Image Credit: Tova Holmes

The “Who Ordered That?” Collider

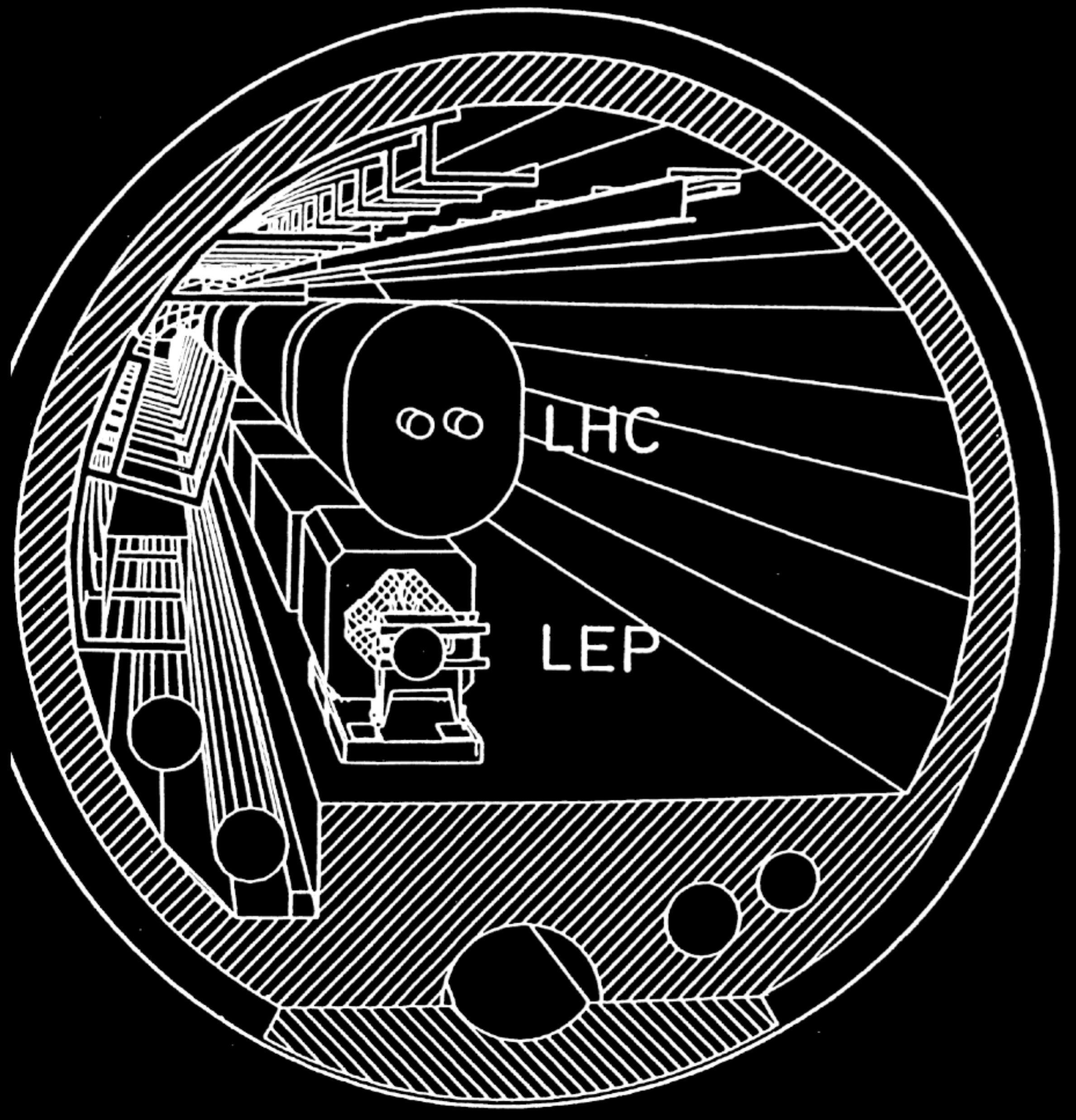
Nathaniel Craig UCSB

Fermilab W&C

26.01.24

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 2024

Vision circa 2024

✓ 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 2024

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+ What is the nature of the neutrino sector?

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+ 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…

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What is the origin of mass?

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"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."

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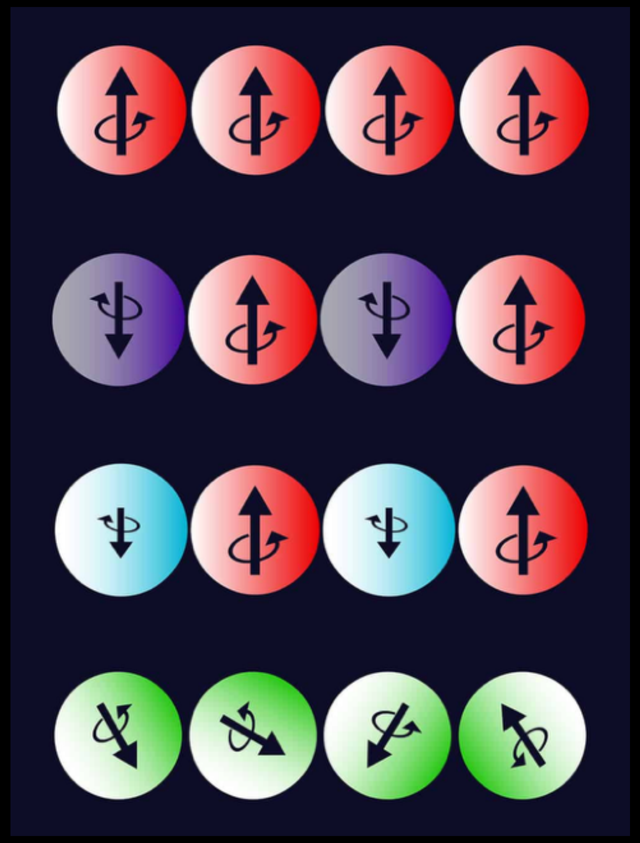
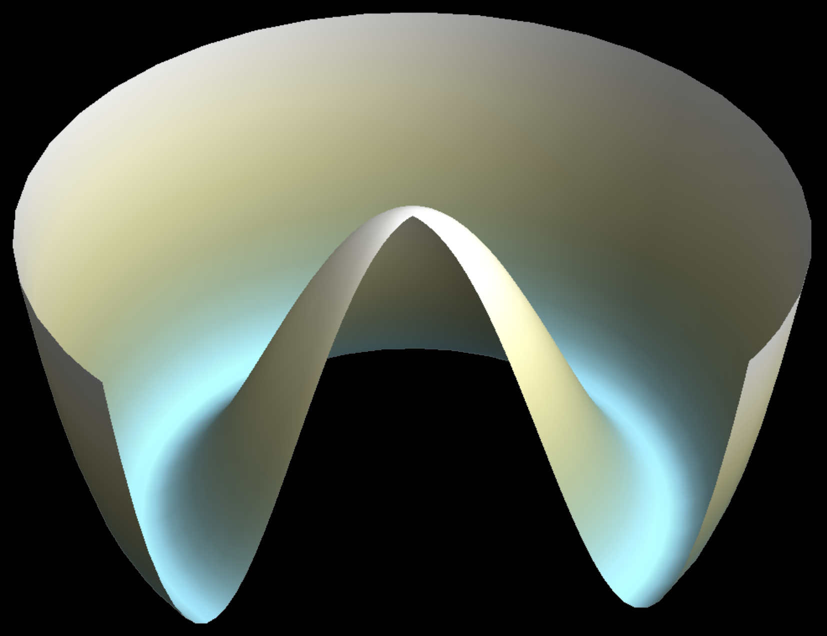
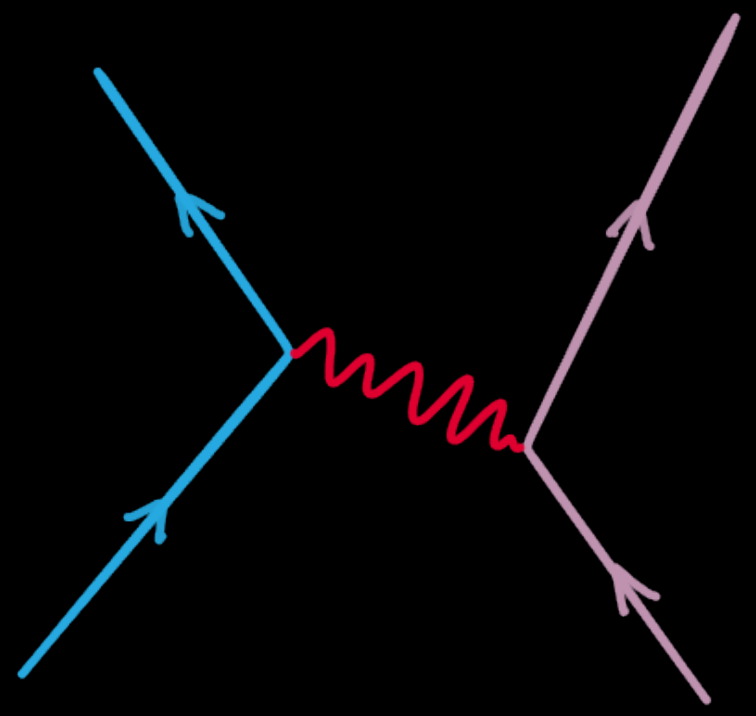
A superconducting analogy:



High-Tc Superconductors

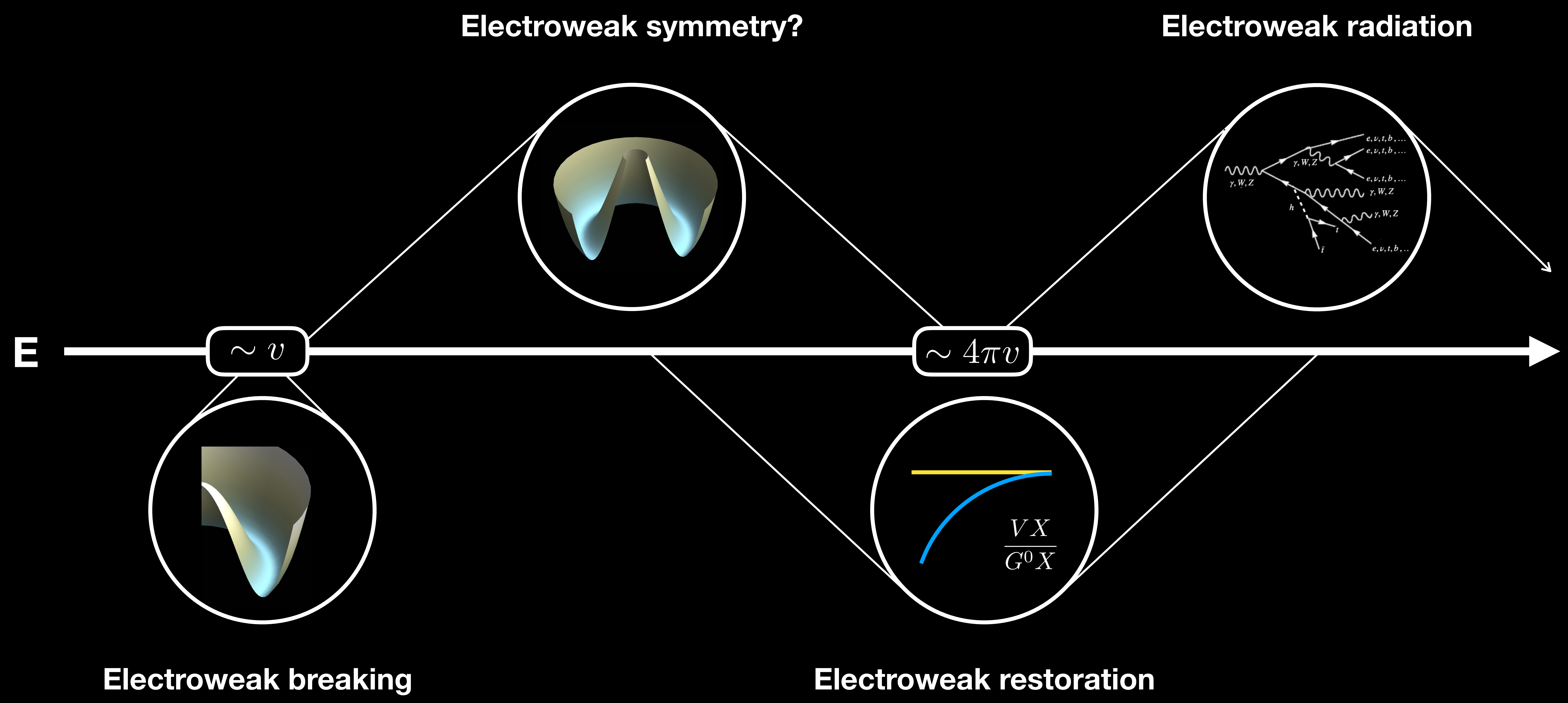


Ginzburg-Landau Theory

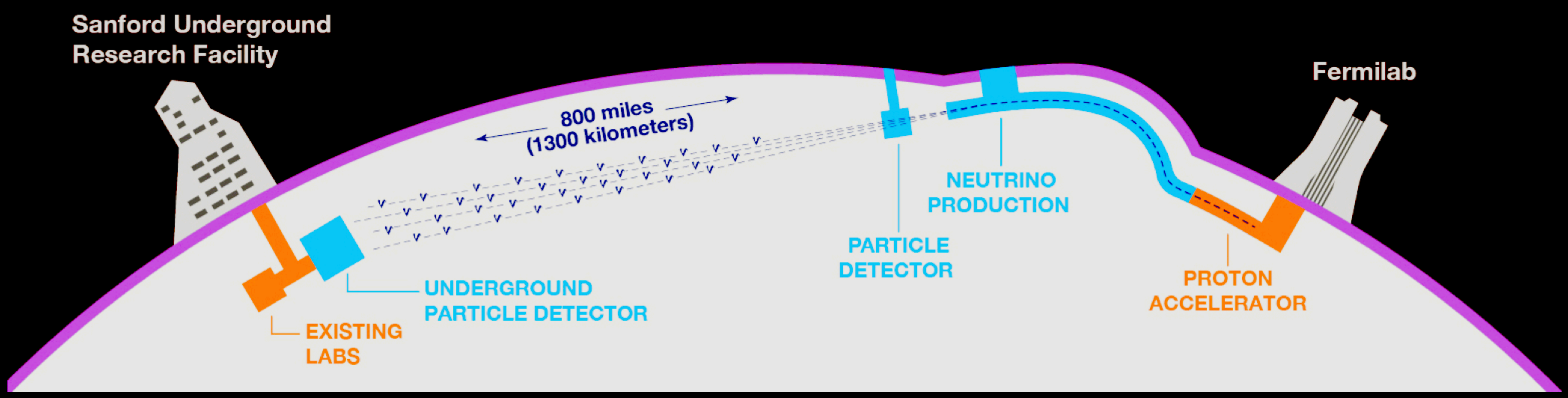


Low-Tc Superconductors (BCS)

The Electroweak Era



The Electroweak Era



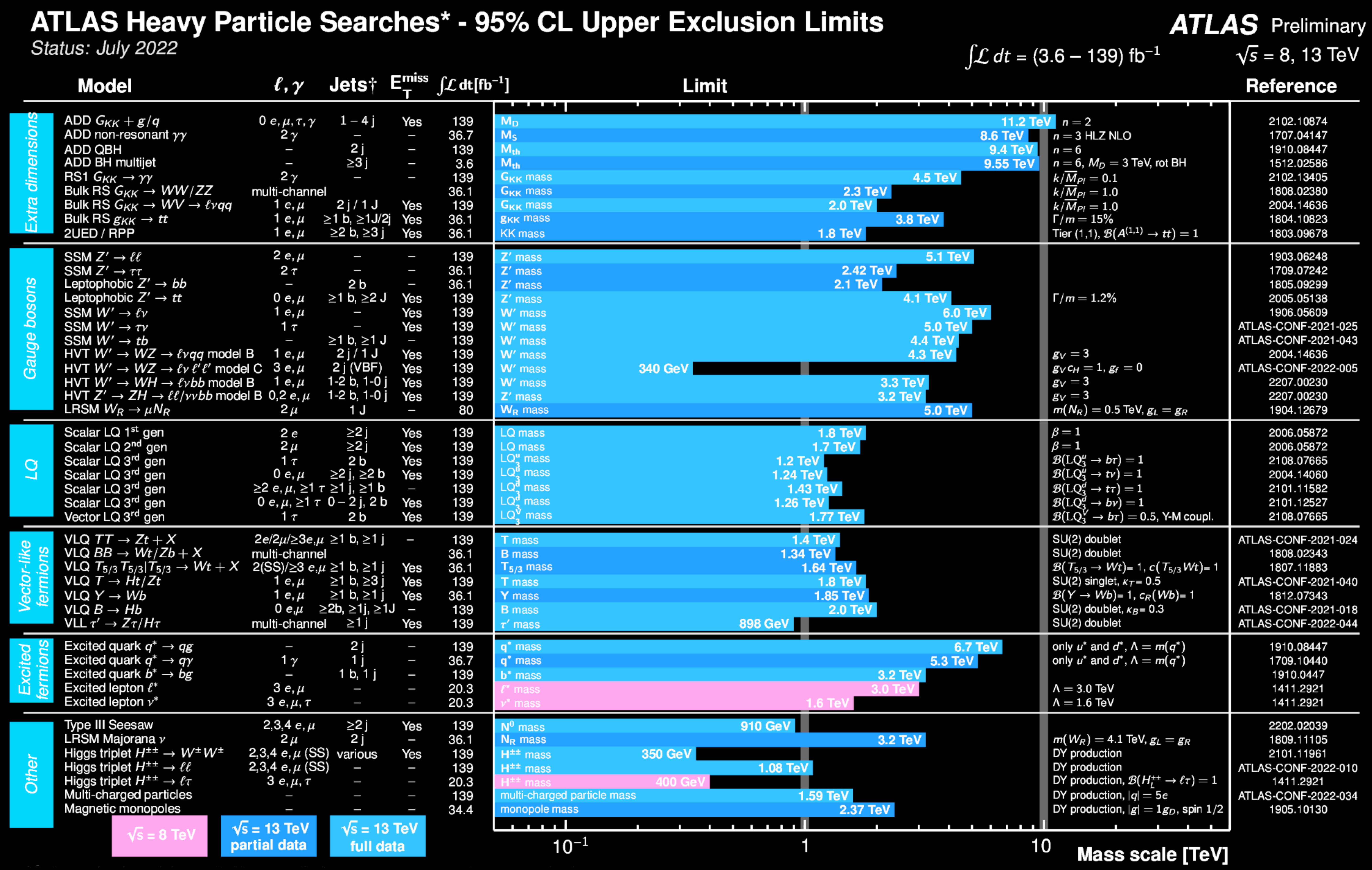
Neutrinos: the purely weak frontier of the Standard Model

Dark sectors: portals are weak interactions & SM electroweak states

weak portal	kinetic mixing portal	neutrino portal	Higgs portal
$g(W_\mu)^i_j \mathcal{O}_j$	$F^{\mu\nu}\mathcal{O}_{\mu\nu}$	$HL^\alpha \mathcal{O}_\alpha$	$\lvert H\rvert^2 \mathcal{O}$

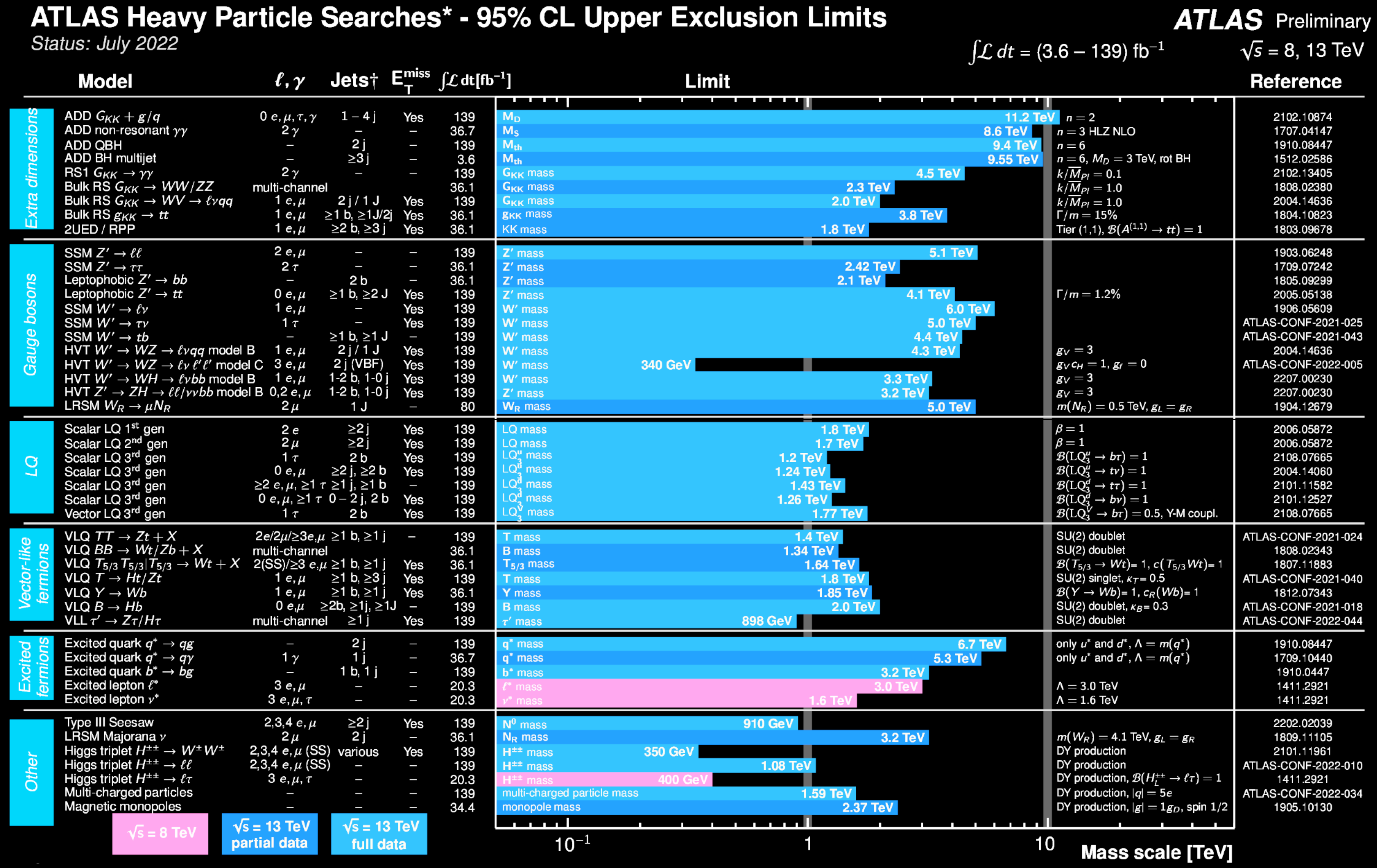
The Electroweak Era

…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 $(1,2)_{3/2}$

The "Who Ordered That?" Collider

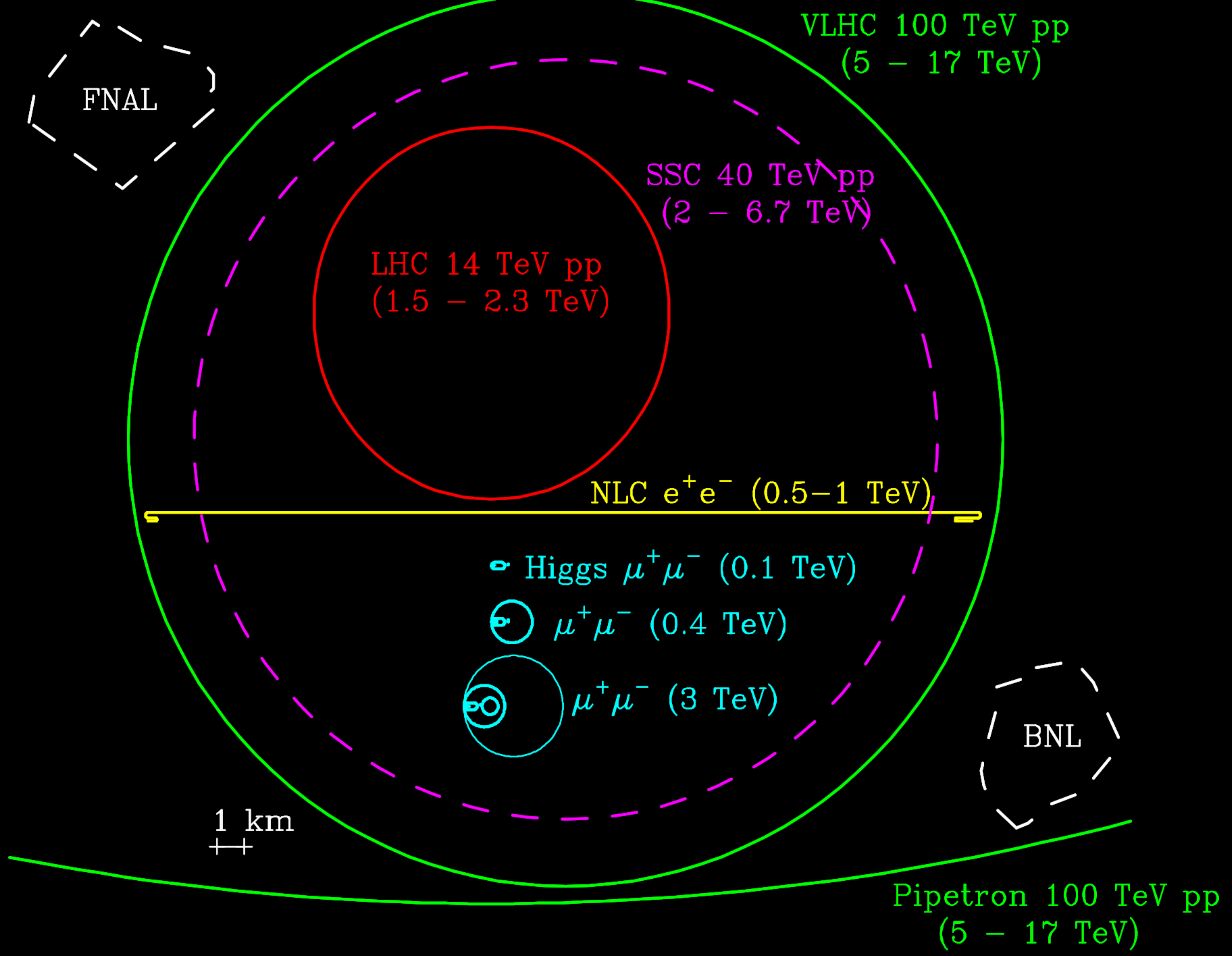
Conventionally: pursue these questions by probing shorter distances with either **precision** (indirect) or **energy** (direct).

Muon colliders blur this dichotomy.

- Colliding elementary particles leverages the **full energy** of the accelerator, with a (relatively) **clean environment.**
- Larger mass of the muon allows a **smaller footprint** & **higher energies** compared to e^+e^- counterparts.

$$P \propto \frac{\gamma^4}{R^2} = \frac{E^4}{m^4 R^2}$$

- **Major challenges:** finite lifetime, cooling, radiation, beam-induced backgrounds.



[Ankenbrandt et al. arXiv:physics/9901022]

The "Who Ordered That?" Collider

(A wholly incomplete timeline)

1968
F. Tikhonin
"On the effects at colliding μ meson beams"

1969
G.I. Budker
"Accelerators and colliding beams"

1979
D. Neuffer
"Colliding Muon Beams at 90 GeV"

1981
Skrinsky, Parkhomchuk
"Methods of cooling beams of charged particles"

1995
Barger, Berger, Gunion, Han
"s channel Higgs boson production at a muon muon collider"

2001-
Muon Ionization Cooling Experiment (MICE)

2010-17
Muon Accelerator Program (MAP)

2015
Antonelli et al.
"Novel proposal for a low emittance muon beam using positron beam on target"
Low Emittance Muon Accelerator (LEMMA) proposal

2019
Input to European Strategy Update

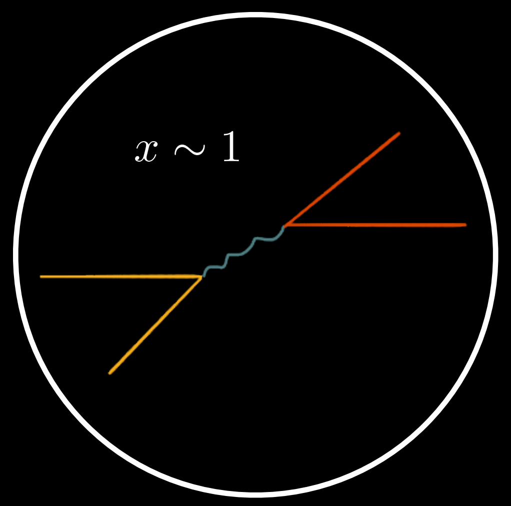
2020-
International Muon Collider Collaboration

2021-23
Snowmass Muon Collider Forum

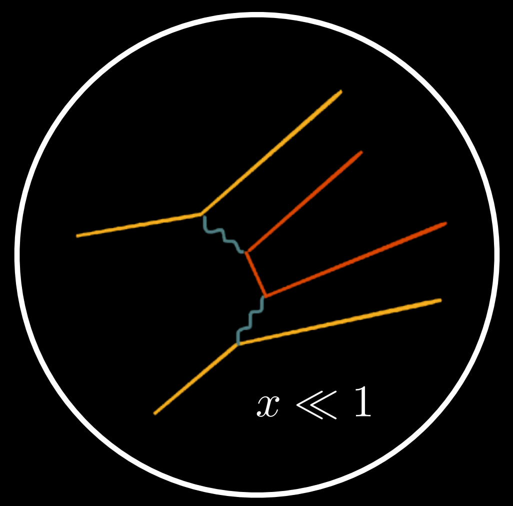
2023 P5 Report

Muon Colliders for the EWK Era

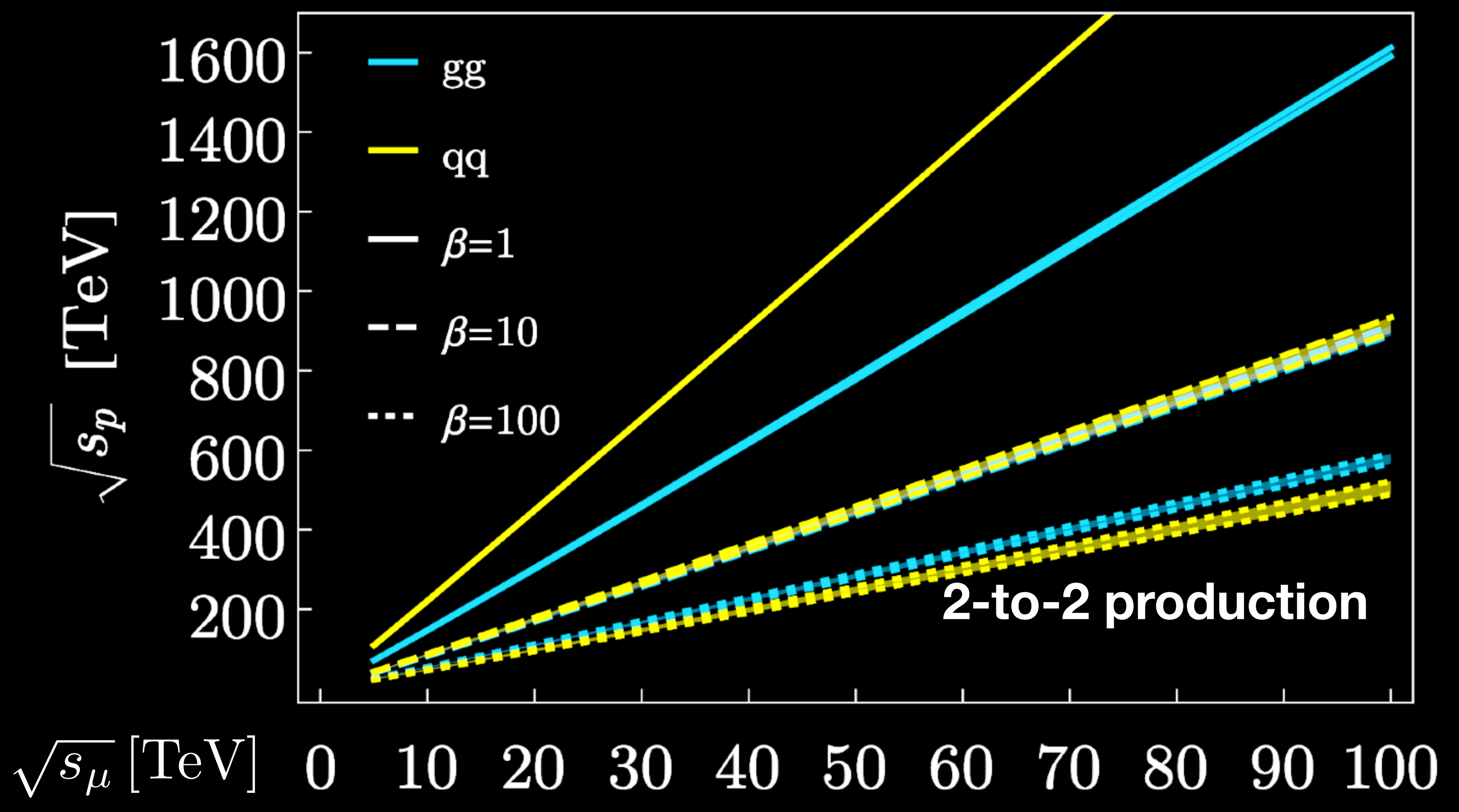
Muon colliders blur the dichotomy of probing microcopic phenomena with **precision** or **energy**.

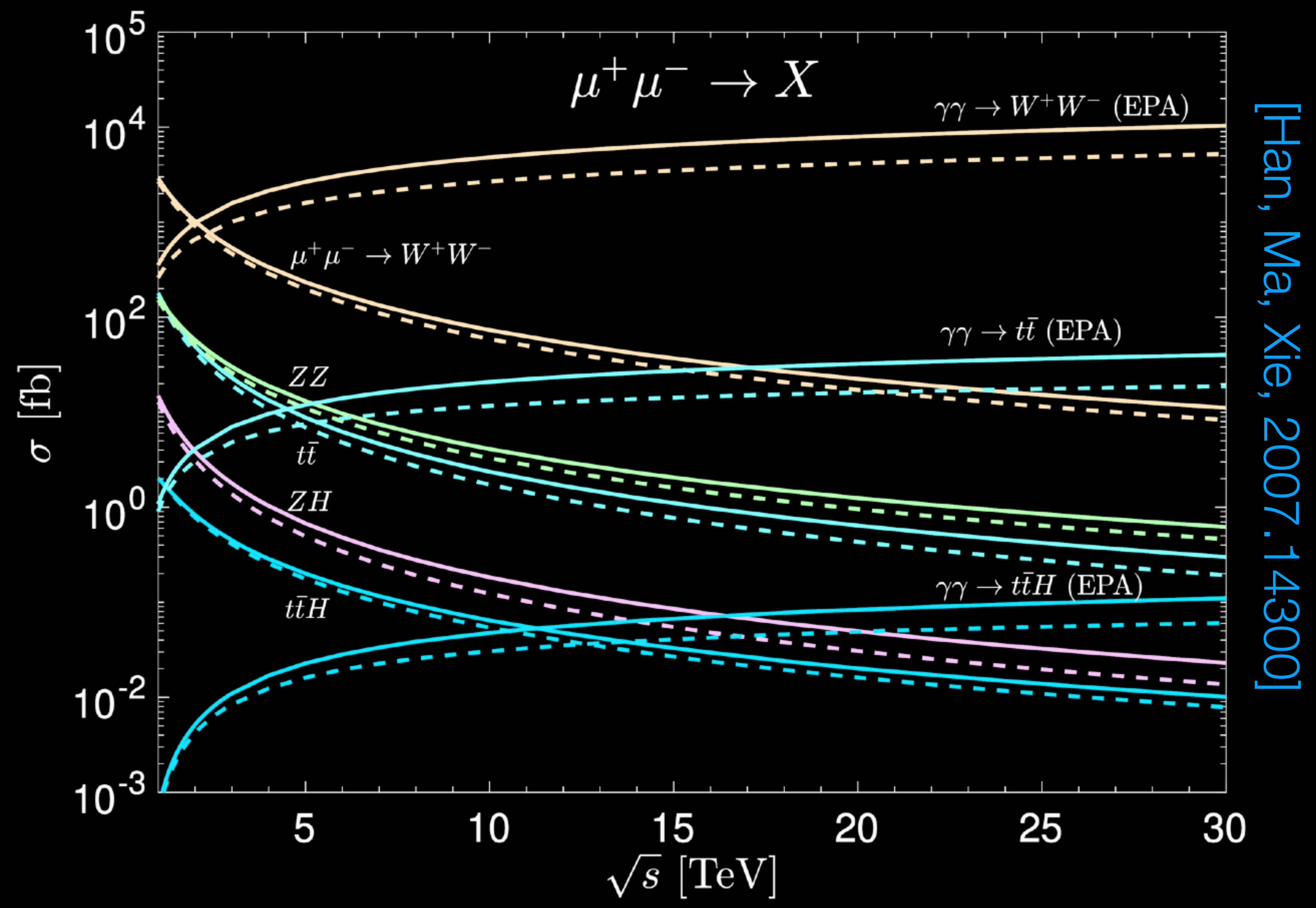


Muon annihilation deploys the entire energy of the collider



Vector boson fusion leverages the muon's virtual boson content

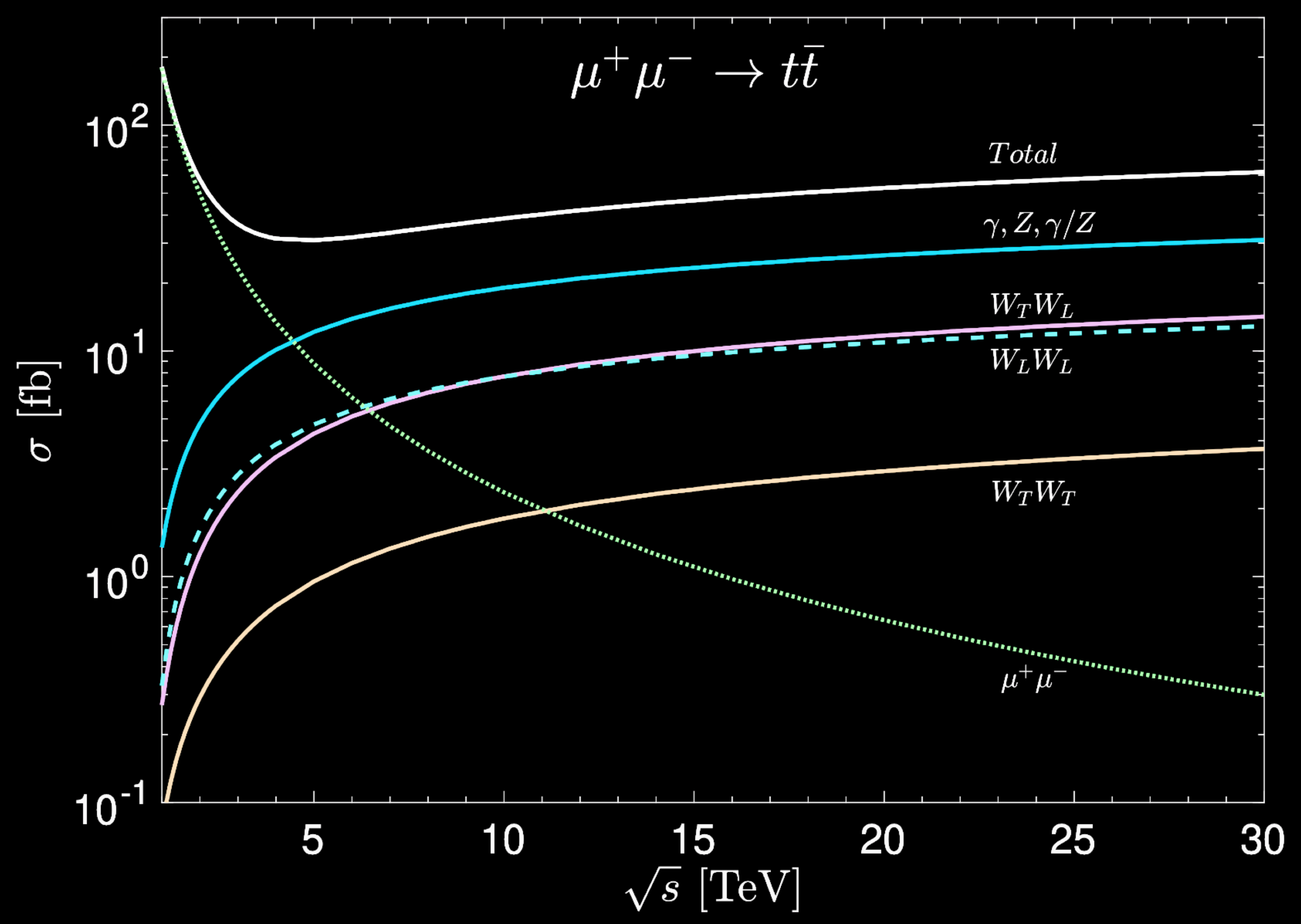




Moreover, muon collider energy in a (relatively) clean environment provides ***precision from energy.***

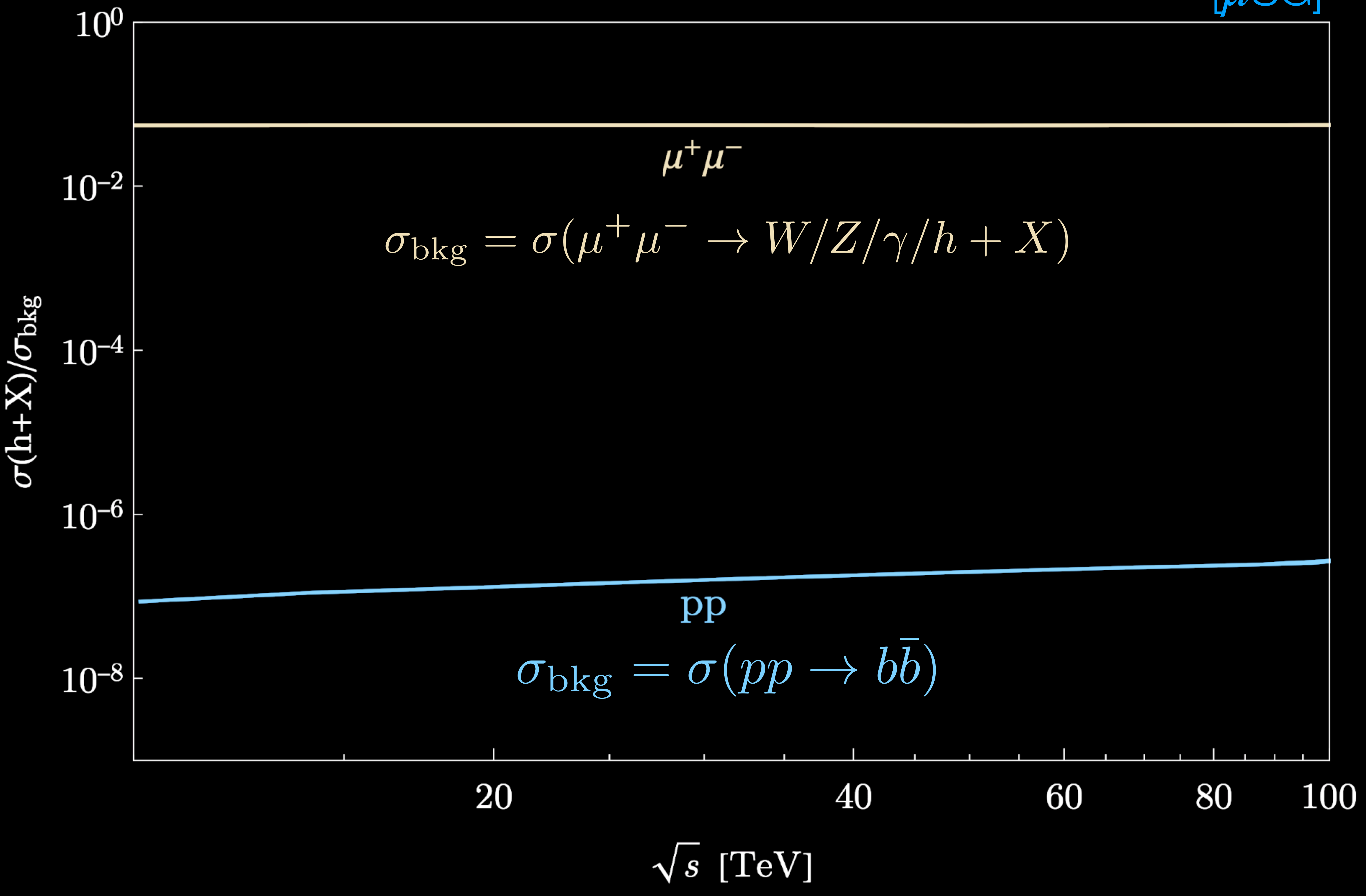
Muon Colliders as EWK Laboratories

[Han, Ma, Xie, 2007.14300]



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

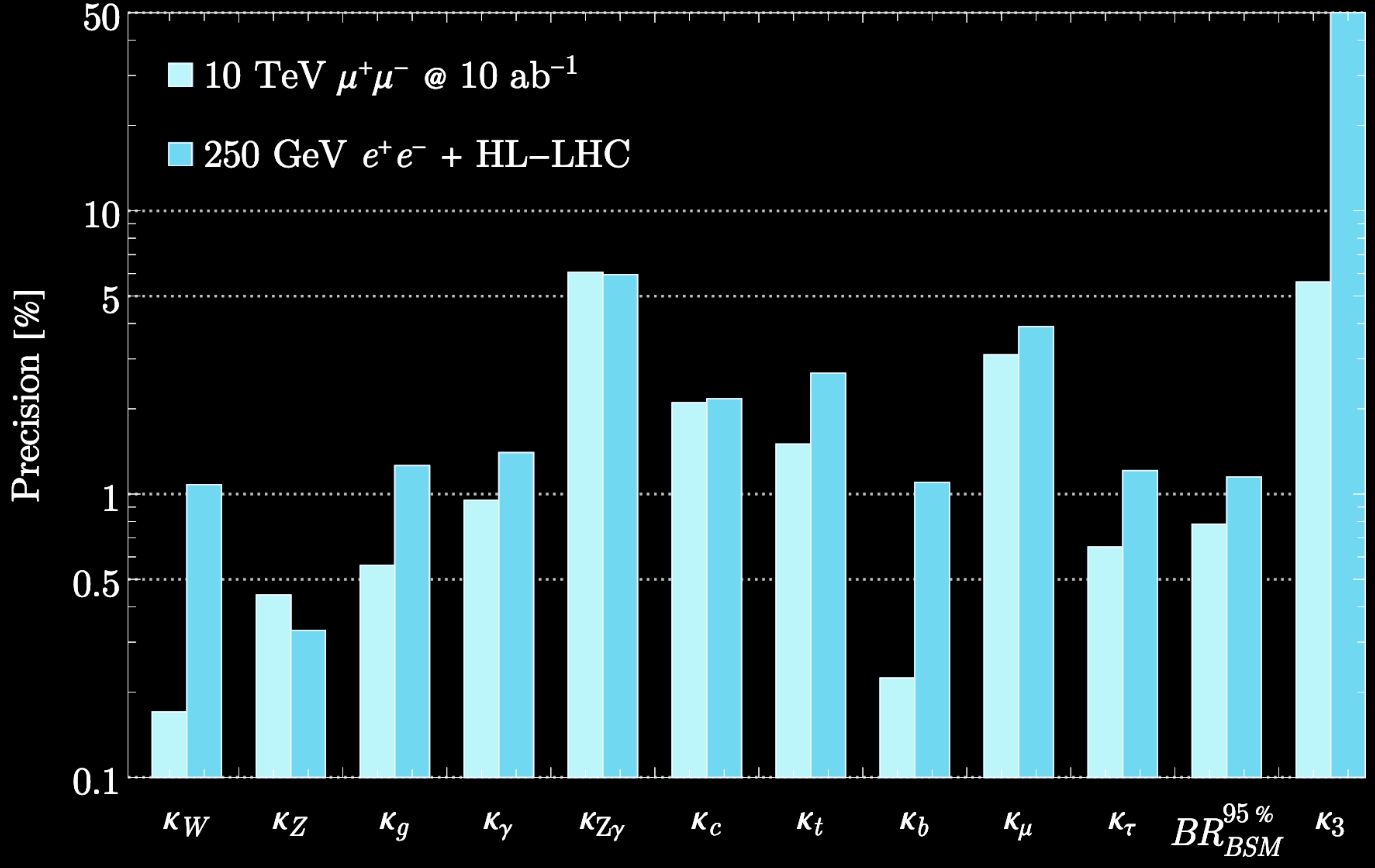
[μSG]



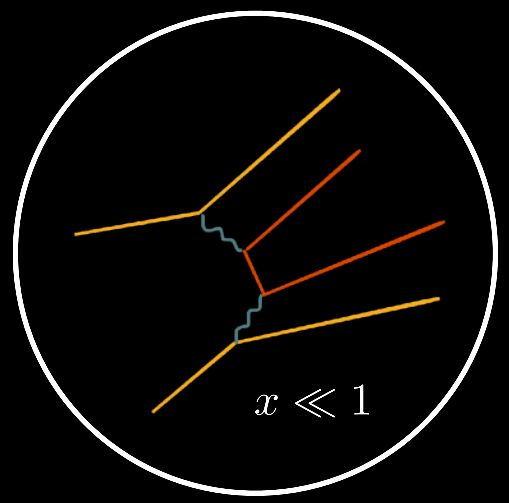
Dominant signals and backgrounds both have electroweak cross sections

How do muons illuminate the physics vision?

What is the Origin of Mass?

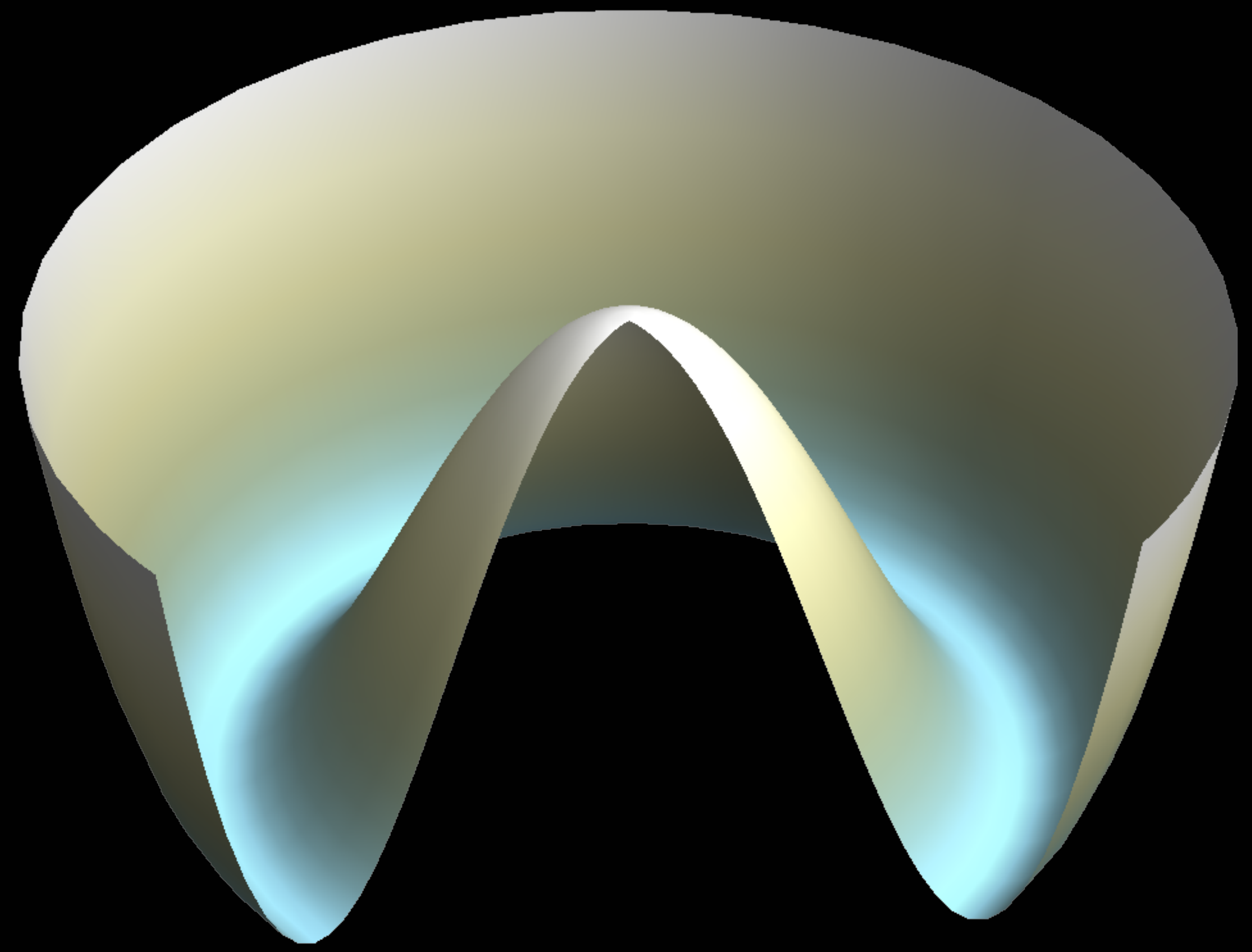


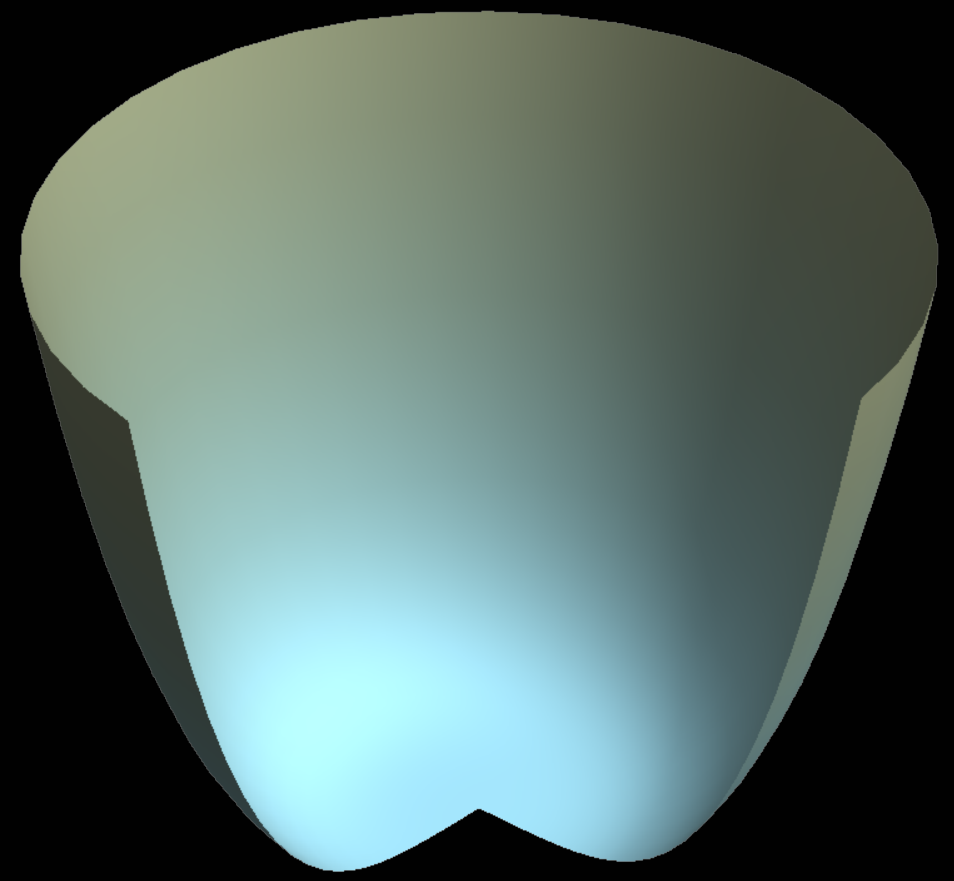
[Forslund & Meade, 2308.02633]

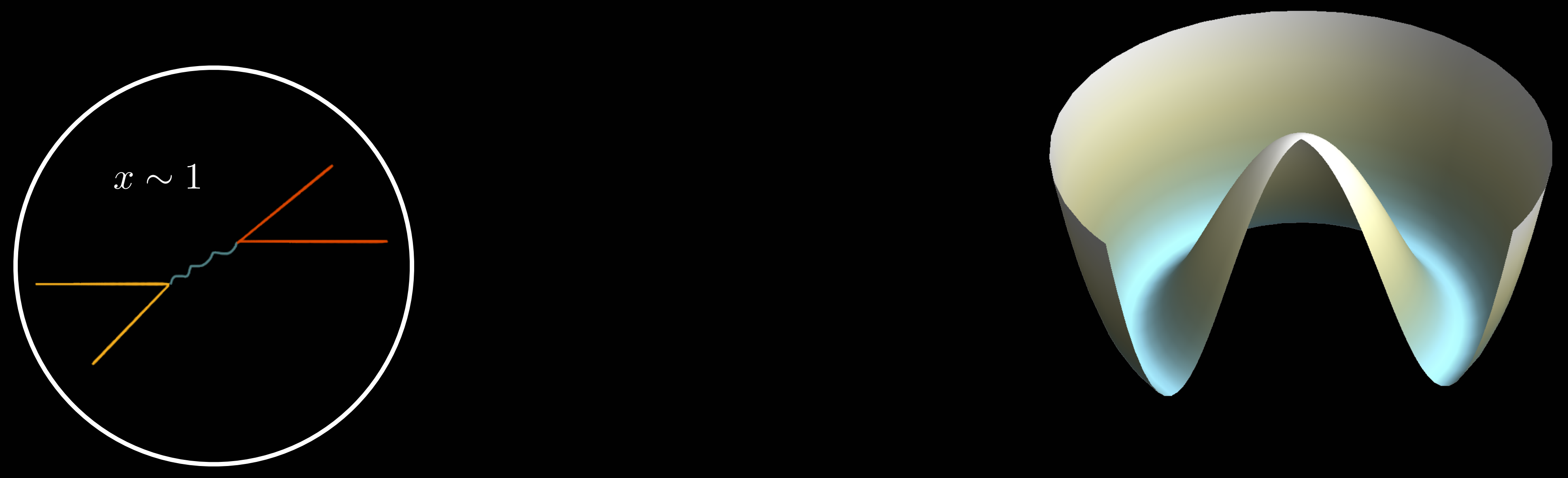


What is the BCS Theory of EWSB?

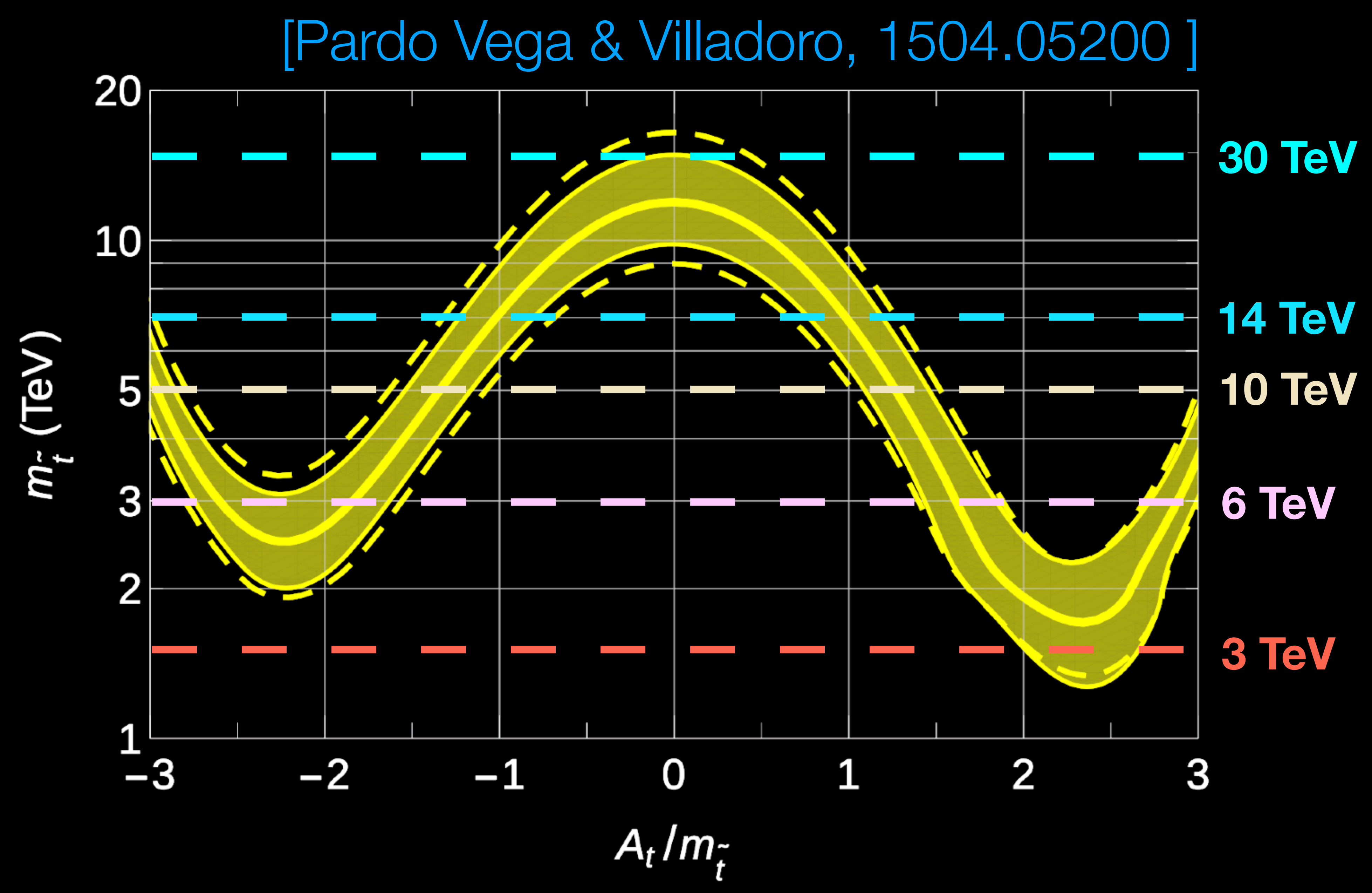
Theories that predict the Higgs mass & EWSB ("solve the hierarchy problem") provide sharp targets for new physics.







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:

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

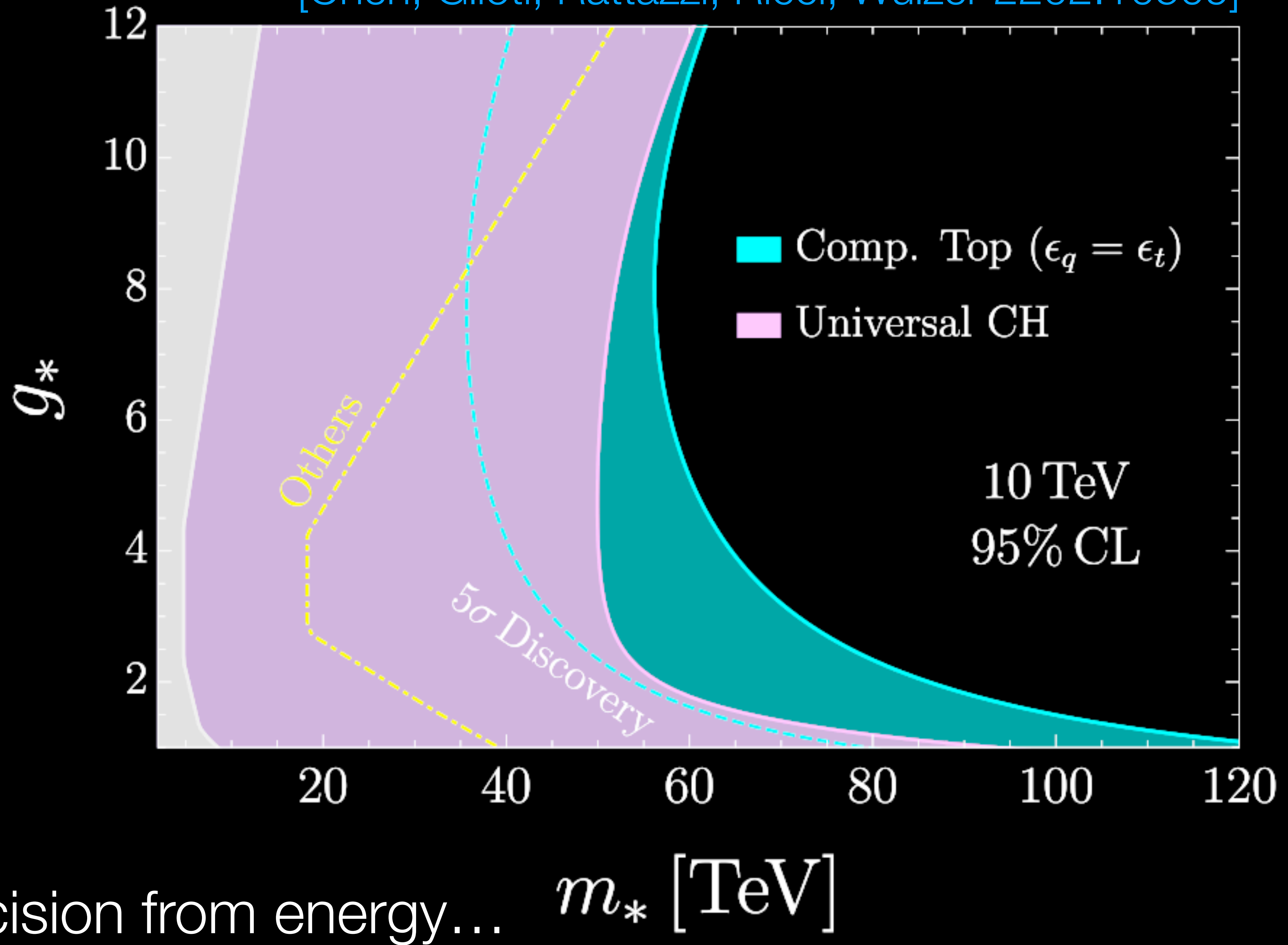
$$\mathcal{O}_{2B} = (\partial_\mu B^{\mu\nu})^2$$

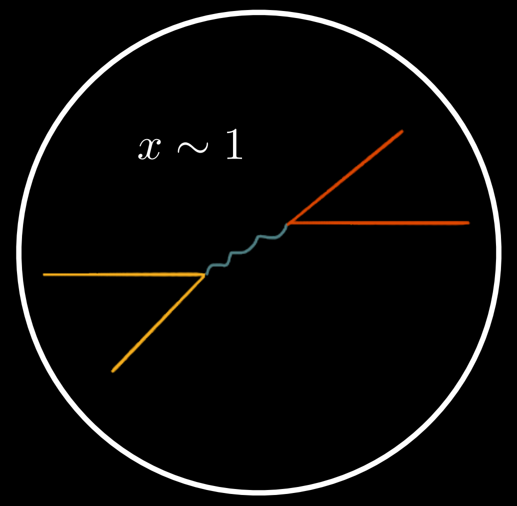
$$\mathcal{O}_W = ig(H^\dagger \sigma^a D_\mu H) D^\nu W^a_{\mu\nu}$$

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

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

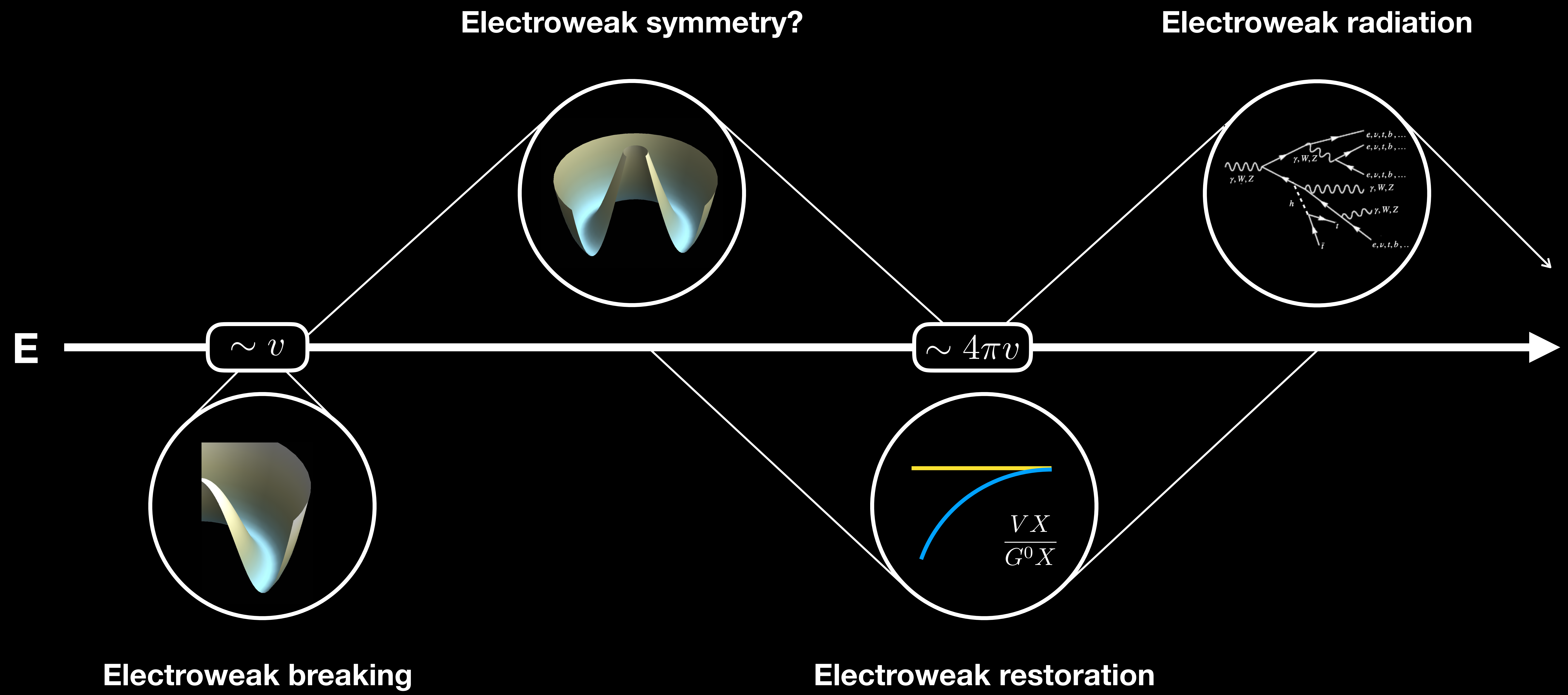
[Chen, Glioti, Rattazzi, Ricci, Wulzer 2202.10509]

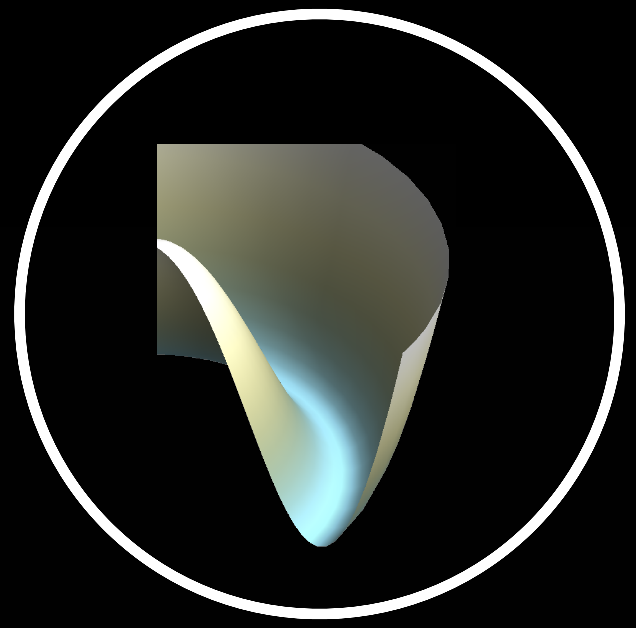




Splendid example of precision from energy…
(See also [Buttazzo, Franceschini, Wulzer 2012.11555])

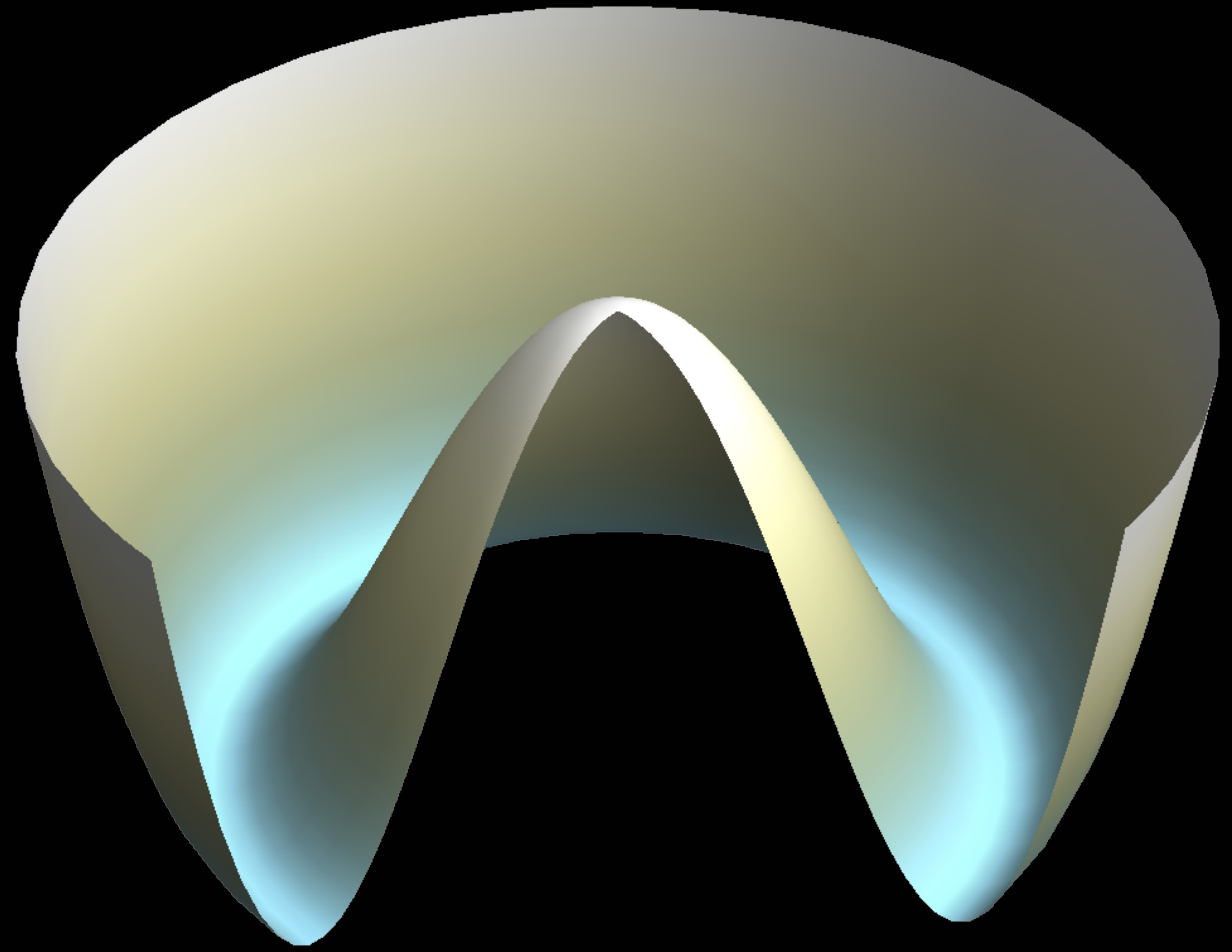
Muon Colliders for the EWK Era

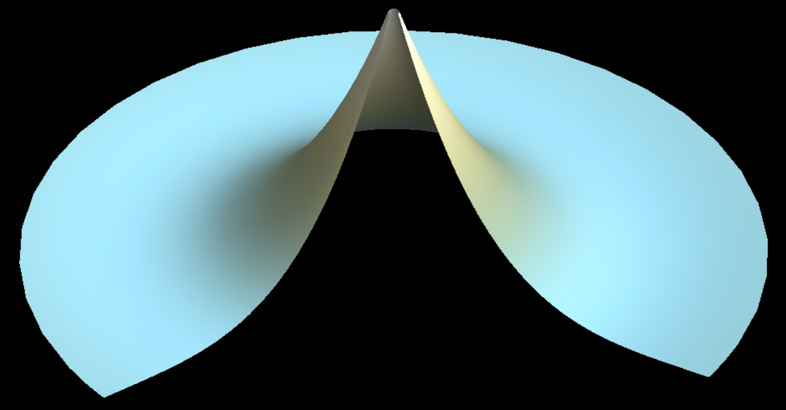


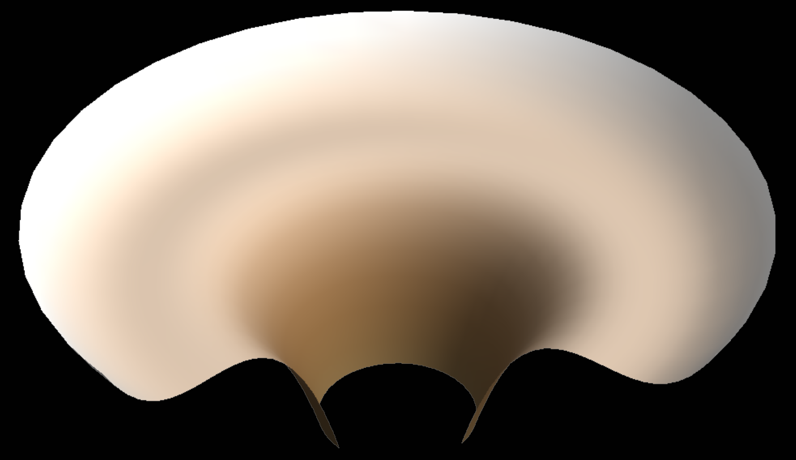


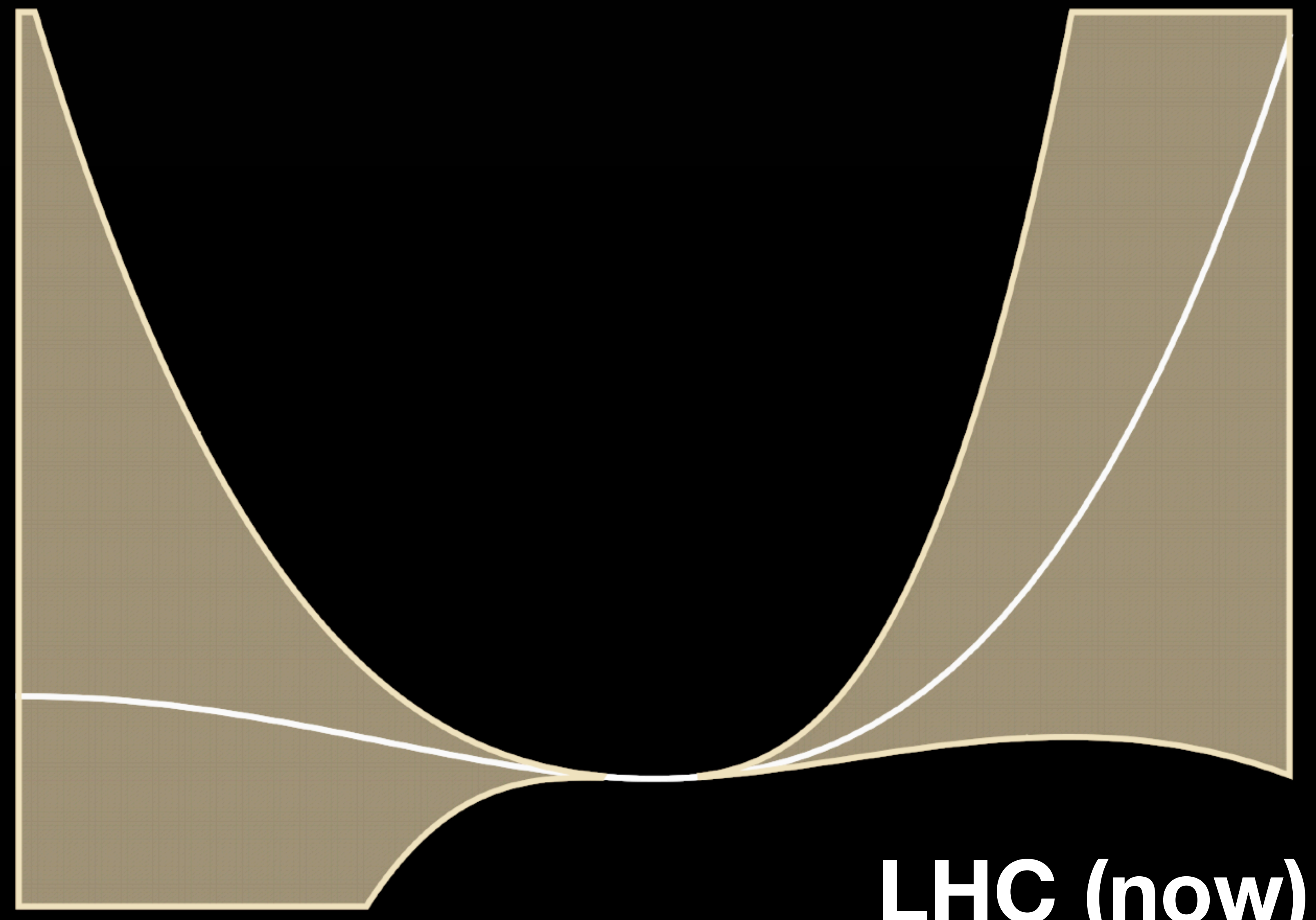
Electroweak Breaking

We do not even know if the Ginzburg-Landau picture is correct for electroweak symmetry.

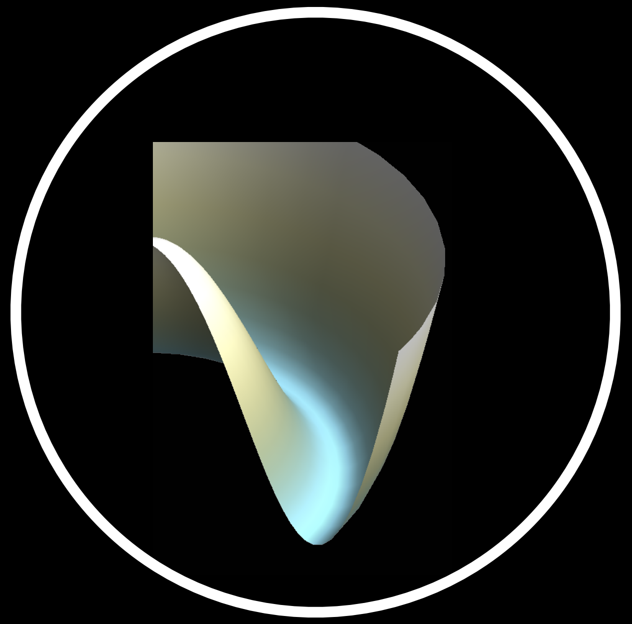






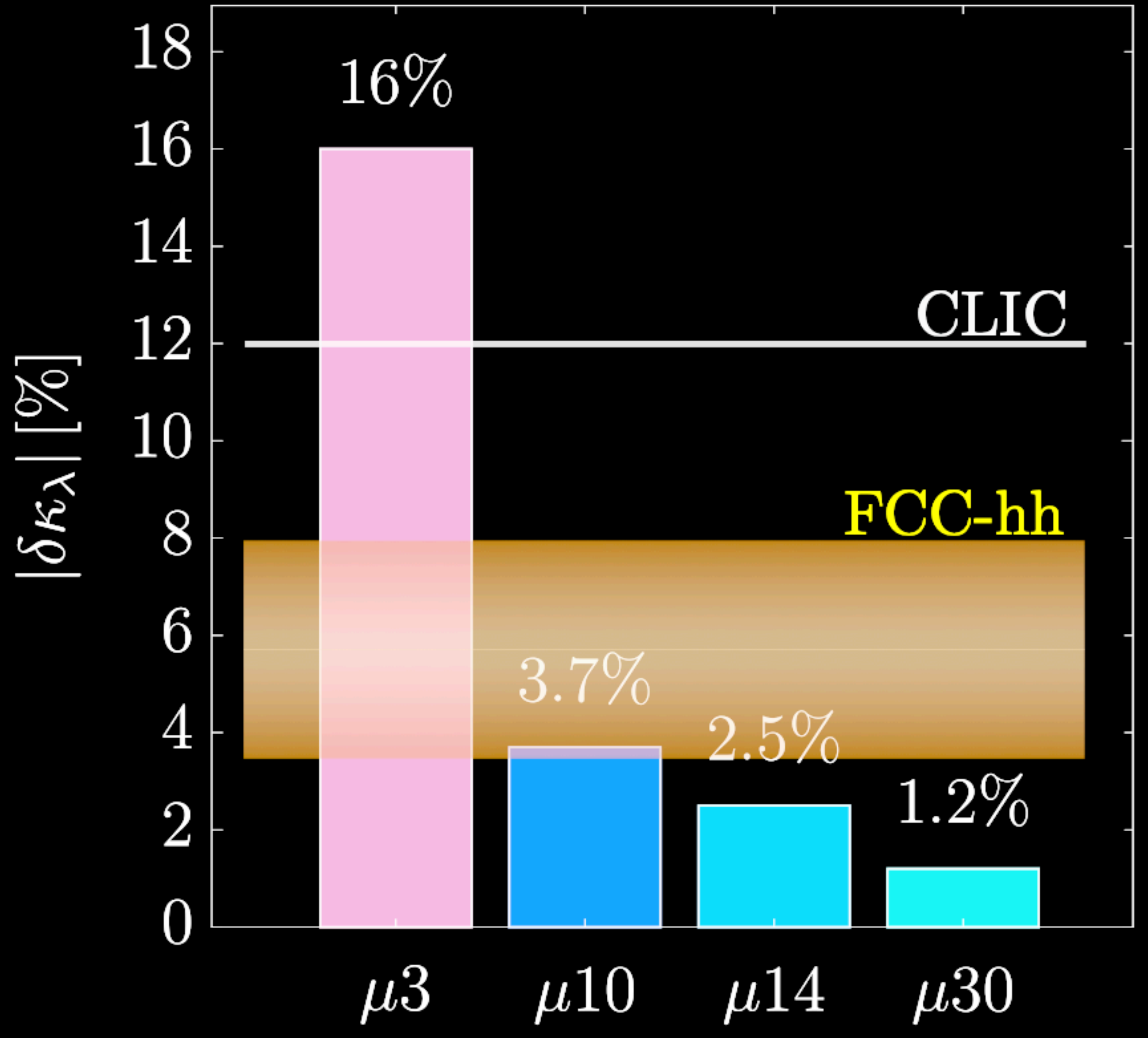


(If you like this way of presenting Higgs self-coupling precision, feel free to use it w/ credit to R. Petrossian-Byrne.)

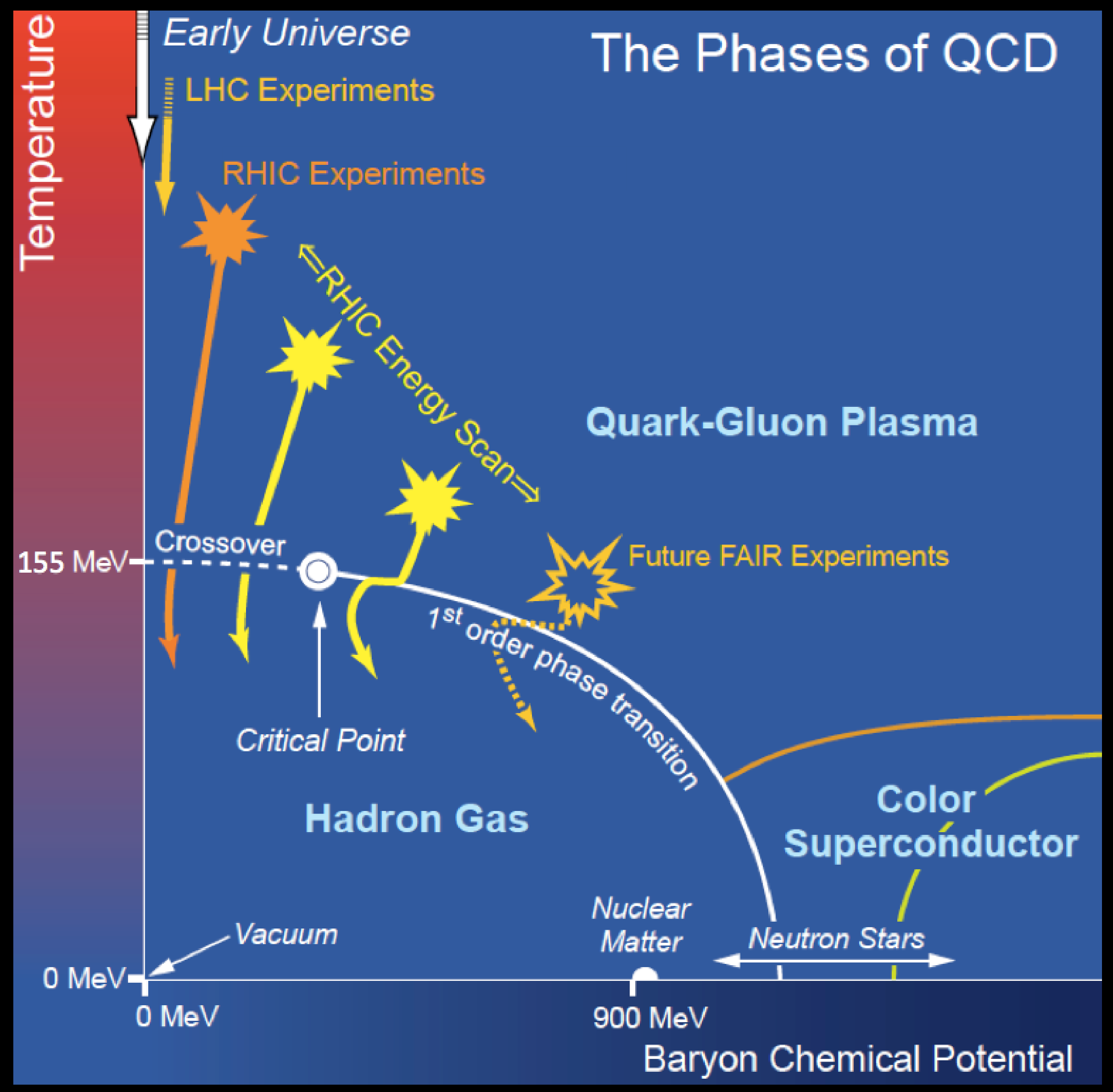


Electroweak Breaking

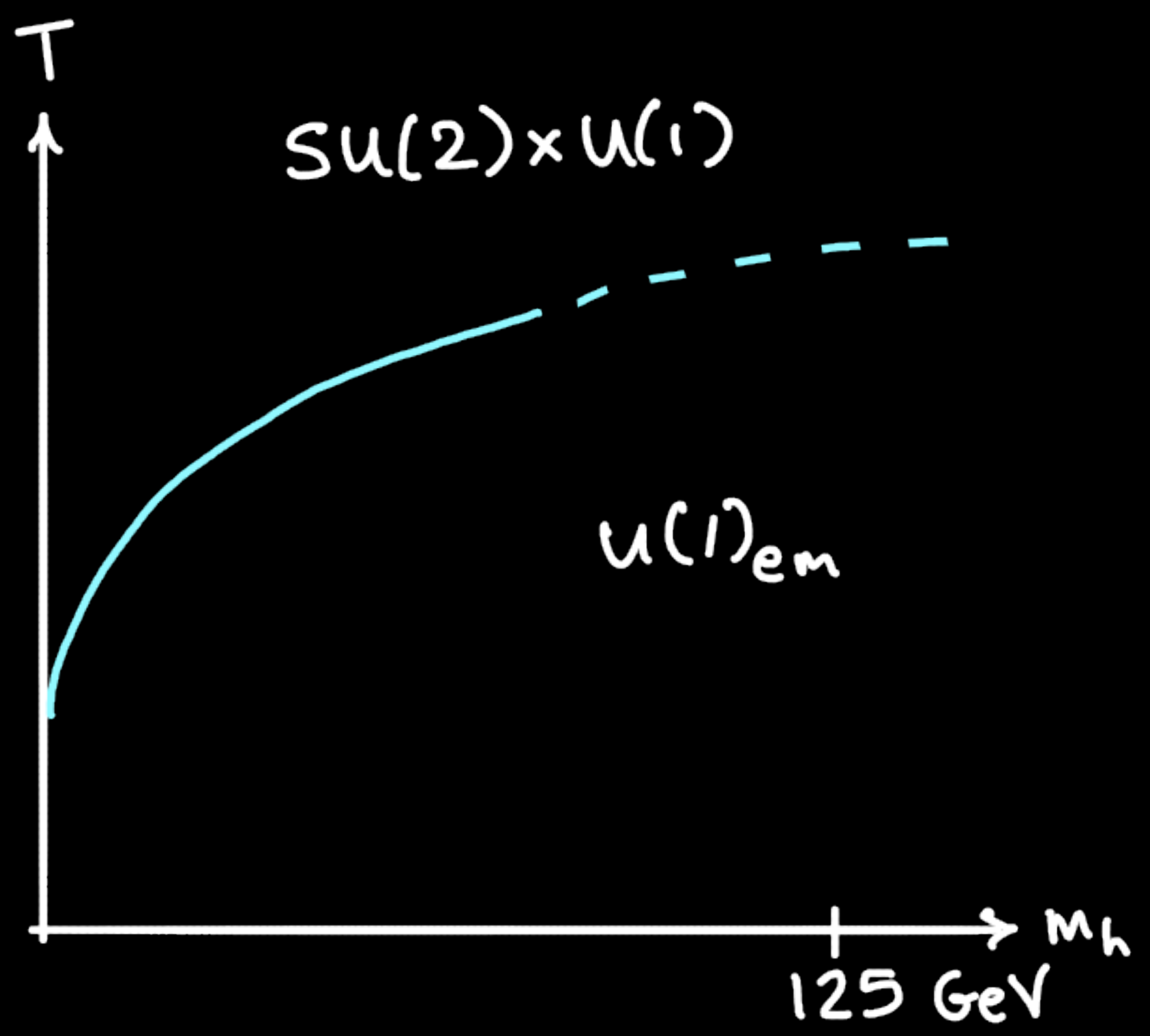
[Accettura et al. 2303.08533]

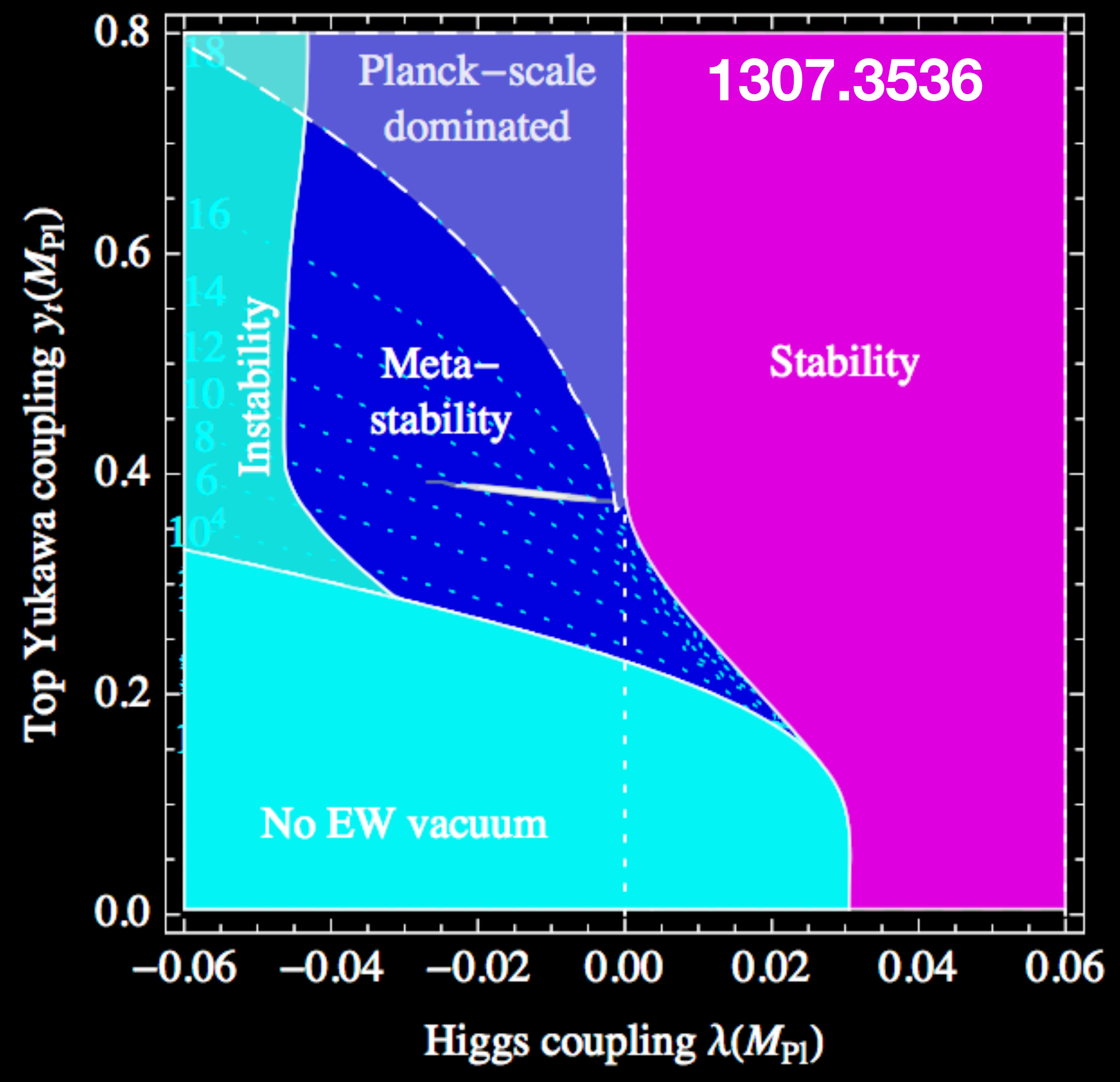


The birth and death of the Universe?



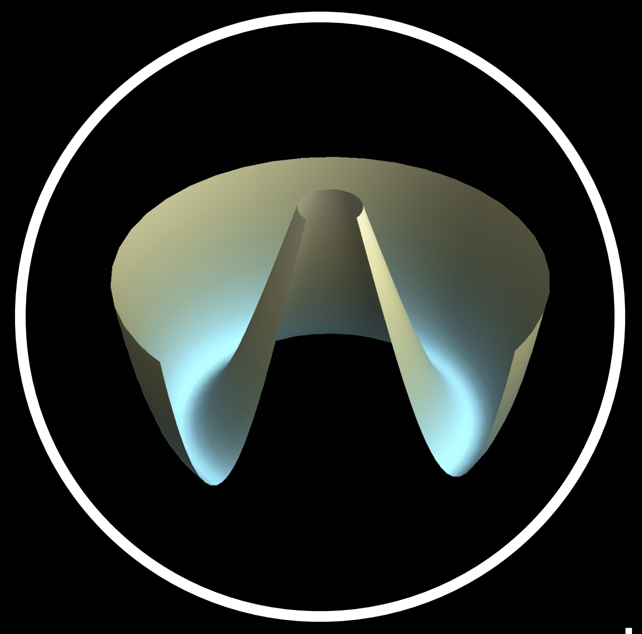
[2015 NSAC LRP / 1501.06477]





First-order electroweak phase transition?

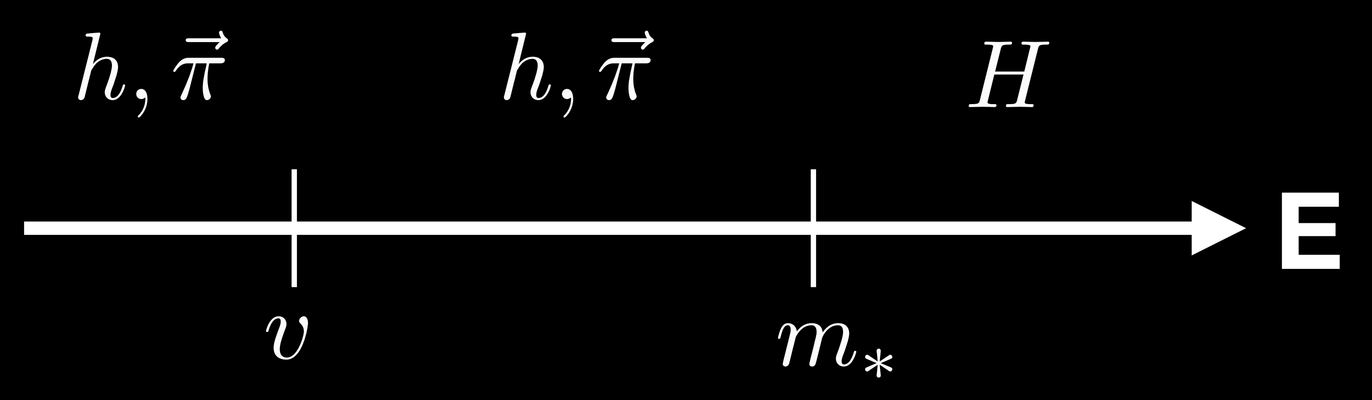
Vacuum stability?

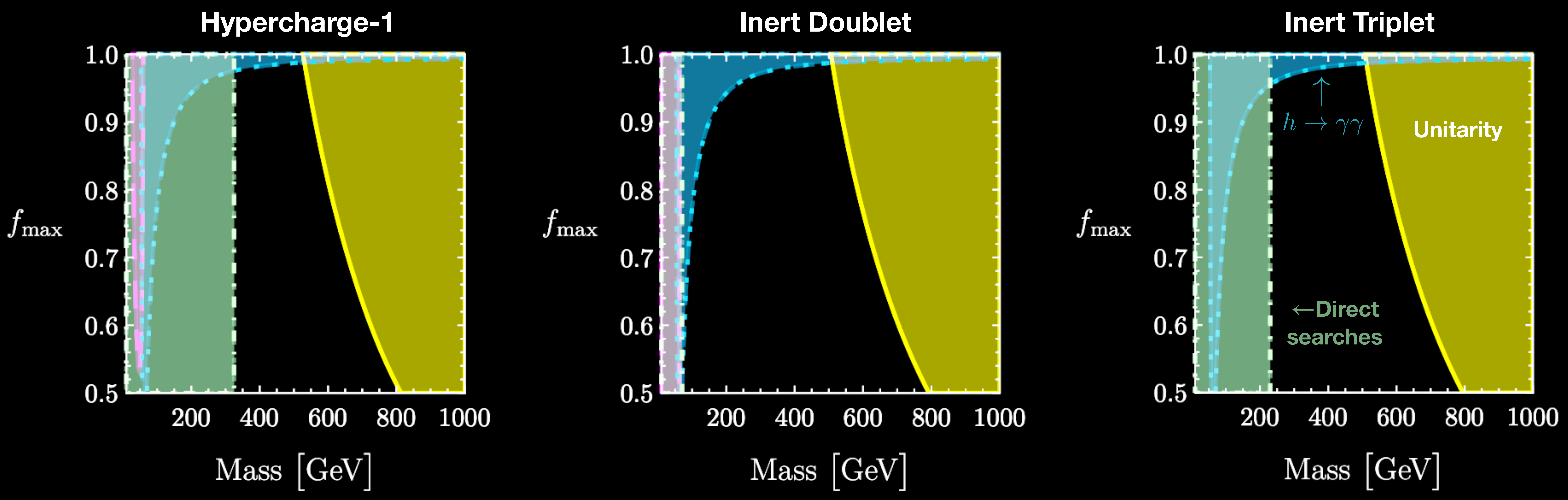


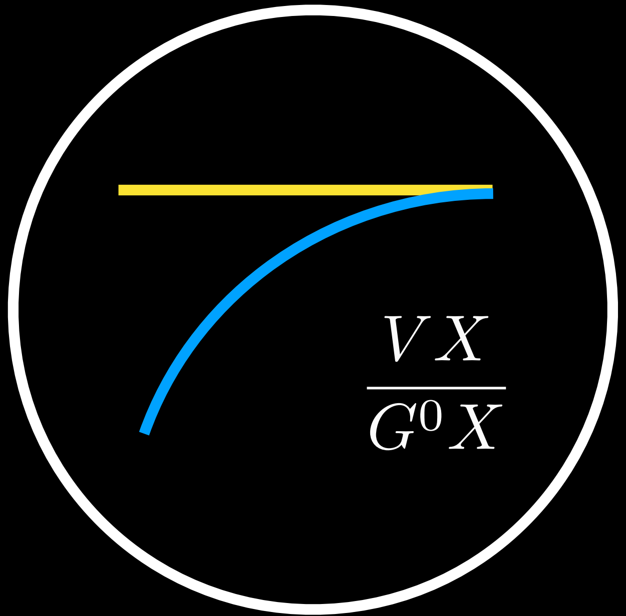
Electroweak Symmetry?

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.

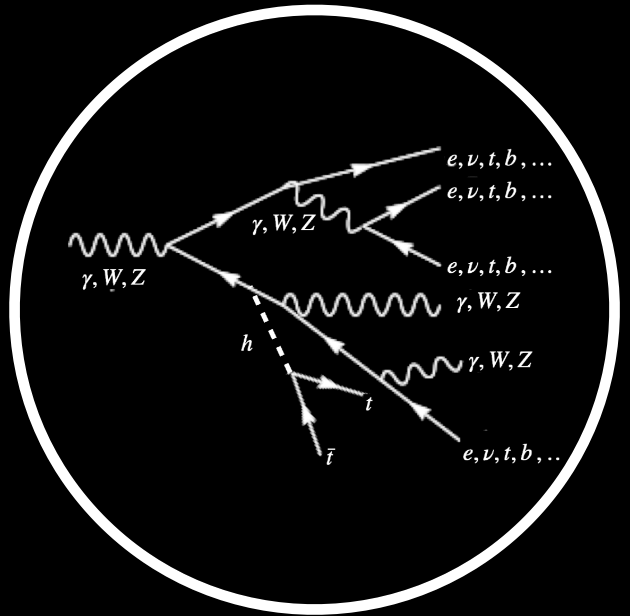
[Banta, Cohen, NC, Lu, Sutherland, 2110.02967]



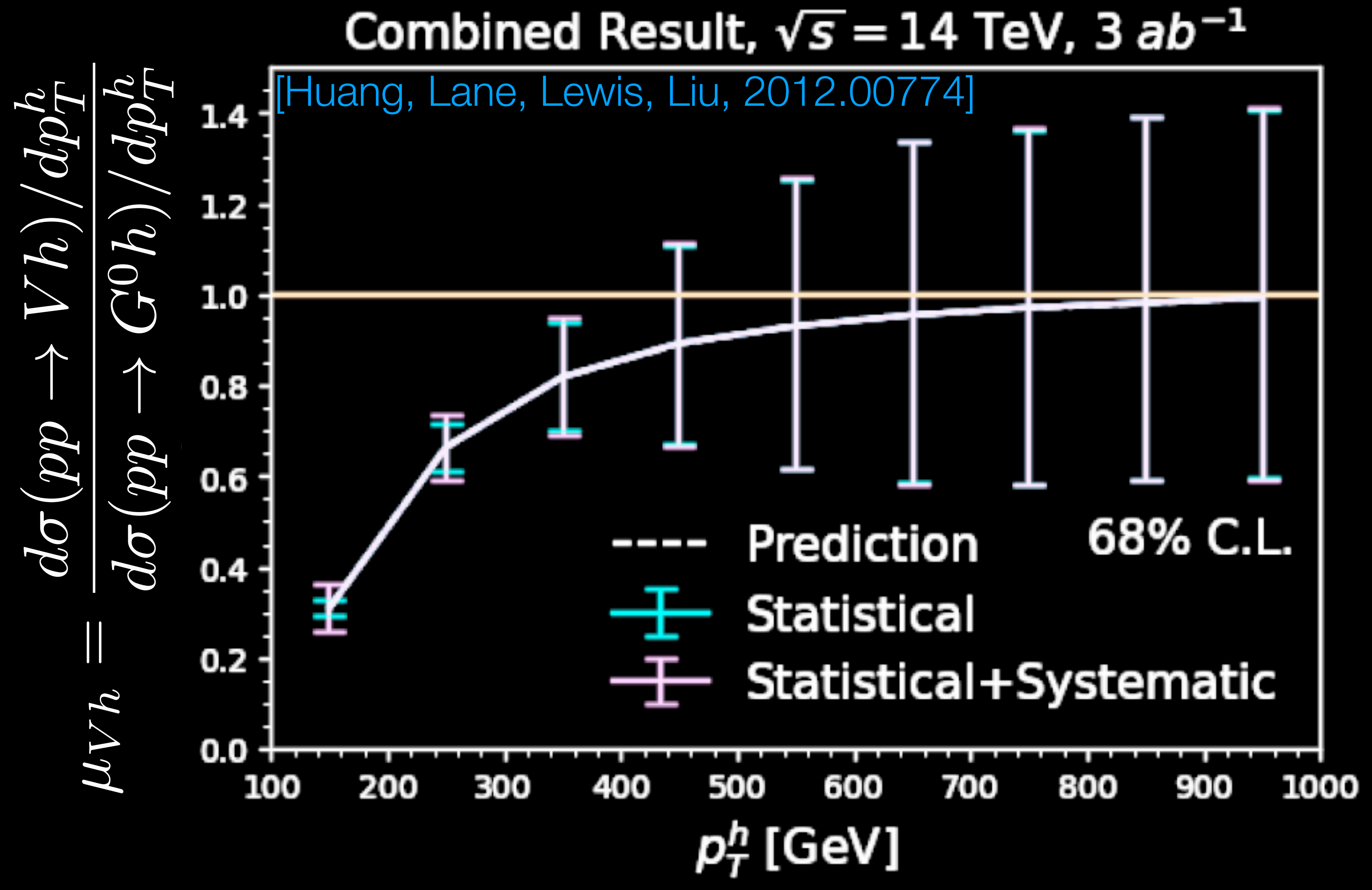




Electroweak Restoration, Electroweak Radiation

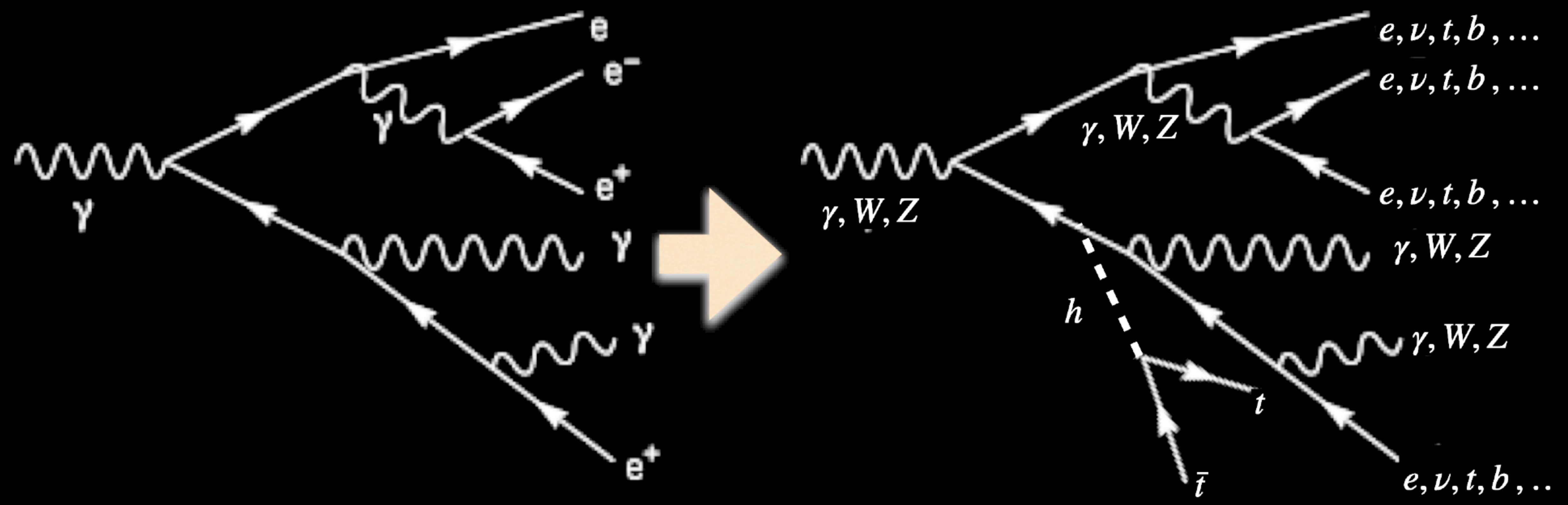


Experimentally demonstrate
Goldstone equivalence



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]]

Vision circa 2024

✓ What is the origin of mass?
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–Frank Close

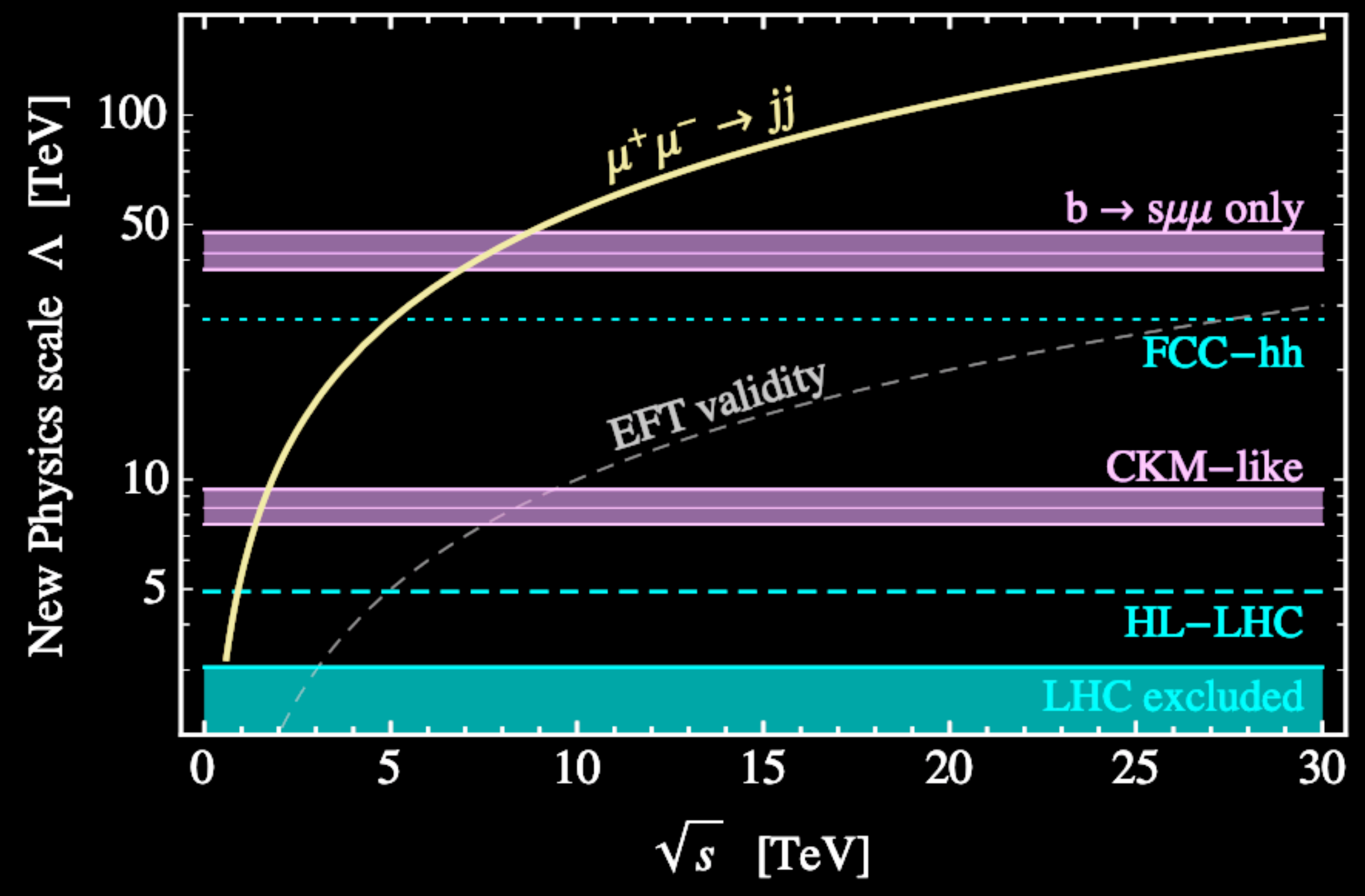
What is the origin of flavor?

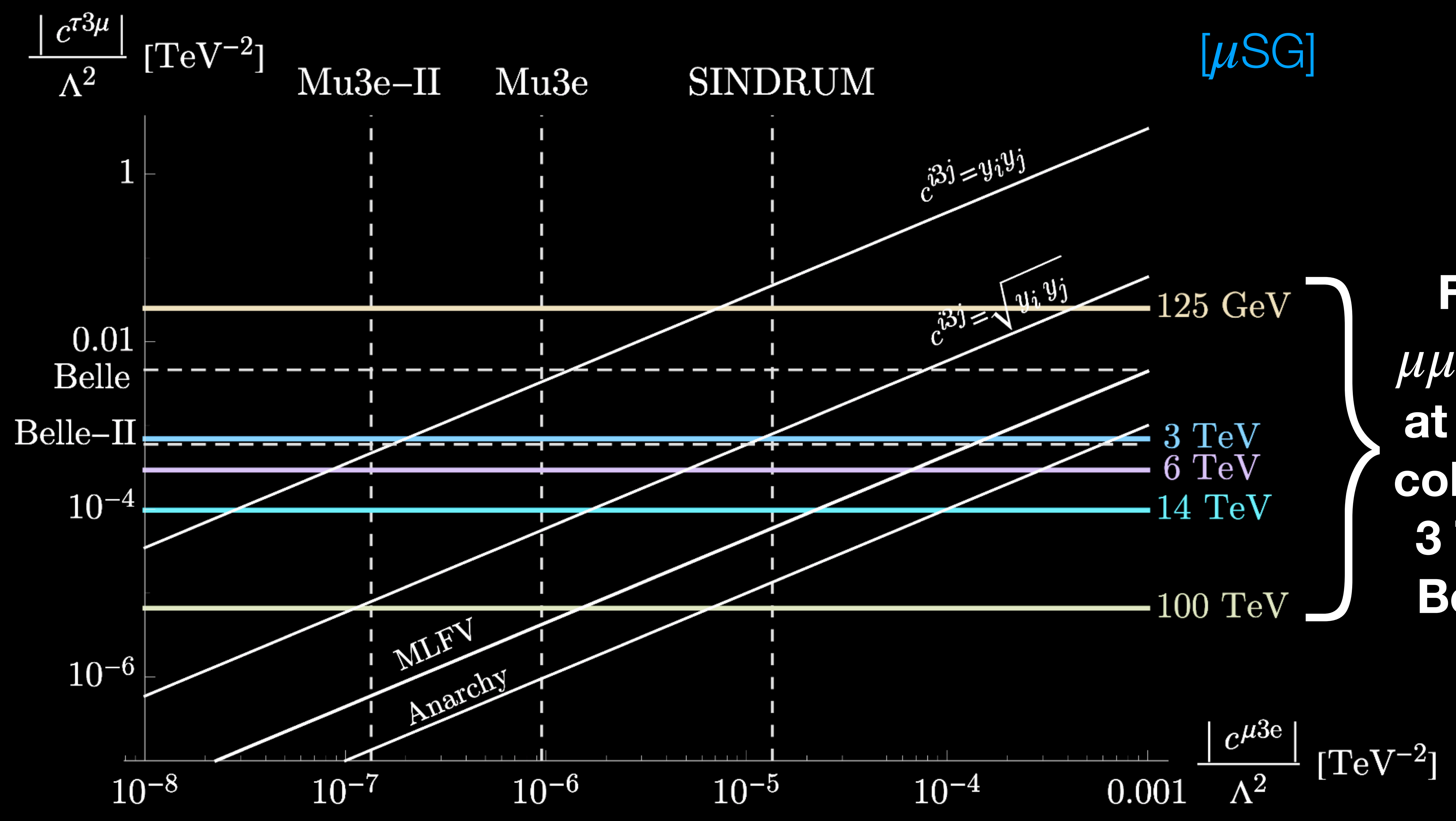
First high-energy accelerator to primarily collide second-generation fermions.

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

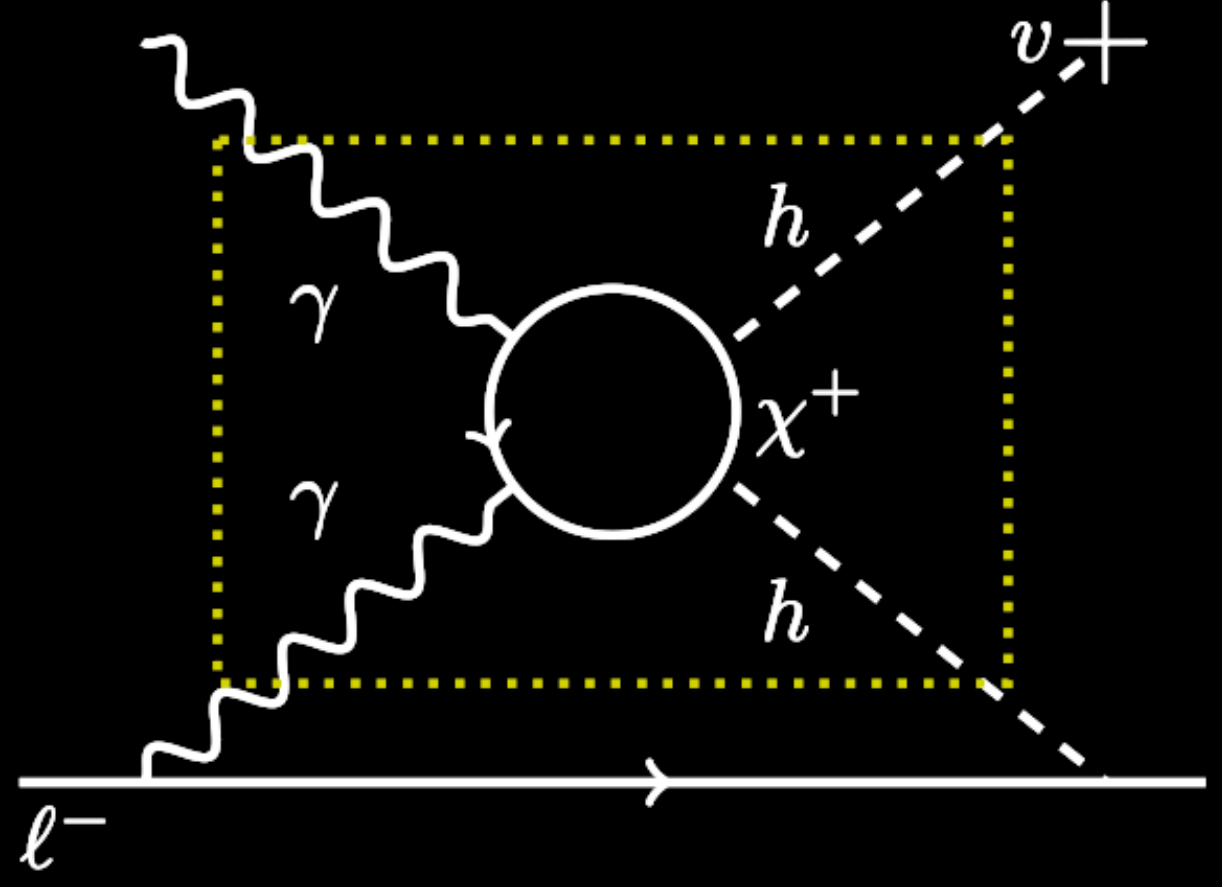
An outstanding probe of explanations for flavor anomalies, indicative of complementarity w/ future signs of flavor violation.

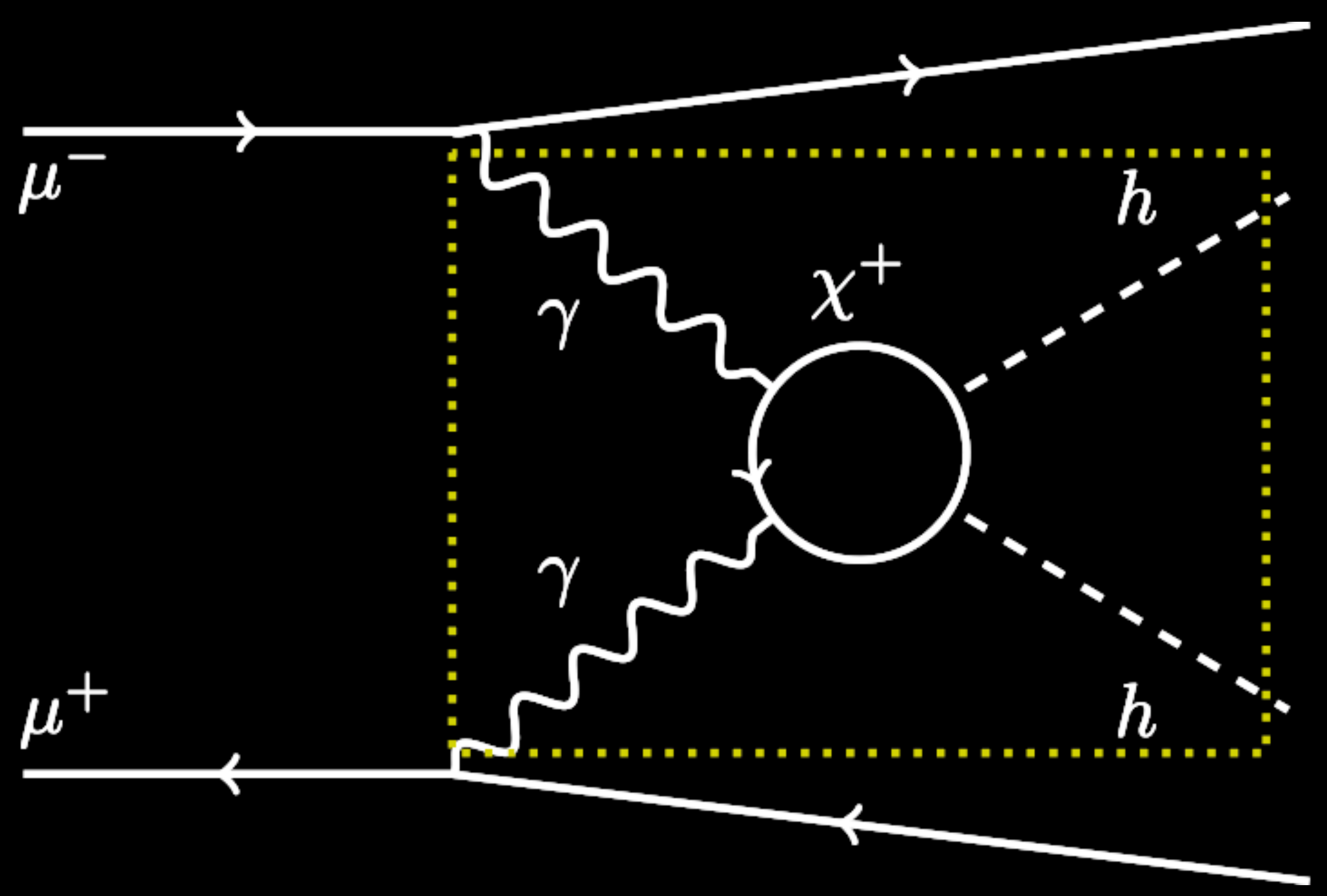
[Huang, Queiroz, Rodejohann, 2101.04956; Huang, Sana, Queiroz, Rodejohann, 2103.01617, Asadi, Capdevilla, Cesarotti, Homiller 2104.05720]

Compelling complementarity

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

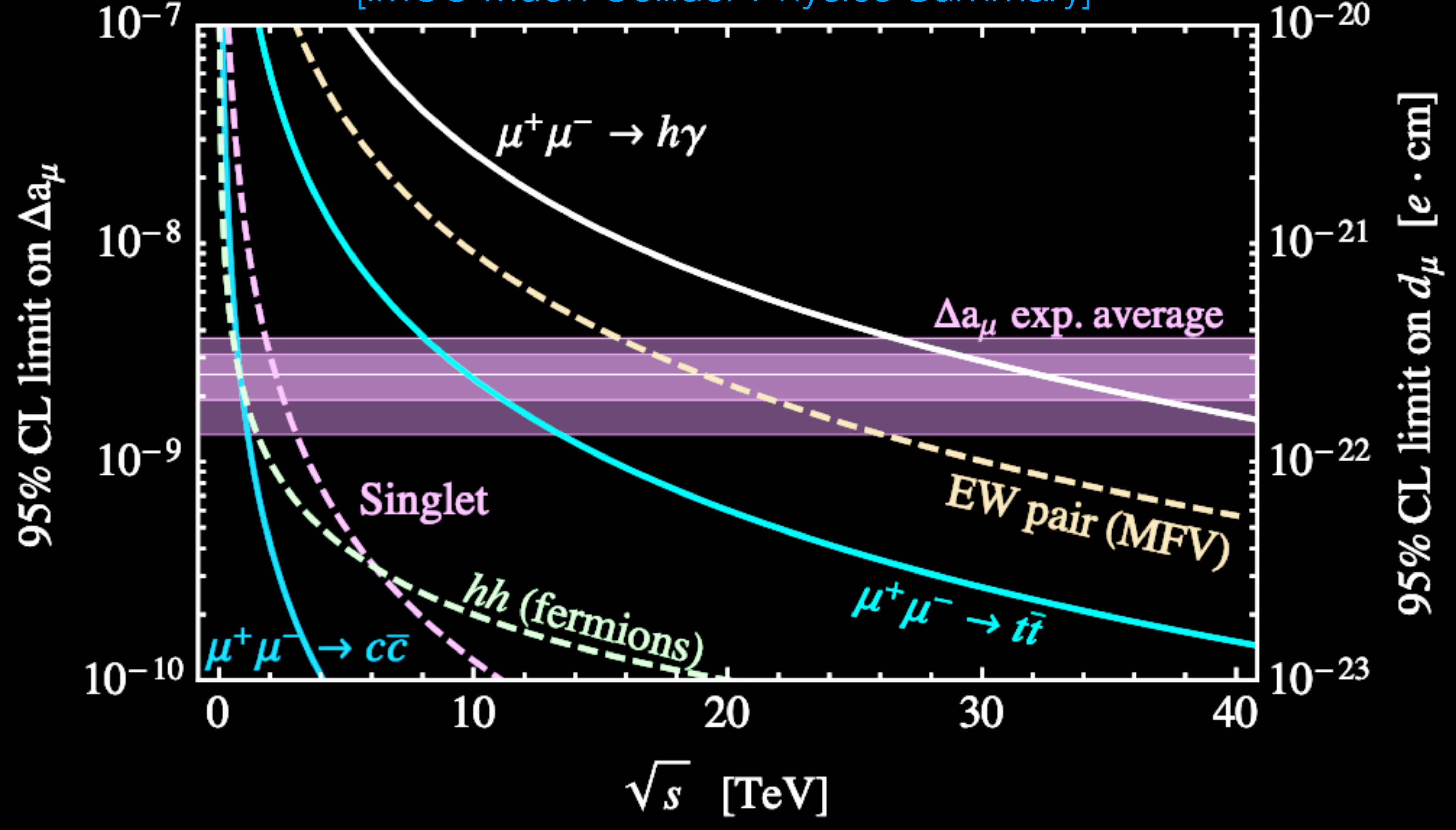
(See also: [Homiller, Lu, Reece 2203.08825])





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]

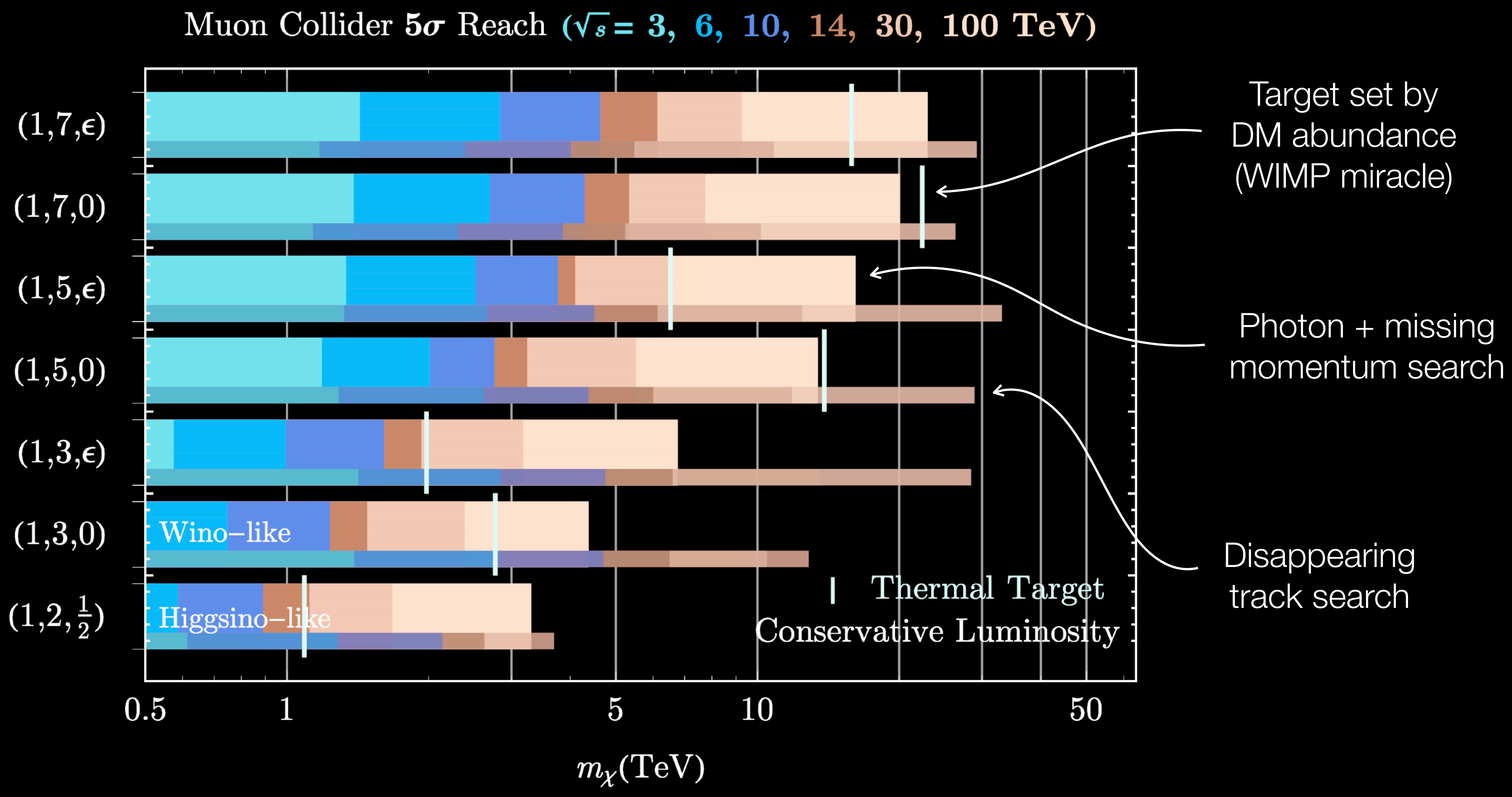
[IMCC Muon Collider Physics Summary]



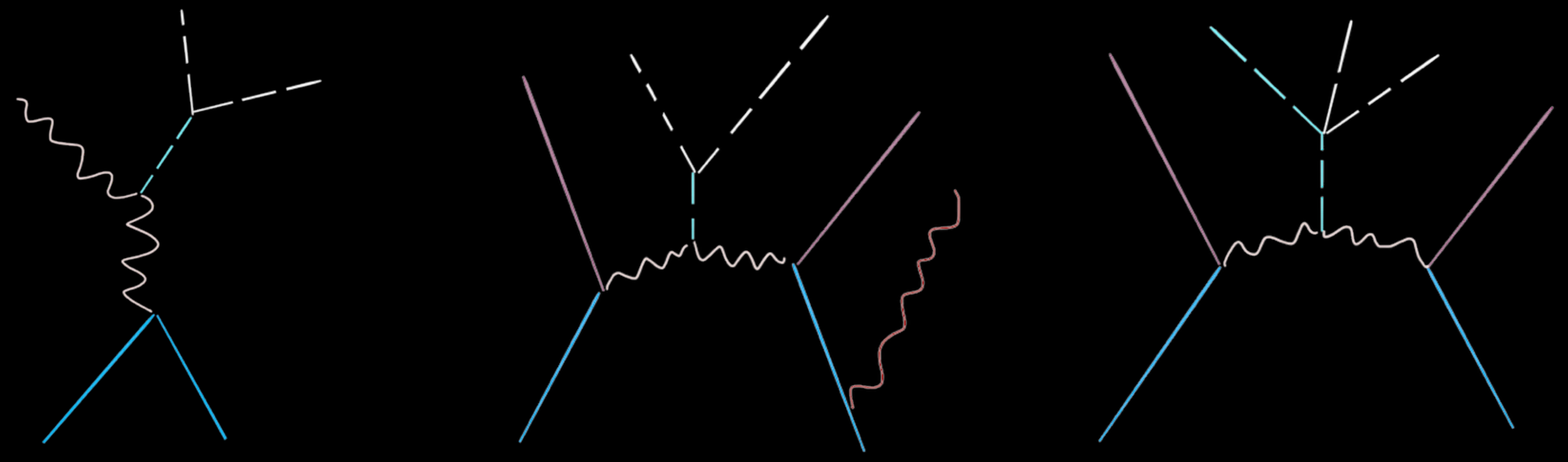
What is the nature of dark matter?

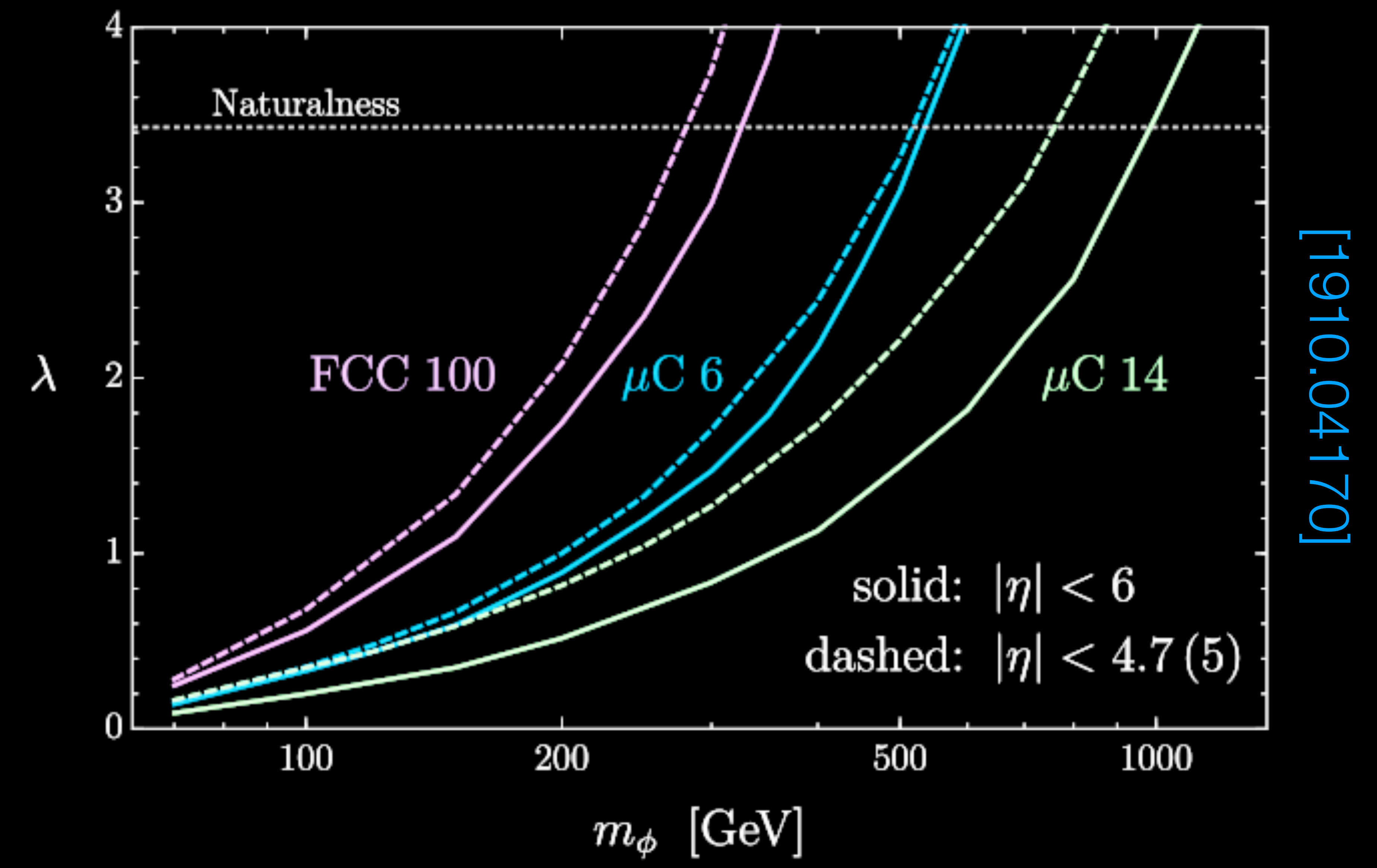
[Han, Liu, Wang, Wang, 2009.11287, lumi updated for μSG], see also [Capdevilla, Meloni, Simoniello, Zurita 2102.11292; Bottaro, Buttazzo et al. 2107.09688 & 2205.04486]

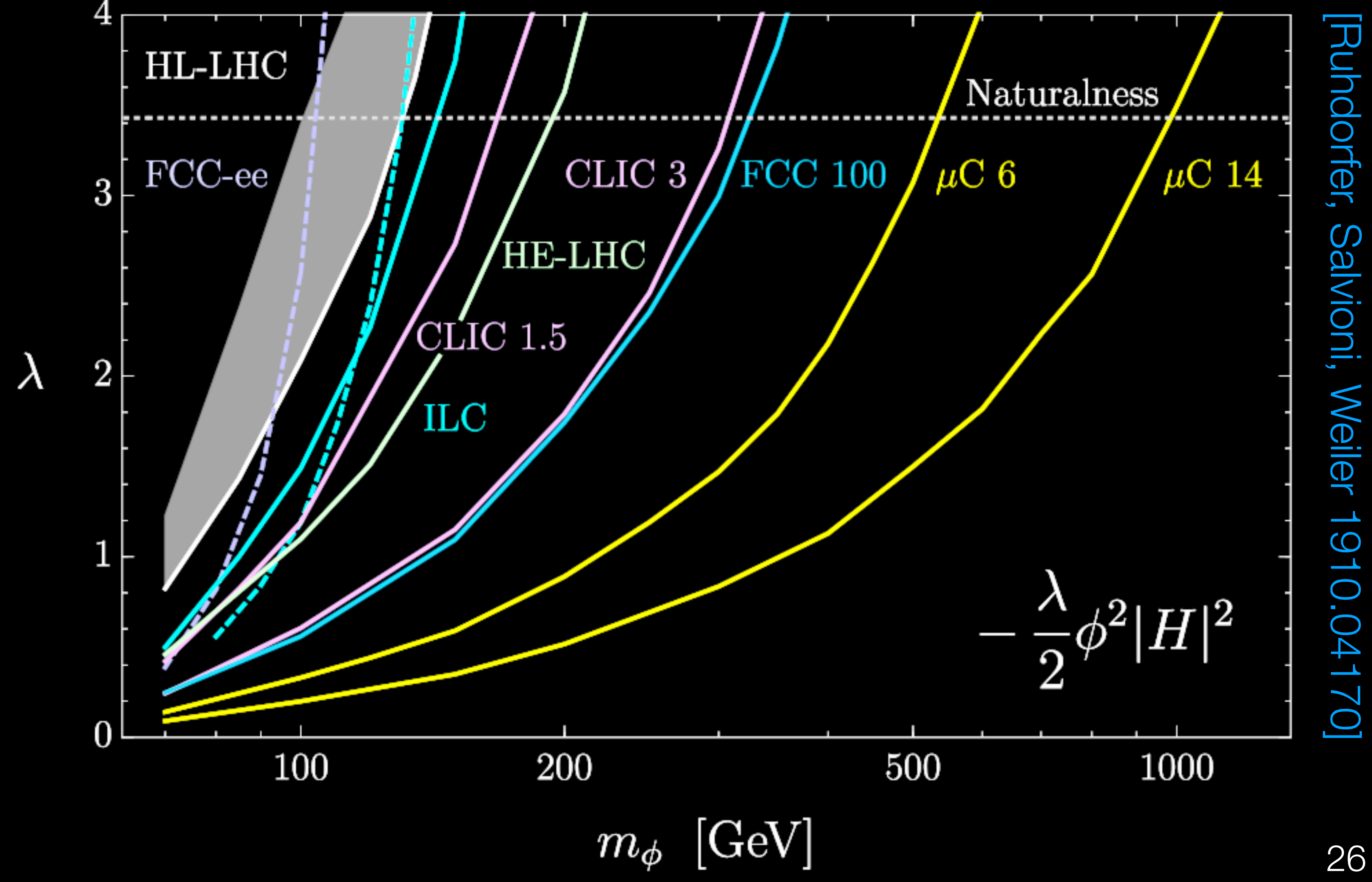
“Minimal dark matter”
(Electroweak multiplet w/ neutral lightest particle)

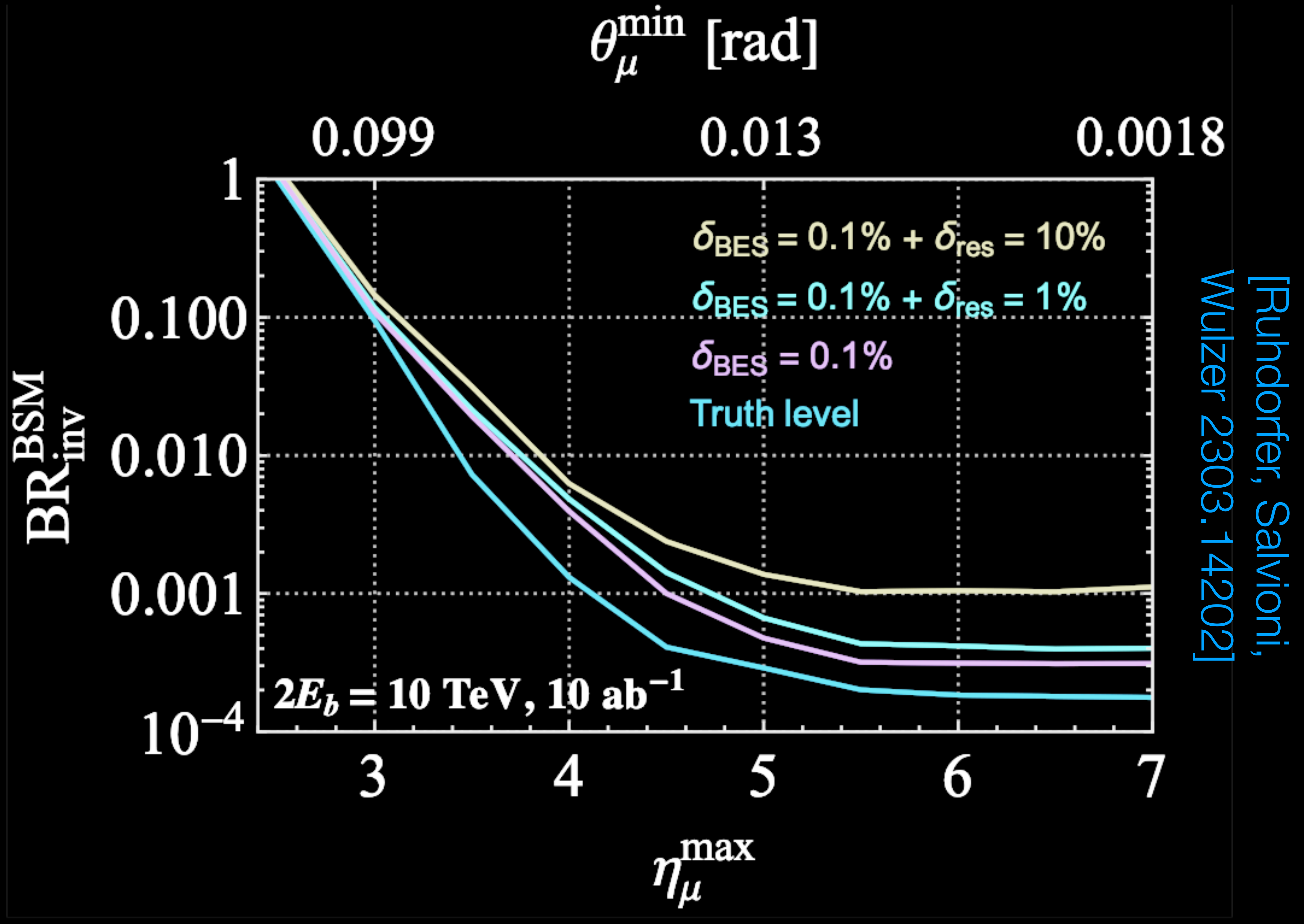


Higgs Portal DM

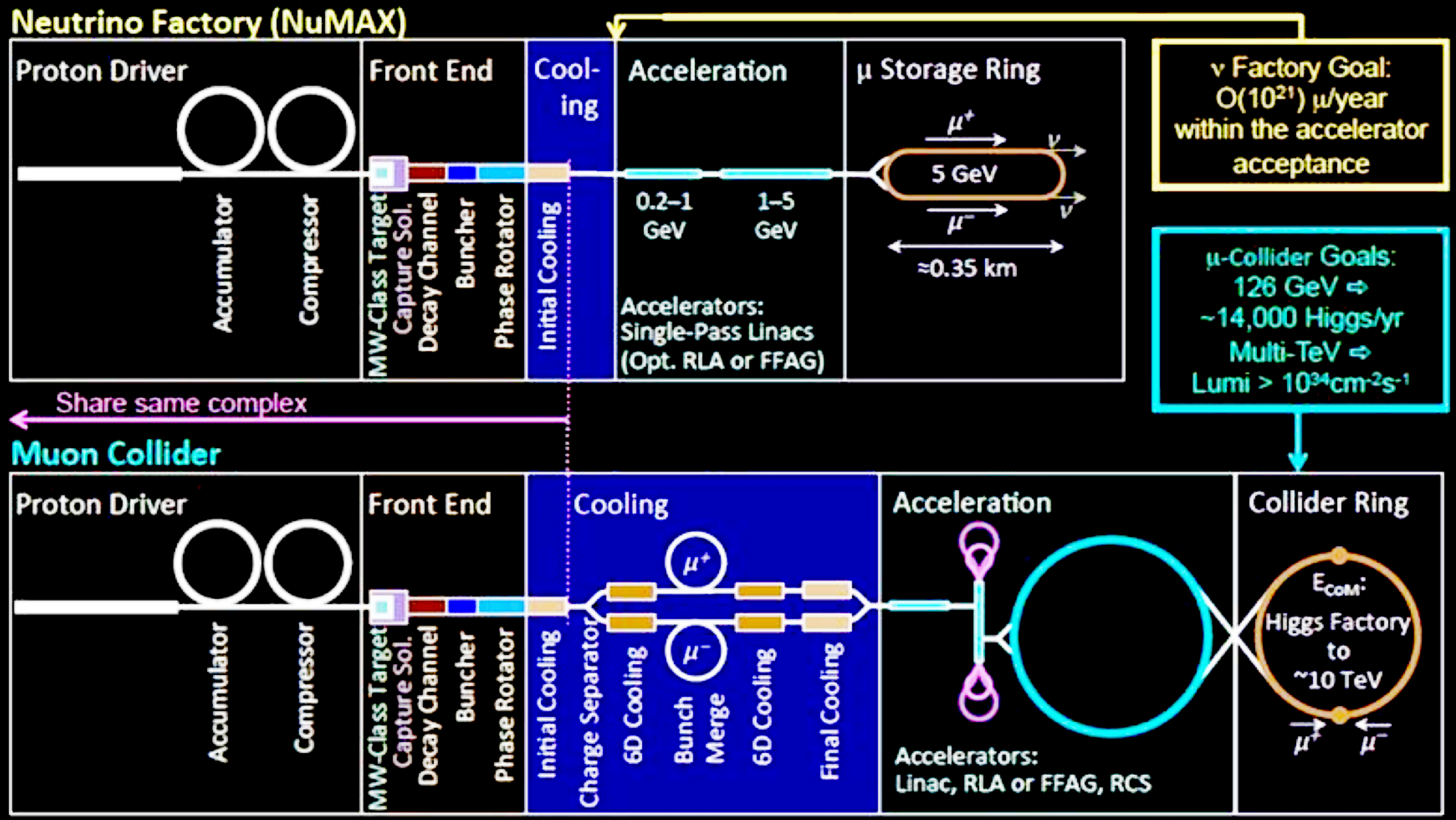






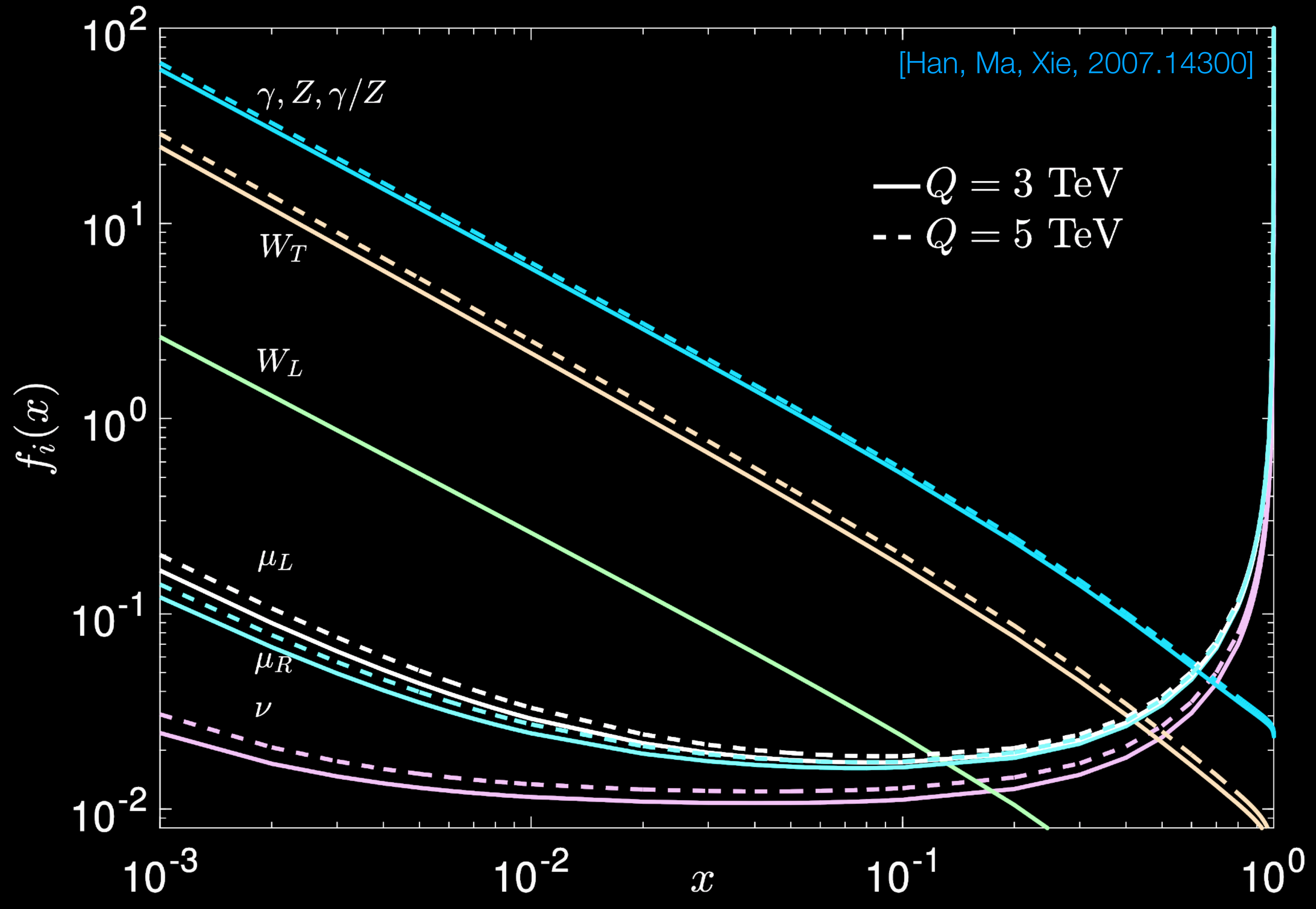


Nature of the Neutrino Sector: $\mu C/\nu F$ Complementarity



[Delahaye et al. 1803.07431]

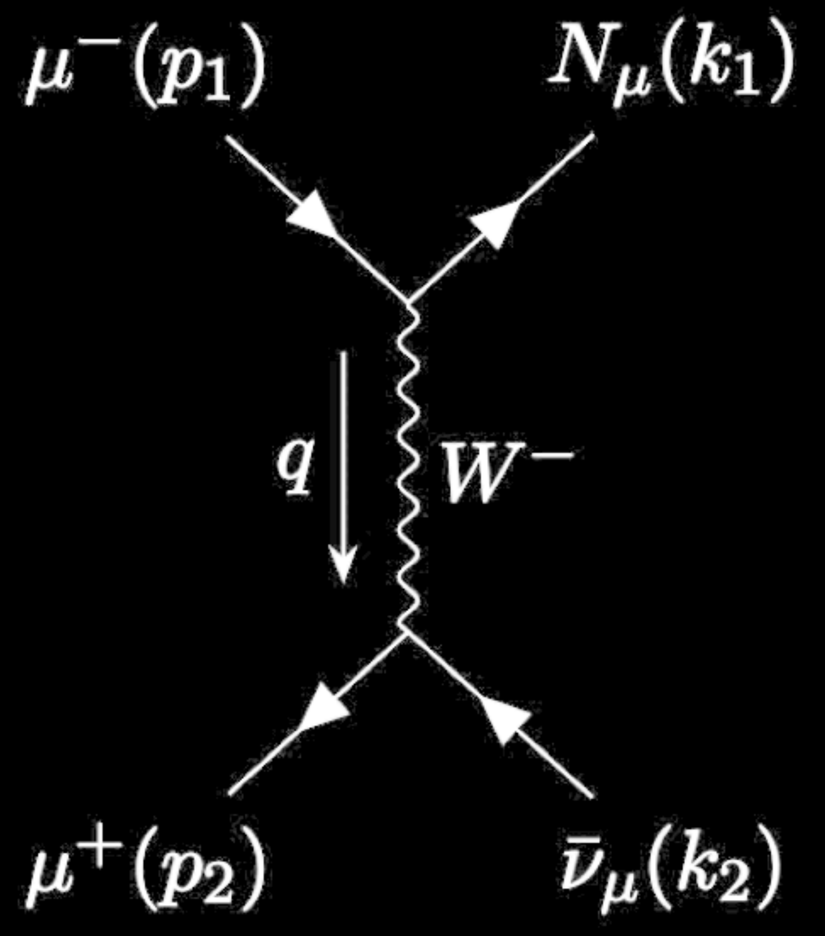
High-energy Neutrinos?

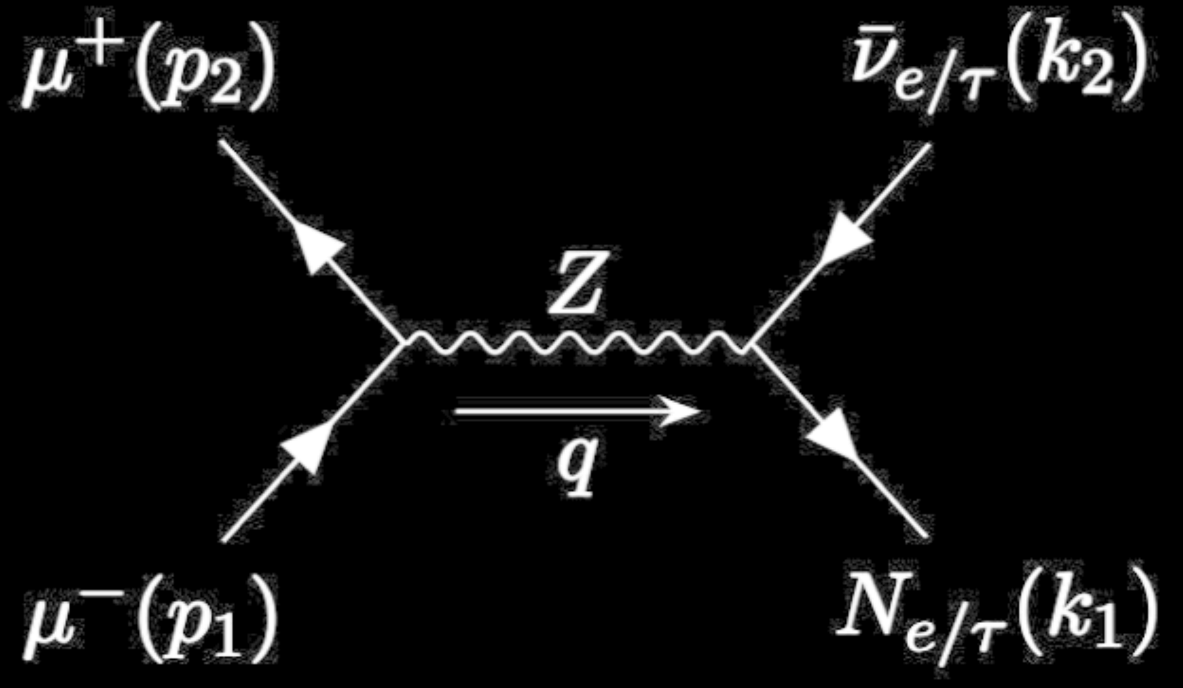


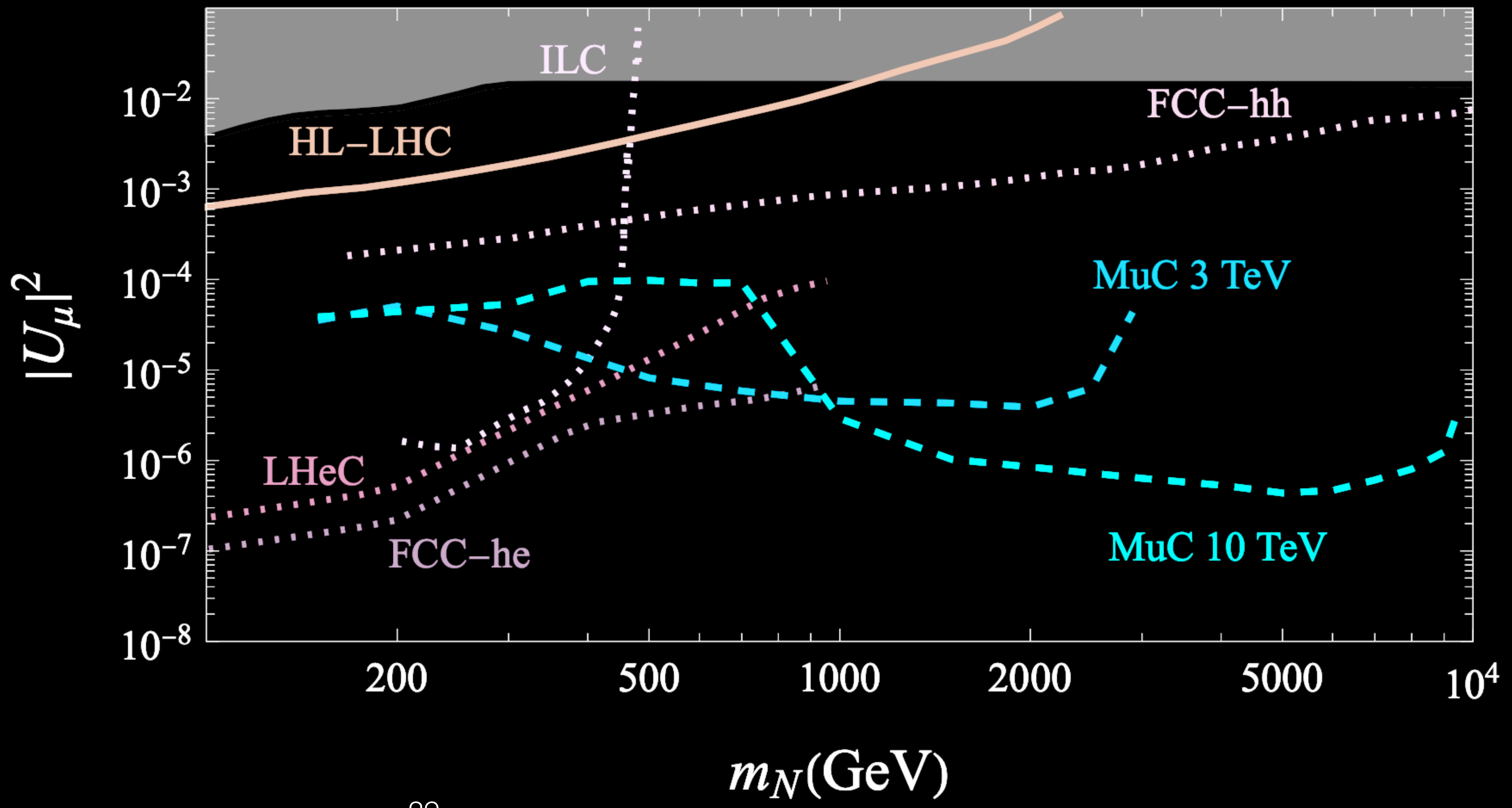
- Neutrino radiation for high-energy fixed target? Akin to FASERν but w/ well-known neutrino flavor composition & spectrum, narrow beam.
- Neutrino-neutrino or neutrino-charged lepton collisions? Probe neutrino interactions, dark sector portals, …

Heavy Neutral Leptons

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







Vision circa 2024

- ✓ 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?

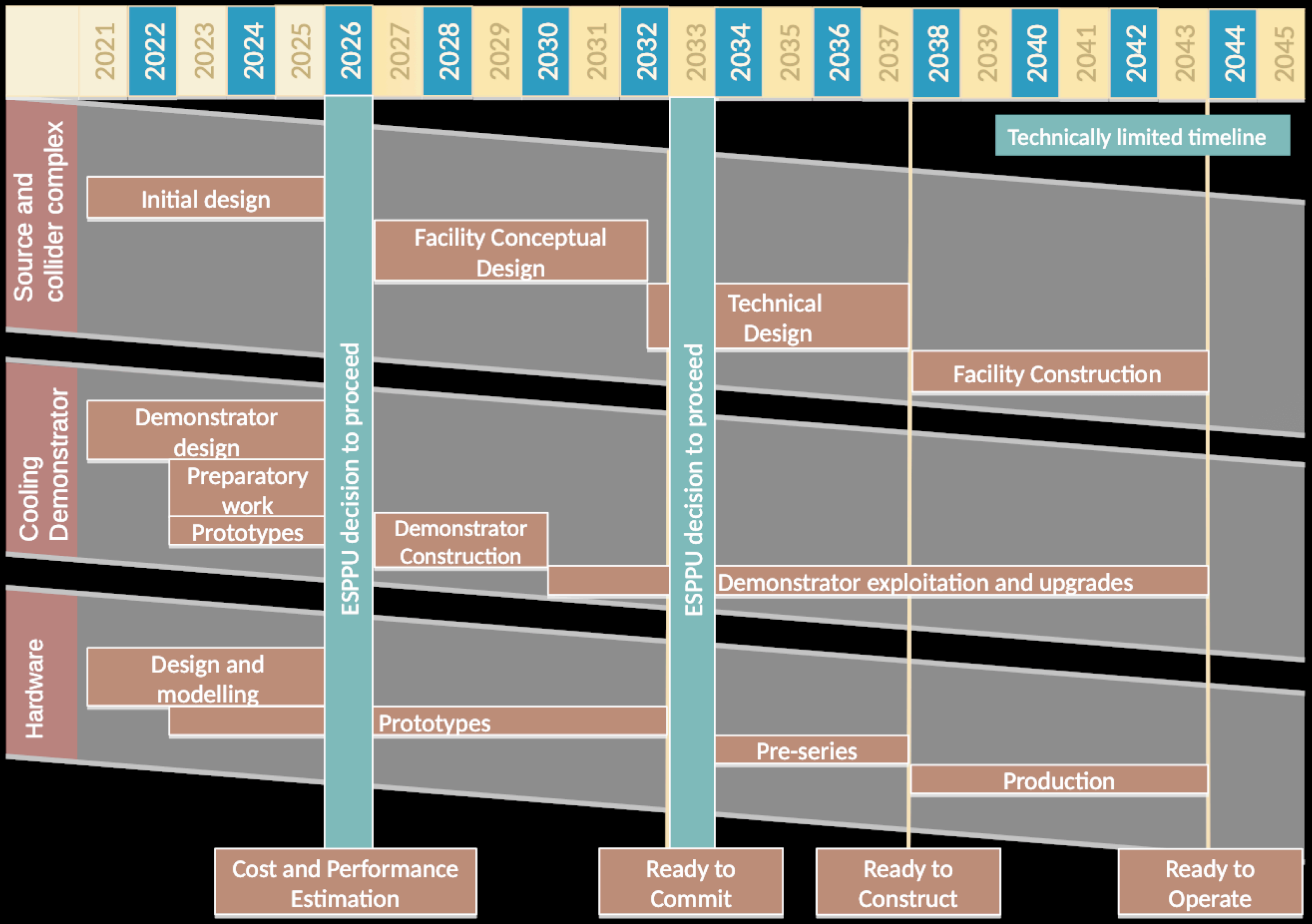
A Higgs! Yet:

✓ “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.”

The 12 ~~miracles~~ challenges

Many thanks to S. Jindariani, D. Schulte, and M. Wing for inputs and useful discussions

	Target	Status	Notes	Future work
Pulse compression	1-3 ns	SPS does O(1) ns	Need higher intensity. O(30) ns loses only factor 2 in the produced muons.	Refine design, including proton acceleration. Accumulation and compression of bunches.
High-power targets	2 MW	2 MW	Available for neutrino and spallation neutrons. Aim for 4 MW to have margin.	Develop target design for 2 MW, O(1) ns bunches create larger thermal shocks. Prototype in 2030s.
Capture solenoids	15 T	13 T	ITER central solenoid.	Study superconducting cables and validate cooling. Investigate HTS cables.
Cooling solenoids	50 T	30-40 T	30 T leads to a factor 2 worse transverse emittance with respect to design.	Extend designs to the specs of the 6D cooling channel. Demonstrator.
RF in magnetic field	>50 MV/m	65 MV/m	MUCOOL published results. Requires test in non-uniform B.	Design to the specs of 6D cooling. Demonstrator.
6D cooling	10^{-5}	0.9 (1 cell)	MICE result (no re-acceleration). Emittance exchange demonstrated at g-2.	Optimise with higher fields and gradients. Demonstrator.
RCS dynamics	-	-	Simulation. 3 TeV lattice design in place.	Develop lattice design for a 10 TeV accelerator ring.
Rapid cycling magnets	2 T/ms 2 T peak	2.5 T/ms 1.81 T peak	Normal conducting magnets. HTS demonstrated 12 T/ms, 0.24 T peak.	Design and demonstration work. Optimise power management and re-use.
Ring magnets aperture	20 T quads	12-15 T (Nb3Sn)	Need HTS or revise design to lower fields.	Design and develop larger aperture magnets, 12-16 T dipoles and 20 T HTS quads.
Collider dynamics	-	-	3 TeV lattice in place with existing technology.	Develop lattice design for a 10 TeV collider.
Neutrino radiation	10 μSv/year	-	3 TeV ok with 200 m deep tunnel. 10 TeV requires a mover system.	Study mechanical feasibility of the mover system impact on the accelerator and the beams.
Detector shielding	Negligible	LHC-level	Simulation based on next-gen detectors.	Optimise detector concepts. Technology R&D.



[IMCC 2203.08033]

COMMUNITY PLANNING 2021

The Future of US Particle Physics

The Energy Frontier Report

2021 US Community Study
on the Future of Particle Physics

organized by
the APS Division of Particles and Fields

For the five year period starting in 2025:

3. Develop an initial design for a first stage TeV-scale Muon Collider in the US,

For the five year period starting in 2030:

3. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider.

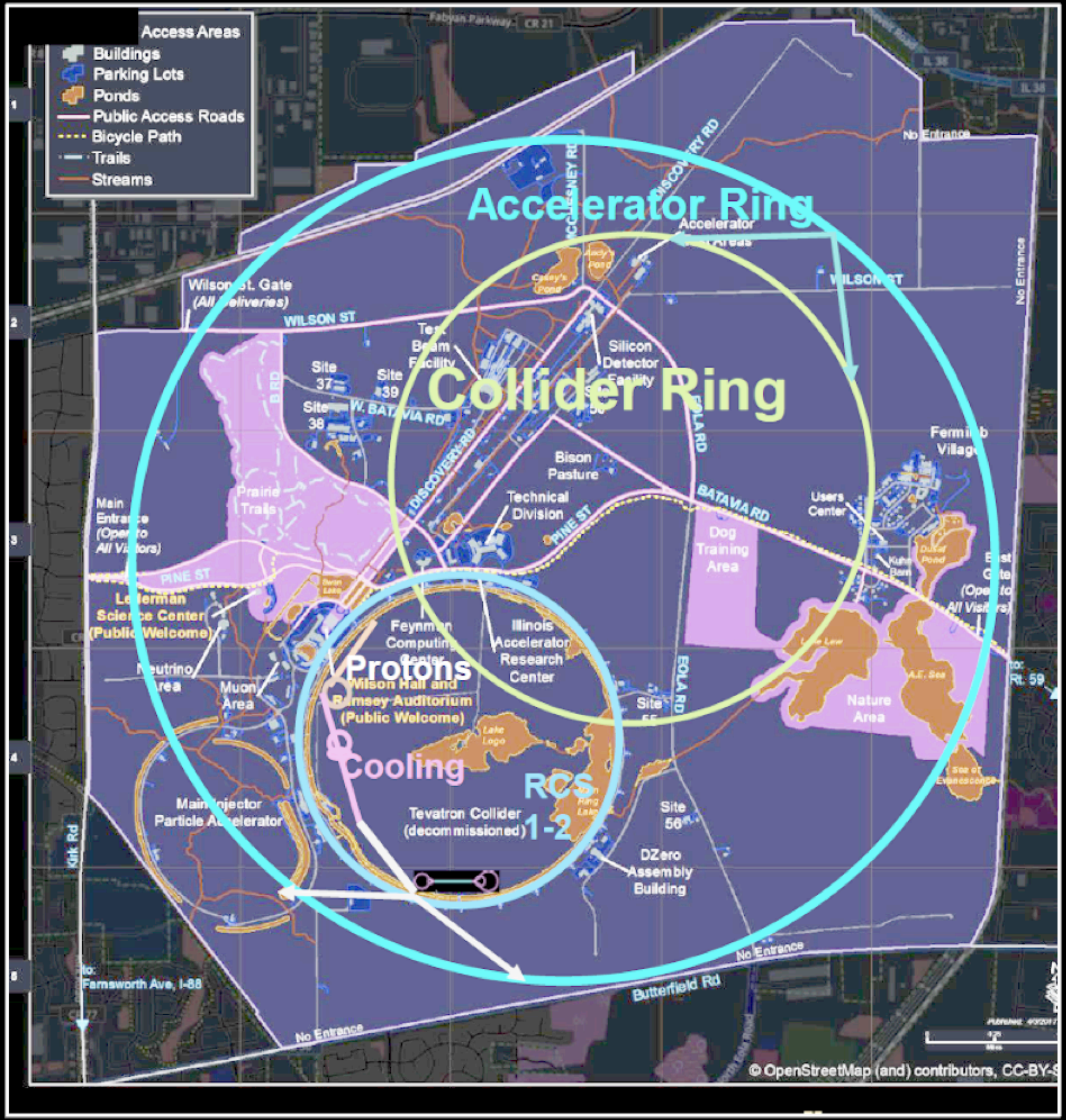
Plan after 2035:

3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,

Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV parton center-of-momentum (pCM) collider. In particular, the muon collider option builds on Fermilab strengths and capabilities and supports our aspiration to host a major collider facility in the US.

As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by advancing critical R&D that can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.

[Bhat, Jindariani, et al 2203.08088]



"We set sail on this new sea because there is new knowledge to be gained, and new rights to be won, and they must be won and used for the progress of all people…We choose to go to the Moon. We choose to go to the Moon... We choose to go to the Moon in this decade…not because it is easy, but because it is hard; because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win."

–John F. Kennedy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across the frontiers of particle physics.


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This is our Muon Shot.