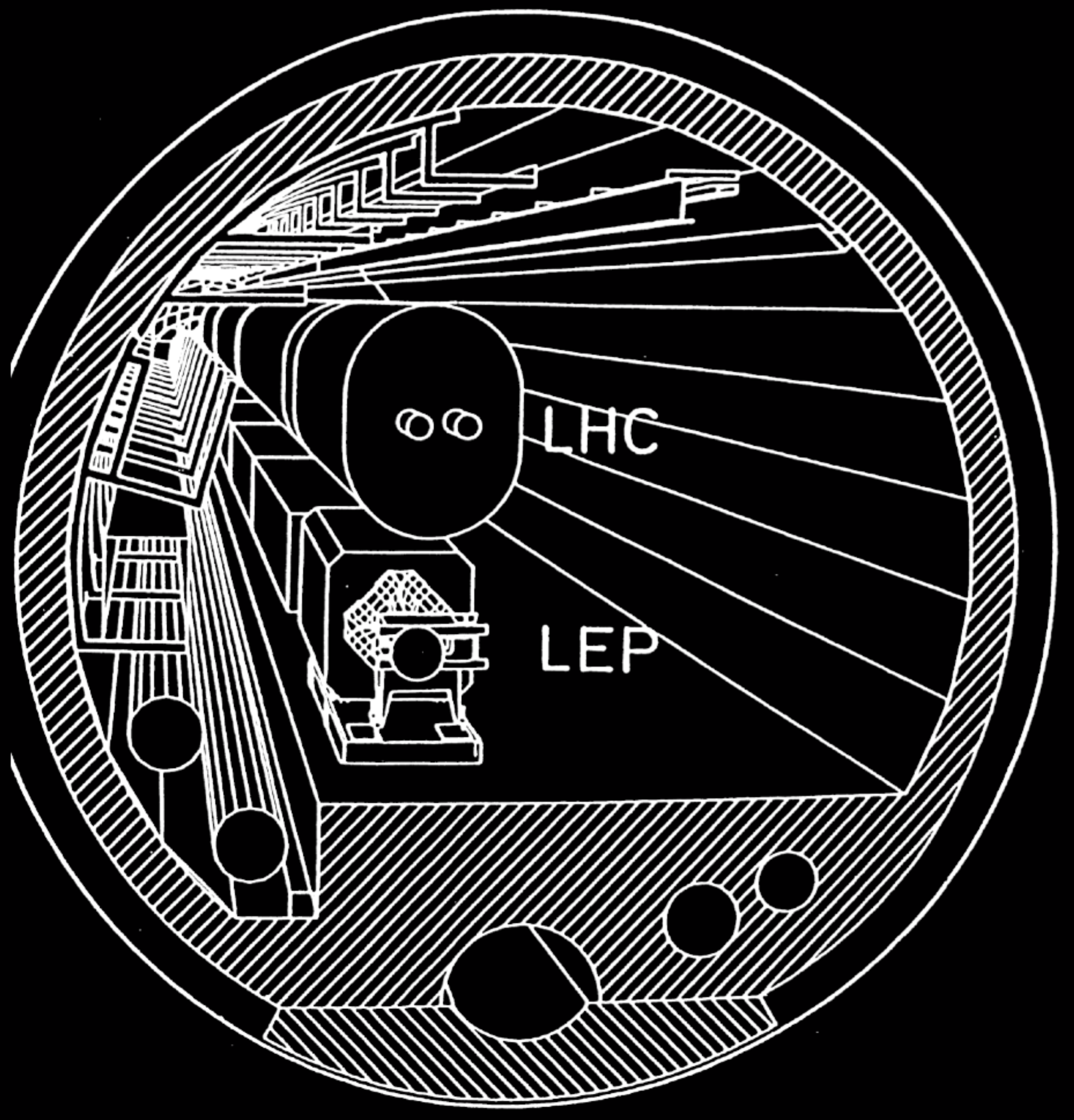
The broad physics case of a muon collider

Nathaniel Craig UCSB

Vision circa 1984

ECFA 84/85
CERN 84-10
5 September 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

Satisfied with these successes, we have now to face deeper questions such as:

> what is the origin of mass?
> what kind of unification may exist beyond the standard model?
> what is the origin of flavour?
> is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

Vision circa 2023

Vision circa 2023

✓ What is the origin of mass?
What kind of unification may exist?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?

Vision circa 2023

✓ What is the origin of mass?
What kind of unification may exist?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?
+ What is the nature of dark matter?

Vision circa 2023

✓ What is the origin of mass?
What kind of unification may exist?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?
+ What is the nature of dark matter?
+ What is the nature of the neutrino sector?

Vision circa 2023

✓ What is the origin of mass?
What kind of unification may exist?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?
+ What is the nature of dark matter?
+ What is the nature of the neutrino sector?

A Higgs! Yet:

“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

What is the origin of mass?

A Higgs! Yet…

“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

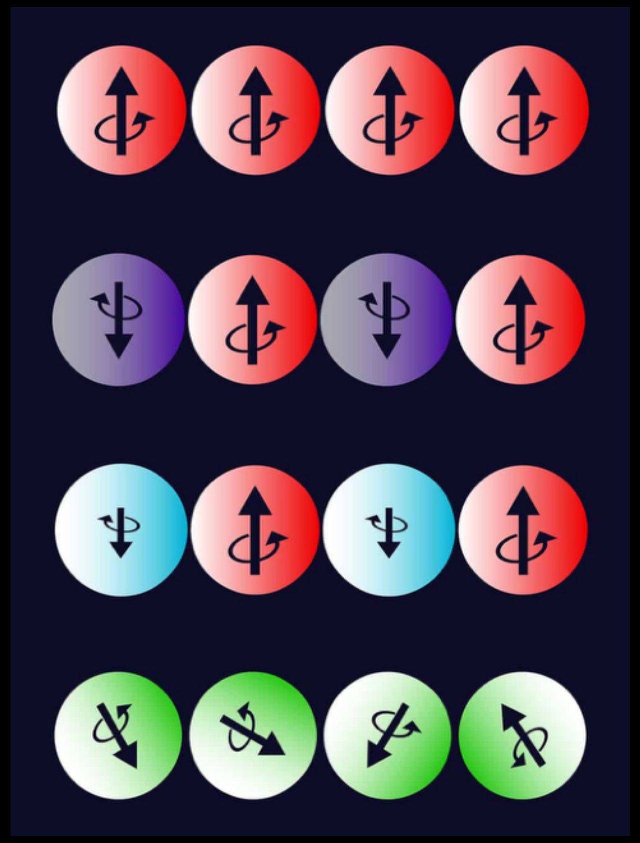
What is the origin of mass?

A Higgs! Yet…

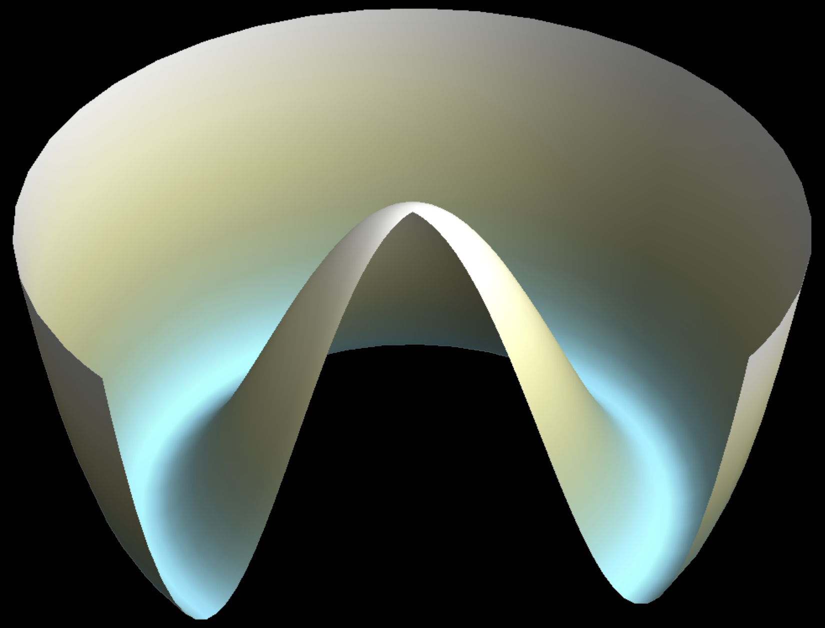
“The more ambitious goal…is to identify and understand the nature of electroweak symmetry breaking, the asymmetry that is key to the material universe. The Higgs boson is but its herald.”

–Frank Close

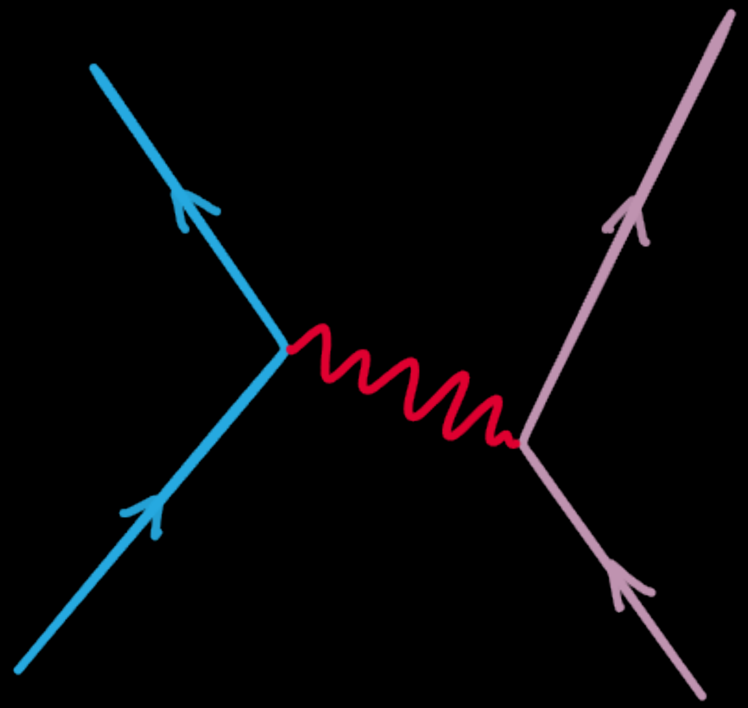
A superconducting analogy:



High-Tc Superconductors

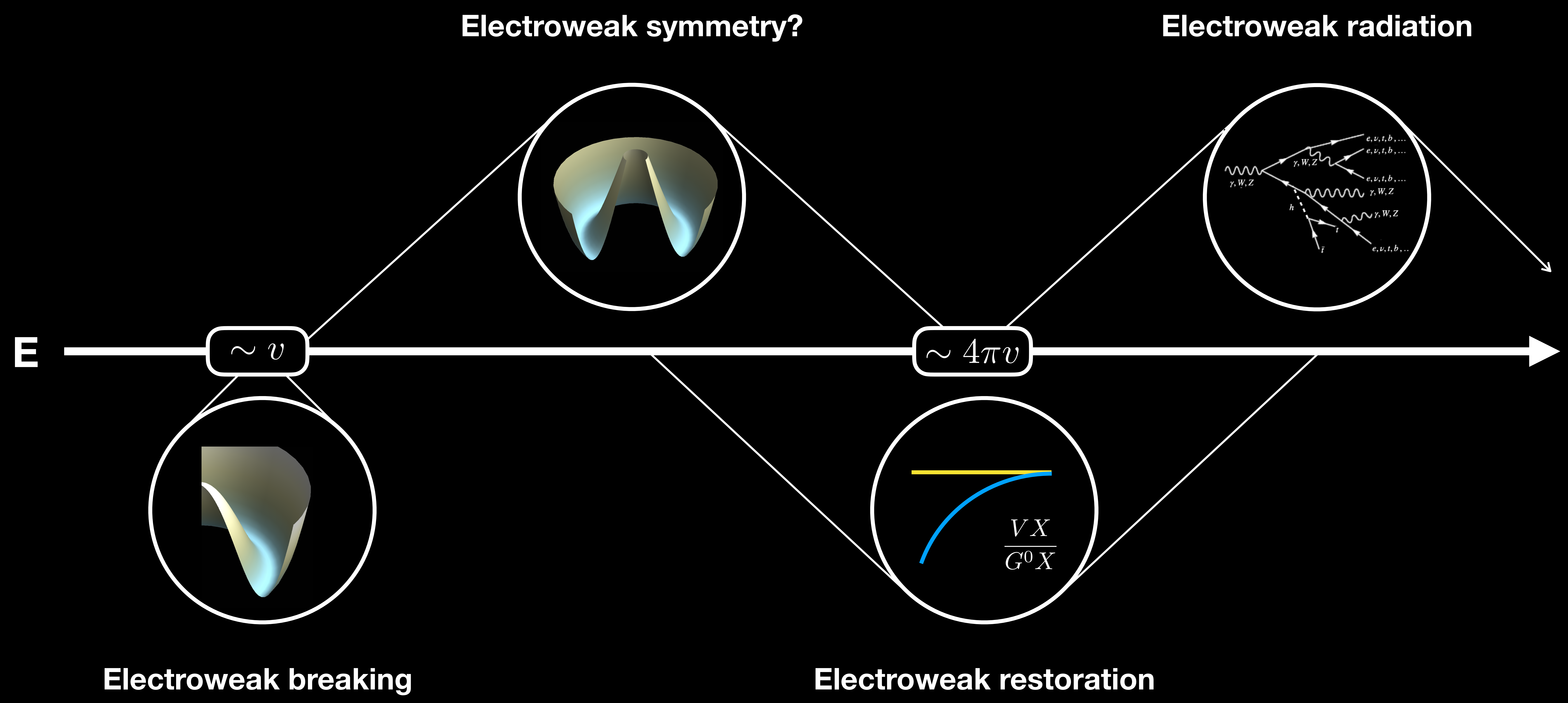


Ginzburg-Landau Theory

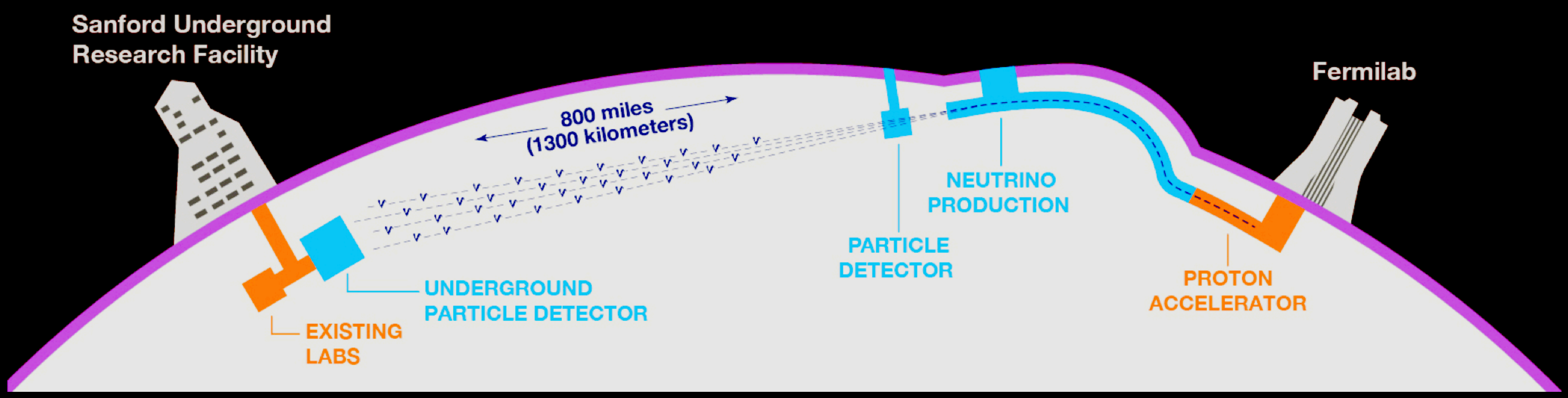


Low-Tc Superconductors (BCS)

The Electroweak Era



The Electroweak Era



Neutrinos: the purely weak frontier of the Standard Model

Dark sectors: portals are weak interactions & SM electroweak states

weak portal

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

kinetic mixing portal

$$F^{\mu\nu}\mathcal{O}_{\mu\nu}$$

neutrino portal

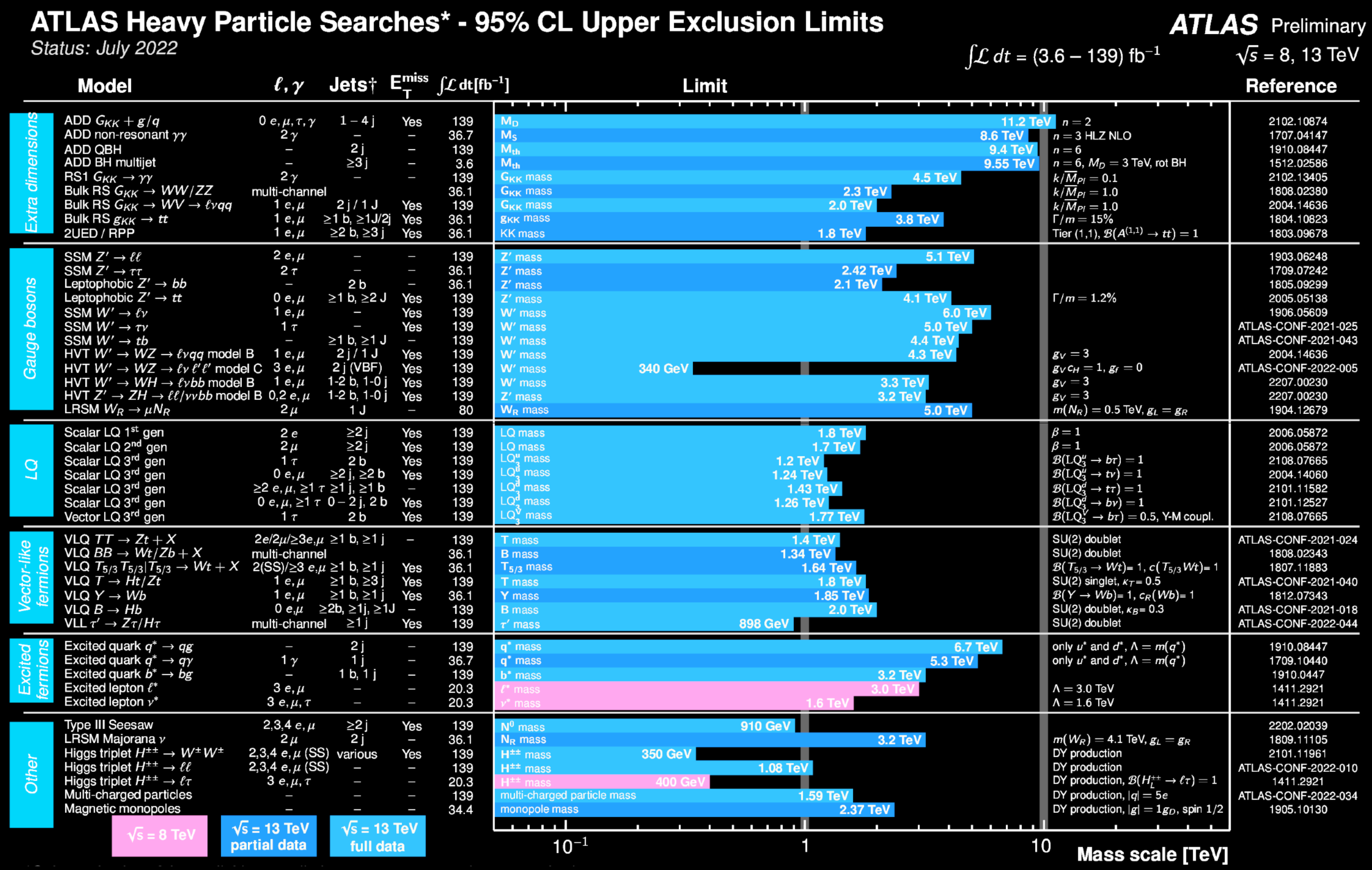
$$HL^\alpha \mathcal{O}_\alpha$$

Higgs portal

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

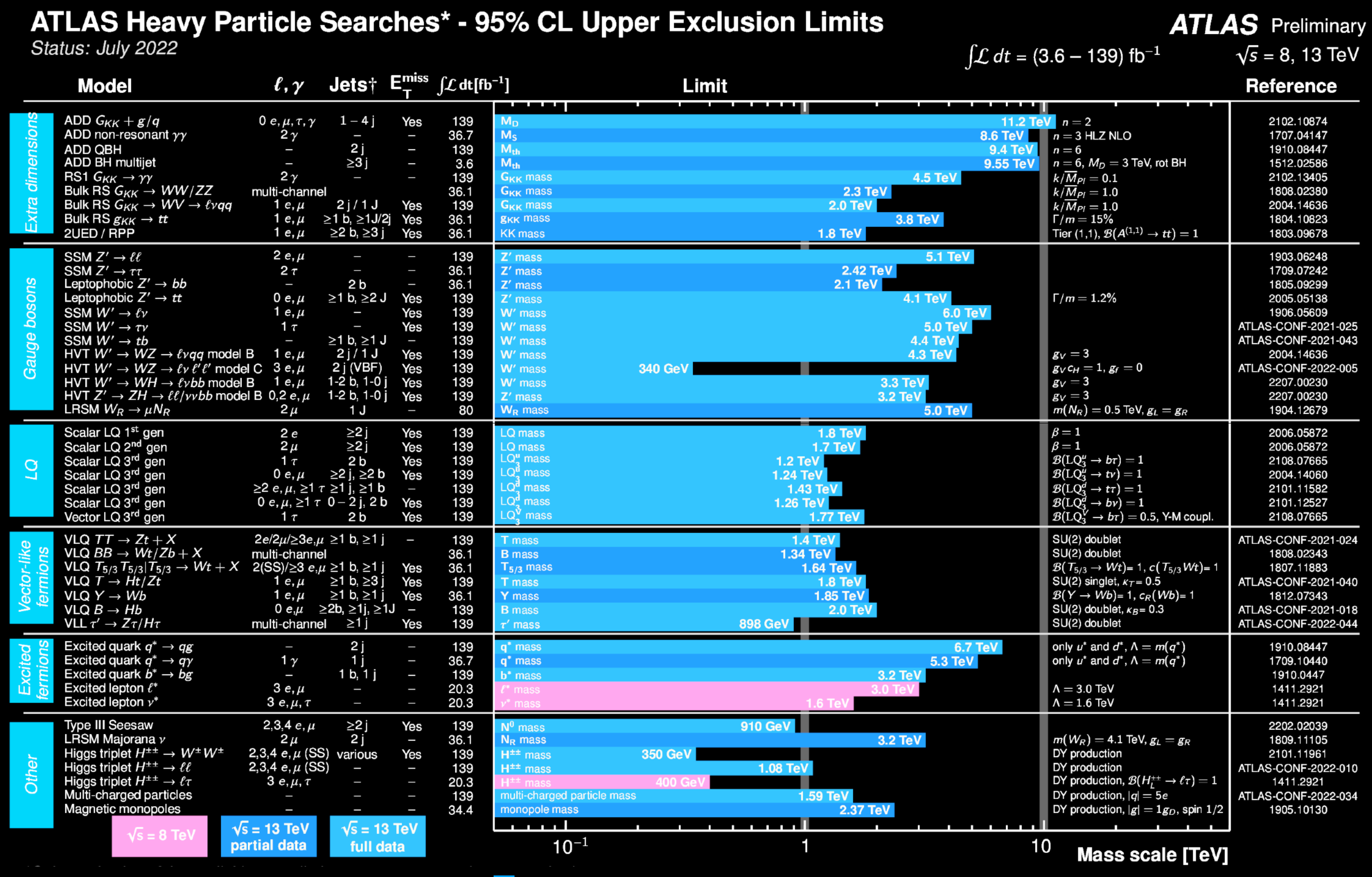
The Electroweak Era

…and exploration after the LHC



The Electroweak Era

…and exploration after the LHC



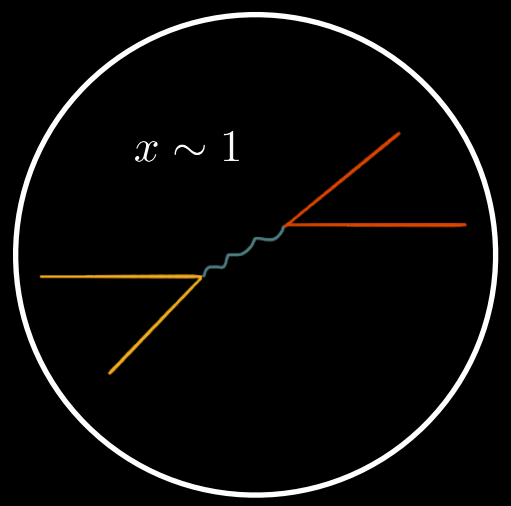
Singlet scalar $(1,1)_0$

Doublet scalar $(1,2)_{1/2}$

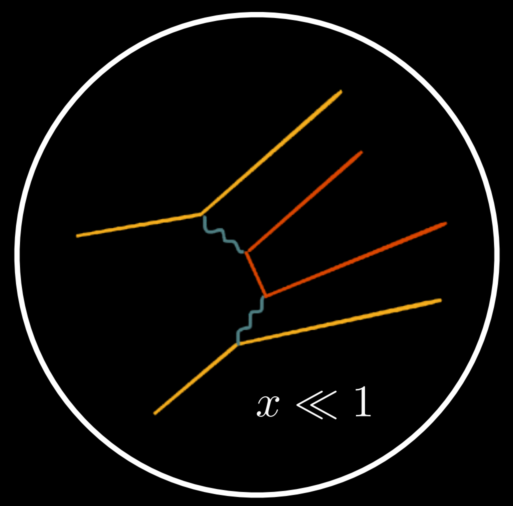
Doublet scalar $(1,2)_{3/2}$

Muon Colliders for the EWK Era

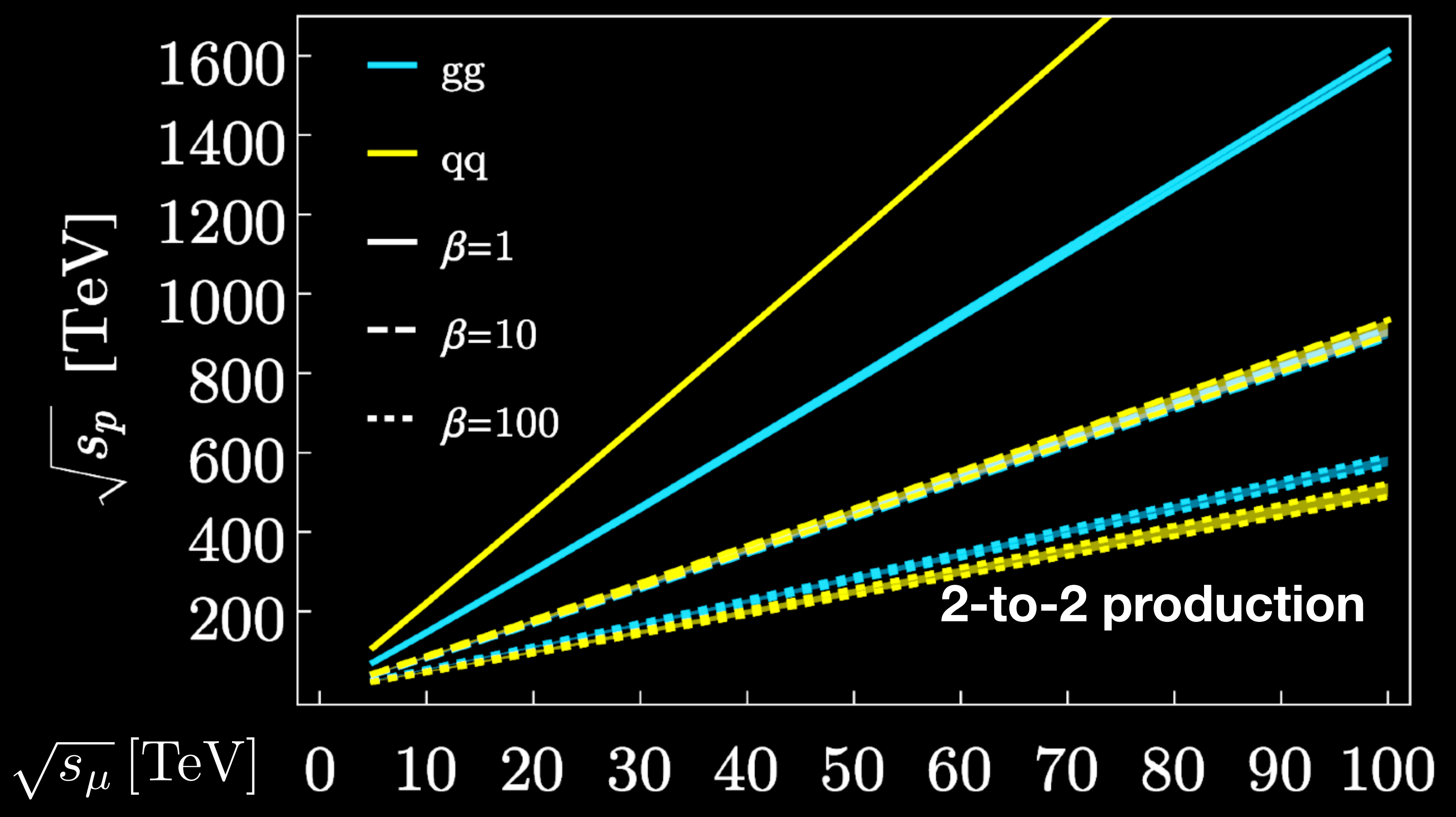
Muon colliders blur the dichotomy of probing micsocopic phenomena with **precision** or **energy**.

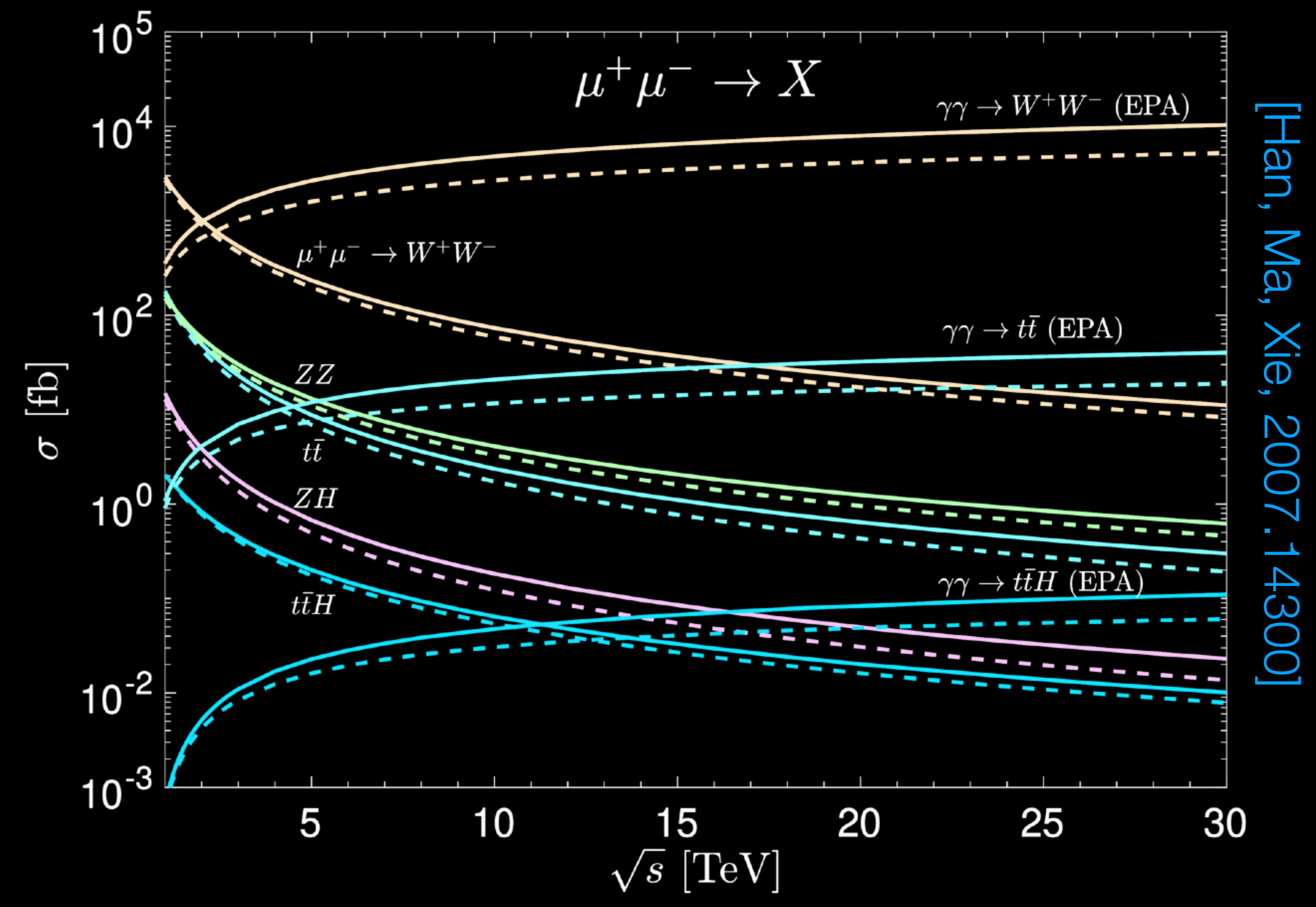


Muon annihilation deploys the entire energy of the collider



Vector boson fusion leverages the muon's virtual boson content

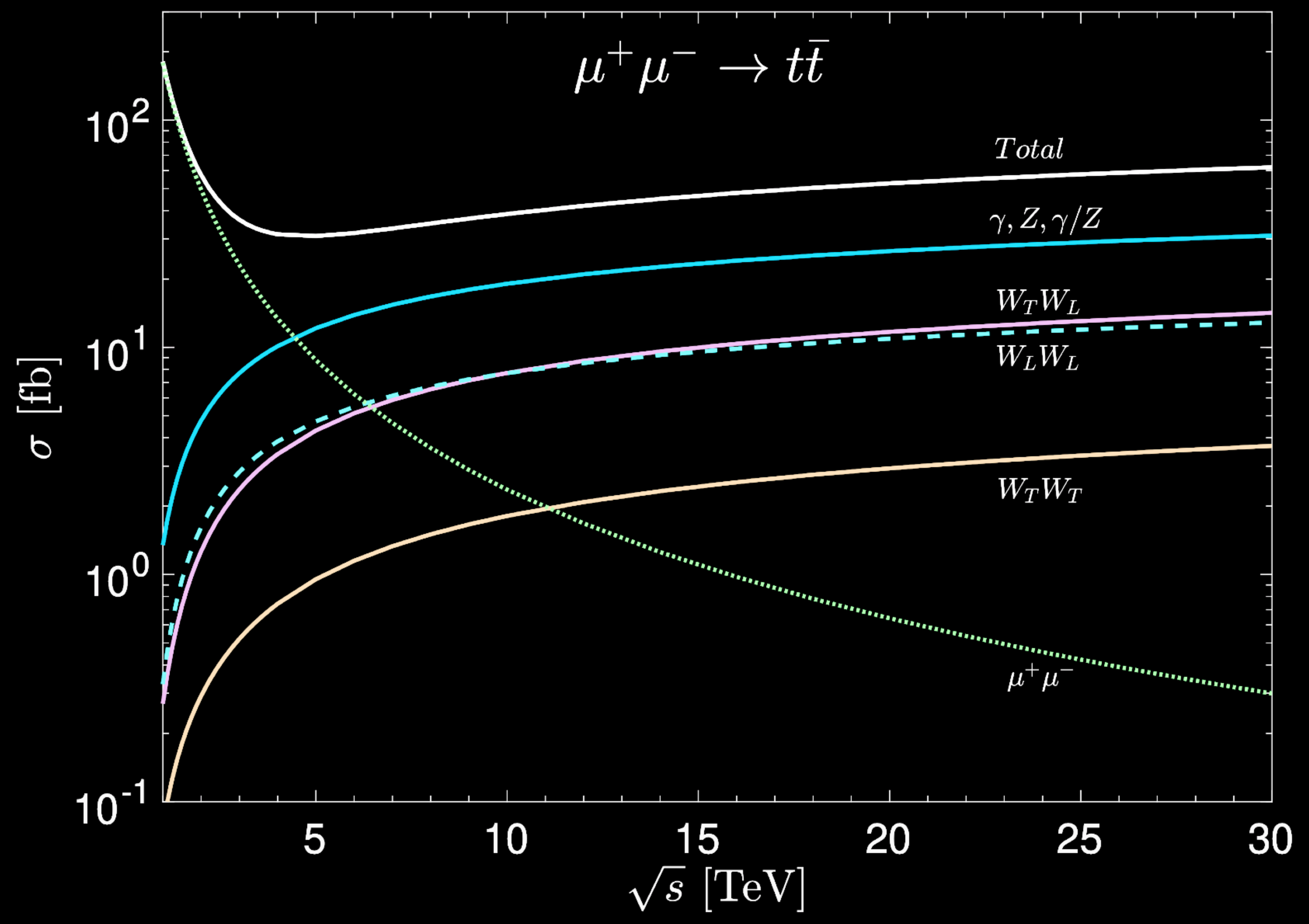




Moreover, muon collider energy in a (relatively) clean environment provides ***precision from energy.***

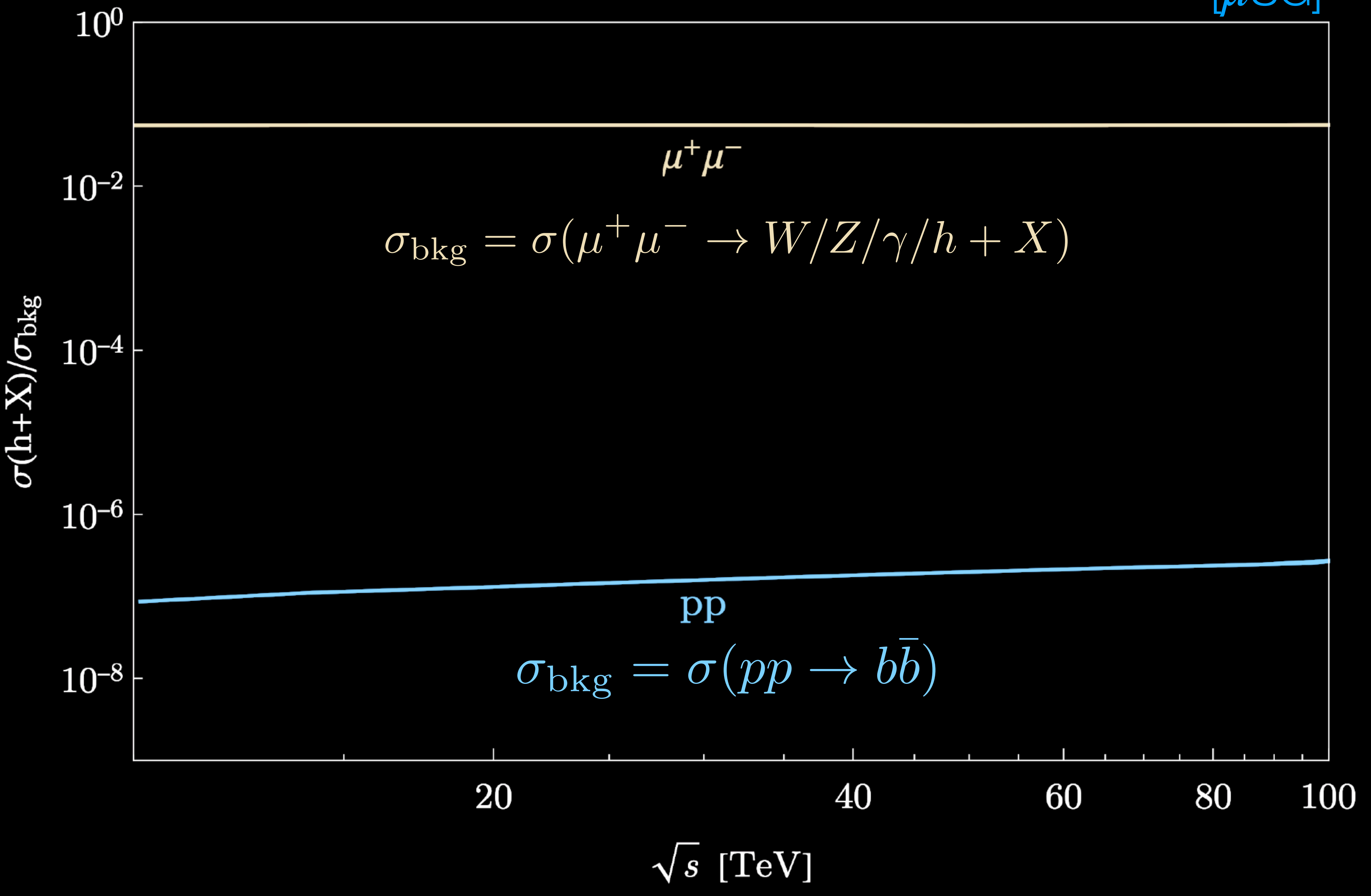
Muon Colliders as EWK Laboratories

[Han, Ma, Xie, 2007.14300]



Longitudinal polarizations play a key role, making an extraordinary laboratory for EWSB

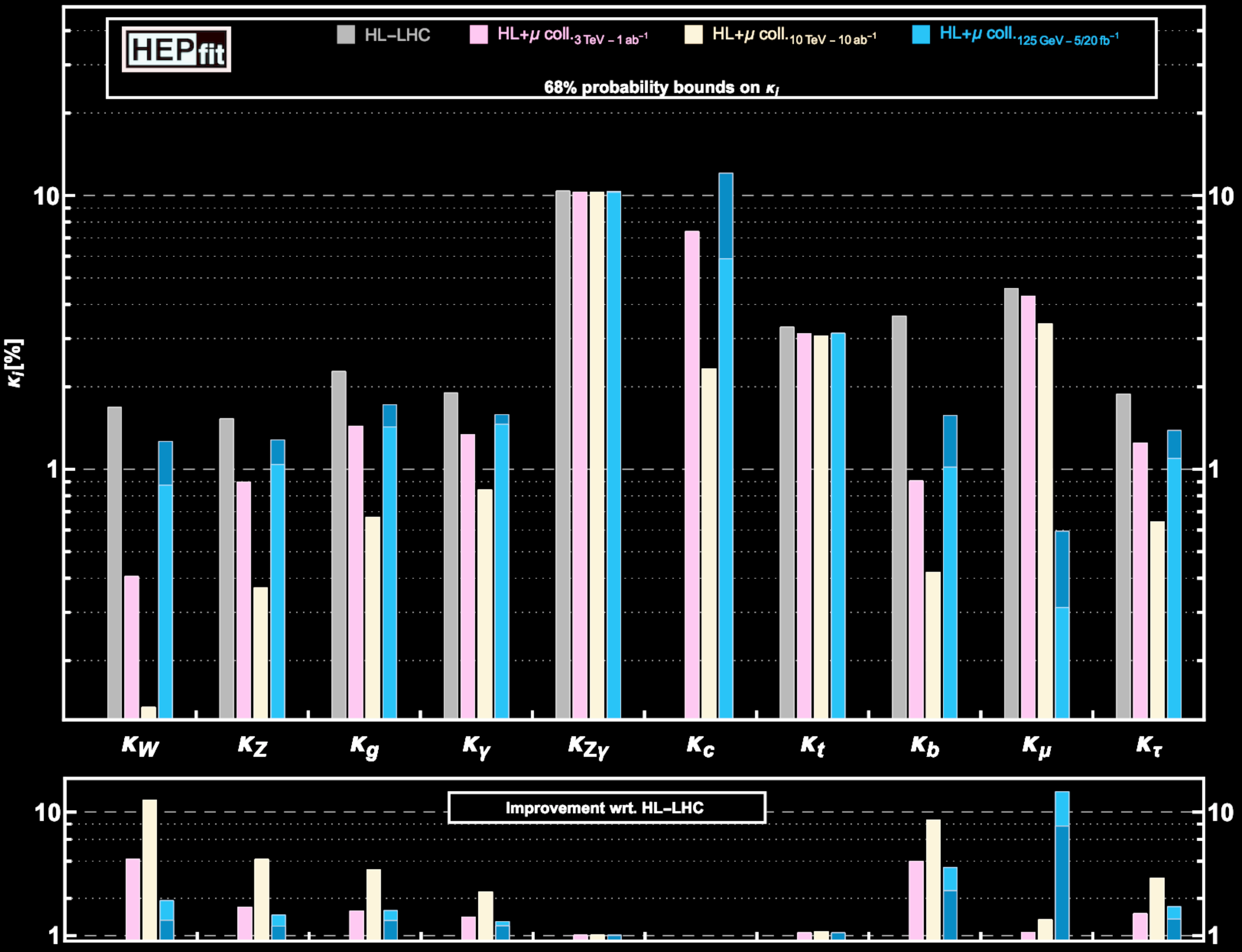
[μSG]



Dominant signals and backgrounds both have electroweak cross sections

How do muons illuminate the physics vision?

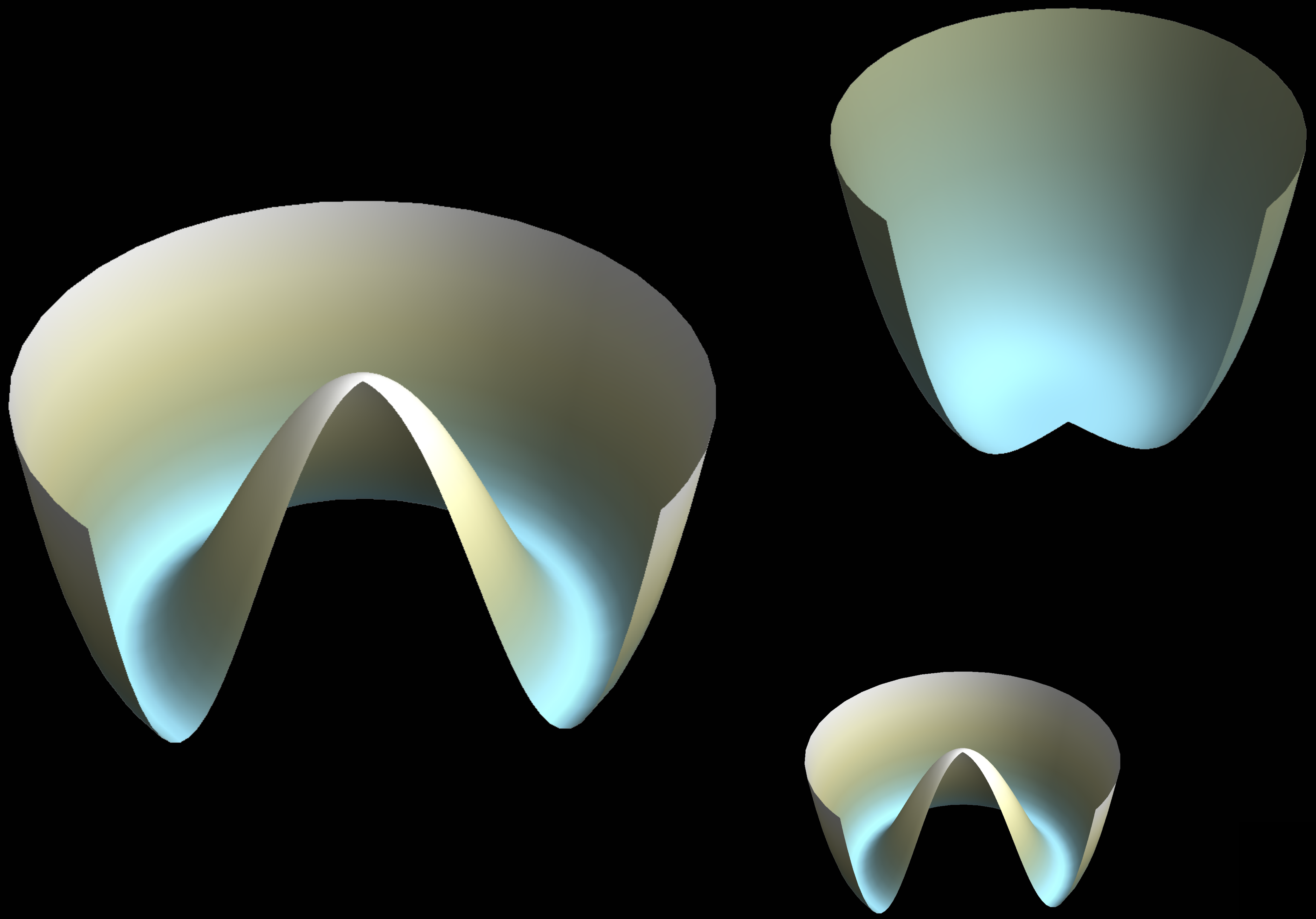
What is the Origin of Mass ?



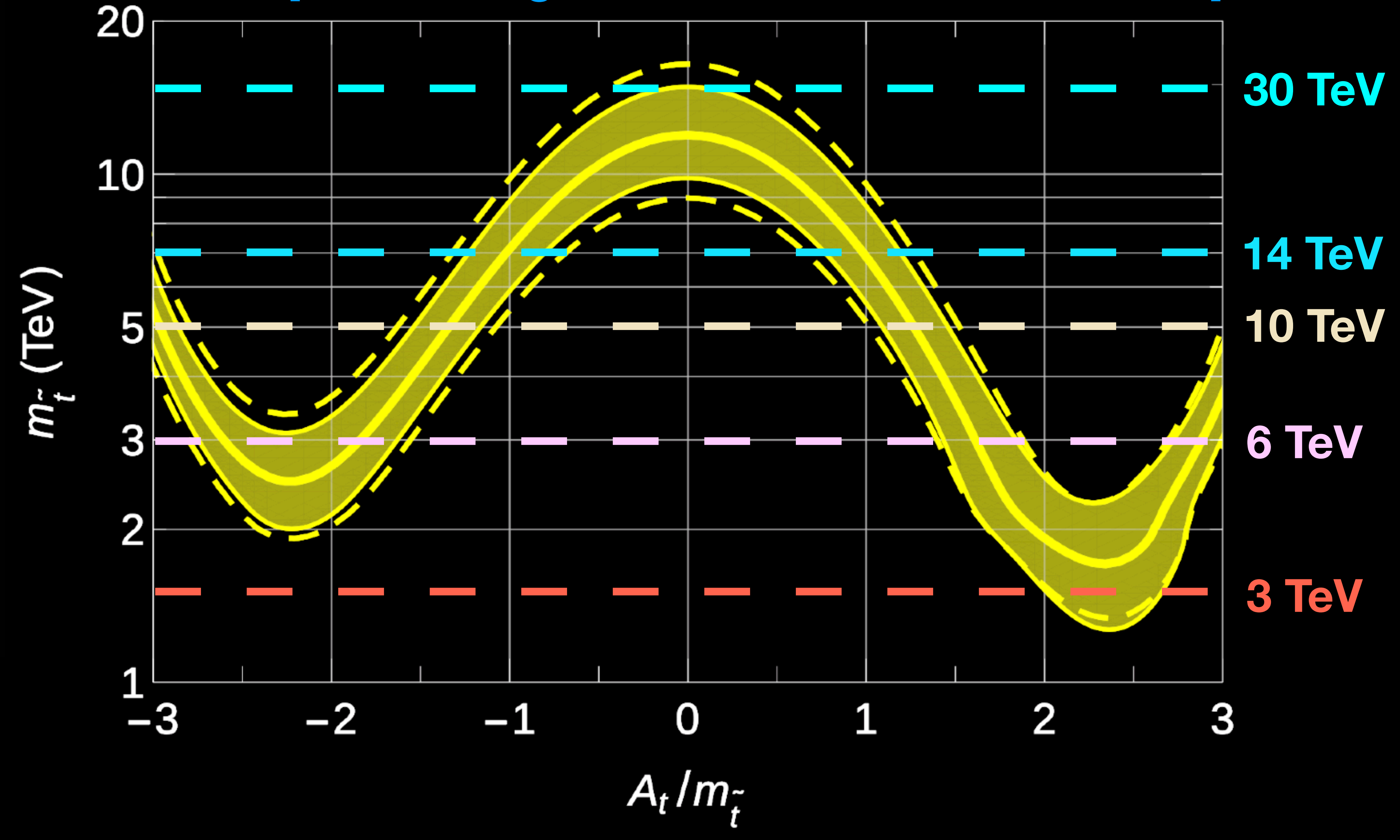
[IMCC 2203.07261]

What is the BCS Theory of EWSB?

Theories that predict the Higgs mass & EWSB provide sharp targets for new physics.



Direct targets set by the observed Higgs mass (e.g. supersymmetry)



What is the BCS Theory of EWSB?

Theories that predict the Higgs mass & EWSB provide sharp targets for new physics.

Compositeness leaves fingerprints in EFT:

$$\mathcal{O}_{2W} = (D_\mu W^{\mu\nu,a})^2$$

$$\mathcal{O}_{2B} = (\partial_\mu B^{\mu\nu})^2$$

$$\mathcal{O}_W = ig(H^\dagger \sigma^a D_\mu H) D^\nu W^a_{\mu\nu}$$

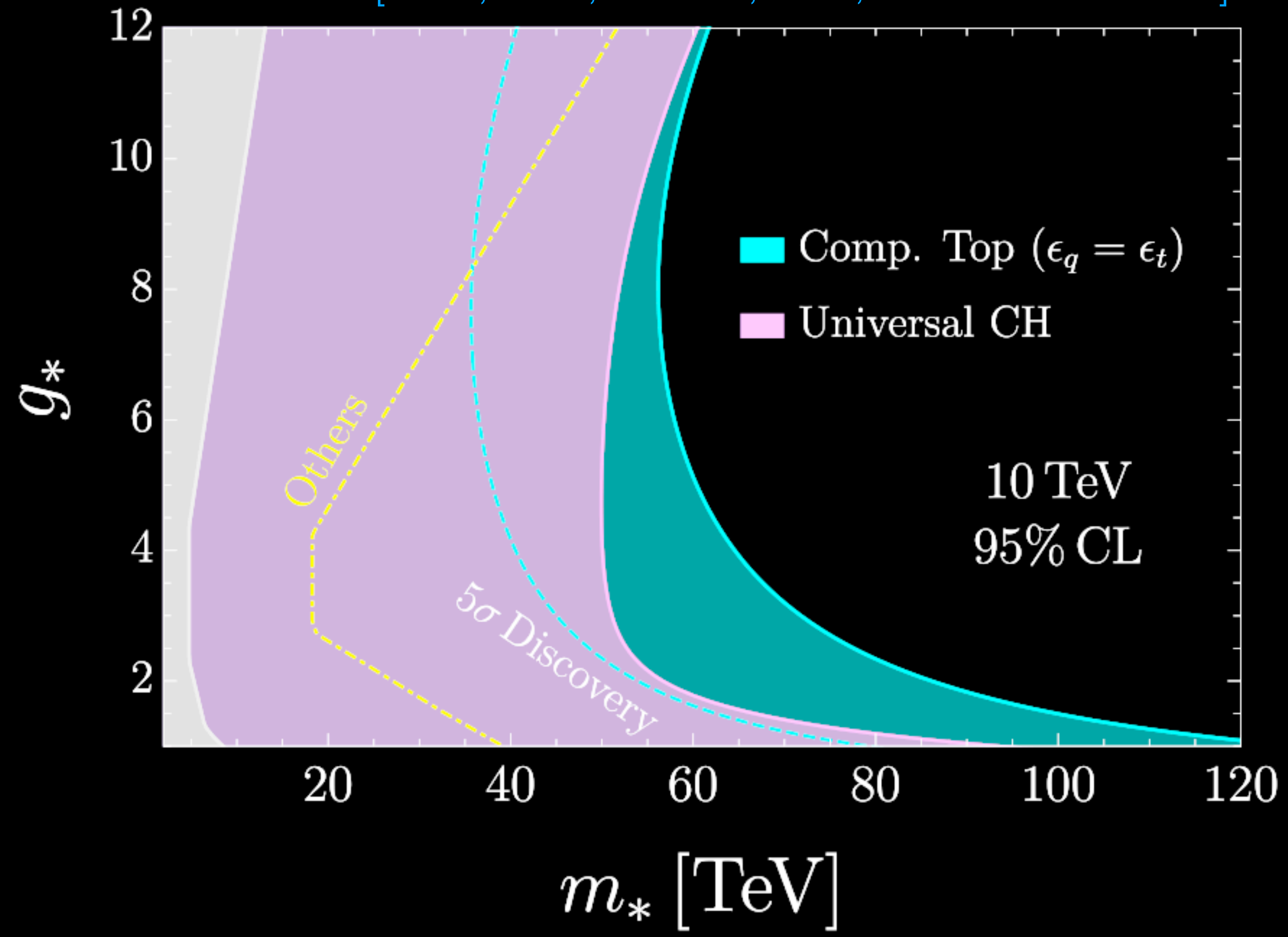
$$\mathcal{O}_B = ig'(H^\dagger D_\mu H)\partial^\nu B_{\mu\nu}$$

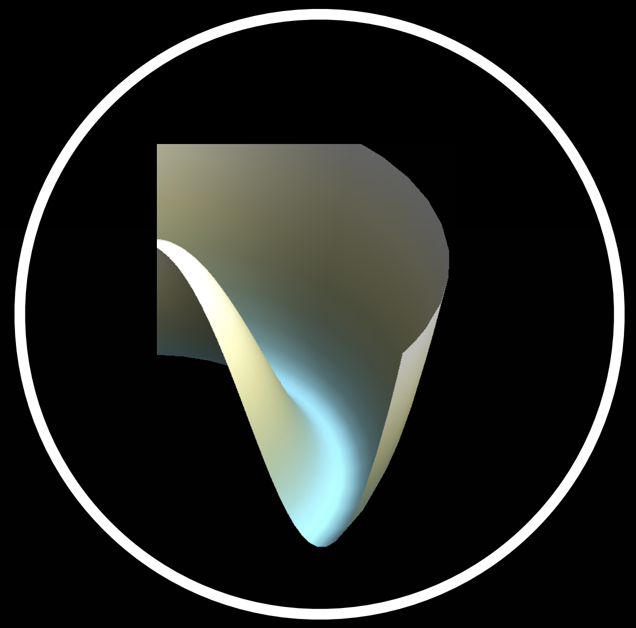
$$\mathcal{O}_{tD} = (\bar{t}\gamma^\mu t)(\partial^\nu B_{\mu\nu})$$

Splendid example of precision from energy…

(See also [Buttazzo, Franceschini, Wulzer 2012.11555])

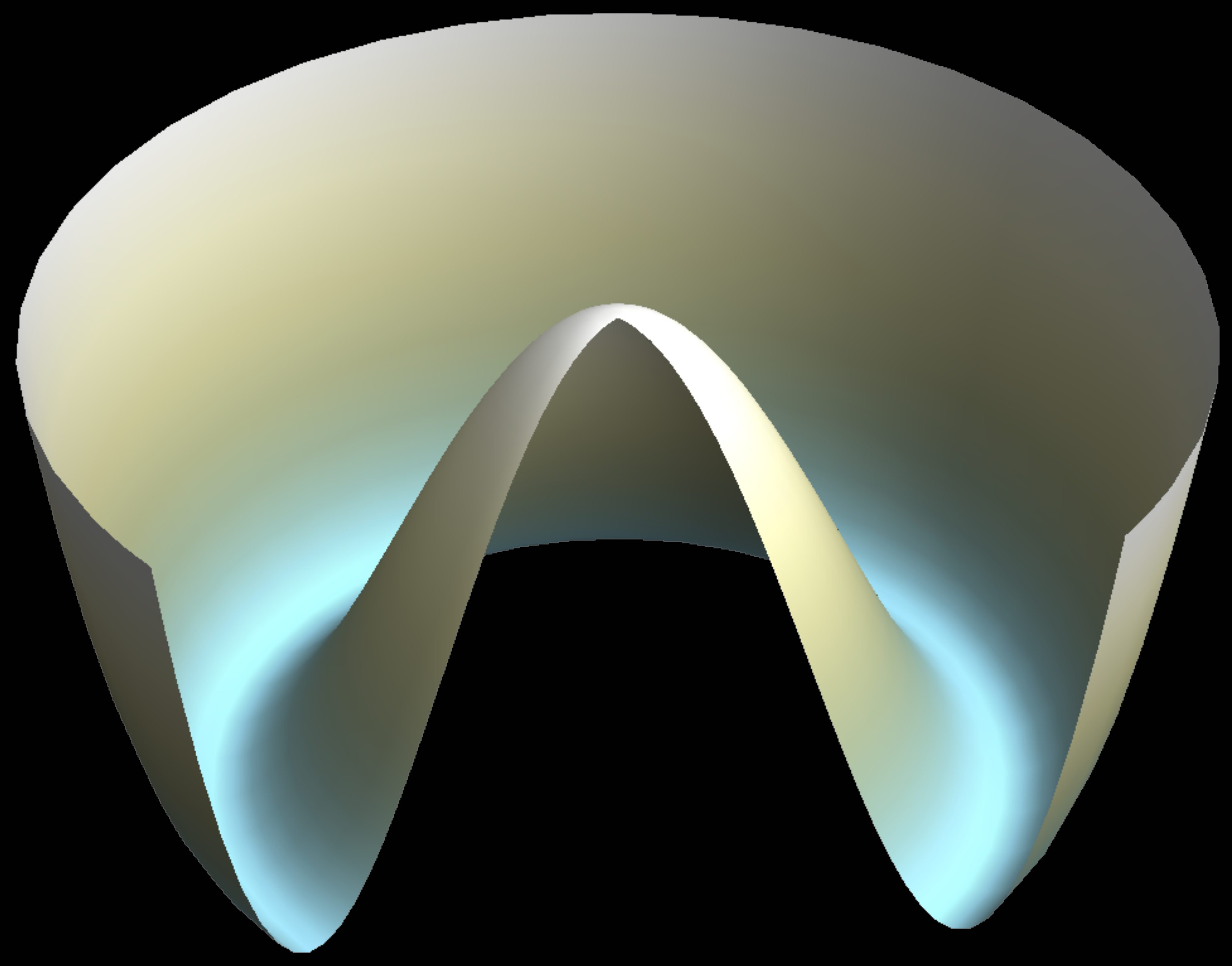
[Chen, Glioti, Rattazzi, Ricci, Wulzer 2202.10509]

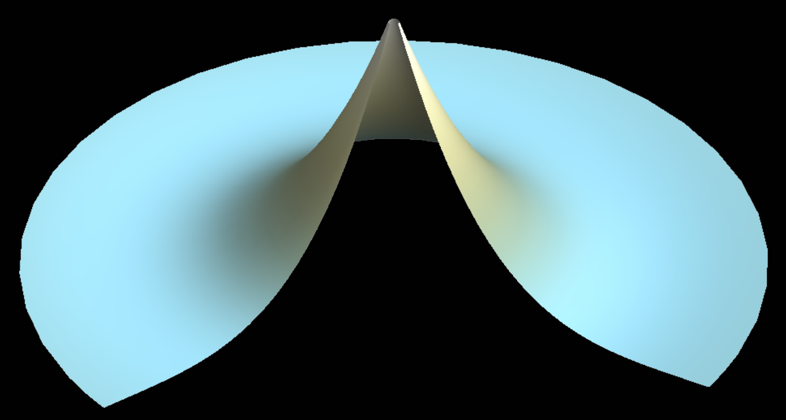


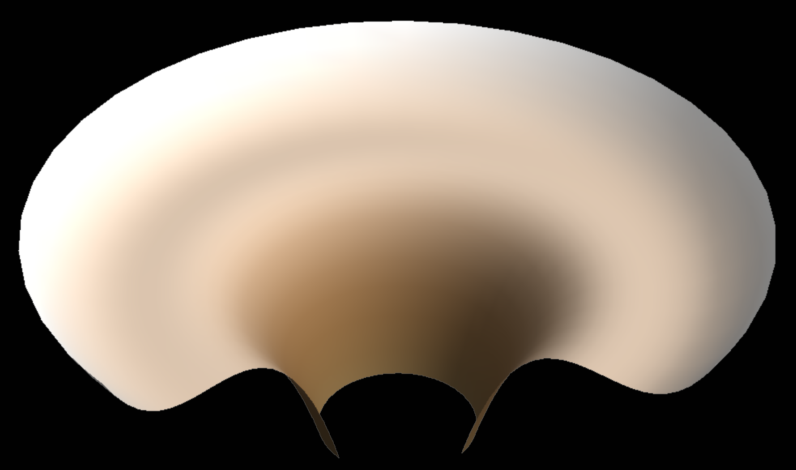


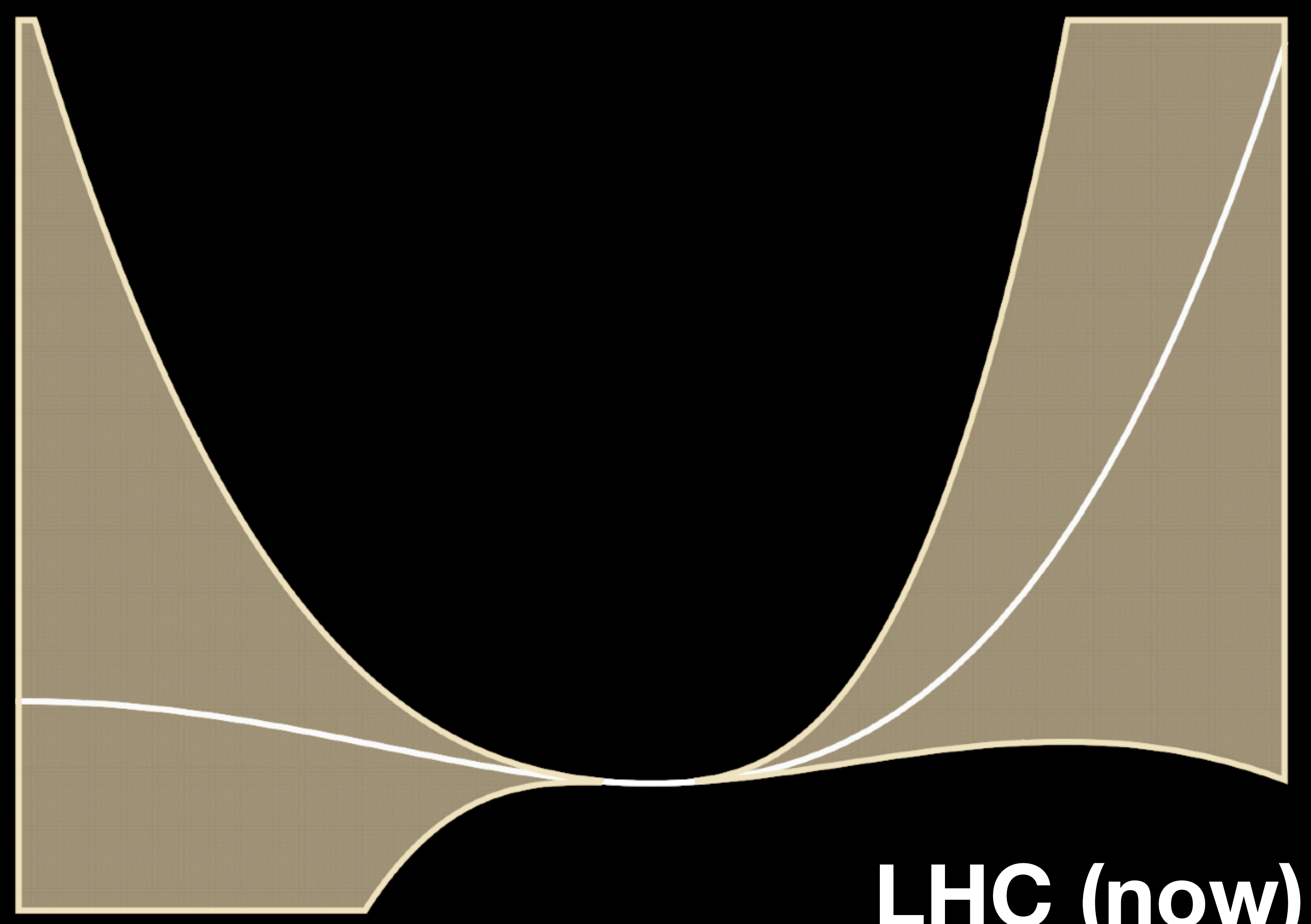
Electroweak Breaking

Our current experimental knowledge of the Higgs potential is far from the cartoon we usually show…





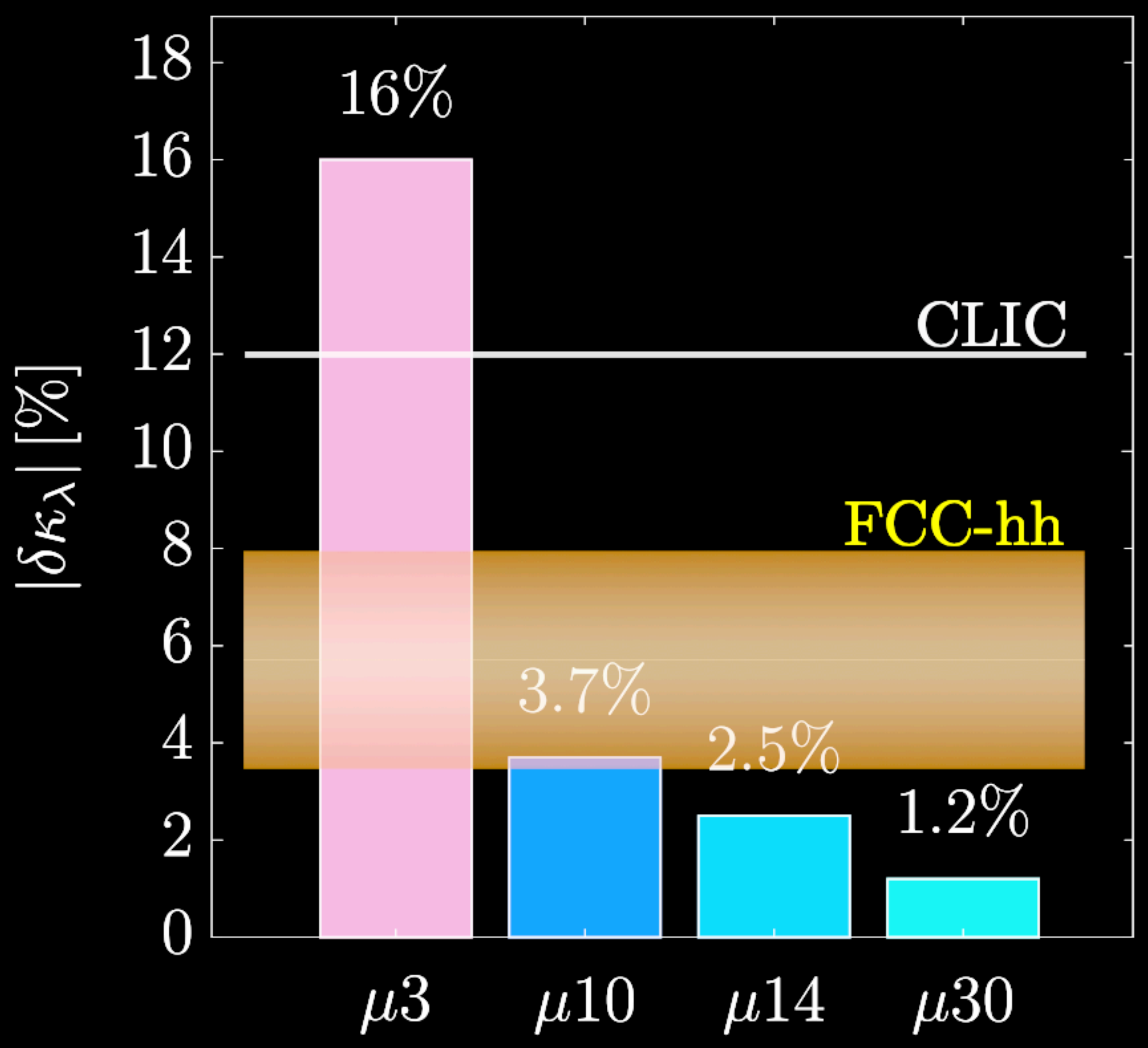




(If you like this way of presenting Higgs self-coupling precision, feel free to use it w/ credit to R. Petrossian-Byrne.)

Electroweak Breaking

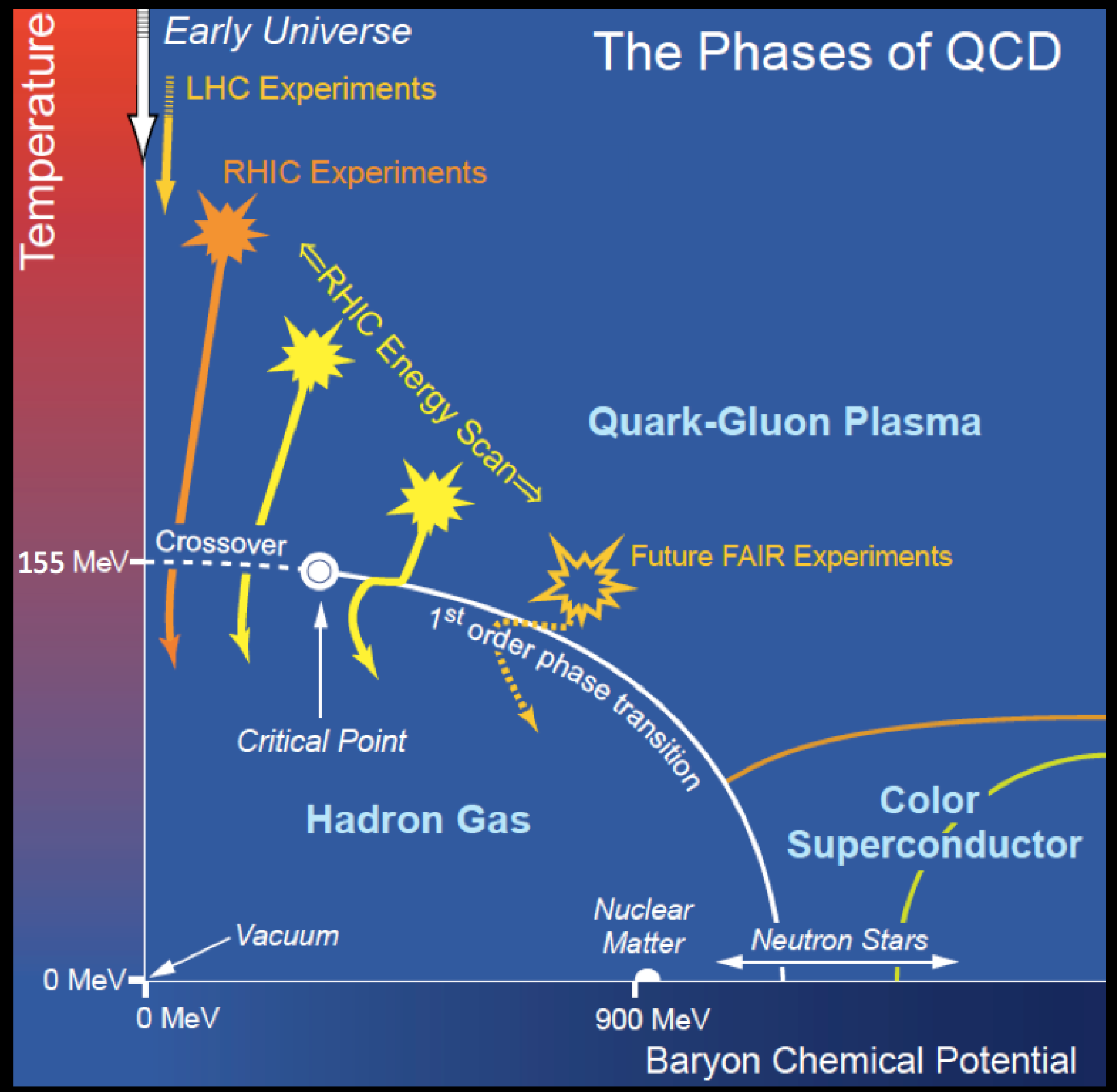
[Accettura et al. 2303.08533]



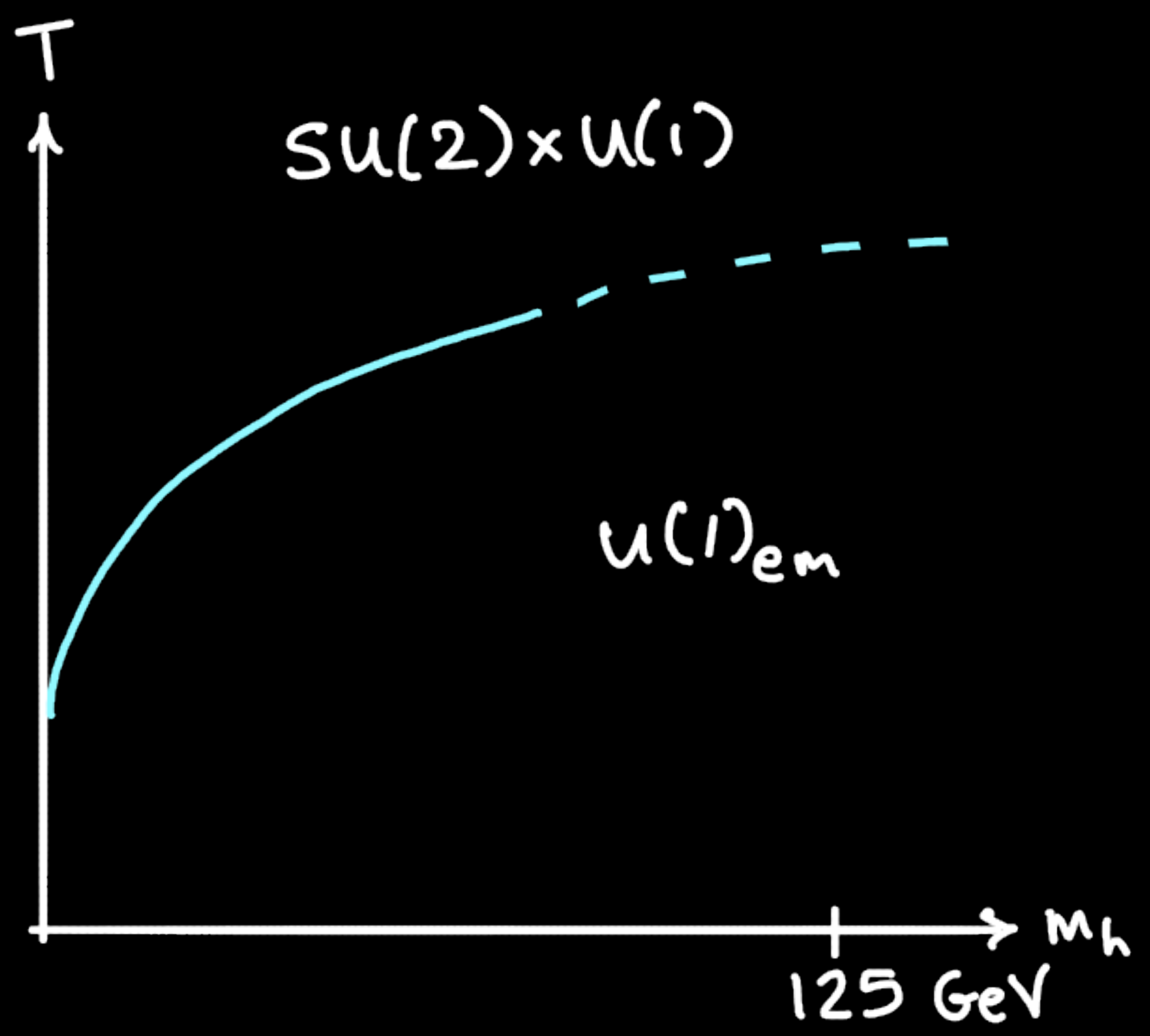
HL-LHC

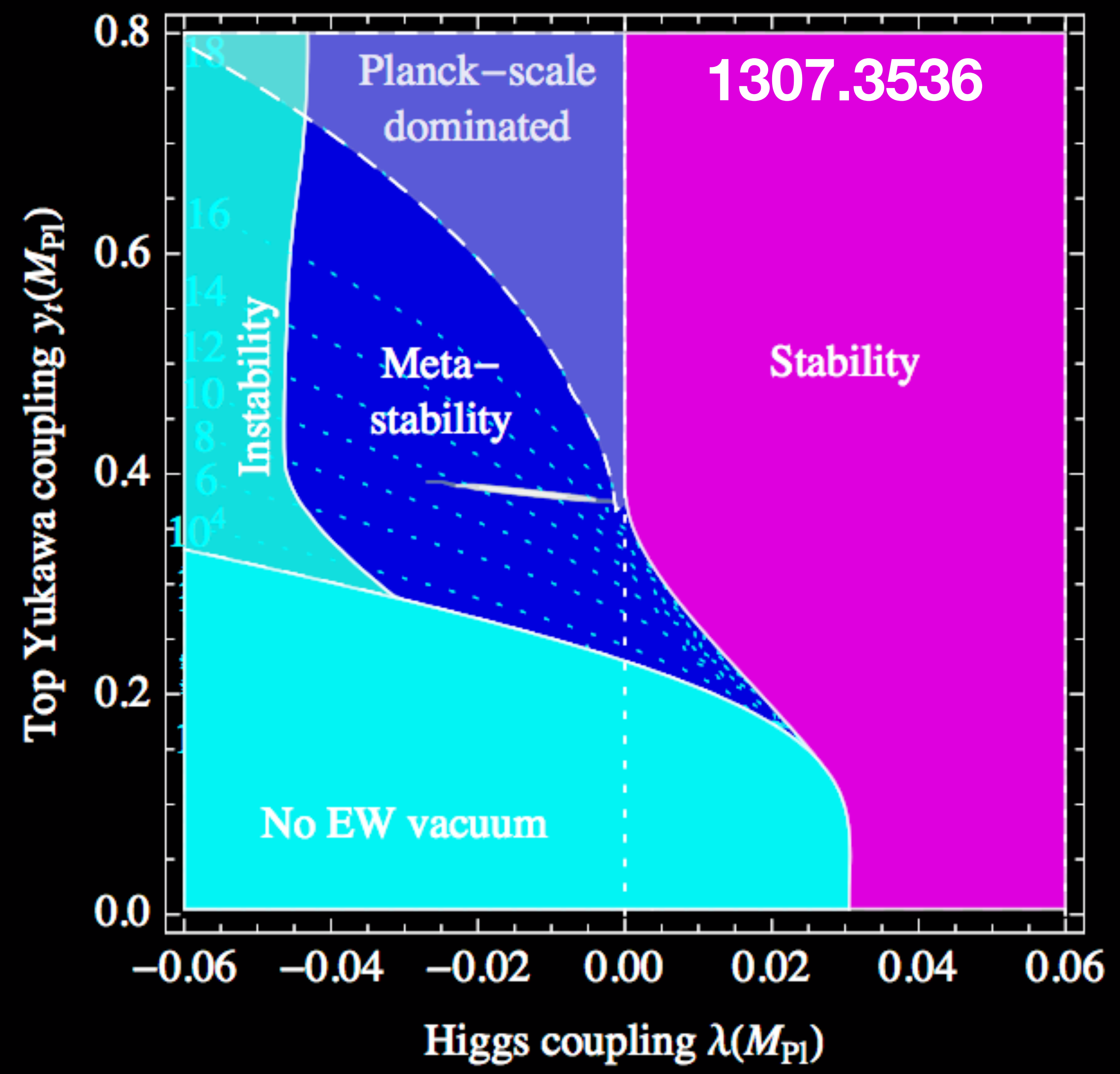
μC (10 TeV)

The birth and death of the Universe?



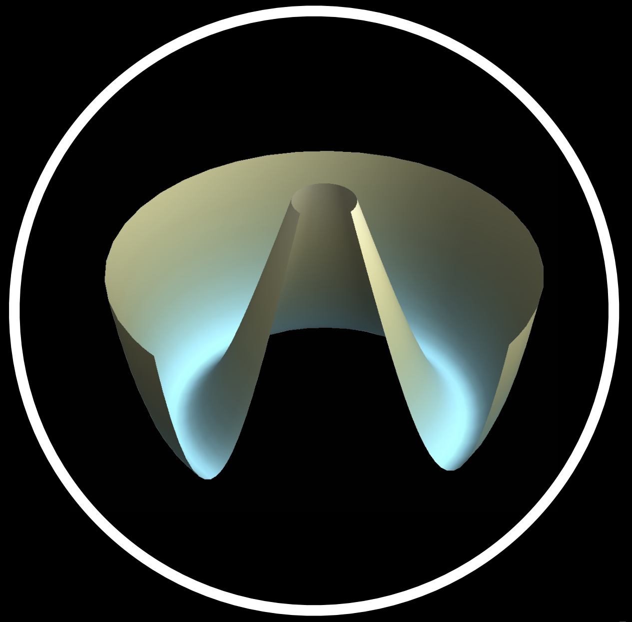
[2015 NSAC LRP / 1501.06477]





First-order electroweak phase transition?

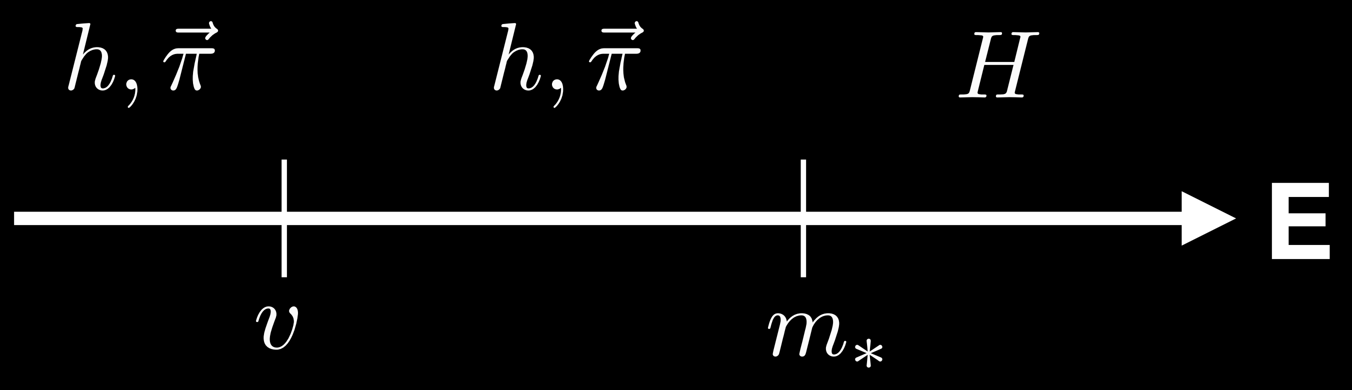
Vacuum stability?

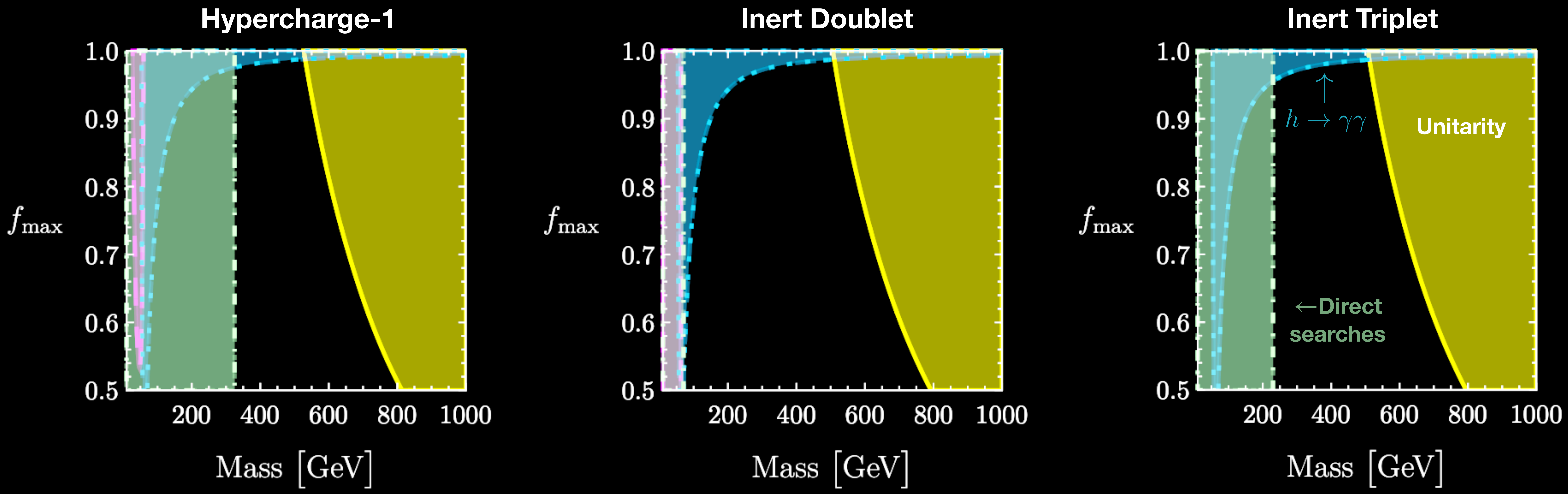


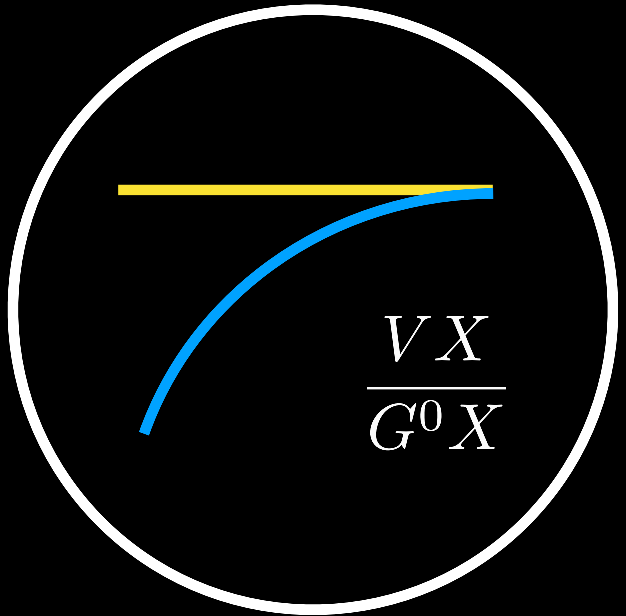
Electroweak Symmetry?

Local EFT of the Higgs does not have electroweak symmetry given e.g. extra EWSB or heavy particles acquiring >1/2 mass from Higgs. Many examples viable, fully covered by 10 TeV μC.

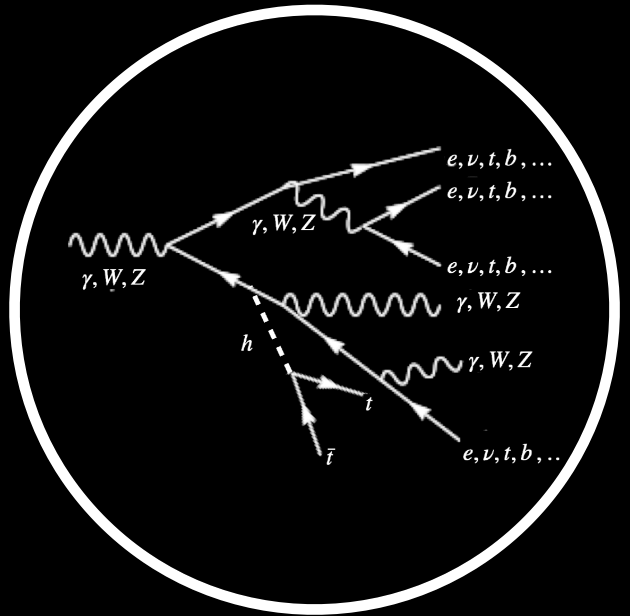
[Banta, Cohen, NC, Lu, Sutherland, 2110.02967]



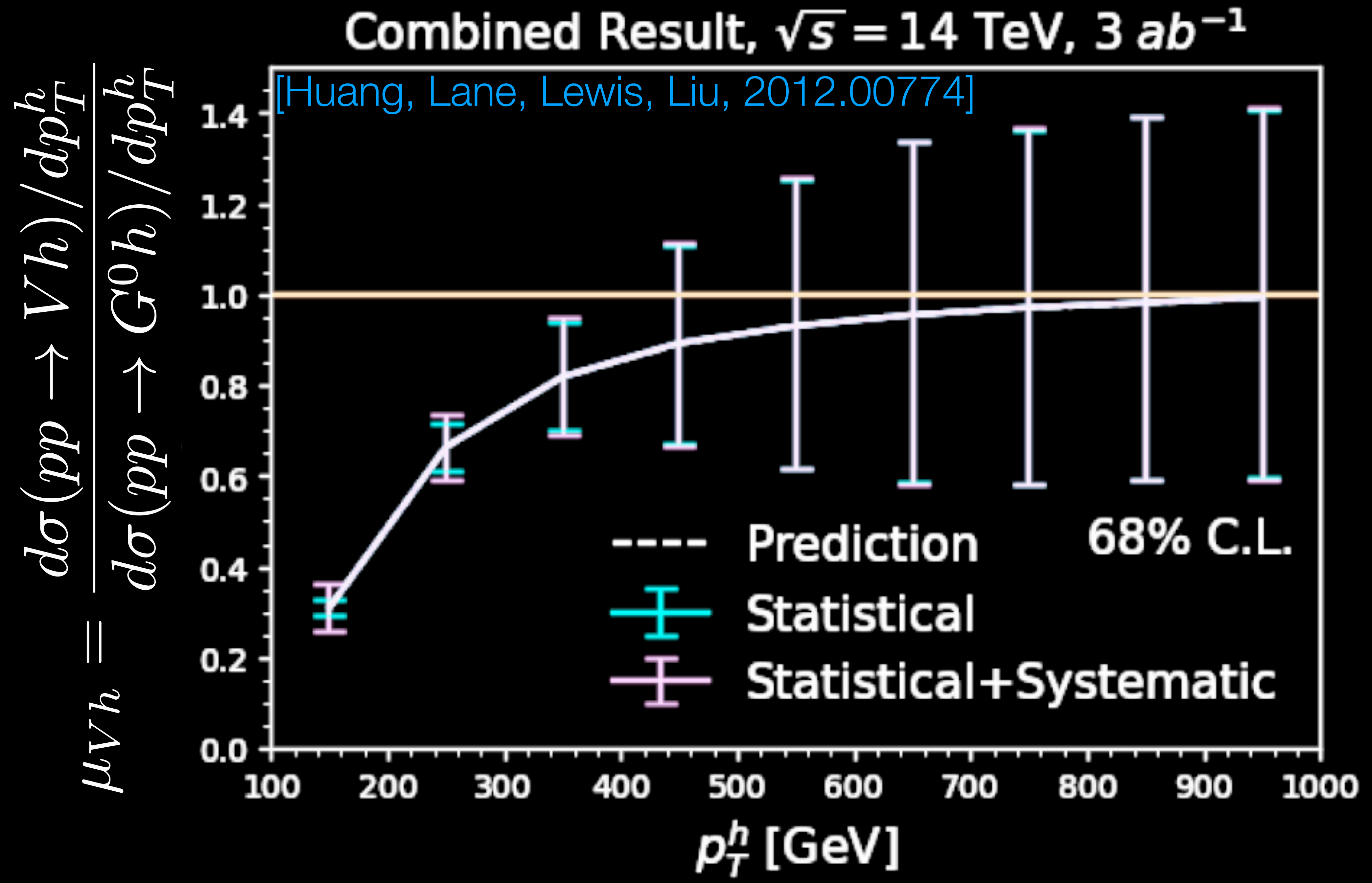




Electroweak Restoration, Electroweak Radiation

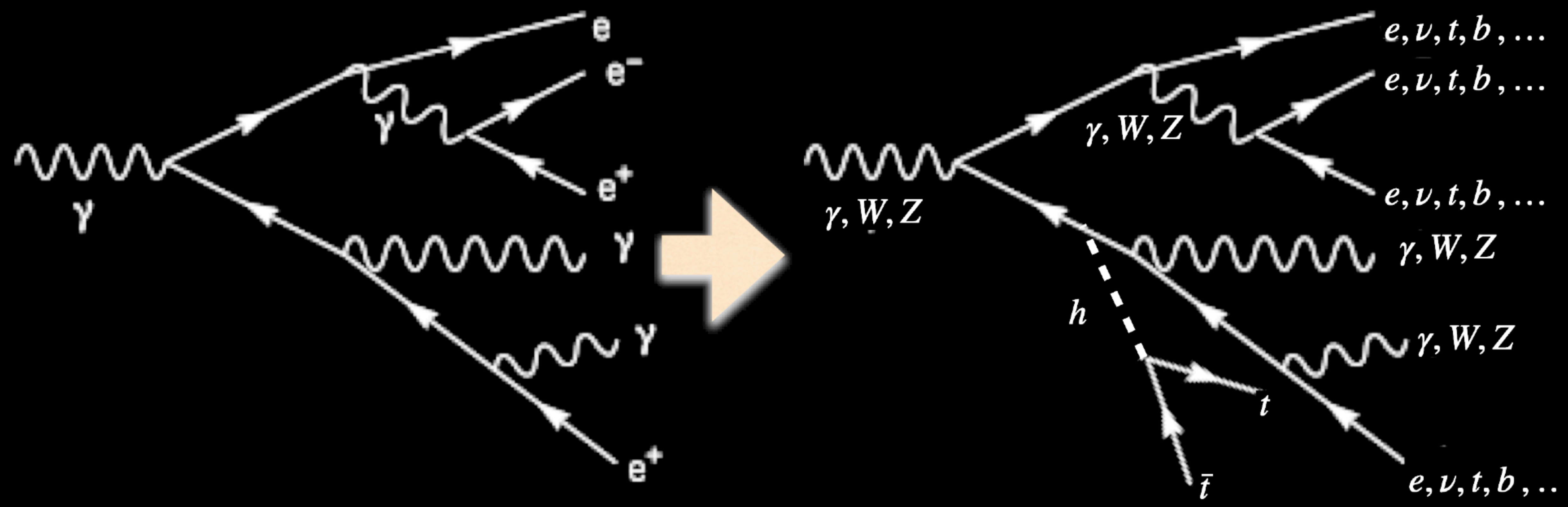


Experimentally demonstrate
Goldstone equivalence



Electroweak radiation:
Sudakov suppression of non-emission
probability becomes significant @ 10 TeV…

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



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

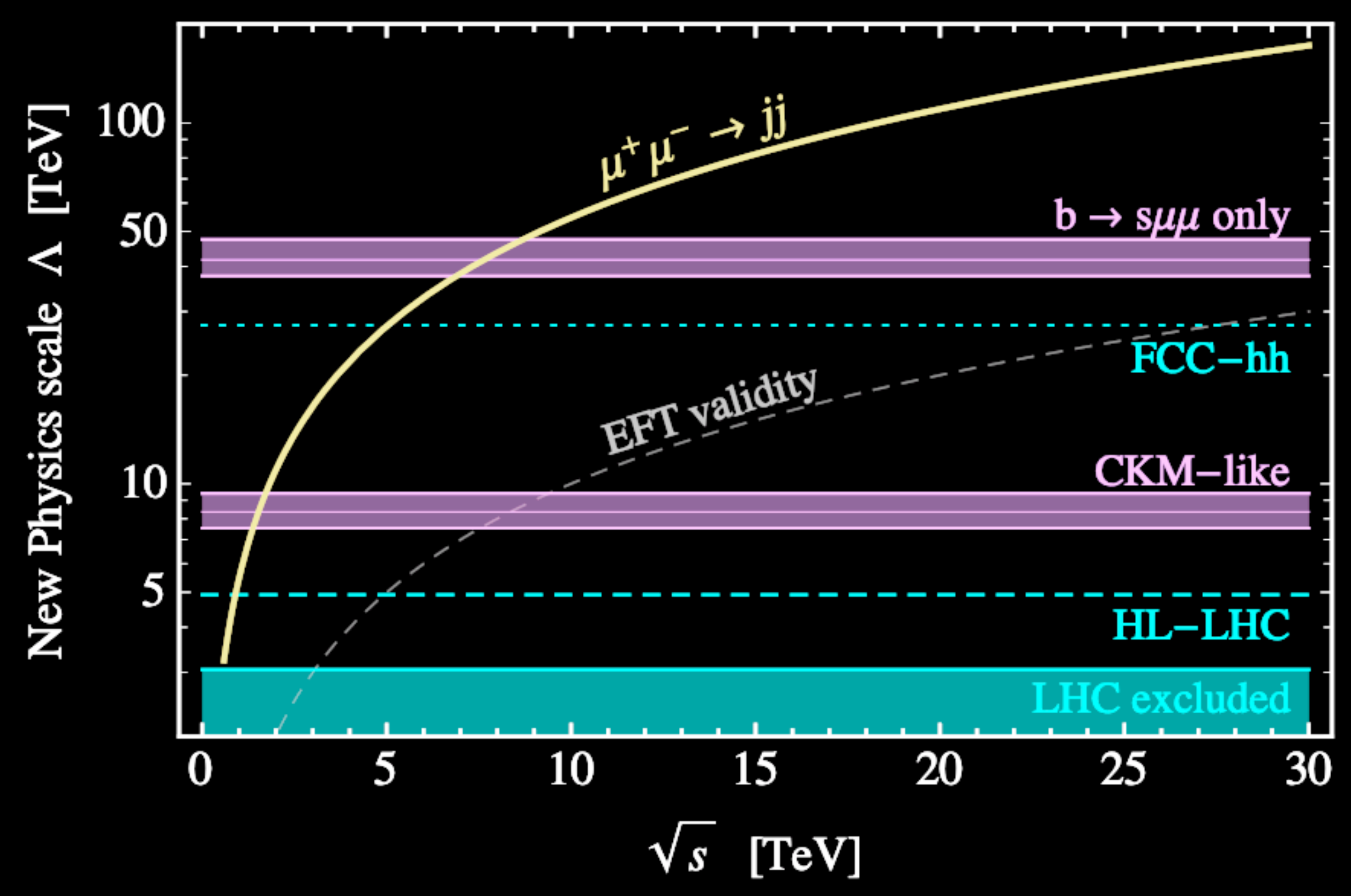
What is the origin of flavor?

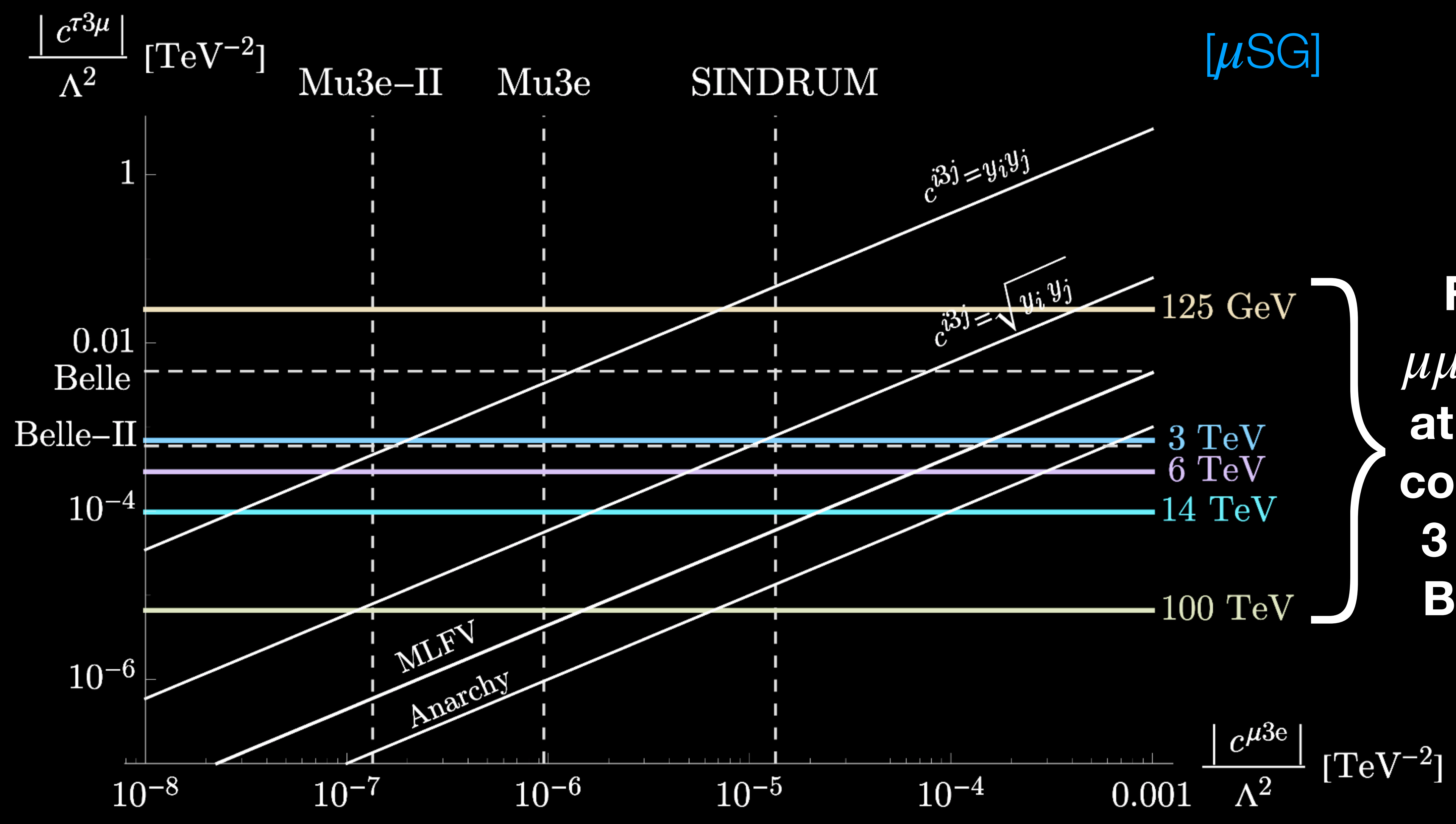
First high-energy accelerator to primarily collide second-generation fermions.

Direct access to hypothetical new particles associated with flavor structure

Indirect access to flavor structure via lepton flavor violating operators

[IMCC Muon Collider Physics Summary]





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

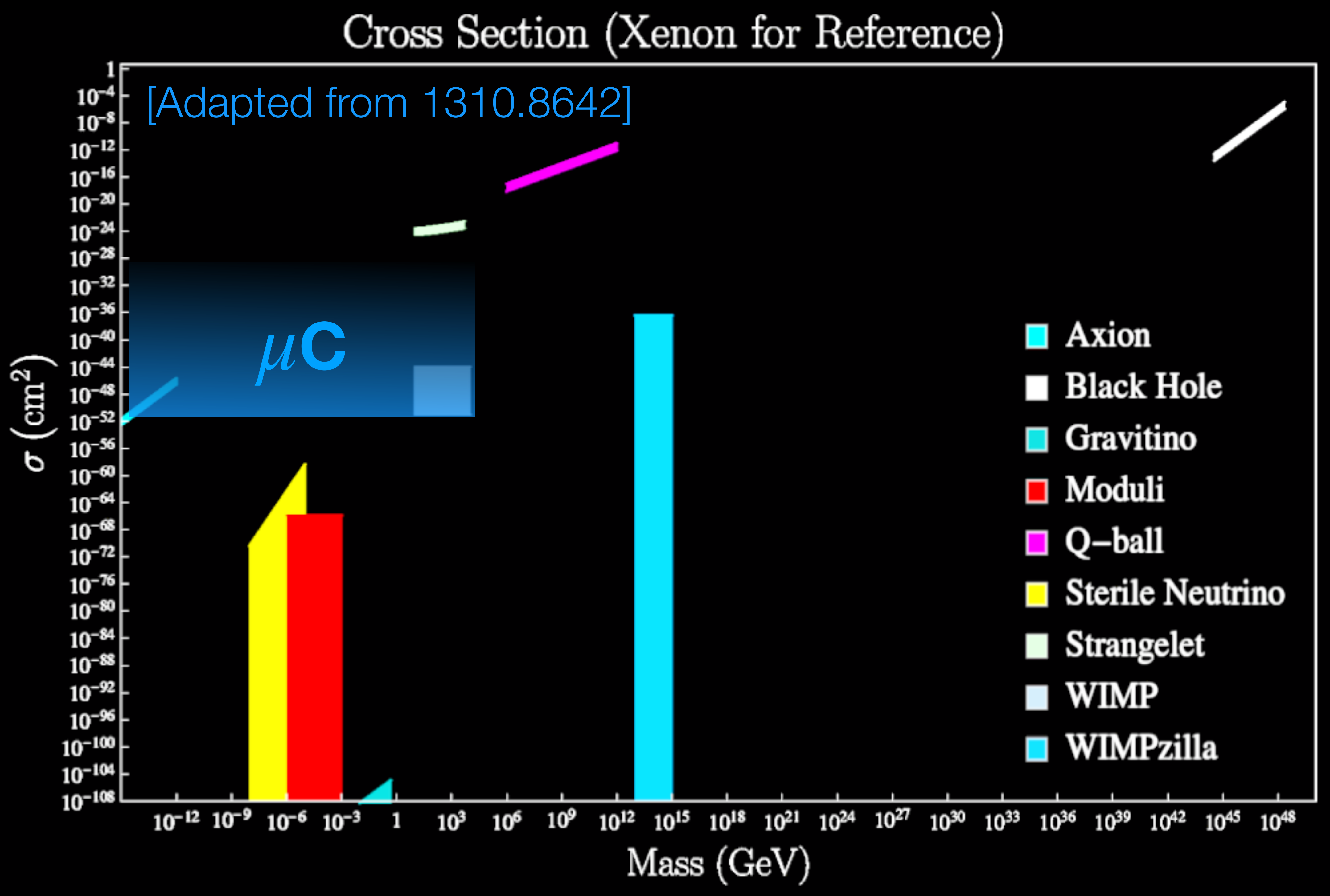
An outstanding probe of explanations for B flavor anomalies, indicative of complementarity w/ future signs of flavor violation.

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

What is the nature of dark matter?

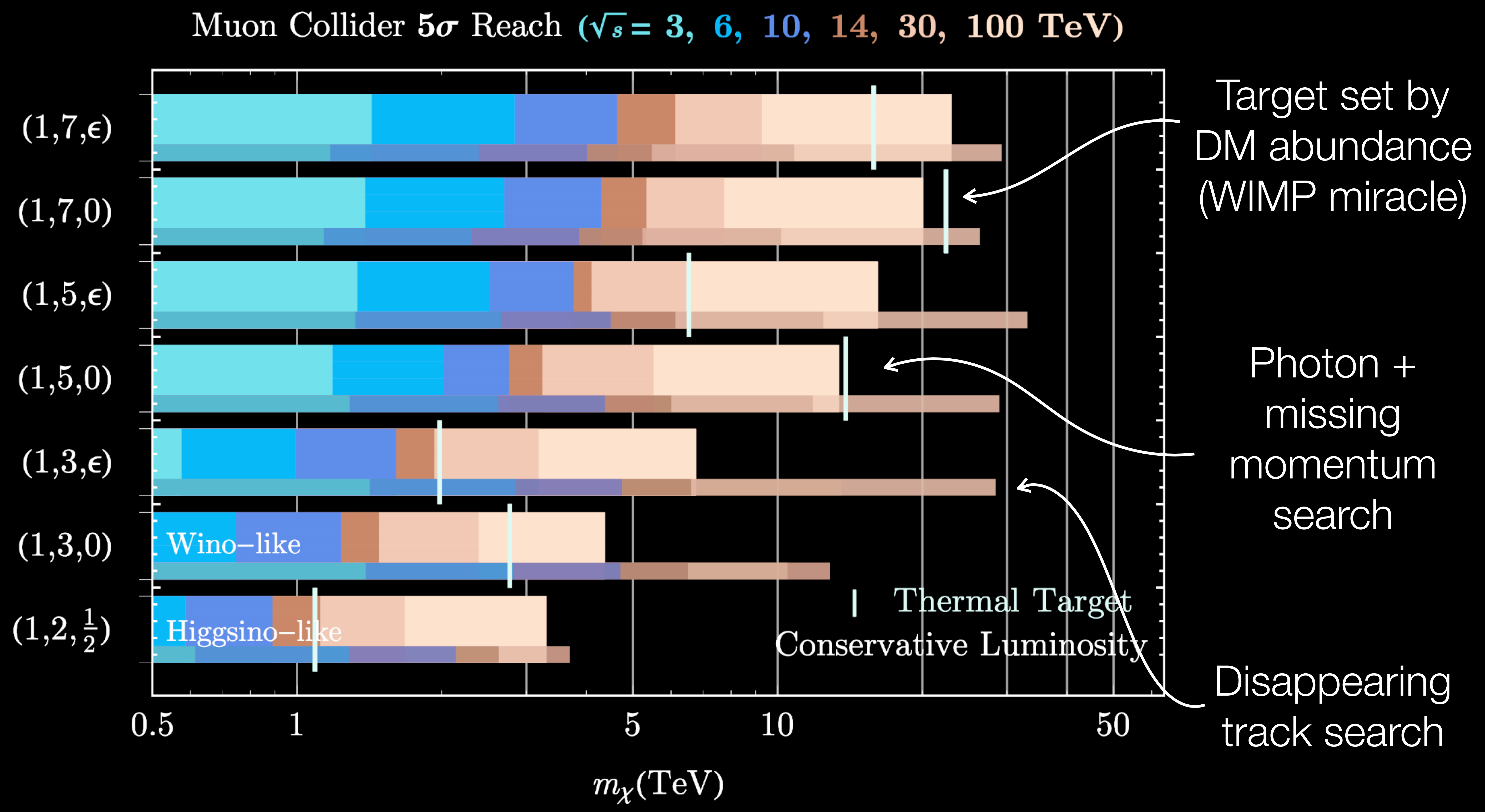
An ideal laboratory for producing & detecting weakly-interacting dark matter.

We know DM is there; coincidence of Ω_b, Ω_{dm} suggests interactions beyond gravitational



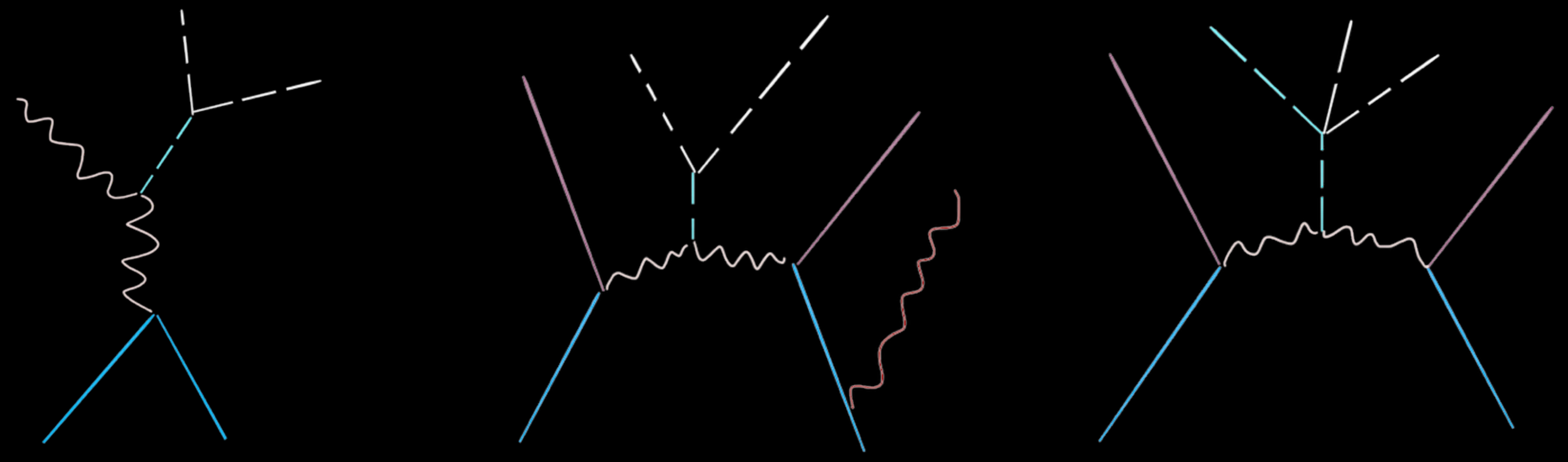
"Minimal dark matter"

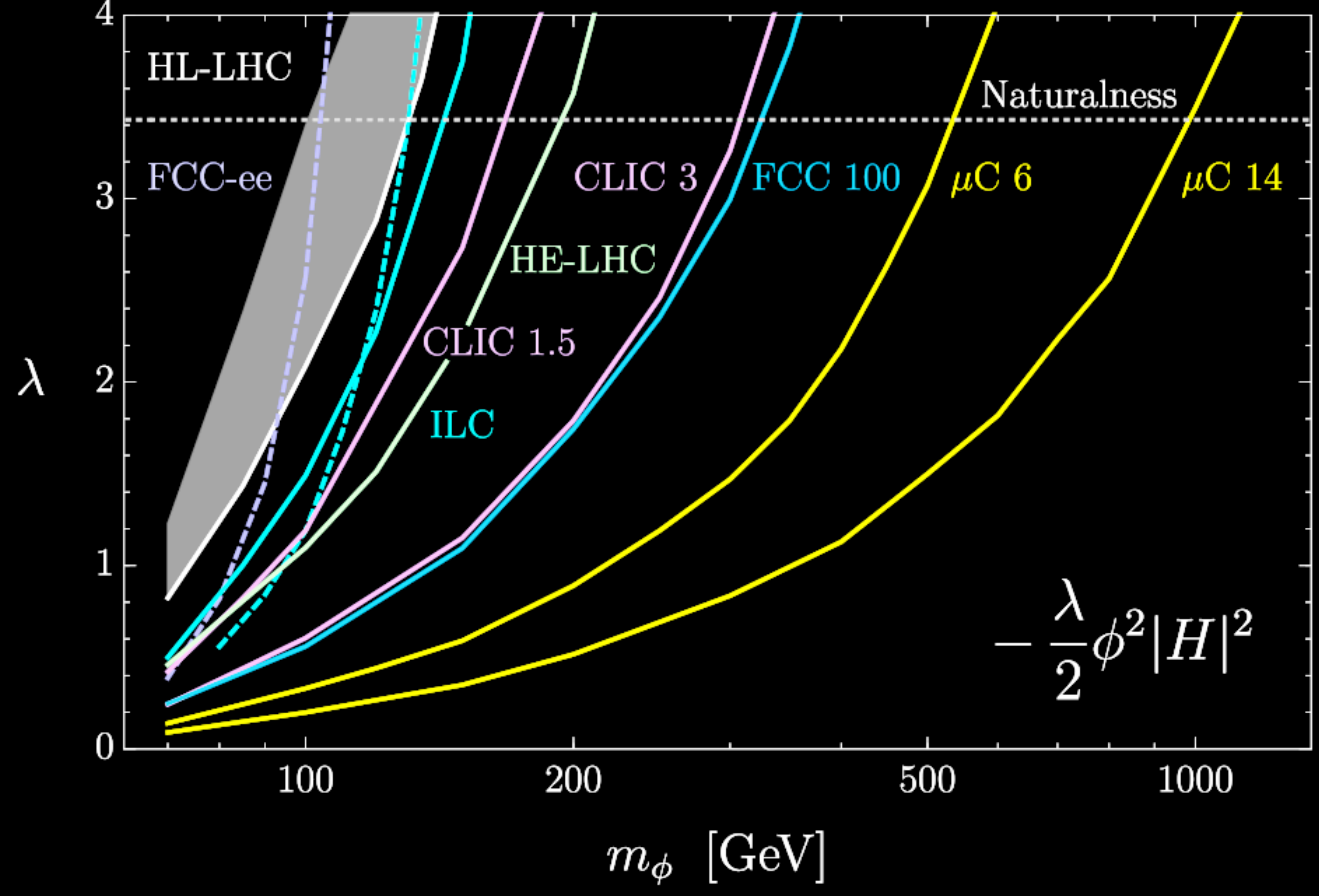
(Electroweak multiplet w/ neutral lightest particle)



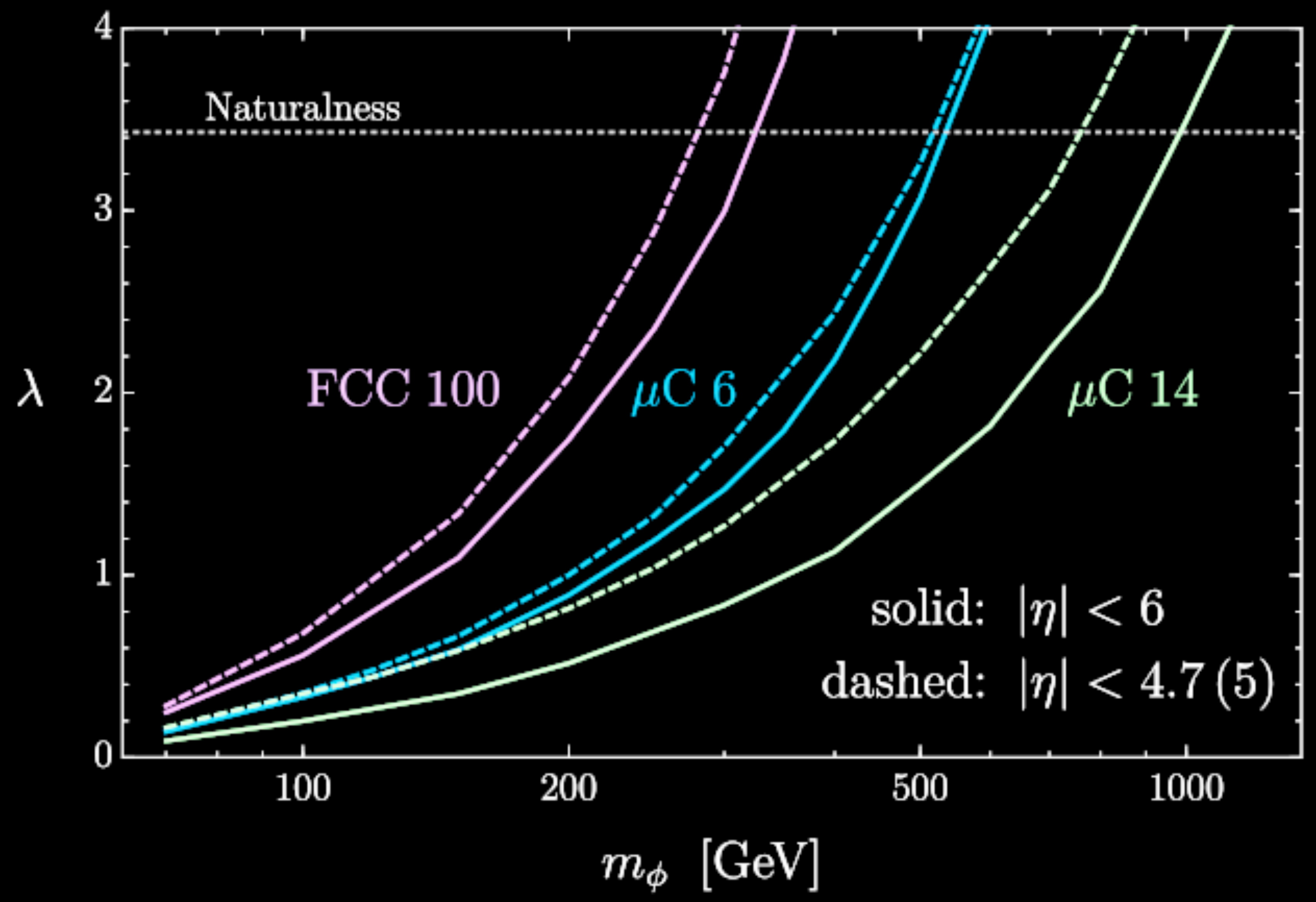
[Han, Liu, Wang, Wang, 2009.11287, lumi updated for μSG], see also [Capdevilla, Meloni, Simoniello, Zurita 2102.11292; Bottaro, Buttazzo et al. 2107.09688 & 2205.04486]

Higgs Portal DM

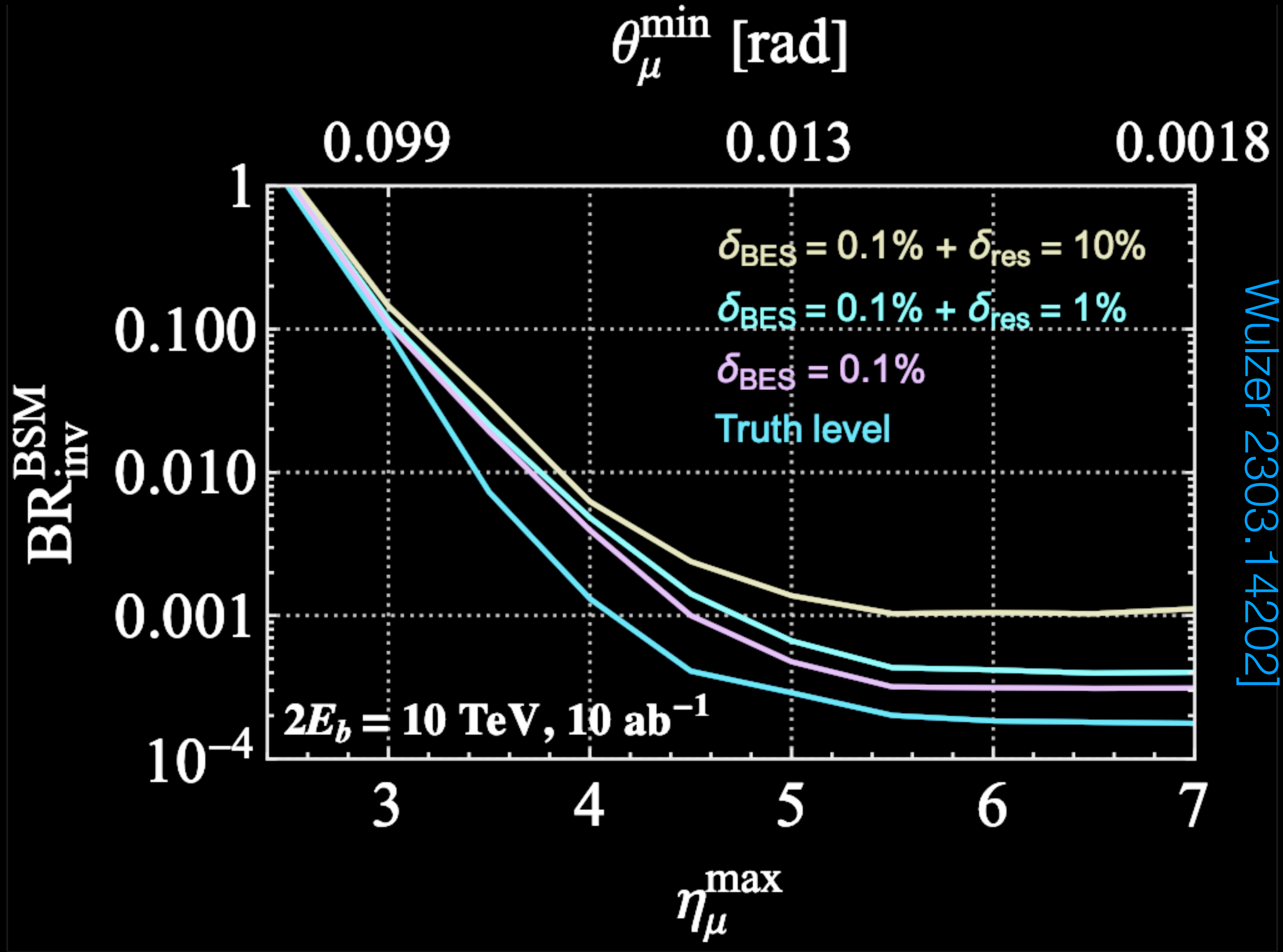




[Ruhdorfer, Salvioni, Weiler 1910.04170]



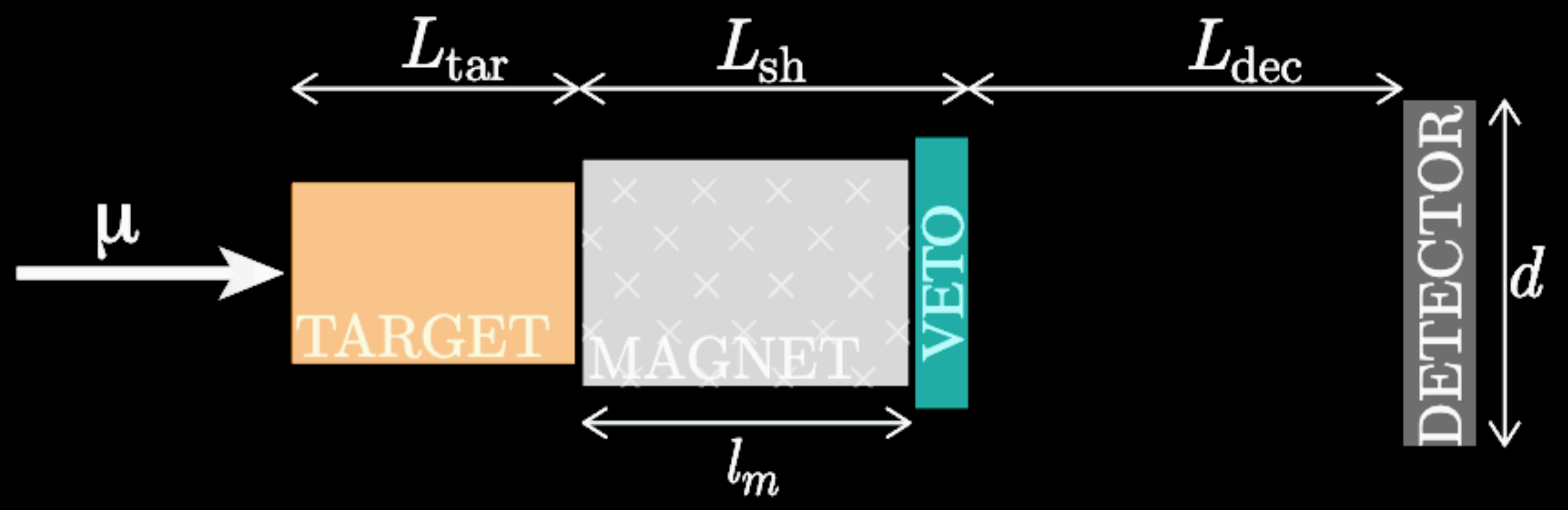
[1910.04170]

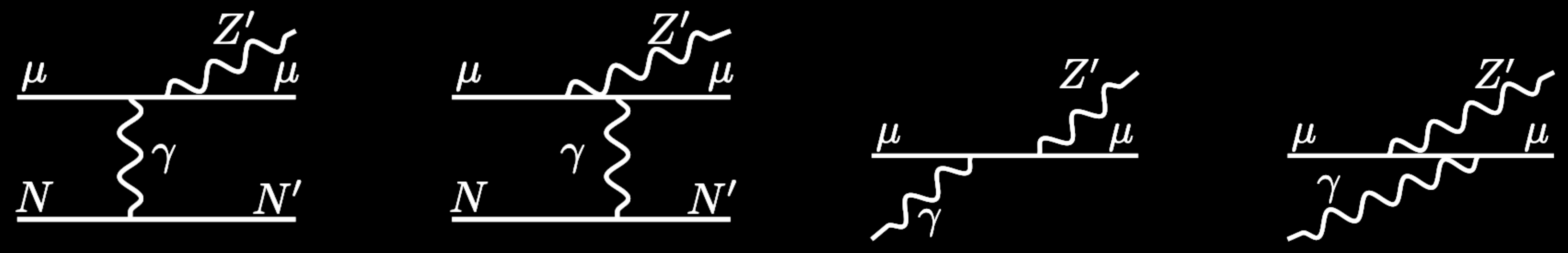


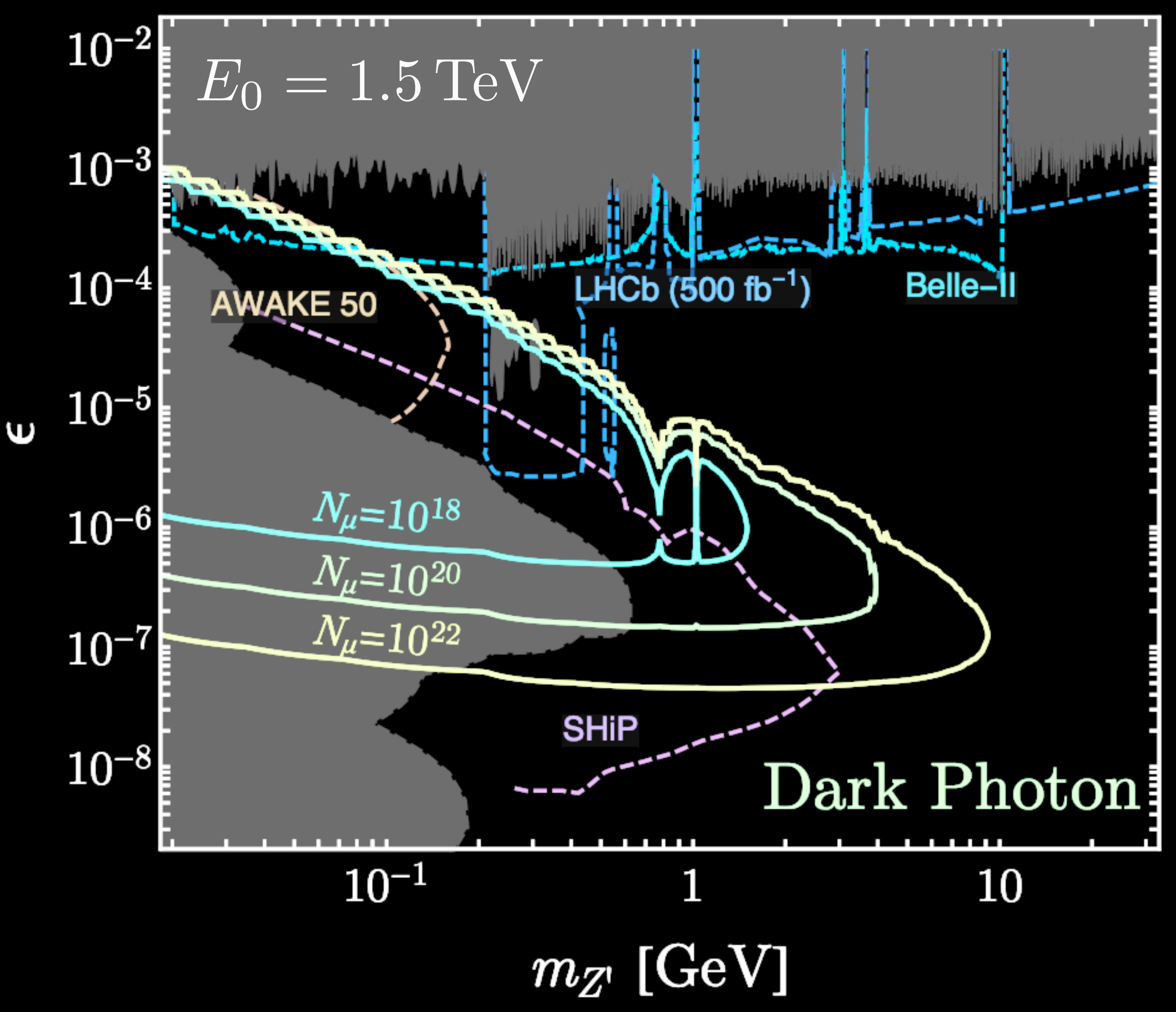
[Ruhdorfer, Salvioni, Wulzer 2303.14202]

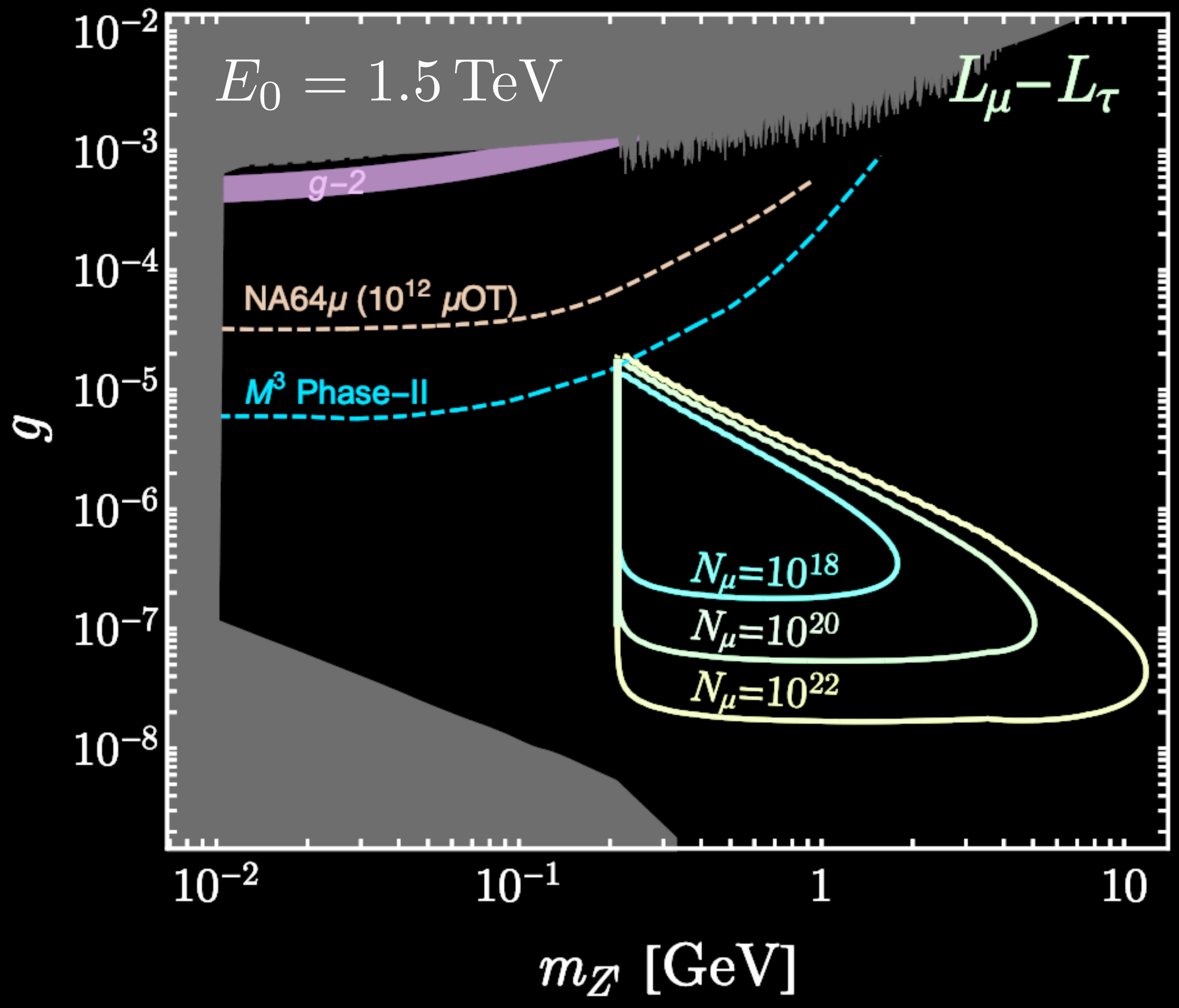
[Cesarotti, Homiller, Mishra, Reece 2202.12302]

Dark Portals: μC Beam Dump?



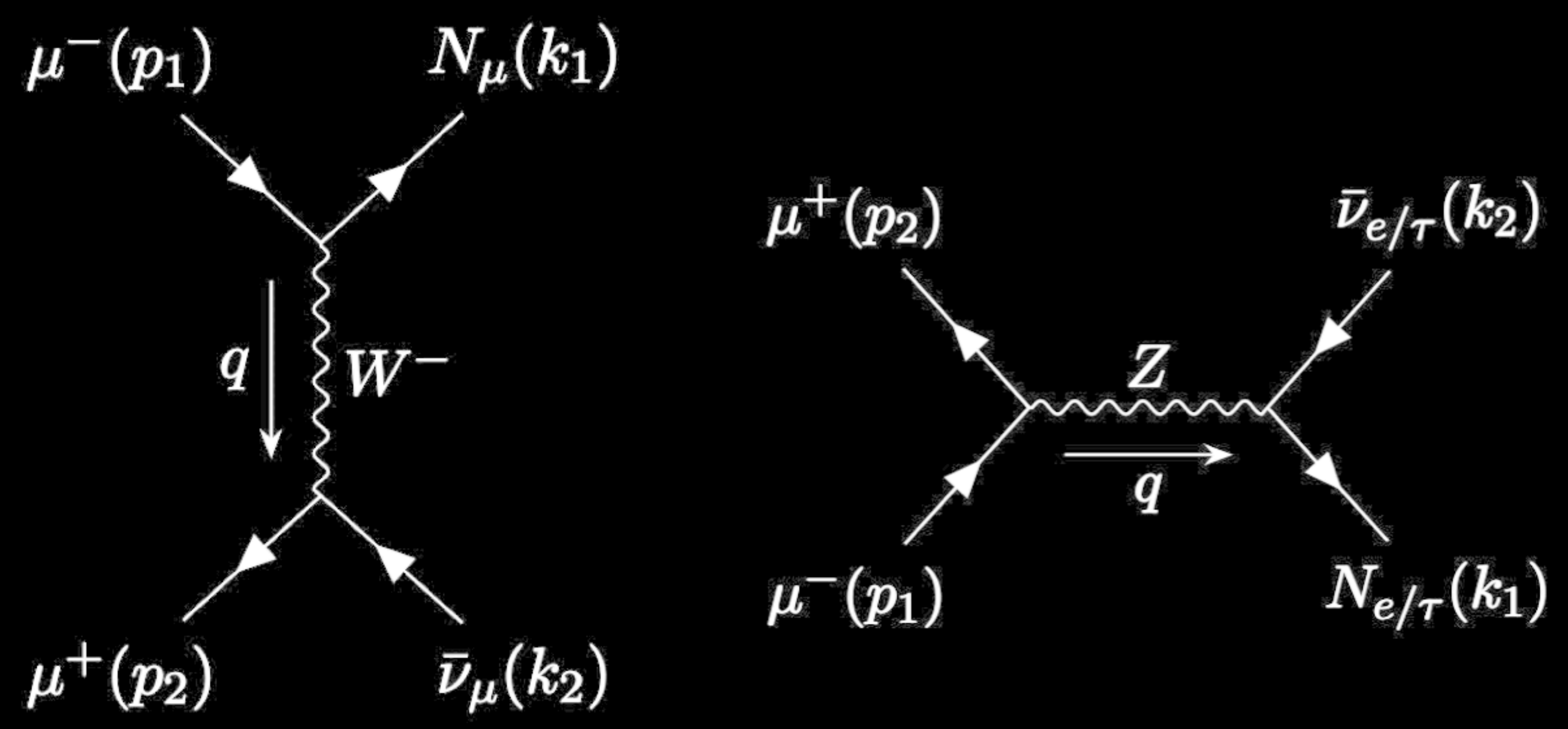


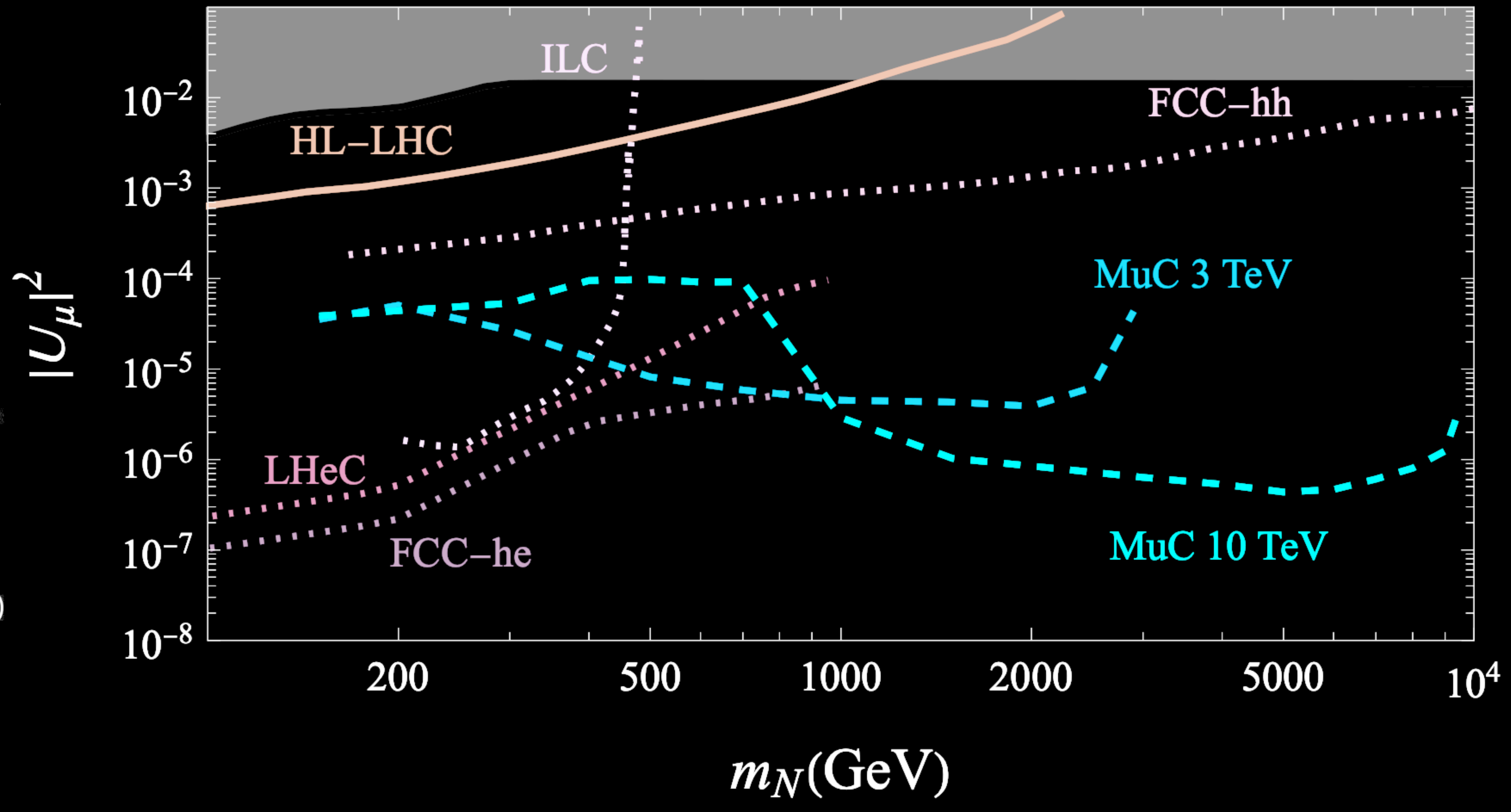




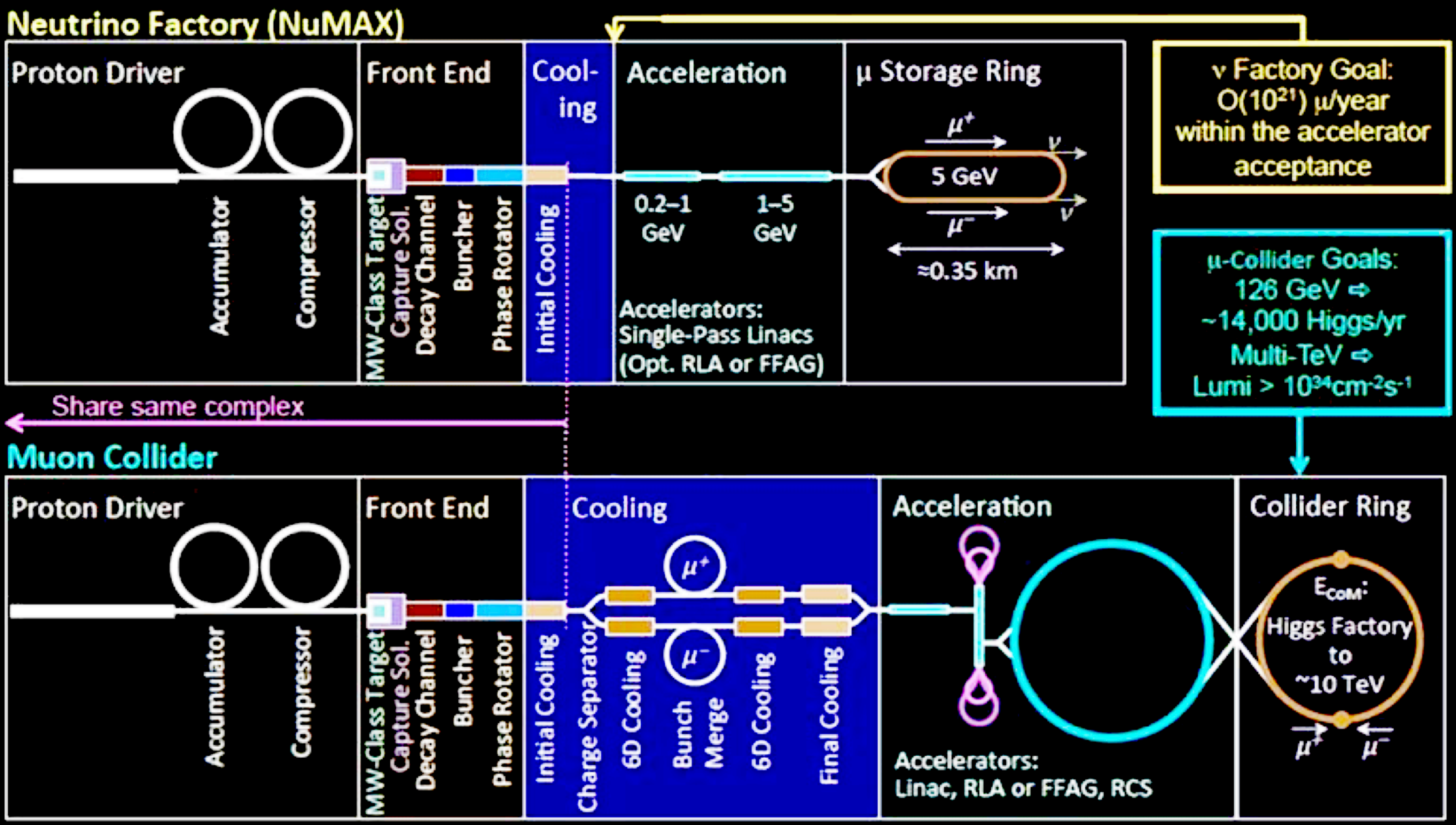
Nature of the Neutrino Sector: Heavy Neutral Leptons

$$\mathcal{L} \supset -\lambda_\nu \bar{L}\tilde{H}N - \frac{m_N}{2}\bar{N}^c N + \text{h.c.}$$



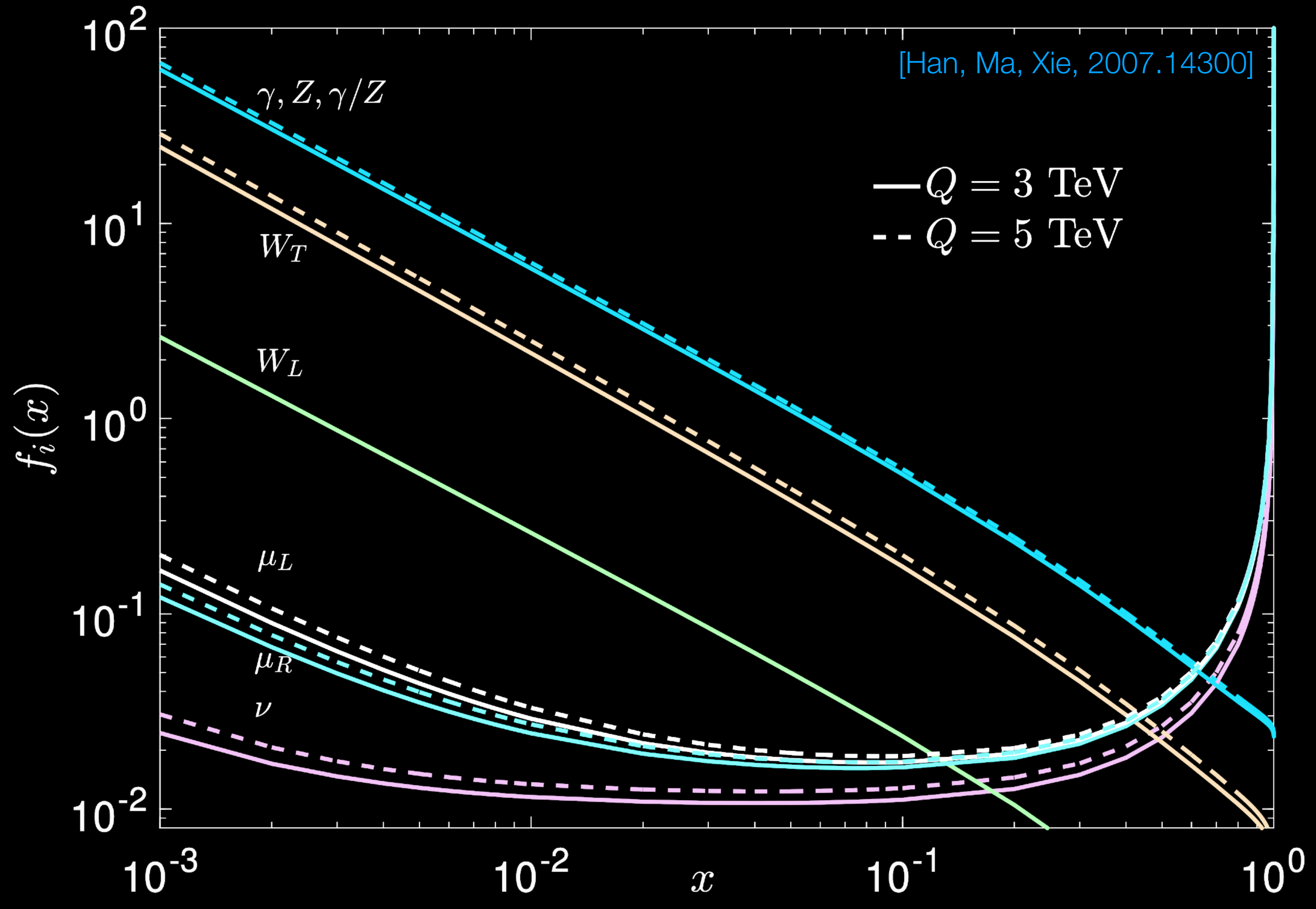


μC/νF Complementarity



[Delahaye et al. 1803.07431]

High-energy Neutrinos?

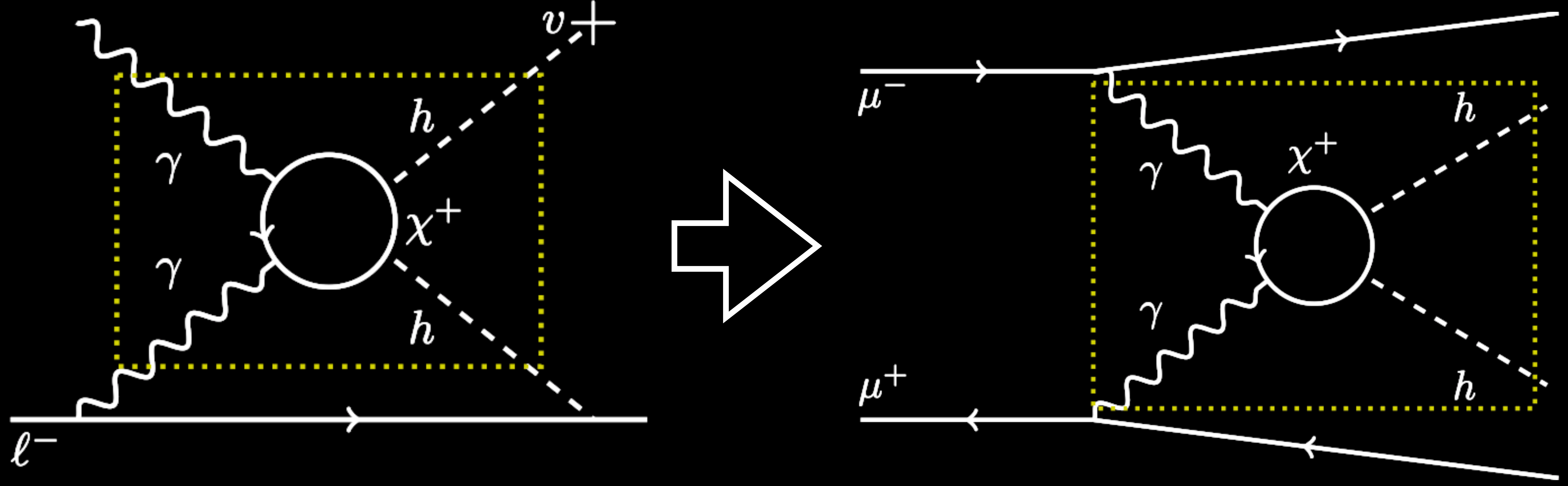


- Neutrino radiation for high-energy fixed target? Akin to FASERν but w/ well-known neutrino flavor composition & spectrum, narrow beam.
- Neutrino-neutrino or neutrino-charged lepton collisions? Probe neutrino interactions, dark sector portals, …

Compelling complementarity

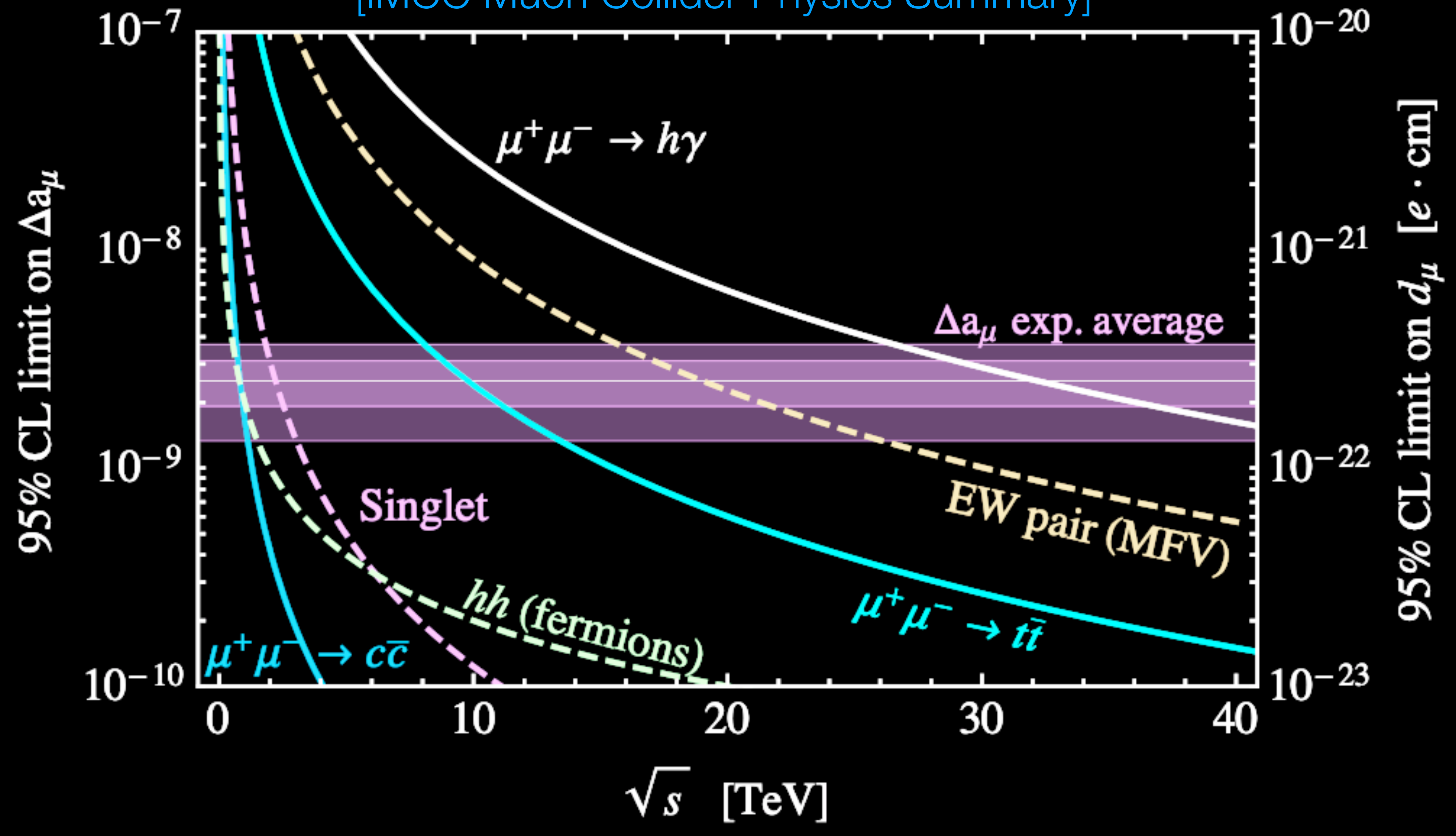
E.g. next-gen. **electron EDM** experiments sensitive to ~20 TeV particles in Barr-Zee diagrams; same diagram probed in muon colliders

(See also: [Homiller, Lu, Reece 2203.08825])



Any new physics contributions to **Muon g-2** efficiently probed at muon colliders [Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277; Buttazzo & Paradisi, 2012.02769; Capdevilla, Curtin, Kahn, Krnjaic, 2101.10334; Chen, Wang, Yao 2102.05619; Yin, Yamaguchi 2012.03928]

[IMCC Muon Collider Physics Summary]



Conclusions

Conclusions

High-energy muon colliders offer the energy, precision, and interactions needed to realize the promise of the electroweak era.

Conclusions

High-energy muon colliders offer the energy, precision, and interactions needed to realize the promise of the electroweak era.

From development to operation, a muon collider will build countless bridges to the diverse frontiers of high-energy physics.

Conclusions

High-energy muon colliders offer the energy, precision, and interactions needed to realize the promise of the electroweak era.

From development to operation, a muon collider will build countless bridges to the diverse frontiers of high-energy physics.

The muons are calling, and we must go.

Conclusions

High-energy muon colliders offer the energy, precision, and interactions needed to realize the promise of the electroweak era.

From development to operation, a muon collider will build countless bridges to the diverse frontiers of high-energy physics.

The muons are calling, and we must go.

Thank you!