BSM Opportunities at the LHC

Zhen Liu
University of Maryland

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A paradigm shift driven by LHC

Models solving multiple puzzle of Nature at once
➔
Models solving >=0 puzzles *but* raising new signatures that can be probed by experiments

LHC experimental colleagues have been creatively on the more established model paradigms, steady & impressive progress all the time;
Our job becomes to Identify:

- opportunities that are missed or overlooked;
- important questions that could be answered;
- new interesting questions about particle physics;

BSM Opportunities at the LHC

Around the Higgs
Go Exotic
Have Fun

Th tally
pl

Disclaimer:
BSM @ LHC a vibrant field,
Selected representative BSM Opportunities at the LHC

Please email me for missing references

Around Higgs

Big Questions centered around Higgs
→
Big Opportunities

- Fundamental or composite?
- Electroweak Phase Transition?
- Higgs portal to new physics?

Higgs Physics is the
central topic
for the current and future (collider) program

BSM Opportunities at the LHC

Around the Higgs

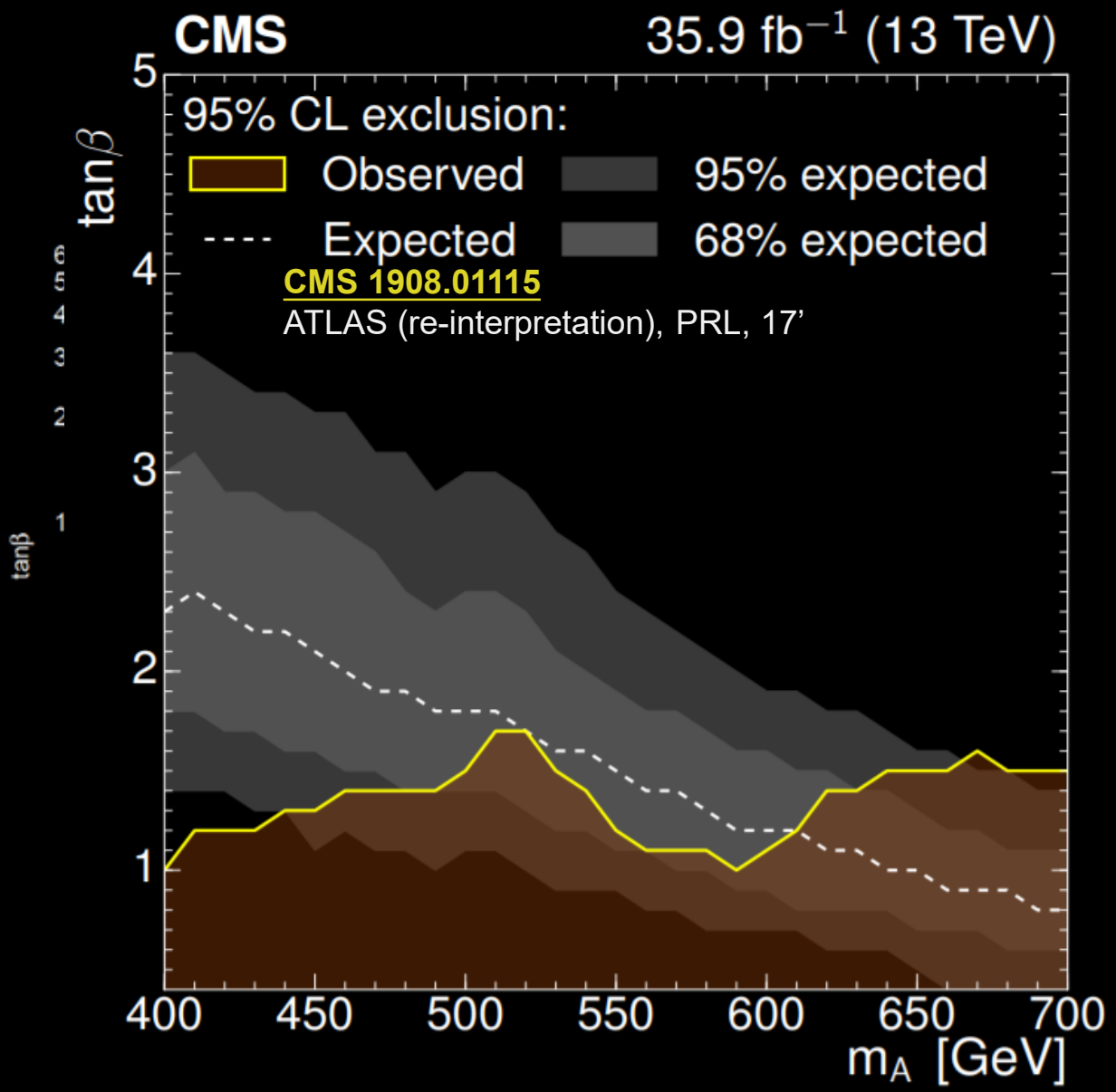
New effects, e.g., interferences;

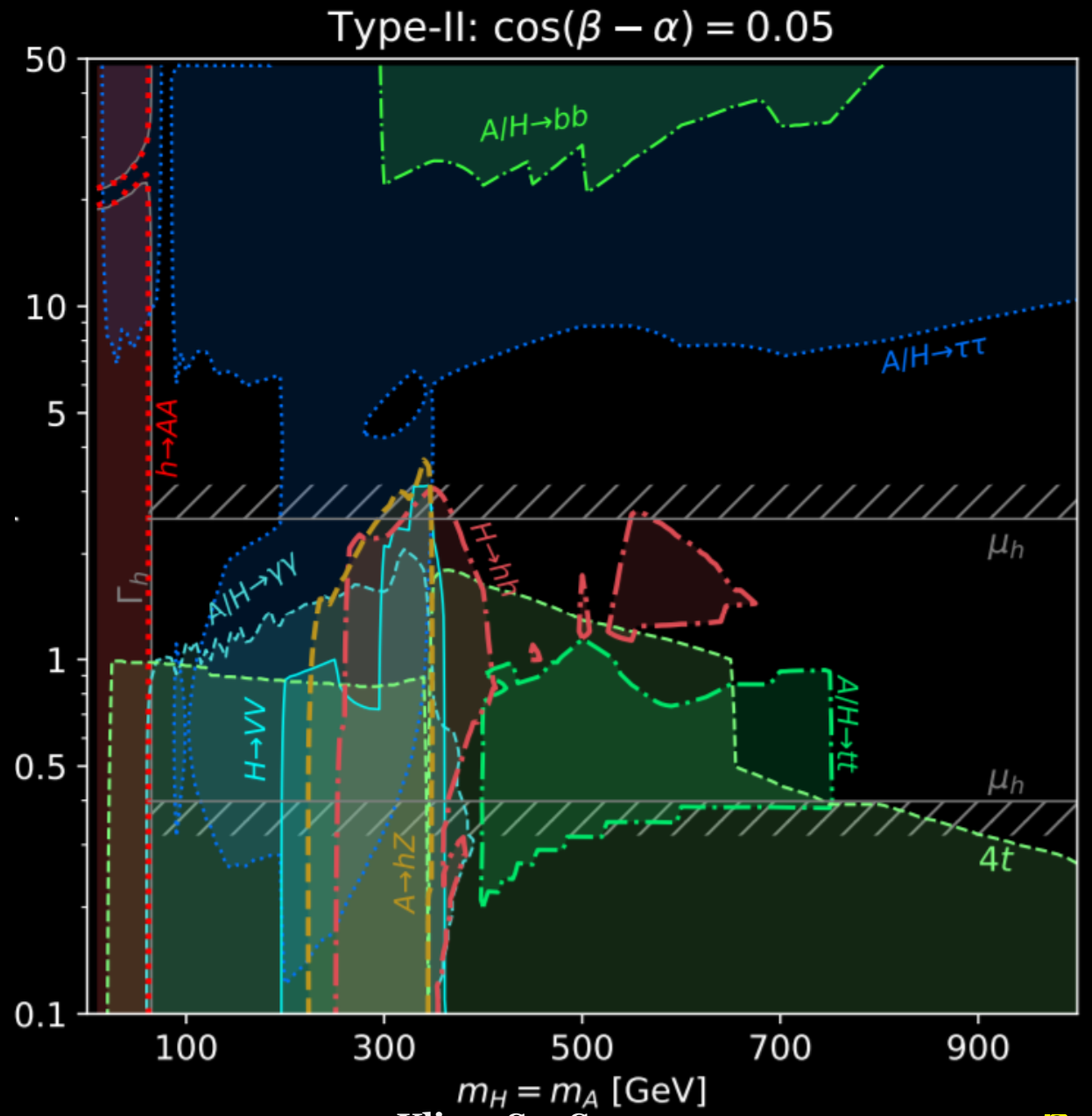
Beyond minimal/vanilla modes, e.g., as portals

Go Exotic

Have Fun

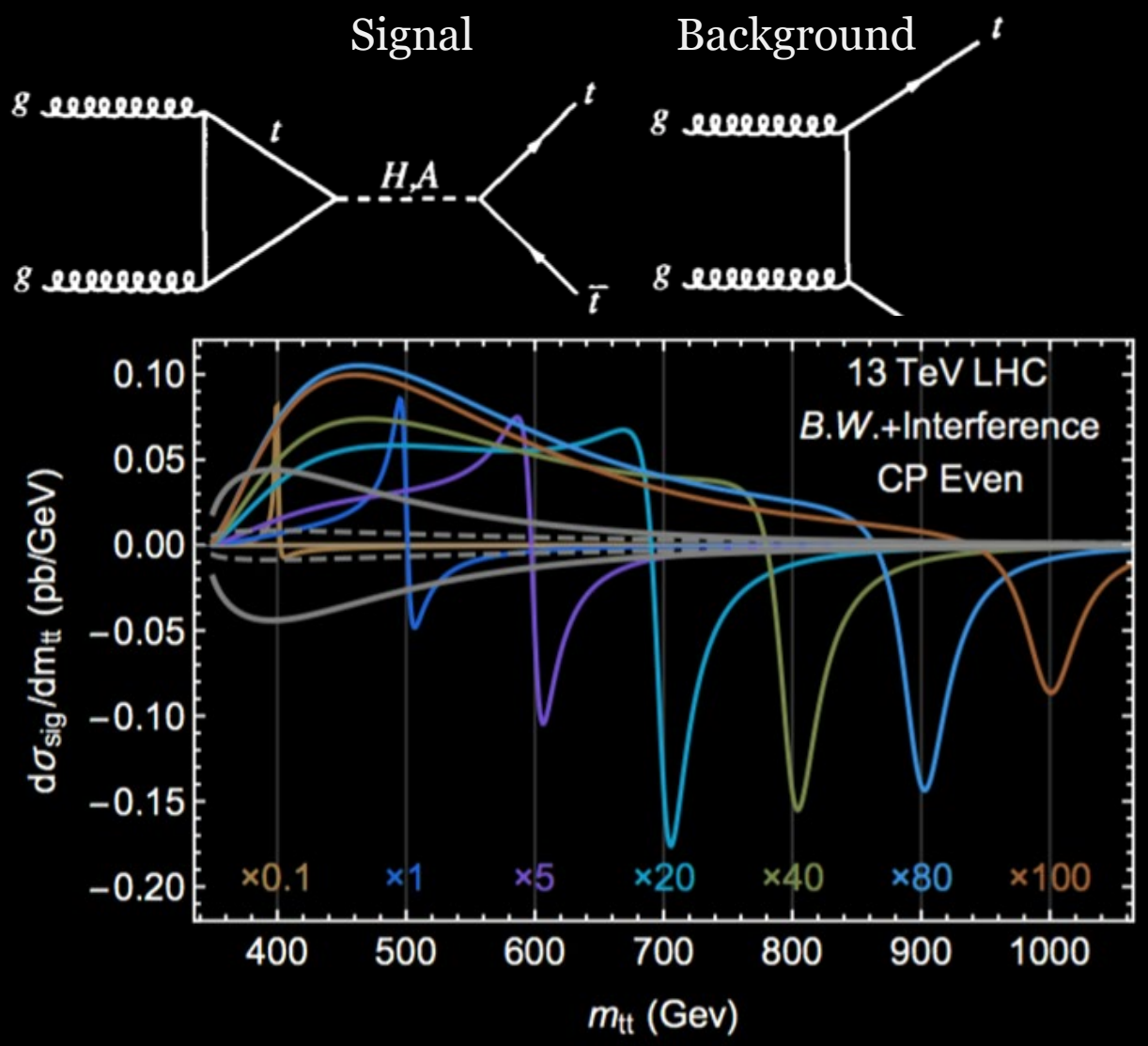
Around Higgs

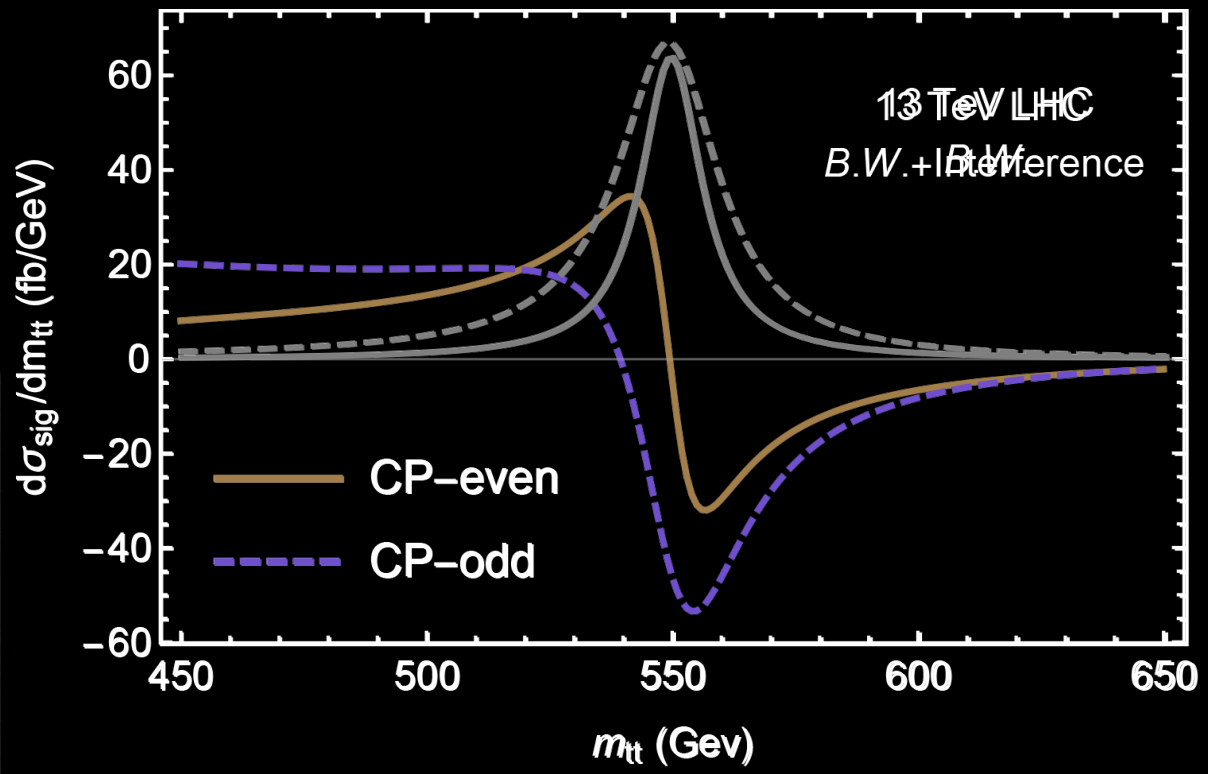




Kling, Su, Su, 2004.04172

One Key ingredient (recent $\phi \to t\bar{t}$ search)

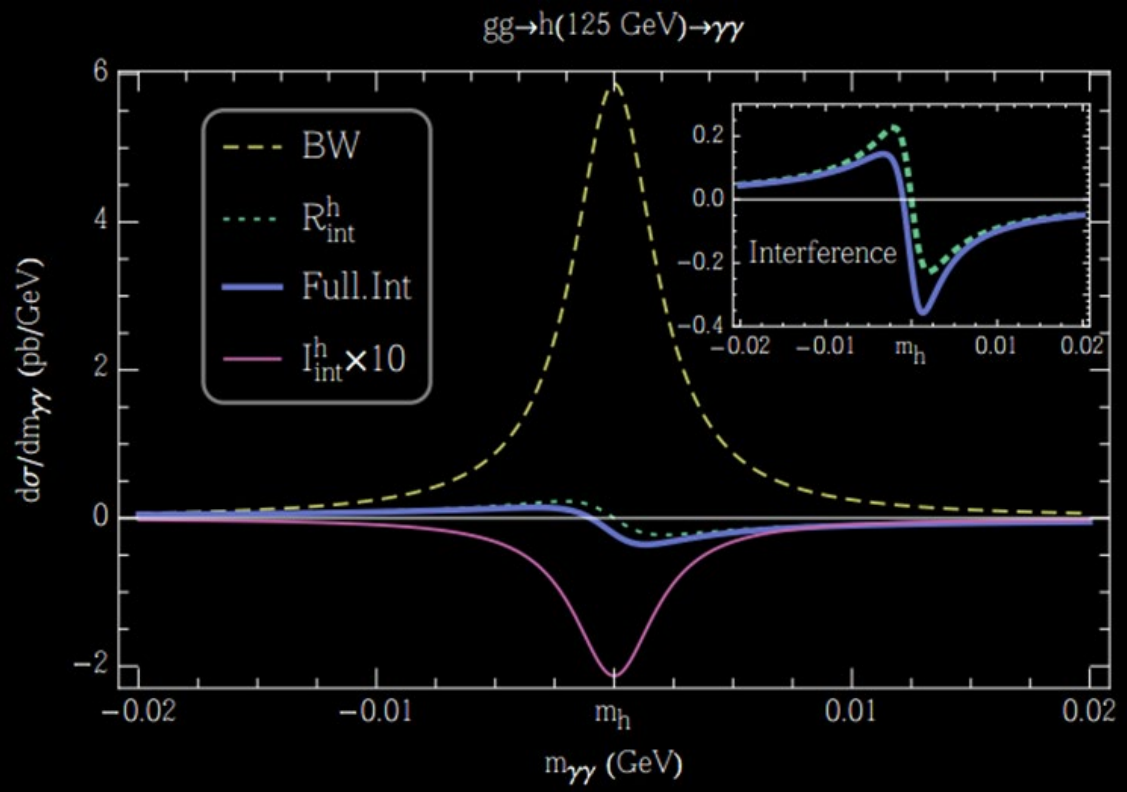


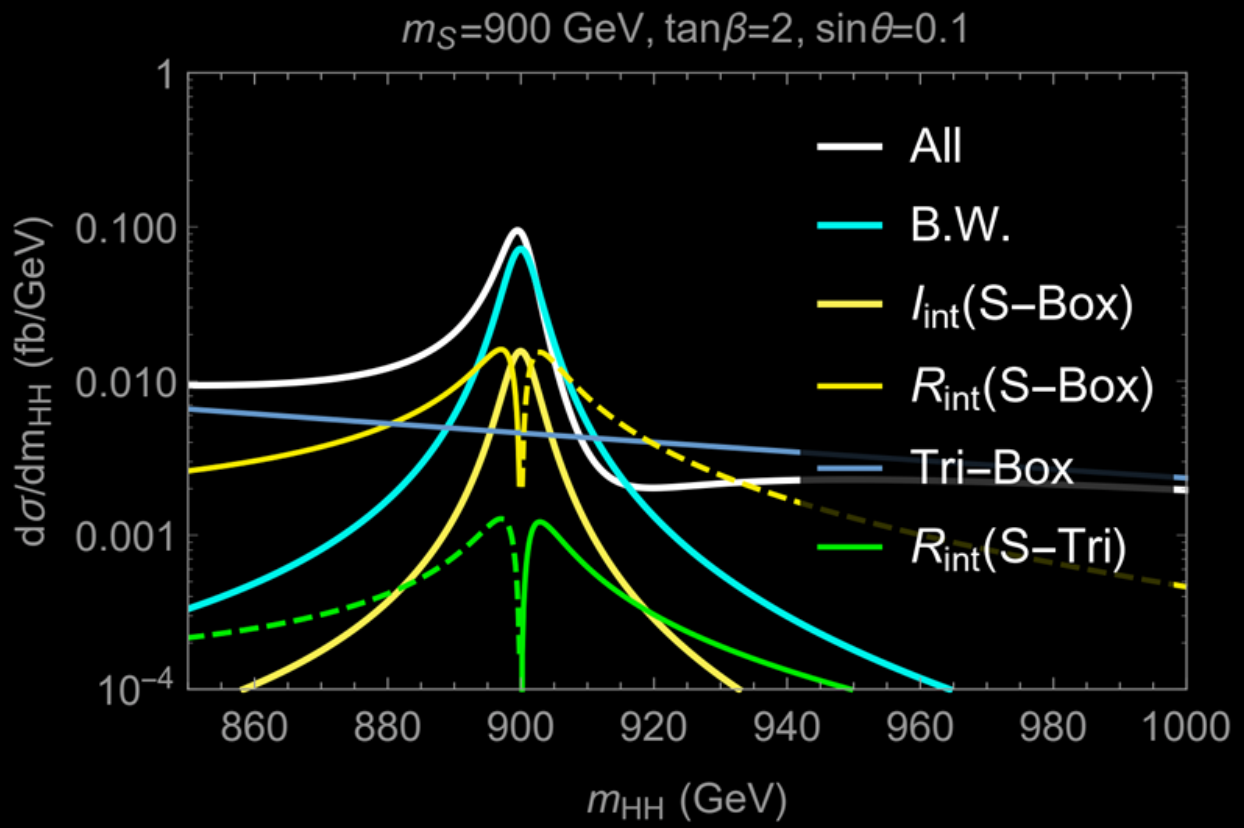


D. Dicus, A. Stange, S. Willenbrock, hep-ph/9404359, Focusing on ttbar @LHC, **M. Carena, ZL, arXiv:1608.07282**
Other channels and effects, including ttH, tH (see in N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang arXiv:1504.04630 and J. Hajer, Y.-Y. Li, T. Liu J. Shiu arXiv:1504.07617, S. Gori, 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), QCD correction, W. Bernreuther, P. Galler, C. Mellein, Z.-G. Si, P. Uwer arXiv:1511.05584), ttbar differential observables (W. Bernreuther, P. Galler, C. Mellein, Z.-G. Si, P. Uwer arXiv:1702.06063; W. Bernreuther, L. Chen, Z.-G. Si, 1805.06658), Machine Learning,

Interferences onsite

Non-factorizable into signal production and decay calculation, either described by standard EFT;
Gain new information about width and strong & weak phase;
Interesting test for Interference.





Dixon, Siu, hep-ph/0302233
Campbell, Carena, Harnik, ZL, 1704.08259
Cjeri, Coradeschi, de Florian, Fidanza, 1706.07331
Maltoni, Mandal, Zhao, 1812.08703
Chen, Heinrich, Jahn, Jones, Kerner, Schlenk, Yokoya 1911.09314
Hoche et al, in progress
Also (real-part interference): Dixon, Li, 1305.3854

Carena, ZL, Riembau, 1801.00794
Kauer, Lind, Maierhoefer, Song, 1905.03296
Other channels: Jung, Sung, Yoon, arXiv:1510.03450, arXiv:1601.00006, (dijets) Martin, 1606.03026, Bhattipirolu, Martin, 2004.06181 see Bhattiprolu's talk yesterday.

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New effects, e.g., interferences;

Beyond minimal/vanilla modes, e.g., as portals

Go Exotic

Have Fun

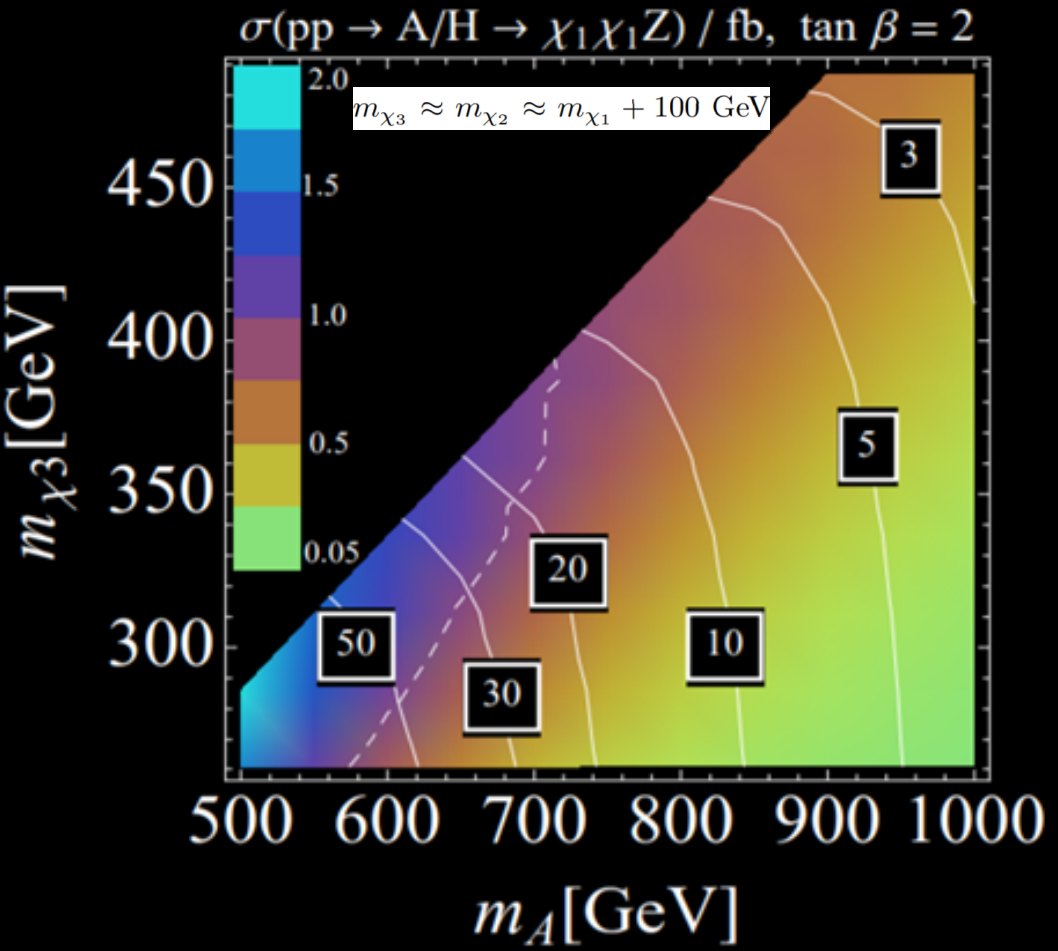
HL-LHC: fest of statistics

* AS PROBES OF HEAVY HIGGS BOSONS

* AS DISCOVERY CHANNELS OF THESE SUSY EW STATES

* AS COMPLEMENTARY COVERAGE IN HEAVY HIGGS PARAMETER SPACE

Heavy Higgs to EWkinos

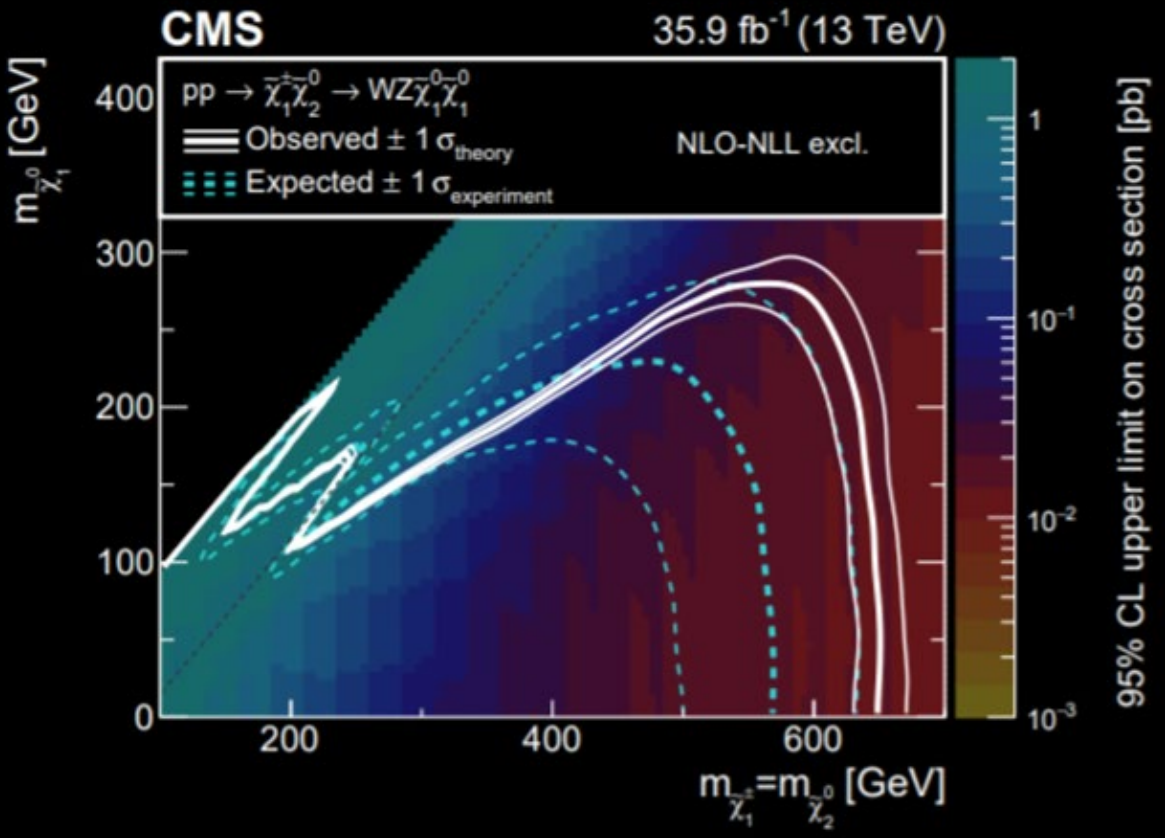


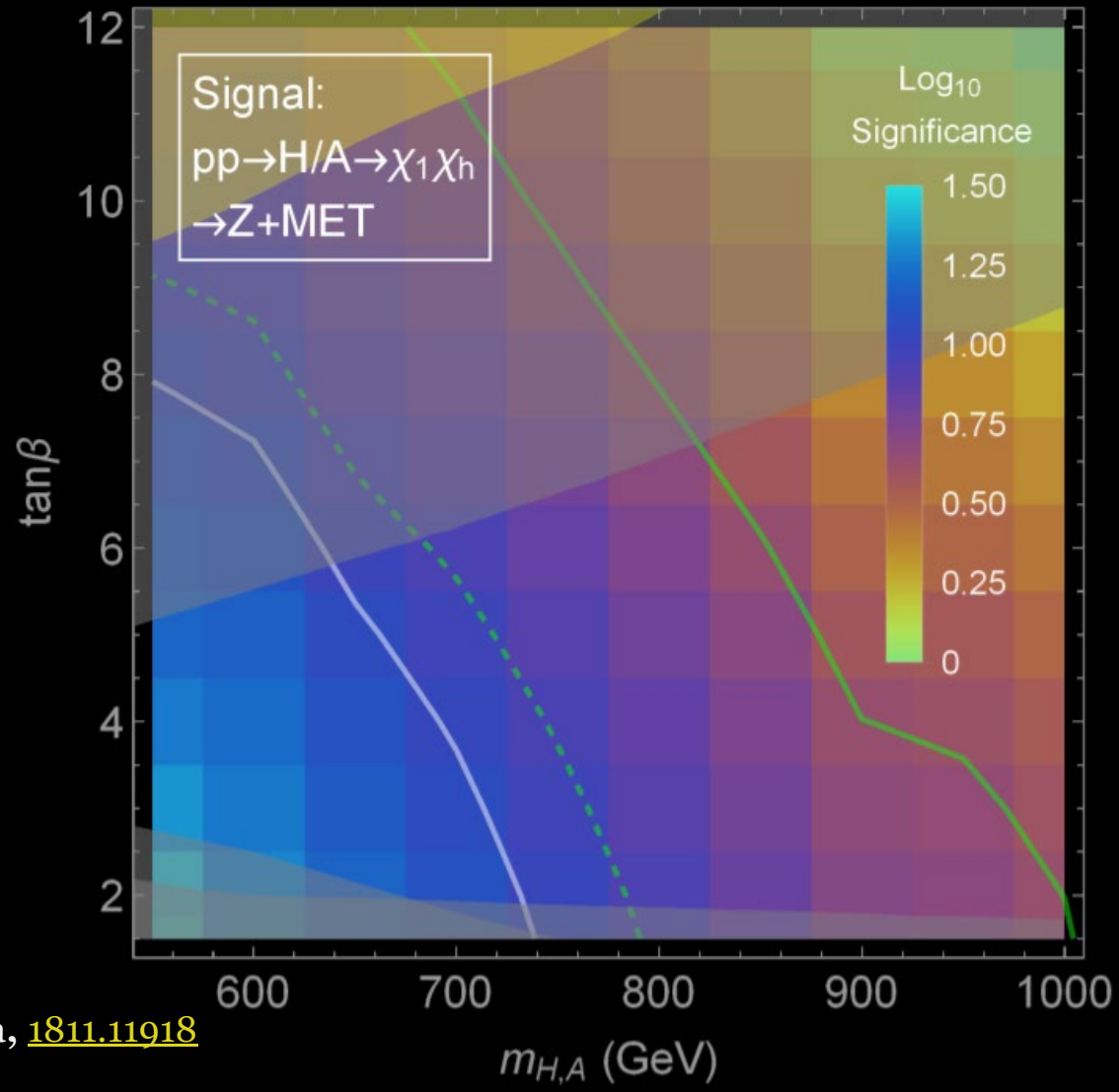
Improving Higgsino coverages at HL-LHC through new channel;

Lower tanβ values really strong due to the larger gg->H,A cross section

S. Gori, ZL, B. Shakya, 1811.11918

Competitive to direct searches





Many works and benchmarks, see LHCXSWG, **S. Gori, ZL, B. Shakya,** 1811.11918
Bahl, Liebler, Stefaniak, 1901.05933
Adhikay, Bhattacherjee, Godbole, Khan, 2002.07137
Canepa, Han, Wang, 2003.05450. See also H. Baer's talk this afternoon and talks in the SUSY sessions. For examples in eRS, see talks by M. Ekhterachian and D. Sathyan in the afternoon.

BSM Opportunities at the LHC

Around the Higgs

- New effects, e.g., interferences;
- Beyond minimal/vanilla modes, e.g., as portals

Go Exotic

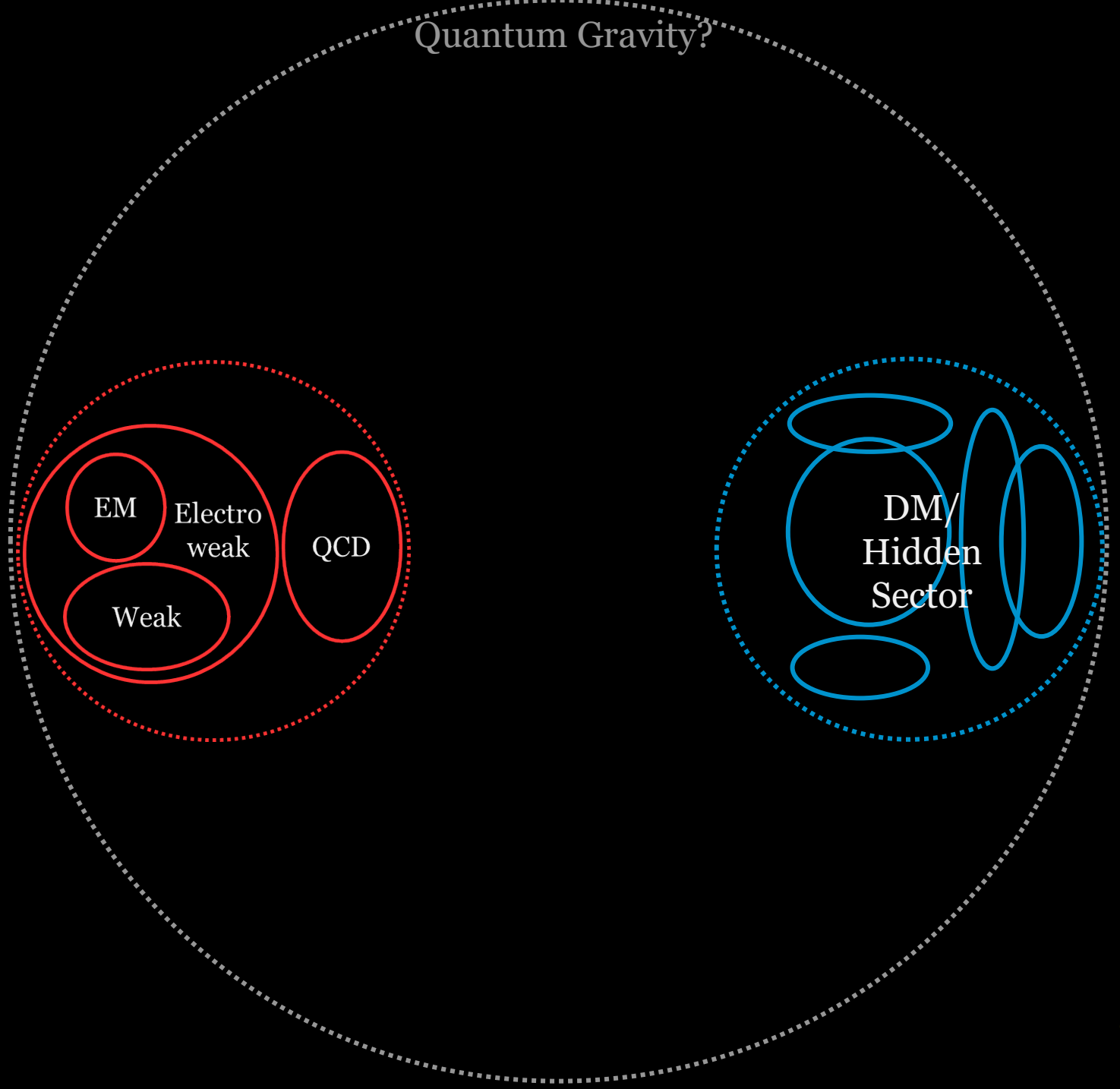
- Hidden sector dynamics
- Long-Lived Particles

Have Fun

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

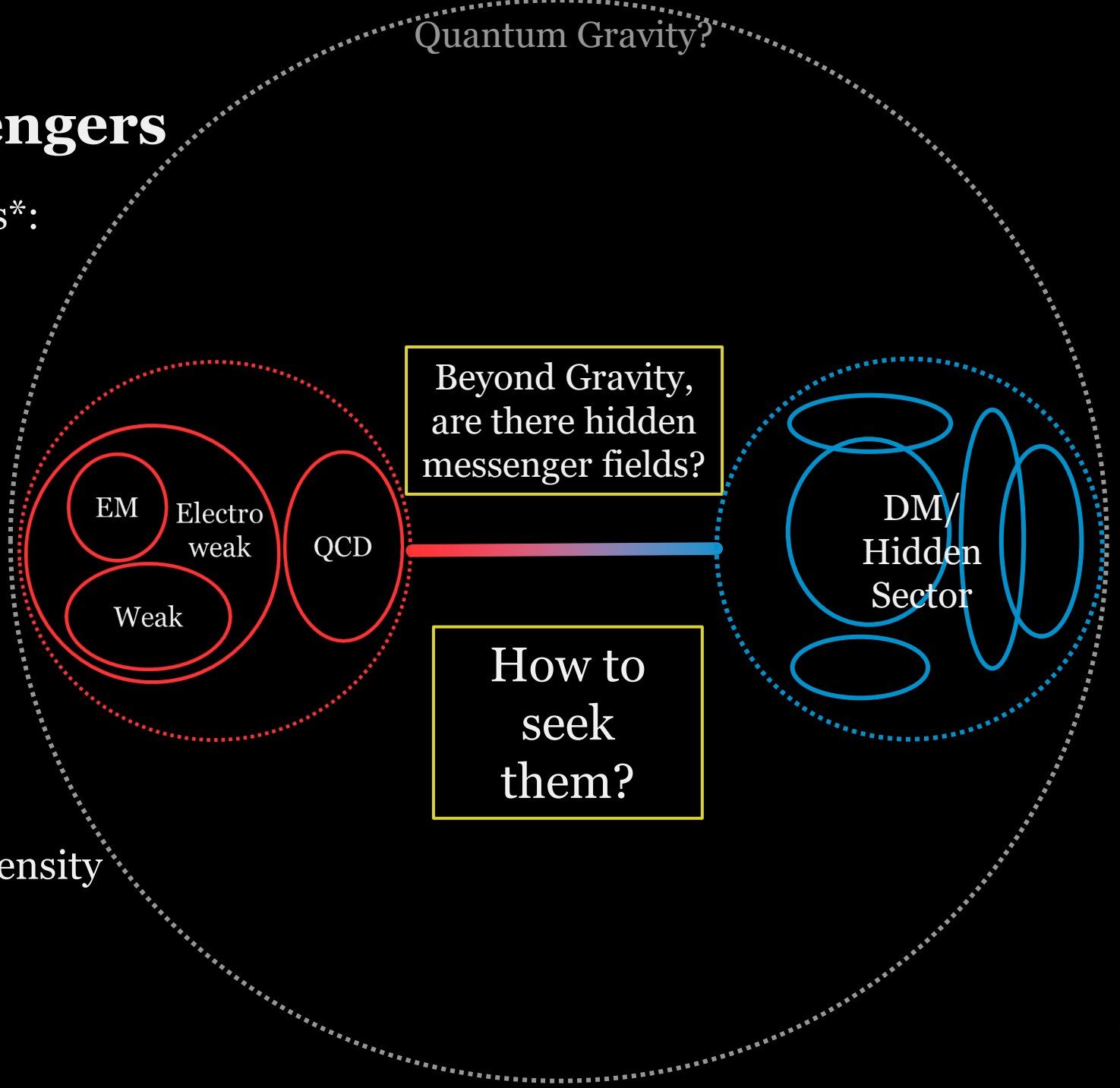


Hidden Sector Messengers

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
  - $\frac{a}{f_a}\left(\frac{\alpha_3}{8\pi}G\tilde{G}+\frac{\alpha_2}{8\pi}W\widetilde{W}+\cdots\right)$

*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

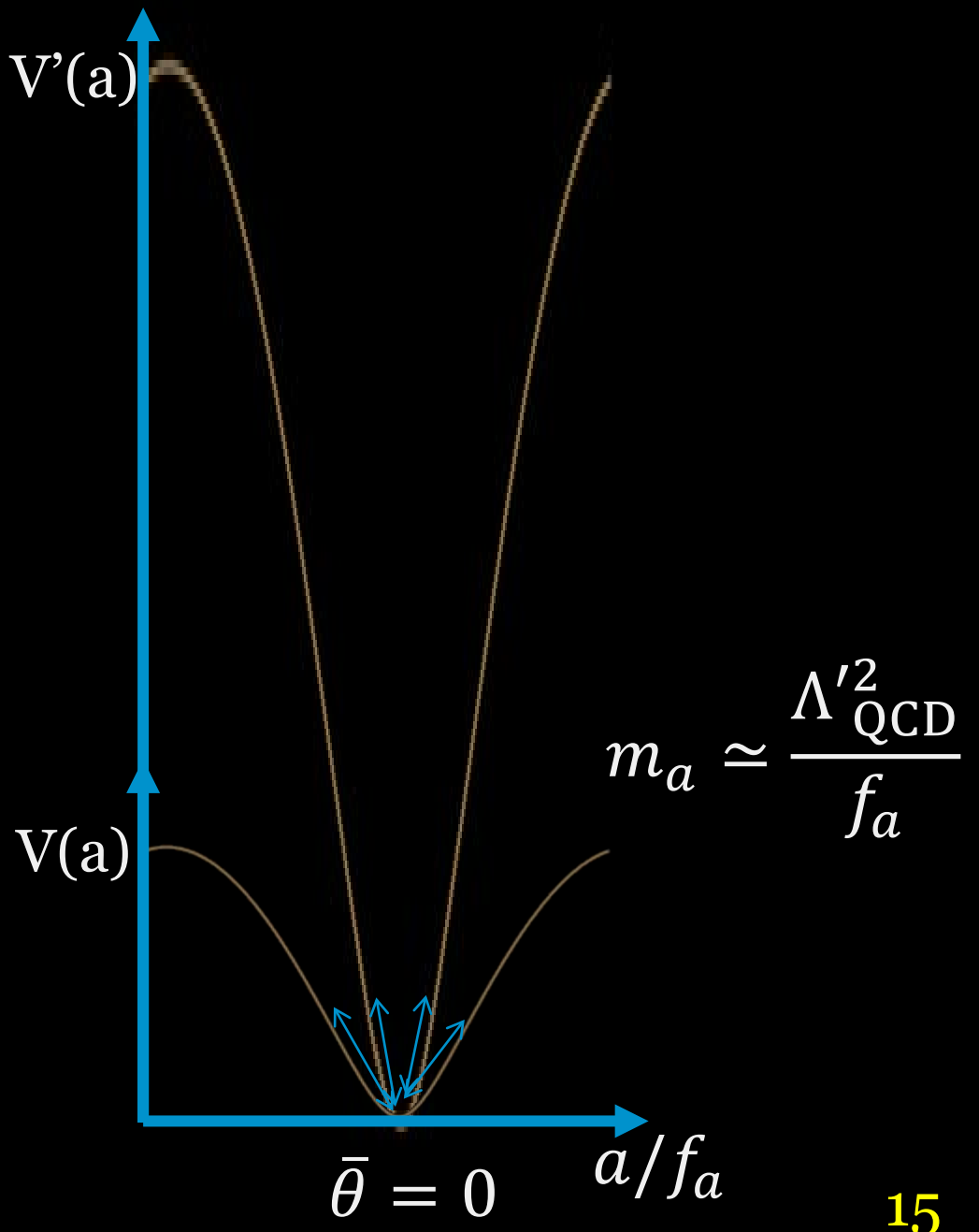
Mass of the axion is a robust prediction

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

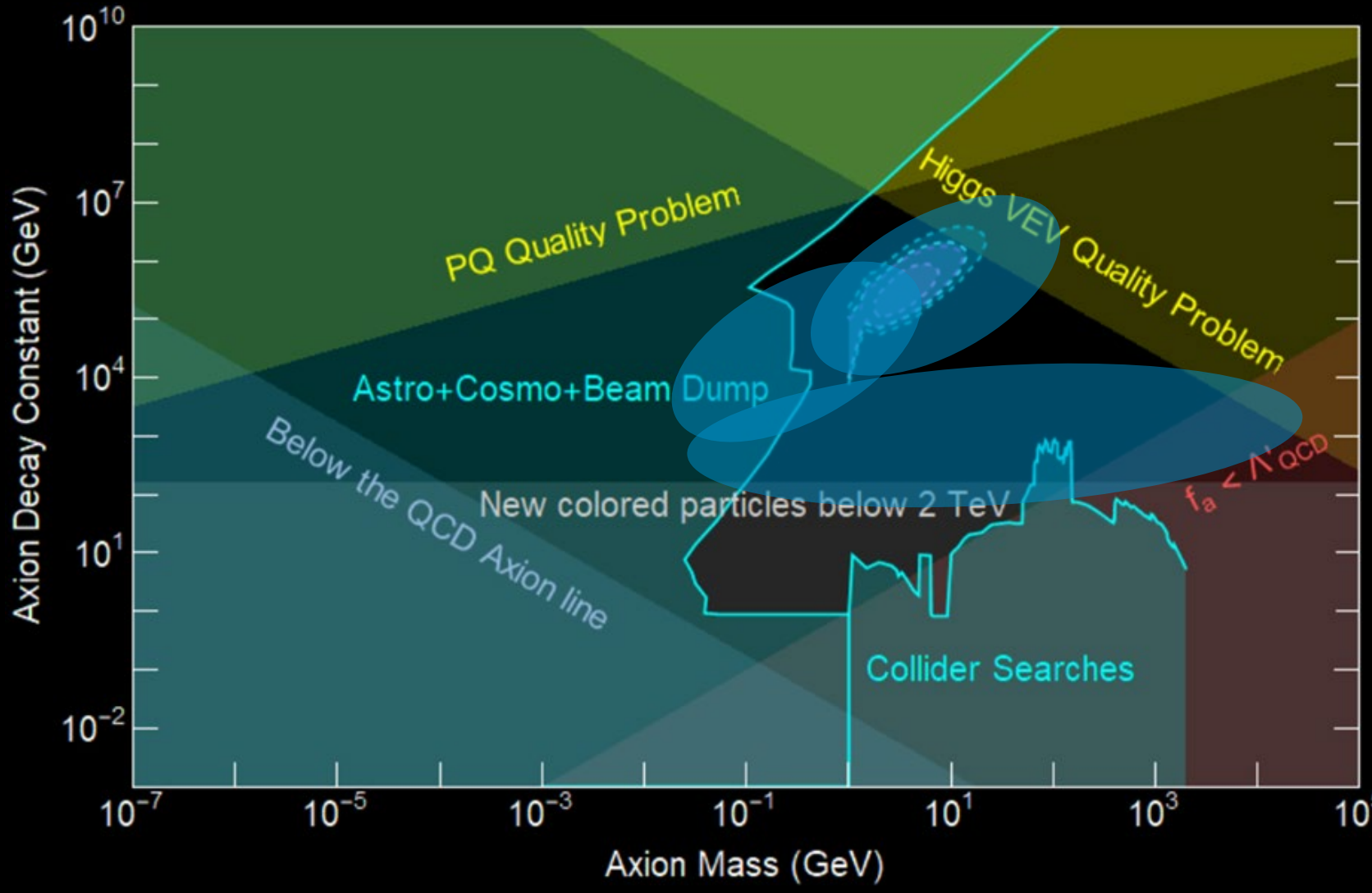
New contributions to the potential and the mass in general will not be aligned with the QCD potential

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

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: light, rarely produced, hadronic states;

Big open windows for well-motivated heavy Axions

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

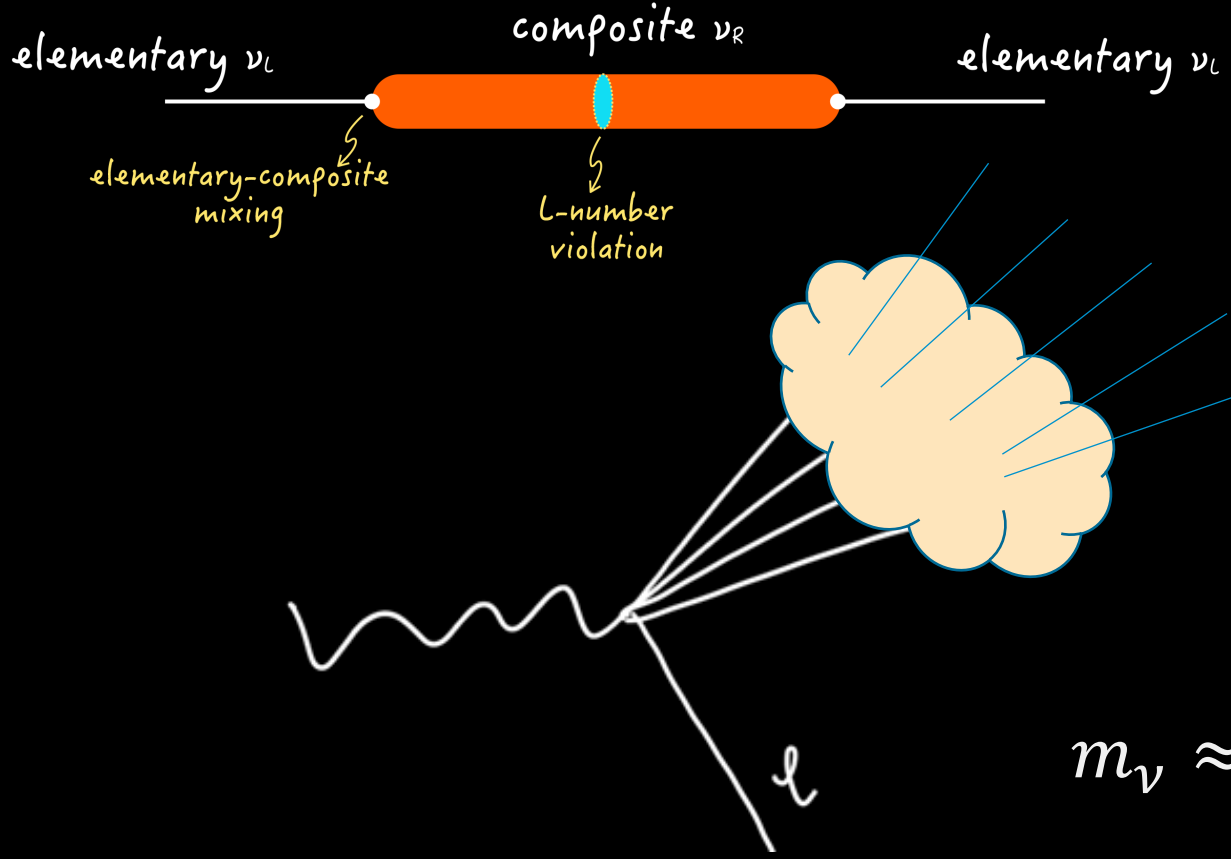
A lot more to explore.

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

See S. Kumar's talk this afternoon

Hook, Kumar, ZL, Sundrum, 1911.12364

Composite Neutrino



A shower of Sterile Neutrinos...

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

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Have Fun

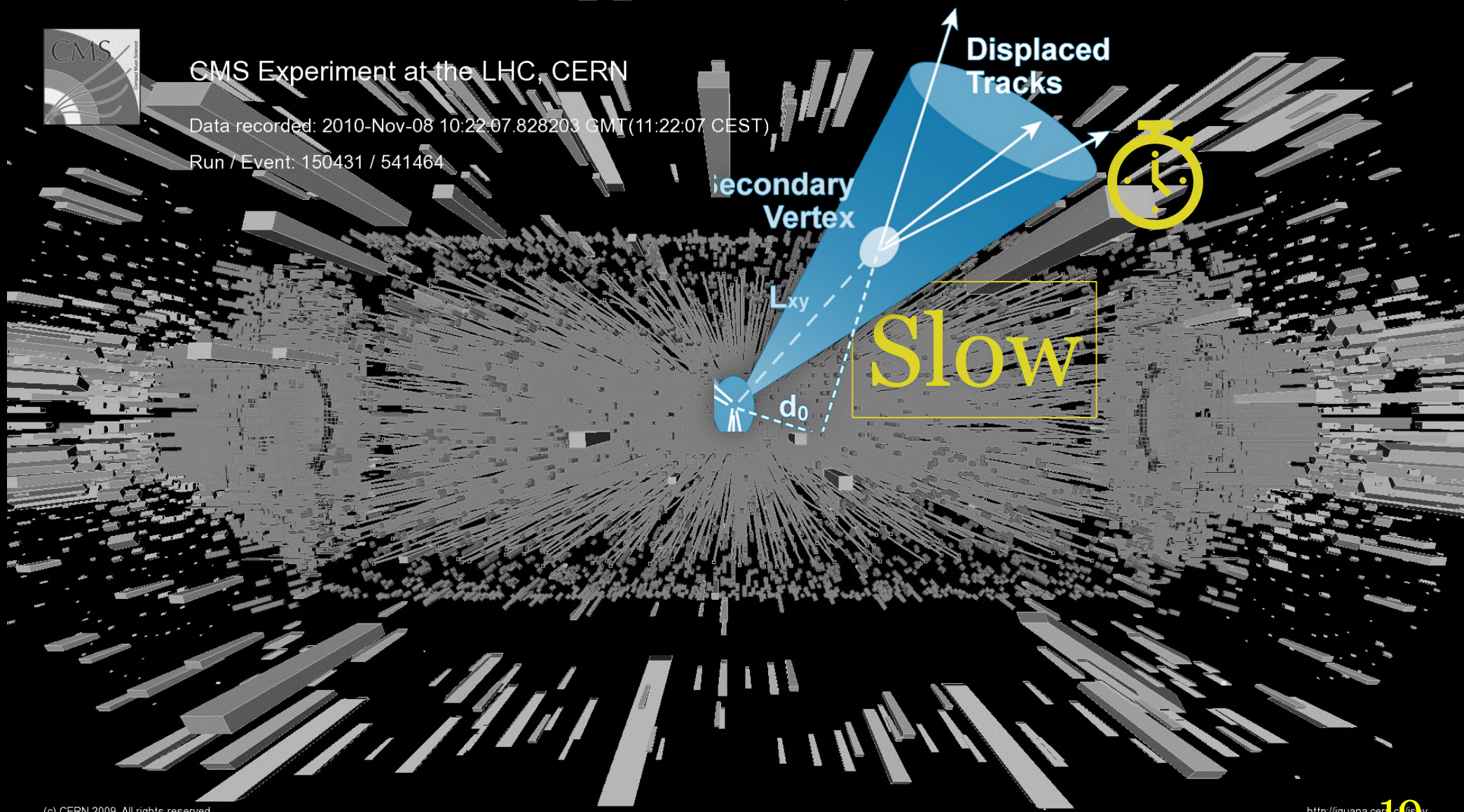
Long-Lived Particles (LLPs) opportunity

☹trigger
☹reconstruction
☹non-standard background

Delay is a universal feature of Long-Lived Particles*

Liu, ZL, Wang, 1805.05957

See the talk by M. Kazana this afternoon



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

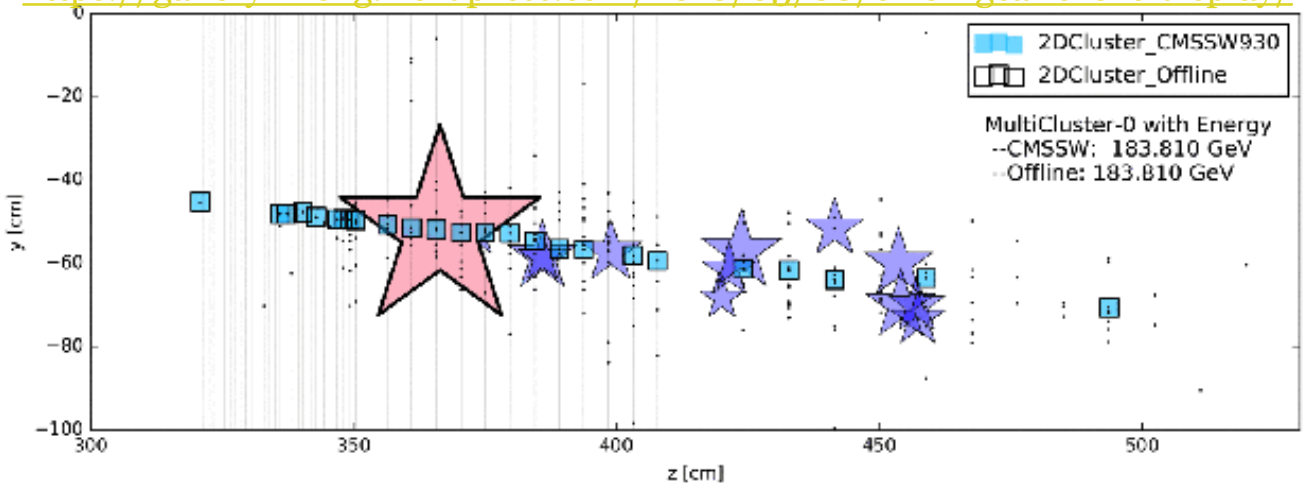
For a LLP community review: 1903.04497

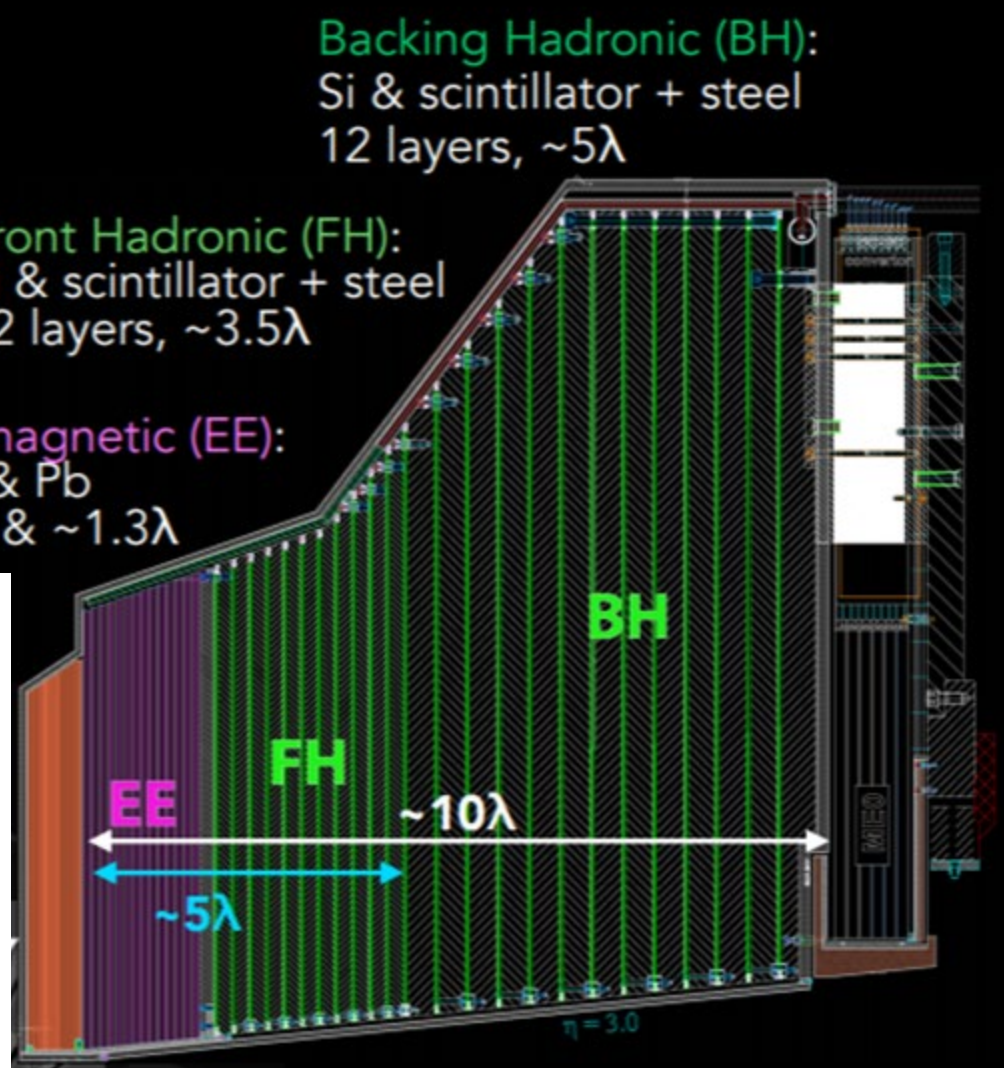
More ideas: High granularity detectors

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/



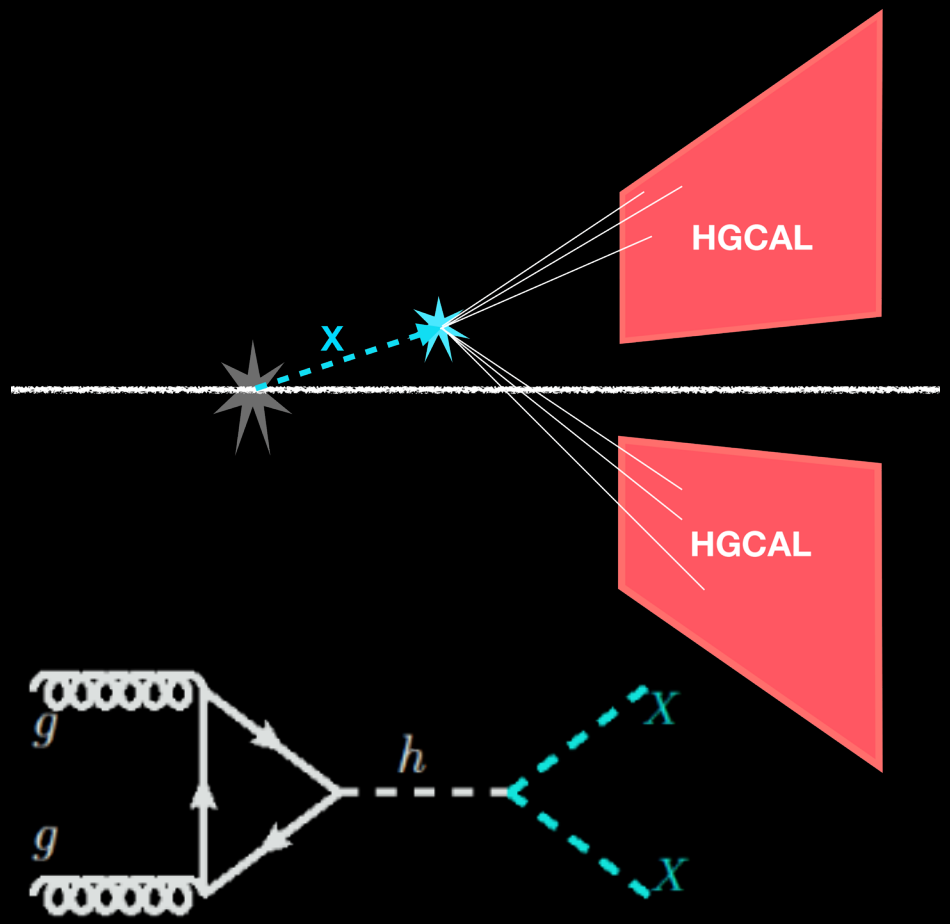


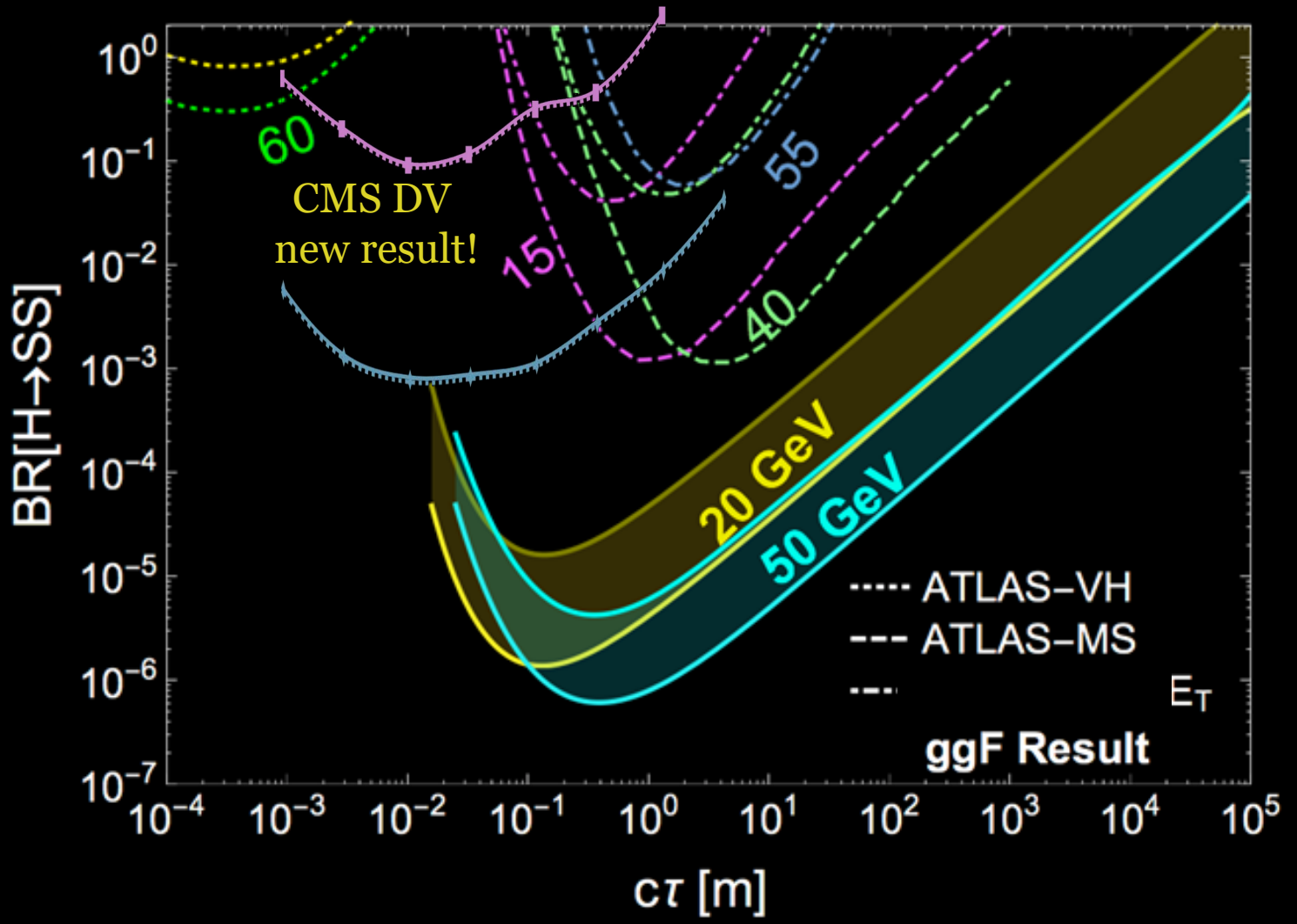
HGCal, see Canepa's talk

endcap

HGCAL potential

Model building: Chacko, Goh, Harnik, hep-ph/0506256, hep-ph/0512088, +Burdman hep-ph/0609152+many… **Pheno:** Craig, Katz, Strassler, Sundrum 1501.05310 +many…



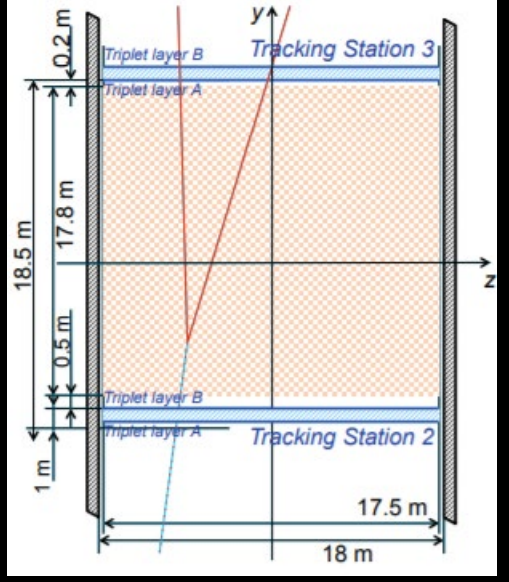


See Xiaoping Wang's talk yesterday

Liu, ZL, Wang, Wang, to appear

See F. Kling's talk yesterday
See Y-D Tsai's talk yesterday

Forward Spectrometer



Expanding the LHC program

- MATHUSLA
- Codex-B
- AL3X
- ANUBIS

Central/Hard LLPs

- FASER
- SHiP
- NA62
- SeaQuest

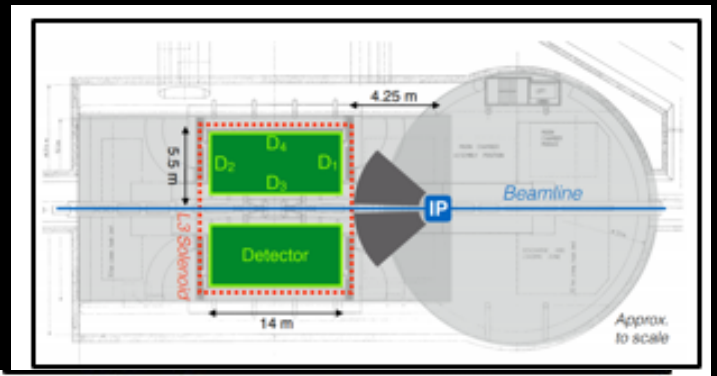
Forward/lighter LLPs

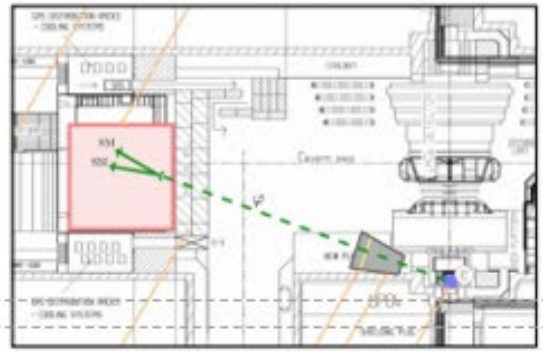
Beamdump experiments

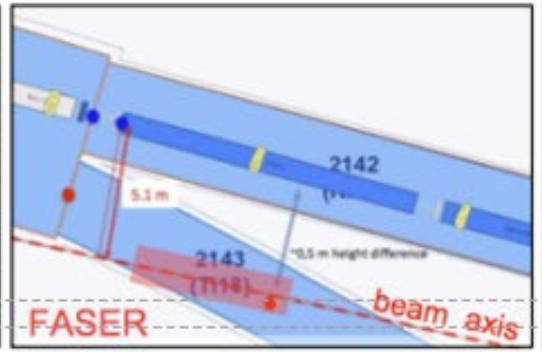
- …
- MoEDAL
- MilliQan

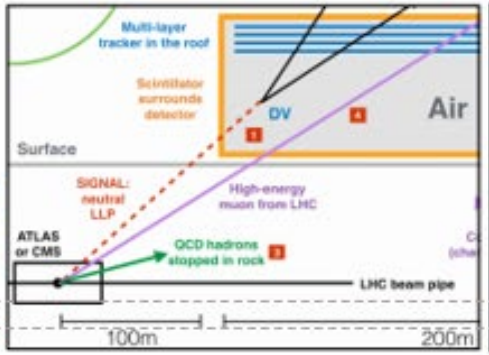
monopole
millicharged particles

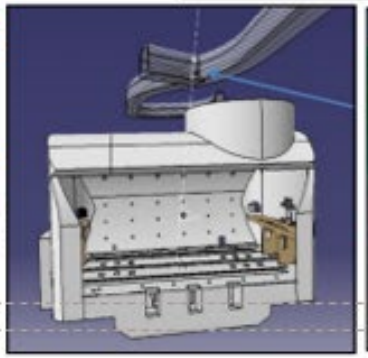
Search for LLPs

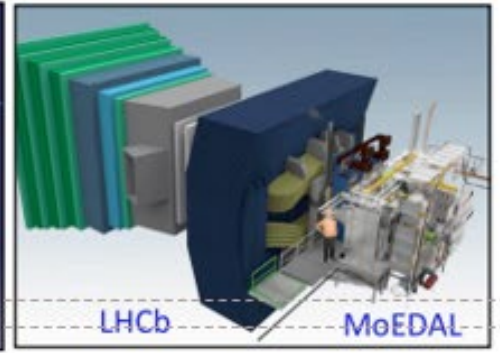












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Have Fun

- Model Agnostic Searches (Anomaly detection)
- Seeing color flow through interference
- New metric definition for machines (& pheno)
- Open data (learn QCD from data?)
- True muonium
- Quirk signatures
- …

See talks at ML4Jets meetings, also talk by P. Shyamsundar

See Cari Cesarotti't talk yesterday;
See Lingfeng Li's talk yesterday;

Outlook

The success of the LHC (and the SM) has triggered a paradigm shift

- chance for us to define new questions/quests, testability is always the backbone;
- work (as a community) less like a boson (no over-density for a given topic);

what hasn't changed is we are driven by curiosity, and
The BSM Opportunities at LHC reside in our creative work!

Many more:
Flavor;
QCD;
EWPO;
Machine Learning;
…

BSM Opportunities at the LHC

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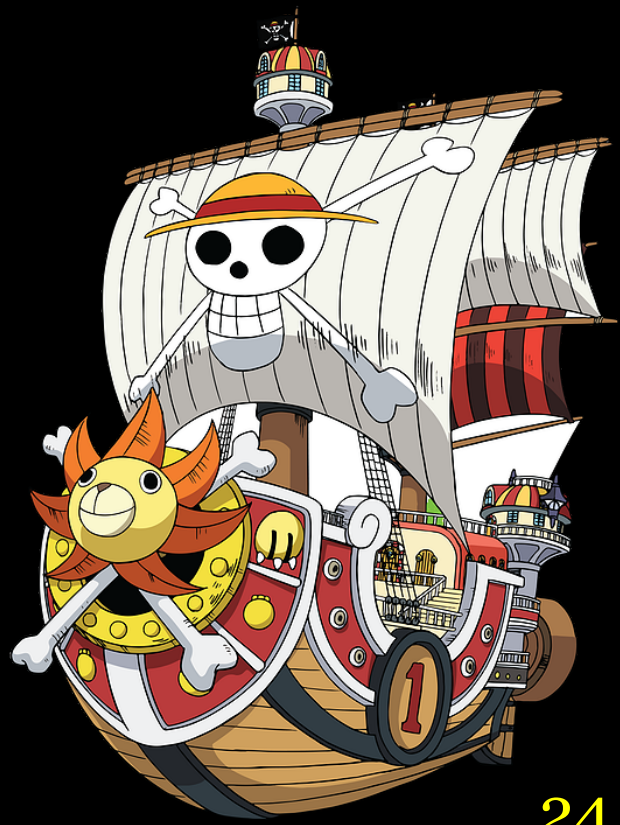
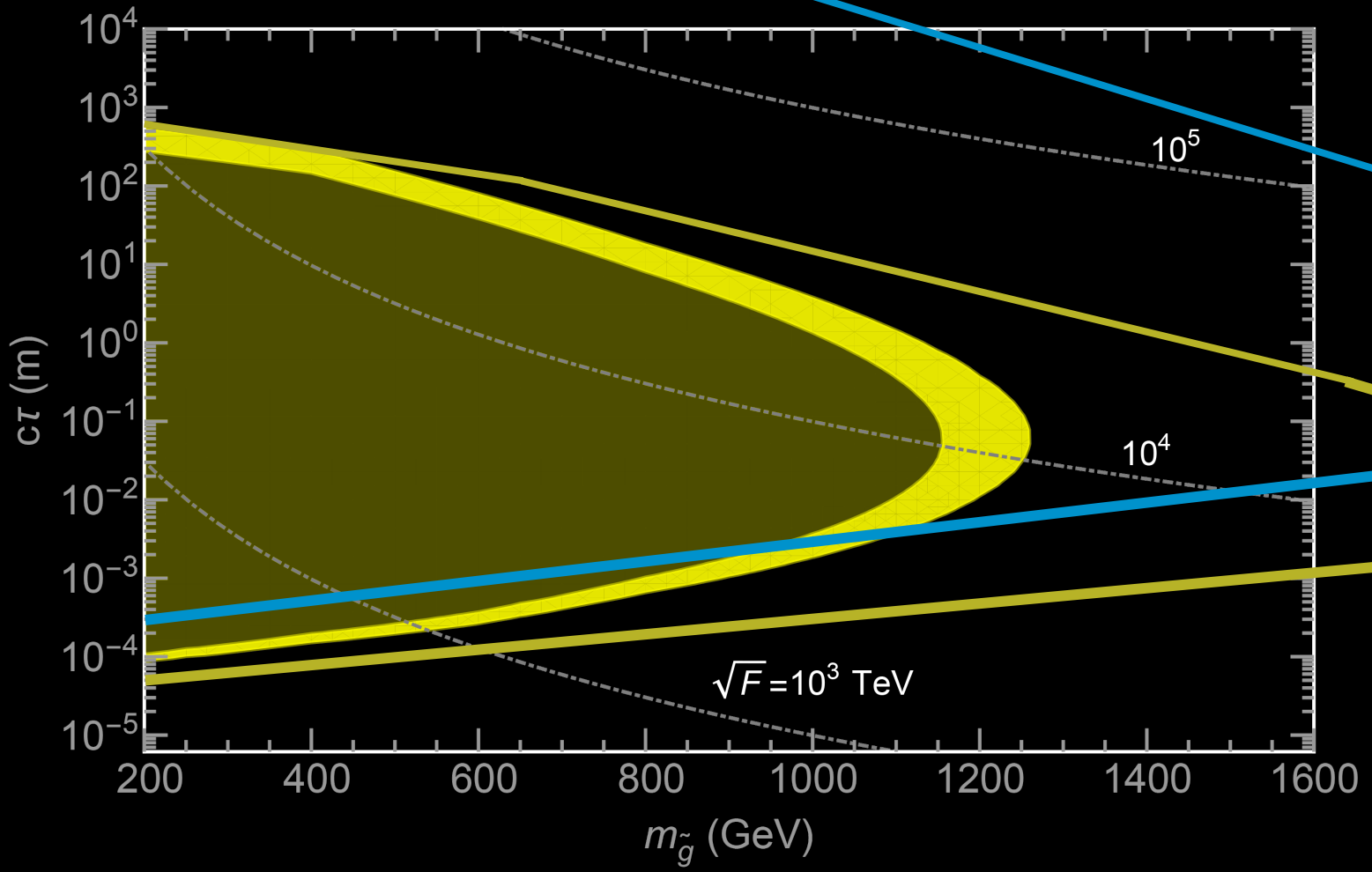
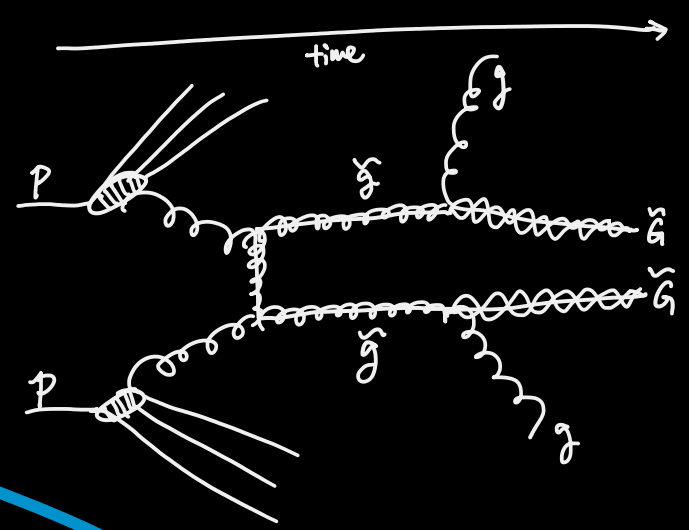


Backup

Late comers will be spotted easily



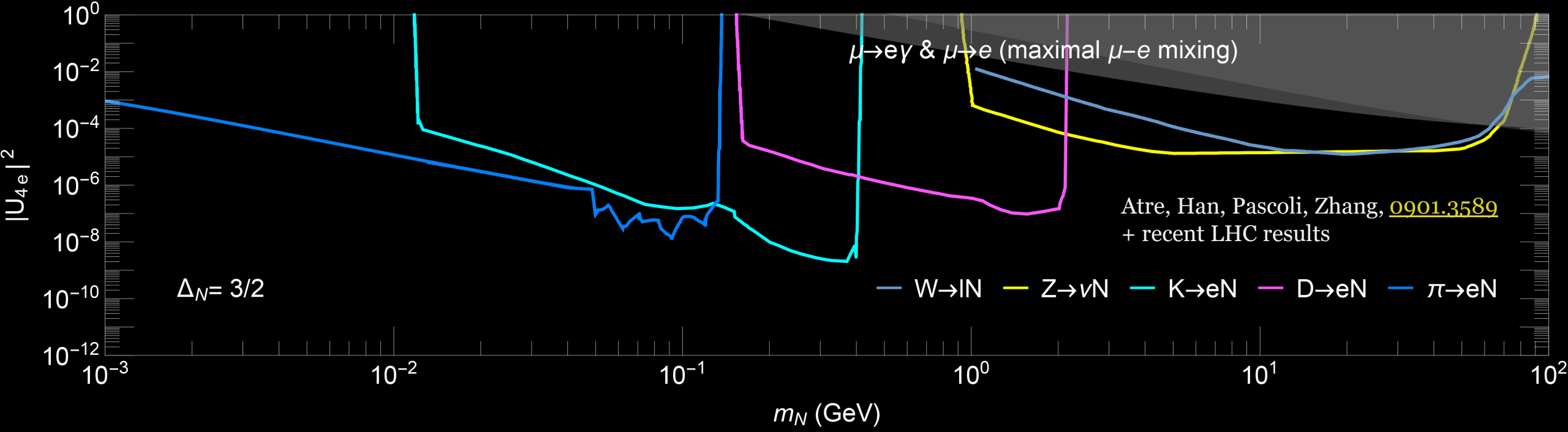


Delayed Jet analysis carried out by CMS

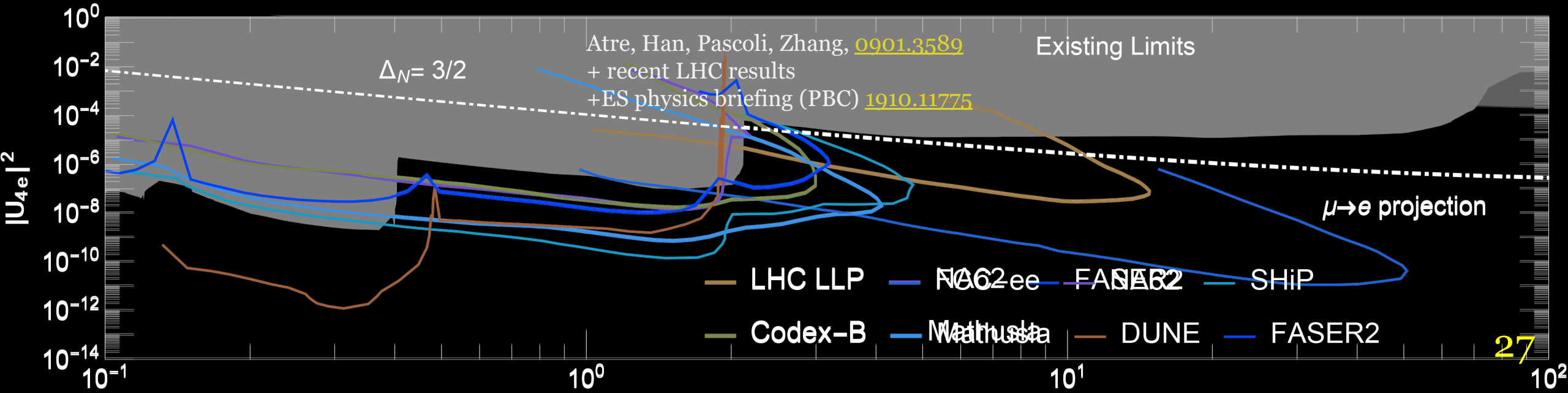
Displaced jet at 13 TeV

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

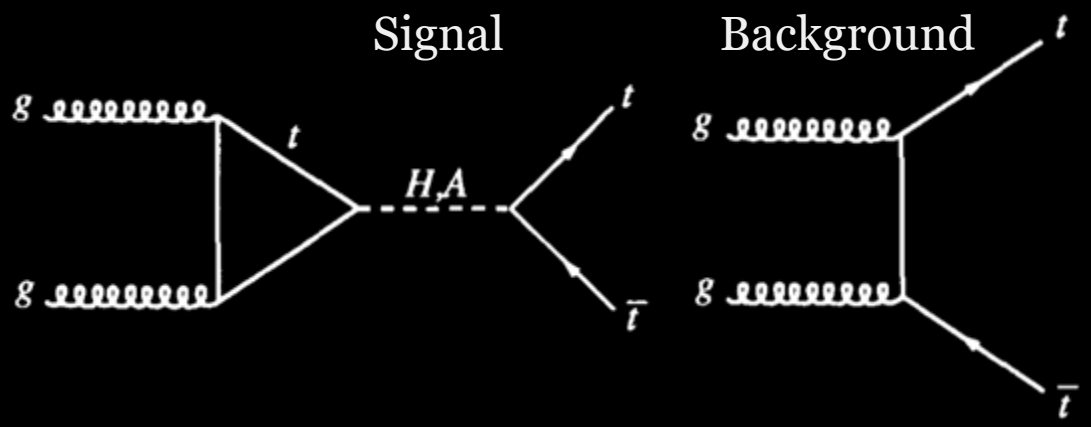
Liu, ZL, Wang, 1805.05957
8 TeV results, ZL, Tweedie, 1503.05923

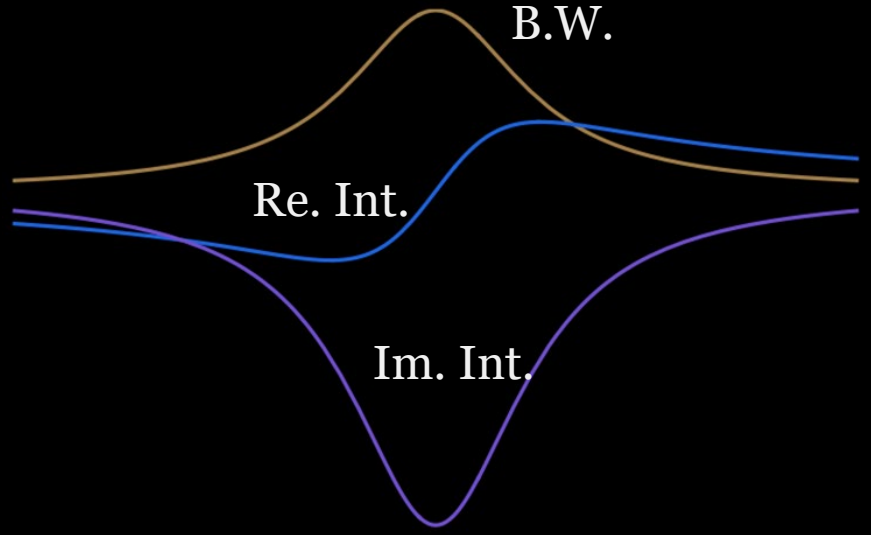


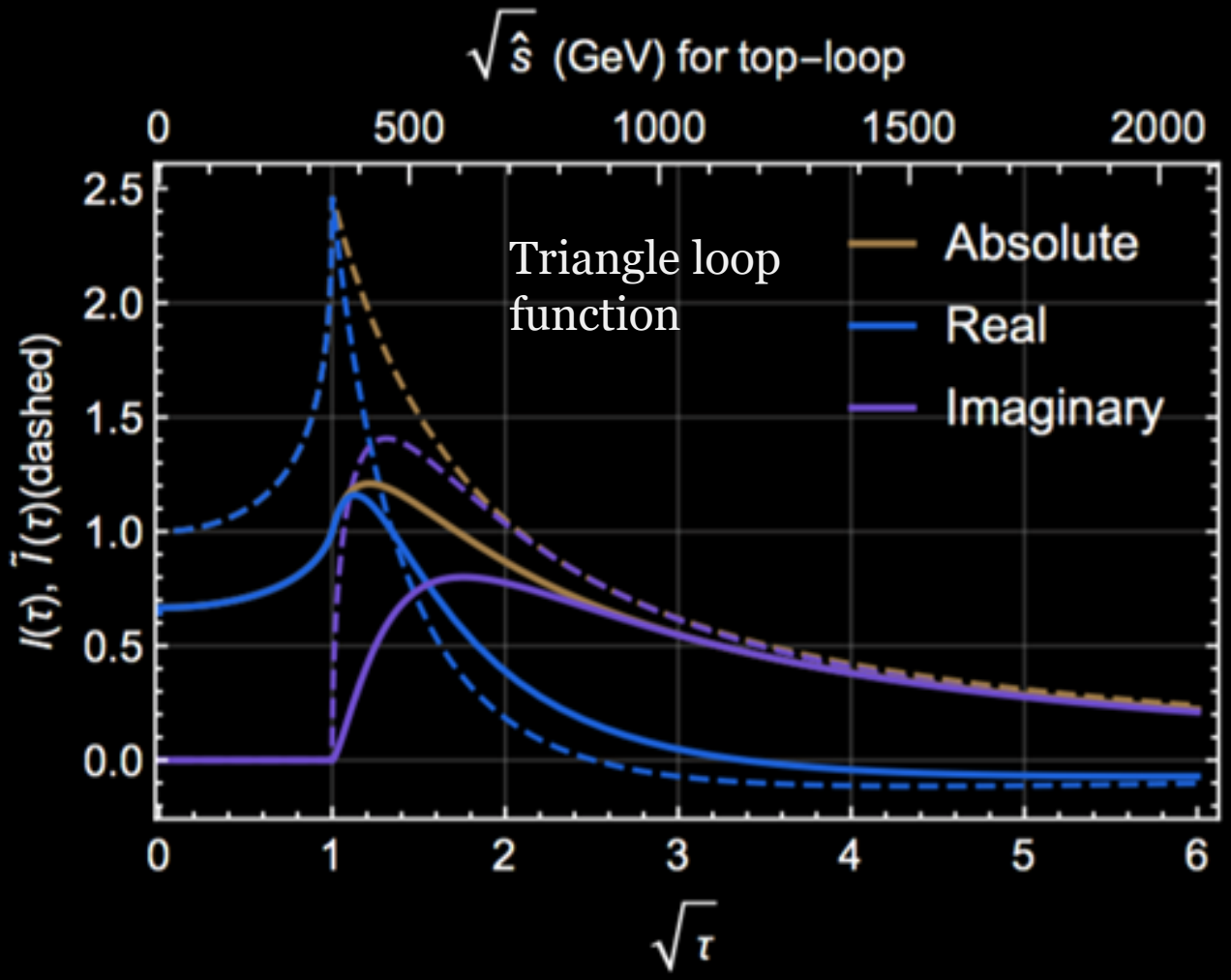
For instance, for Sterile Neutrinos



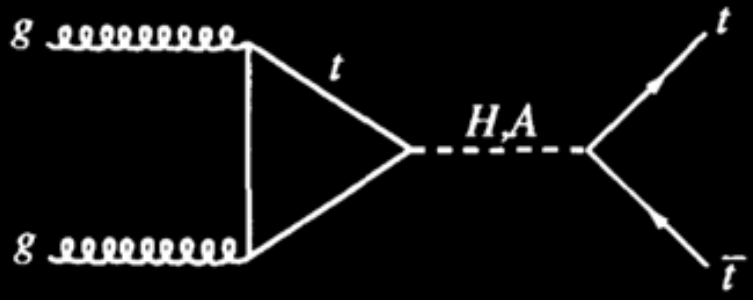
Unfamiliar look of heavy Scalars

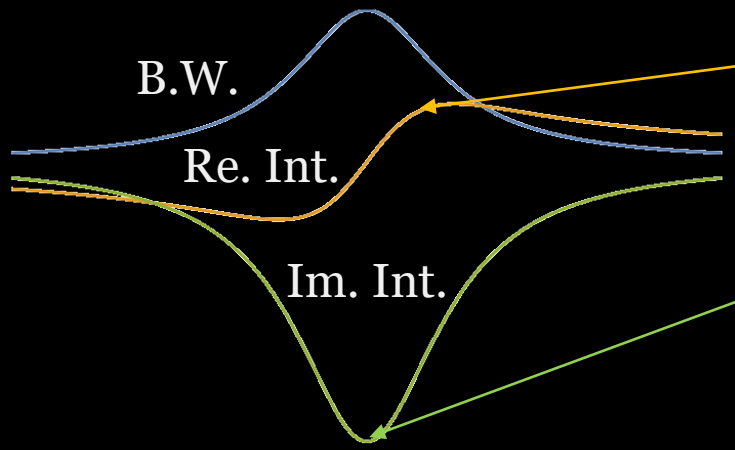


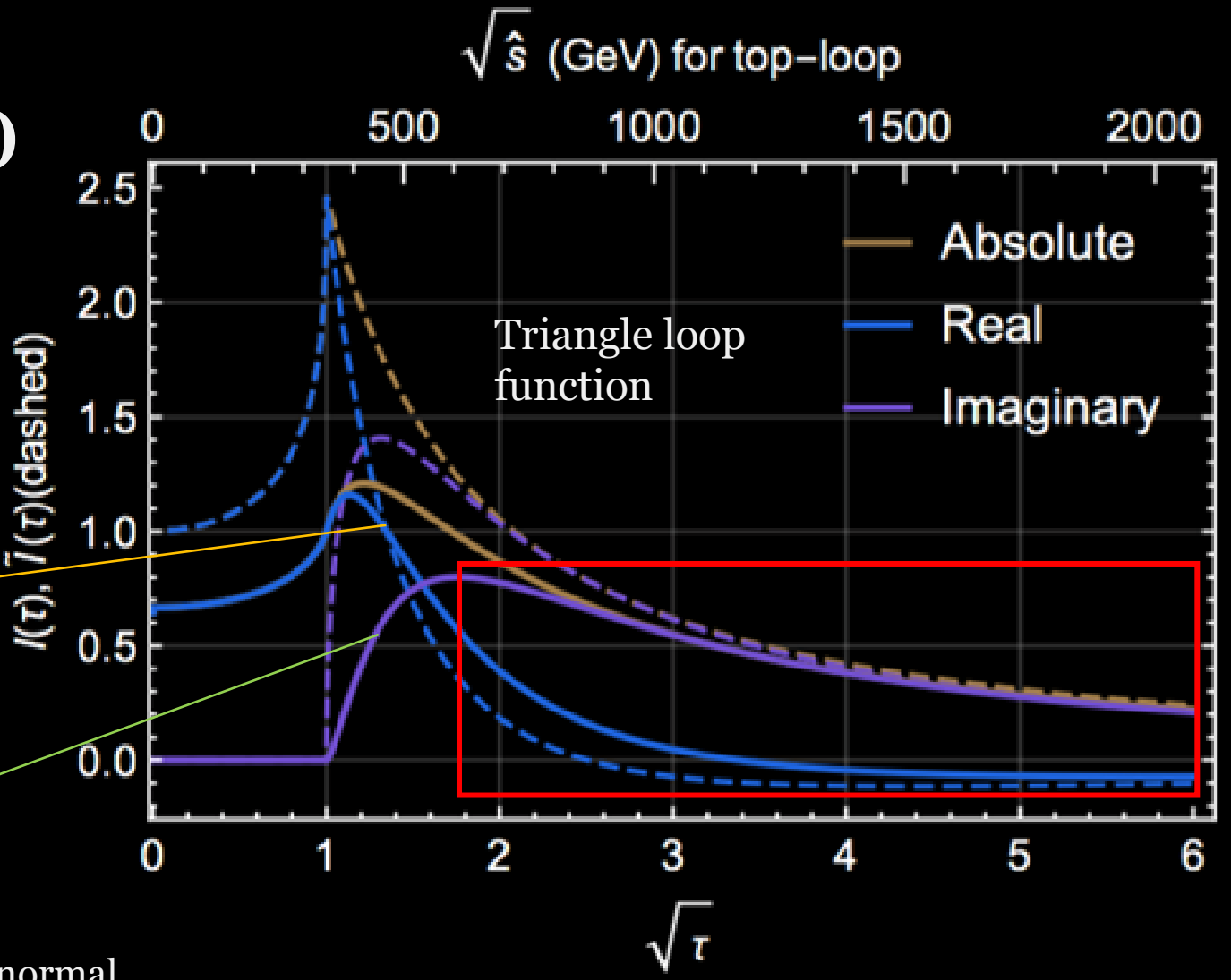




Challenges (interferences)





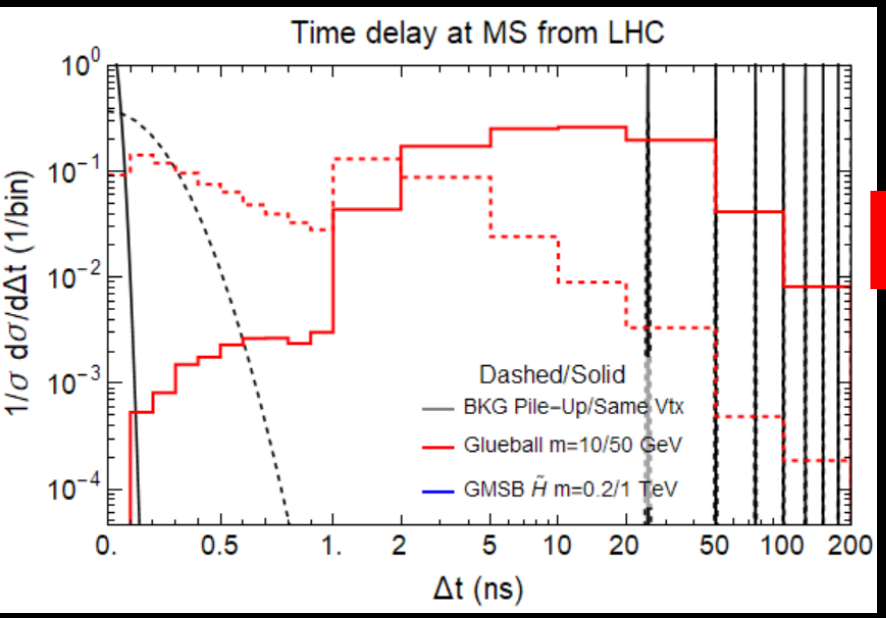


Background real
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)
Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

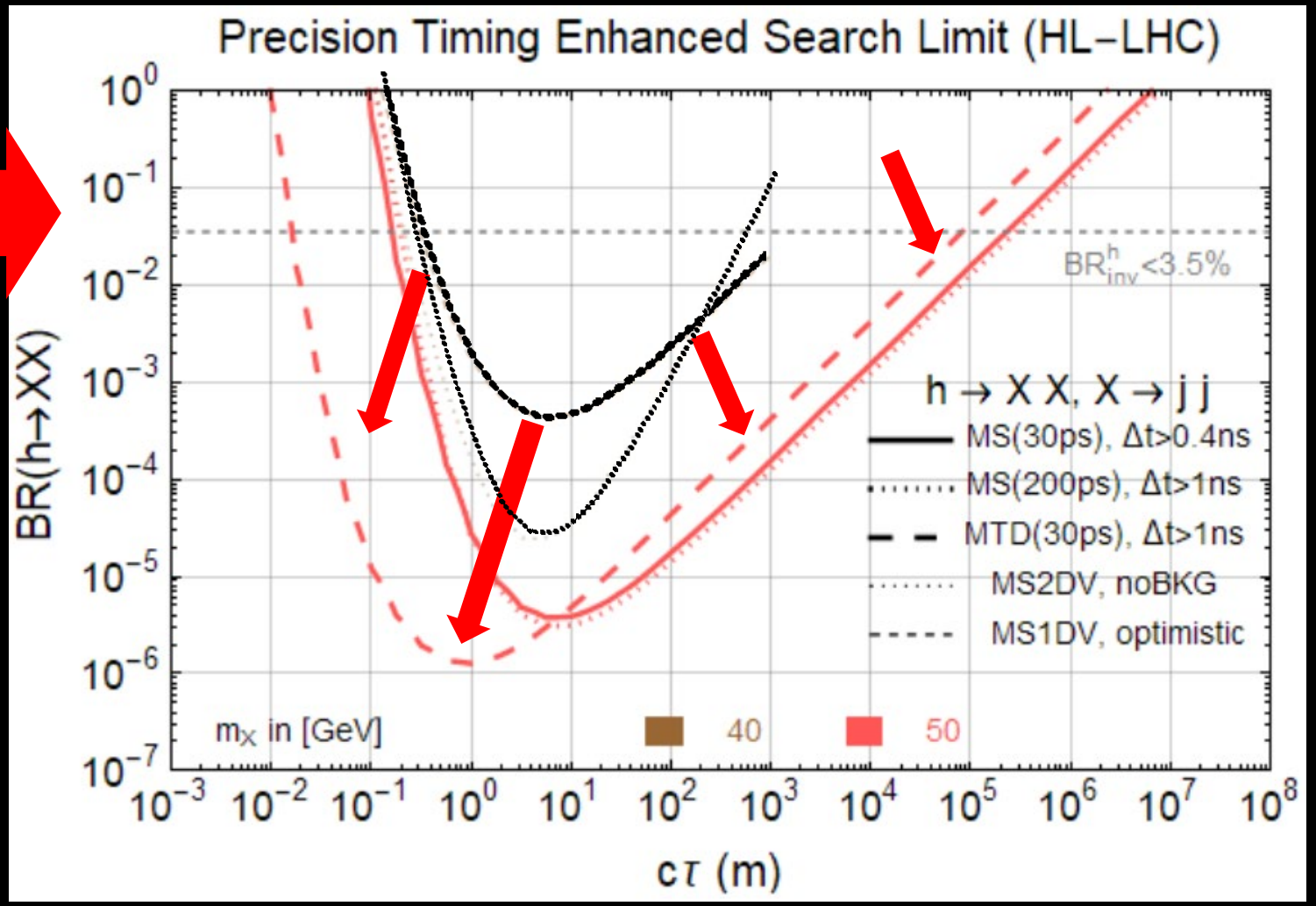
Once across the threshold, imaginary piece arises drastically and the real piece decreases.

A strong phase
``insensitive"* to phase in the Yukawa as the signal amplitudes is proportional to $|y_t|^2$.
*subject to difference in loop functions. Very typical in hadron physics, also used in leptogenesis

Higgs to LLPs: LLP triggers greatly boost the reach



A lot new ideas and possibilities to improve the Higgs to long-lived particles searches.



J. Liu, ZL, LT Wang, 1805.05957

As simple as QCD:
Dimensional transmutation generates small scales

… 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

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

$$\Lambda_{\mathrm{QCD}'} \qquad \left(\frac{\Lambda_{\mathrm{QCD}'}}{M}\right)^3 \qquad \Lambda_{\mathrm{QCD}'}\left(\frac{\Lambda_{\mathrm{QCD}'}}{M}\right)^5$$

Consider the compositeness in general CFT

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

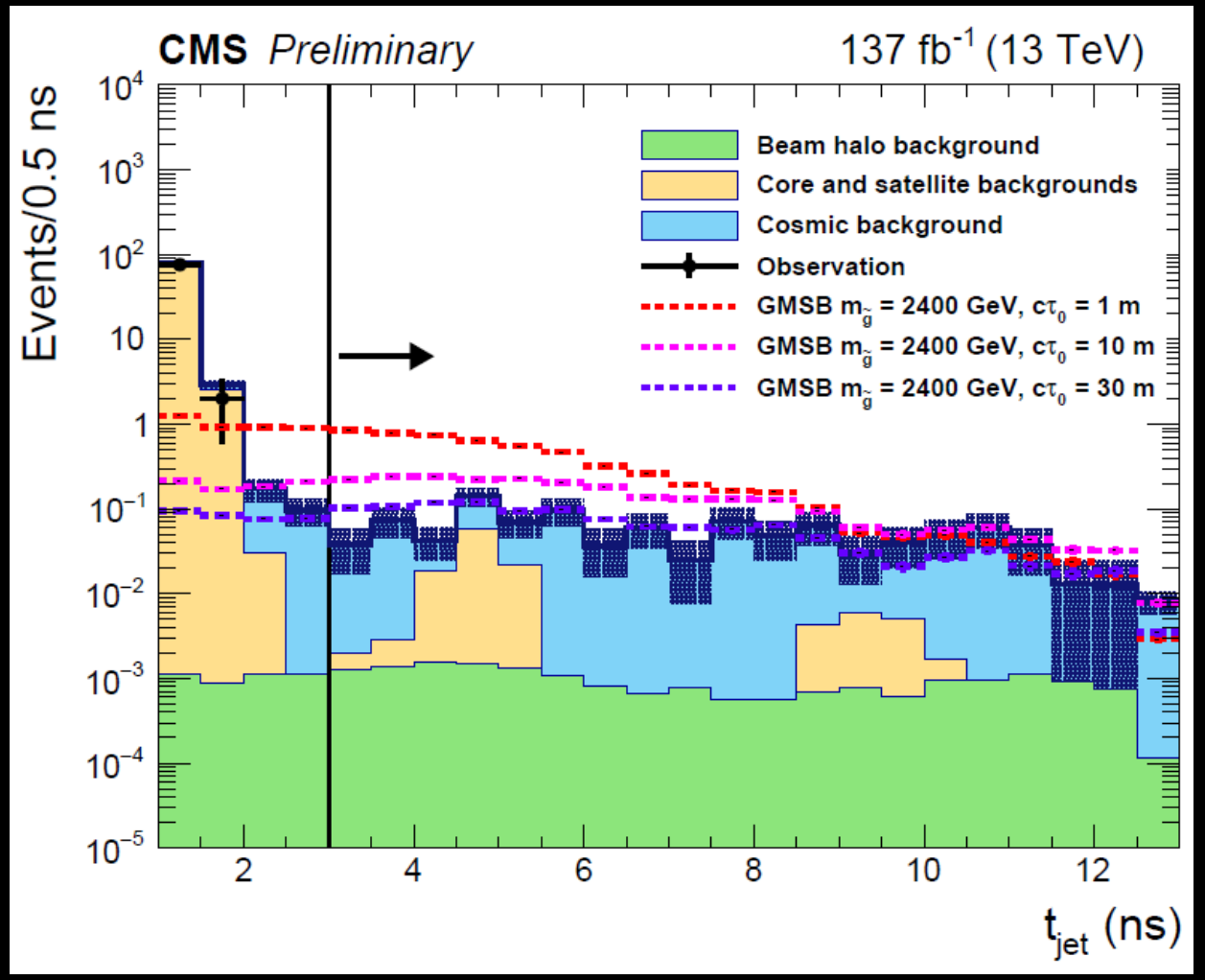
CFT deformation generates

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

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

Chacko, Fox, Liu, Harnik, to appear

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

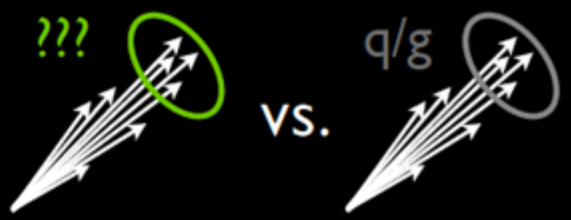
Cosmics small (for this analysis, no need to do cosmic veto yet but there are many ways) and scale with time but not luminosity

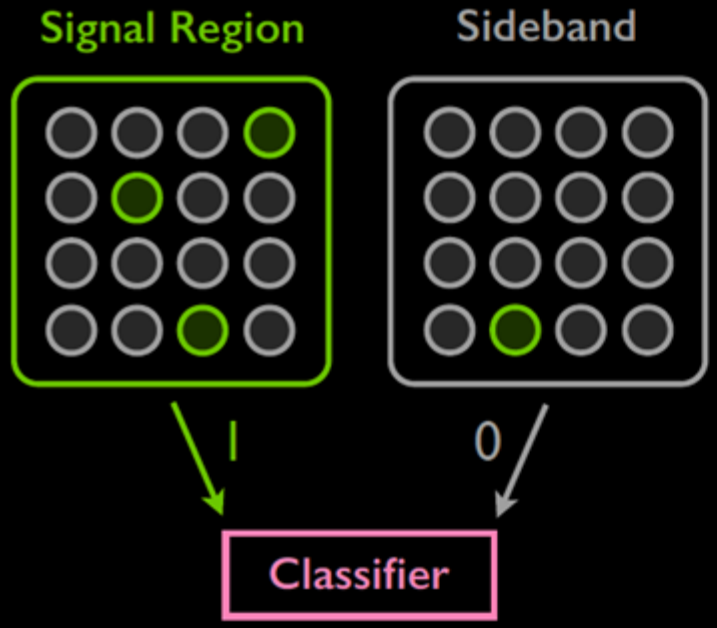
Lot of theory & experimental activities:

- 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
- …

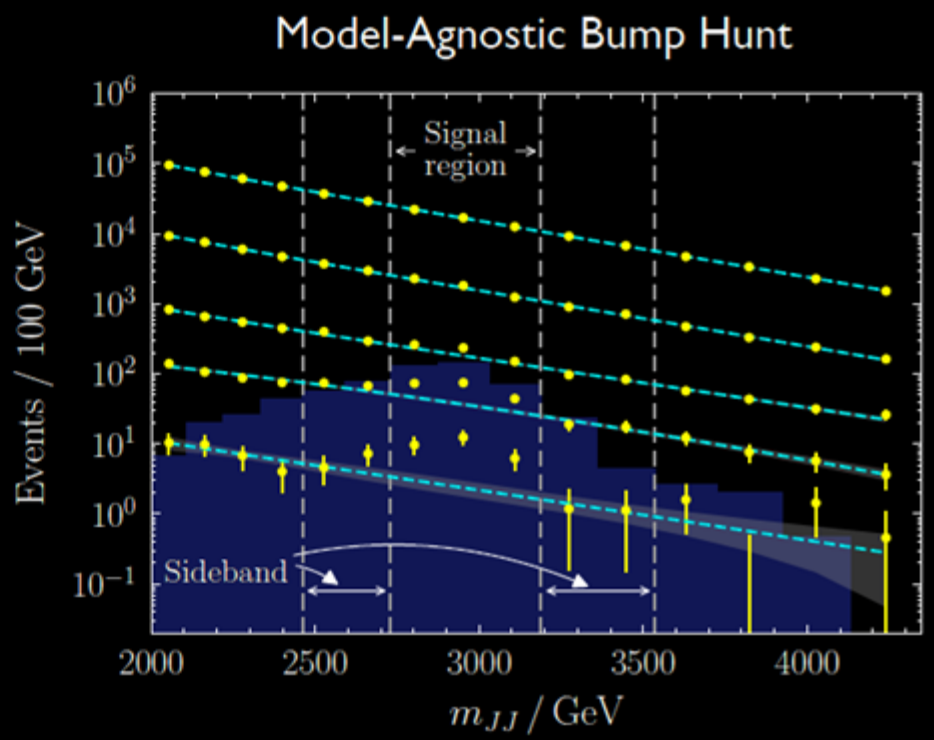
CWoLa Hunting

Using "Classification Without Labels"





With enough data, monotonic w.r.t. optimal classifier (!)



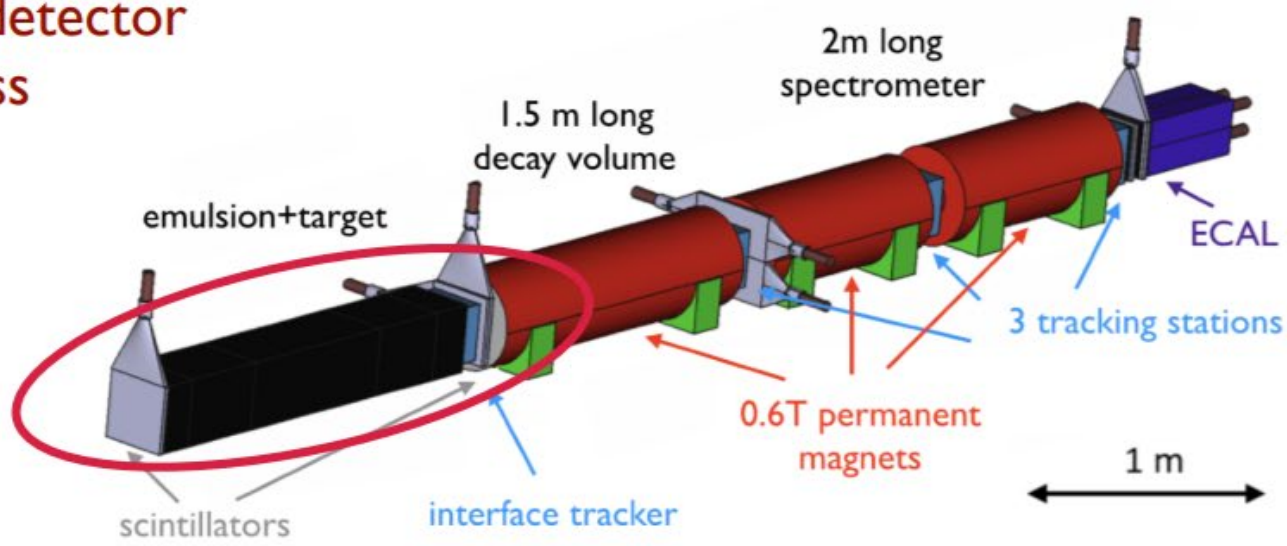
[Collins, Howe, Nachman, 1805.02664, 1902.02634; using Metodiev, Nachman, JDT, 1708.02949; see also Blanchard, Flaska, Handy, Pozzi, Scott, 1303.1208; Cranmer, Pavez, Louppe, 1506.02169]

$SU(2) \leftrightarrow SU(2)'$
$SU(3) \leftrightarrow SU(3)'$
$U(1) \leftrightarrow U(1)'$ or $U(1) \leftrightarrow U(1)$

- track impact parameter (|do| < 15 cm),
- track curvature (1/R ∝ q/pT < 1/(1.8 m)),
- track eta |η| < 2.4
- track time to (|to| < 6 ns)
- track z- coordinate (|zo| < 15 cm)

Cut(set) x	1	2	3	4	5	6	7	8	9	1+2	123	4+5	6+7	8+9	4567	1245	1289	124567
ϵ_x	9.7^{-1}	8.6^{-2}	2.3^{-1}	5.1^{-2}	6.8^{-1}	1.6^{-2}	3.1^{-1}	4.5^{-2}	1.5^{-2}	8.4^{-2}	8.2^{-2}	4.9^{-2}	3.0^{-3}	4.9^{-4}	1.6^{-4}	3.7^{-3}	1.8^{-5}	1.0^{-5}
ρ_{1x}									−0.5									
ρ_{2x}			+1.5	−0.1					−0.3			−0.1	−0.1	−0.3				
ρ_{3x}		+1.5		−0.6	−0.2		−0.1		+0.7	+1.5		−0.6	−0.1	+1.1	−0.7	+1.4	+1.5	+1.5
ρ_{4x}		−0.1	−0.6		+0.3	+0.1	+0.1	+0.1	−1.9	−0.1	−0.2			−1.0			—	
ρ_{5x}			−0.2	+0.3					−0.9					−0.2			−0.2	
ρ_{6x}				+0.1			−0.5	−0.5	−0.3			+0.1		+0.4			—	
ρ_{7x}			−0.1	+0.1		−0.5		+0.7	−0.7			+0.2		−0.2		+0.2	−0.1	
ρ_{8x}				+0.1		−0.5	+0.7		−0.3			+0.1	+0.7		+1.0	+0.2		—
ρ_{9x}	−0.5	−0.3	+0.7	−1.9	−0.9	−0.3	−0.7	−0.3		−0.8	−0.8	−2.1	−0.2		—	−2.2		—

- dedicated FASERν neutrino detector in front of FASER
  * 25cm x 25cm x 1.3m emulsion detector
  * tungsten target with 1.2 ton mass
  * ~ 20000 ν_μ, ~ 2000 ν_e, ~ 20 ν_τ



- TeV energy range currently unconstrained
  * this allows to probe neutrino cross sections at TeV for all 3 flavors