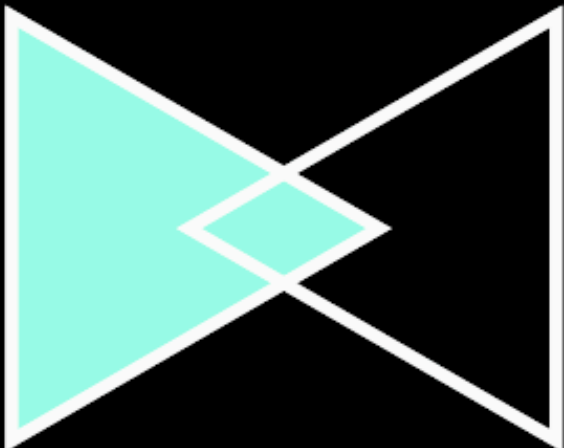
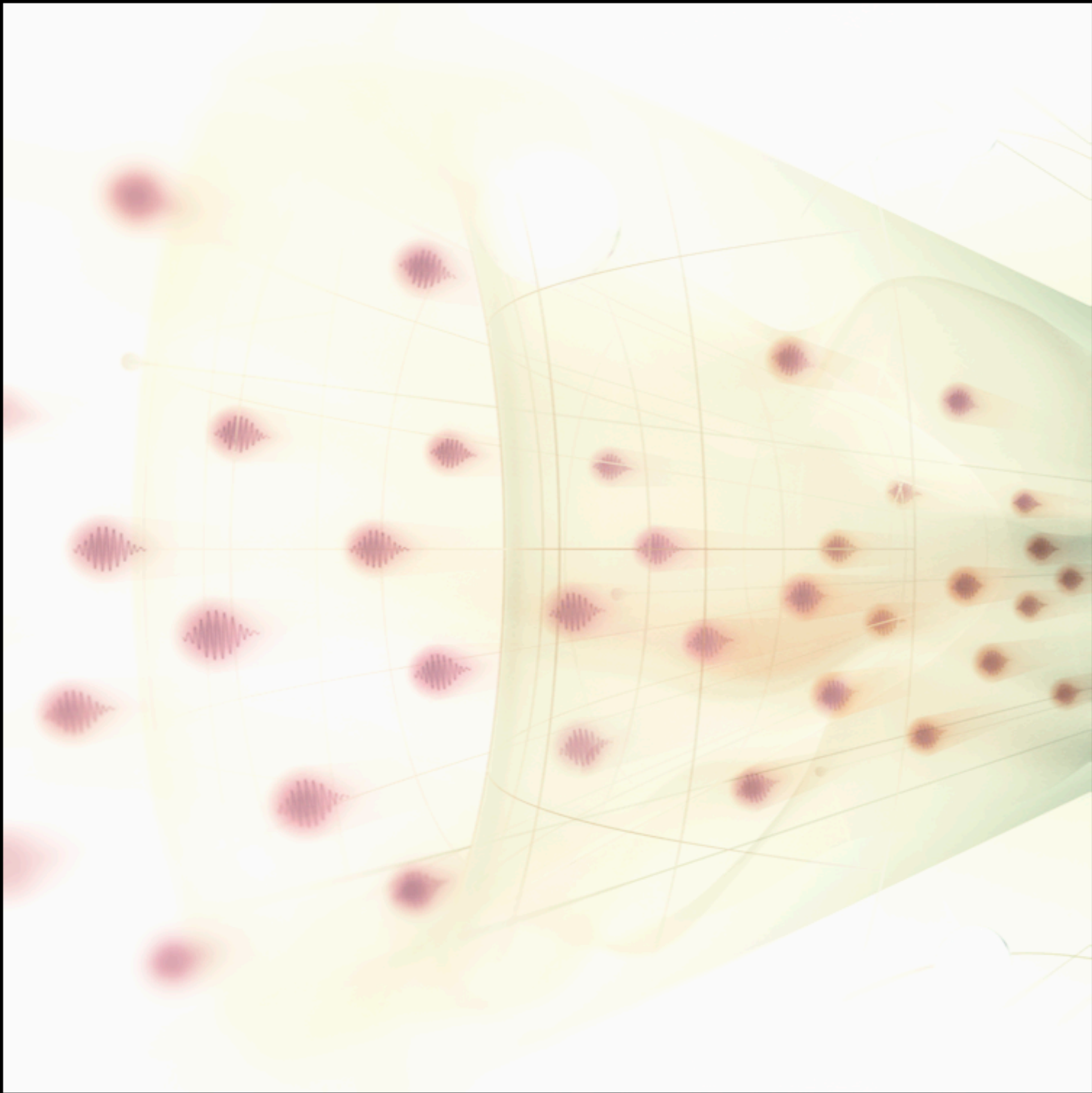


Physics at the Muon Collider

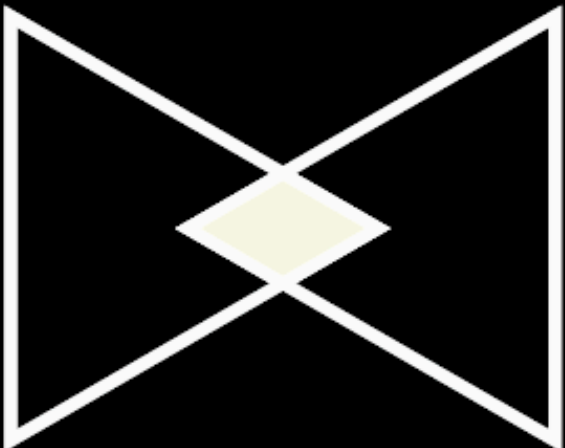
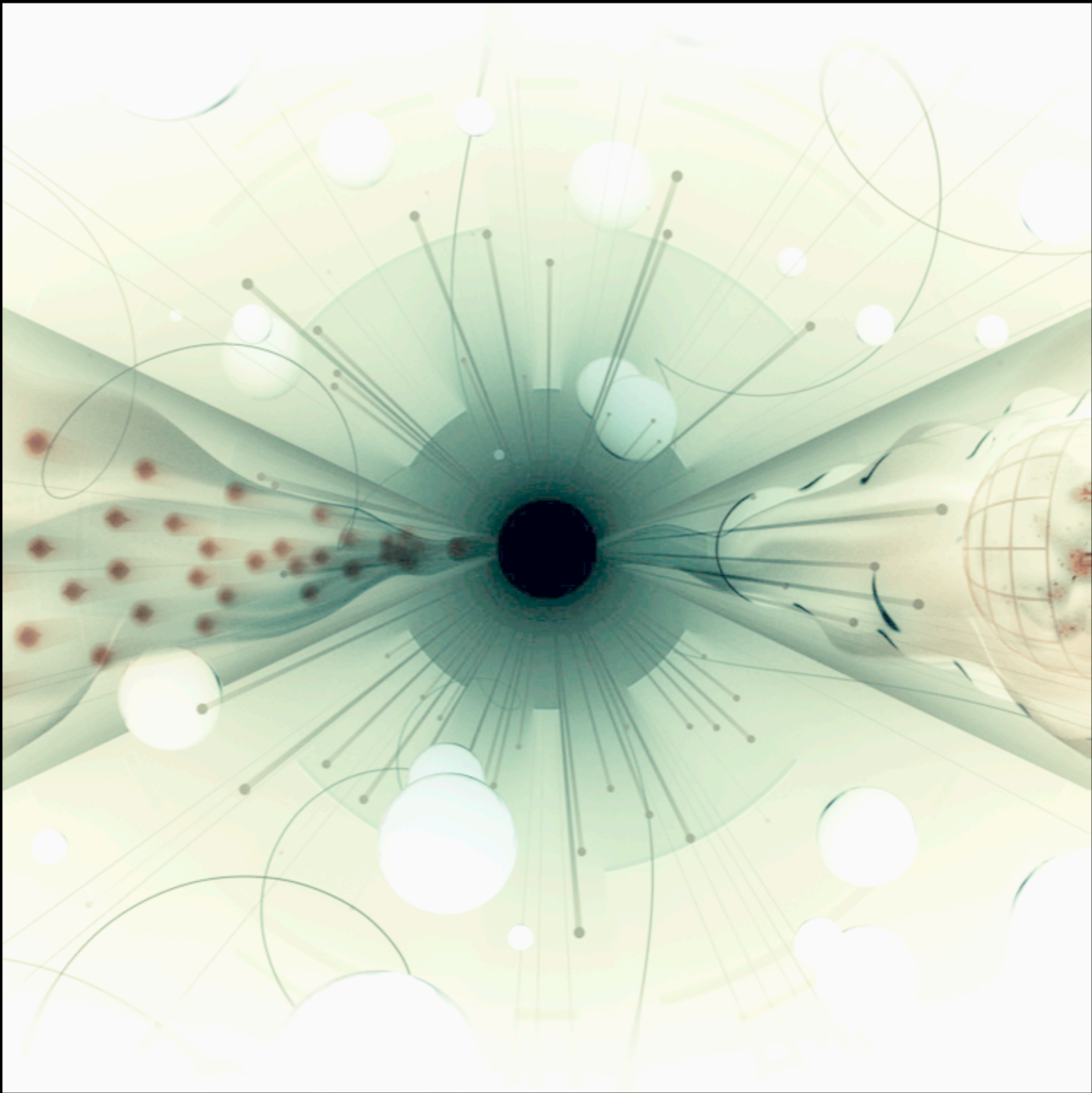
Nathaniel Craig 



**Decipher
the
Quantum
Realm**

**Elucidate the Mysteries
of Neutrinos**

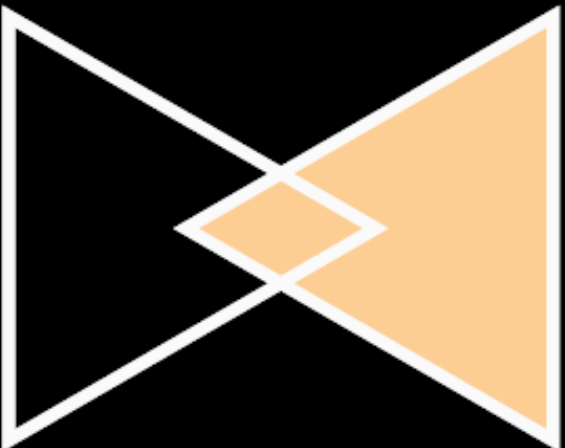
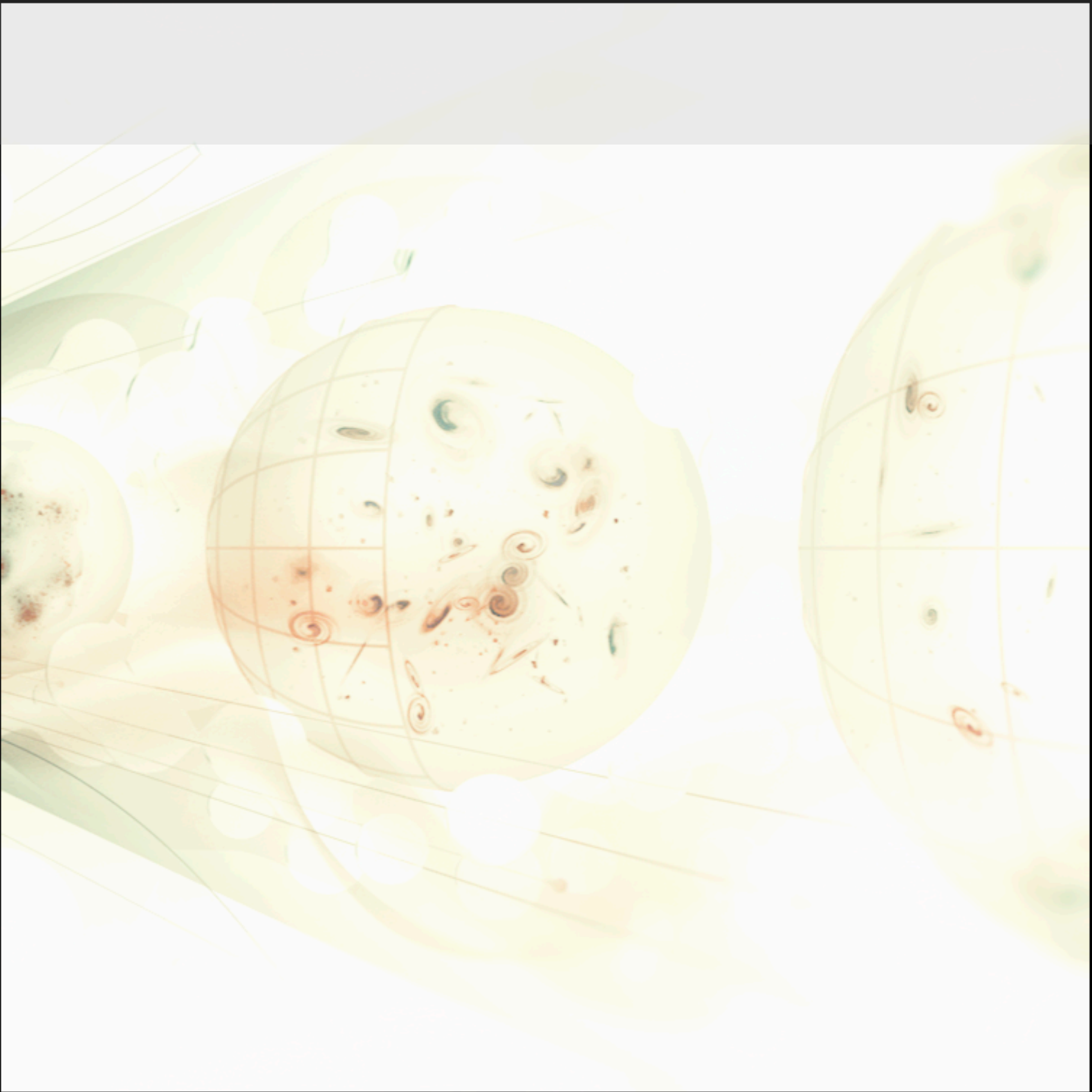
**Reveal the Secrets of
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**Explore
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**Search for Direct Evidence
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**Pursue Quantum Imprints
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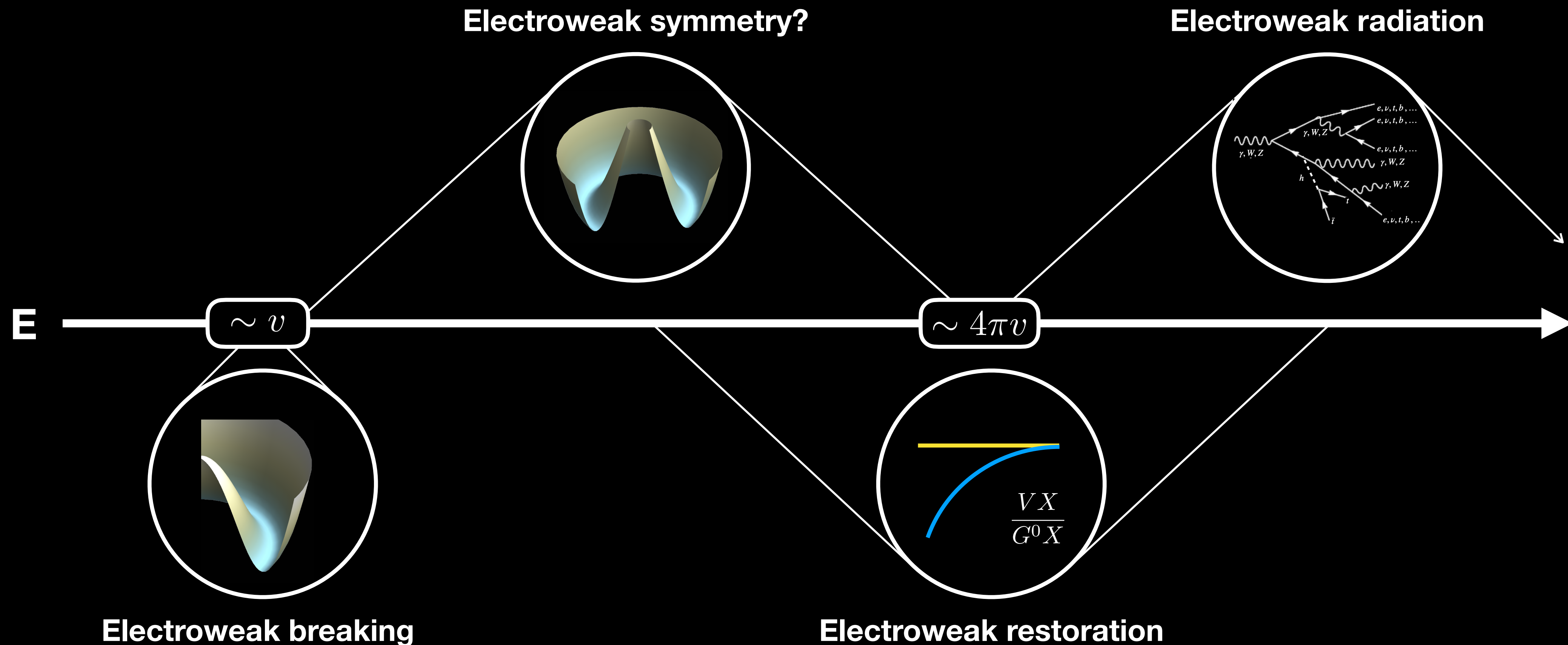
**Illuminate
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**Determine the Nature
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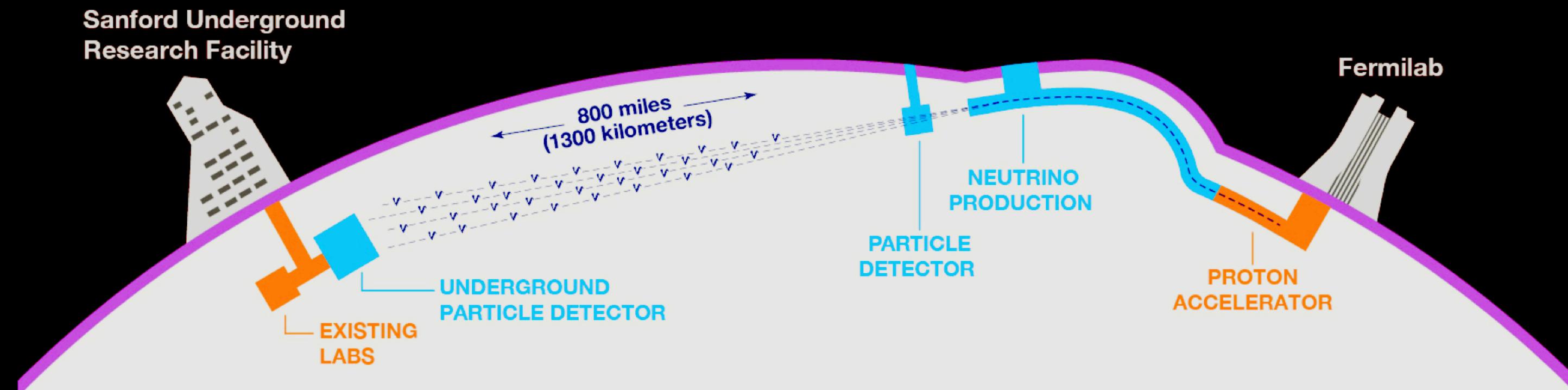
**Understand What Drives
Cosmic Evolution**

The Electroweak Era

“The more ambitious goal...is to identify and understand the nature of electroweak symmetry breaking, the asymmetry that is key to the material universe. The Higgs boson is but its herald.” — *Frank Close*



The Electroweak Era



Neutrinos: the purely weak frontier of the Standard Model

Dark sectors: portals are weak interactions & SM electroweak states

weak portal

$$g(W_\mu)^i_j \mathcal{O}_j$$

Higgs portal

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

neutrino portal

$$HL^\alpha \mathcal{O}_\alpha$$

axion portal

$$\mathcal{O} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

The Electroweak Era

...and exploration after the LHC

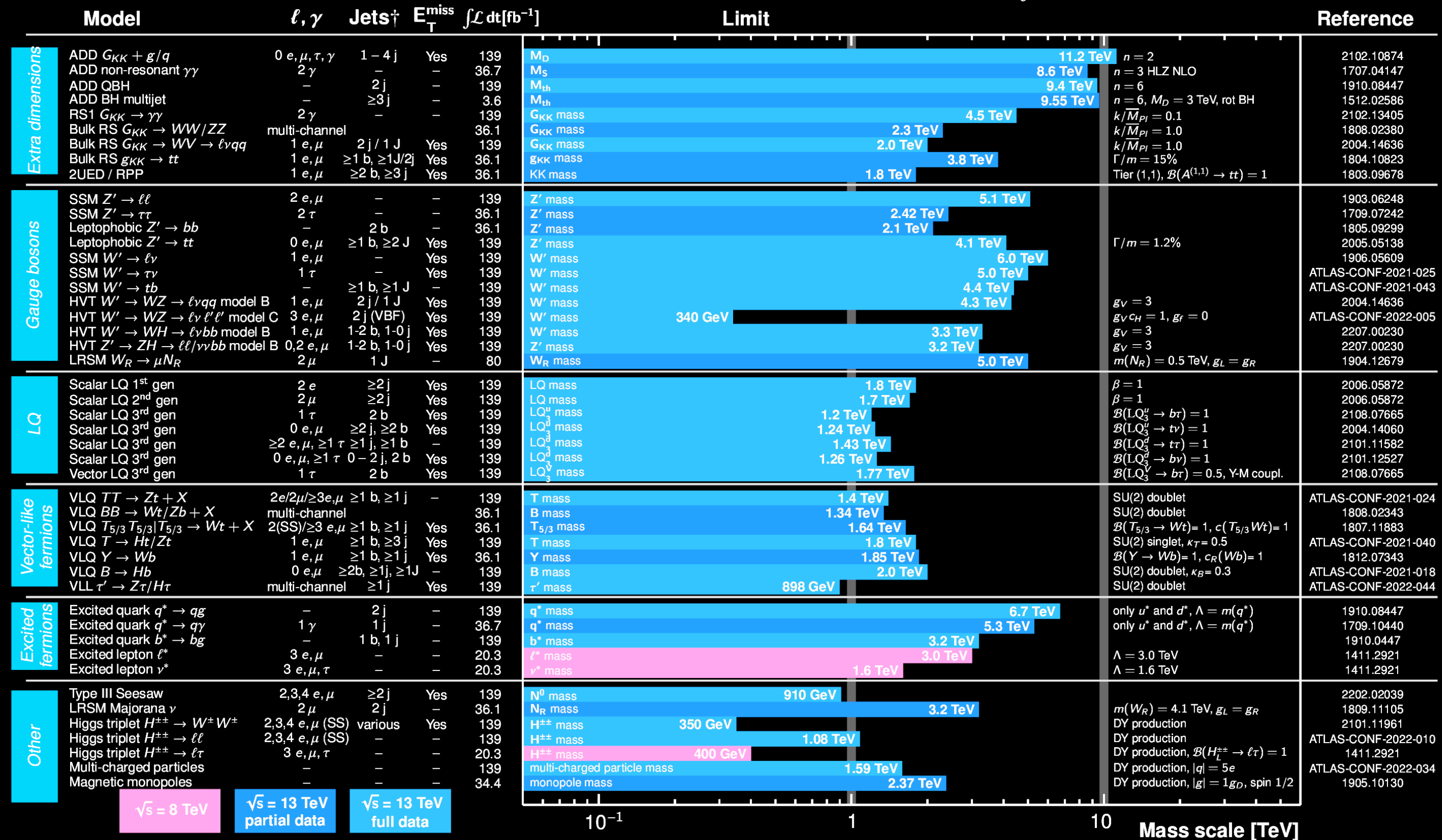
ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

ATLAS Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$



$\sqrt{s} = 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$ partial data $\sqrt{s} = 13 \text{ TeV}$ full data

10⁻¹ 1 10 Mass scale [TeV]

The Electroweak Era

...and exploration after the LHC

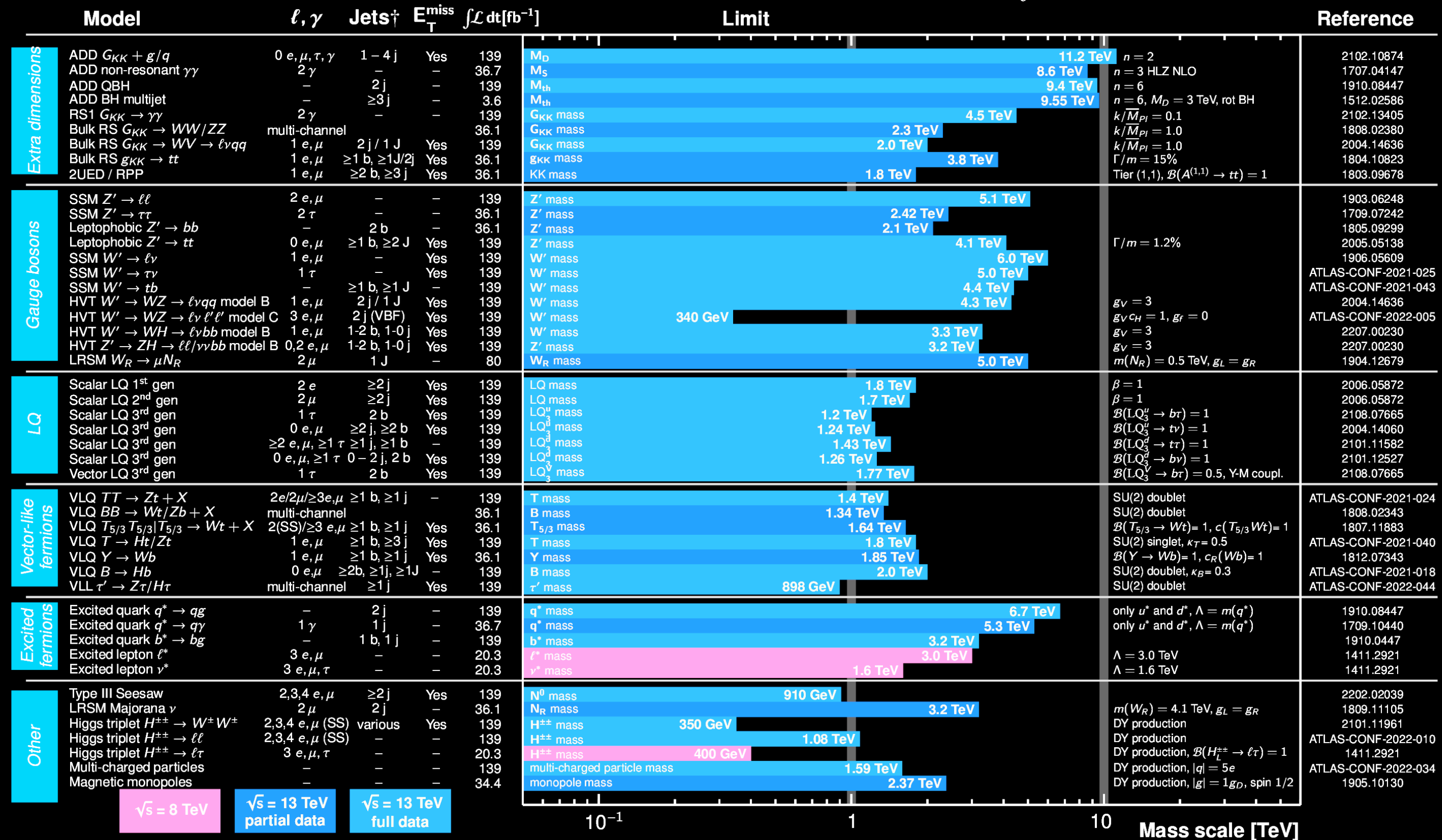
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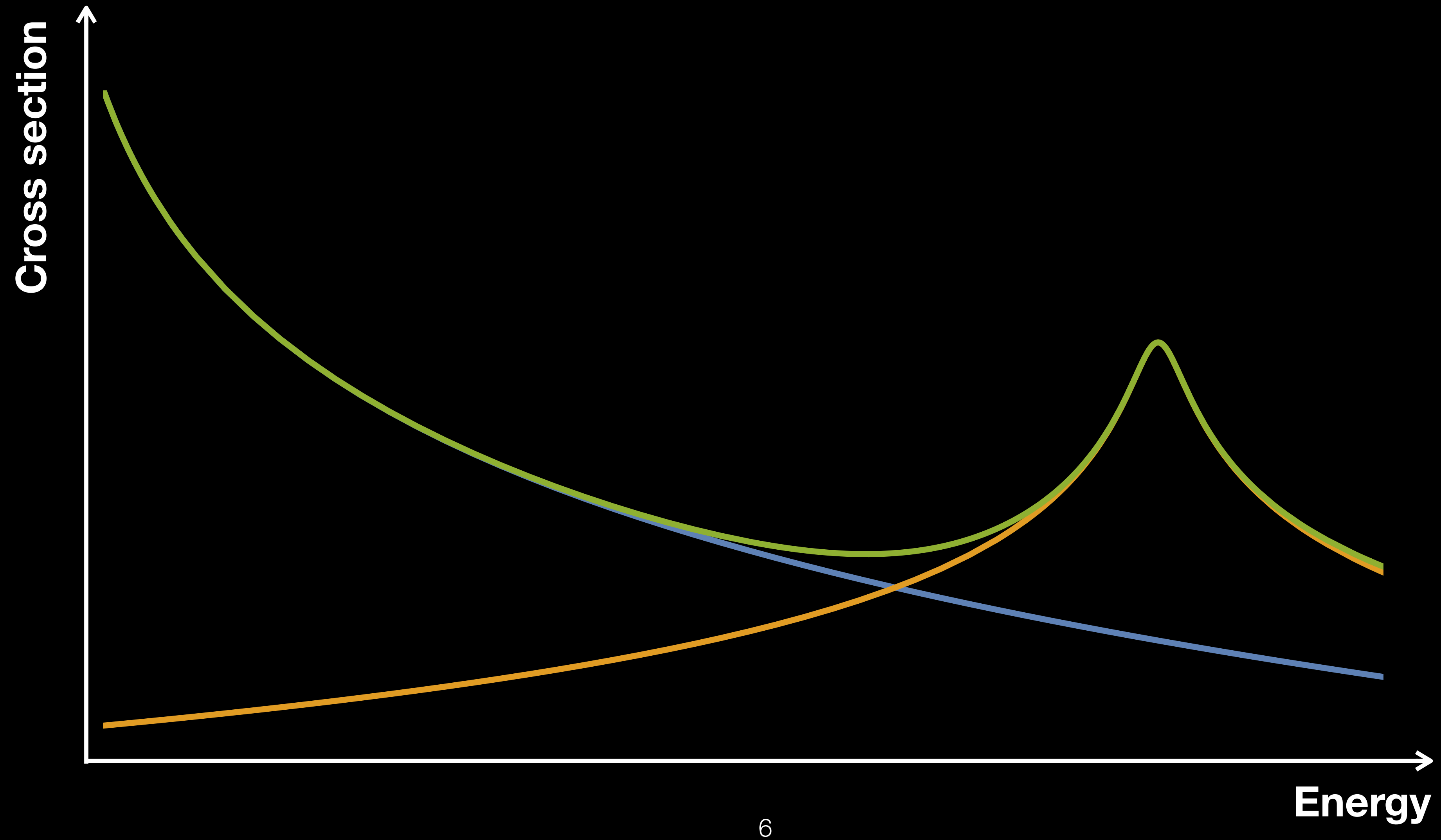
$\sqrt{s} = 8, 13 \text{ TeV}$



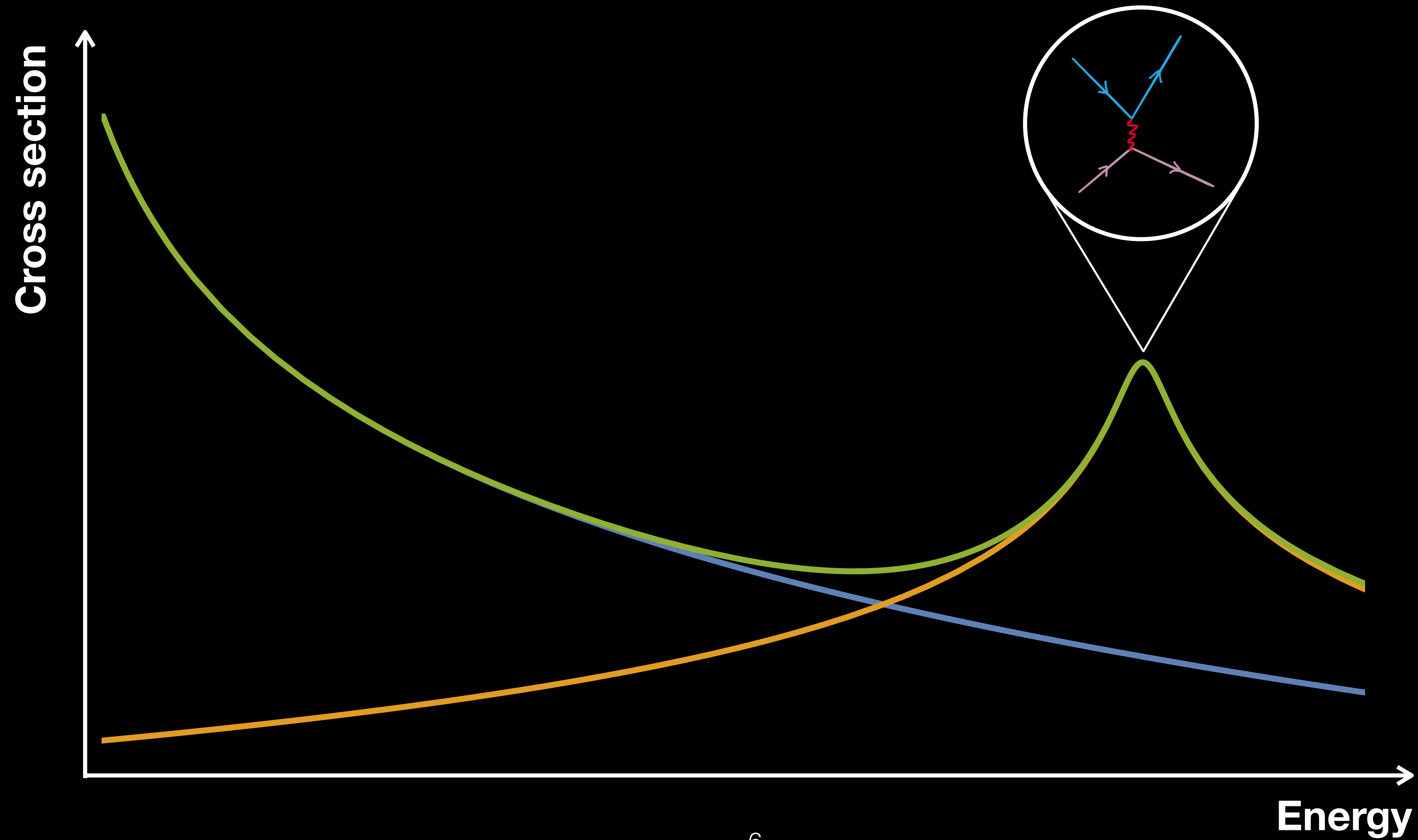
$\sqrt{s} = 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$ partial data $\sqrt{s} = 13 \text{ TeV}$ full data

Singlet scalar $(1, 1)_0$ ■
 Doublet scalar $(1, 2)_{1/2}$ ■
 Doublet scalar $(1, 2)_{3/2}$ ■

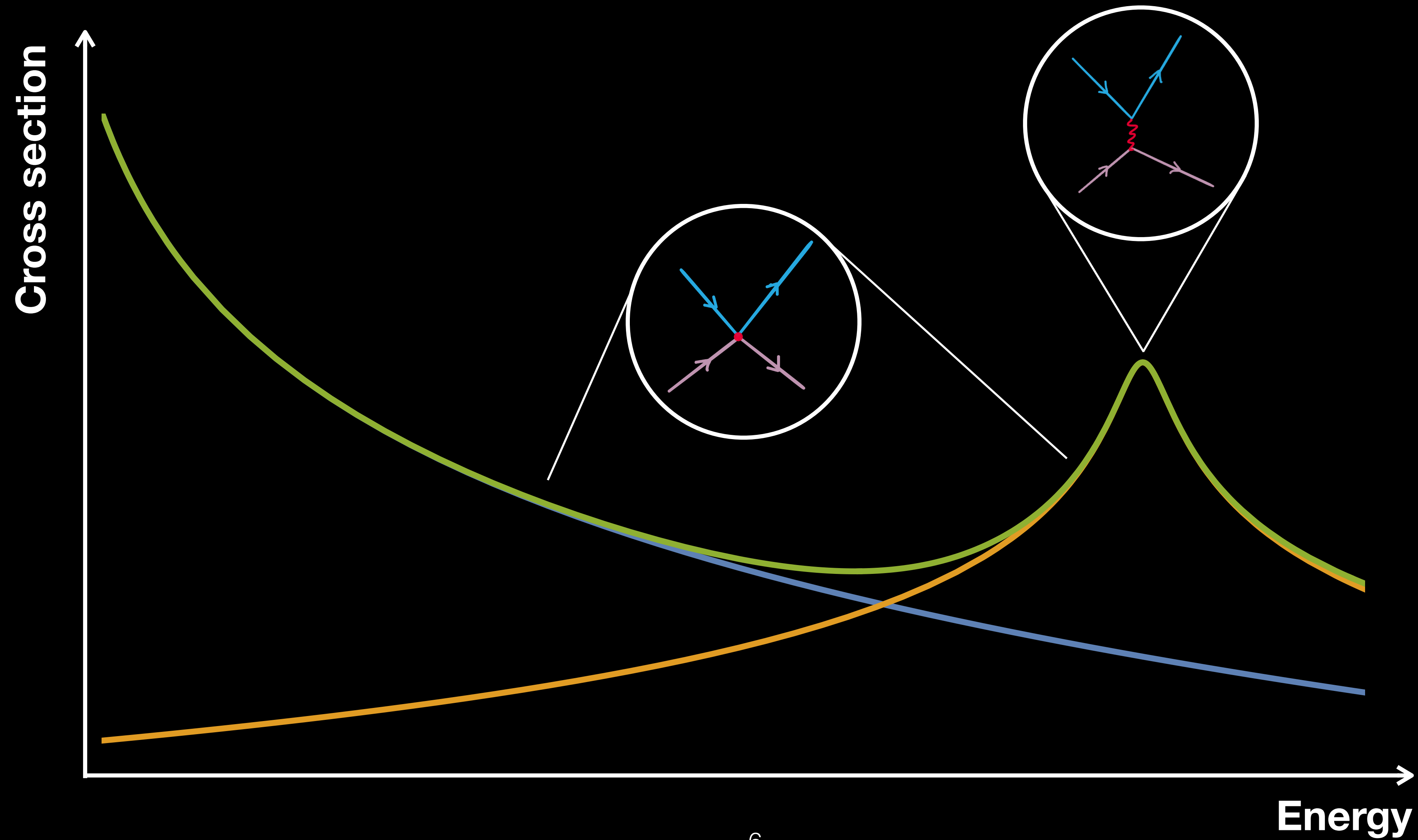
Paths to Discovery



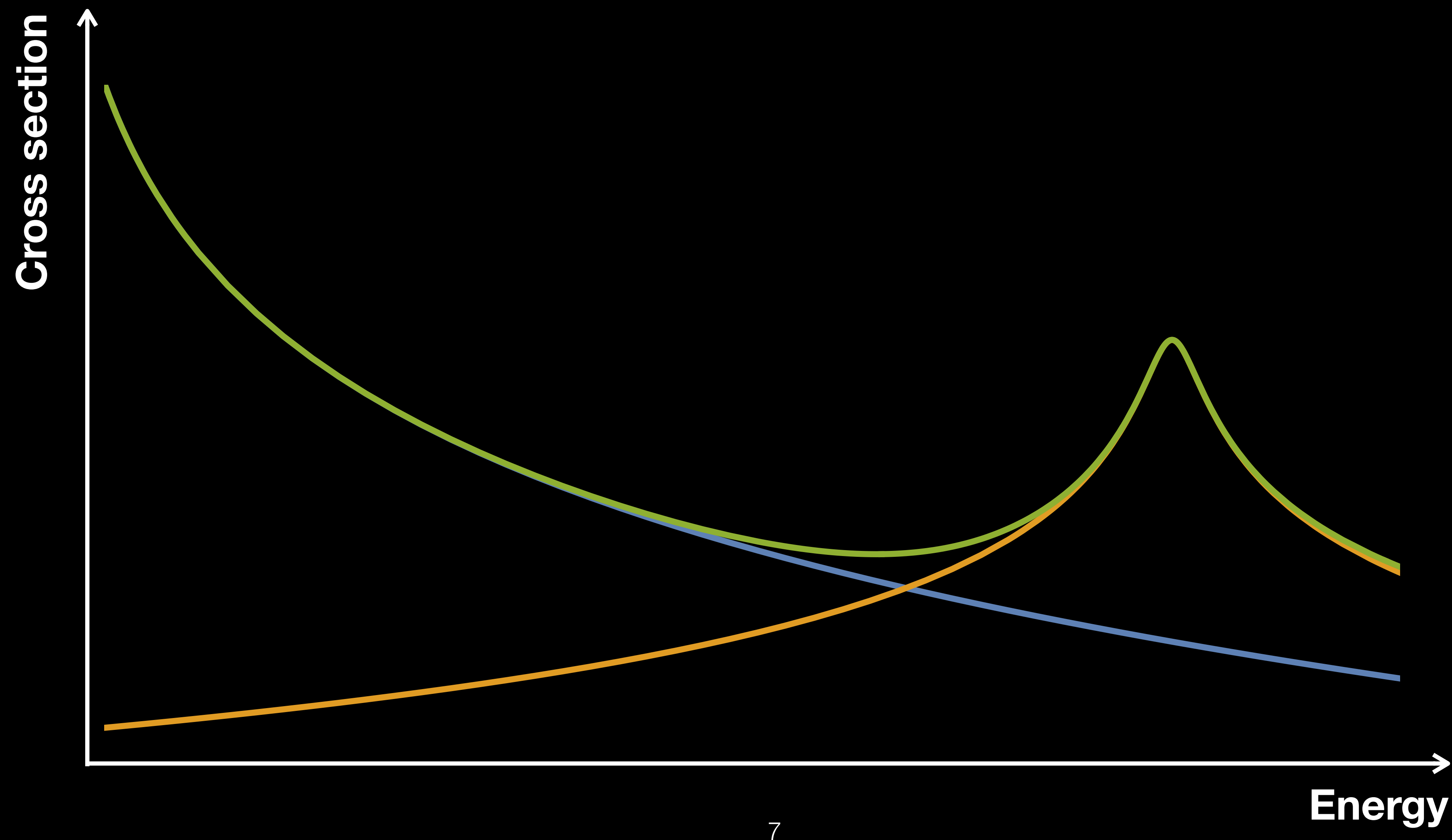
Paths to Discovery



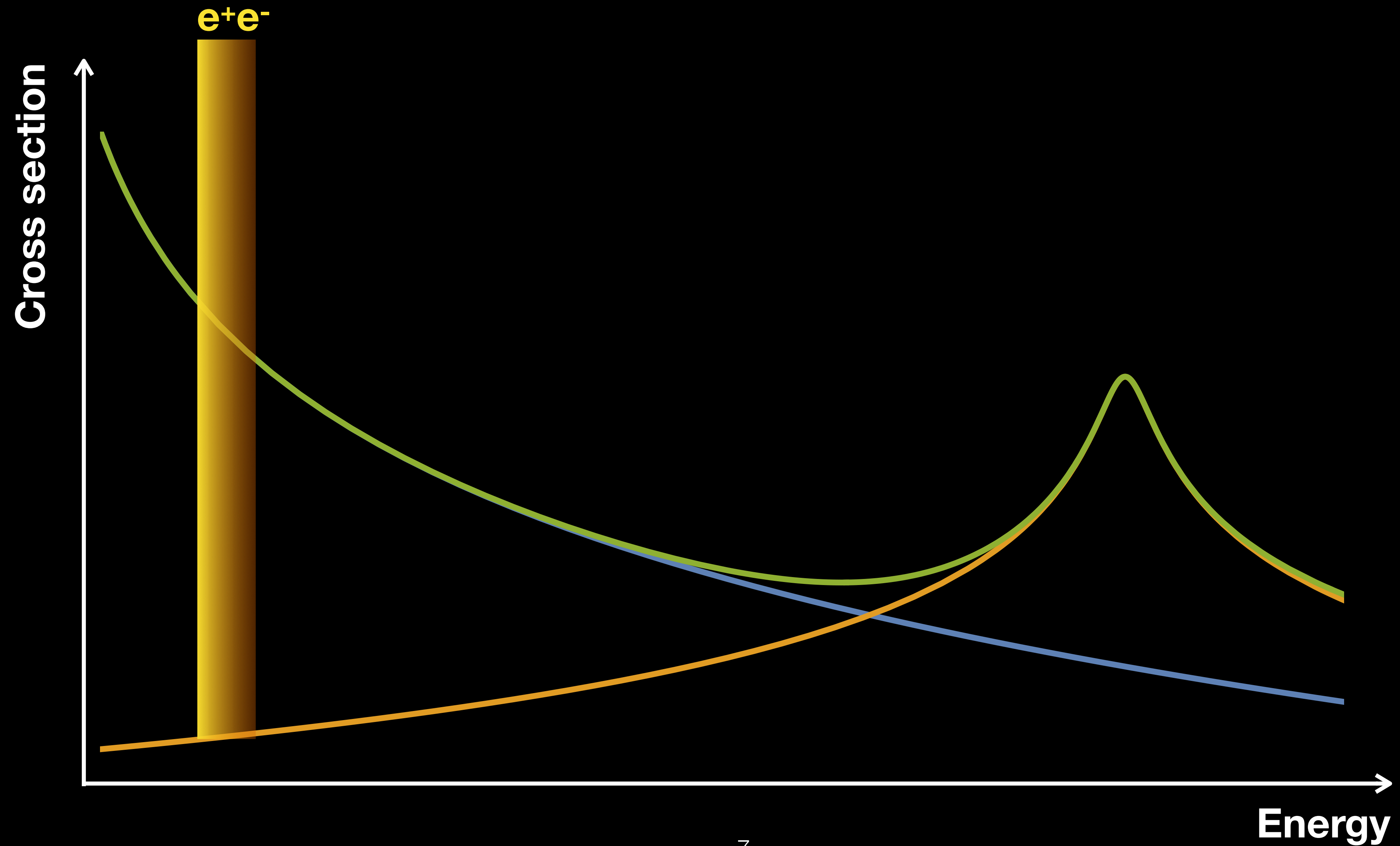
Paths to Discovery



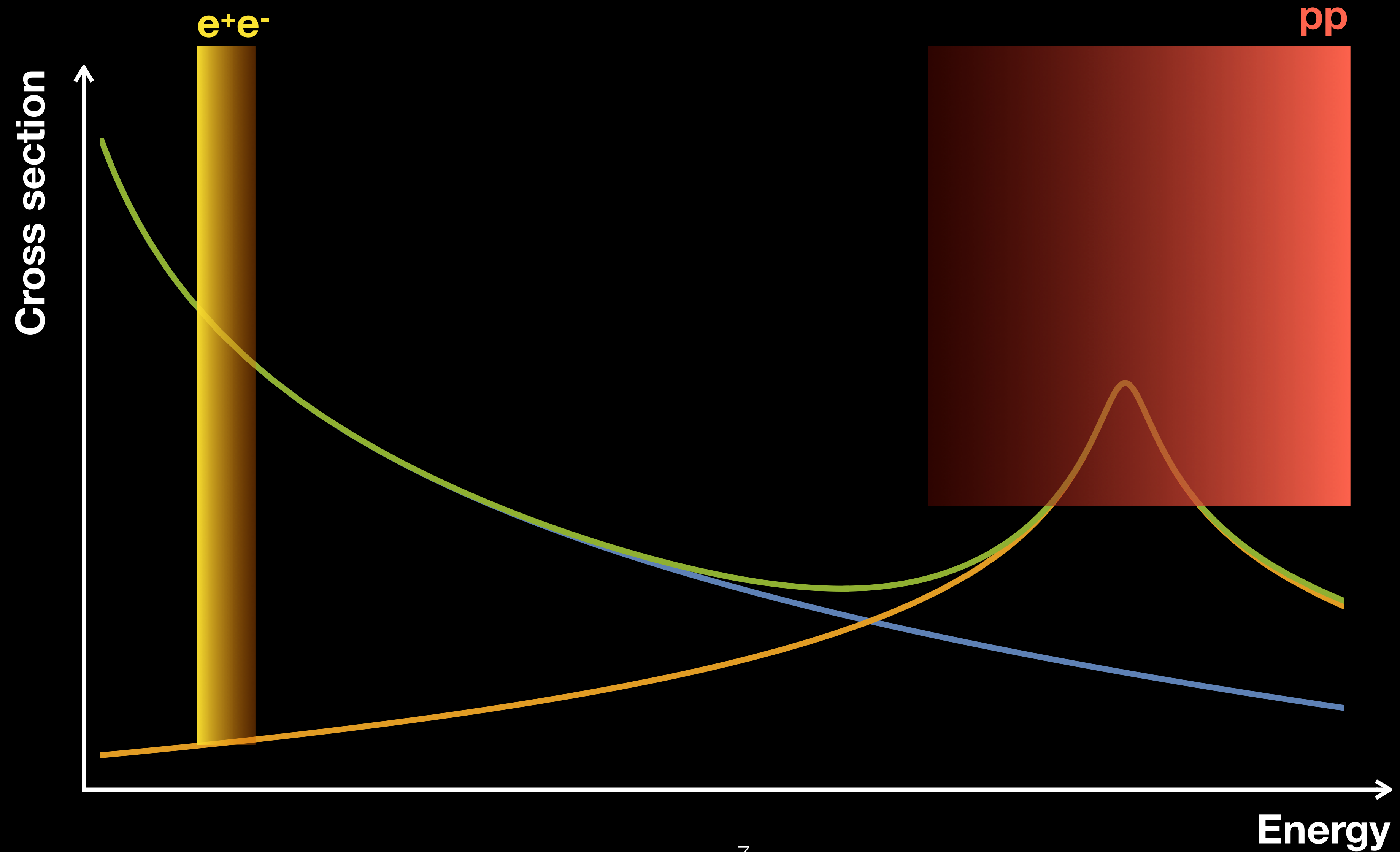
Machines for Discovery



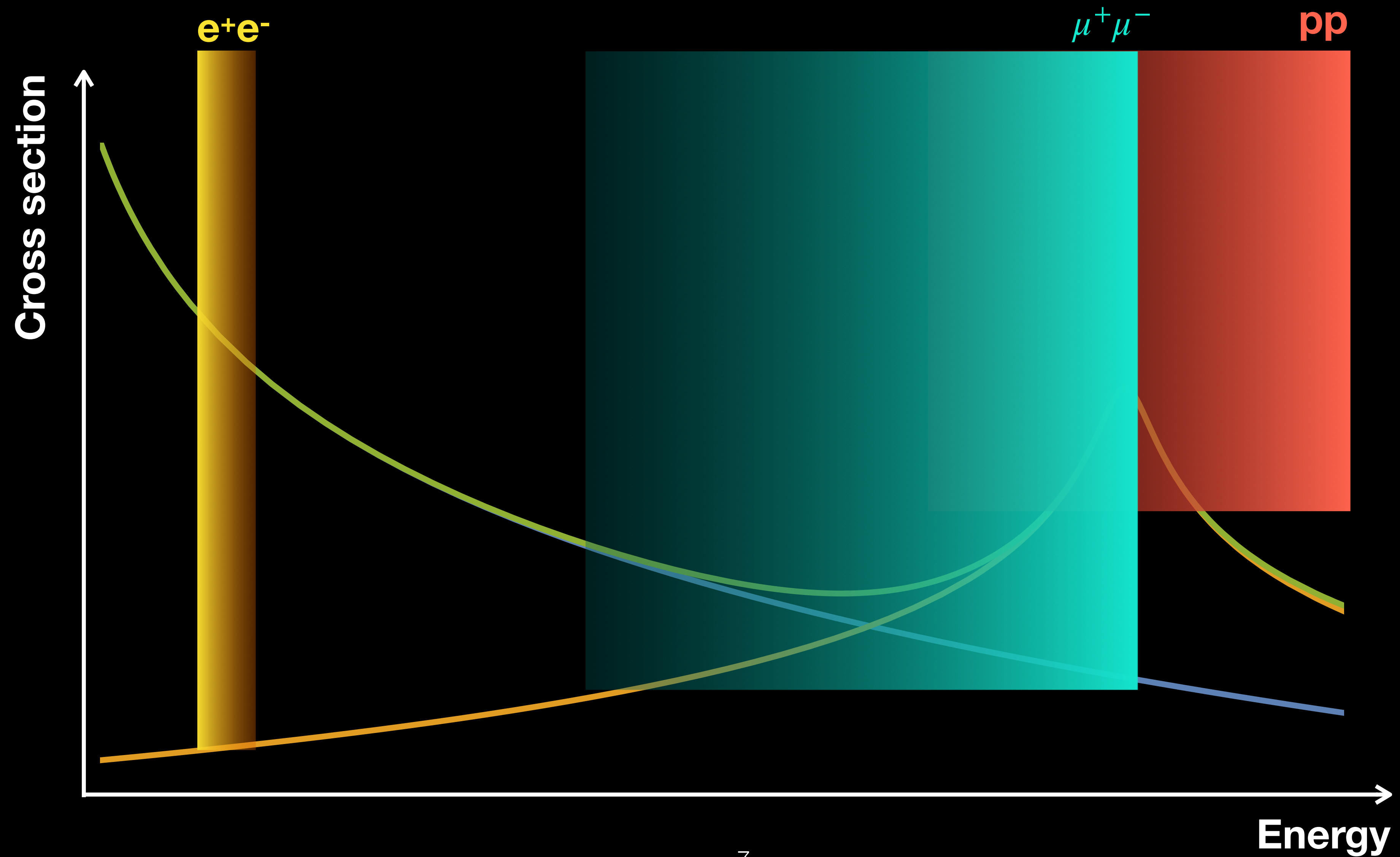
Machines for Discovery



Machines for Discovery

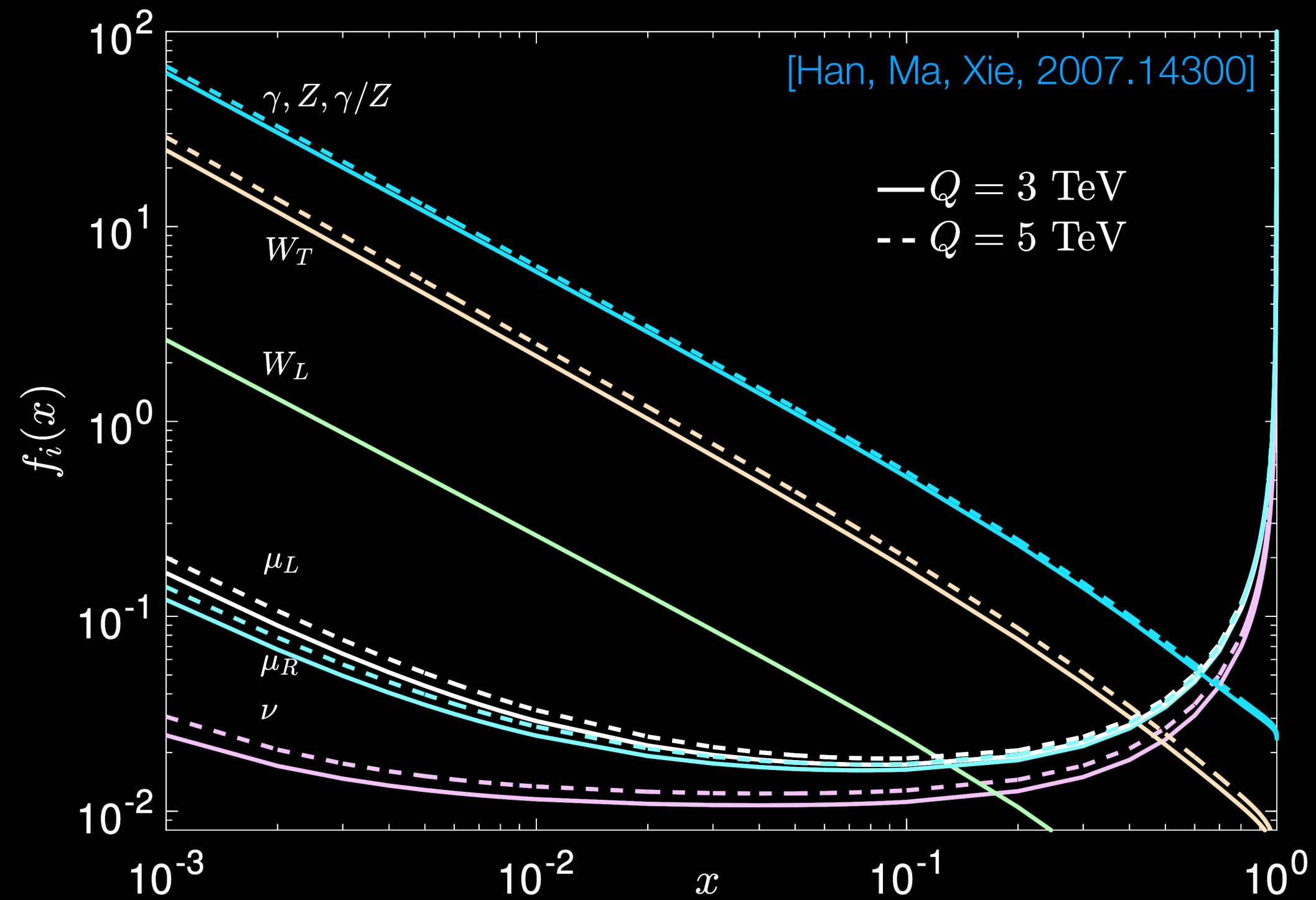


Machines for Discovery

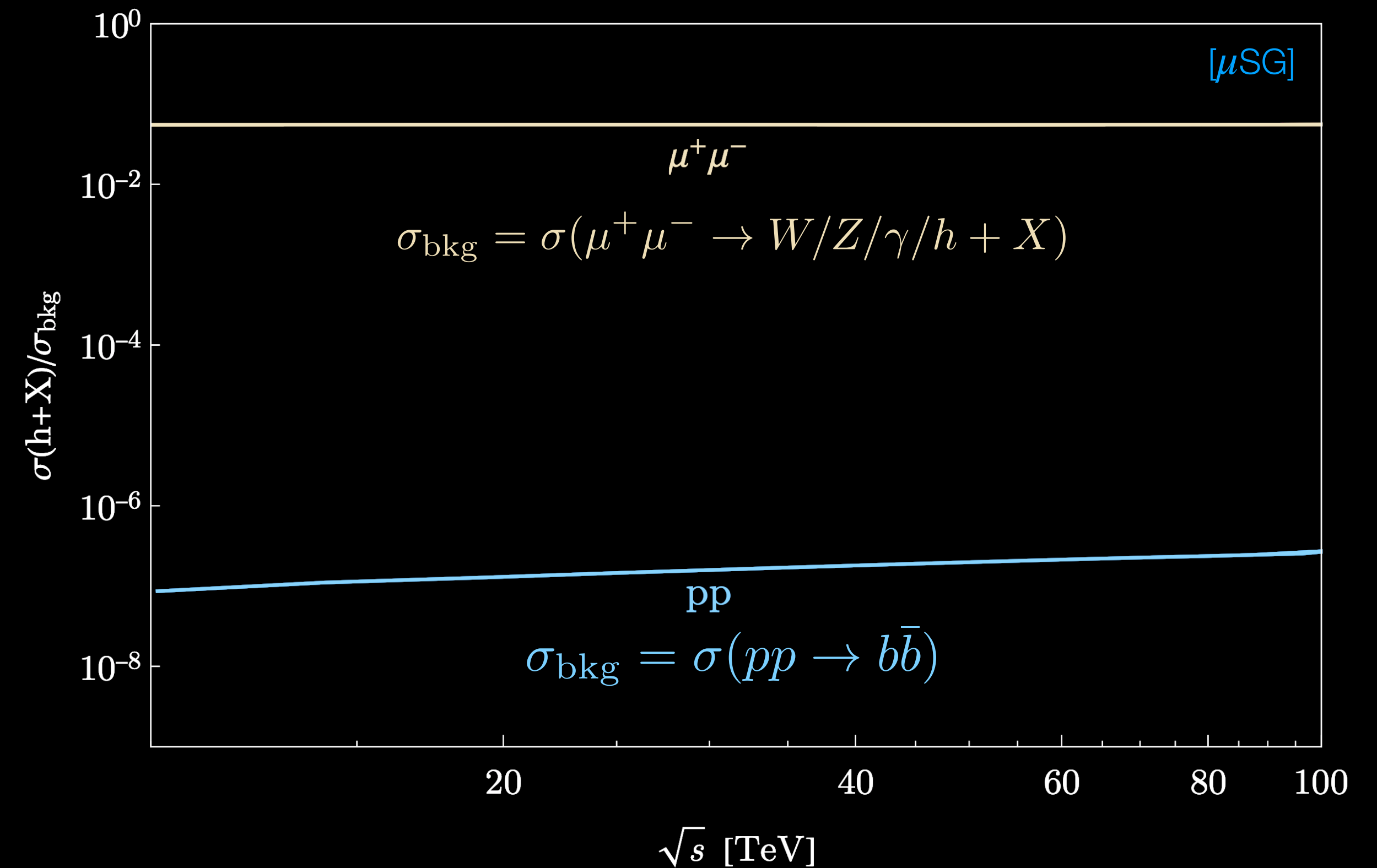


Why Muon Colliders?

1. Weak and flavorful production modes

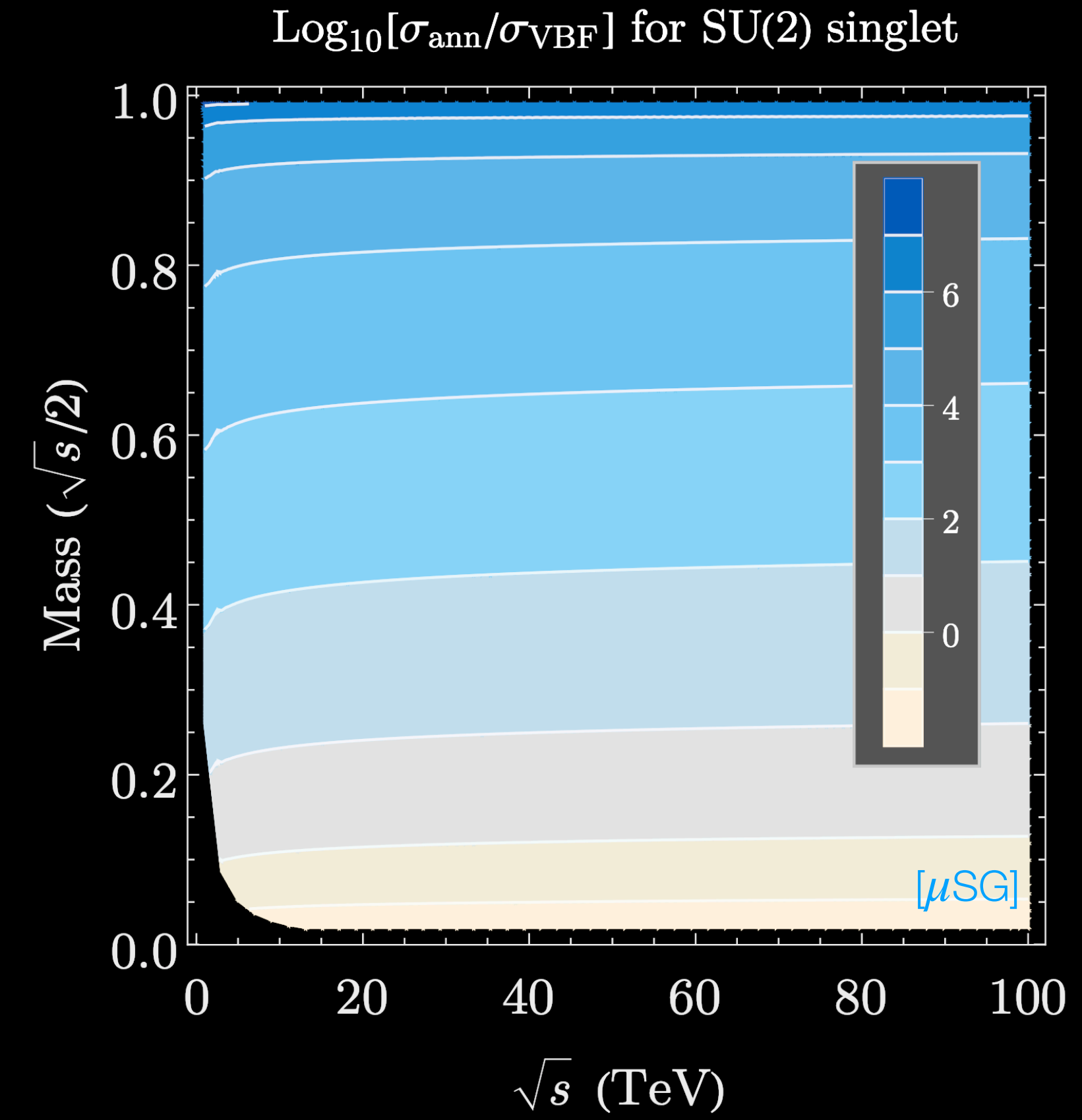
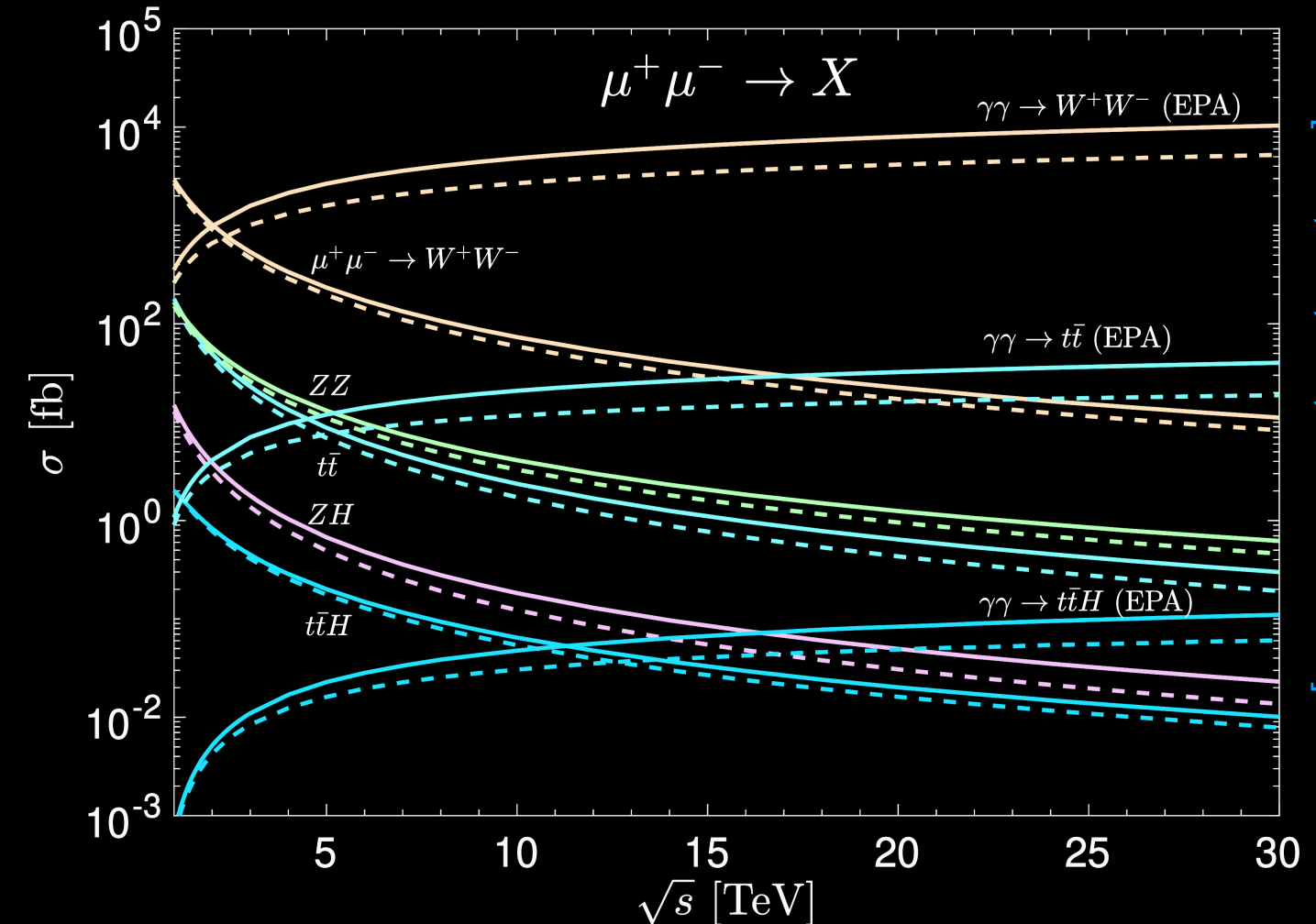
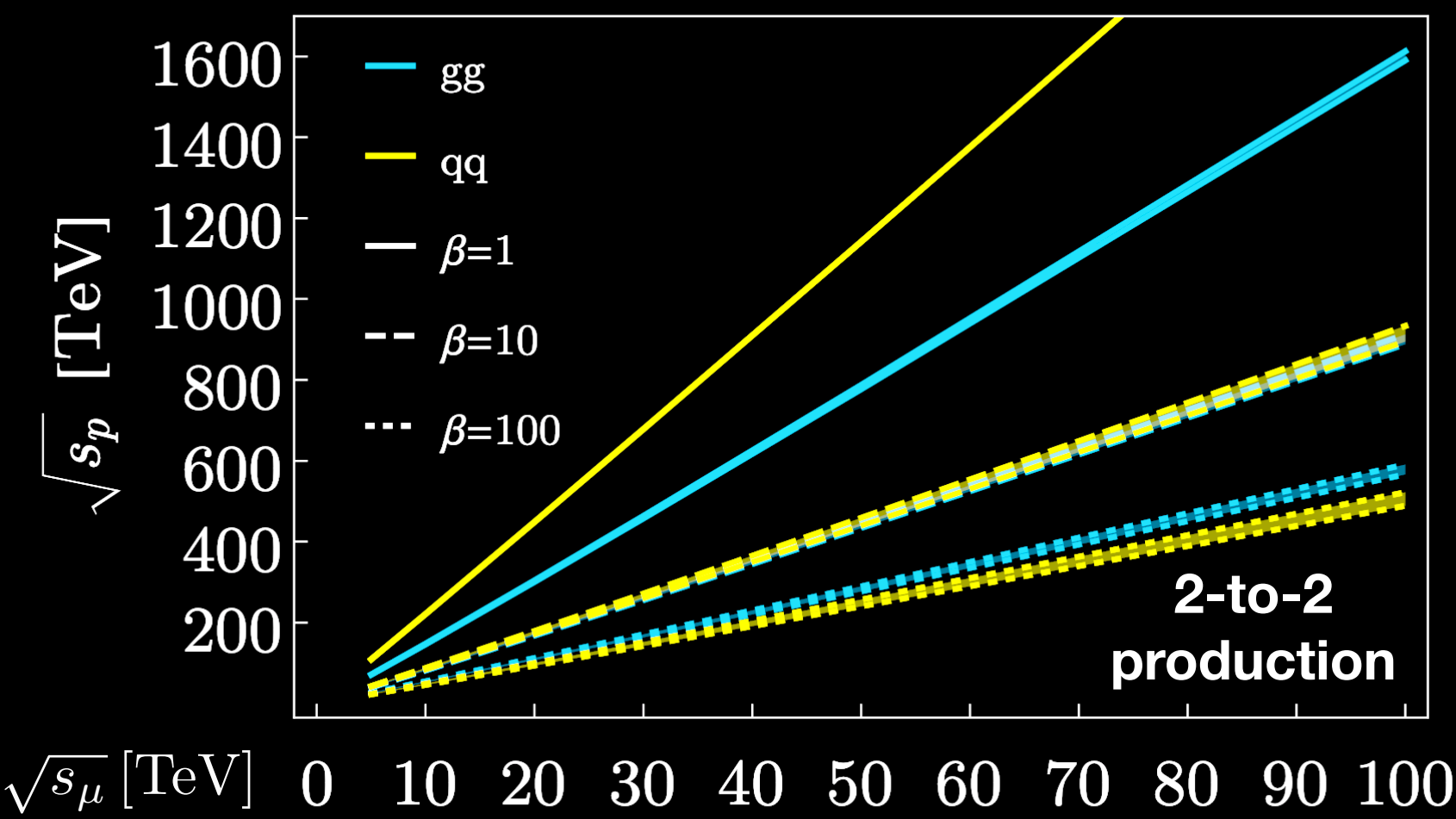
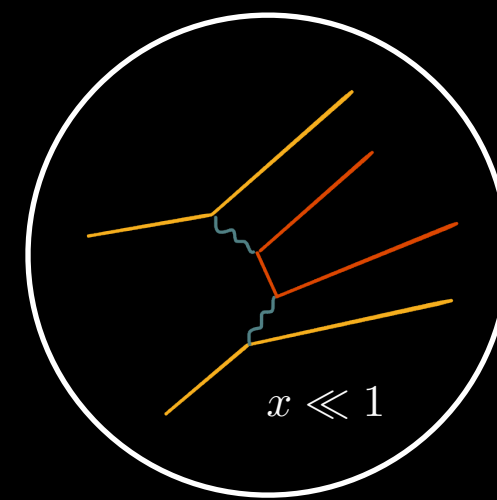
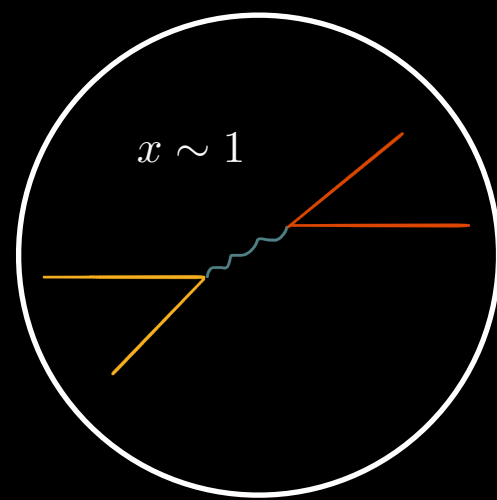


2. Modest irreducible backgrounds



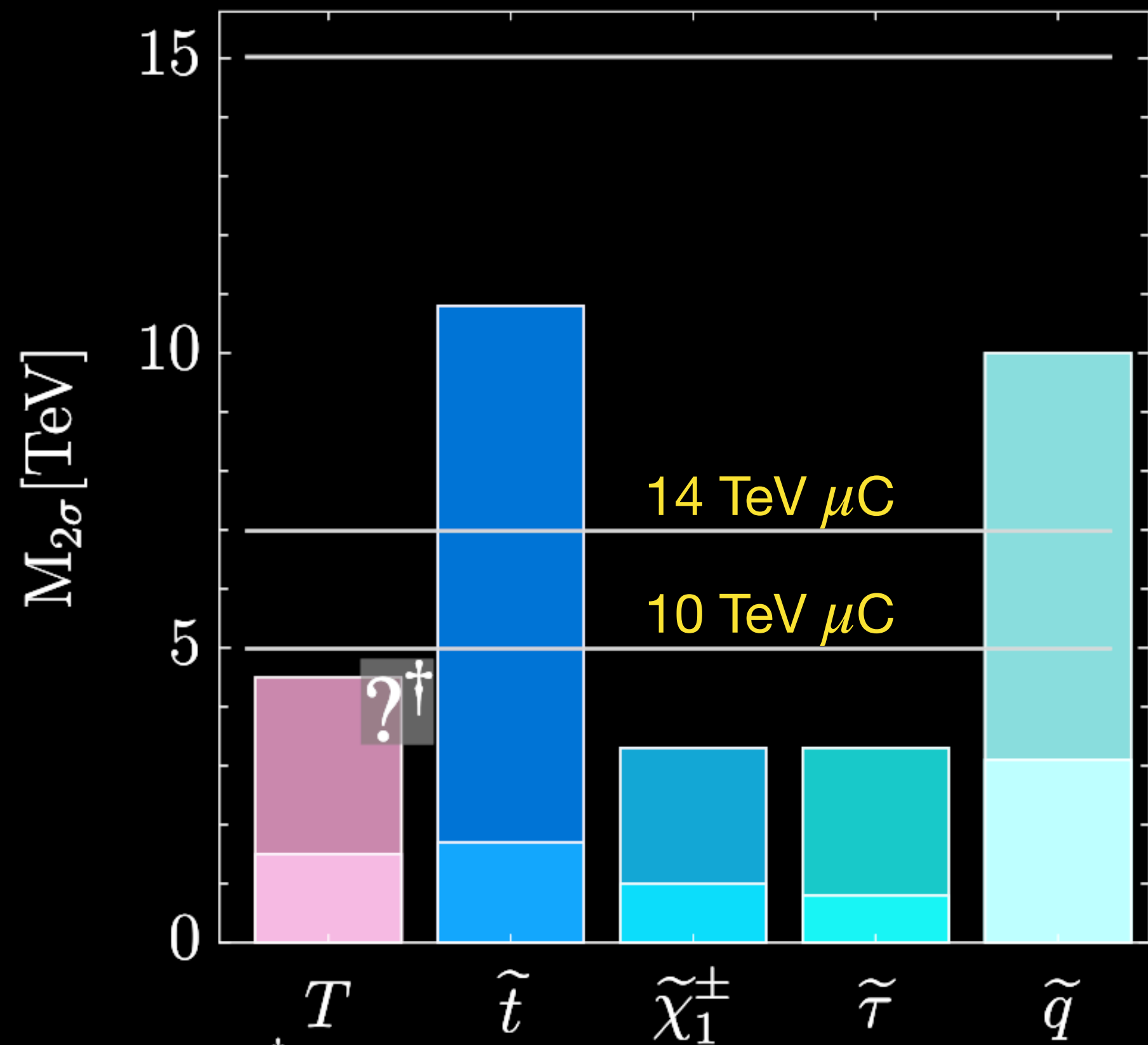
Why Muon Colliders?

3. Annihilation + VBF offers kinematic reach and considerable rate



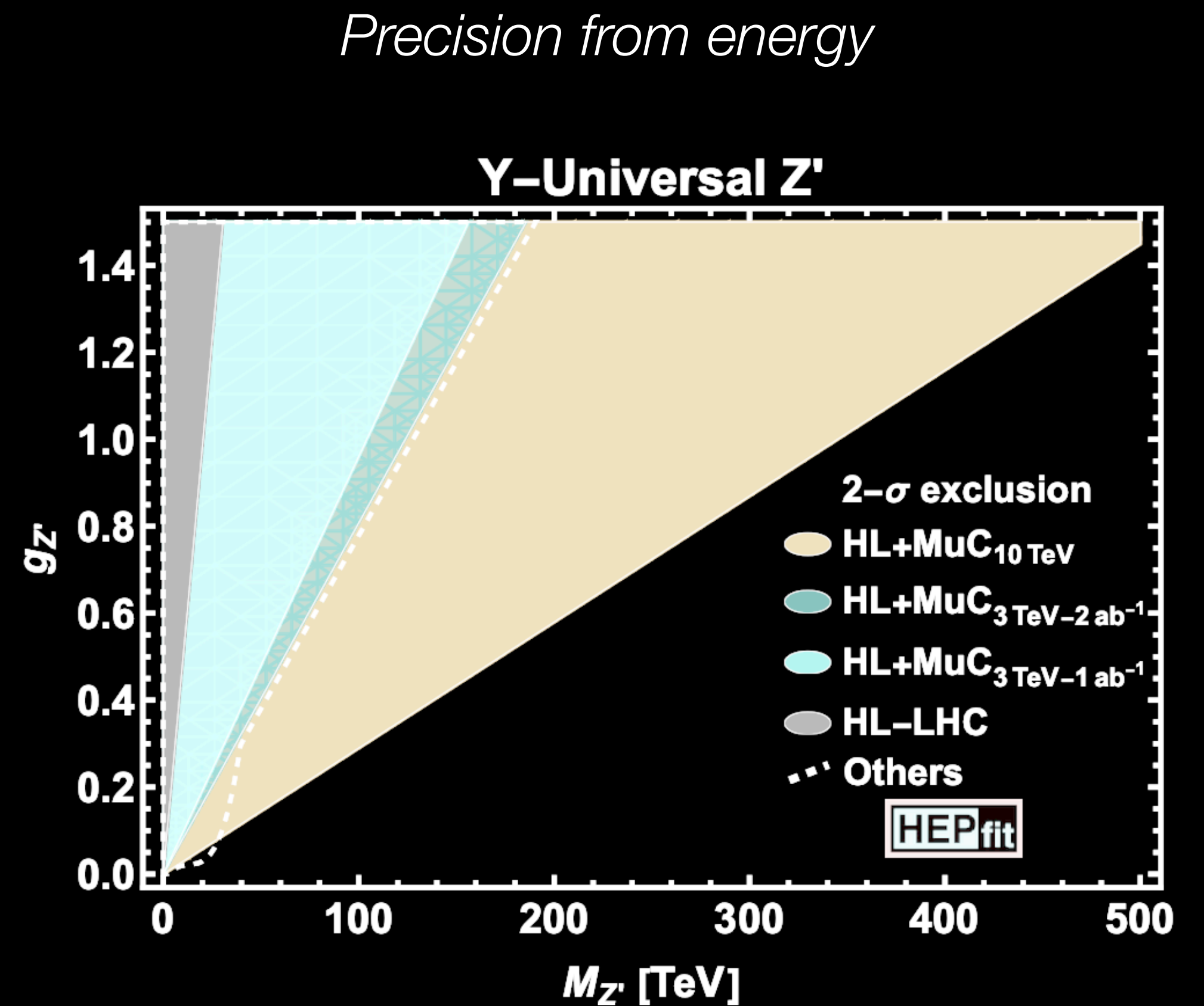
Why Muon Colliders?

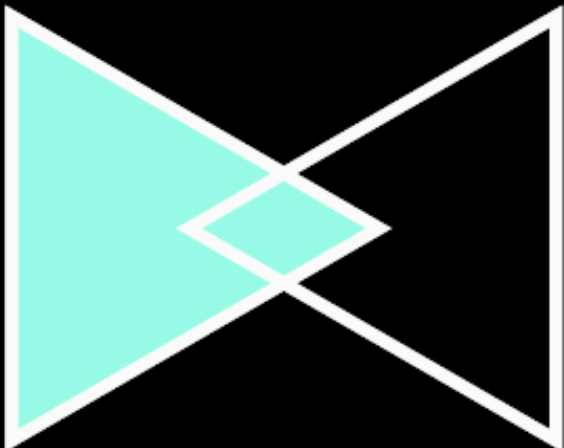
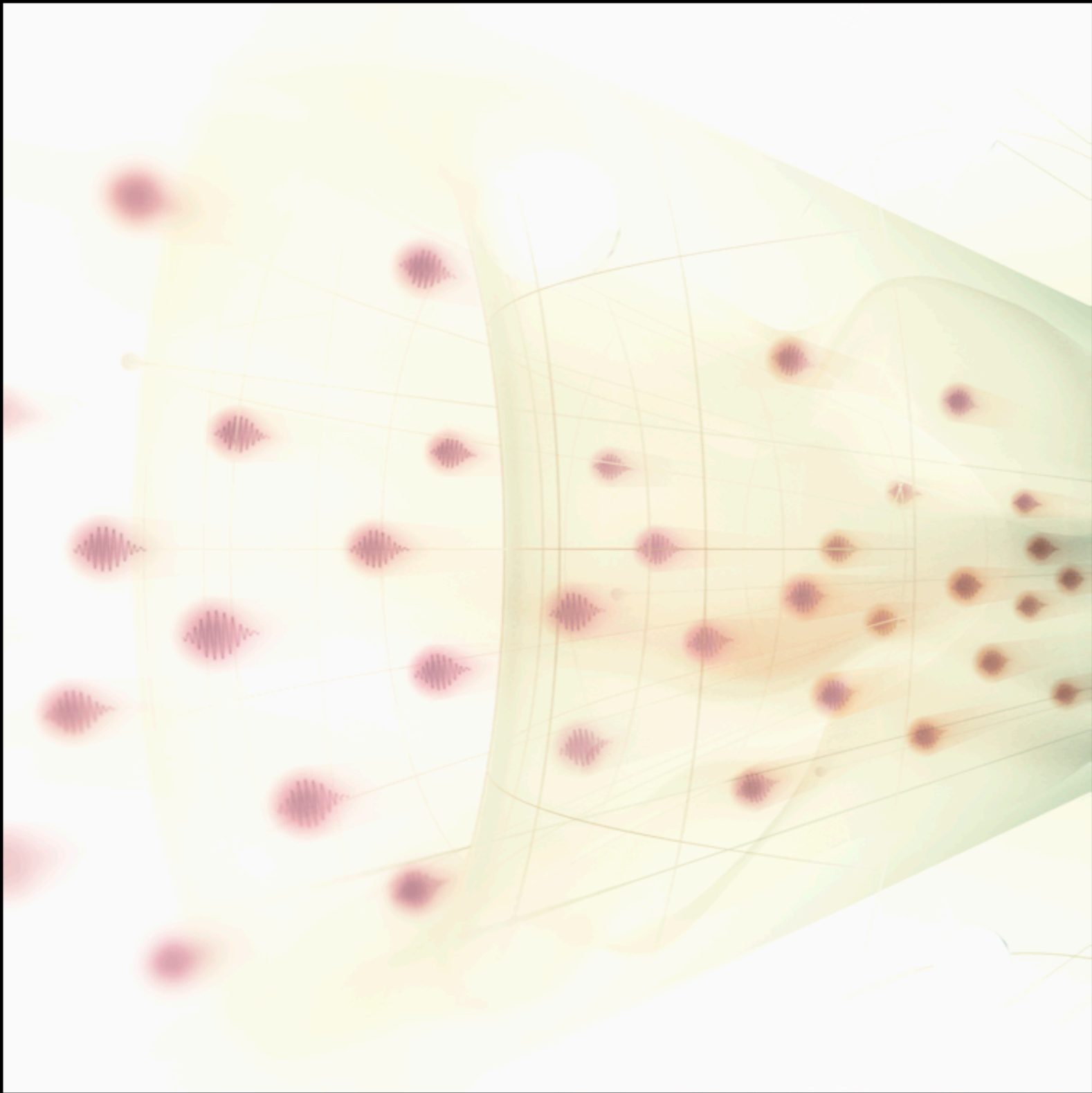
Discover distinctive particles up to $\sim \sqrt{s}/2$



† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

Indirect access to much higher scales

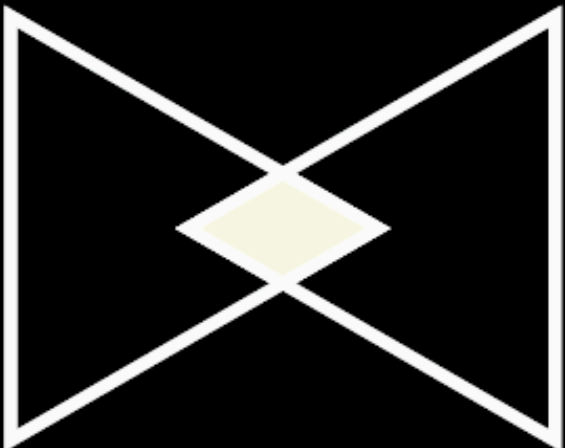
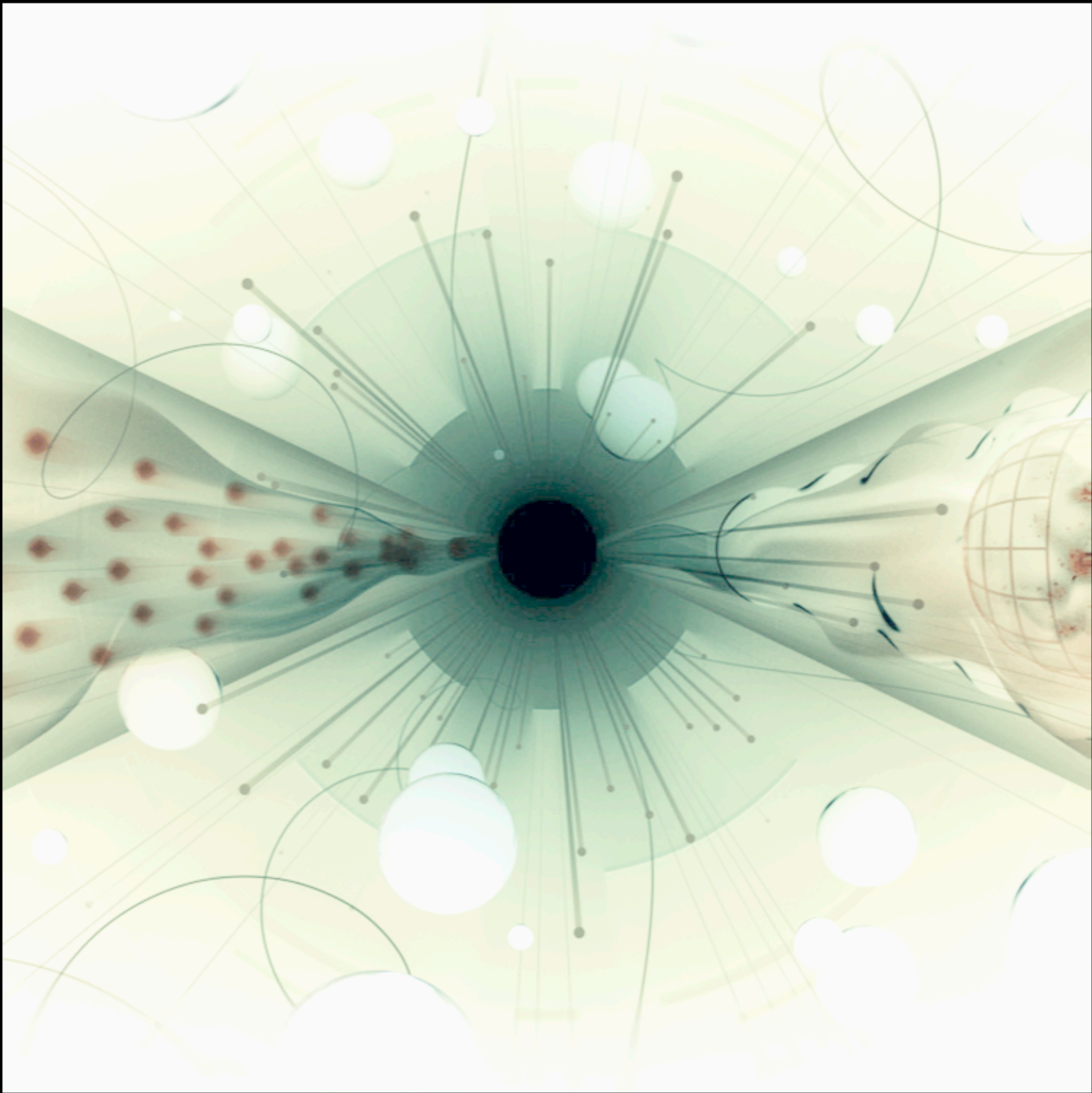




**Decipher
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**Elucidate the Mysteries
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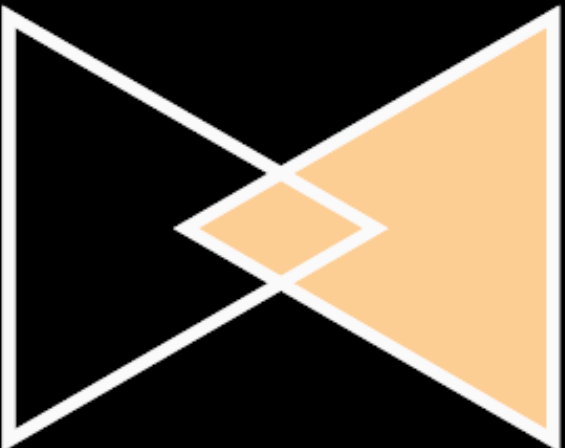
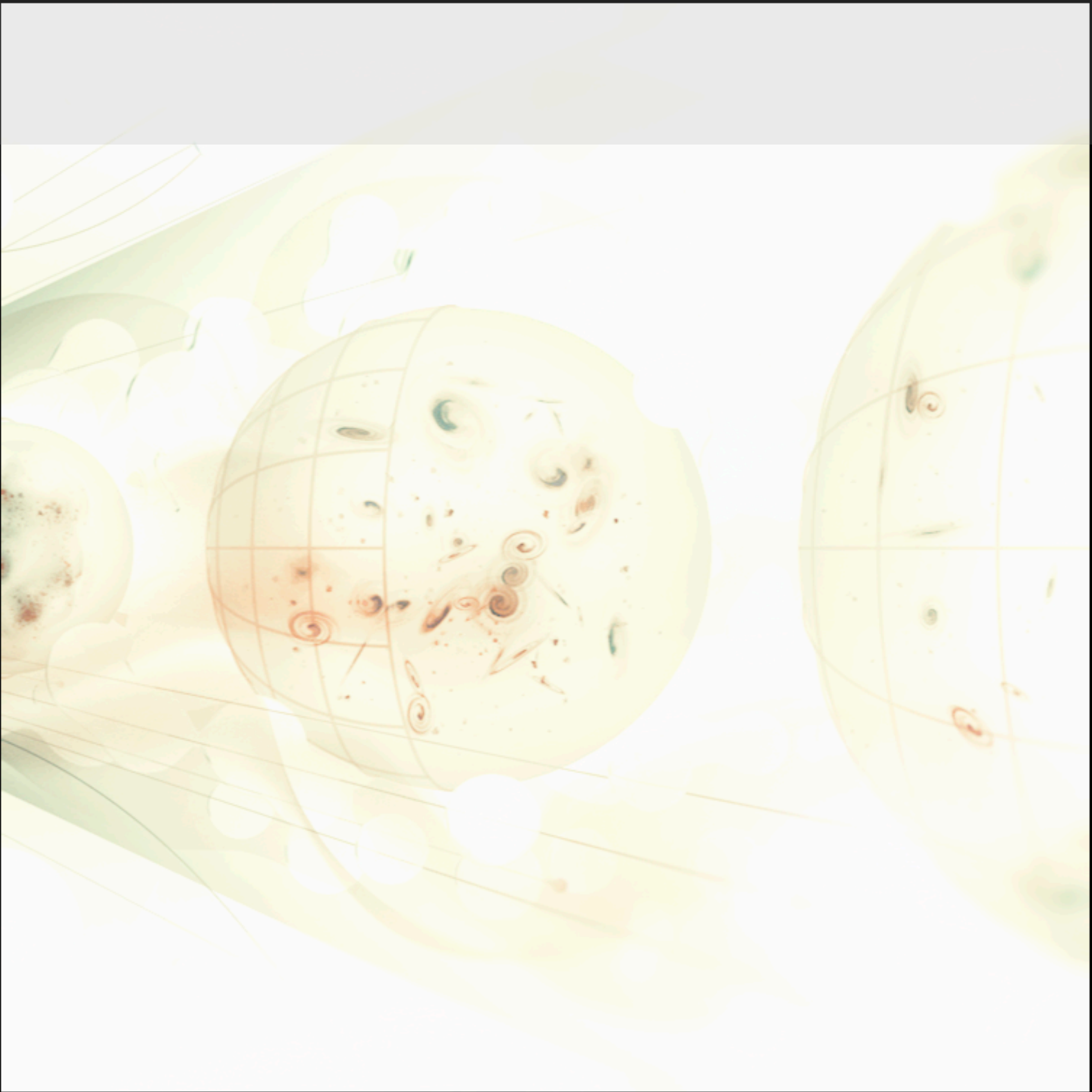
**Reveal the Secrets of
the Higgs Boson**



**Explore
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**Search for Direct Evidence
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**Pursue Quantum Imprints
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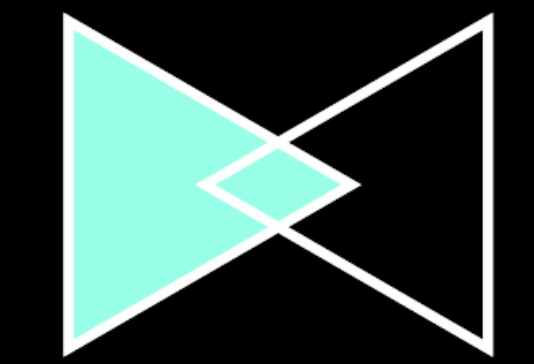


**Illuminate
the
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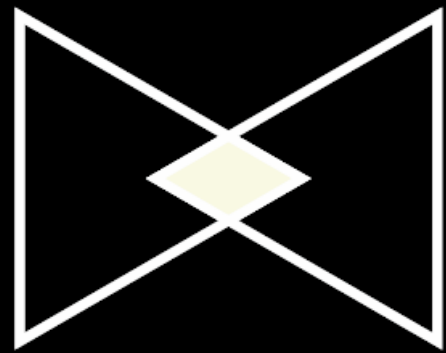
**Determine the Nature
of Dark Matter**

**Understand What Drives
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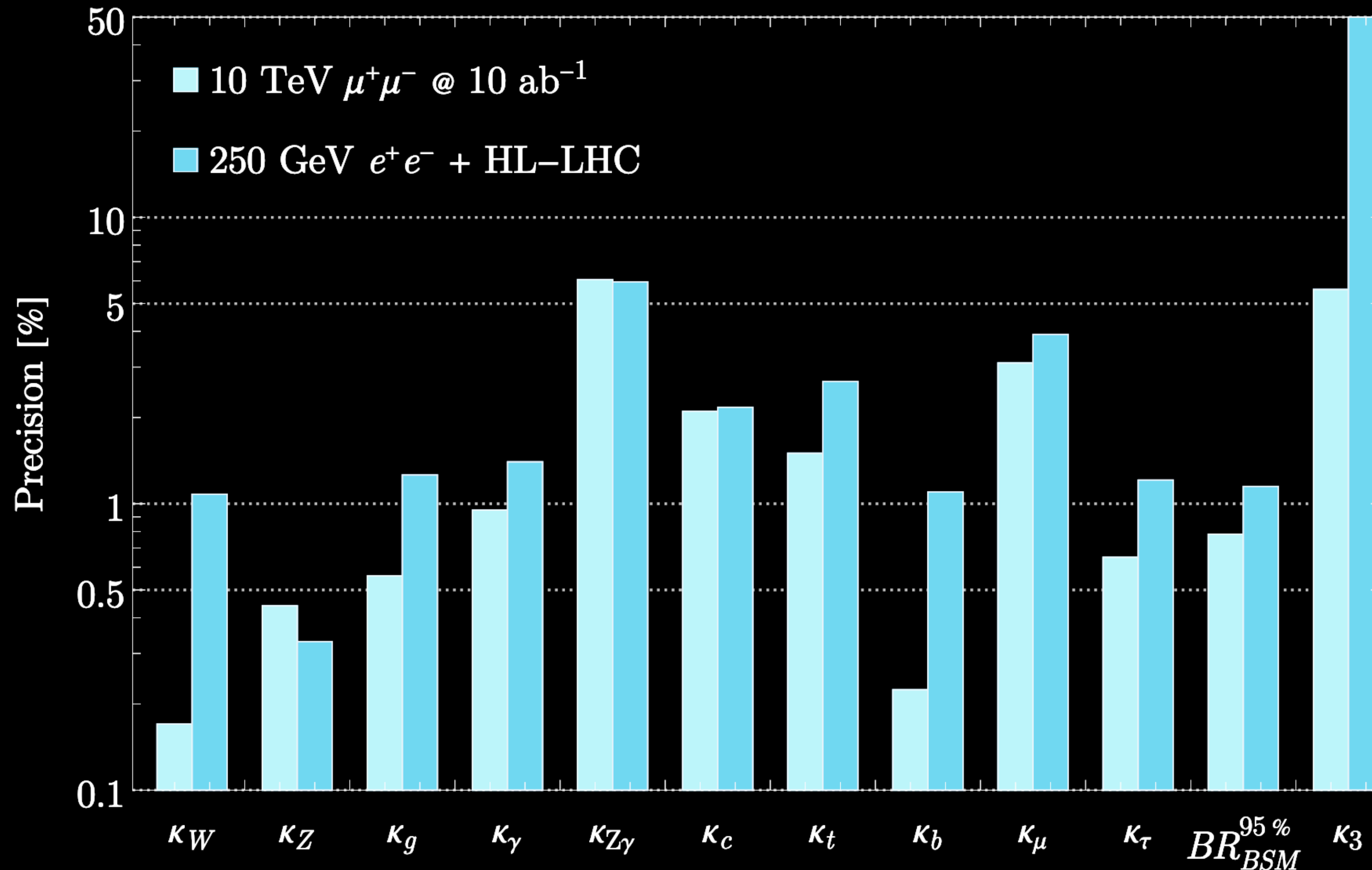
Secrets of the Higgs



Reveal the Secrets of
the Higgs Boson

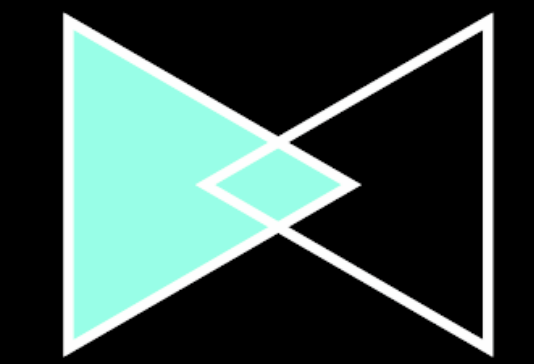


Pursue Quantum
Imprints of New
Phenomena

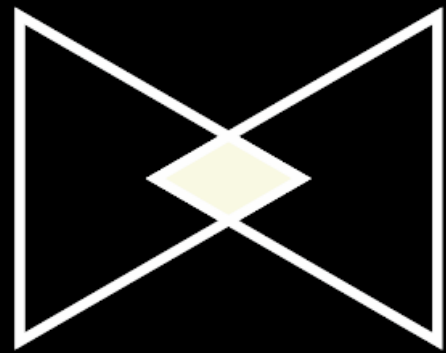


[Forslund & Meade, 2308.02633]

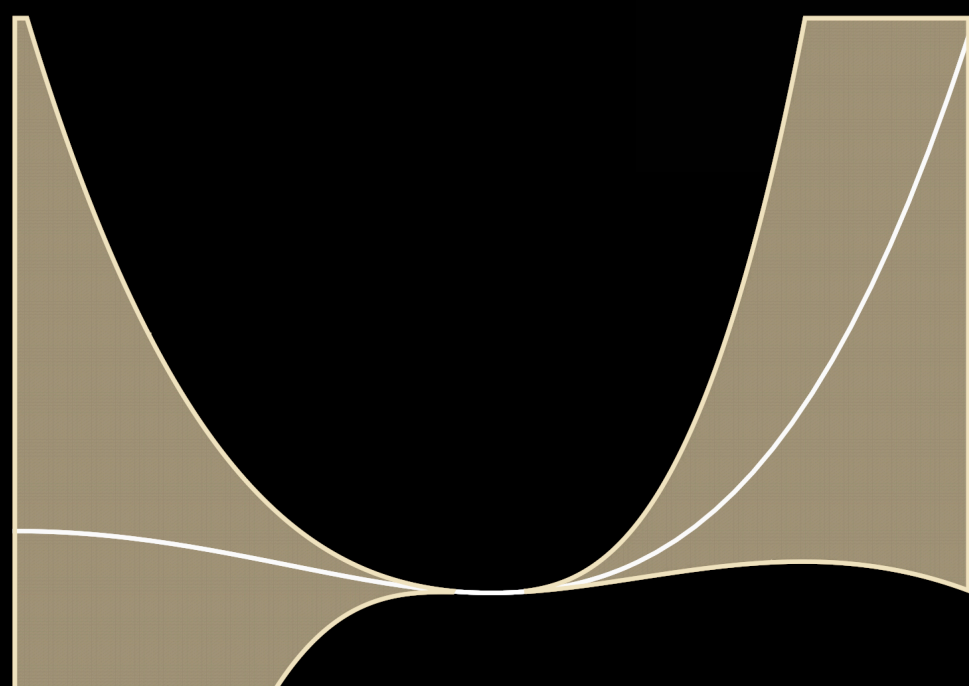
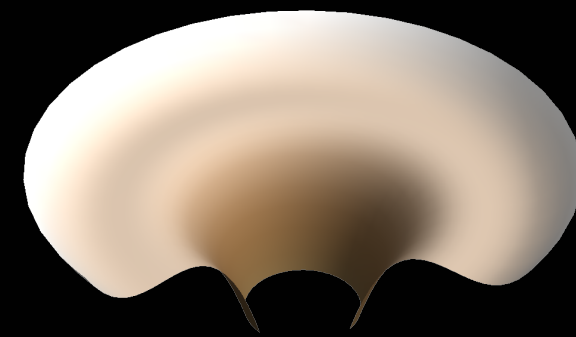
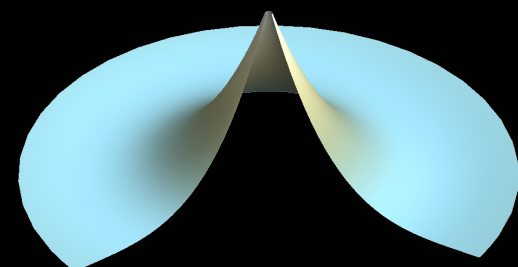
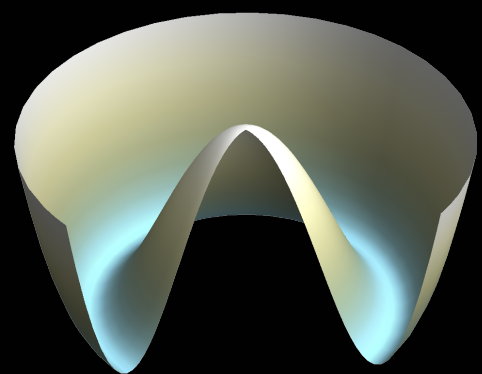
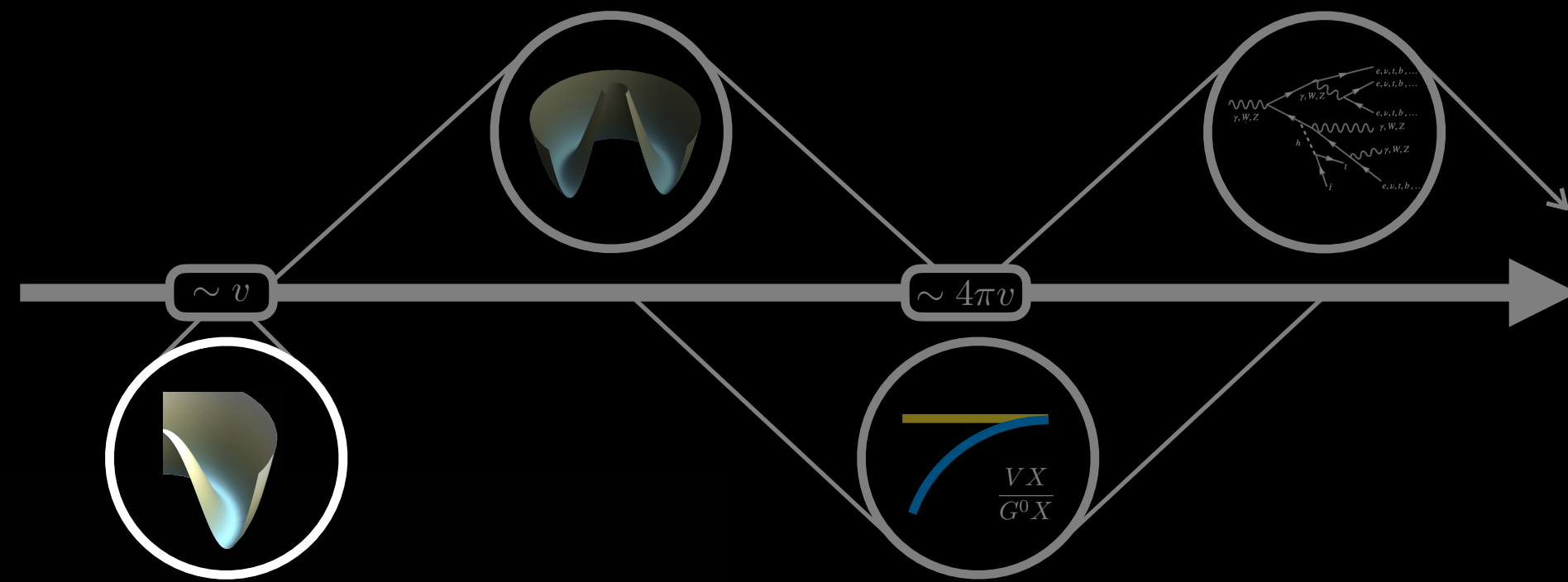
Electroweak Breaking



Reveal the Secrets of the Higgs Boson



Pursue Quantum Imprints of New Phenomena

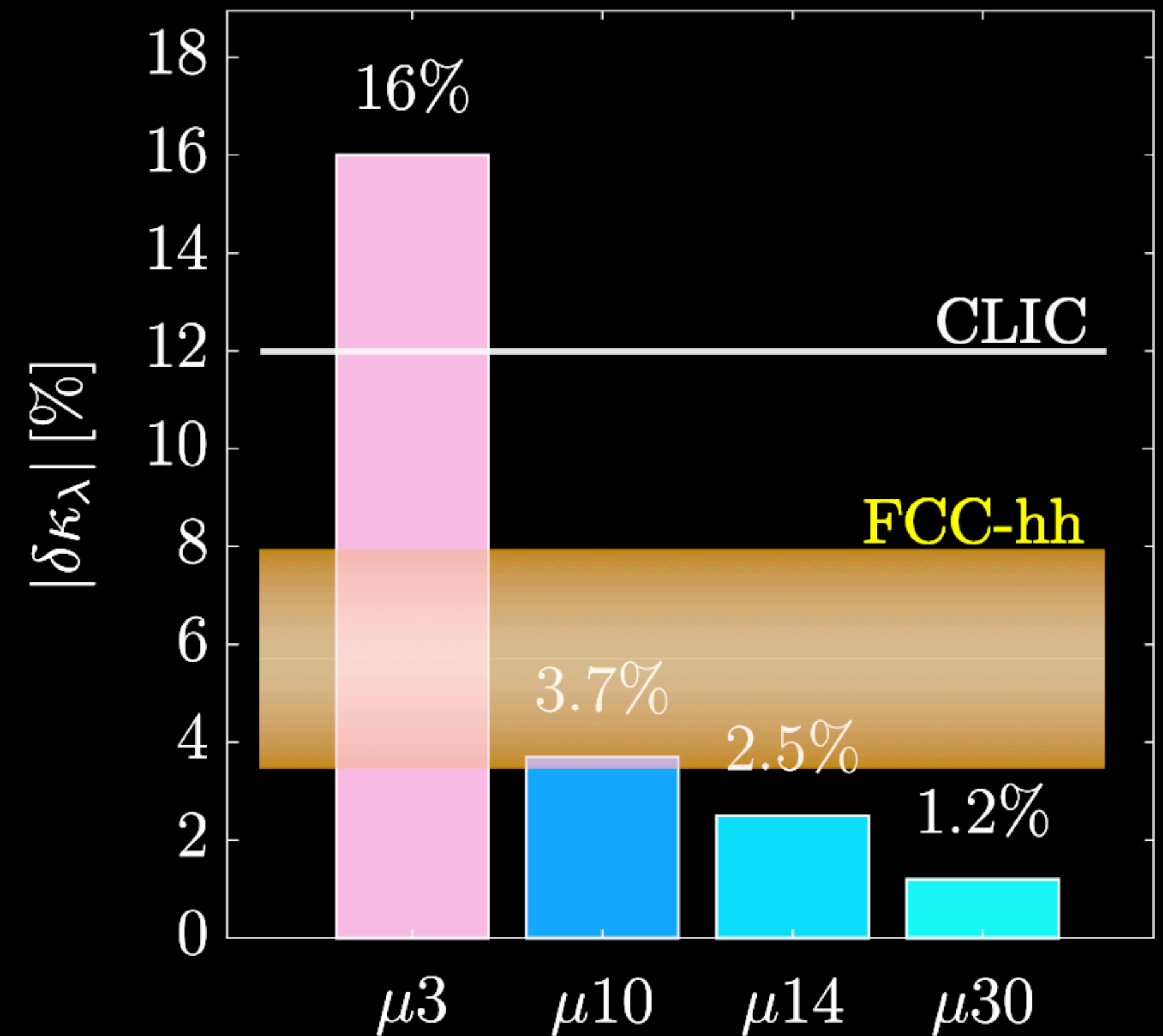


LHC (now)

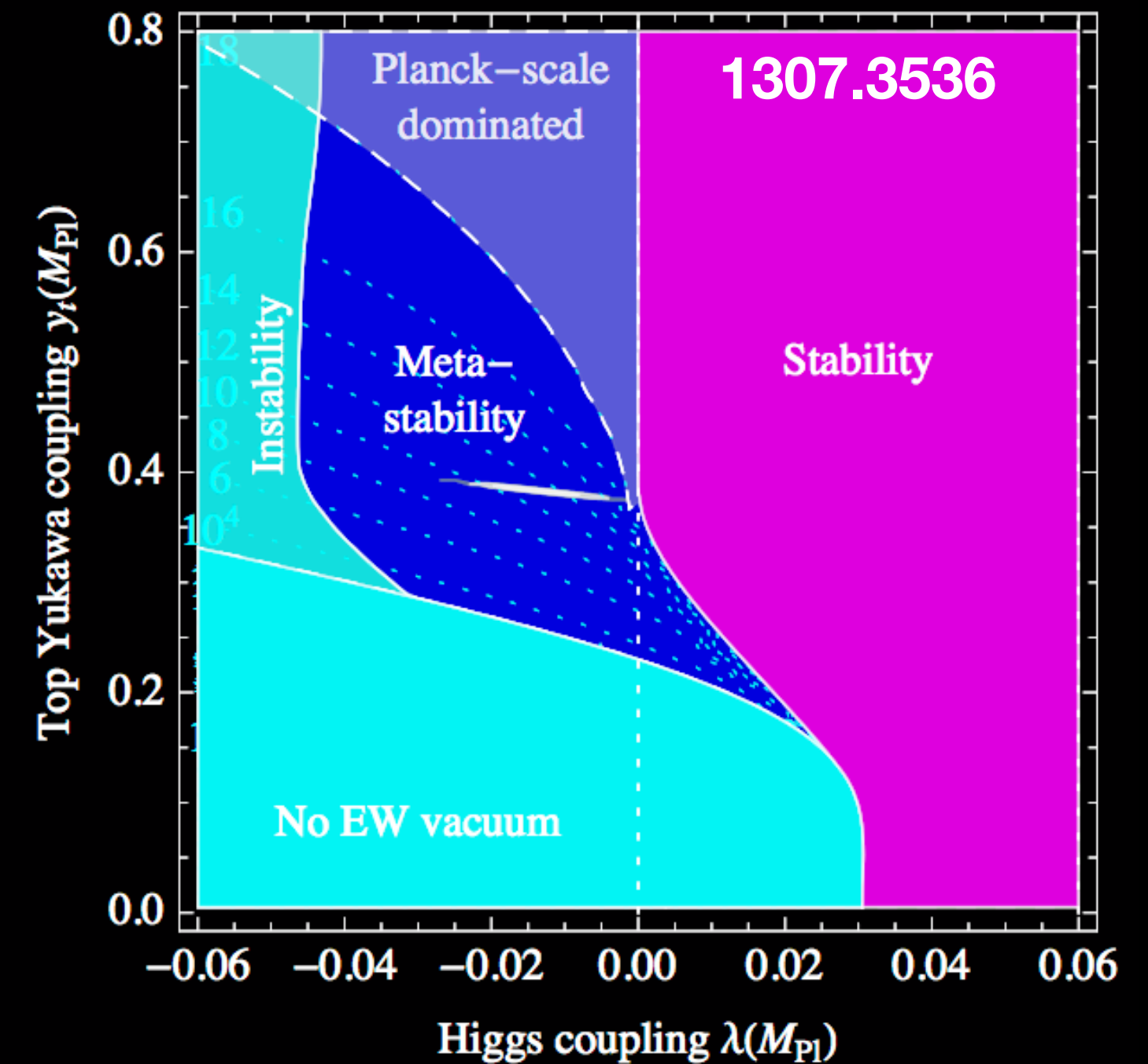
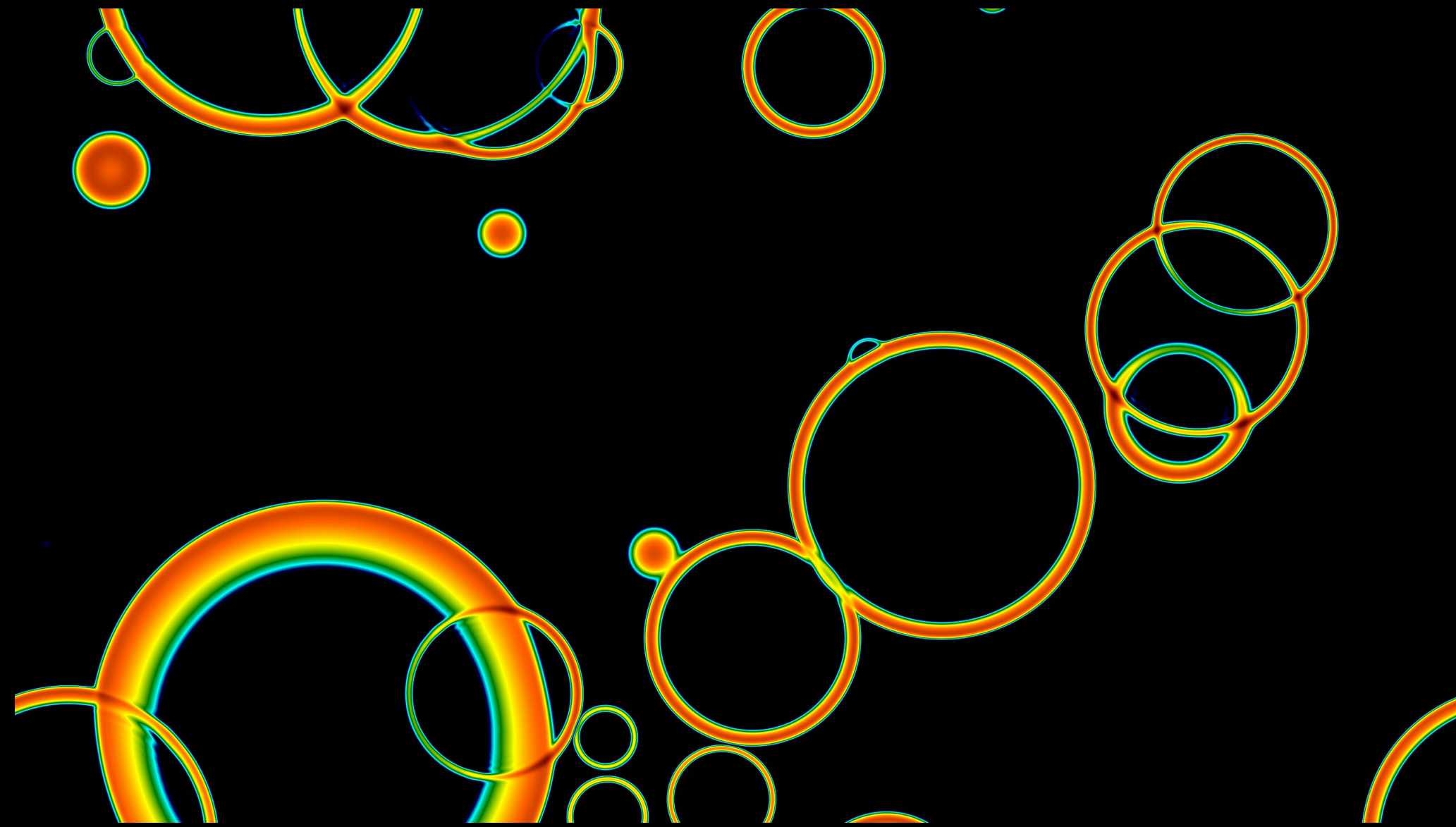


μC (10 TeV)

[Accettura et al. 2303.08533]

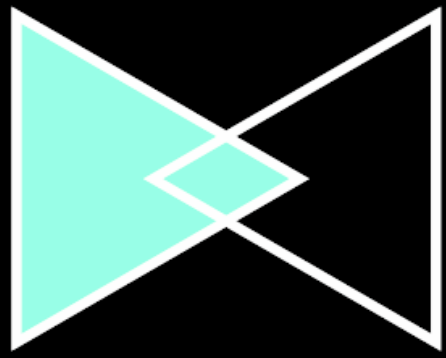


The birth and death of the Universe?



First-order electroweak phase transition?

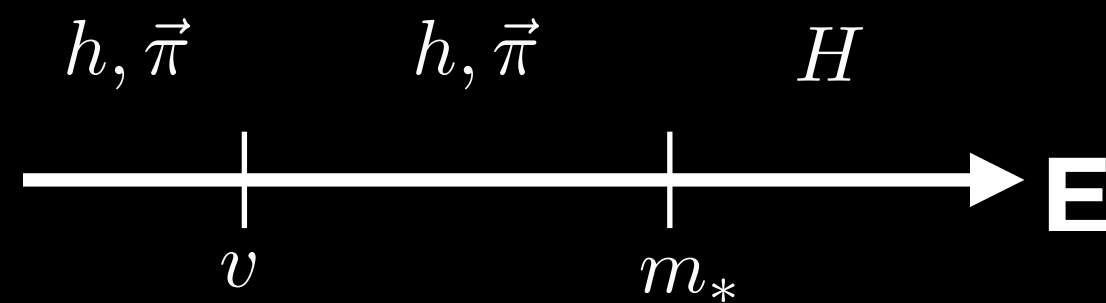
Vacuum stability?



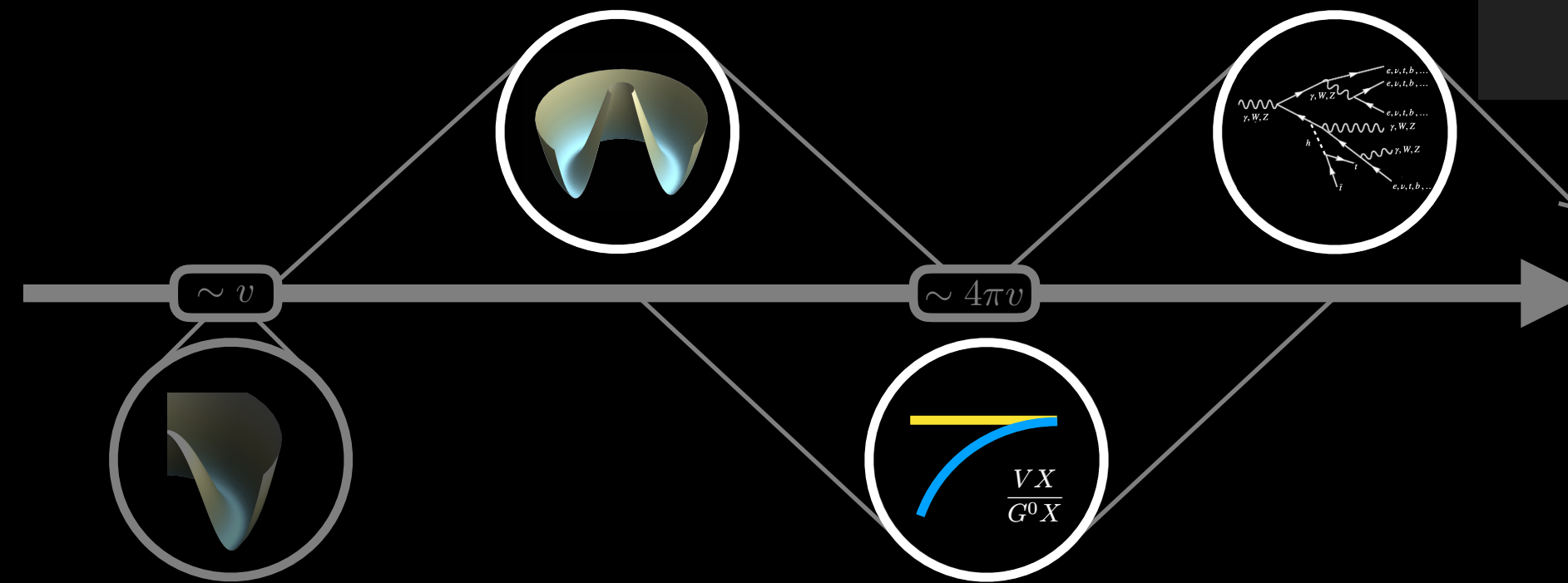
Reveal the Secrets of the Higgs Boson

Electroweak symmetry?:

Local EFT of the Higgs only has EWK symmetry if no extra EWSB or new particles acquiring most mass from Higgs. Fully covered by 10 TeV μC .



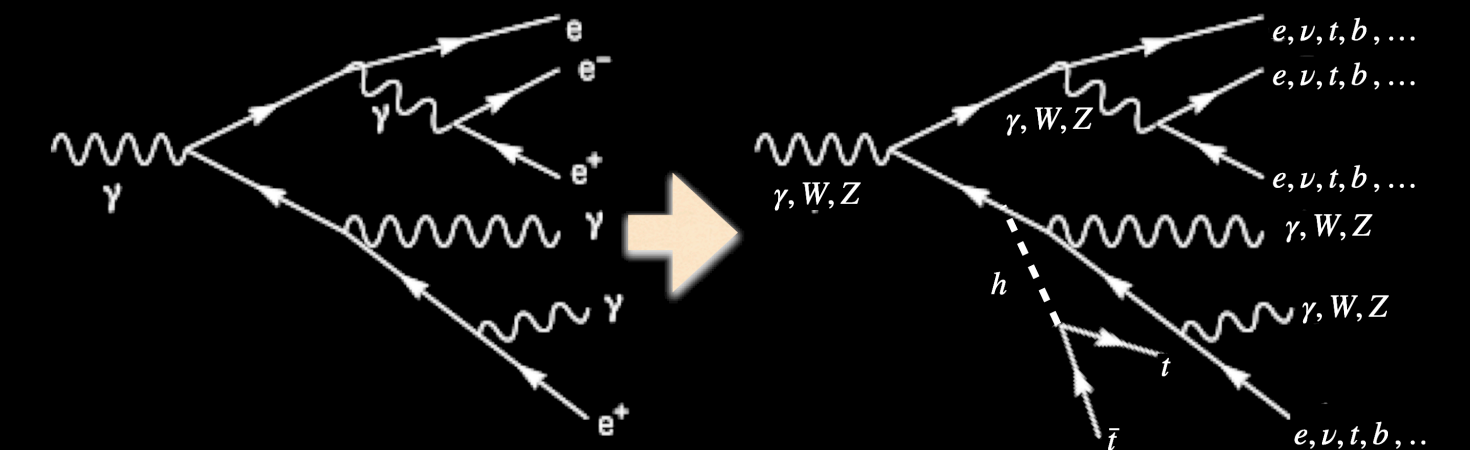
[Banta, Cohen, NC, Lu, Sutherland, 2110.02967]



Electroweak radiation:

Sudakov suppression of non-emission probability becomes significant @ 10 TeV...

$$\exp \left[-\text{Casimir} \times \frac{g^2}{16\pi^2} \log^2 \left(\frac{E_{\text{cm}}^2}{m_W^2} \right) \right] \approx \exp [-1]$$

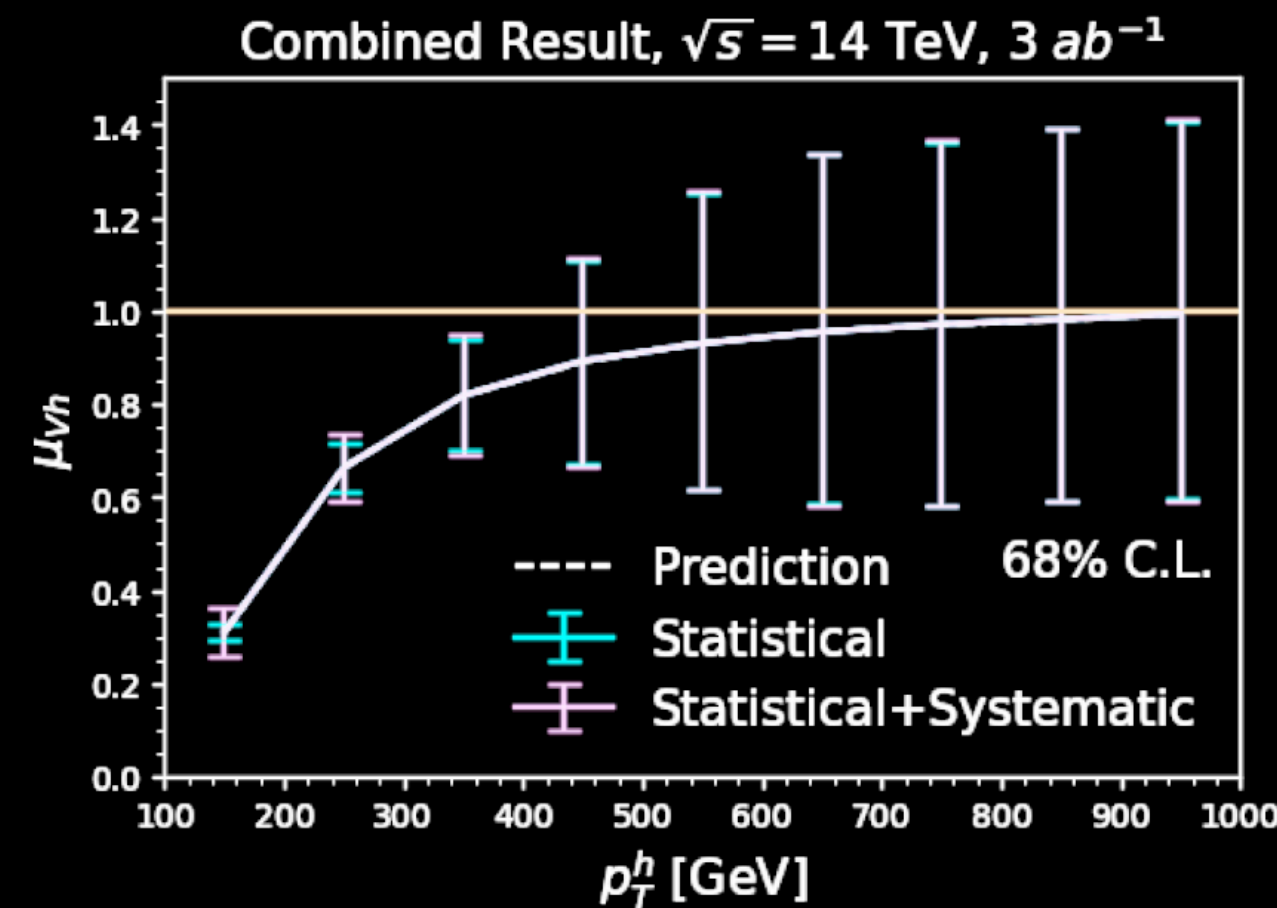


[Wulzer; Chen, Glioti, Rattazzi, Ricci, Wulzer 2202.10509; Nardi, Ricci, Wulzer 2405.08220]

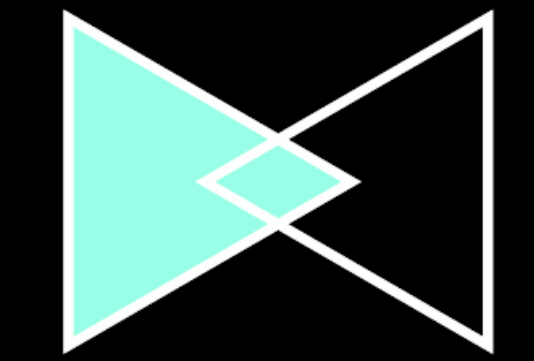
Electroweak restoration:

Experimentally demonstrate Goldstone equivalence

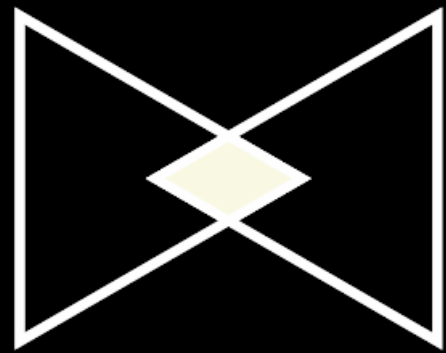
[Huang, Lane, Lewis, Liu, 2012.00774]



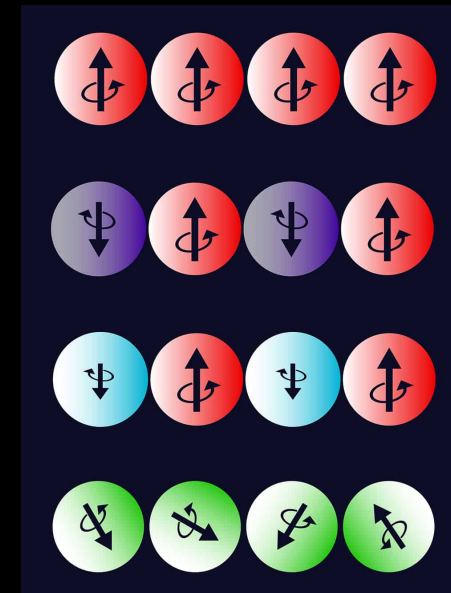
Predict the Higgs Mass



Reveal the Secrets of the Higgs Boson

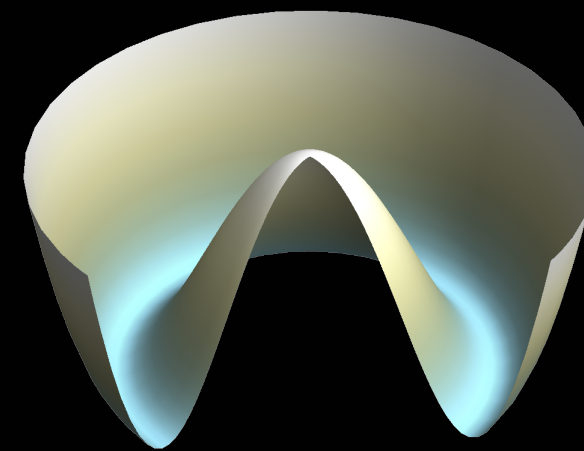
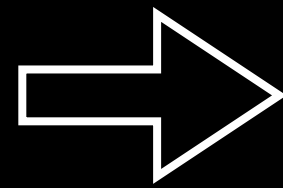


Search for Direct Evidence of New Particles

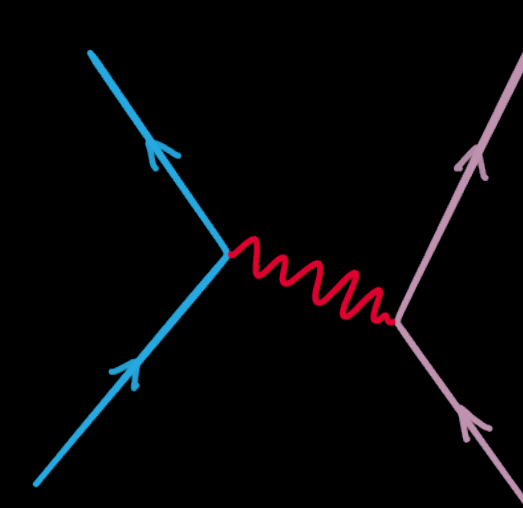
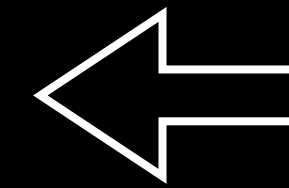


High-Tc Superconductors

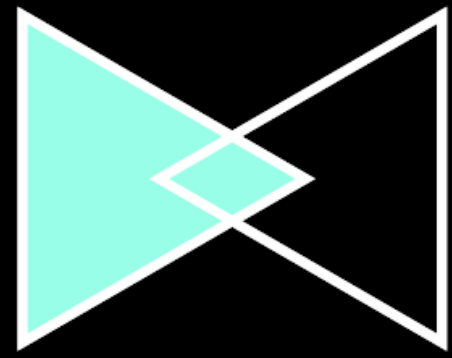
A superconducting analogy:



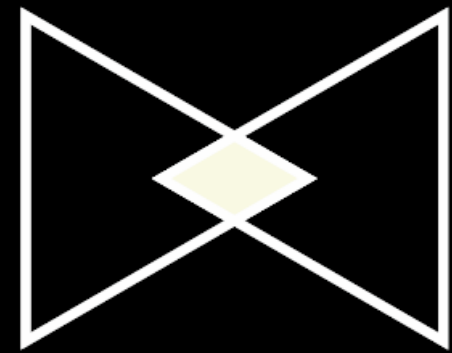
Ginzburg-Landau Theory



Low-Tc Superconductors (BCS)



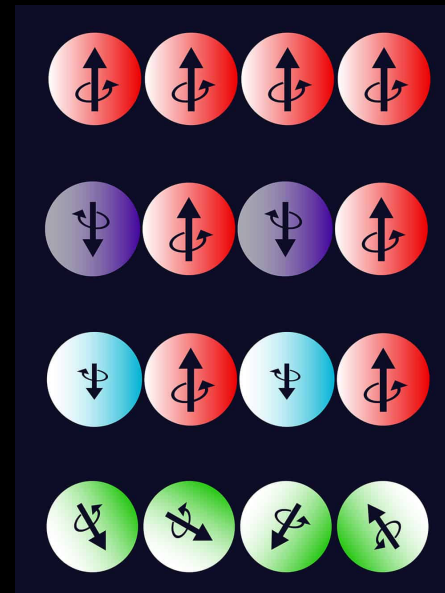
Reveal the Secrets of the Higgs Boson



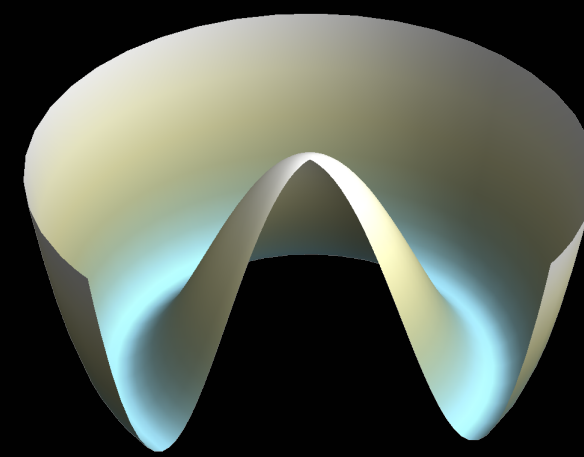
Search for Direct Evidence of New Particles

Predict the Higgs Mass

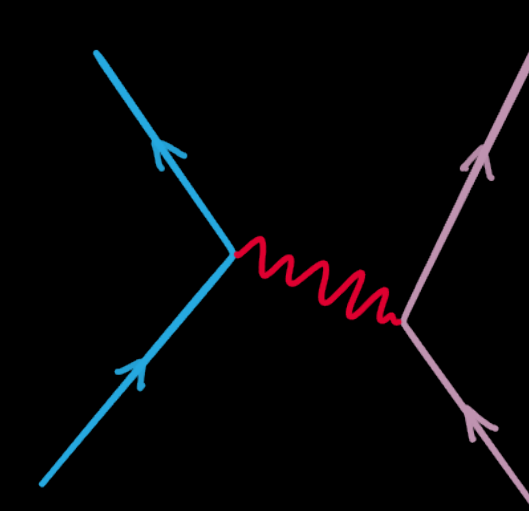
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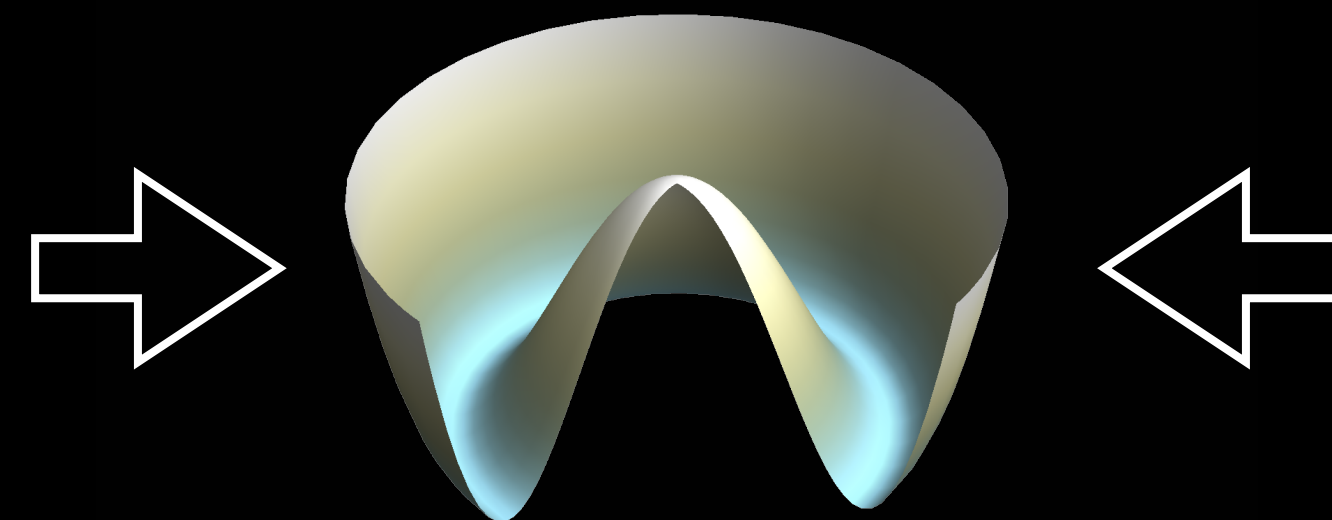
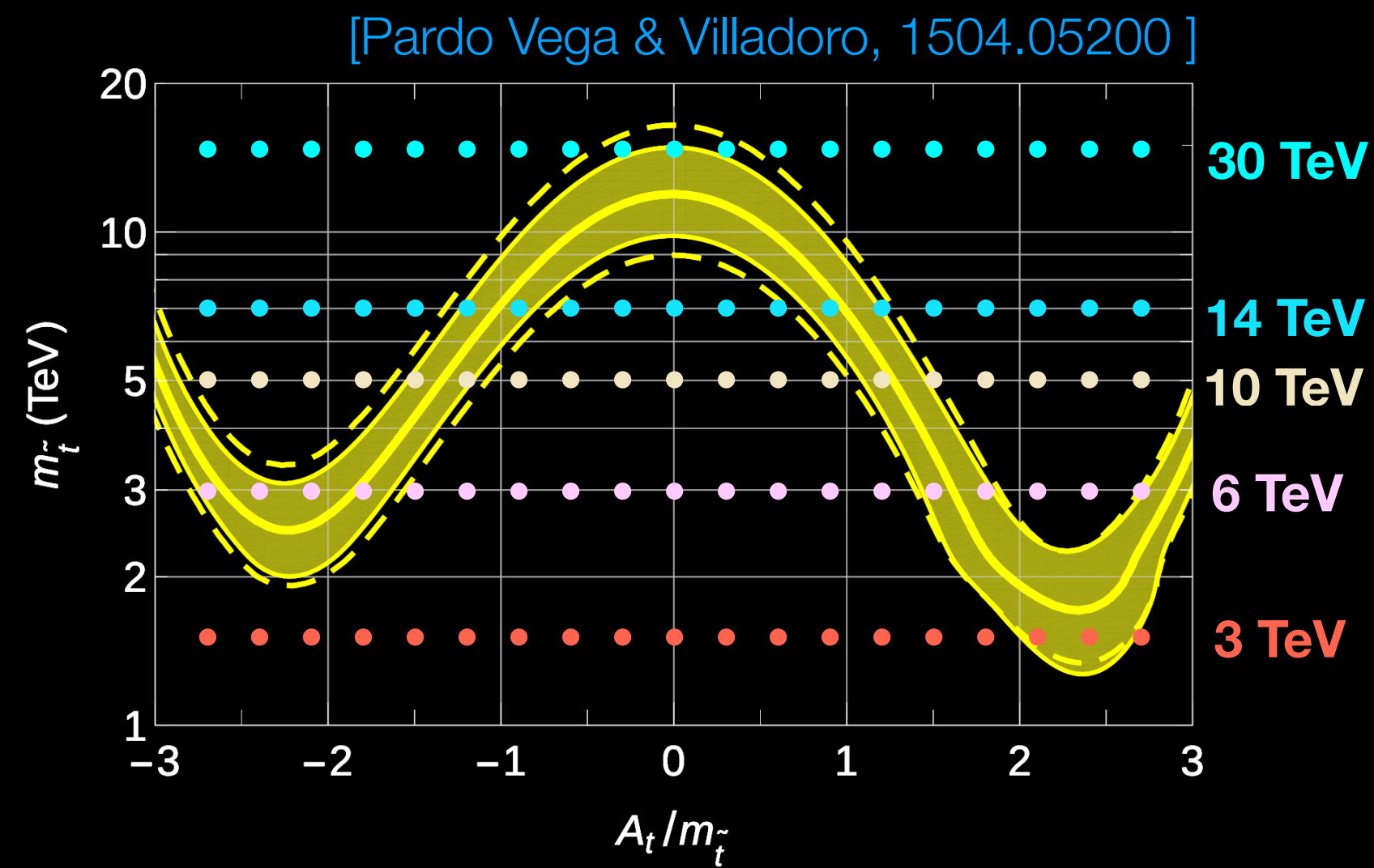
High-Tc Superconductors



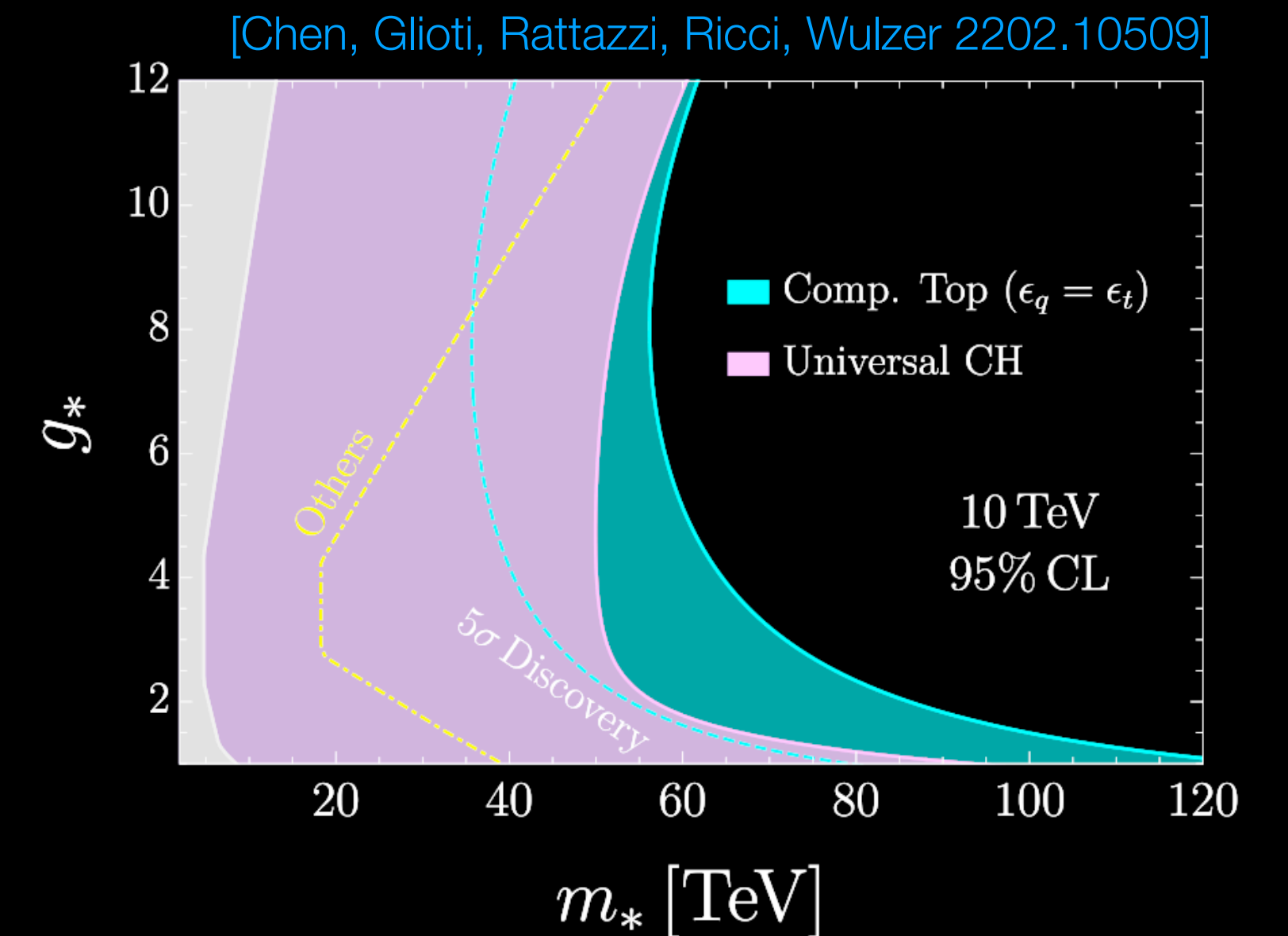
Ginzburg-Landau Theory



Low-Tc Superconductors (BCS)



Higgs Potential

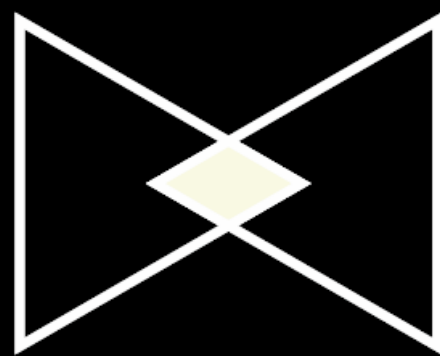


Origins of Flavor

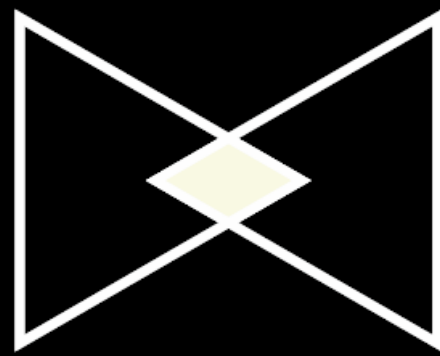
First high-energy accelerator to primarily collide second-generation fermions.

Direct access to hypothetical new particles associated with flavor structure

Indirect access to flavor structure via lepton flavor violating operators

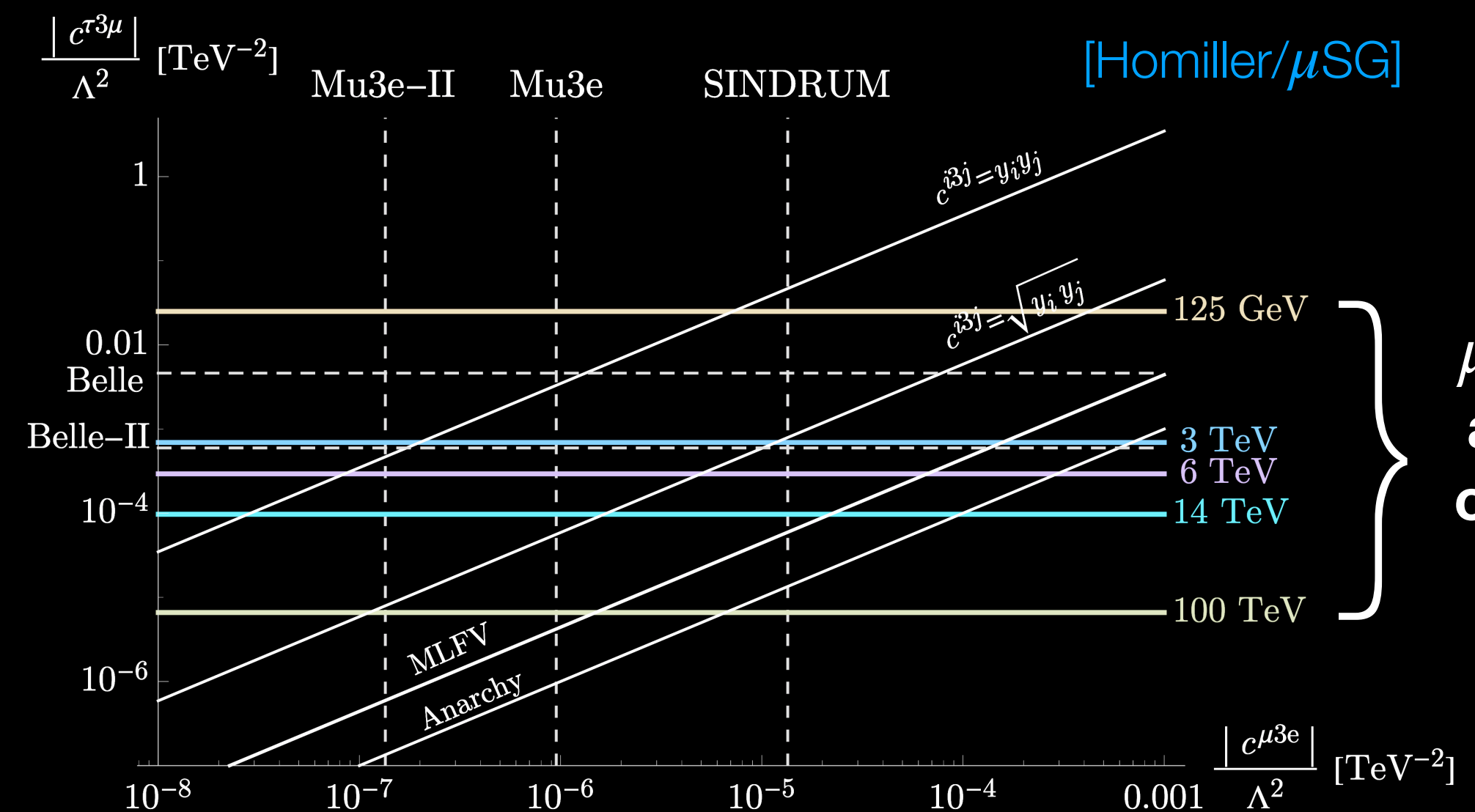
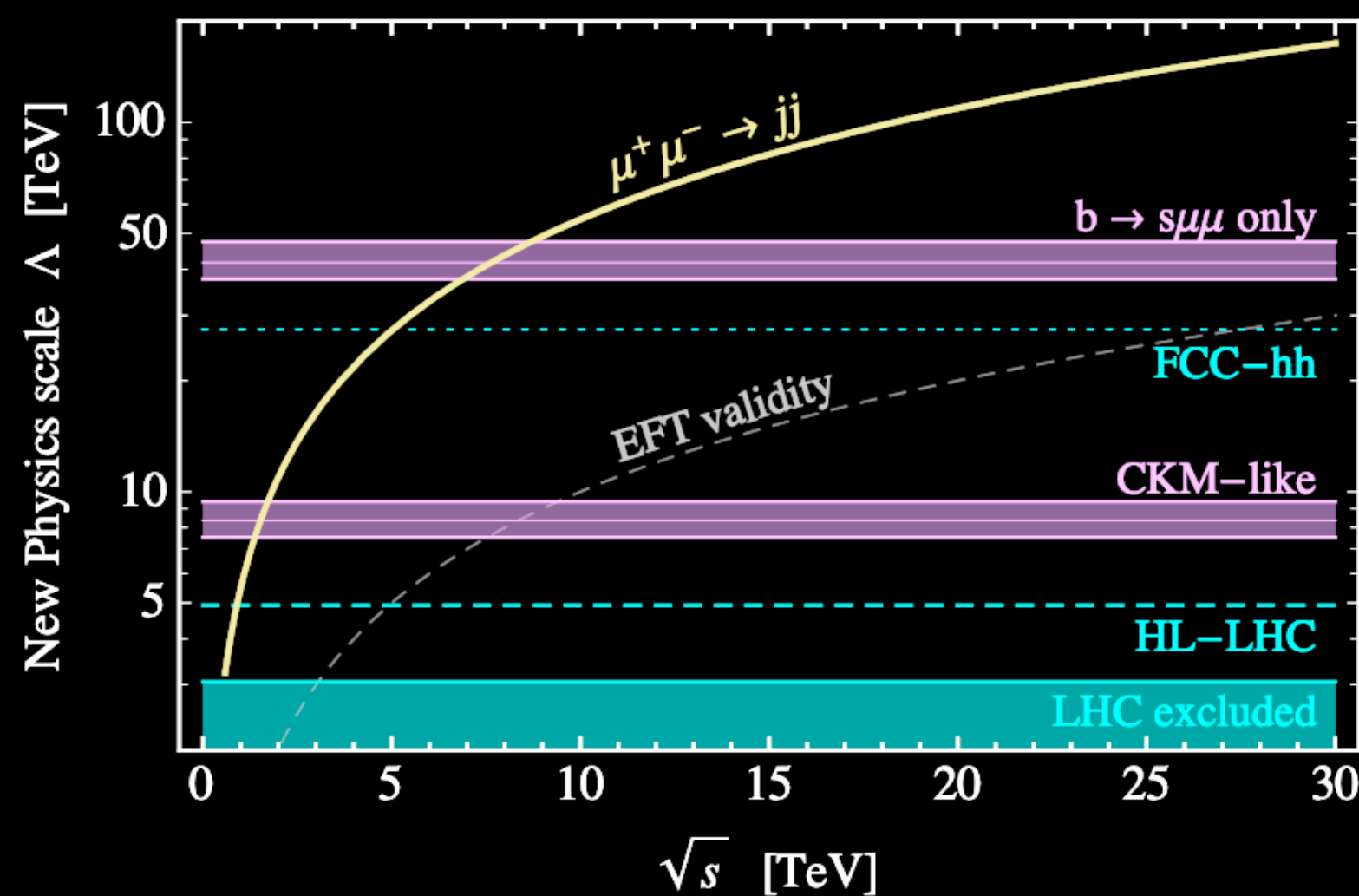


Pursue Quantum Imprints of New Phenomena



Search for Direct Evidence of New Particles

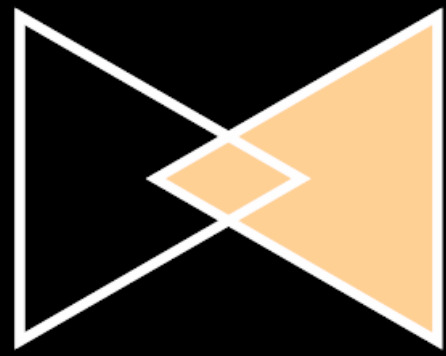
[IMCC Muon Collider Physics Summary]



From $\mu\mu \rightarrow \mu\tau$ at muon colliders, 3 TeV ~ Belle-II

An outstanding probe of flavor anomalies, indicative of complementarity w/ future signs of flavor violation.

[Huang, Queiroz, Rodejohann, 2101.04956; Huang, Sana, Queiroz, Rodejohann, 2103.01617, Asadi, Capdevilla, Cesarotti, Homiller 2104.05720, ...]



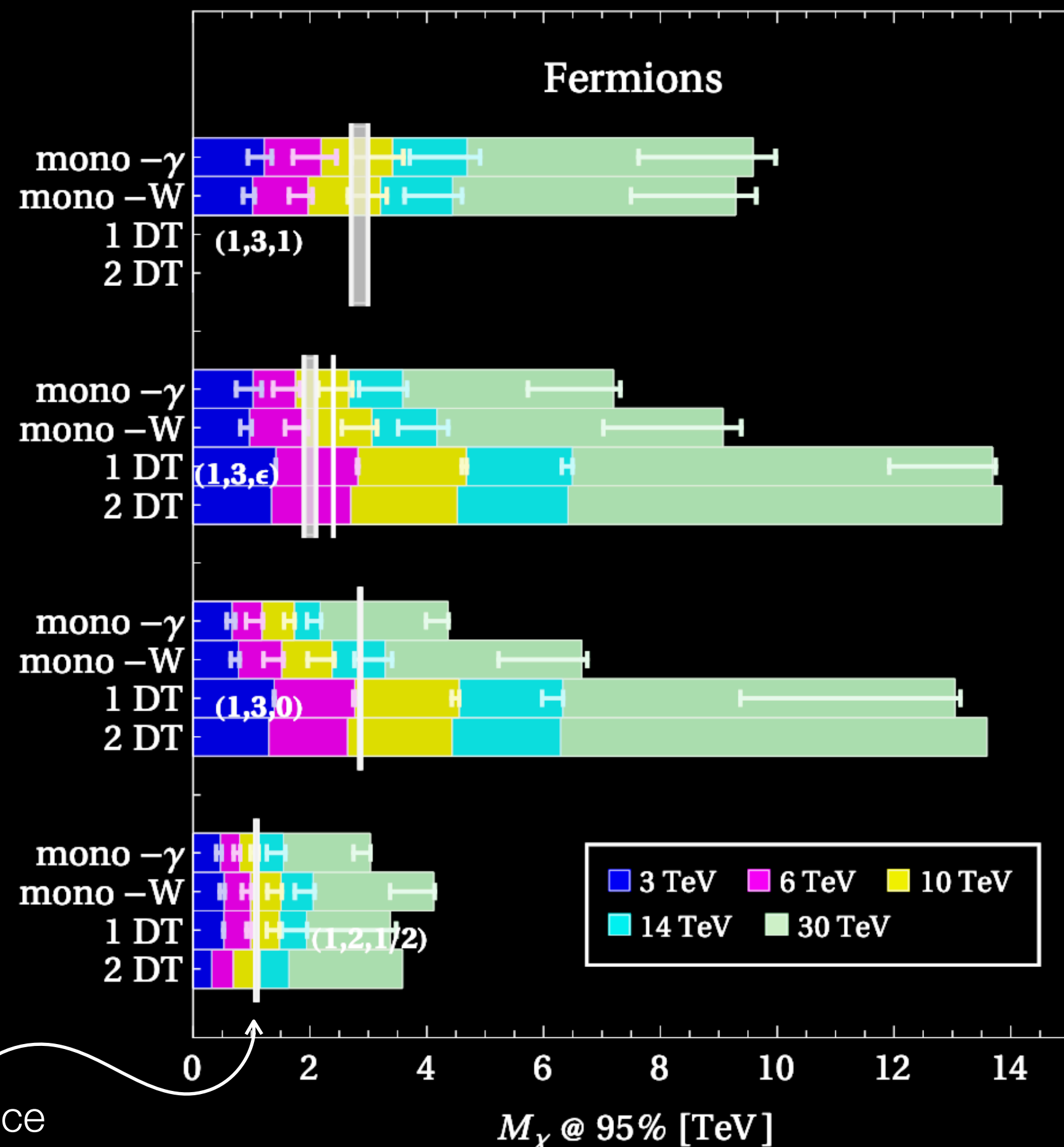
Determine the Nature
of Dark Matter

Nature of Dark Matter

“Minimal dark matter”

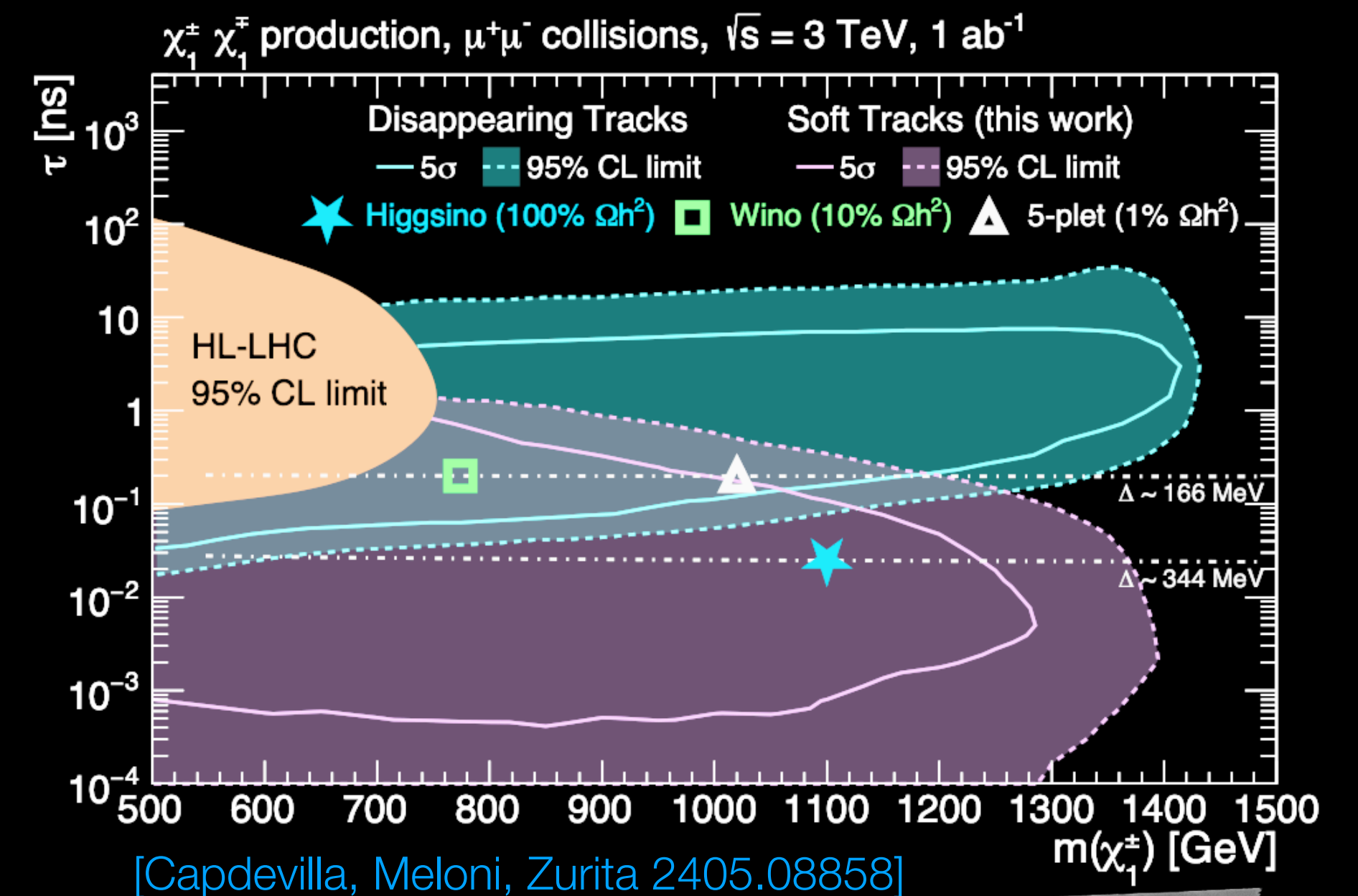
(Electroweak multiplet w/ neutral lightest particle)

[“Towards a Muon Collider,”
Accettura et al.
2303.08533 &
Bottaro et al.
2205.04486,]
see also [Han,
Liu, Wang,
Wang,
2009.11287,
Capdevilla,
Meloni,
Simoniello, Zurita
2102.11292;
Bottaro et al.
2107.09688]



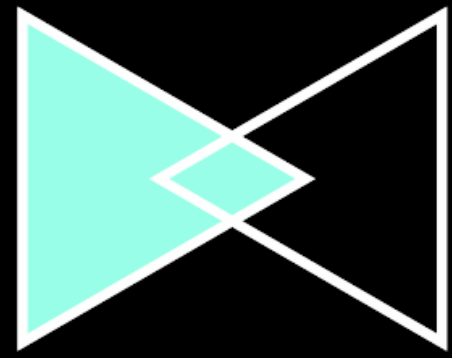
Target set by DM abundance
(WIMP miracle)

*Electroweak doublet (“higgsino”)
thermal relic plausibly discoverable
at 3 TeV using soft tracks*



[Capdevilla, Meloni, Zurita 2405.08858]

See R. Capdevilla's talk

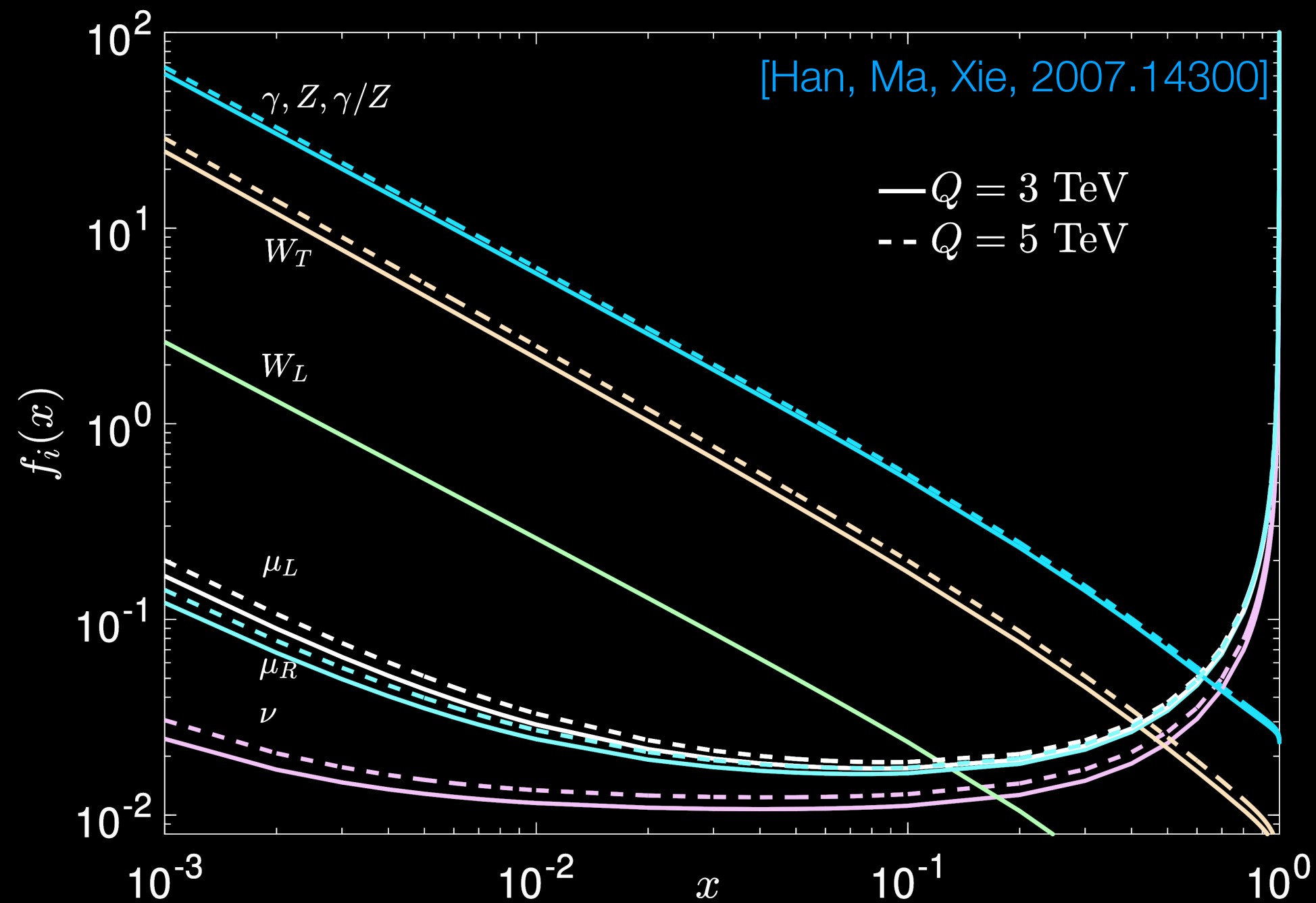


The Neutrino Sector

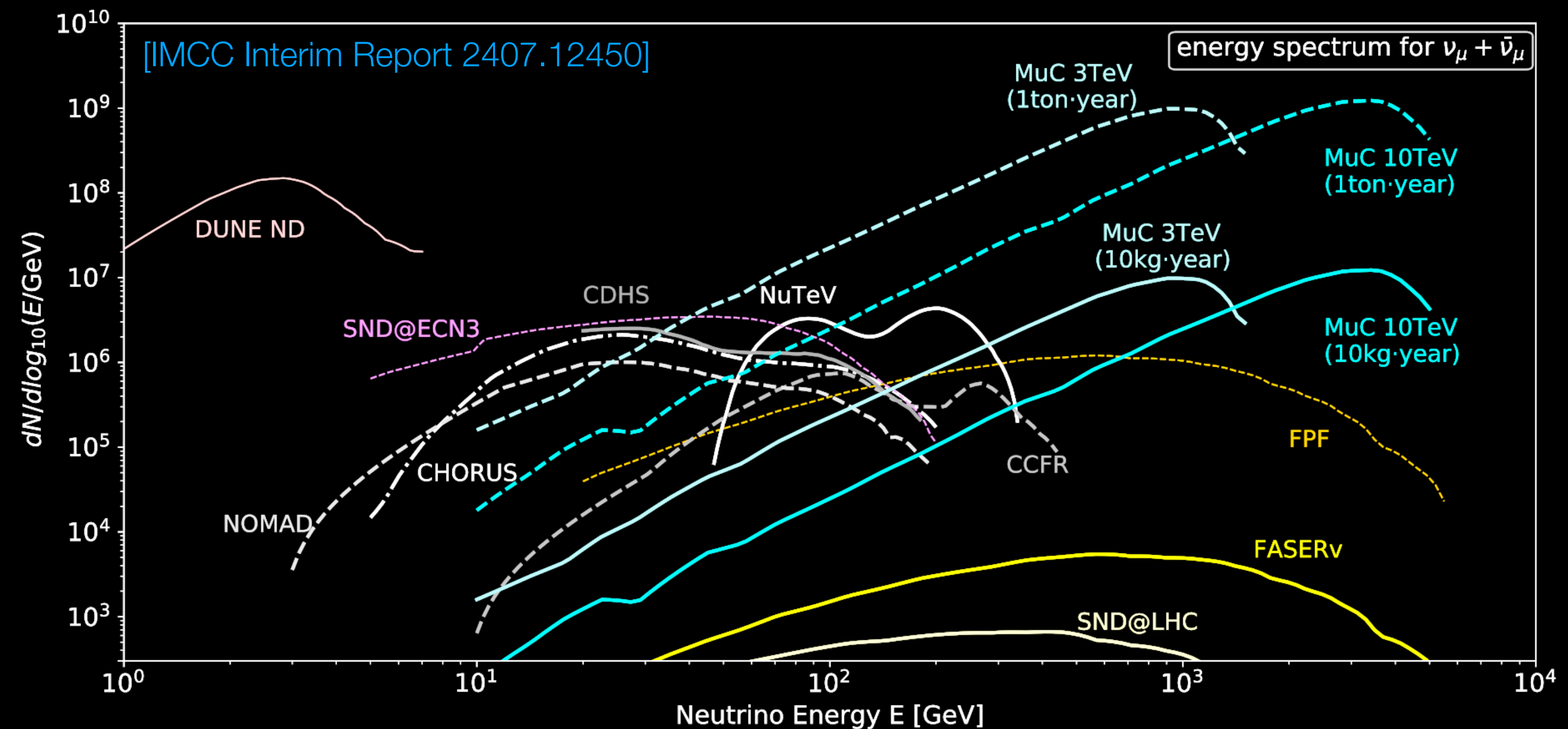
Elucidate the
Mysteries of Neutrinos

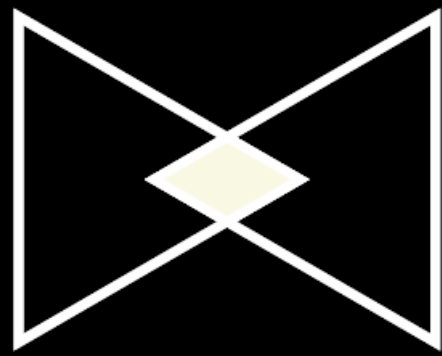
Beyond the familiar synergies between muon colliders & neutrino factories:

1. Opportunities from high-energy neutrinos at the interaction point



2. Opportunities from high-energy neutrinos at a forward detector





Search for Direct Evidence of New Particles

Dark Sectors

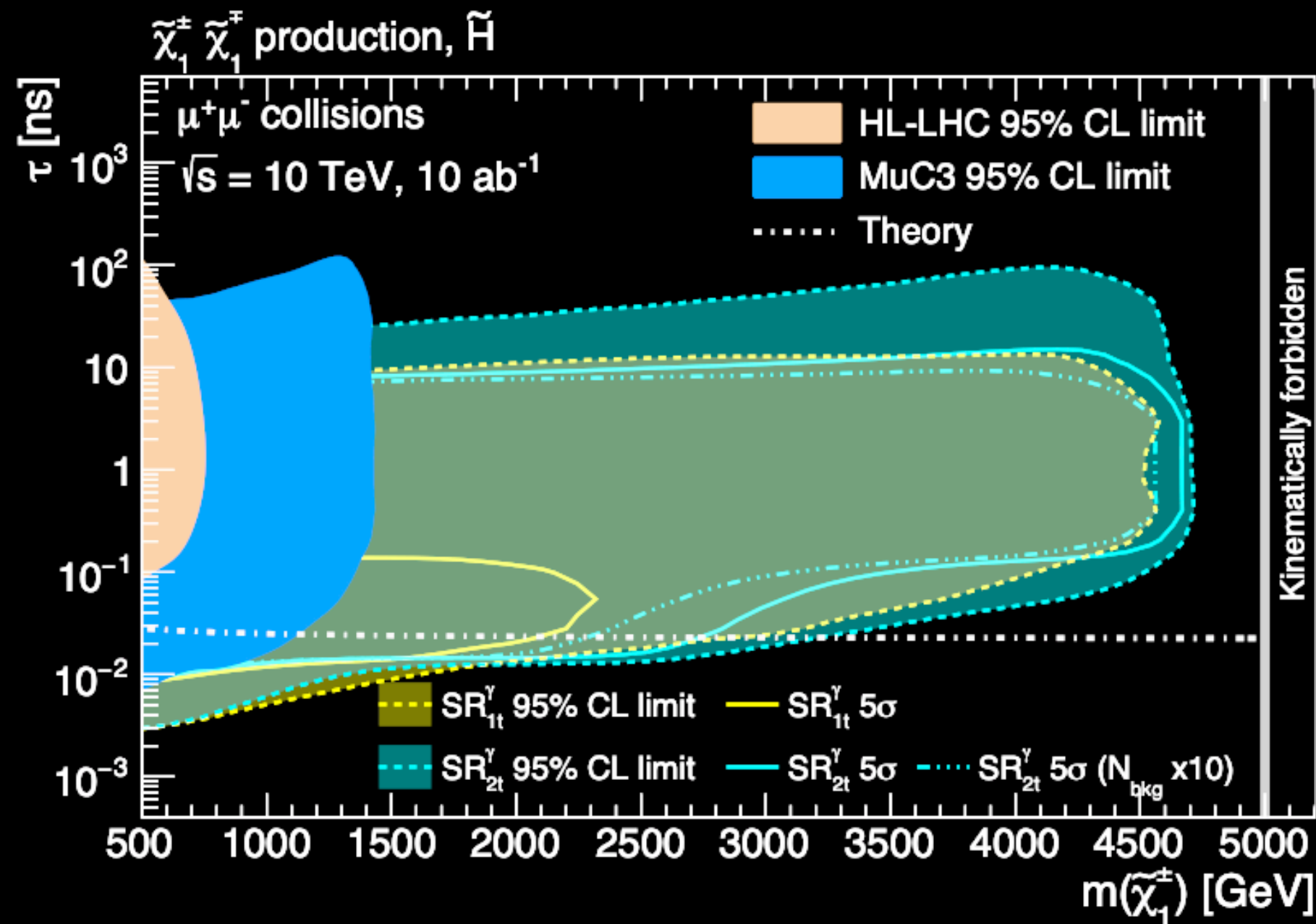
weak portal

$$g(W_\mu)^i_j \mathcal{O}_j$$

Higgs portal

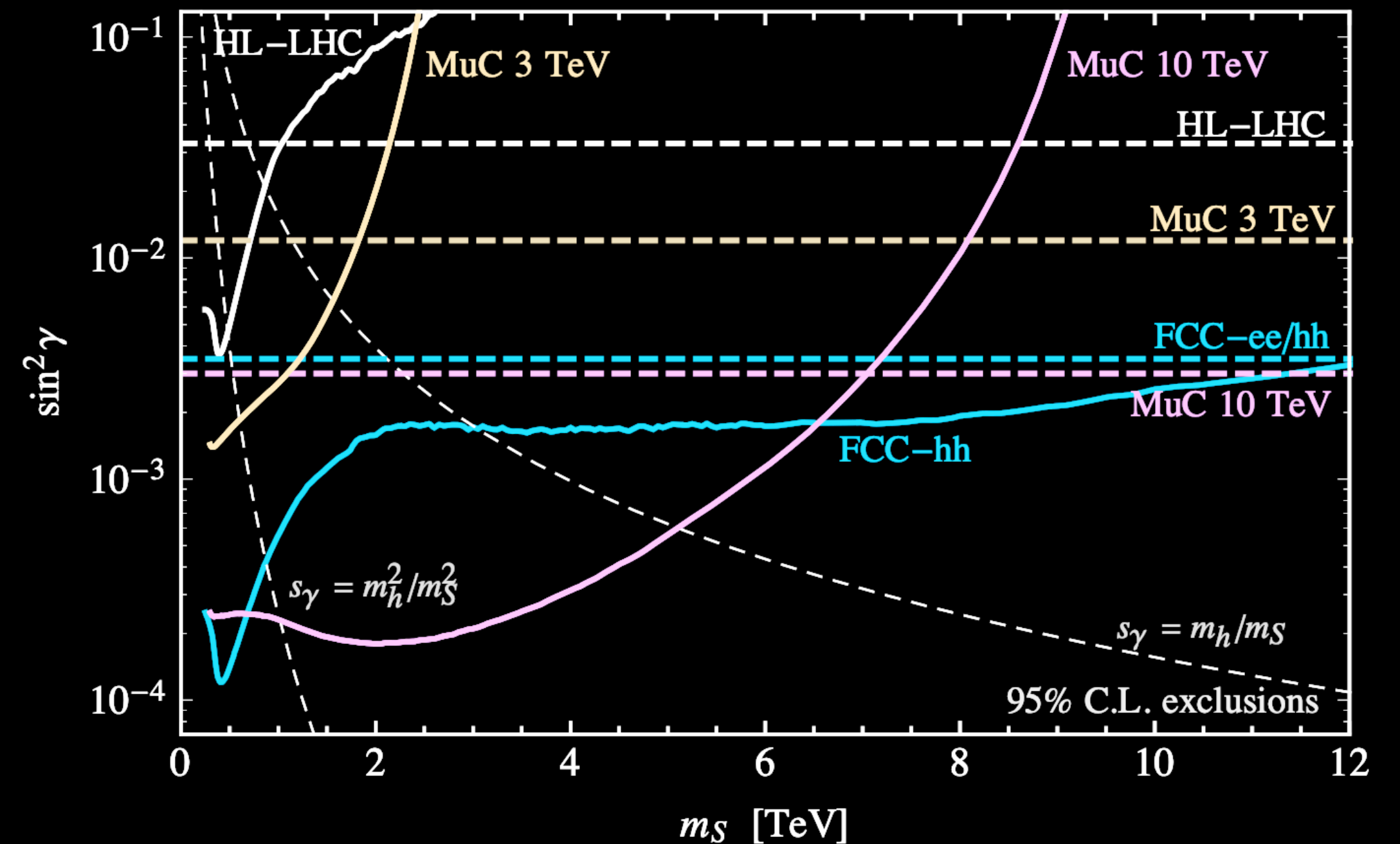
$$|H|^2 \mathcal{O}$$

Electroweak multiplets

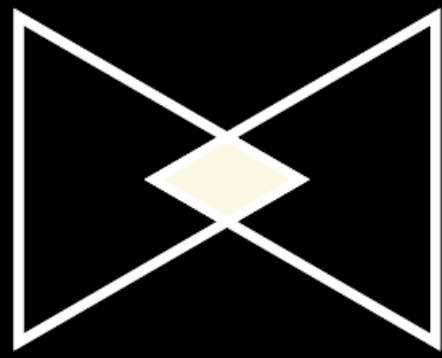


[Capdevilla, Meloni, Simoniello, Zurita 2102.11292]

Linearly mixed singlet scalar



[Buttazzo, Redigolo, Sala, Tesi, 1807.04743]



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Dark Sectors

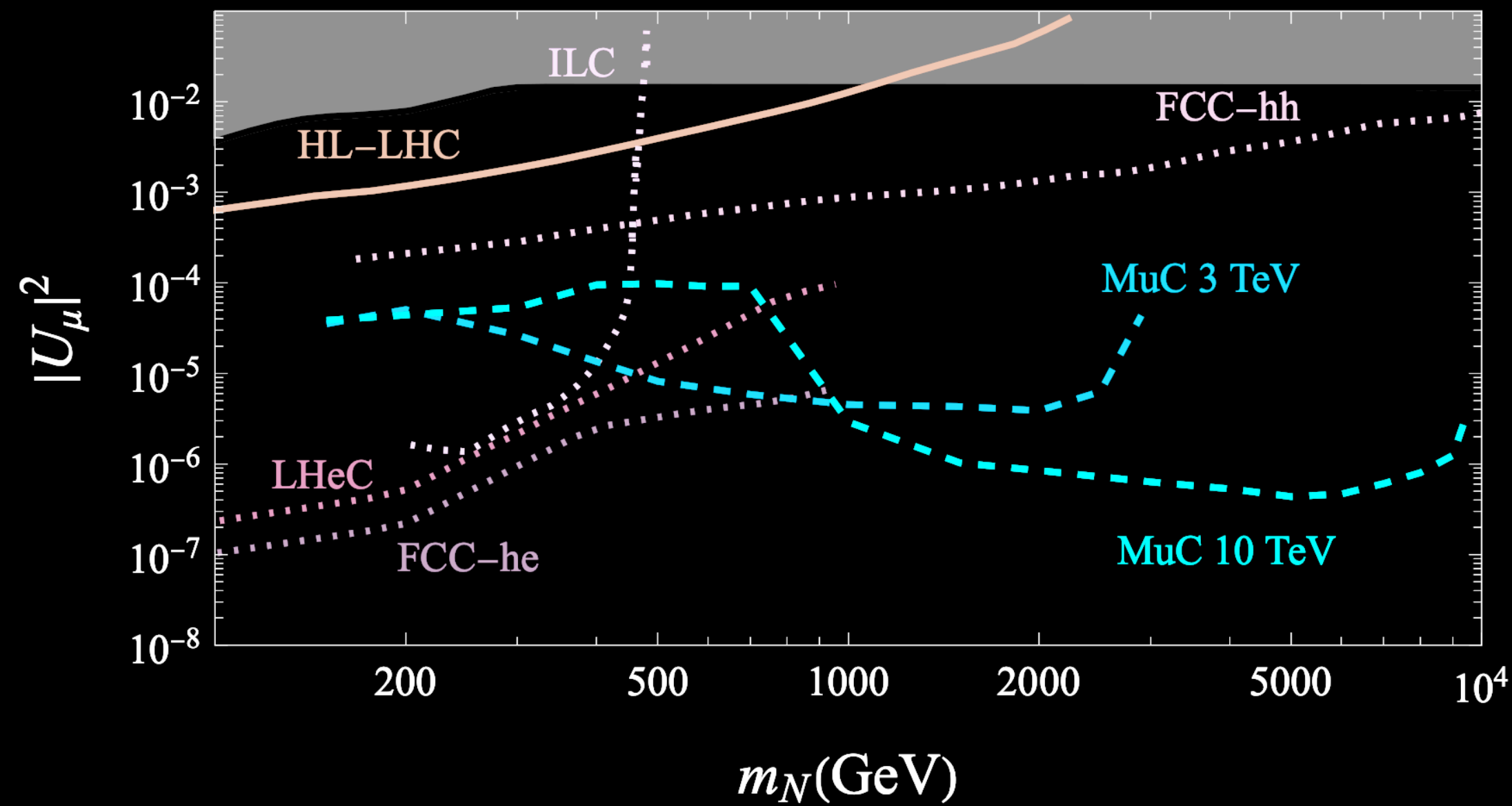
neutrino portal

$$HL^\alpha \mathcal{O}_\alpha$$

axion portal

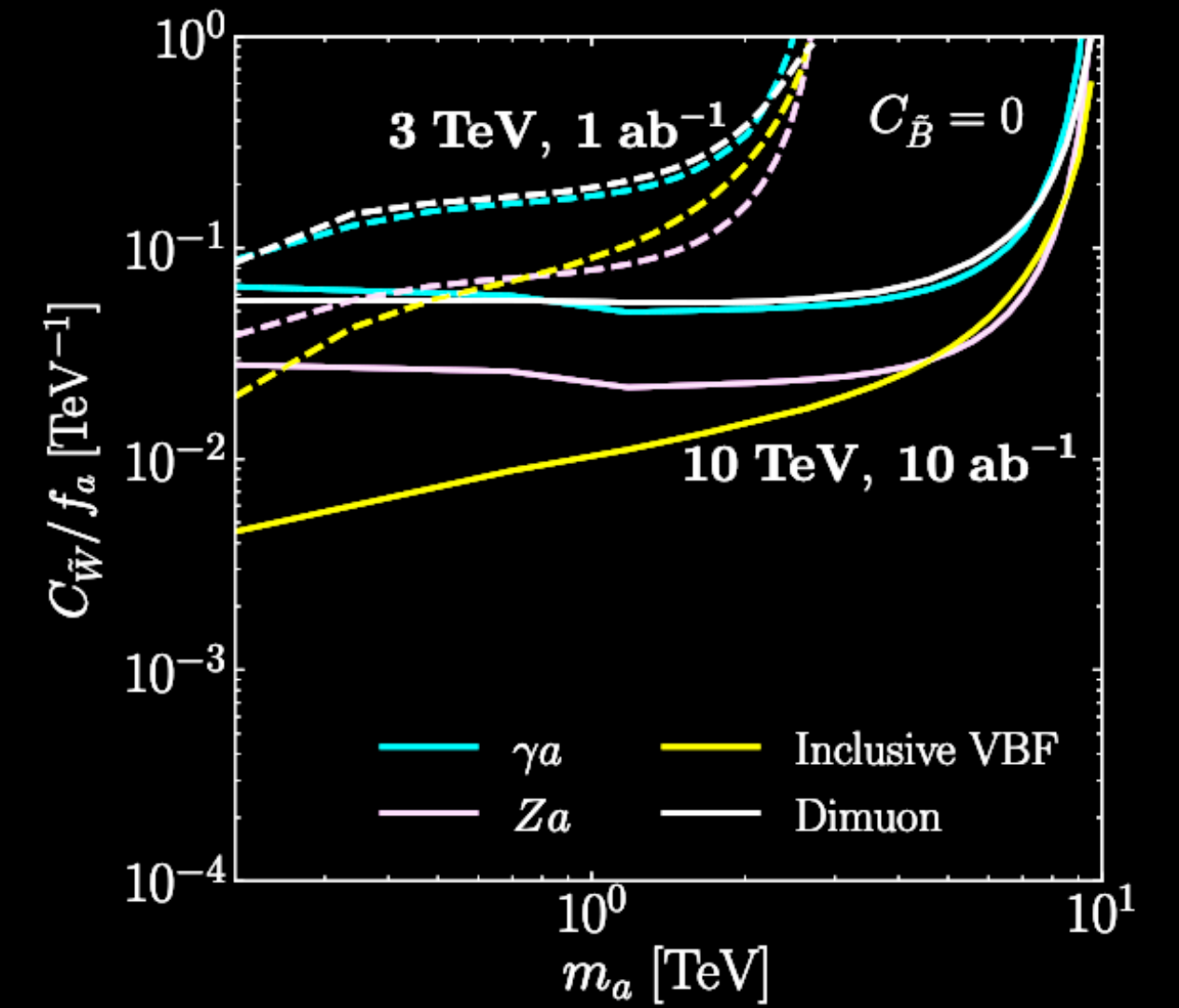
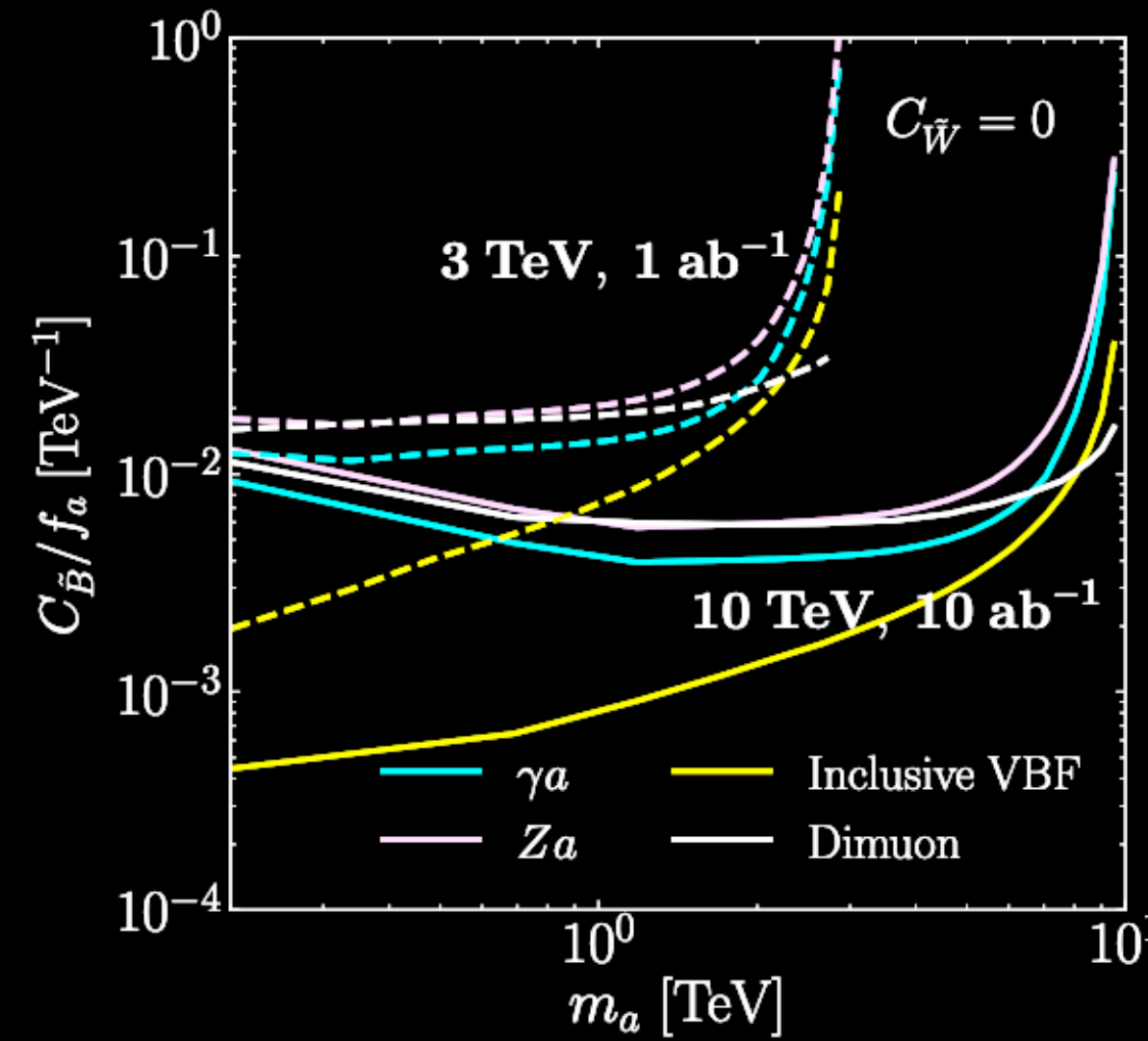
$$\mathcal{O} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Heavy neutral leptons

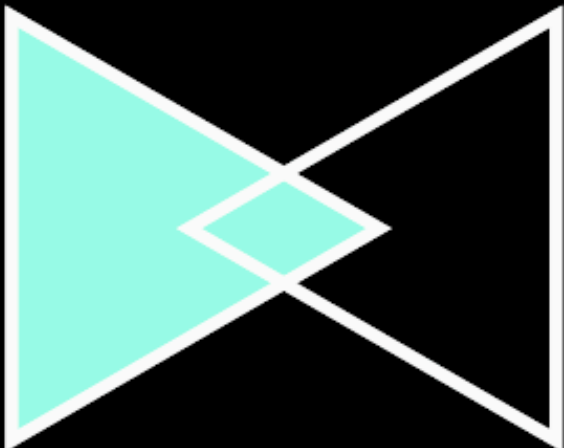
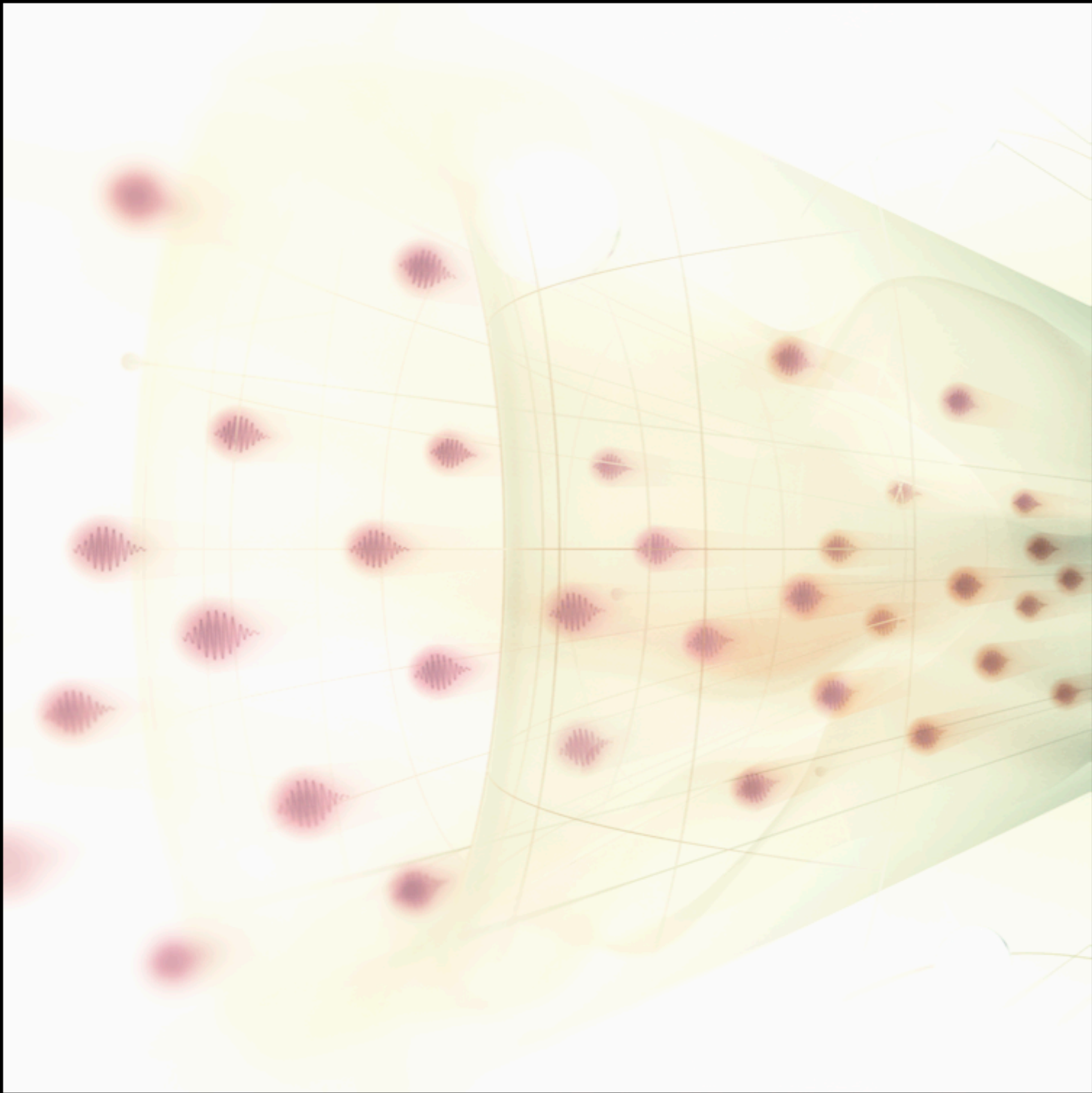


[Li, Liu, Lyu 2301.07117]

Axion-like Particles



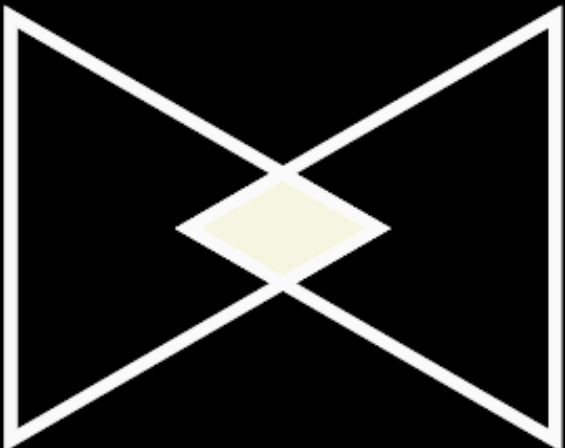
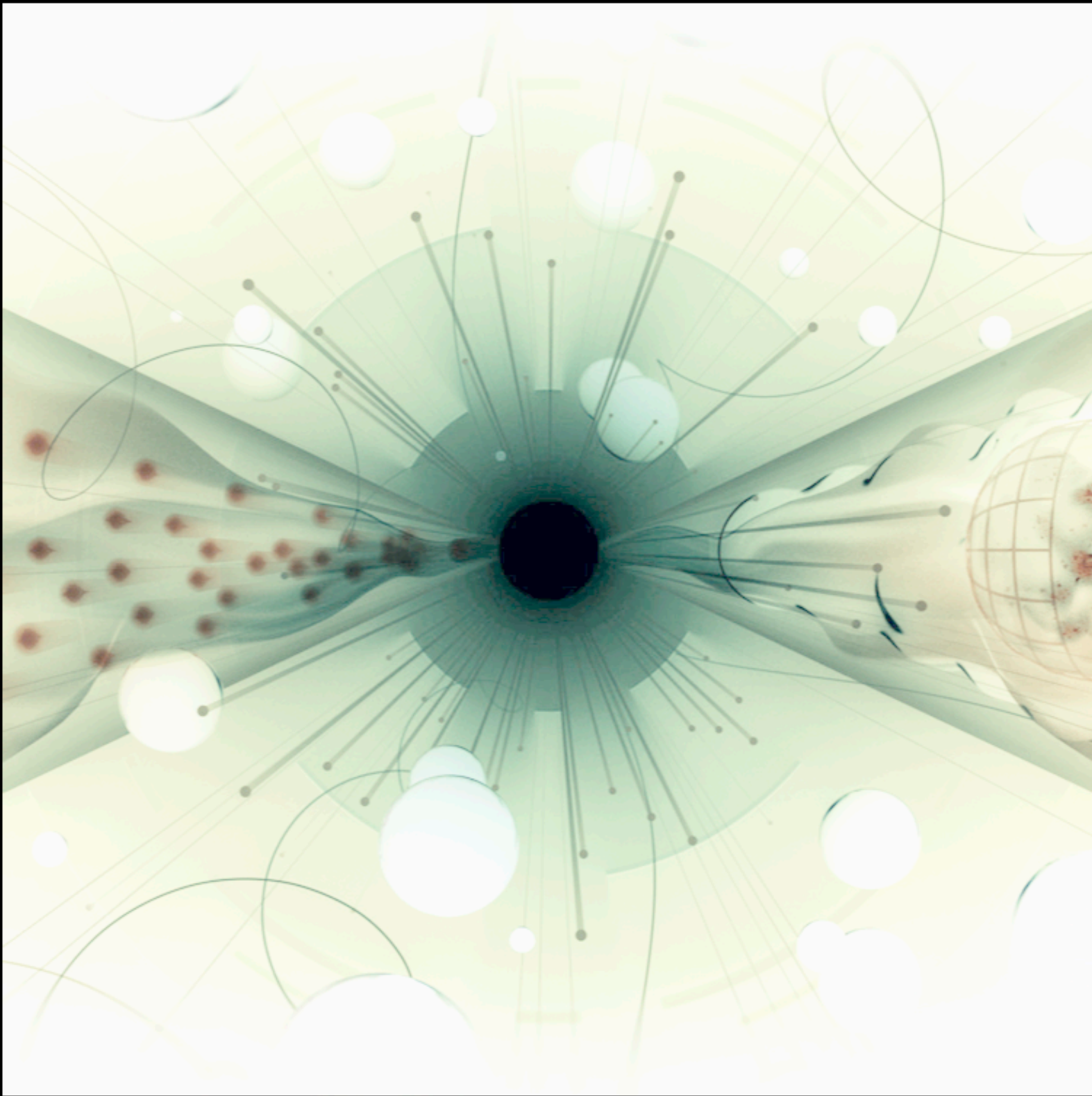
[Han, Li, Wang 2203.05484]



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**Elucidate the Mysteries
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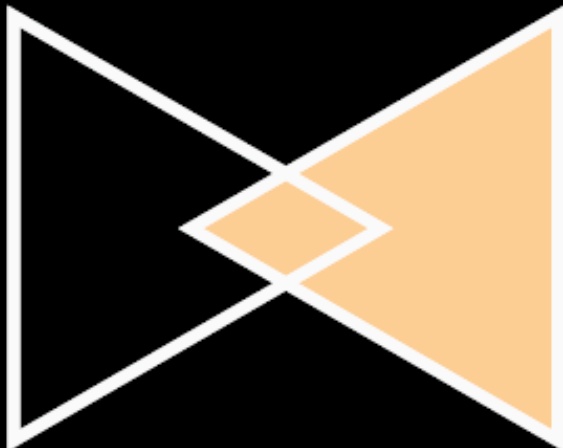
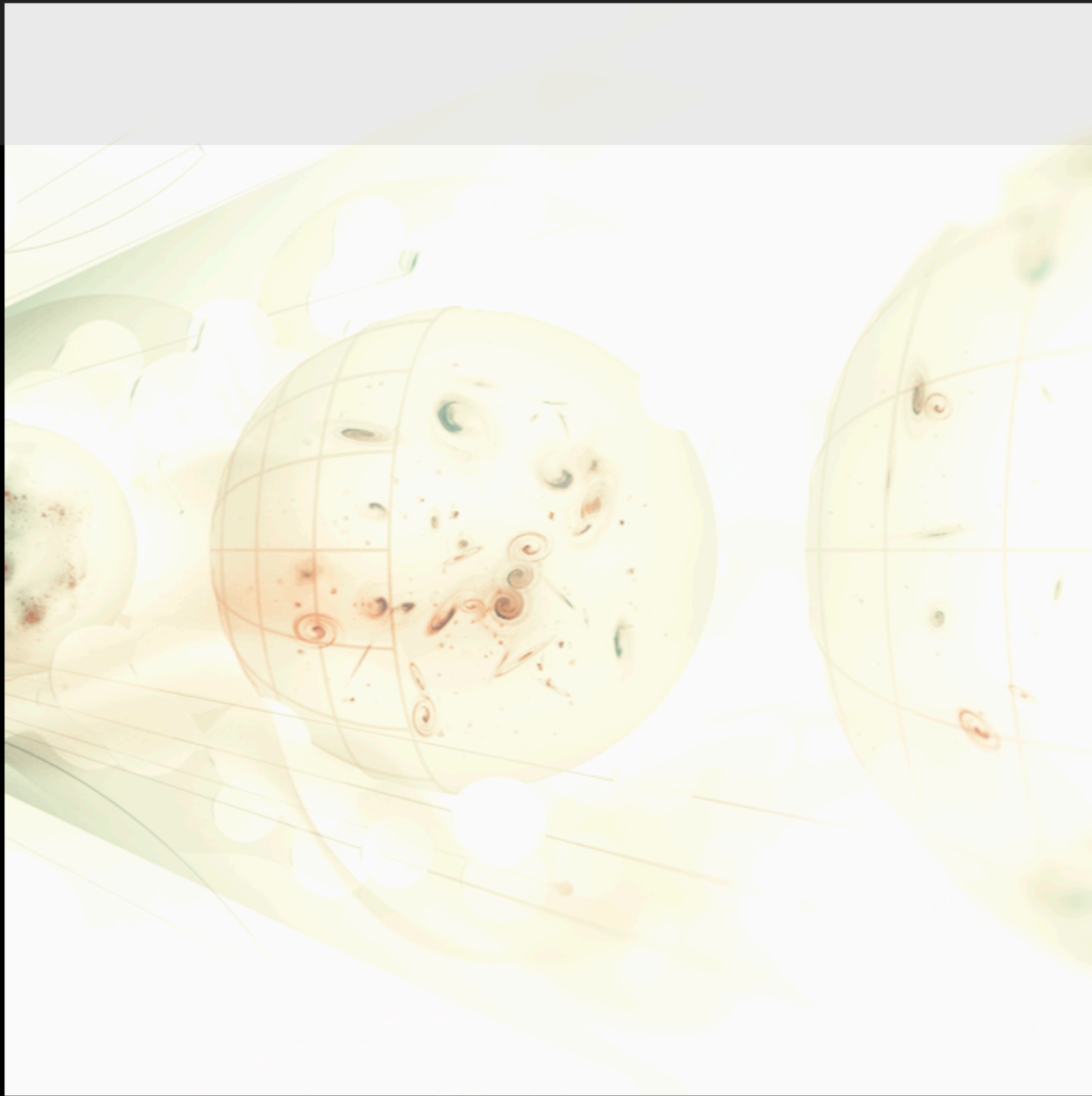
**Reveal the Secrets of
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**Explore
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**Search for Direct Evidence
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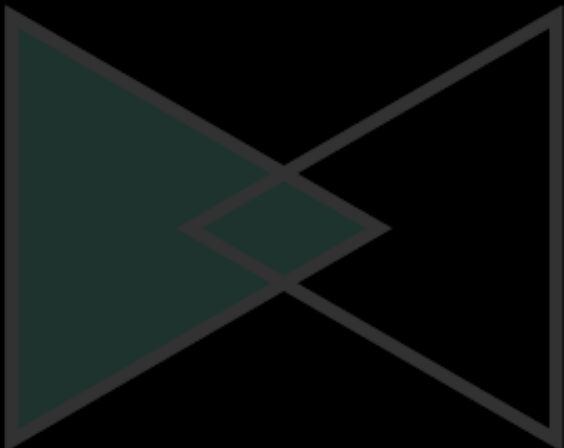
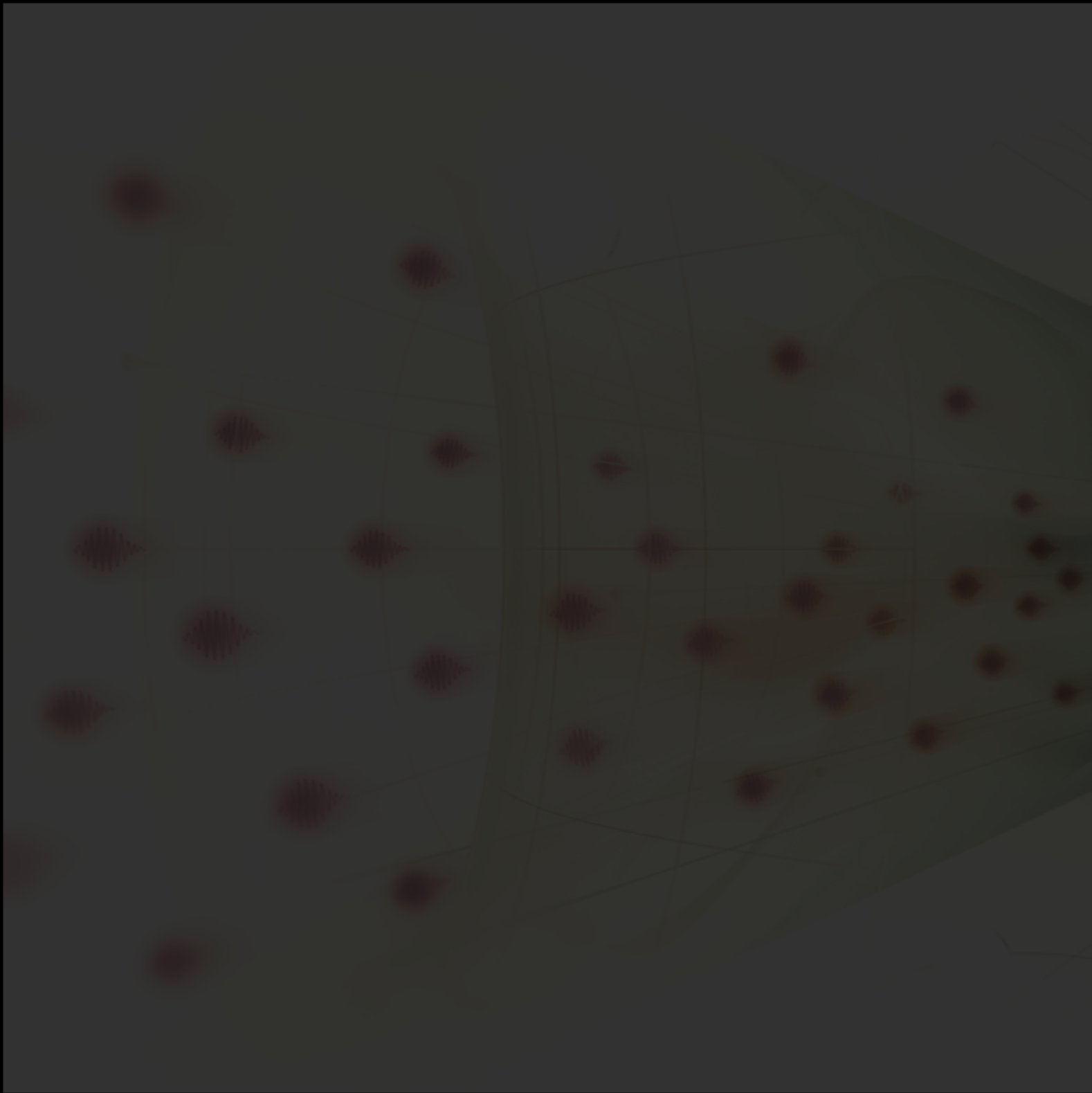
**Pursue Quantum Imprints
of New Phenomena**



**Illuminate
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Hidden
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**Determine the Nature
of Dark Matter**

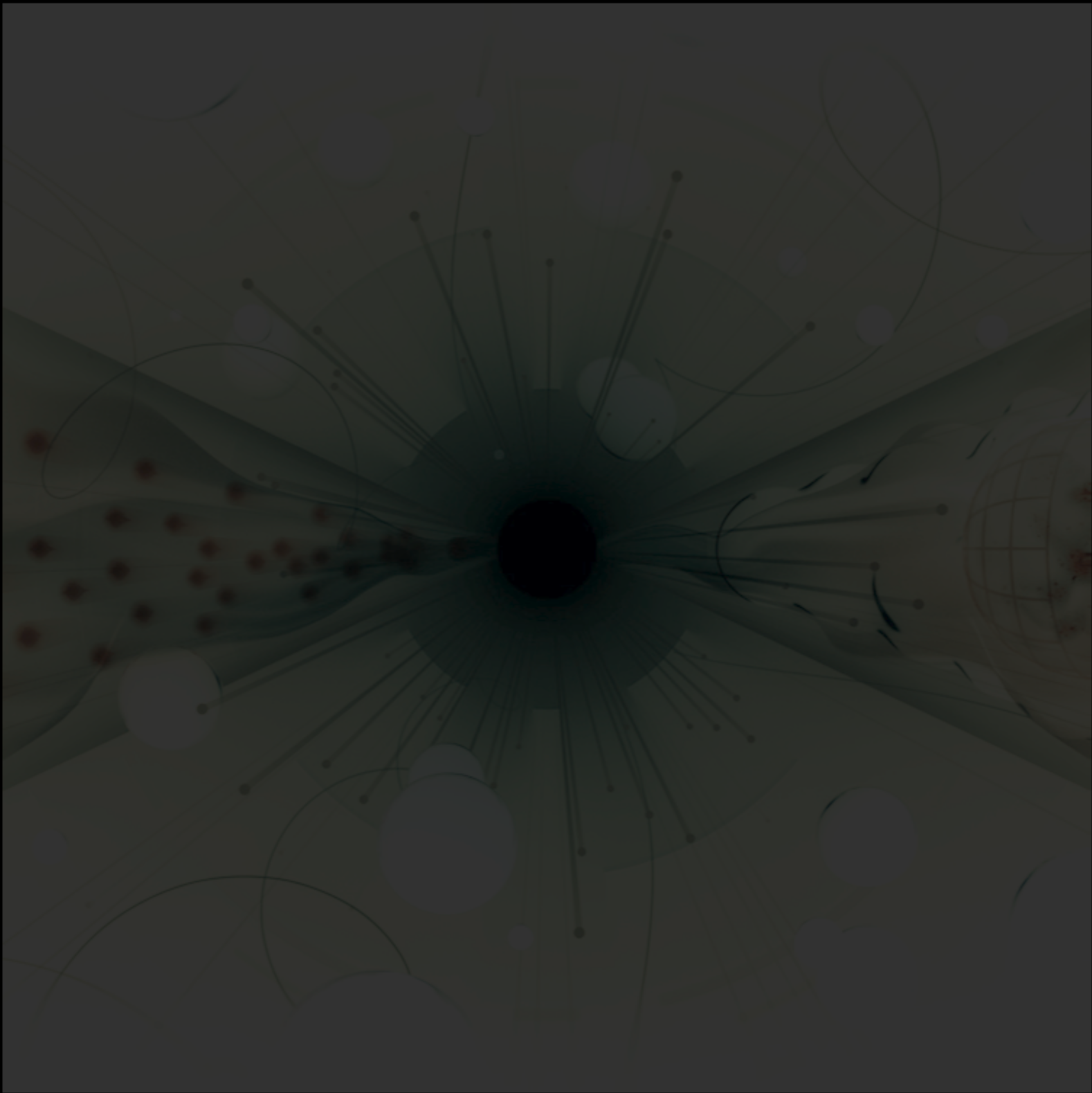
**Understand What Drives
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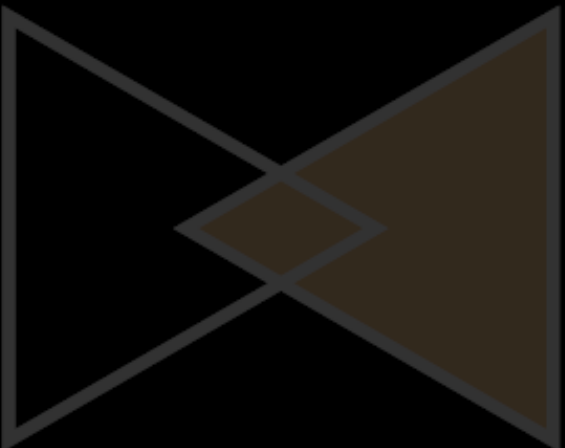
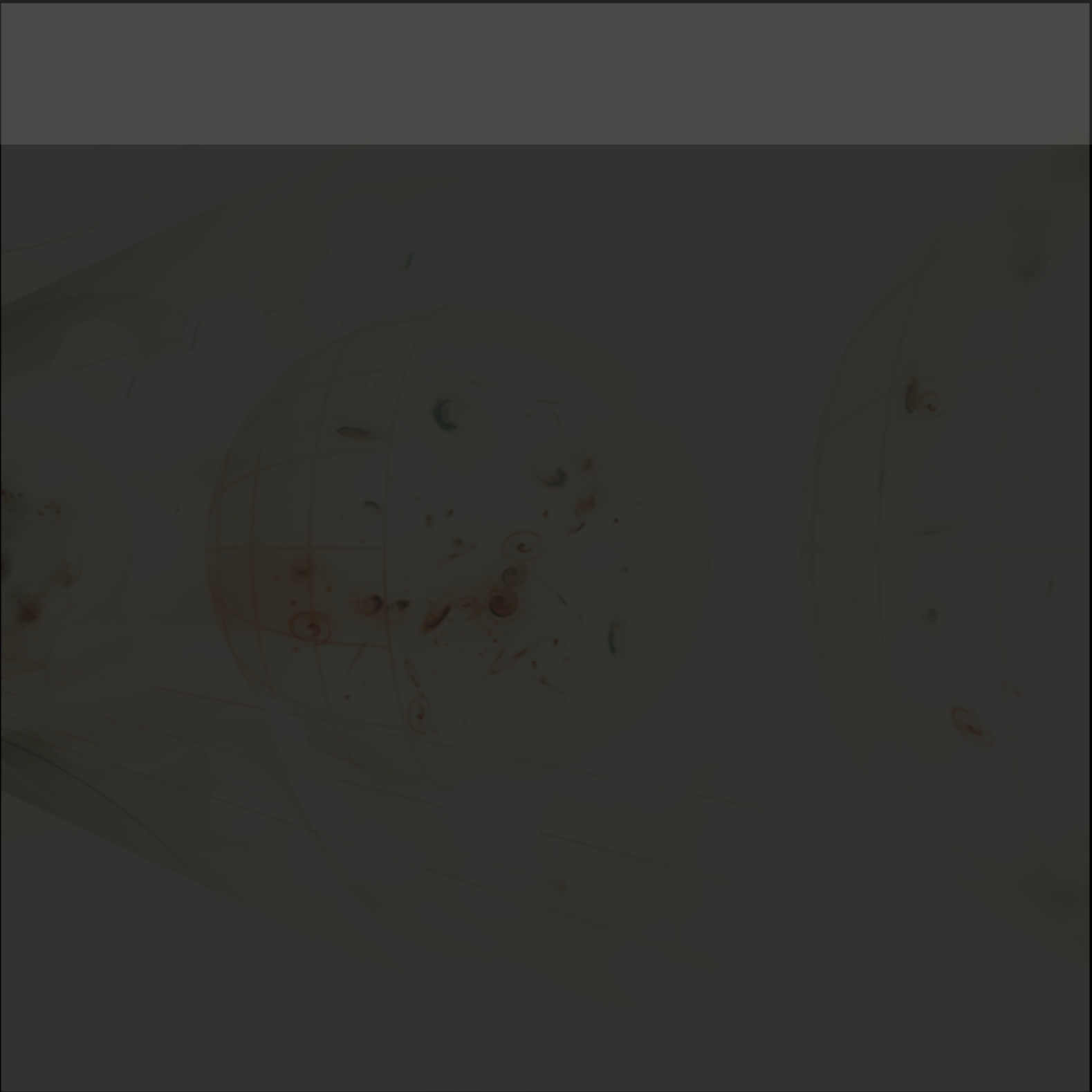
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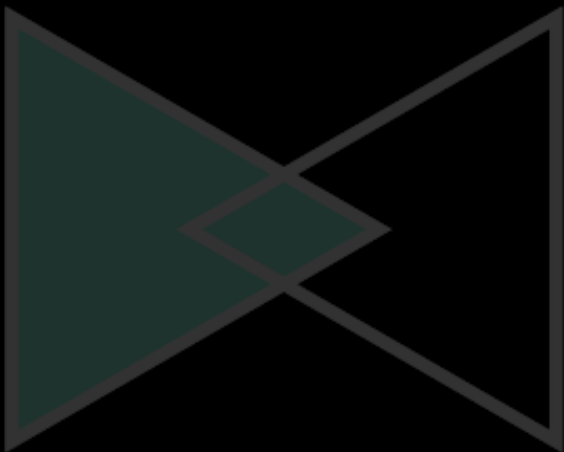


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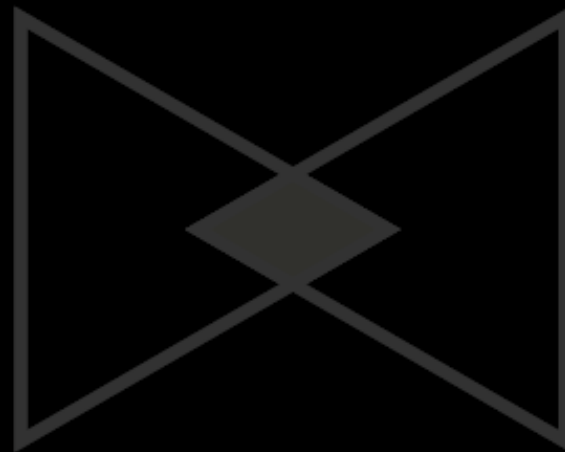
We set sail on this new sea because there is new knowledge to be gained across the frontiers of particle physics.



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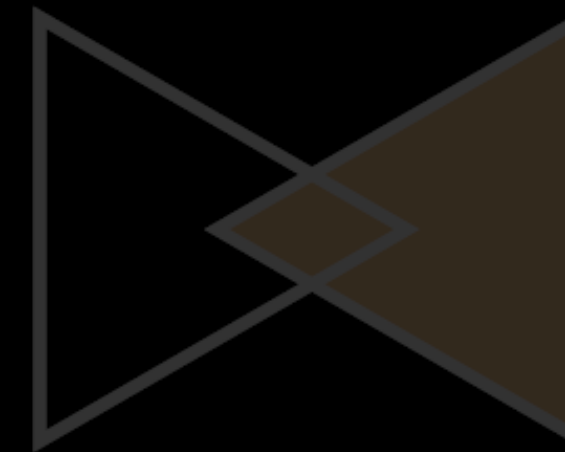
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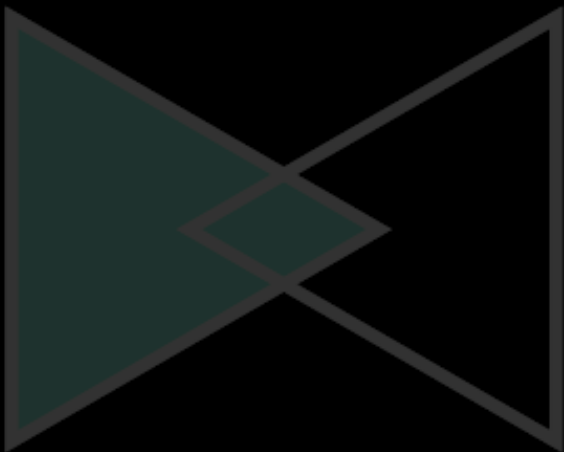


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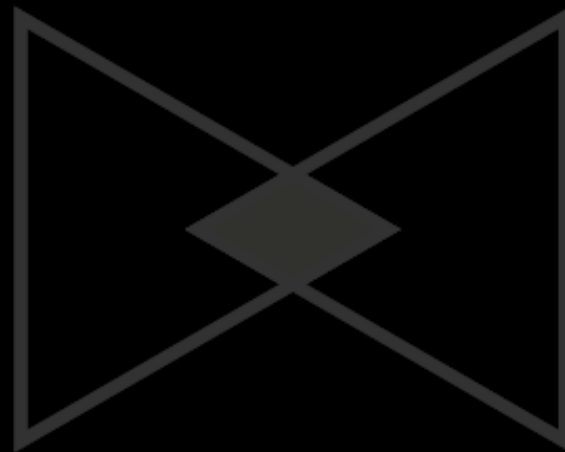
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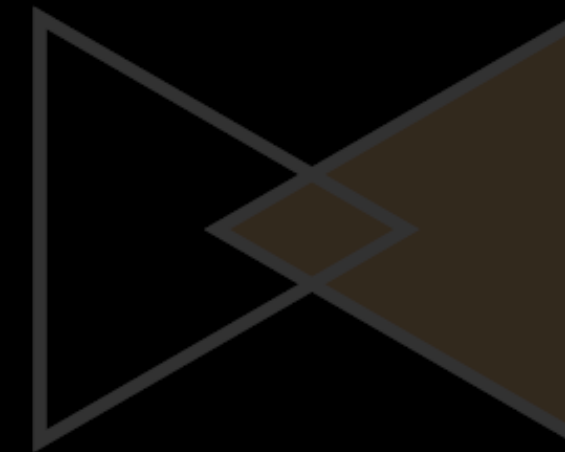
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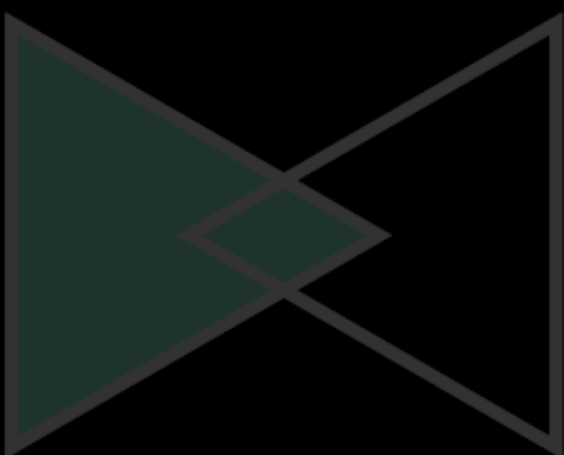
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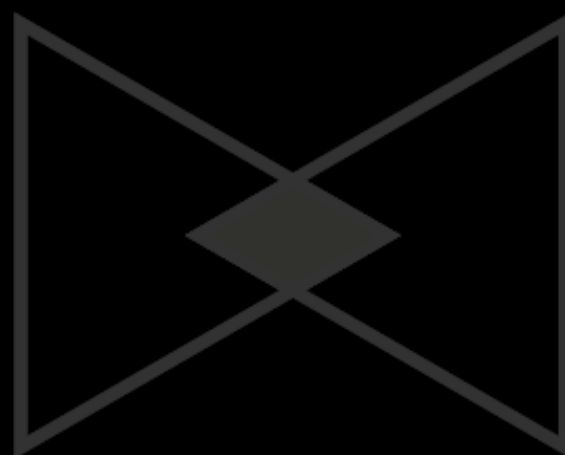
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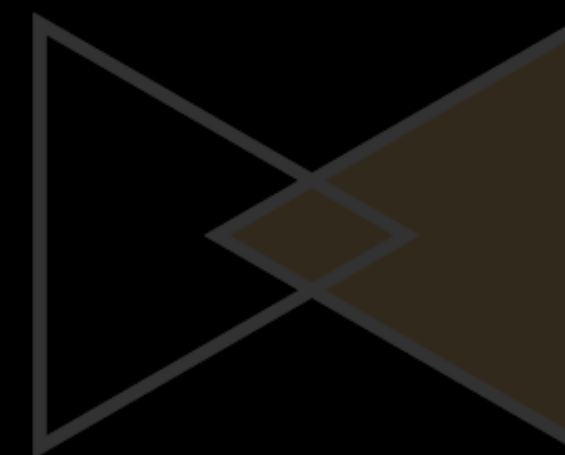
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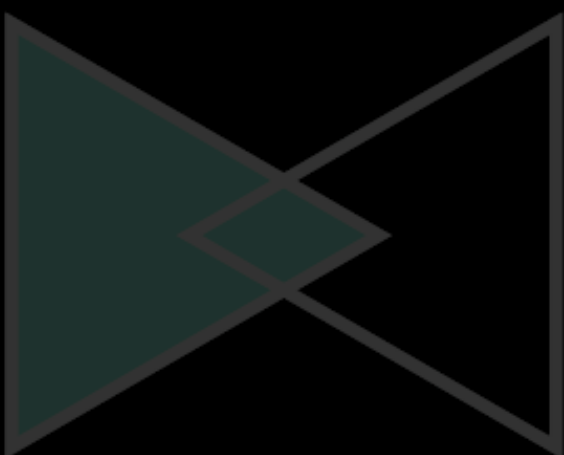
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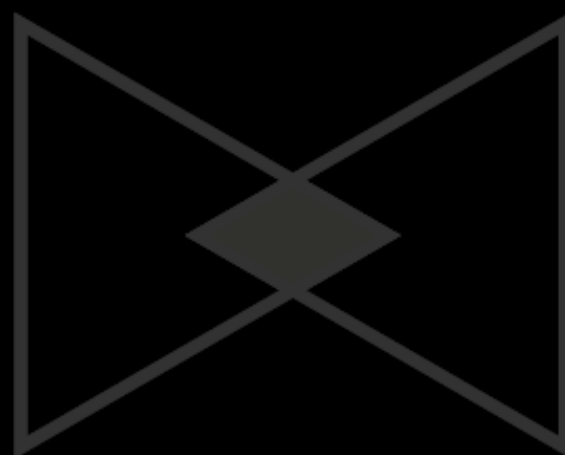
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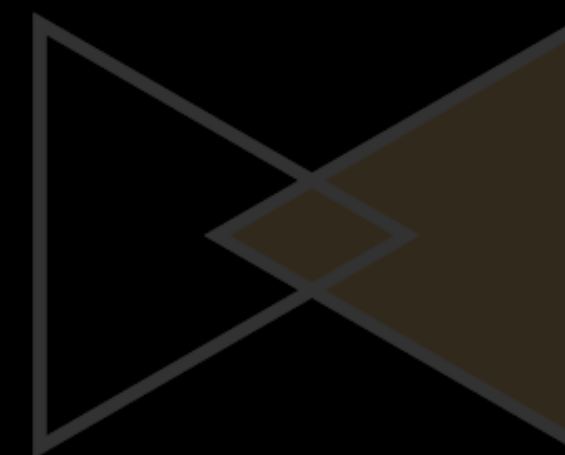
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