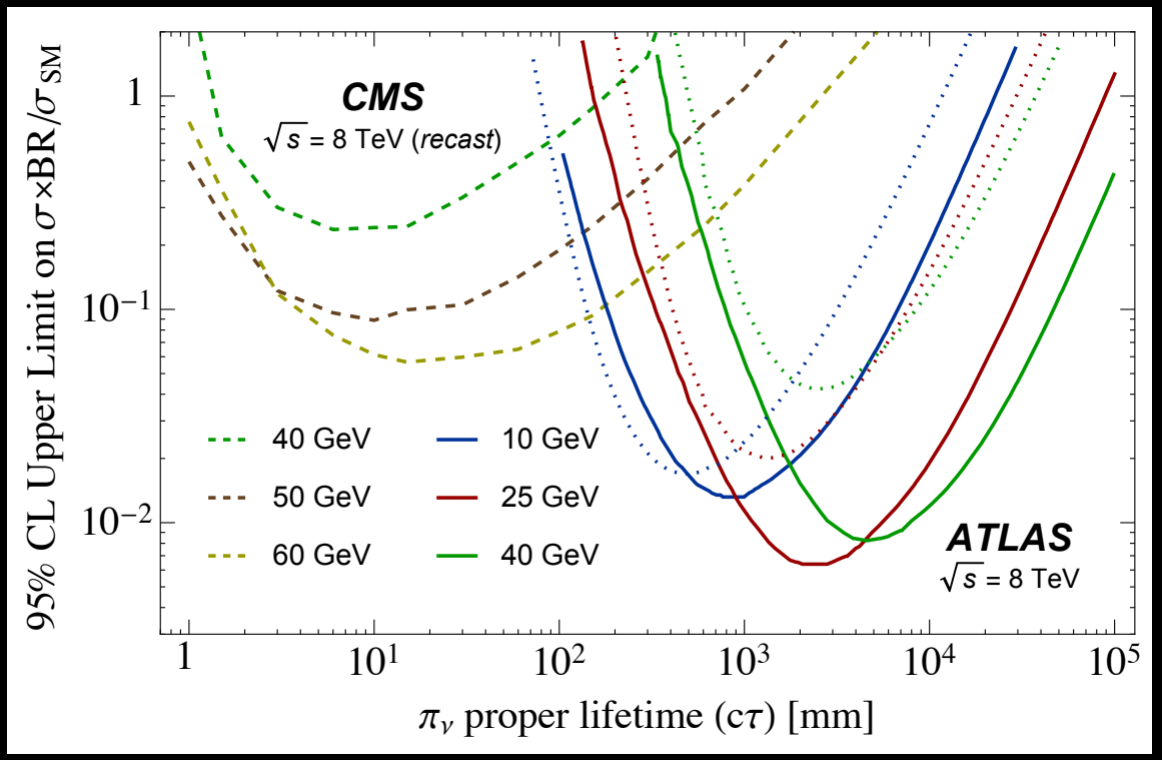
# LHC progress: Higgs decays to LLPs (hadronic)

Csaki, Kuflik, Lombardo, Slone, 1508.01522




Back in 2015, no such limit existed, very few LLP searches (the plot was a re-interpretation for SUSY LLP searches), also see ZL, Tweedie, 1503.05923

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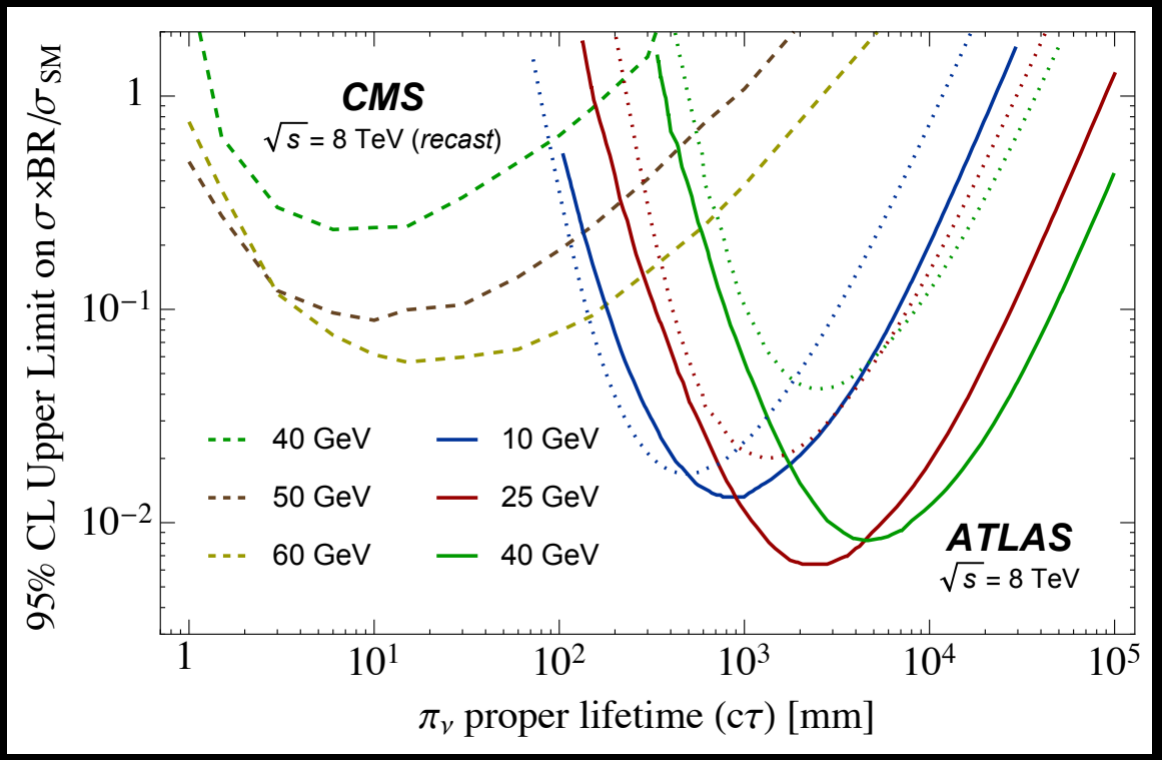


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Now, tons of searches for various final states with new triggers, reconstructions, etc.

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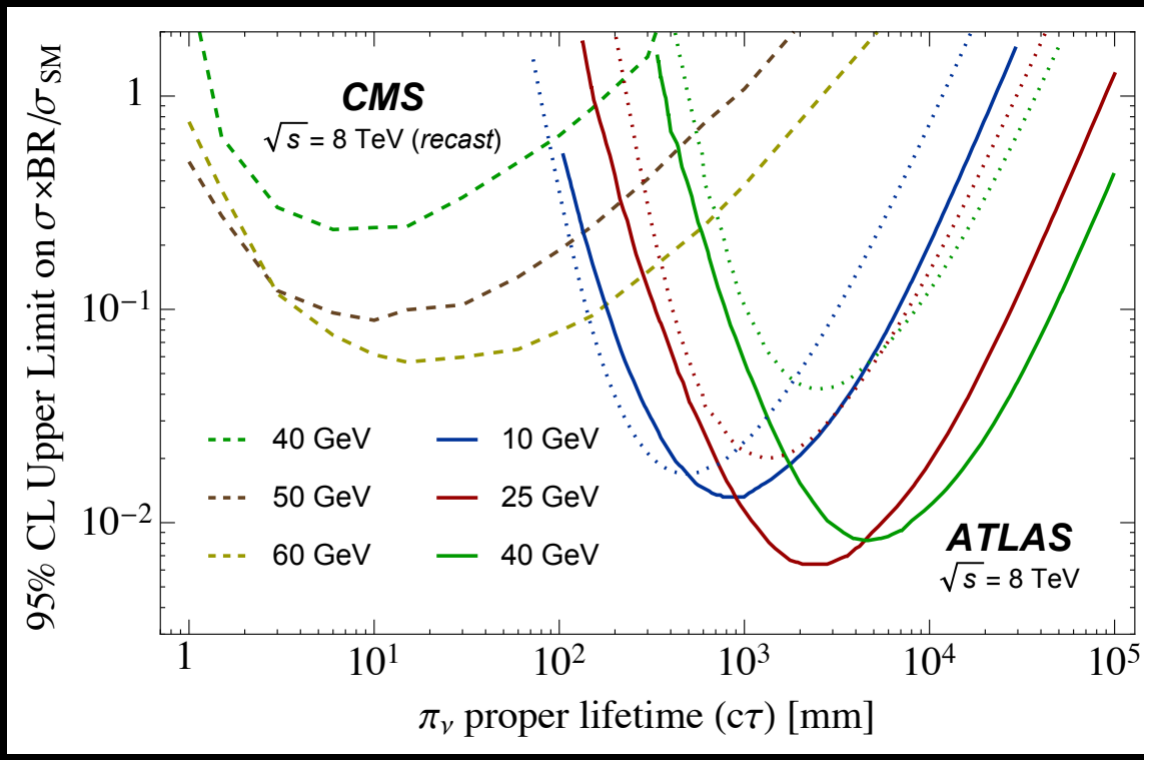
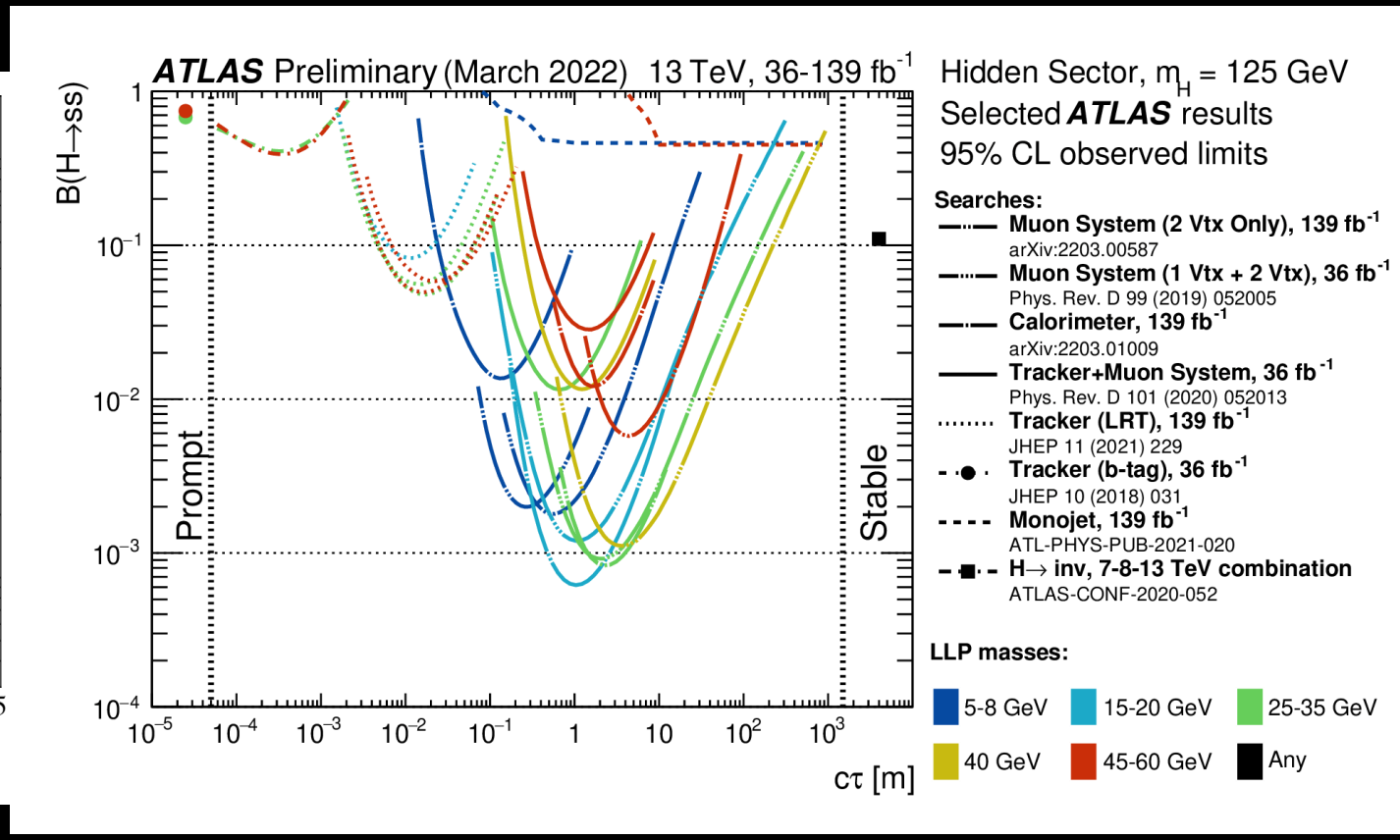
Csaki, Kuflik, Lombardo, Slone, 1508.01522

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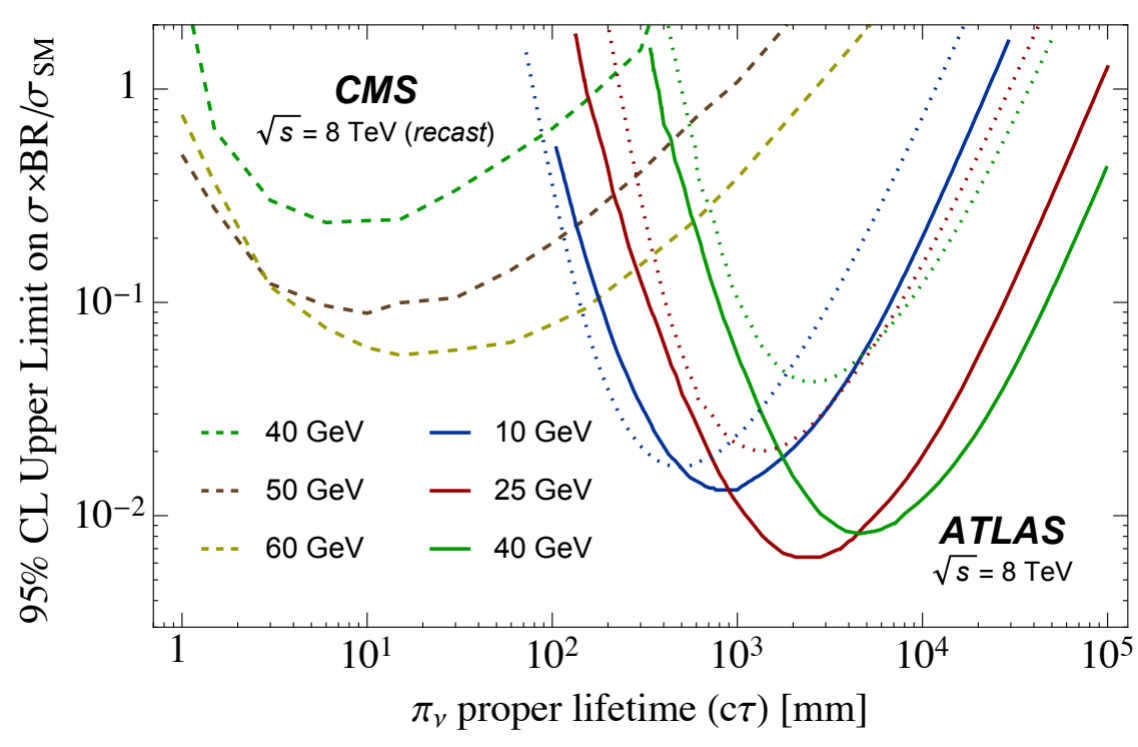


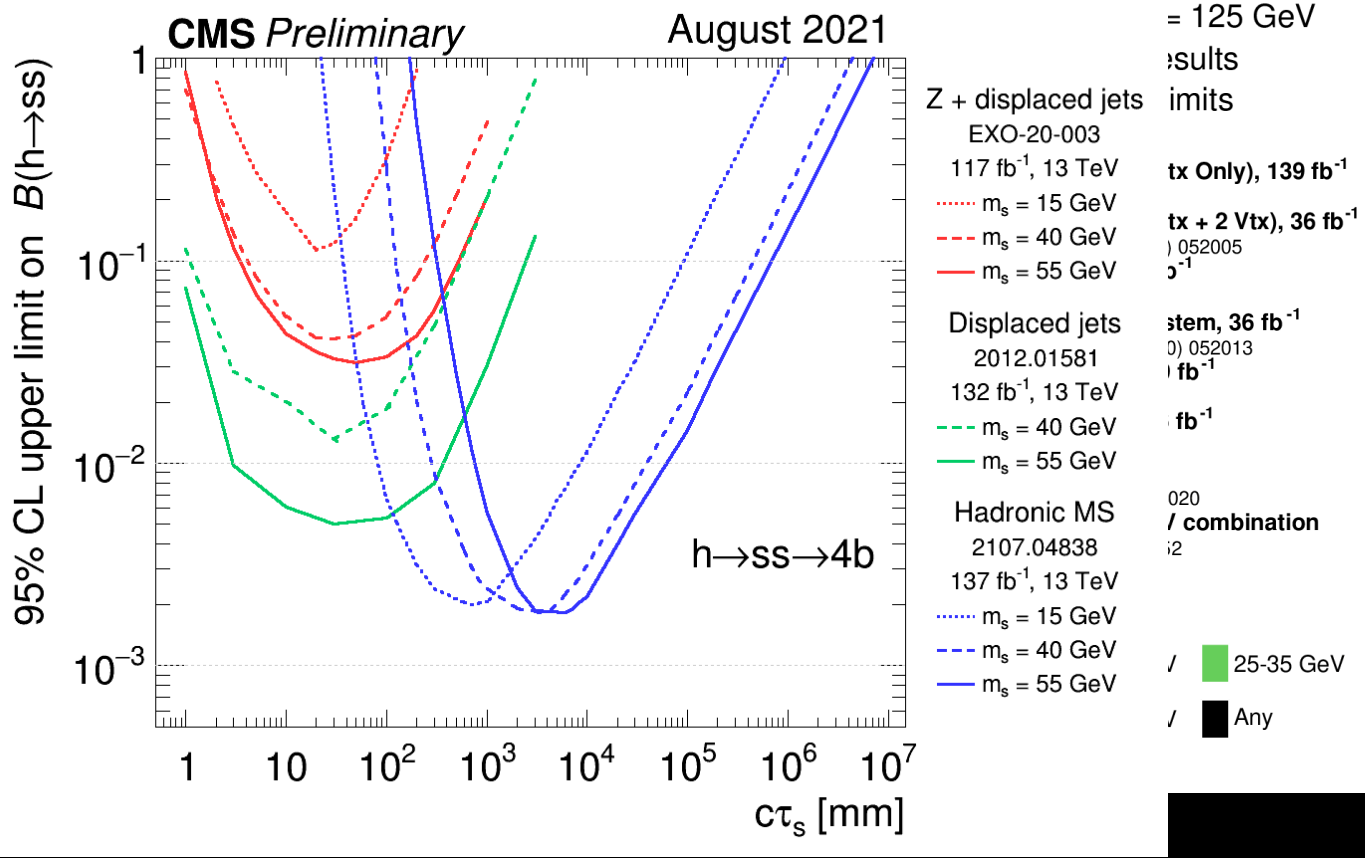


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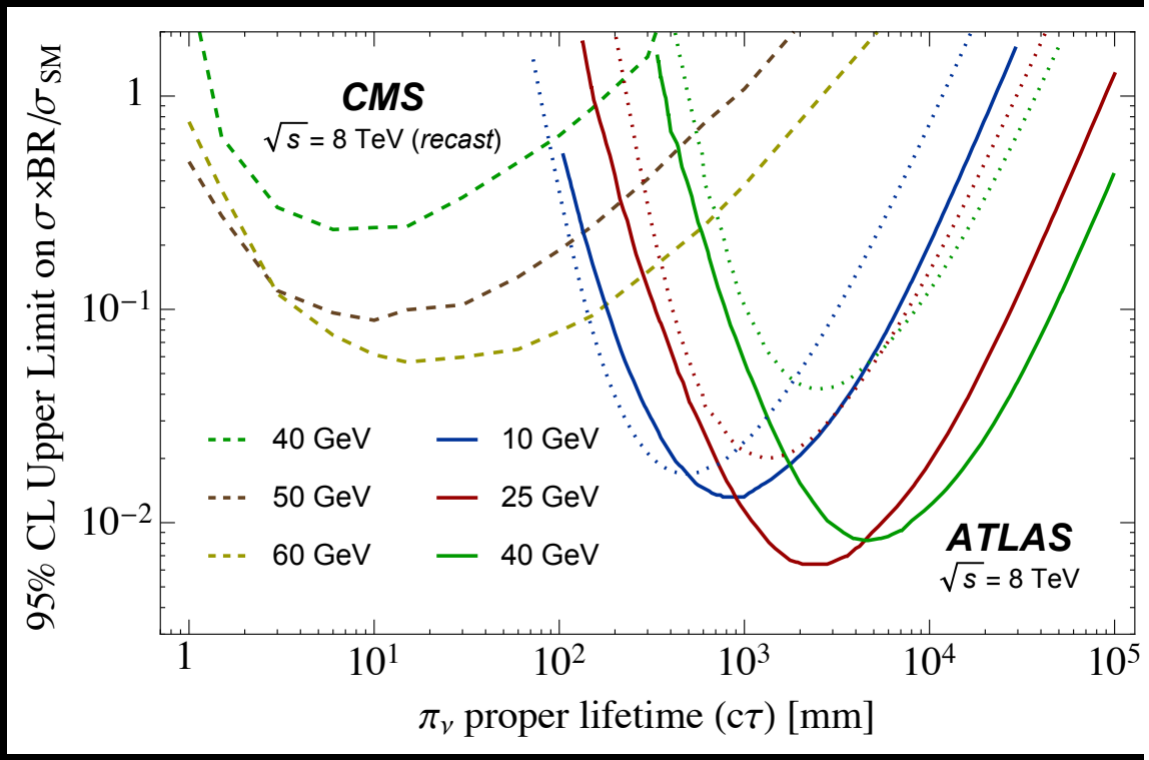


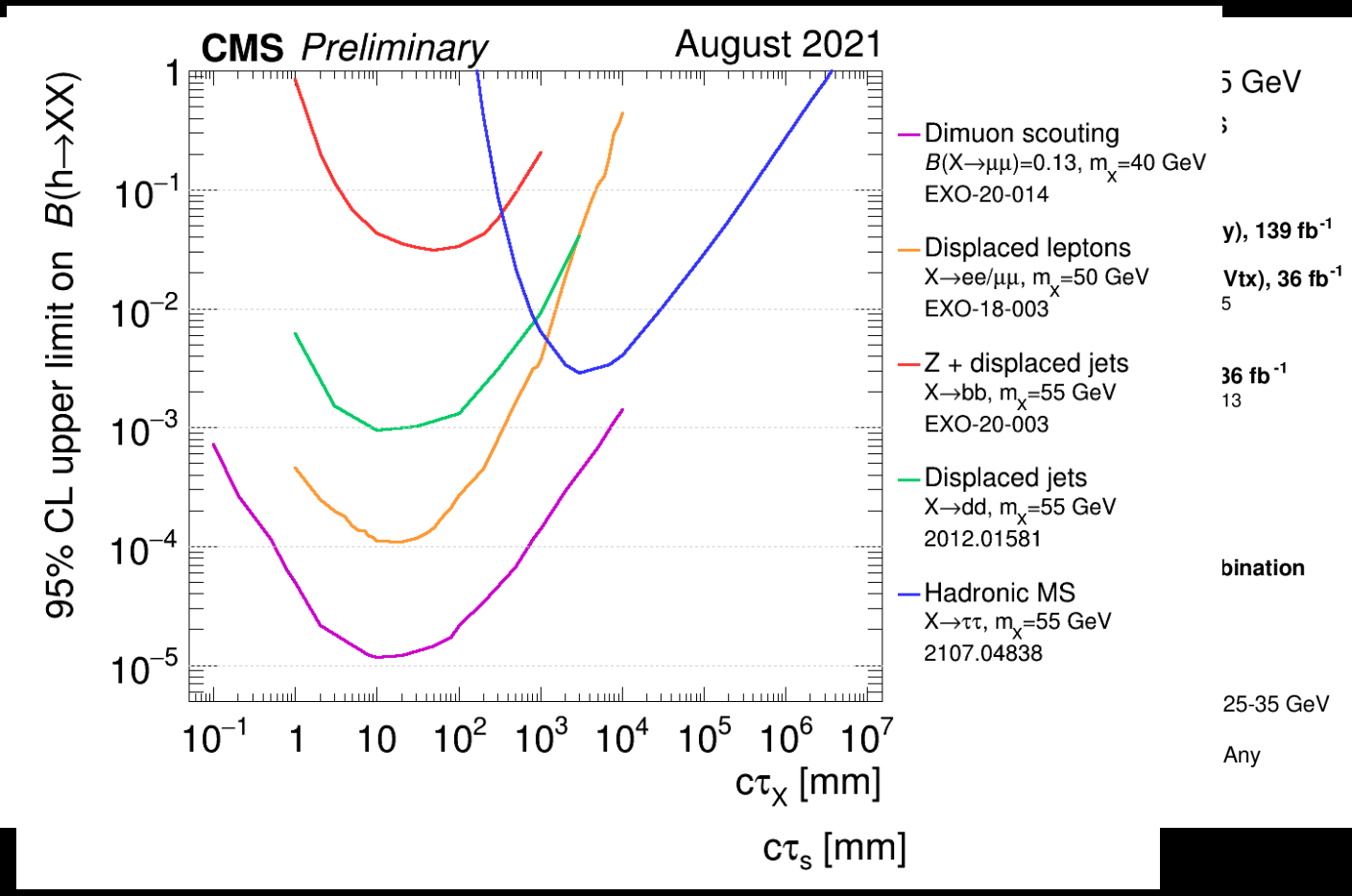


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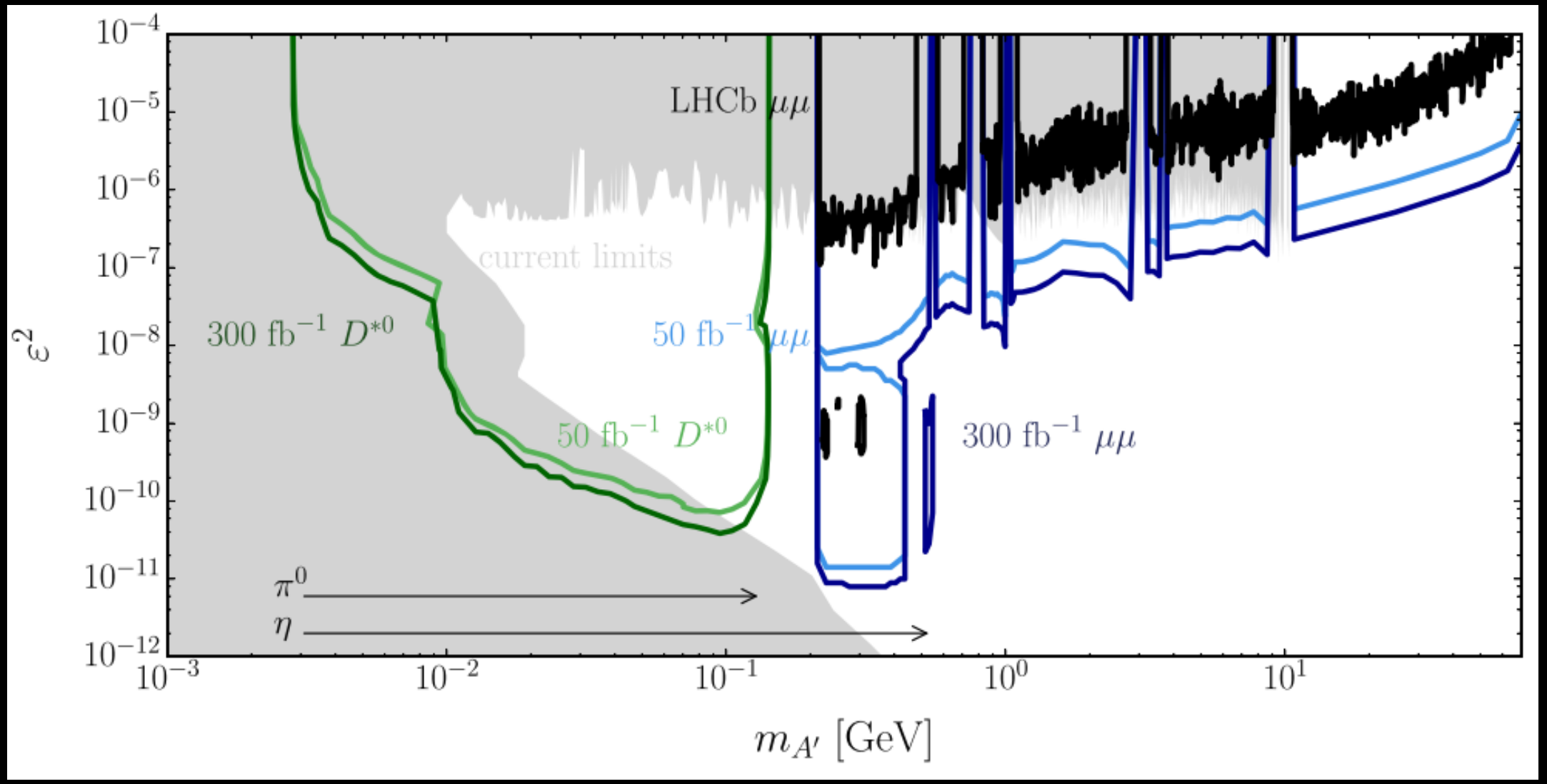

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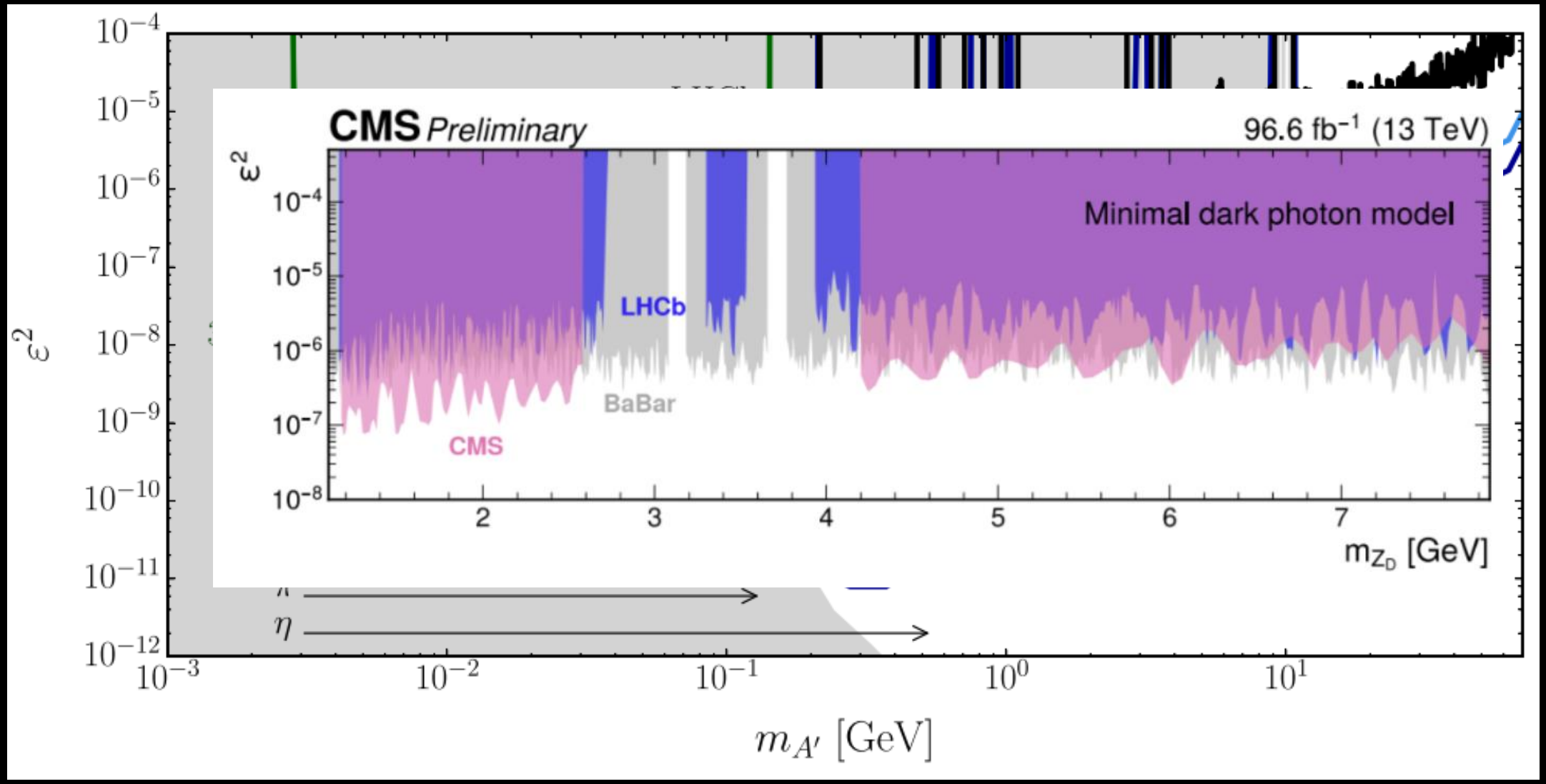

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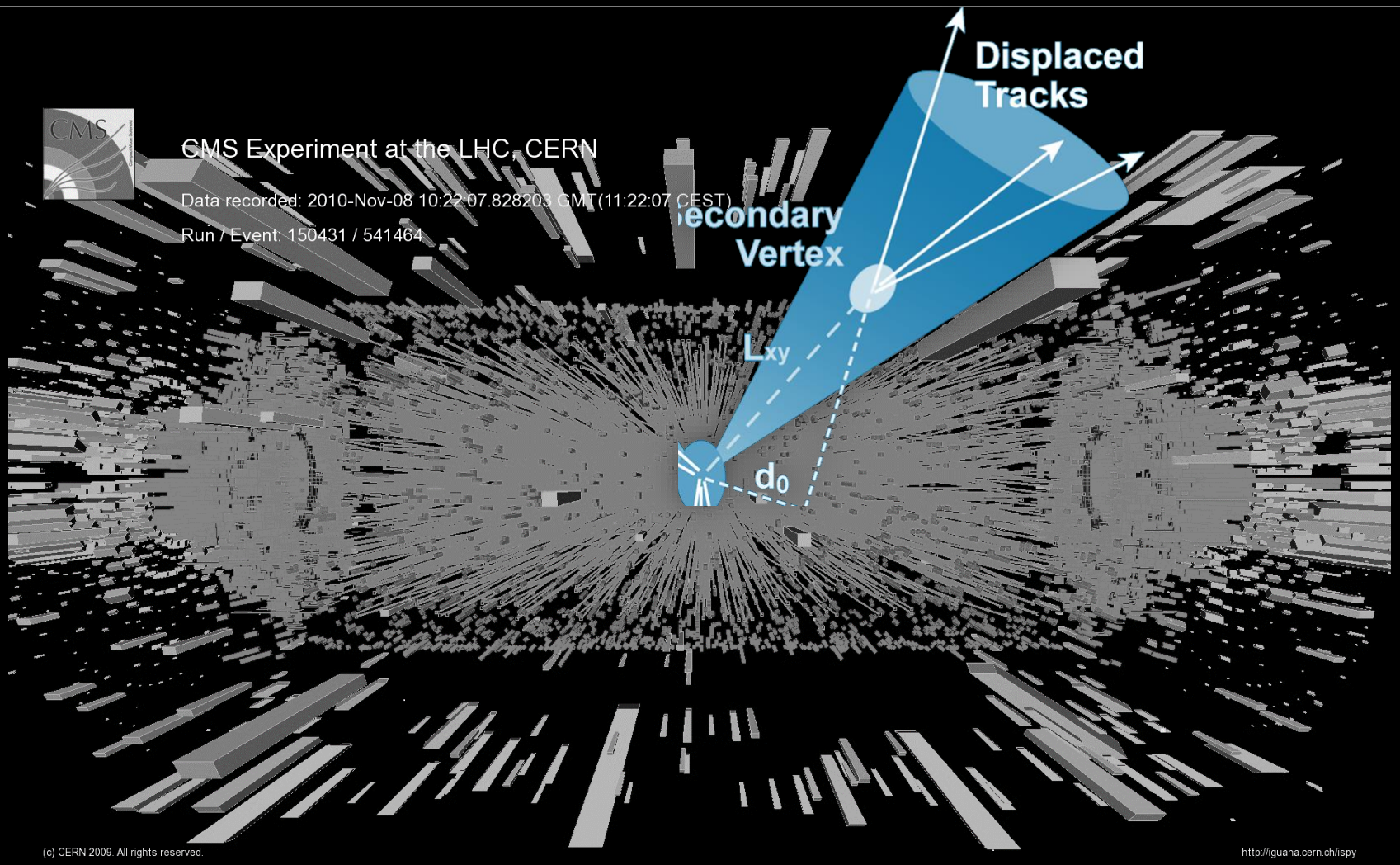
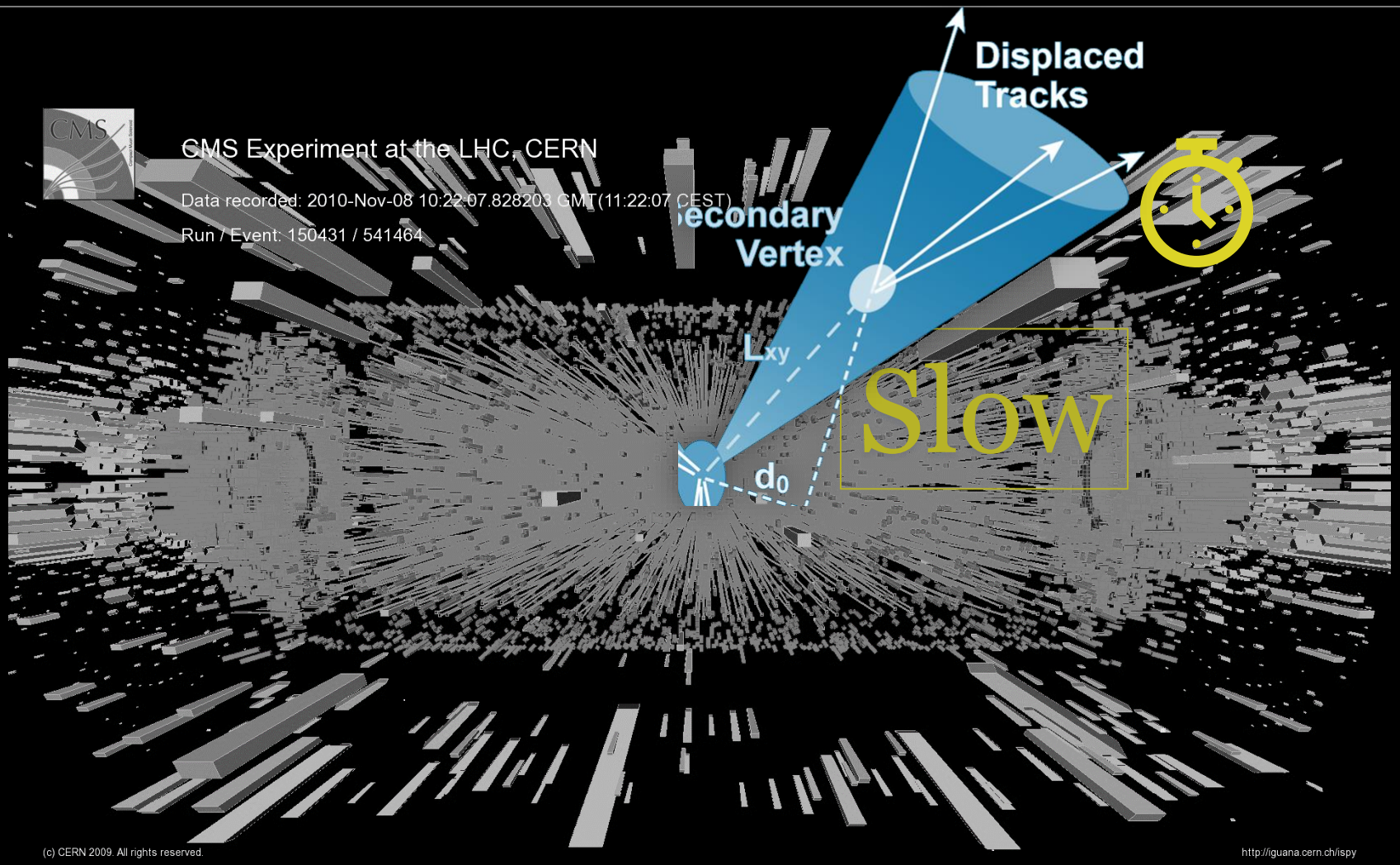


# New information to be explored: Timing

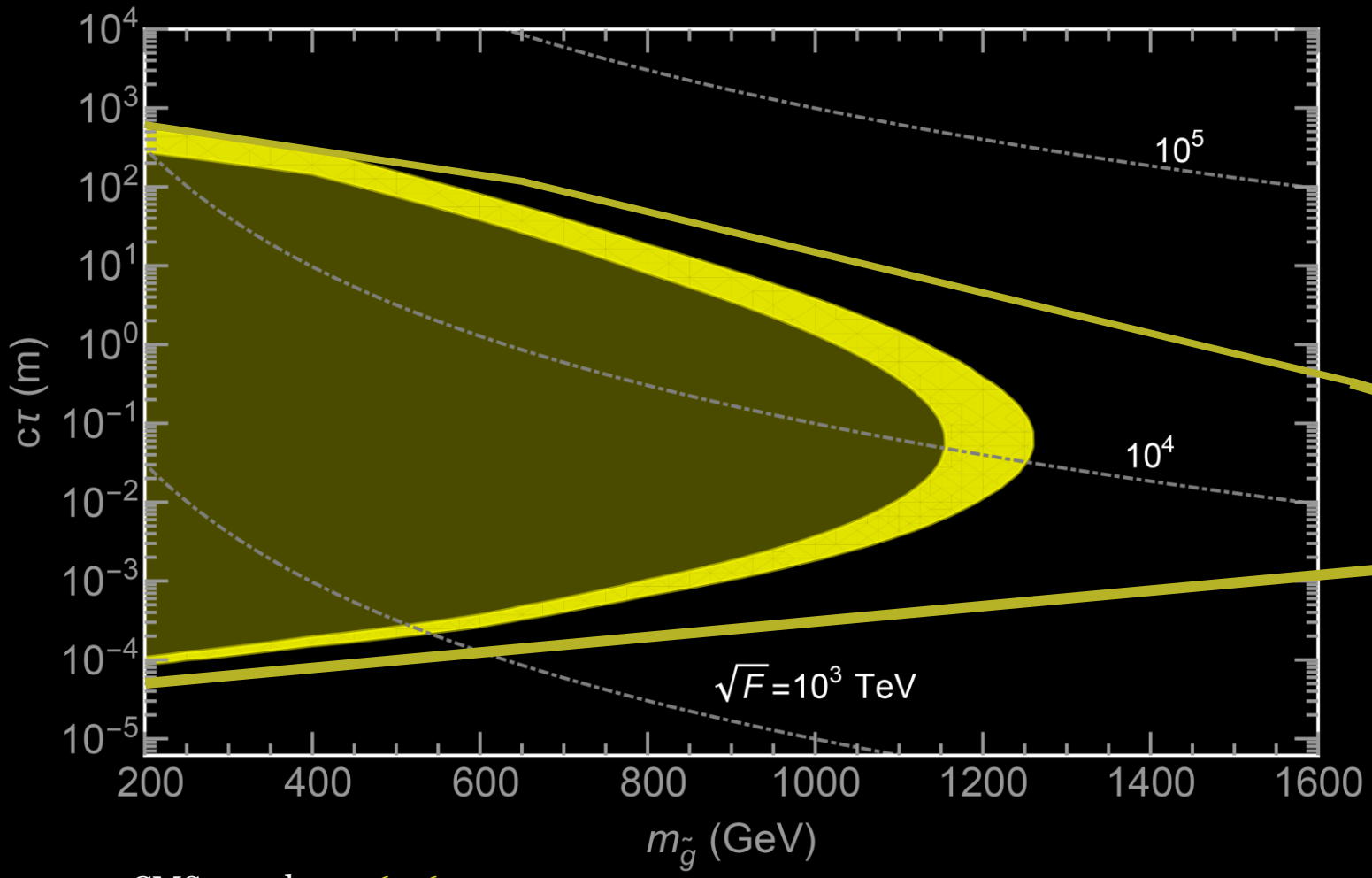
Delay is a universal feature of Long-Lived Particles*

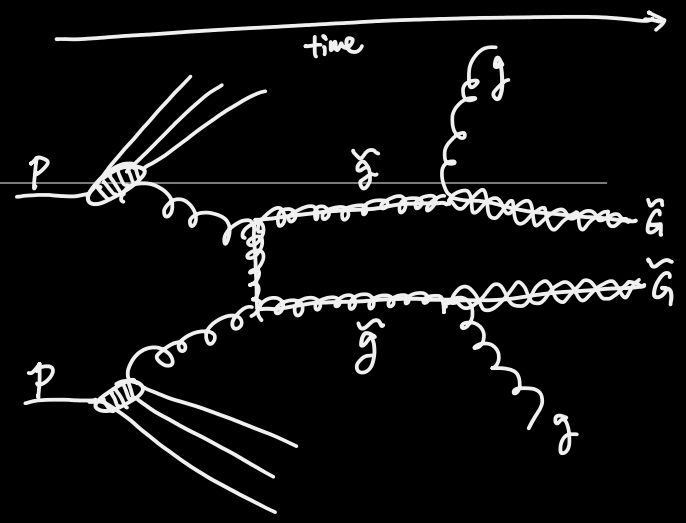
Liu, ZL, Wang, 1805.05957




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

# Late comers will be spotted easily




Displaced jet at 13 TeV, 39 $fb^{-1}$

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

CMS search, 1906.06441
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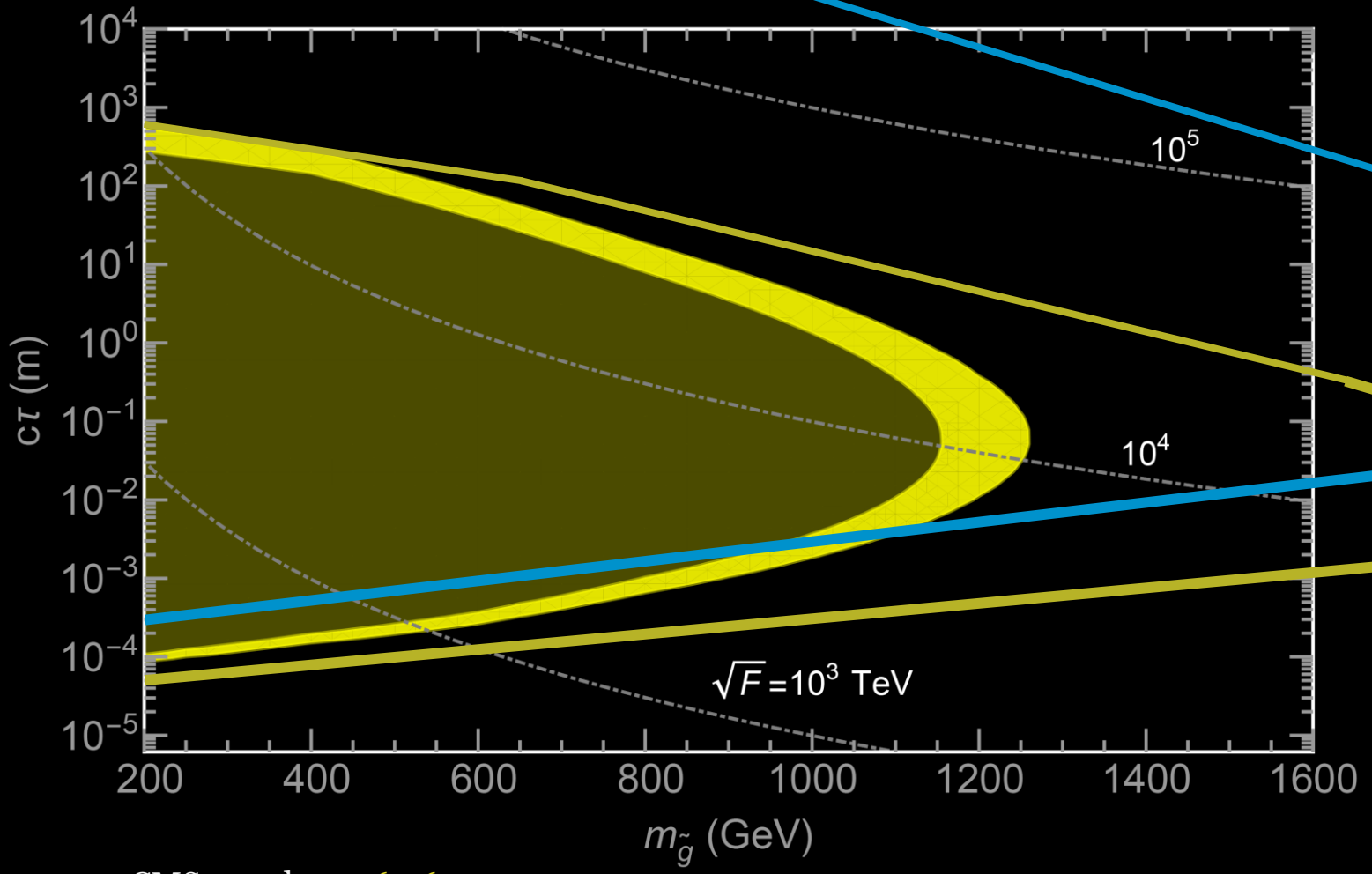


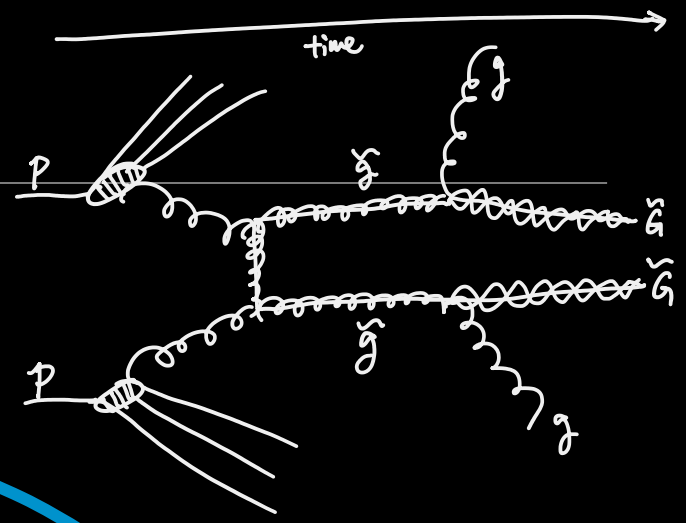


Delayed Jet analysis carried out by CMS, 139 $fb^{-1}$

Displaced jet at 13 TeV, 39 $fb^{-1}$

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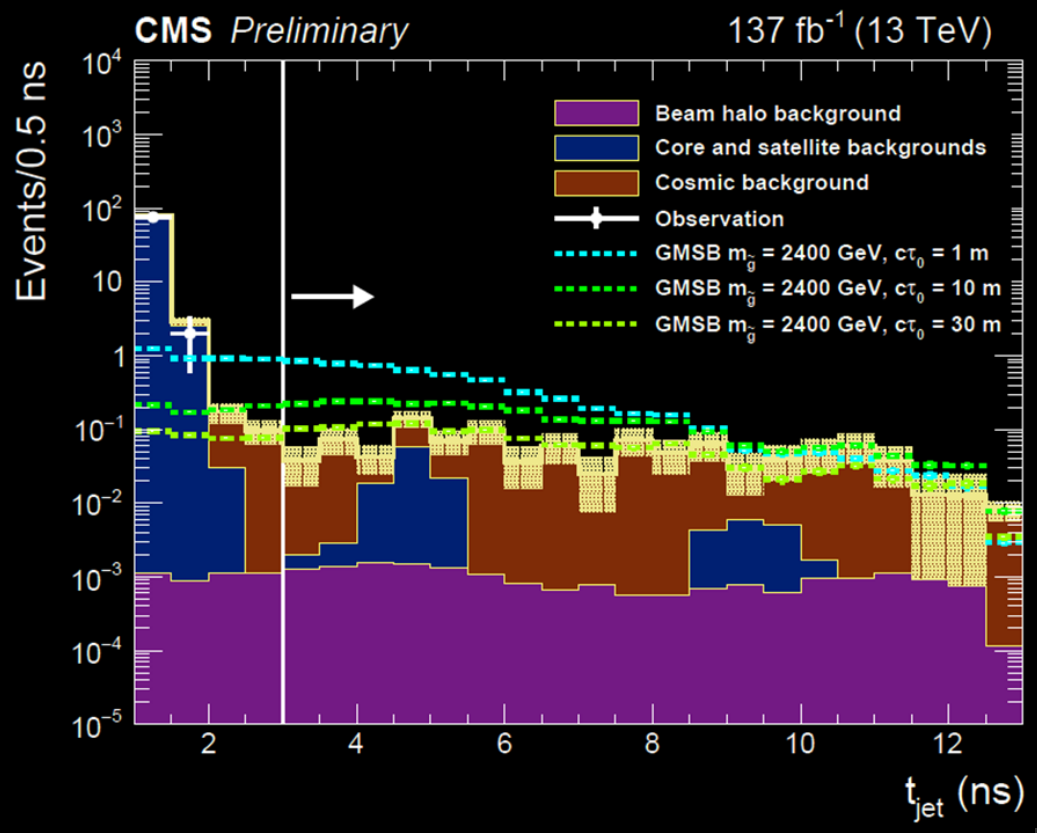
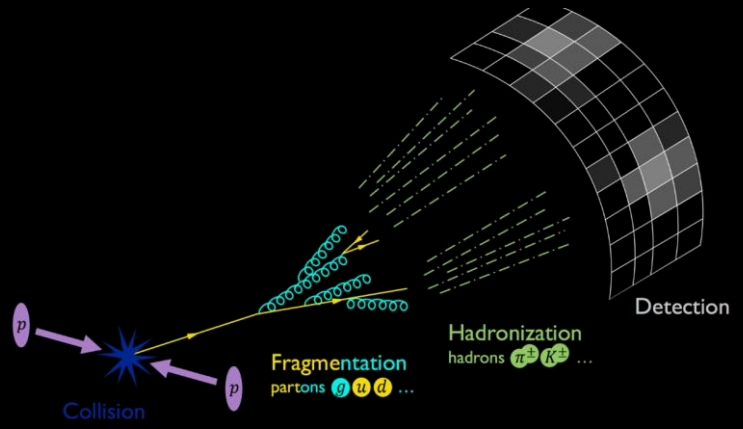
# What is the time of a jet?

Theoretically and experimentally interesting




The pioneering delayed jet search used median time, clearly having large room to improve.

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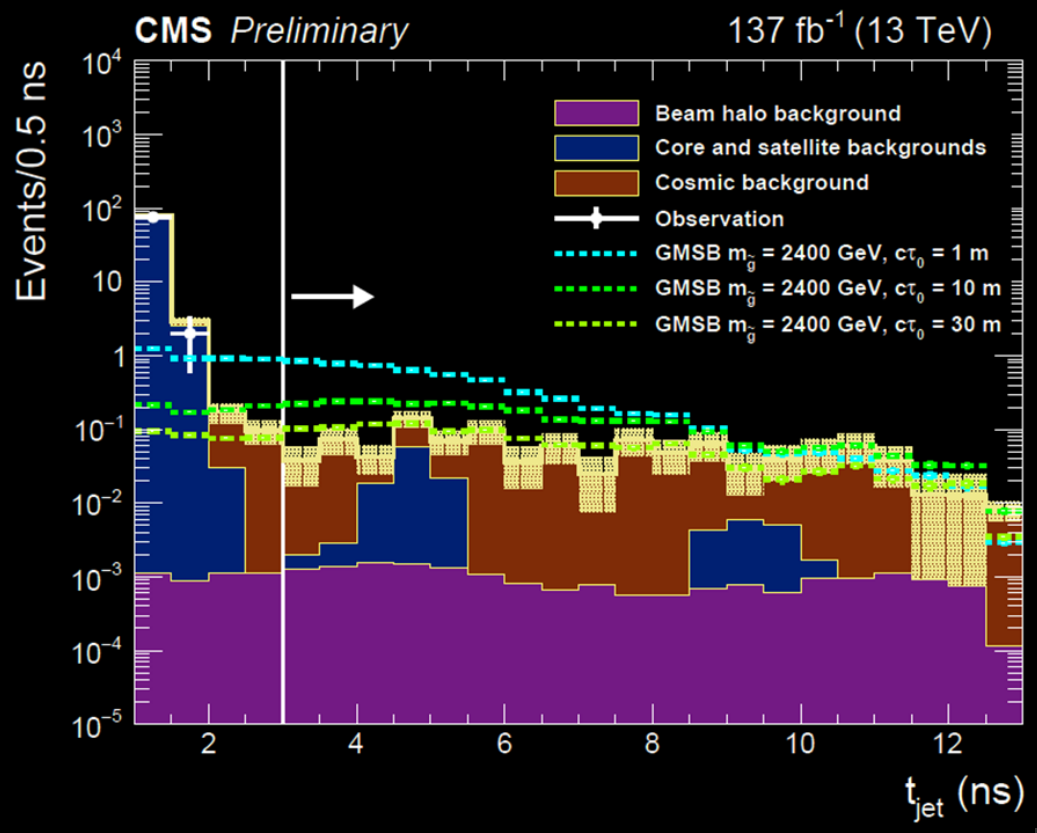
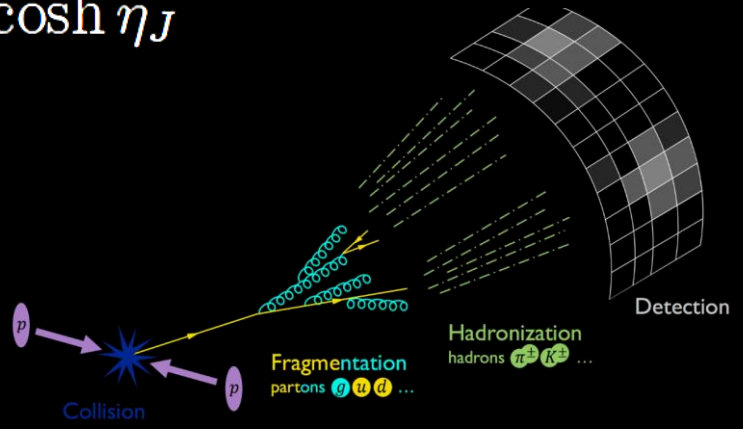



$$t_J^{\{\text{median,hardest,random}\}} = t_{\{i_m,i_h,i_r\}} = \frac{r_T}{c}\cosh\eta_{\{i_m,i_h,i_r\}}$$

$$t_J^{\text{null}} = \frac{r_T}{c}\frac{|\vec{p}_J|}{p_{T,J}} = \frac{r_T}{c}\cosh\eta_J$$

$$t_J^{\text{kinematic}} = \frac{r_T}{c}\frac{E_J}{p_{T,J}}$$

$$t_J^{\text{average}} = \frac{1}{N}\sum_{i=1}^{N} t_i$$




$$t_J^{p_T} = \frac{1}{p_{T,S}}\sum_{i=1}^{N} p_{T,i}t_i, \qquad p_{T,S} = \sum_{i=1}^{N} p_{T,i}$$

$$t_J^{(\alpha,\beta,\gamma)} \propto \sum_{i\in\text{jet}} (p_{T,i})^{\alpha}(\Delta R_i)^{\beta} t_i^{\gamma}$$

Chiu, ZL, Low, Wang, 2109.01682

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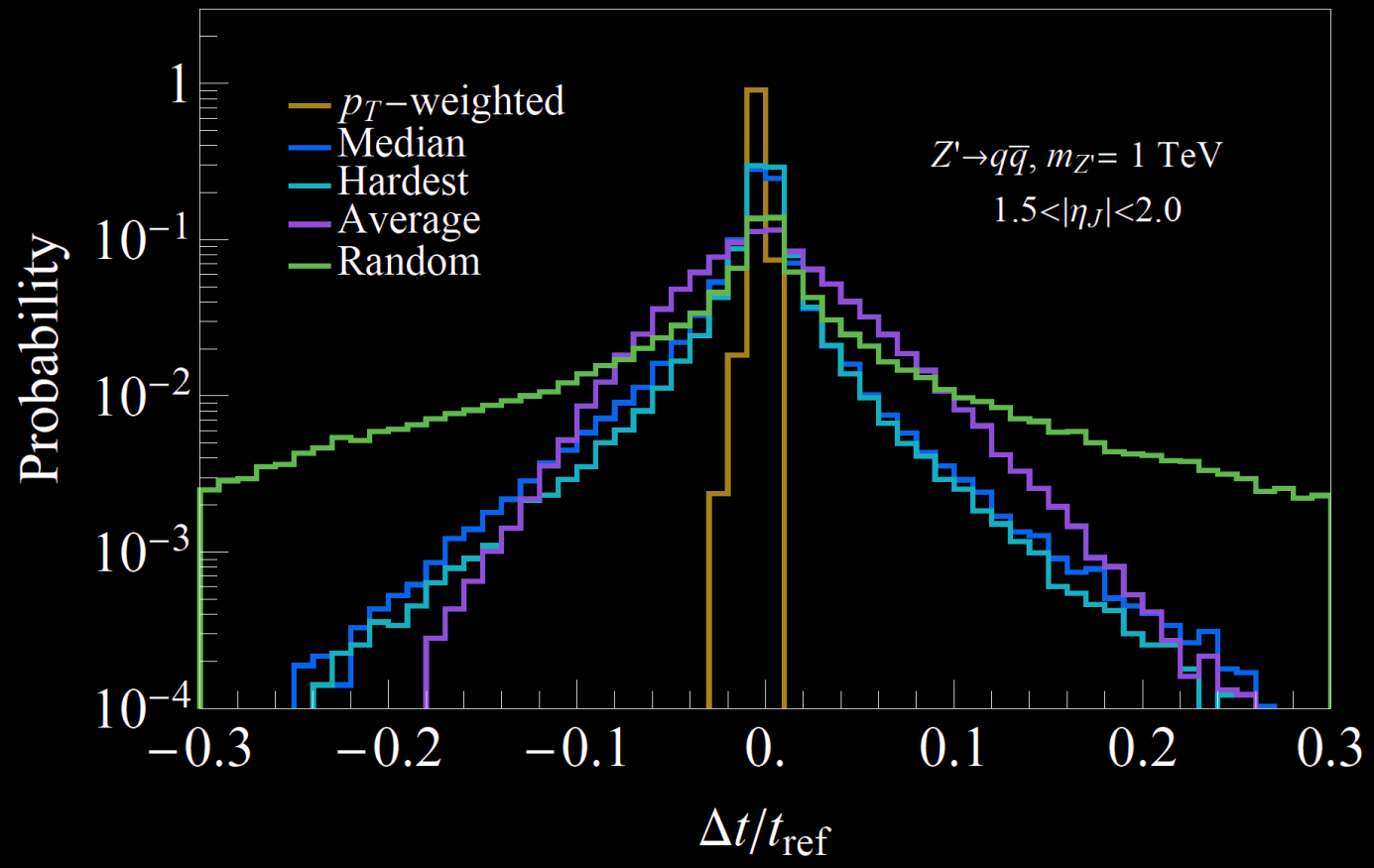
# Tackle Time: what is the time of a jet?




pT-weighted time provides the best convergence, and hence the quasi-optimal experimental definition of the jet time.
It is also IR-safe and calculable quantity.
Other jet time definitions spreads out driven by soft/colinear behaviors, further imprinted by geometrical effects..

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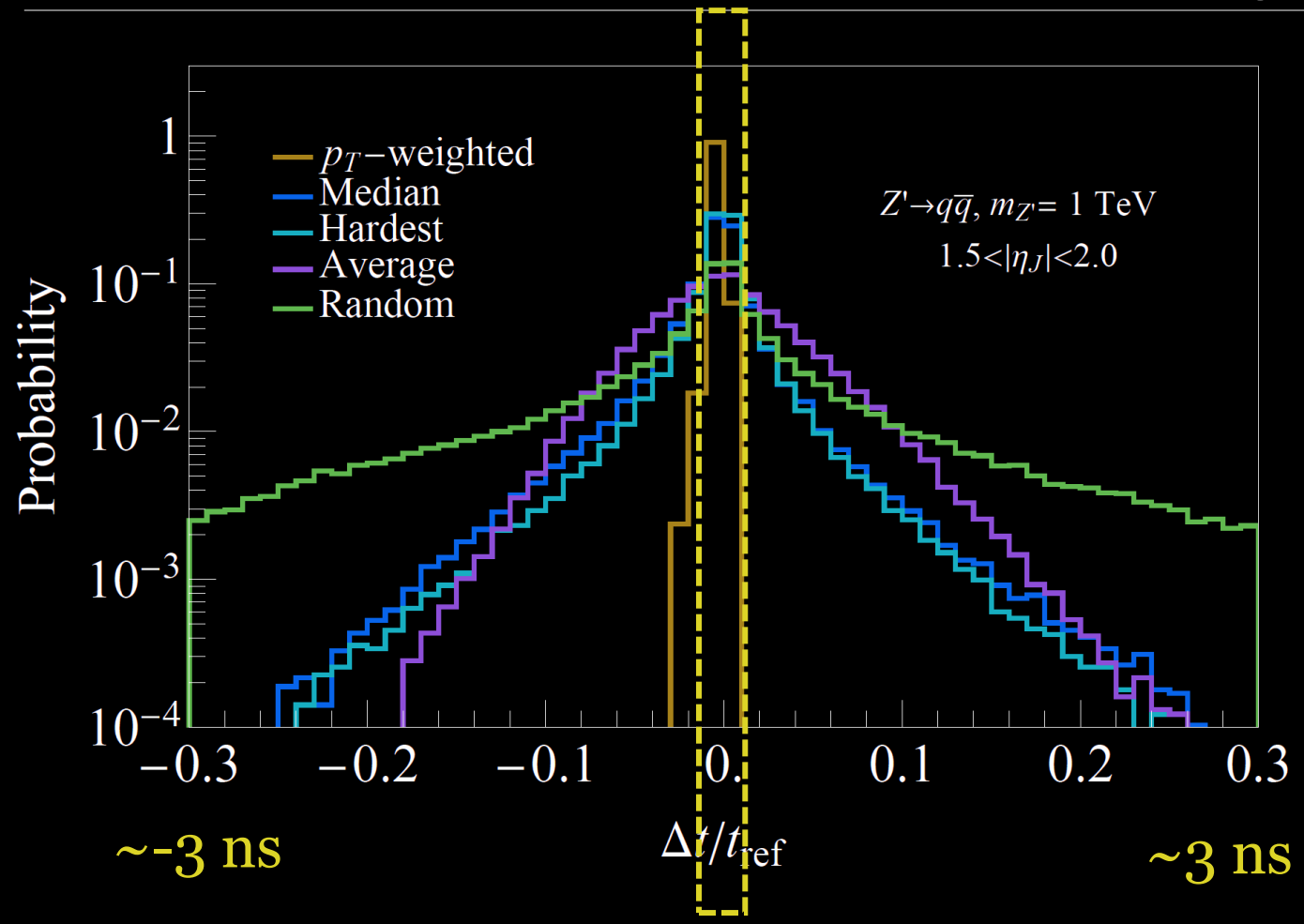


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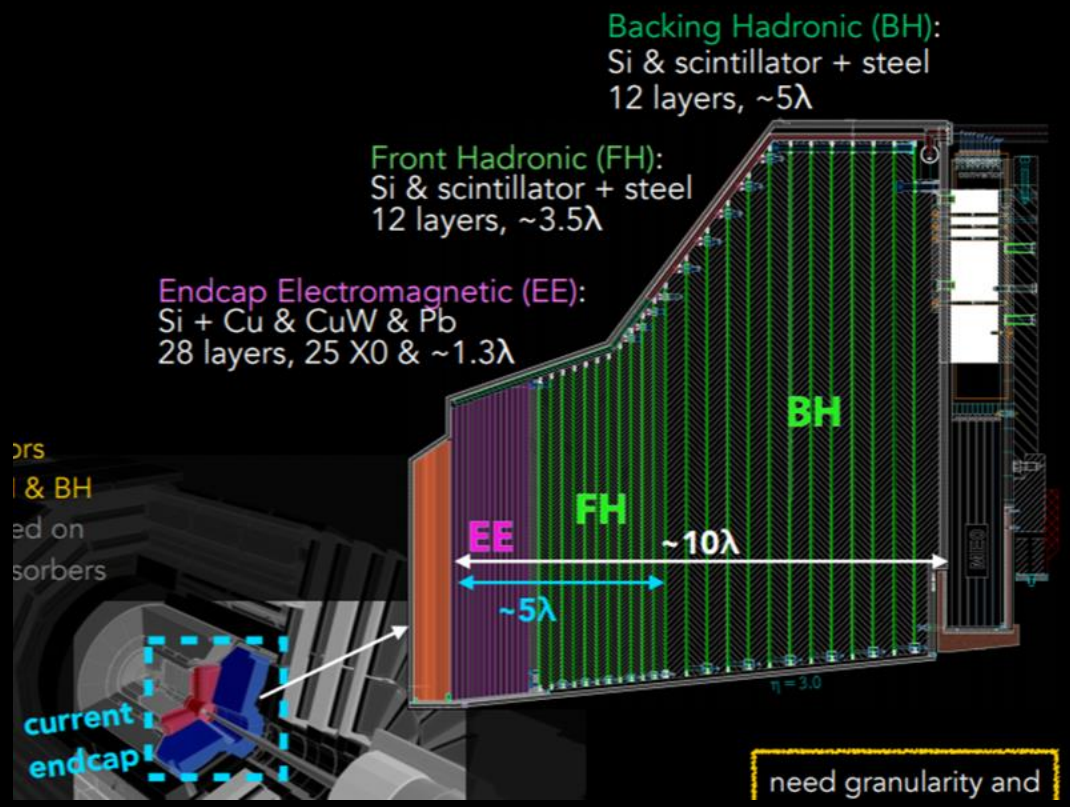
# Realize the true power of LHC

Displaced tracks trigger, Timing in trigger
LLP searches in all subsystems, e.g.,

- muon spectrometer
- HGCal, HGTD, Mip Timing Detector

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## Expanding LHC program

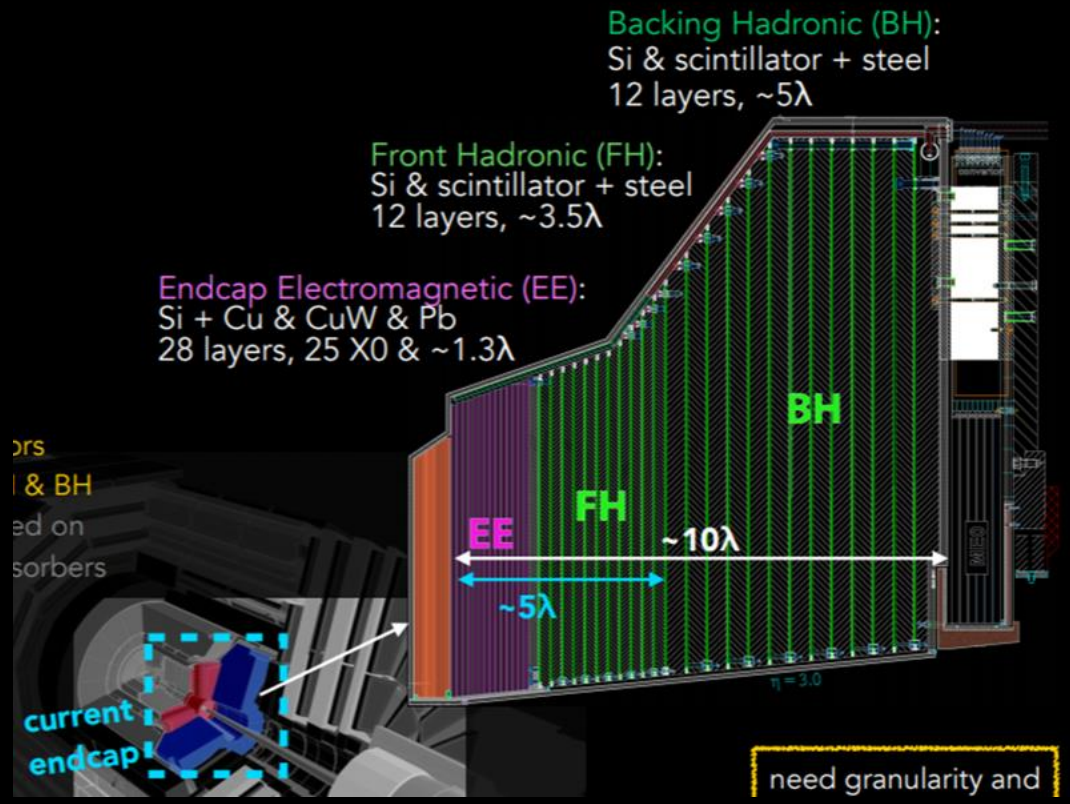
MATHUSLA
Codex-B
AL3X
ANUBIS
} Central/Hard LLPs

FASER, FPF
(SND), SHiP
NA62
SeaQuest
... } Forward/light LLPs

Beamdump experiments

MoEDAL
MilliQan } monopole
millicharged particles

} Search for LLPs

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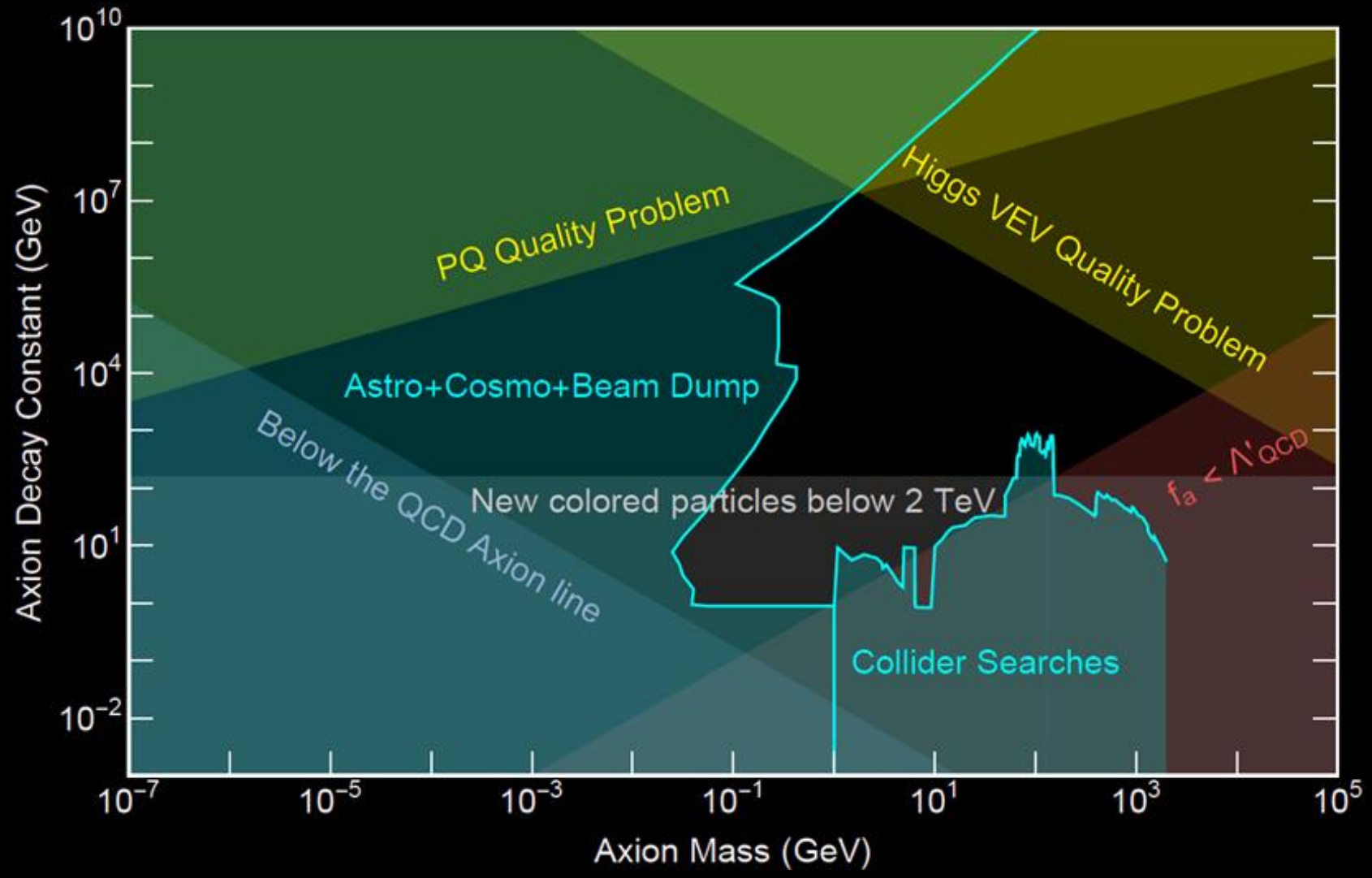
Also general (prompt) Collider Pheno: Bauer, Neubert, Thamm, 1708.00443, + Heiles 1808.10323 + Renner, Schnubel, 2110.10698 and many more from various groups.

# Possible for heavy Axions




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.

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

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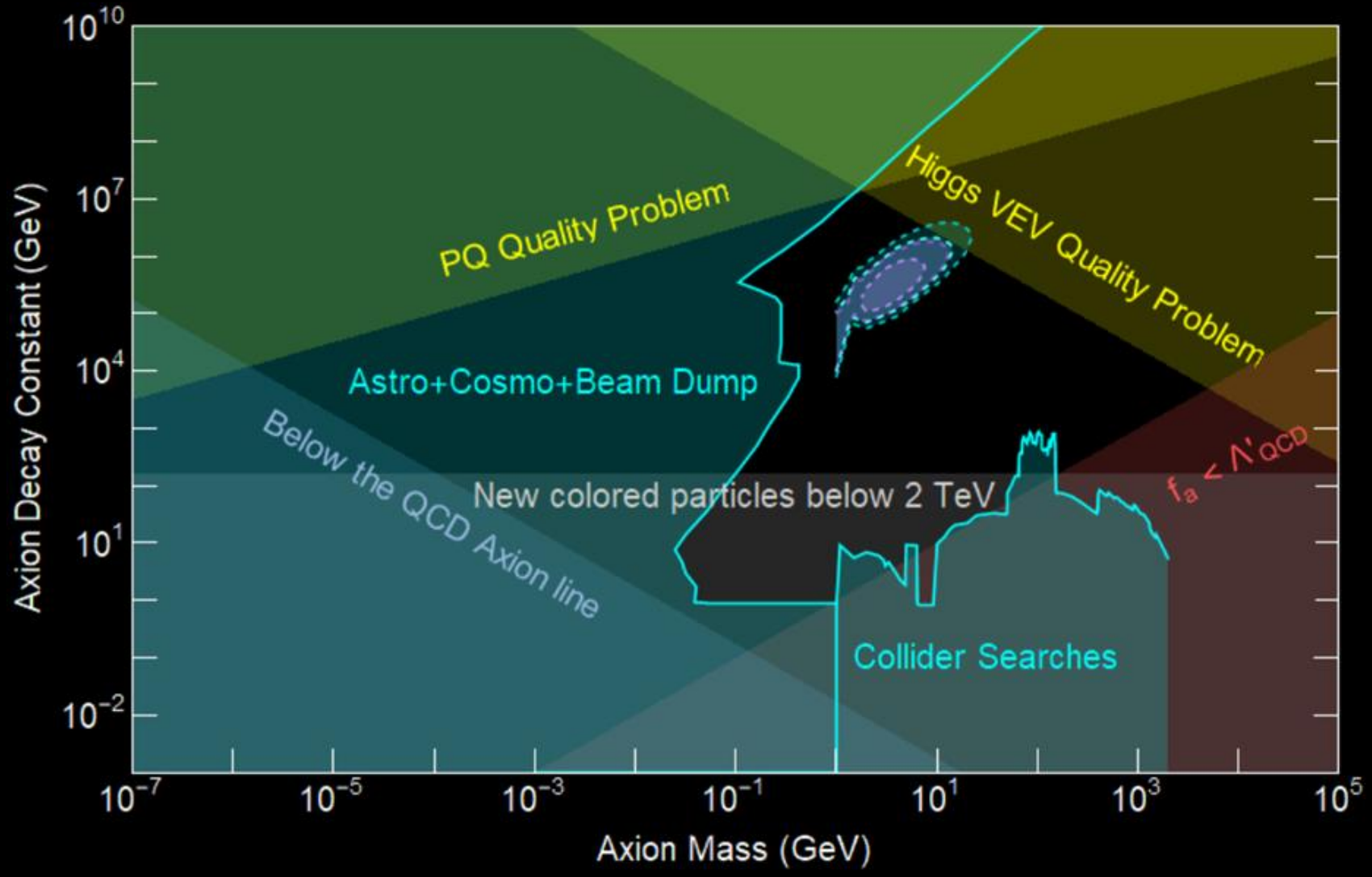


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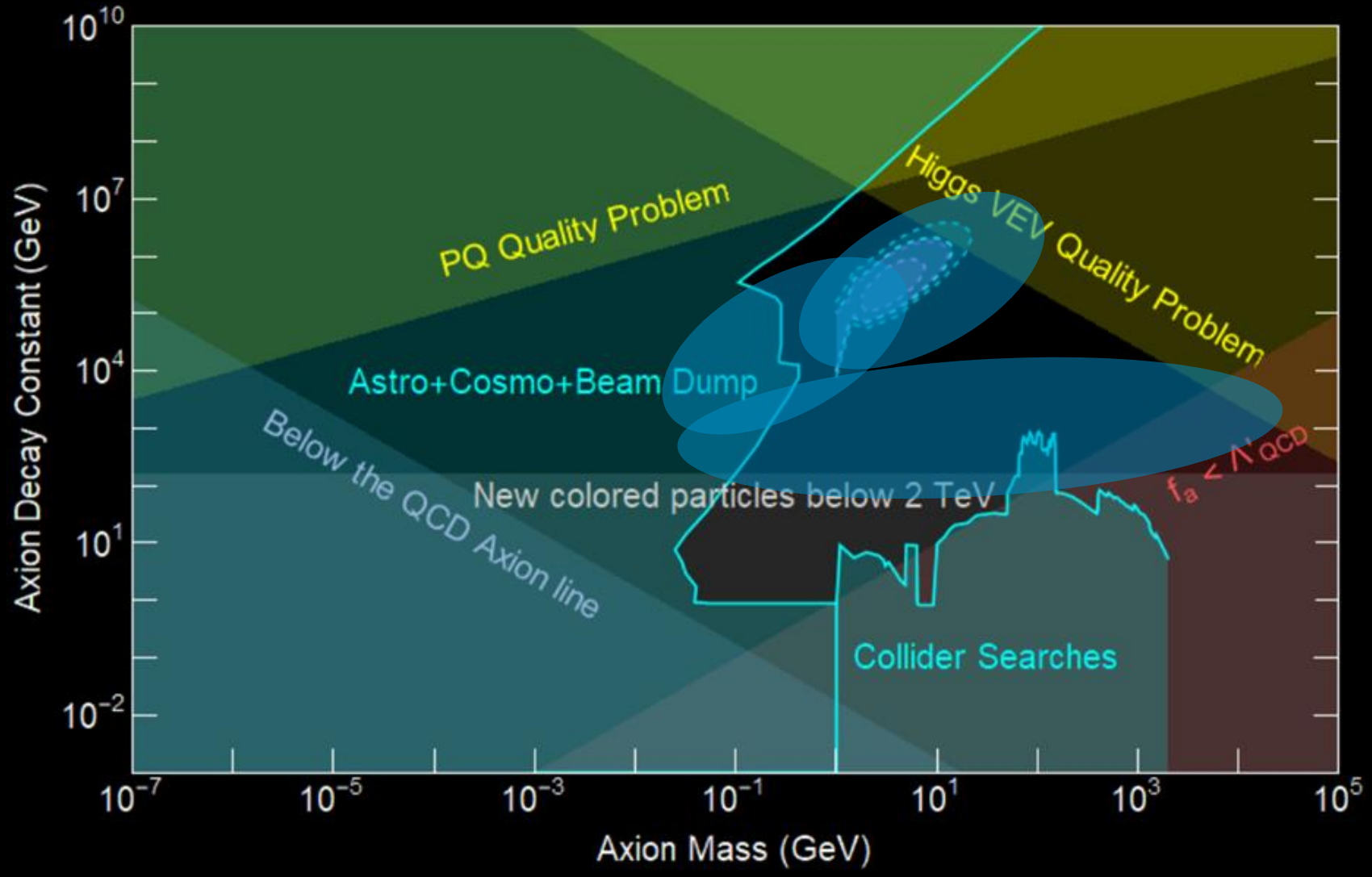


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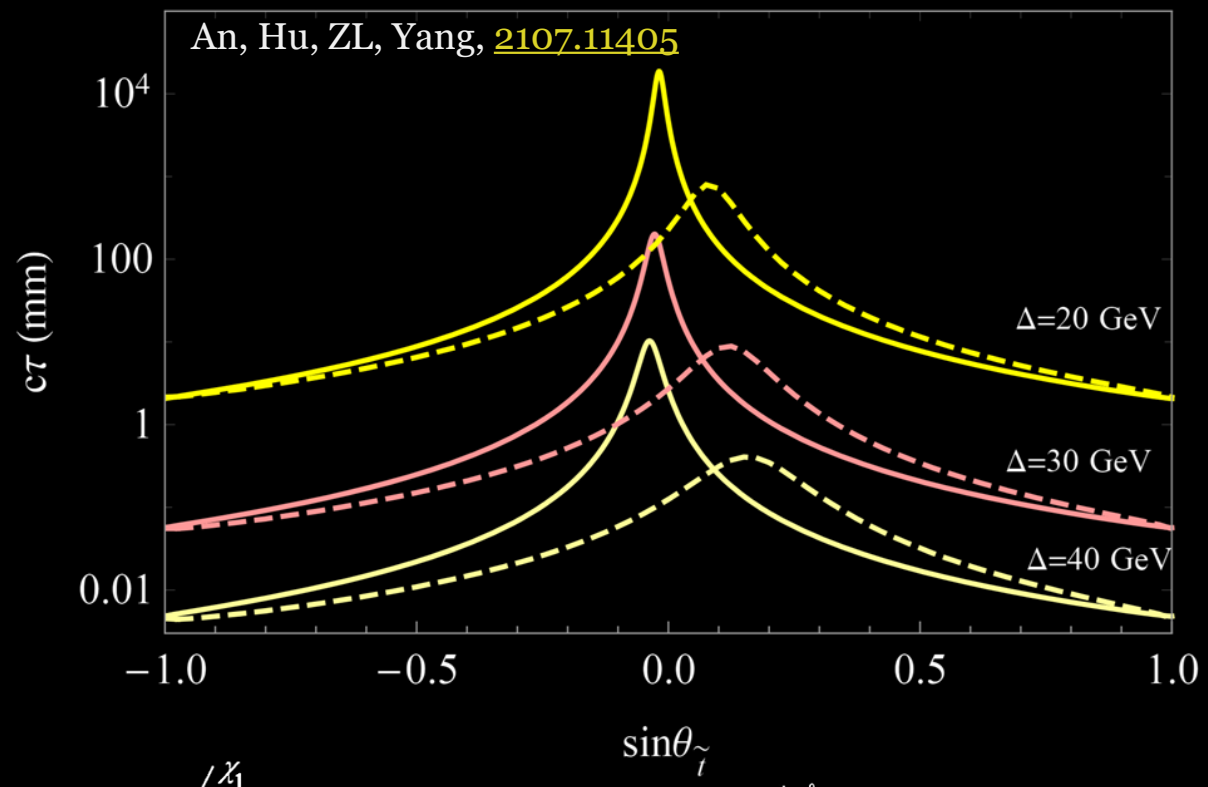
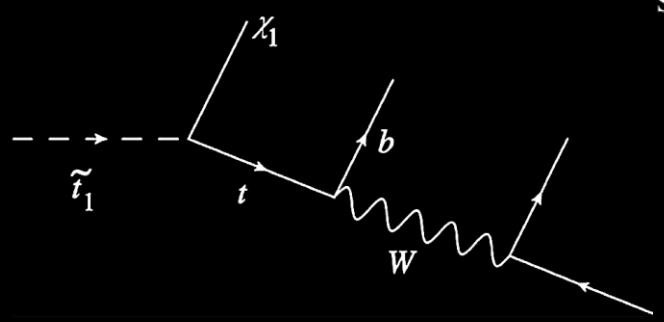
# Characters of the adventure

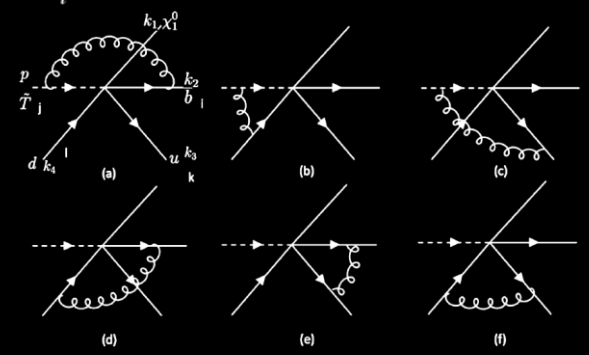
- Deep
  - Beyond the classical level
  - +beyond
- Broad
  - Long-Lived Particles
  - +beyond
- Open
  - Open to non-traditional targets

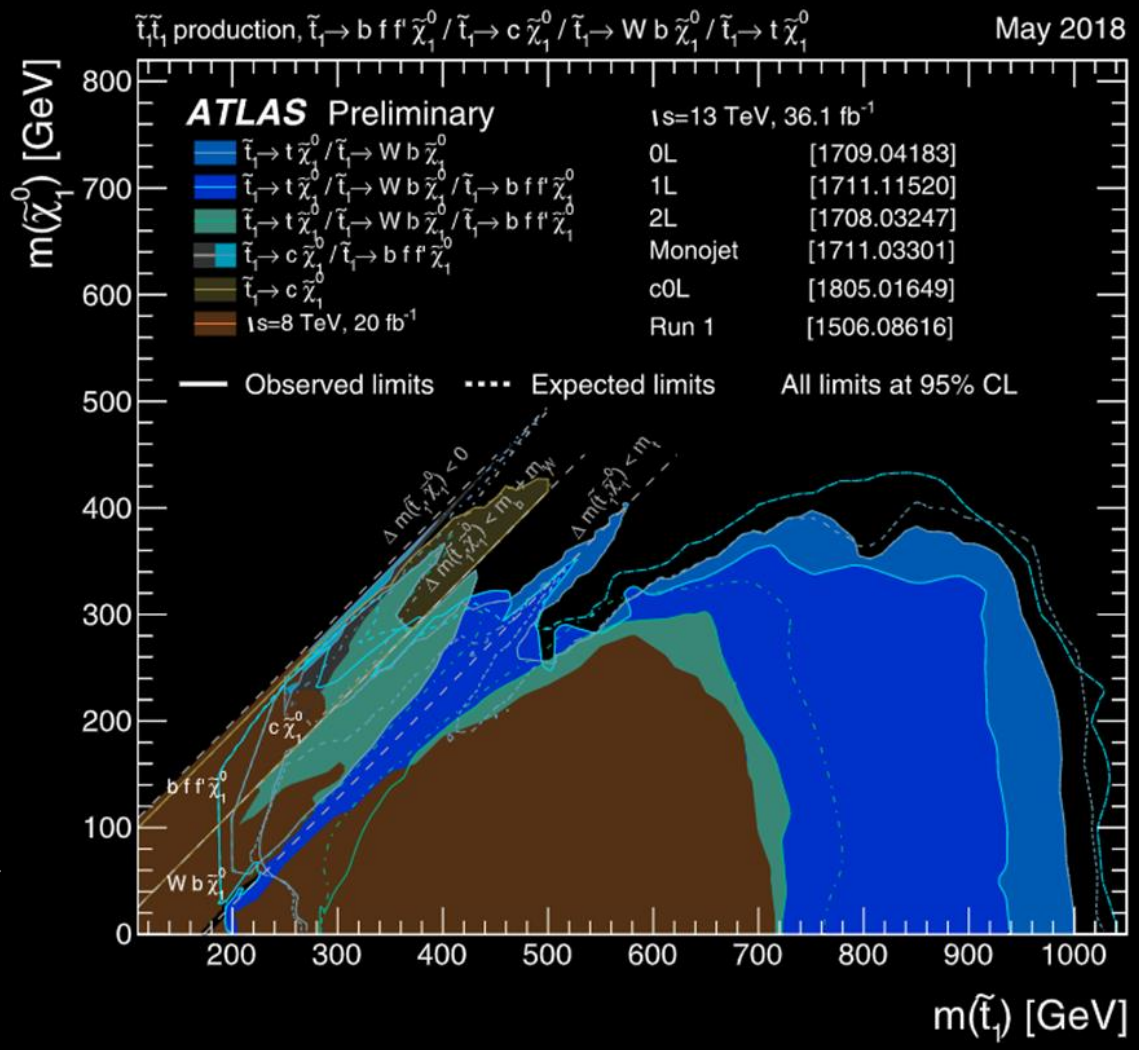
# Coannihilation and LLP

Mono-jet + (soft) displaced tracks



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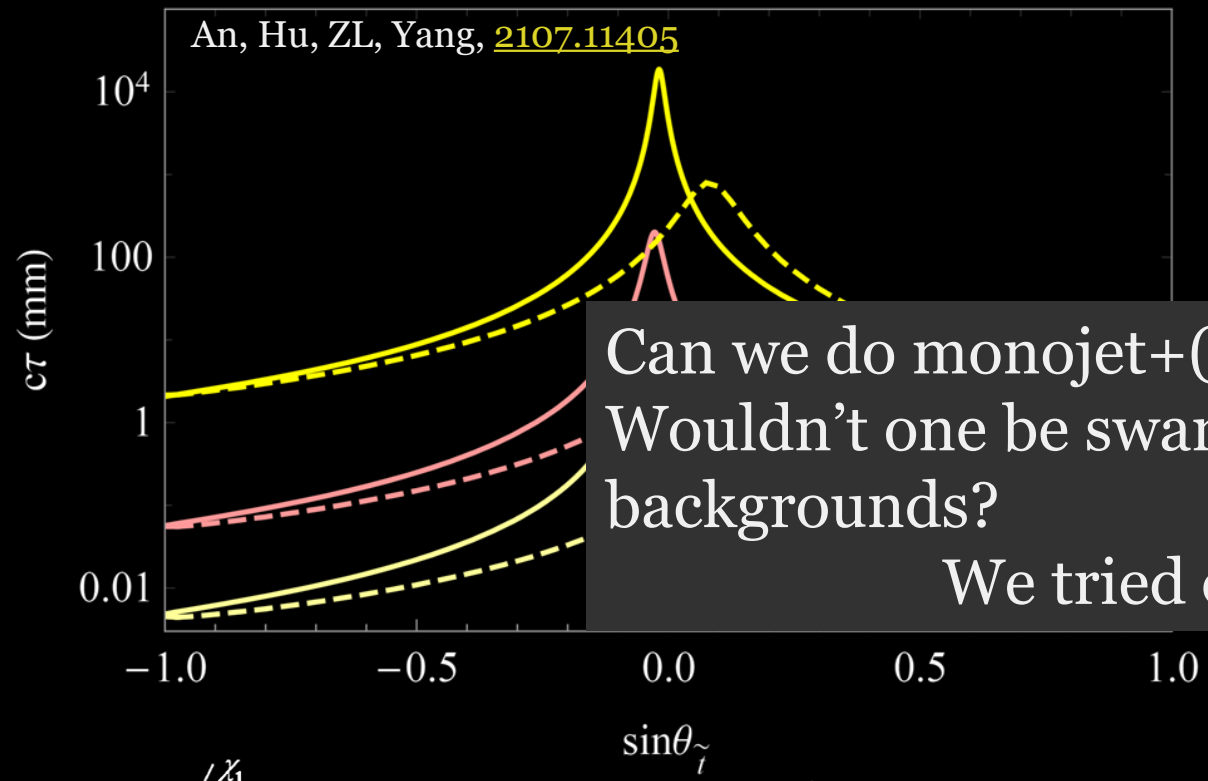
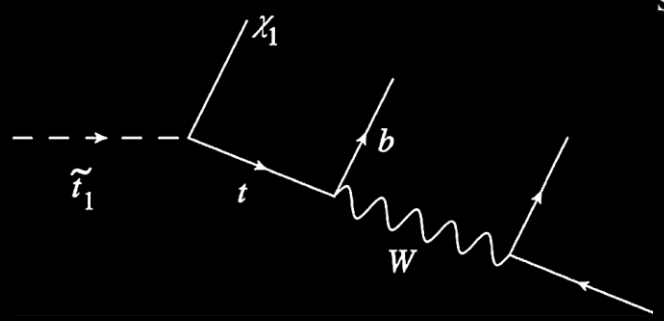
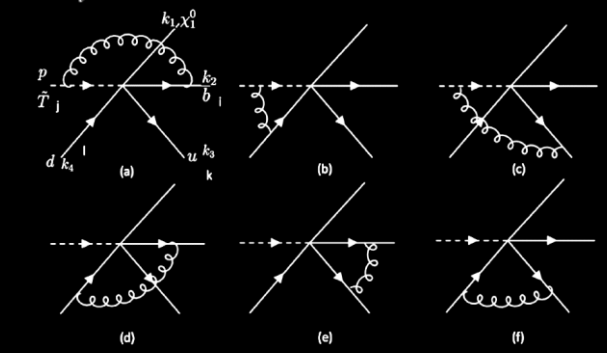
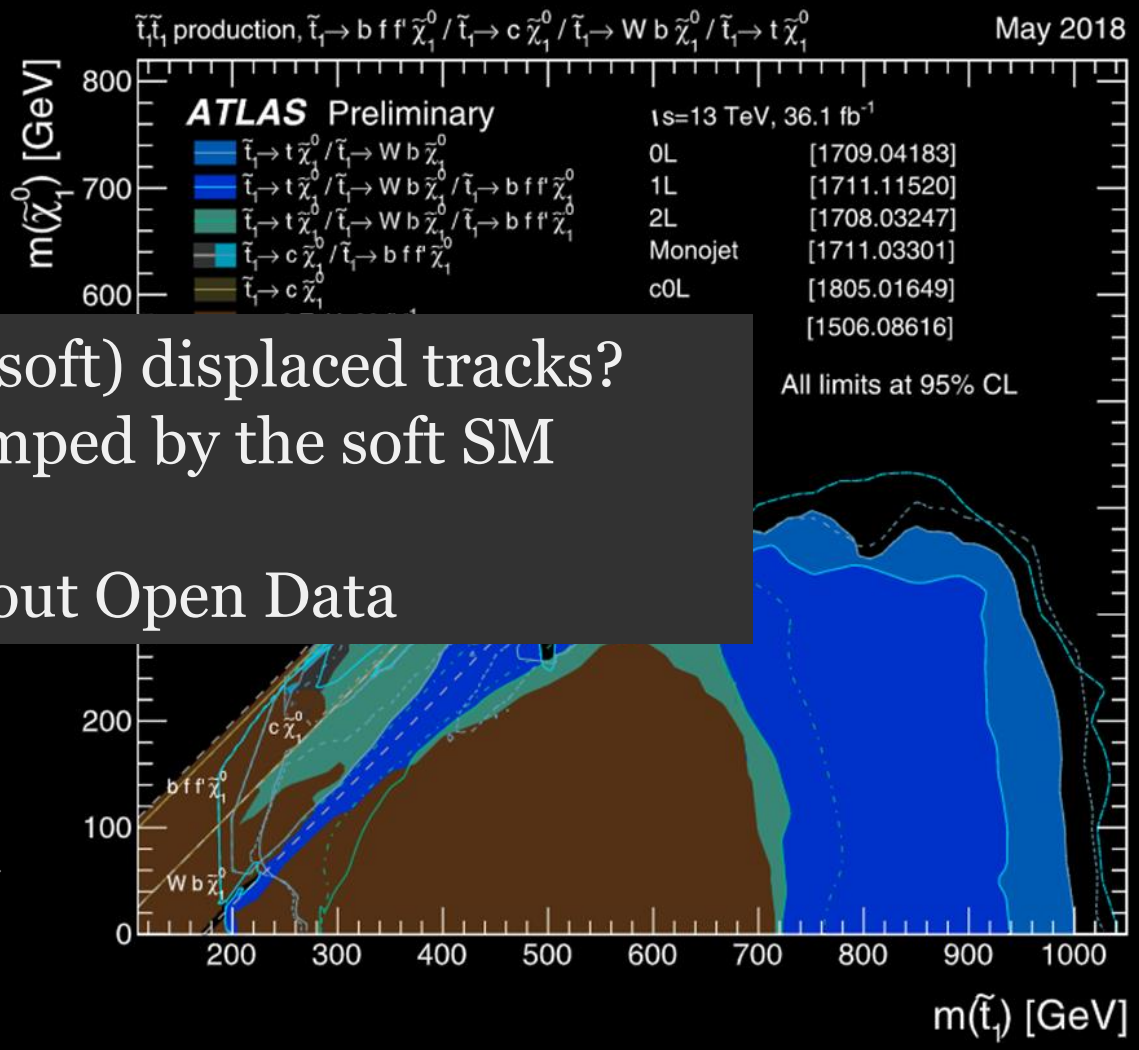


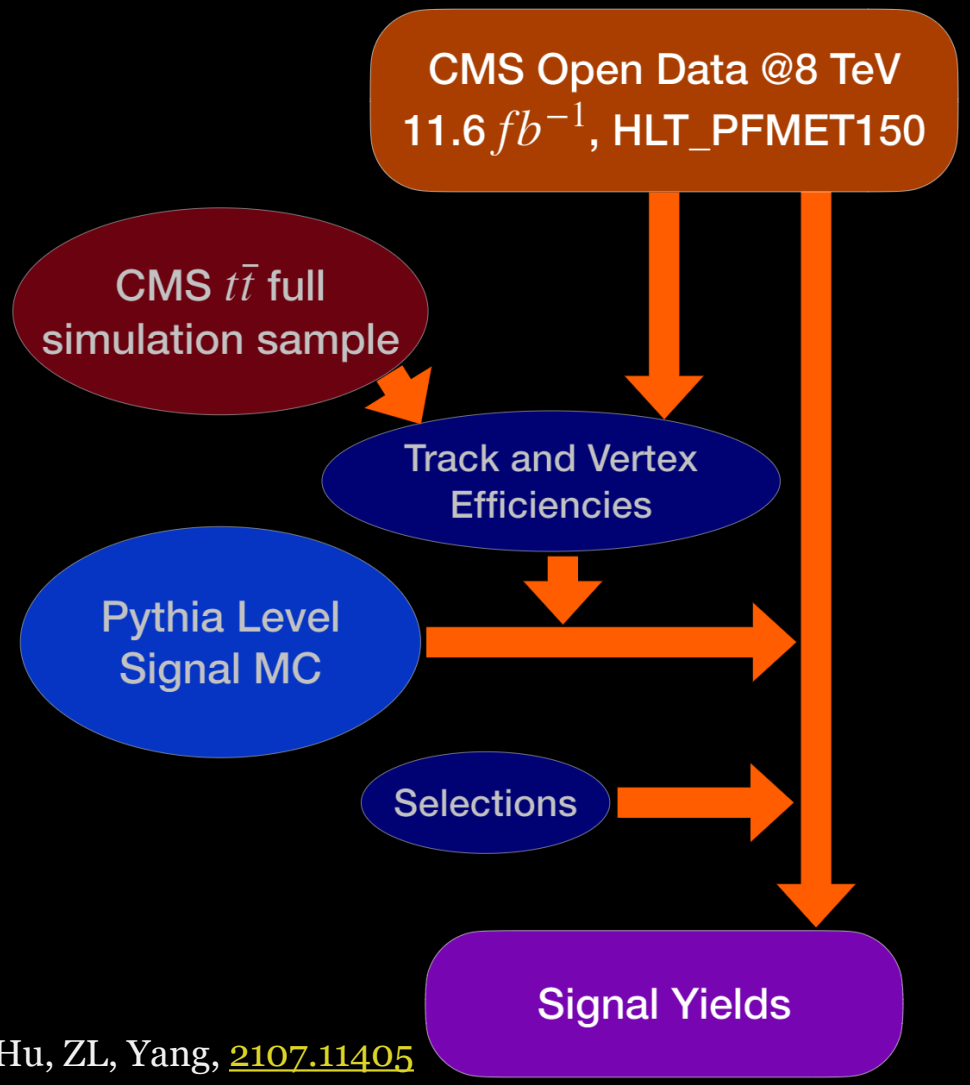



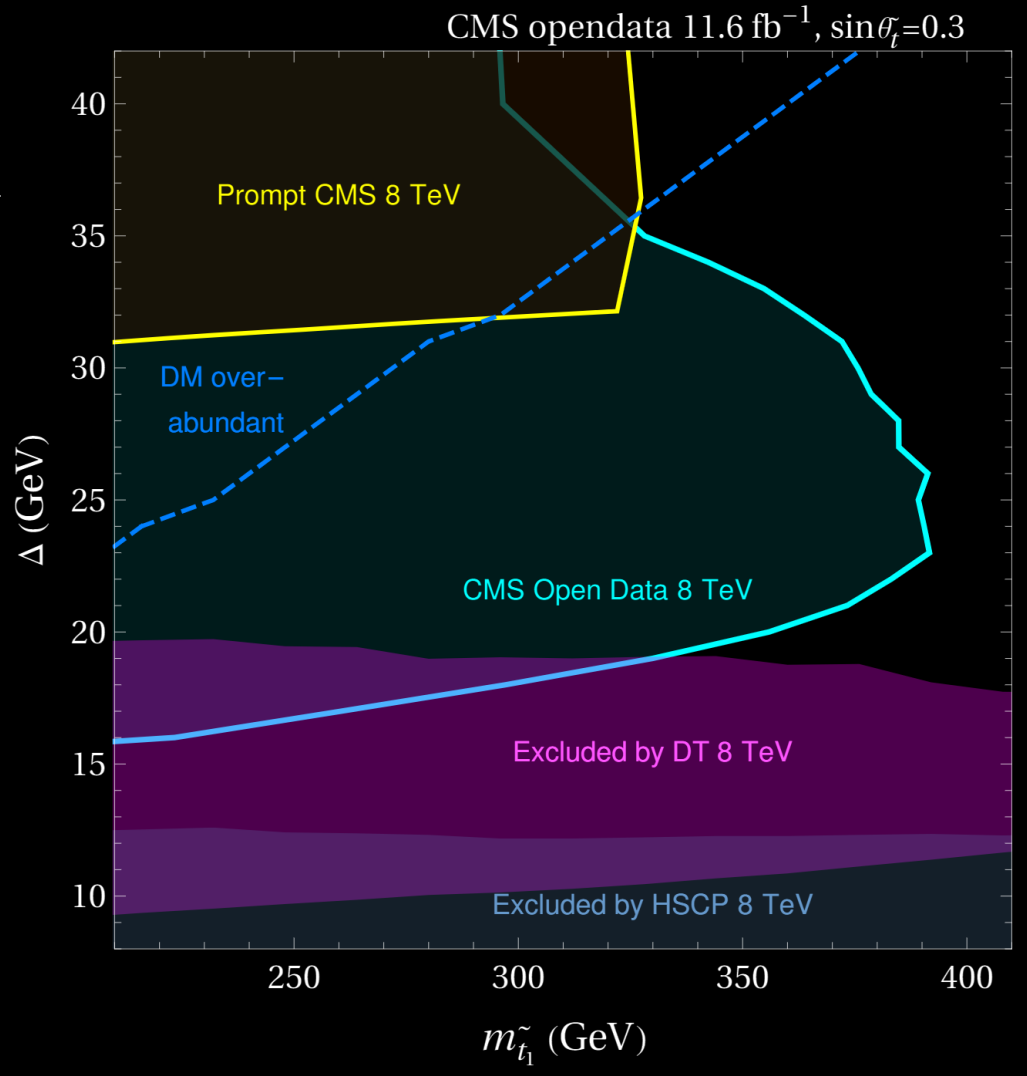




Can we do monojet+(soft) displaced tracks? Wouldn't one be swamped by the soft SM backgrounds?

We tried out Open Data

# New results from Open Data




An, Hu, ZL, Yang, 2107.11405

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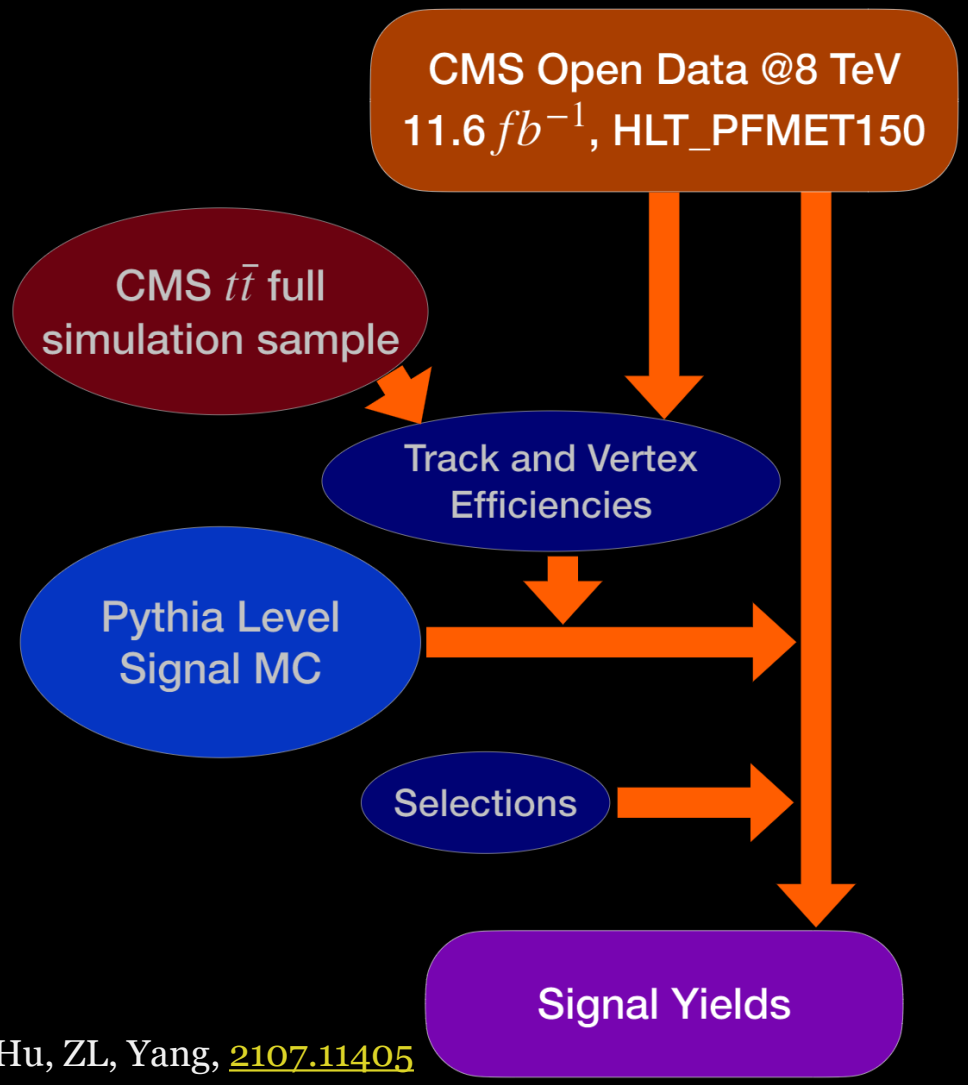


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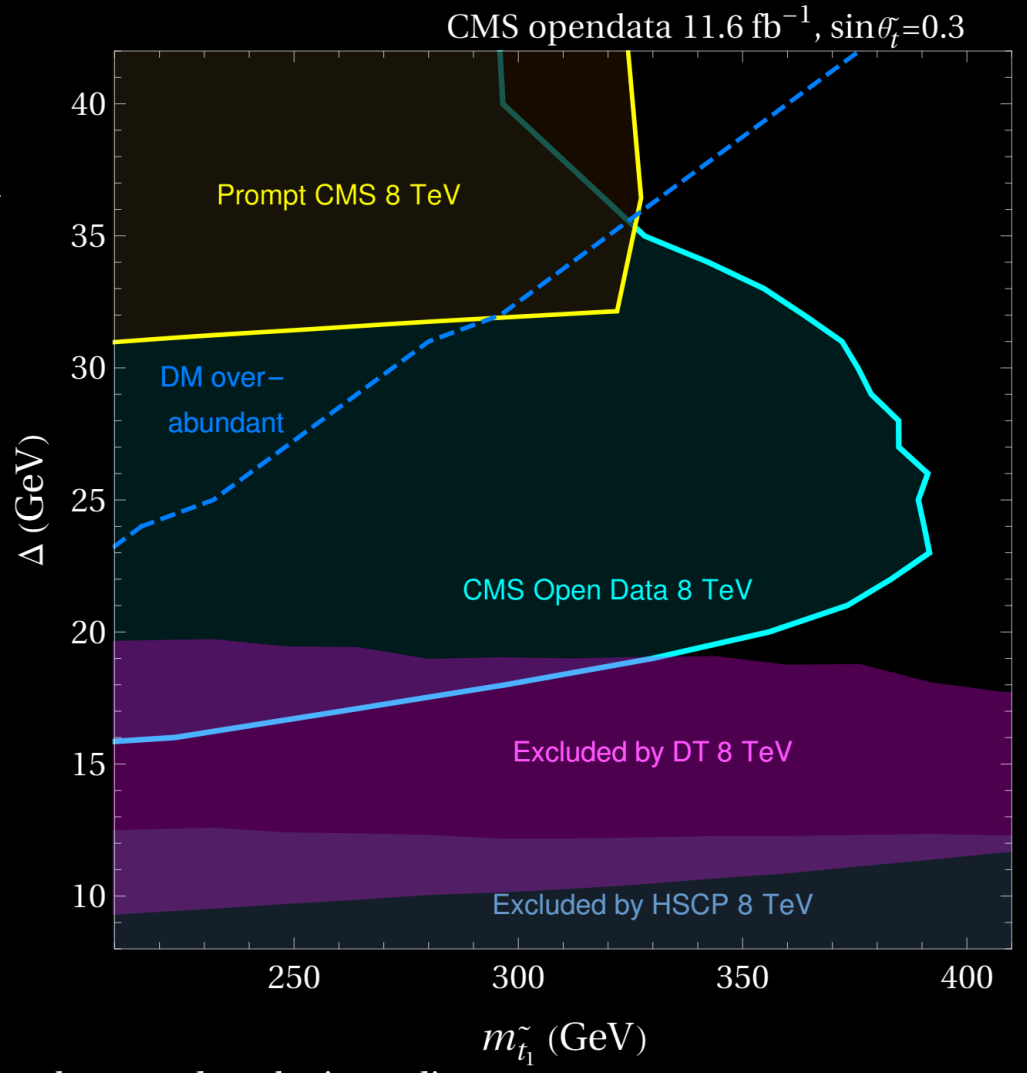



See also for other open data physics studies,
A. Larkoski, S. Marzani, J. Thaler, A. Tripathee, and W. Xue 1704.05066,
A. Tripathee, W. Xue, A. Larkoski, S. Marzani, and J. Thaler 1704.05842,
M. Andrews, J. Alison, S. An, P. Bryant, B. Burkle,S.
Gleyzer, M. Narain, M. Paulini, B. Poczos, and E. Usai 1902.08276,
P. T. Komiske, R. Mastandrea, E. M. Metodiev,P. Naik, and J. Thaler 1908.08542,
C. Cesarotti, Y. Soreq, M. J. Strassler, J. Thaler, and W. Xue 1902.04222.

# Shower of Heavy Neutral Leptons

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

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

# Shower of Heavy Neutral Leptons

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

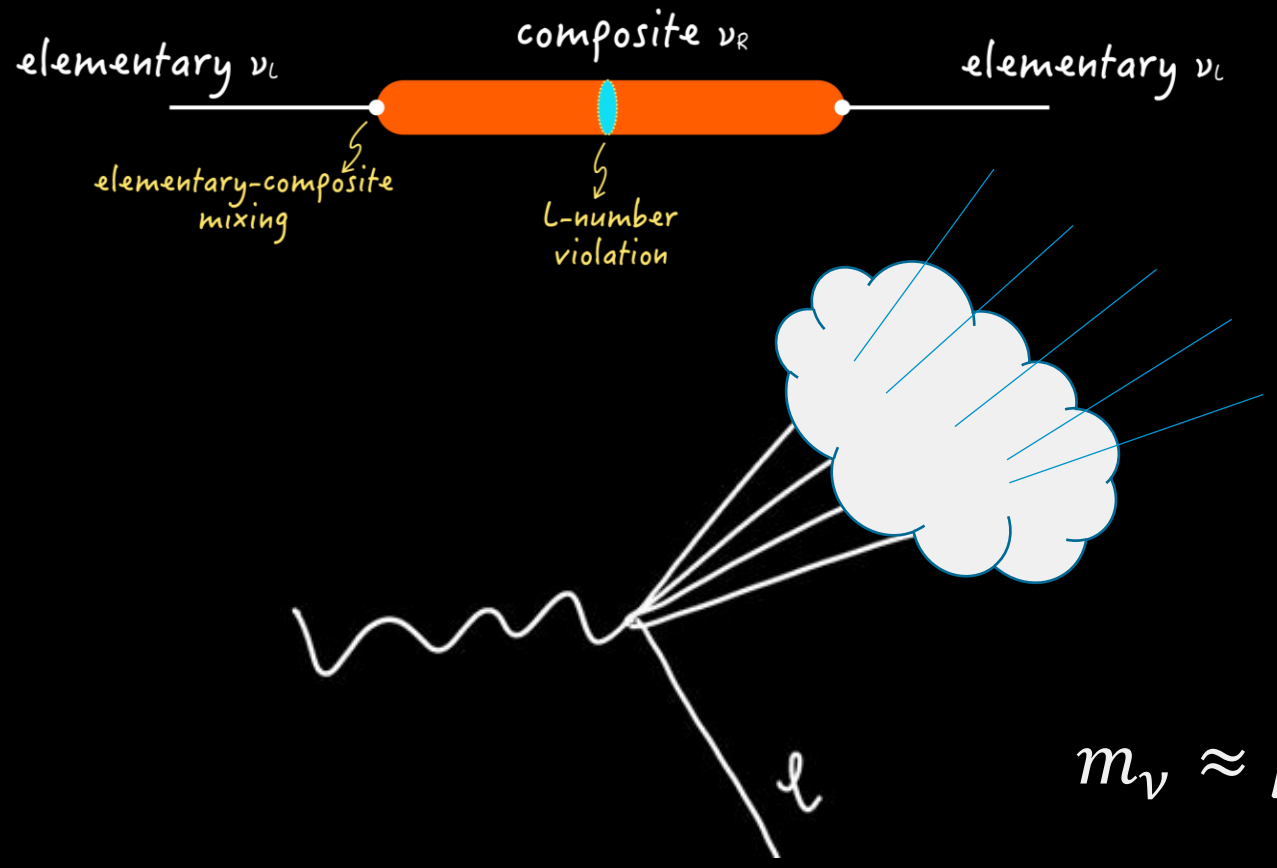
$$L_{IR} \ni -m_N \bar{N} N - (\lambda \bar{L}\tilde{H} N_R + \mu N_L^2 + h.c.)$$

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

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

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, 2012.01443

# Shower of Heavy Neutral Leptons




A shower of Sterile Neutrinos…

Chacko, Dev, ZL, Sanket, to appear

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

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

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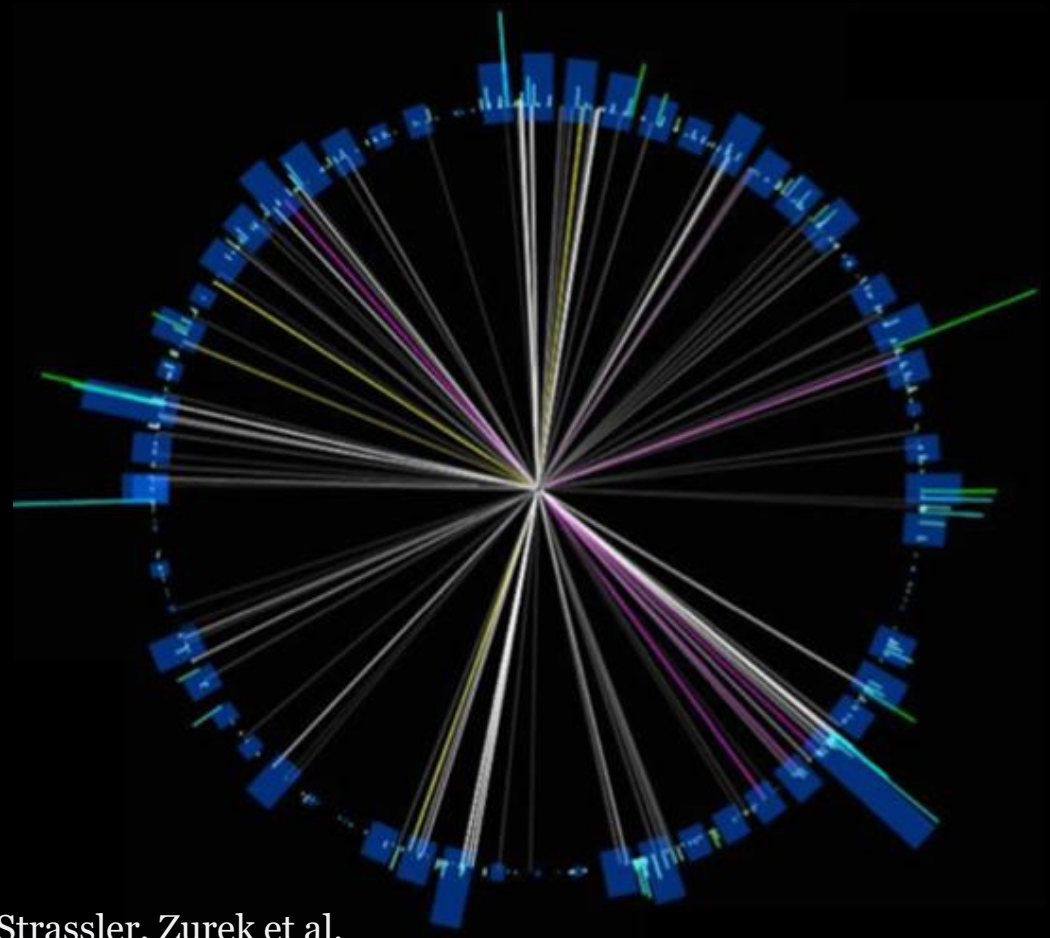
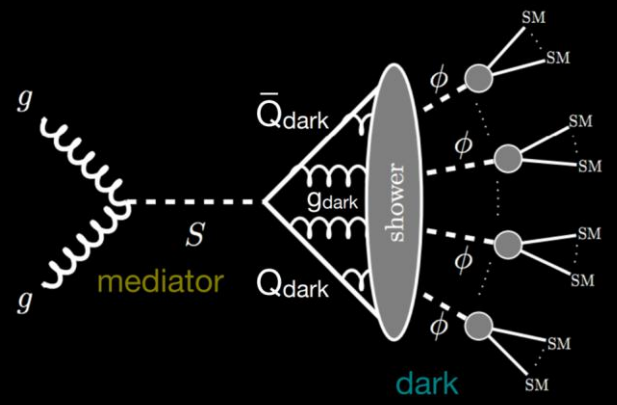
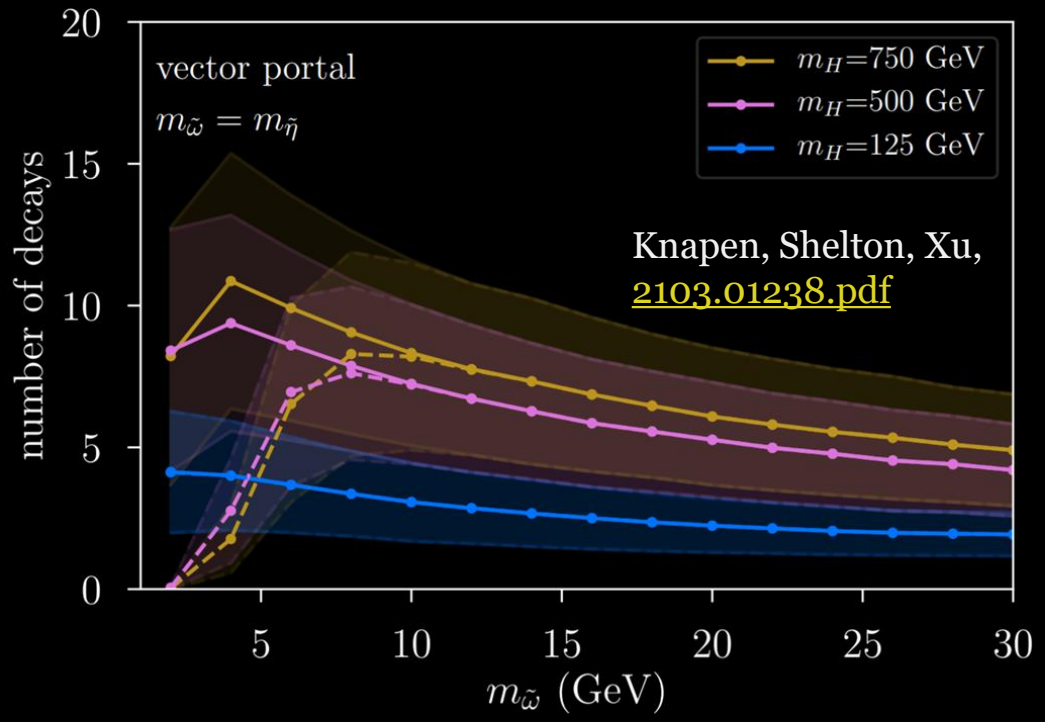
# More generally, dark showers in various forms





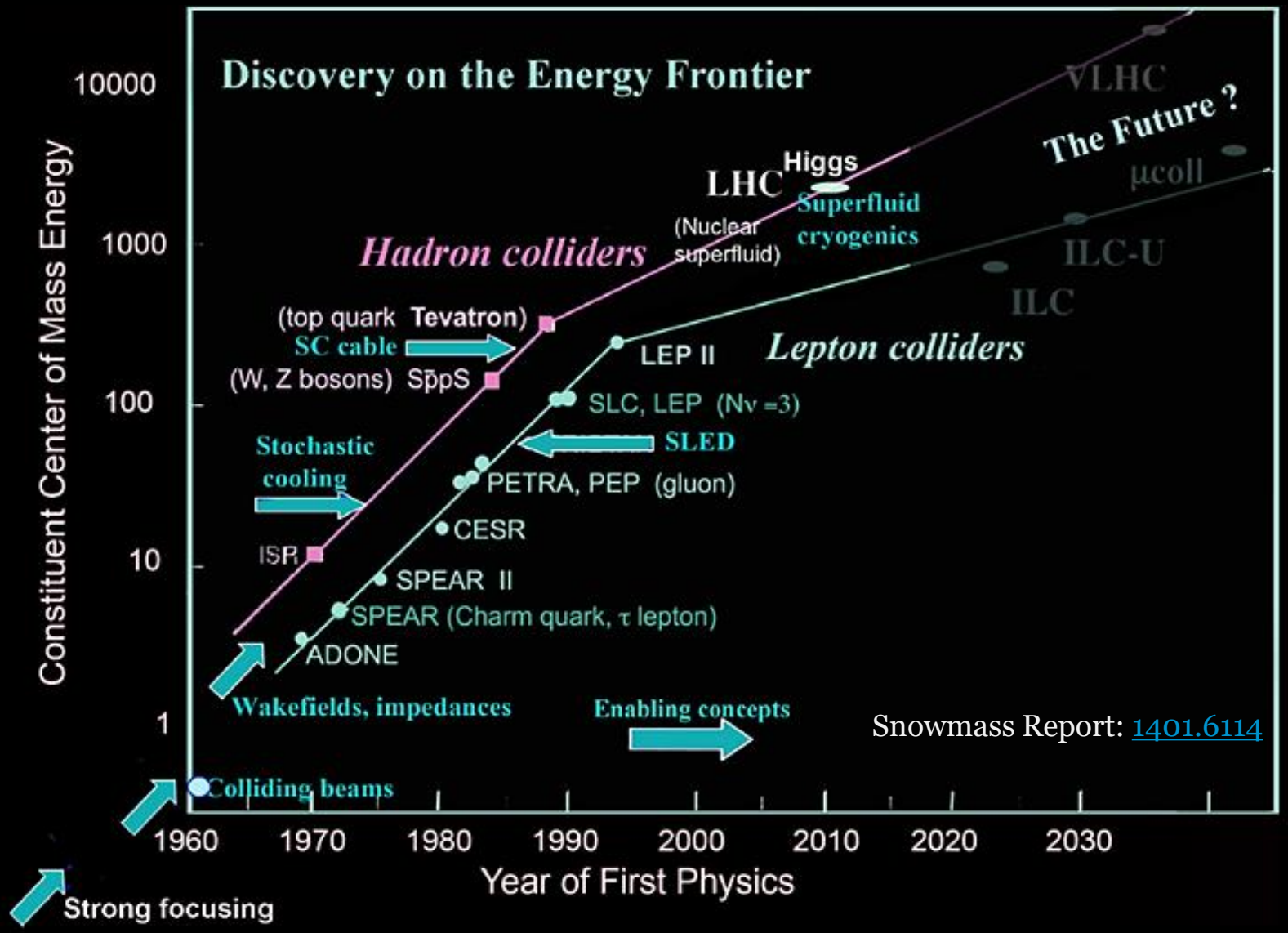

Knapen, Shelton, Xu, 2103.01238.pdf

e.g., Strassler, Zurek et al,
Knapen, Pagan Griso, Papucci, Robinson, 1612.00850
Pierce, Shakya, Tsai, Zhao, 1708.05389
Recent development could help catching certain dark showers
Cesarotti, Thaler, 2004.06125, Cesarotti, Reece, Strassler, 2009.08981

# Future Colliders

AI-generated image of Melbourne in the near future

# High Energy Drives

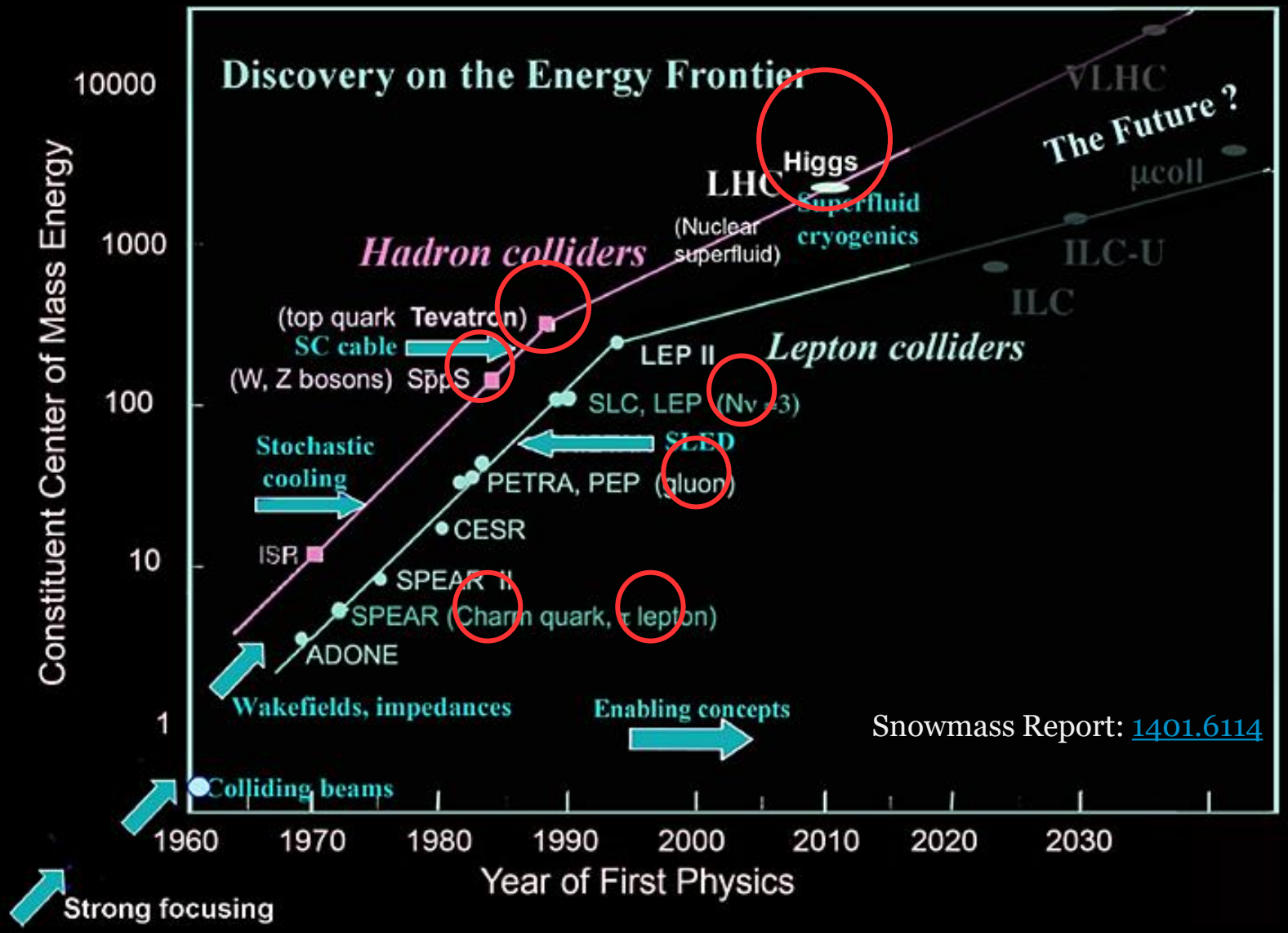



Snowmass Report: 1401.6114

The forefront of tech & ambitions leads to discoveries.

The dream for high energy machines persists in our field.

# High Energy Drives

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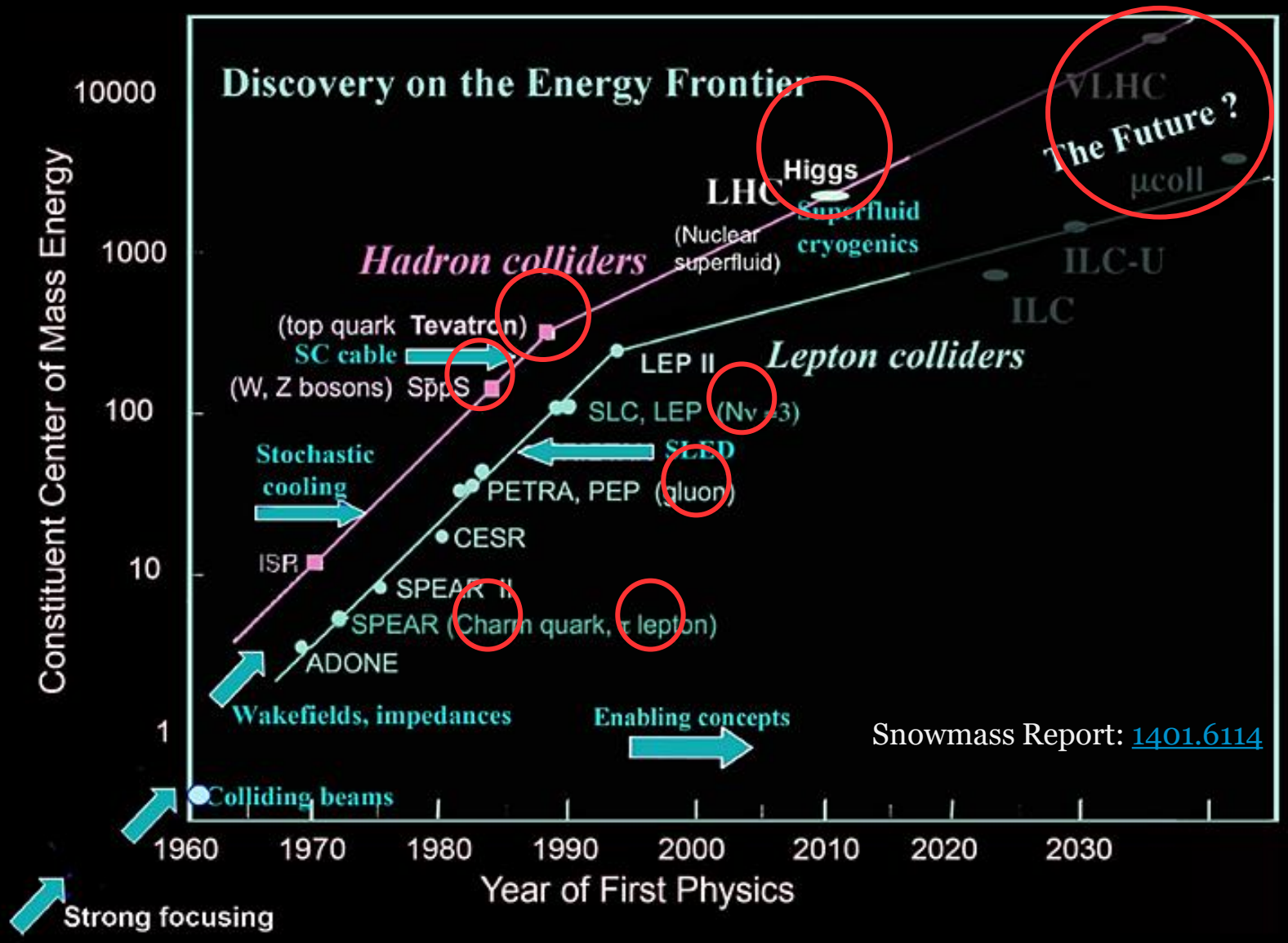


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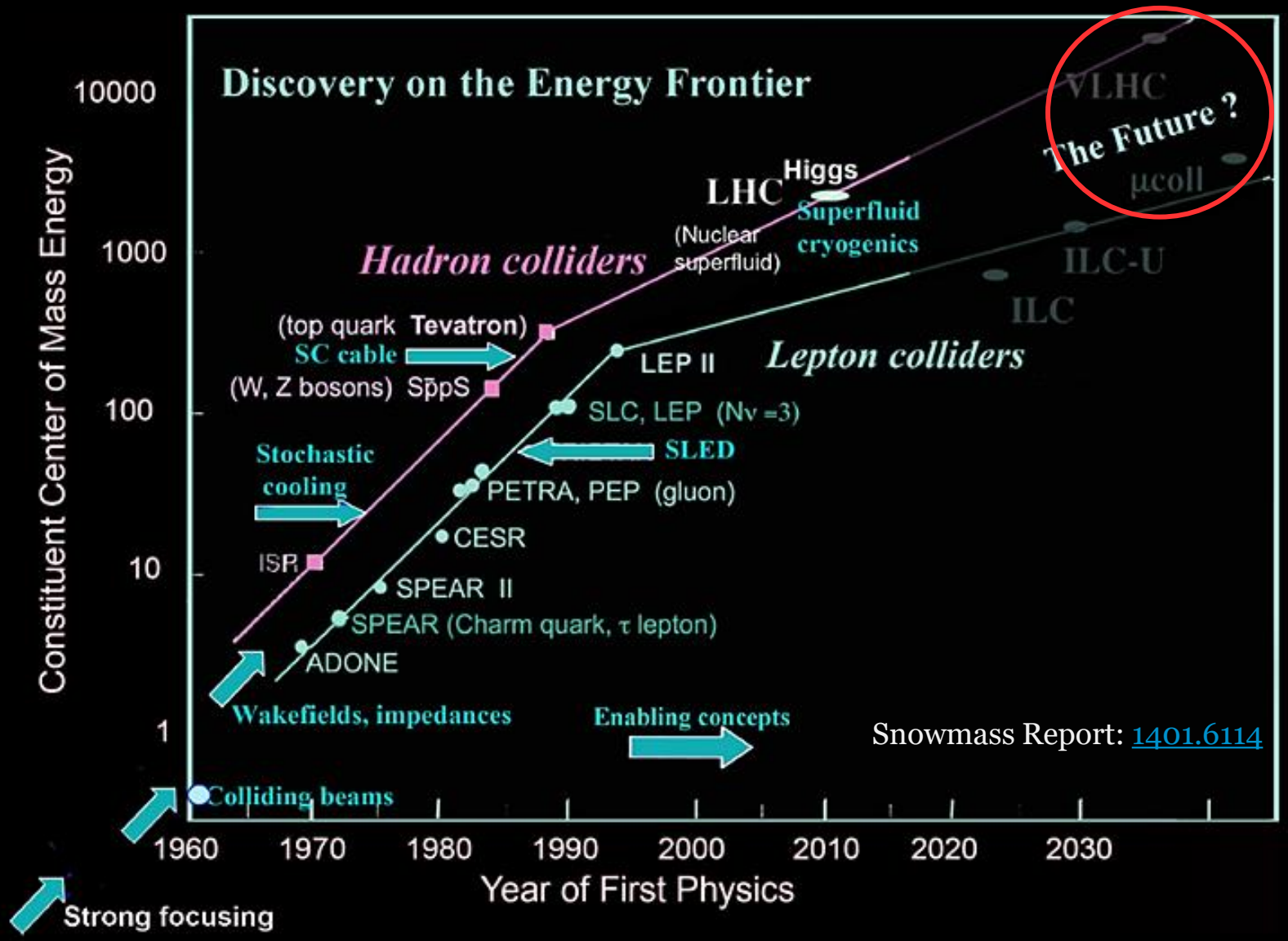
# High Energy Rules

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The forefront of tech & ambitions leads to discoveries.

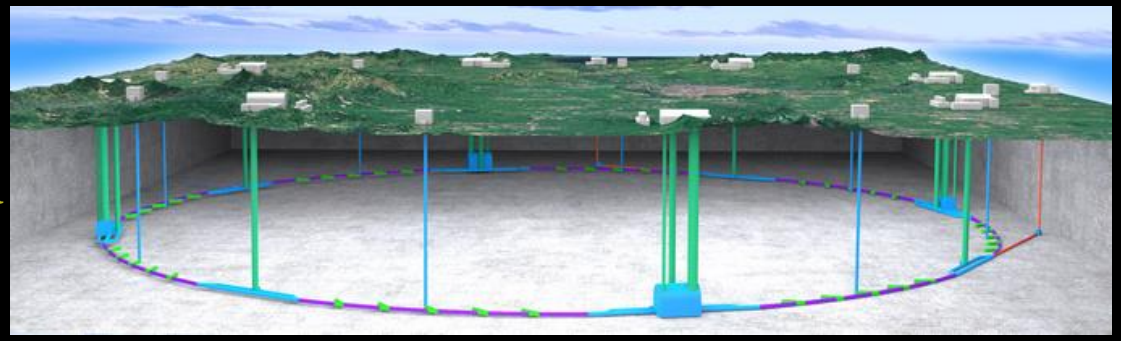
The dream for high energy machines persists in our field.

People's perspectives change over time, now:

- there are excitement/call for future high energy colliders from theory, accelerator, and experimental community.
- Interesting aspects of physics to be examined.

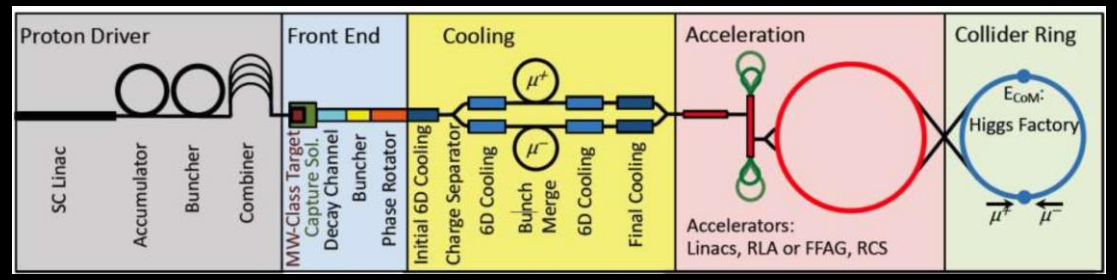
# Future Collider Options

China



~CEPC ($e^+e^-$) 240 GeV Higgs + pp (~100 TeV)

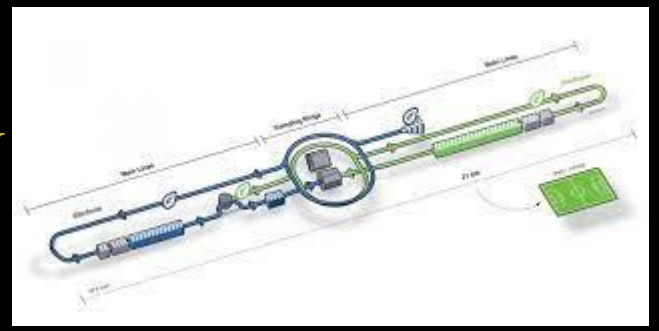
USA?




Muon collider, Higgs, 3~14 TeV

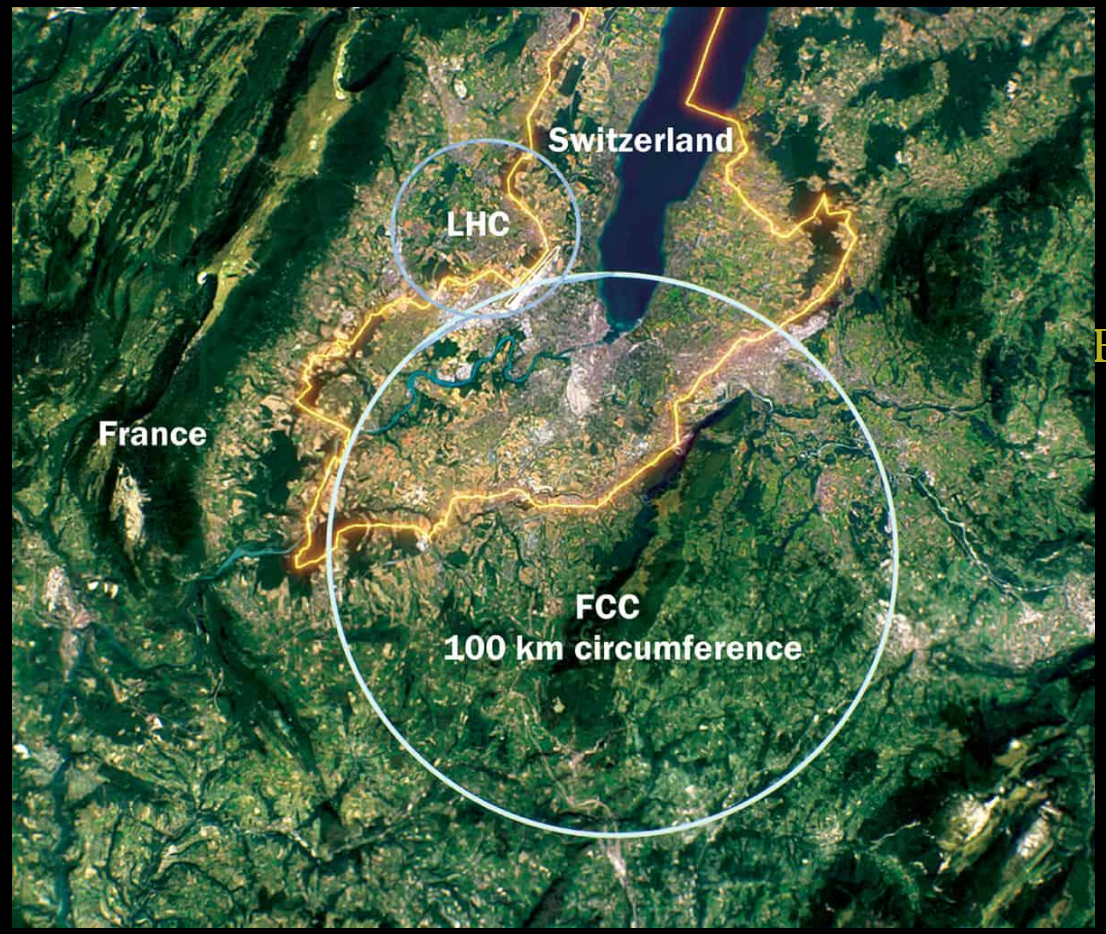
Plasma Wakefield Acceleration-based, LC $e^+e^-$

JAPAN



30 – 50 km ILC ($e^+e^-$)
250 GeV Higgs
+ ~1 TeV

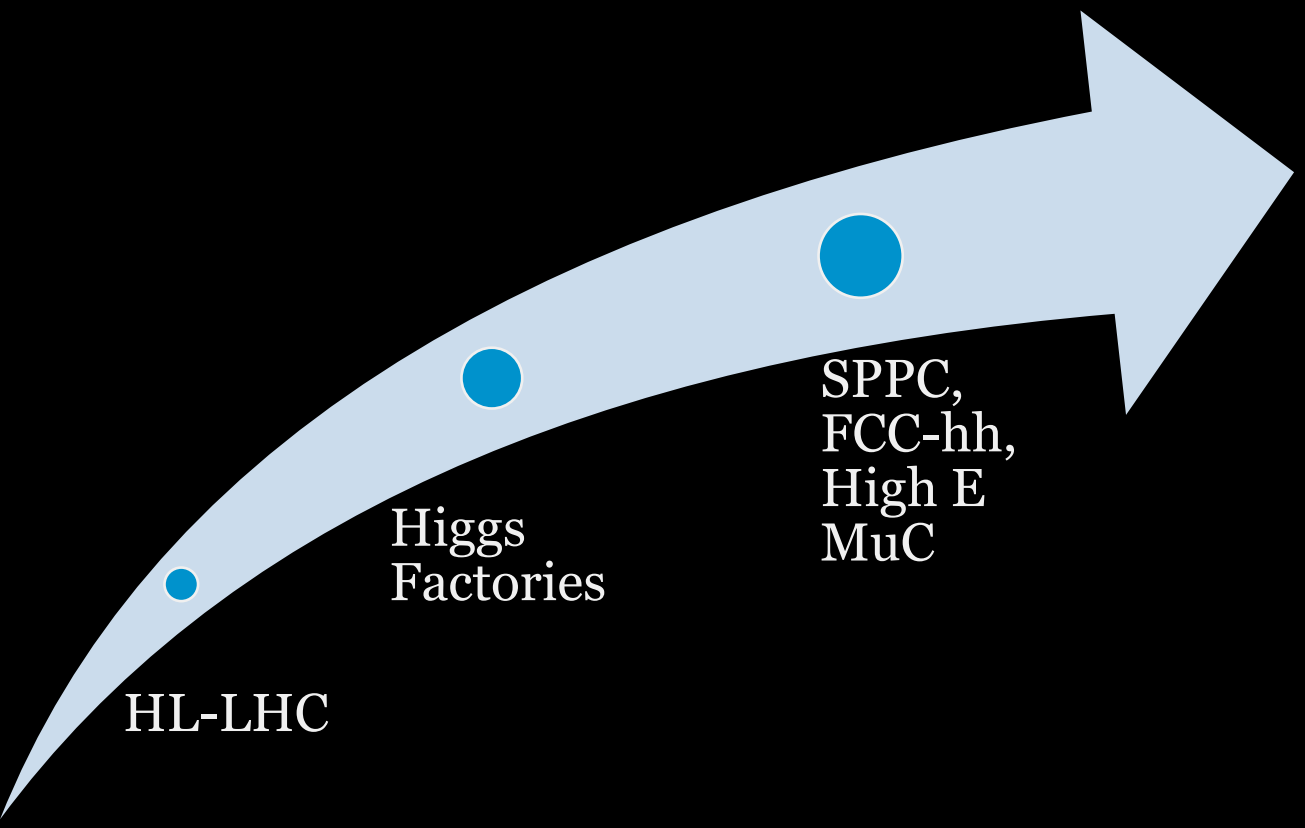
Europe

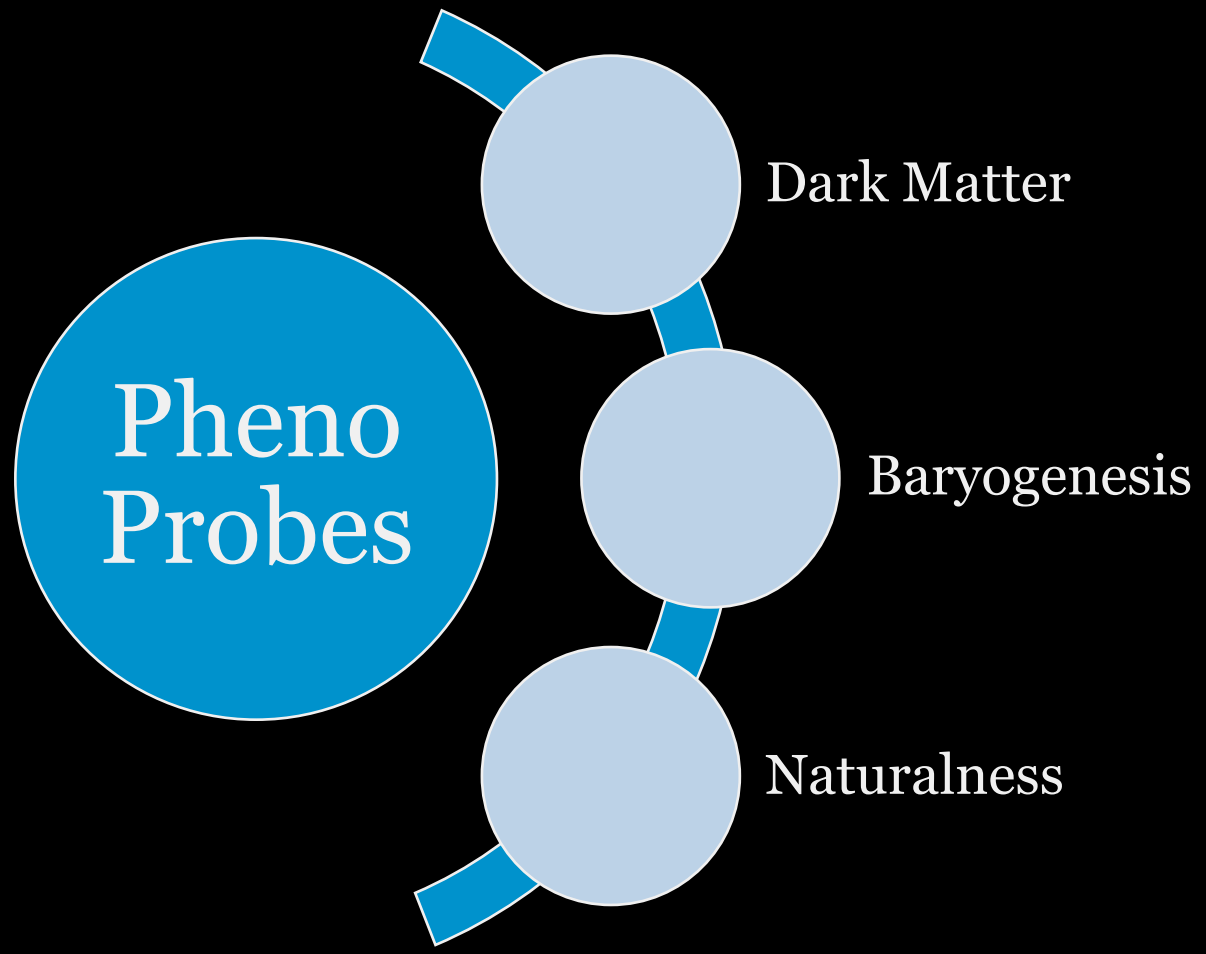



~100 km FCC
$e^+e^-$ (Z factory, 240 GeV Higgs + 365 GeV Top)
ep, pp (~100 TeV)

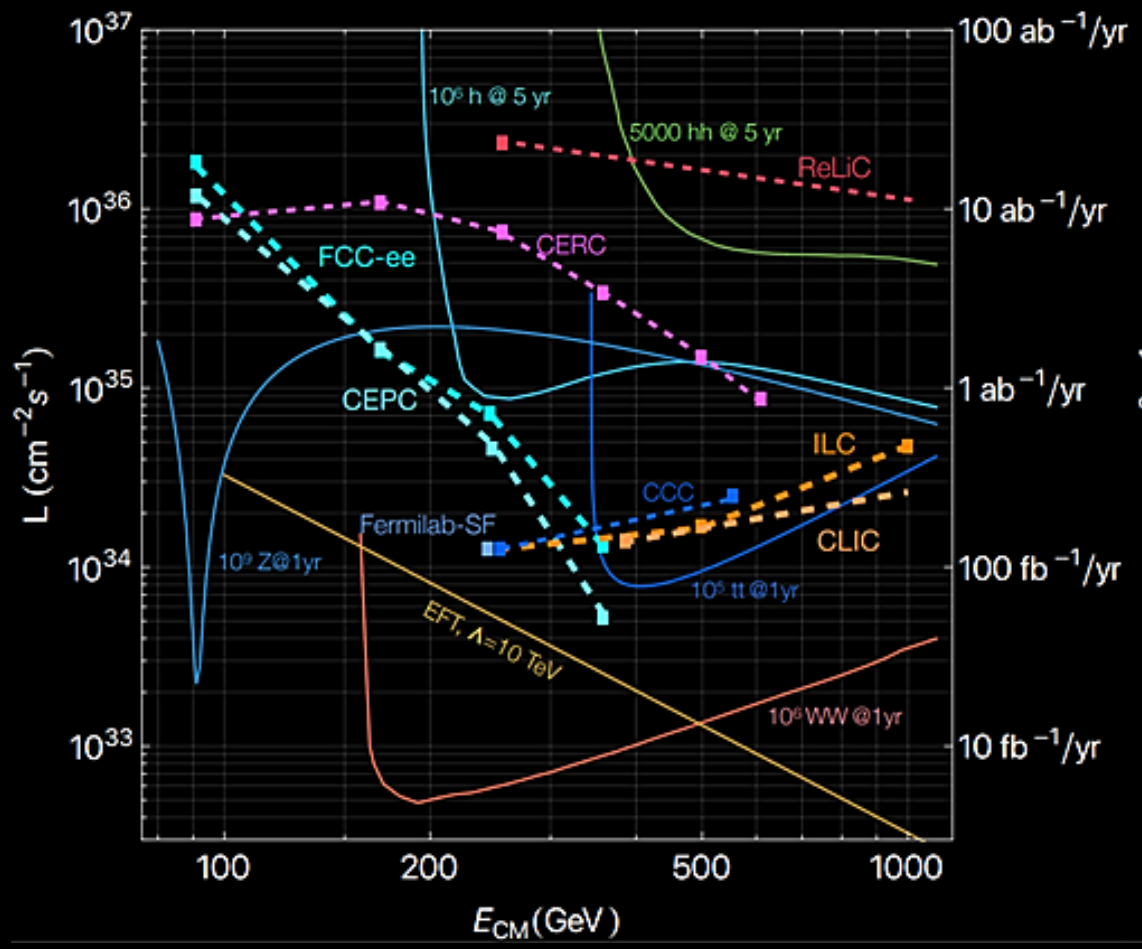
# We want collider(s) with all its potential realized

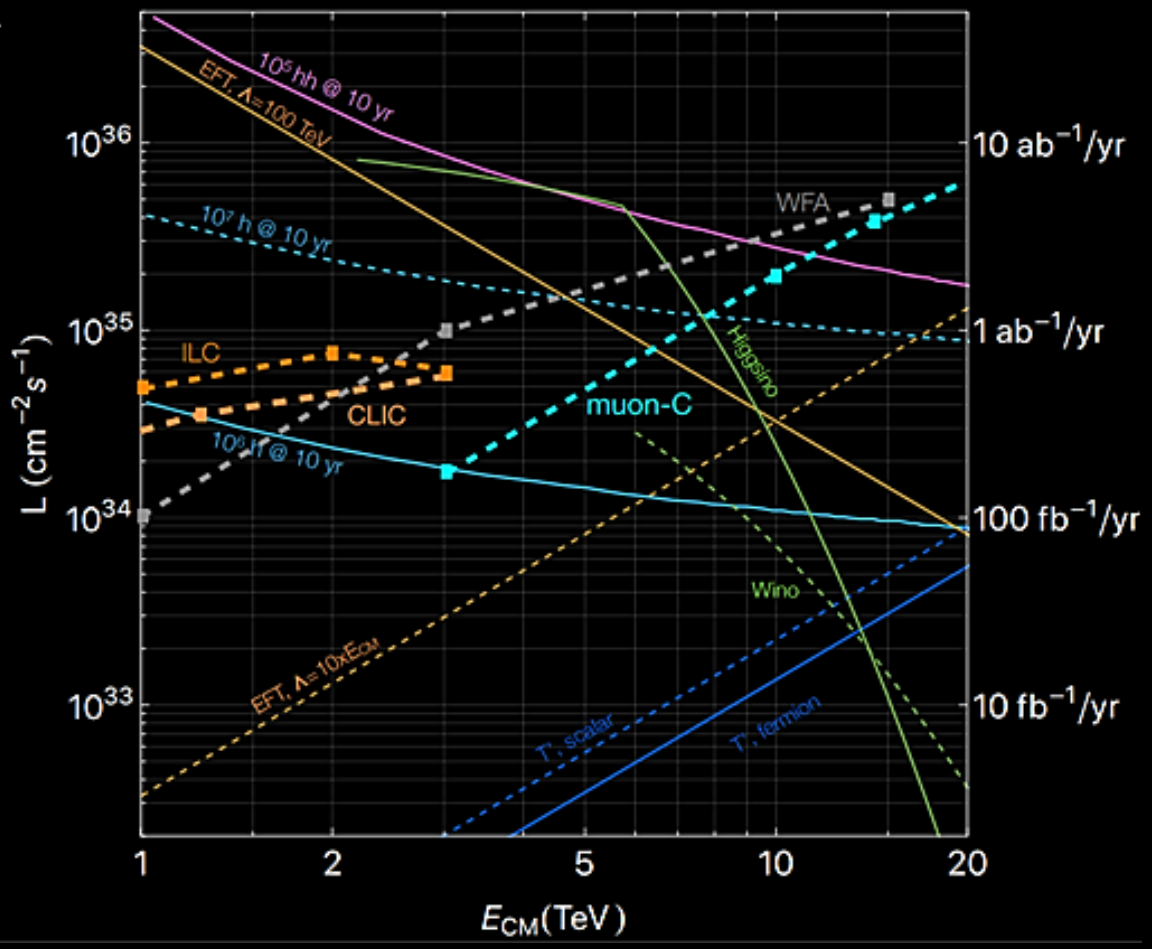
Physics Driver



# Distinctive Physics Programs

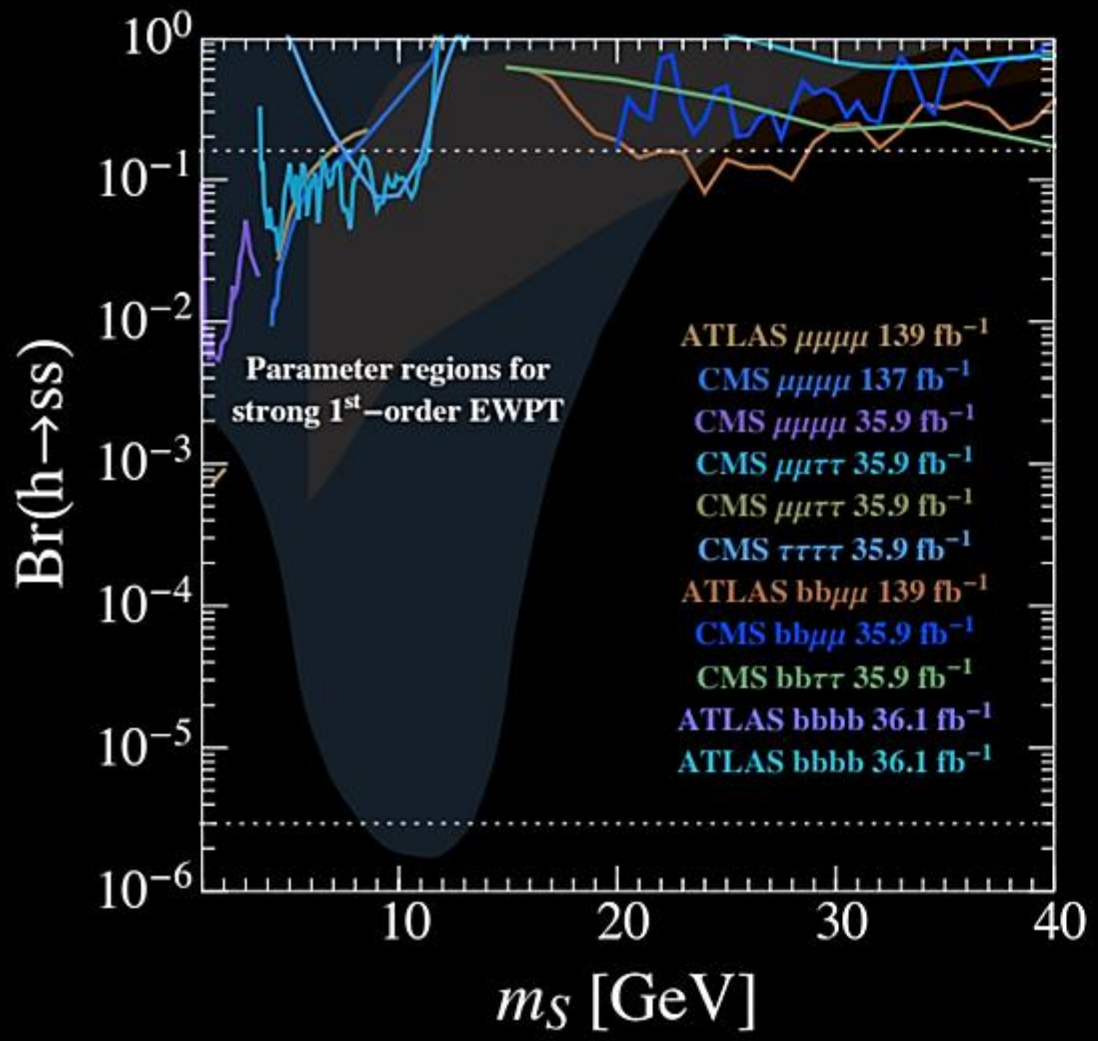


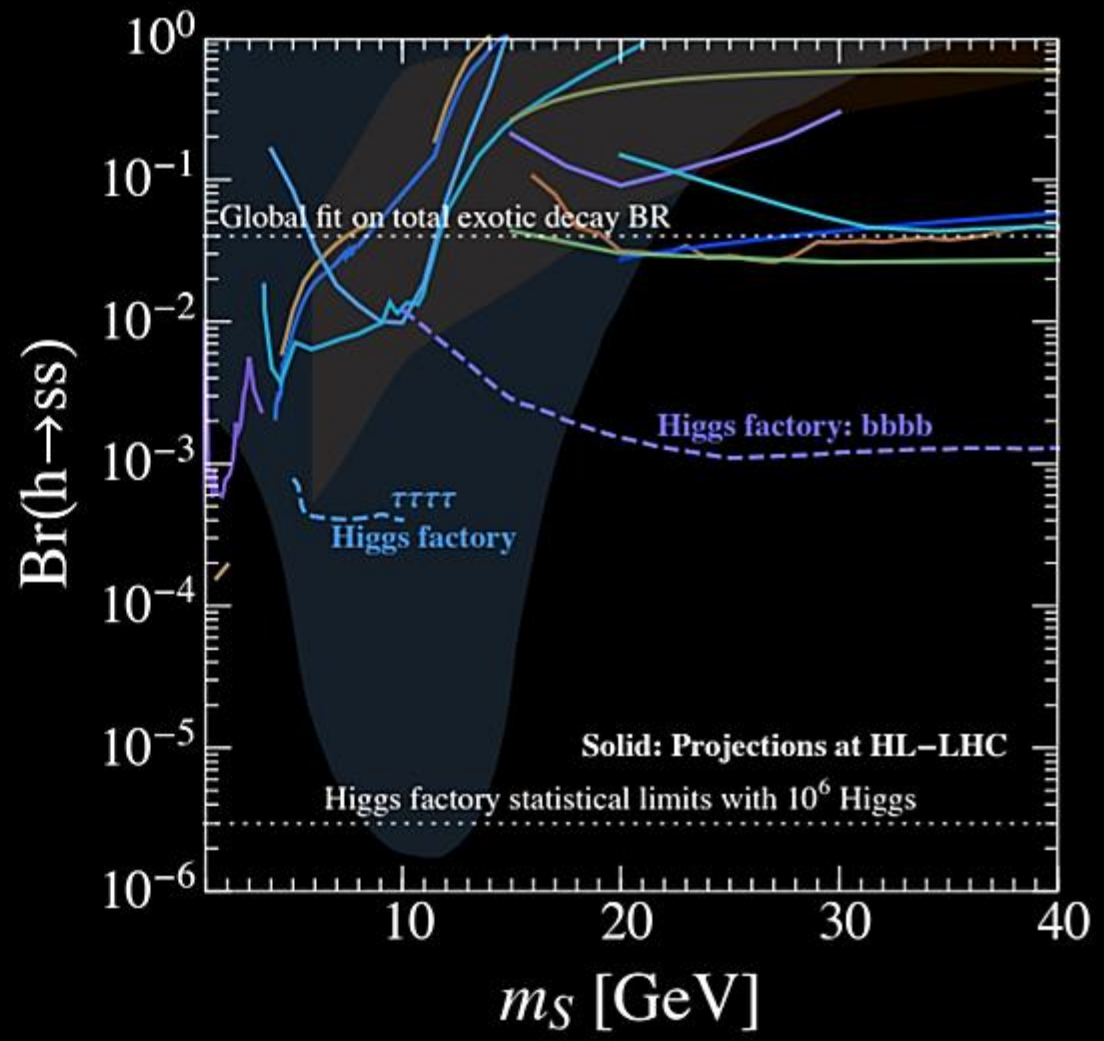




Many future collider options and excitement!

ZL, Wang, 2205.00031; Input for Implementation Task Force (ITF) for Snowmass2021.

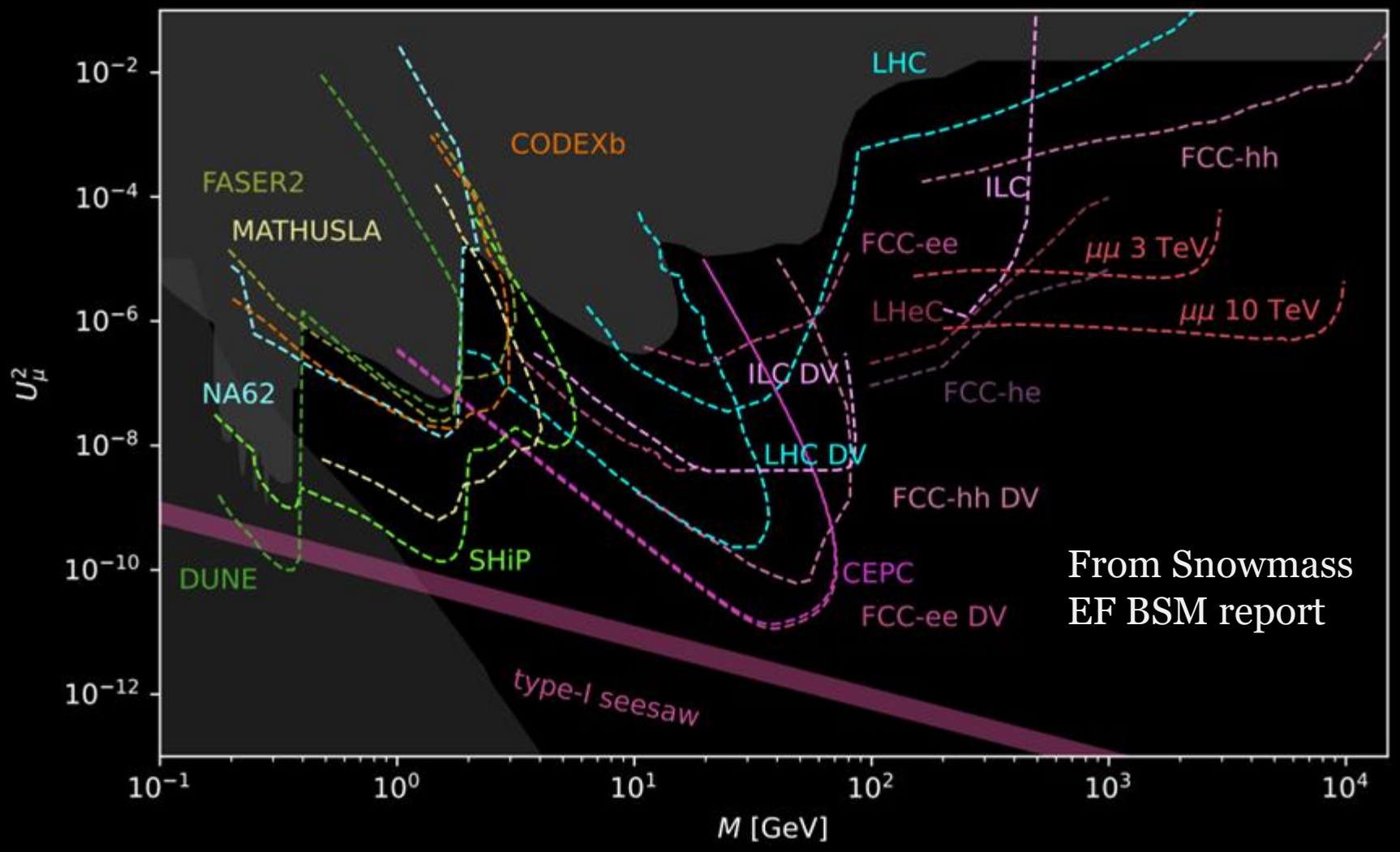
# Higgs Exotic Decays to light Higgs pairs




Carena, Kozaczuk, ZL, Ou, Ramsey-Musolf, Shelton, Wang, Xie, 2203.08206

# Hidden Neutrino Explaining Lightness of Neutrino mass




From Snowmass EF BSM report

The bottom left "type-I seesaw" represents the most pessimistic seesaw benchmarks. In general multi-generation seesaw, the motivated parameter regions spans over the space above that line, very much like the inverse seesaw spectra.

Peiran Li, ZL, Kun-Feng Lyu, 2301.07117
T.H. Kwok, L. Li, T. Liu and A. Rock, 2301.05177
K. Mekała, J. Reuter and A.F. Zarnecki, 2301.02602

# New Physics Opportunities at the LHC and Beyond

- Deep
  - Beyond the classical level
- Broad
  - Long-Lived Particles
- Open
  - Open to non-traditional targets

Future Colliders!

I couldn’t cover many precious topics, such as Machine Learning, Anomaly detection, Flavour program, complementarity with intensity, astrophysics, cosmology, quantum sensing, etc.

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