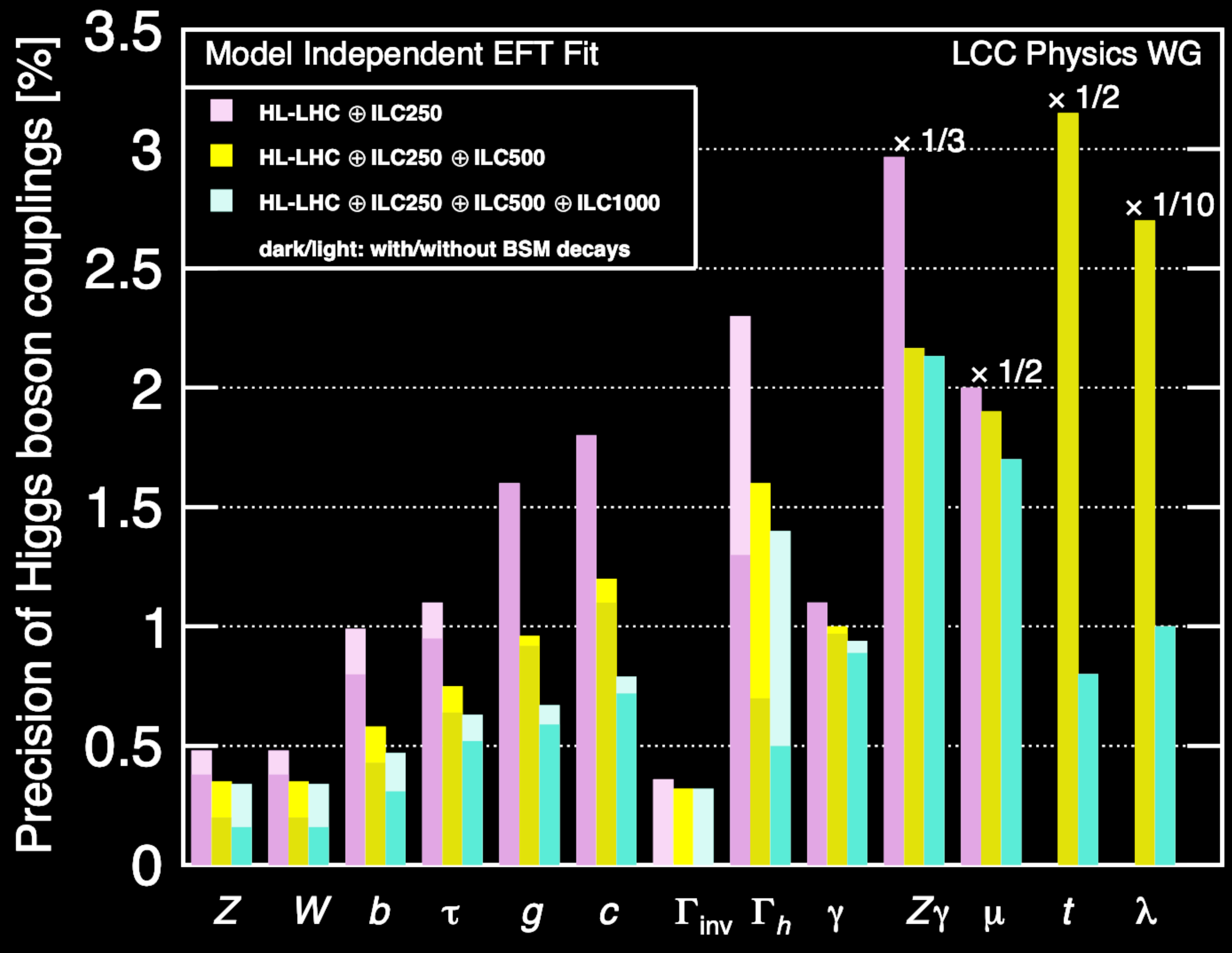
Physics Case for Precision Measurements at a Higgs Factory

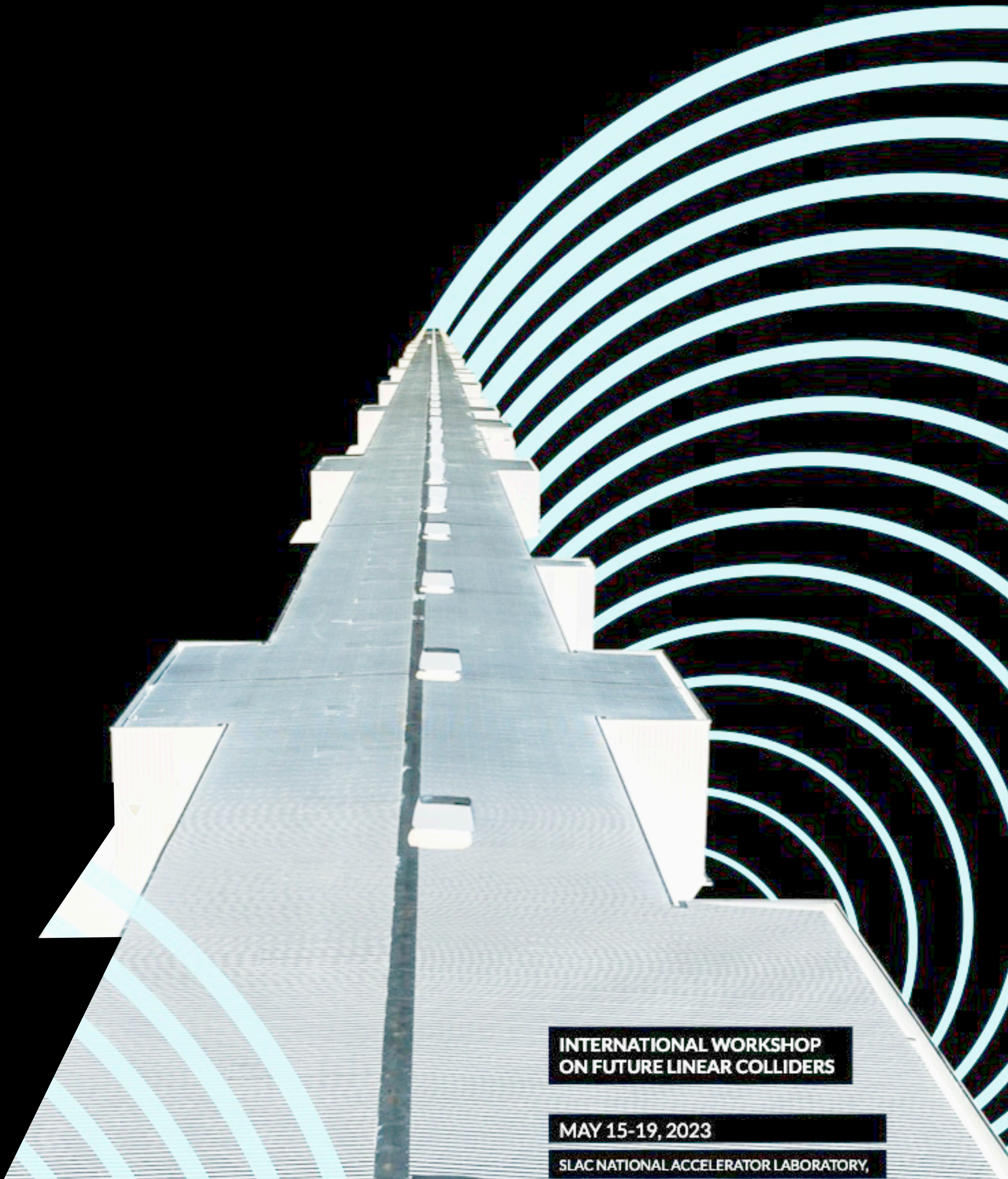
Nathaniel Craig

UCSB

LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS



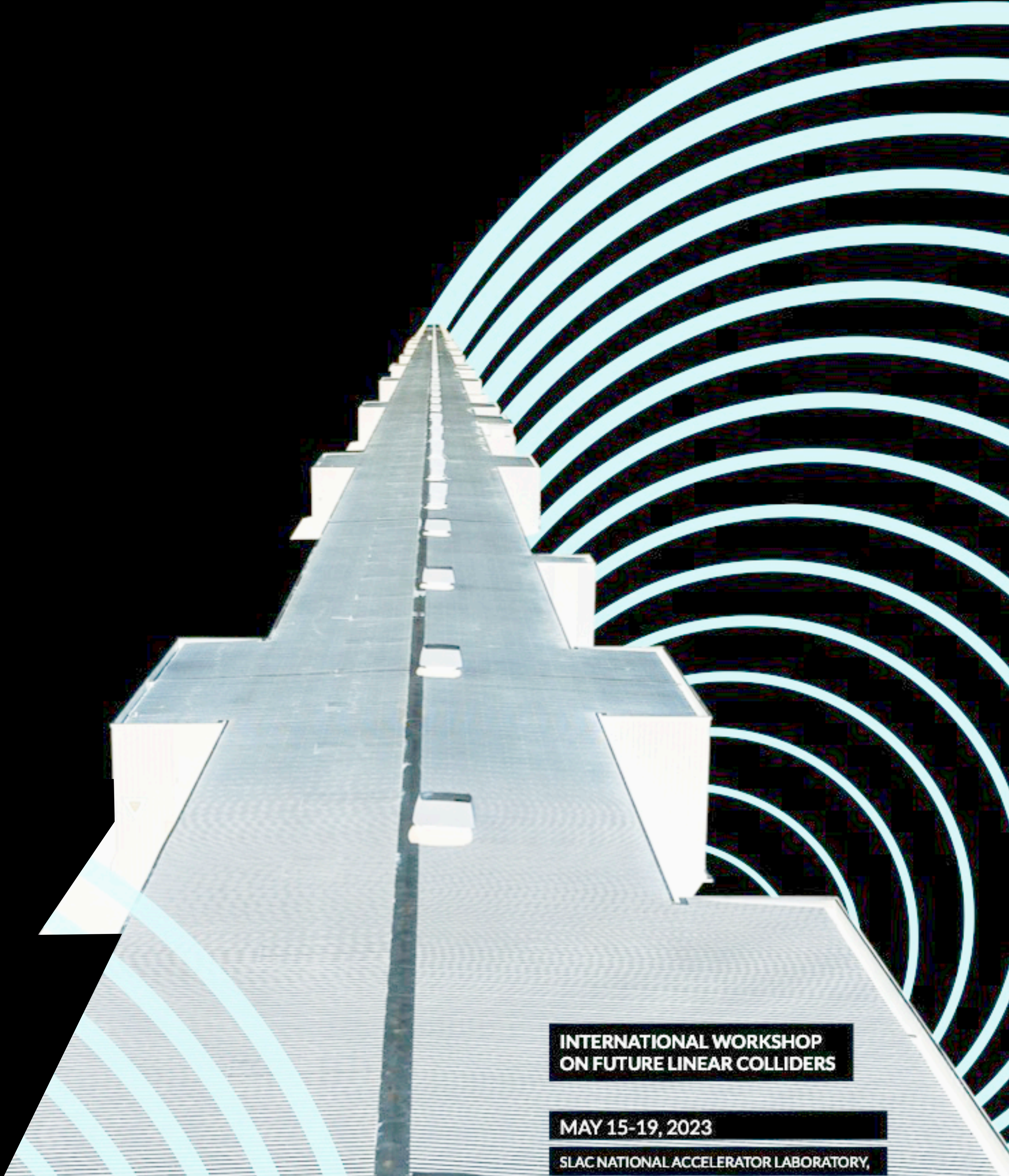
What are qualitative targets for Higgs precision in an era of exploration?



*ILC250/500/1000 as illustration of linear colliders more broadly

Seven Questions

Does the Higgs…



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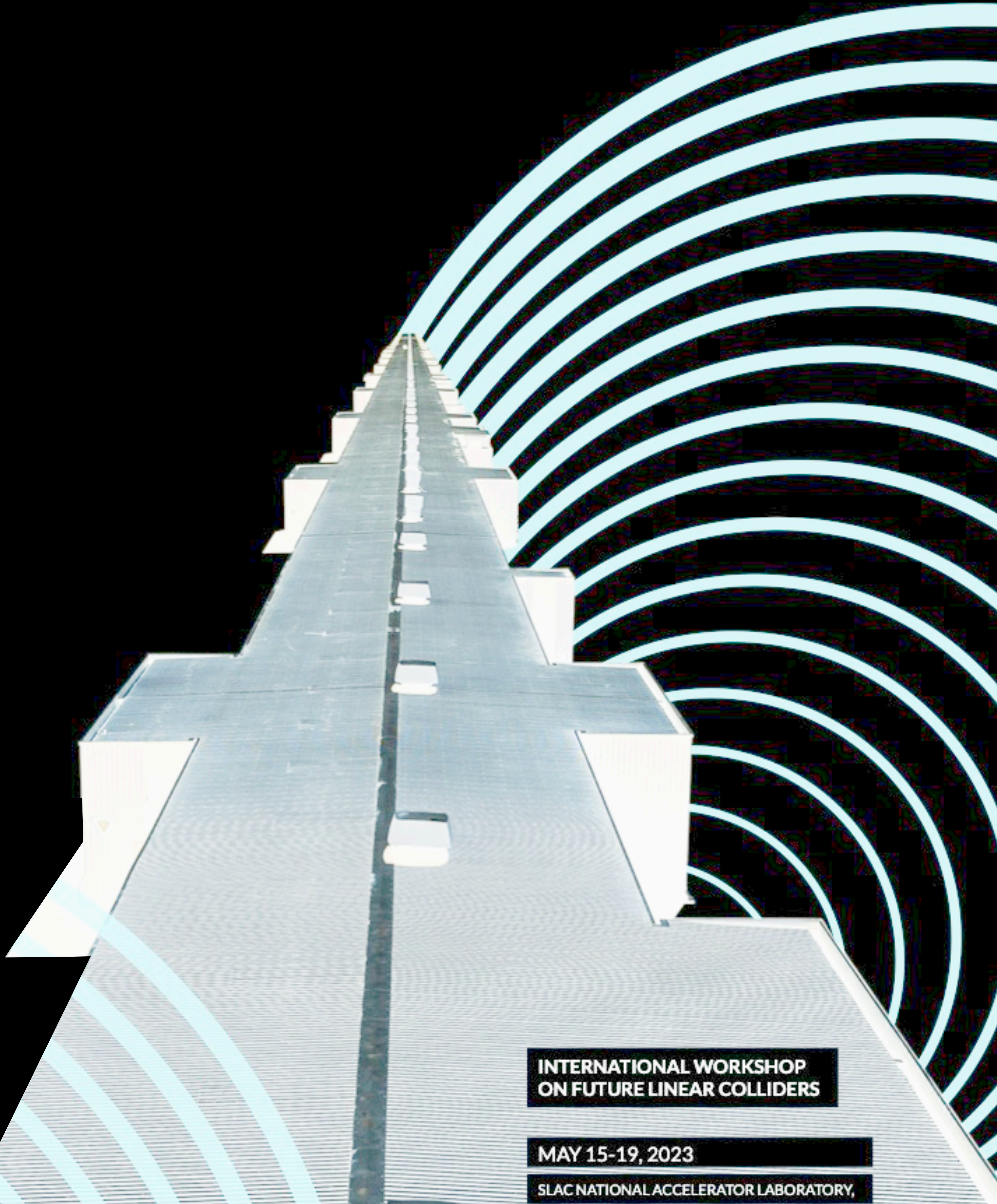
Does the Higgs…

1. …have a size?



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Does the Higgs…

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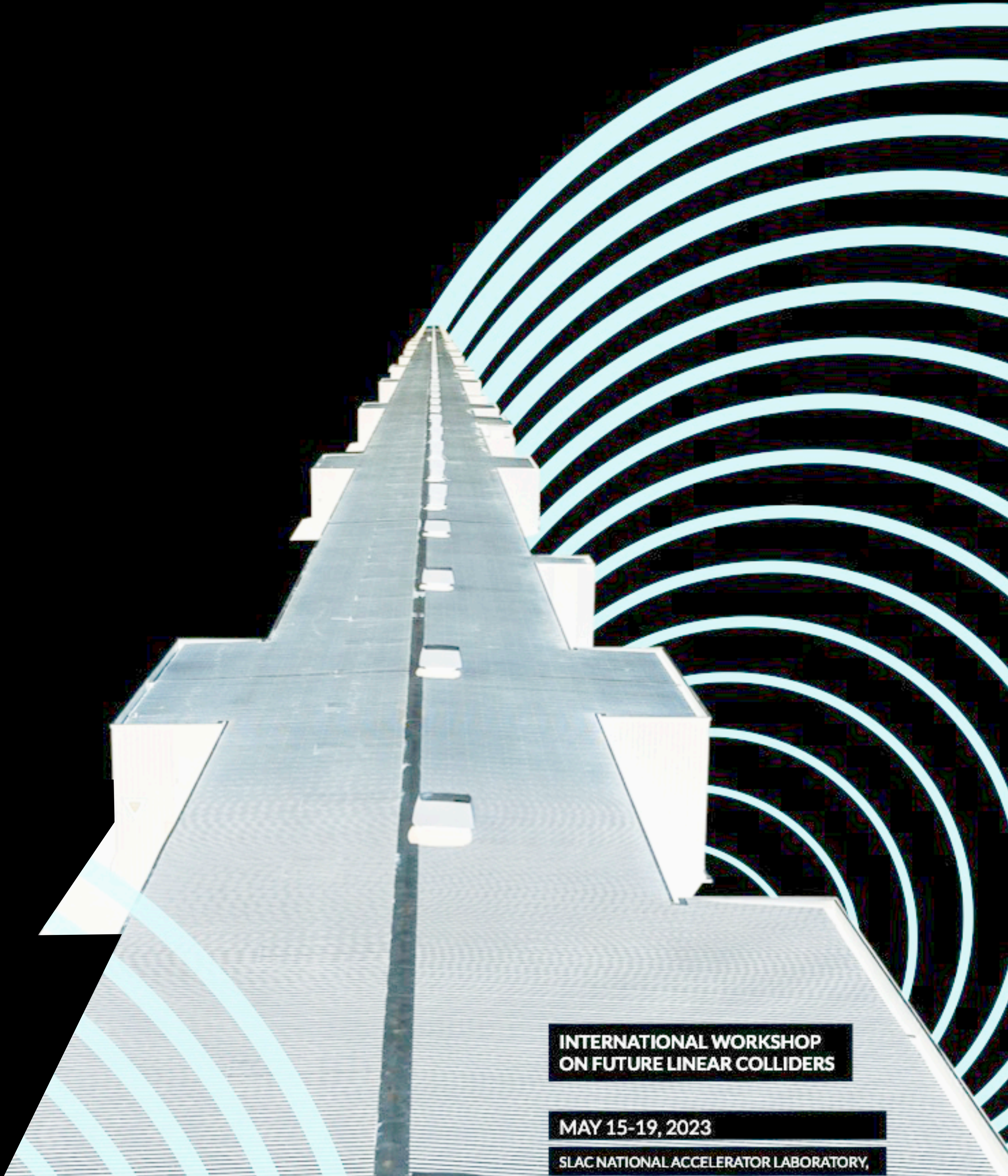
2. …interact with itself?



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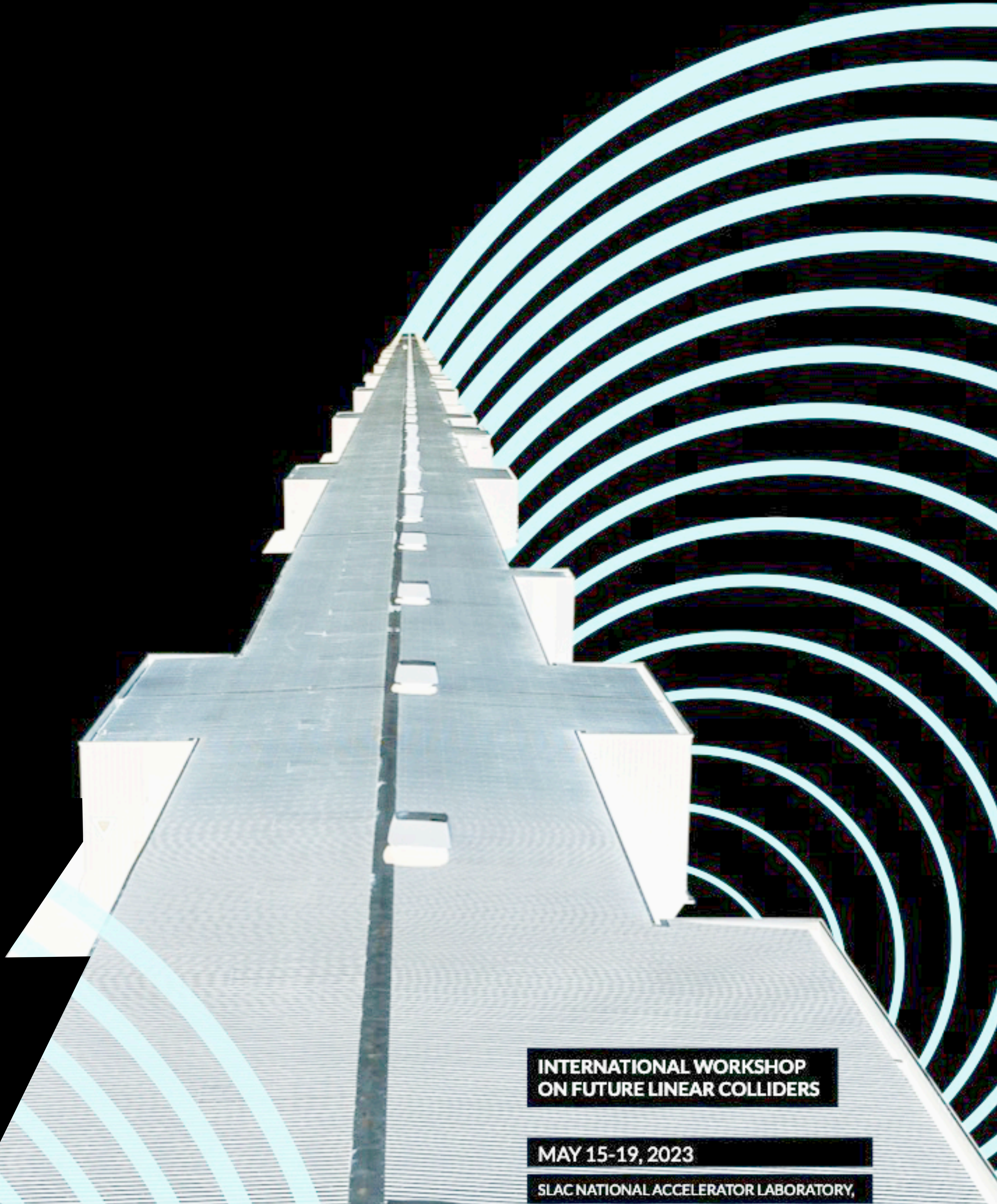
3. …mediate a yukawa force?



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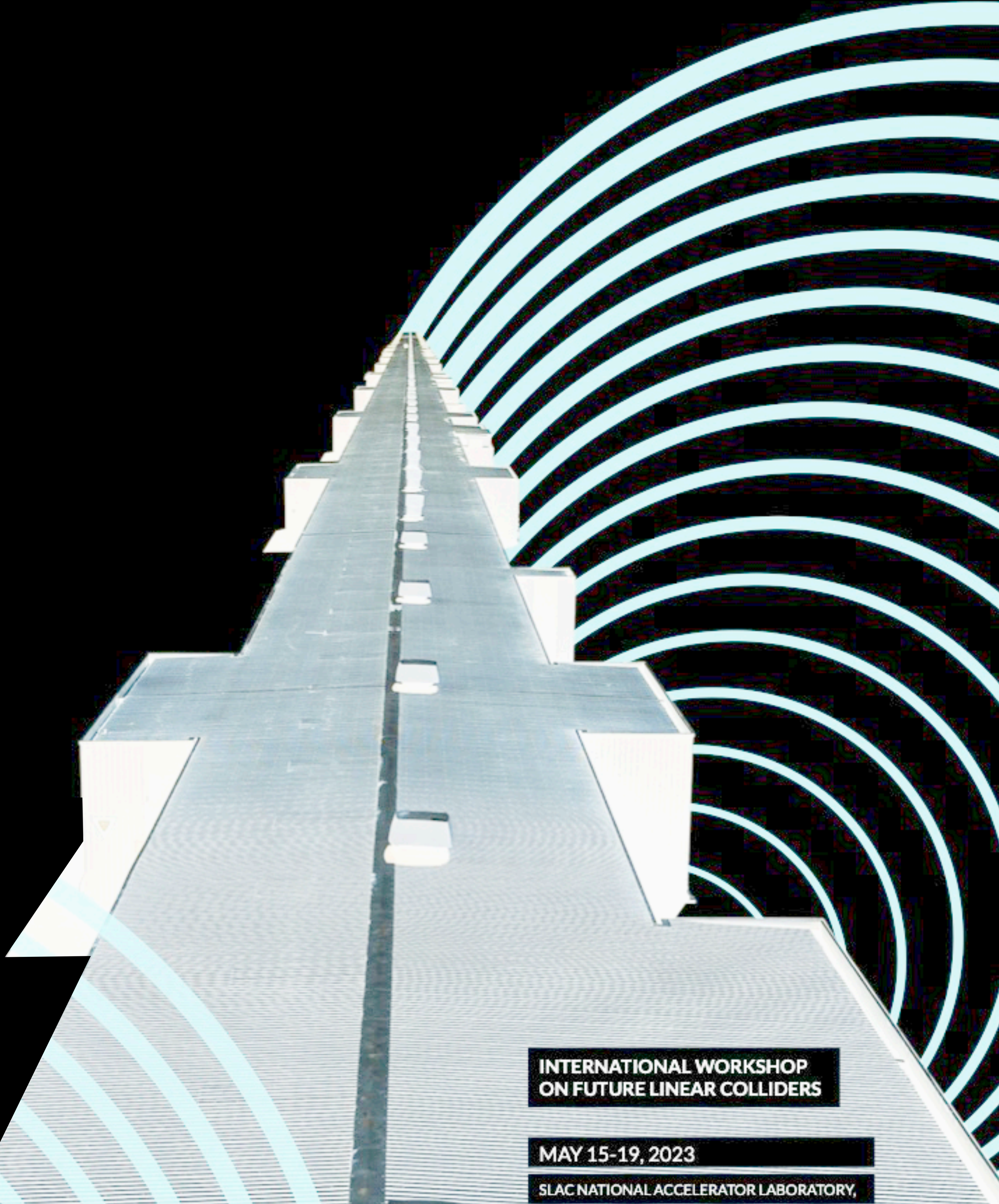

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Does the Higgs…

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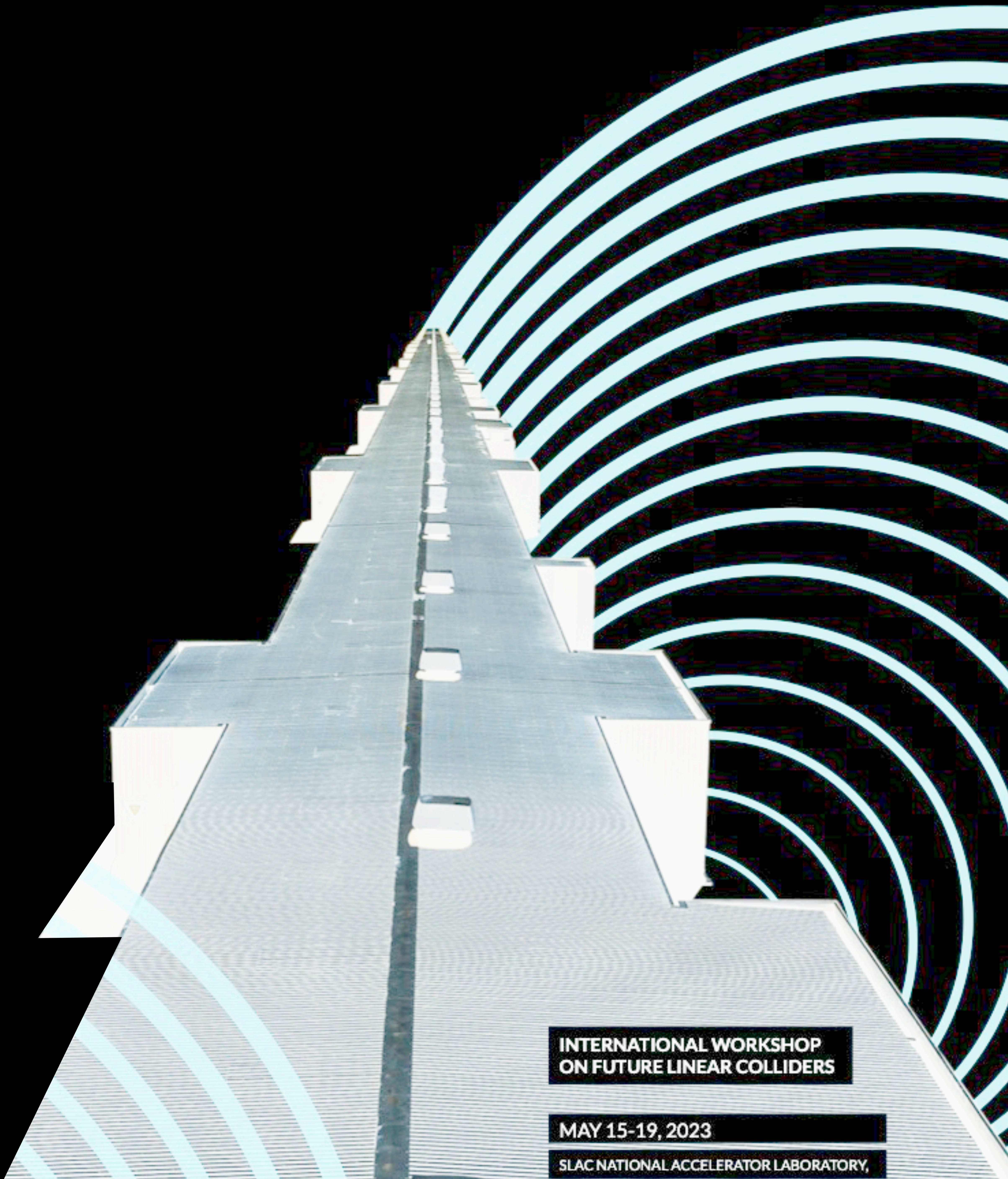

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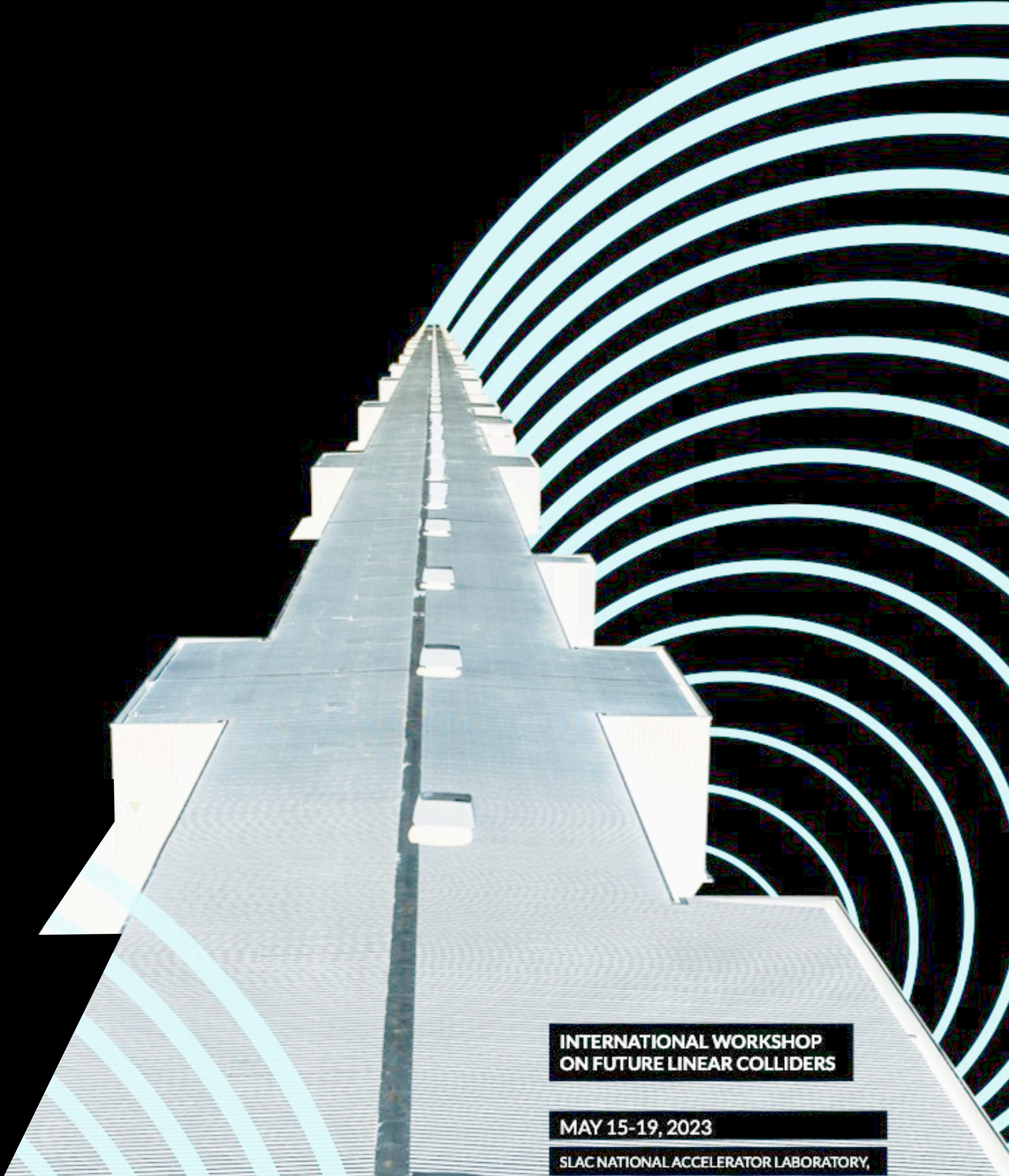

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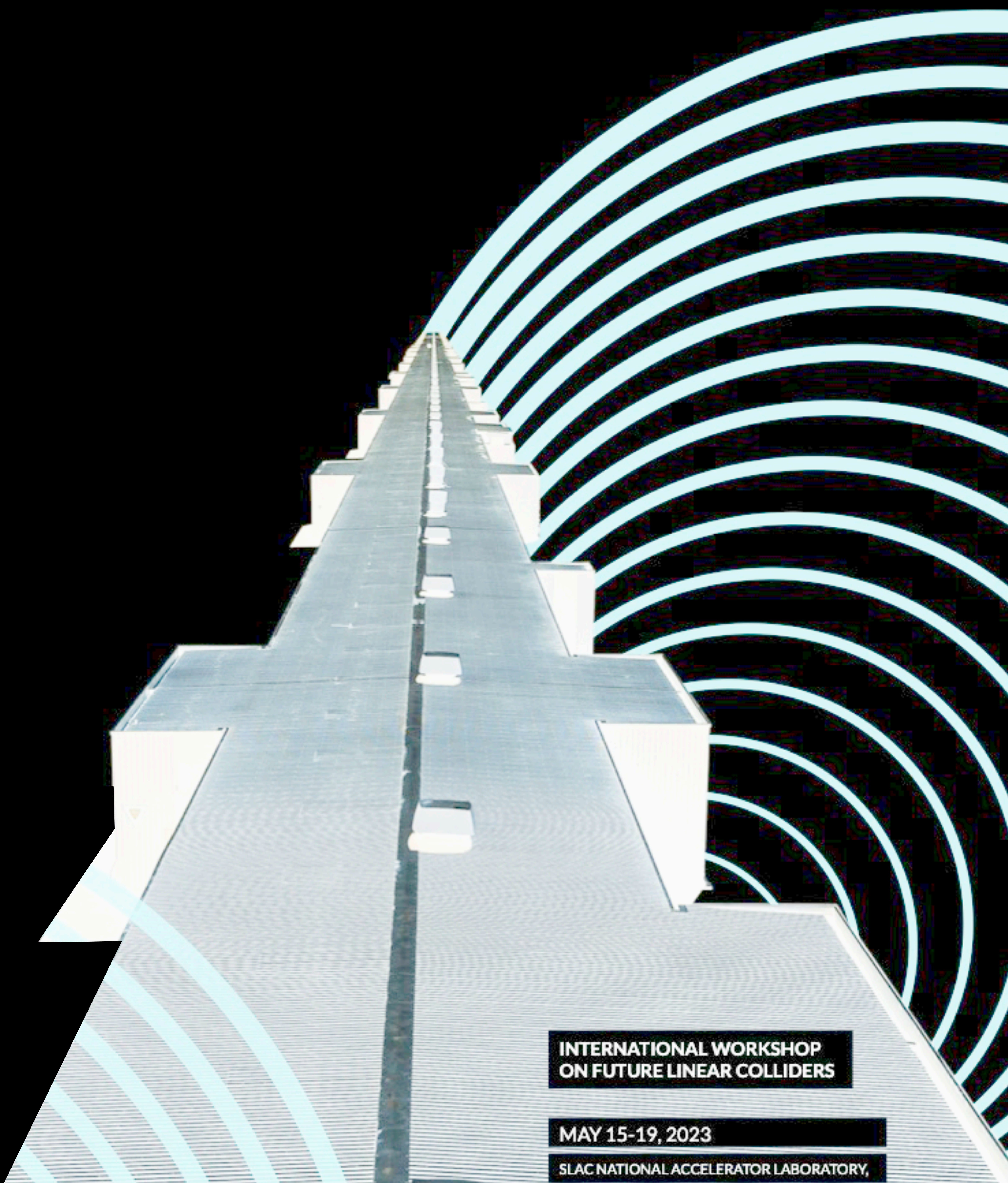

A Fundamental Scalar?

Figure of merit: Higgs “size” vs Compton wavelength. Beginning to probe the size of the Higgs at the LHC, but not yet to π-like compositeness

More precisely: bound “size” corrections, e.g. $\mathcal{O}_H = \frac{1}{2\Lambda^2}\left(\partial_\mu |H|^2\right)^2$

Now

$\frac{1}{4m_h}$

HL-LHC

$\frac{1}{10m_h}$

ILC500
(for example)

$\frac{1}{33m_h}$

[1905.03764]

Higgs factories will ultimately probe size of the Higgs well beyond this, providing strong evidence that the Higgs is elementary. *If not, abundant new physics awaits.*

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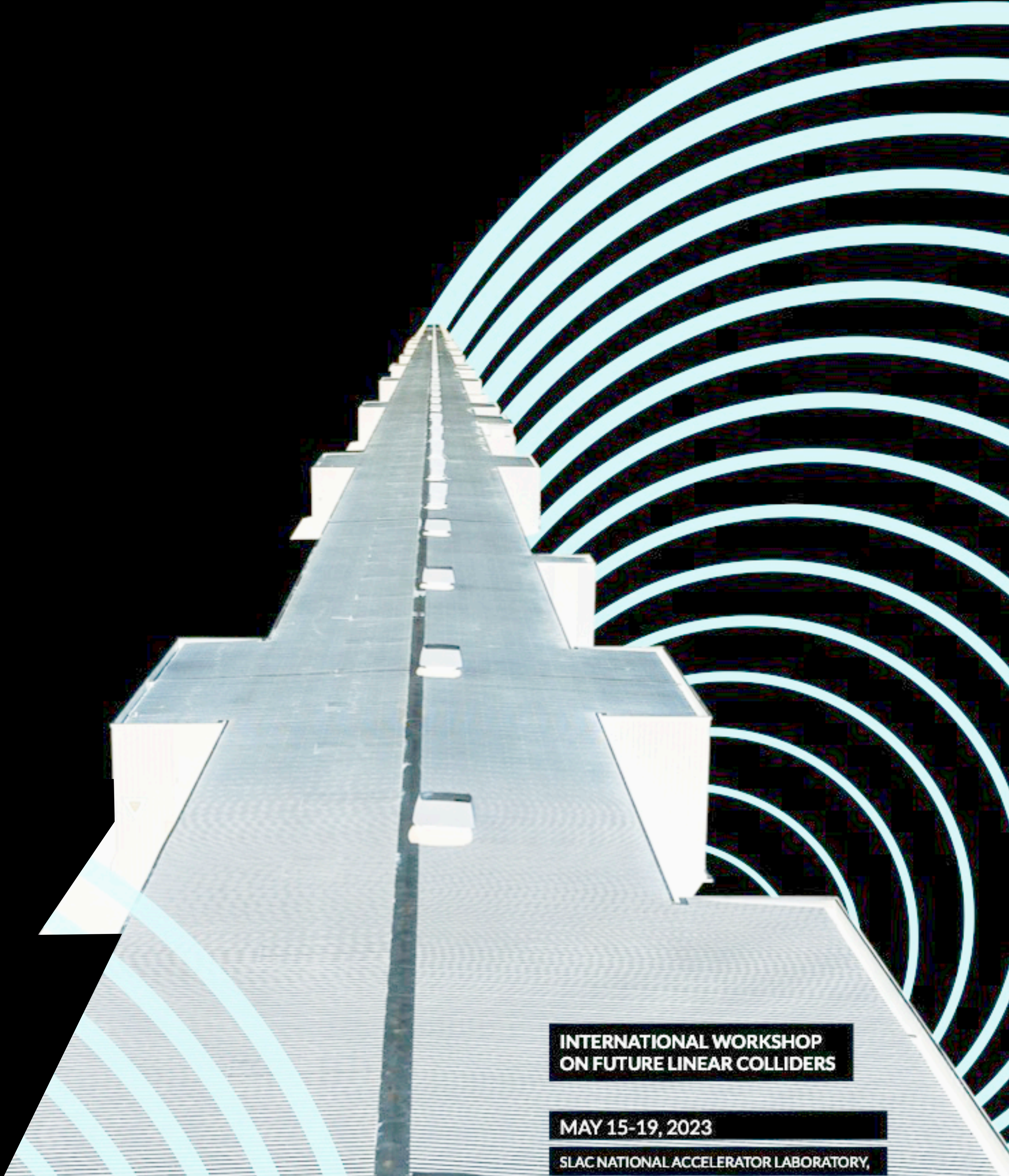
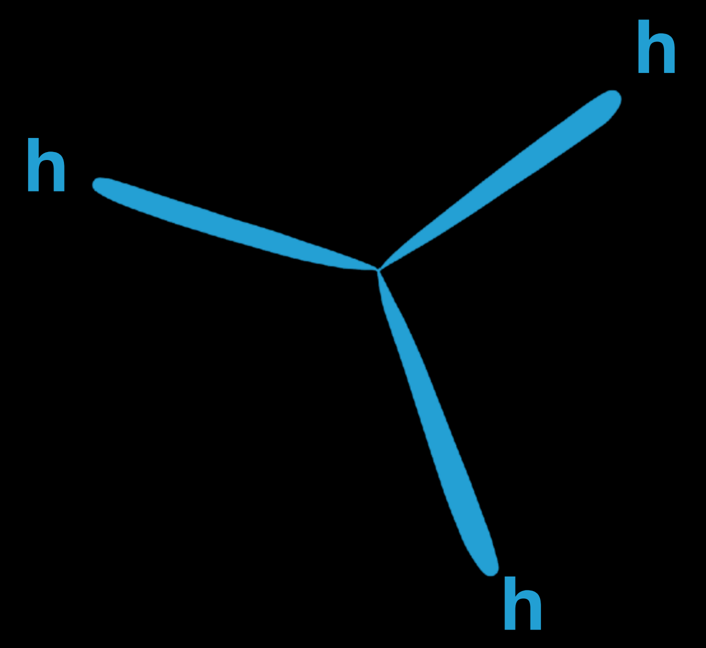
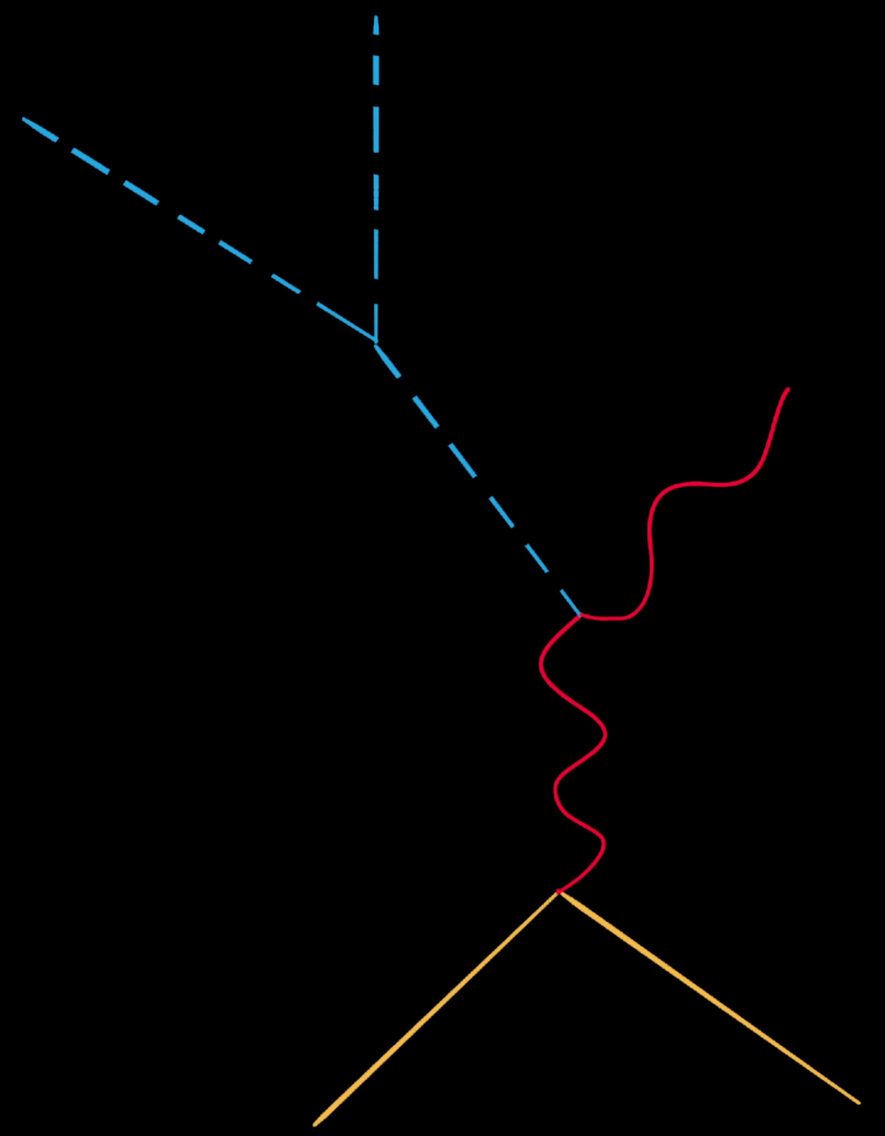


A Self-Interacting Particle?

A self-interacting Higgs (as SM predicts) would be unlike anything yet seen in nature; all other interactions change particle identity.



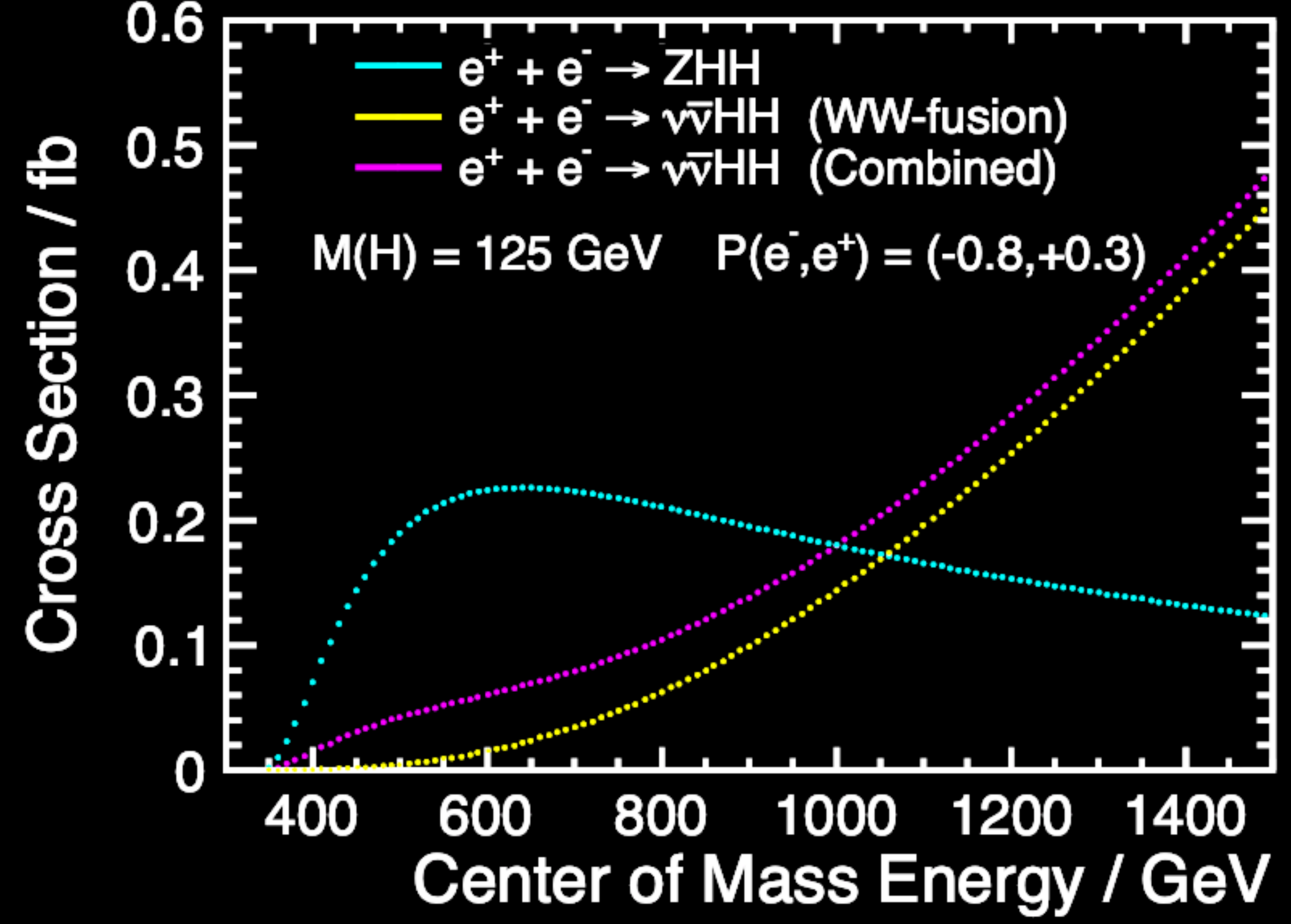


Classically test Higgs self-coupling via Higgs pair production.

ILC 4/ab @ 500 GeV: test Higgs self-interactions at ~**27%** level
(Improved b-tag, added modes →20% [Dürig '16])

ILC 8/ab @ 1 TeV: ~**10%** level

Further implications: see M. Perelstein's talk



[1903.01629]

Quantum mechanically test Higgs self-coupling via virtual corrections [McCullough 1312.3322]

Multiple c.o.m. energies matter: 49% @ ILC250 → 38% @ ILC250/350/500

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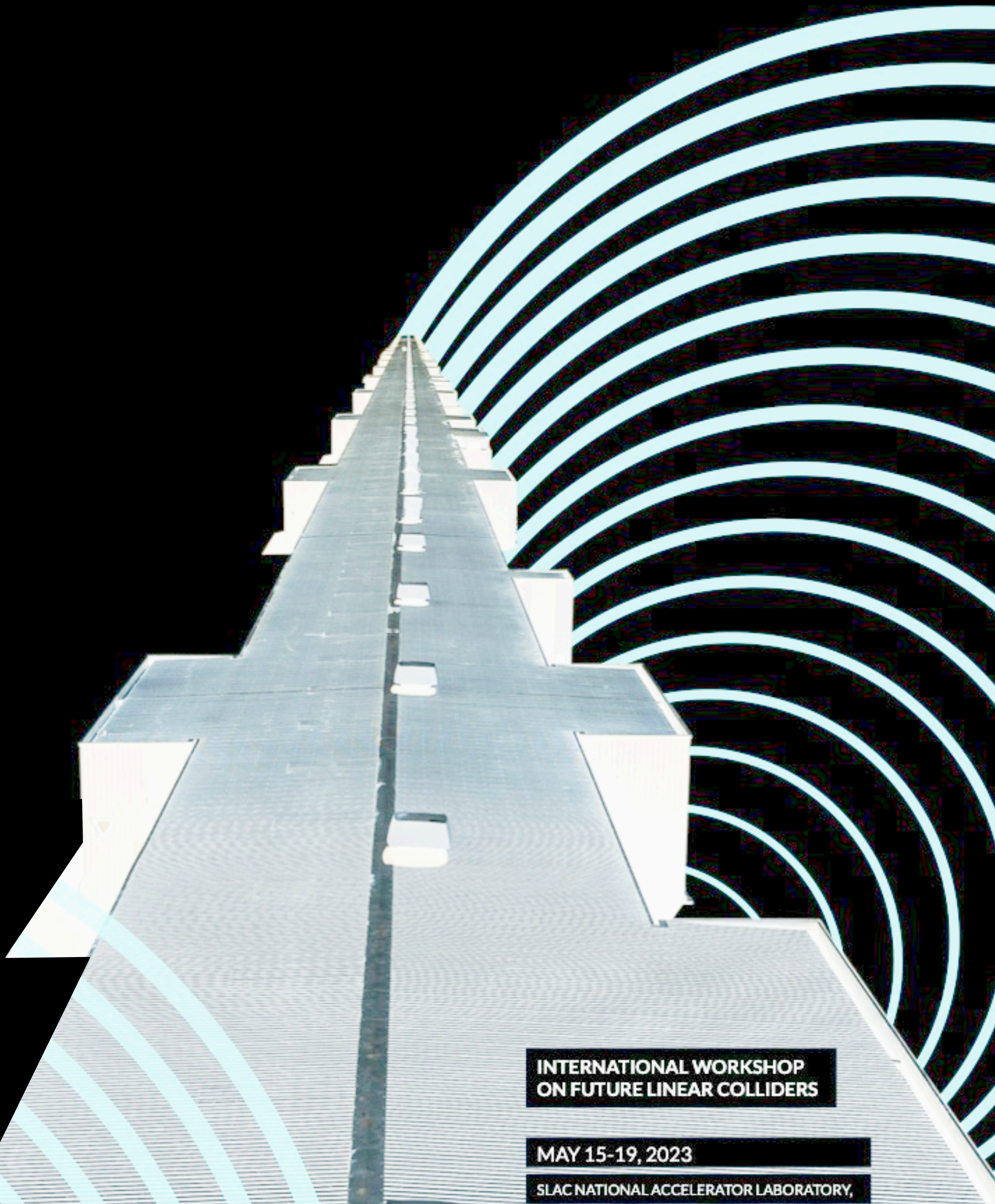
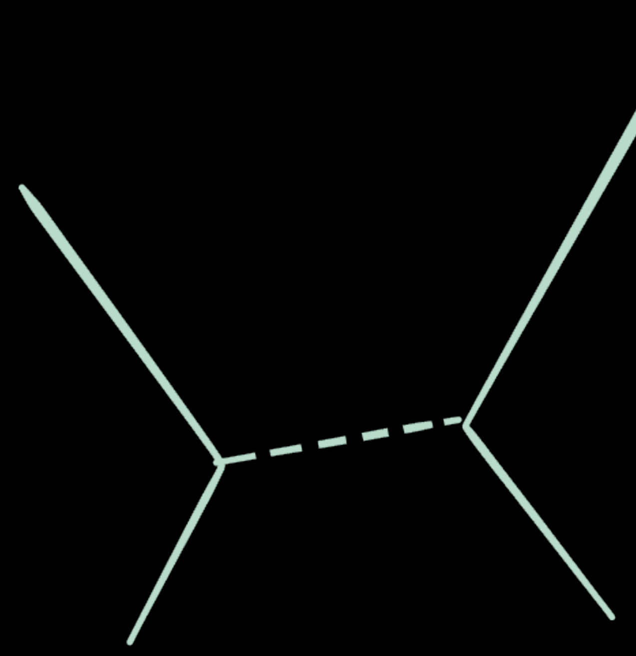


A Yukawa Force?

Yukawa force between fundamental particles: never seen until now



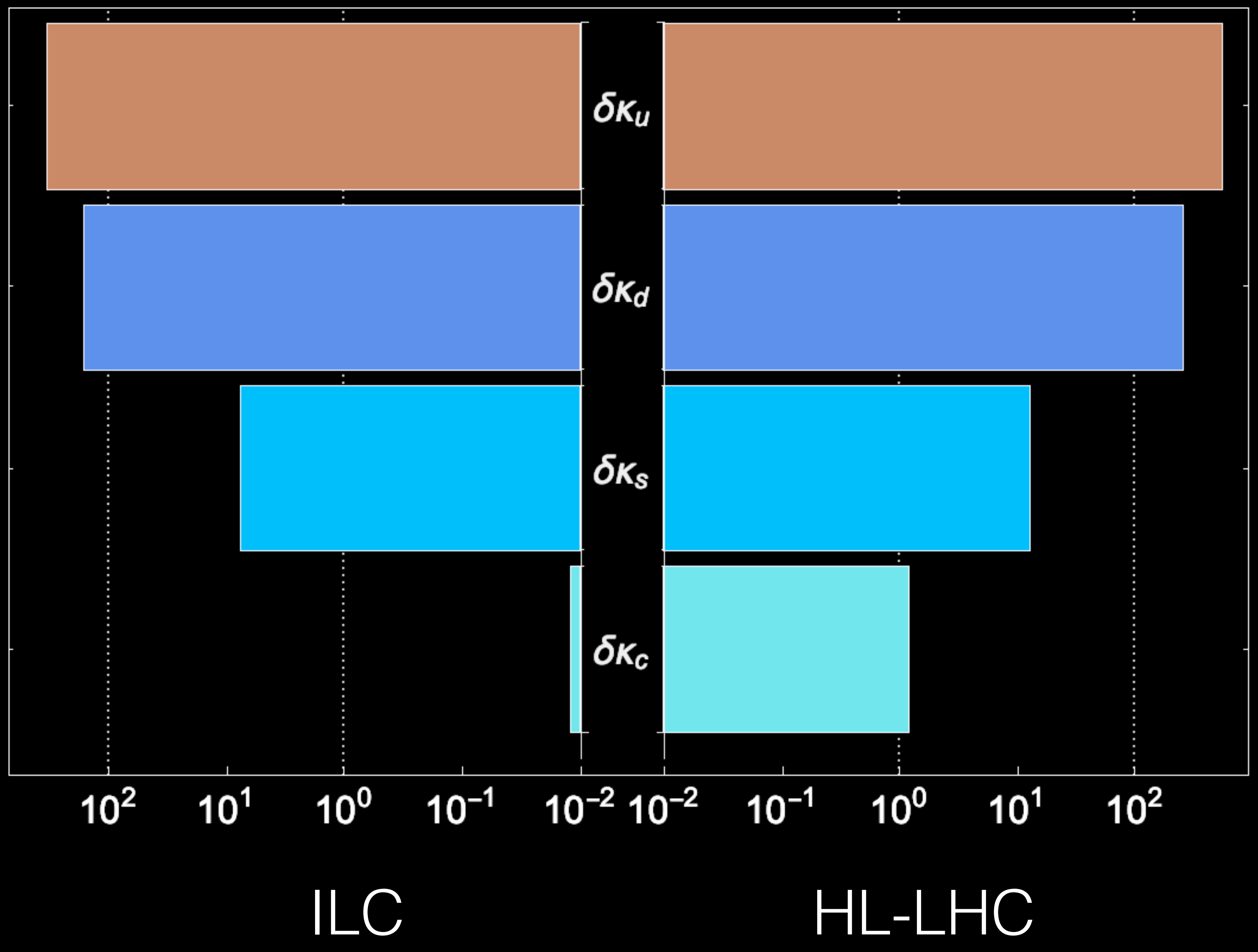
$$\frac{V_{\text{Higgs}}(r)}{V_{\text{Weak}}(r)} \sim \frac{y^2}{g^2} e^{-(m_h - m_Z)r}$$

Established by >5σ observation of ttH, H→bb and H→ττ in LHC Run 2

“Is this any less important than the discovery of the Higgs boson itself? My opinion: no, because fundamental interactions are as important as fundamental particles”

— G. Salam

Focus now on 2nd generation.
Lightness makes flavor puzzle compelling, couplings could hold key to flavor puzzle.



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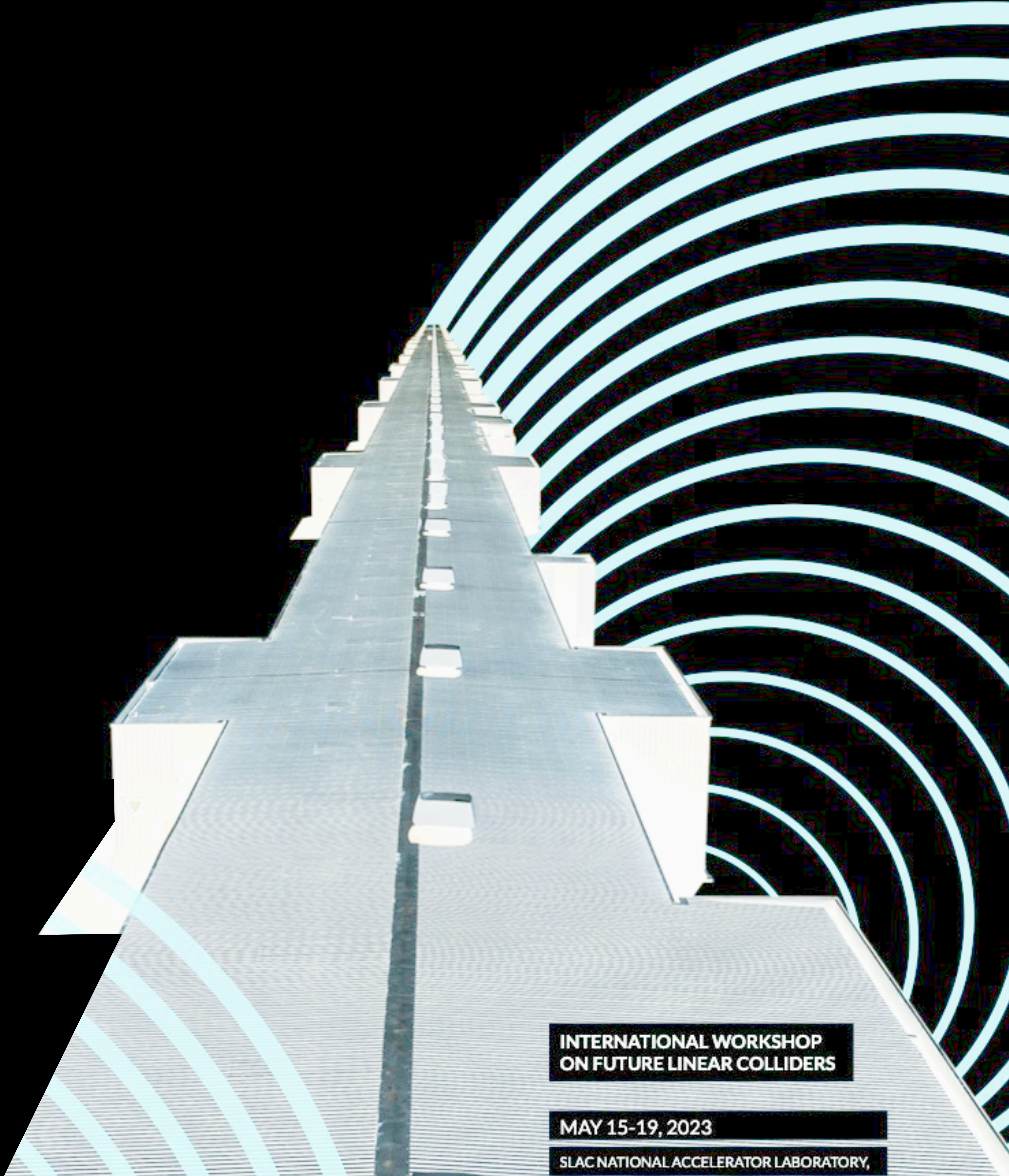
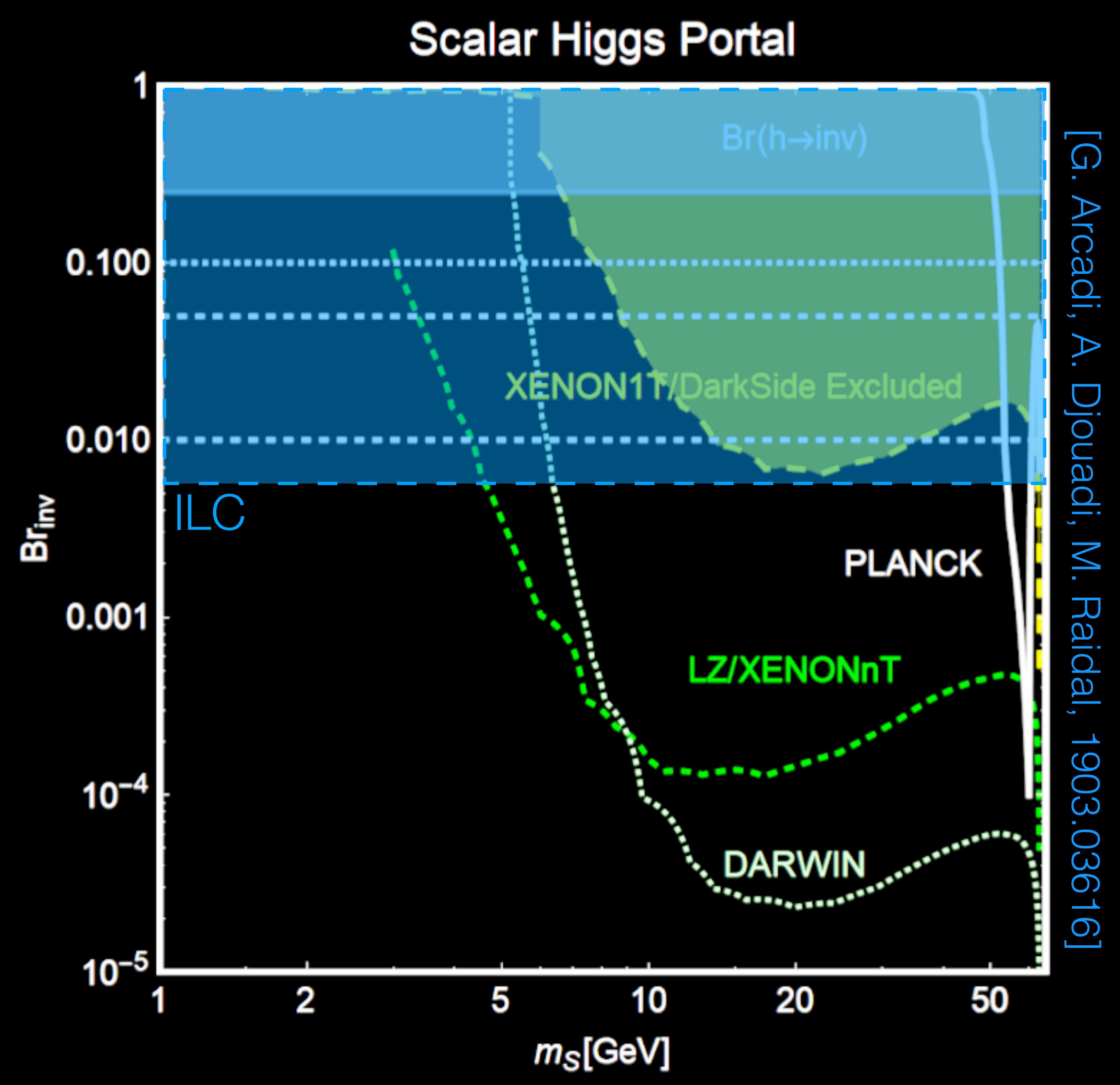
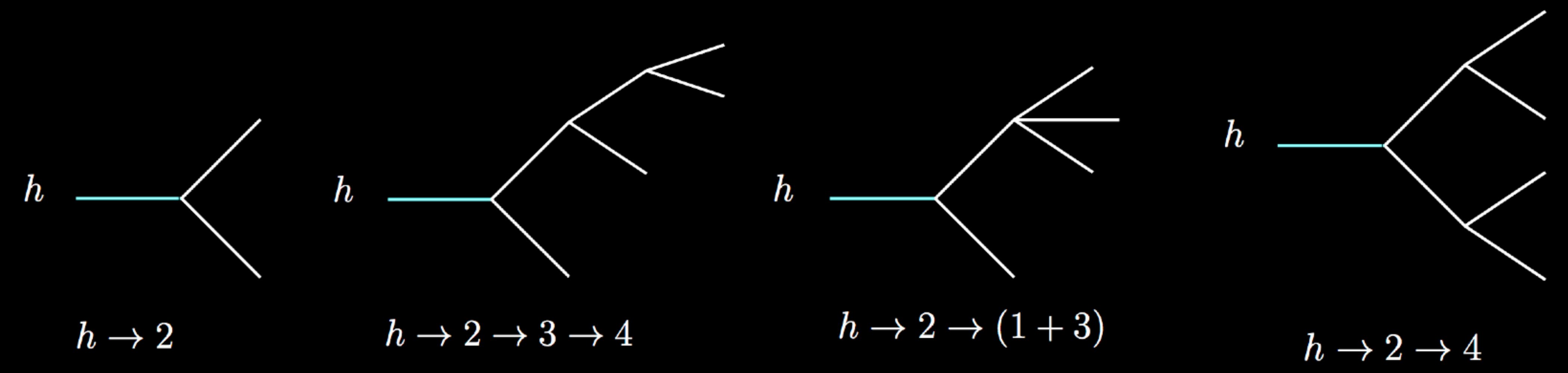


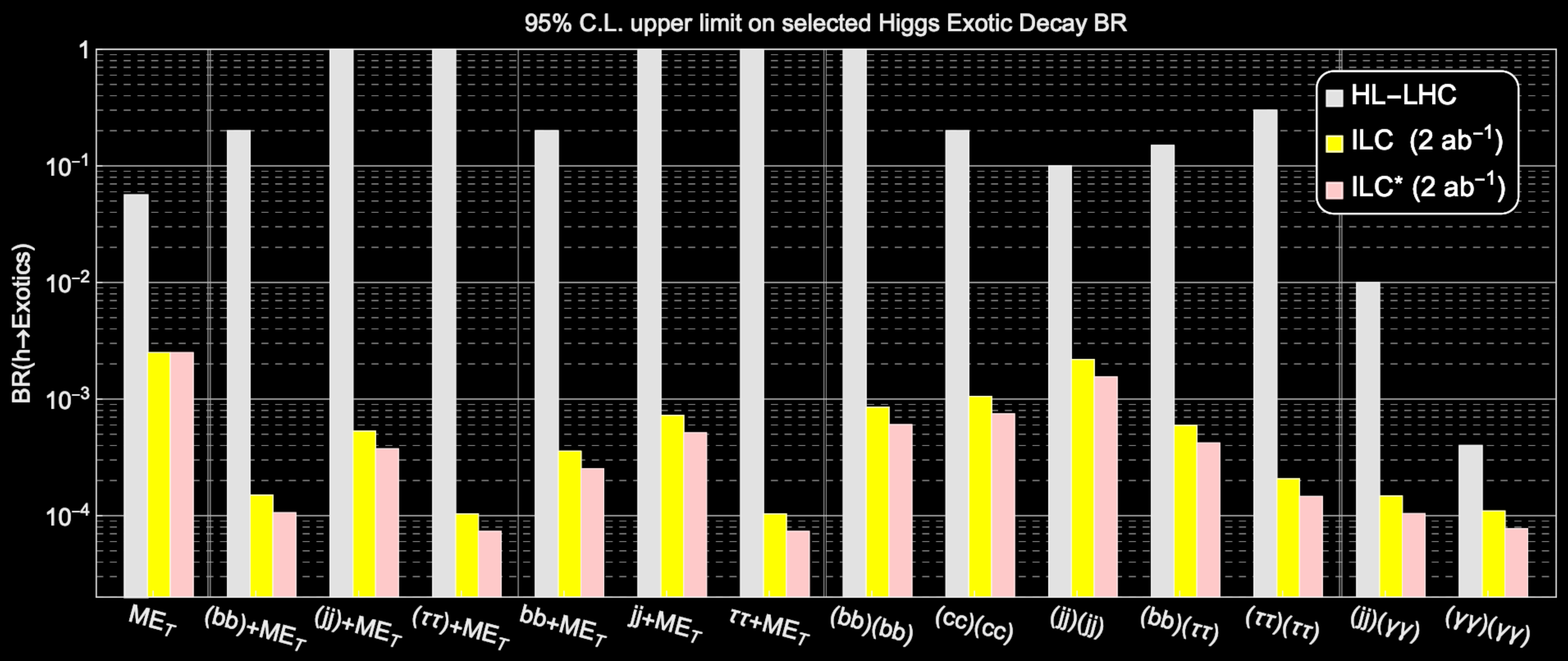
A portal to the dark sector?

$$\mathcal{L} \supset |H|^2 \mathcal{O}$$

Higgs a (the?) primary portal for coupling to SM-neutral sectors







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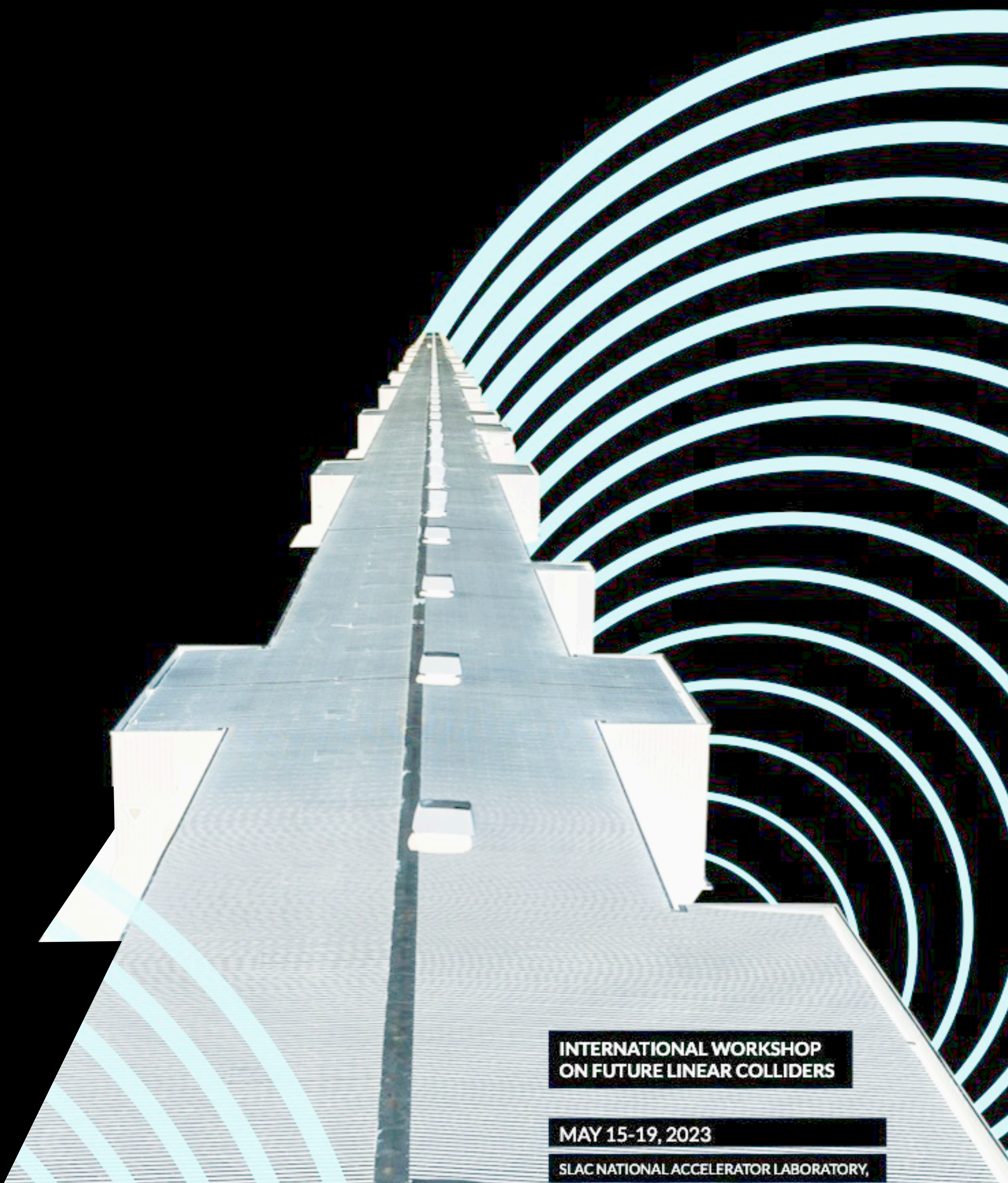
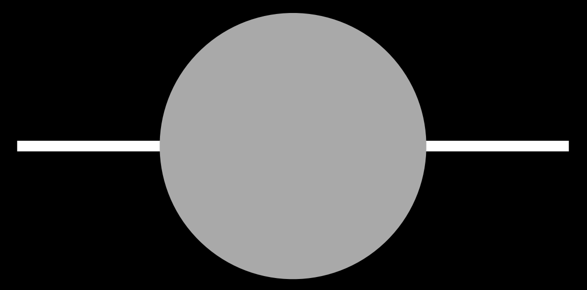
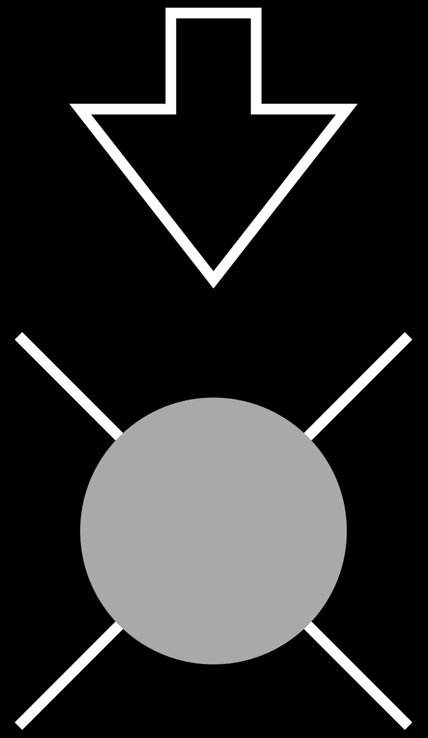


Naturalness Strategy

There are now many ways of explaining EWSB and predicting the Higgs mass using symmetries. But what is the bottom line? What's the ultimate target for symmetry-based naturalness?



$m^2|H|^2$



$\mathcal{O}_H = \left(\partial|H|^2\right)^2$

$$\delta m_h^2 \sim 10 \times \frac{y_t^2}{16\pi^2} \times m_*^2$$

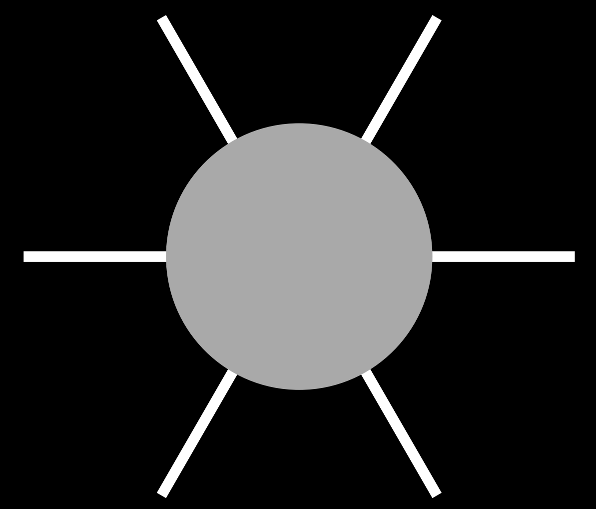
$$\Delta \equiv \frac{\delta m_h^2}{m_h^2} \sim 10 \times \frac{y_t^2}{16\pi^2} \times \frac{m_*^2}{m_h^2}$$

$$c_H \sim \frac{y_t^2}{16\pi^2} \times \frac{y_t^2}{m_*^2}$$

$$\delta\kappa_i \equiv c_H v^2 \sim \frac{y_t^2}{16\pi^2} \times \frac{y_t^2}{\lambda_h} \times \frac{m_h^2}{m_*^2}$$

$$\delta\kappa_i \sim 10 \times \left(\frac{y_t^2}{16\pi^2}\right)^2 \times \frac{y_t^2}{\lambda_h} \times \Delta^{-1} \Rightarrow \boxed{\delta\kappa_i \sim 0.1 - 1\%}$$

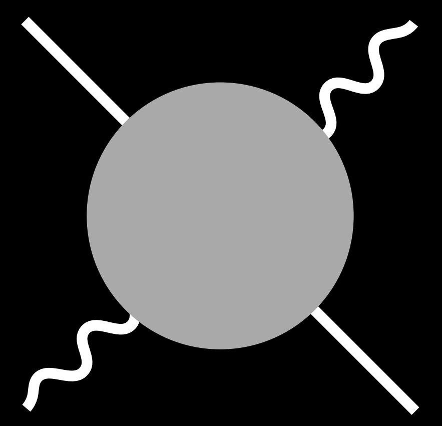
Naturalness Strategy



$\mathcal{O}_6 = |H|^6$

$$c_6 \sim \frac{y_t^2}{16\pi^2} \times \frac{y_t^4}{m_*^2} \qquad \delta\kappa_\lambda \equiv c_6 v^2/\lambda_h \sim \frac{y_t^2}{16\pi^2} \times \left(\frac{y_t^2}{\lambda_h}\right)^2 \times \frac{m_h^2}{m_*^2}$$

$$\delta\kappa_\lambda \sim 10 \times \left(\frac{y_t^2}{16\pi^2}\right)^2 \times \left(\frac{y_t^2}{\lambda_h}\right)^2 \times \Delta^{-1} \quad \Rightarrow \quad \boxed{\delta\kappa_\lambda \sim 1 - 10\%}$$



$\mathcal{O}_{FF} = g^2 |H|^2 F_{\mu\nu} F^{\mu\nu}$

$$c_{FF} \sim 0.1 \times \frac{y_t^2}{16\pi^2} \times \frac{1}{\mu_*^2} \qquad \delta\kappa_\gamma \equiv 16\pi^2 c_{FF} v^2 \sim 0.1 \times \frac{y_t^2}{\lambda_h} \times \frac{m_h^2}{\mu_*^2}$$

$$\delta\kappa_\gamma^{\text{super}} \sim \frac{y_t^2}{16\pi^2} \times \frac{y_t^2}{\lambda_h} \times \Delta^{-1} \quad \Rightarrow \quad \boxed{\delta\kappa_\gamma \sim 1 - 10\%}$$

$$\delta\kappa_\gamma^{\text{hyper}} \sim \left(\frac{y_t^2}{16\pi^2}\right)^2 \times \Delta^{-1} \quad \Rightarrow \quad \boxed{\text{Too small}}$$

Charged states: μ_*

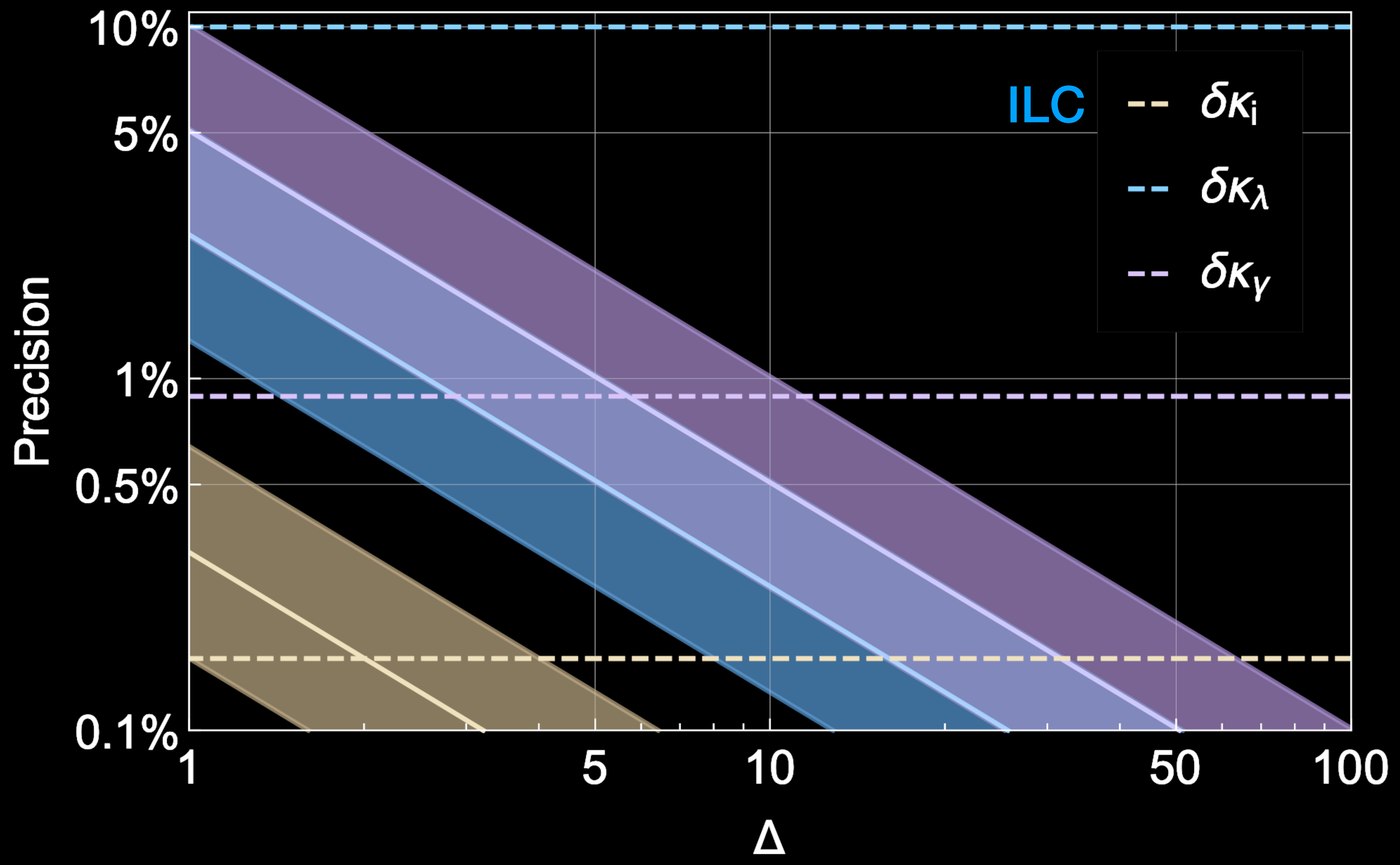
Super-soft: $\mu_* = m_*$

Hyper-soft: $\mu_* = (g_*/\sqrt{\lambda_h}) m_*$

[Contino et al '17]

Naturalness Strategy

Concrete theories: see M. Perelstein's talk



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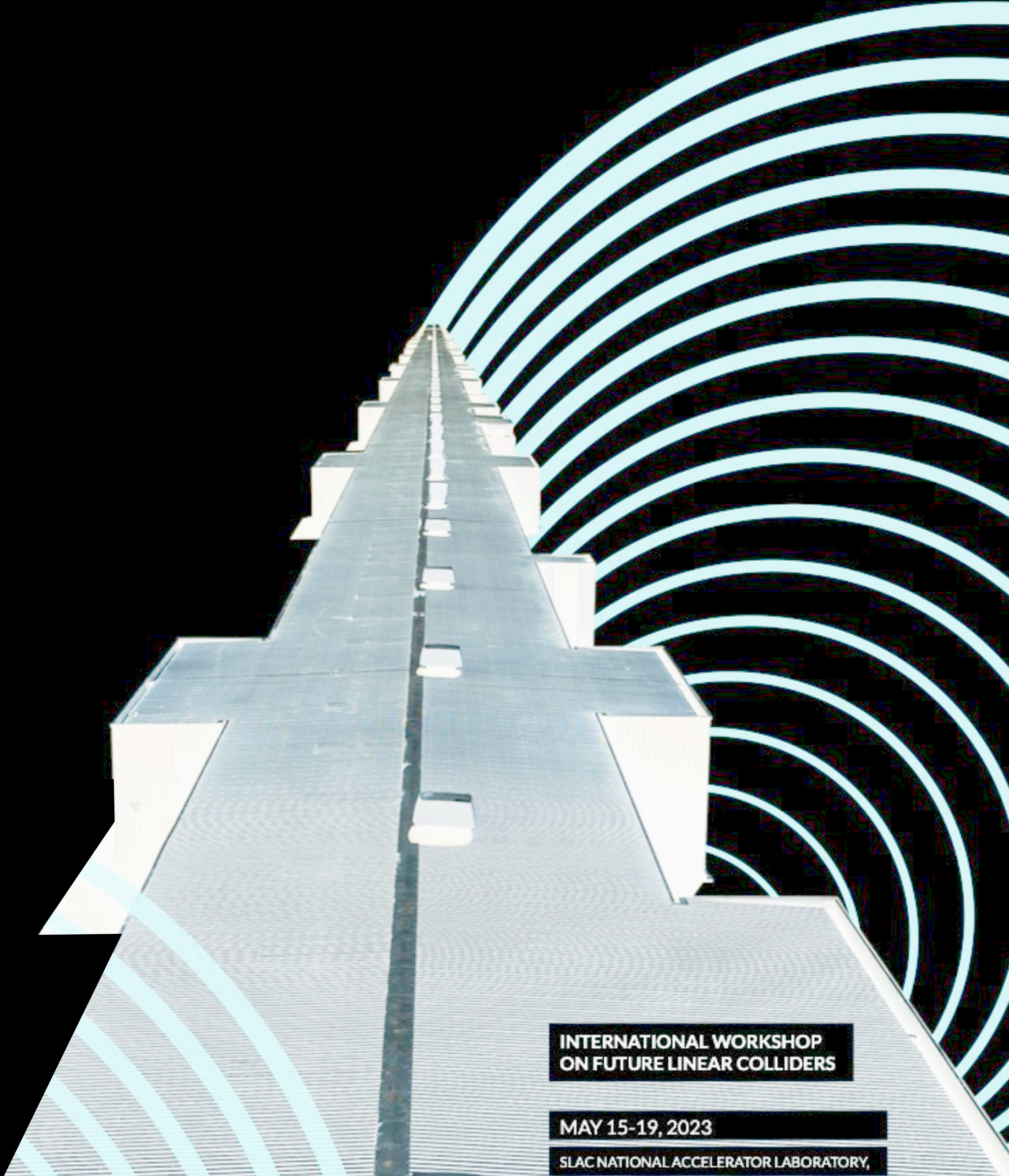
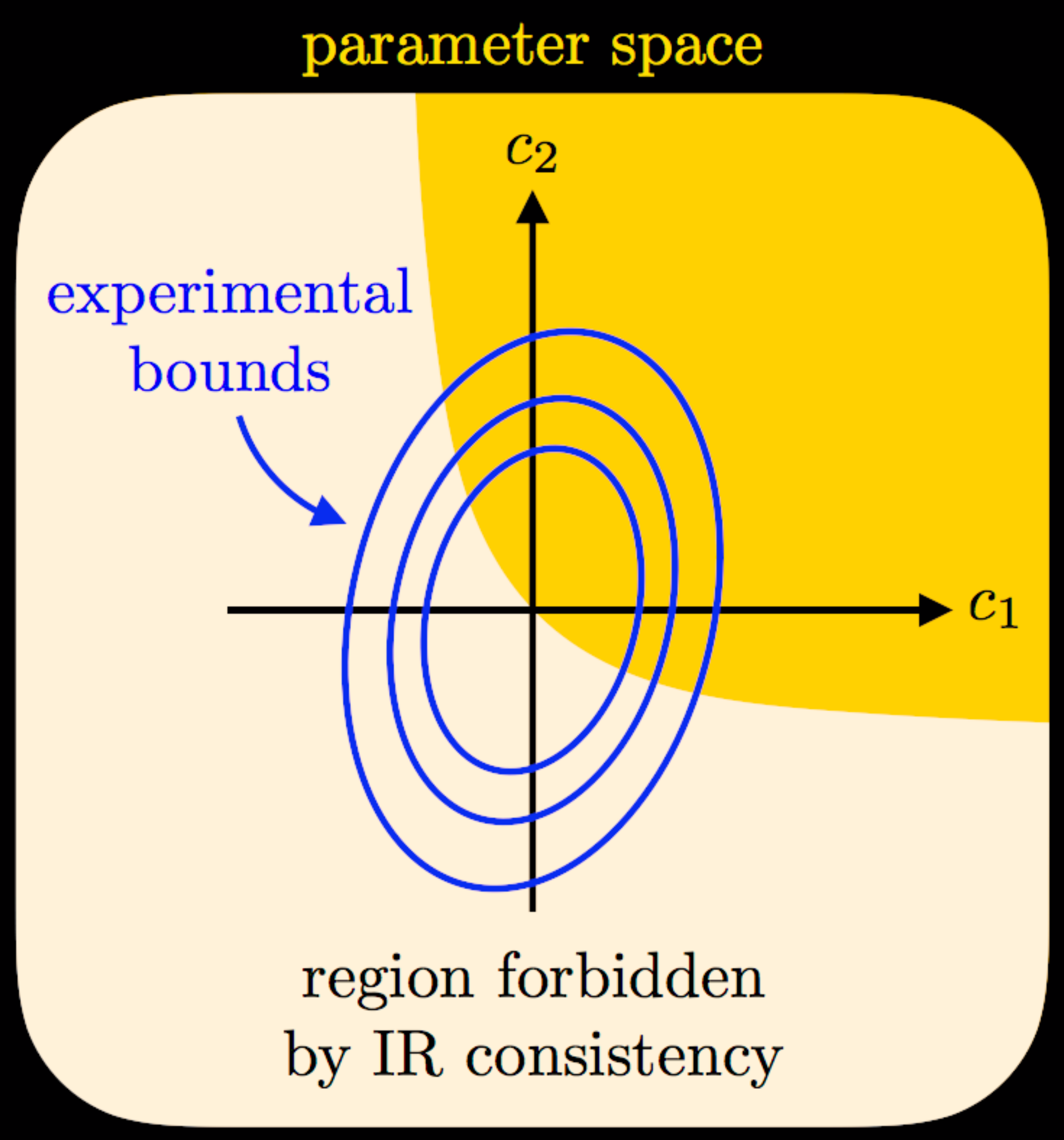


Thinking Positively

Locality, **unitarity**, and **analyticity** constrain EFT corrections to SM ("positivity bounds")

Long history, revived in [Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi '06; Distler, Grinstein, Porto, Rothstein '06; …]

More recently: extensive application directly to Wilson coefficients in SMEFT, e.g. [Bellazzini, Riva 1806.09640; Zhang, Zhou 1808.00010; Bi, Zhang, Zhou 1902.08977; Remmen, Rodd 1908.09845; Remmen, Rodd, 2004.02885; Zhang, Zhou 2005.03047; Fuks, Liu, Zhang, Zhou 2009.02212; Yamashita, Zhang, Zhou 2009.04490; Remmen, Rodd 2010.04723; Gu, Wang, Zhang 2011.03055; Trott 2011.10058; Bonnefoy, Gendy, Grojean 2011.12855; Li, Yang, Xu, Zhang, Zhou 2101.01191, …]



[Remmen & Rodd, 1908.09845]

Improve global fits by imposing positivity bounds

OR

Interpret as experimental tests of bedrock principles of QFT.

(Ideally do both)

Thinking Positively

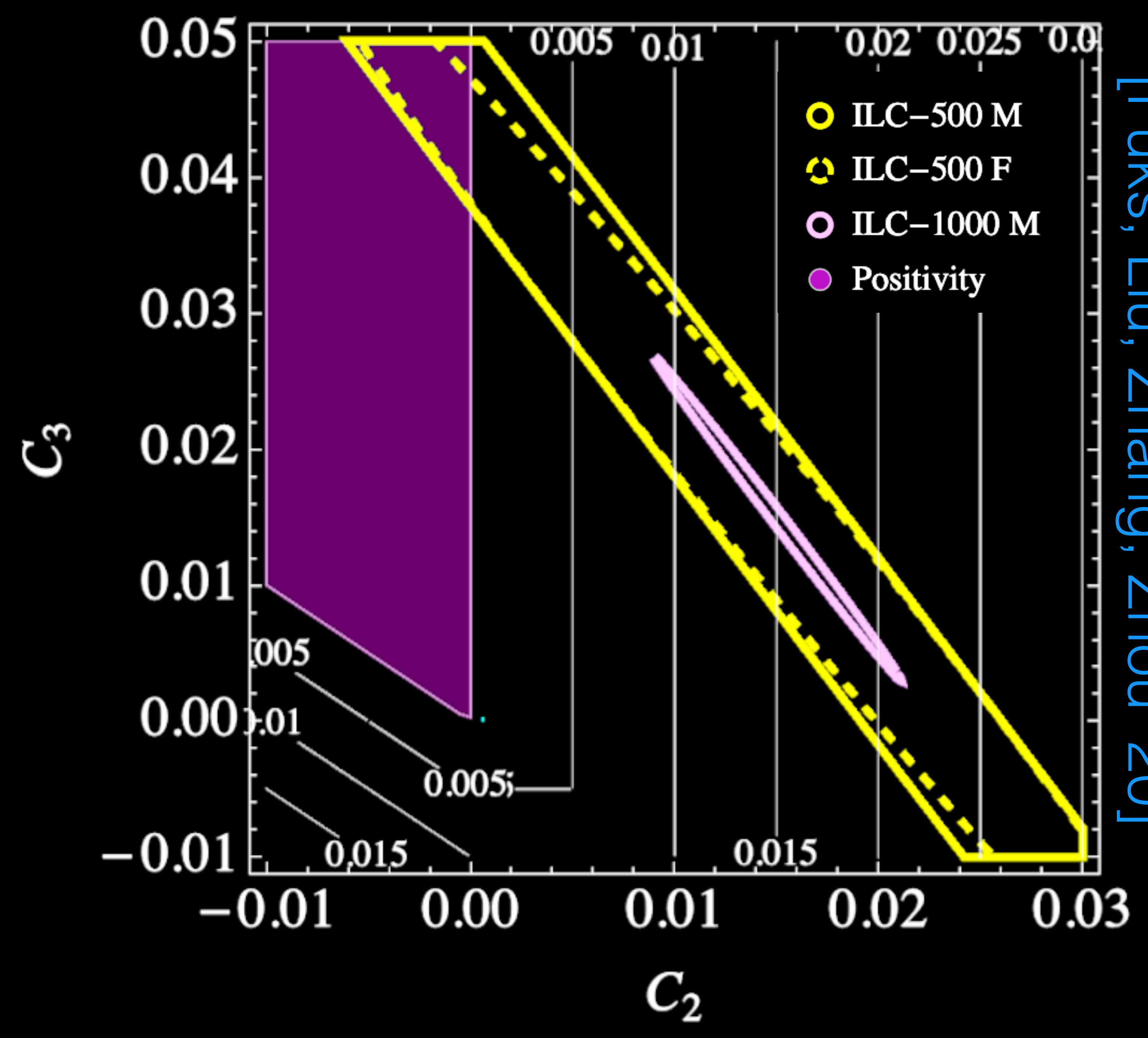
d=6: UV-sensitive positivity bounds, sum rules. **d=8**: UV-insensitive positivity bounds

Naive expectation: dim-8 operator effects always subleading

Reality: often leading due to non-interference thms and more pragmatic non-interference effects (color, phase space, …)

Thus far: primarily applied to aQGCs @ LHC
[Bellazzini & Riva '18, Zhang & Zhou, '18,…]

Interesting prospects in $e^+e^- \to e^+e^-, \gamma\gamma$ @ILC
[Fuks, Liu, Zhang, Zhou '20, Gu, Wang, Zhang '20]



[Fuks, Liu, Zhang, Zhou '20]

Positivity bounds also imply d=8 deviations are robust against cancellations, giving a guaranteed probe of UV physics with precision measurement.

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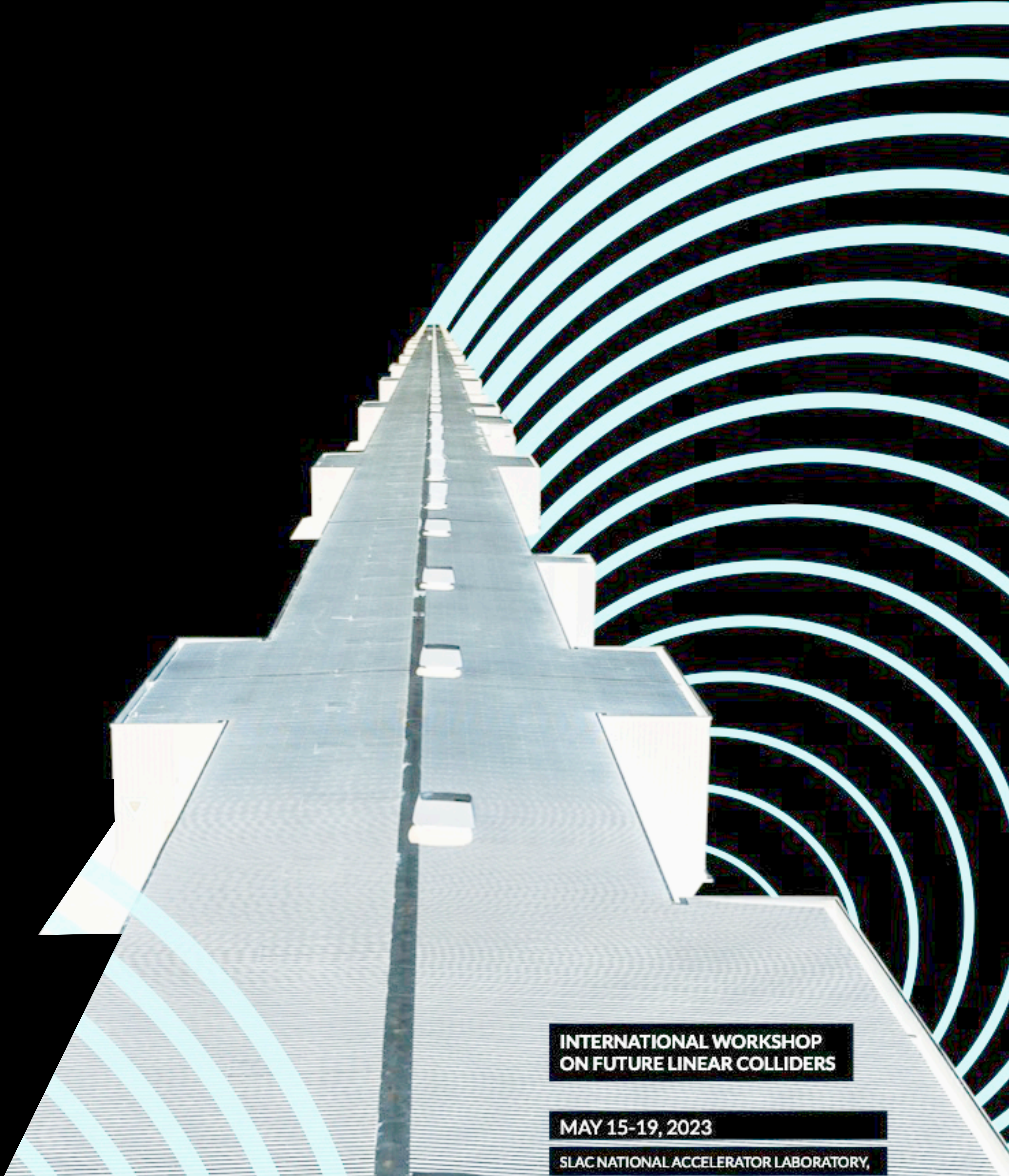
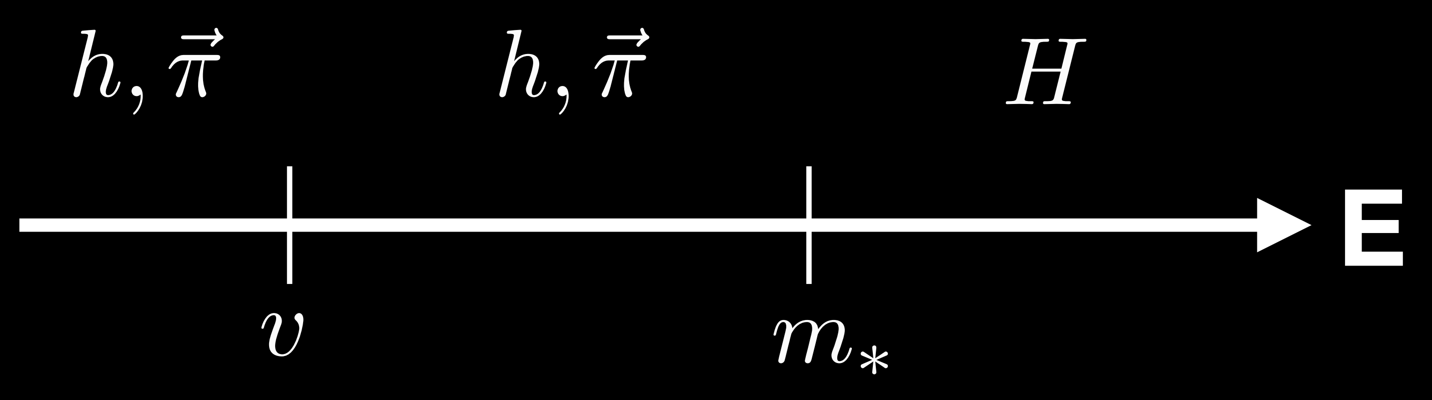
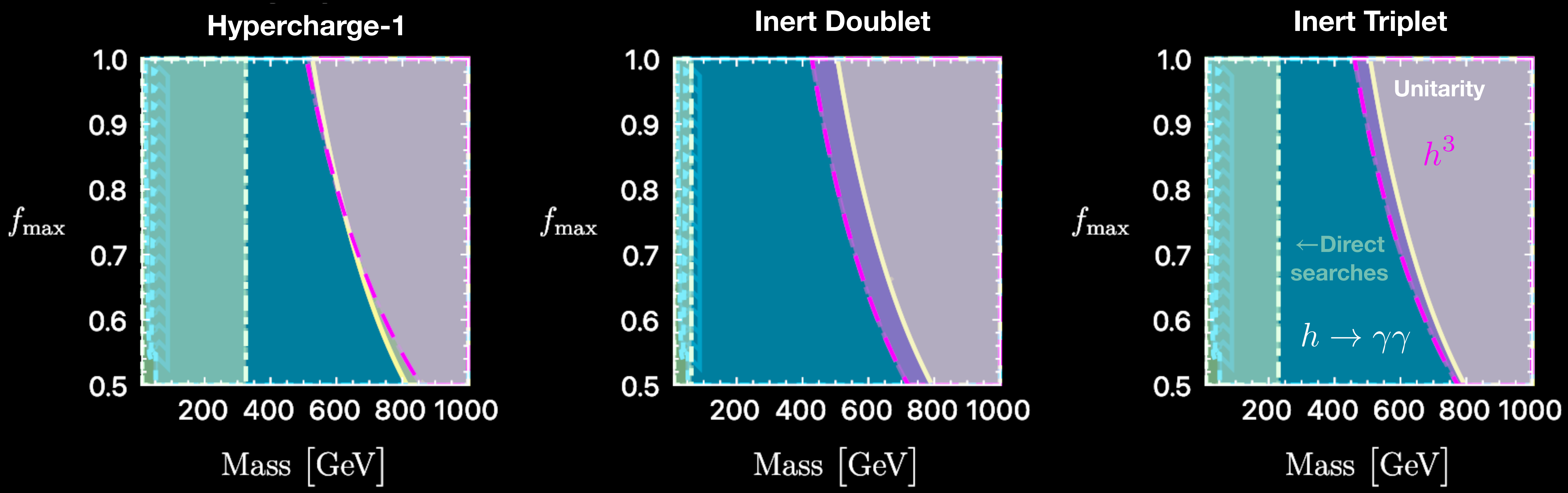


Non-decoupling new particles?

Local EFT of the Higgs + SM particles does not linearly realize electroweak symmetry if new UV particles acquire more than half of their mass from the Higgs. Many examples currently viable [Banta, Cohen, NC, Lu, Sutherland, 2110.02967]



ILC coverage of non-decoupling scalars



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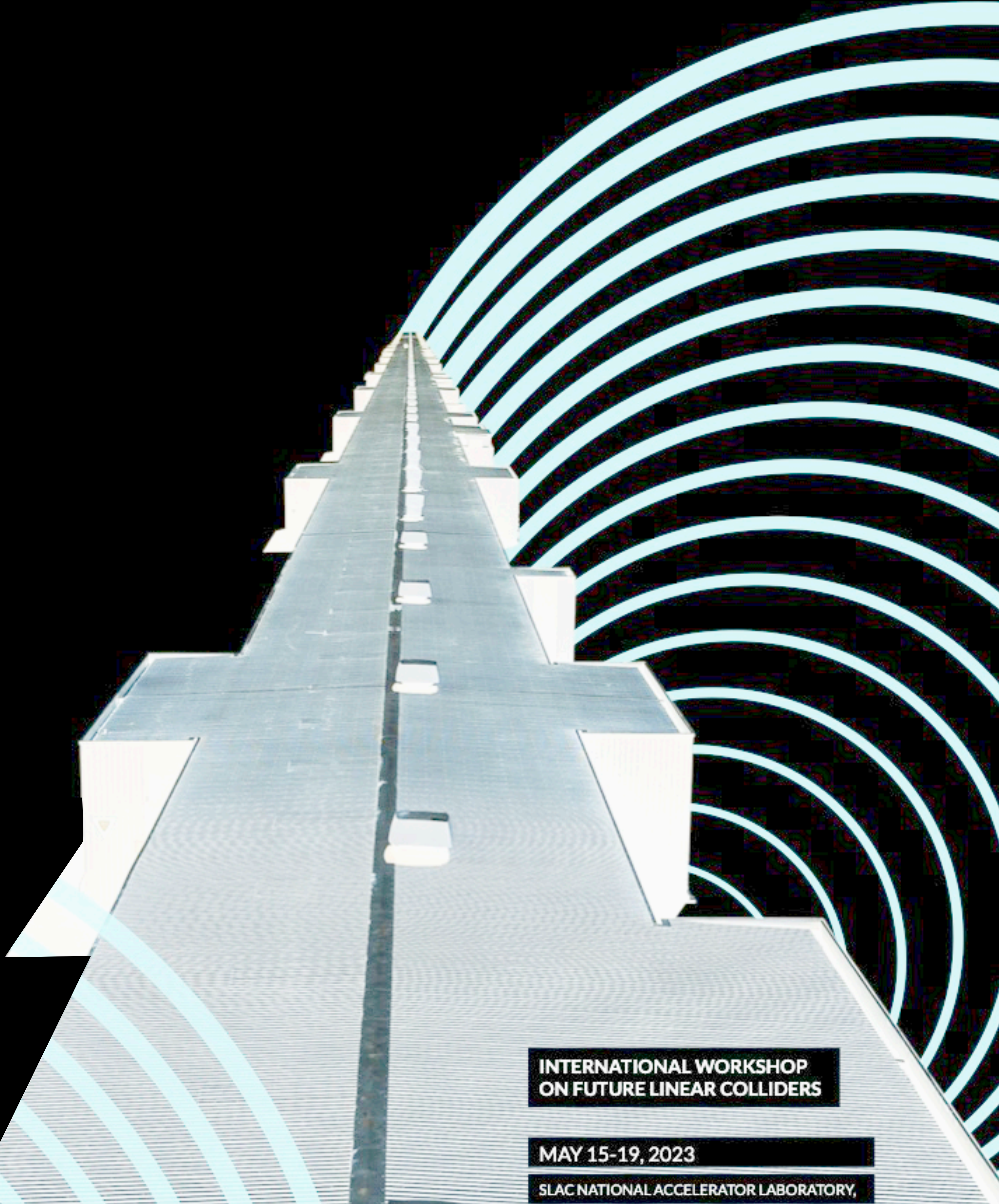

Physics Case for Precision Measurements at a Higgs Factory, and how do we communicate about it?

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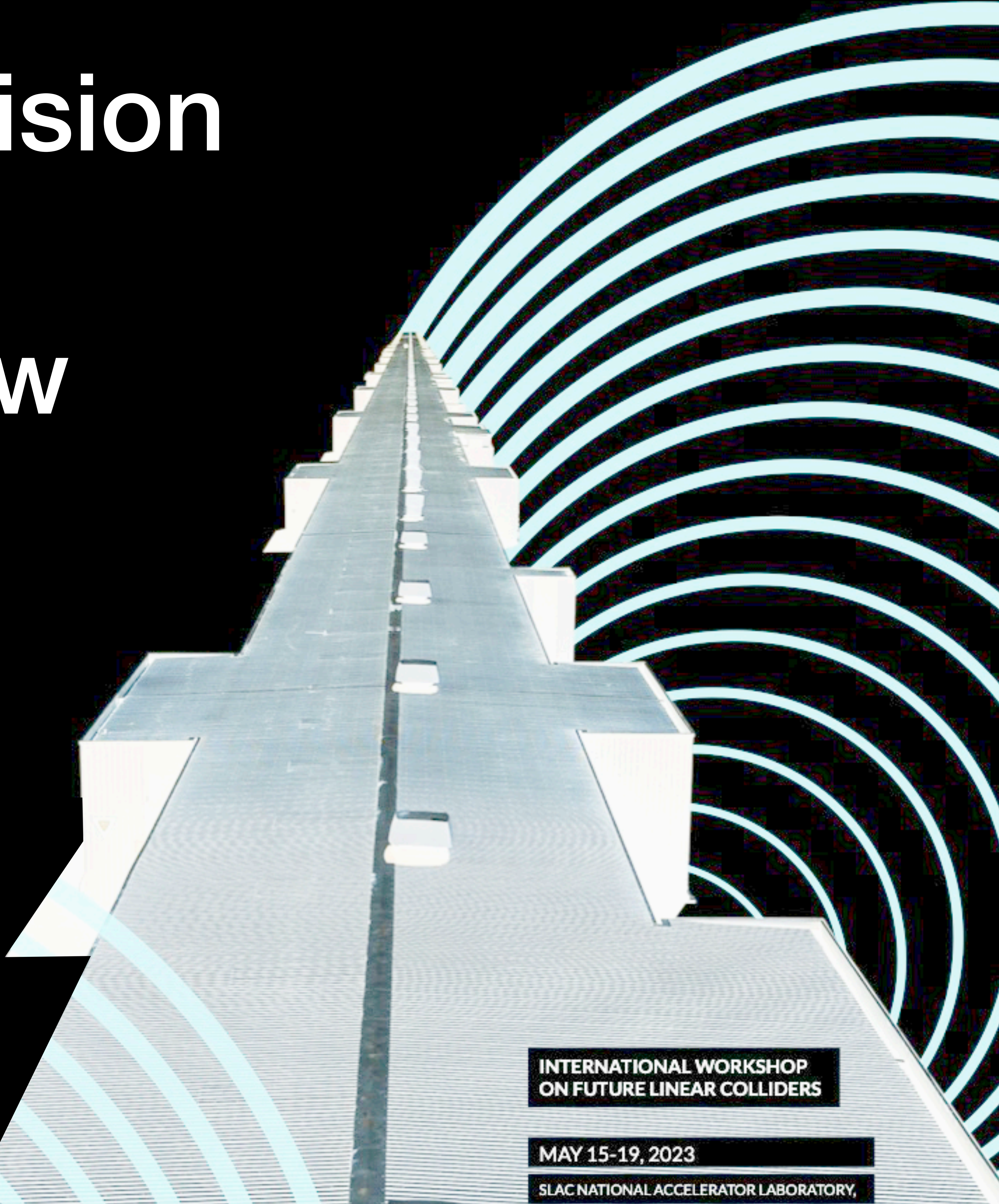

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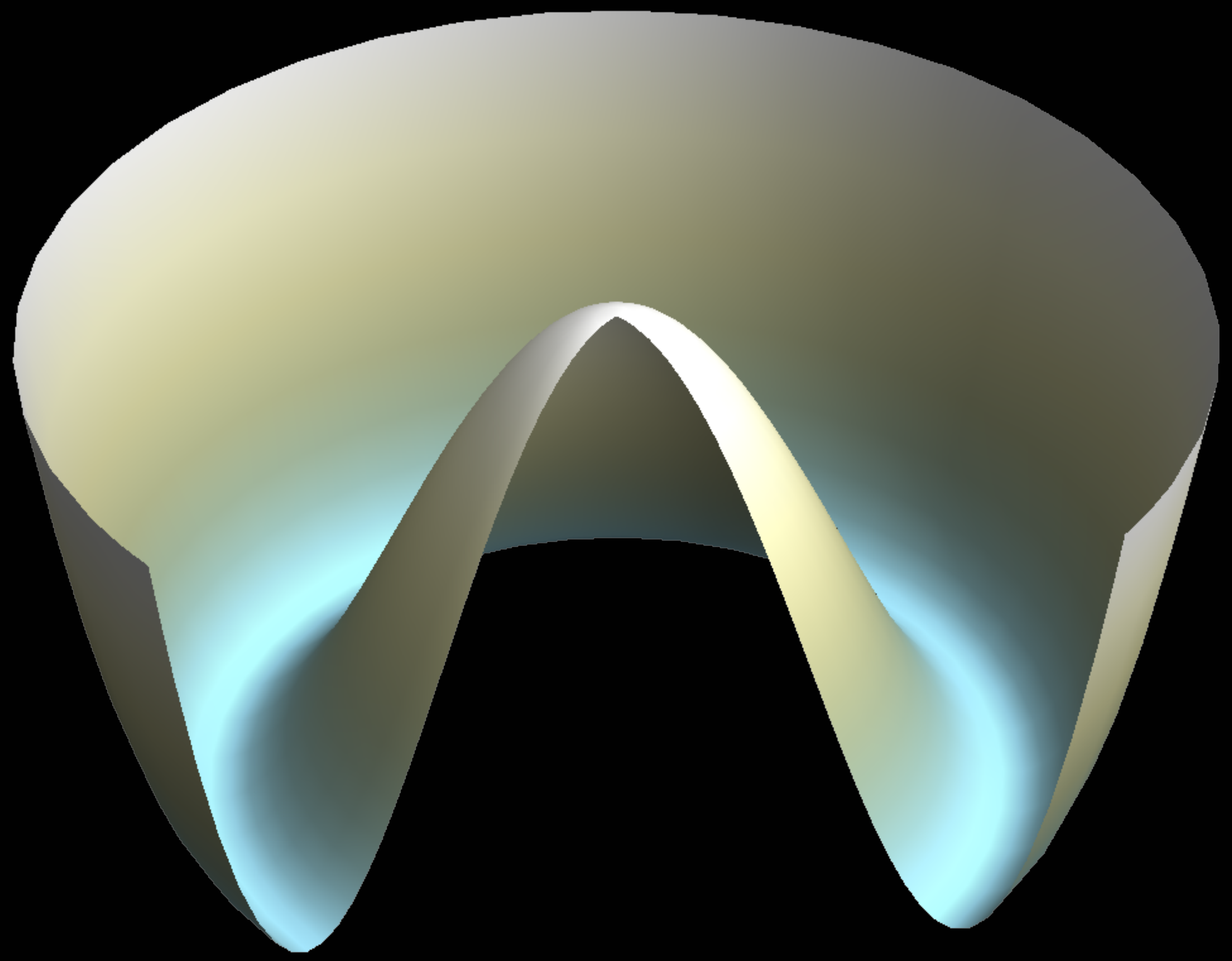
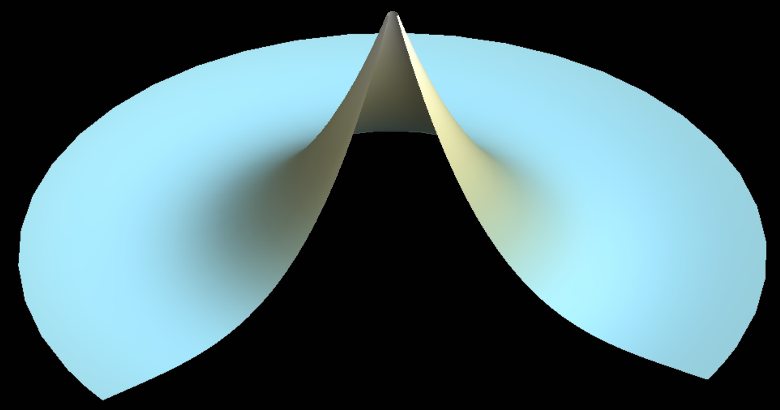
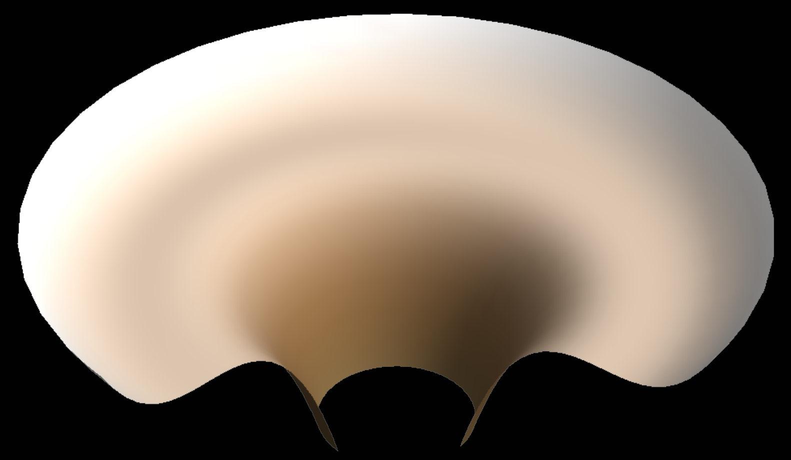
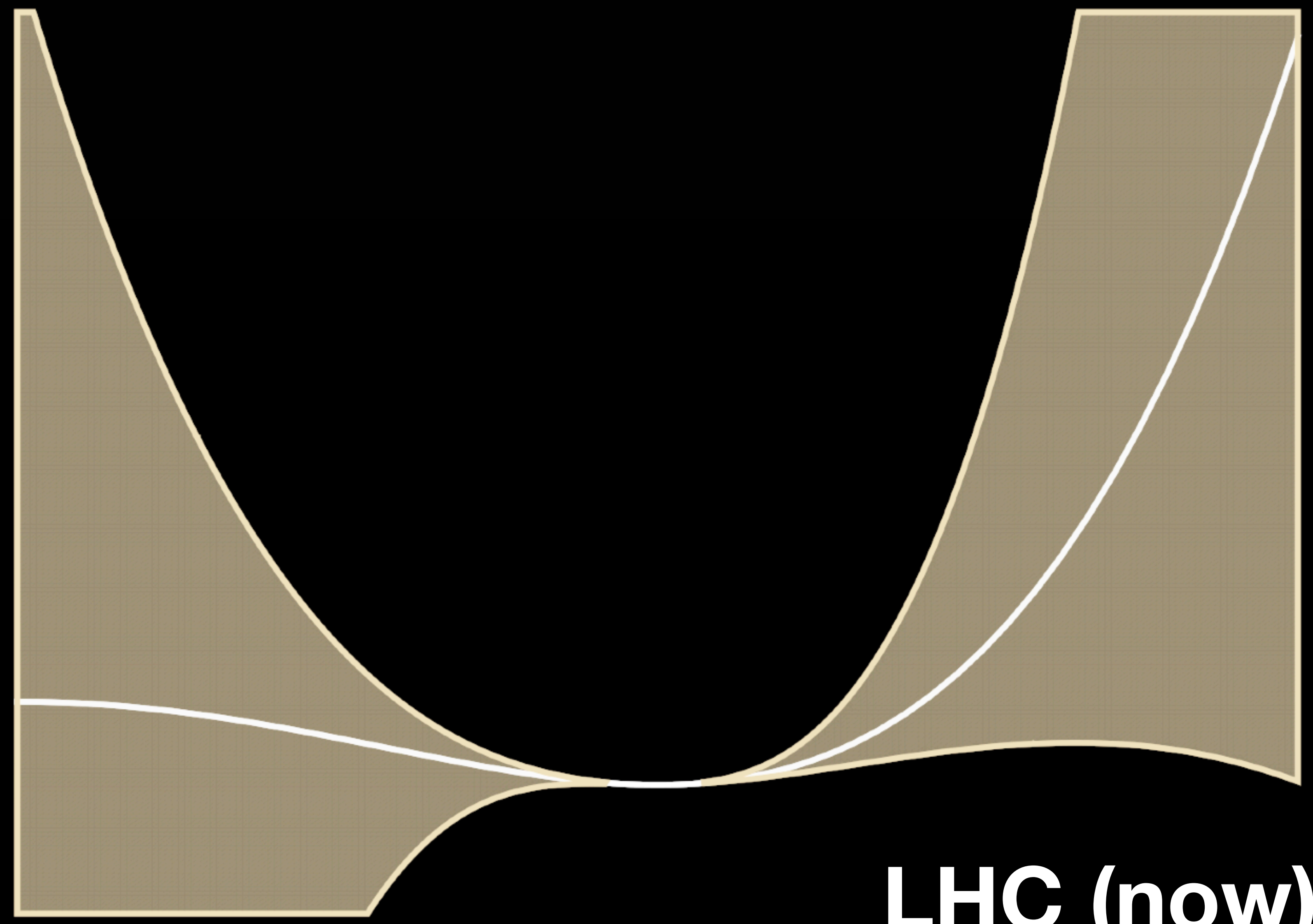
Is it the SM Higgs?





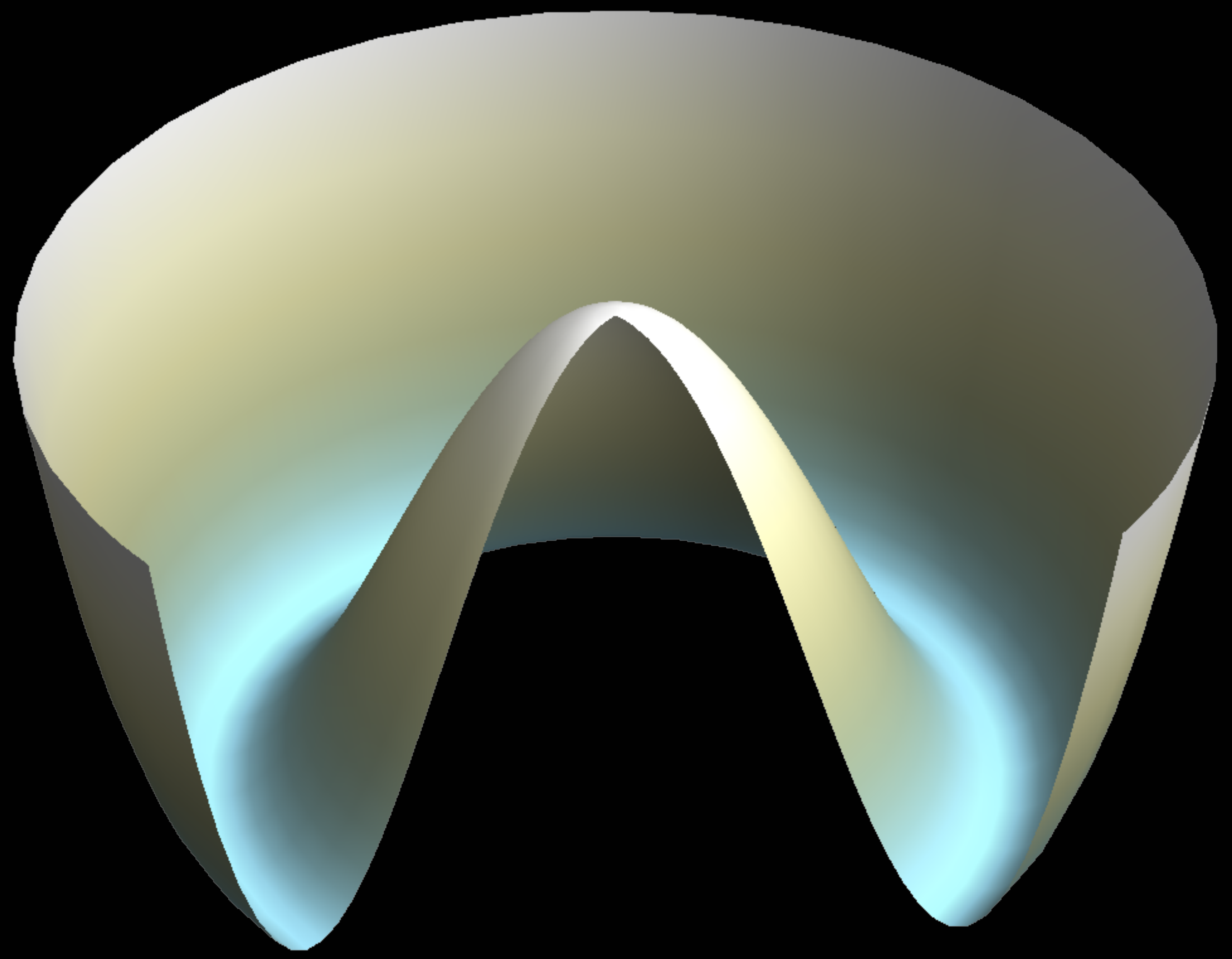




LHC (now)

(If you like this way of presenting Higgs self-coupling precision, please feel free to use it! The inspiration came from conversations with R. Petrossian-Byrne.)

Is it the SM Higgs?



Imaging the Higgs?

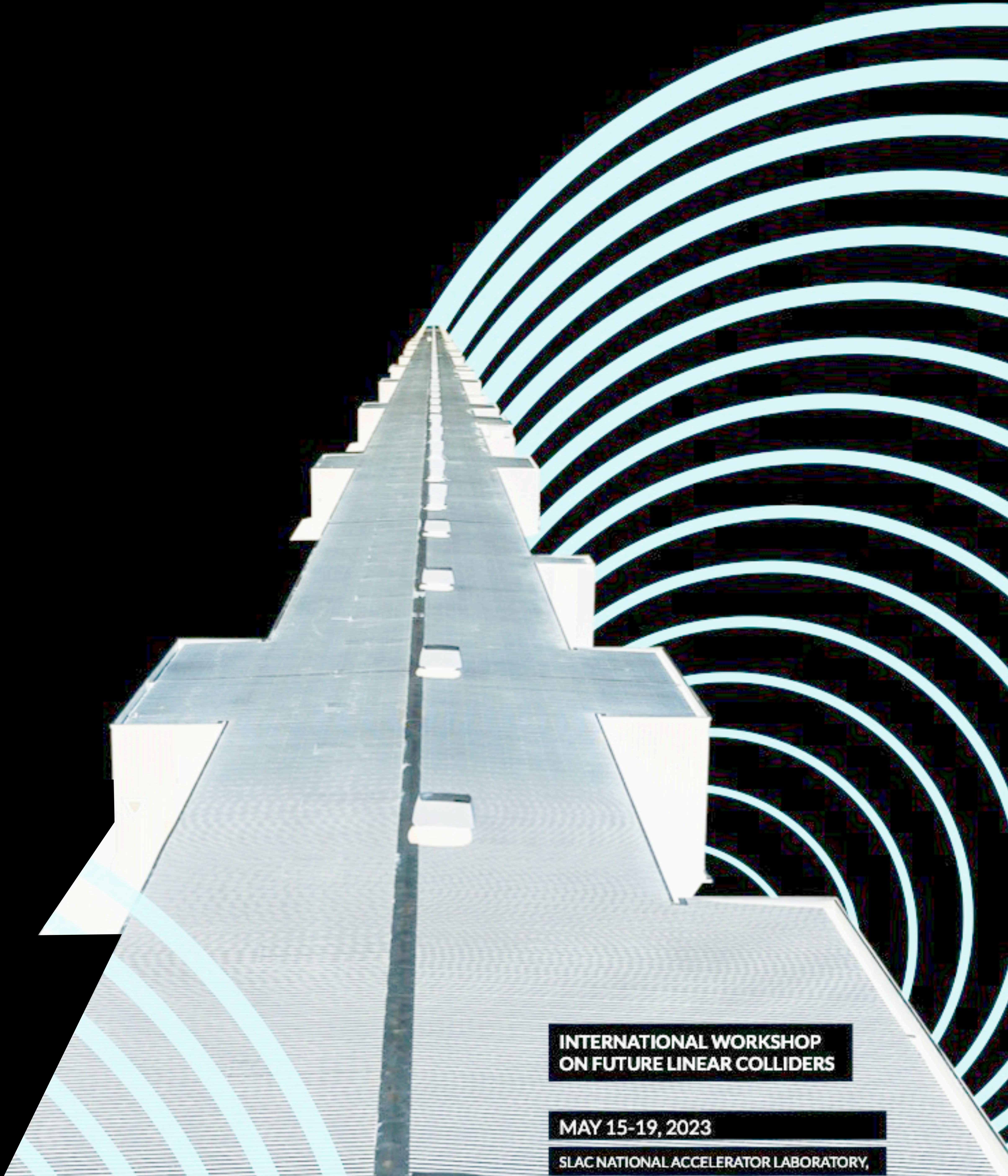
EHT image of M87

"Both because EHT measurements are sparse and because absolute phase calibration at millimeter wavelengths is impossible, recovering an image from EHT observations is a difficult and ill-posed problem. Images must be reconstructed using algorithms that find the best-fit images to data under a (hopefully minimal) set of additional assumptions about the source structure."

— Andrew Chael (Princeton/EHT)

Summing over individual Higgs particle decays to a given final state (e.g. $\gamma\gamma$) "images" the Higgs field in that channel. Are there better ways to visualize Higgs data & convey the majesty of precision measurement?

Thank you!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