Future Colliders

Invisibles25 Workshop

Cari Cesarotti - CERN-TH Fellow

September 4, 2025

Outline

Why should we continue building colliders?

What options are there for future colliders?

What are the relative strengths of these options?

What is the reach of these machines for BSM physics?

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Why should we continue building colliders?

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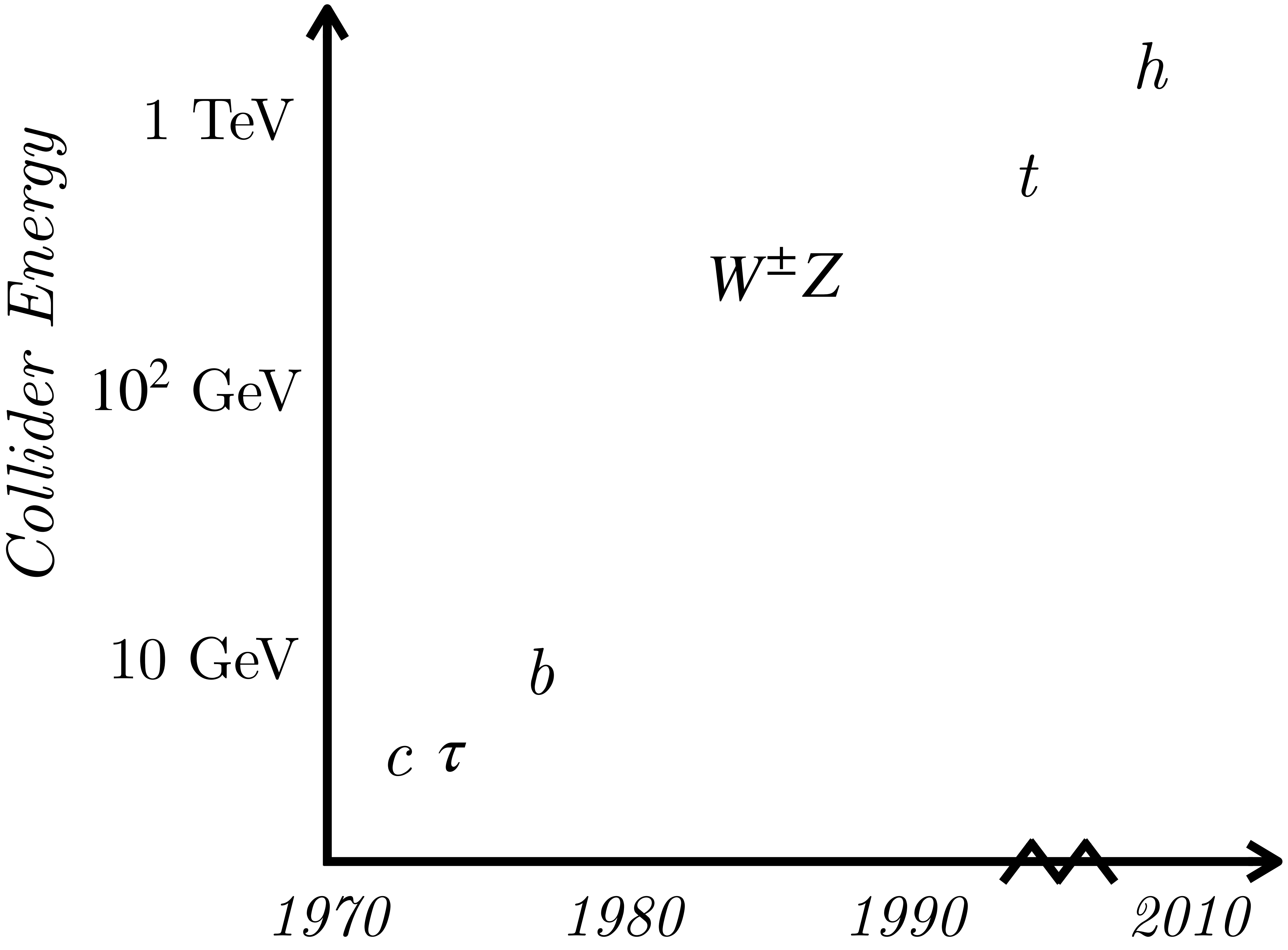
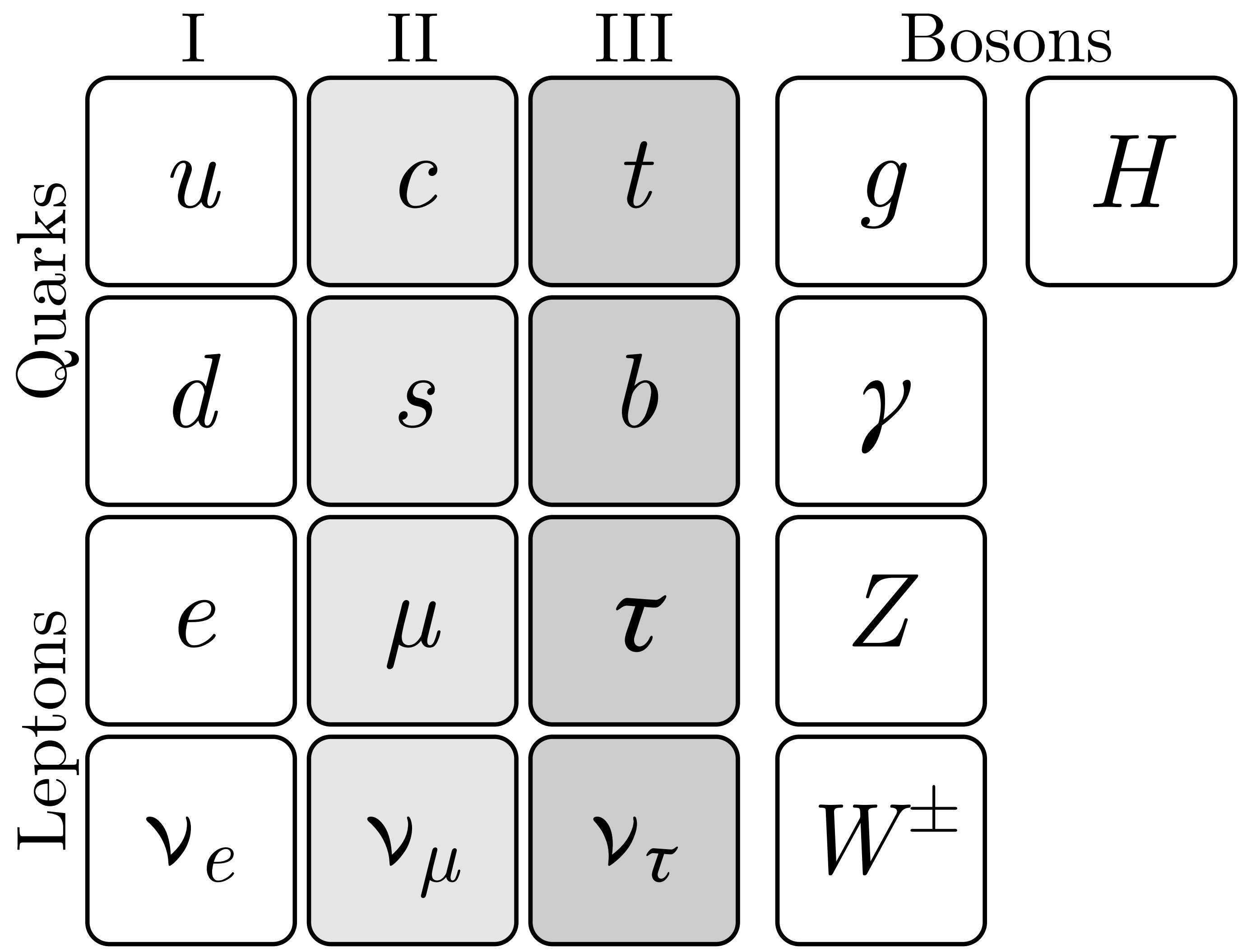
Continuing Colliders

The goal of particle physics is to understand the most fundamental degrees of freedom and their interactions



Higher energies at colliders have lead to understanding of...



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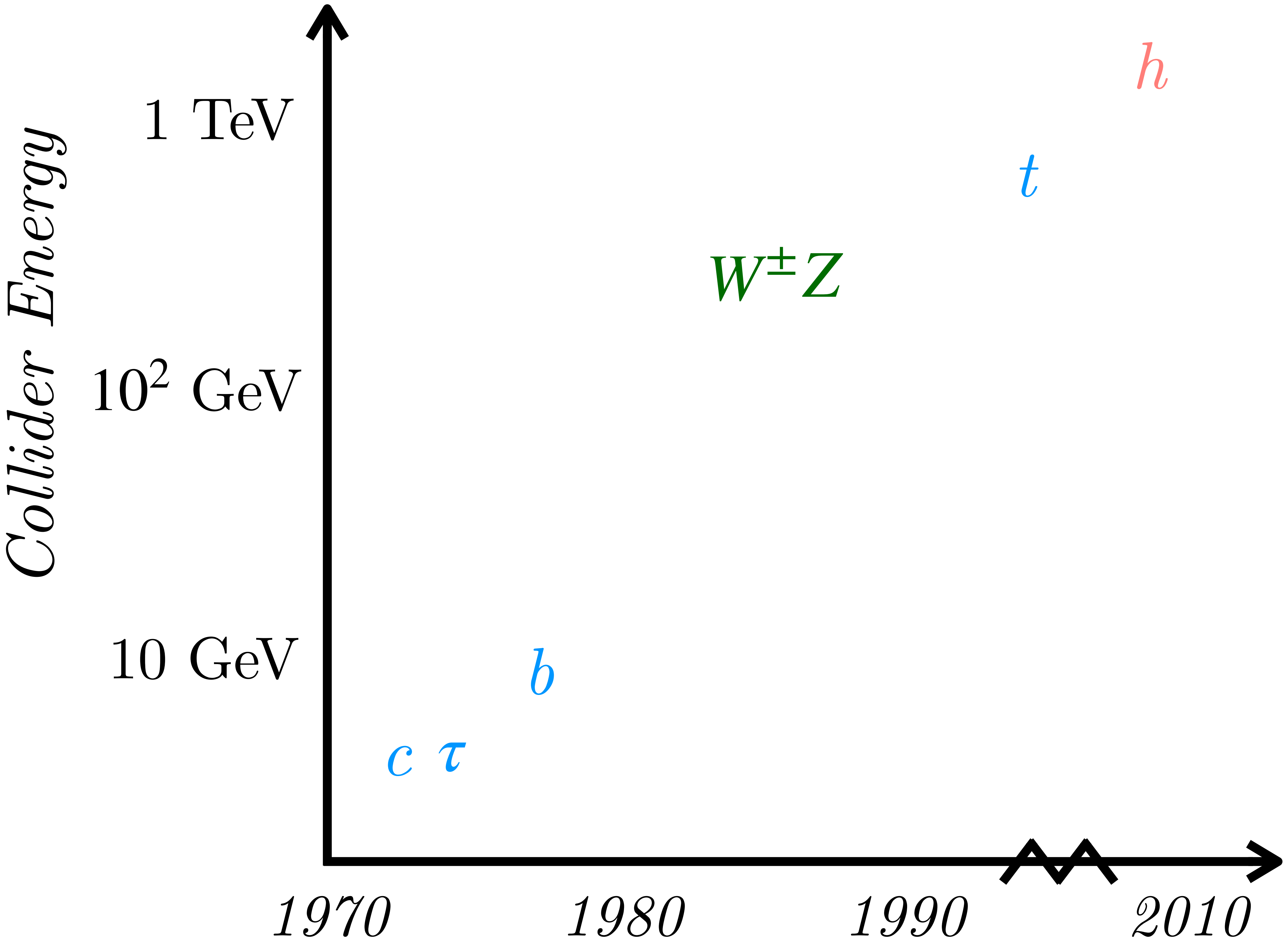


Higher energies at colliders have lead to understanding of...

2nd and 3rd Generation Particles

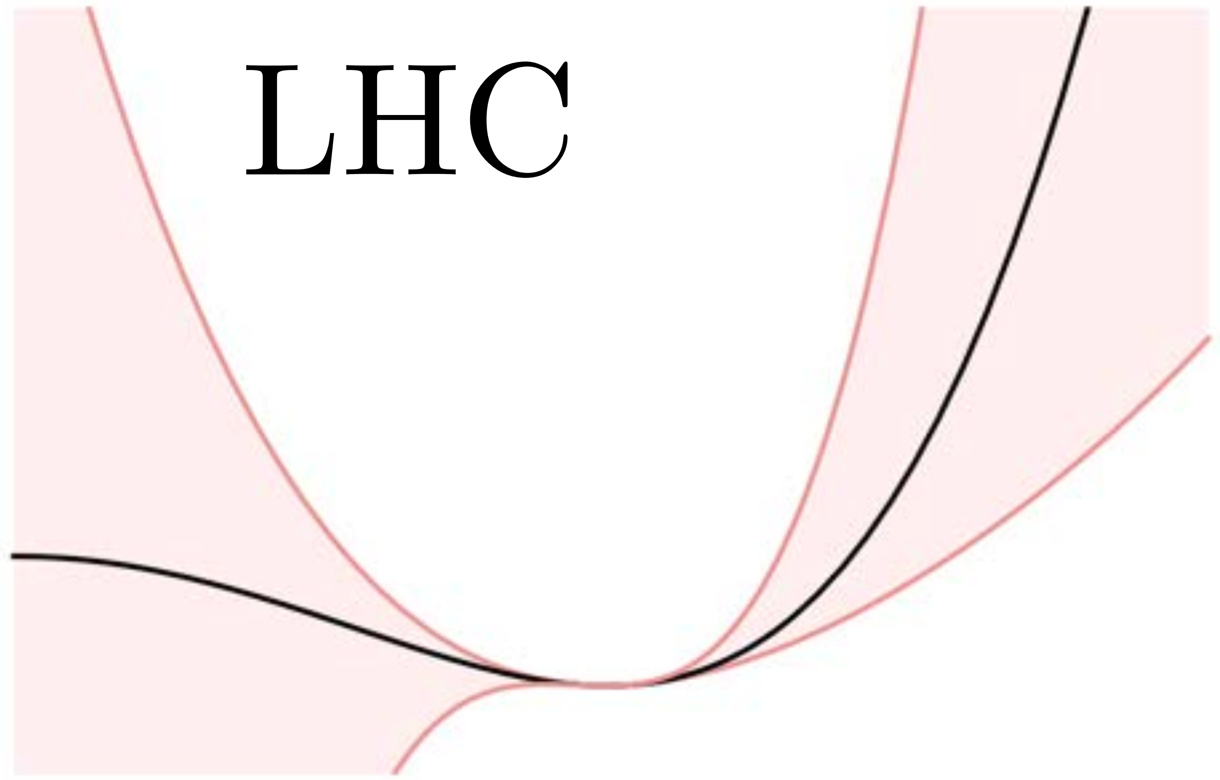
$SU(2) \times U(1)$ Electroweak Symmetry

Higgs mechanism

Continuing Colliders

...but open questions remain in the Standard Model (SM)

- Higgs properties?
- Electroweak symmetry breaking?
- Origin of flavor?
- Strong CP?
- ...



Continuing Colliders

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...and even more exist *beyond* the SM (BSM)

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- Dark matter?
- Baryon-antibaryon asymmetry?
- Anomalies in precision measurements?
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Colliders are general-purpose experiments

Broad searches for NP $\Longrightarrow$ empirical hints

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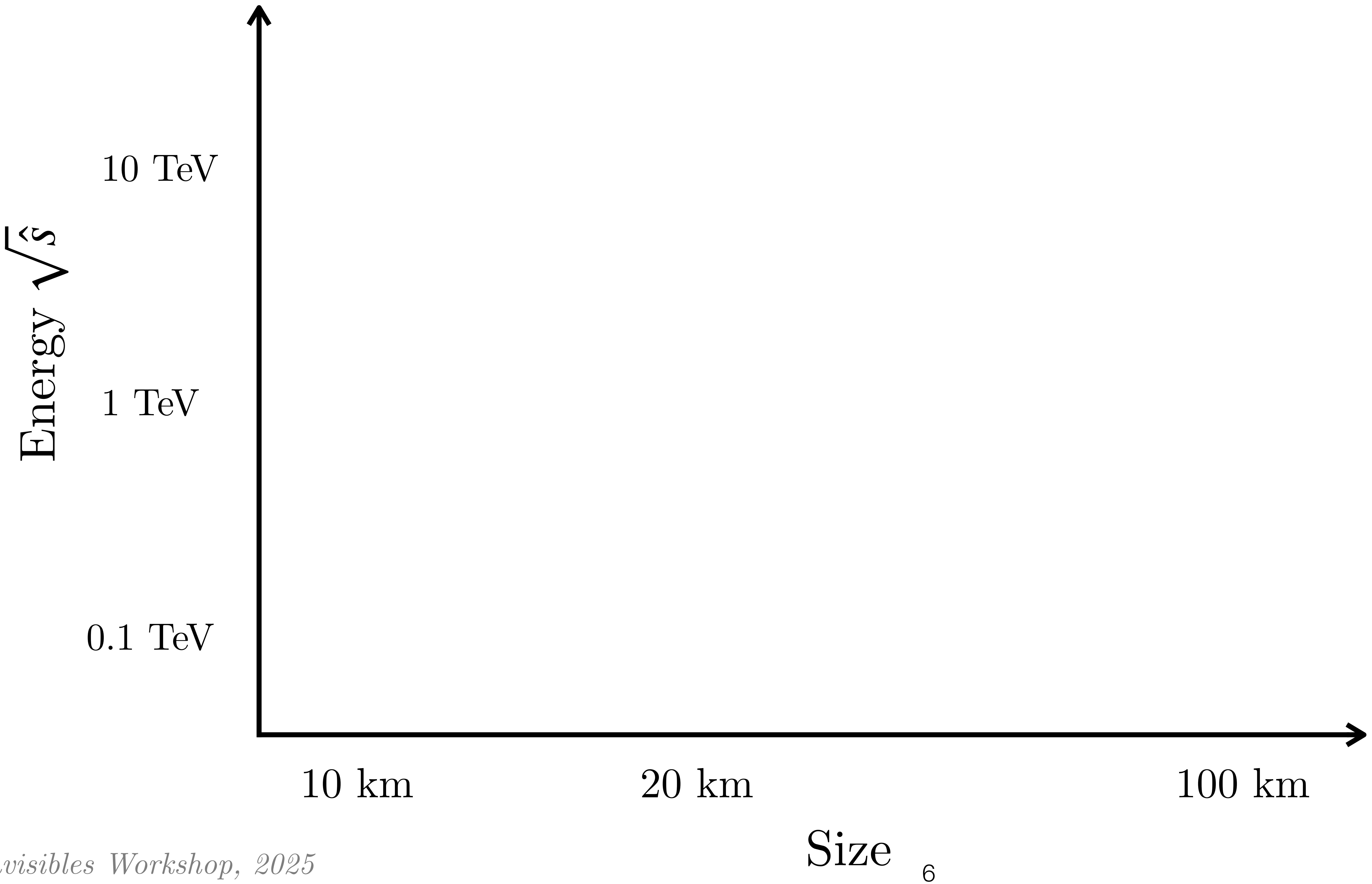

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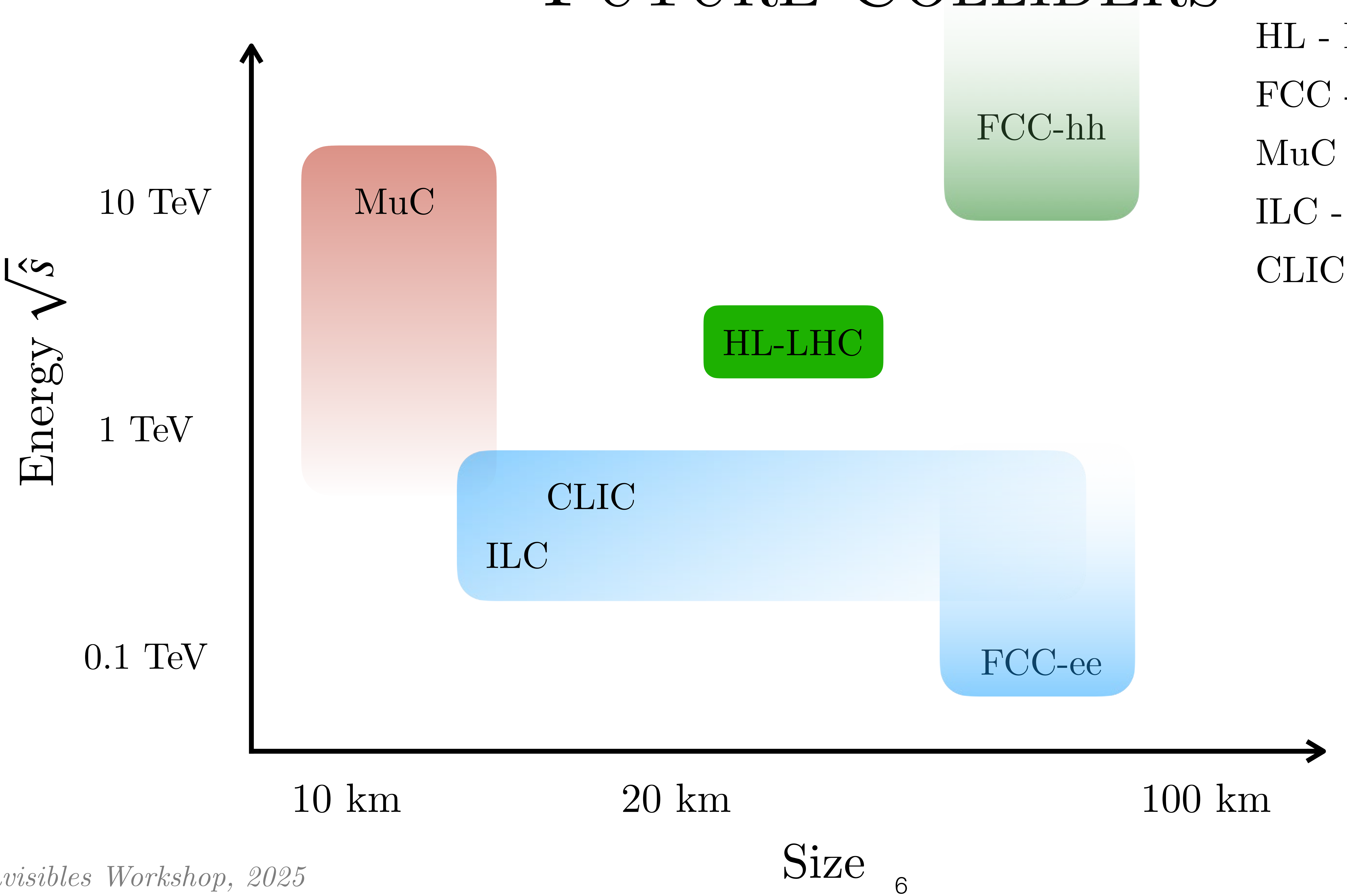

HL - High Luminosity
FCC - Future Circular Collider
MuC - Muon Collider
ILC - Int. Linear Collider
CLIC - Compact Linear Collider

e^+e^-
$\mu^+\mu^-$
pp

FCC-ee ↔ CEPC
FCC-hh ↔ SPPC

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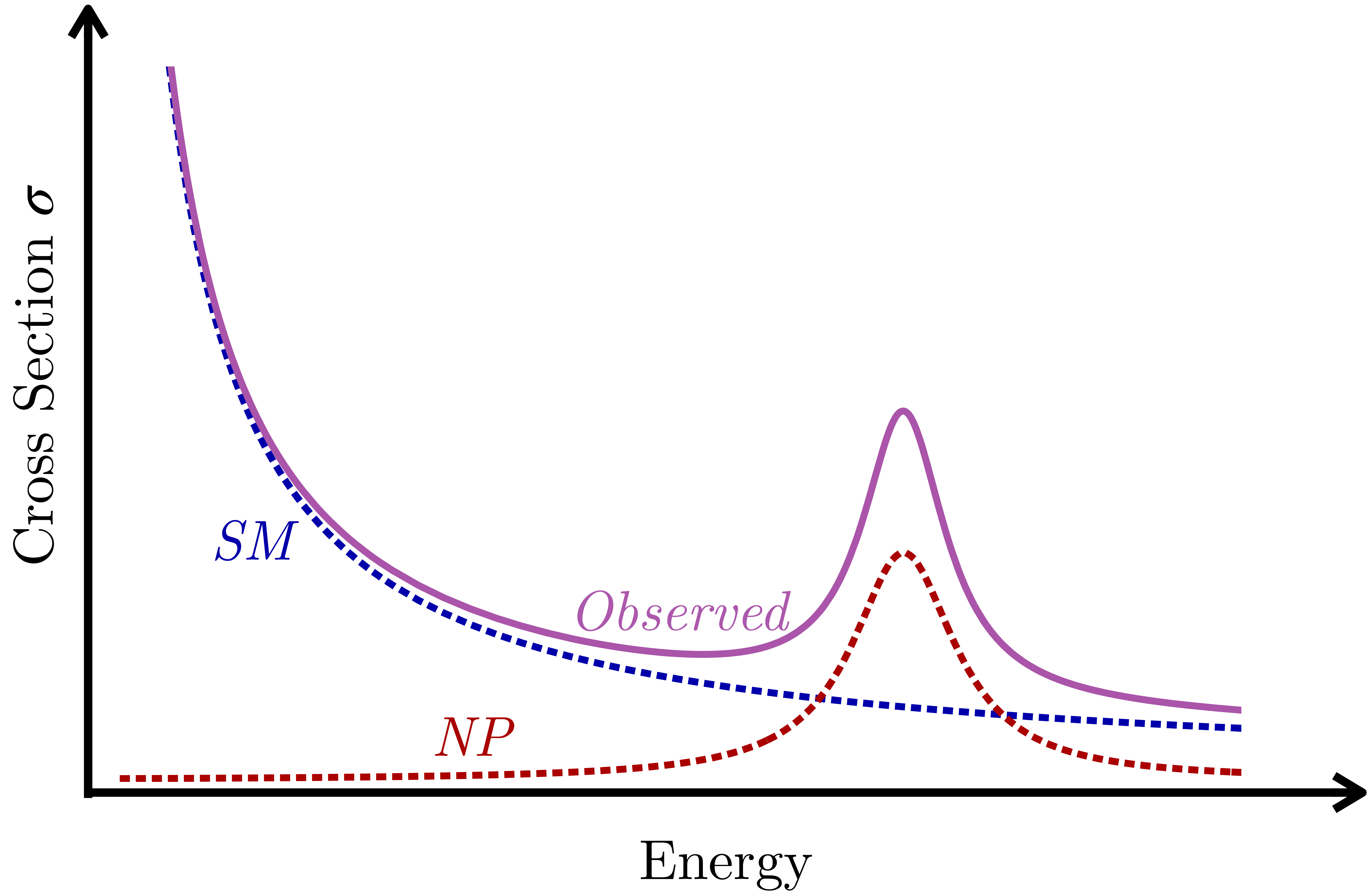
Future Colliders

Two avenues for progress:

Precision or *Discovery* machines



Future Colliders

Two avenues for progress:

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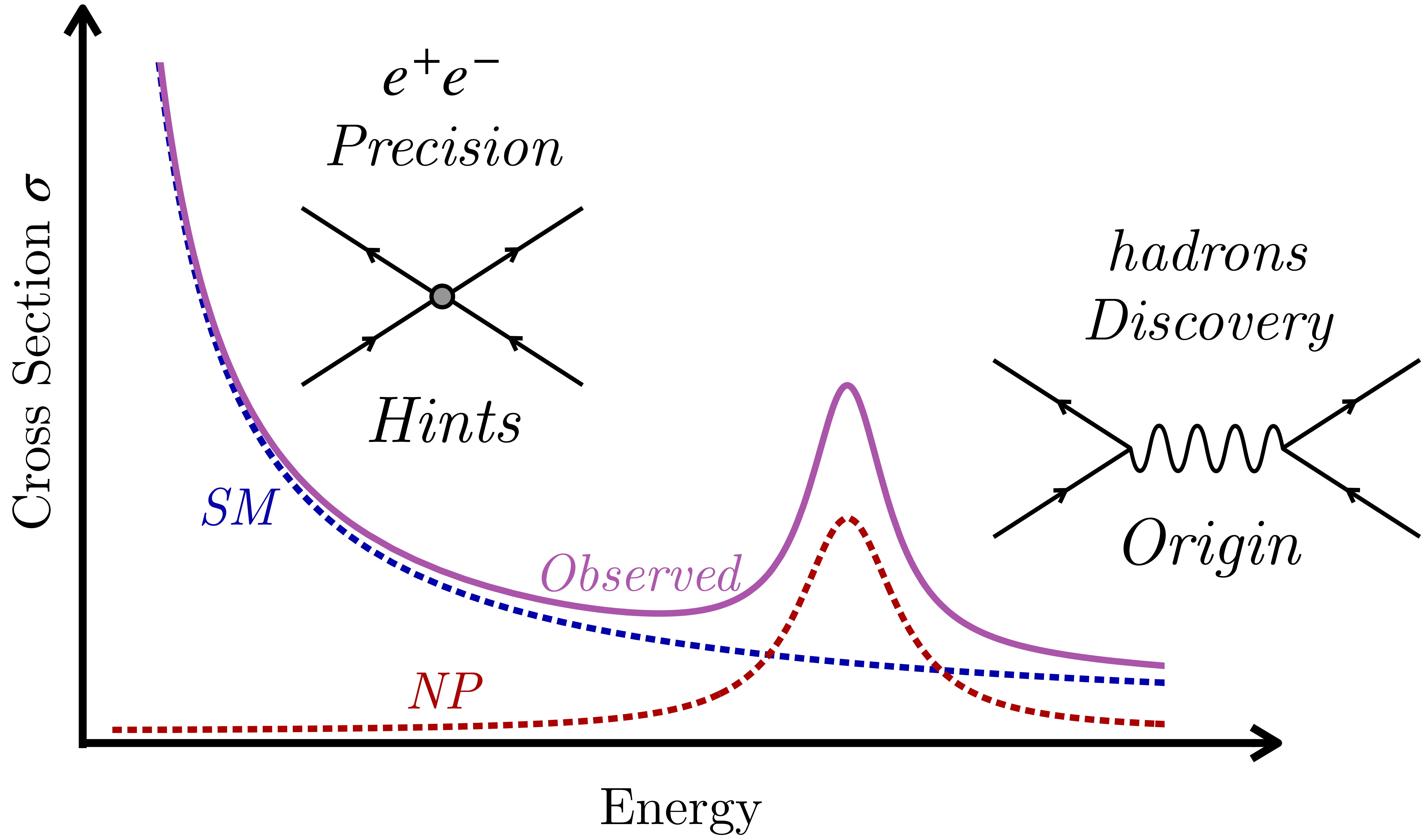
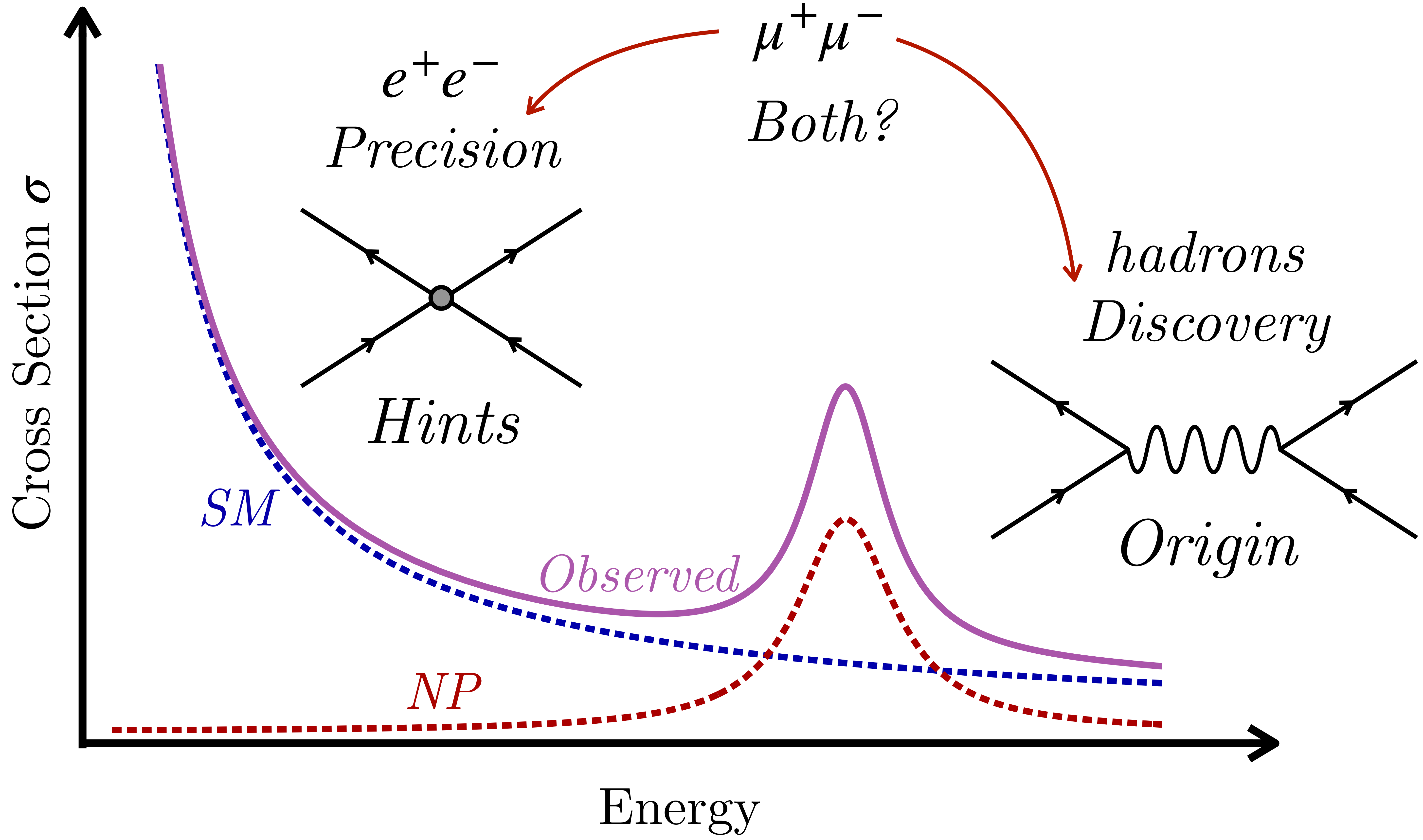


Future Colliders

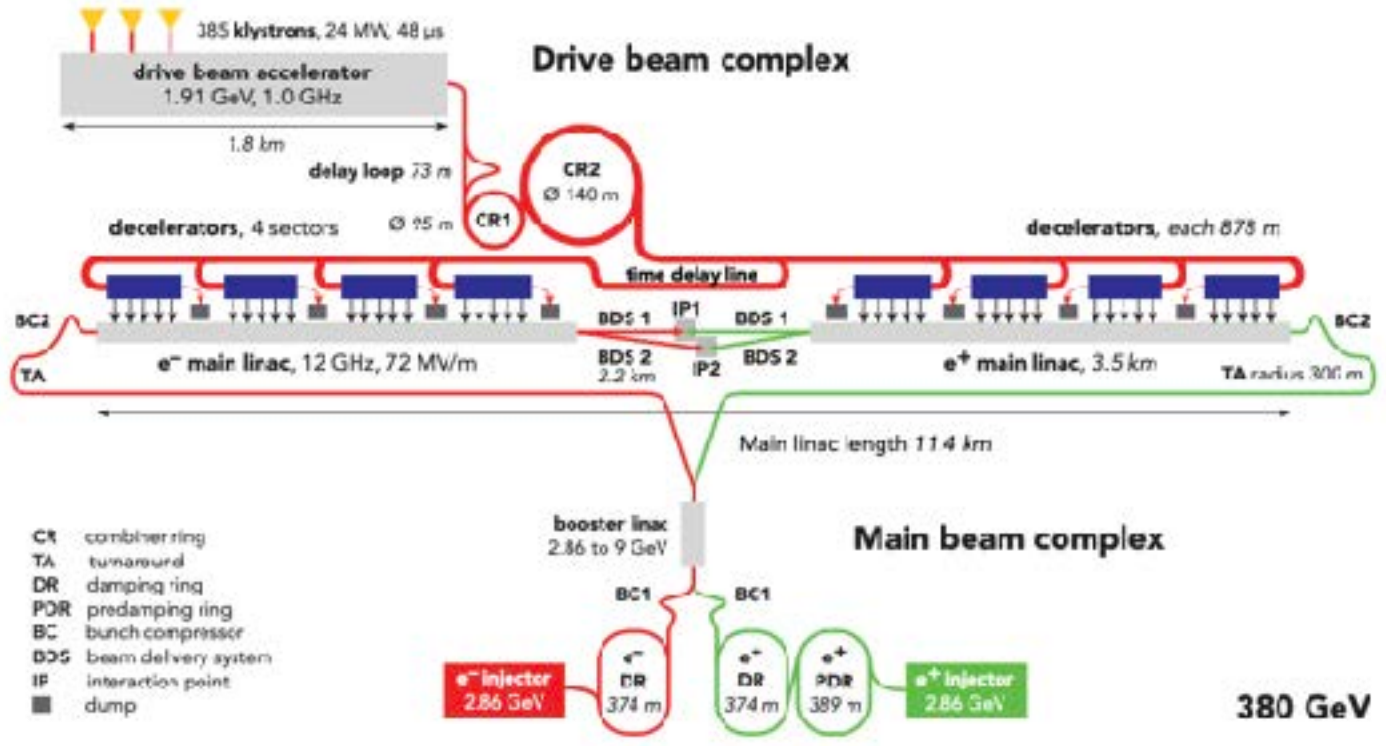
Two avenues for progress:

Precision or *Discovery* machines

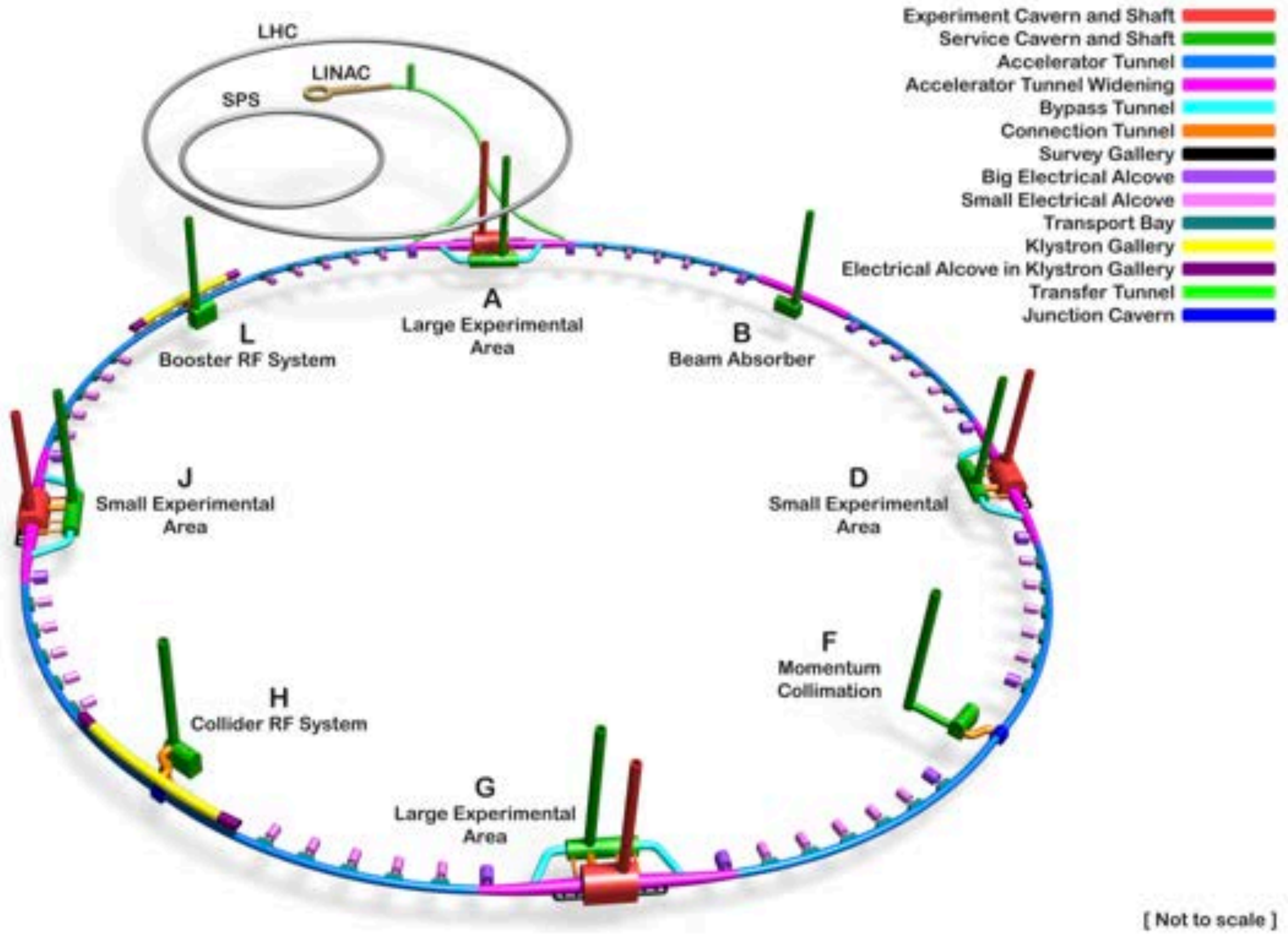


LINEAR VS. CIRCULAR

Ex. CLIC



Ex. FCC



Linear vs. Circular

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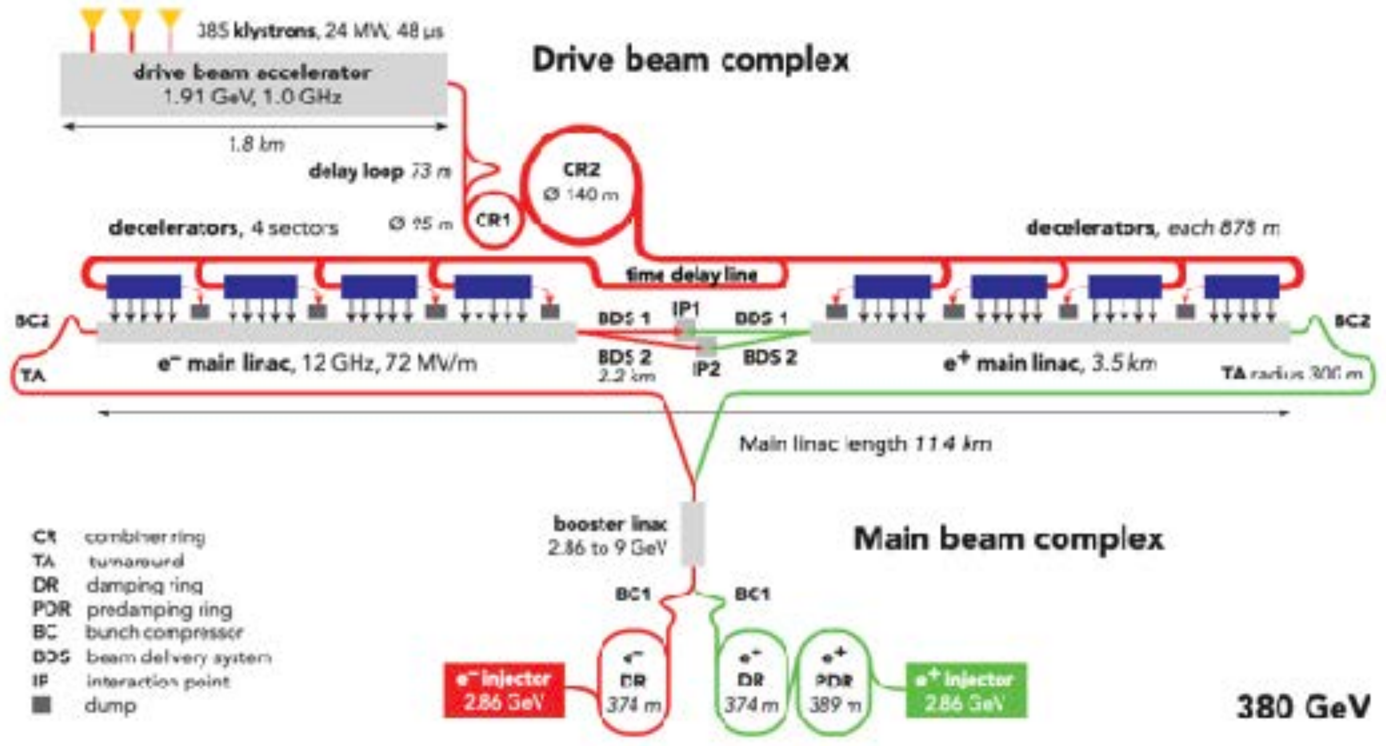
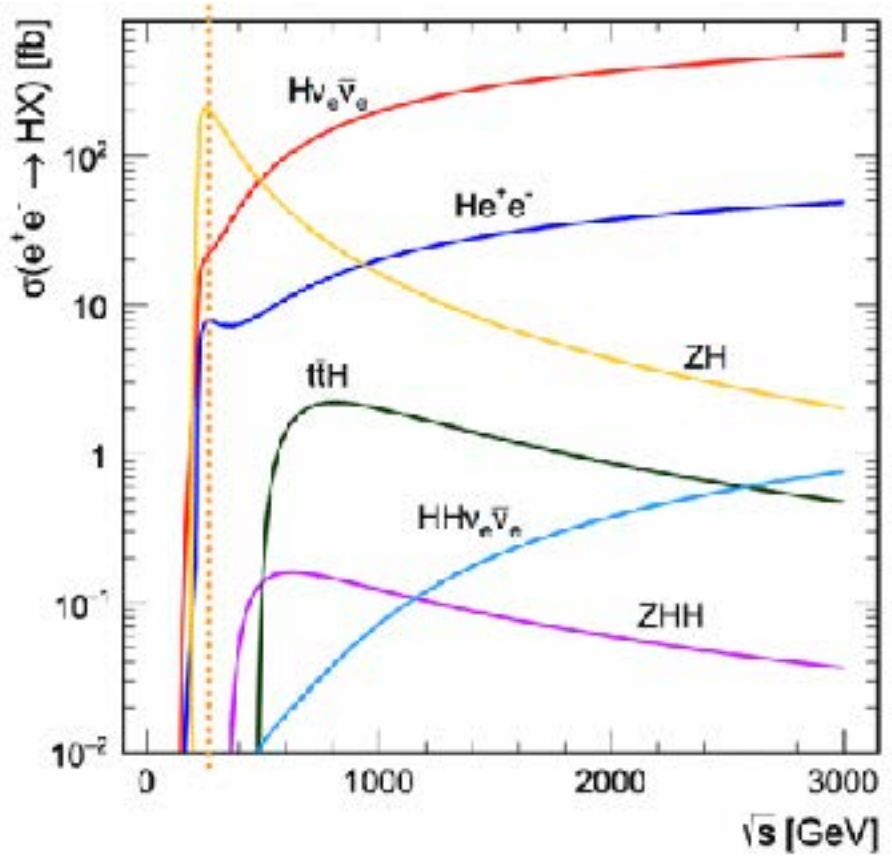


- Precision machines (250 - 550 GeV)
- Lepton colliders (e^+e^-)
- Higgs factory, top physics
- Upgrade $\sqrt{s}$ *option*



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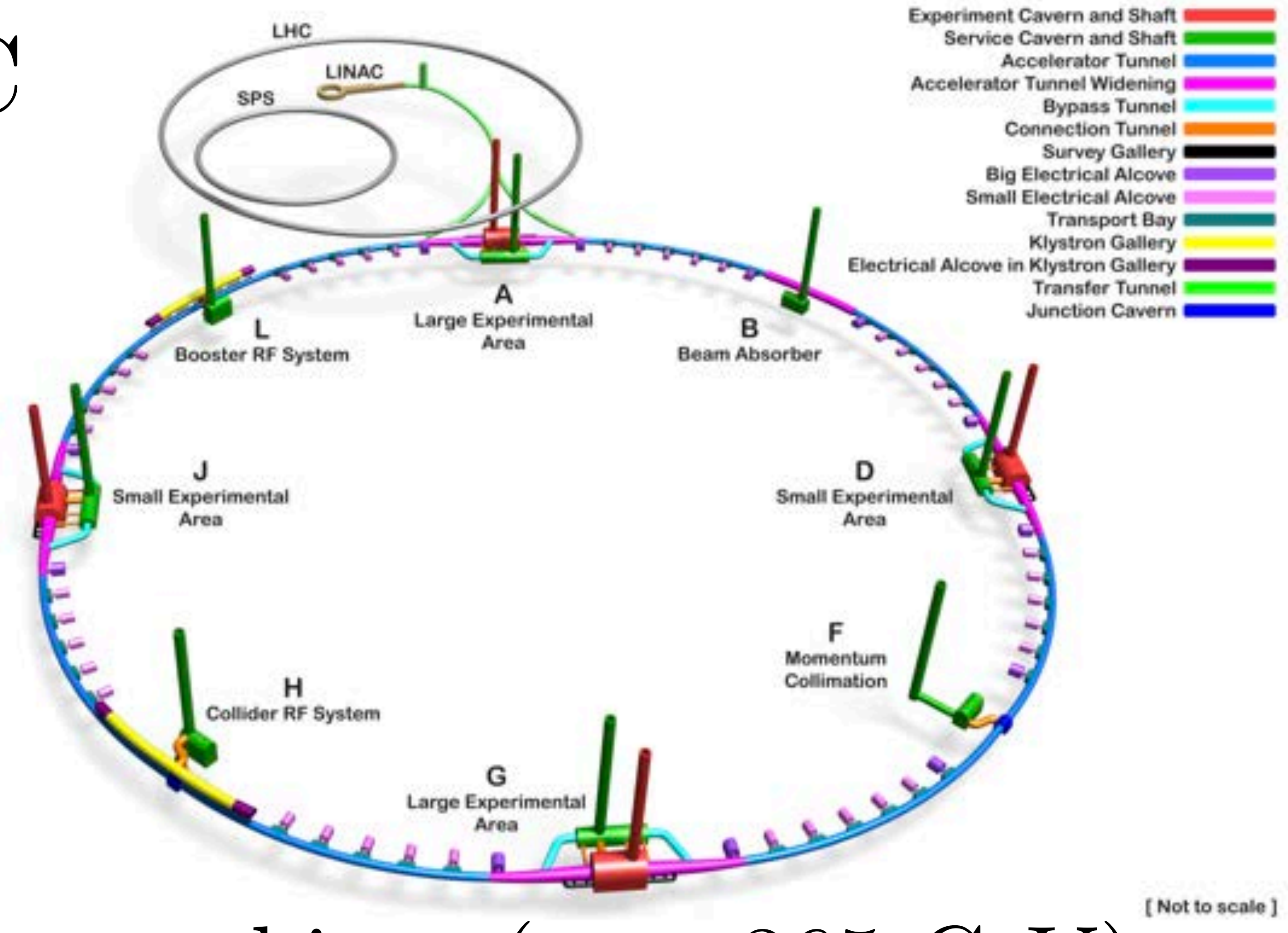
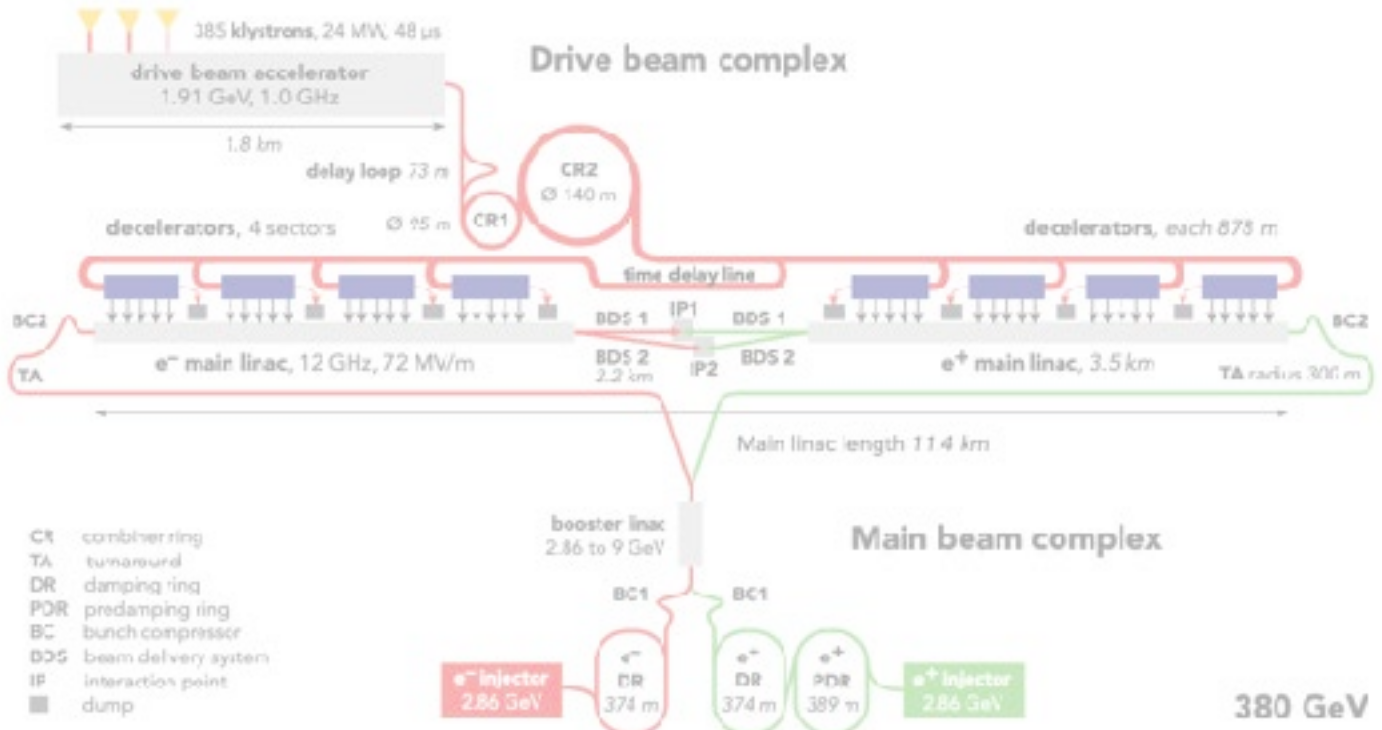


- Precision machines (m_Z - 365 GeV)
- Lepton or hadron colliders
- Higgs factory, electroweak precision, energy frontier
- Upgrade $\sqrt{s}$ ($e^+e^- \to pp$)

Linear vs. Circular

Ex. CLIC



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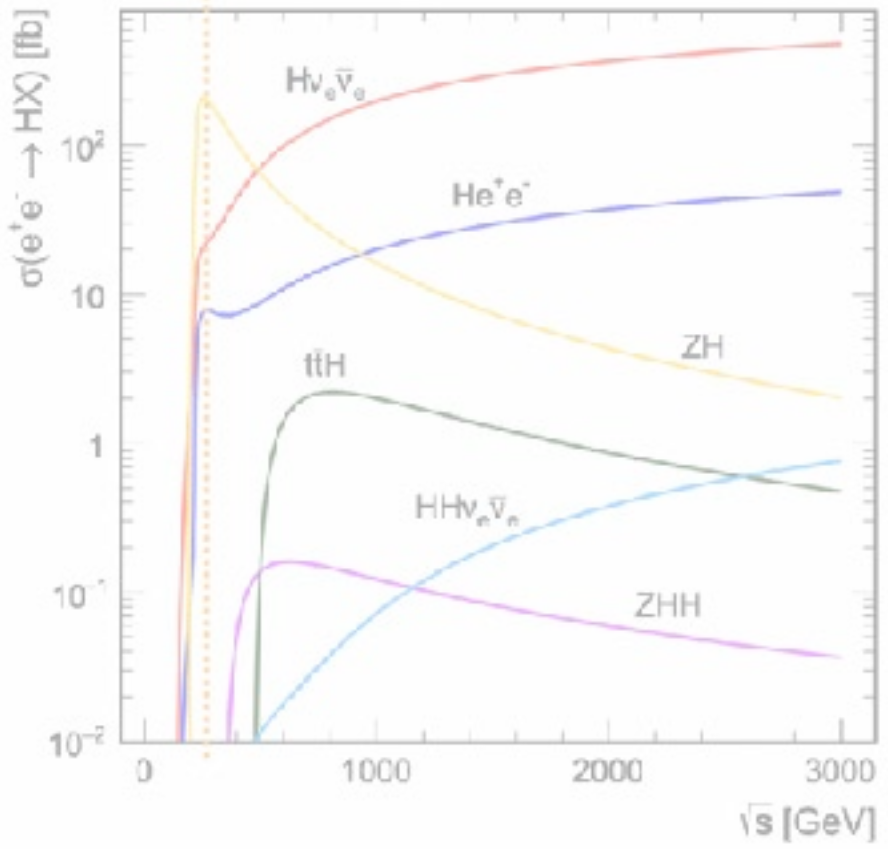
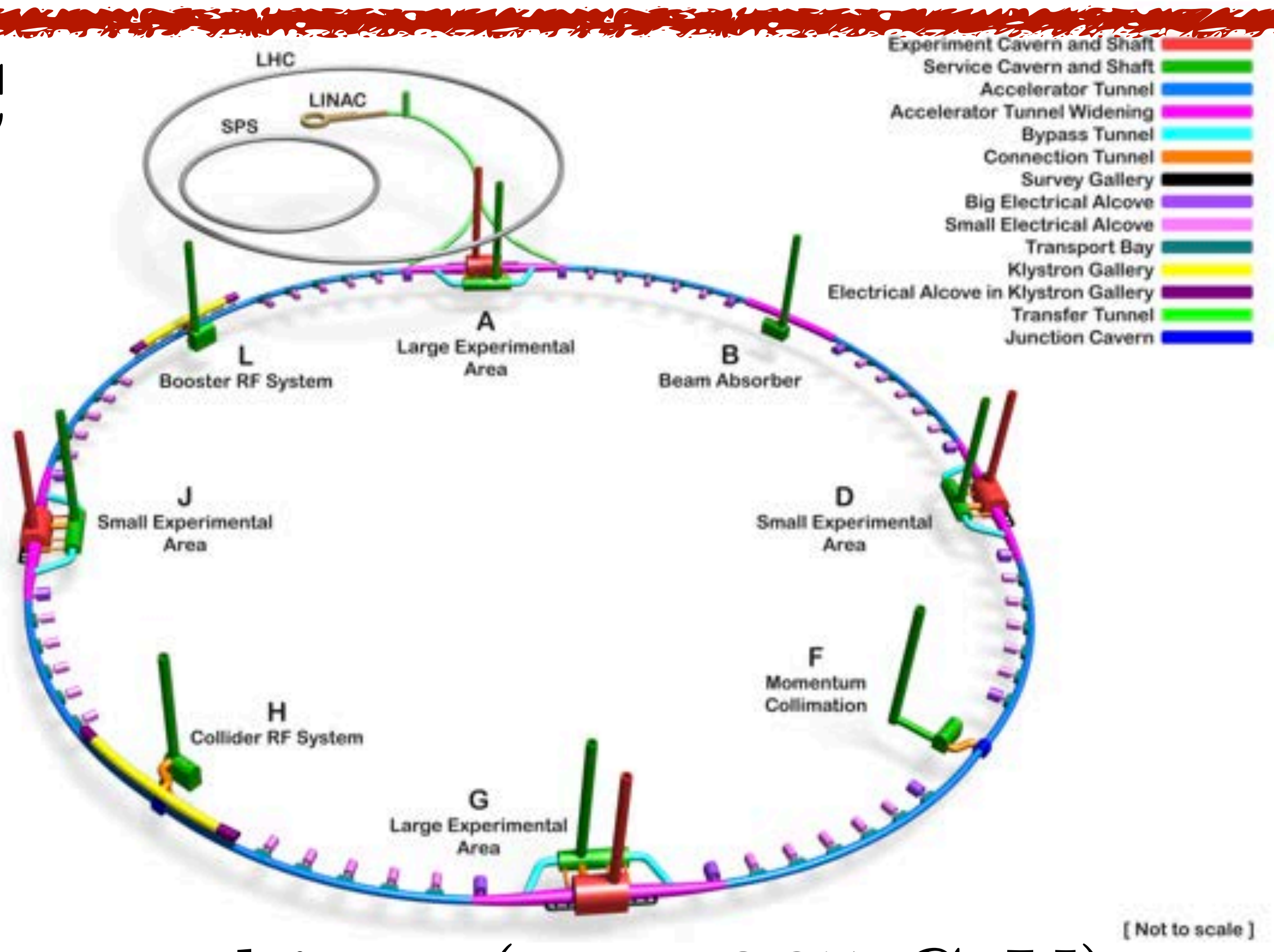


Ex. FCC



- Precision machines (m_Z - 365 GeV)
- Lepton or hadron colliders
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Most likely option

Comparison of Future Colliders

pp

$\mu^+\mu^-$

e^+e^-

Circular

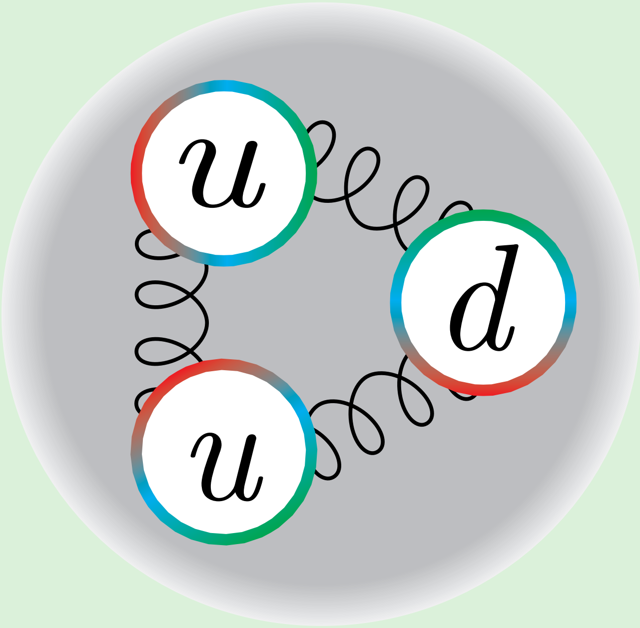
Linear

Comparison of Future Colliders

pp

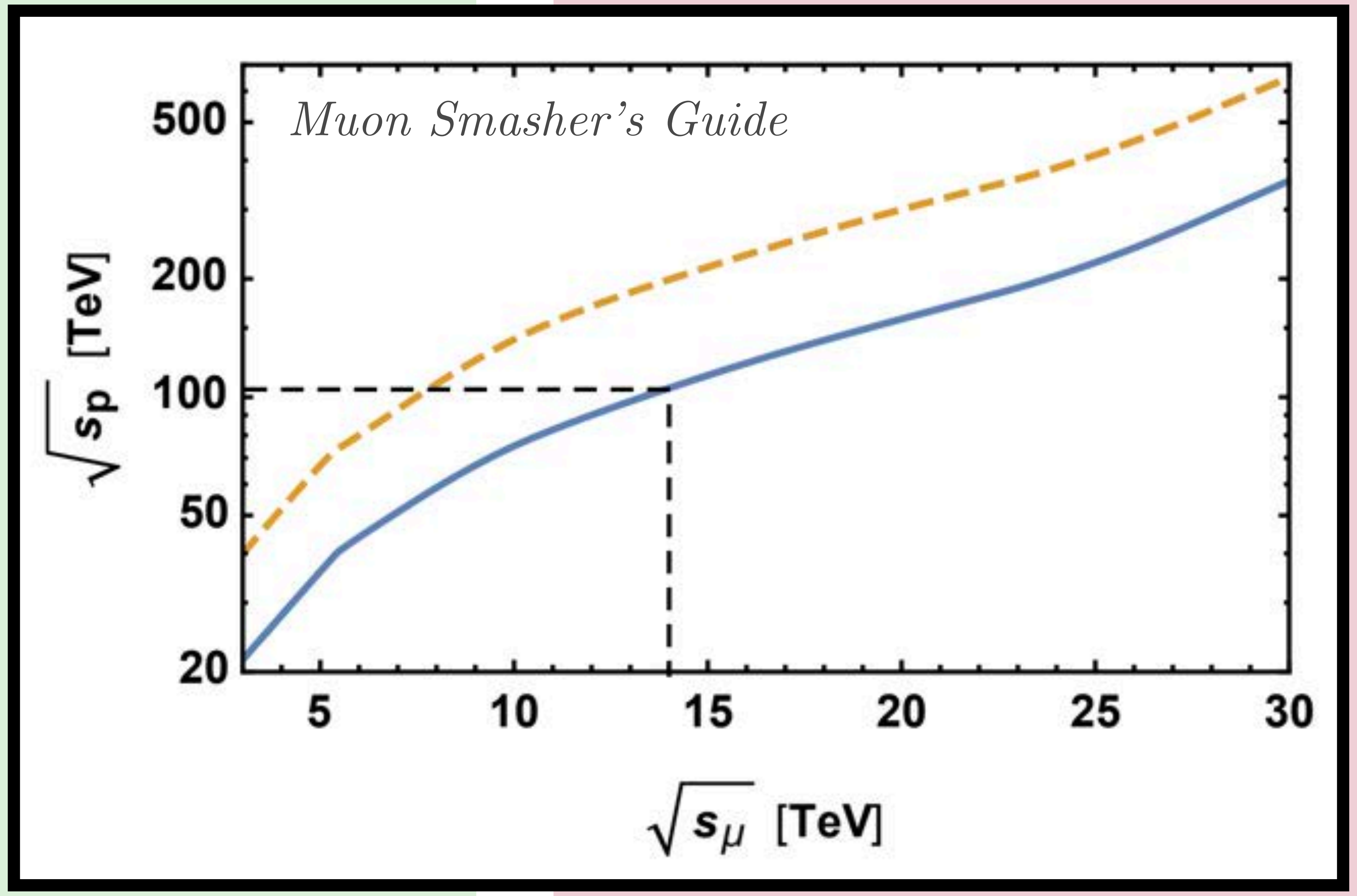
Composite

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



$\mu^+\mu^-$

Muon Smasher's Guide '19



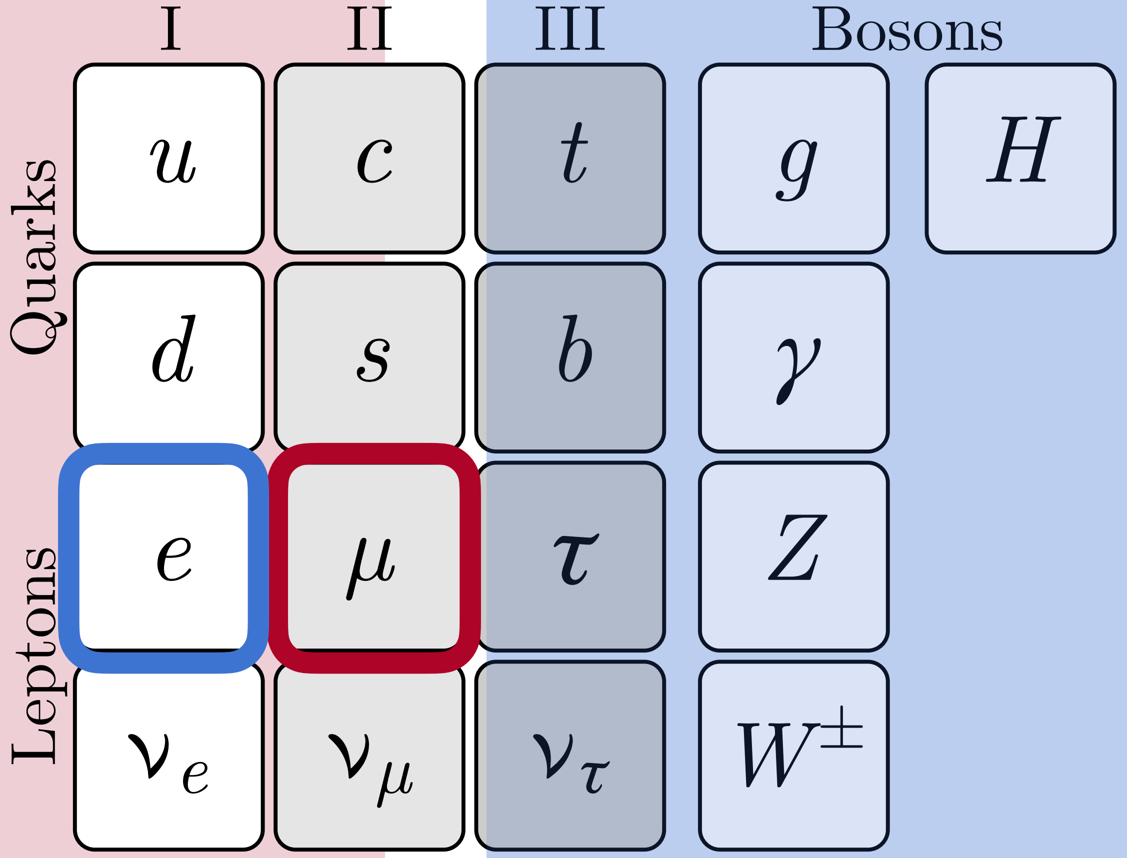
e^+e^-

Circular

Linear

Fundamental

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



Comparison of Future Colliders

pp

$\mathcal{O}(100)$ TeV

$\mu^+\mu^-$

$\mathcal{O}(1-10)$ TeV

Synchrotron Radiation

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

$$P_\mu/P_e \sim 10^{-9}$$

e^+e^-

Circular

$\mathcal{O}(300)$ GeV

Linear

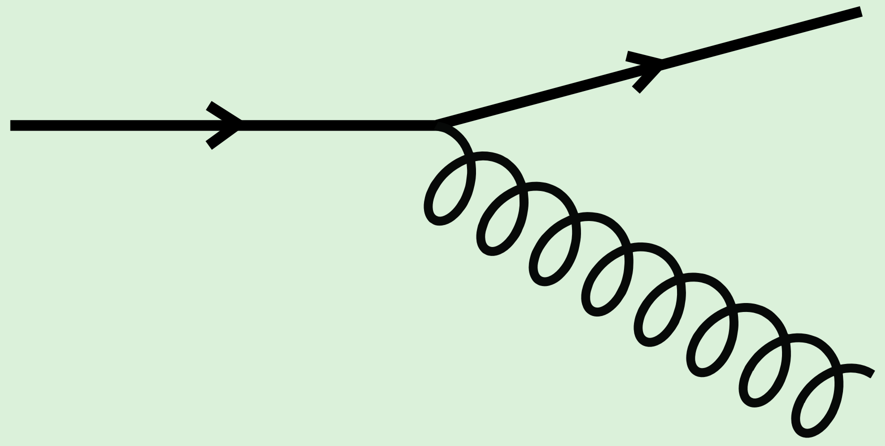
$\lesssim 3$ TeV

Comparison of Future Colliders

pp

$\mathcal{O}(100)$ TeV

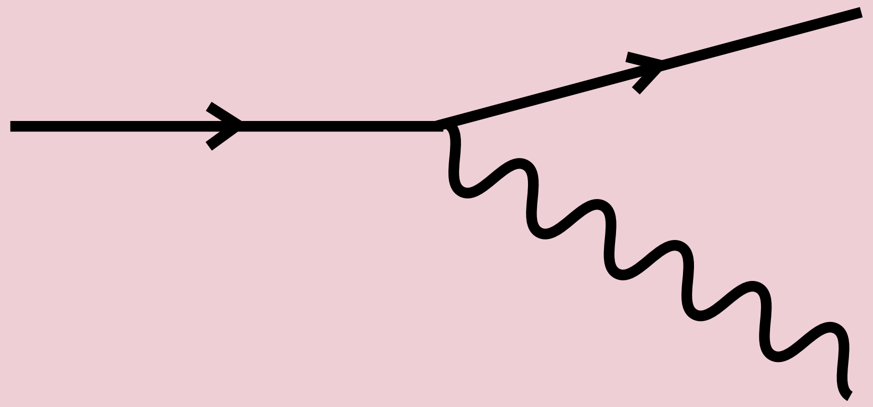
QCD



$\mu^+\mu^-$

$\mathcal{O}(1-10)$ TeV

Electroweak



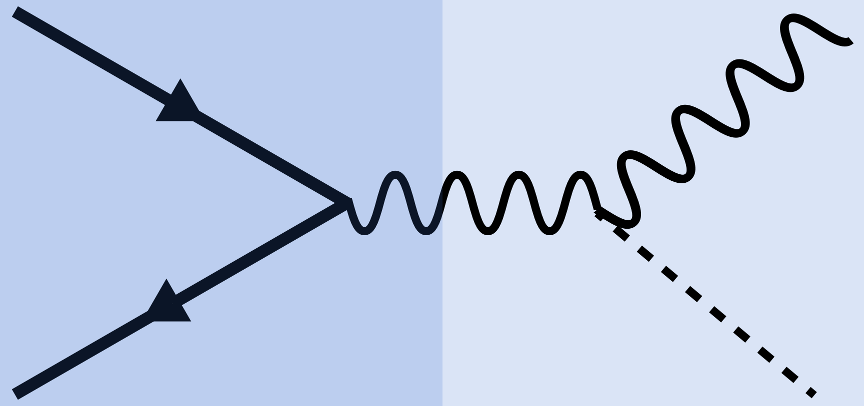
e^+e^-

Circular *Linear*

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs



Comparison of Future Colliders

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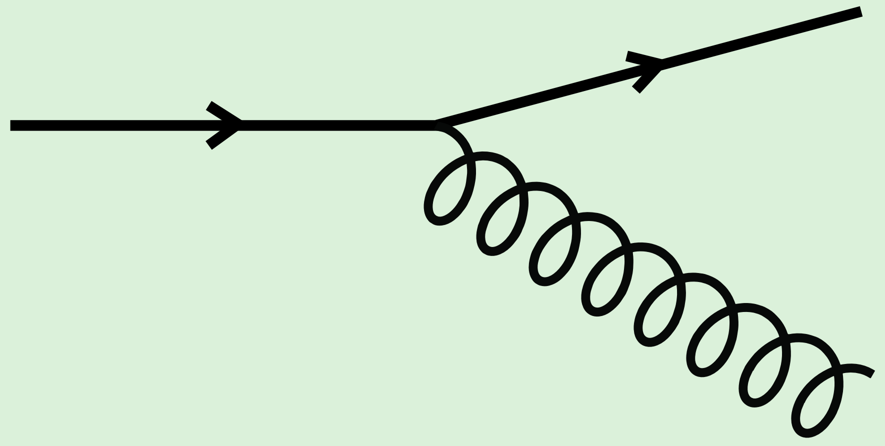
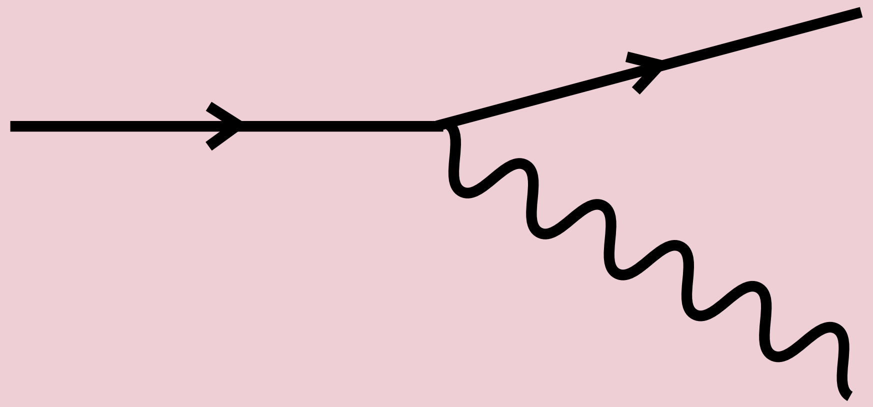


Pro
High energy, known

$\mu^+\mu^-$

$\mathcal{O}(1-10)$ TeV

Electroweak



Pro
High energy & precision

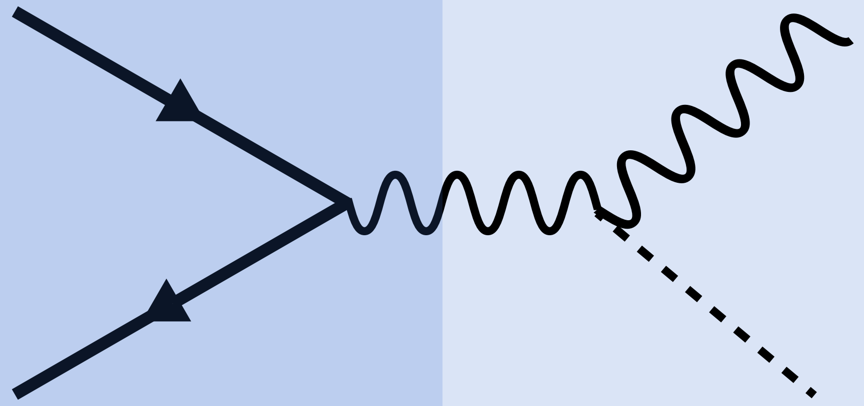
e^+e^-

Circular | *Linear*

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs



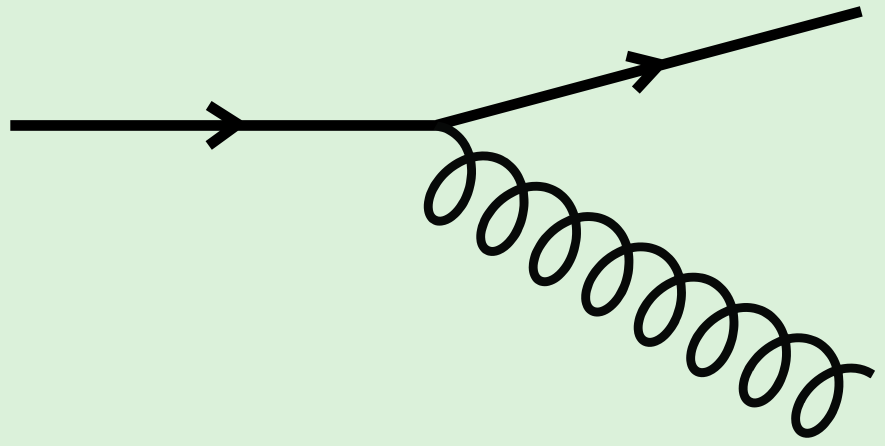
Pro
Precision, known, upgrades

Comparison of Future Colliders

pp

$\mathcal{O}(100)$ TeV

QCD



Pro

High energy, known

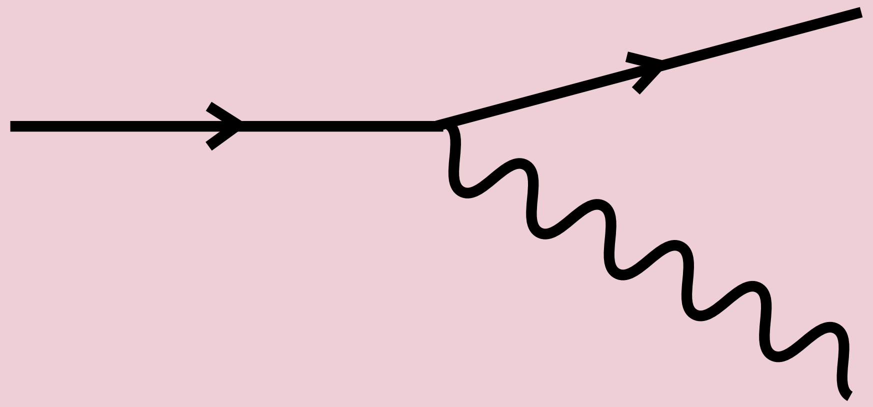
Con

Far future, new technology

$\mu^+\mu^-$

$\mathcal{O}(1-10)$ TeV

Electroweak



Pro

High energy & precision

Con

Undemonstrated technology

(Muons decay, muon cooling)

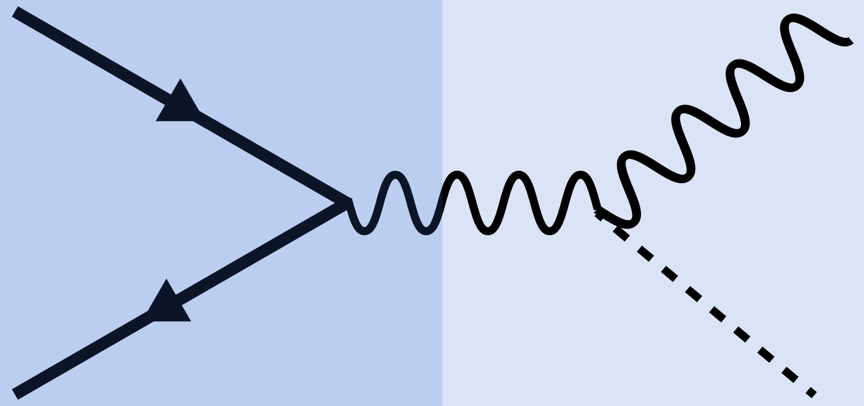
e^+e^-

Circular | *Linear*

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs



Pro

Precision, known, upgrades

Con

Low Energy, *Funding Uncertain*

ARE MUON COLLIDERS AN OPTION?

We are at the stage of R&D, but no showstoppers are identified.

Muons would be the first unstable particle to be accelerated and collided

Subsystems: Costs and Risks *2024

	Approx. % of the Total Cost	Approx. Luminosity Risk Factor
Proton Driver and Targetry	15 - 20 %	10^{1-2}
Muon Cooling	10 - 15 %	10^{3-4}
Acceleration	30 - 60 %	10^{1-2}
Collider	25 - 40 %	10^{0-1}
TOTAL	**12 - 18 B$** *ITF?	**10^{5-9}**

Aug 08, 2025 Vladimir SHILTSEV 5

V. Shiltsev

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Aug 08, 2025 Vladimir SHILTSEV 5

→

Subsystems: Costs and Risks *2025

	Approx. %* Total Cost	Subsystem Cost Risk	Collider Energy Risk	Avg. Risk Luminosity
p-Driver&Targetry	15 - 20 %	~40 %	-	x 1/20
Muon Cooling	10 - 15 %	~20 %	-	x 1/50
Acceleration	30 - 60 %	~20 %	~20%	x 1/10
Collider	25 - 40 %	~10 %	~30%	x 1/10
TOTAL	**17±4 BCHF** *IMCC	**±30%** *IMCC	**~30 %**	**$10^{2.5-5}$**
TOTAL* (2024)	12 - 18 B\$ *ITF?	-	-	10^{5-9}

V. Shiltsev

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Linear vs. circular; hadrons vs. leptons; high-energy vs. precision

What are the relative strengths of these options?

Leptons are fundamental; hadrons push energy frontier

What is the reach of these machines for BSM physics?

EFT precision probes 1-100 TeV*, energy frontier directly probes 10* TeV

BSM At Colliders

Note: this talk is *not* meant to be a laundry list of completed studies at machines that do not yet exist

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It *is* meant to be an introduction to the physics case of potential machines

The goal is to get members of the community who might not often think about colliders (*you all*) to think about what the *physics priorities are* and *how colliders can achieve them*

BSM Physics at Precision Machines

Possible precision machines

Circular e^+e^- Collider

e.g. FCC-ee/CEPC

6×10^{12} Z

240 GeV, 10 ab^{-1}

$\sim 2m_t$, ~ 1 ab^{-1}

Linear e^+e^- Collider

e.g. CLIC/ILC/C^3

250/380/550 GeV, ~ 1 ab^{-1}

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Generation-dependent couplings

Exotic Higgs Phenomena

Dark Photons

Exotic/Rare EW Phenomena

EFT Sensitivity to UV Physics

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Dark Photons

EFT

} Let's explore these with the lens of *motivated* BSM questions

BSM Physics at Precision Machines

What is the UV nature of the Higgs?

Generation-dependent couplings

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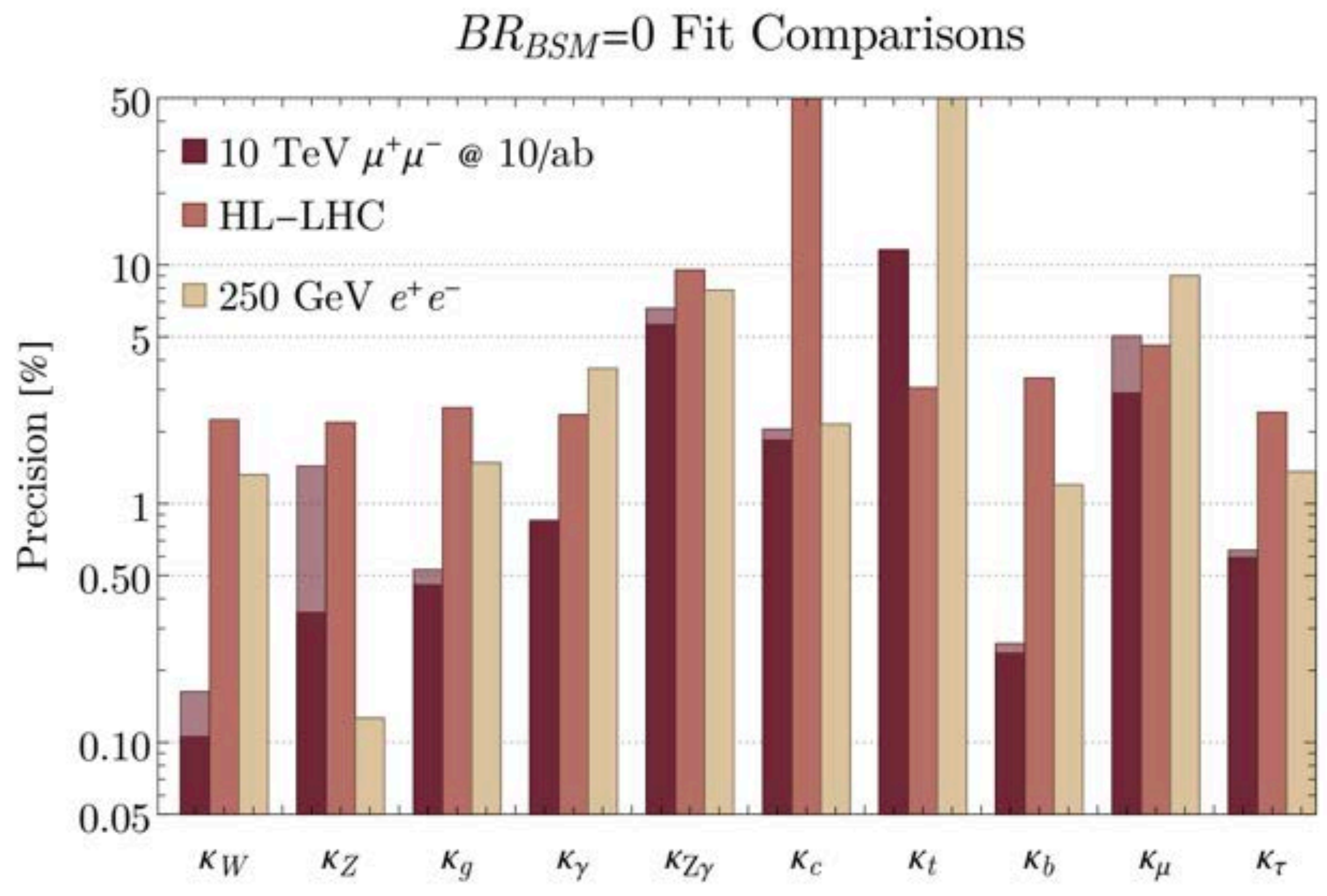
Exotic/Rare EW Phenomena

Dark Photons

EFT

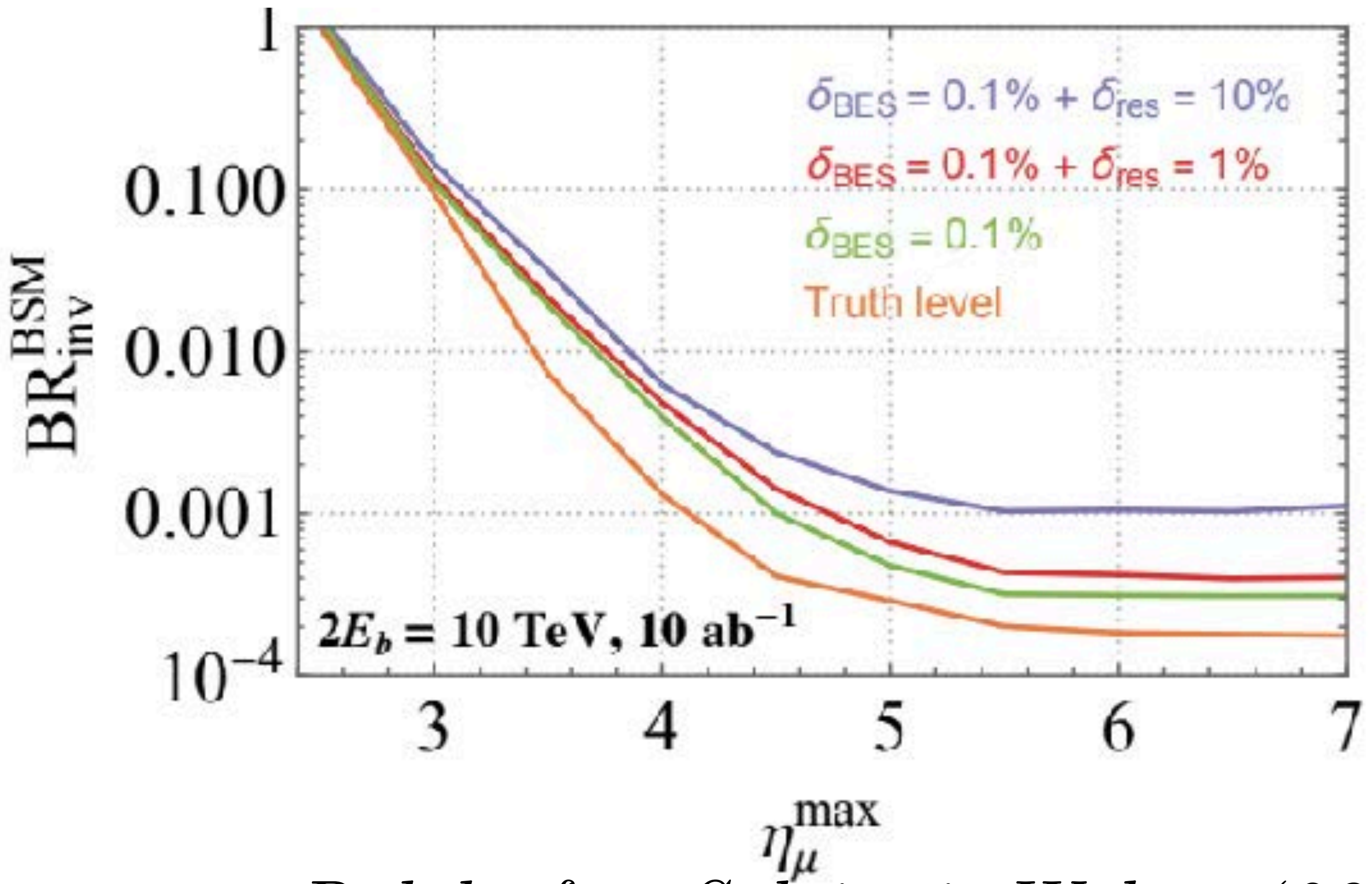


Forslund & Meade '23

κ-framework comparison

H → *inv*

Muon Collider



Ruhdorfer, Salvioni, Wulzer '23
Li, Liu, Lyu '24

BSM Physics at Precision Machines

Generation-dependent couplings

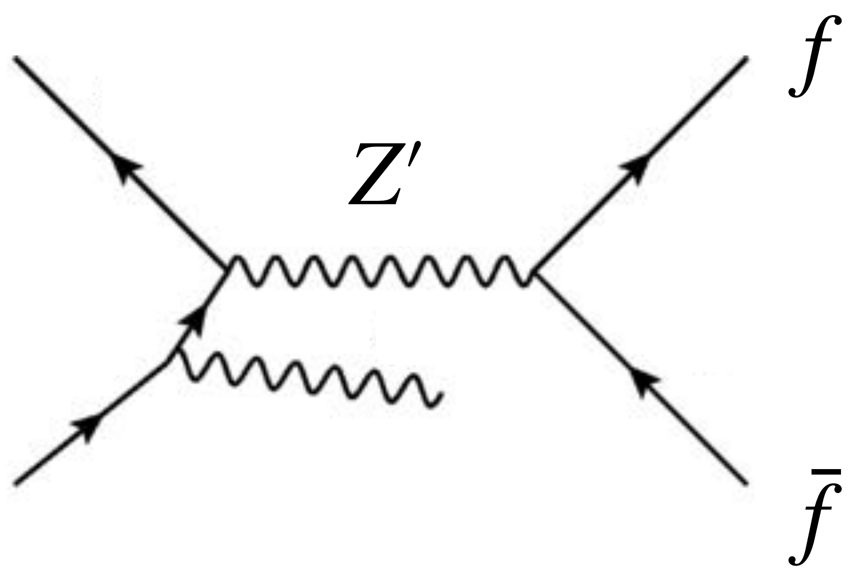
Exotic Higgs Phenomena

Exotic/Rare EW Phenomena

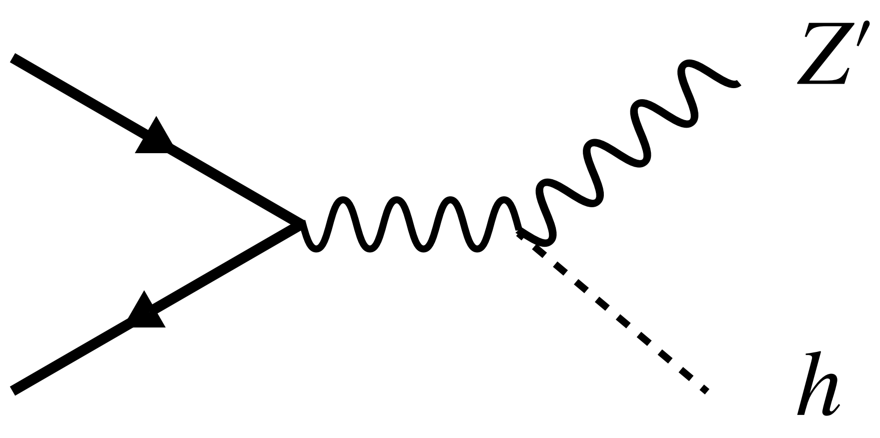
Dark Photons

EFT

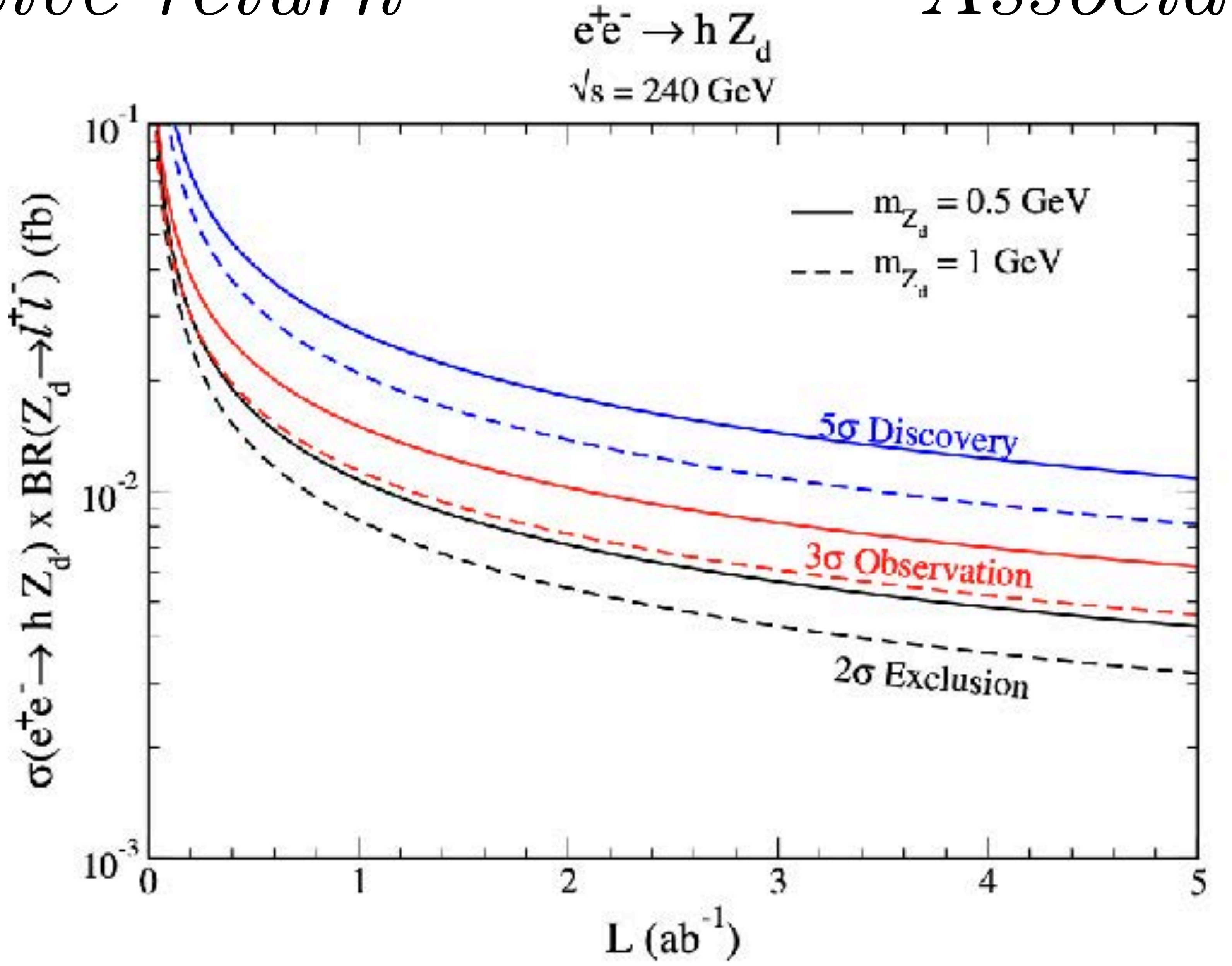
How does the SM couple to DM?



Radiative return



Associated Production



Giffin, Lewis, Zhang '20

BSM Physics at Precision Machines

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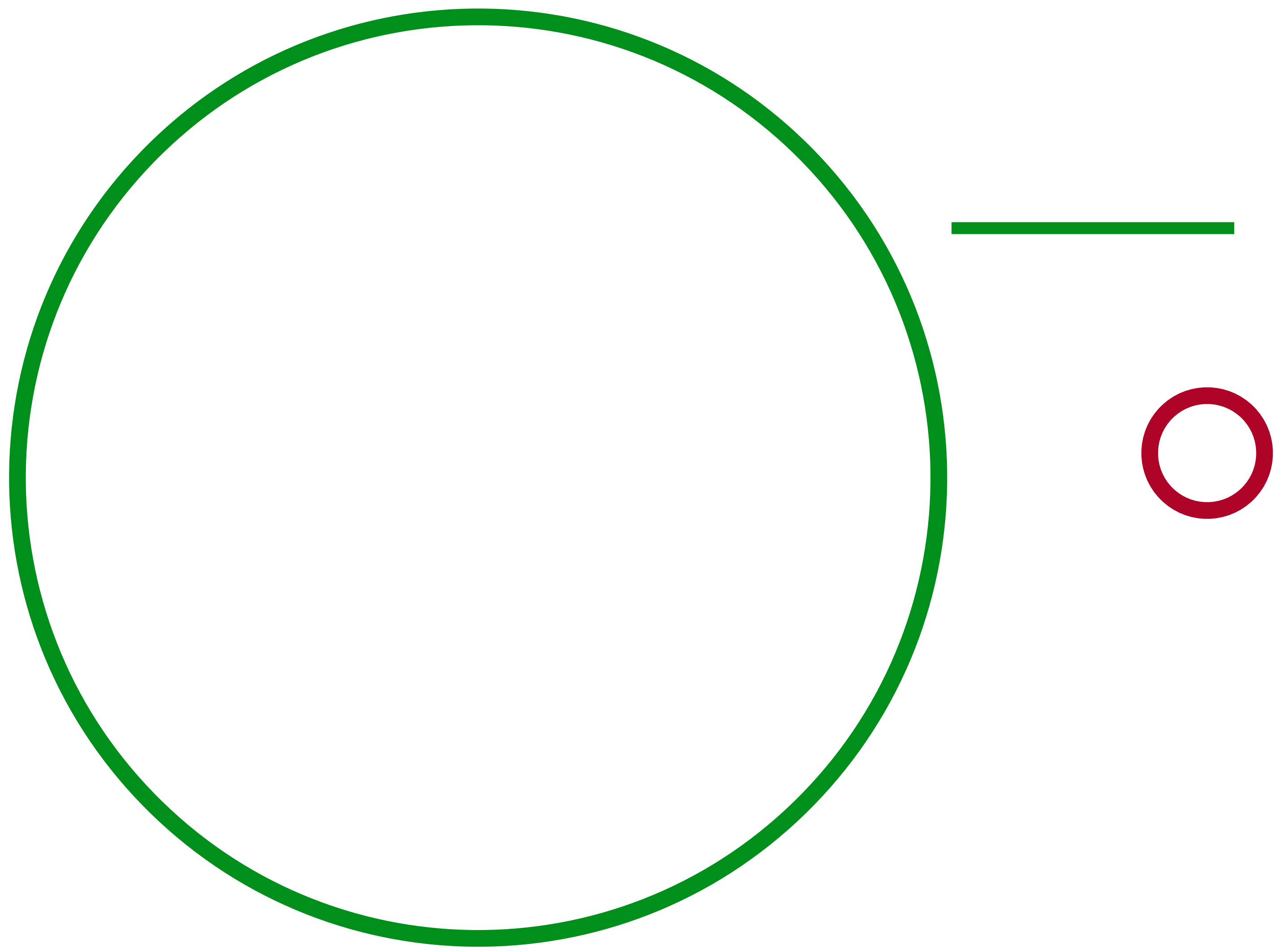
EFT



With low-energy precision, likely scenario is not *discovery* but an *indicator* $\Longrightarrow$

BSM Physics at Energy-Frontier Machines

Possible energy-frontier machines

Hadron Collider

e.g. FCC-hh/SppC

$\mathcal{O}(100)$ TeV, 10 ab^{-1}

Linear e^+e^- Collider

e.g. CLIC/ILC/C^3

$1 - 3$ TeV ~ 1 ab^{-1}

Muon Collider

10 TeV, 10 ab^{-1}

Heavy New Physics

Energy $\Leftrightarrow$ Precision

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Heavy New Physics

Energy ⇔ Precision

BSM Physics at Energy-Frontier Machines

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Hadron Collider	Linear e^+e^- Collider	Muon Collider
e.g. FCC-hh/SppC	*e.g. CLIC/ILC/C^3*	
$\mathcal{O}(100)$ TeV, 10 ab^{-1}	$1-3$ TeV ~ 1 ab^{-1}	10 TeV, 10 ab^{-1}

Heavy New Physics

Energy ⇔ Precision

Hard to overstate the importance of pushing energy frontier

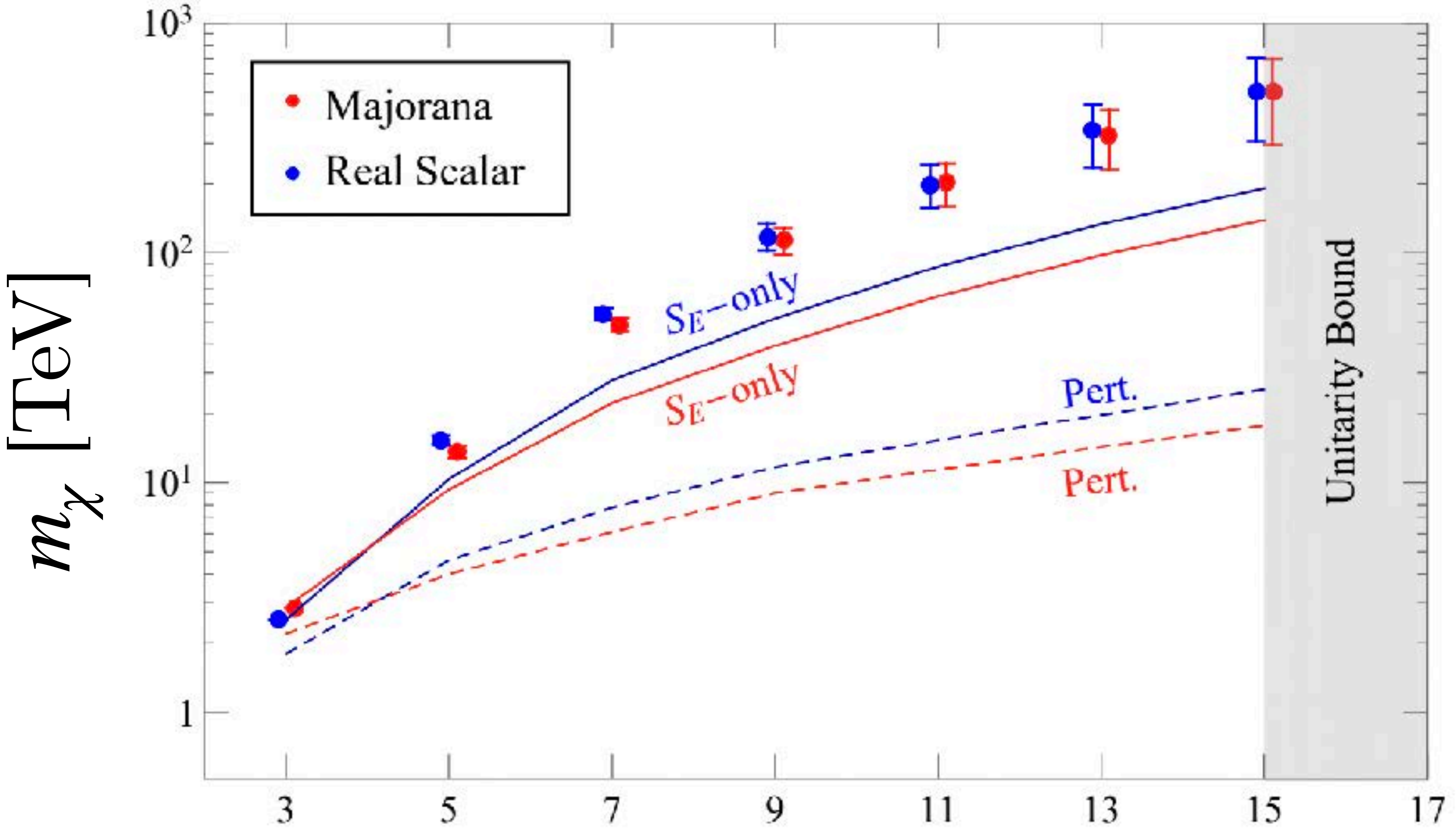
KEY BENCHMARK: WIMP @ FUTURE COLLIDERS

Electroweak multiplets can arise in SUSY scenarios & explain DM abundance

n-plet

$$\begin{pmatrix} \vdots \\ \chi^+ \\ \chi^0 \\ \chi^- \\ \vdots \end{pmatrix}$$

Thermal Mass



EW n-plet	Mass [TeV]
$2_{1/2}$	1.08
3_0	2.86
$4_{1/2}$	4.8
5_0	13.6
5_1	9.9
$6_{1/2}$	31.8
7_0	48.8
9_0	113

Predicted at $\sim$ TeV scale

$\Delta m \sim \mathcal{O}(100)$ GeV

Disappearing track

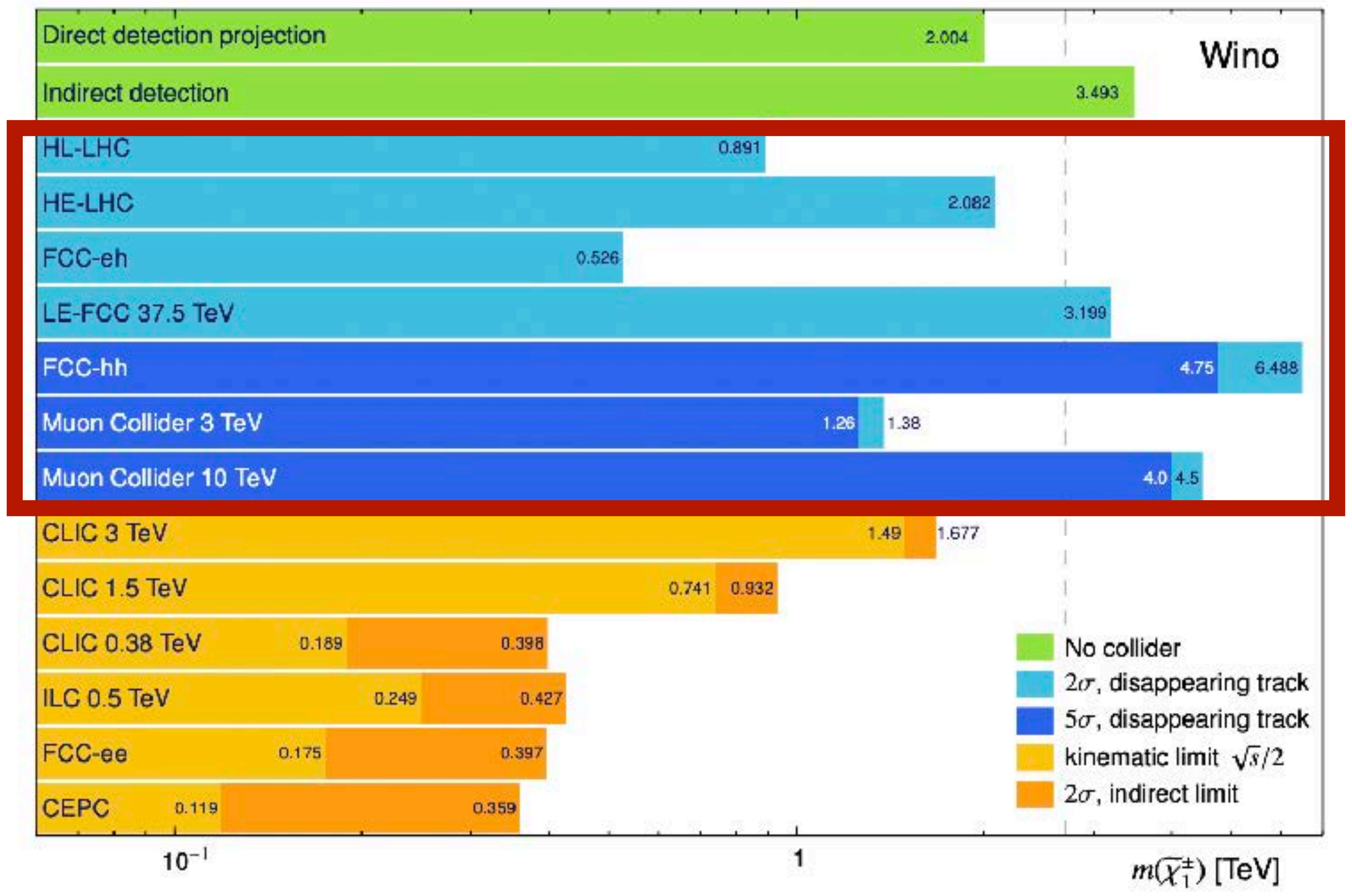
Han, Liu, Wang, Wang '20 *Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22*

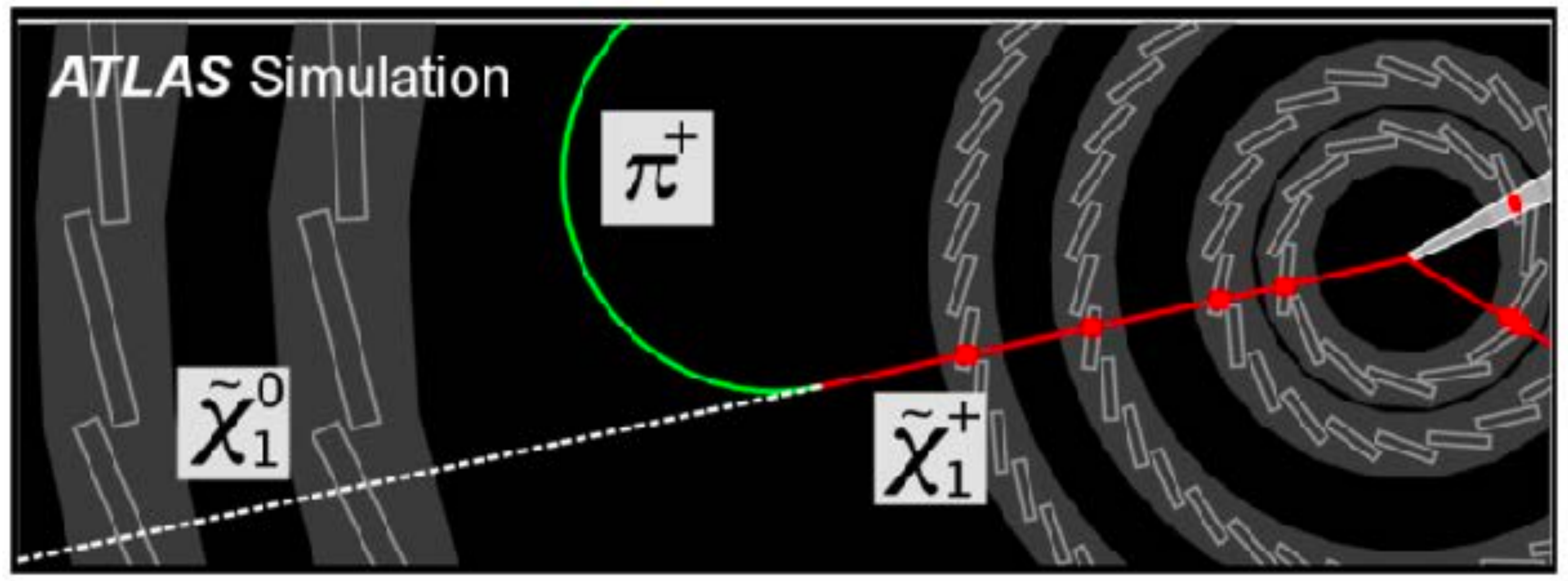
Key Benchmark: WIMP @ Future Colliders

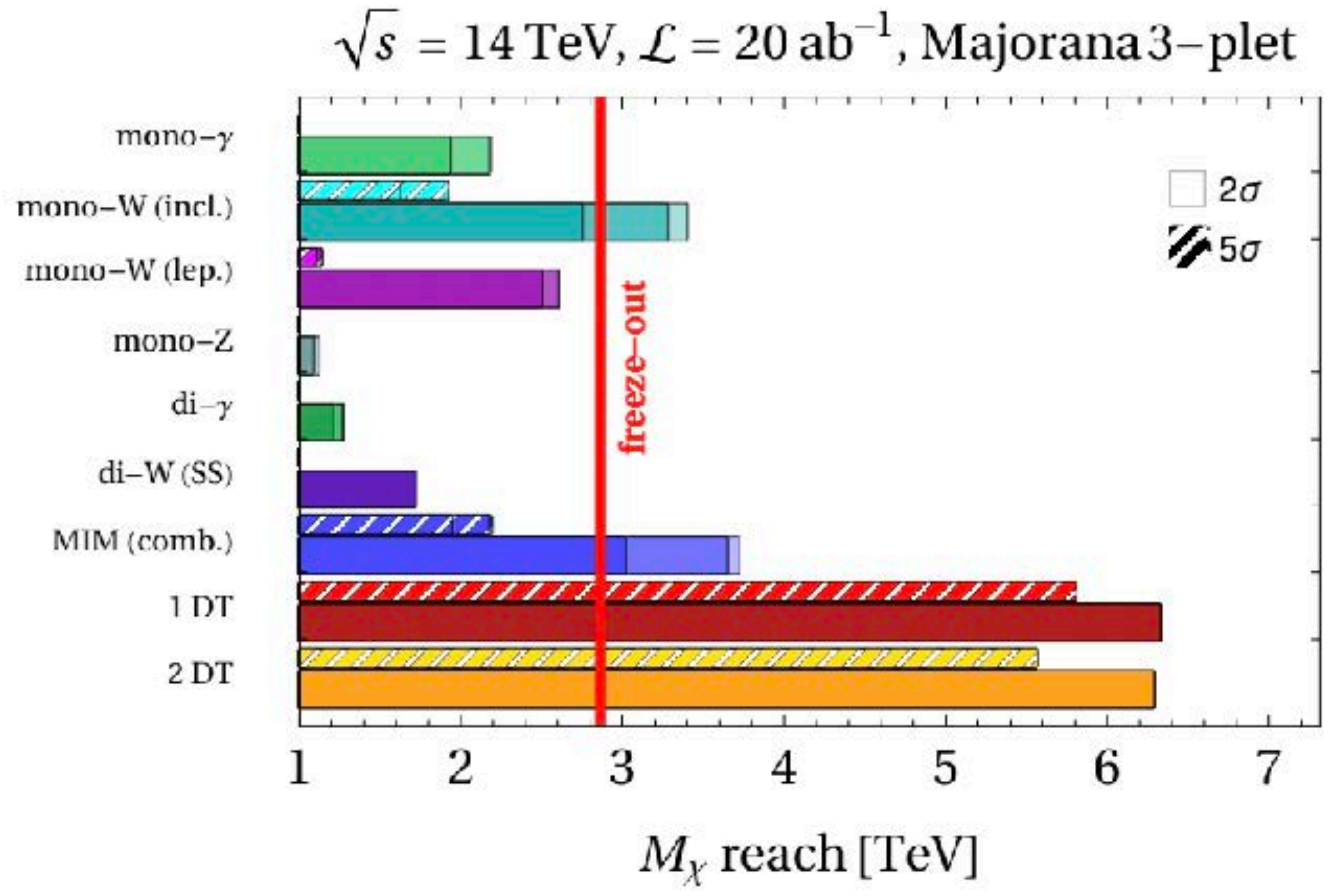
Energy frontier machines can definitively probe thermal DM scenarios

n-plet

$$\begin{pmatrix} \vdots \\ \chi^+ \\ \chi^0 \\ \chi^- \\ \vdots \end{pmatrix}$$







Saito, Svada, Terashi, Asai '19

Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

R. Capdevilla, F. Meloni, R. Simoniello, J. Zurita 23

Are there other options?

Remember: future colliders are at varying degrees of maturity and engineering... still room for physics input

The future is flexible

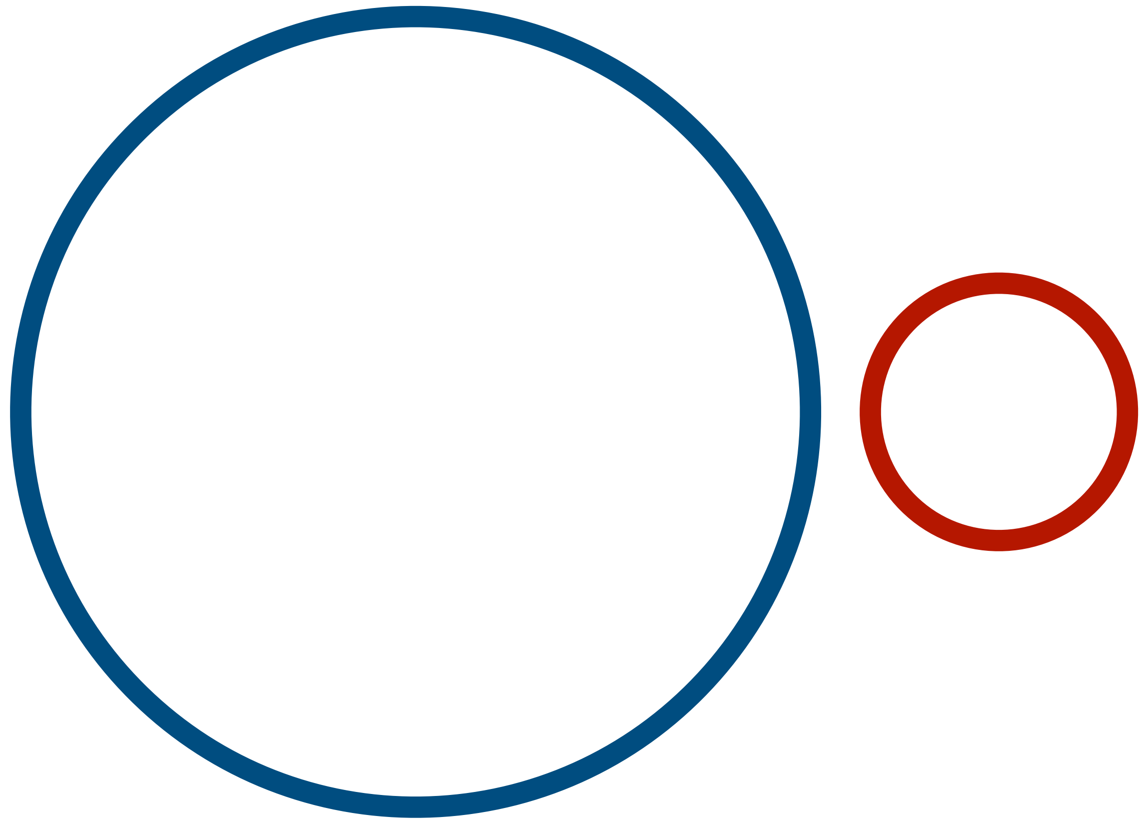
Are there other options?

Remember: future colliders are at varying degrees of maturity and engineering... still room for physics input

The future is flexible

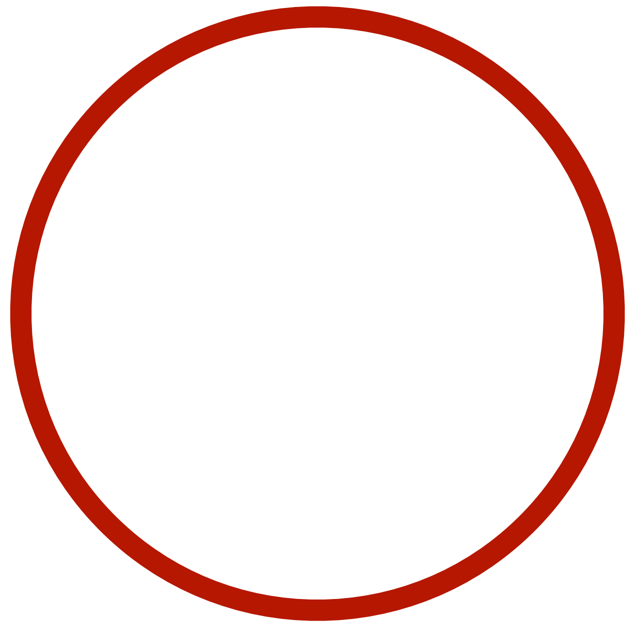
FCC-ee, low-lumi MuC

Precision from FCC-ee
10 TeV at 1 ab^{-1} MuC



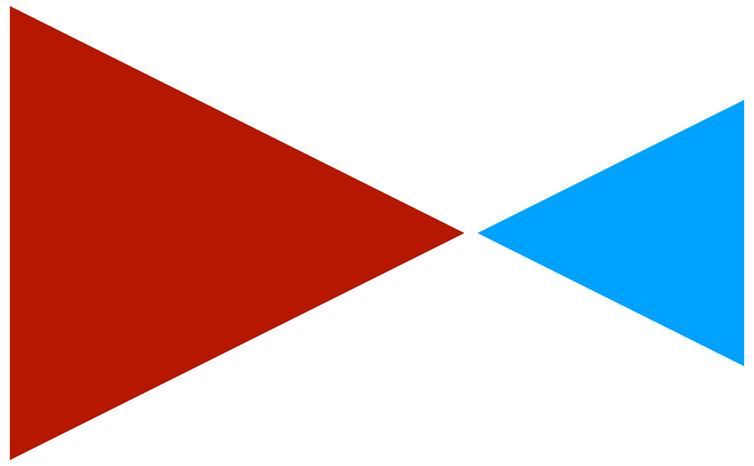
LHC Tunnel MuC

30 TeV



Asymmetric MuC

$e^-\mu^+$ Collider
VBF Production



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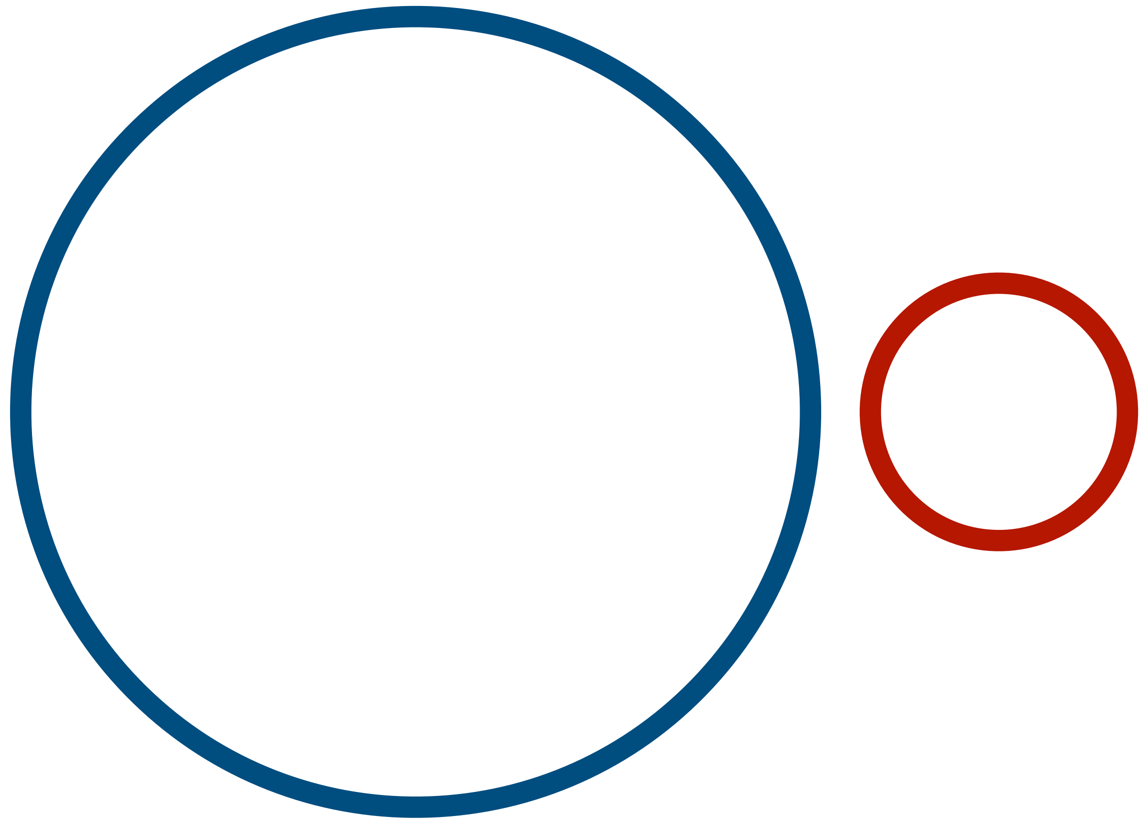

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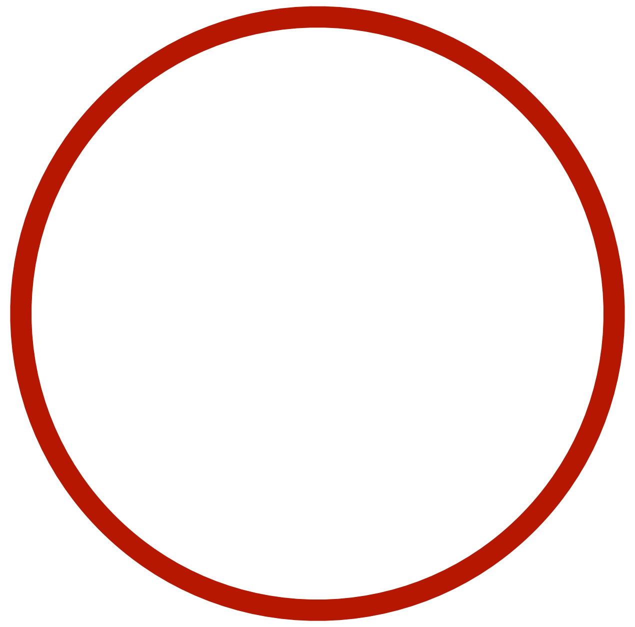

Asymmetric MuC

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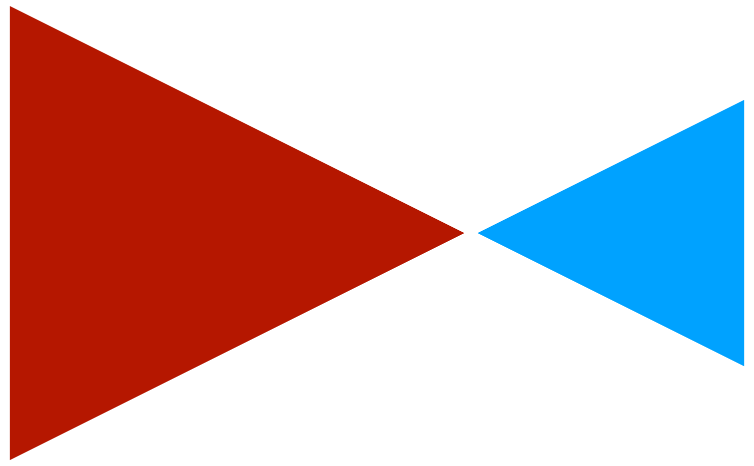
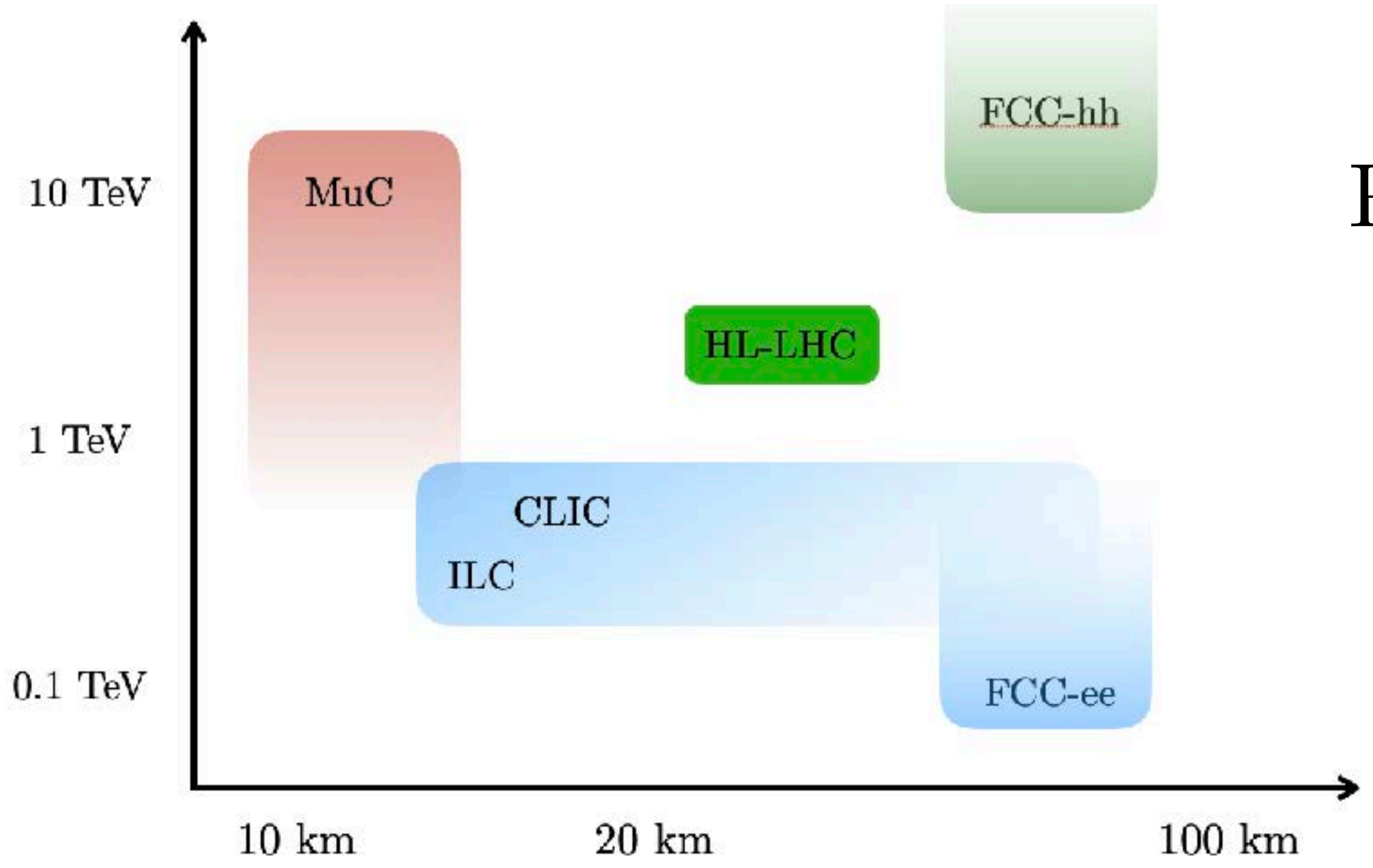


And more!

Outlook

Colliders are complementary to cosmological or astronomical experiments

Clean laboratory setting can break redundancy of model possibilities



Precision & energy probe different models

Particle physics is in need of *direction*; colliders can provide empirical evidence to motivate theory efforts

The time to build the physics case is now.

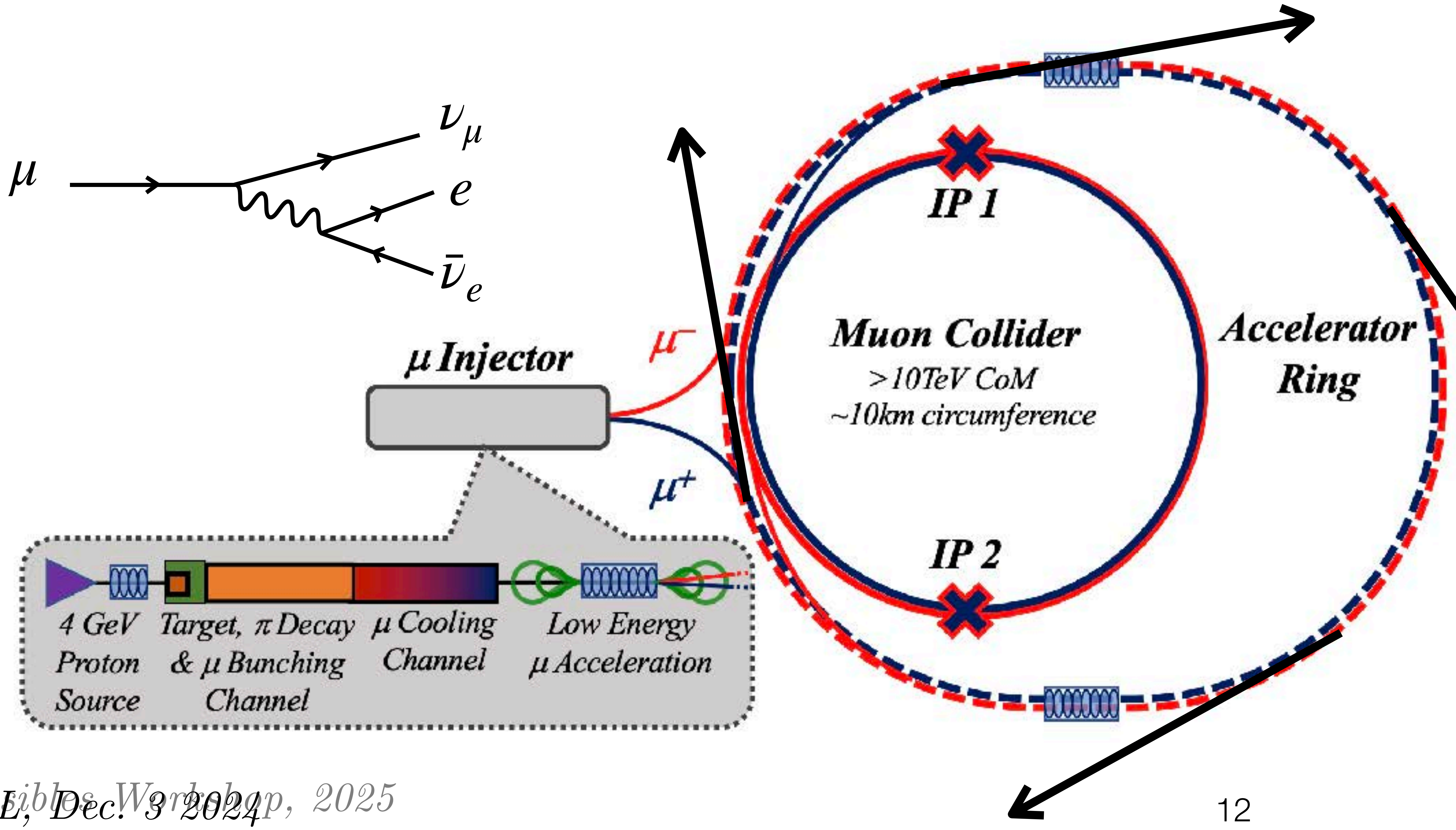
Backup Slides

Challenges of MuC

Muons Decay

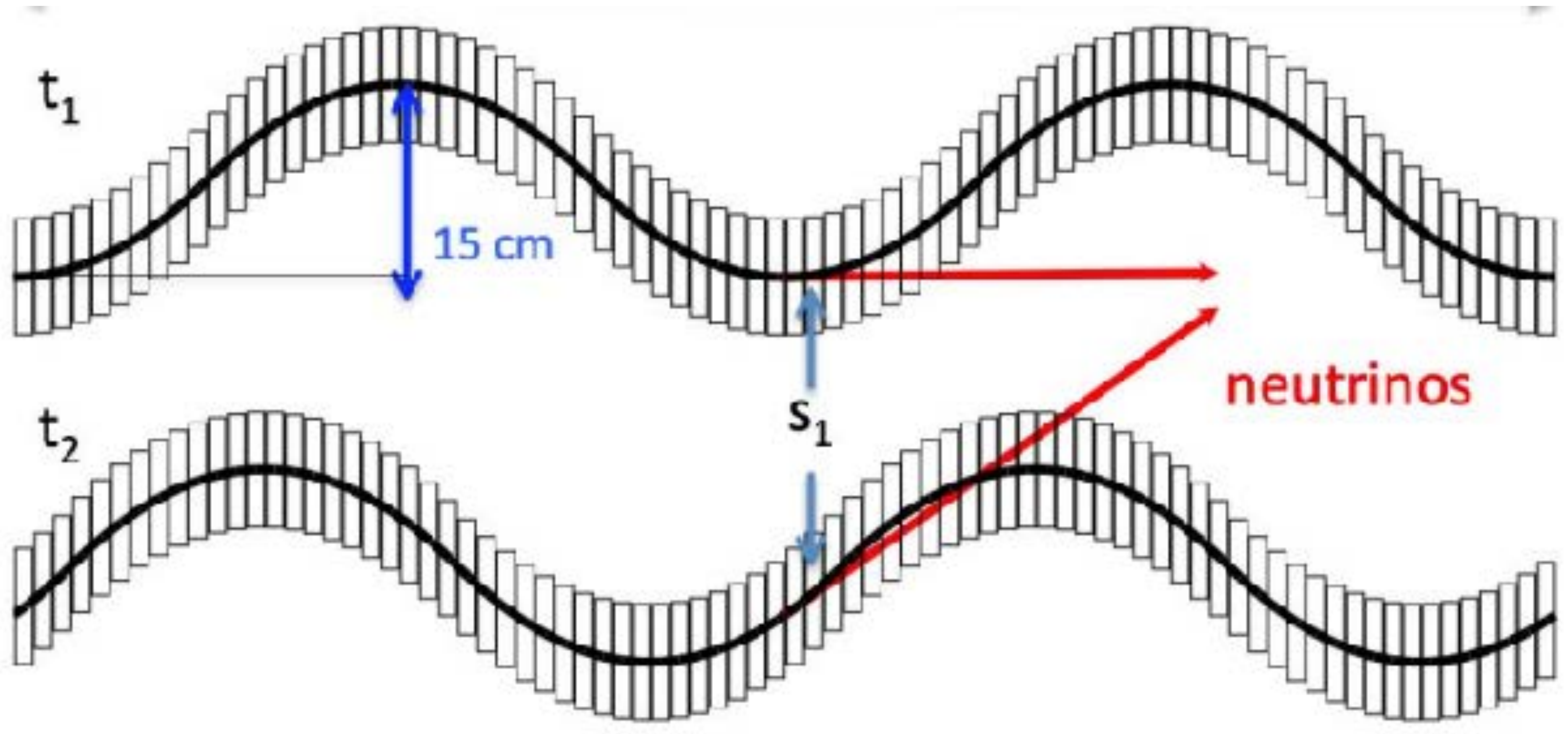
Beam-induced background from decay products

Mitigated with timing, kinematics, and shielding



Neutrinos interact at high energy

Make ring deep & diffuse the beam



Sketch credit: D. Schulte

Cesarotti

Muon Collider Status

1960-80s

Muon collider first ideas

2011-2014

Muon Accelerator Program (MAP)

2019

Muon Ionization Cooling Demonstrated

2020

EU Strategy: Set up collaboration

International MUON Collider Collaboration

2023

P5 Outcome: *"This is our muon shot"*

2026

EU Strategy

R&D

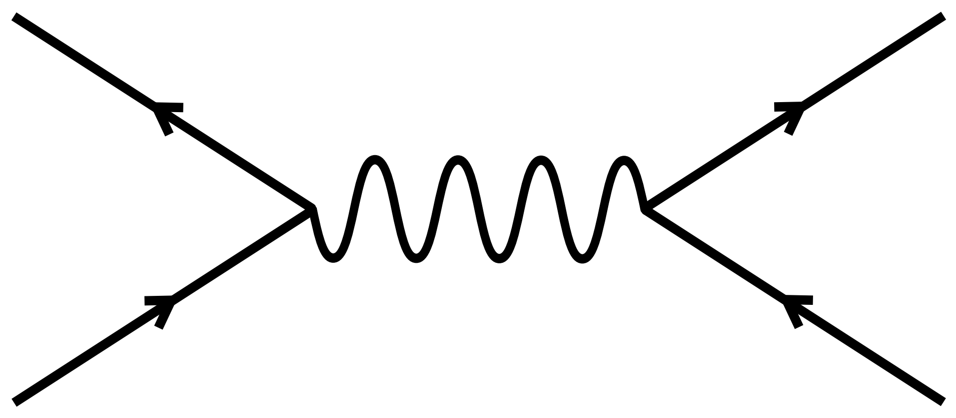
$\sim$ 50M/year $\times$ 10 years

Cesarotti

Comparison of Future Colliders

CC $\in$ *Accettura et al, Towards a Muon Collider '23* · ***CC*** $\in$ *IMCC, Interim Report '24*

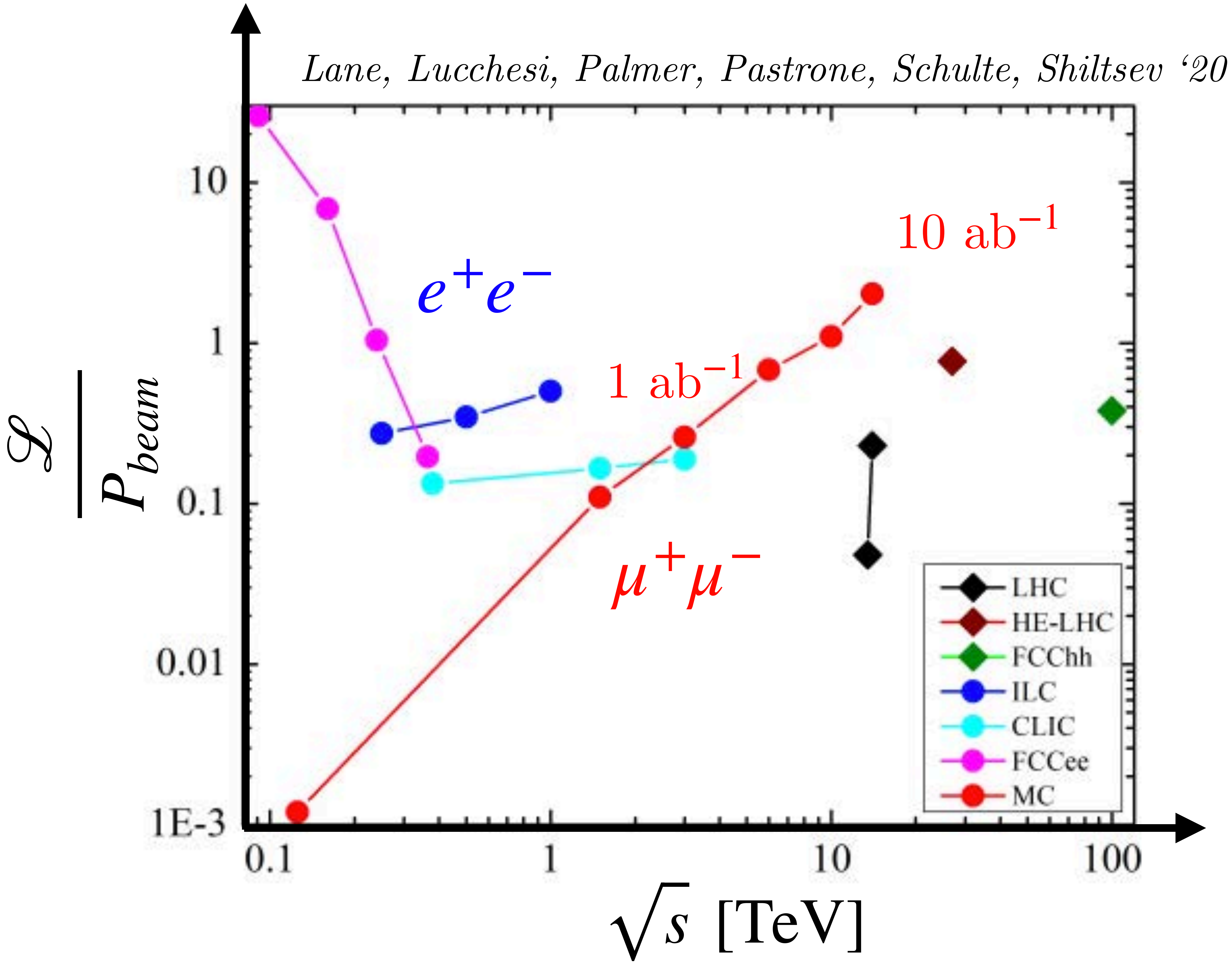
Muon Colliders have *higher* luminosity at higher energy



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

$$\mathscr{L} \sim E^2$$

Linear colliders have $\mathscr{L}/P \sim$ const., *quadratic* E scaling demands *quadratic* power consumption



Challenges of Muon Colliders

Production as tertiary beam

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

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

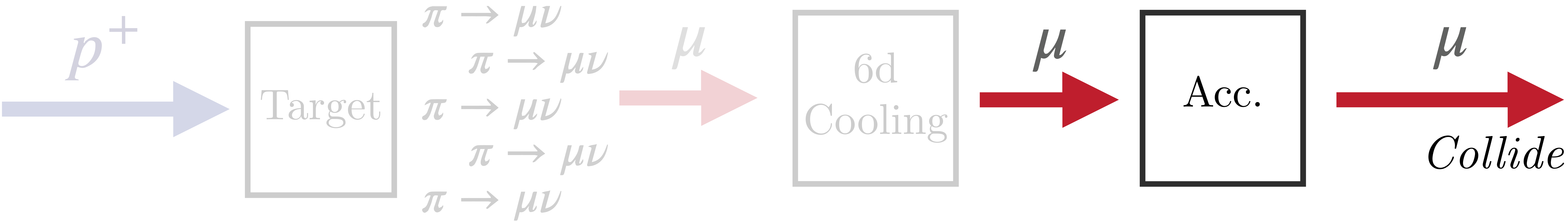
Cooling into single collimated bunch

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

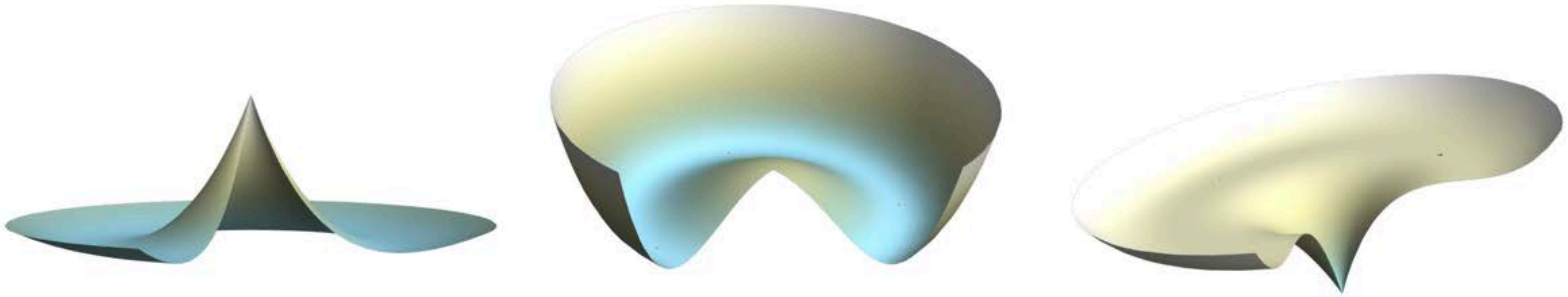
Acceleration and collision

Too quick to ramp up magnets

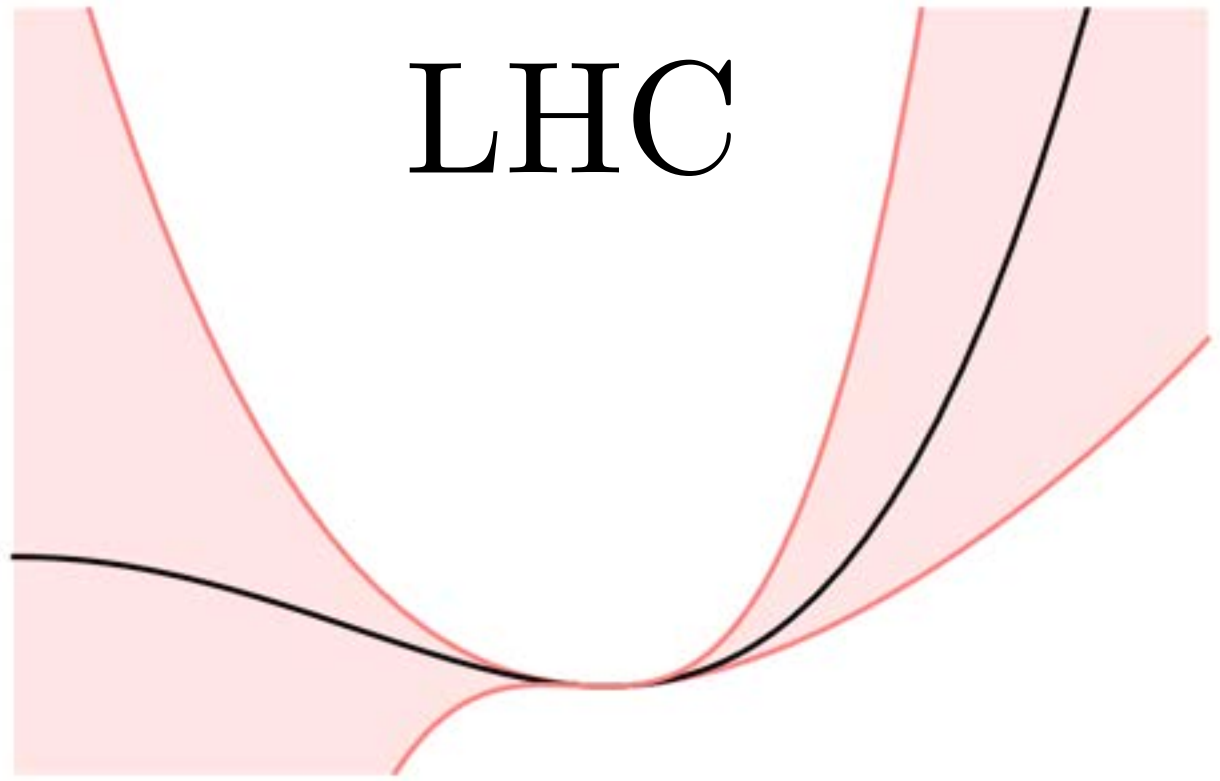
Decay products give beam-induced background



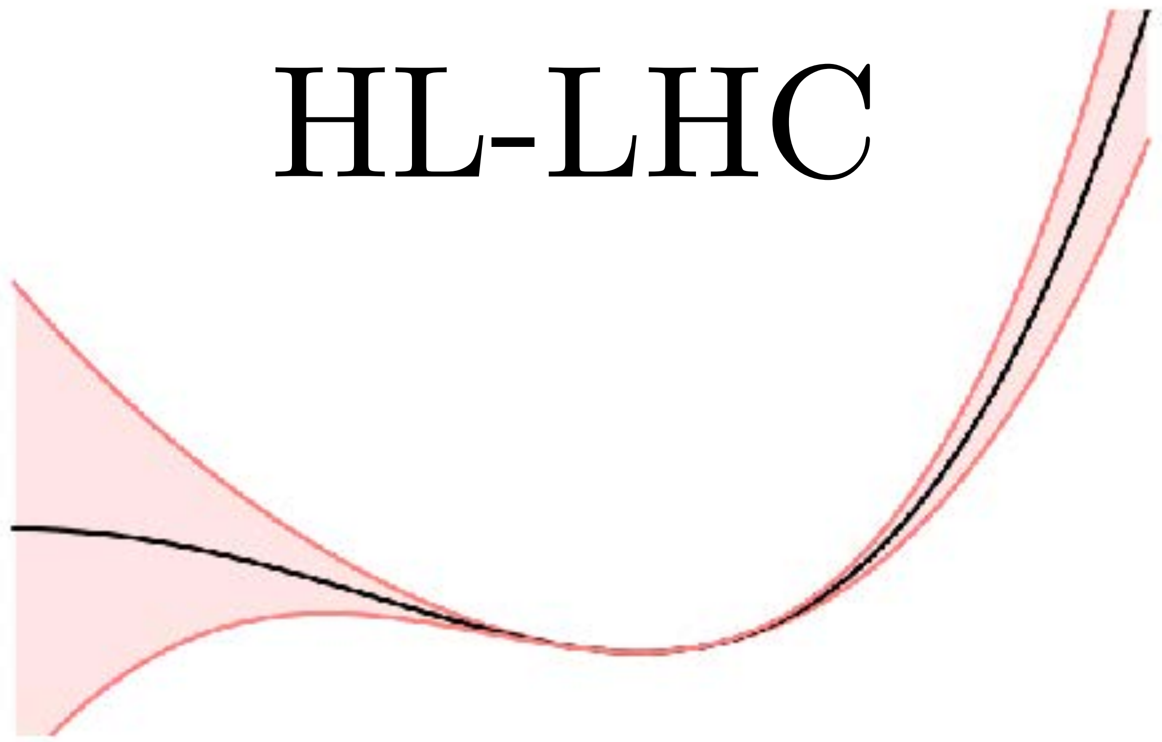
Higgs Potential



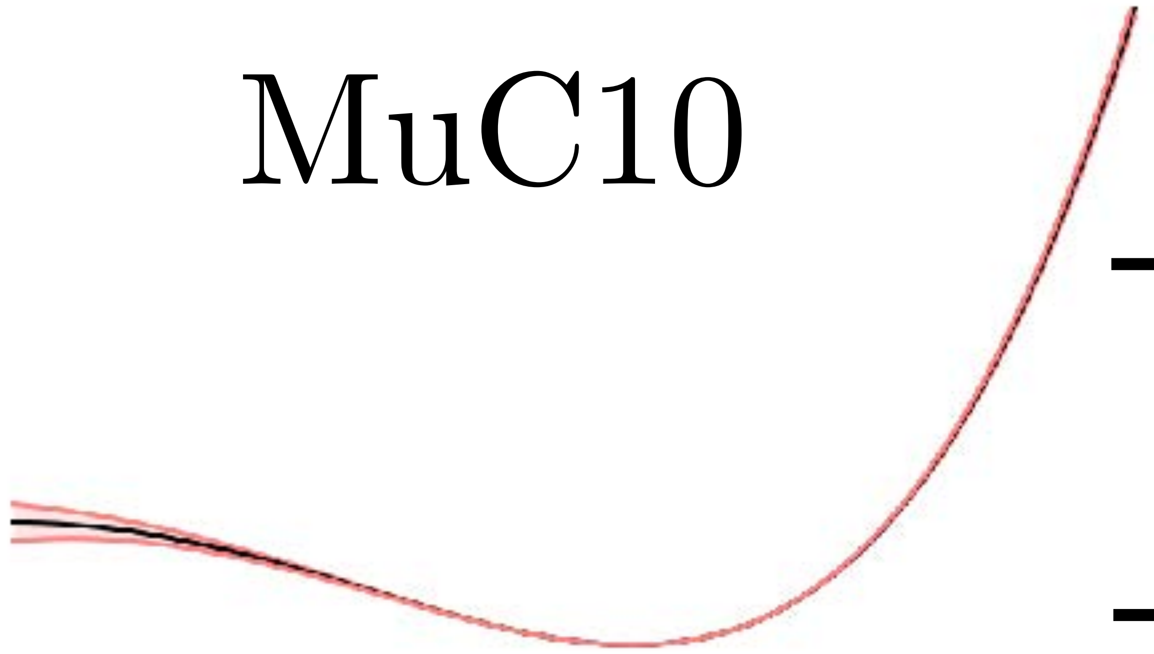
LHC



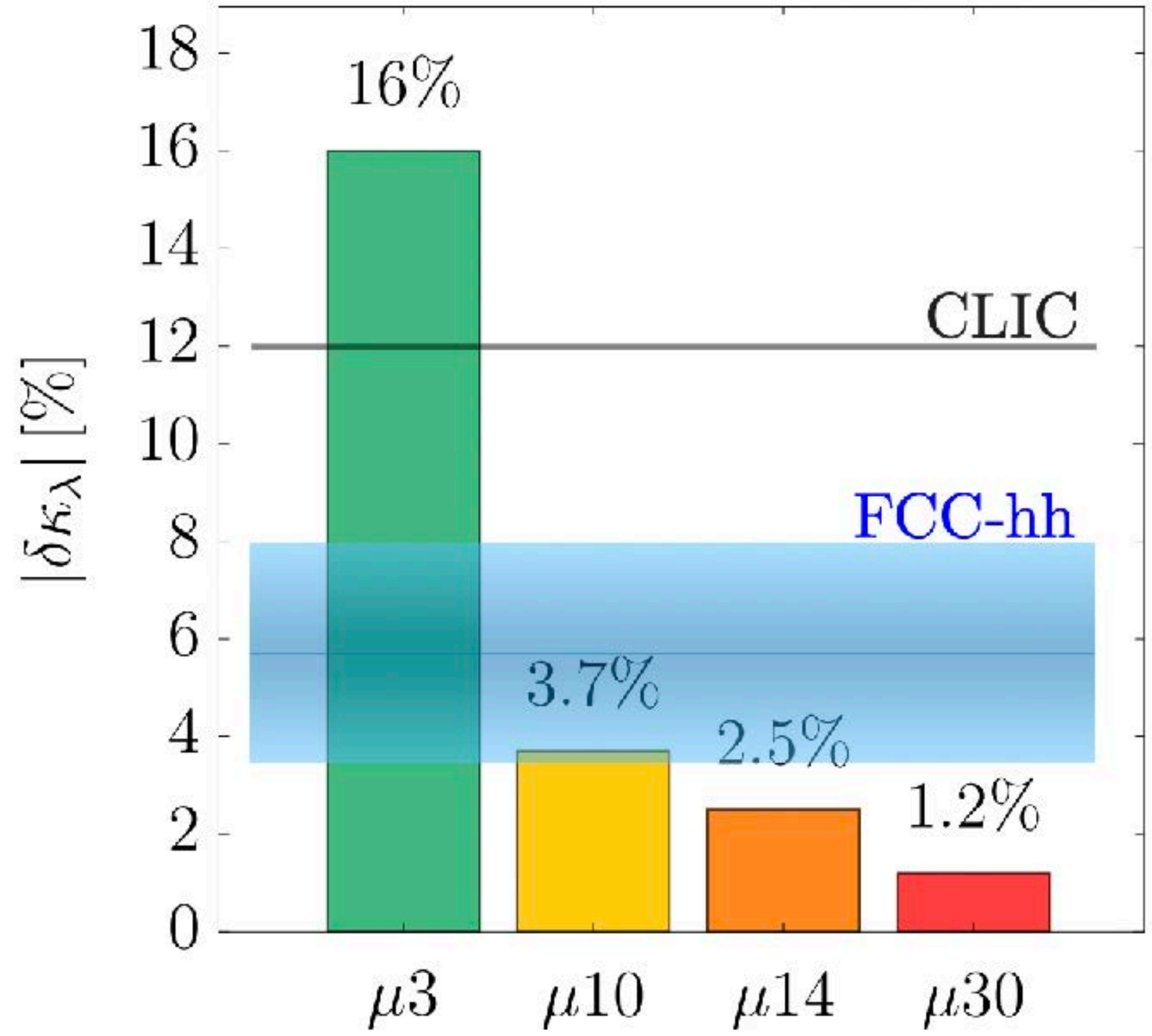
HL-LHC

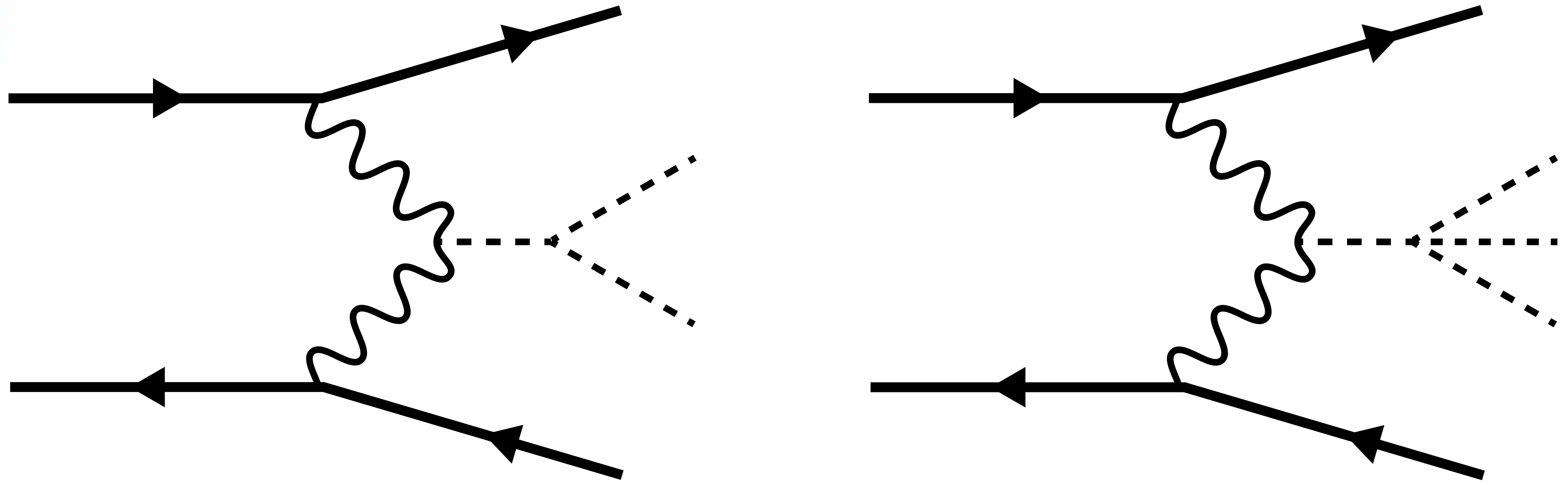


MuC10



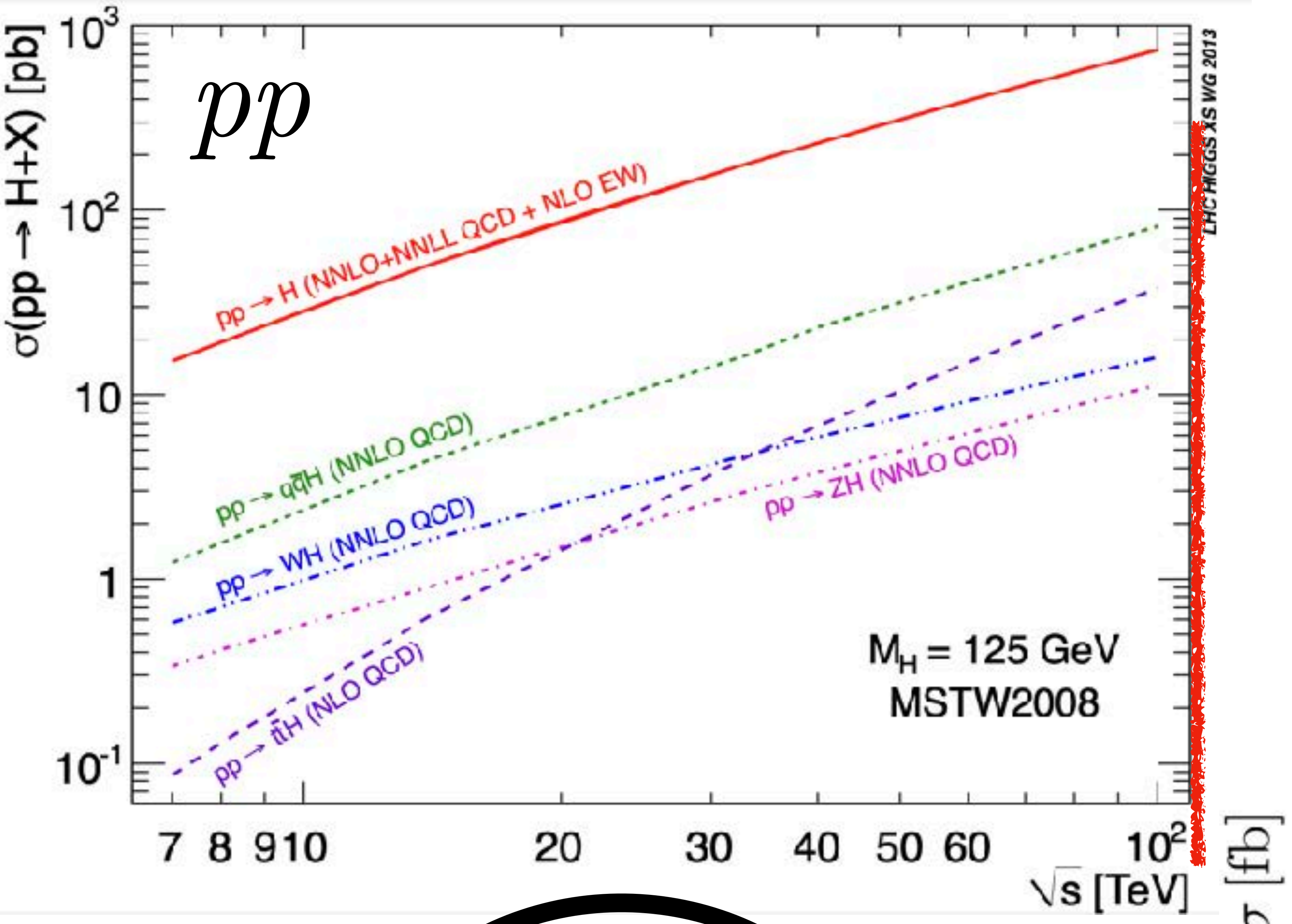
Towards a Muon Collider 23

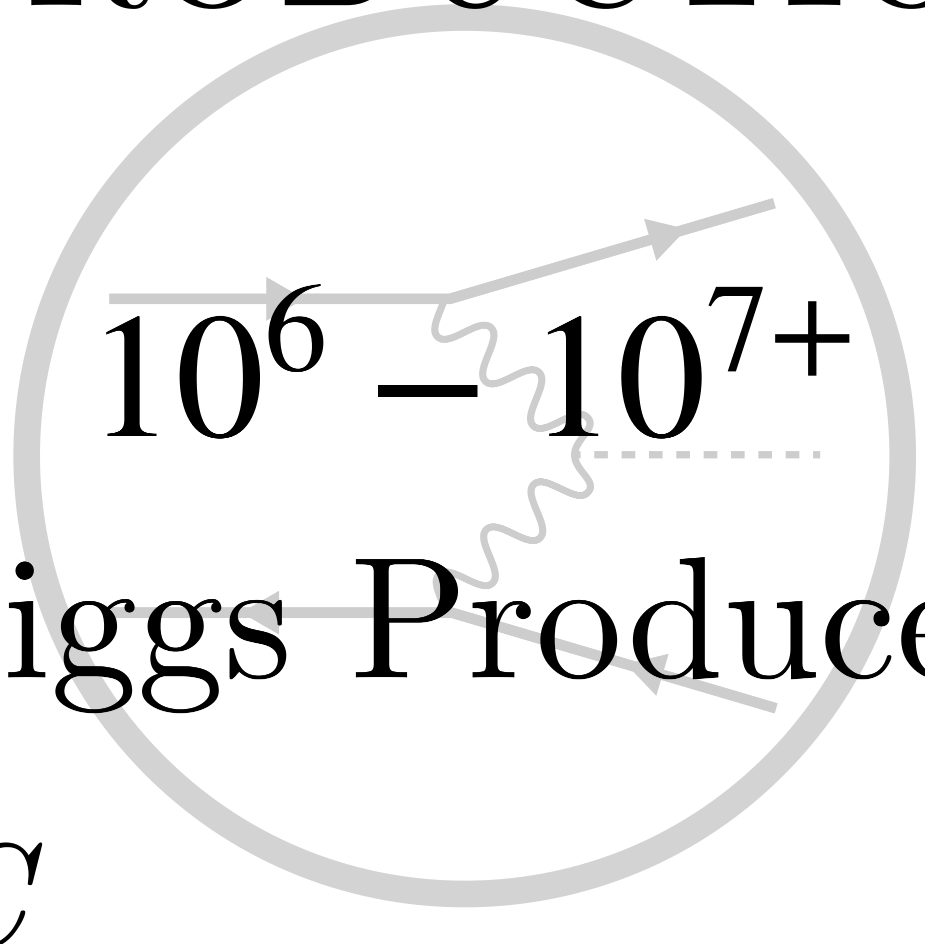




Higgs Production

LHC HIGGS WG



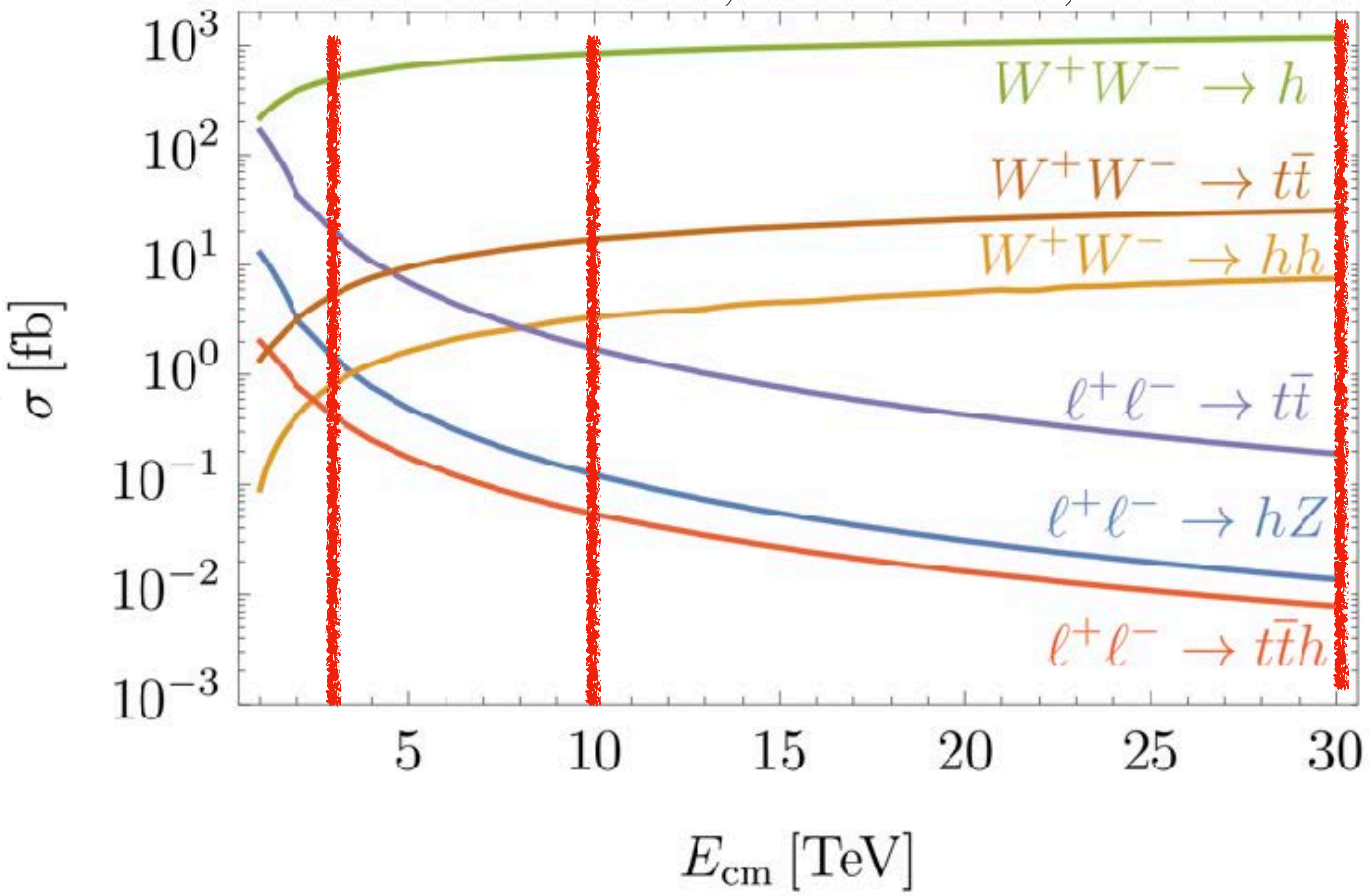


$10^6 - 10^{7+}$

Higgs Produced

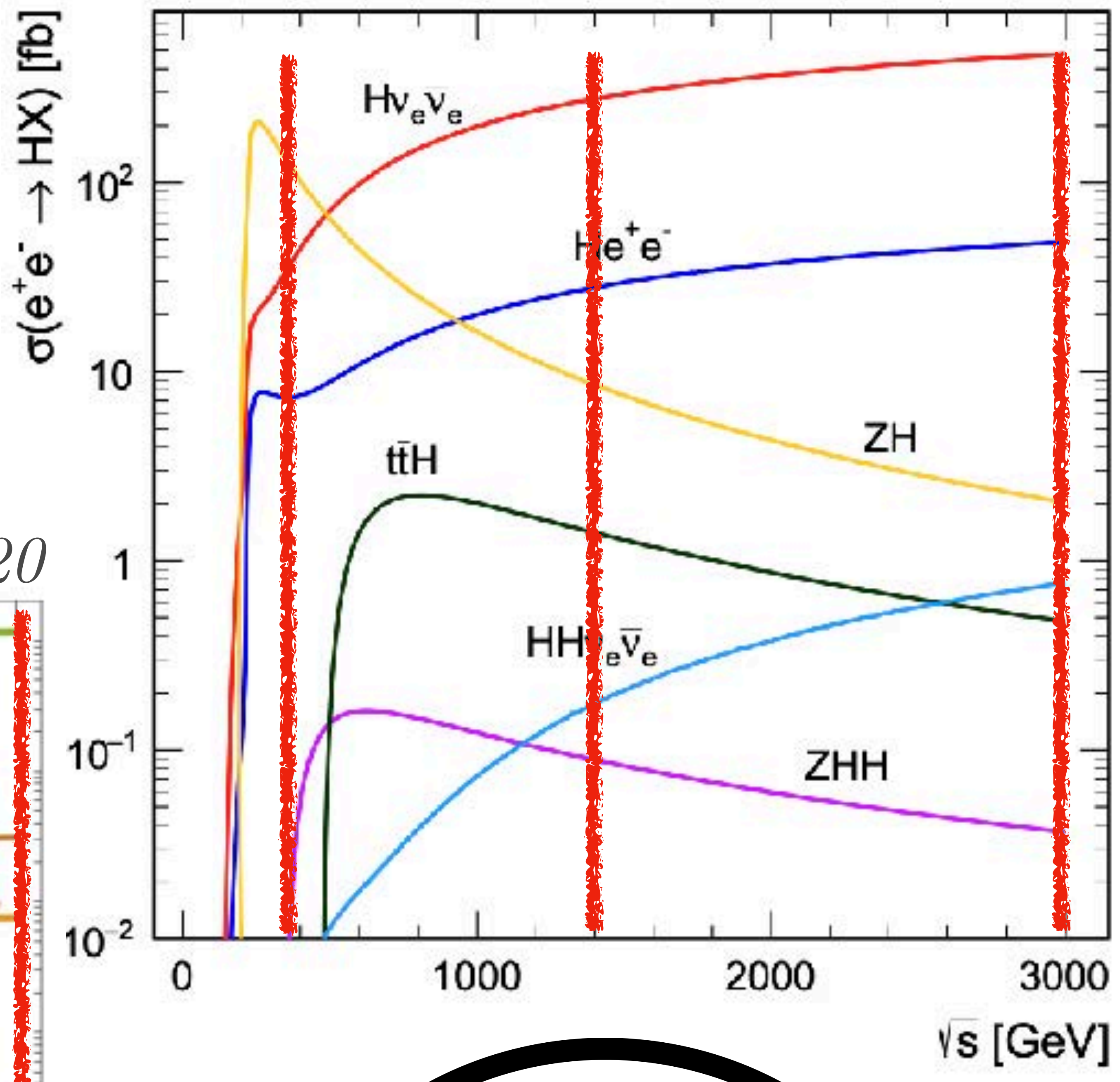
MuC

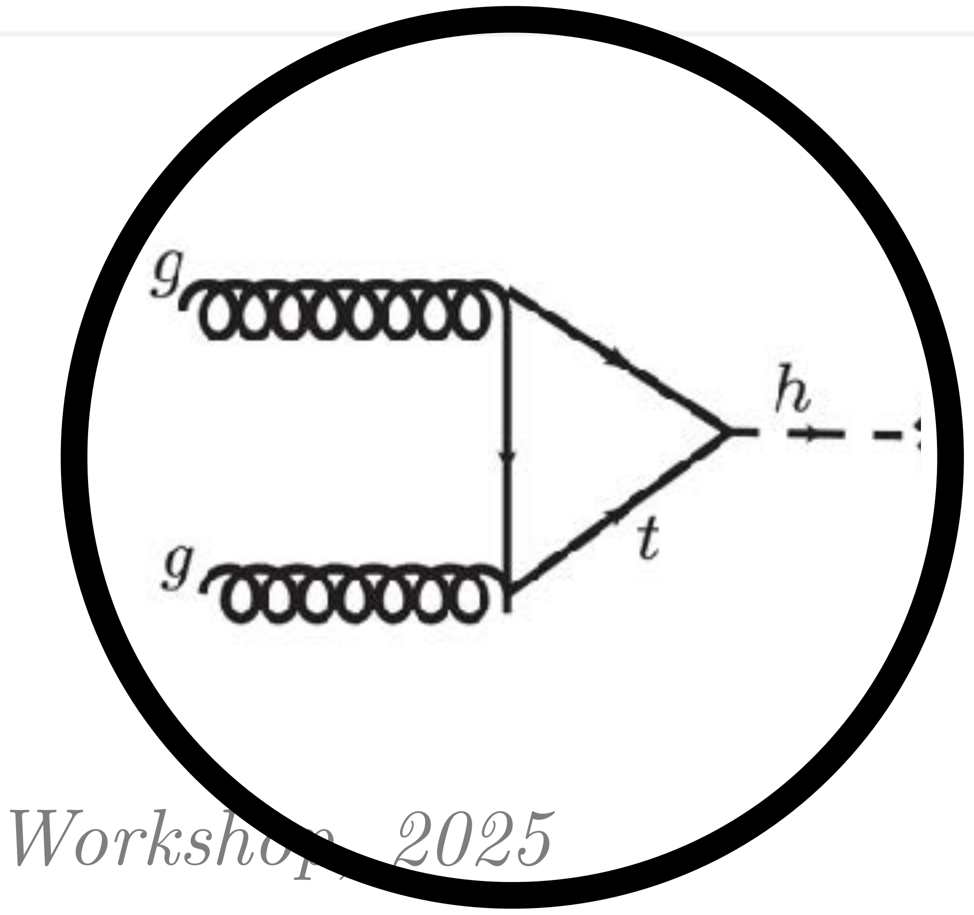
Buttazzo, Franceschini, Wulzer '20

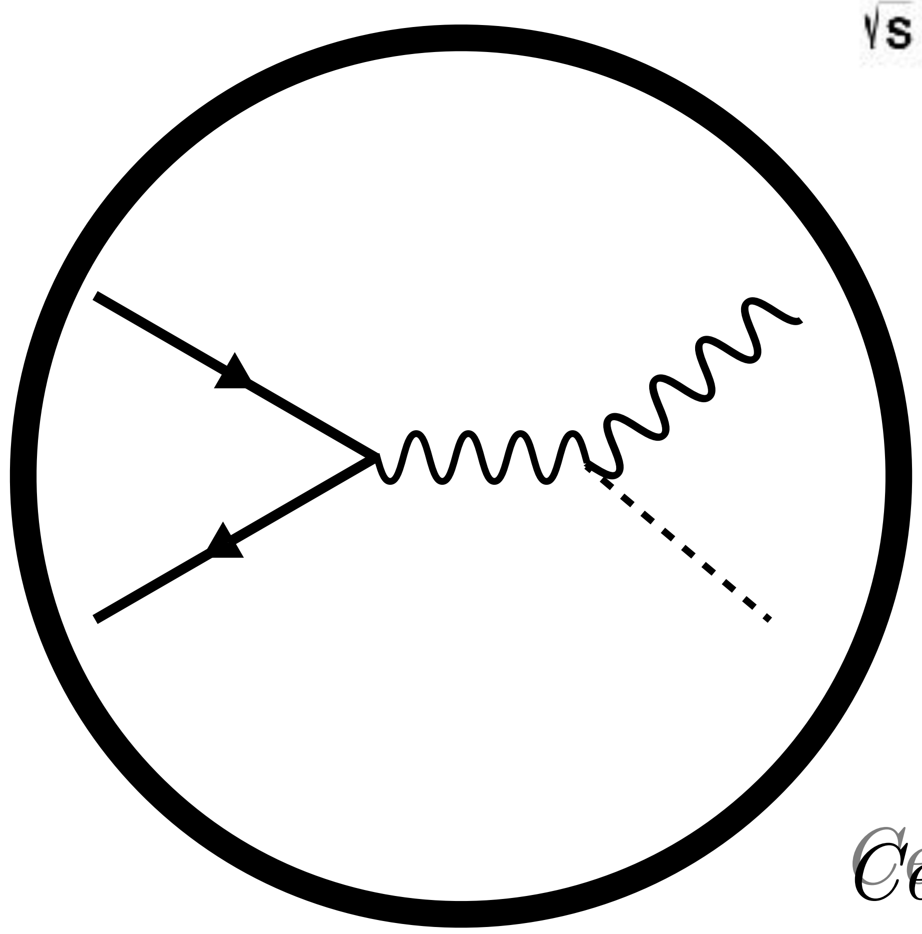


CLiC Summary Report

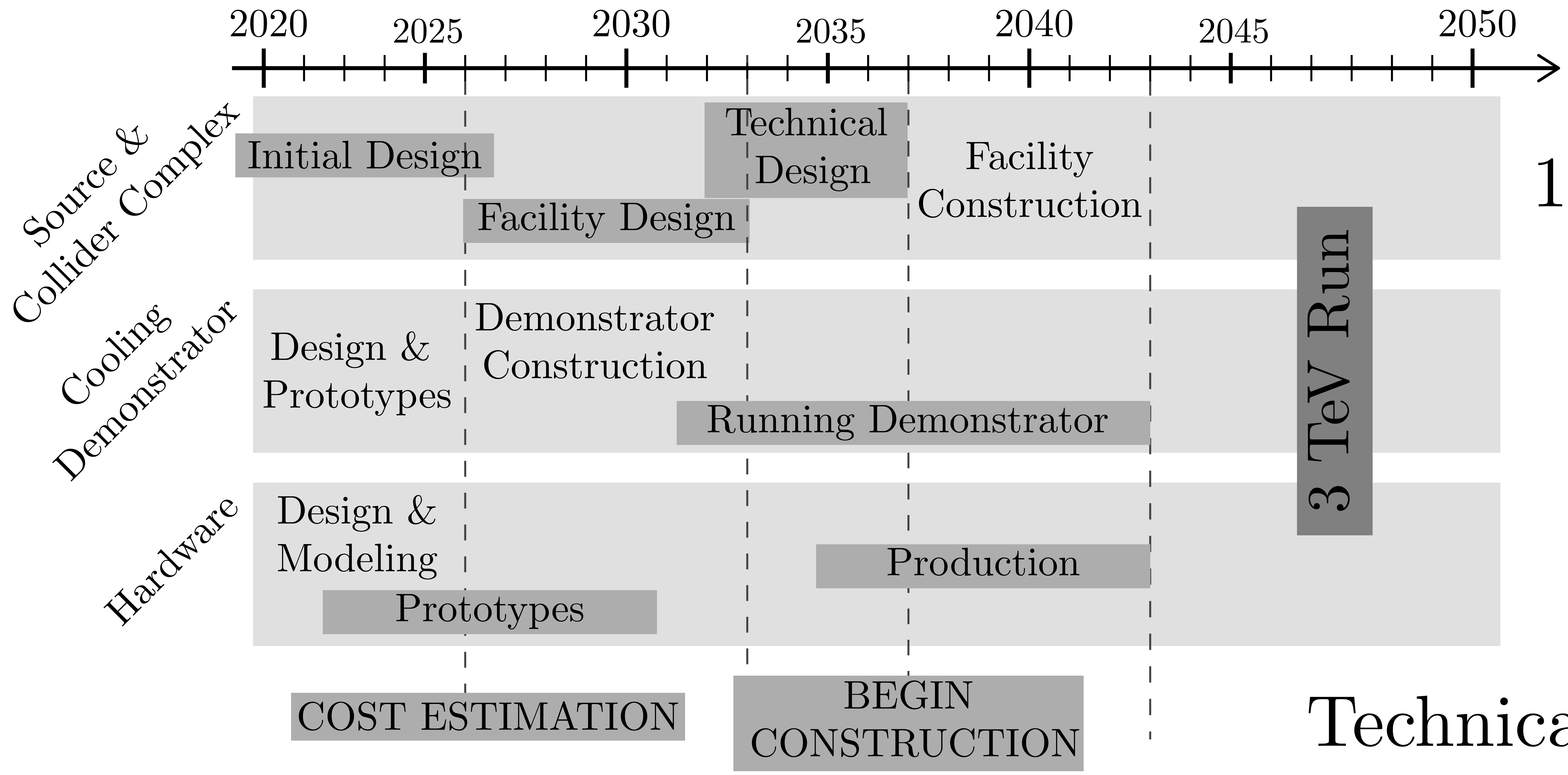
e^+e^-







Muon Collider Timescales



2055: 10 TeV Run?

Technically Limited Timeline*

BSM Physics at Energy Frontier Machines

If we don't see on-shell new physics, where do we look?

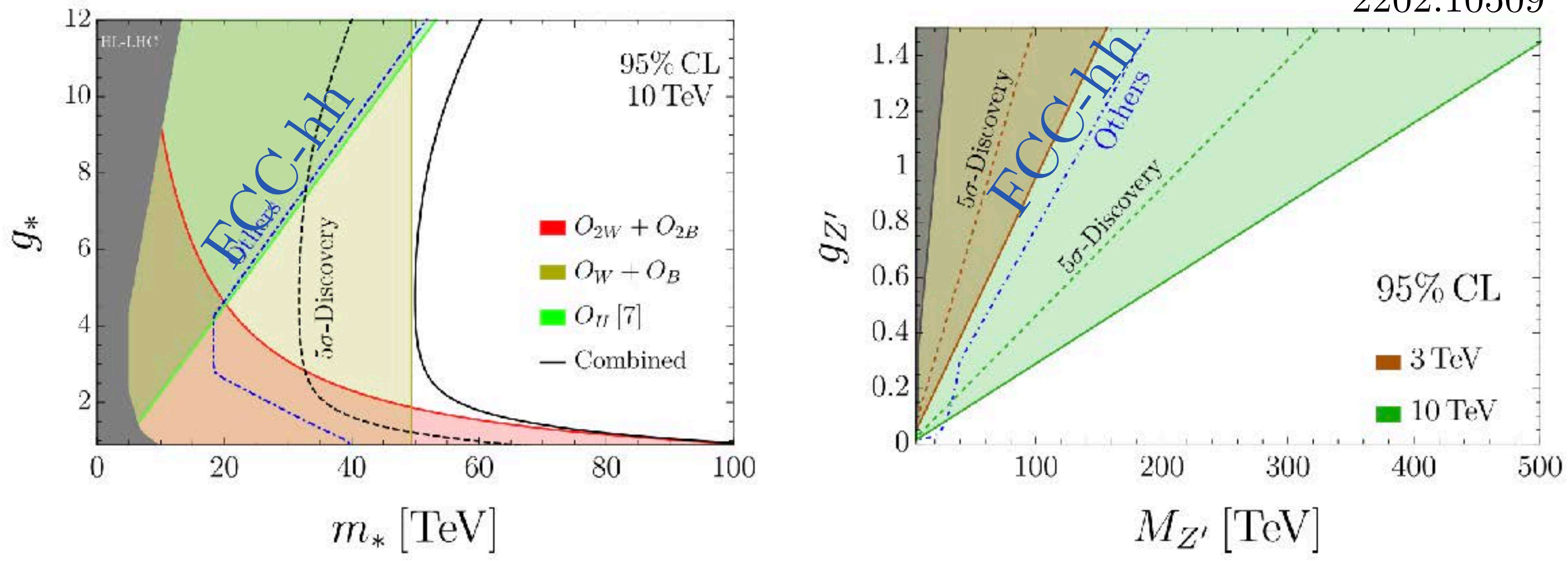
EFT Framework, again

Heavy Degrees of Freedom

Precision: $\frac{\Delta \mathcal{O}}{\mathcal{O}} \sim g^2 \frac{E^2}{\Lambda^2}$

Energy ⇔ Precision

2202.10509



Model details aren't too important, look at that mass reach!

Leptophilic Dark Matter

(At lepton colliders)

Consider other paradigms beyond the WIMP that could be both (thermal) dark matter and discoverable at colliders

For example, a model with a scalar portal that couples *leptophilically* (proportional to Yukawa couplings)

$$\mathcal{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l \bar{l} \qquad g_l = g_e \frac{m_l}{m_e}$$

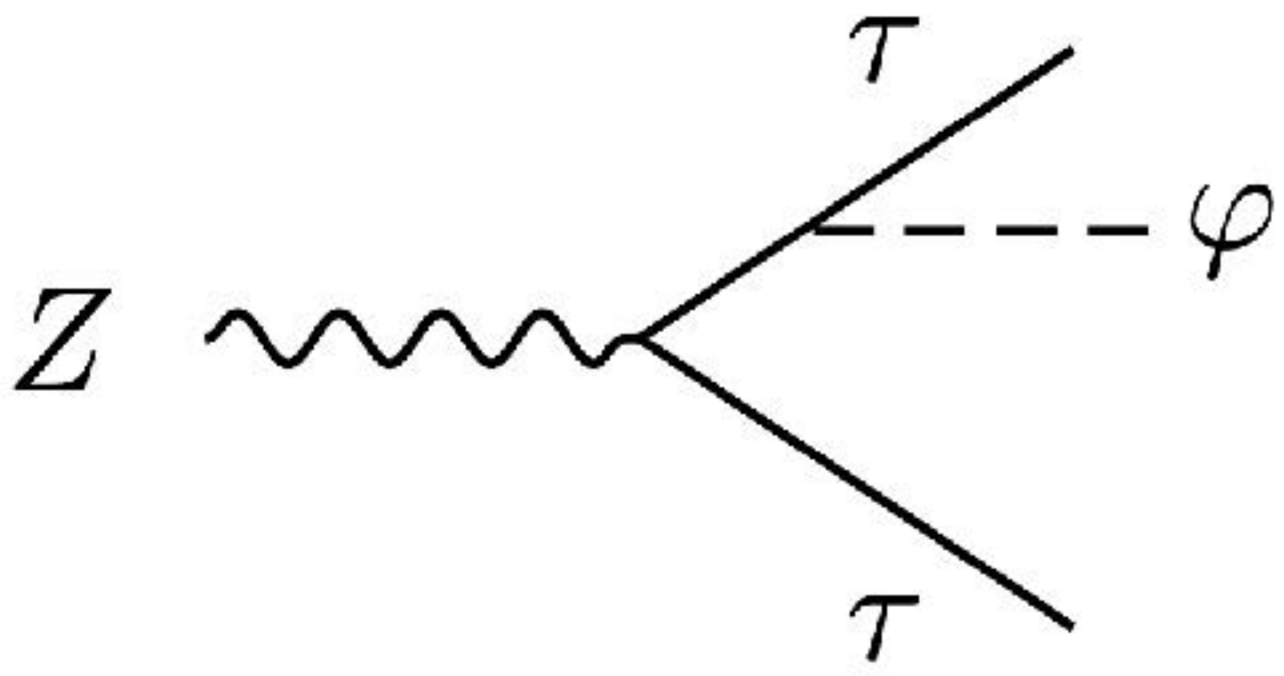
D' Ambrosio, Giudice, Isidori, Strumia '02

Leptophilic Dark Matter

For FCCee, sensitivity is going to *light, weakly coupled* states

Tera-Z Run

Strongest bound set by to $Z \to \tau\tau$



Allows access to 3rd gen particles

Improves bounds from LEP

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

Bound set by uncertainty in BR

Previous LEP: $(1.7 \times 10^7\ Z\text{'s})$

$$\Gamma(Z \to \tau\tau) = 84.08 \pm 0.22 \text{ MeV}$$

FCCee Tera-Z: $(10^{12}\ Z\text{'s})$

$$\Delta\Gamma \times \sqrt{N_{LEP}/N_{FCC}}$$

Assume primary improvements come from statistics

CC, Krnjaic '24

Cesarotti

Leptophilic Dark Matter

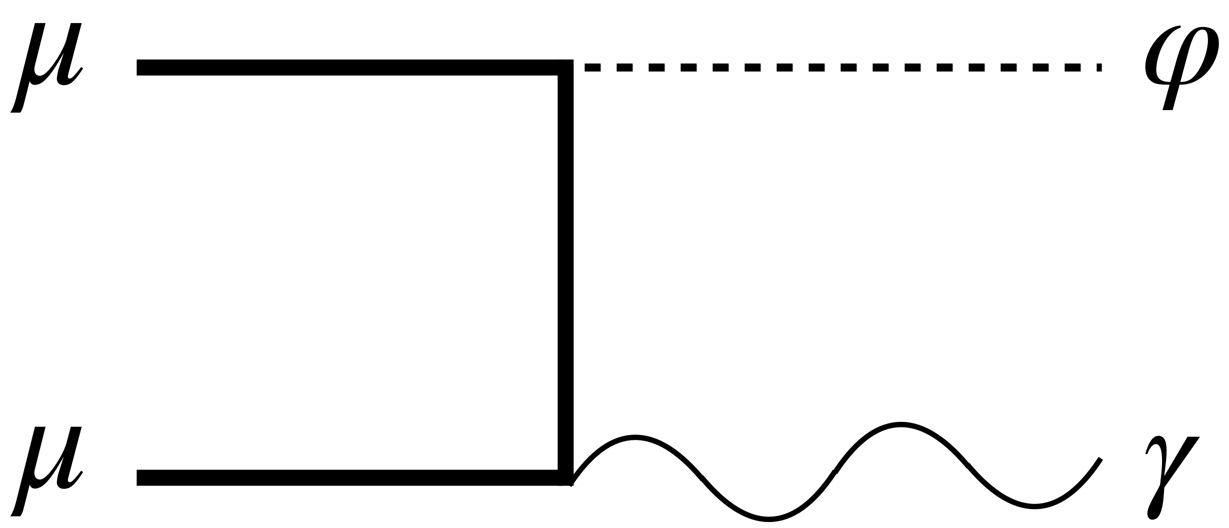
For MuC, sensitivity is going to be to *heavy* states

$$\mathcal{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

Mono-X Search

$$\mu^+\mu^- \to \varphi\gamma$$

$$E_\gamma \sim \sqrt{s}/2$$



$$\sqrt{s} = 3,\ 10\ \text{TeV}$$

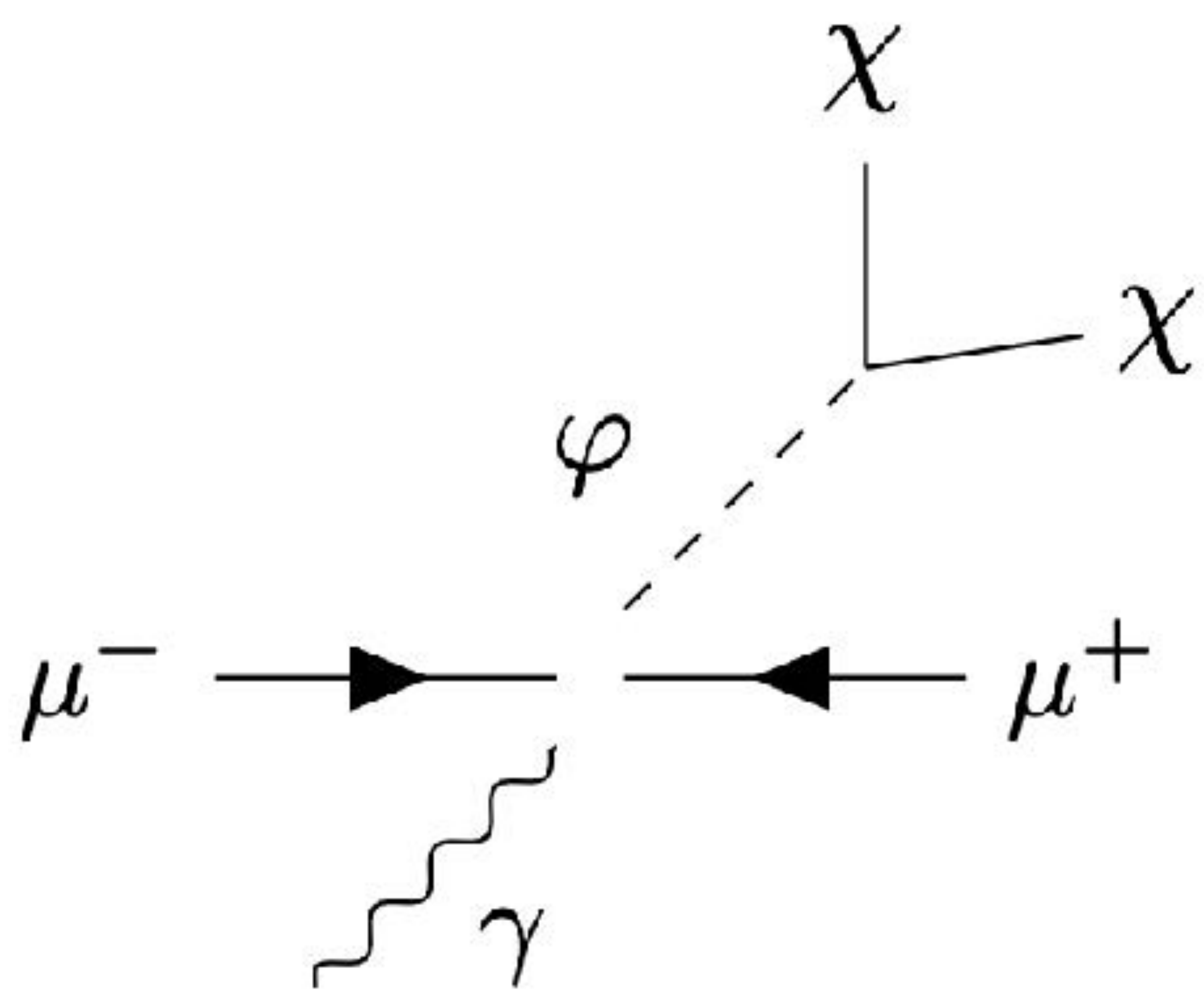
$$\sigma_E = 3\%$$

$$\mathcal{L} = 1,\ 10\ \text{ab}^{-1}$$

$$|\eta| < 2.5$$

Primary Background:

$$\mu^+\mu^- \to \nu\bar{\nu}\gamma$$



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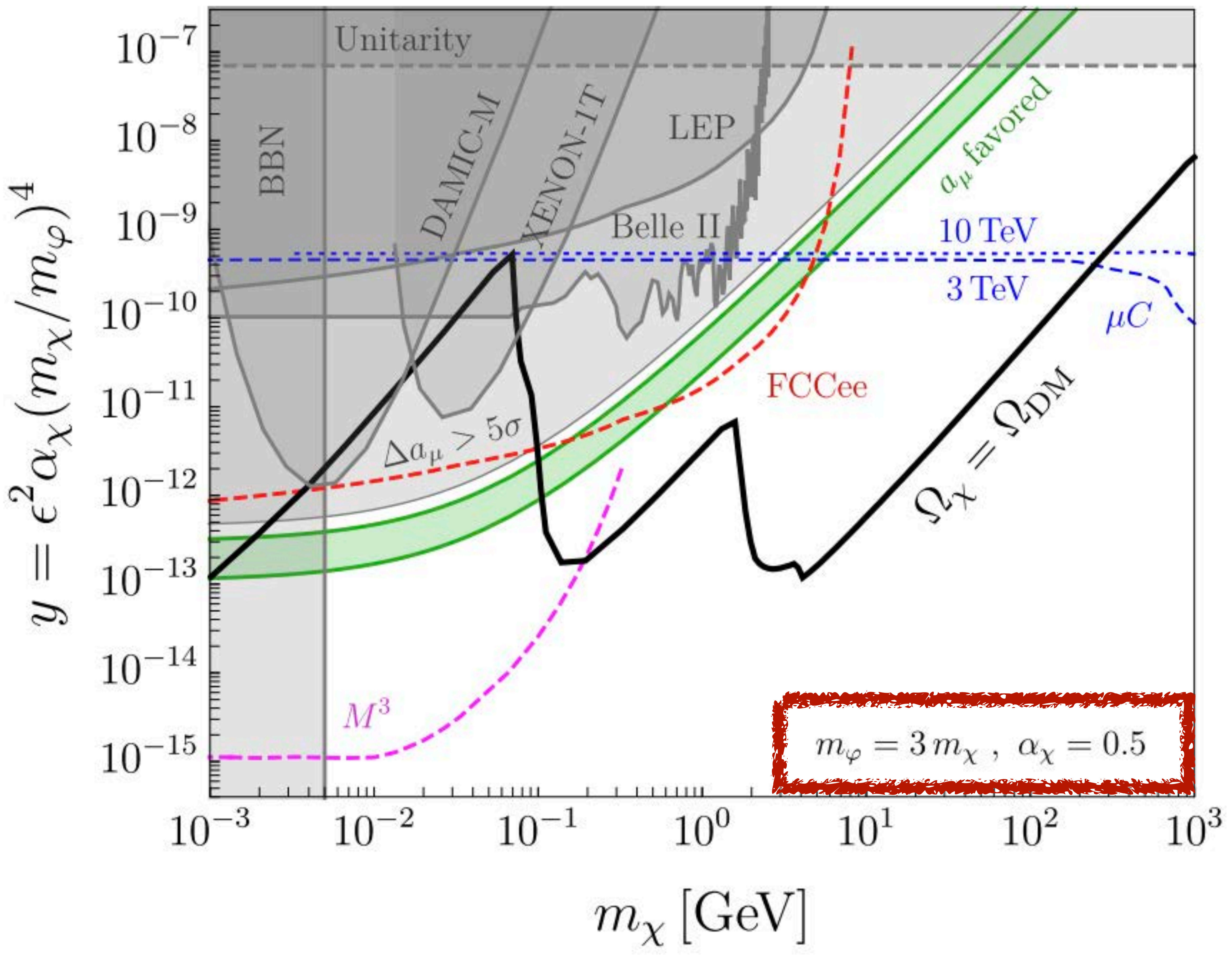
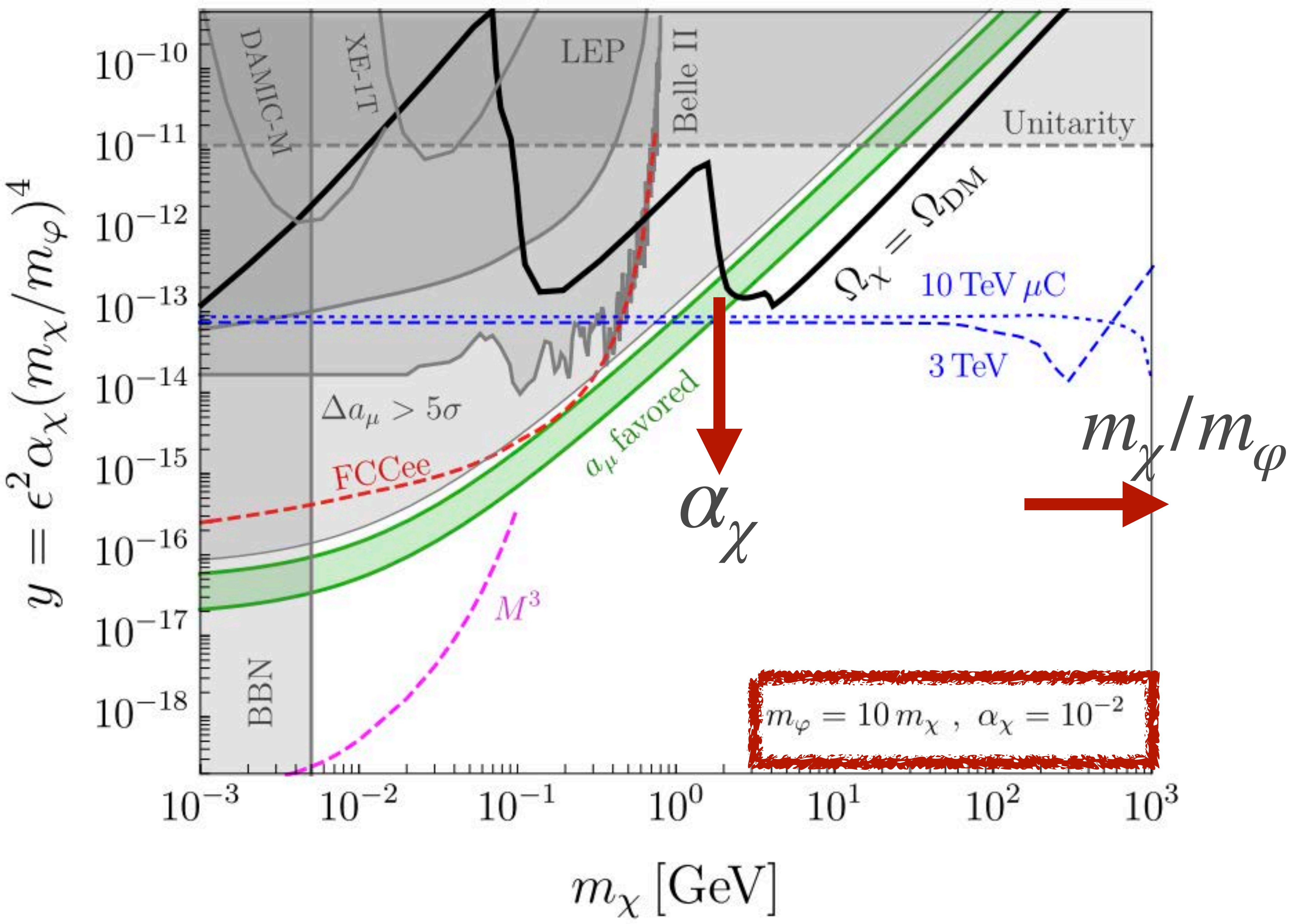
Leptophilic Dark Matter

FCCee & MuC probe *complementary* regions





CC, Krnjaic '24

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BSM Physics at Precision Machines

Why is there symmetry breaking in flavor couplings?

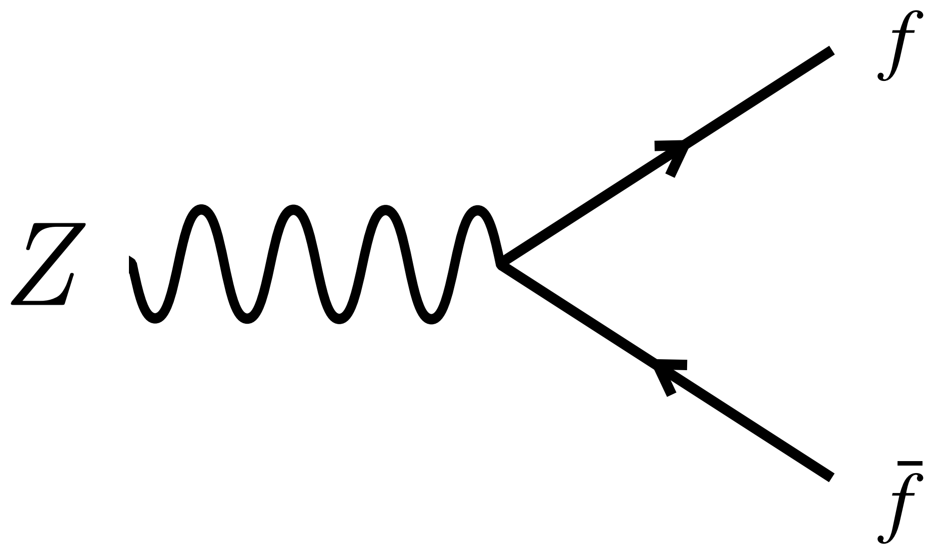
Generation-dependent couplings

Exotic Higgs Phenomena

Exotic/Rare EW Phenomena

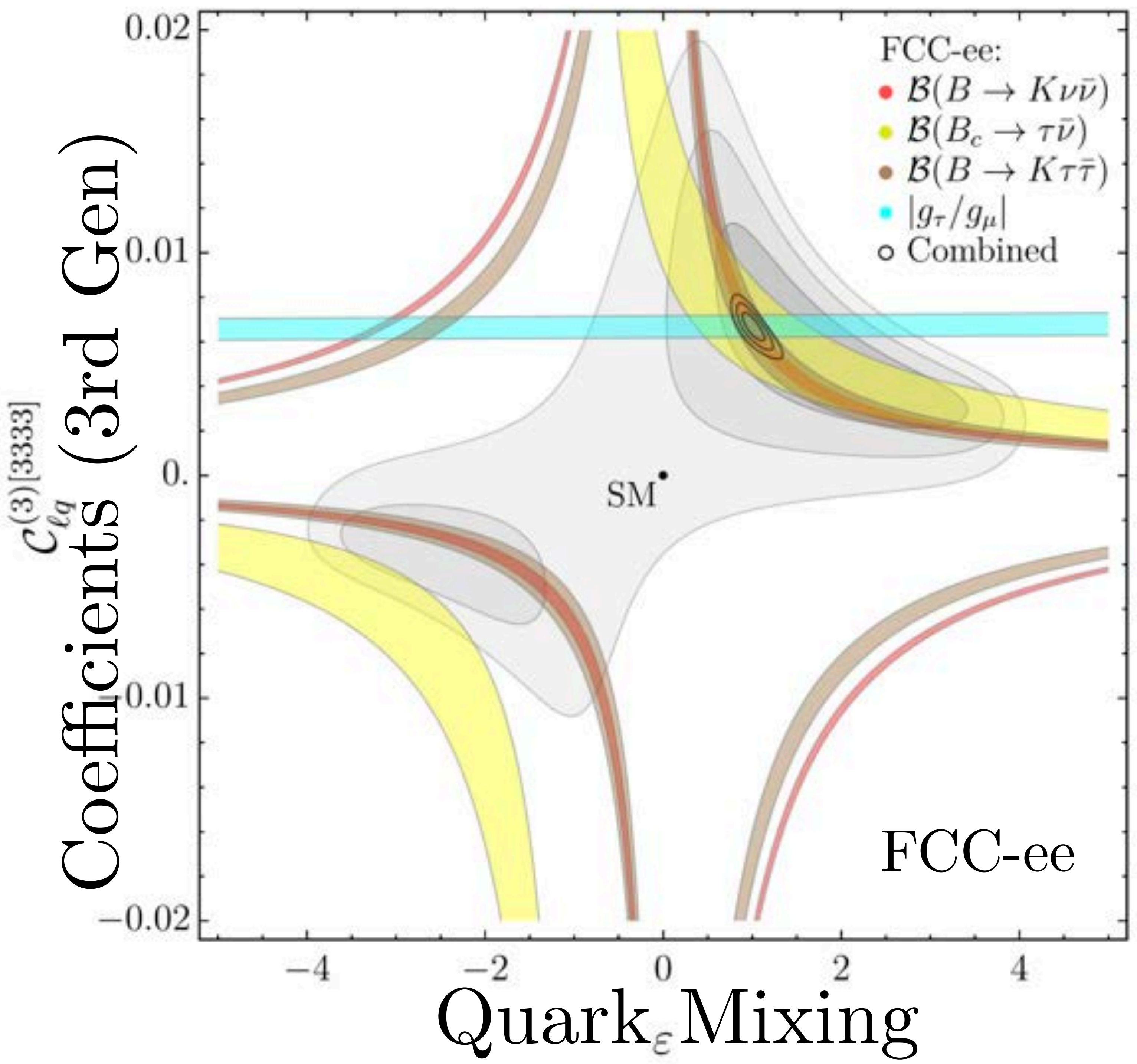
Dark Photons

EFT



Tera Z:
Access to 2nd and 3rd Generation

2503.17019



Ex. Effective Operators in Semi-leptonic B decays

$$e^+e^- \to Z \to b\bar{b}$$

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} - \frac{2}{v^2}\sum_k \mathcal{C}_k^{[f]} Q_k$$

(See also 2408.03992)

BSM Physics at Precision Machines

What can low energy teach us about high energy?

Generation-dependent couplings

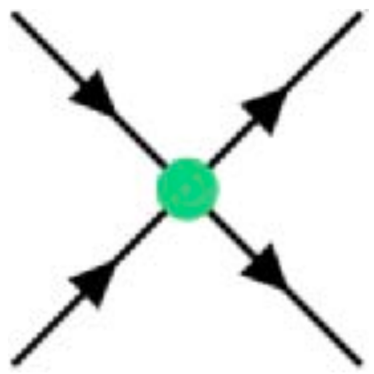
Exotic Higgs Phenomena

Exotic/Rare EW Phenomena

Dark Photons

EFT

SM Modifications



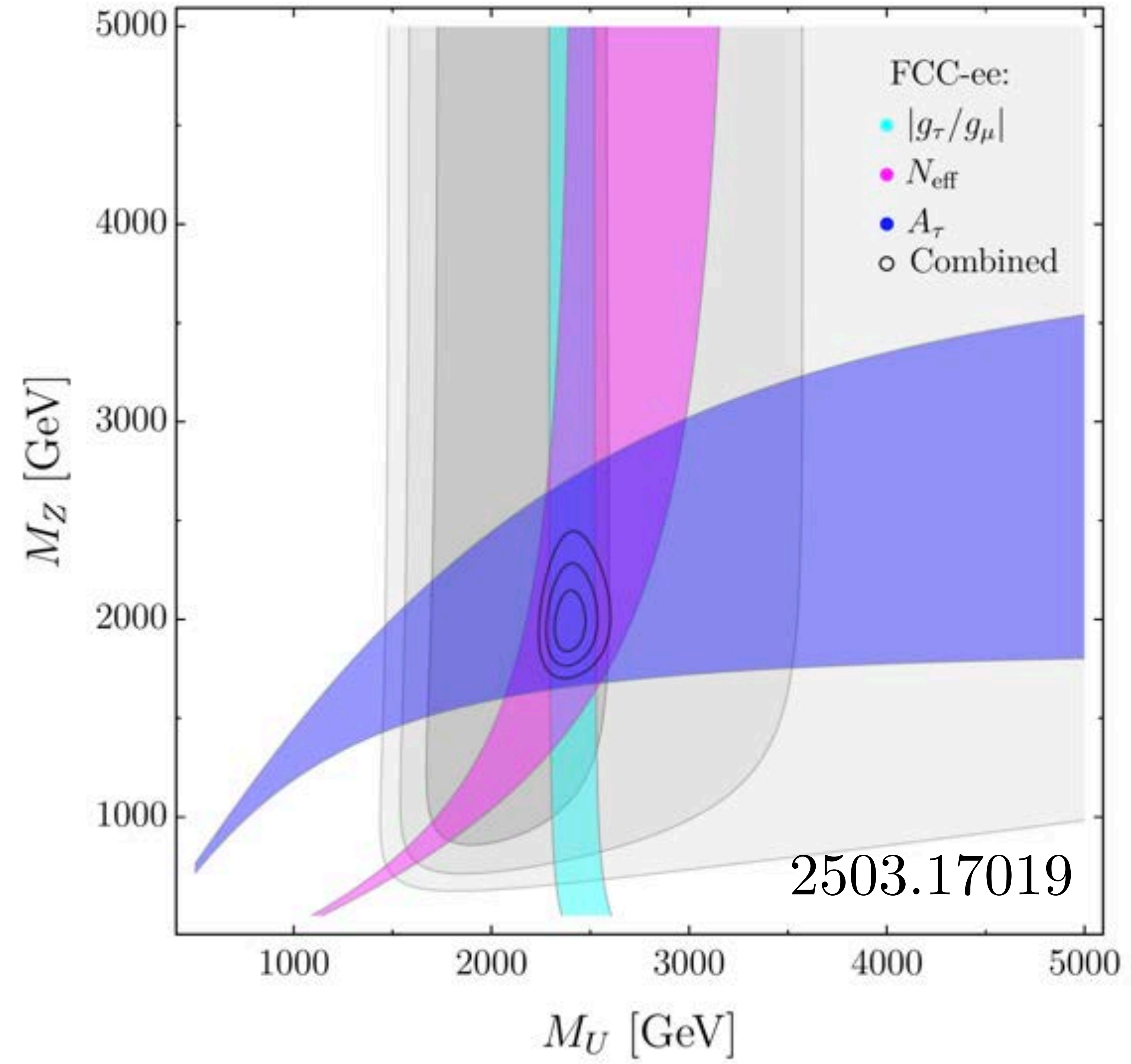
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} - \frac{2}{v^2}\sum_k \mathcal{C}_k^{[f]} Q_k$$

coeff.	Current data				Future (pre-FCC)		FCC proj.	
	Λ_1 [TeV]	Obs.	Λ_2 [TeV]	Obs.	Λ [TeV]	Obs.	Λ [TeV]	Obs.
$\mathcal{C}_{\ell\ell}^{[ijji]}$	-4.5	τ LFU	4.5	τ LFU	4.5	τ LFU	20.8	τ LFU
$\mathcal{C}_{\ell\ell}^{[i33i]}$	-4.5	τ LFU	4.5	τ LFU	4.5	τ LFU	20.8	τ LFU
$\mathcal{C}_{H\ell}^{(3)[33]}$	-4.8	τ LFU	4.1	τ LFU	4.4	τ LFU	20.4	τ LFU
$\mathcal{C}_{H\ell}^{(3)[ii]}$	-4.2	τ LFU	4.7	τ LFU	4.2	τ LFU	20.3	τ LFU
$\mathcal{C}_{\ell q}^{(3)[3333]}$	-2.2	R_D/R_{D^*}	-0.9	τ LFU	1.9	R_D/R_{D^*}	5.6	τ LFU

⋮

Model Interpretation

SM + U Leptoquark + Z'



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(See also 2408.03992)