Physics Prospects for High-Energy Future Colliders

Higgs 2023 Conference

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Cari Cesarotti

Postdoctoral Fellow

MIT CTP

Higgs and High Energy

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What are the details of EWSB?

What is the form of the Higgs Potential?

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Is the Higgs connected to BAU?

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Need to probe **well above** v to $\Lambda \sim$ TeV to explore

Higgs Factory vs. High Energy

A Higgs factory alone **can't answer** all open questions about the Higgs

$$E \gtrsim \text{TeV}$$

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Multiple Higgs Production

$\downarrow$

Higgs self-couplings

$$\mathscr{L} \supset \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

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Precision with Energy

$\downarrow$

$$H^\dagger H \mathcal{O}_{NP} \to \frac{v^2}{\Lambda_{NP}^2}$$

On-shell production of new states

Higgs and High Energy

We can use EFT approaches, cosmological probes to test predictions…

…but we need clean empirical evidence of what's beyond the TeV frontier

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→ Construction of multi-TeV ***future collider***

Higgs & EW Physics is SM **"no-lose"** motivation

Image by DALLE 3

Future Colliders

High-Energy Colliders

There are two (three) paradigms for high-energy future colliders

Hadron Colliders

Lepton Colliders

Linear v. *Circular*

High-Energy Colliders

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Hadron Colliders

HL-LHC

SPPC

FCC-hh

Lepton Colliders

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Lepton Colliders

CLIC

Muon Collider

Linear v. *Circular*

High-Energy Colliders

There are two (three) paradigms for high-energy future colliders

Hadron Colliders

HL-LHC
SPPC
FCC-hh

Pros

Expertise & confidence
High-energy collisions

Cons

Very large footprint
Costly in time & money

Linear v. *Circular*

High-Energy Colliders

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CLIC

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Muon Collider

Luminosity Losses

Pros

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Completely Novel Machine

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Hadron Colliders

HL-LHC

SPPC

FCC-hh

Lepton Colliders

CLIC

Muon Collider

These are **complimentary machines** and the existence of one doesn't negate the motivation for another

Linear v. *Circular*

Hadron Colliders

HL-LHC

SPPC & FCC-hh

Hadron Colliders

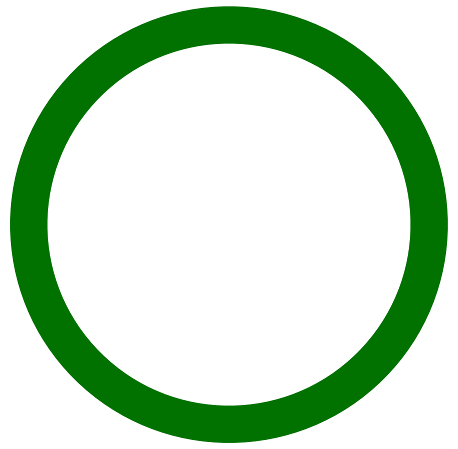
HL-LHC

$\sqrt{s} = 14$ TeV

$\int L dt = 3$ ab^{-1}

2030-2040s

SPPC & FCC-hh



HL-LHC

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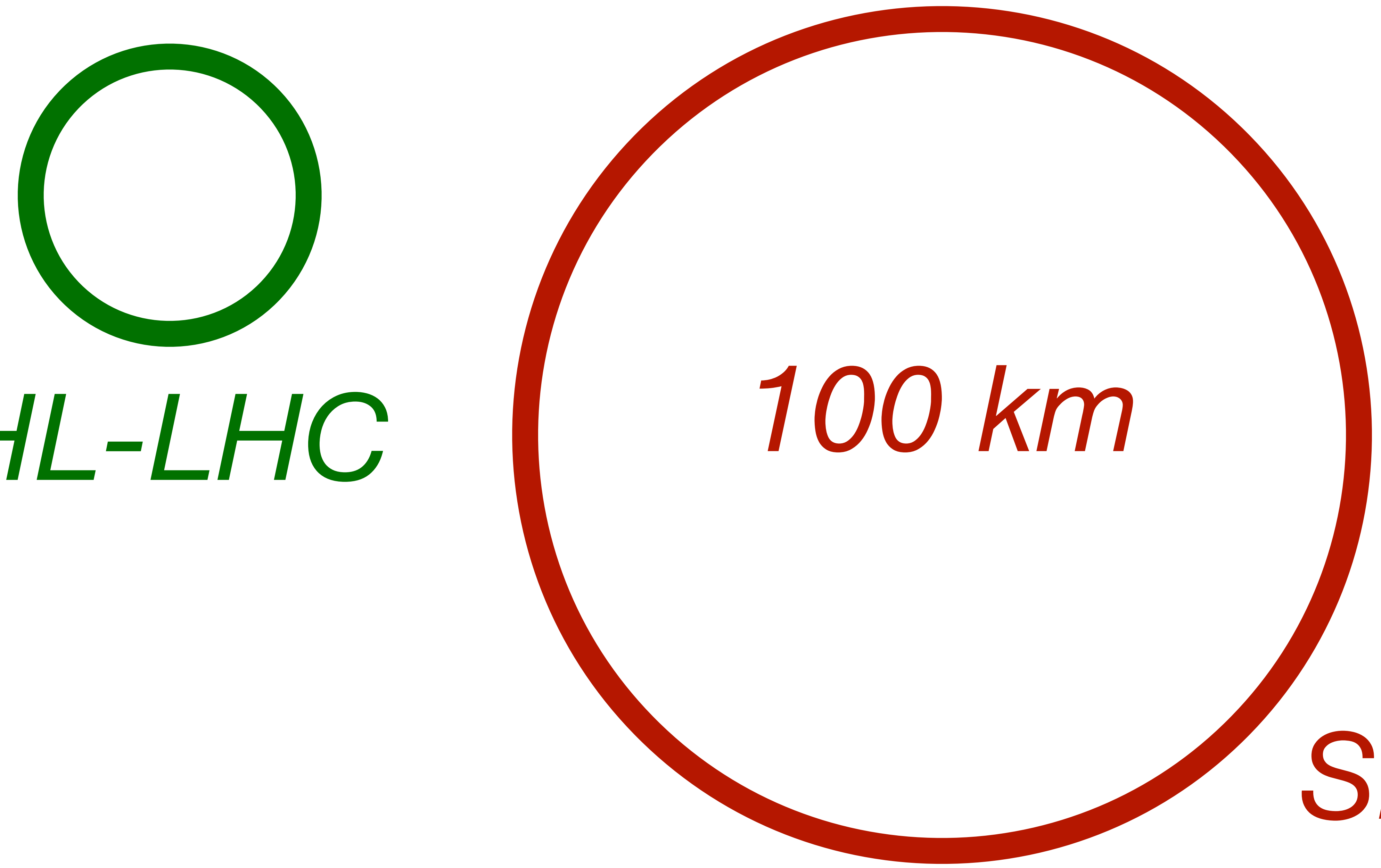
pp machines

Upgrades from ee Higgs Factories

$\sqrt{s} = 70/80 - 100$ TeV



Hadron Colliders

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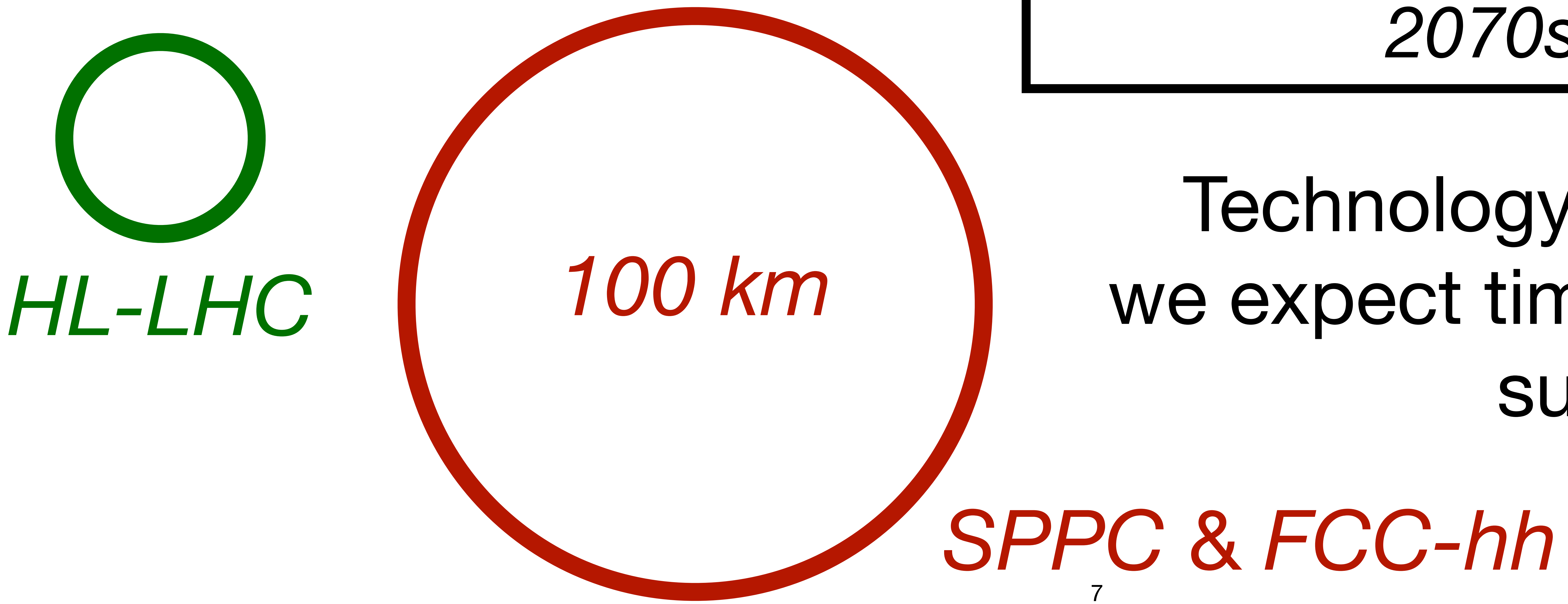
Upgrades from ee Higgs Factories

$\sqrt{s} = 70/80 - 100$ TeV

2070s to 2080s?



Technology isn't **ready**, but we expect time & money will be sufficient

Linear Lepton (e^+e^-) Colliders

CLIC Stage 2 & 3

Because leptons are **fundamental** all the energy is available at collisions

Linear Lepton (e^+e^-) Colliders

CLIC Stage 2 & 3

$\sqrt{s} = 1.5$ TeV $\rightarrow 3$ TeV

$\int Ldt = 2.5$ ab$^{-1} \rightarrow 5$ ab^{-1}

Operation: 2030s - 2060s?

Because leptons are **fundamental** all the energy is available at collisions

11 to 50 km

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Operation: 2030s - 2060s?

Because leptons are **fundamental** all the energy is available at collisions

$$P \propto \gamma^4 \sim \left(\frac{E}{m}\right)^4$$

TeV-scale e^+e^- colliders must be **linear** colliders otherwise power loss due to synchrotron radiation is insurmountable

11 to 50 km

Circular Lepton Colliders → Muon Collider (MuC)

Only **potentially feasible way** to access TeV energy with lepton circular collider

MuC

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MuC

$$\sqrt{s} = 3,\ 10,\ 14 - 30?\ \text{TeV}$$

$$\int L\, dt = 1,\ 10,\ 30\ \text{ab}^{-1}$$

Late 2040s - 2050?

Circular Lepton Colliders → Muon Collider (MuC)

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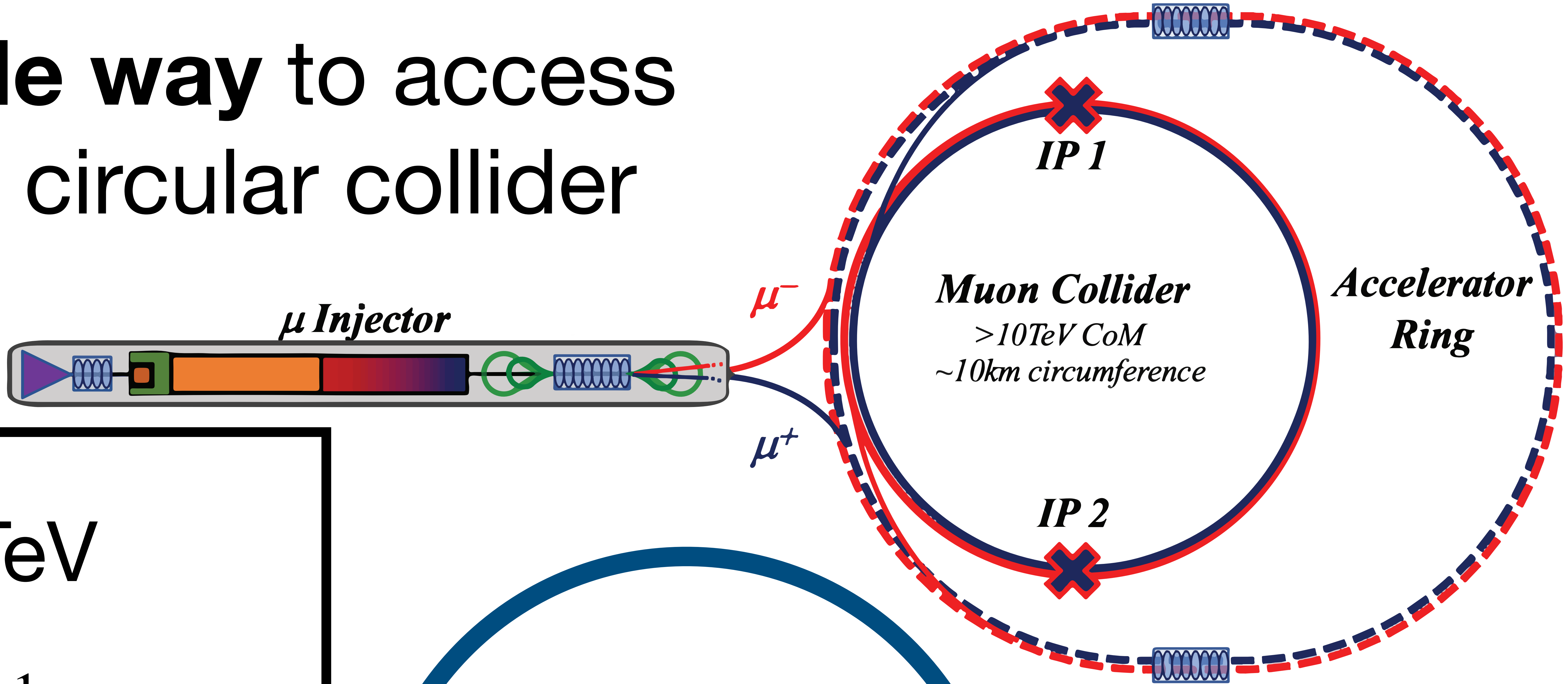

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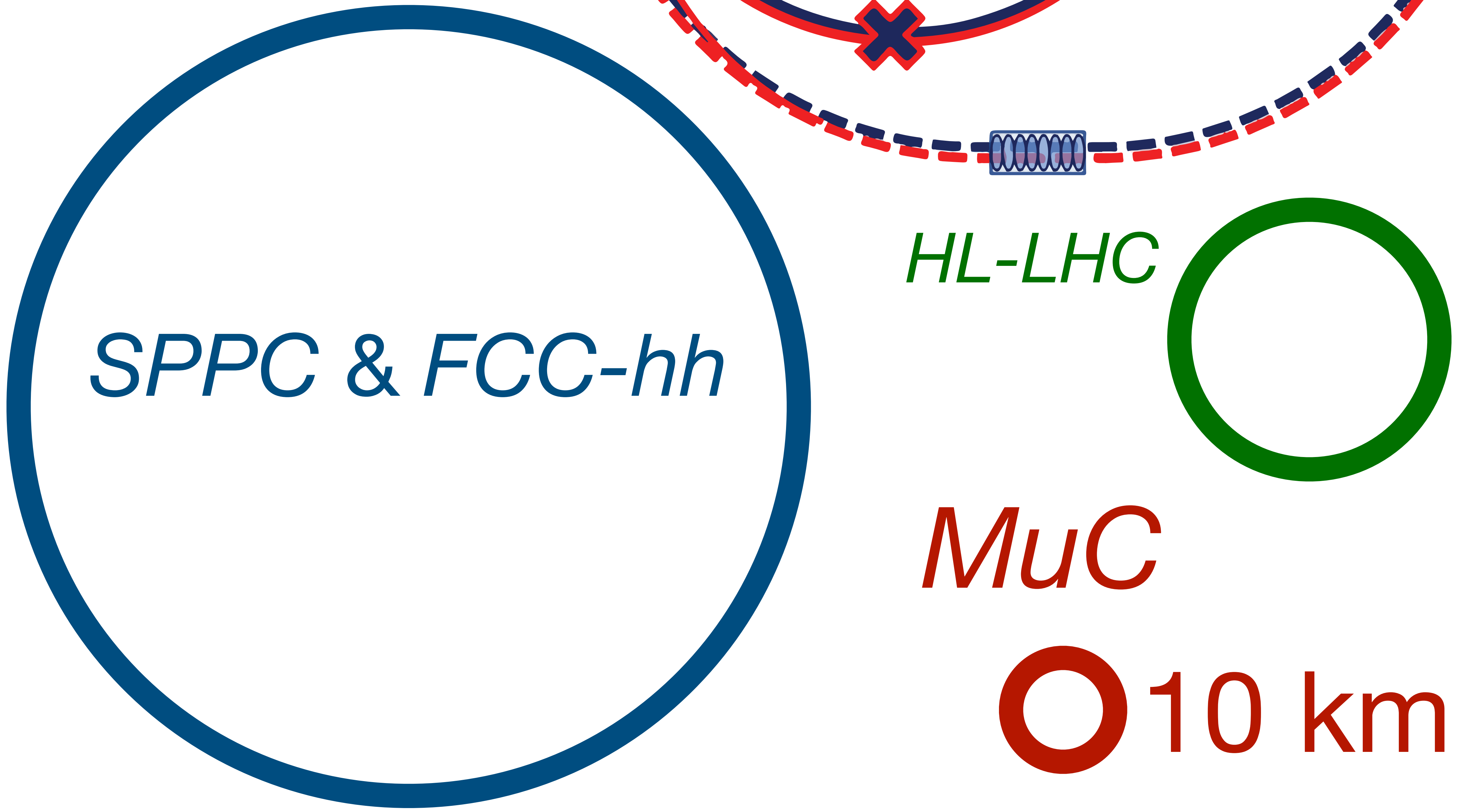

Circular Lepton Colliders → Muon Collider (MuC)

Only **potentially feasible way** to access TeV energy with lepton circular collider

Staging facilities (low energy runs) are still flexible and intended to ensure there is **no large gap** in a collider program

125 GeV, 3 TeV Stage are discussed but not **fixed**

Late 2040s - 2050?

IP 1

...lerator ...ing

MuC

10 km

Comparison of MuC to Other Colliders

pp

$\mu^+\mu^-$

e^+e^-

Comparison of MuC to Other Colliders

pp

Composite

$\sqrt{\hat{s}} \ll \sqrt{s}$

$\mu^+\mu^-$

e^+e^-

Fundamental

$\sqrt{\hat{s}} \sim \sqrt{s}$

Comparison of MuC to Other Colliders

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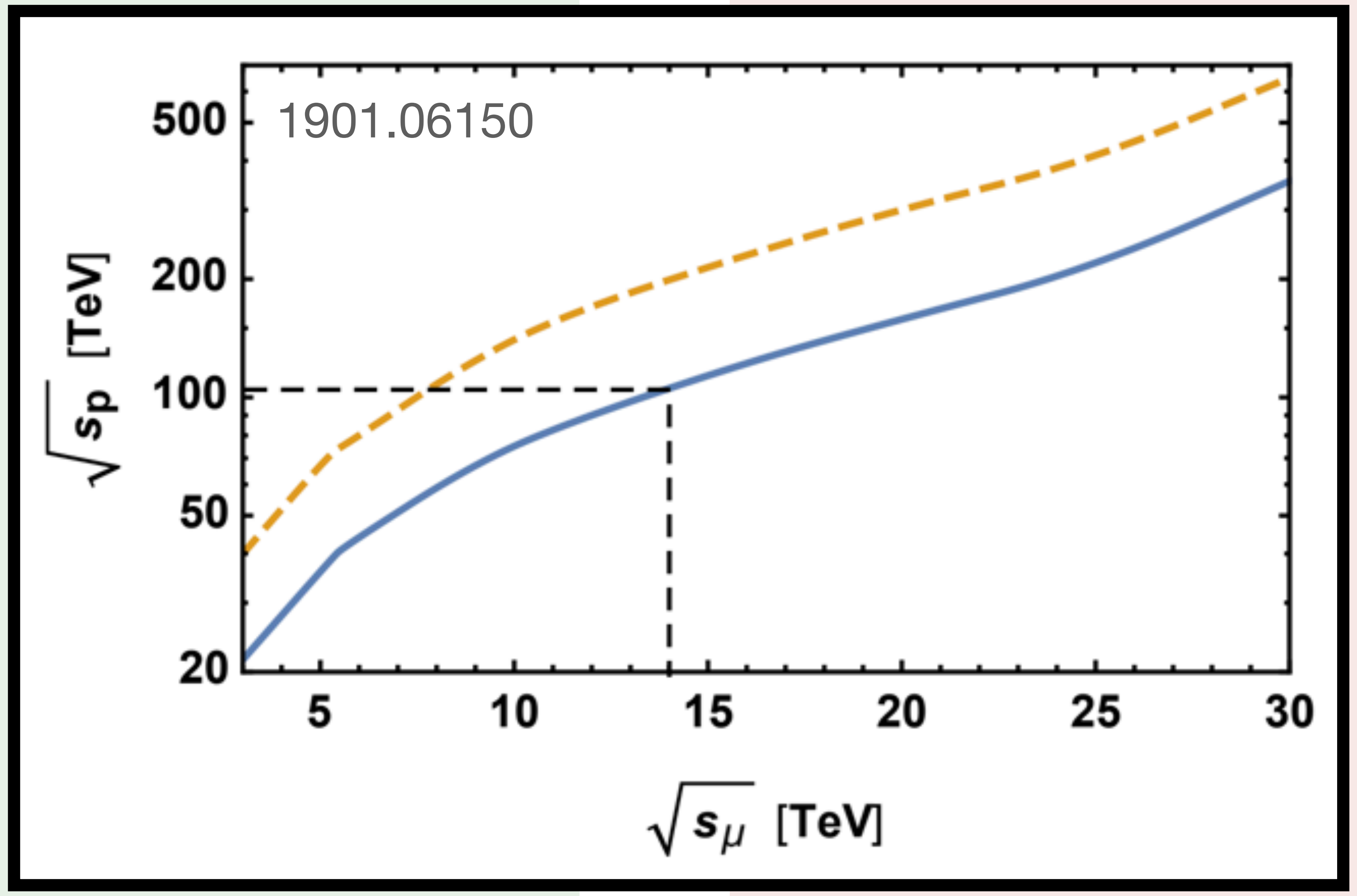

Roughly order-of-magnitude improvement

Comparison of MuC to Other Colliders

pp

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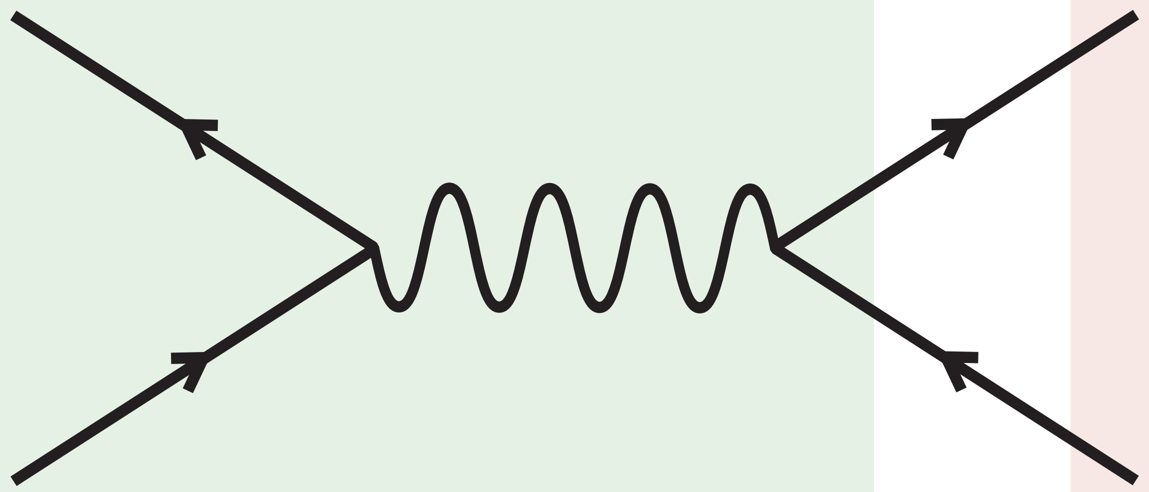
$\sqrt{\hat{s}} \ll \sqrt{s}$

$\mu^+\mu^-$

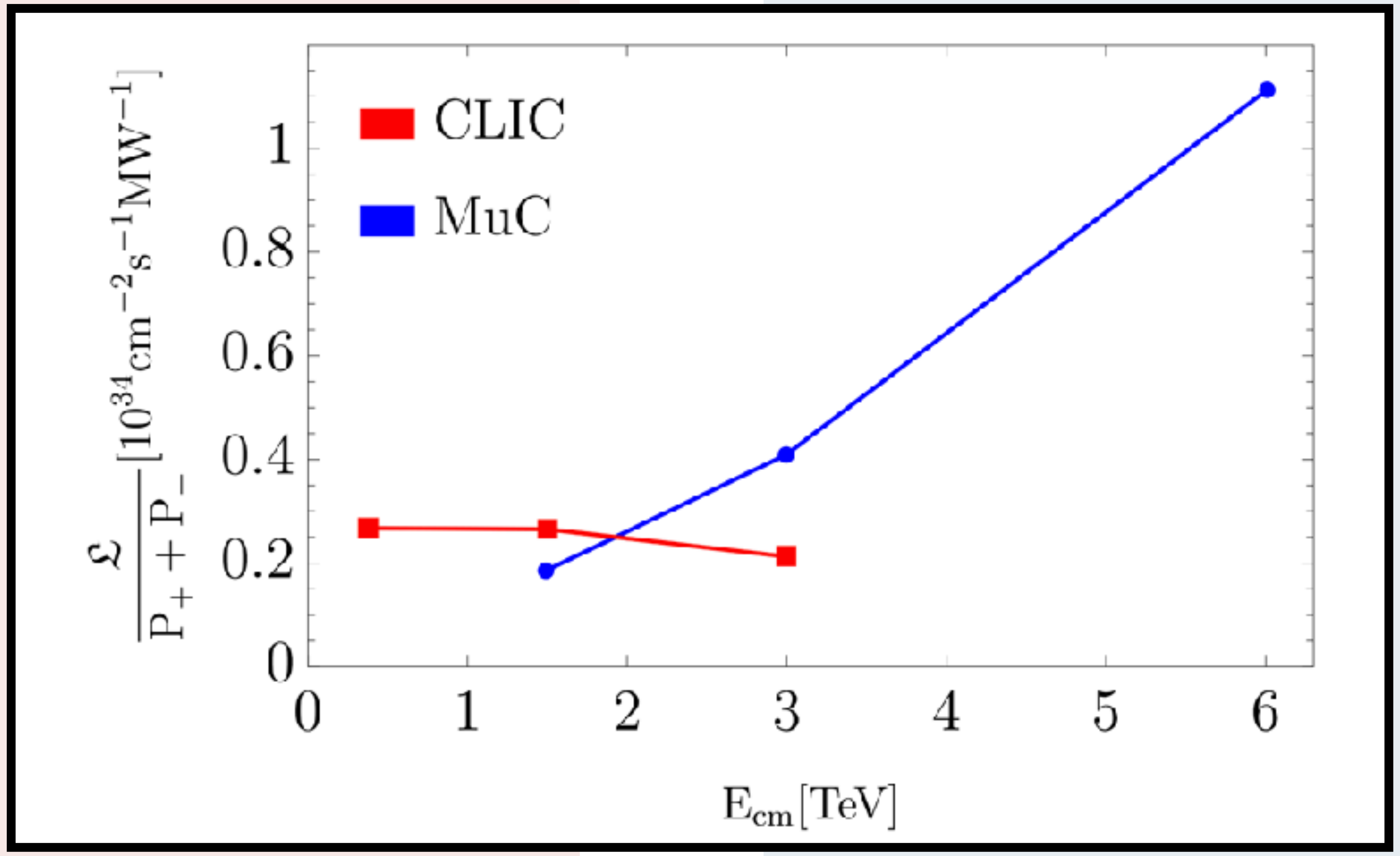
e^+e^-

Fundamental

$\sqrt{\hat{s}} \sim \sqrt{s}$



$\sim \frac{1}{s}$



Luminosity loss without recirculating particles

Comparison of MuC to Other Colliders

pp

Composite

$\sqrt{\hat{s}} \ll \sqrt{s}$

~ 100 TeV

$\mu^+\mu^-$

Fundamental

$\sqrt{\hat{s}} \sim \sqrt{s}$

$\sim 10 - 100$ TeV

e^+e^-

~ 3 TeV

Comparison of MuC to Other Colliders

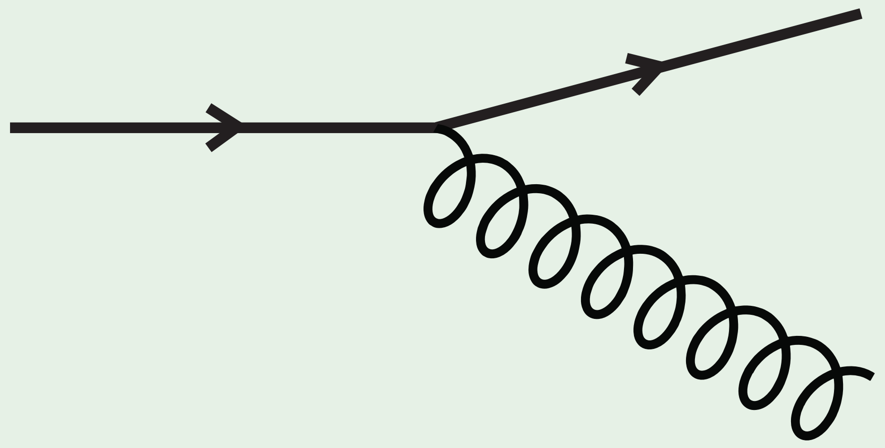
pp

Composite

$\sqrt{\hat{s}} \ll \sqrt{s}$

~ 100 TeV

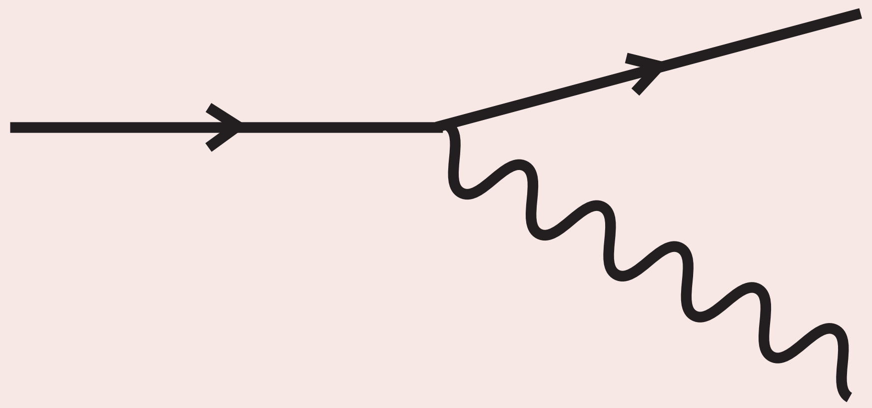
QCD



$\mu^+\mu^-$

$\sim 10 - 100$ TeV

Electroweak



e^+e^-

Fundamental

$\sqrt{\hat{s}} \sim \sqrt{s}$

~ 3 TeV

Ideal for studying EW Phenomena

QCD vs EW bgd

Comparison of MuC to Other Colliders

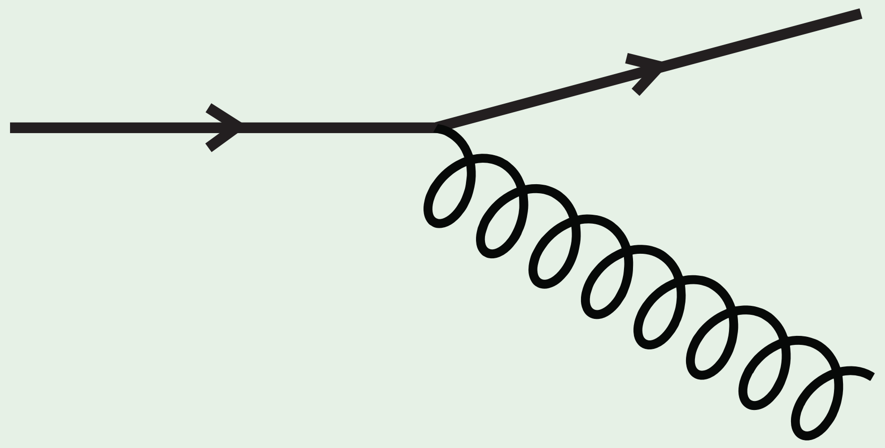
pp

Composite

$\sqrt{\hat{s}} \ll \sqrt{s}$

~ 100 TeV

QCD



1^{st}

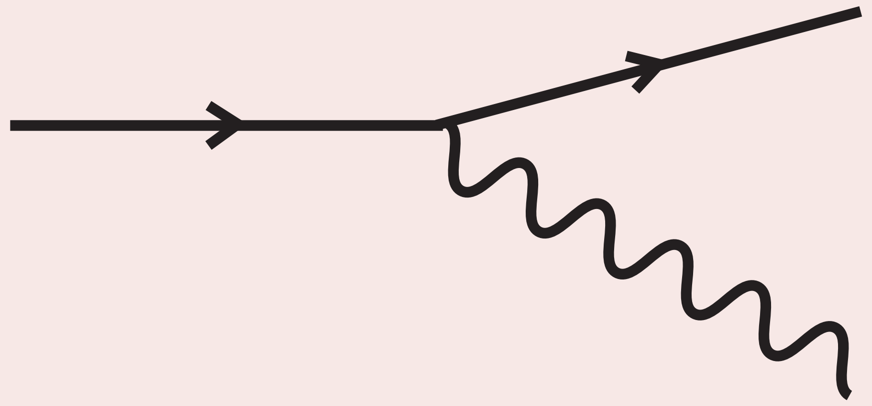
$\mu^+\mu^-$

Fundamental

$\sqrt{\hat{s}} \sim \sqrt{s}$

$\sim 10 - 100$ TeV

Electroweak



2^{nd}

Insight to flavor structure

e^+e^-

~ 3 TeV

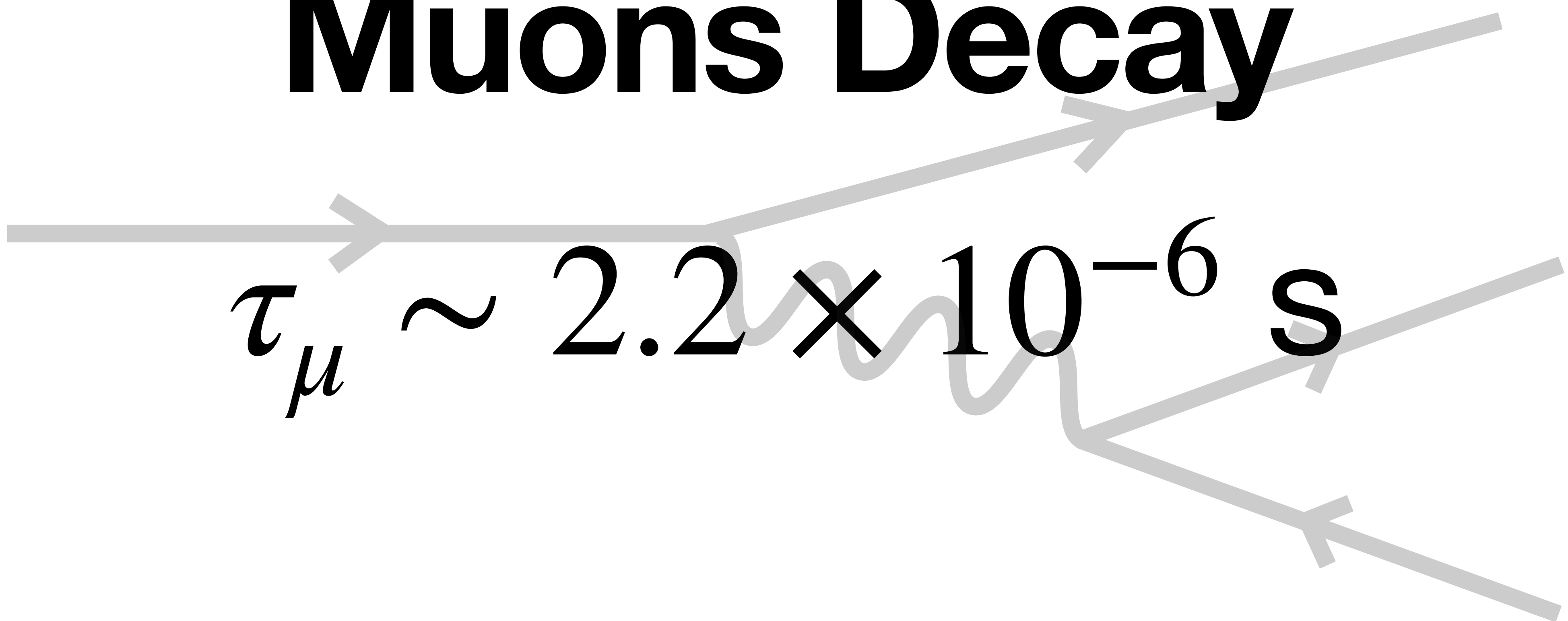
1^{st}

Comparison of MuC to Other Colliders

pp	$\mu^+\mu^-$	e^+e^-
Discovery	Discovery & Precision	Precision

Challenges of a Muon Collider

Muons Decay



$$\tau_\mu \sim 2.2 \times 10^{-6}\ \mathrm{s}$$

Challenges of a Muon Collider

Muons Decay

$$\tau_\mu \sim 2.2 \times 10^{-6}\ \text{s}$$

Production as tertiary beam

$\Delta p/p \sim \mathcal{O}(1)$

Cooling into single collimated bunch

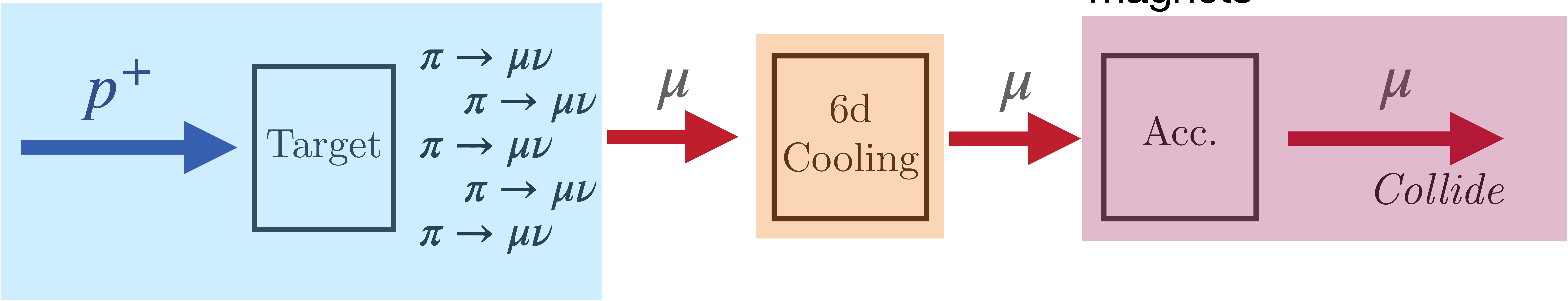
$0.9^{120} \sim 10^{-6}$

Acceleration and collision

Too quick to ramp up magnets

BIB: Beam induced background

Detector, ν radiation



Challenges of a Muon Collider

Muons Decay

A **future Muon Collider** needs serious R&D.

If it is proven technologically **feasible** it would be an amazing novel probe of high-energy phenomena

We could see the **10 TeV frontier** in the next 30 years!

$\pi \to \mu\nu$

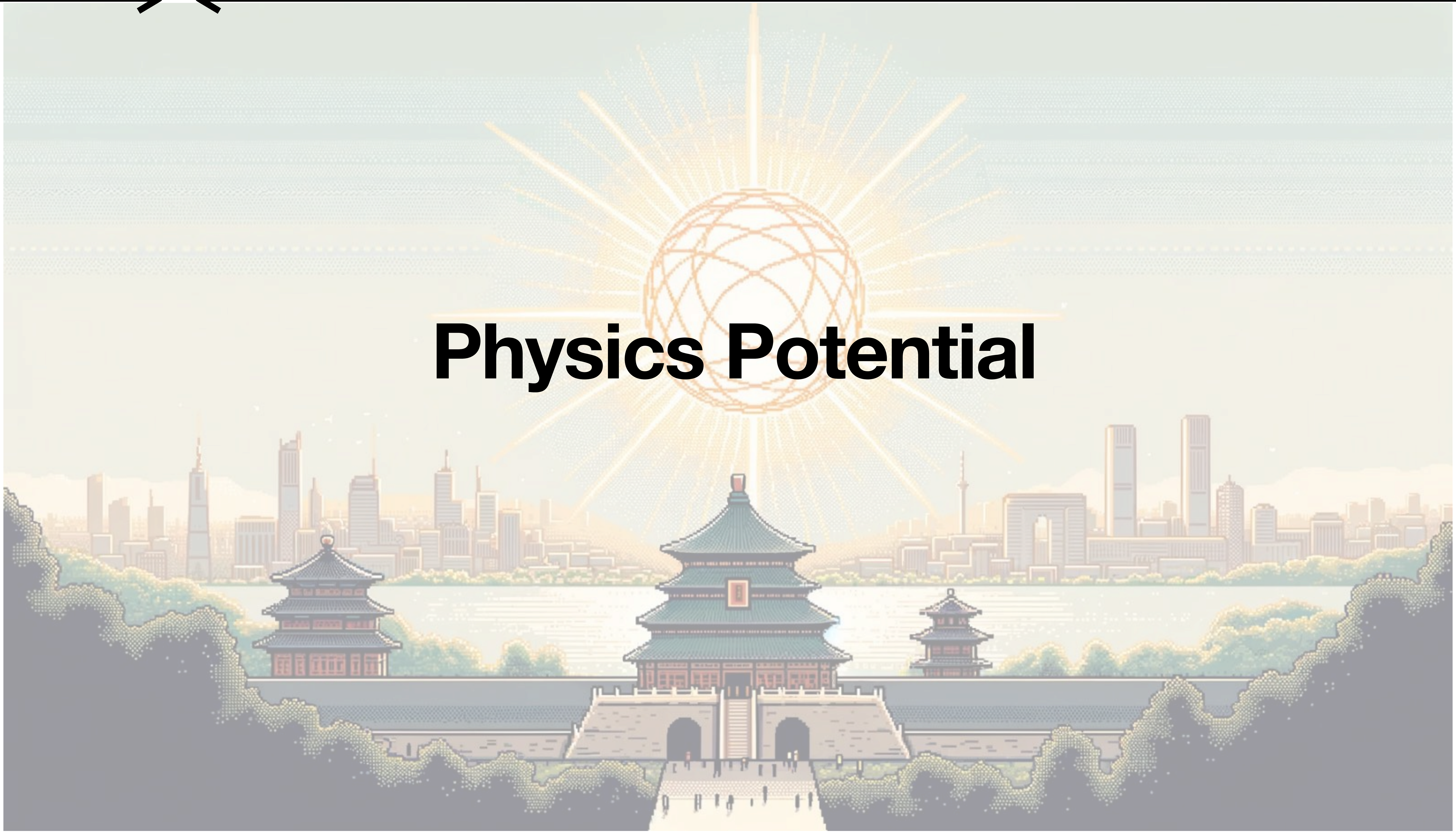
Which Future Collider?

All possible future colliders have varying degrees of shovel-readiness, novel physics reach, time scales, etc.

As a community, we should focus building the **strongest physics case possible** to inform the decision process

Image by DALLE 3

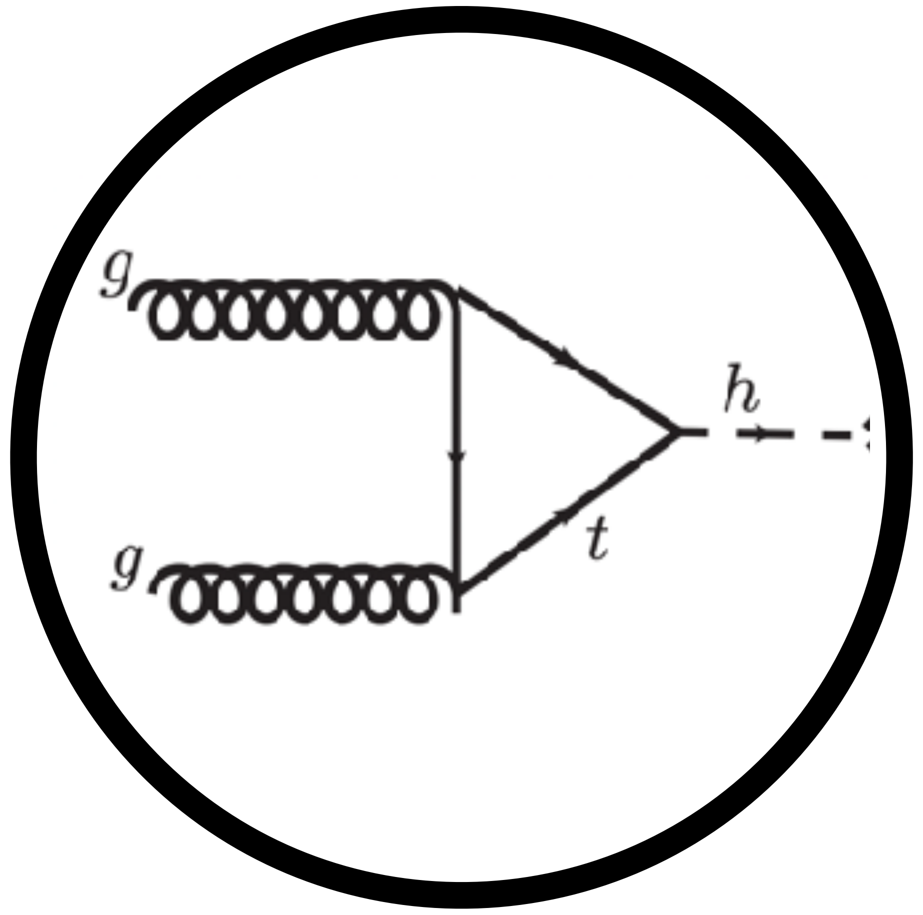
Physics Potential

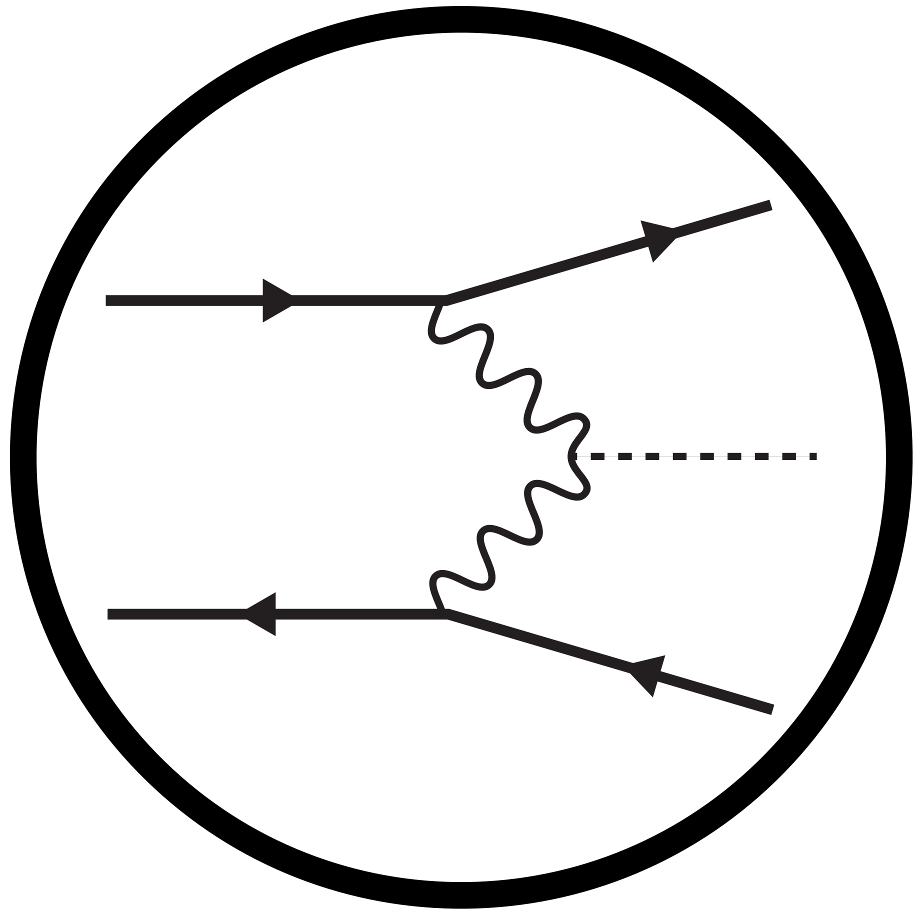


Higgs Production

pp Collider

l^+l^-Collider

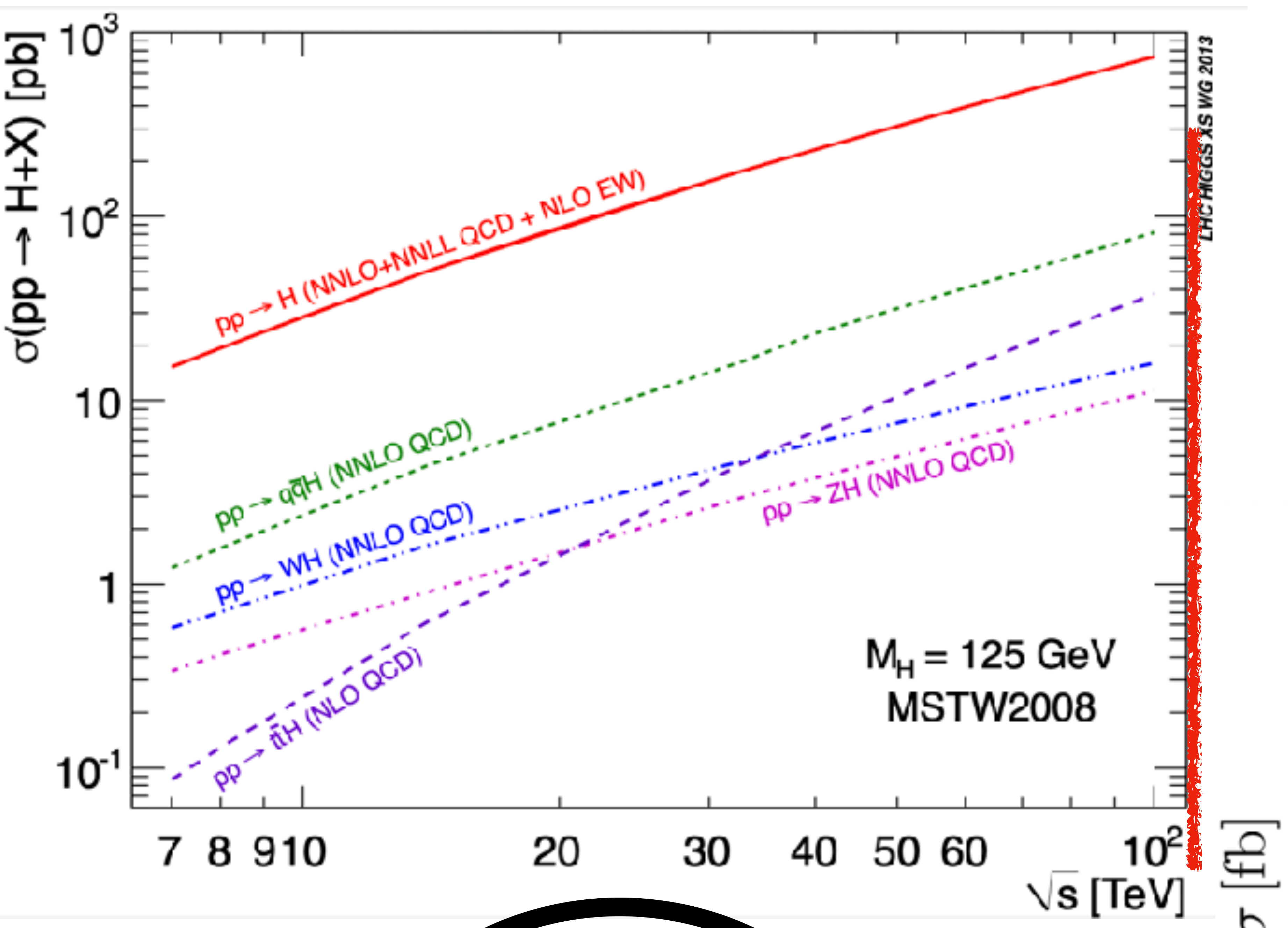


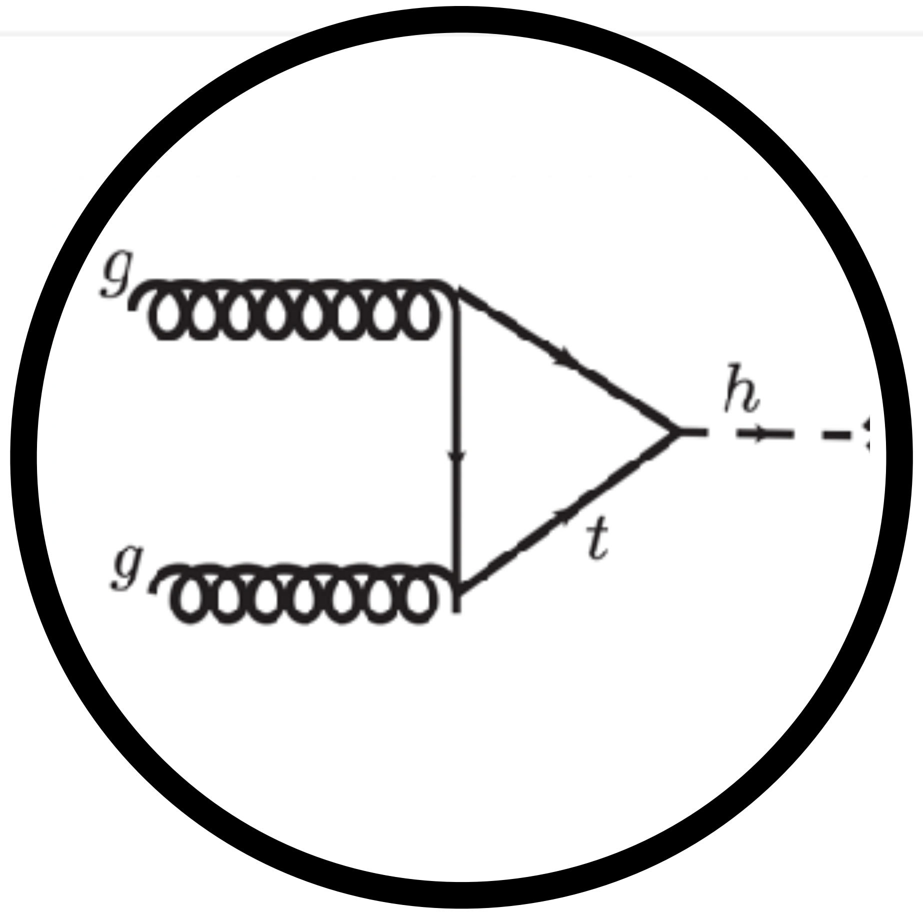


Higgs Production

p^+p^-

LHC HIGGS WG



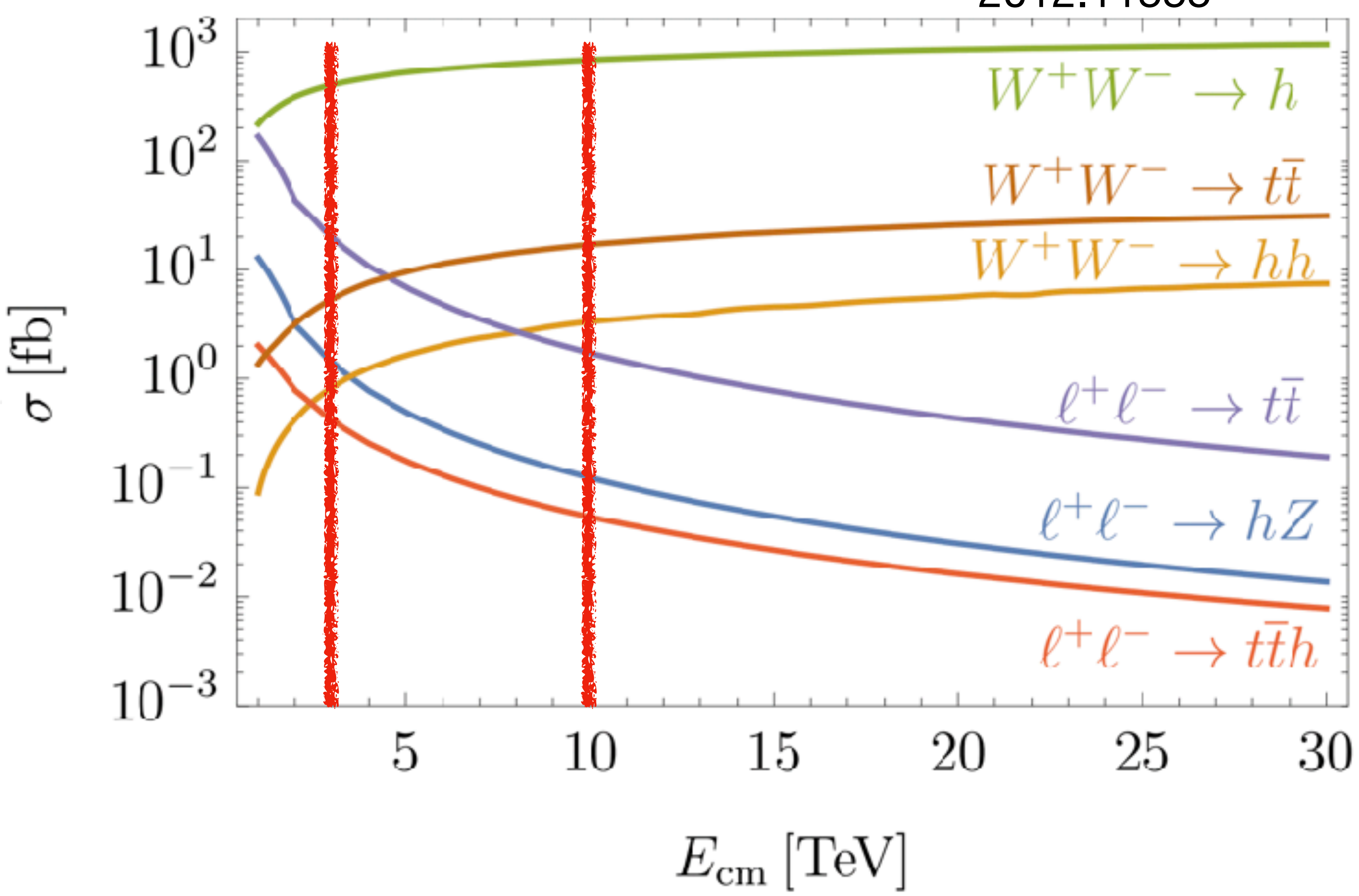


$$10^6 - 10^7$$

Higgs Produced

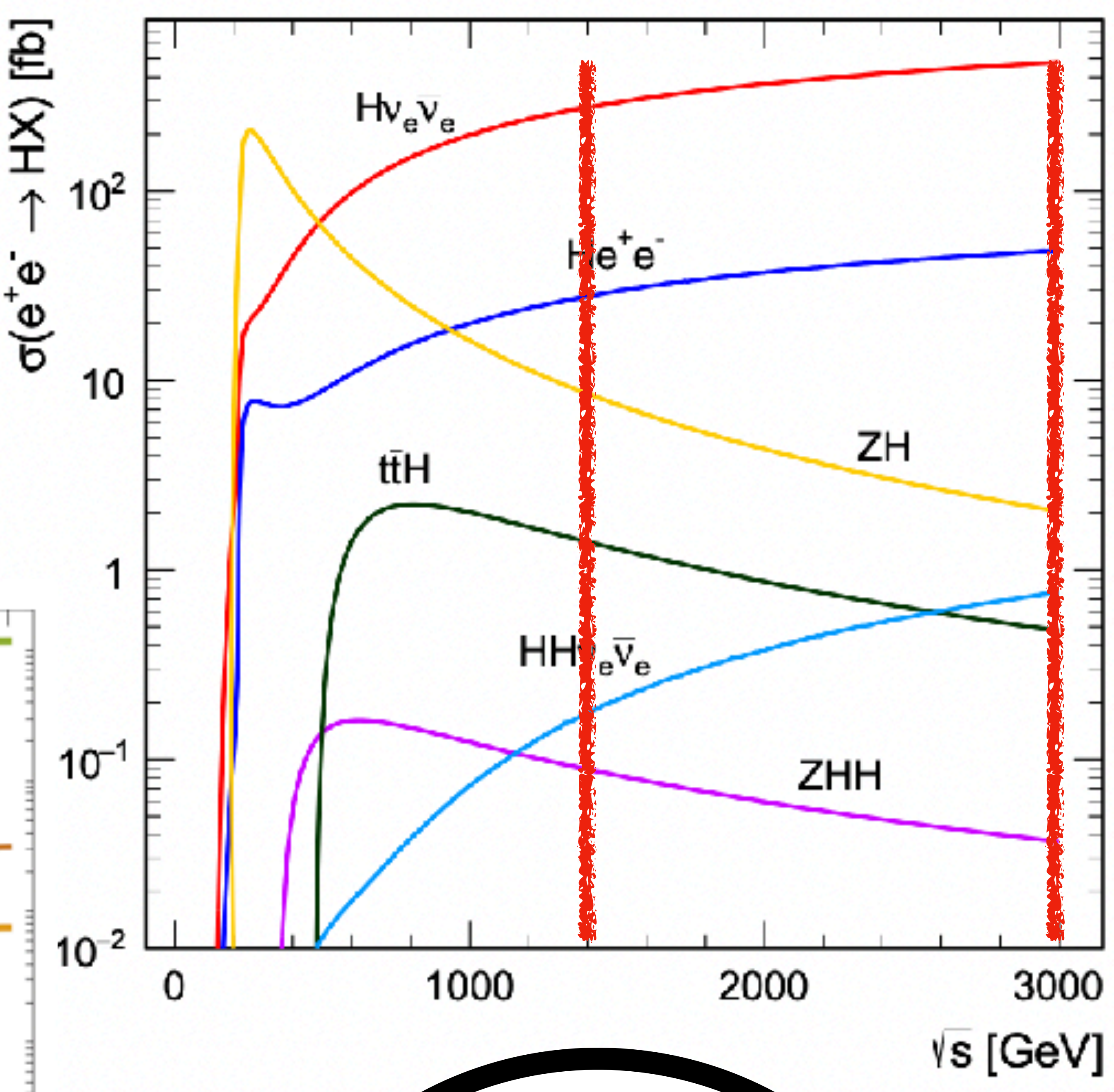
MuC

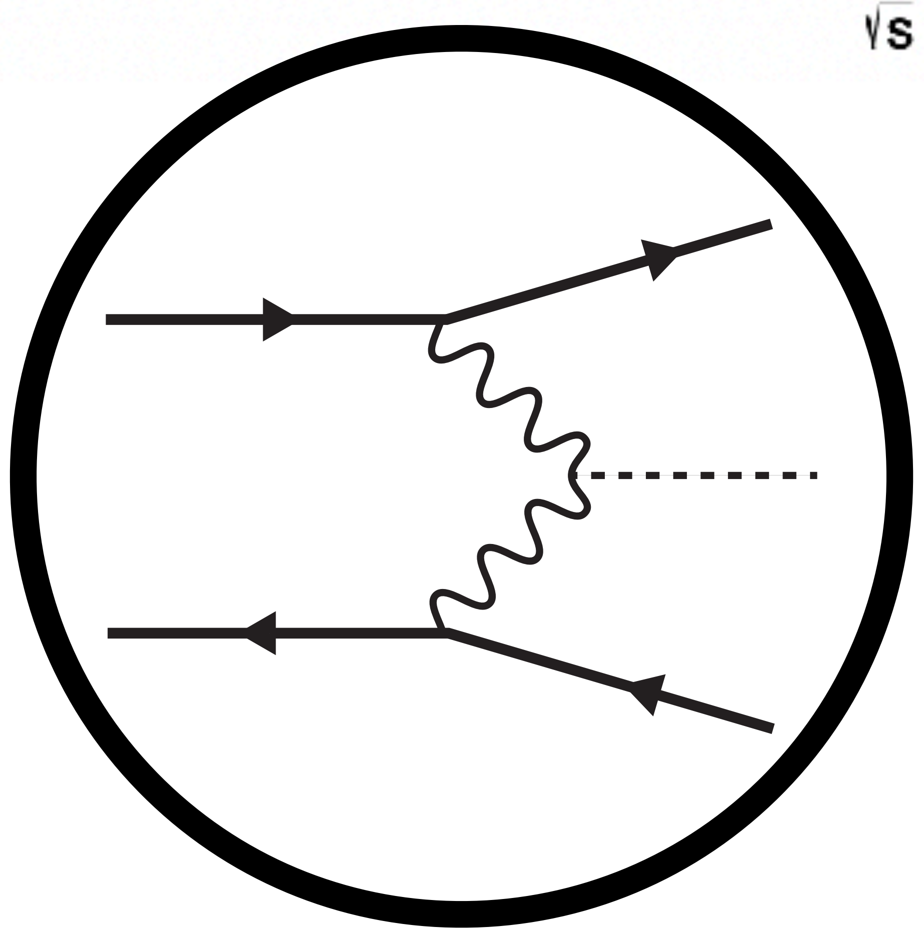
2012.11555



1812.06018

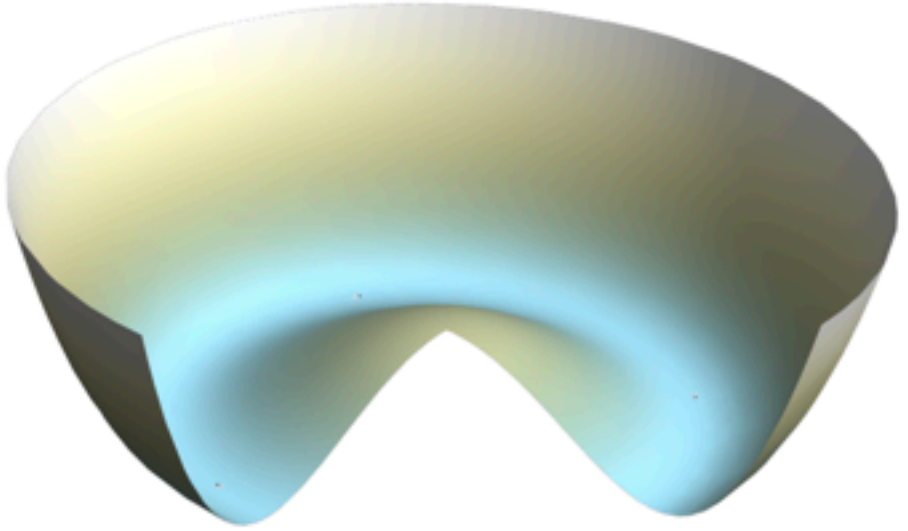
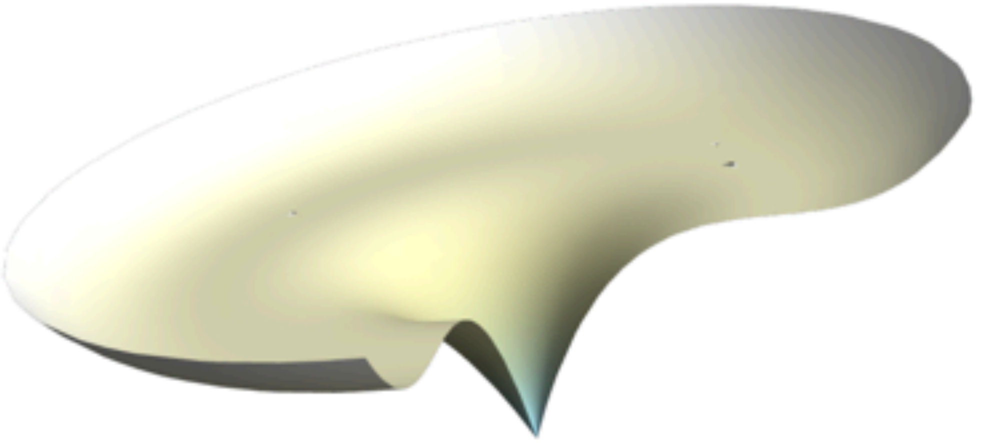
e^+e^-

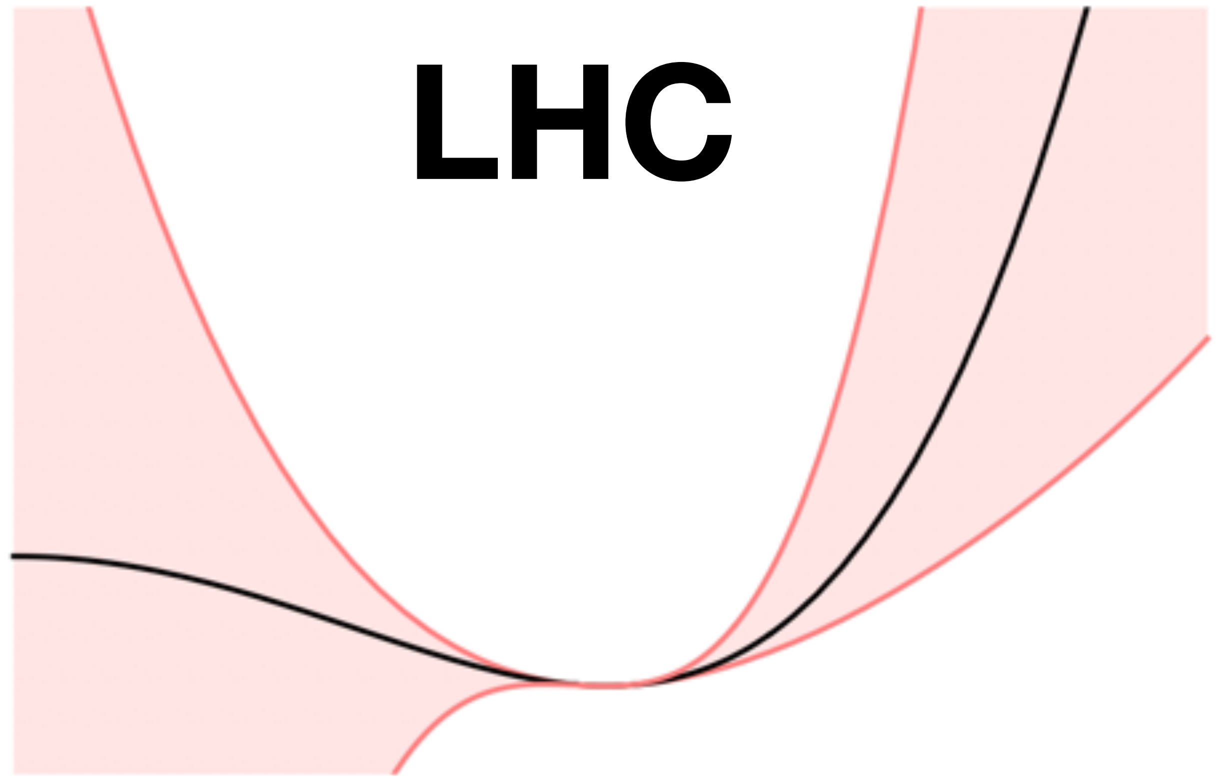




Example: Higgs Potential

Slide Credit: P Meade, N Craig, R. Petrossian Byrne



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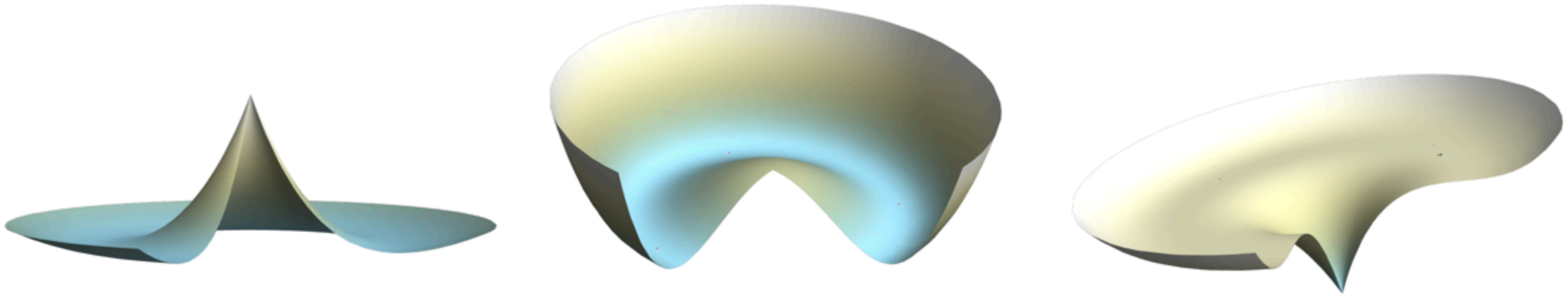

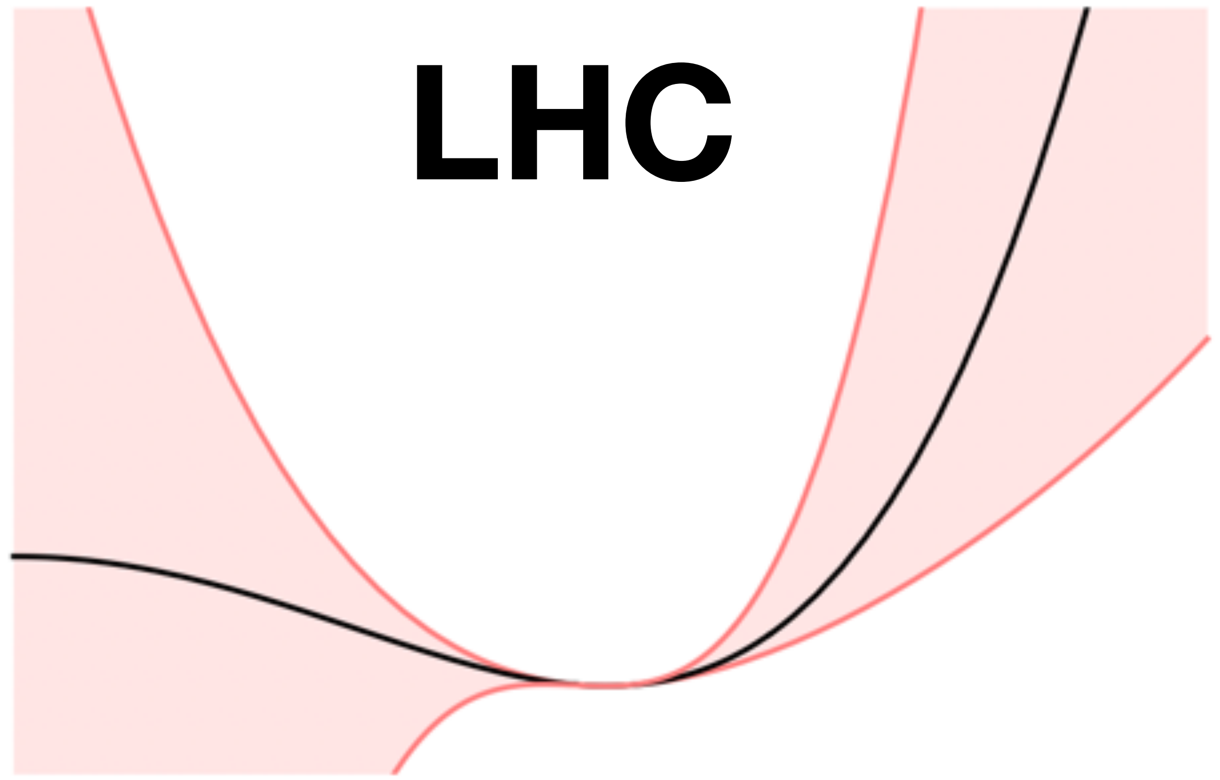

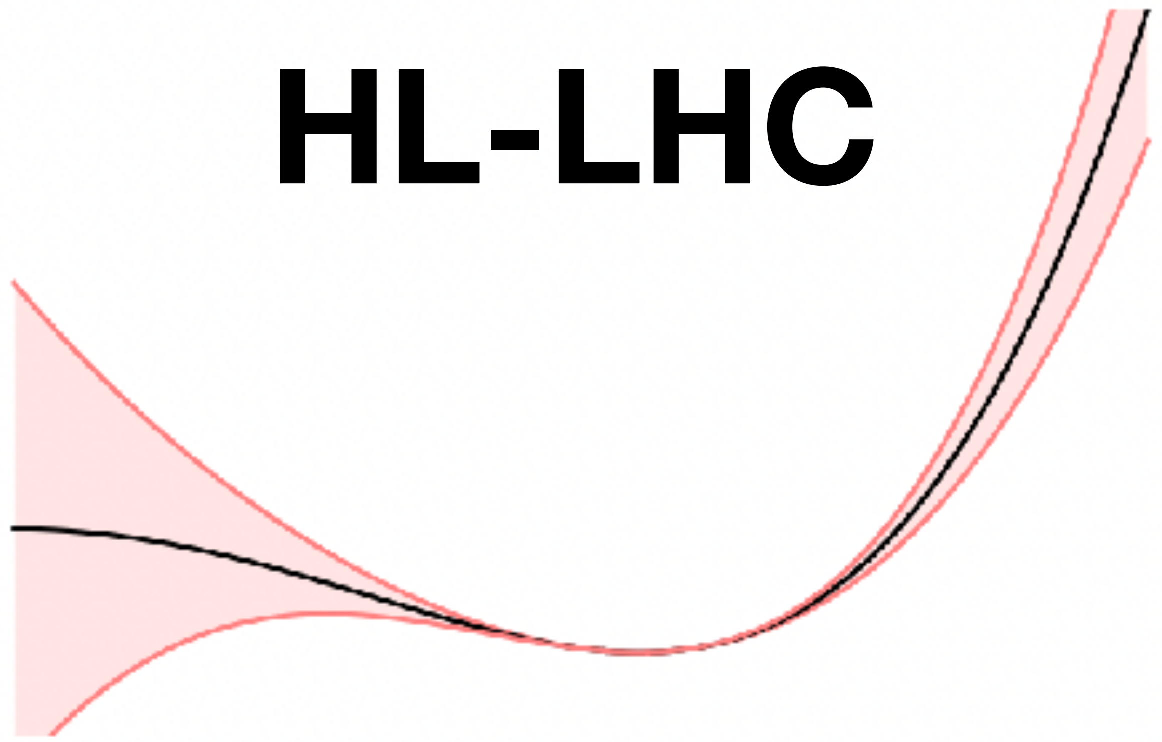

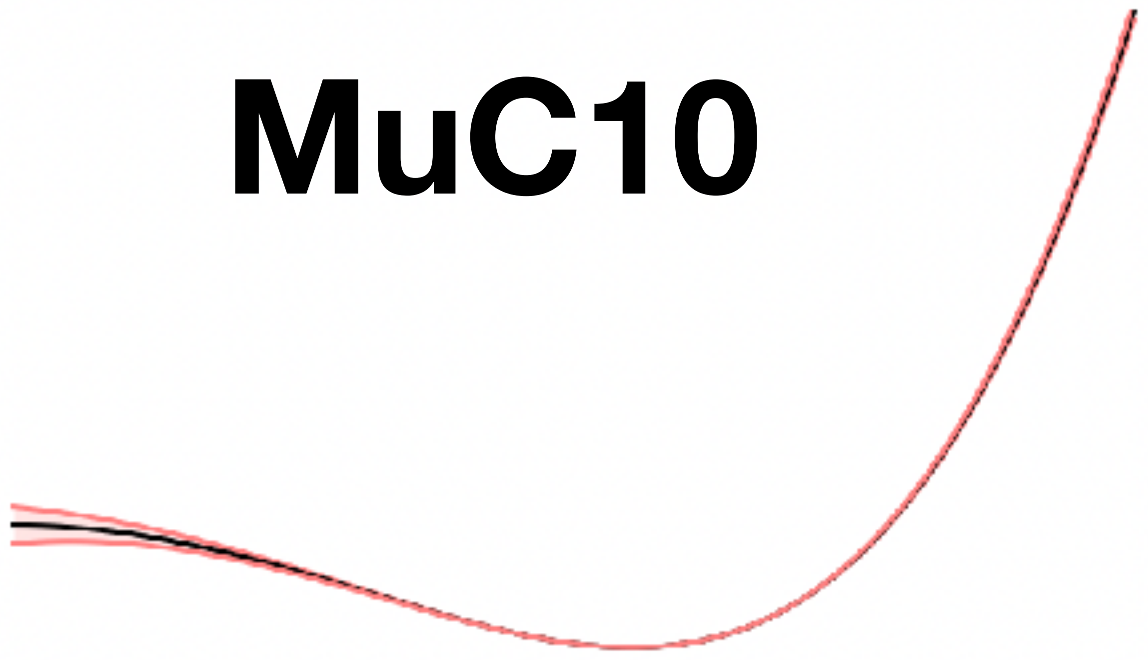

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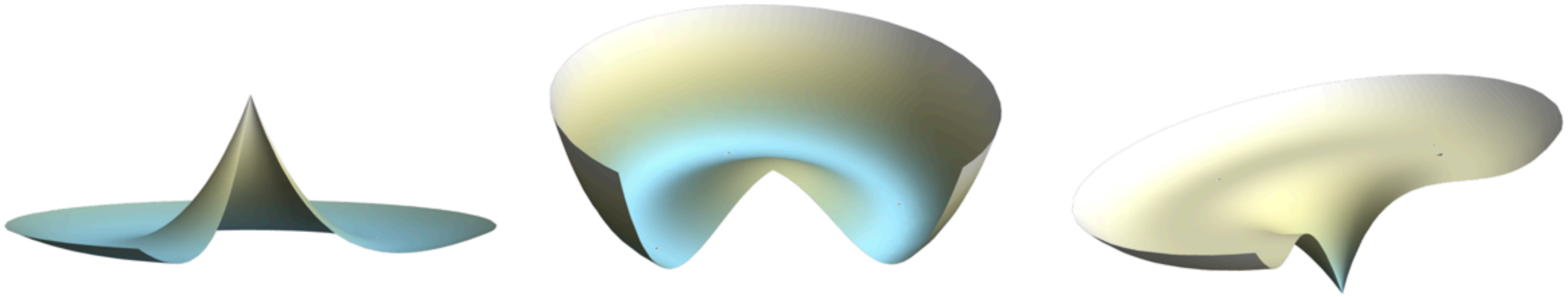

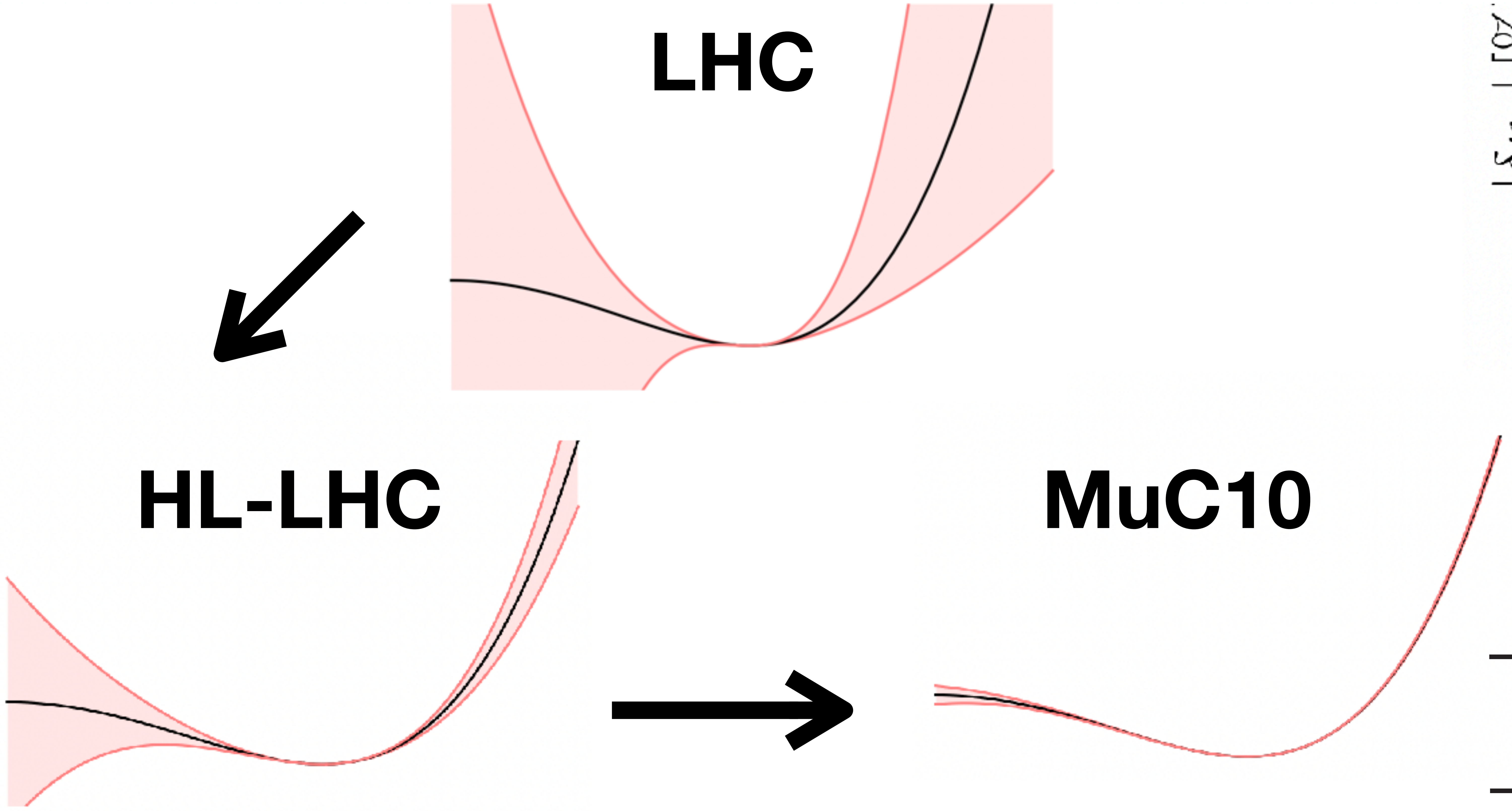

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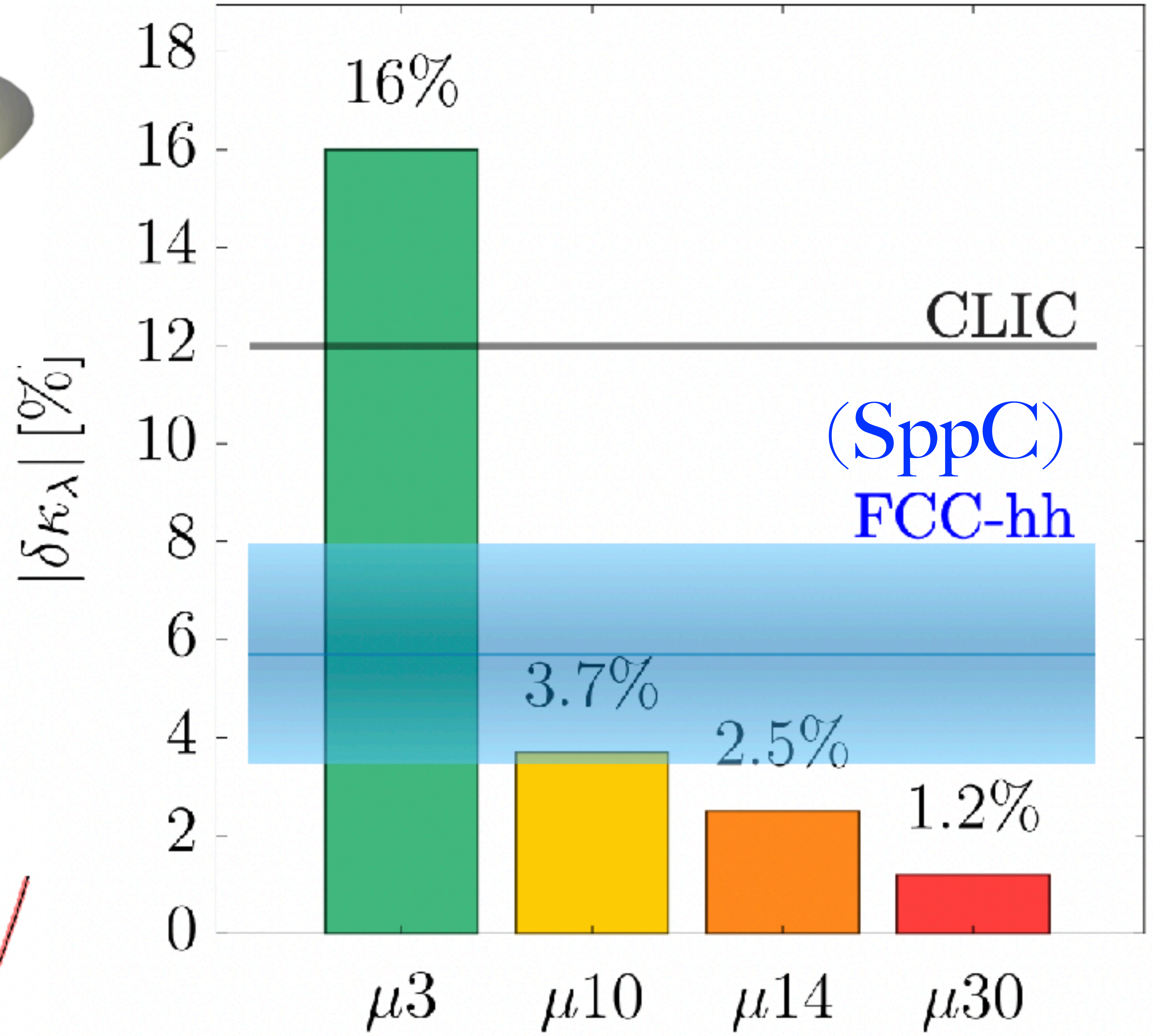

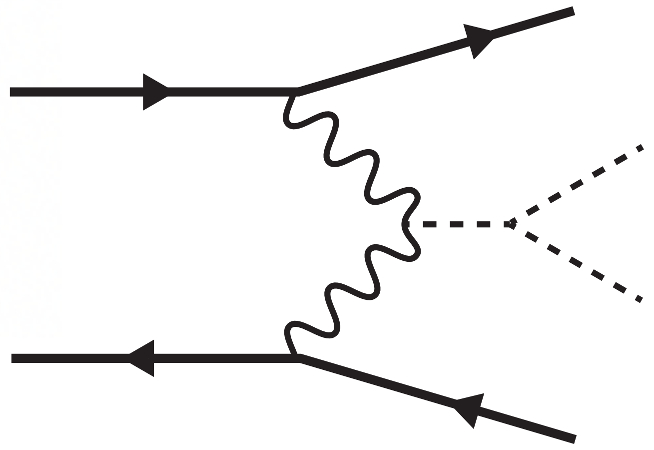

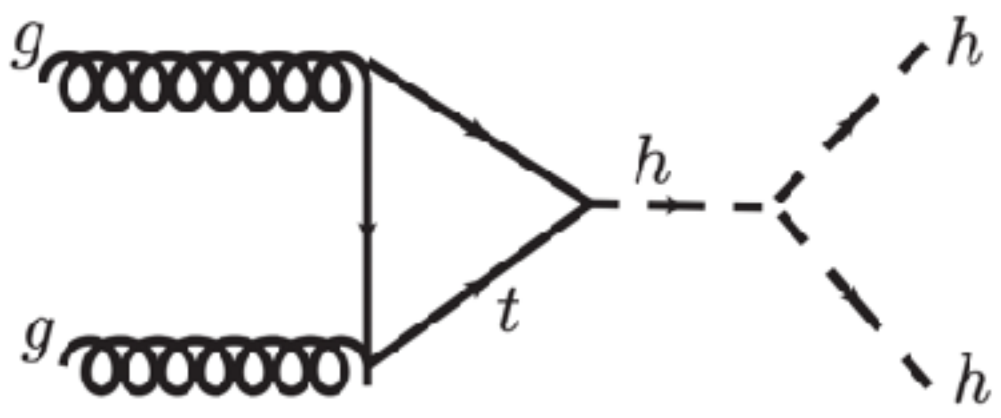

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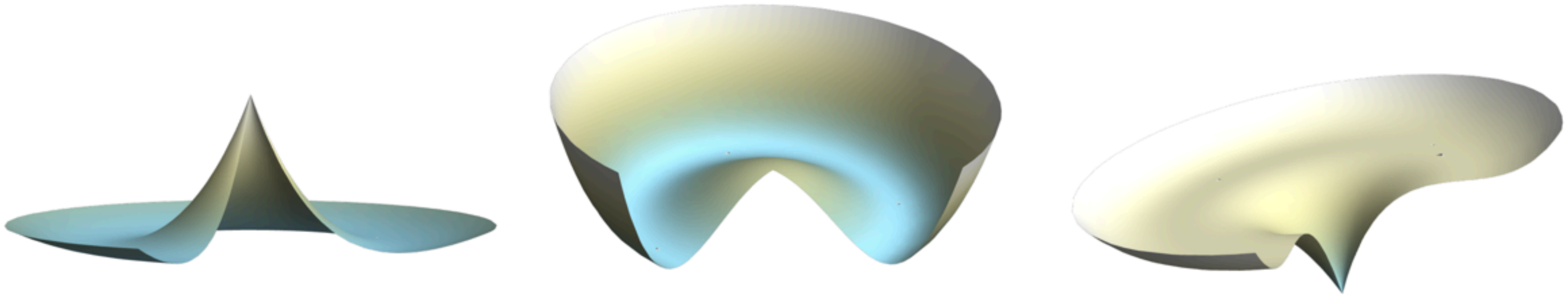

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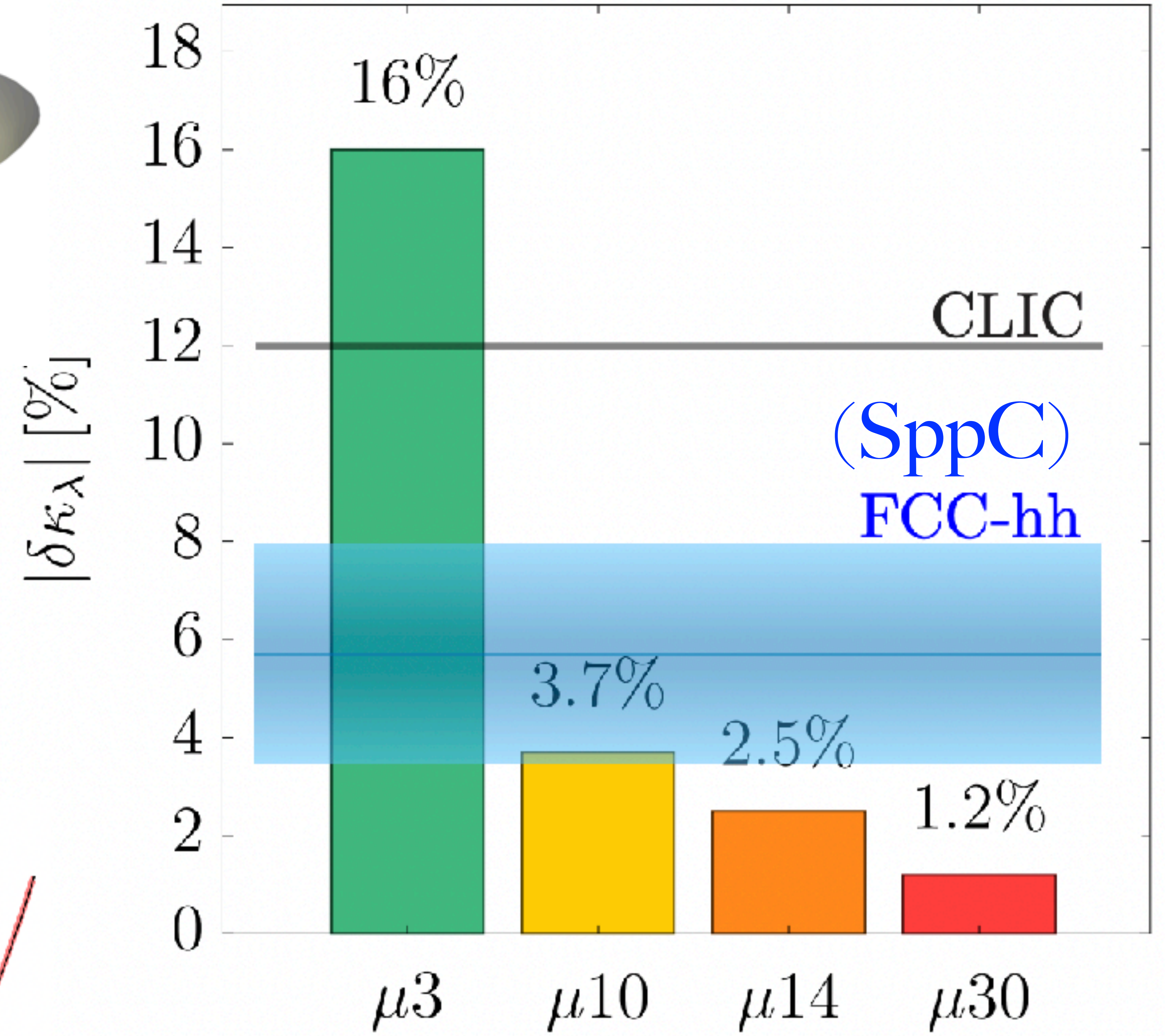
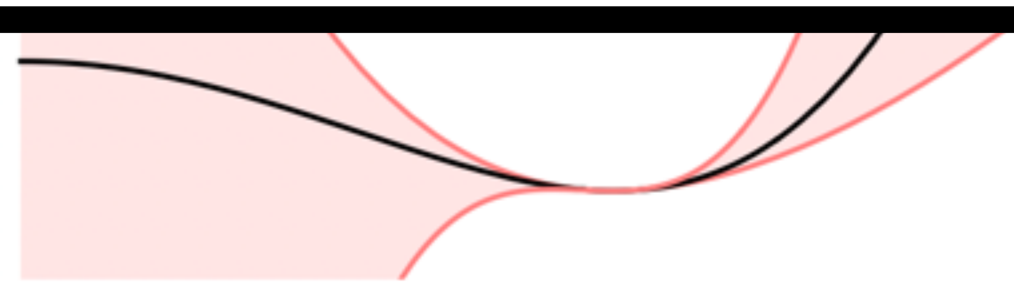
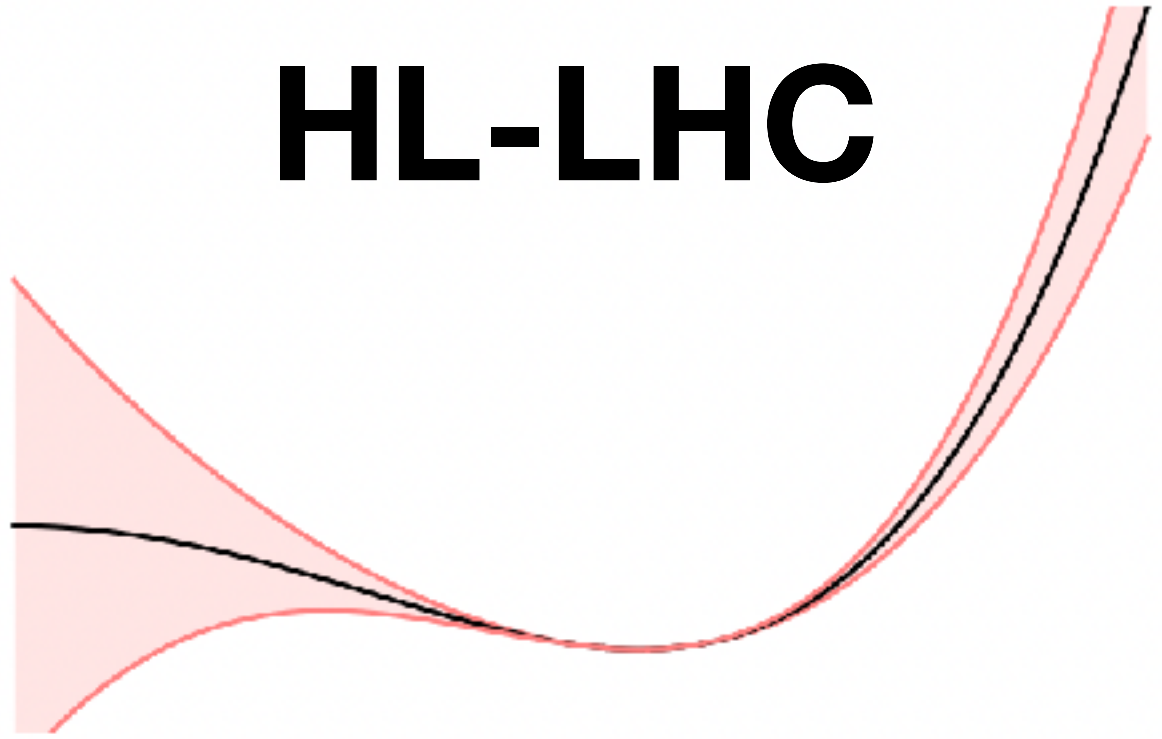


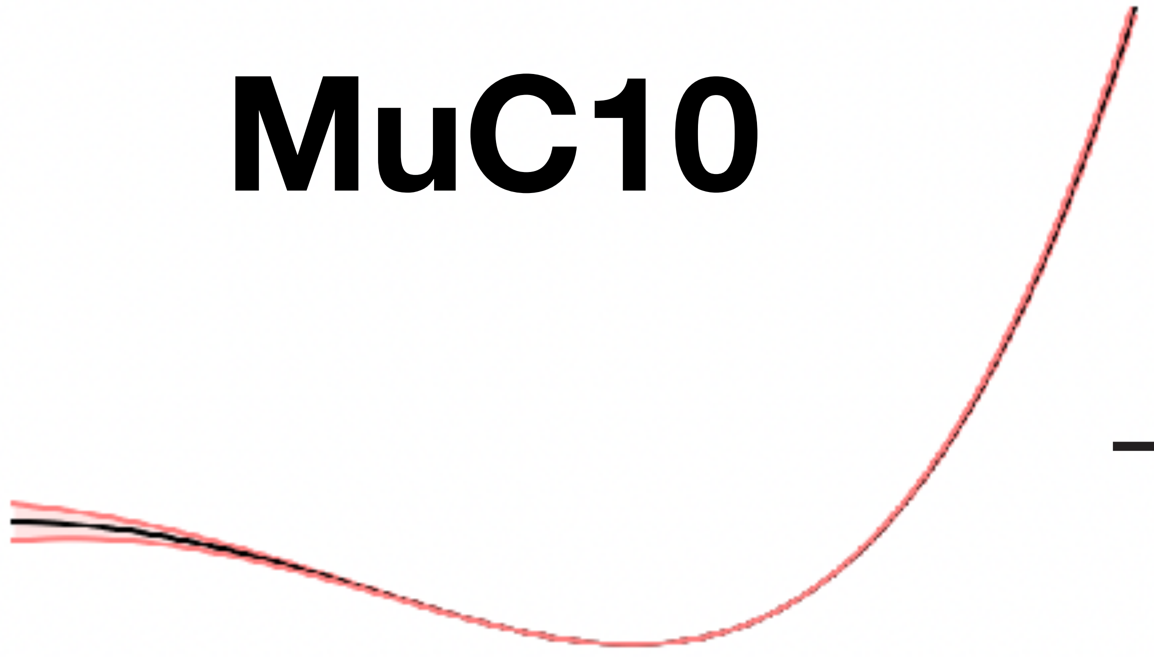
Measuring quartic coupling **needs** high energy

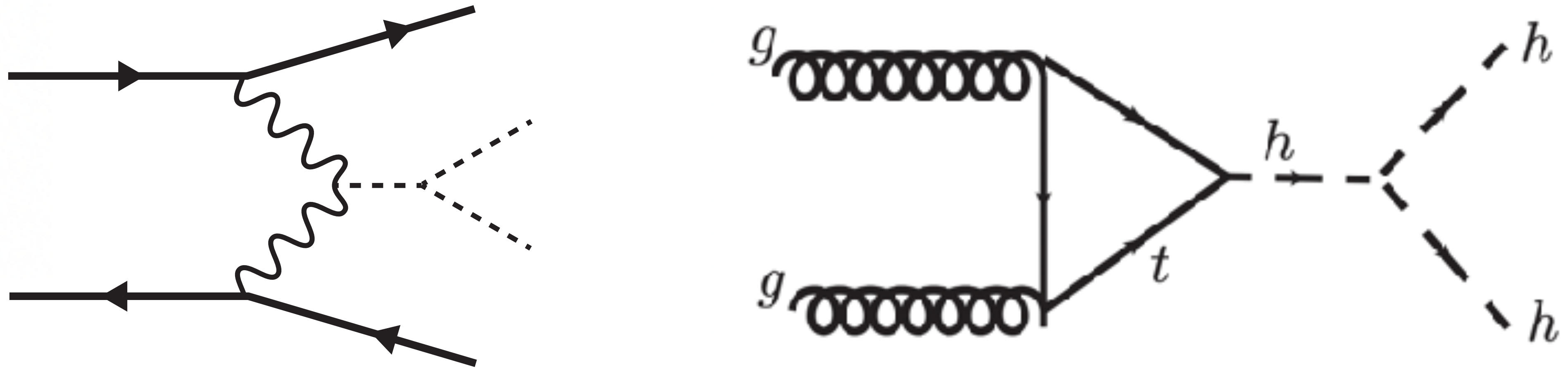


HL-LHC

MuC10







Example: Higgs Couplings

1905.03764

kappa-0	HL-LHC	CLIC 380	CLIC 15000	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.7	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c [%]	—	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	—	—	2.7	—	—	—	1.0
κ_b [%]	3.6	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	320$\star$	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.0	1.3	0.88	1.3	1.4	0.73	0.44

Scenario	BR_{inv}	BR_{unt}
kappa-0	fixed at 0	fixed at 0

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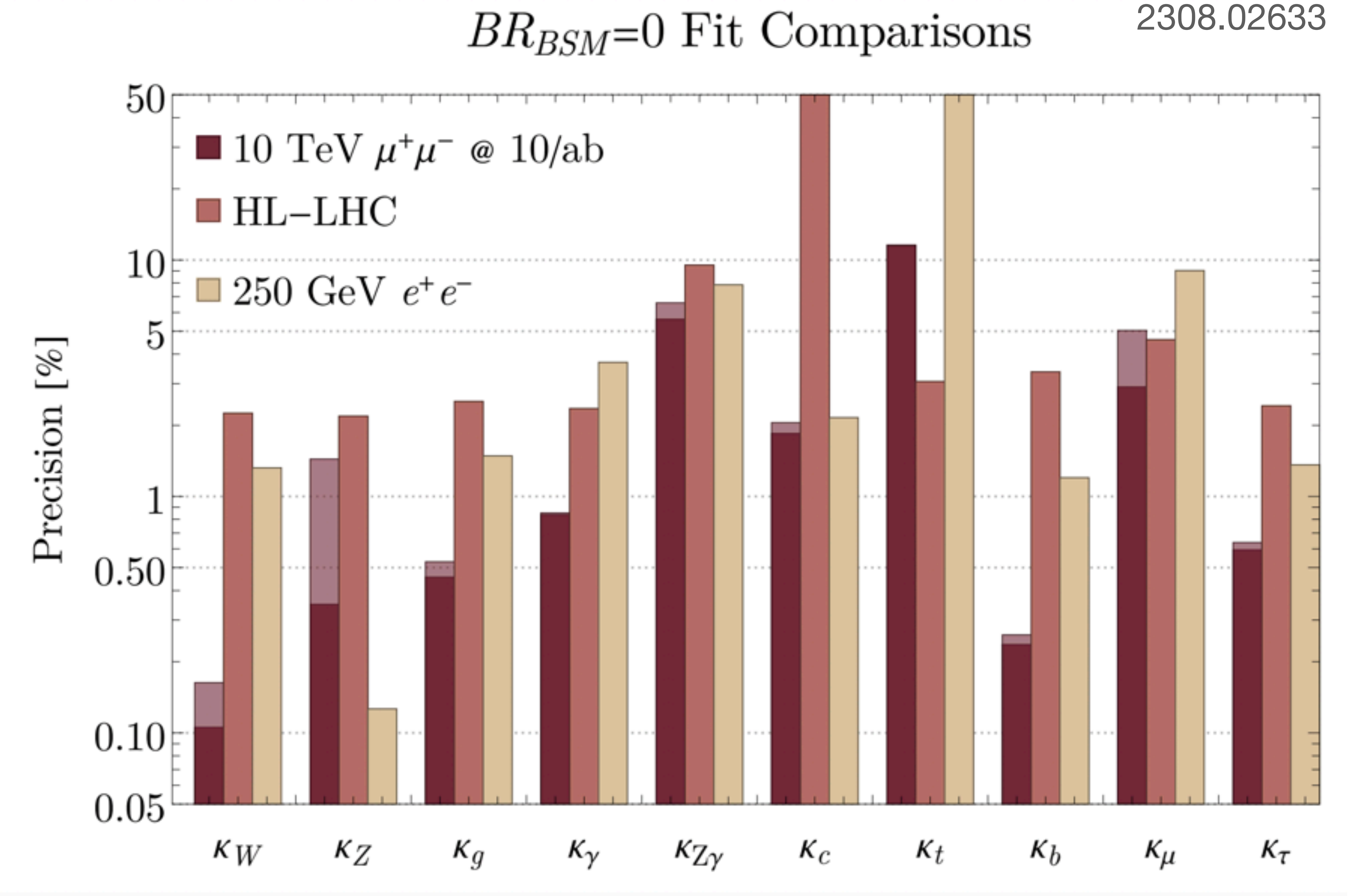

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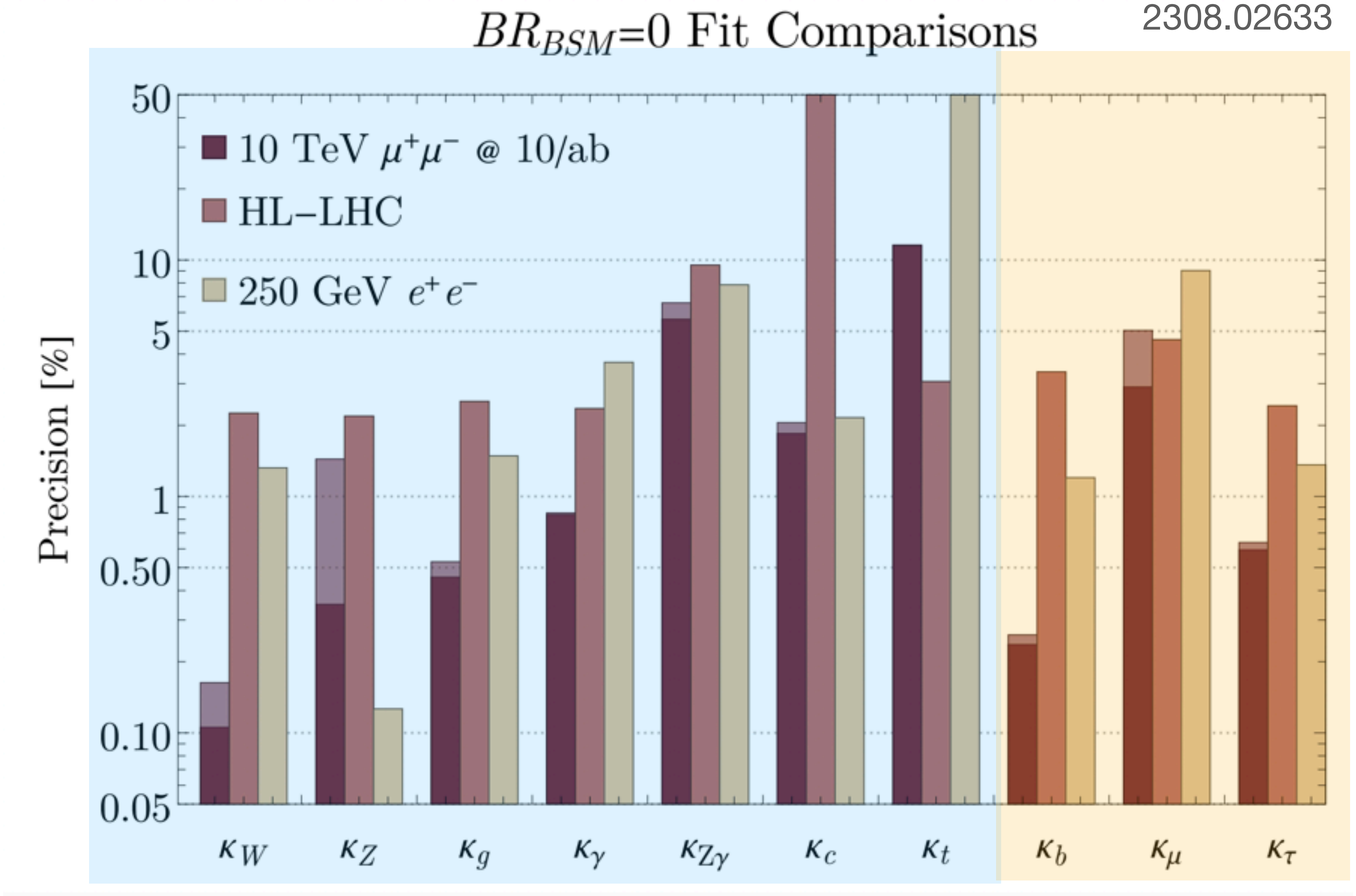
kappa-0	HL-LHC	CLIC 380	CLIC 15000	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.7	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.0	1.3	0.88	1.3	1.4	0.73	0.44

Scenario	BR_{inv}	BR_{unt}
kappa-0	fixed at 0	fixed at 0

Order of magnitude improvements for the 10 TeV Machines

2308.02633



Example: New Physics with Higgs Mixing

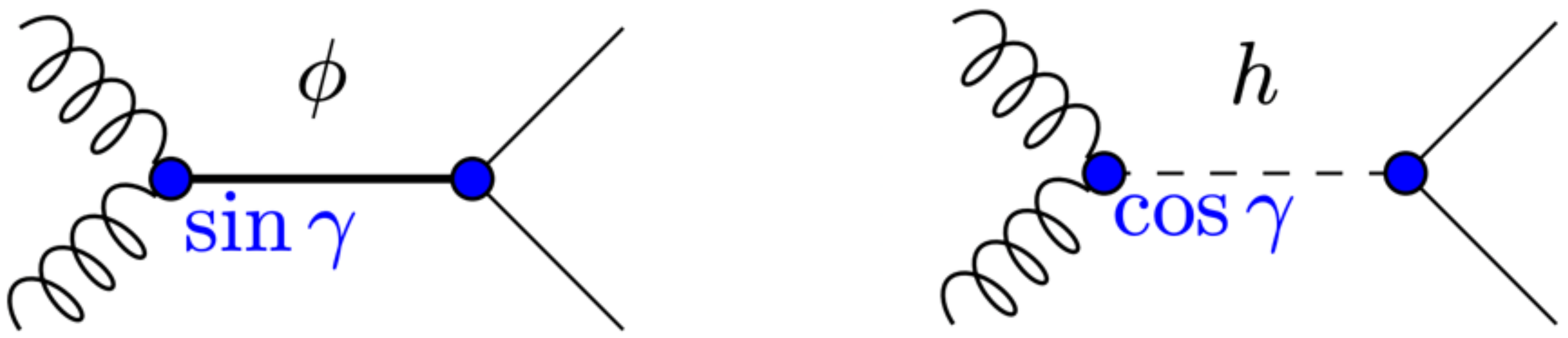
1807.04743

Benchmark model: New singlet S mixes with Higgs

$$h = h_0 \cos\gamma + S \sin\gamma$$

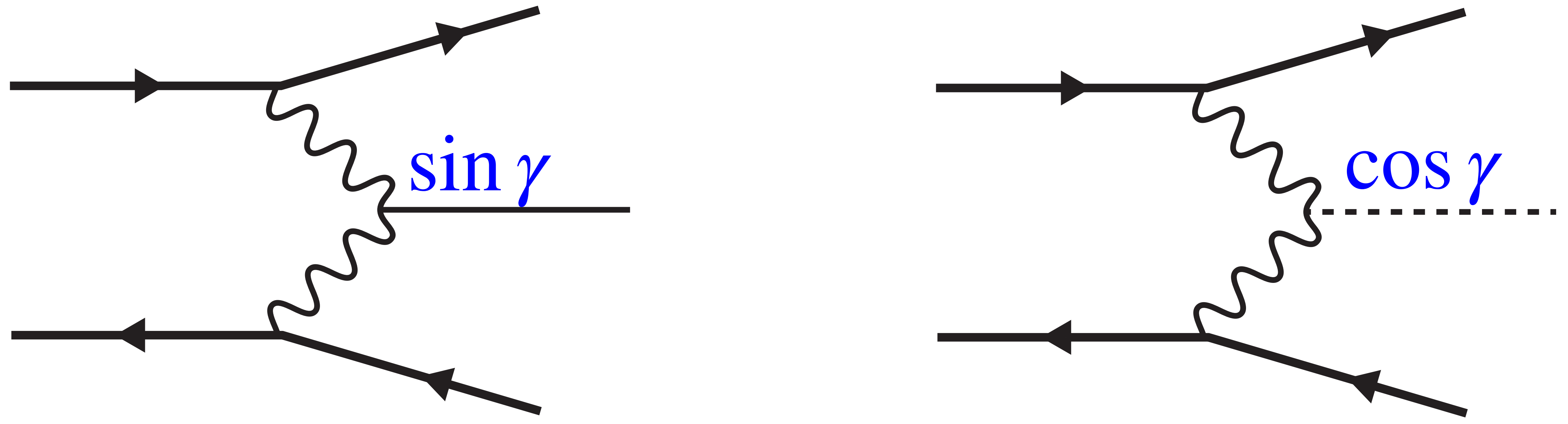
$$\phi = S \cos\gamma - h_0 \sin\gamma$$

pp Collider Production



Credit: D. Buttazzo

l^+l^- Collider Production



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1807.04743

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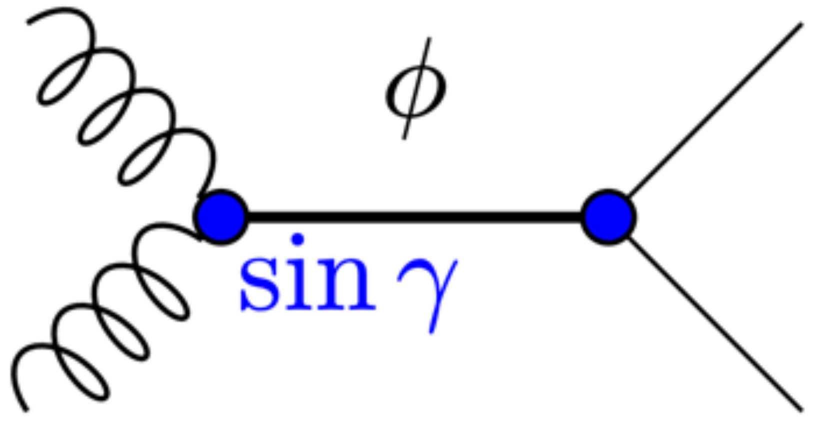
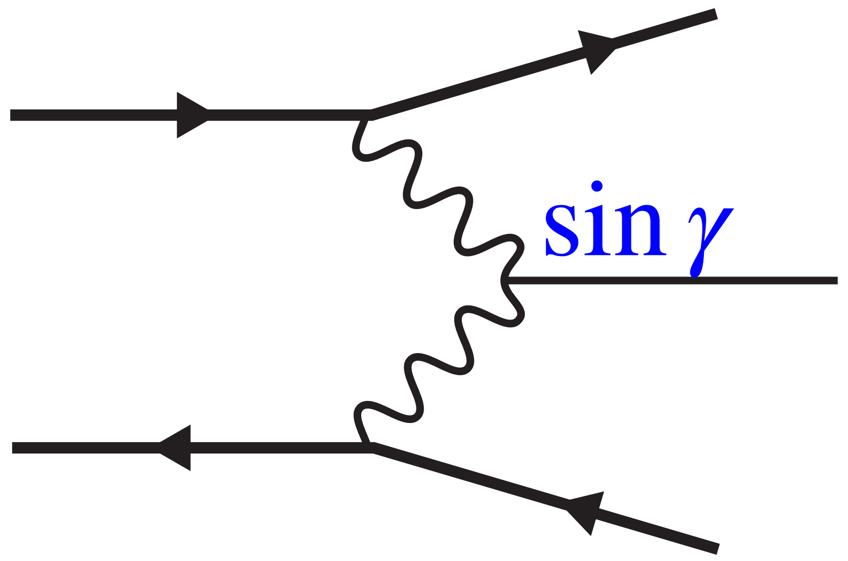
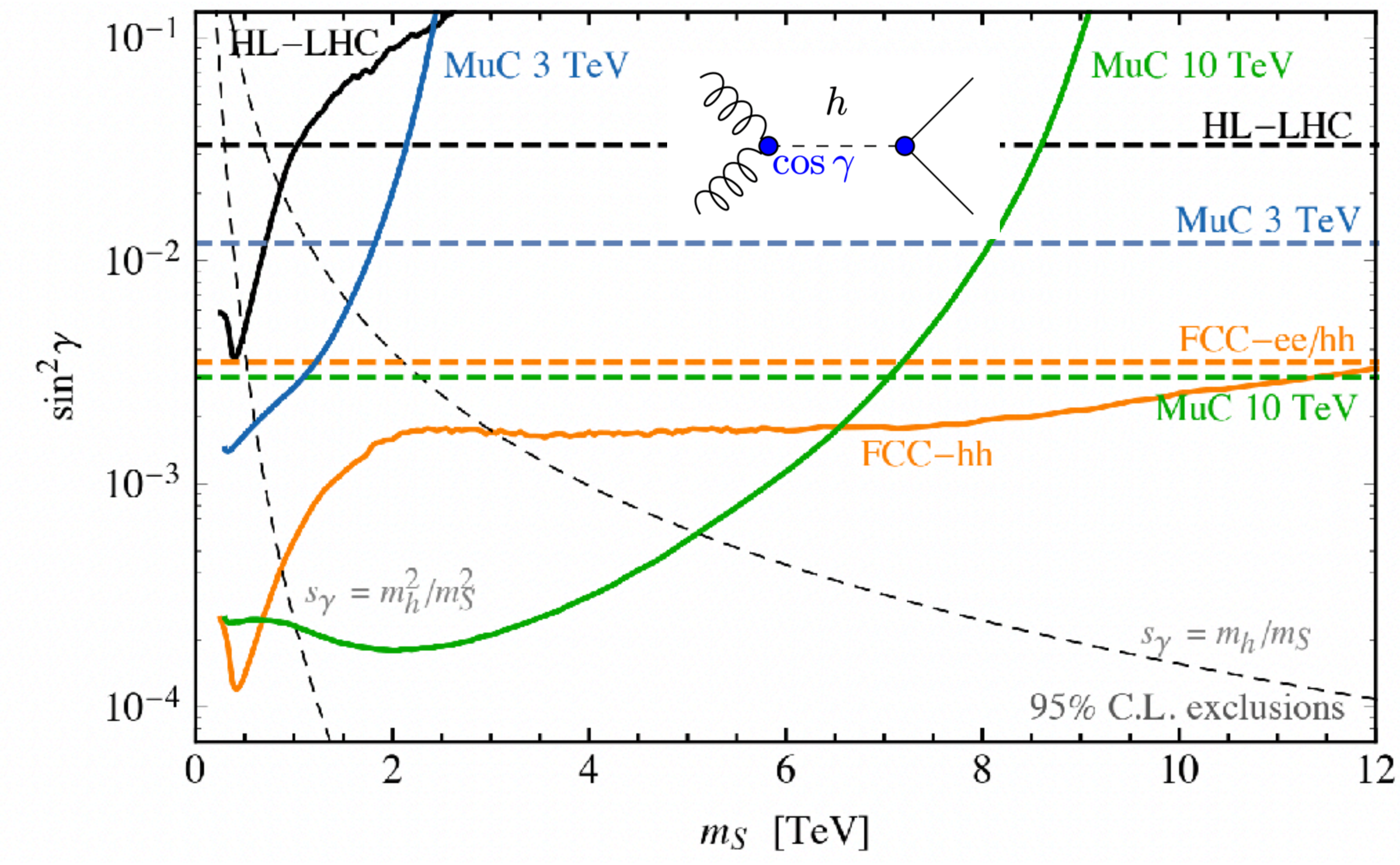
$$\phi = S \cos\gamma - h_0 \sin\gamma$$

$$\phi \to hh, ZZ, WW$$







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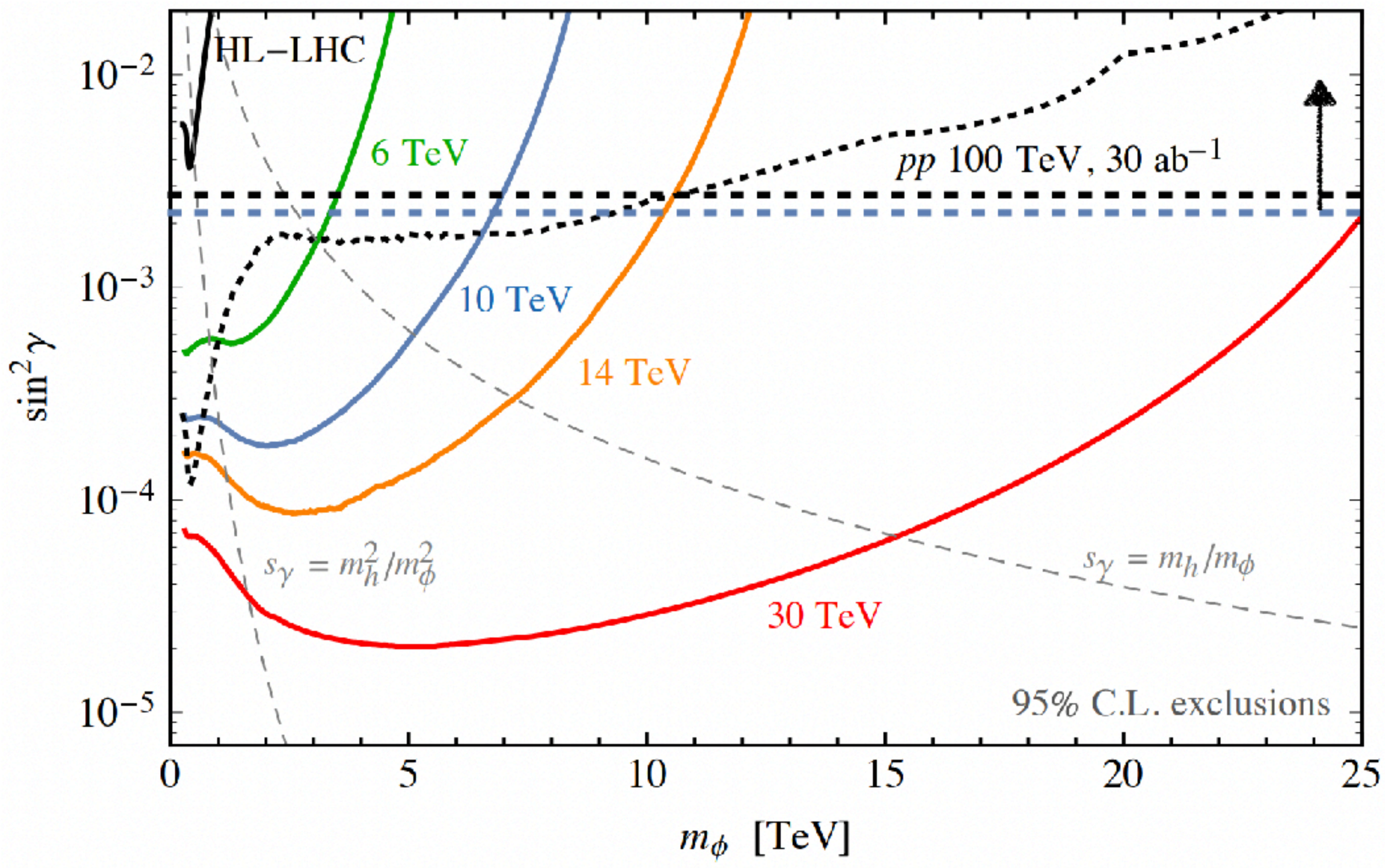


Example: Higgs Compositeness

High energy probes **compositeness**

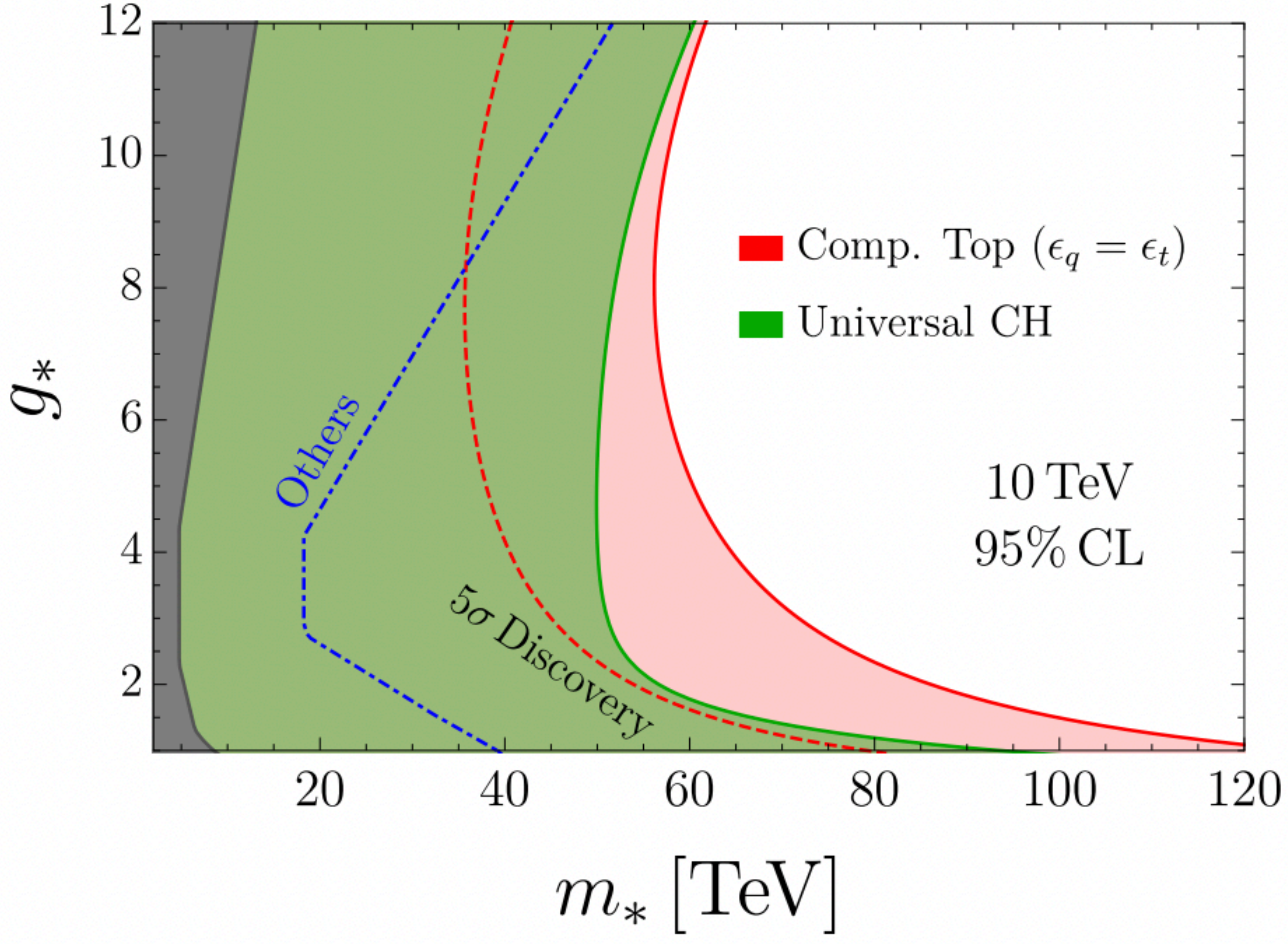
$$E \sim \frac{1}{r}$$

High-energy **fundamental** particles are best probes

Depends on Higgs & VV-hh coupling precision

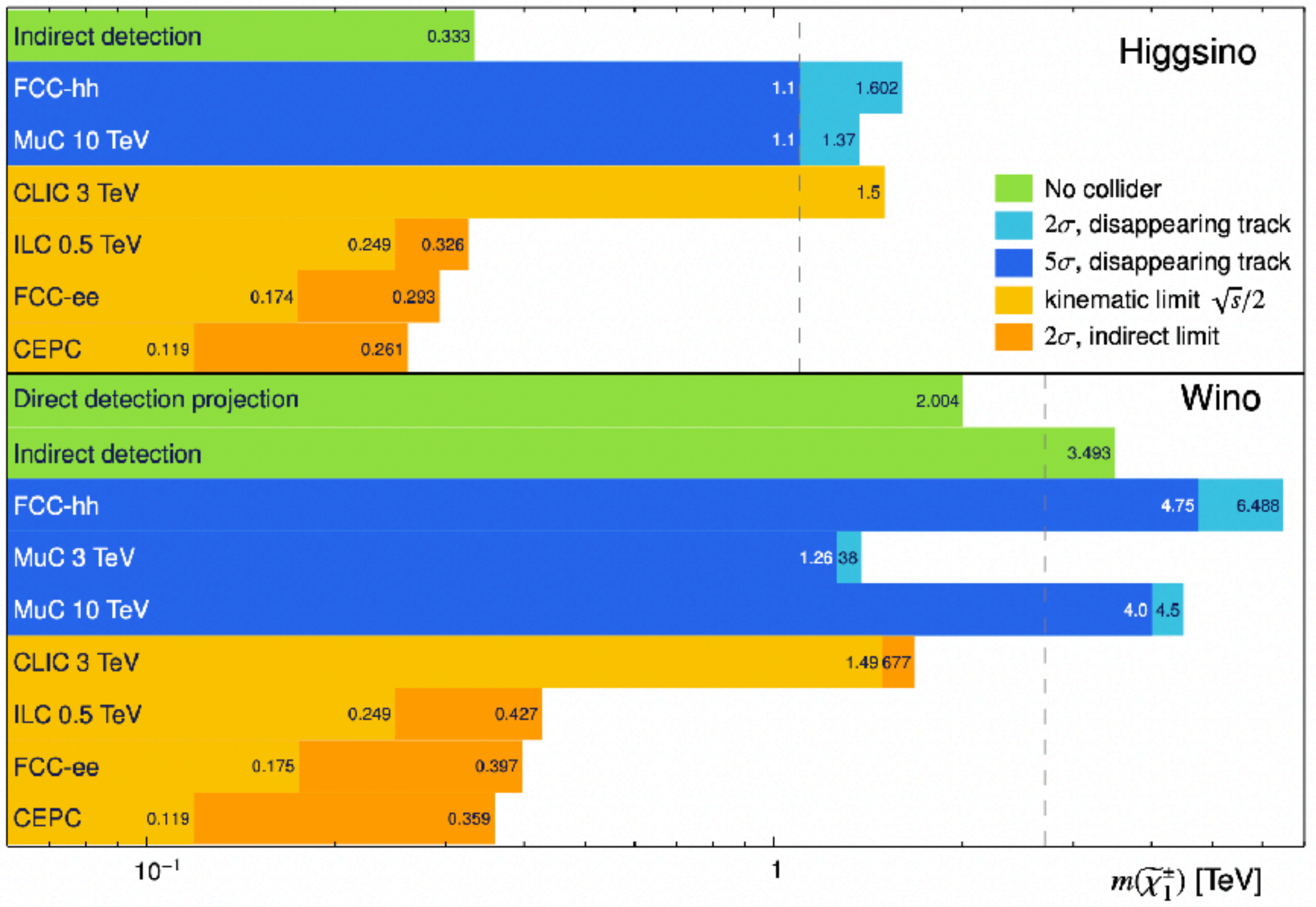
$$\frac{c_{\phi,6,y_f}}{\Lambda^2} = \frac{g_\star^2}{m_\star^2}, \qquad \frac{c_{W,B}}{\Lambda^2} = \frac{1}{m_\star^2}, \qquad \frac{c_{2W,2B}}{\Lambda^2} = \frac{1}{g_\star^2}\frac{1}{m_\star^2},$$
$$\frac{c_T}{\Lambda^2} = \frac{y_t^4}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\gamma,g}}{\Lambda^2} = \frac{y_t^2}{16\pi^2}\frac{1}{m_\star^2},$$
$$\frac{c_{\phi W,\phi B}}{\Lambda^2} = \frac{g_\star^2}{16\pi^2}\frac{1}{m_\star^2}, \frac{c_{3W}}{\Lambda^2} = \frac{1}{16\pi^2}\frac{1}{m_\star^2}. \qquad (38)$$

2202.10509



Example: SUSY & DM

Different sensitivity corresponds to **energy**, relevant **backgrounds**, and detector performance/acceptance

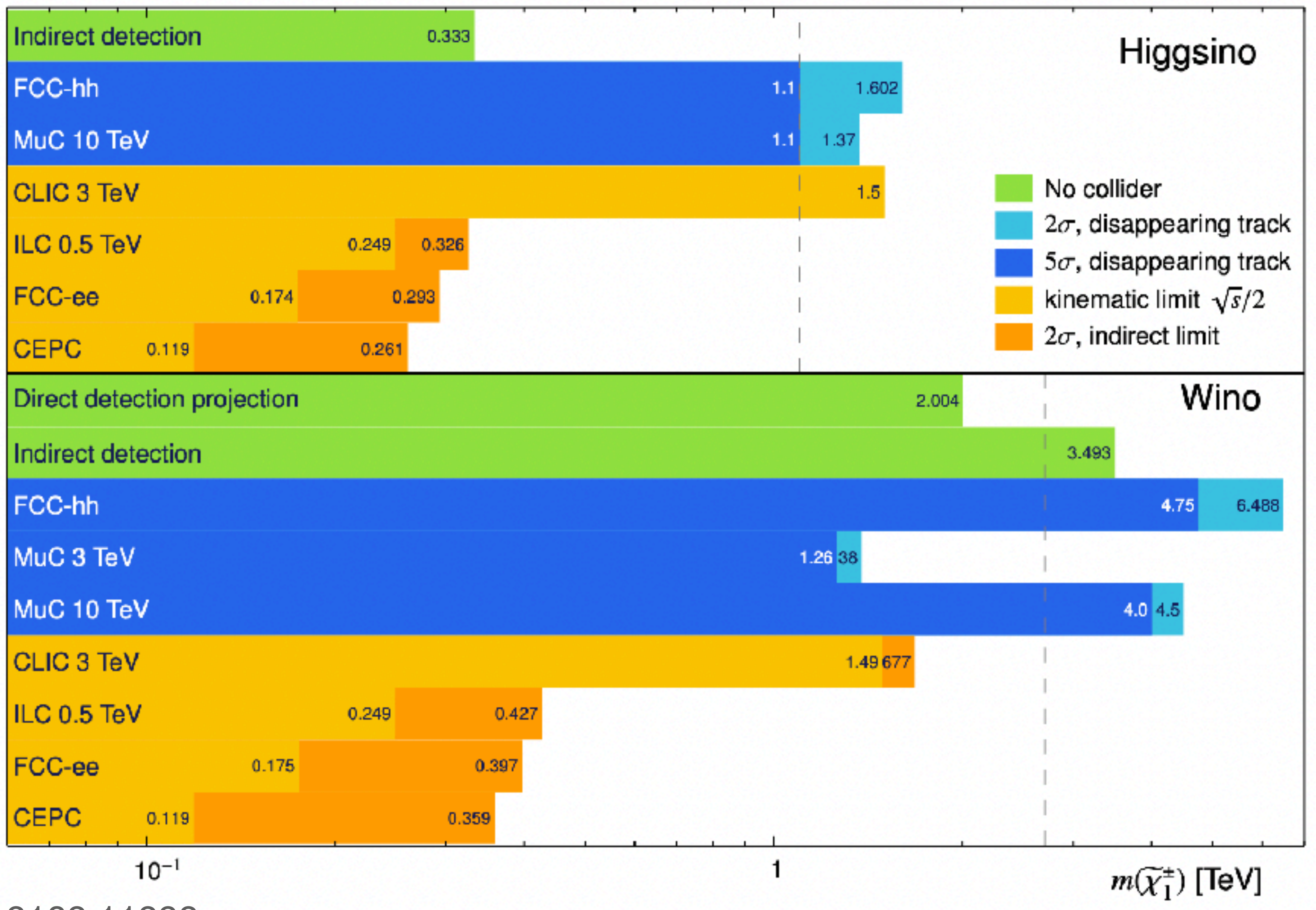


2102.11292

We **need** high energy

Example: SUSY & DM

Different sensitivity corresponds to **energy**, relevant **backgrounds**, and detector performance/acceptance



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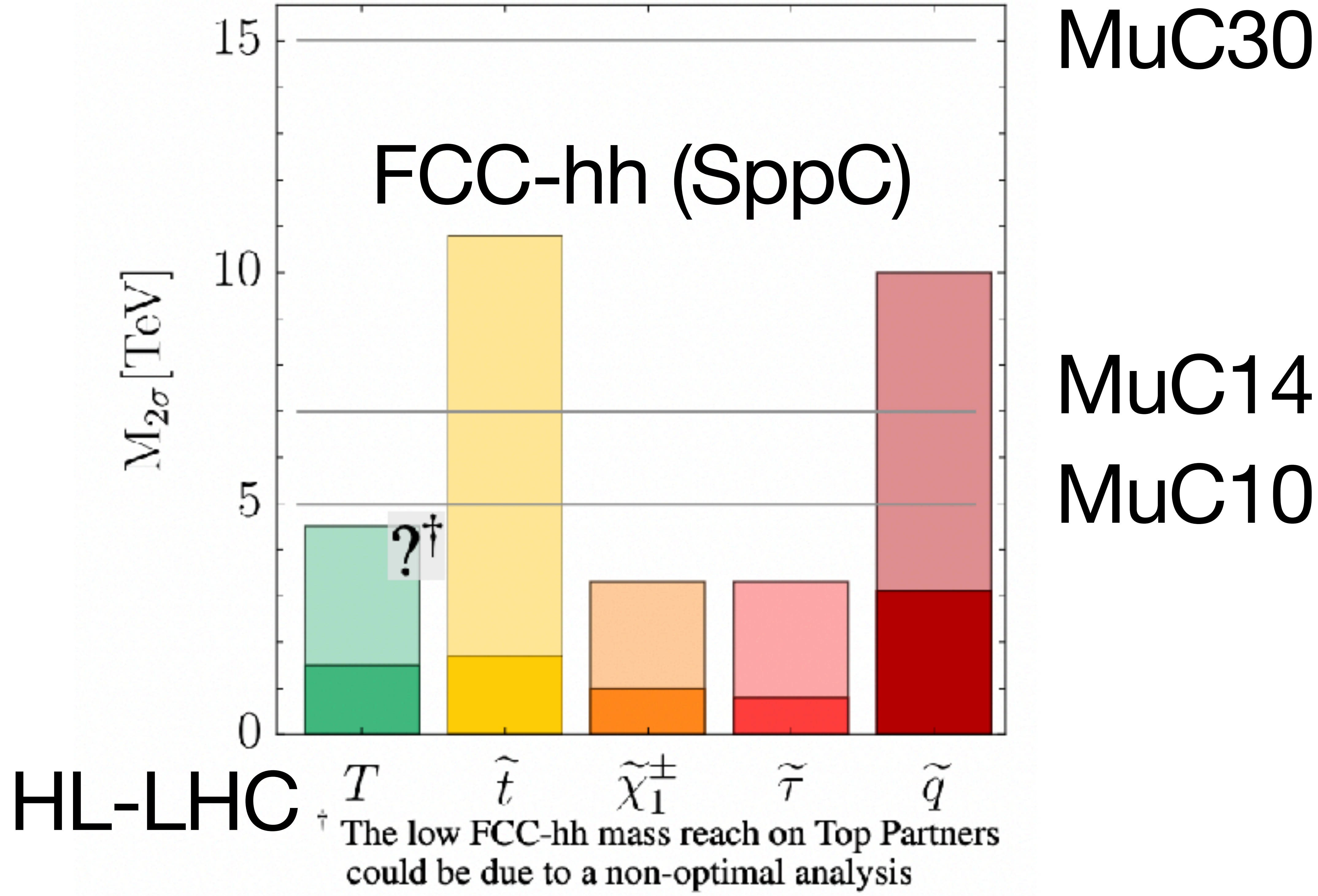


pp colliders have better reach on color-charged particles

Conclusions

A Higgs factory alone **cannot fully explore** the many open questions of the Higgs & EW Sector

We need an energy frontier machine $E >$ TeV to study important questions

The physics potential of **hadron & lepton** colliders are **complementary**

A completely novel (albeit risky) collider like a muon collider can often **improve physics reach** the most and is worth the investment

Back-ups

Muon collider physics potential

A high-energy muon collider is a **dream machine**: allows to probe unprecedented energy scales, exploring many different directions at once!

High-rate measurements

Higgs, self coupling, rare decays, top quarks, …

Direct searches

Pair production, Resonances, VBF, Dark Matter, …

High-energy probes

Di-boson, di-fermion, tri-boson, EFT, compositeness, …

EW radiation

SM physics, neutrinos, NP searches, precision, …

Muon physics

Lepton Flavor Universality, $b \to s\mu\mu$, muon g-2, …

Slide Credit: D. Buttazzo

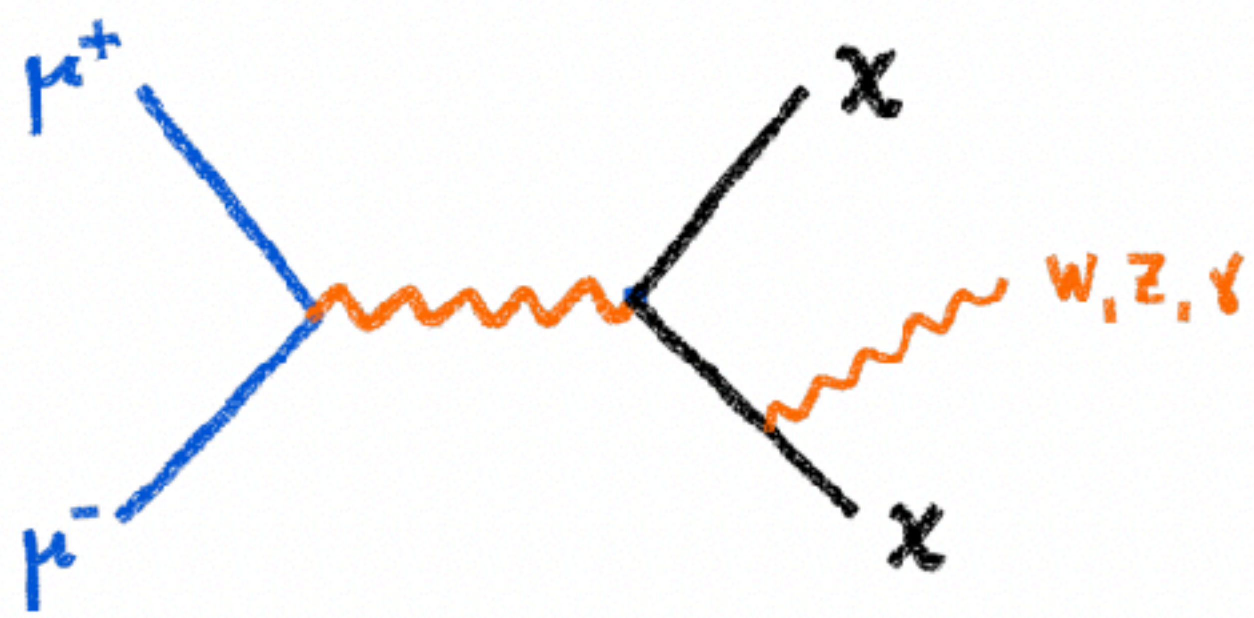
Example: WIMP Dark Matter

- Mono-γ/W/Z signals: $\mu\bar{\mu} \to \chi\bar{\chi} + X$

  DM pair production + EW radiation

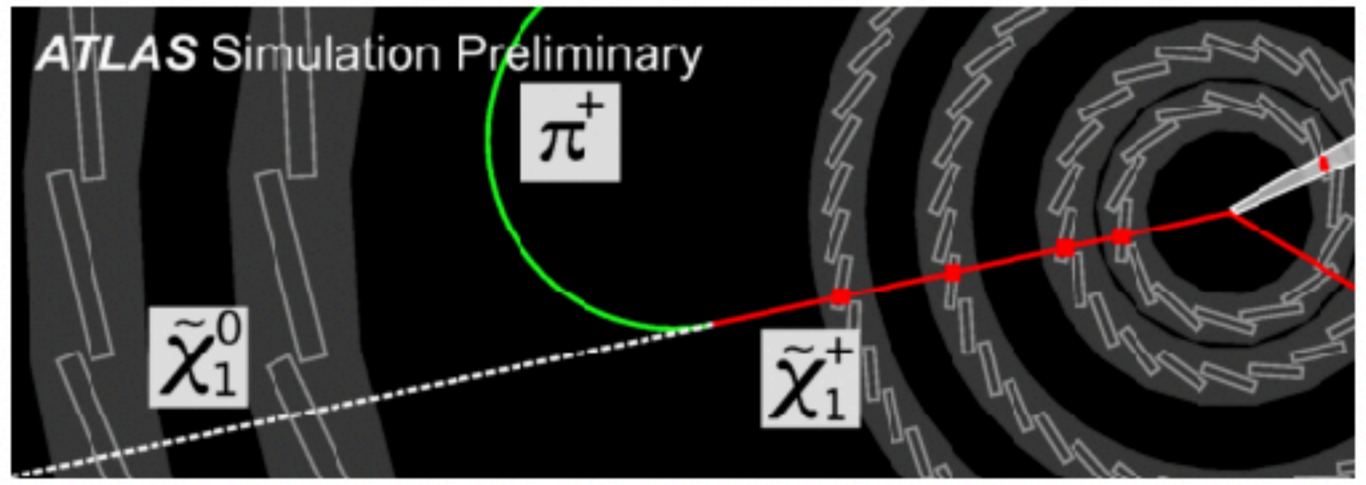
  Han et al. 2009.11287

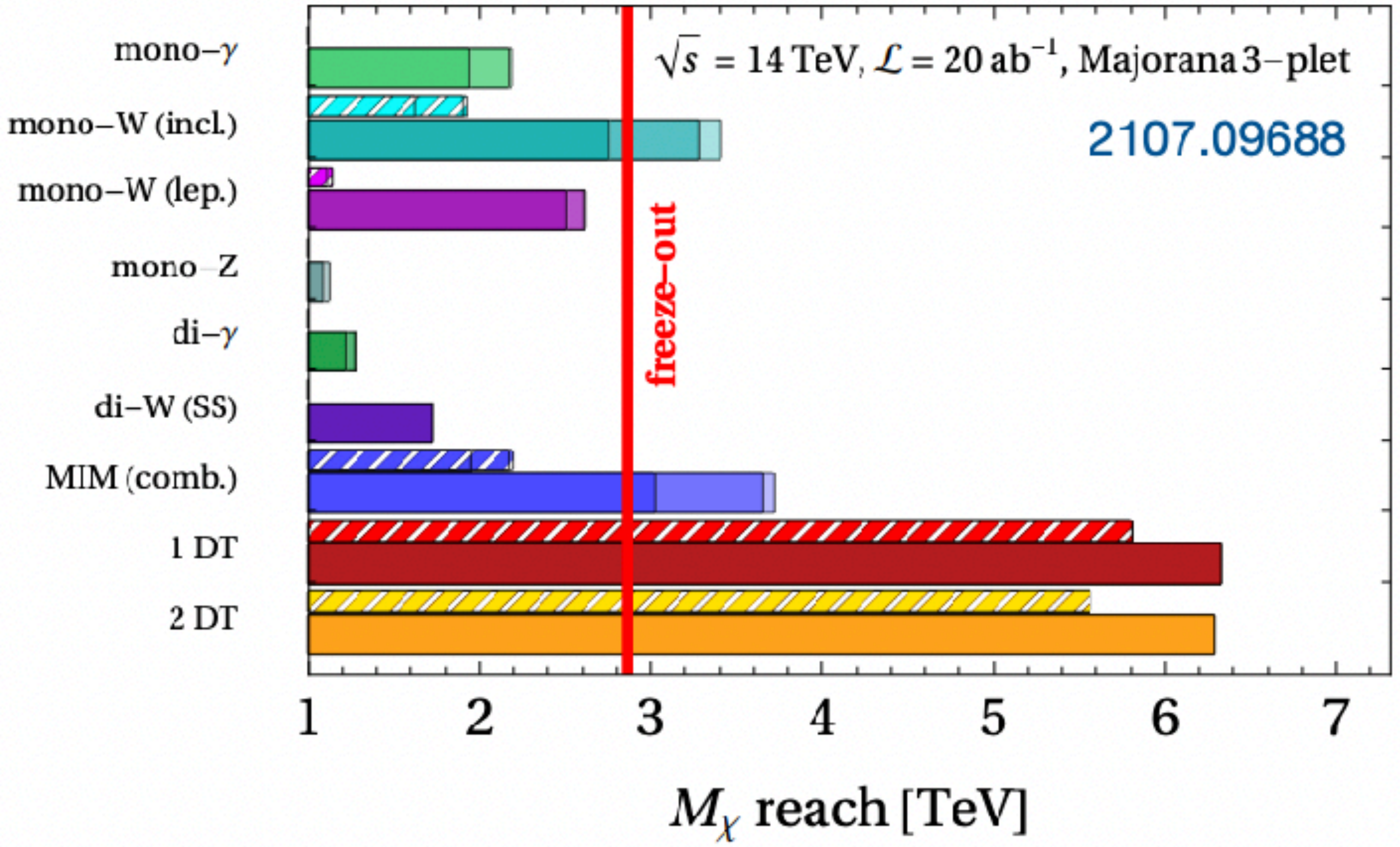
  Bottaro et al. 2107.09688, 2205.04486



- Disappearing tracks: charged components of χ can be long-lived $\chi^{\pm} \to \chi^0 \pi^{\pm}$

  Capdevilla et al. 2102.11292





µC can probe all relevant WIMP candidates!

Reach at hadron collider much lower, due to PDF suppression

Cirelli, Sala, Taoso 1407.7058

Slide Credit: D. Buttazzo

Slide Credit: D. Stratakis

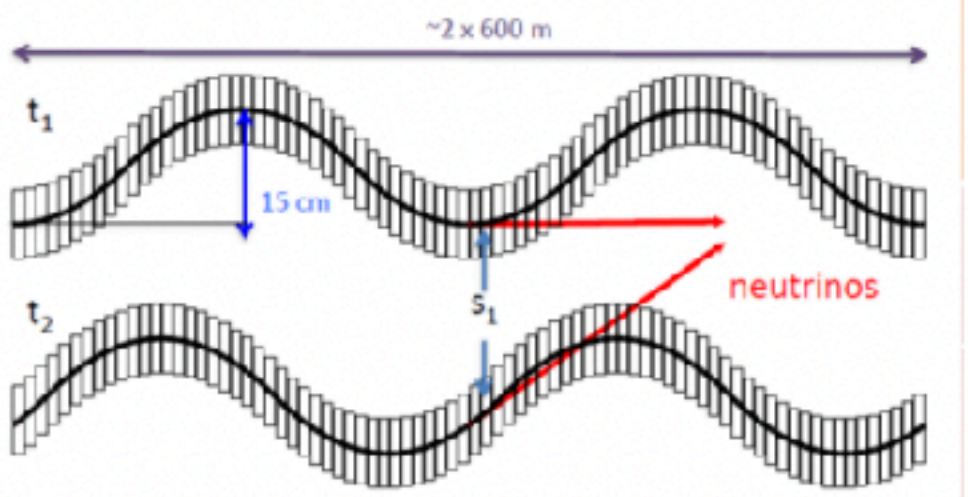
What has changed since over the last years?

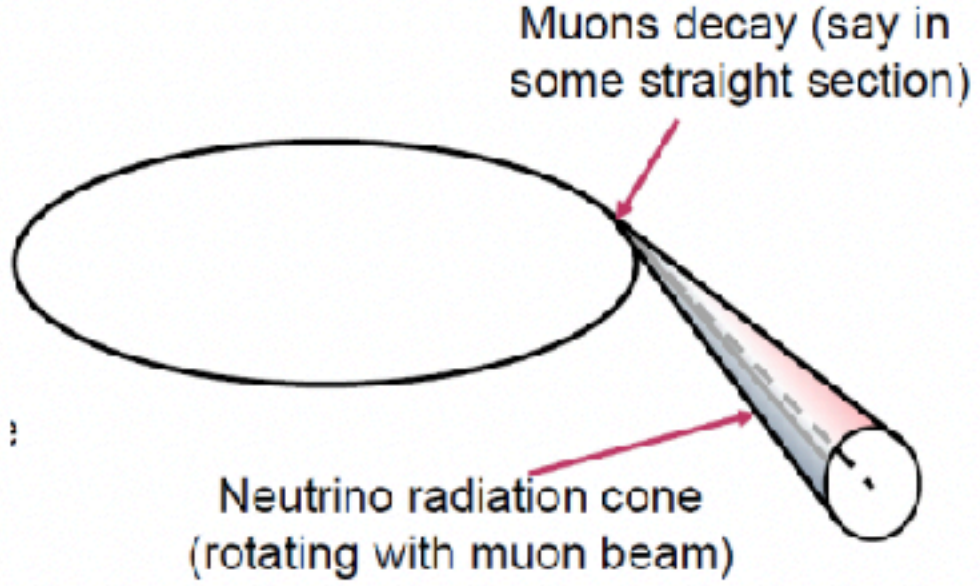
- Lattice design
  - Developed designs for all MuC subsystems, including a promising solution for a neutrino flux mitigation system
- Targets
  - Significant developments on MW-class target concepts due to the strong demand by many experiments.
- Magnet technology
  - Development of high-field solenoids & dipoles with specs close to the MuC needs
- RF technology
  - Demonstrated high-gradient operation of NC cavities in B-fields (50 MV/m @ 3T)
  - SCRF cavity gradients for a MuC are within reach of current technology
- Ionization cooling concept demonstration
  - Physics of ionization cooling has been demonstrated and results are published

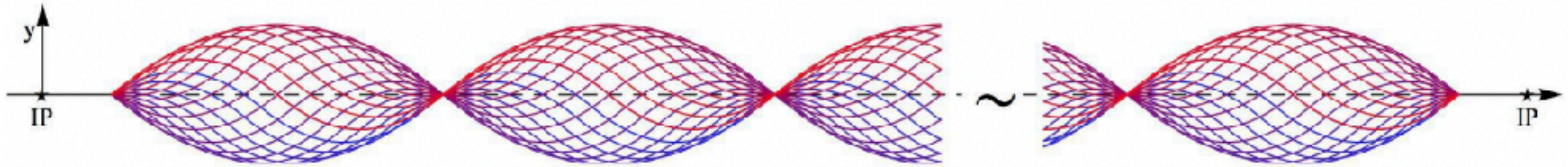
Slide Credit: D. Stratakis

Neutrino flux mitigation system

Solution: A mechanical system that will disperse the neutrino flux by periodically deforming the collider ring arcs vertically with remote movers;



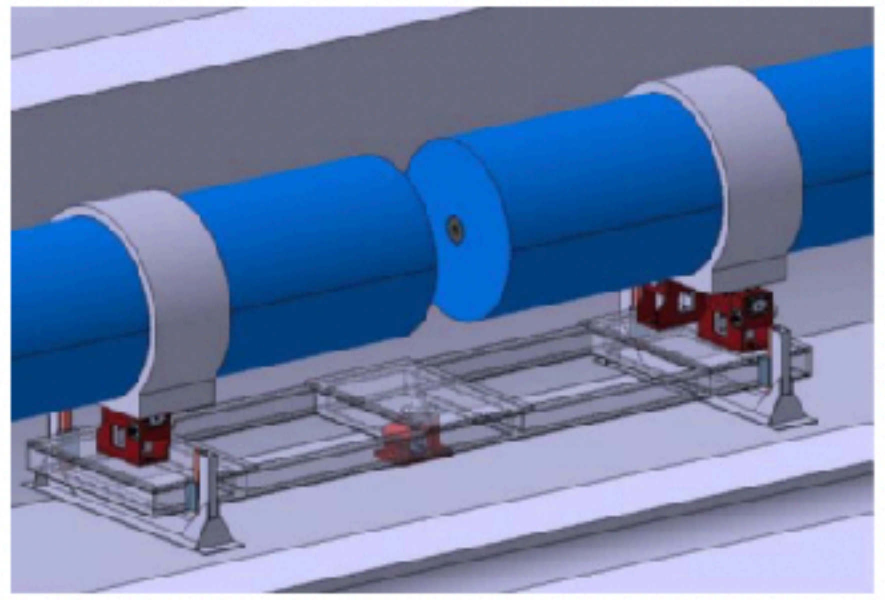




Vertical slope modulation ~ 1 mrad

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

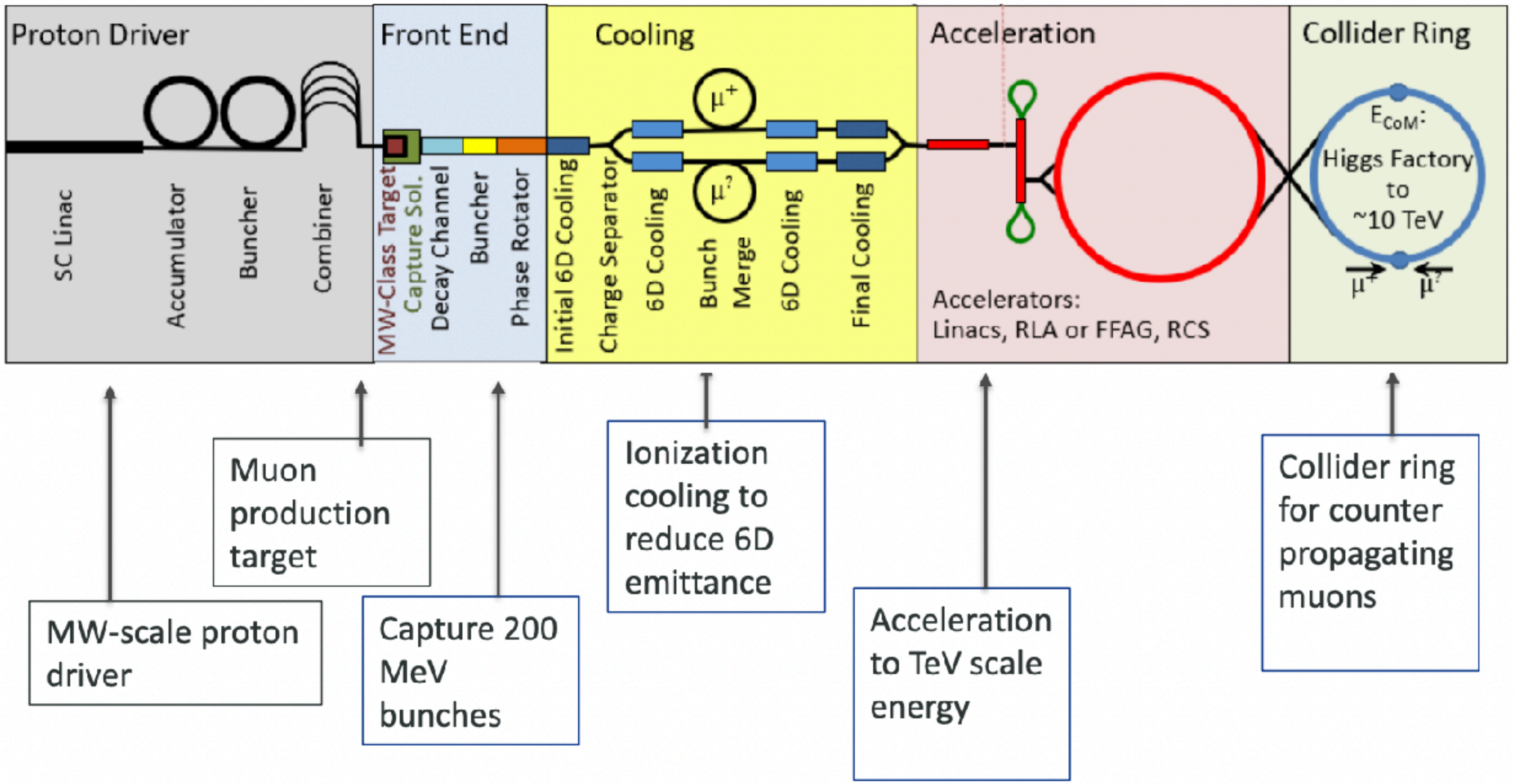


Legal limit: 1 mSv/year
MAP goal: <0.1 mSv/year
IMCC goal: <10 μSv/year
LHC : <5 μSv/year

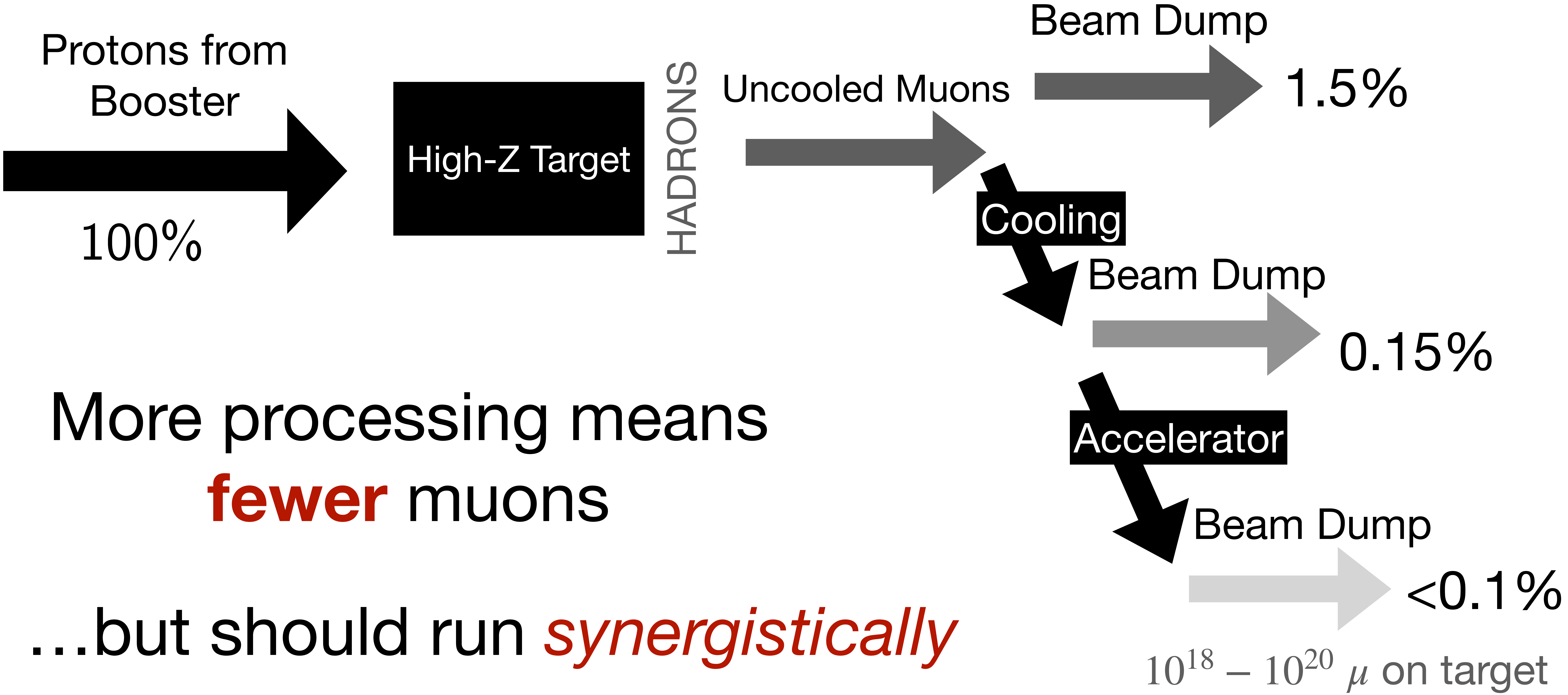
Requires significant R&D and proof-of principle tests

Machine overview

Slide Credit: D. Stratakis



Demonstrators & Beam Dumps



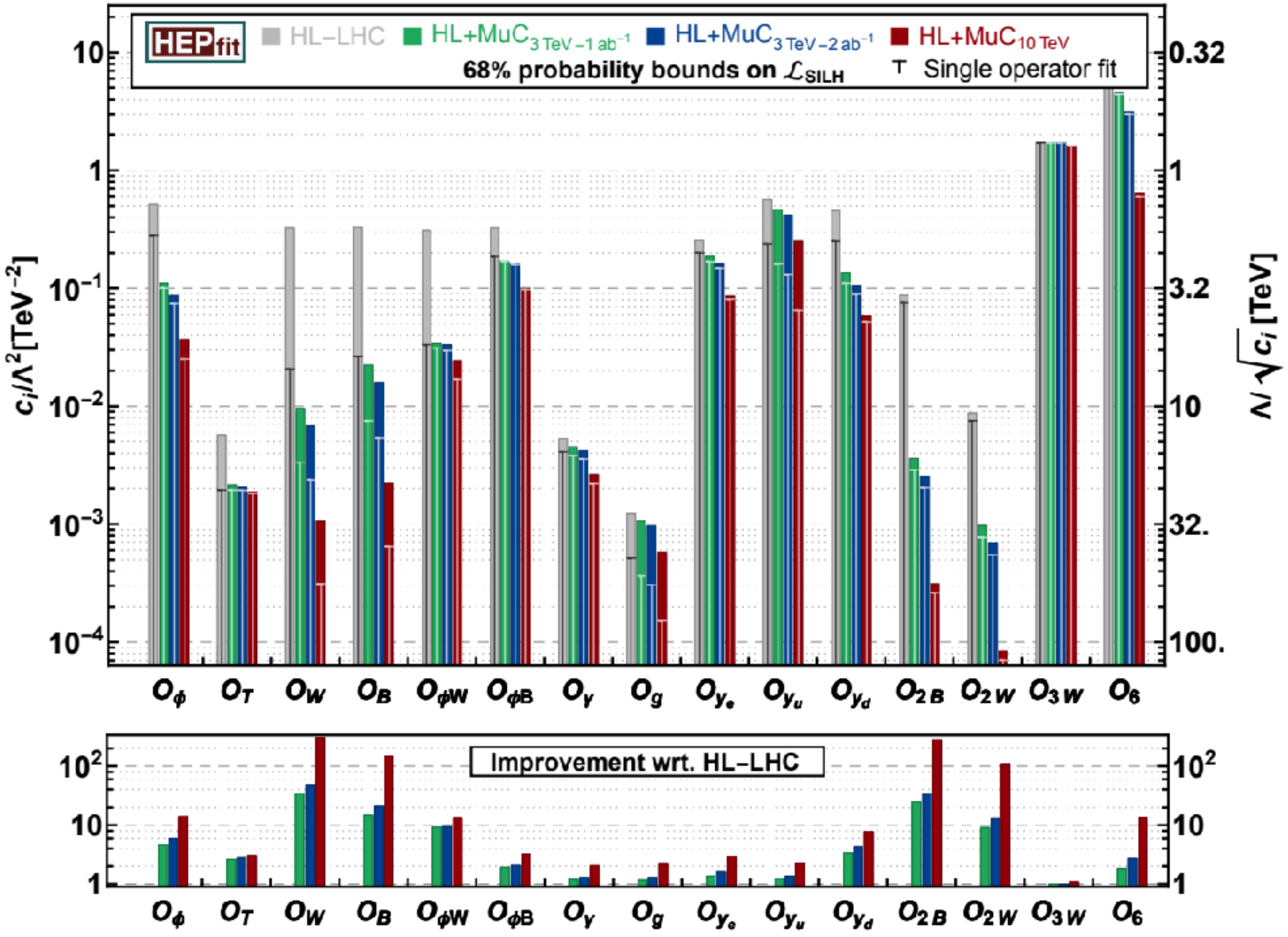
More processing means **fewer** muons

…but should run *synergistically*

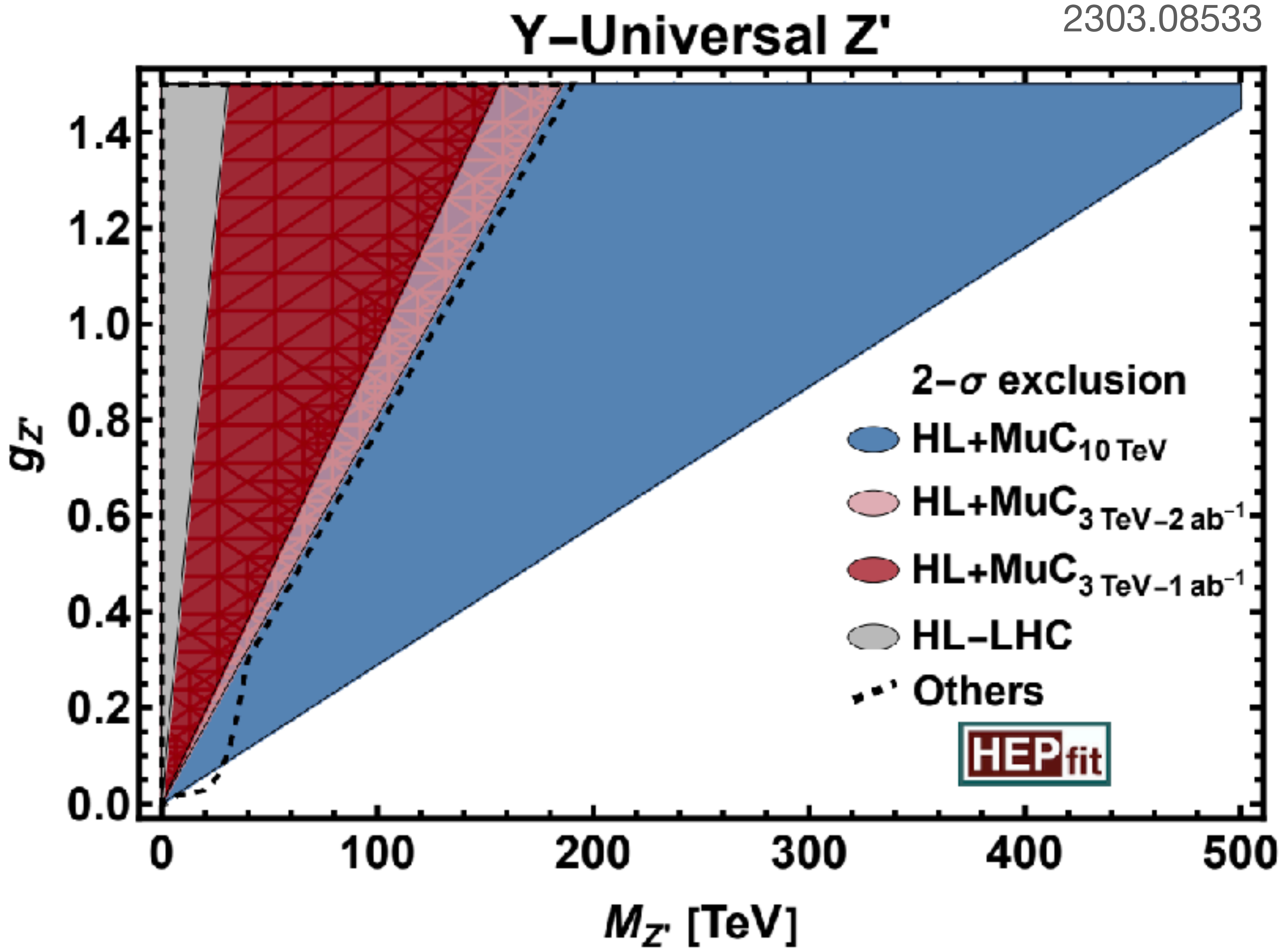
Physics Reach of MuC

Indirect Production (EFT Approach)

1910.14012



2303.08533



Demonstrator Facility Beam Dump

Late 2030s? 2040ish 2050ish

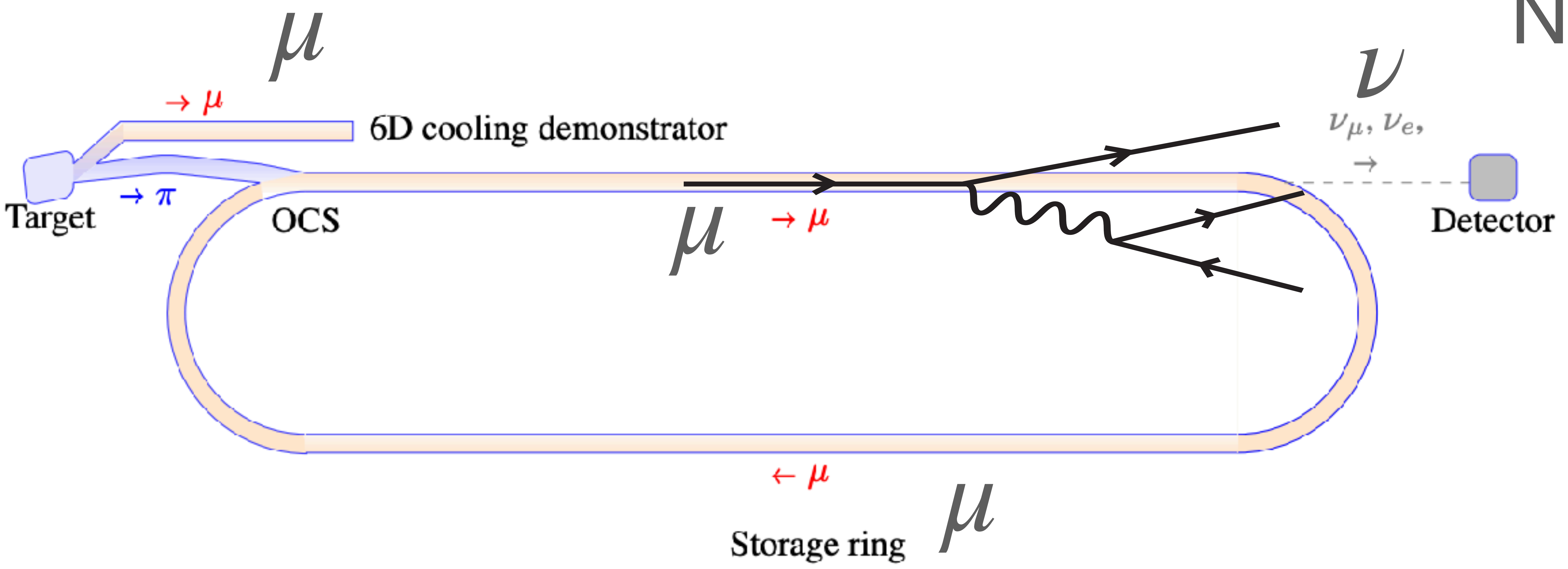
2310.16110

Mild Acceleration:
Cooling & Synergies

Higgs Threshold MuC

3, 10 TeV MuC

Motivation:
Neutrino Facilities?



2203.07545