The Physics potential of a Future Muon Collider

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INFN Seminar

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A *MUON* COLLIDER? IS THAT EVEN POSSIBLE?

We think so… but first we need R&D

A muon collider is not at the same maturity as a future e^+e^- collider

If proven feasible, a muon collider is uniquely capable of discovering new fundamental physics at energies orders of magnitude beyond the reach of the LHC

OUTLINE

Why should we continue the collider physics program?

How do muon colliders compare to other future colliders?

What are the biggest challenges for a muon collider?

What physics can we do at muon colliders?

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To understand the UV nature of the universe

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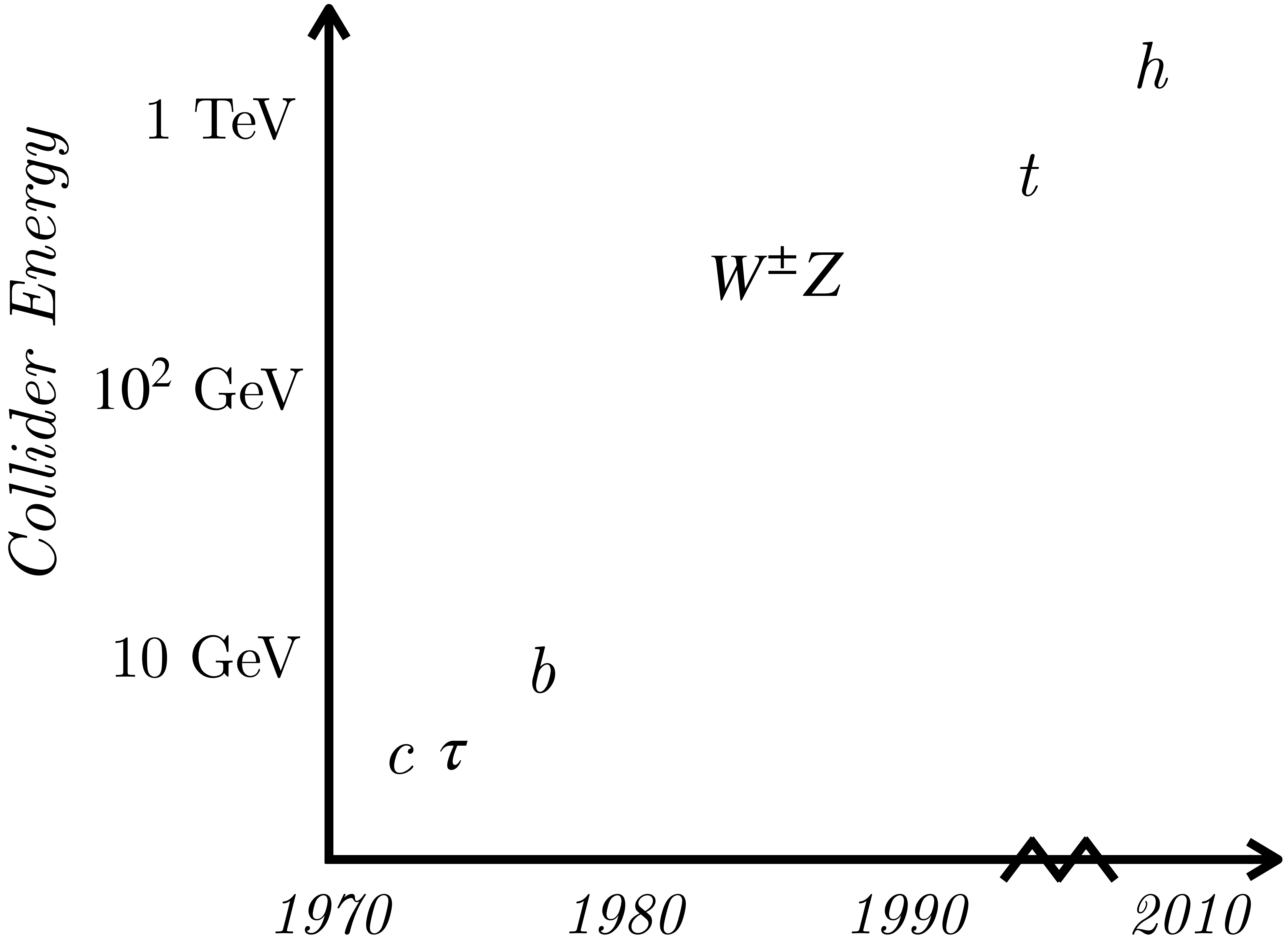
Where do we stand

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...

	I	II	III	Bosons	
Quarks	u	c	t	g	H
	d	s	b	γ	
Leptons	e	μ	τ	Z	
	ν_e	ν_μ	ν_τ	$W^{\pm}$	

WHERE DO WE STAND

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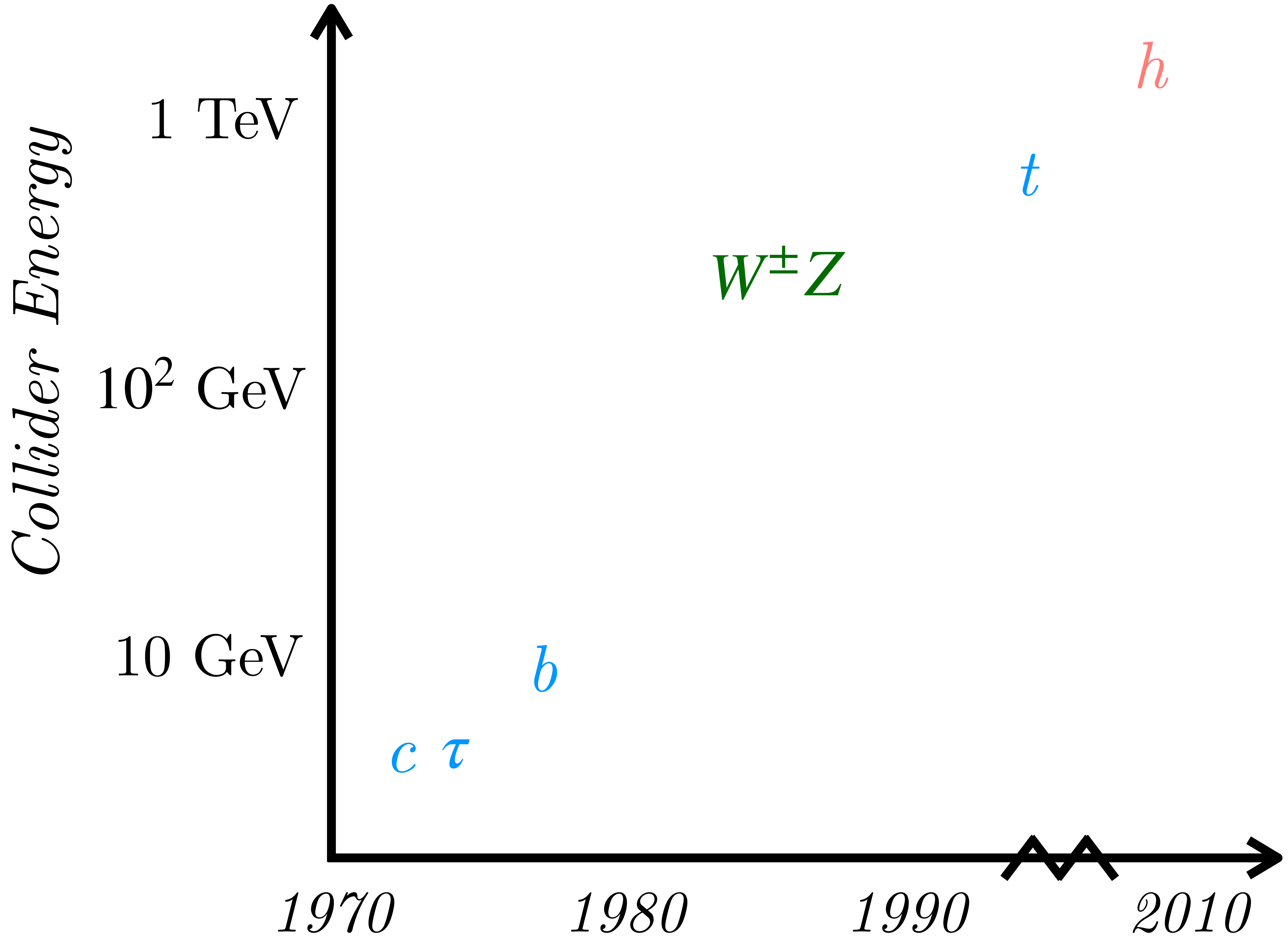


Higher energies at colliders have lead to understanding of...

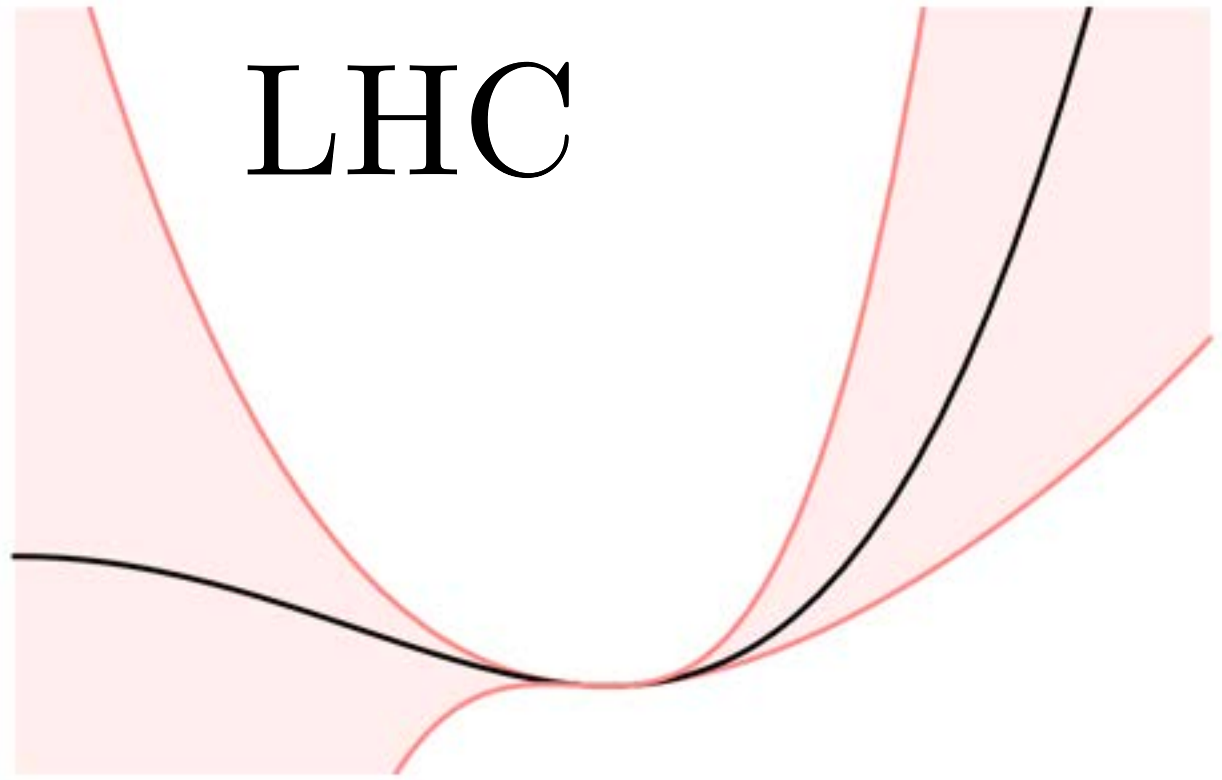
2nd and 3rd Generation Particles

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

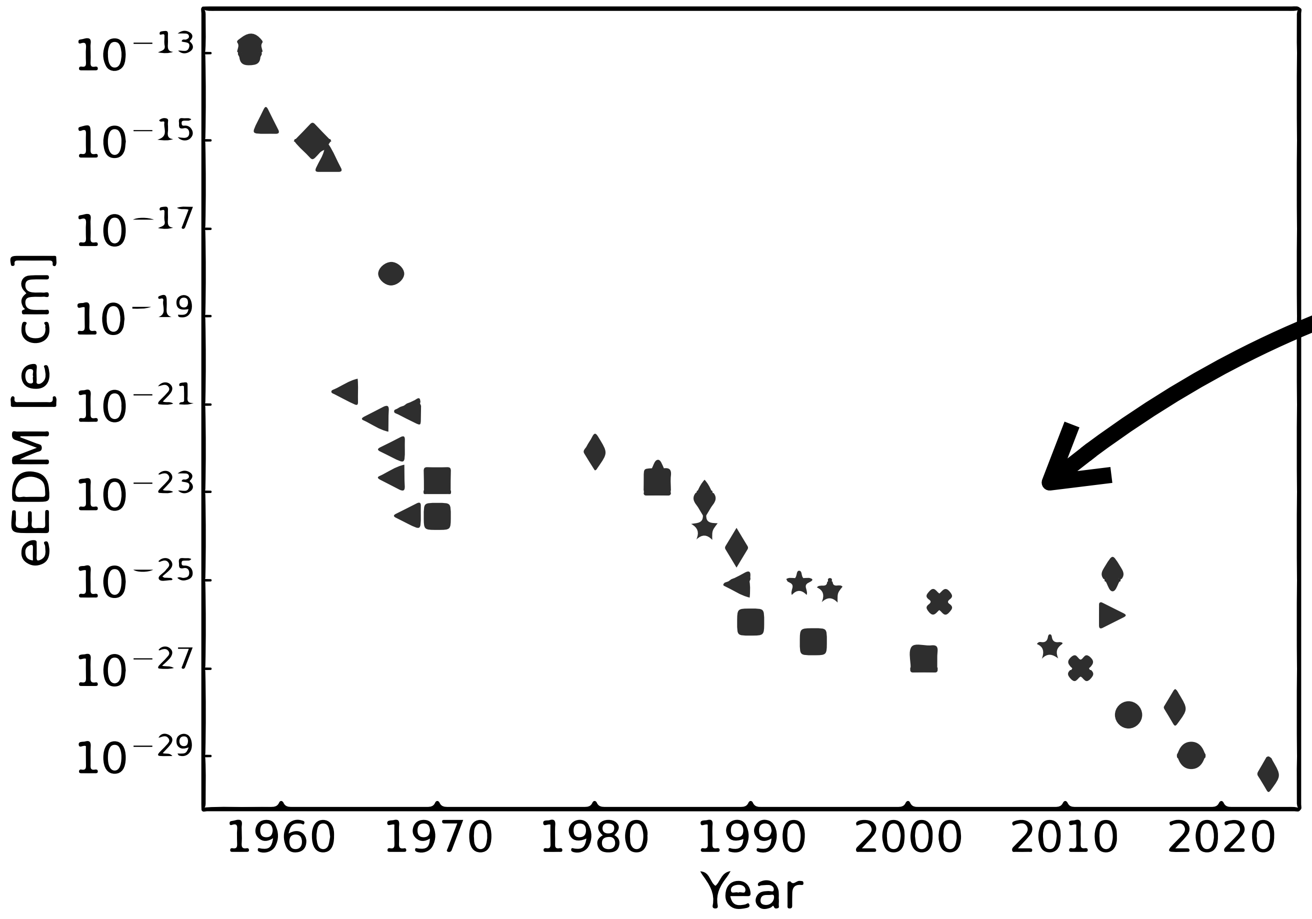
Higgs mechanism

Open Questions in Particle Physics

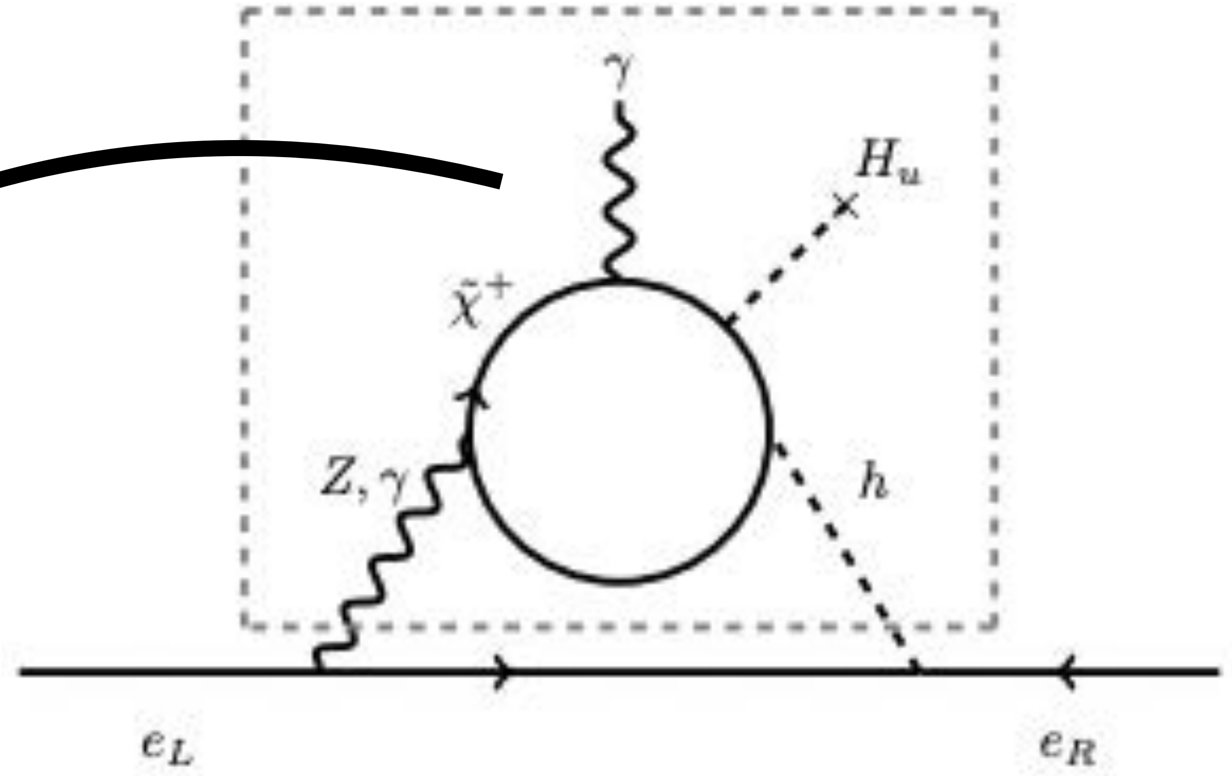
...but open questions remain in the Standard Model (SM)



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



***CC**, Lu, Nakai, Parikh, Reece ‘18*

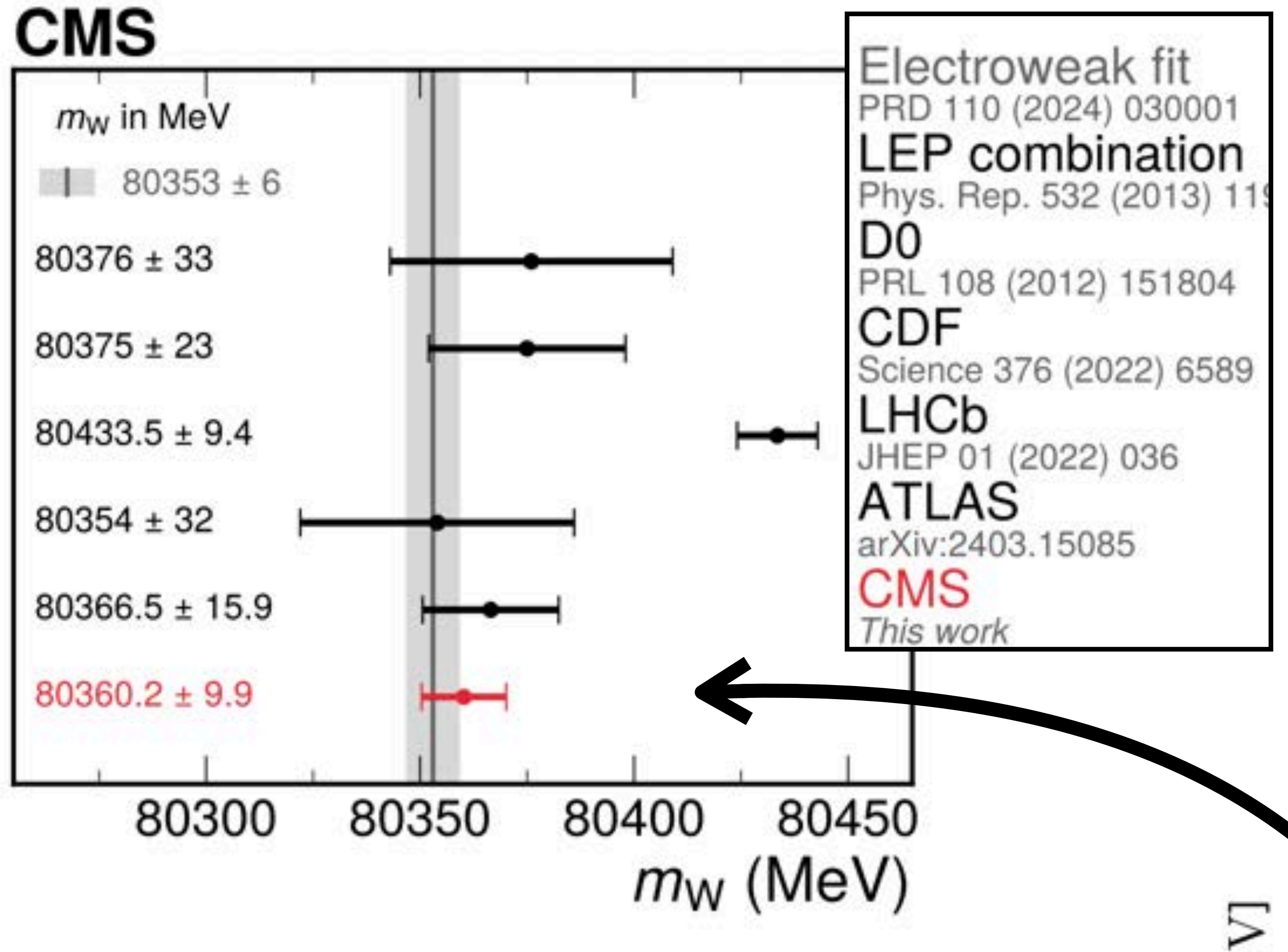


SM Prediction

OPEN QUESTIONS IN PARTICLE PHYSICS

...but open questions remain in the Standard Model (SM)
...and even more exist *beyond* the SM (BSM)

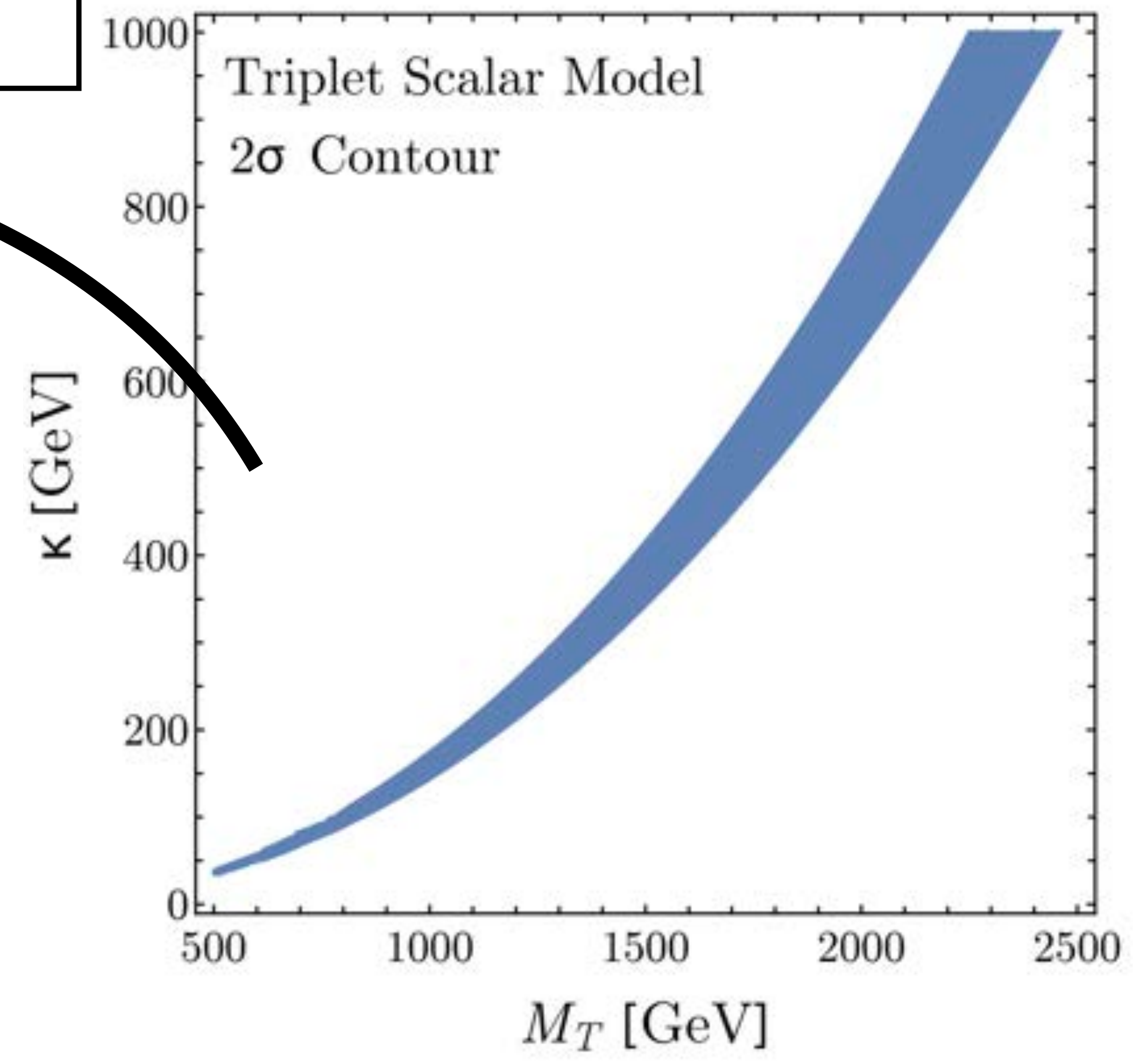
- Dark matter?
- Baryon-antibaryon asymmetry?
- Anomalies in precision measurements?
- ...

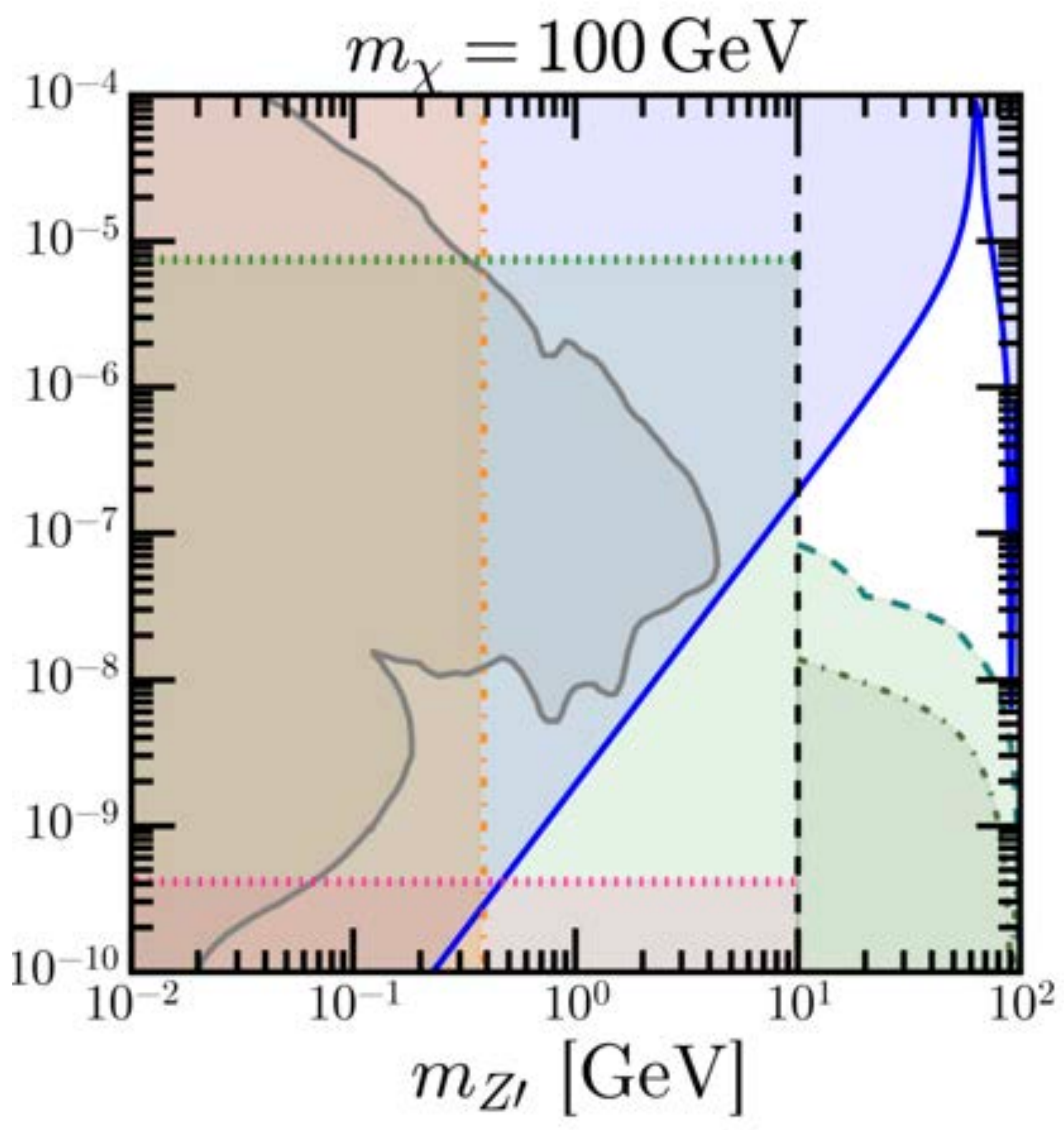


W mass measurements

$$\mathscr{L} \supset \kappa\phi^a H^\dagger \sigma^a H$$

*Asadi, **CC**, Fraser, Homiller, Parikh '22*





*Hu, **CC**, Slatyer '25*

Experiment to inform theory

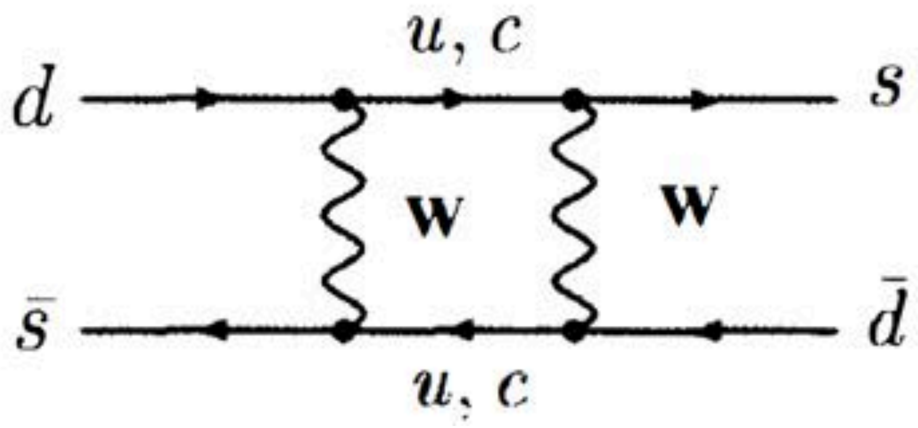
We do not have a singular guiding theory to tell us where to look for BSM

Theory can be driven by empirical evidence

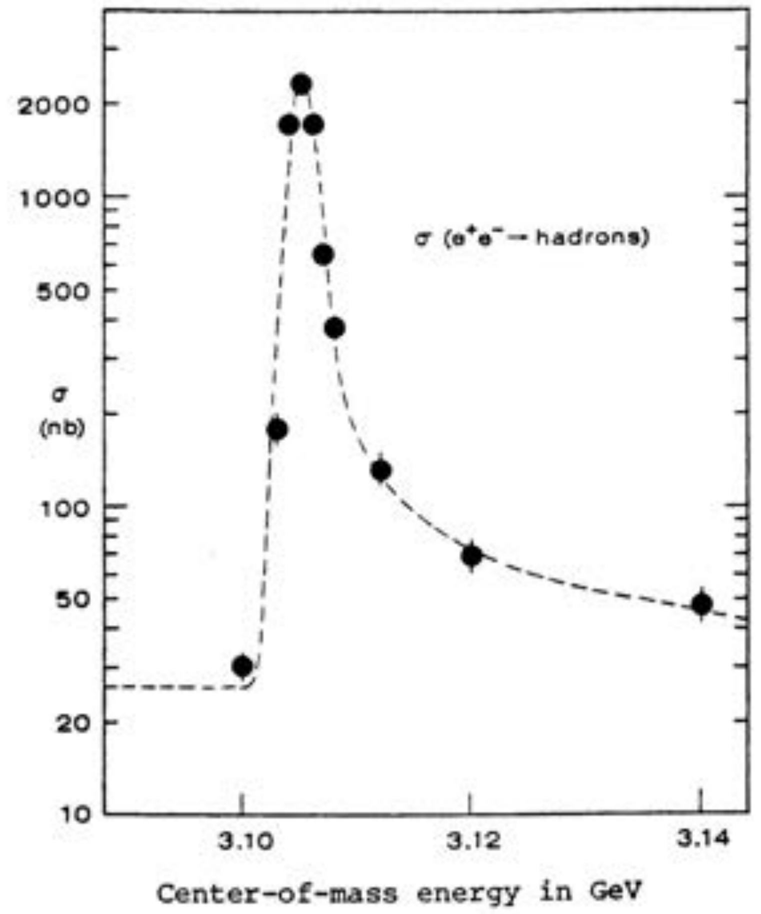
With inherently motivated BSM theories, we can target compelling theories

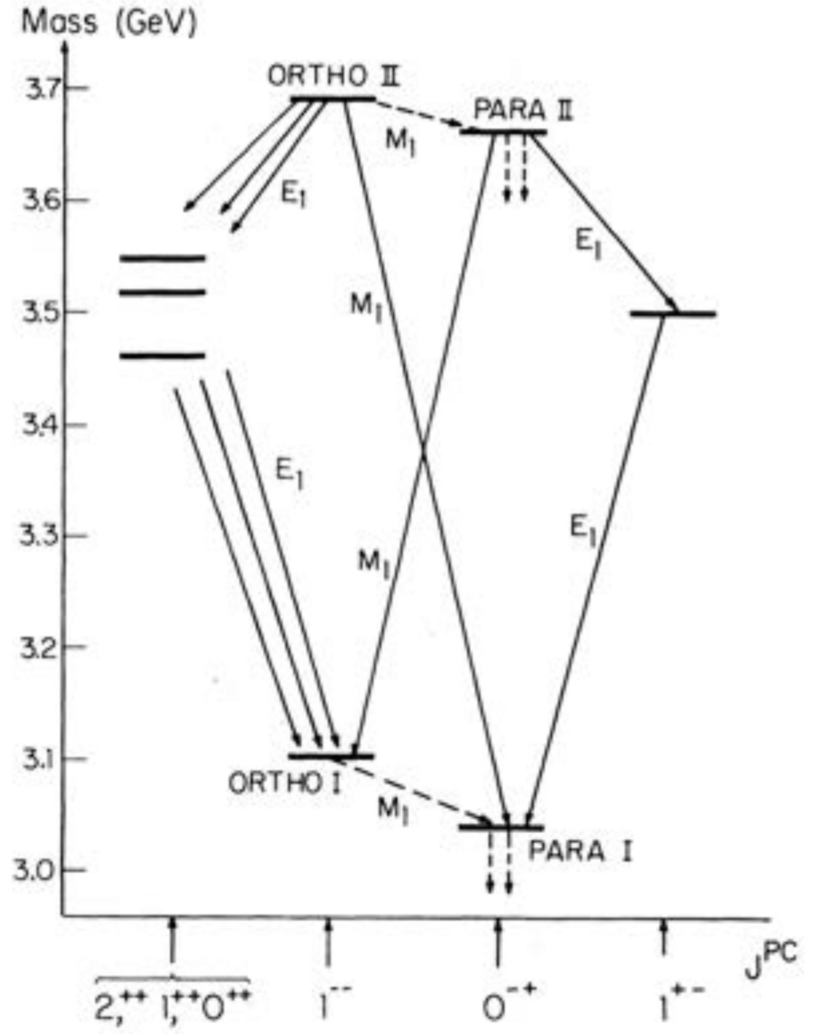
Now is the era of exploration and general purpose experiments

GIM '70



SLAC & BNL '74





Appelquist, De Rújula, Glashow, Politzer '74

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Precision and energy frontier machine

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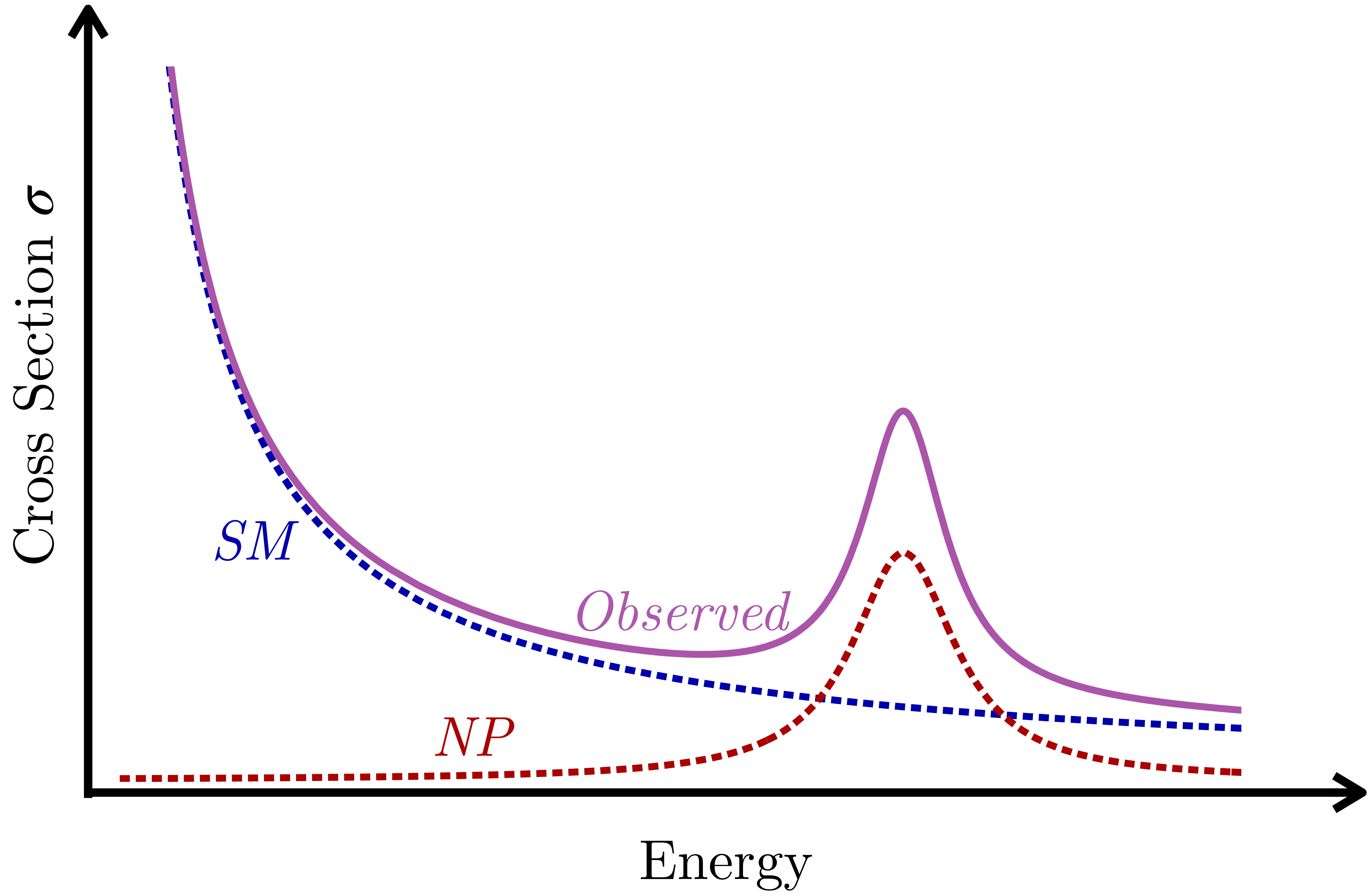
FUTURE COLLIDERS

Two avenues for progress:

Precision or Discovery machines



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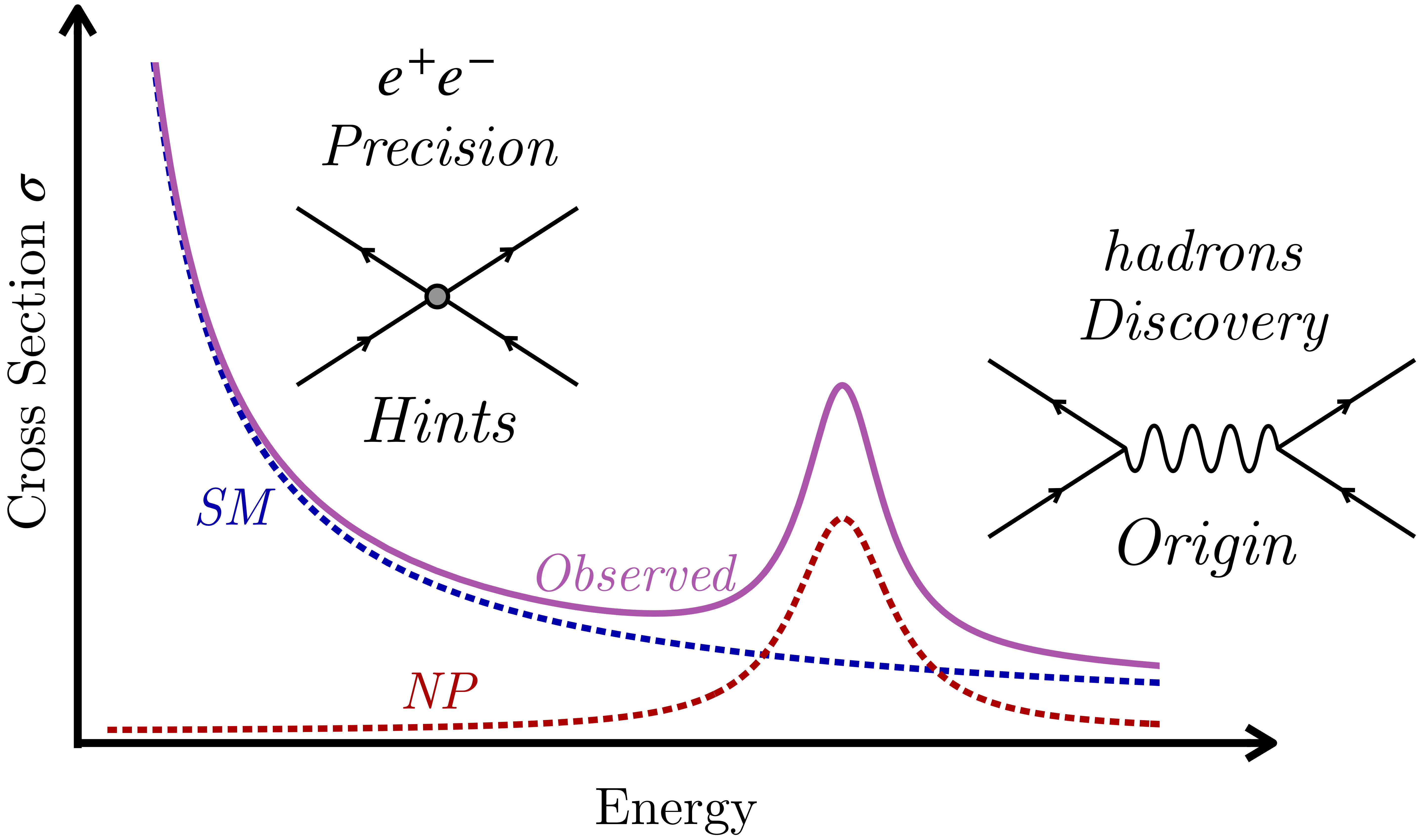
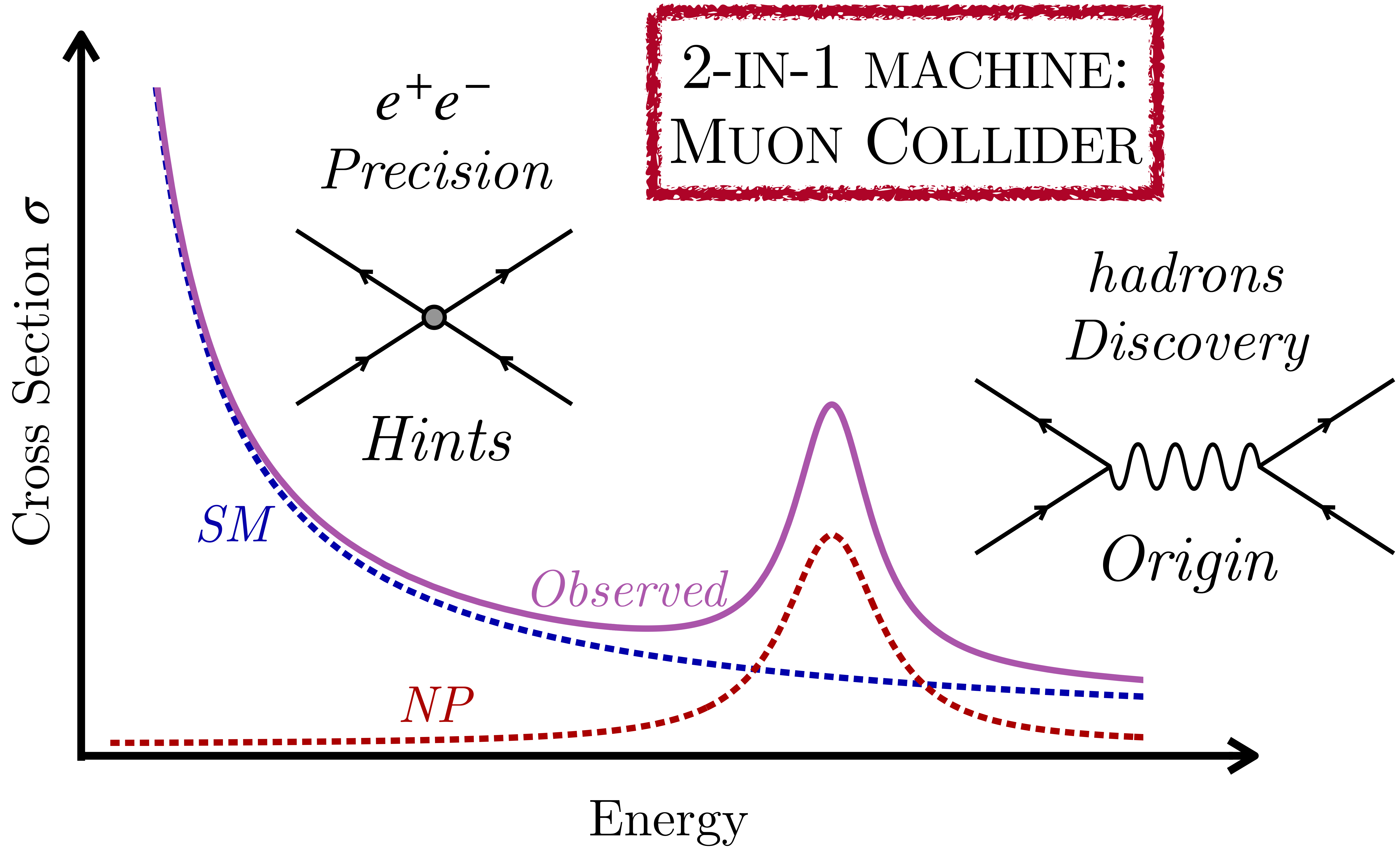


FUTURE COLLIDERS

Two avenues for progress:

Precision or Discovery machines

2-IN-1 MACHINE: MUON COLLIDER



CC ∈ *Accettura et al, Towards a Muon Collider '23* · ***CC*** ∈ *IMCC, Interim Report '24* · ***CC*** ∈ *Muon Collider ESPPU '25*

COMPARISON OF FUTURE COLLIDERS

pp	$\mu^+\mu^-$	e^+e^-	
		Circular	*Linear*

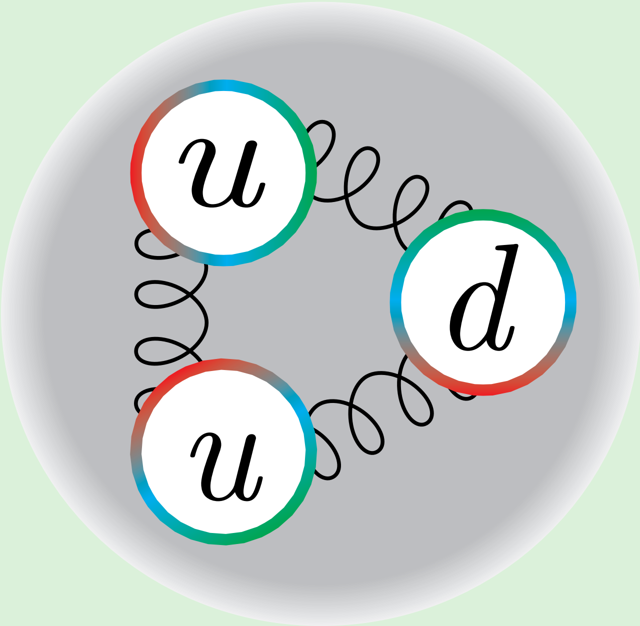
***CC* ∈ Accettura et al, Towards a Muon Collider '23 · *CC* ∈ IMCC, Interim Report '24 · *CC* ∈ Muon Collider ESPPU '25**

COMPARISON OF FUTURE COLLIDERS

pp

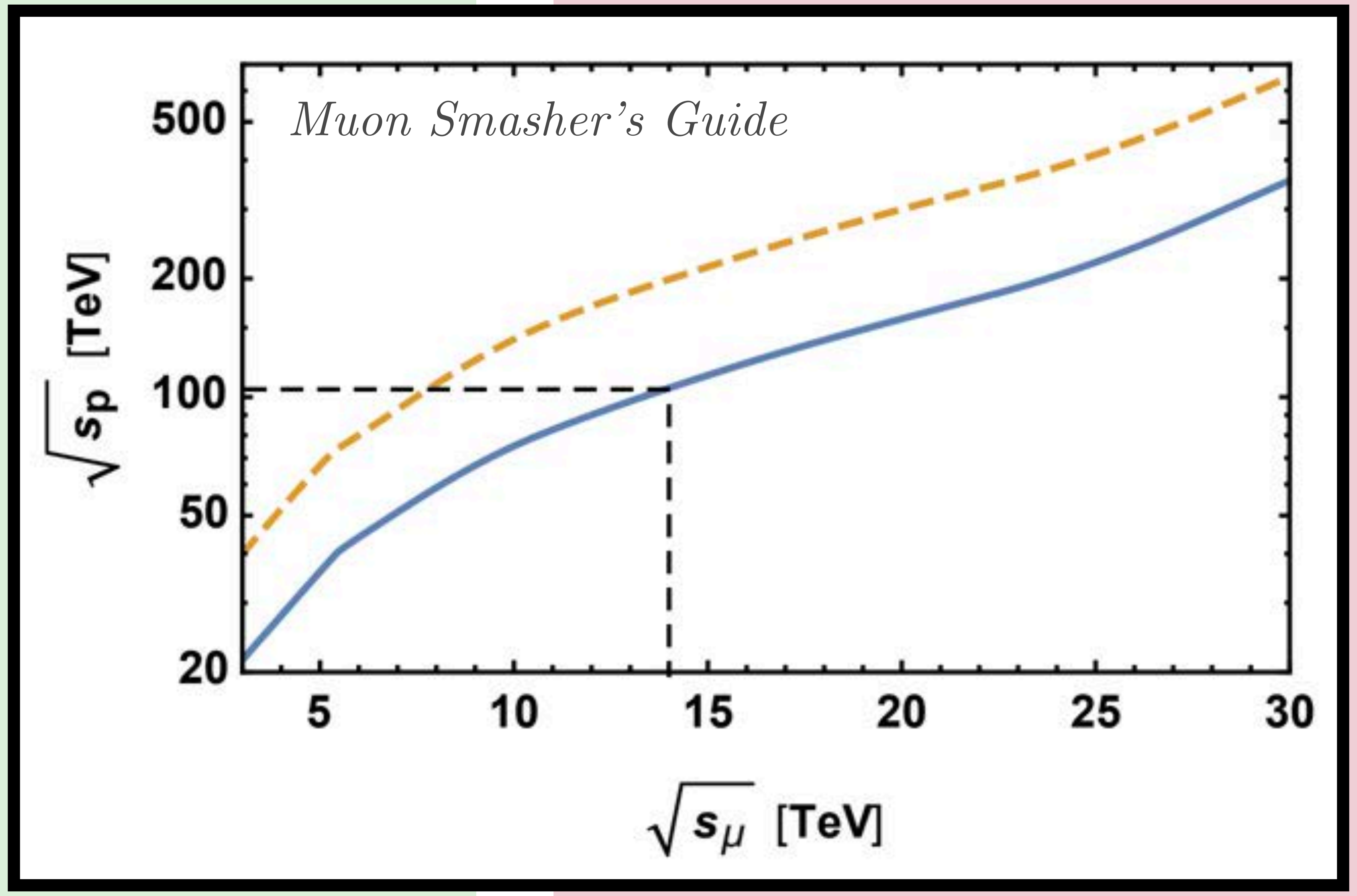
Composite

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



$\mu^+\mu^-$

Muon Smasher's Guide '19



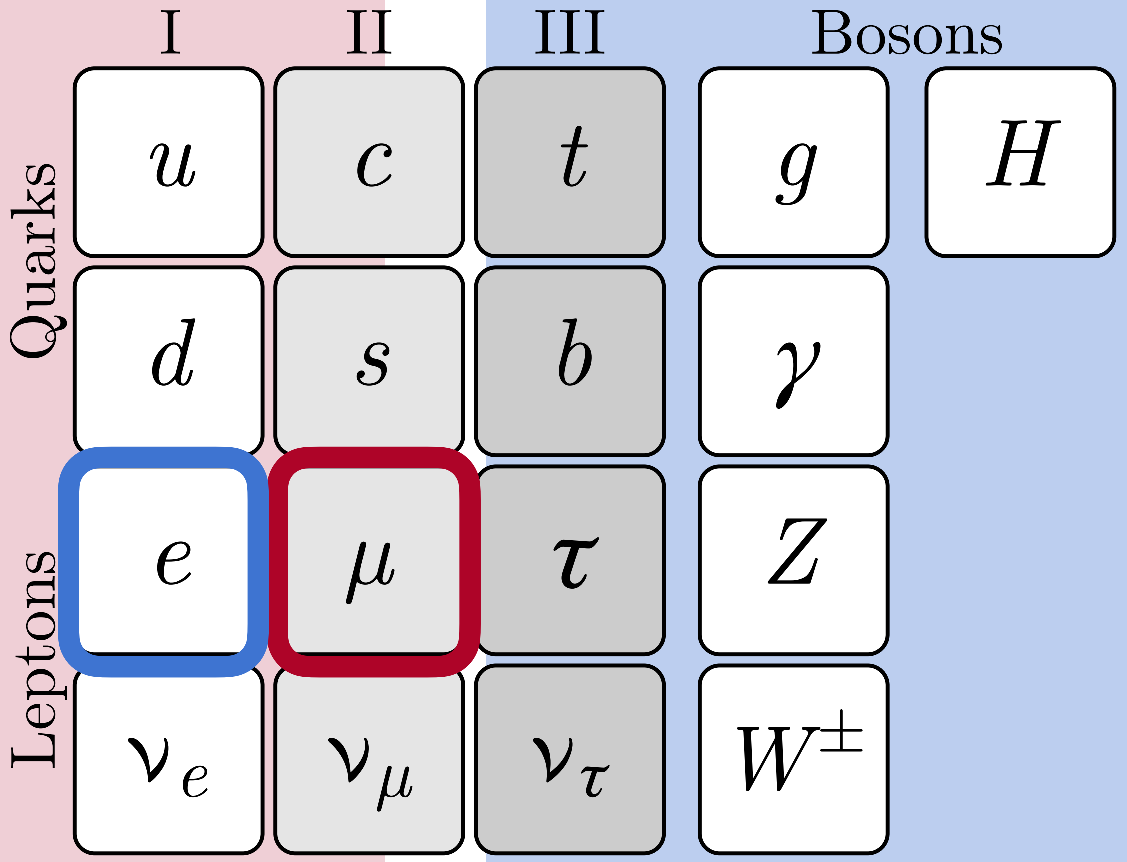
e^+e^-

Circular

Linear

Fundamental

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



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COMPARISON OF FUTURE COLLIDERS

pp

$\mathcal{O}(85+)$ 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

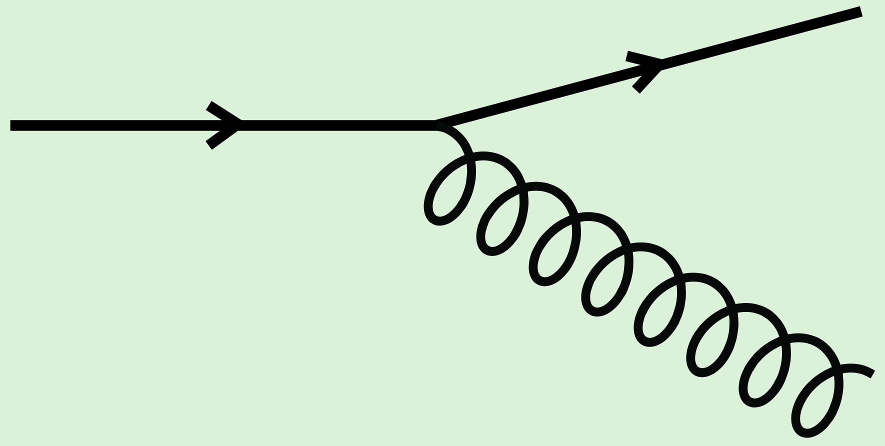
CC $\in$ *Accettura et al, Towards a Muon Collider '23* · ***CC*** $\in$ *IMCC, Interim Report '24* · ***CC*** $\in$ *Muon Collider ESPPU '25*

Comparison of Future Colliders

pp

$\mathcal{O}(85+)$ TeV

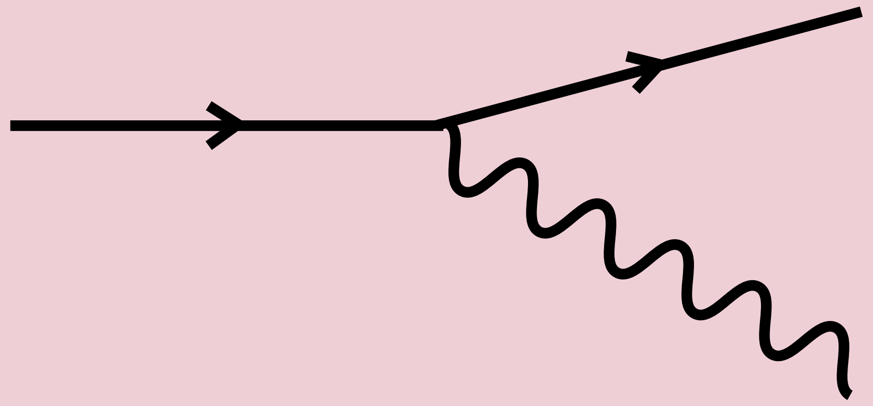
QCD



$\mu^+\mu^-$

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

Electroweak



e^+e^-

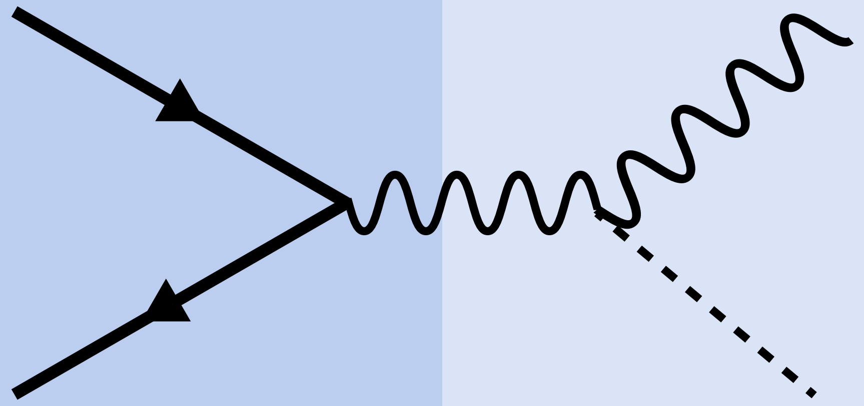
Circular

Linear

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs



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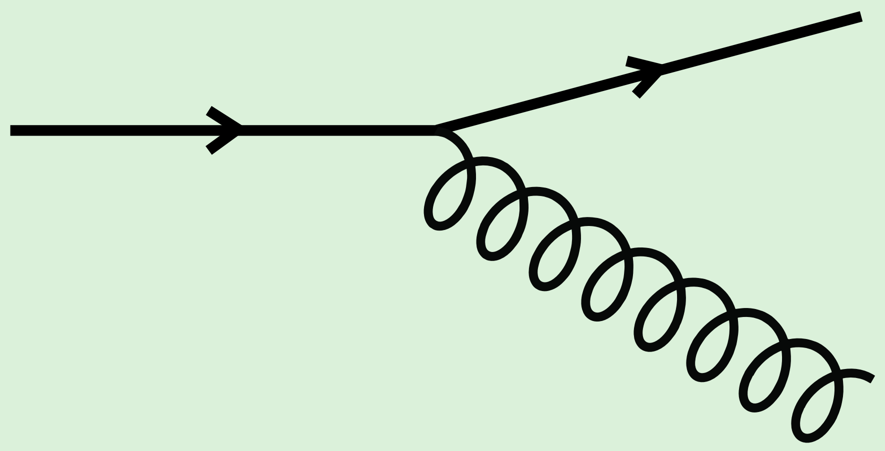
$\mathcal{O}(85+)$ TeV

QCD



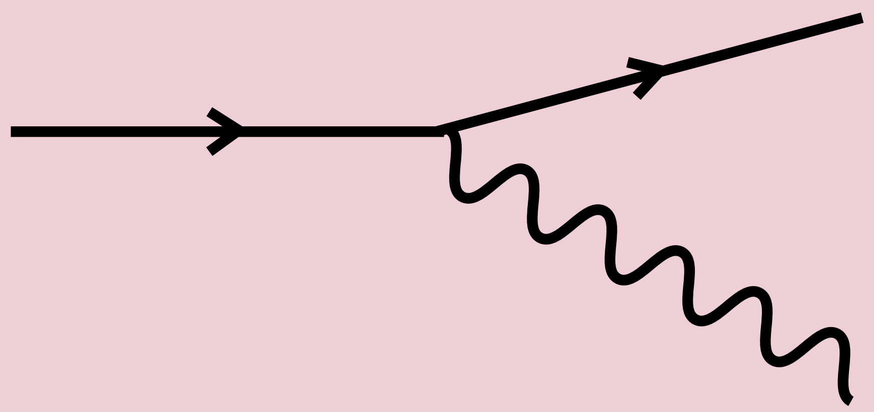
Pro

High energy, known

$\mu^+\mu^-$

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

Electroweak



Pro

High energy & precision

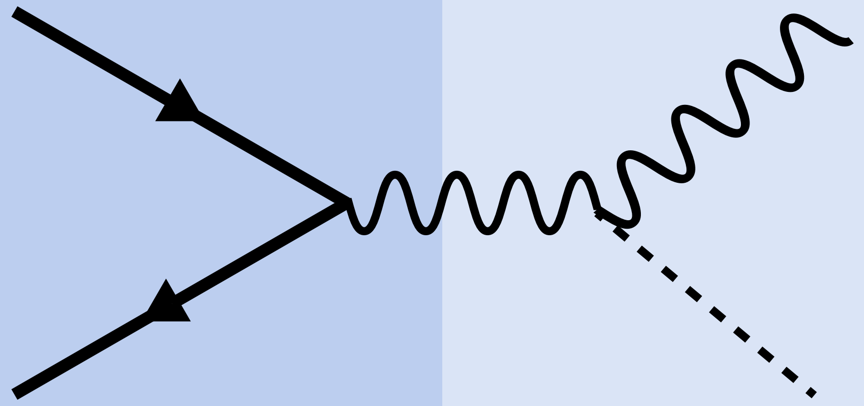
e^+e^-

Circular *Linear*

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs



Pro

Precision, known, upgrades

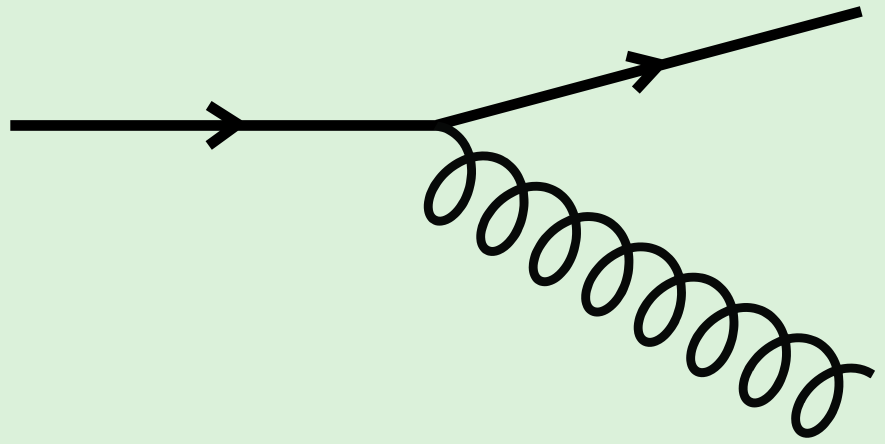
CC *∈ Accettura et al, Towards a Muon Collider '23 ·* ***CC*** *∈ IMCC, Interim Report '24 ·* ***CC*** *∈ Muon Collider ESPPU '25*

COMPARISON OF FUTURE COLLIDERS

pp

$\mathcal{O}(85+)$ TeV

QCD



Pro

High energy, known

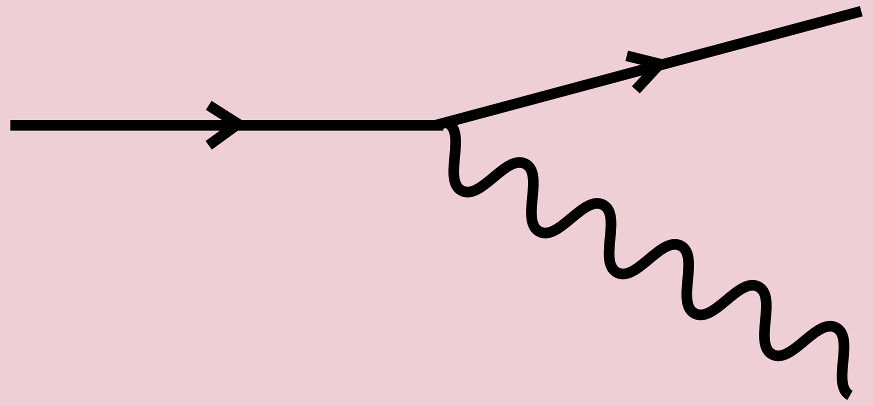
Con

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^-

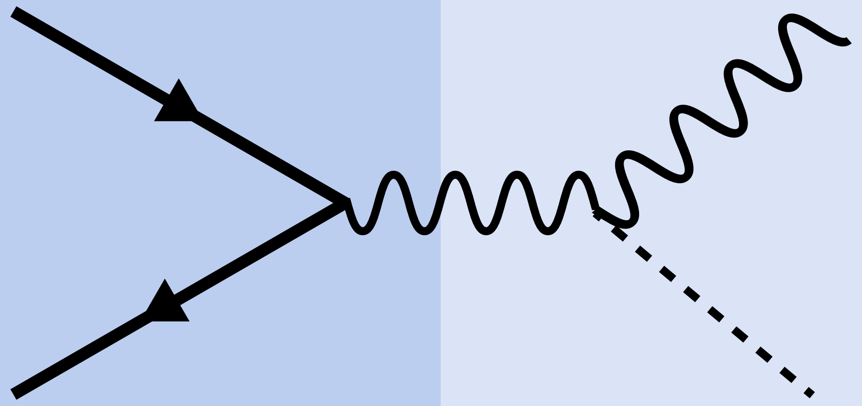
Circular

Linear

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs



Pro

Precision, known, upgrades

Con

Low Energy,

Funding

Uncertain

Max 3 TeV

*Not to Scale

COMPARISON OF FUTURE CIRCULAR COLLIDERS

pp

FCC-hh

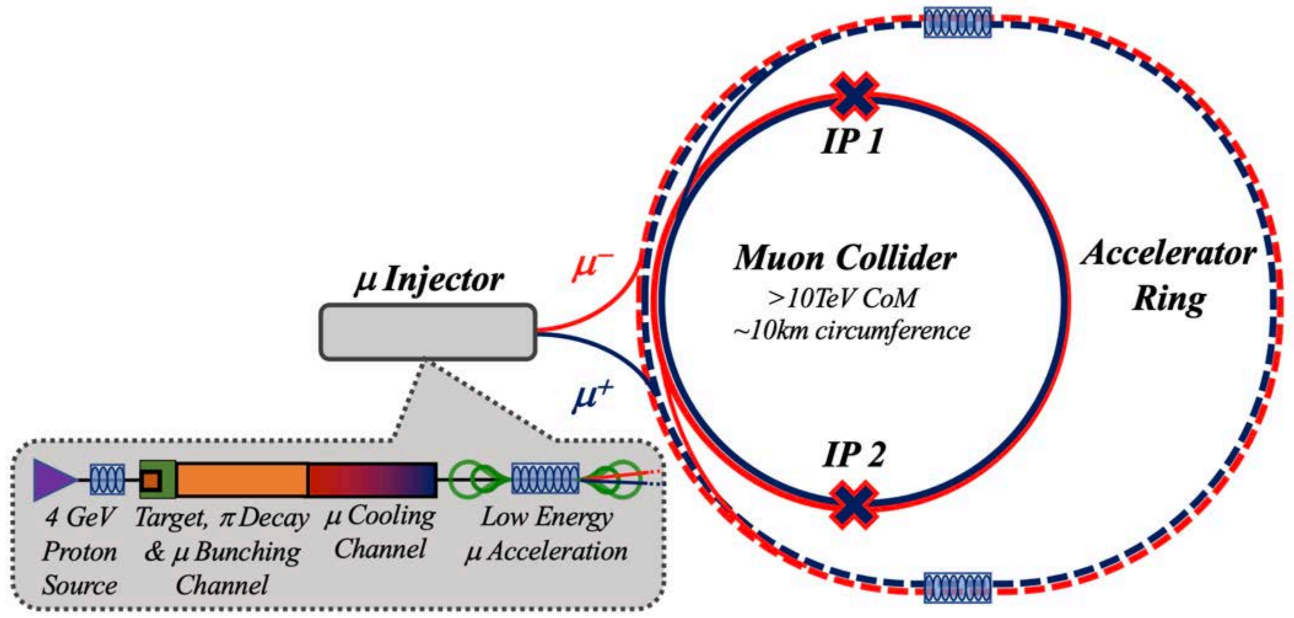
$\mathcal{O}(91\text{ km})$

$\sqrt{s} = 85+$ TeV

$\mu^+\mu^-$

MuC

$\mathcal{O}(10\text{ km})$



$\sqrt{s} = 3$ TeV (energy stage)

$\sqrt{s} = 10$ TeV

e^+e^-

FCC-ee

$\mathcal{O}(91\text{ km})$

$\sqrt{s} \sim m_Z - 350$ GeV

*Not to Scale

COMPARISON OF FUTURE CIRCULAR COLLIDERS

pp

$\mu^+\mu^-$

MuC

$\mathcal{O}(10\text{ km})$

e^+e^-

FCC

$\mathcal{O}(91$

CC-ee

(91 km)

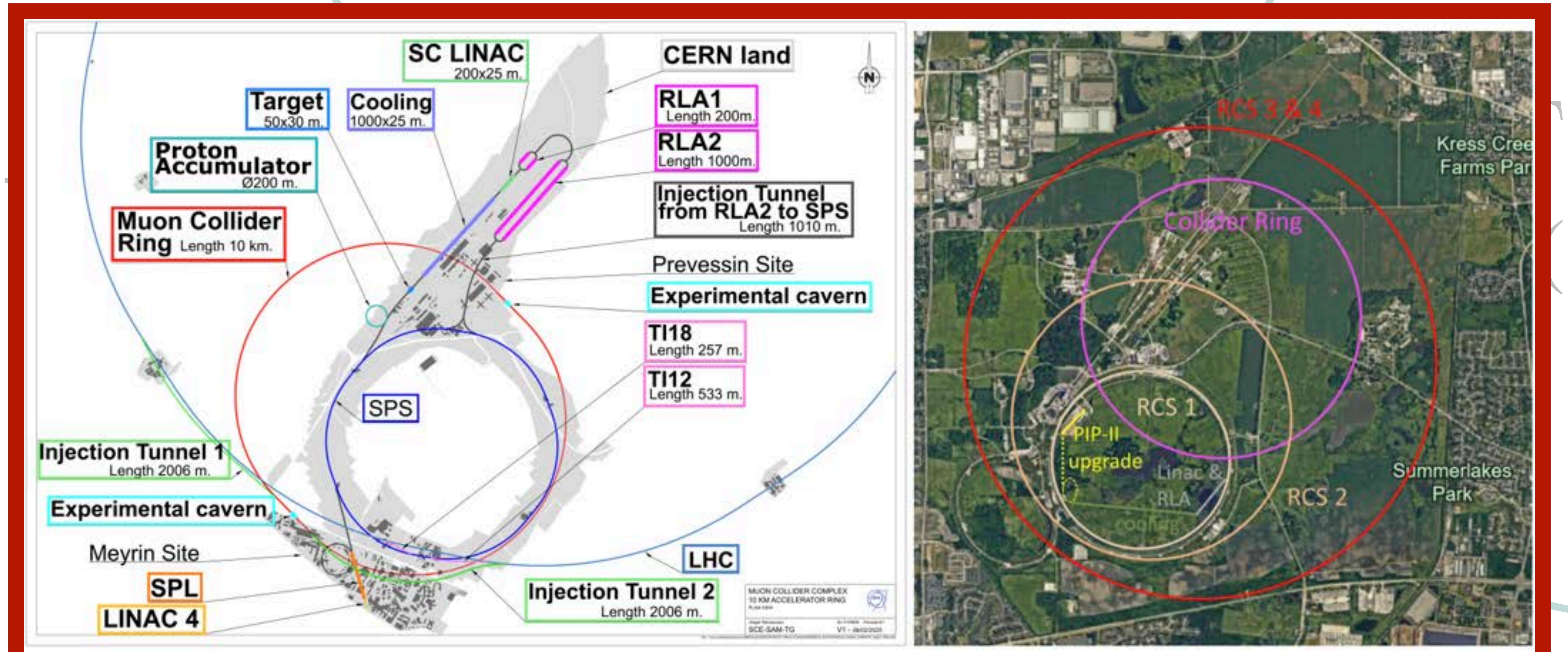


Figure 1.7.1: Conceptual layout of the muon collider at CERN (left) and Fermilab (right).

$\sqrt{s} = 85+$ TeV

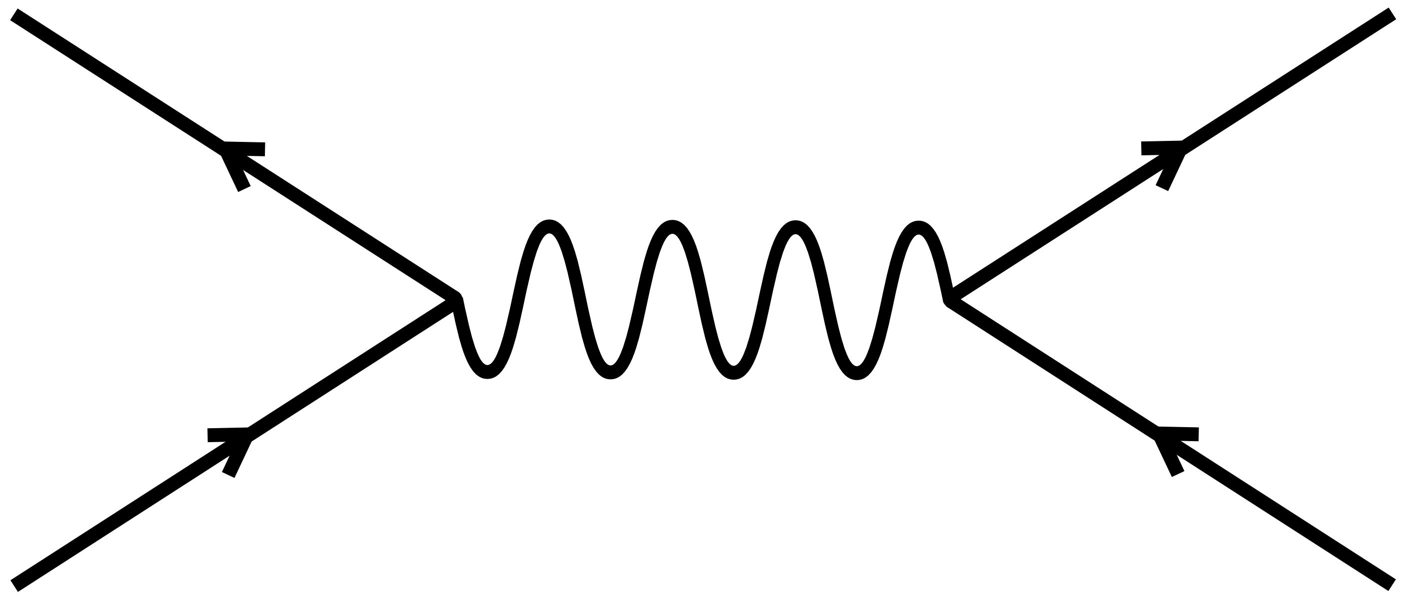
$\sqrt{s}$ $m_Z - 350$ GeV

COMPARISON OF FUTURE LEPTON COLLIDERS

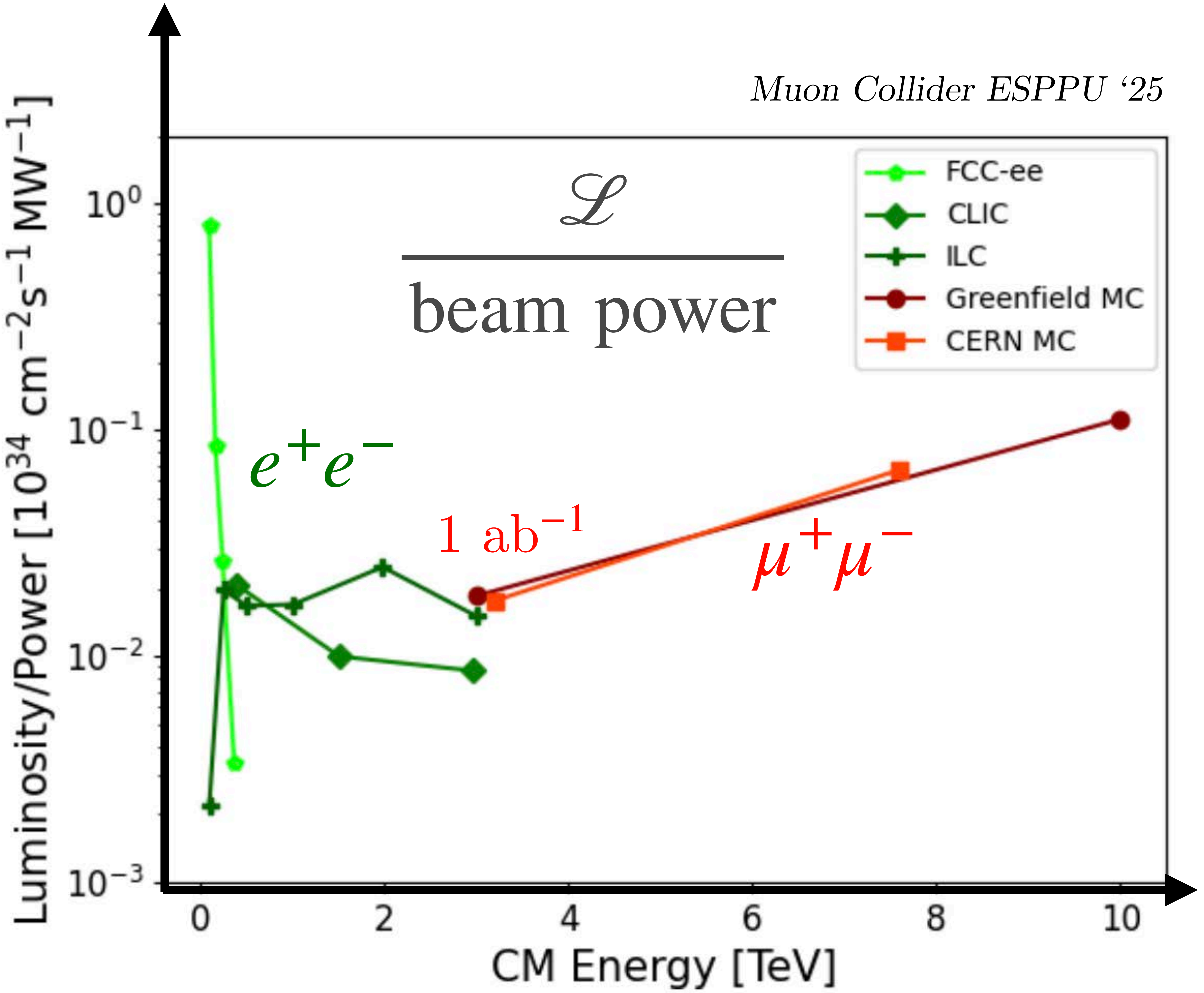
Muon colliders gain energy and luminosity more efficiently

Heavy searches are s-channel processes

Need to maintain luminosity



$$\mathscr{L} \sim \frac{N_\mu}{\text{bunch}} \times E^2 \sim \frac{1}{s}$$



MUON COLLIDER STAGING

10 TeV at 10 km collision ring requires 16 T magnets (like FCC-hh)

Energy Stage

3 TeV benchmark

Reuse all cooling & acceleration

(*except collision ring*)

Possible with existing magnet technology

Luminosity Stage

10 TeV at 1 ab^{-1}

Reuse much of infrastructure

(*replace* 11 T → 16 T *magnets*)

Possible with existing magnet technology

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10 TeV at 1 ab^{-1}

Reuse much of infrastructure

(*replace* 11 T → 16 T *magnets*)

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Makes the most sense in global context?

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What are the biggest challenges for a muon collider?

Muons decay

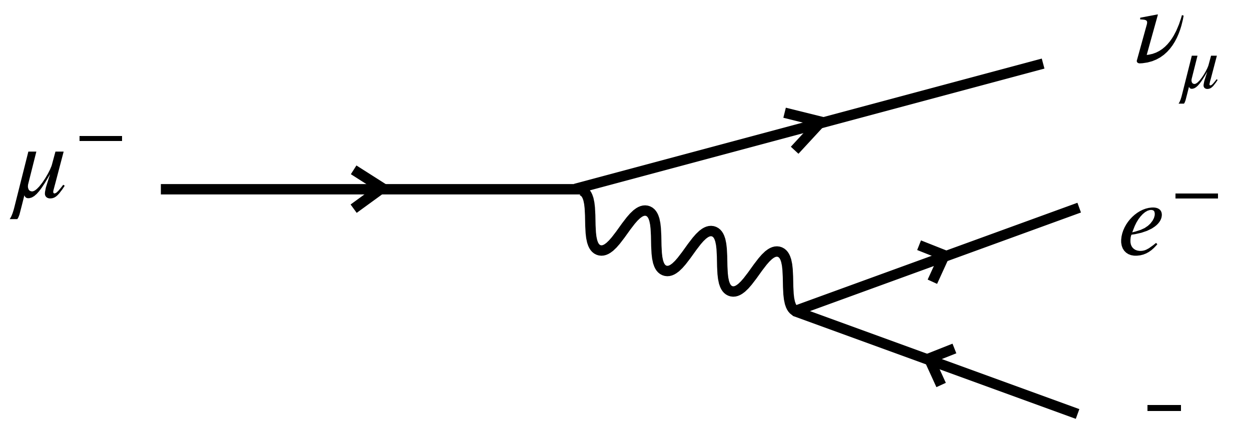
What physics can we do at muon colliders?

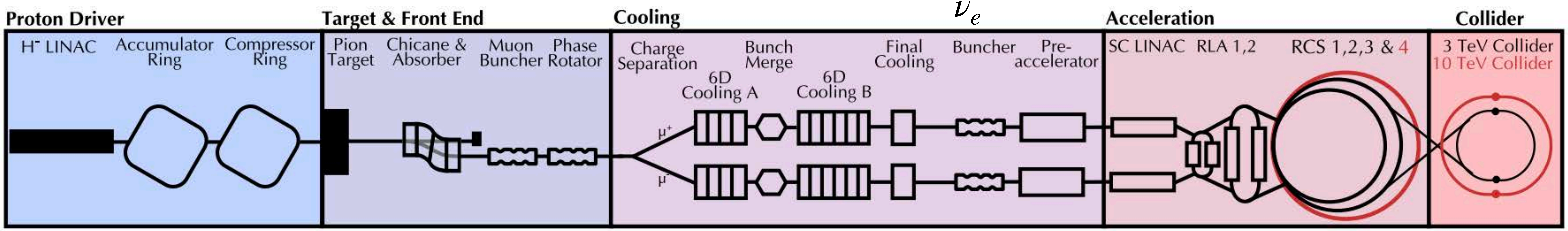
Electroweak · Heavy BSM · Flavor Couplings · ν studies...

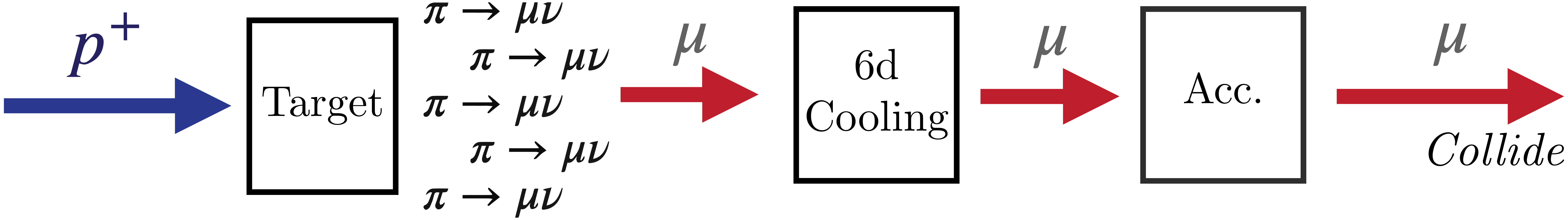
CHALLENGES OF MUC

Muons decay.

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







p^+

Target

$\pi \rightarrow \mu\nu$

$\pi \rightarrow \mu\nu$

$\pi \rightarrow \mu\nu$

$\pi \rightarrow \mu\nu$

$\pi \rightarrow \mu\nu$

μ

6d Cooling

μ

Acc.

μ

Collide

CHALLENGES OF MUC

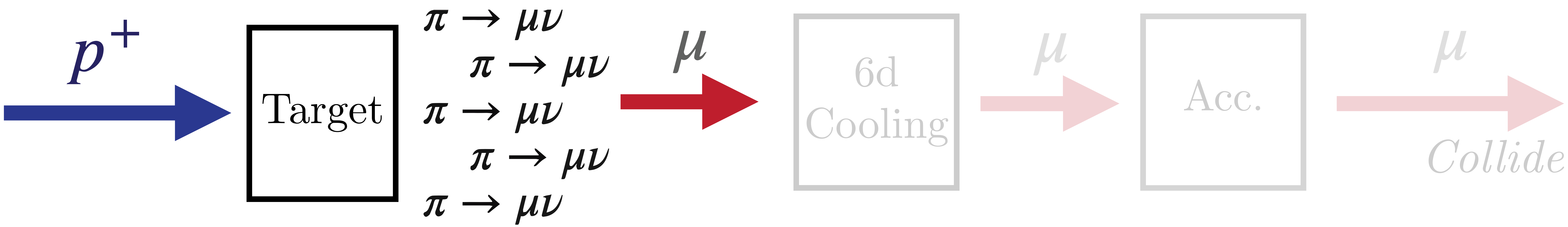
Muons decay.

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

PRODUCTION

Tertiary beam

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



Challenges of MuC

Muons decay.

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

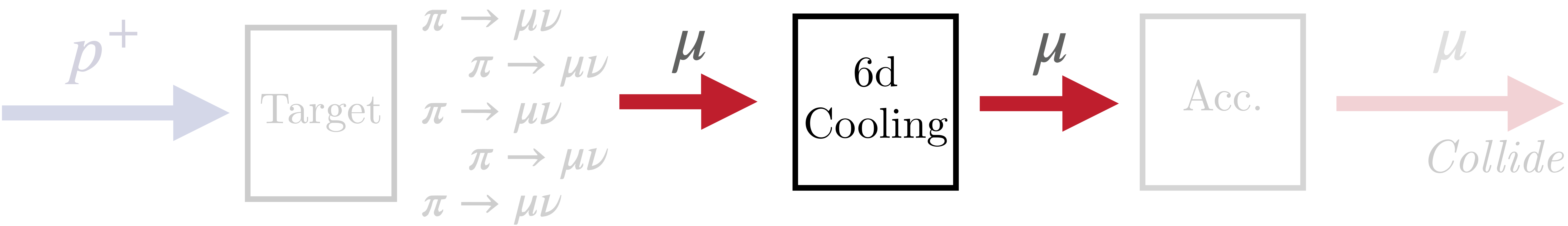
Production

Tertiary beam

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

Cooling into single collimated bunch

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



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Production

Tertiary beam

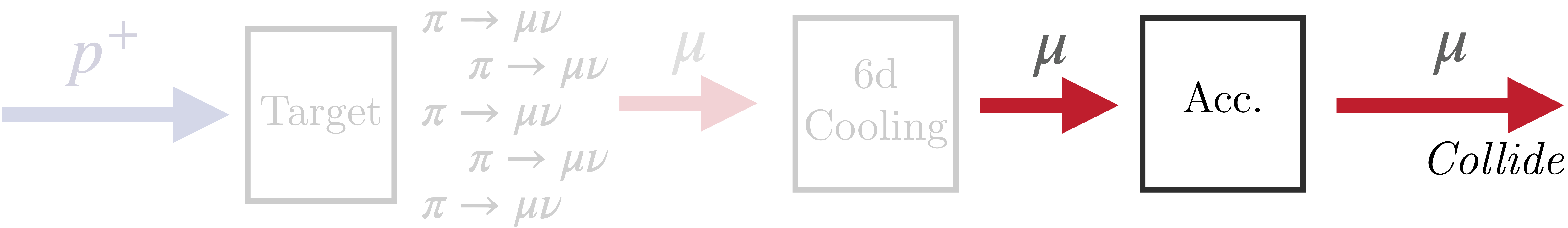
$$\Delta p/p \sim \mathcal{O}(1)$$

Cooling into single collimated bunch

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

Acceleration and collision

Too quick to ramp up magnets



Challenges of MuC

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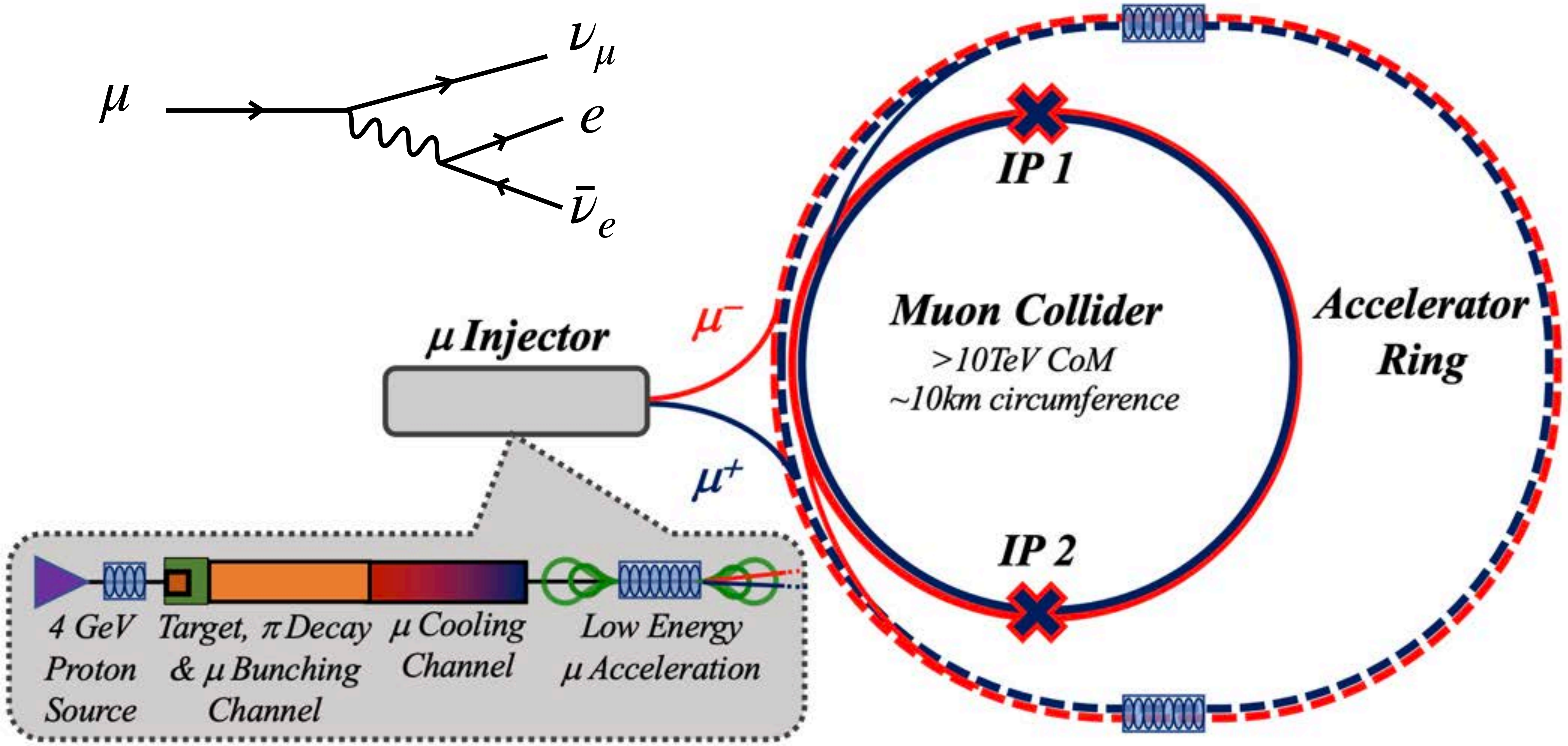

CHALLENGES OF MUC

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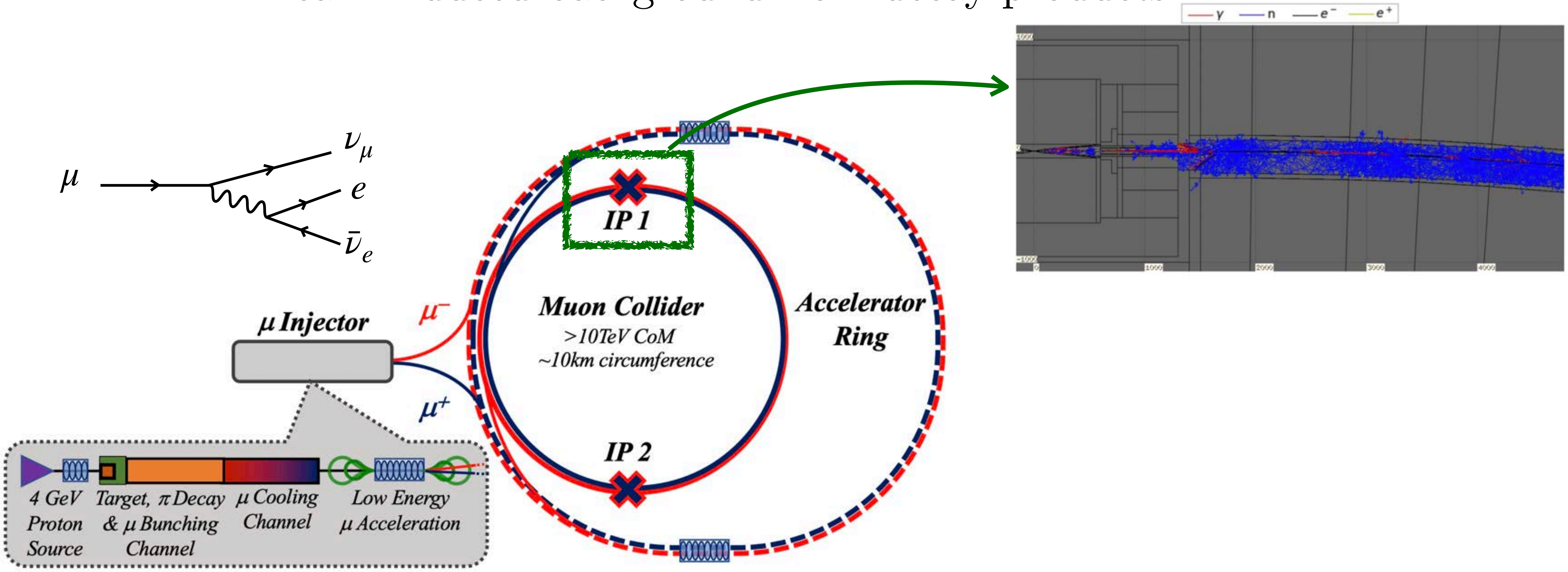
Beam-induced background from decay products



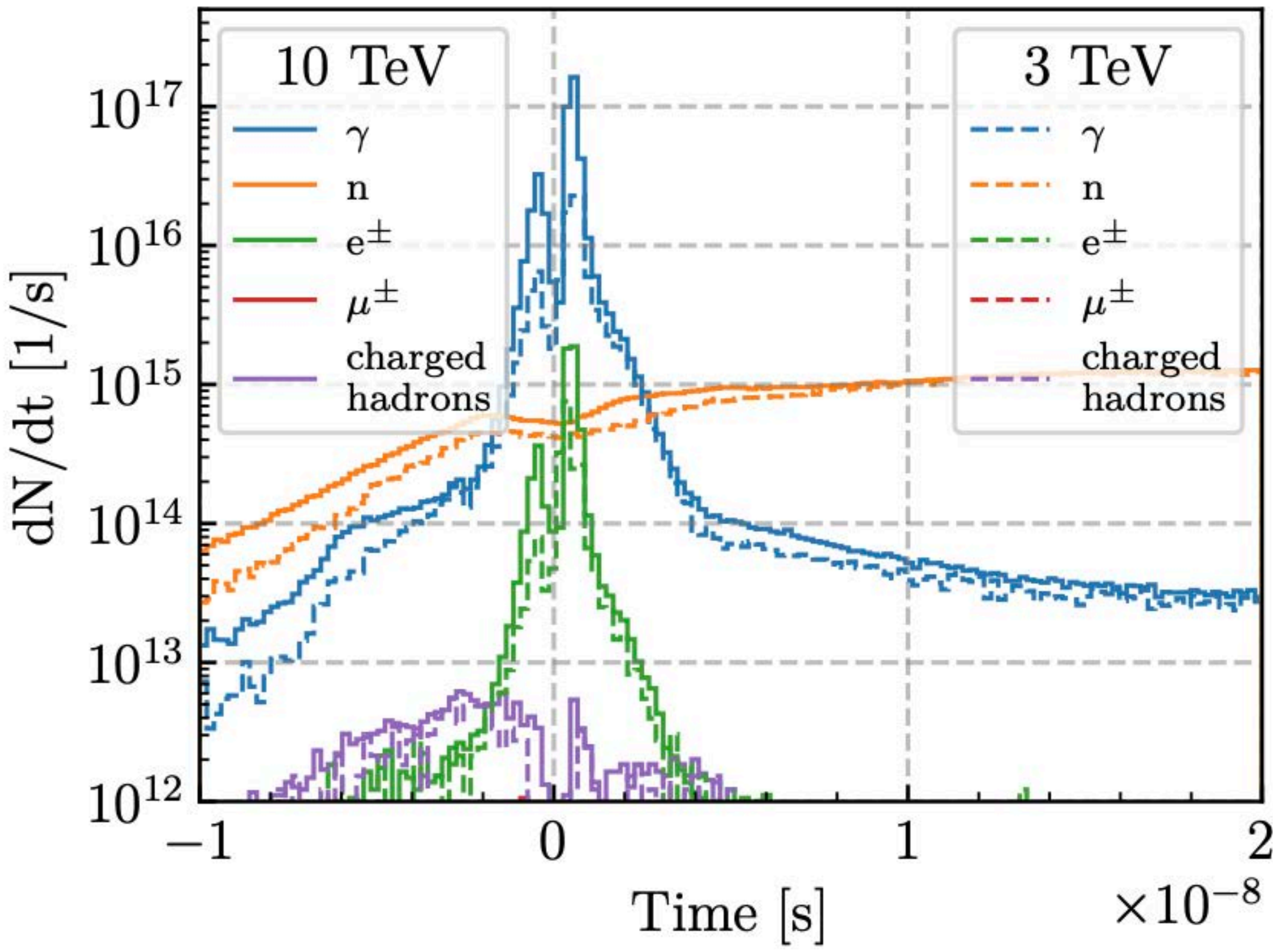
Challenges of MuC

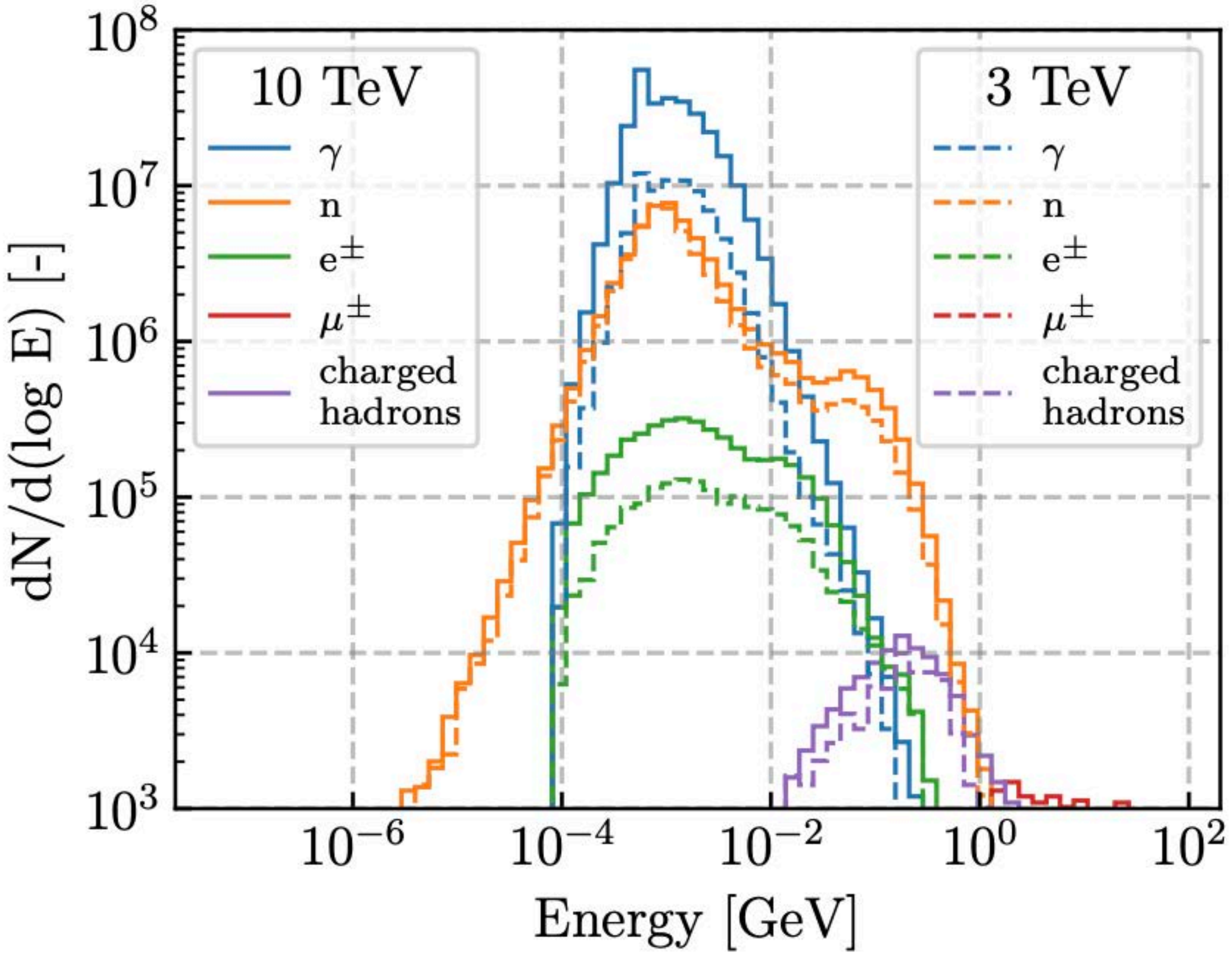
Muons decay.

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

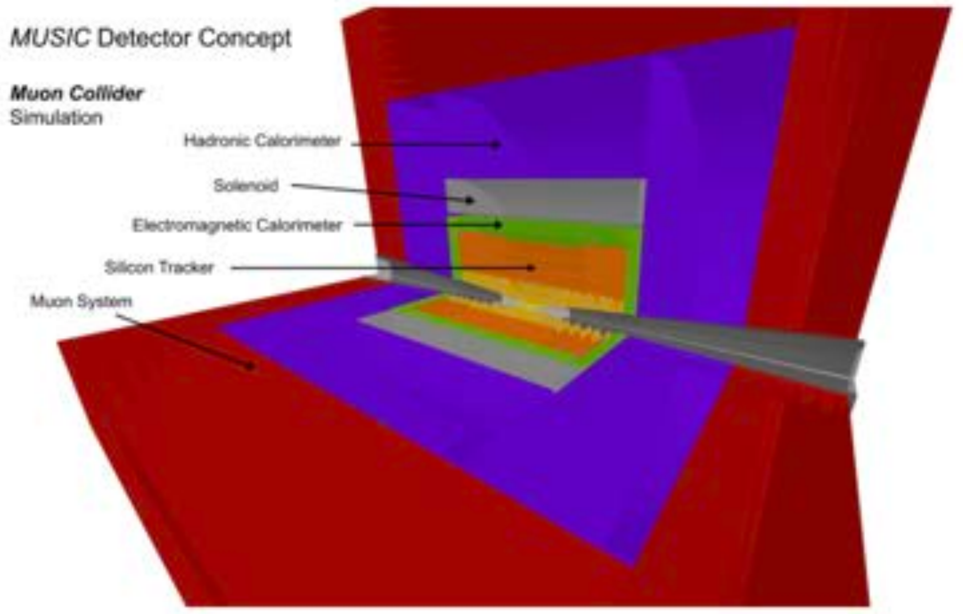
Beam-induced background from decay products

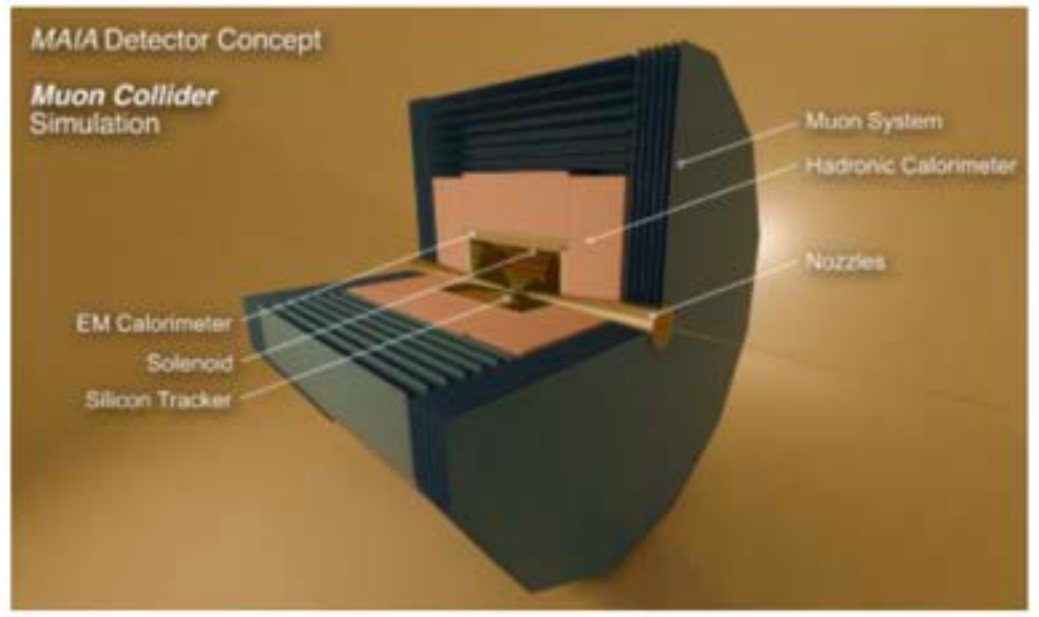
→ Mitigated with timing, kinematics, and shielding





MUSIC





MAIA

Challenges of MuC

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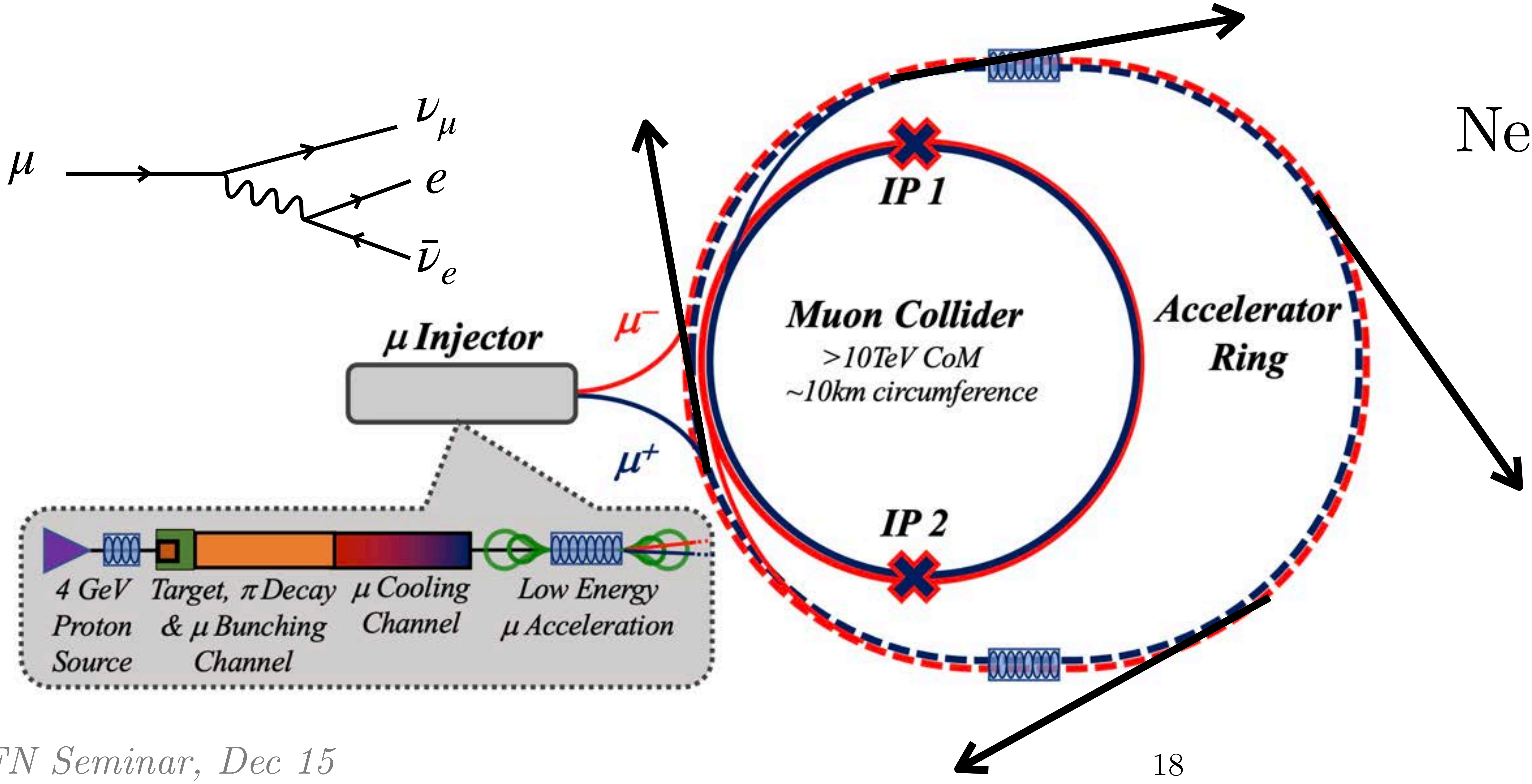
Beam-induced background from decay products

→ *Mitigated with timing, kinematics, and shielding*



Neutrinos interact at high energy

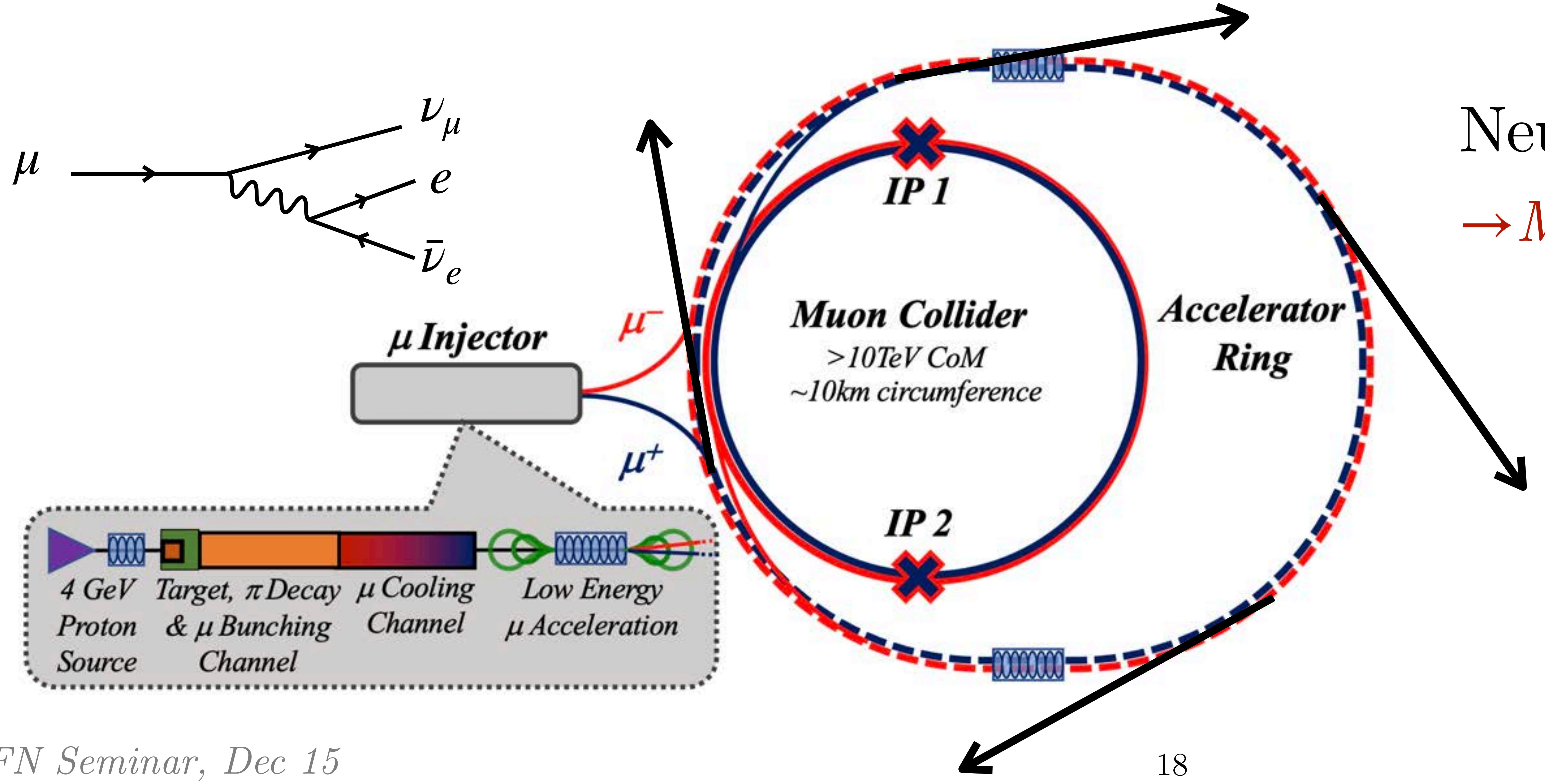
Challenges of MuC

Muons decay.

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

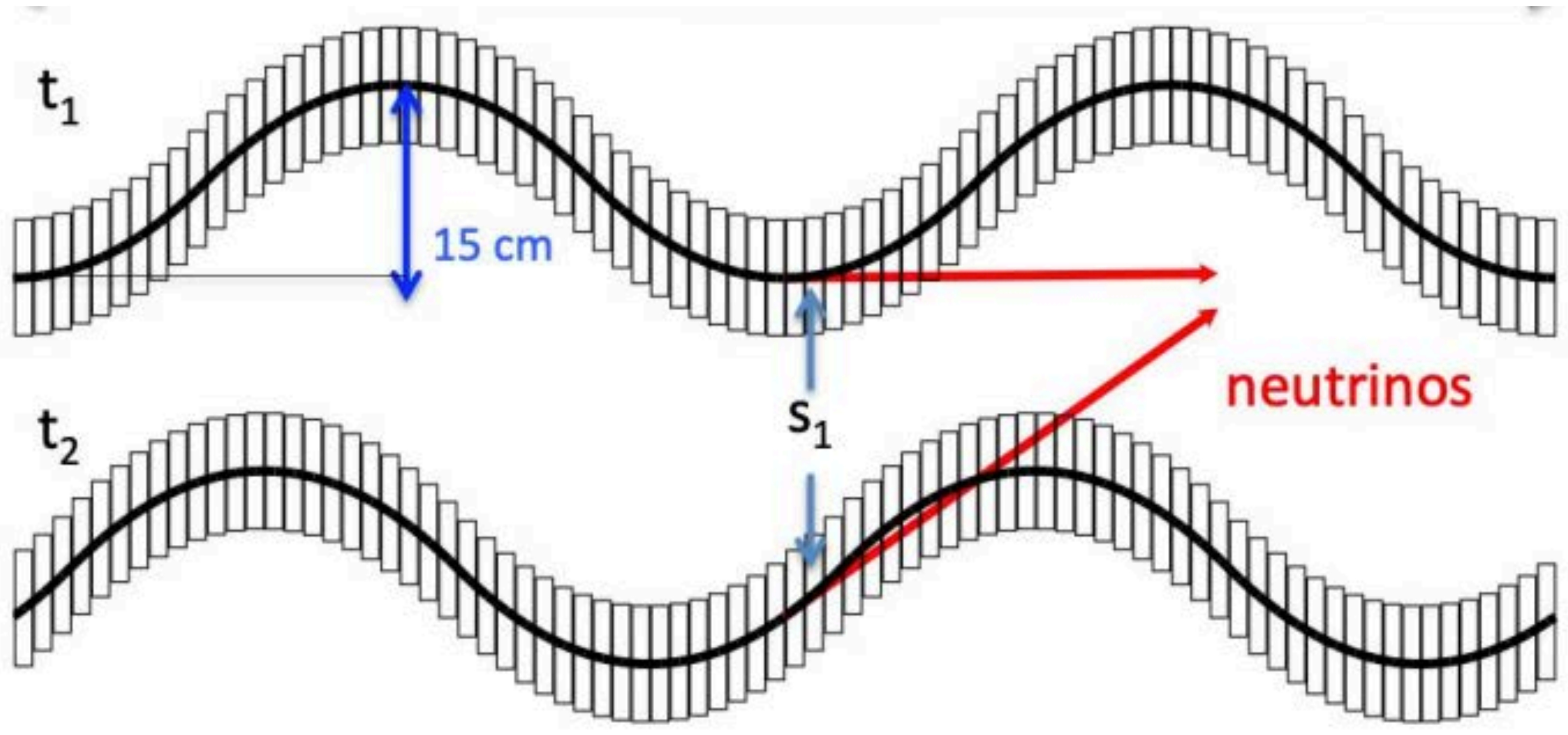
Beam-induced background from decay products

→ *Mitigated with timing, kinematics, and shielding*



Neutrinos interact at high energy

→ *Make ring deep & diffuse the beam*



Sketch credit: D. Schulte

Slide Credit: F. Meloni & A. Wulzer

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

Slide Credit: F. Meloni & A. Wulzer

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"

2025

NAS:
"Muon collider is US priority"

2026

EU Strategy

R&D

$\sim$ 50M/year × 10 years

OUTLINE

Why should we continue the collider physics program?

To understand the UV nature of the universe

How do muon colliders compare to other future colliders?

Precision and energy frontier machine

What are the biggest challenges for a muon collider?

Muons decay

What physics can we do at muon colliders?

Electroweak · Heavy BSM · Flavor Couplings · ν studies...

PHYSICS REACH OF MUC

What are most relevant physics scenarios?

Electroweak Precision

Direct & Indirect BSM Production

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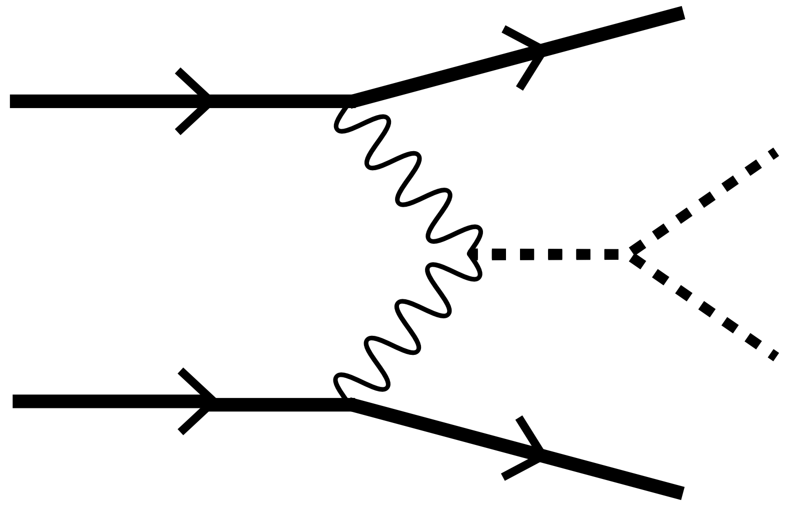
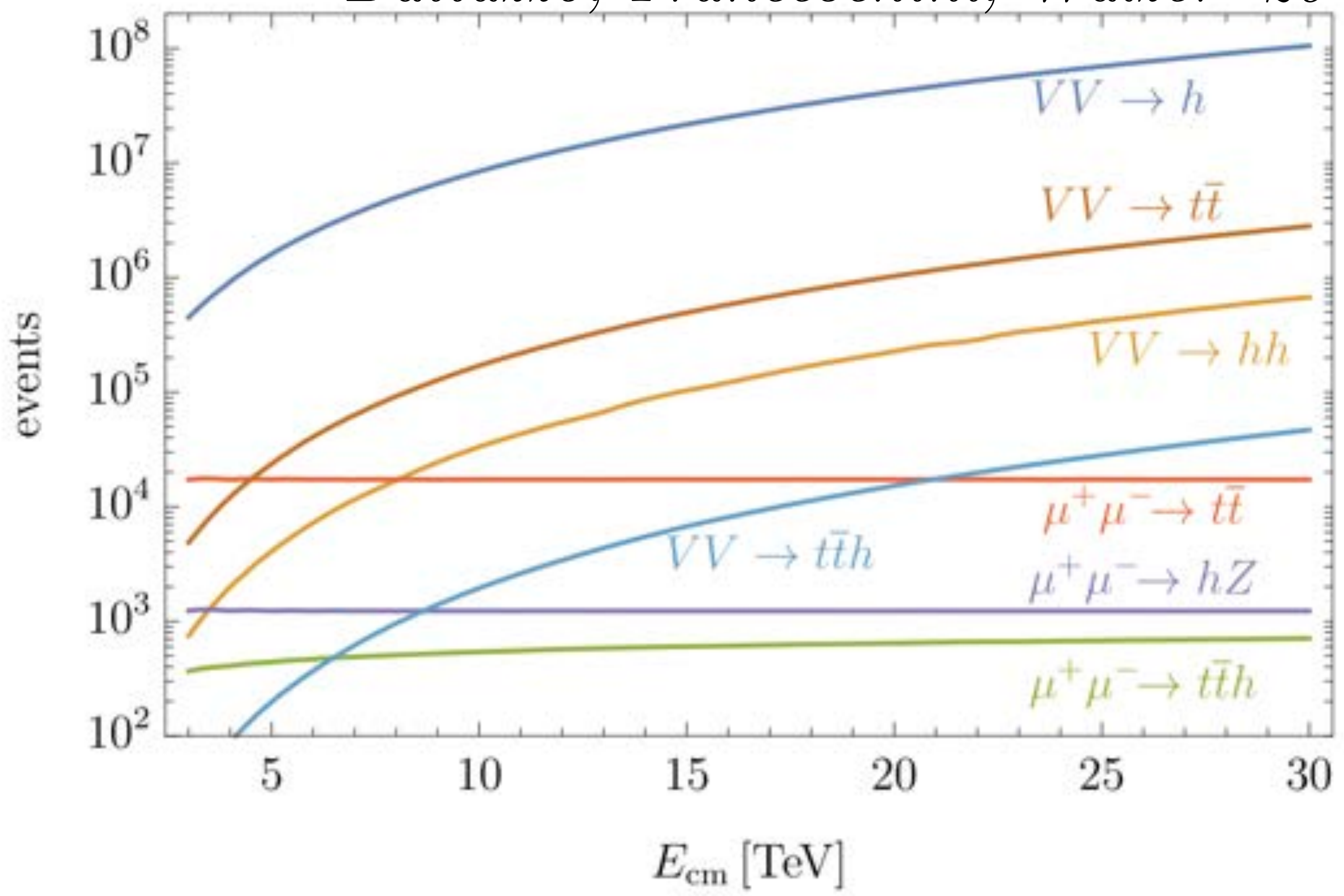
Direct & Indirect BSM Production

"Deliverables"

Higgs · EWSB · VBF



Buttazzo, Franceschini, Wulzer '20



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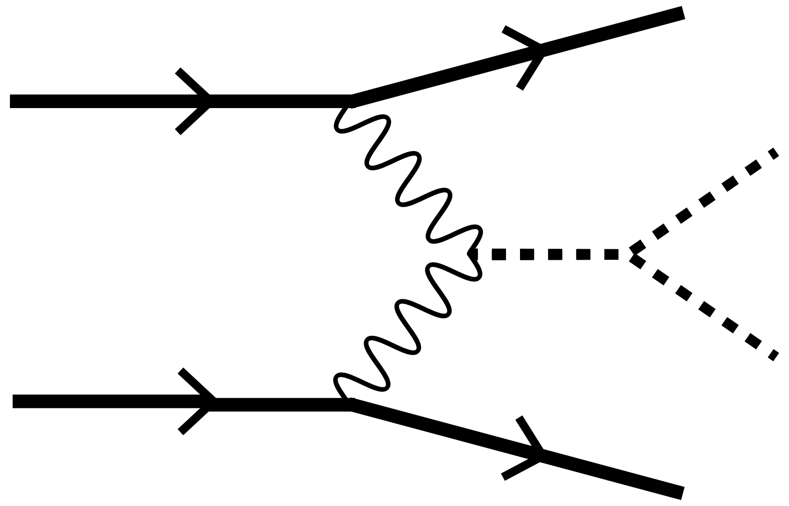

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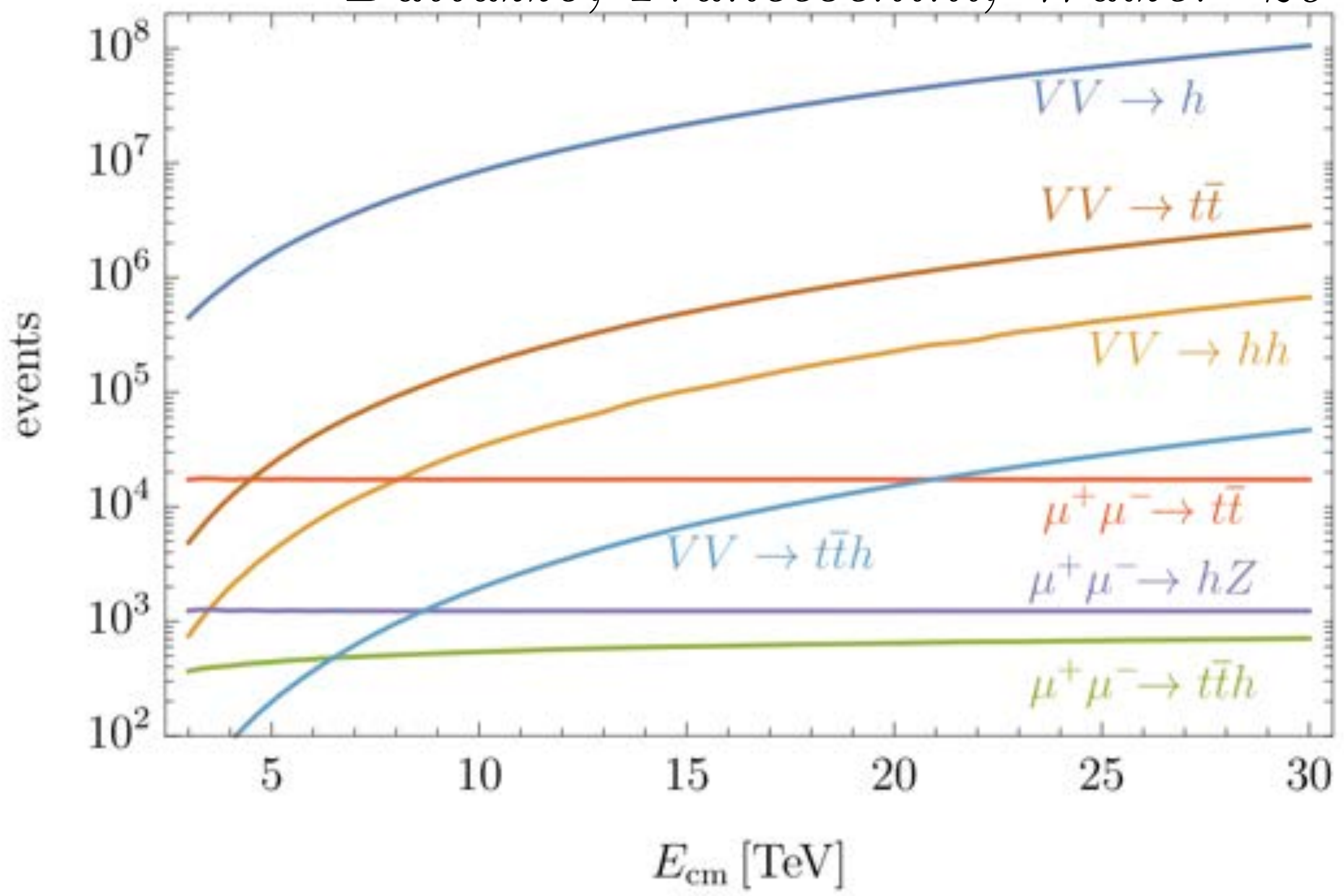
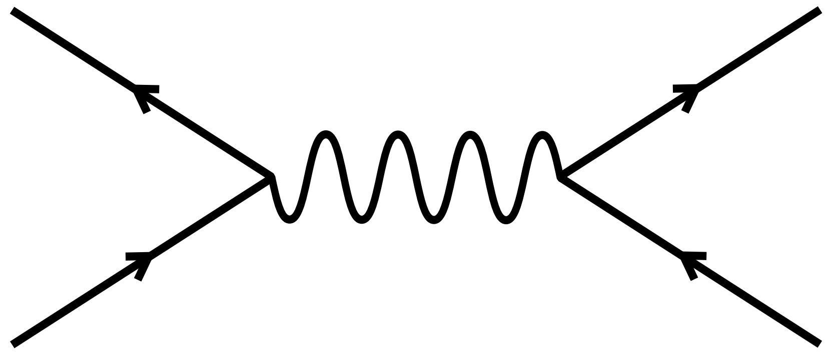


Direct & Indirect BSM Production

"Exploration Era"

New Physics Pair Production



$$m_{NP} \sim \sqrt{s}/2$$

Heavy Flavor Couplings

$$\mathscr{L} \supset g\frac{m_l}{v}\phi\bar{l}l$$

EFTs

$$[\mathcal{O}] = 6 \to g^2\frac{E^2}{\Lambda_{NP}^2}$$

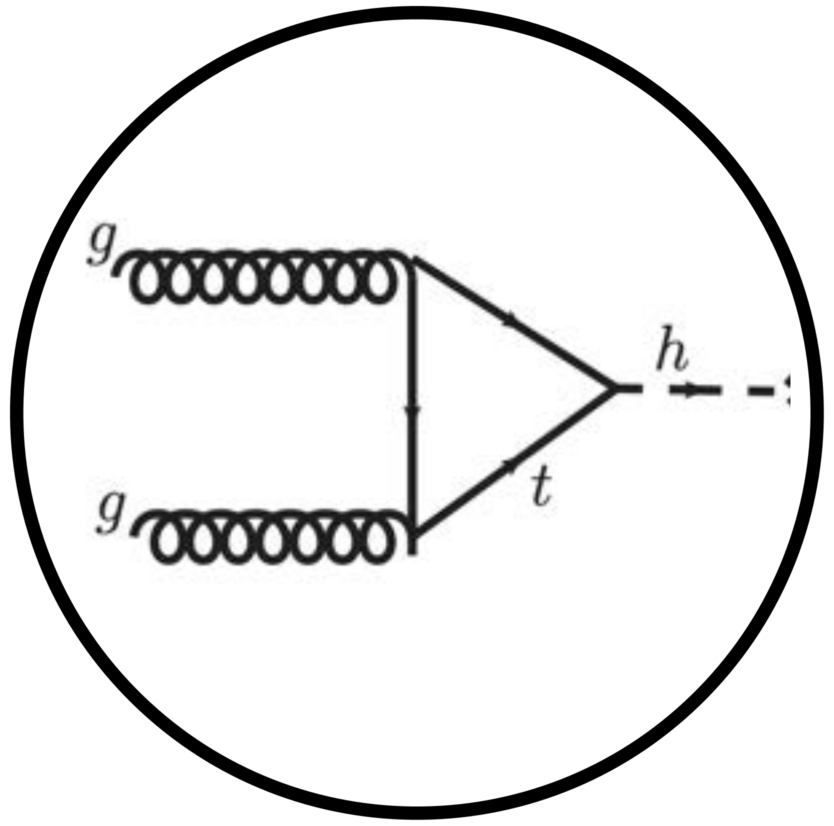
Electroweak Precision

“Deliverables”

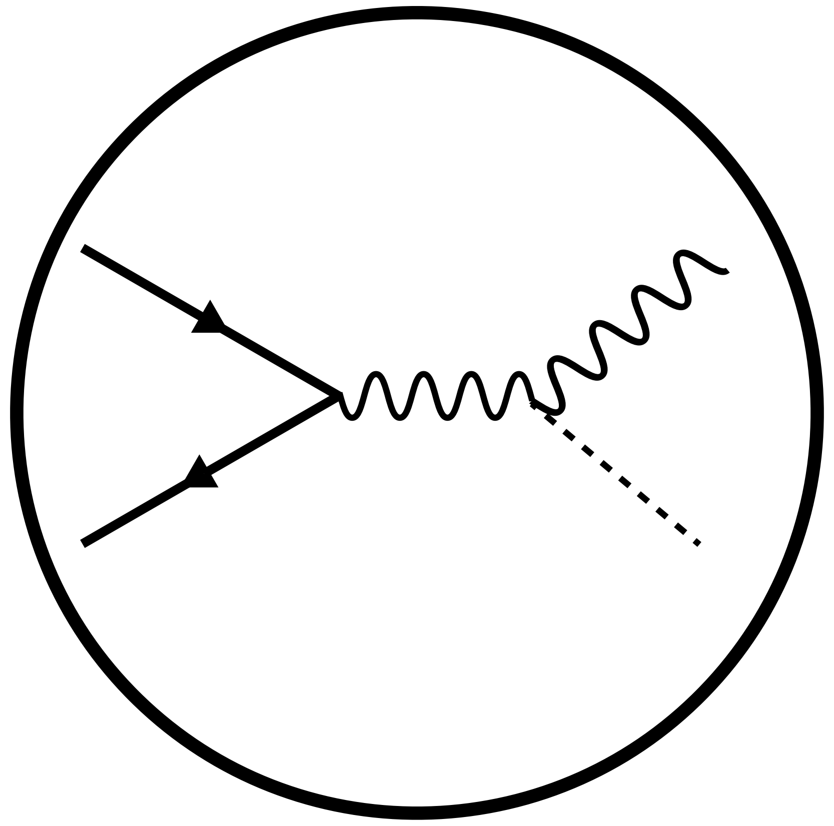
HIGGS PHYSICS AT MUON COLLIDERS

HIGGS PRODUCTION

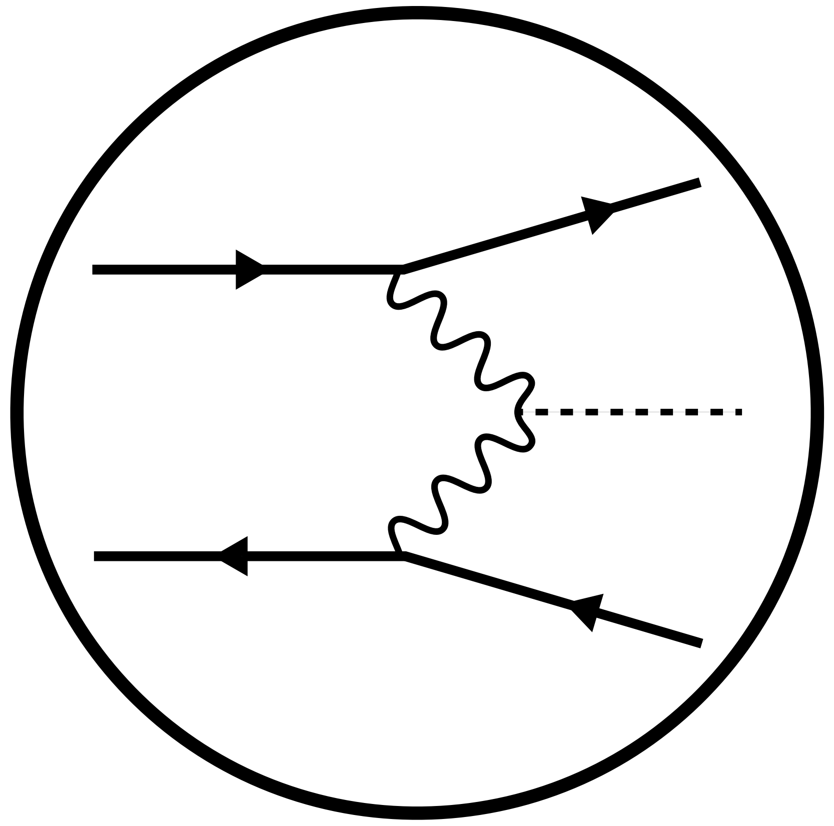
Hadron Colliders



Lepton Colliders



Low Energy

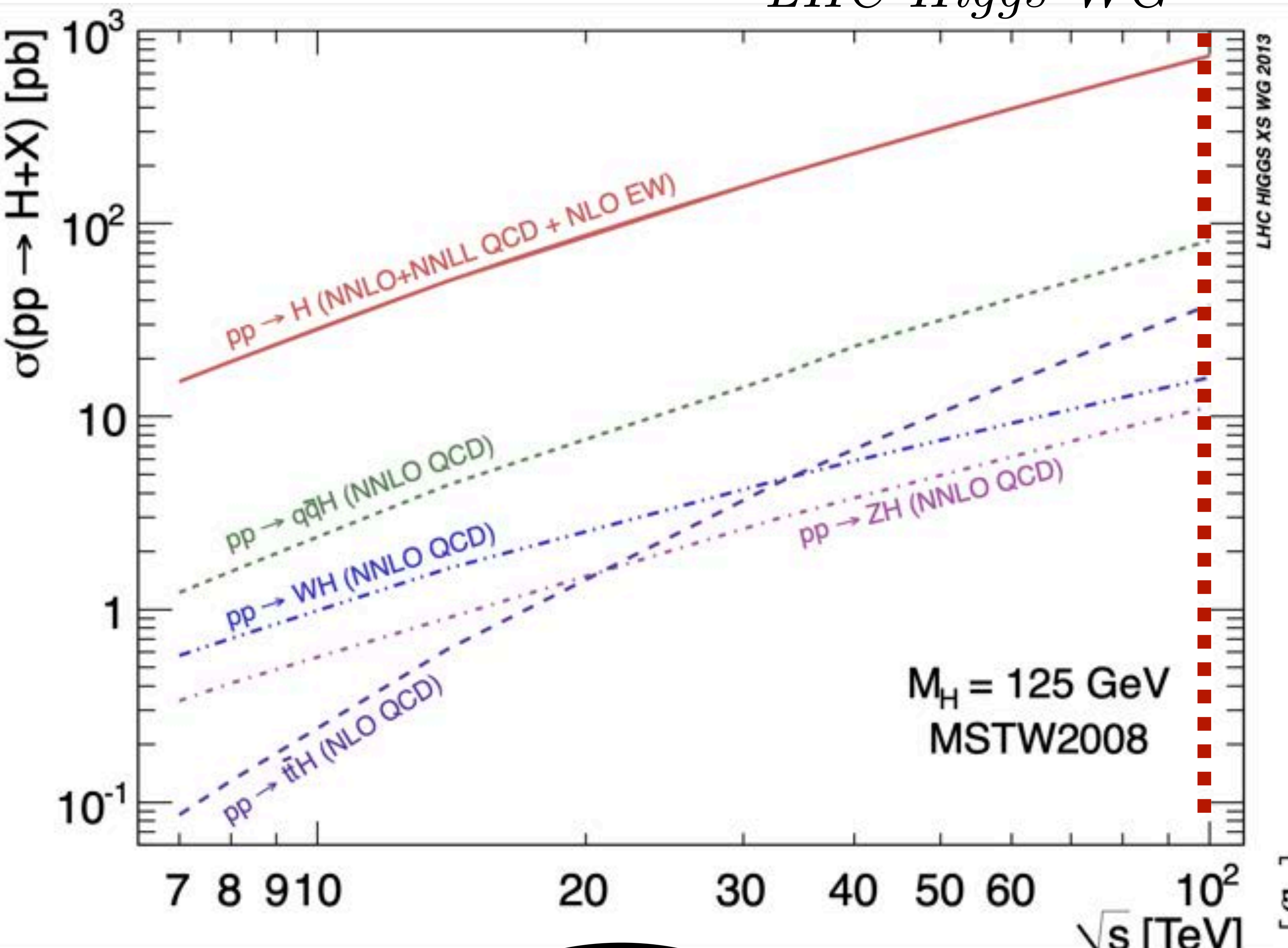


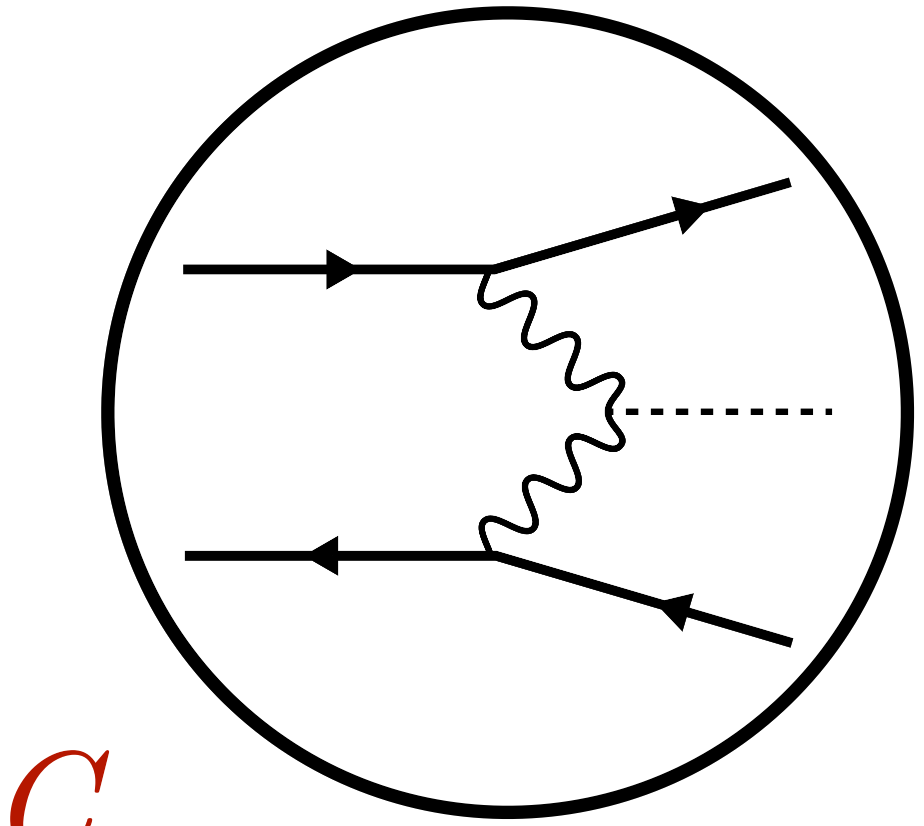
High Energy

HIGGS PRODUCTION

pp

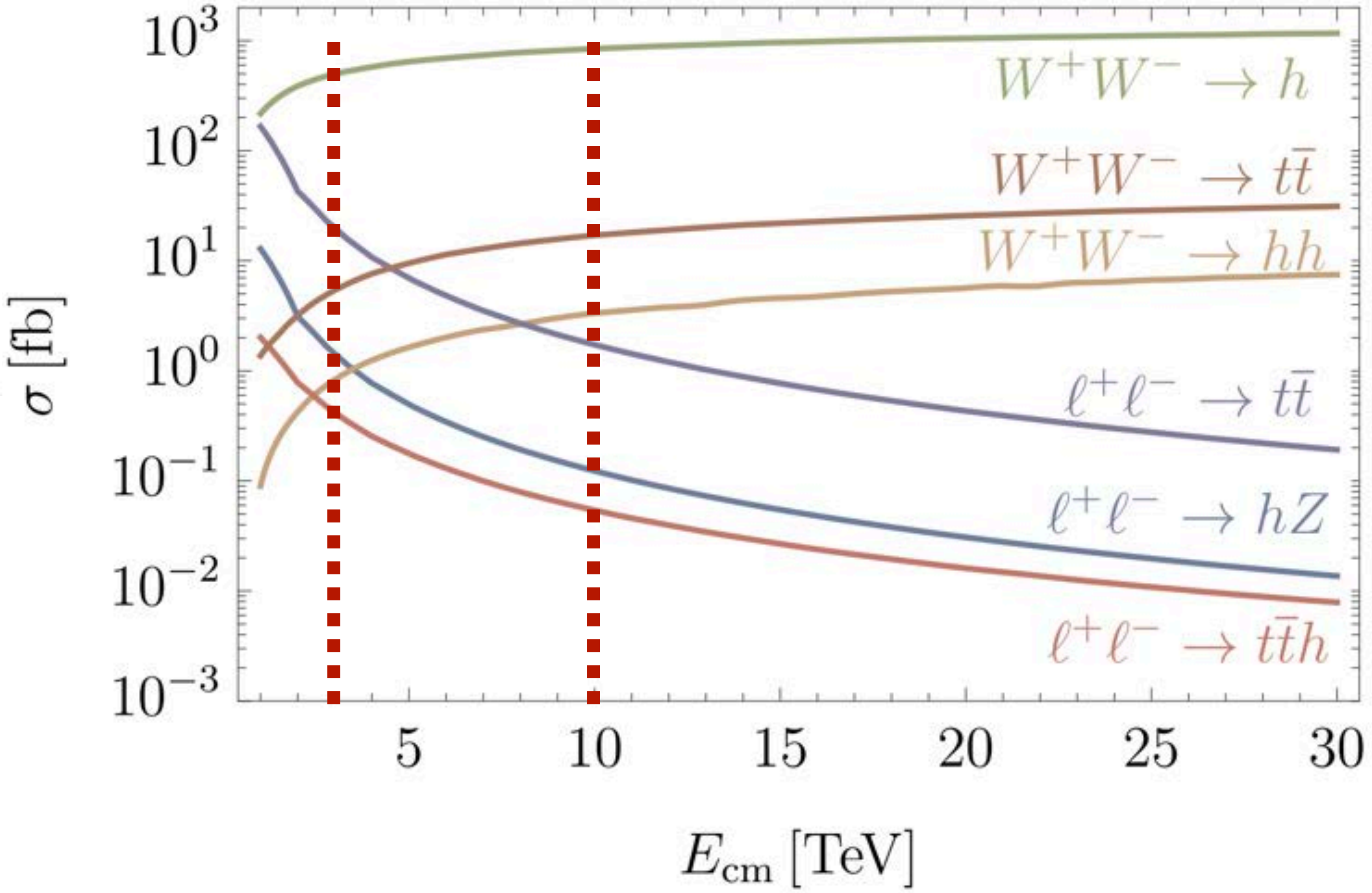
LHC Higgs WG





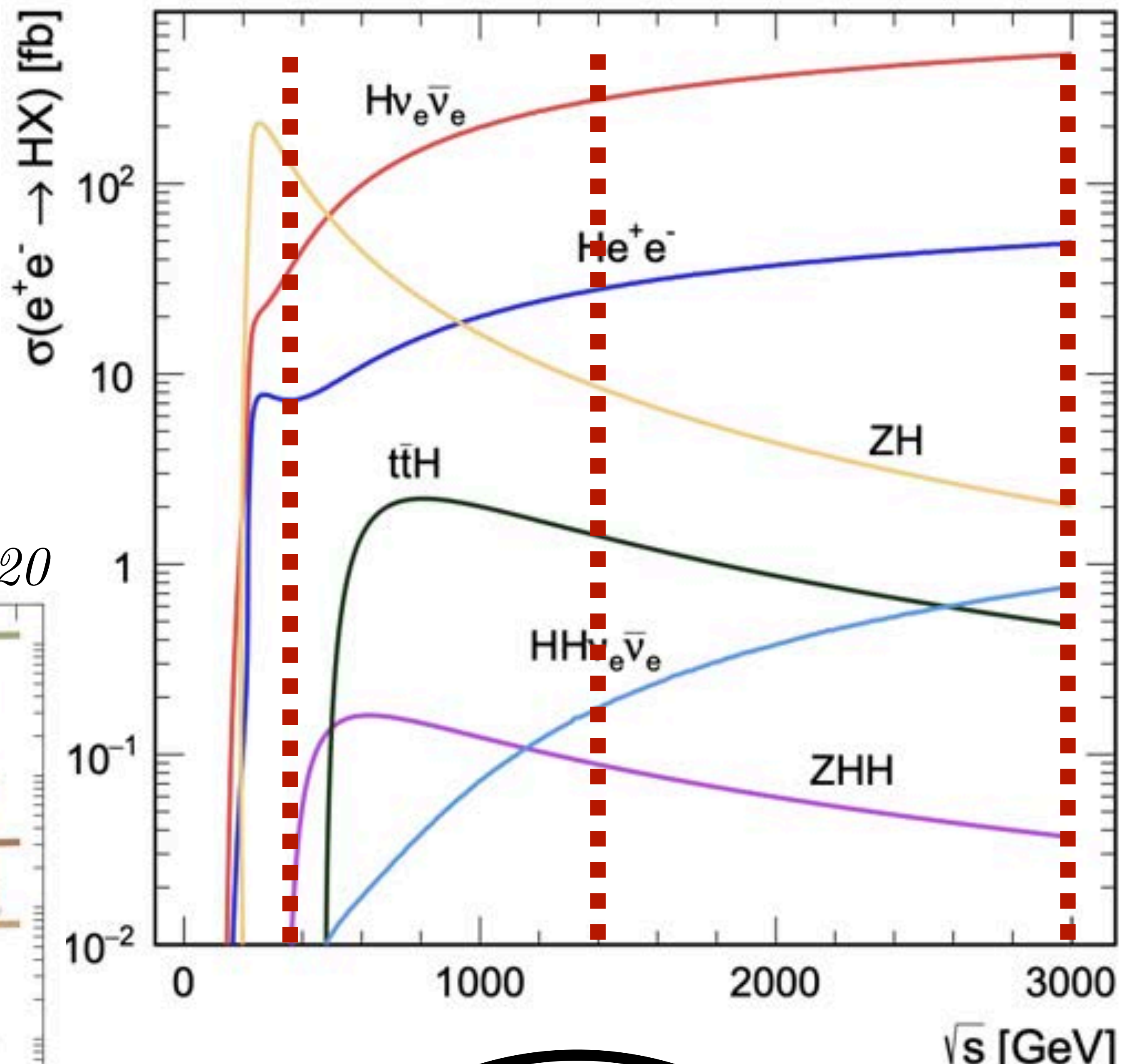
MuC

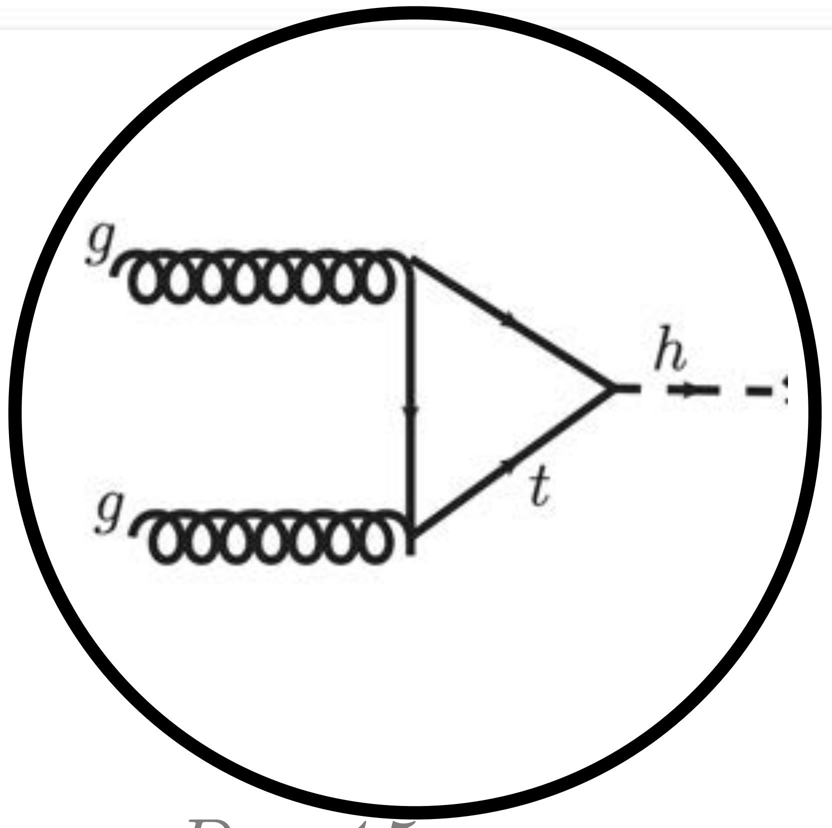
Buttazzo, Franceschini, Wulzer '20

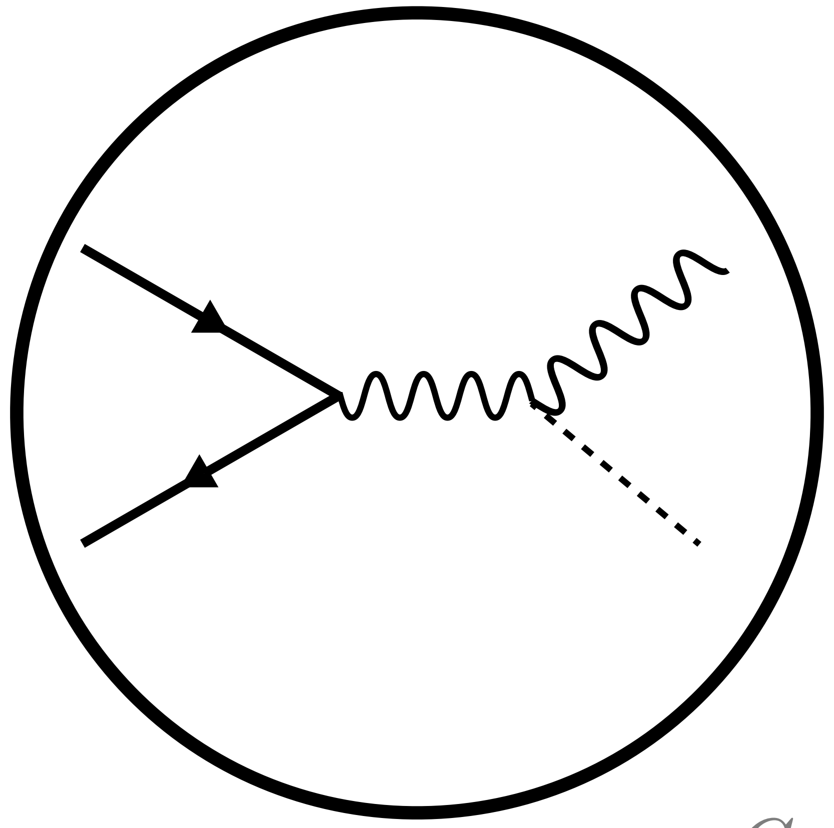


CLiC Summary Report

e^+e^-

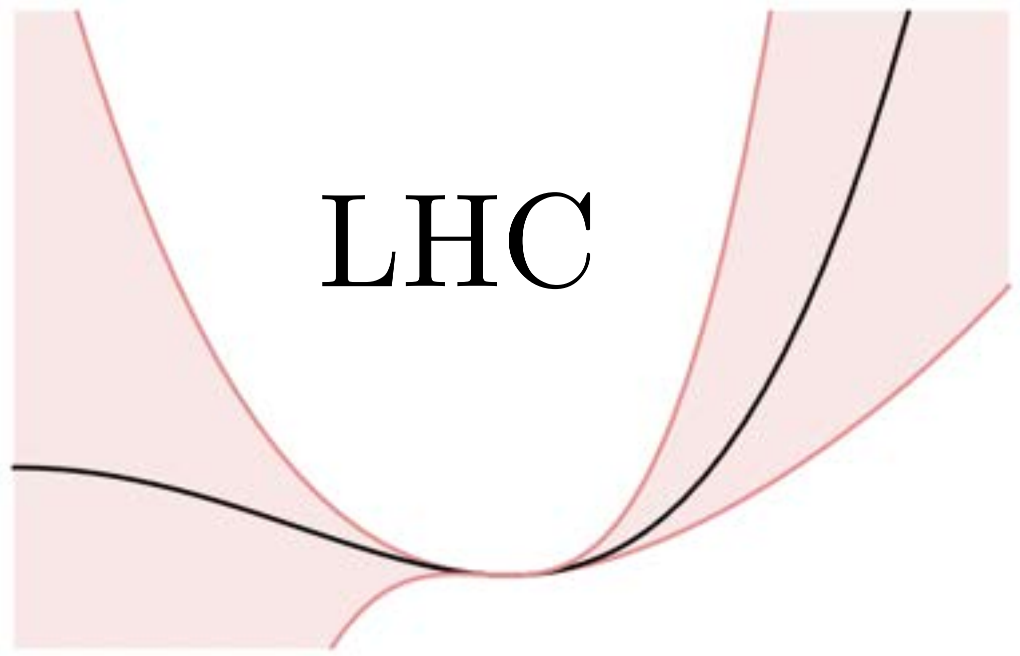






Slide Credit: P Meade, N Craig, R. Petrossian Byrne

HIGGS POTENTIAL



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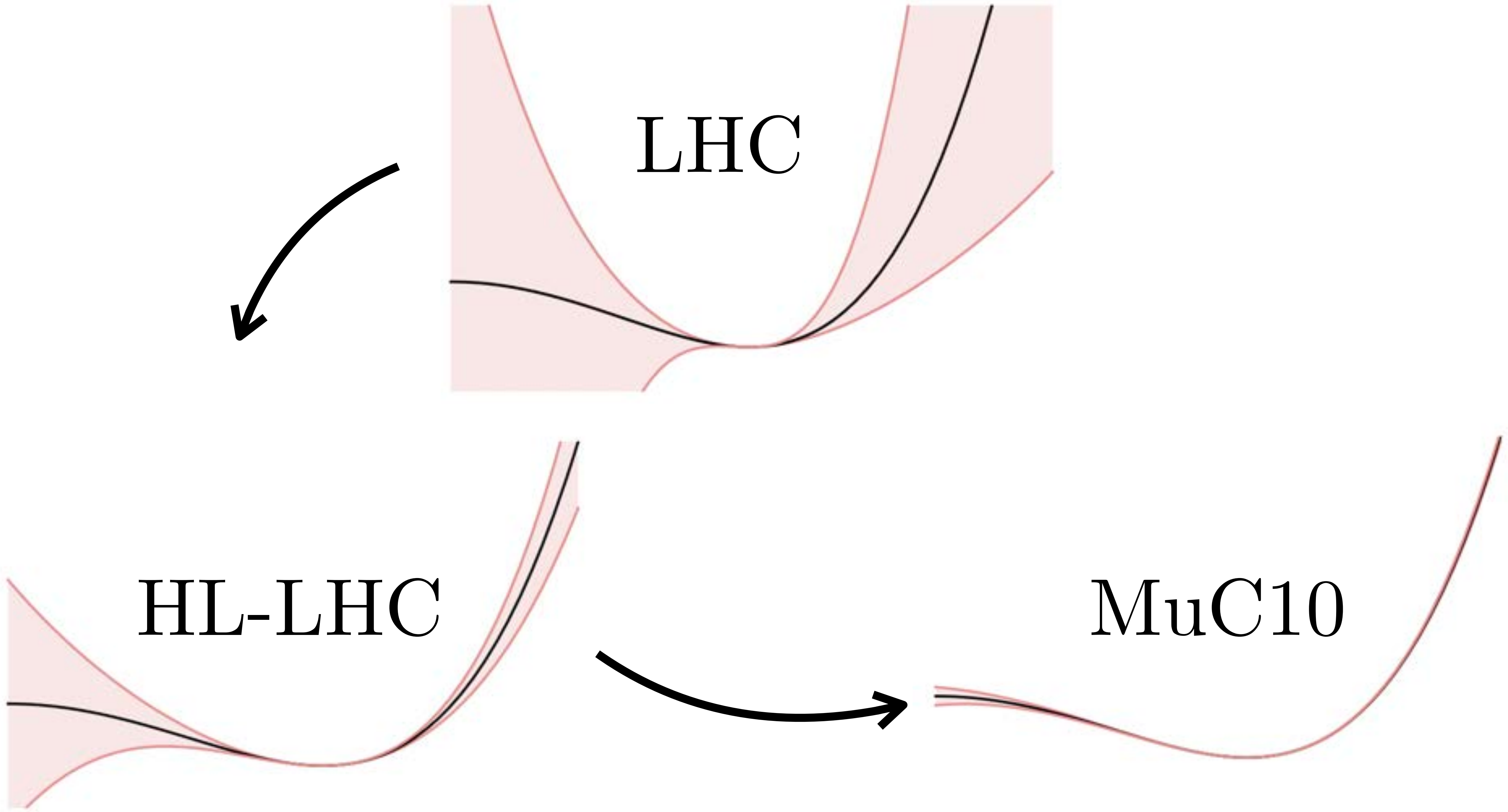


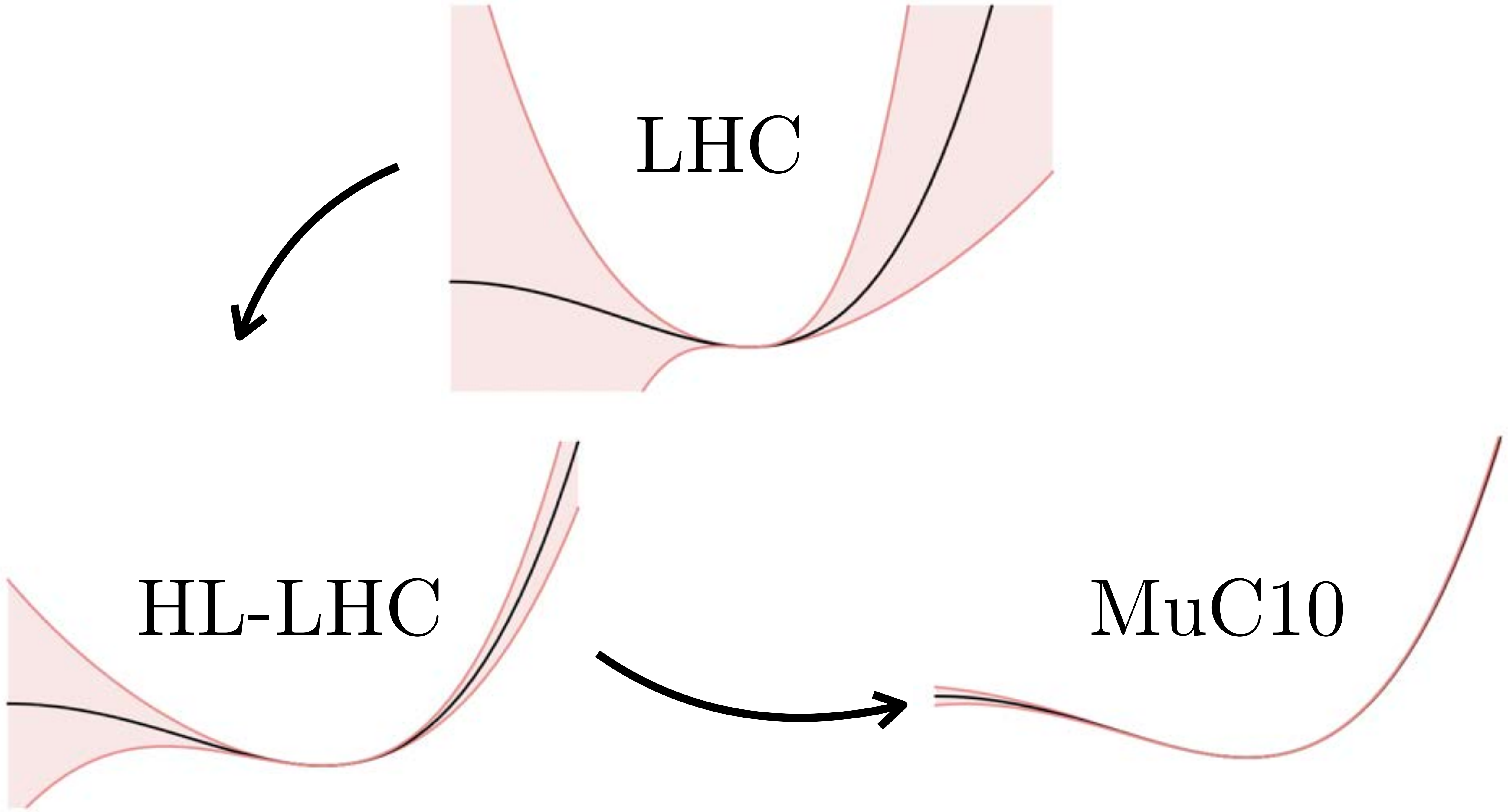
LHC

HL-LHC

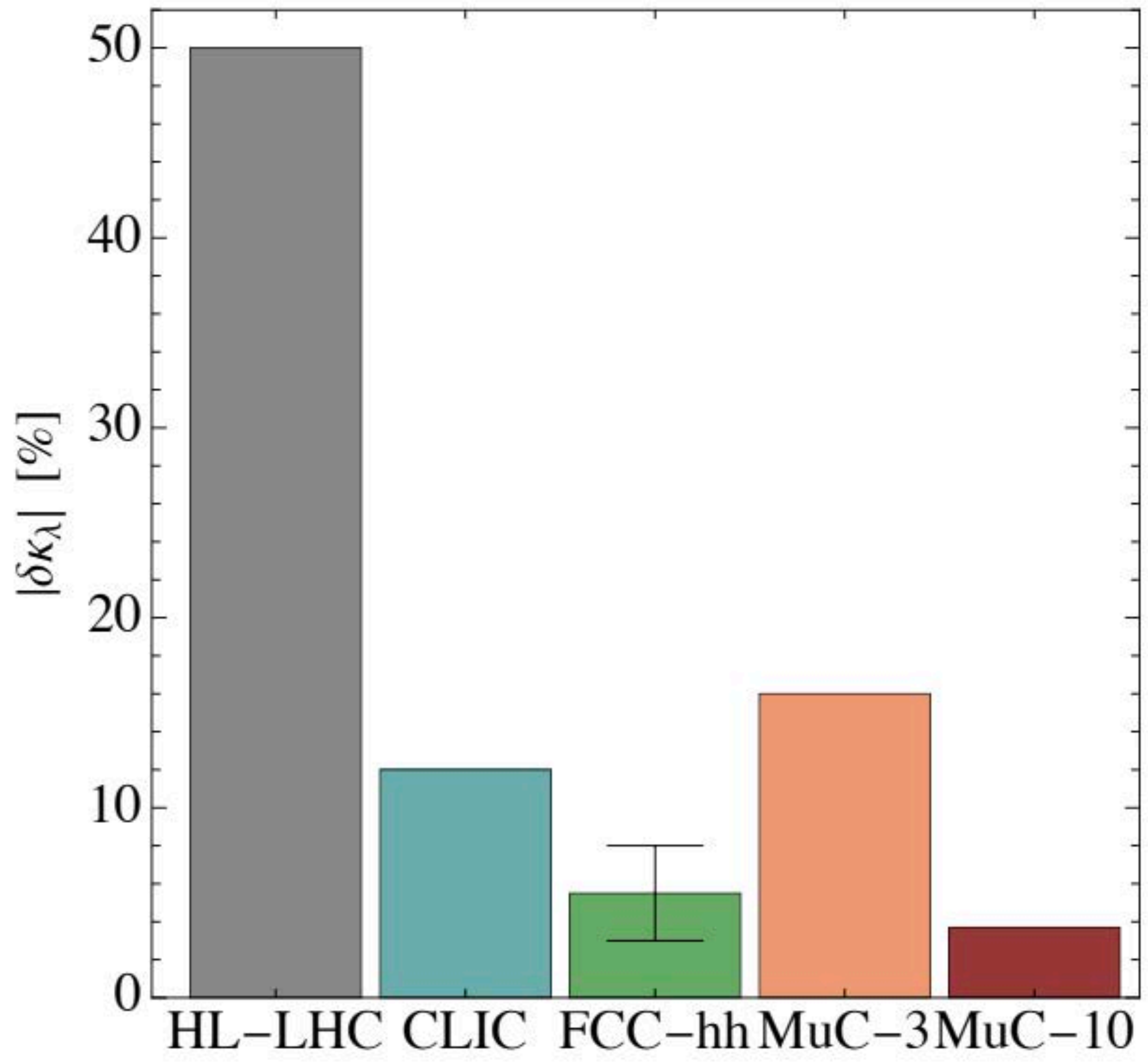
MuC10

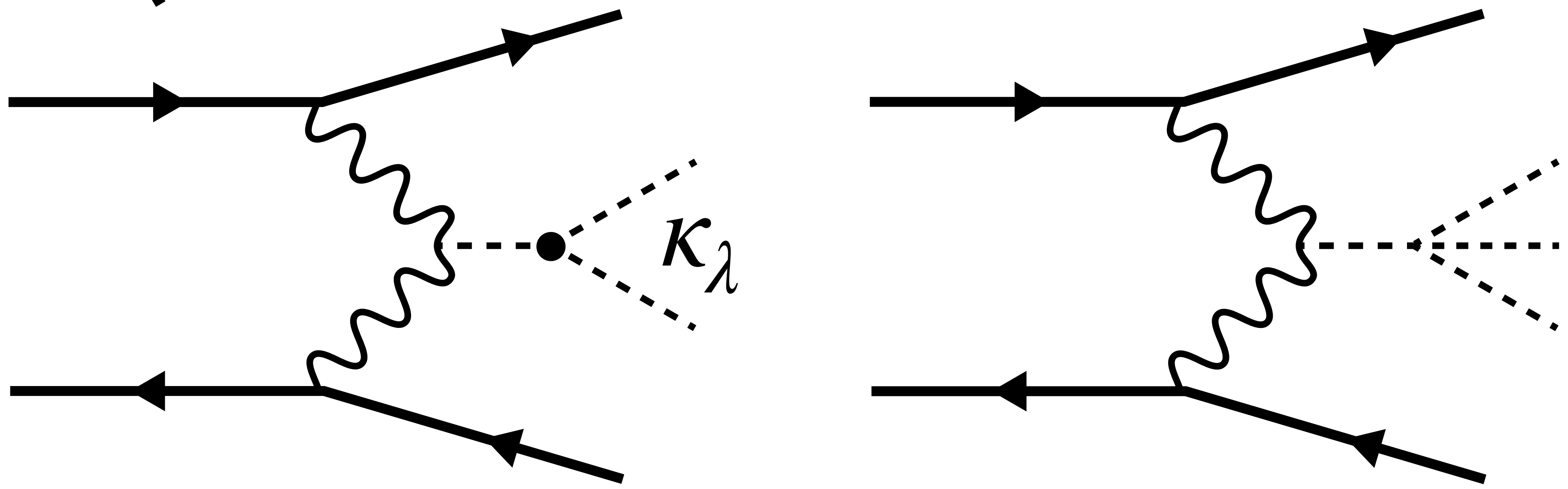
Slide Credit: P Meade, N Craig, R. Petrossian Byrne

Higgs Potential



Towards a Muon Collider '23

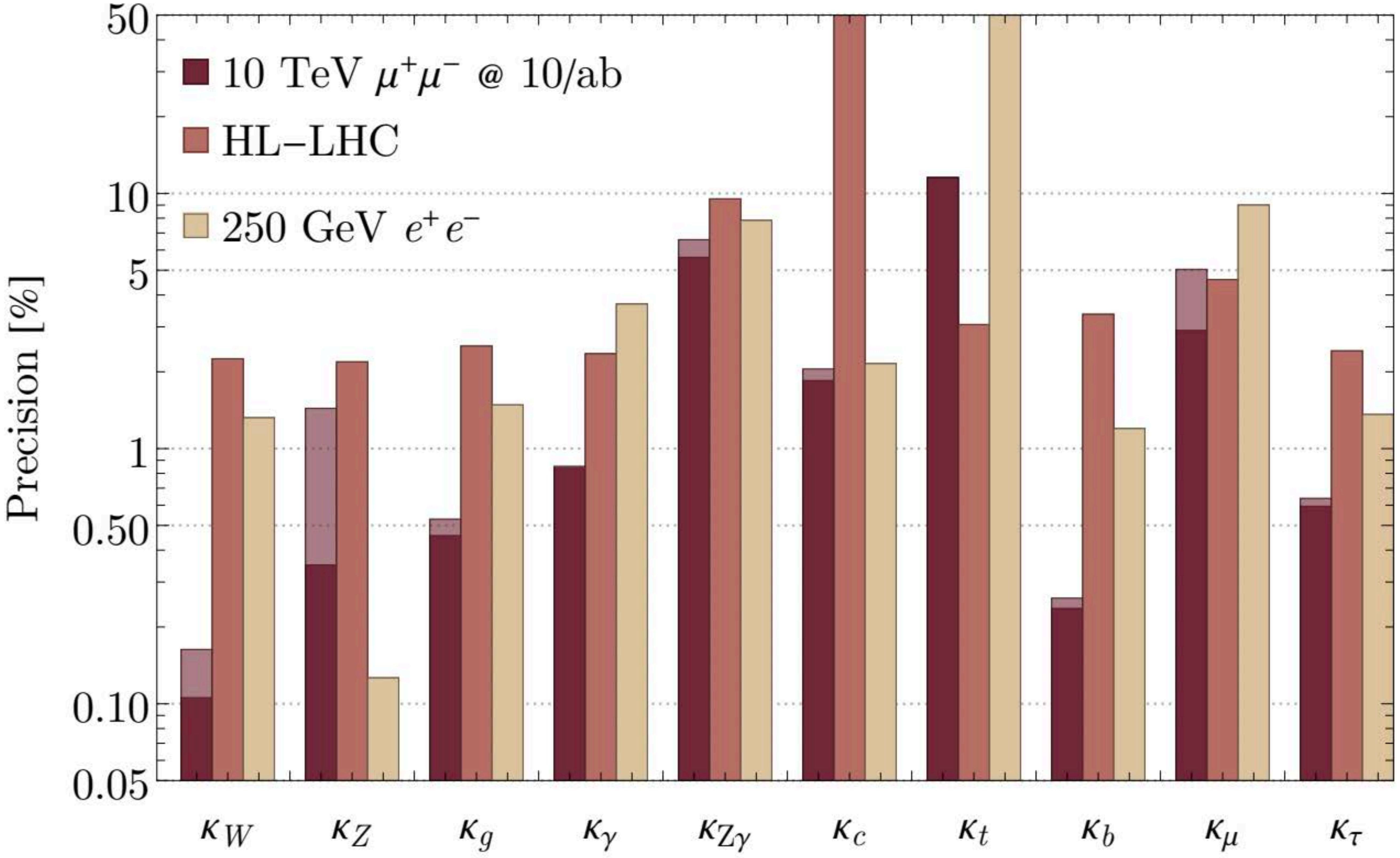


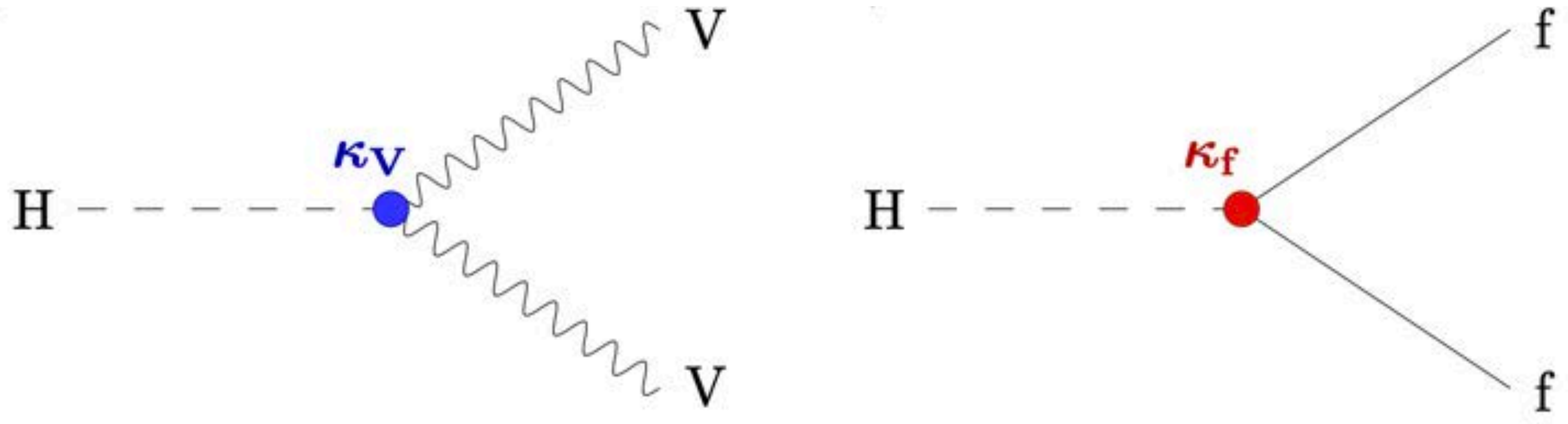


HIGGS COUPLINGS

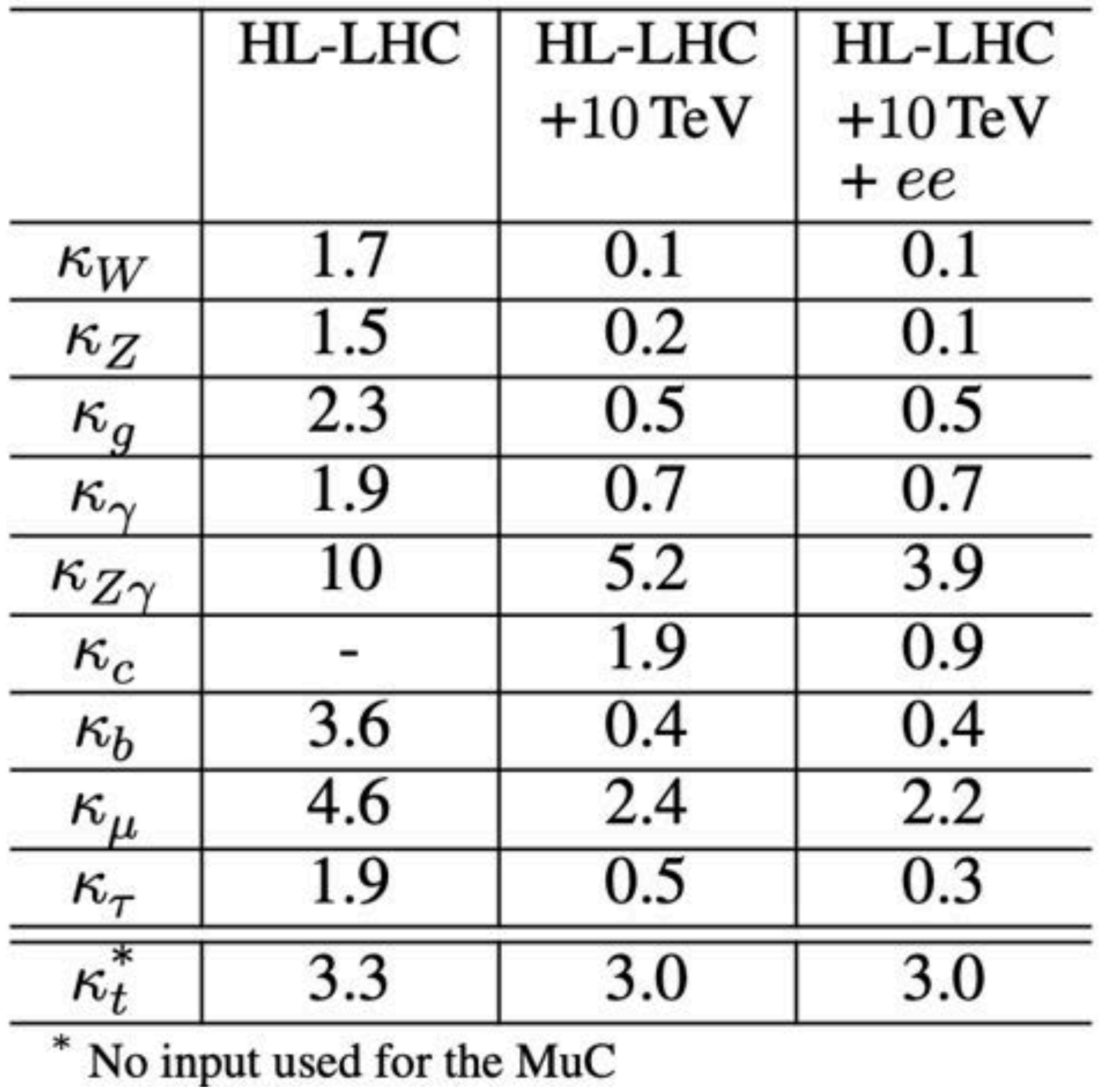
Compare improvement on precision Higgs measurements across machines

Forslund & Meade '23





Muon Collider ESPPU '25



	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + *ee*
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.2	0.1
κ_g	2.3	0.5	0.5
κ_γ	1.9	0.7	0.7
$\kappa_{Z\gamma}$	10	5.2	3.9
κ_c	-	1.9	0.9
κ_b	3.6	0.4	0.4
κ_μ	4.6	2.4	2.2
κ_τ	1.9	0.5	0.3
κ_t^*	3.3	3.0	3.0

* No input used for the MuC

HIGGS COUPLINGS

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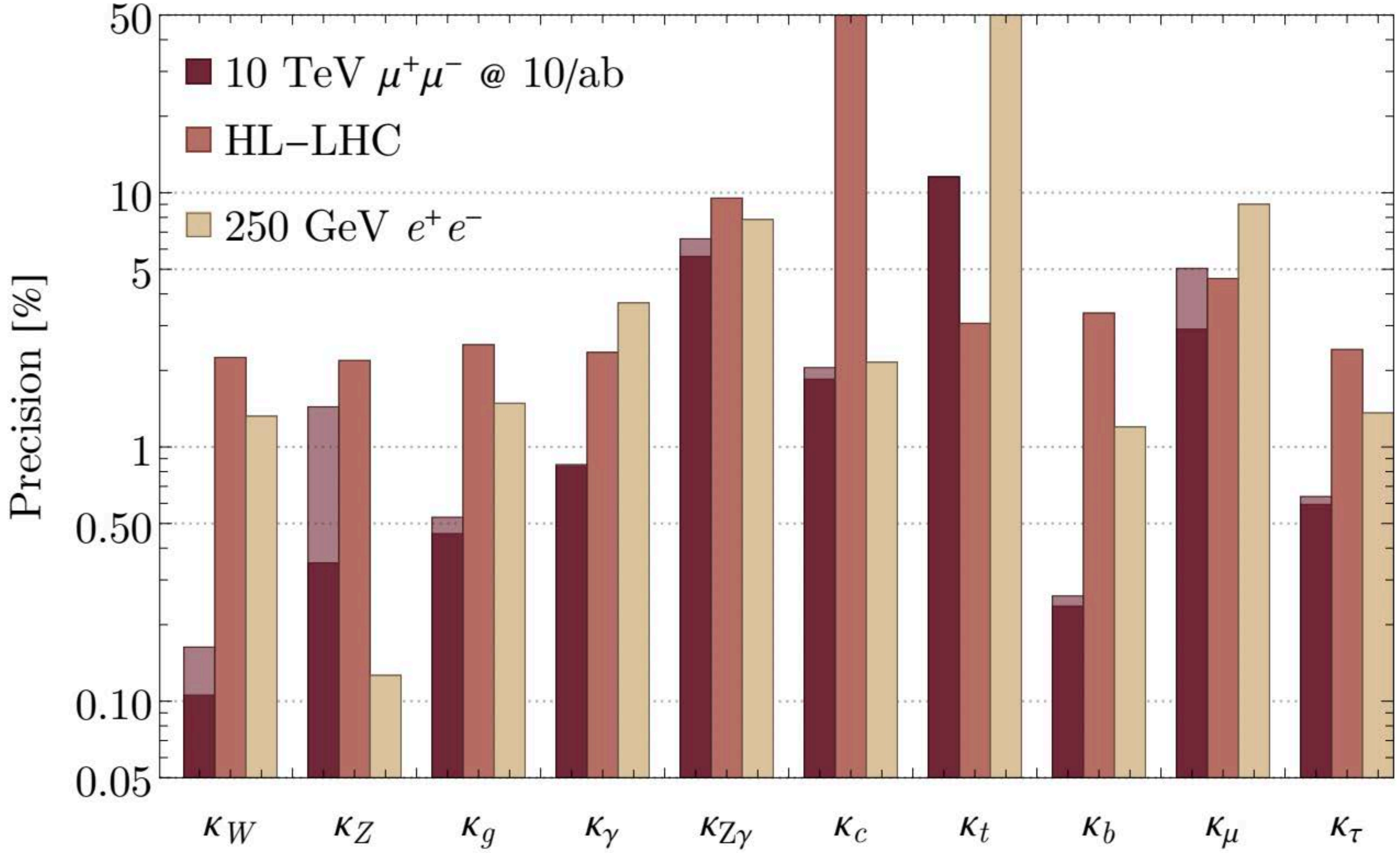
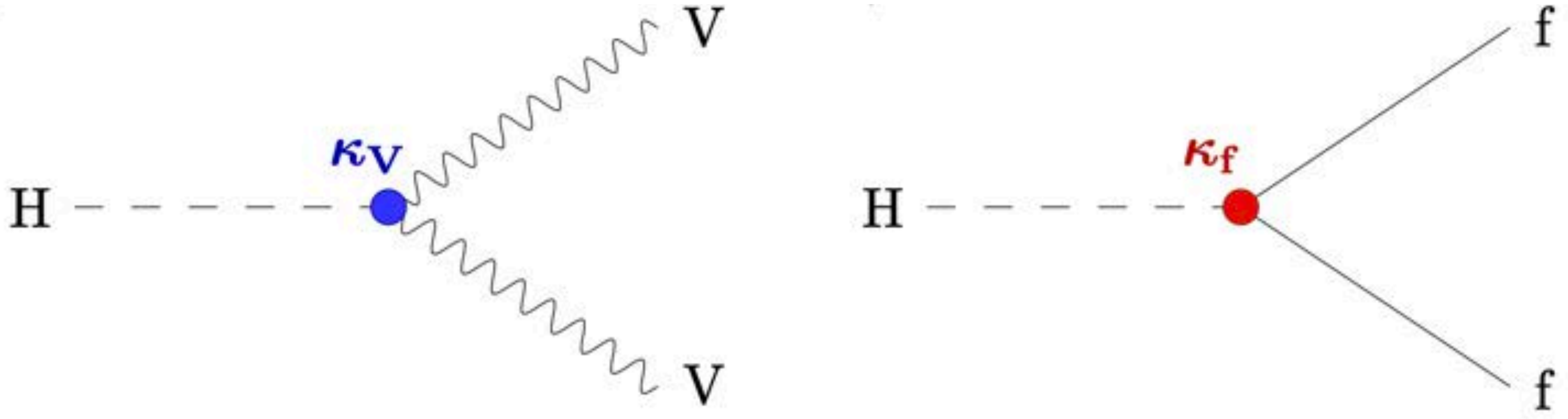




Reach of $\mathcal{O}(10^6)$ Higgs can be up to an order of magnitude more precise than HL-LHC

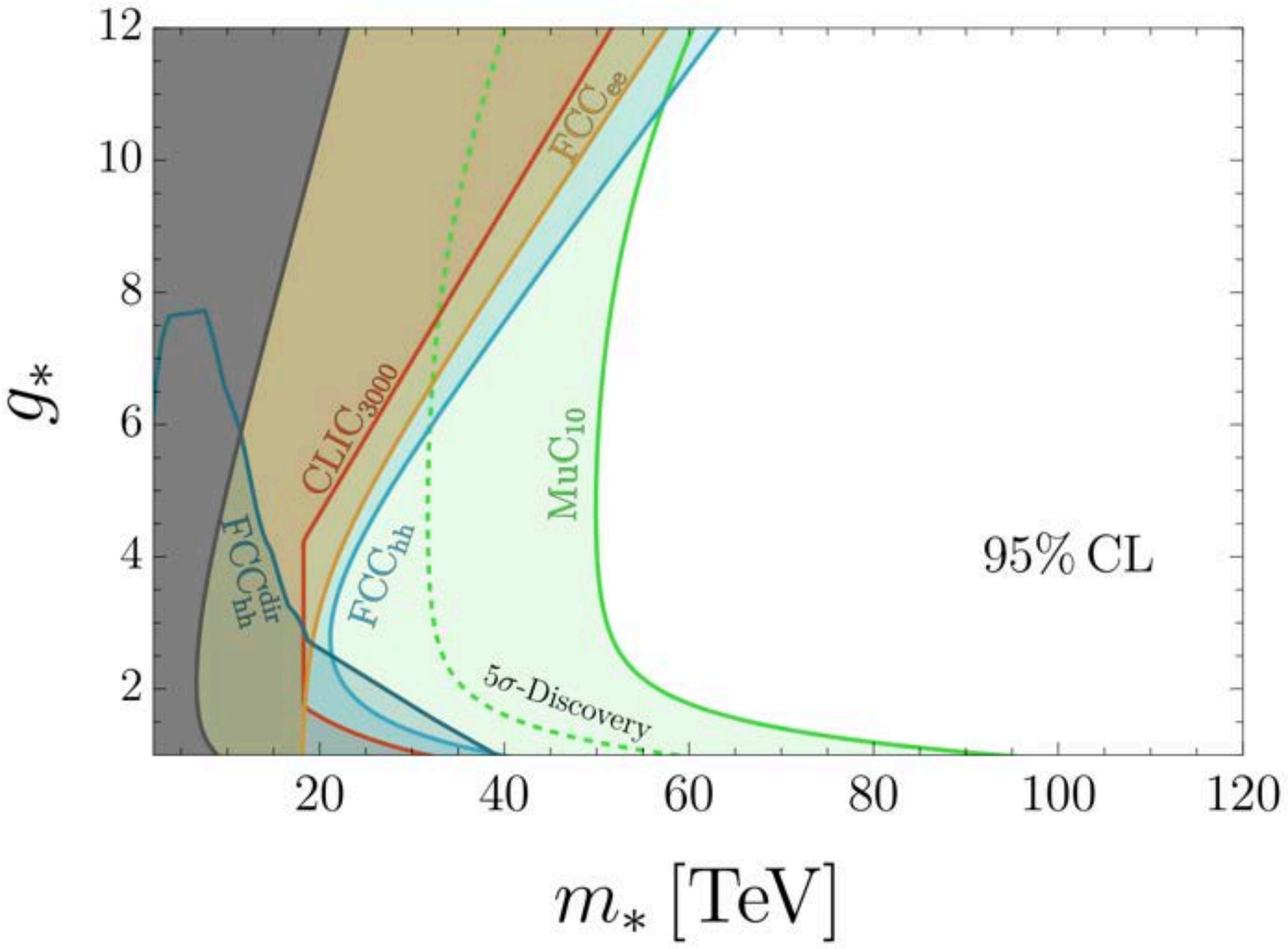
10 TeV MuC is a Higgs Factory

HIGGS & BEYOND

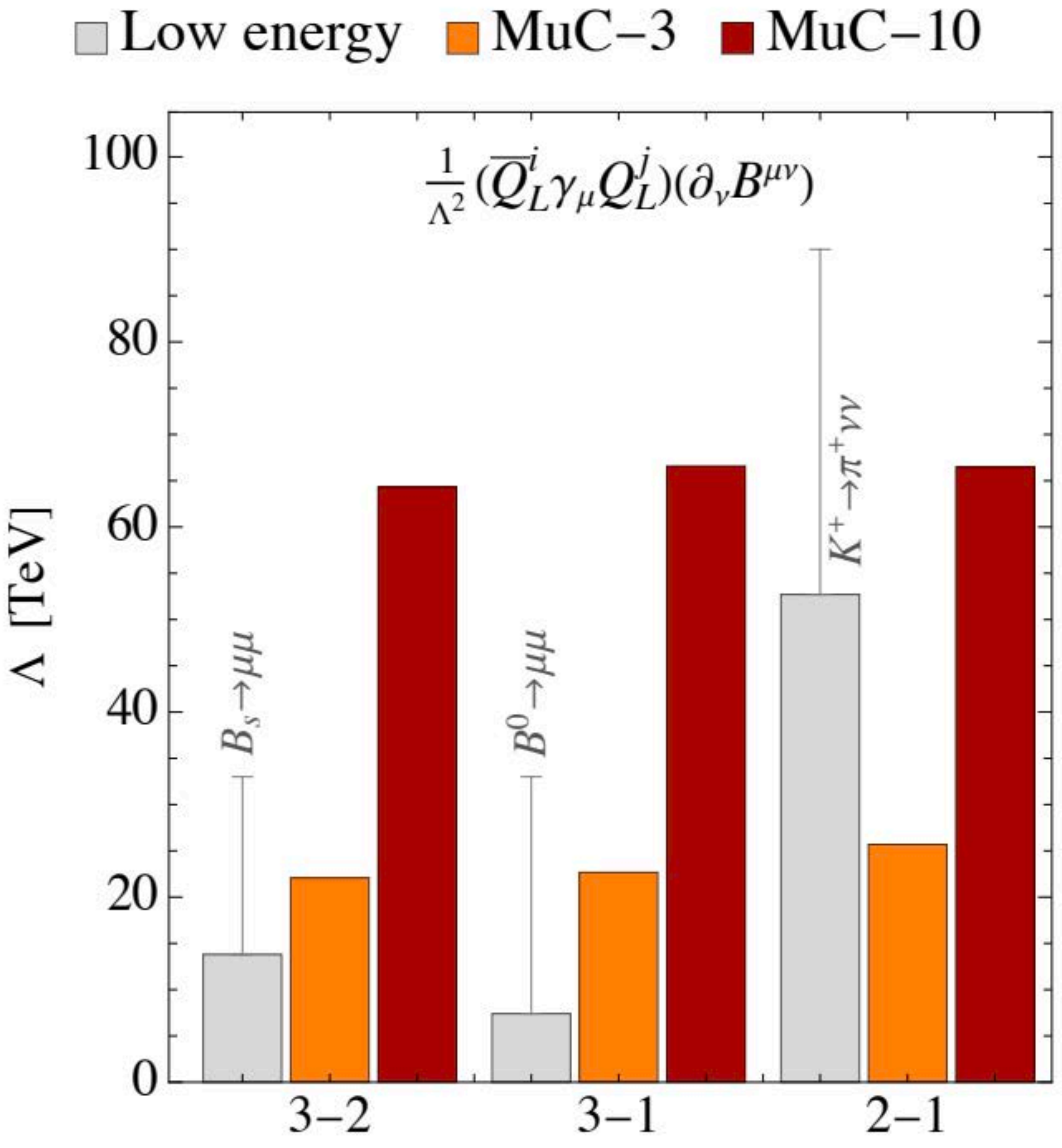
Other SM deliverables include:

Higgs Compositeness

Panico & Wulzer '15

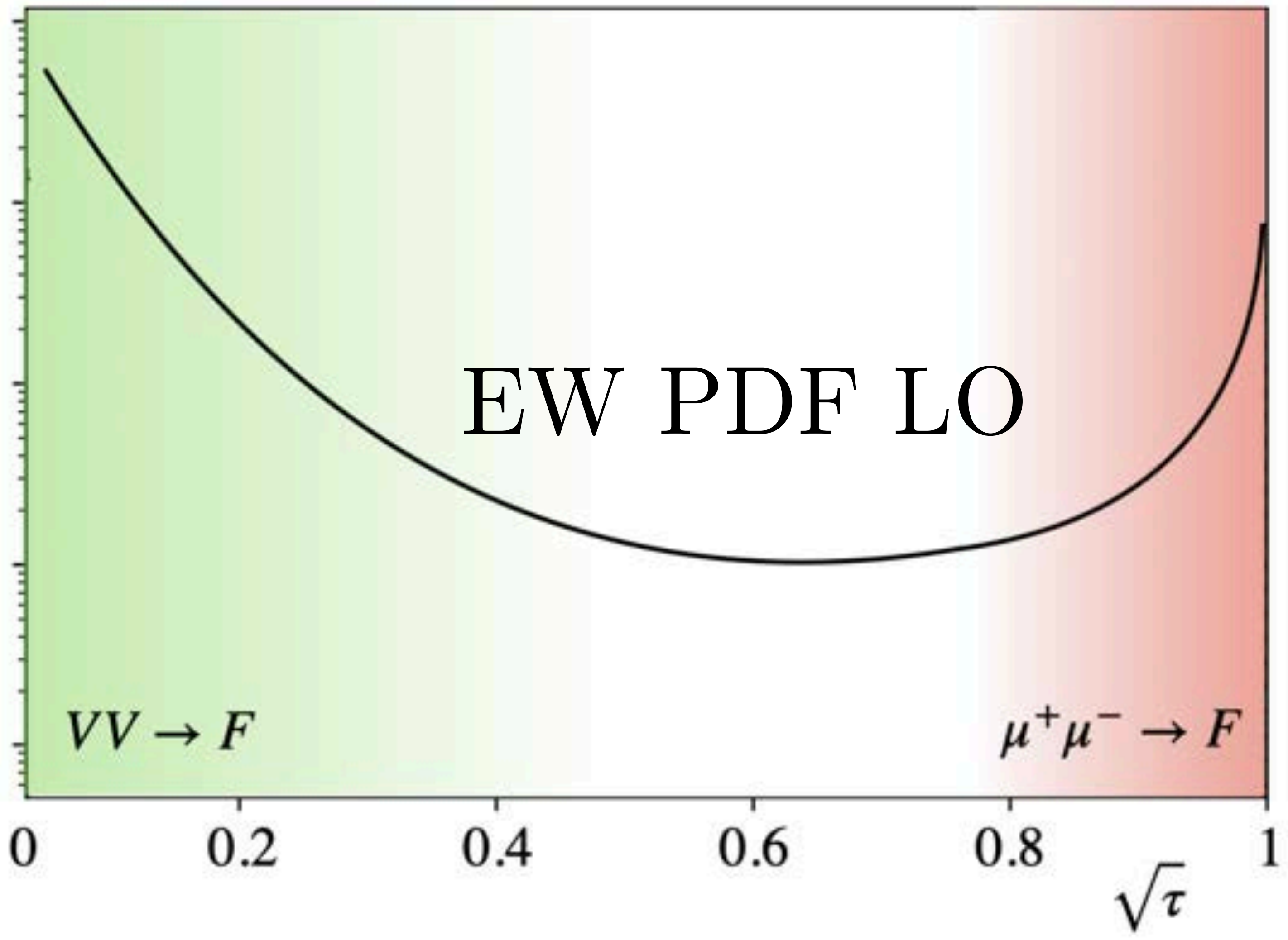


Flavor Violating Operators



LHCb, Belle II, NA62, etc.

High-Energy EW



Frixione, Maltoni, Pagani, Zaro '25

…and more!

Direct Searches

“Exploration Era”

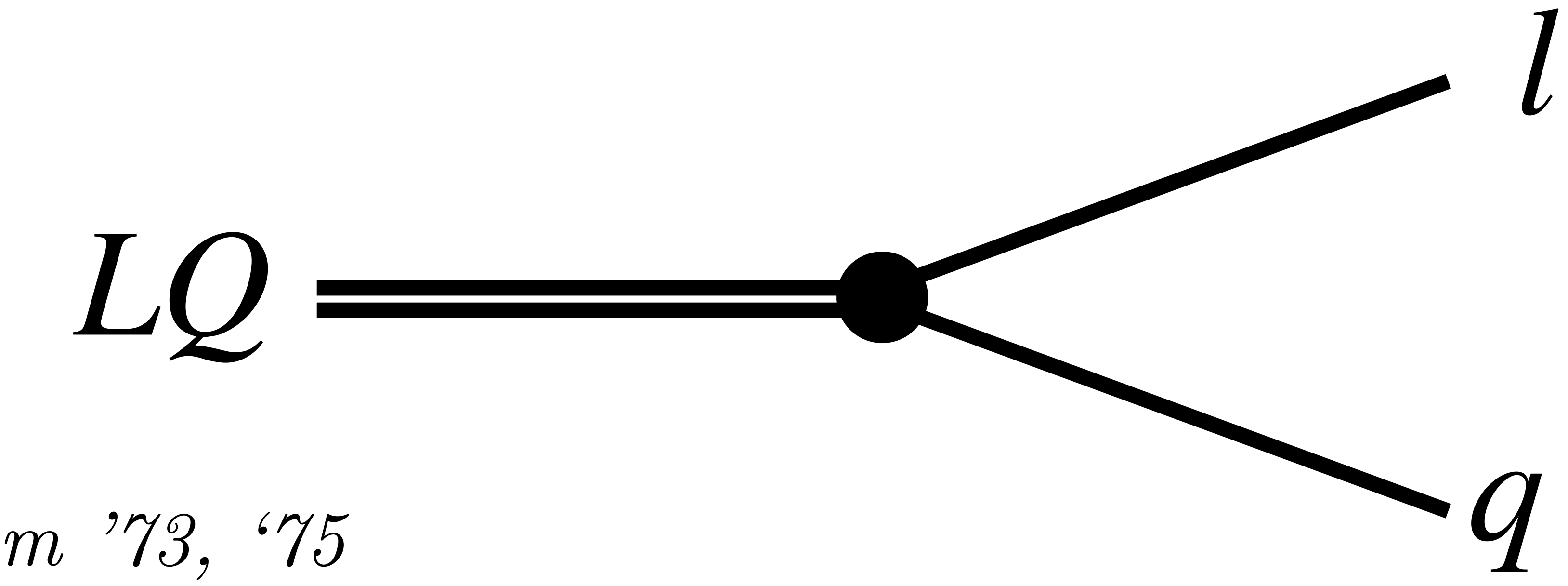
BSM BENCHMARKS

BSM AT MUC: LEPTOQUARKS

*Asadi, Capdevilla, **CC**, Homiller, '21*

Consider a BSM benchmark model: the *leptoquark*

New particle that can arise from Grand Unification Theories (GUT)



Pati, Salam '73, '75

Georgi, Glashow '74

Broad class of NP model

- Low representation of GUT symmetry
- SUSY models (squarks in RPV)
- Flavor anomalies
- …

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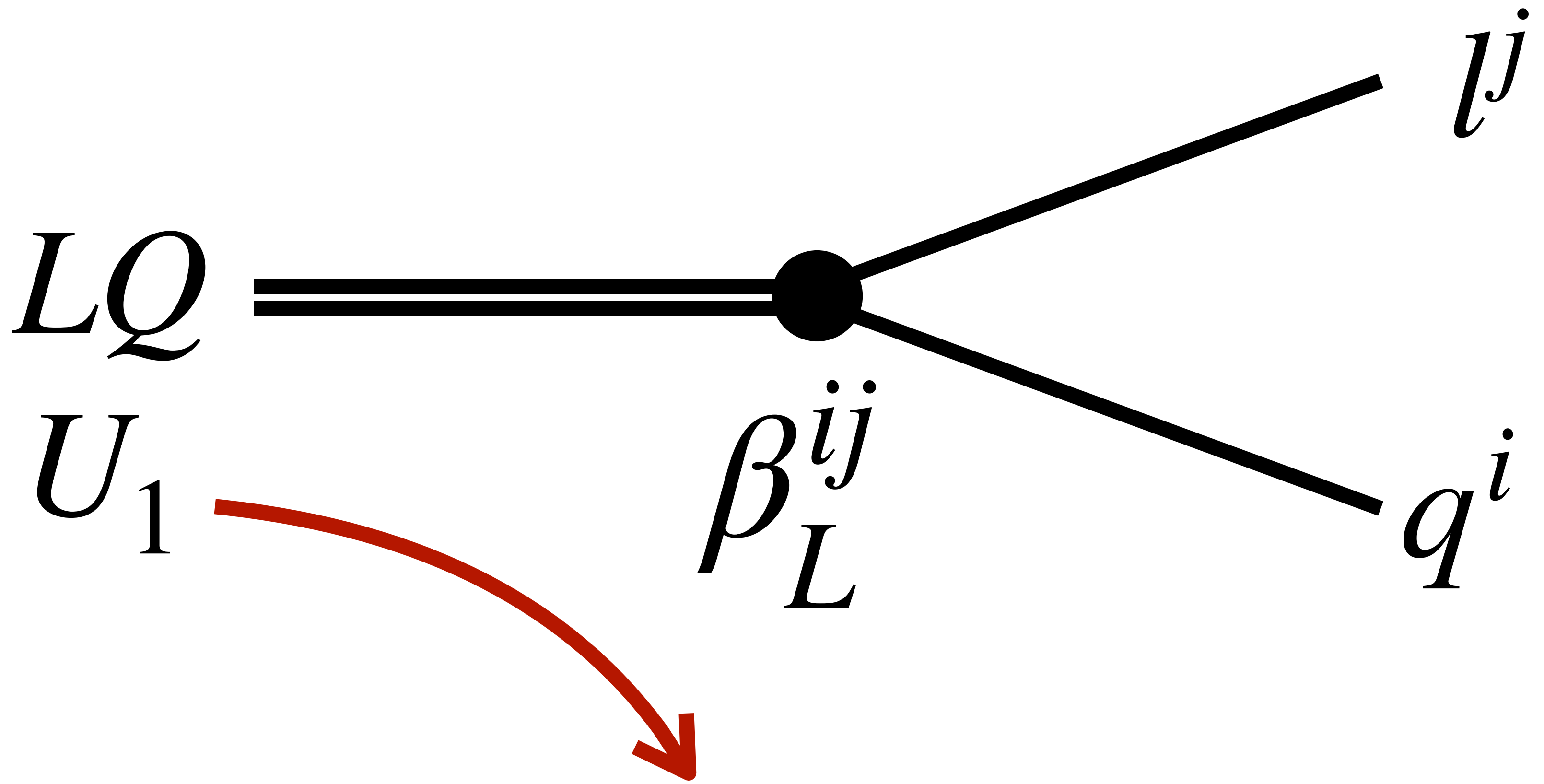

$$U_1 = (3,1)_{2/3}$$

$$\mathscr{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} U_1^{\mu} \left(\beta_L^{ij} \bar{Q}_L^i \gamma_\mu L_L^j + \text{hc} \right)$$

Broad class of NP model

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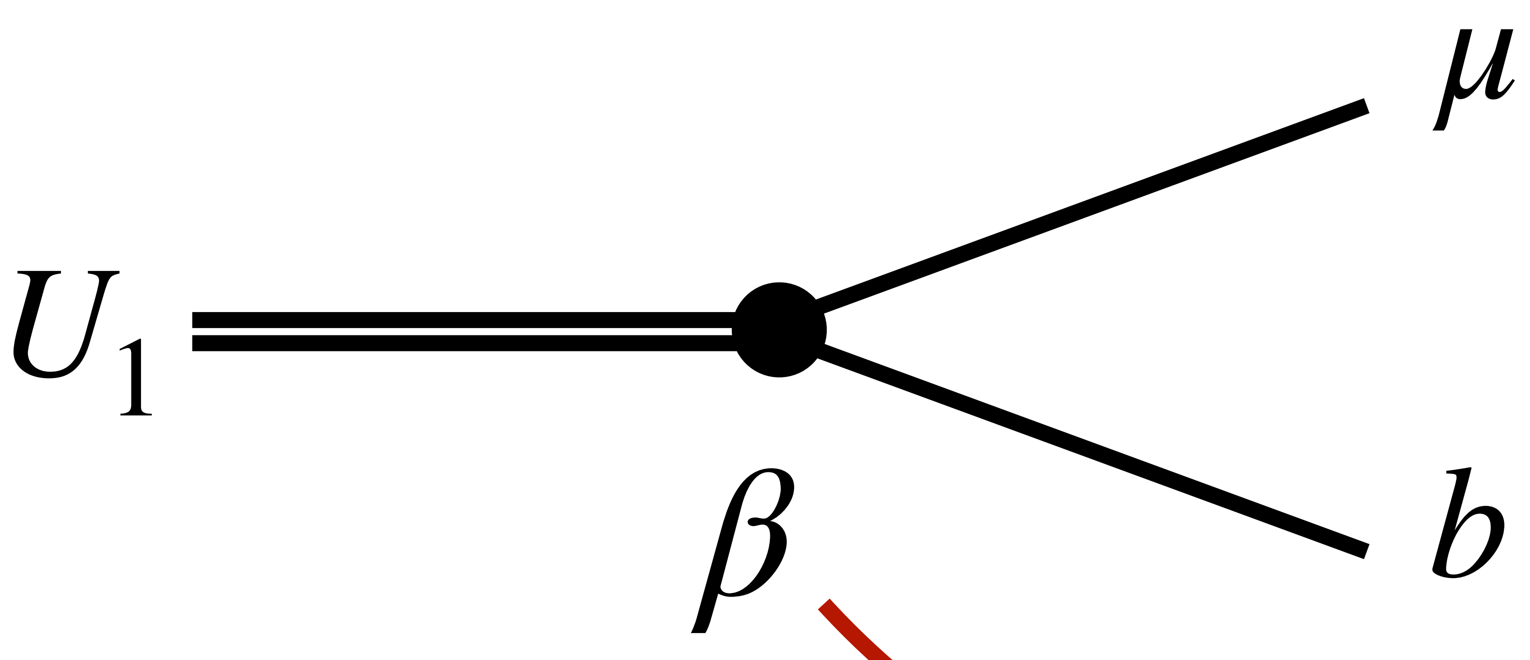
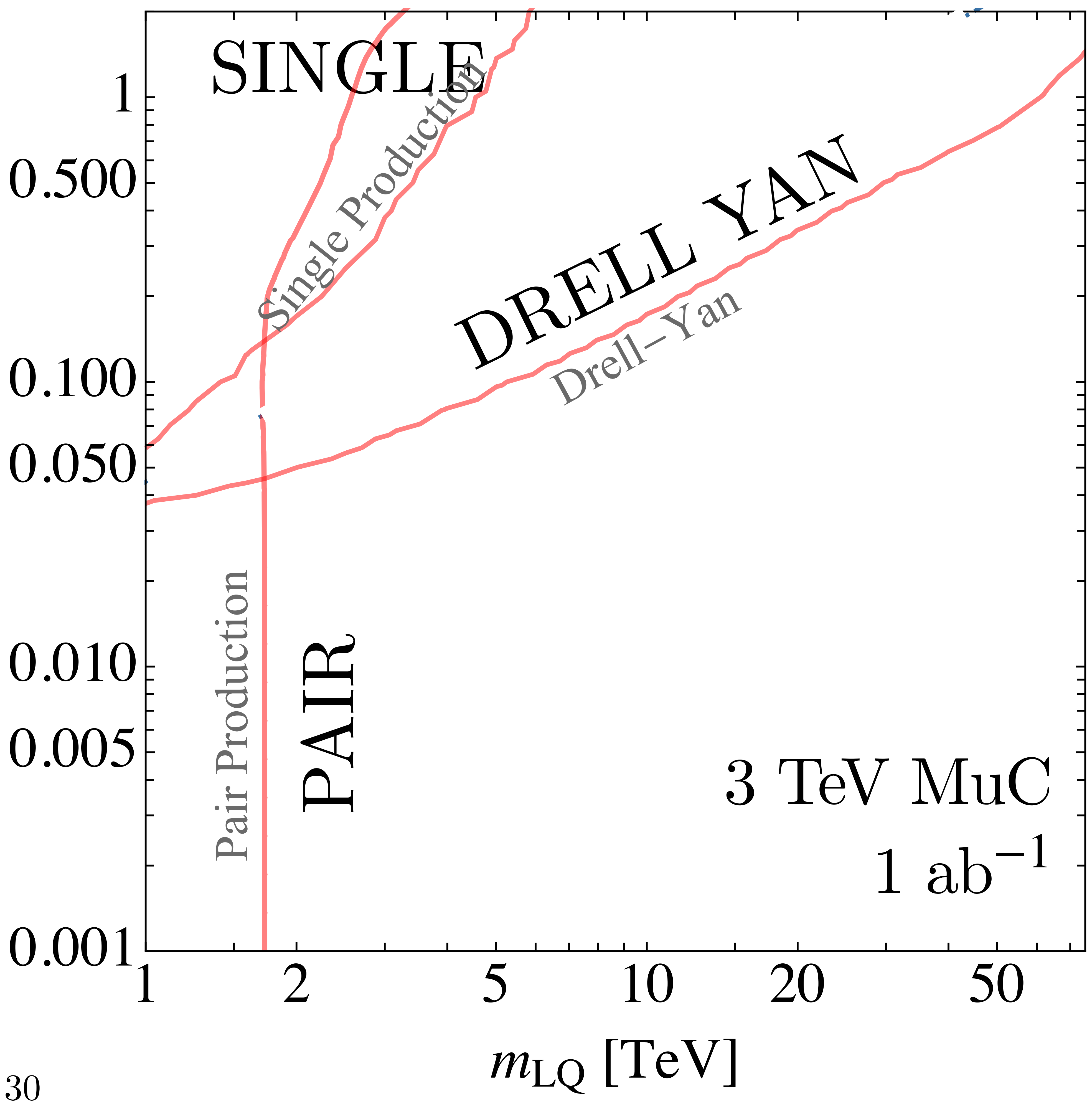
For benchmark choice of couplings, 5σ reach at 3 TeV MuC



$$\mathscr{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} U_1^{\mu} \left(\beta_L^{ij} \bar{Q}_L^i \gamma_\mu L_L^j + \text{h.c.} \right)$$

$$\beta_L^{ij} = \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{ccc|c} e & \mu & \tau & \\ 0 & 0 & 0 & d \\ 0 & \beta & 0.1 & s \\ 0 & \boxed{\beta} & 1 & b \end{array}$$

β



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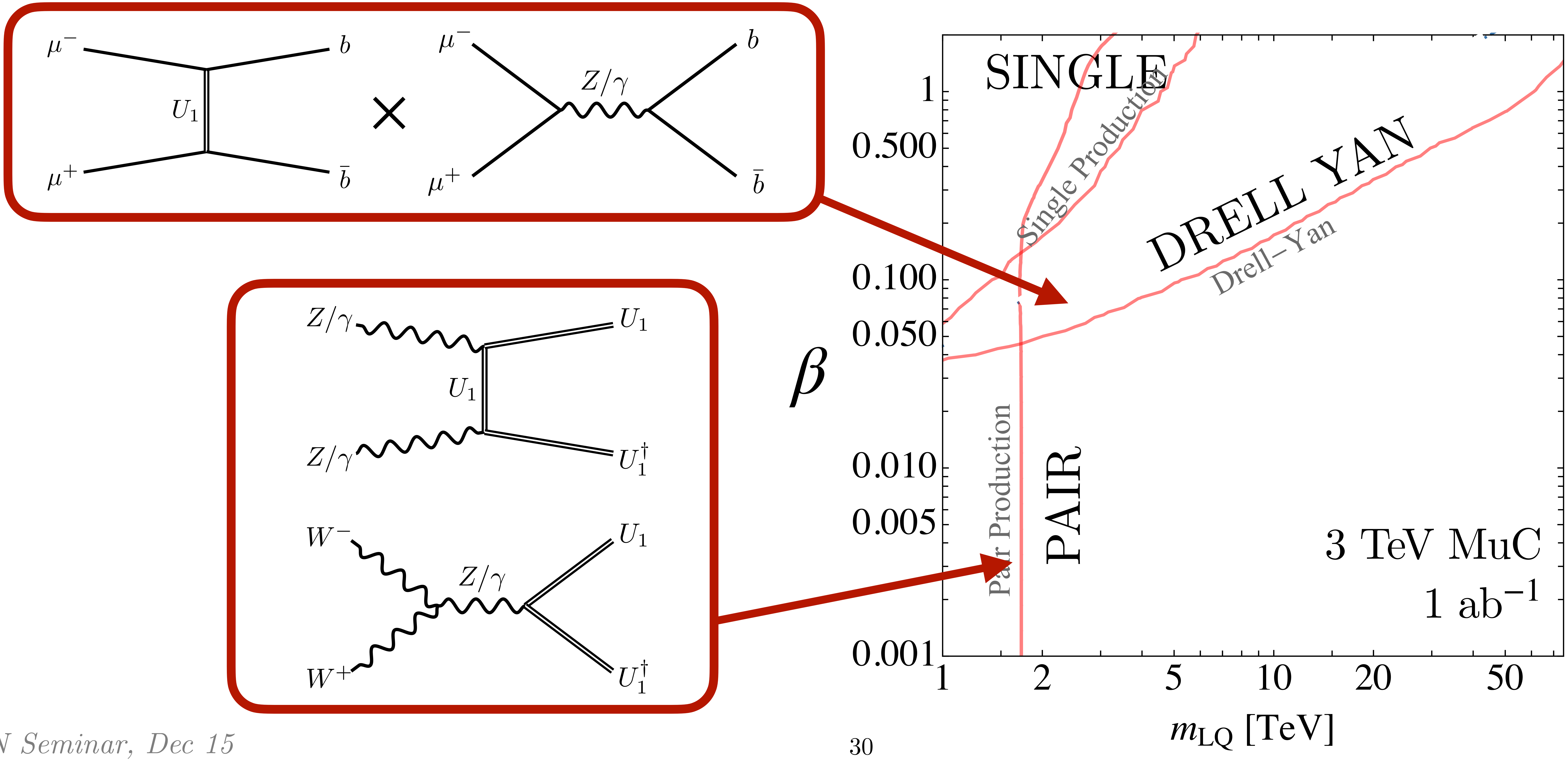

BSM AT MUC: LEPTOQUARKS

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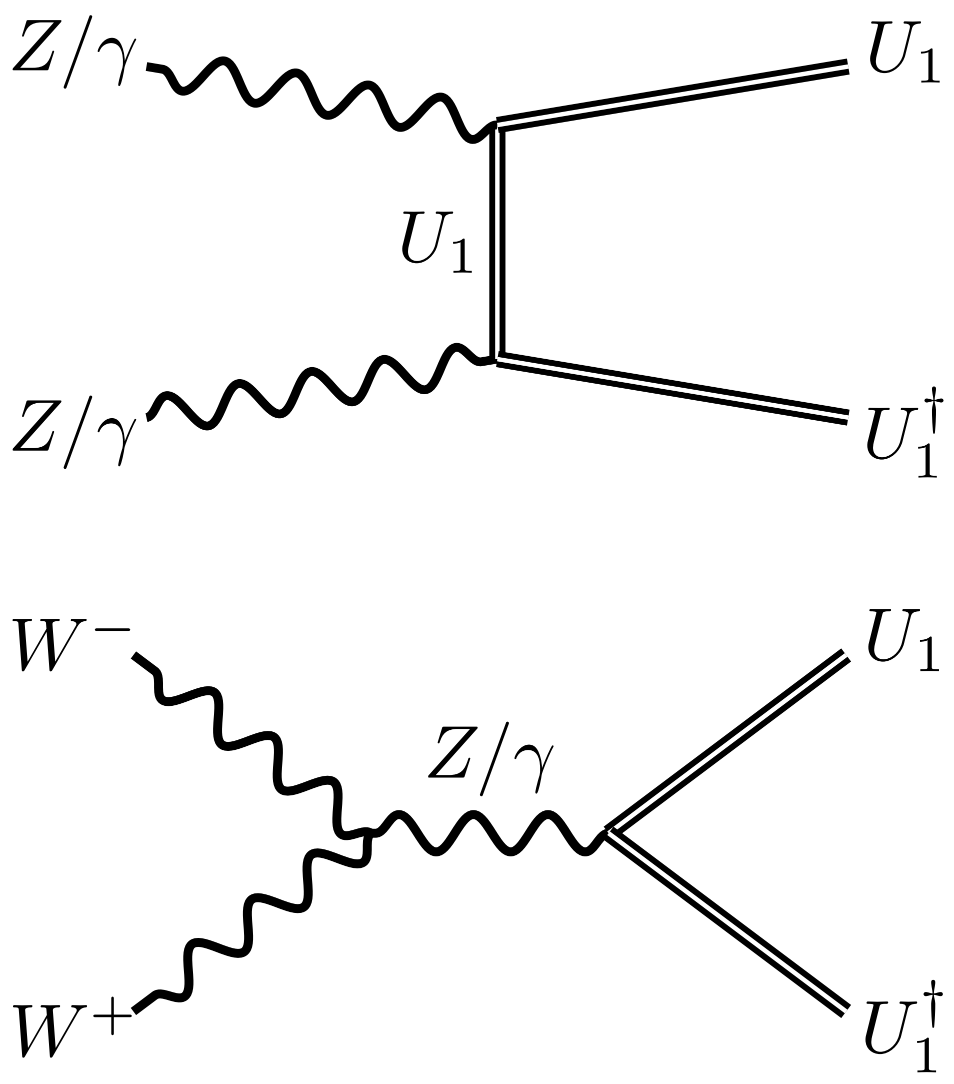
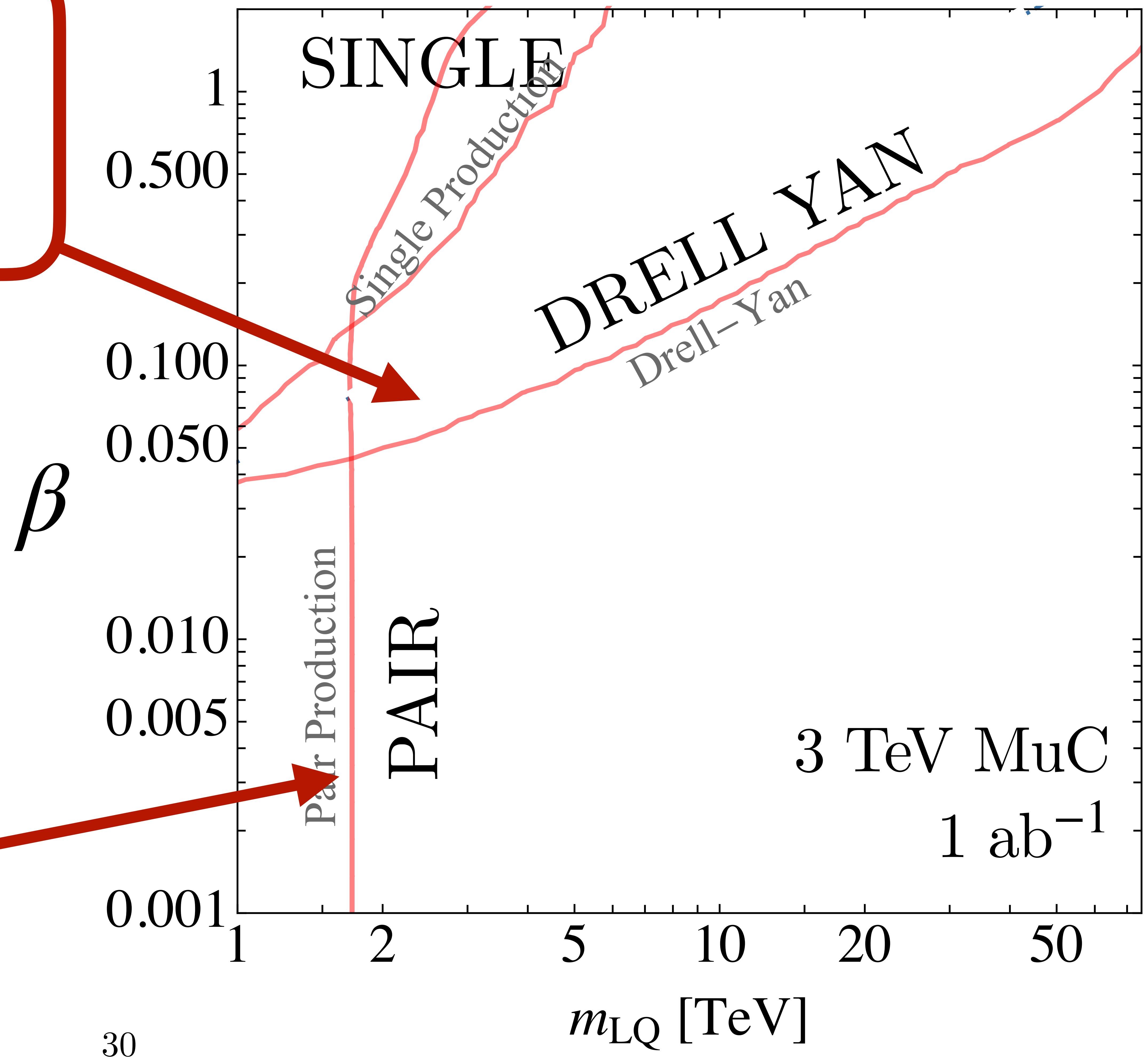
MuC can indirectly probe states with energies larger than $\sqrt{s}$





BSM AT MUC: LEPTOQUARKS

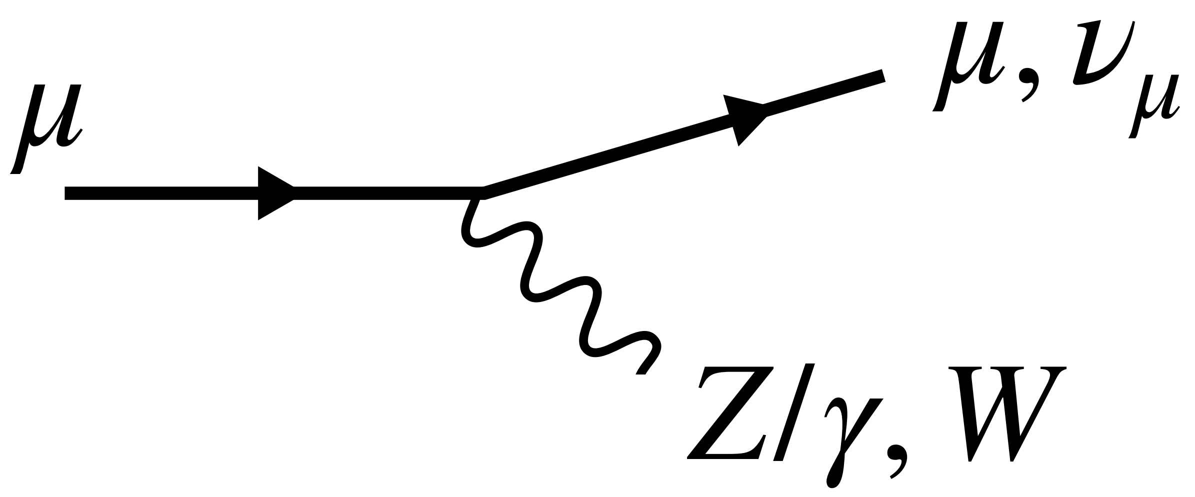
*Asadi, Capdevilla, **CC**, Homiller, '21*

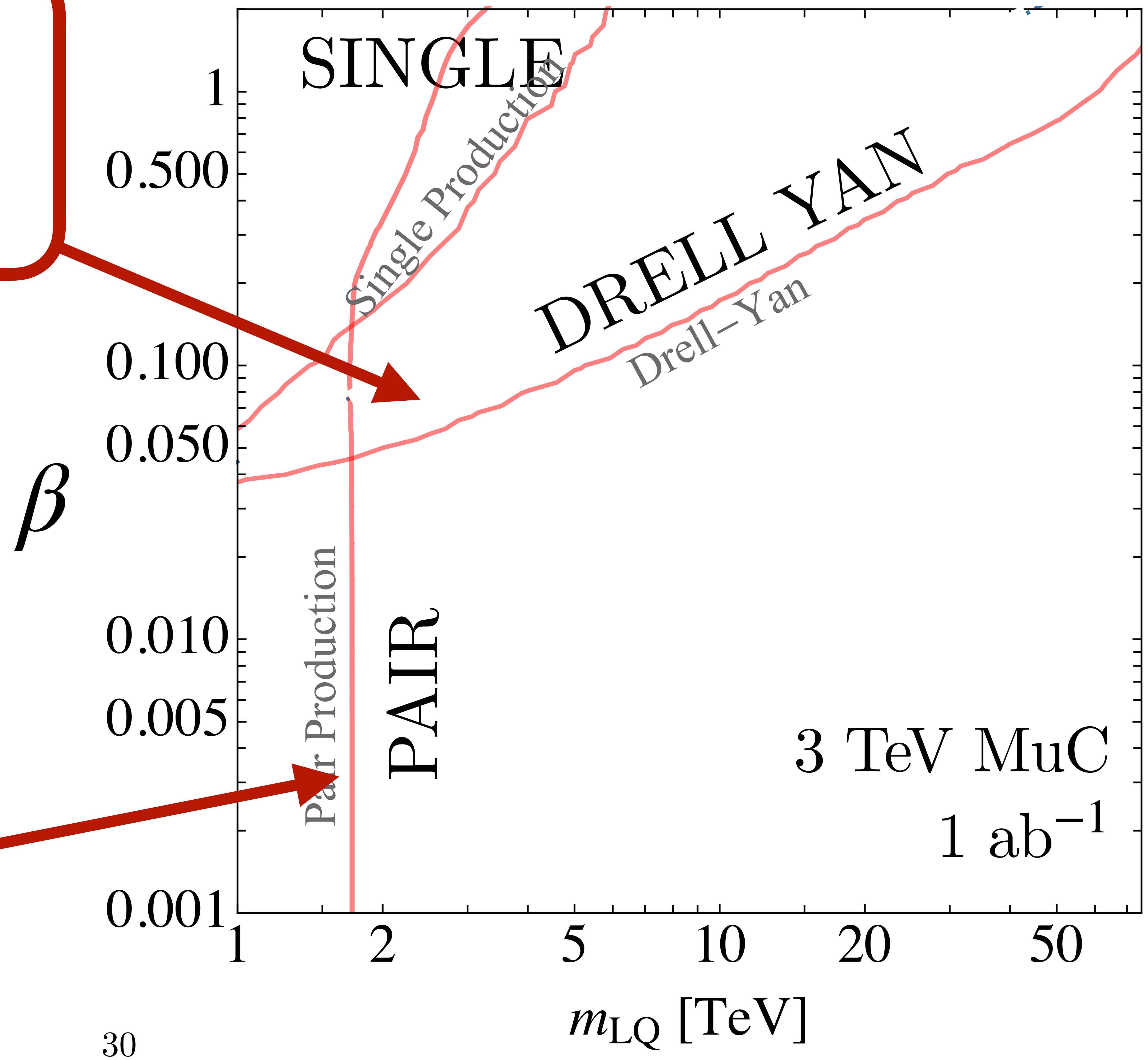
For benchmark choice of couplings, 5σ reach at 3 TeV MuC

MuC can indirectly probe states with energies larger than $\sqrt{s}$

Muons have PDFs too!

Muon colliders are also gauge boson colliders





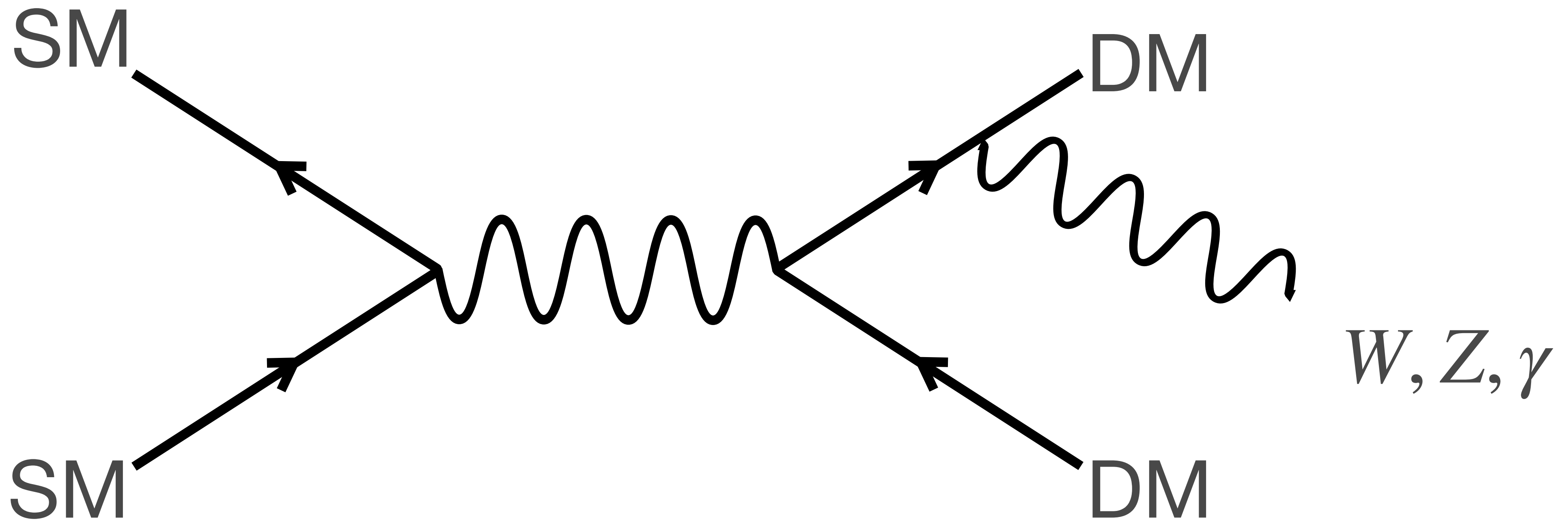
Direct Searches

“Exploration Era”

DARK MATTER BENCHMARKS

BSM AT MUC: WIMP DARK MATTER

Muon collider is ideal for dark matter models coupling to EW bosons—like Weakly Interacting Massive Particles



Mono-X

$\mu^+\mu^- \to \chi\bar{\chi} + X$

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

Relic Abundance

$$\Omega h^2 \sim 0.2 \times \left(\frac{m_{DM}}{\text{TeV}}\right)^2 \times \left(\frac{0.3}{g'}\right)^4$$

Weak-scale couplings & mass

10 GeV $< m_\chi <$ 100 TeV

Dark matter is neutral component in SU(2) n-plet

Han, Liu, Wang, Wang '20

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

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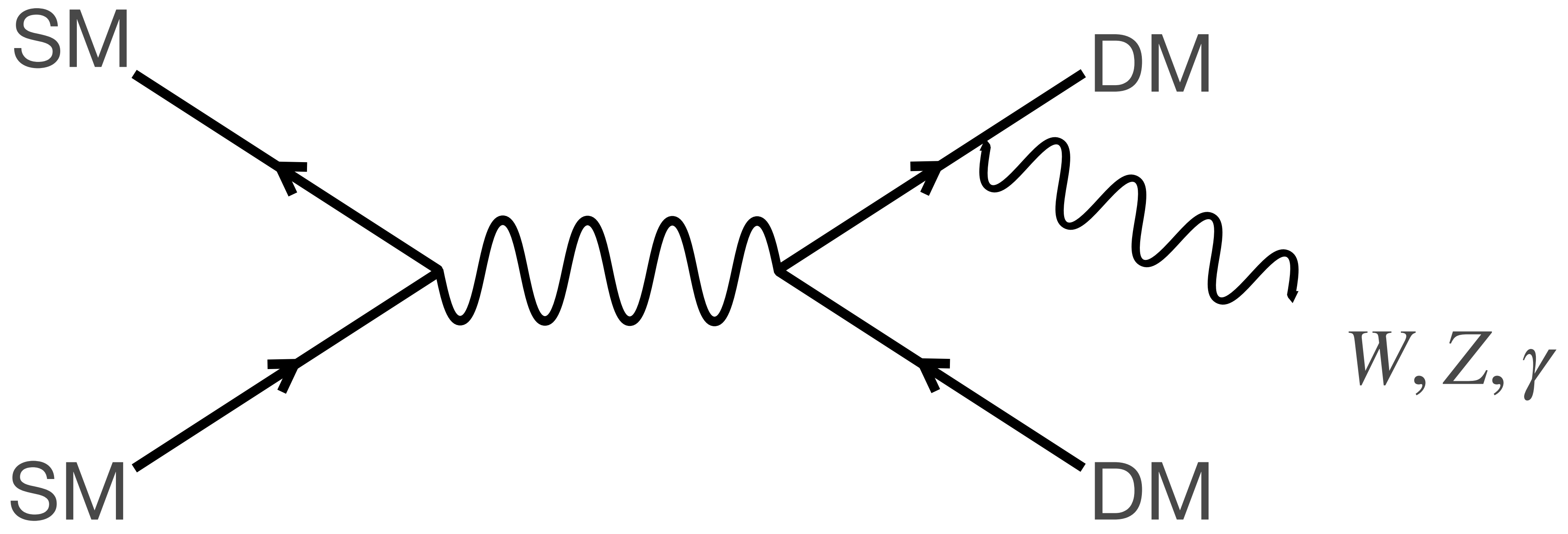

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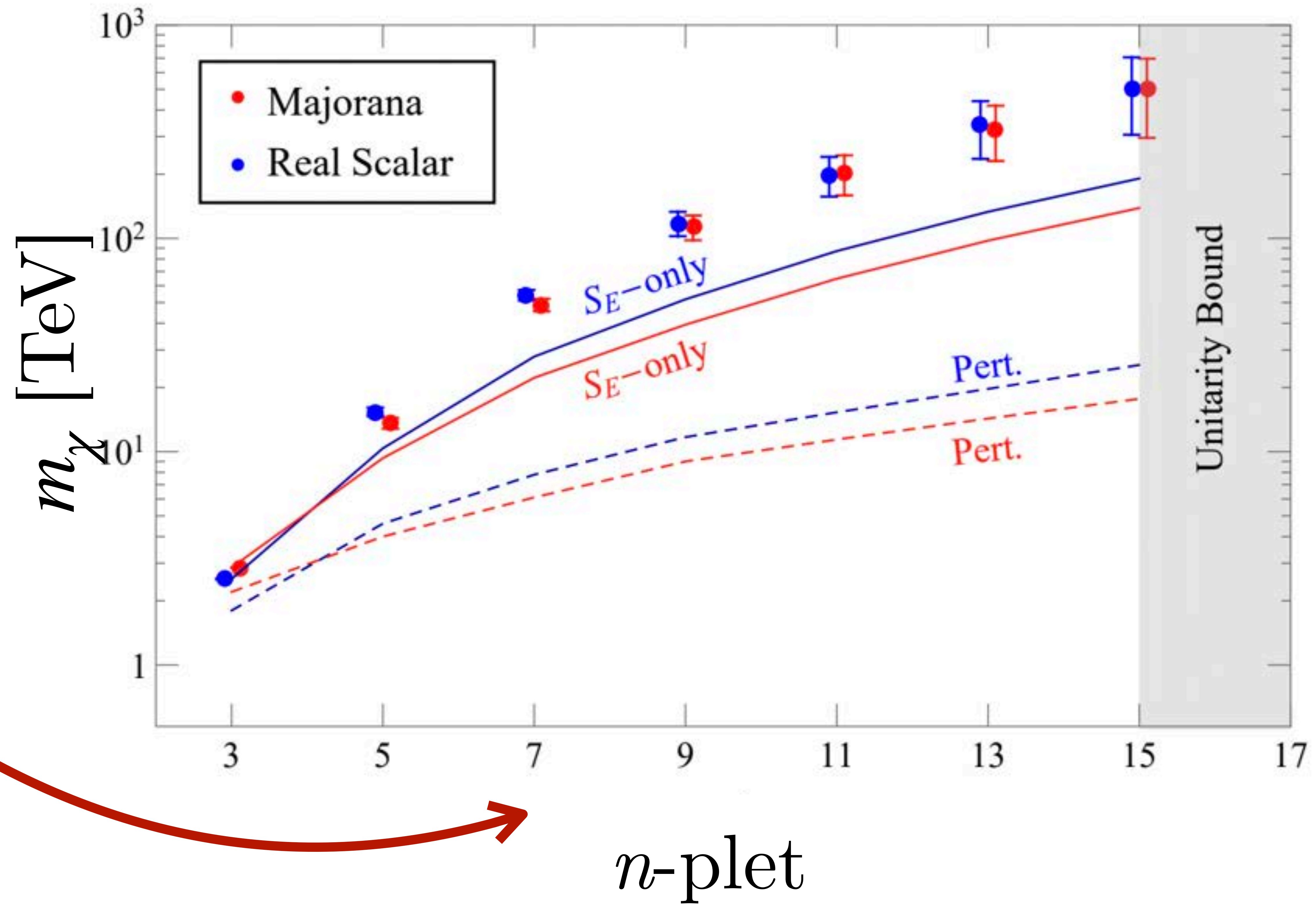


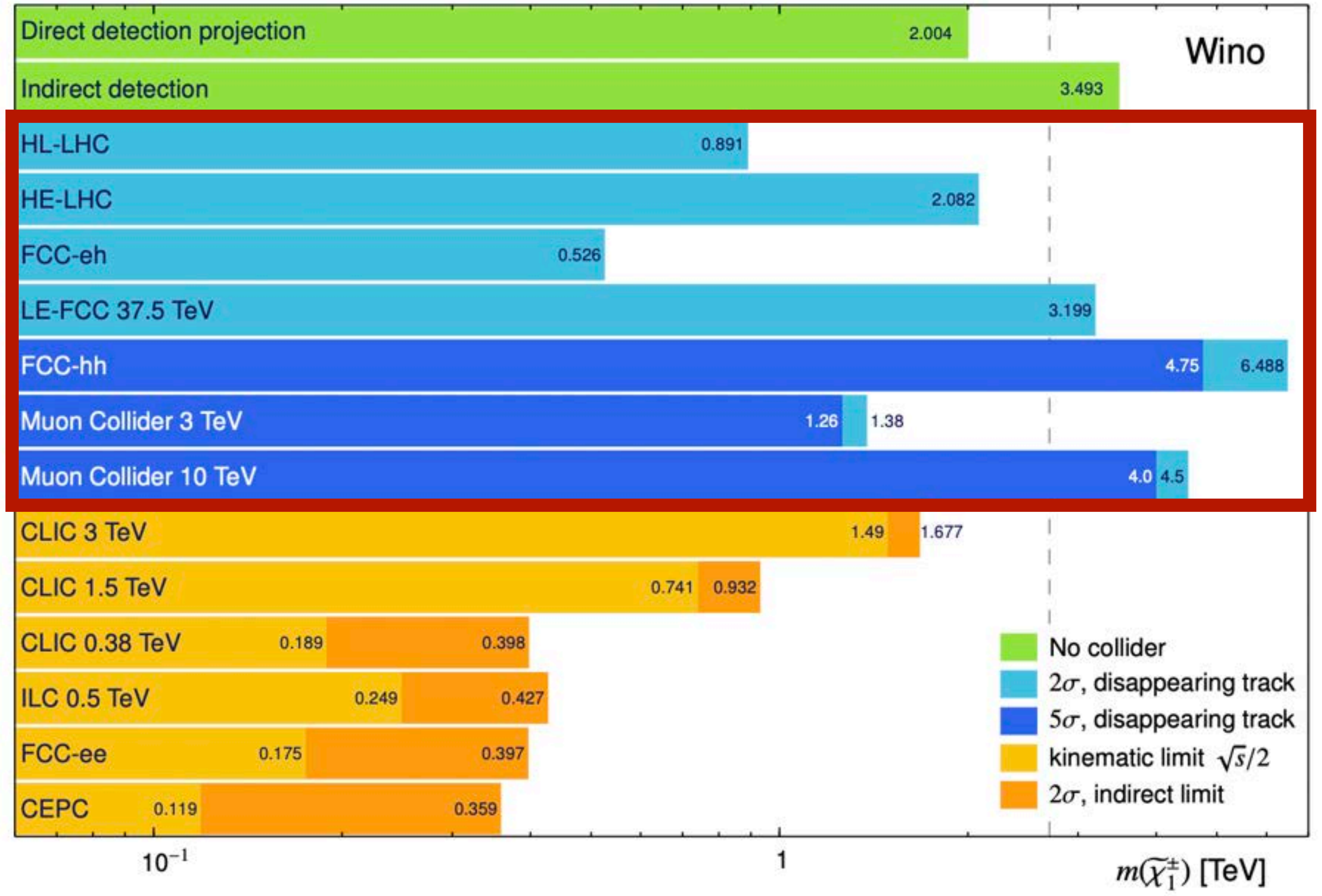
Collider scale dark matter

Han, Liu, Wang, Wang '20

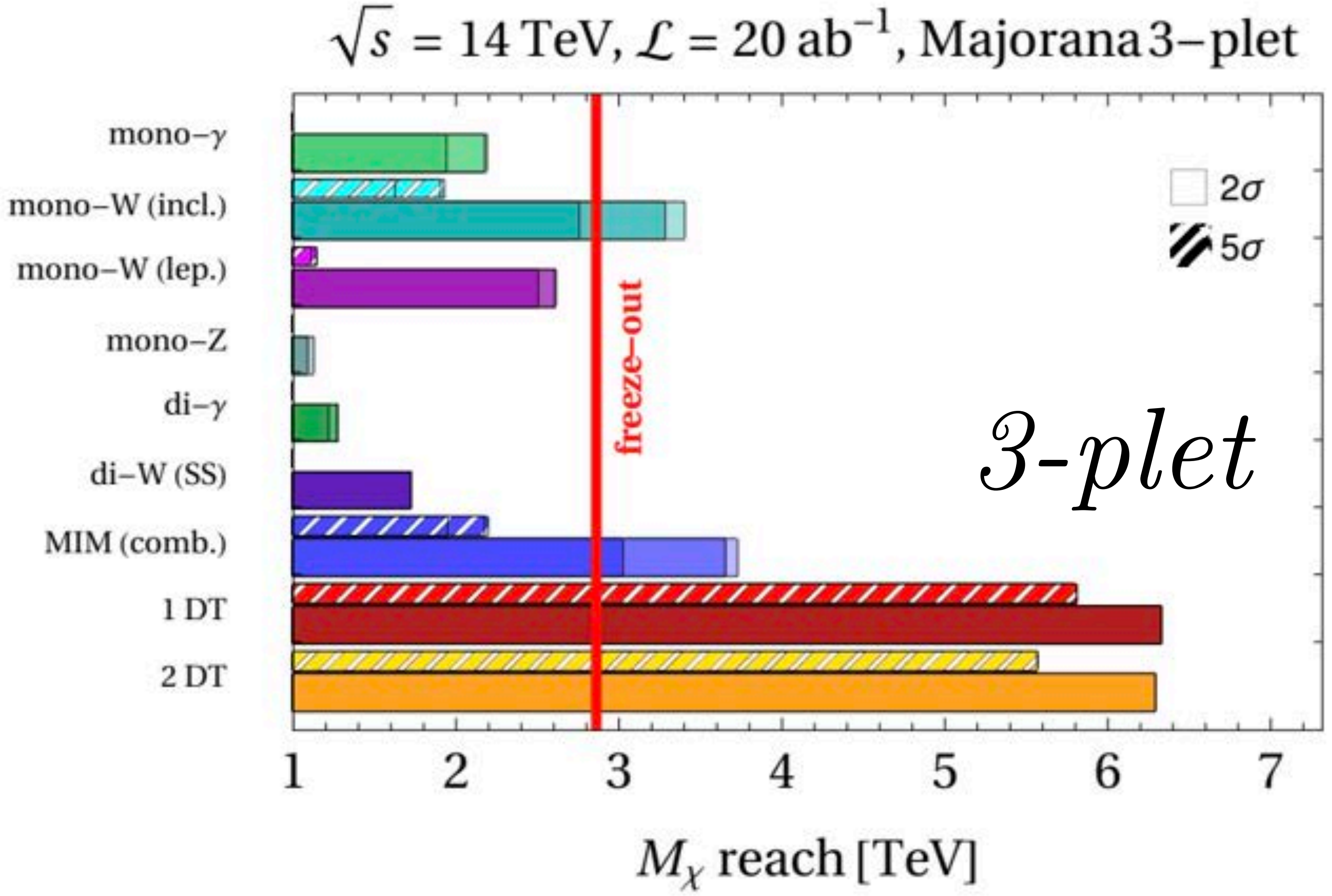
Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

BSM AT MUC: WIMP DARK MATTER

Example: Wino



Muon Collider Reach



3-plet

Saito, Svada, Terashi, Asai '19

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

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

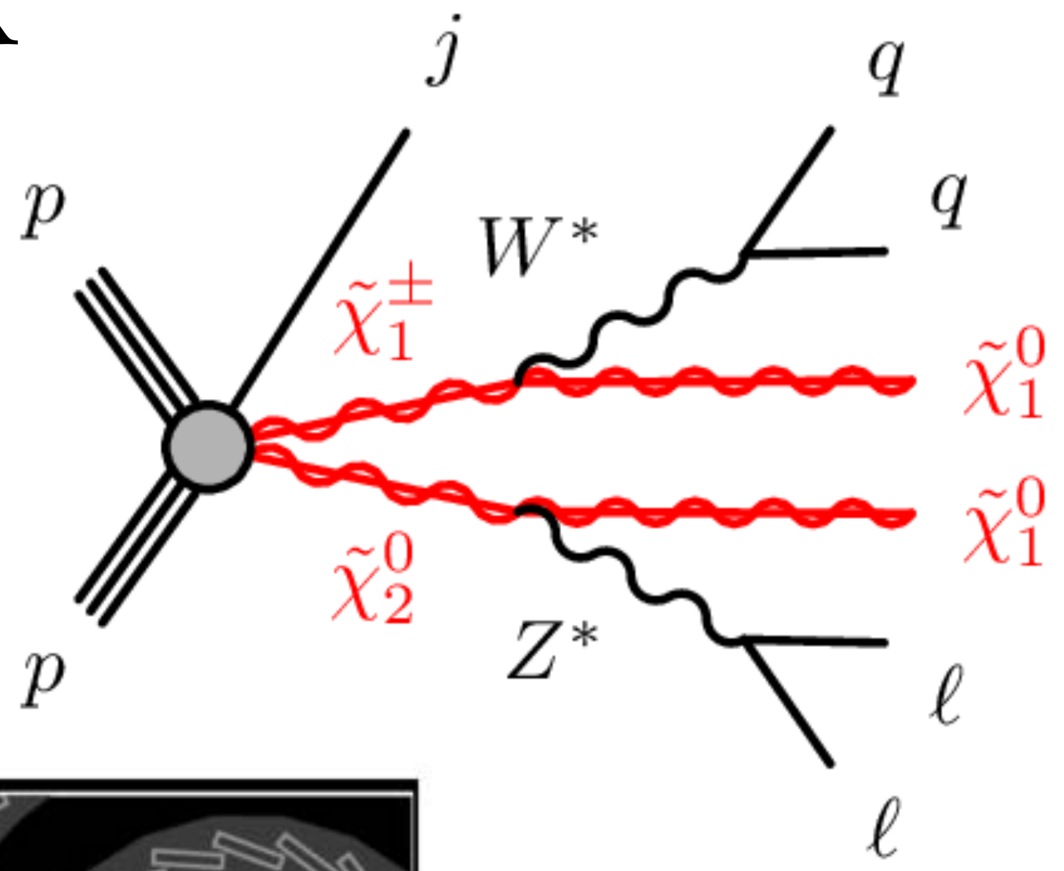
BSM AT MUC: WIMP DARK MATTER

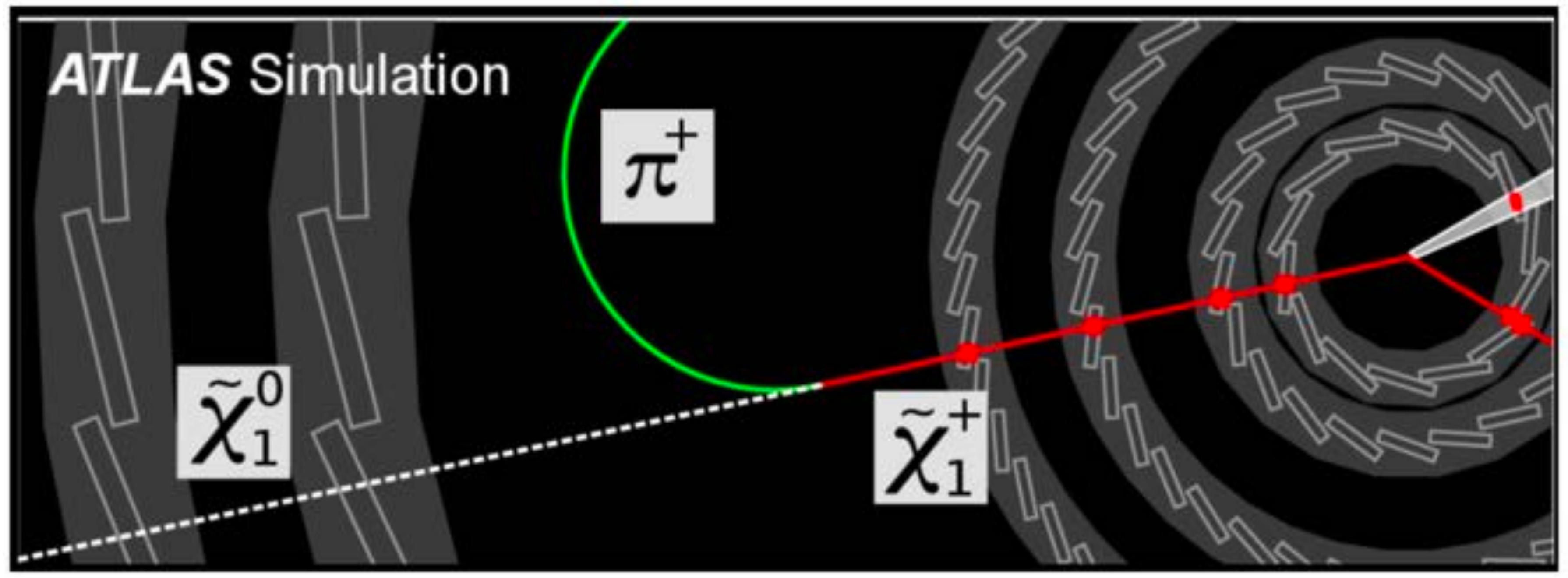
Sensitivity can dramatically improve with analysis strategy

Ex: Disappearing Track

$$ff \to \chi^+\chi^-$$

$$\chi^\pm \to \chi^0\pi^\pm$$





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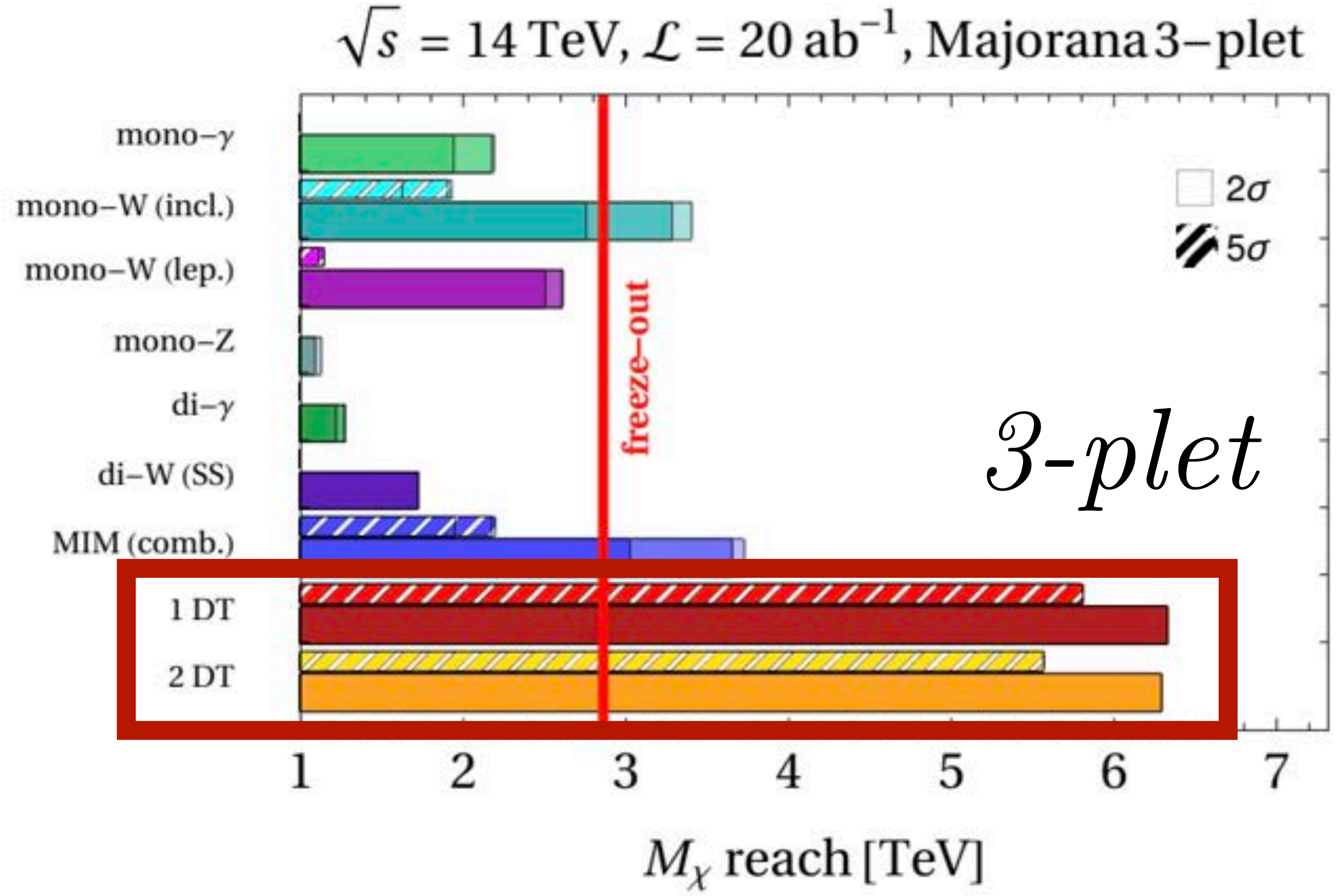

Illustrates importance of theory work to influence detector design

DM AT MUC: LEPTOPHILIC DM

***CC**, Krnjaic,'24*

Consider a potential benchmark dark matter (DM) model that is particularly suited to the strengths of a MuC

Example: fermionic DM model with a scalar portal that couples *leptophilically*

χ is DM

φ is portal

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

$$g_l = g_e \frac{m_l}{m_e}$$

(proportional to Yukawa couplings)

D'Ambrosio, Giudice, Isidori, Strumia '02

DM AT MUC: LEPTOPHILIC DM

***CC**, Krnjaic,'24*

Observed relic abundance Ω_χ sets relations between parameters

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

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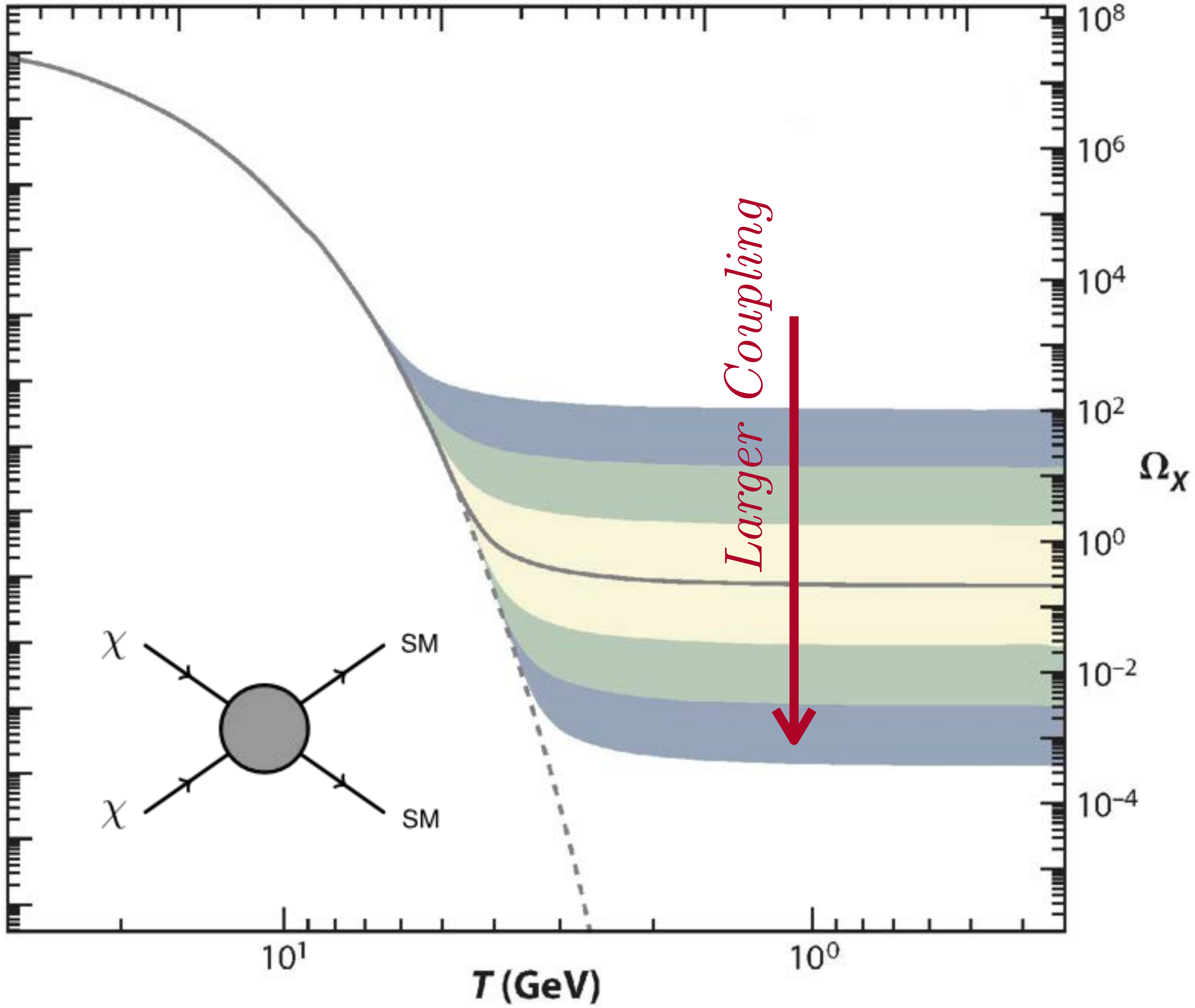

DM AT MUC: LEPTOPHILIC DM

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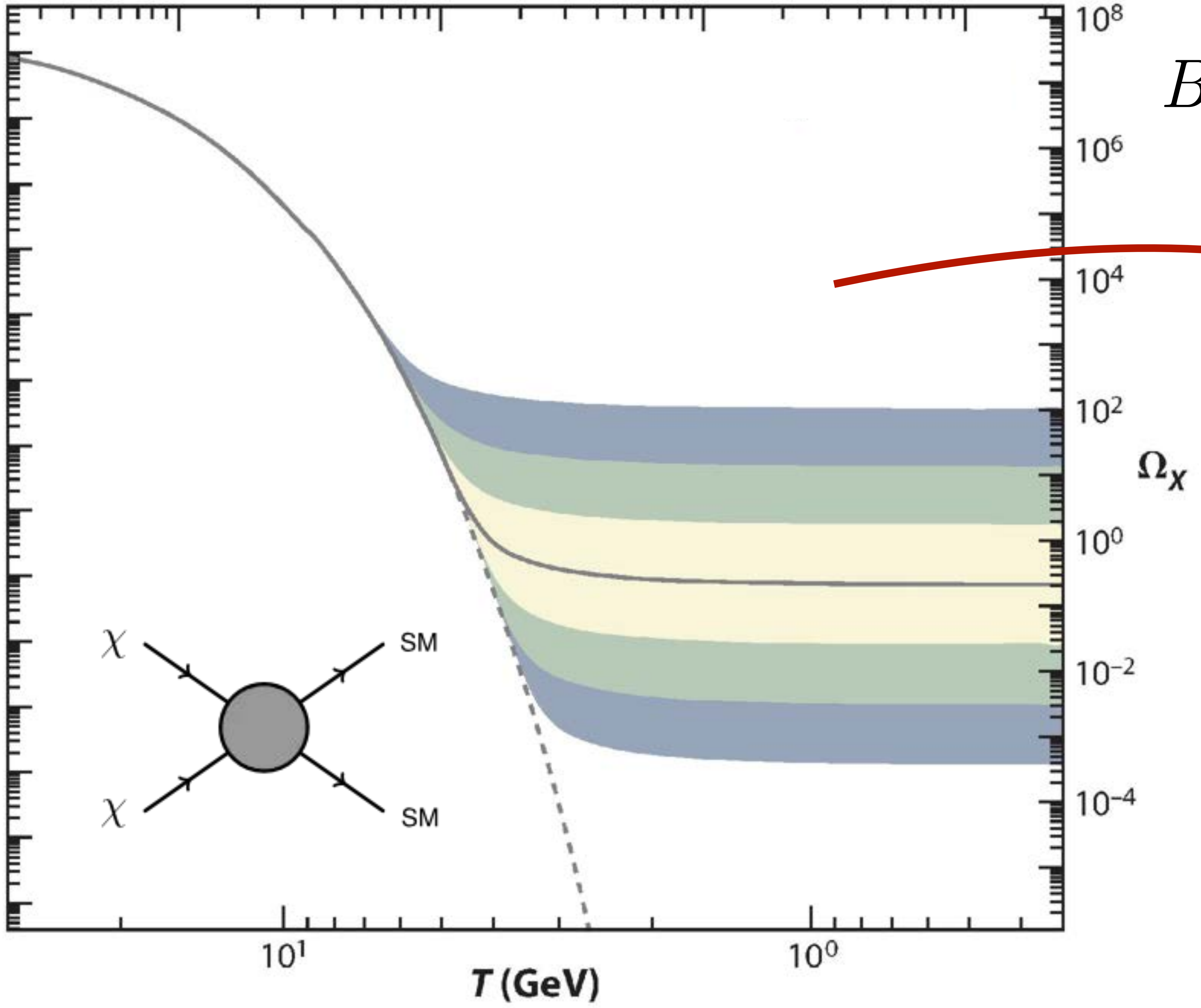
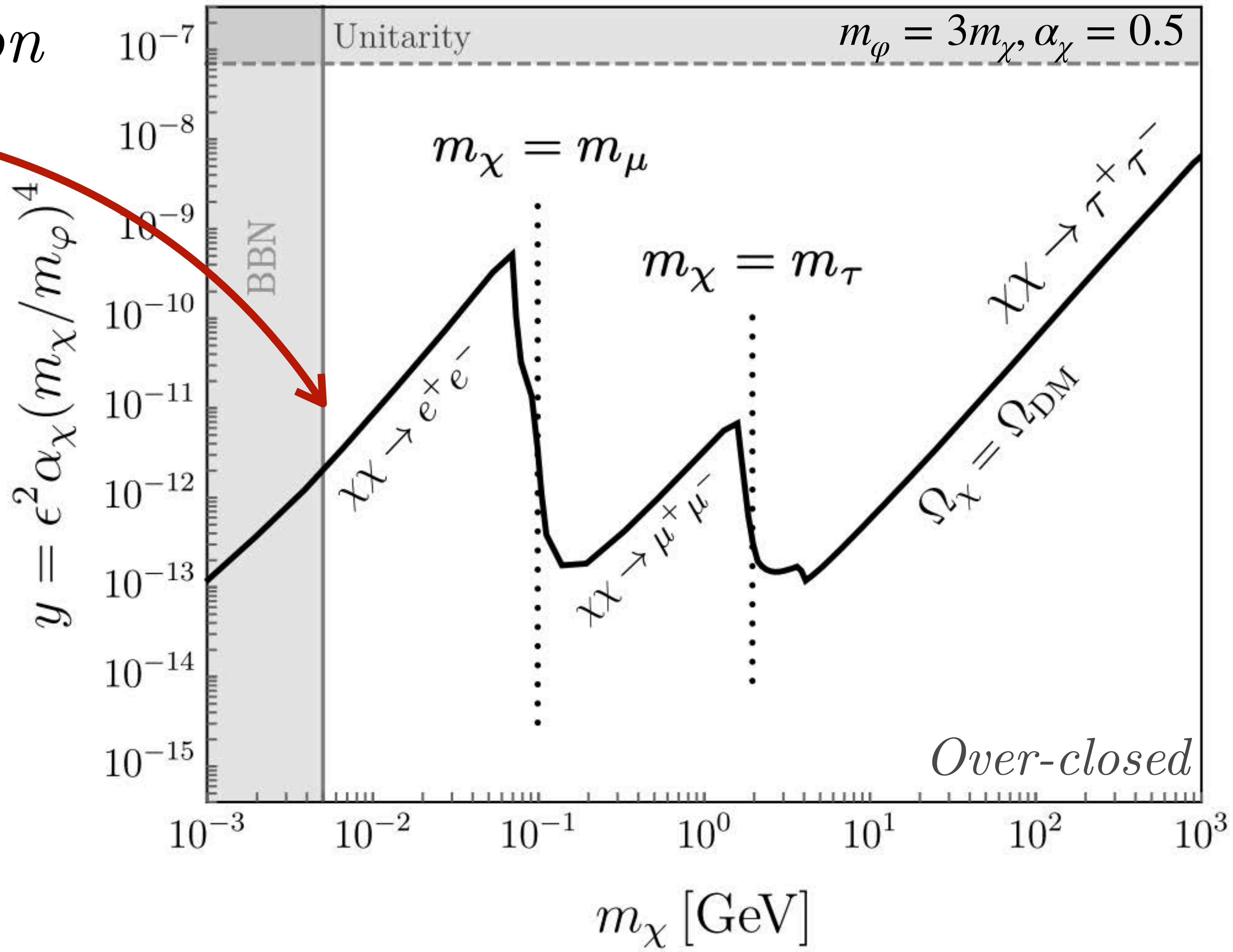


Boltzmann Equation

Thermal Target



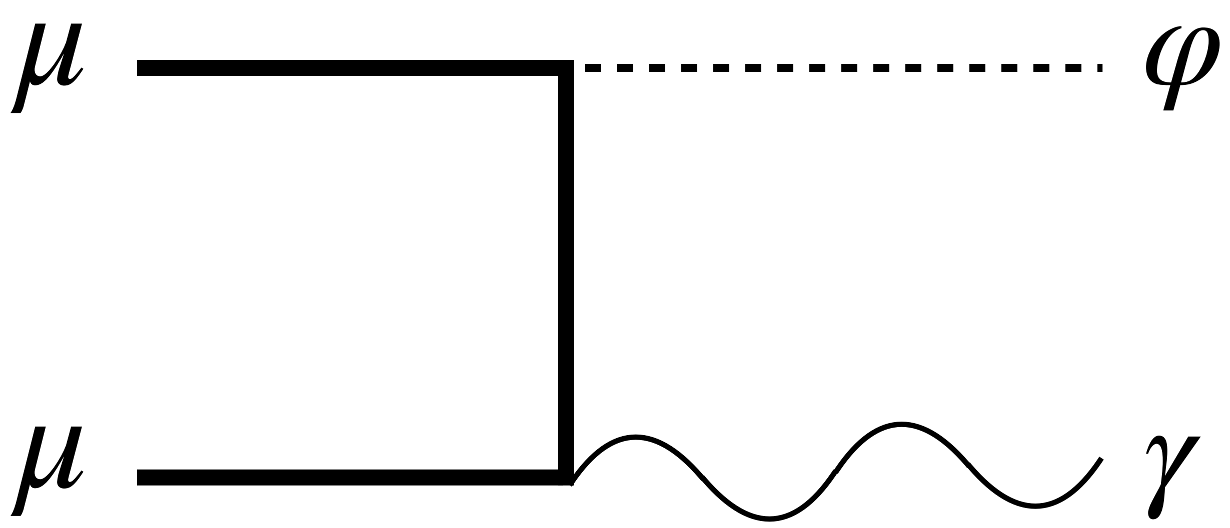
DM AT MUC: LEPTOPHILIC DM

***CC**, Krnjaic,'24*

The improved sensitivity at MuC is because of the second generation coupling and the increased available energy

Mono-X Search

$$\mu^+\mu^- \to \varphi\gamma = \gamma\not{E}$$



$$E_\gamma = \frac{s - m_\varphi^2}{2\sqrt{s}}$$

Background:

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

DM AT MUC: LEPTOPHILIC DM

***CC**, Krnjaic,'24*

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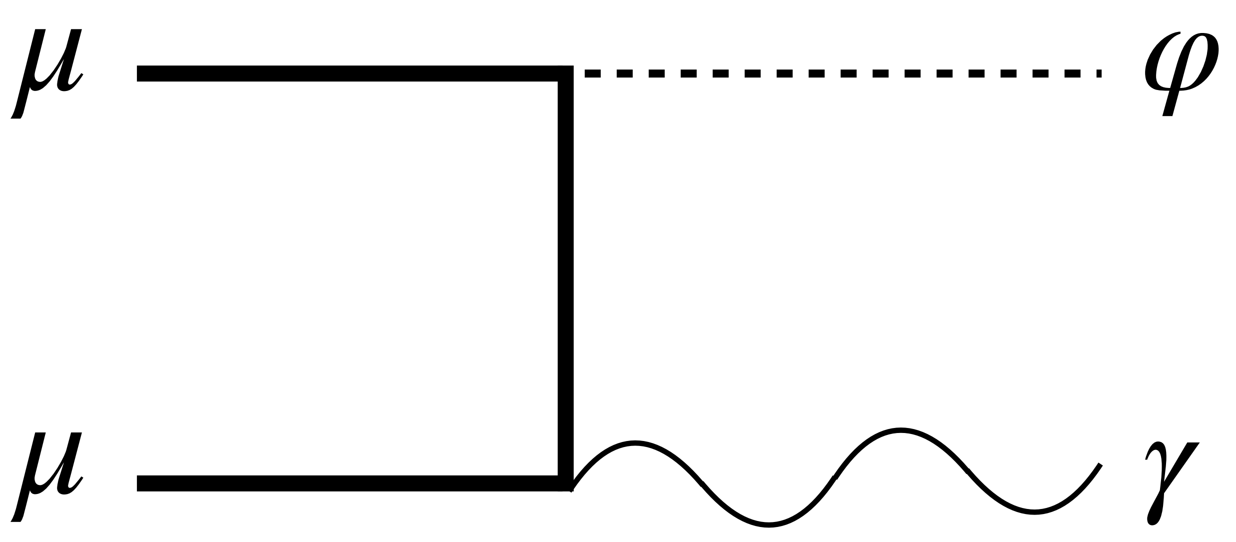
Mono-X Search

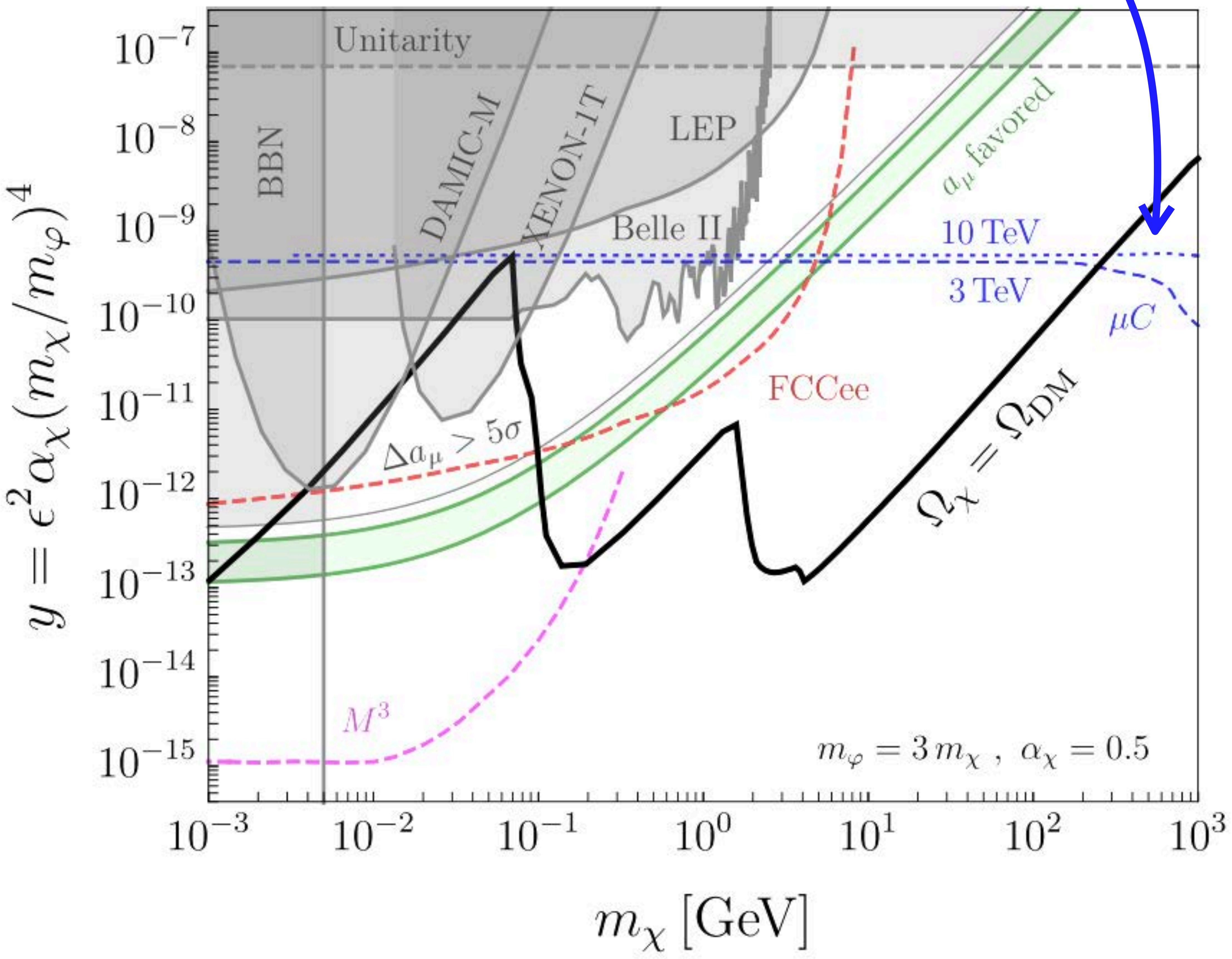
$$\mu^+\mu^- \to \varphi\gamma = \gamma\not{E}$$



$$E_\gamma = \frac{s - m_\varphi^2}{2\sqrt{s}}$$

Background:

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



Bonus

“Exploration Era”

AUXILIARY EXPERIMENTS

Auxiliary Muon Beams

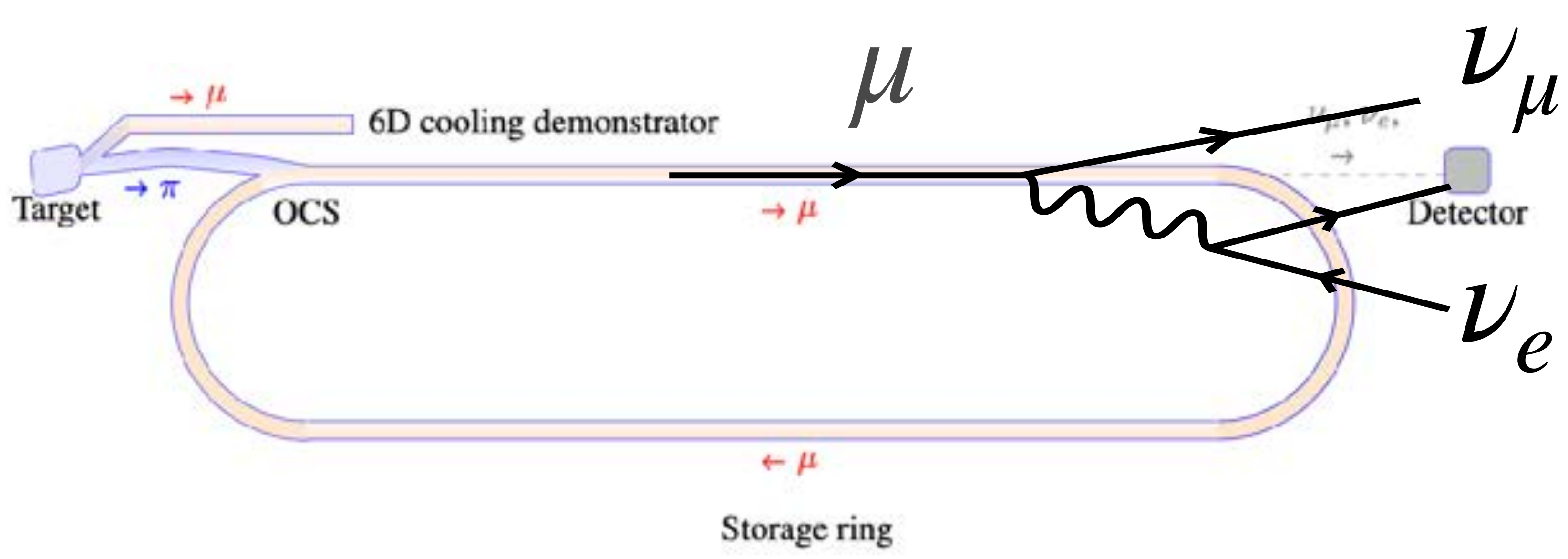
__CC__, Homiller, Mishra, Reece '22 · __CC__, Gambhir '23

Muon beams will be a necessary part of muon collider R&D

Future muon colliders *require* R&D—

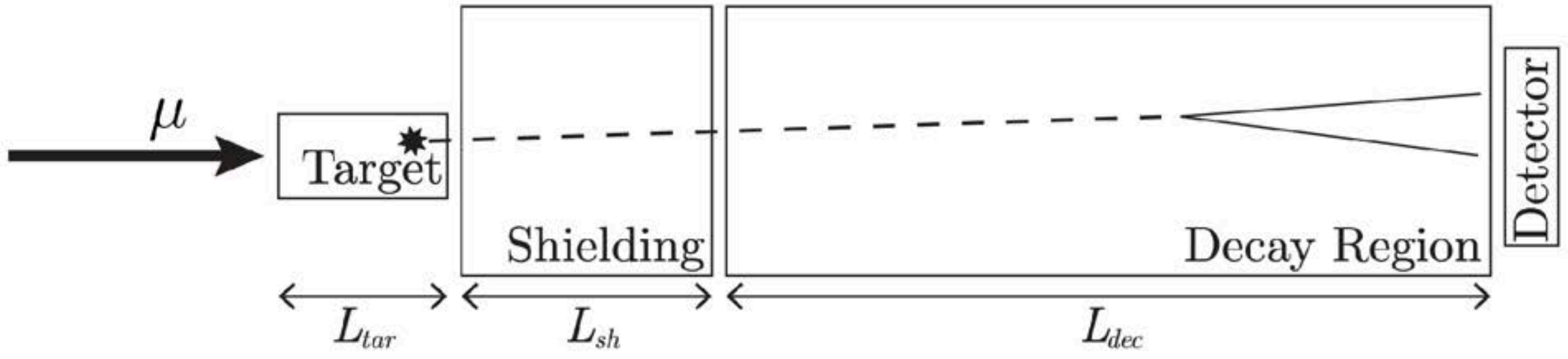
we should take full advantage of staged μ beam

Neutrino Synergies



NuSTORM '23

Weakly Coupled New Physics



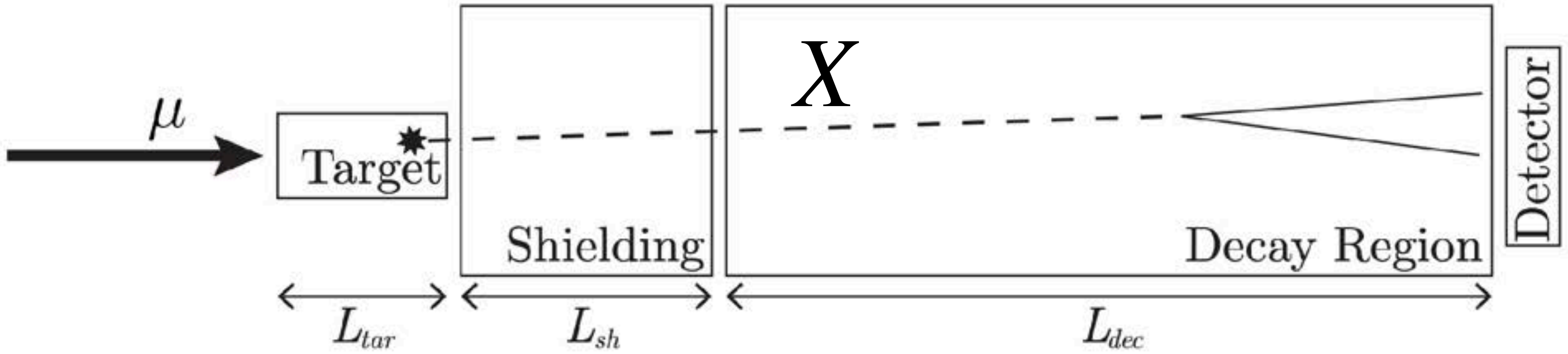
__CC__, Homiller, Mishra, Reece '22 · __CC__, Gambhir '23

AUXILIARY MUON BEAMS

***CC**, Homiller, Mishra, Reece '22 · **CC**, Gambhir '23*

Beam dumps are economical auxiliary experiments with complementary physics reach to the full collider

$$E_{CoM} \sim \sqrt{2E_\mu m_N}$$



...but enhancement on σ of Avogadro's Number

$$\sim 6 \times 10^{23}$$

AUXILIARY MUON BEAMS

***CC**, Homiller, Mishra, Reece ’22 · **CC**, Gambhir ’23*

Beam dumps are economical auxiliary experiments with complementary physics reach to the full collider

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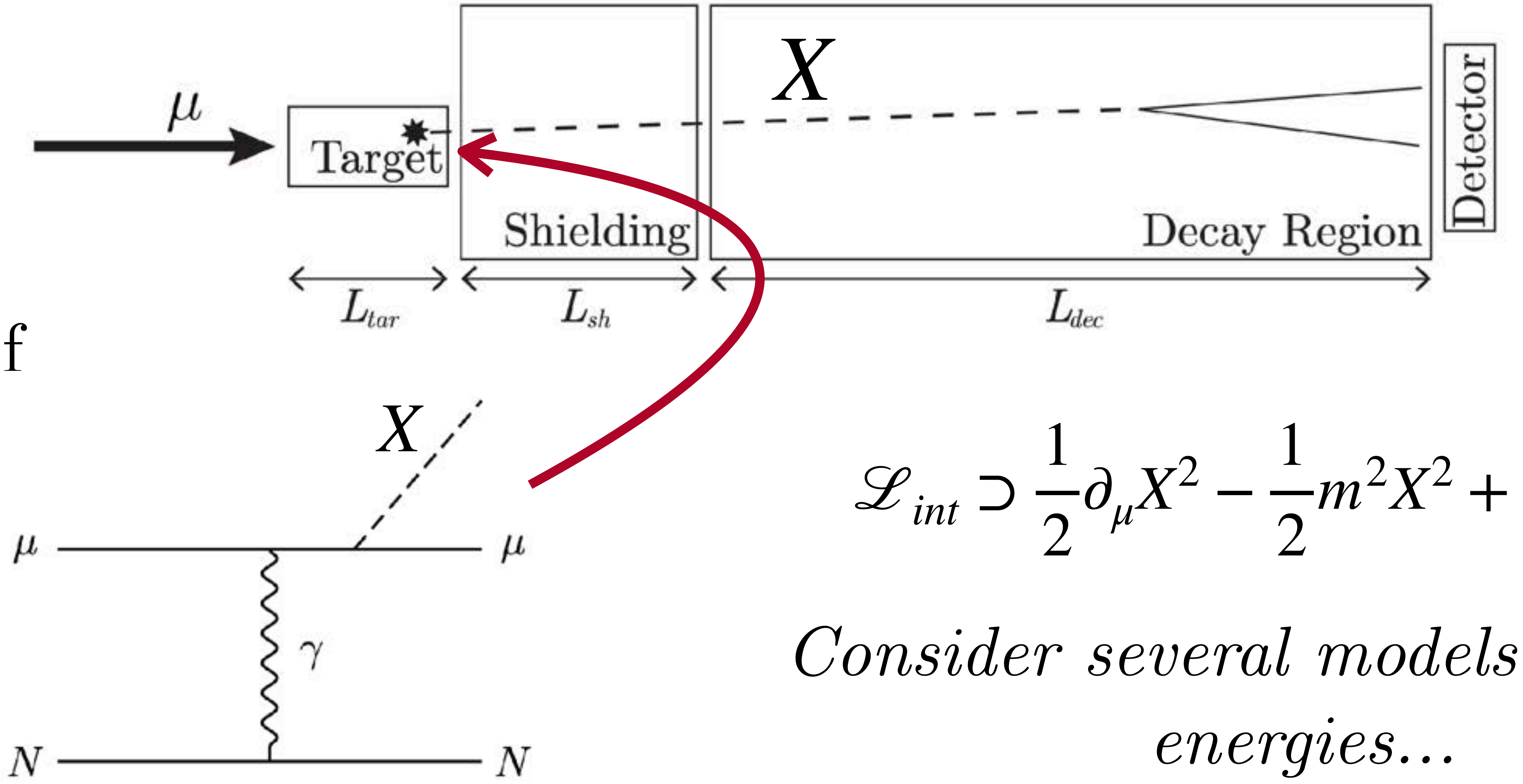


…but enhancement on σ of Avogadro’s Number

$$\sim 6 \times 10^{23}$$

$$\mathscr{L}_{int} \supset \frac{1}{2}\partial_\mu X^2 - \frac{1}{2}m^2X^2 + ig_X\mathcal{O}_{\bar{f}fX}$$

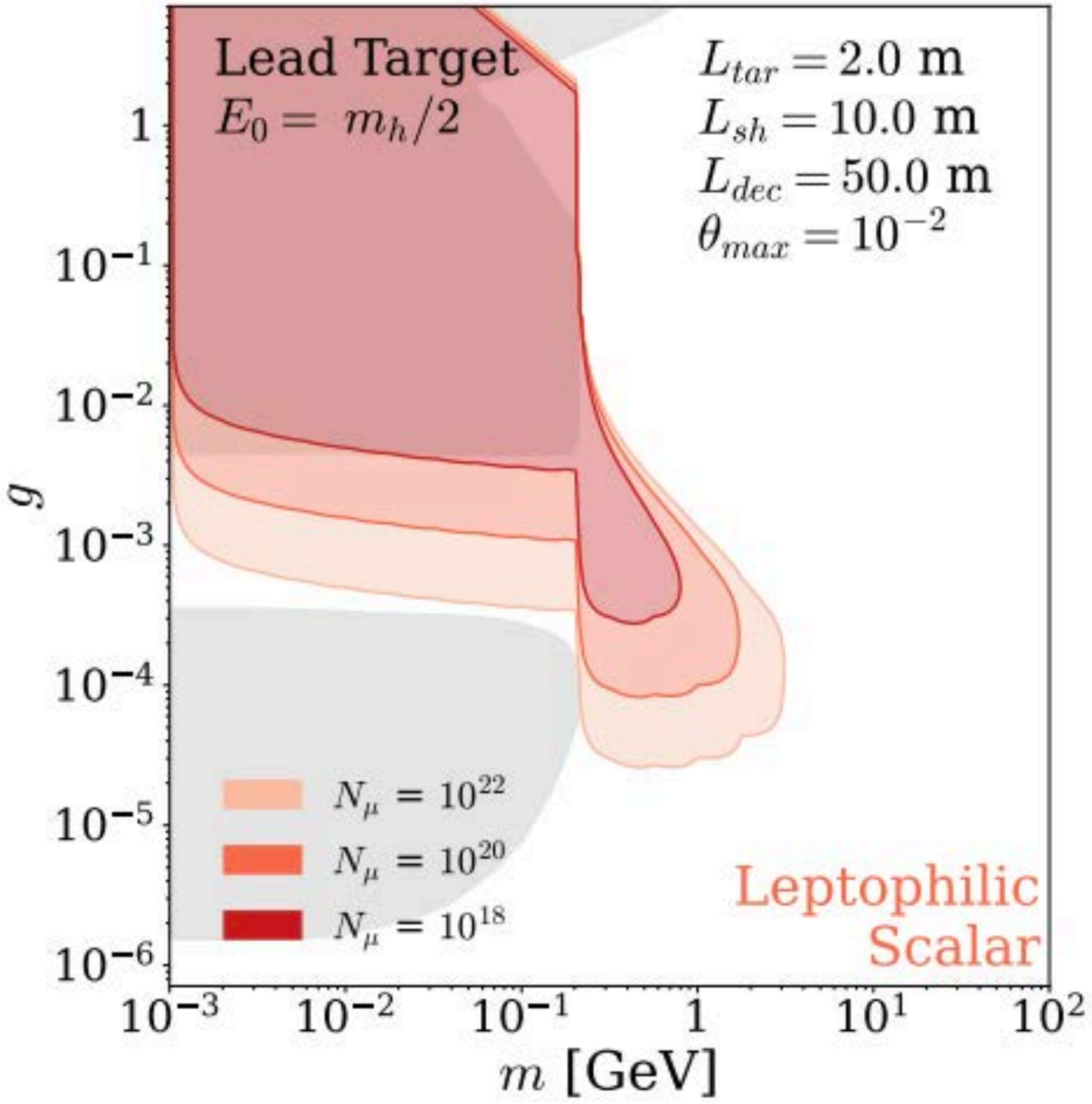
Consider several models at various energies…

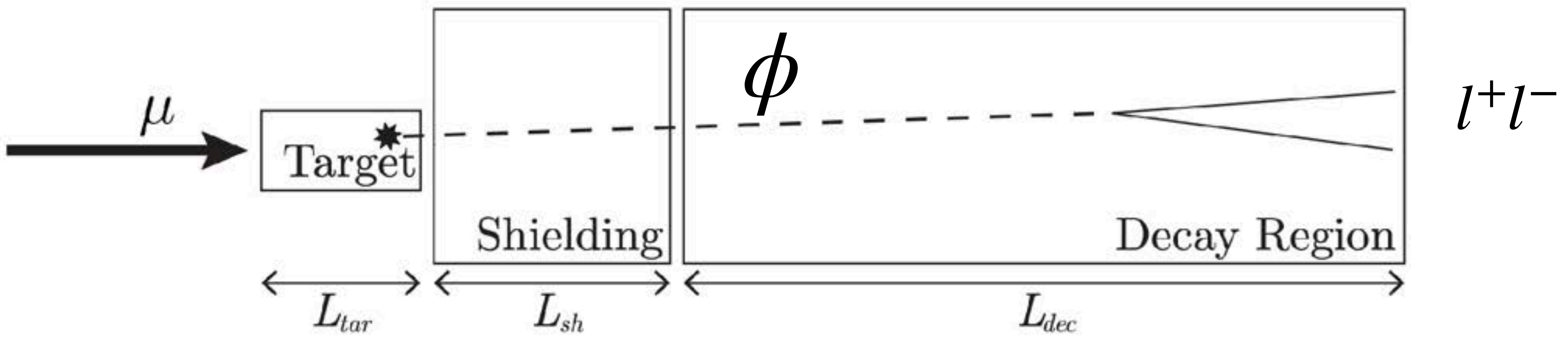
Auxiliary Muon Beams

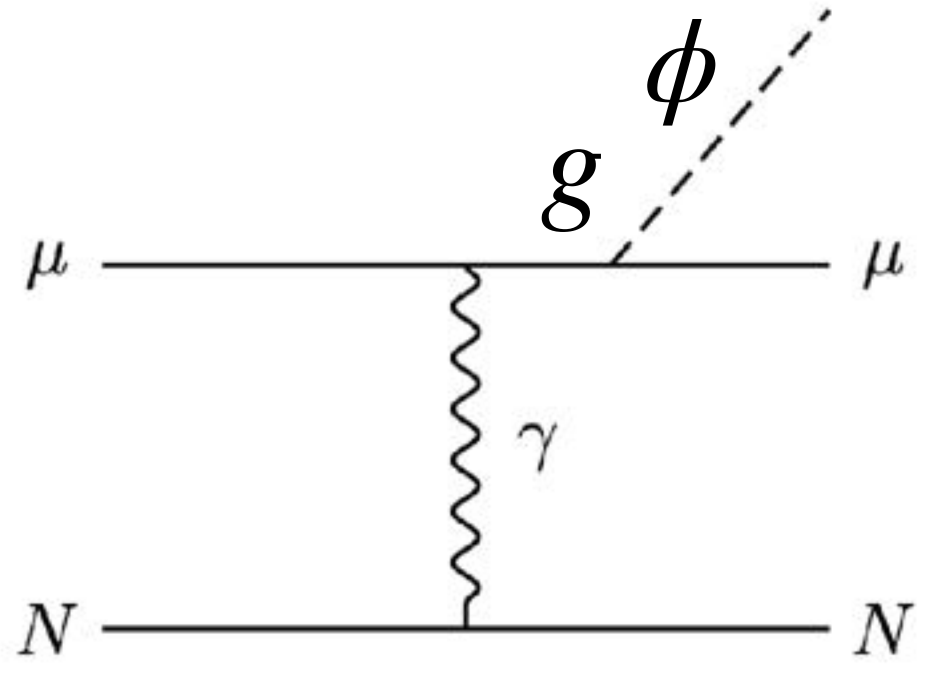
***CC**, Homiller, Mishra, Reece ’22 · **CC**, Gambhir ’23*

With R&D program, energy-staged beam will be online well before full collider

Low Energy (63 GeV)







$$\mathscr{L}_{int} \supset -ig\phi\bar{\psi}\psi$$

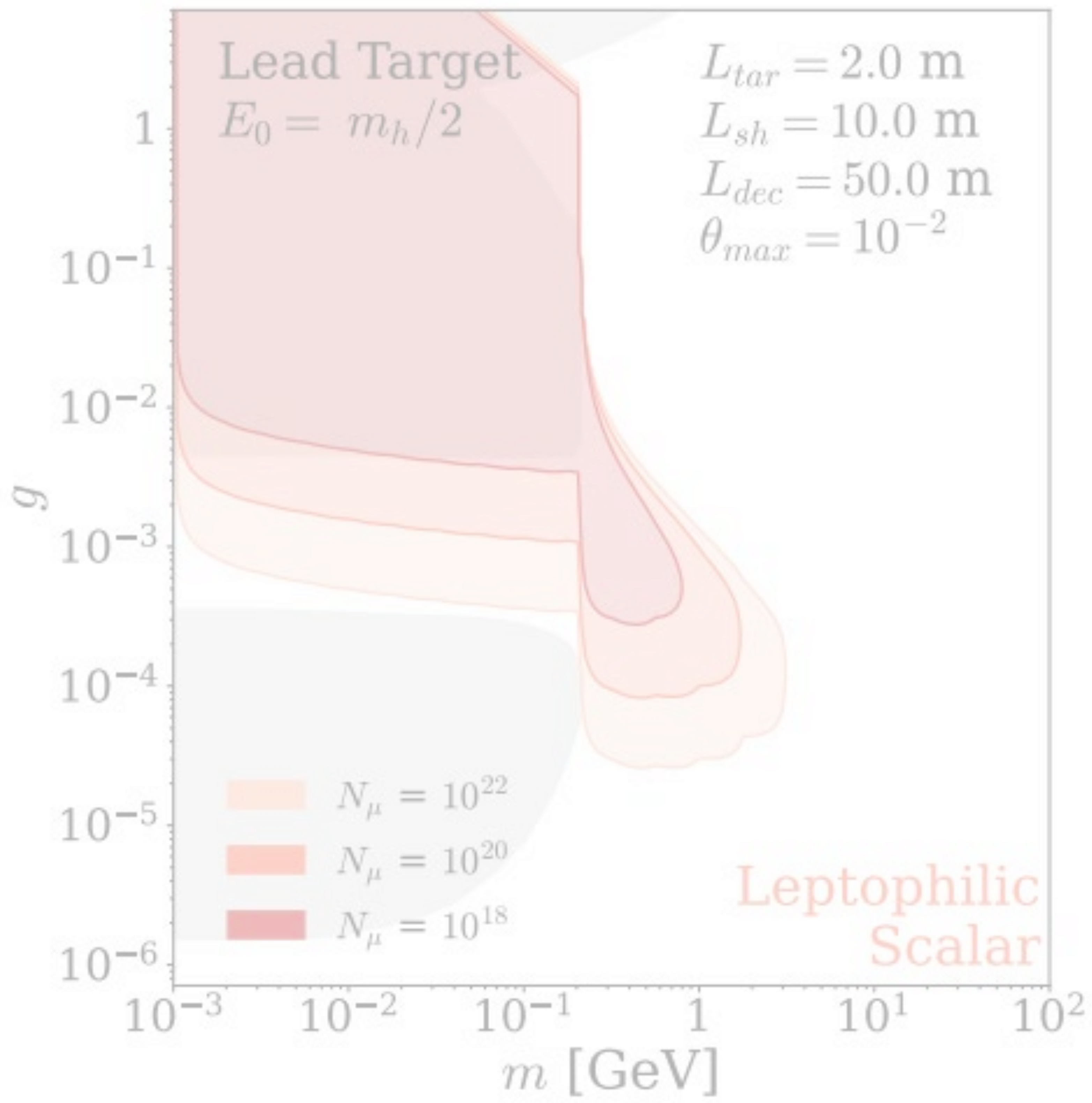
AUXILIARY MUON BEAMS

***CC**, Homiller, Mishra, Reece '22 · **CC**, Gambhir '23*

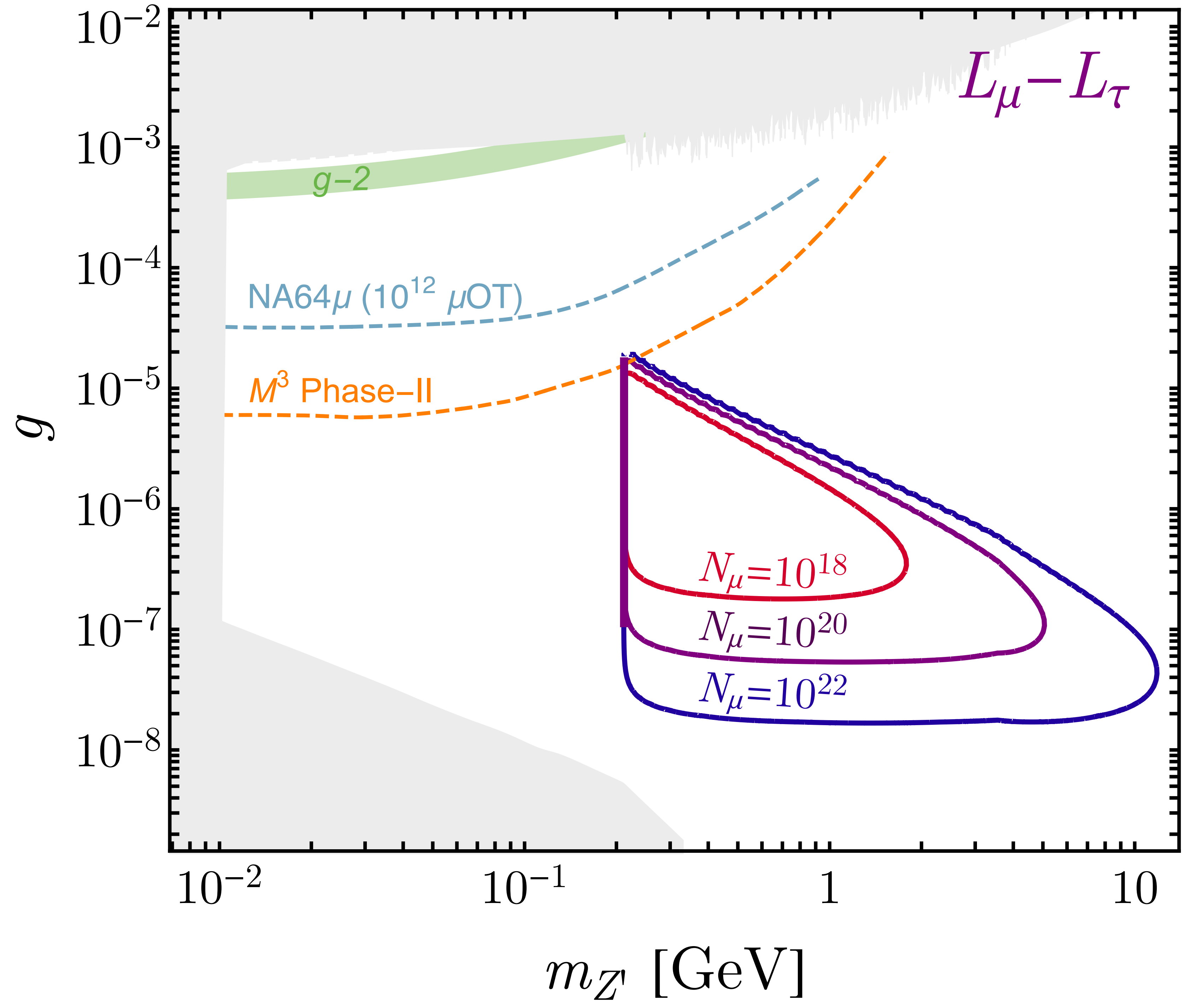
With R&D program, energy-staged beam will be online well before full collider

Luminosity at MuC goes with muon/bunch *squared* $\mathscr{L} \sim n_\mu^2$

Low Energy (63 GeV)



Energy Stage (1.5 TeV)



Gauged $L_\mu - L_\tau$

Probes unexplored space because of μ beam

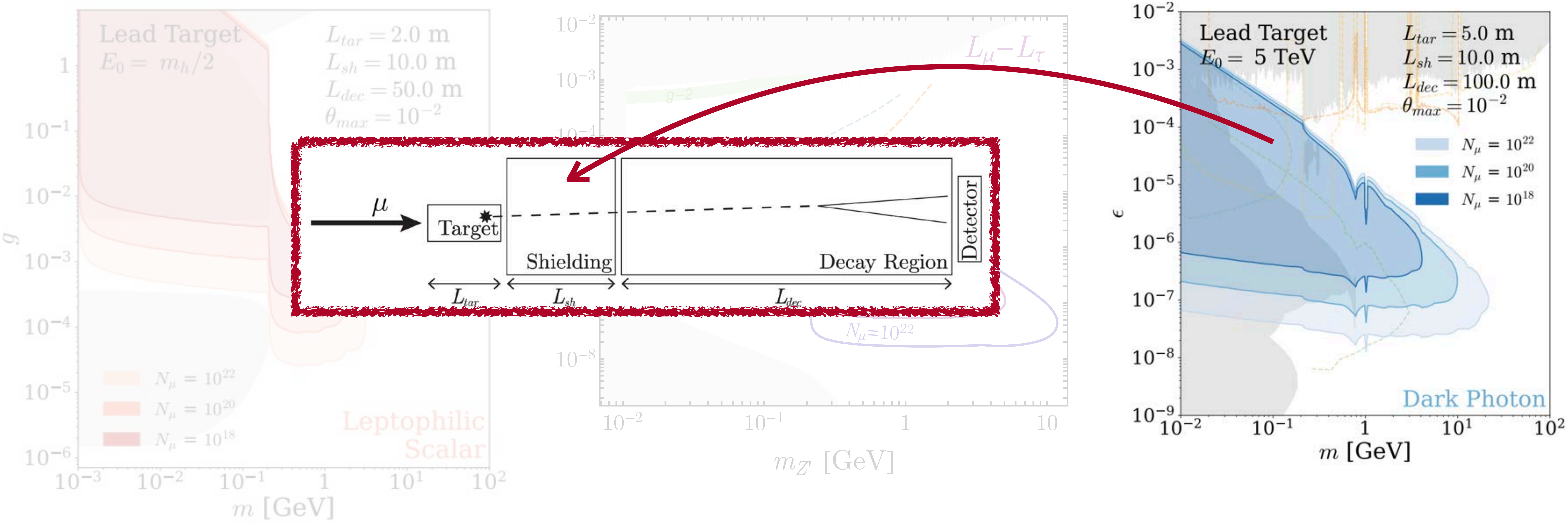
Auxiliary Muon Beams

***CC**, Homiller, Mishra, Reece '22 · **CC**, Gambhir '23*

With R&D program, energy-staged beam will be online well before full collider

Luminosity at MuC goes with muon/bunch *squared* $\mathscr{L} \sim n_\mu^2$

Low Energy (63 GeV) Energy Stage (1.5 TeV) Full Energy (5 TeV)

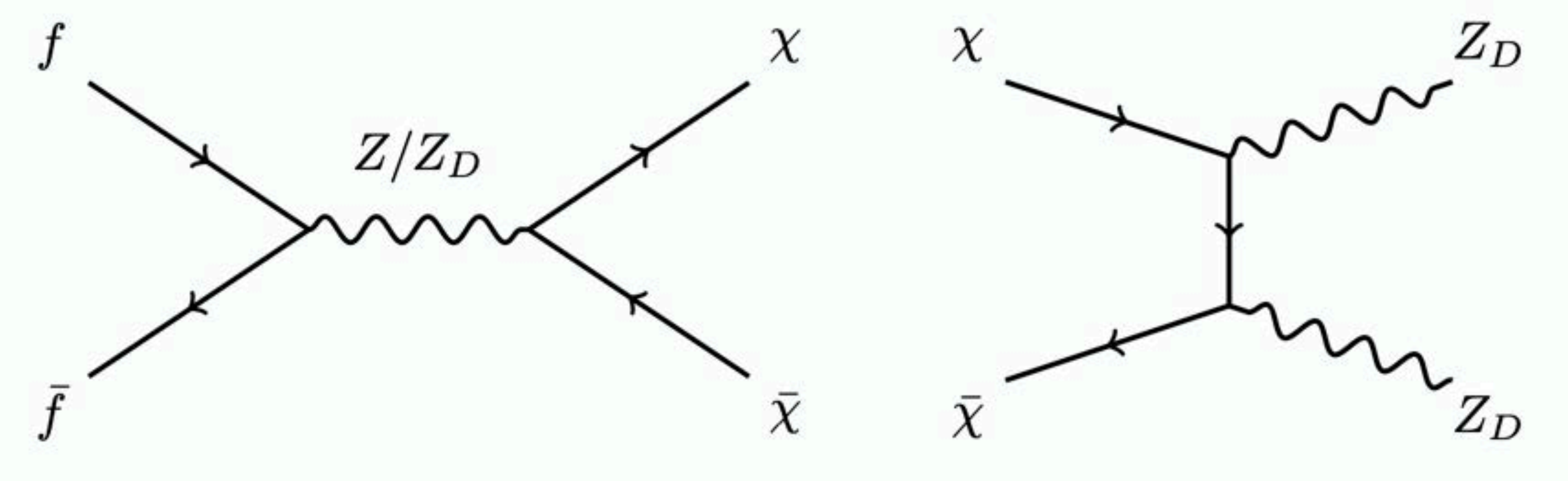


DARK MATTER AND BEAM DUMPS

*Alenezi, **CC**, Gori, Shelton '25*

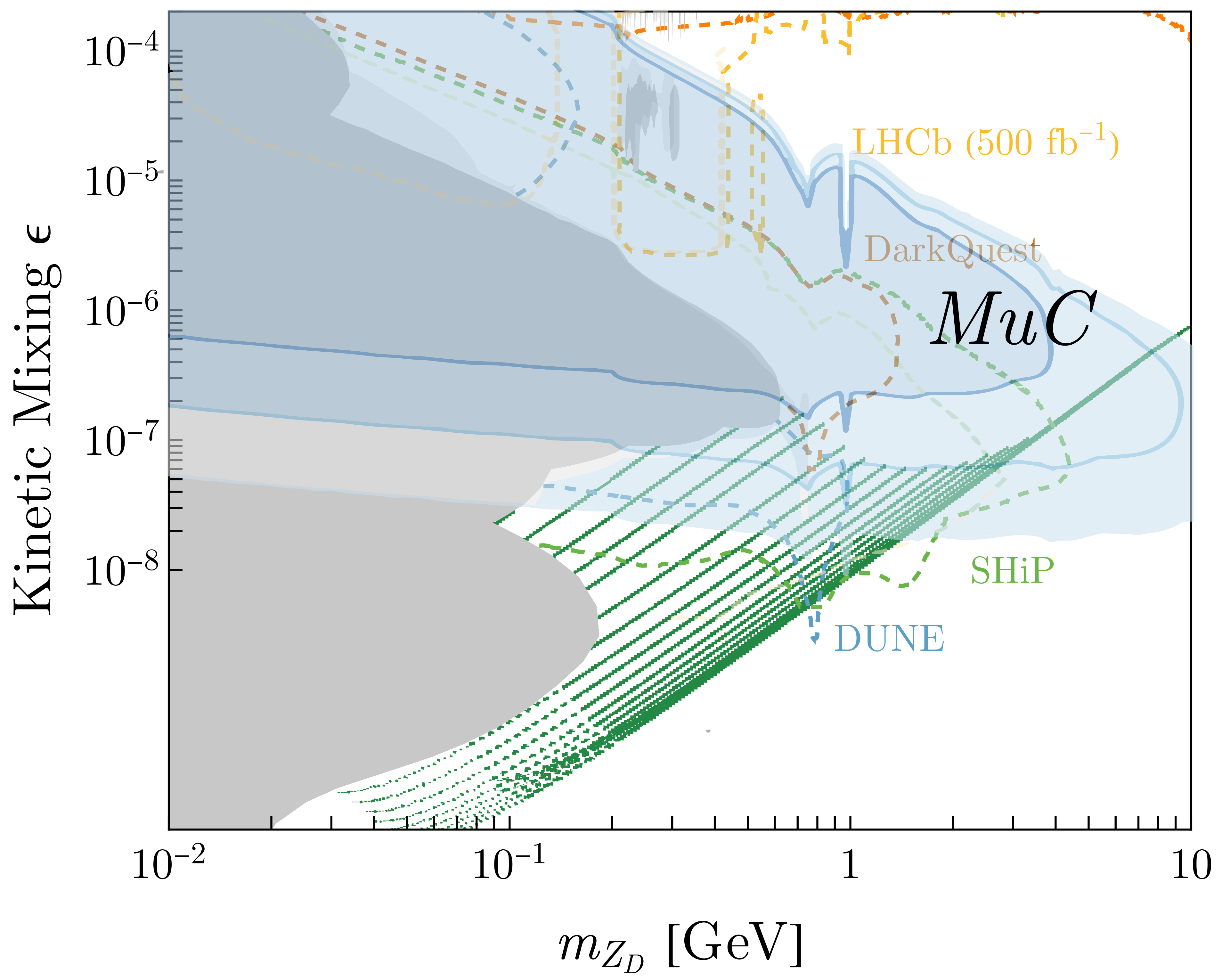
Beam dumps can probe parameter space of minimal DM complementary to *direct detection* and *indirect detection* experiments

$SU(2)_L \times U(1)_Y \times U(1)_D$



$\chi, Z_D \qquad m_\chi \gg m_{Z_D}$

Auxiliary experiments can address fundamental BSM questions



OUTLOOK FOR MUON COLLIDER

A muon collider presents unique advantages to push the energy and precision machine together.

Unlike other collider options, the proposed project (10 TeV) is not at the limits of technology.

As theorists, we need input. For experimentalists, they need design targets.

The energy frontier has always taught us something new about the laws of nature; we should ensure there are multiple avenues to pursue it.

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As theorists, we need input. For experimentalists, they need design targets.

The energy frontier has always taught us something new about the laws of nature; we should ensure there are multiple avenues to pursue it.

Now is the time for R&D.

Backups

MuC Run Parameters

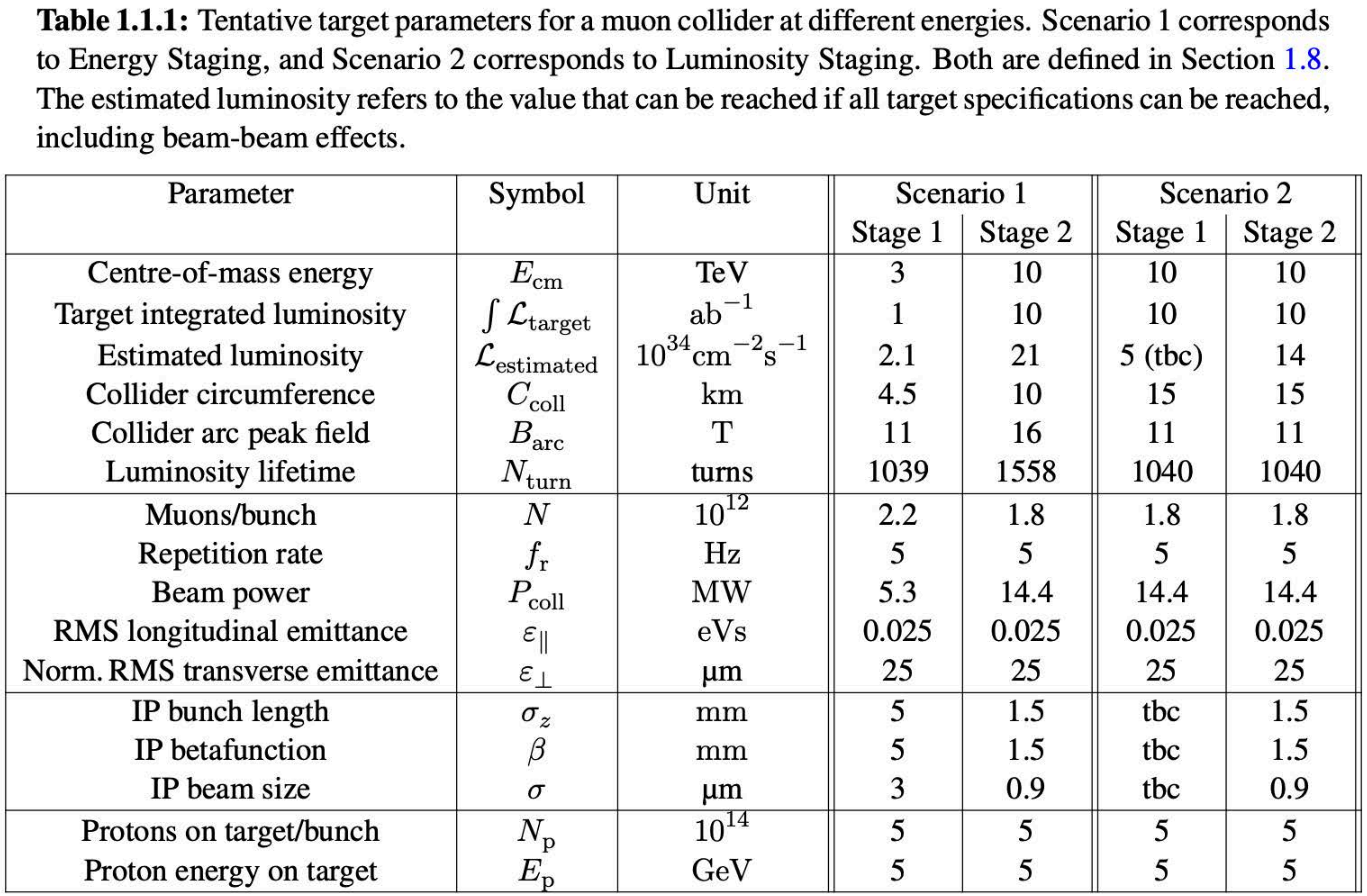


Table 1.1.1: Tentative target parameters for a muon collider at different energies. Scenario 1 corresponds to Energy Staging, and Scenario 2 corresponds to Luminosity Staging. Both are defined in Section 1.8. The estimated luminosity refers to the value that can be reached if all target specifications can be reached, including beam-beam effects.

Parameter	Symbol	Unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	10	10
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.1	21	5 (tbc)	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5	5	5
Proton energy on target	E_{p}	GeV	5	5	5	5

Muon Collider ESPPU '25

MuC Detector Benchmarks

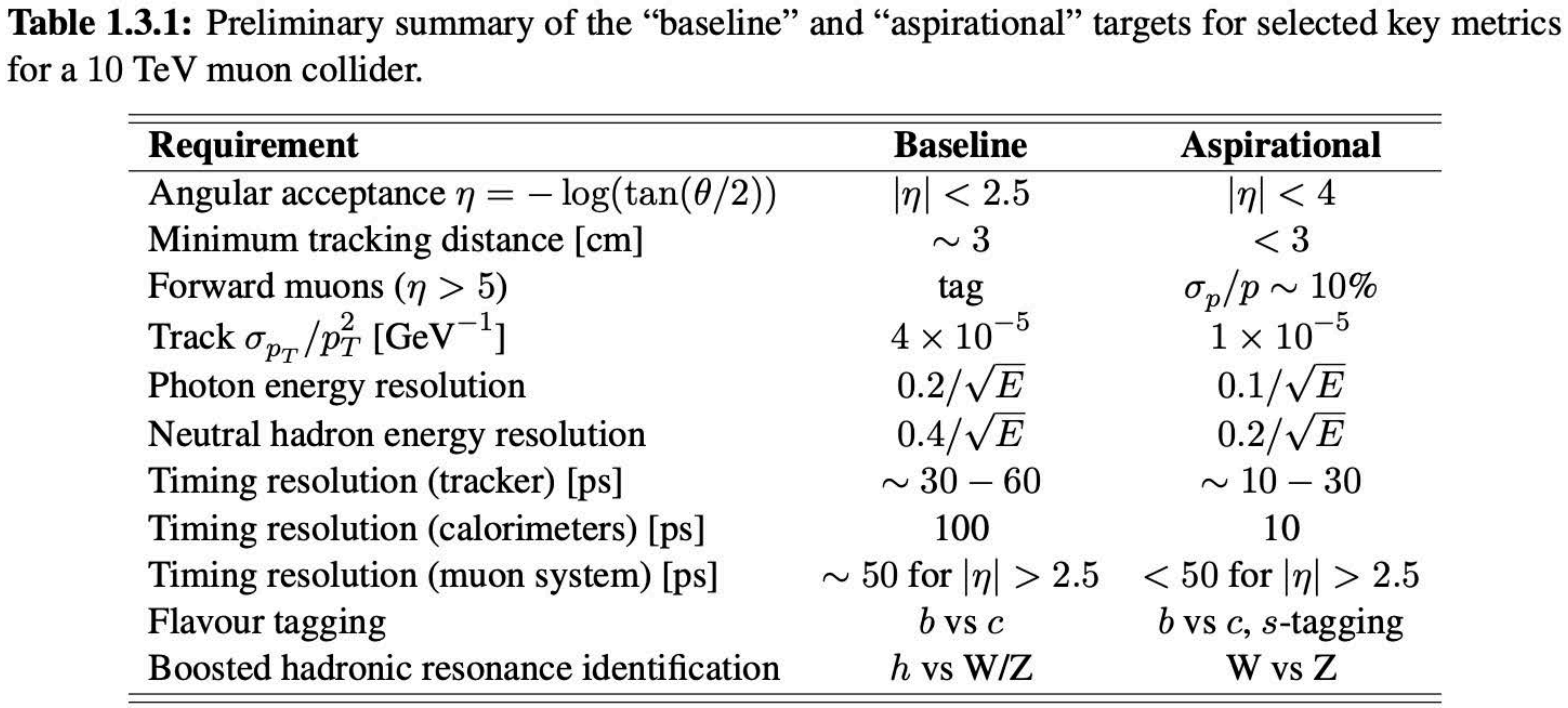


Table 1.3.1: Preliminary summary of the "baseline" and "aspirational" targets for selected key metrics for a 10 TeV muon collider.

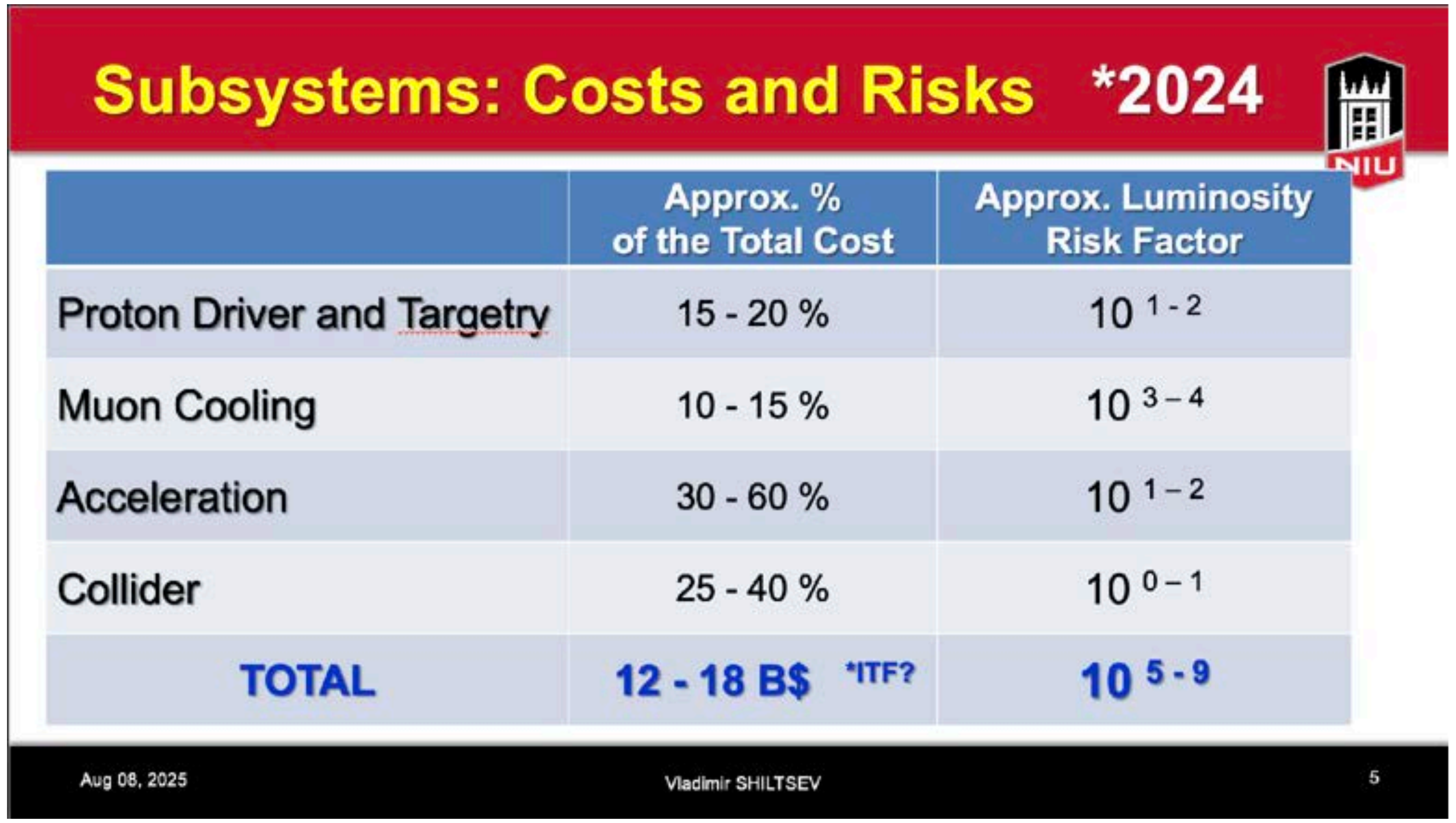
Requirement	**Baseline**	**Aspirational**
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance identification	h vs W/Z	W vs Z

Muon Collider ESPPU '25

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

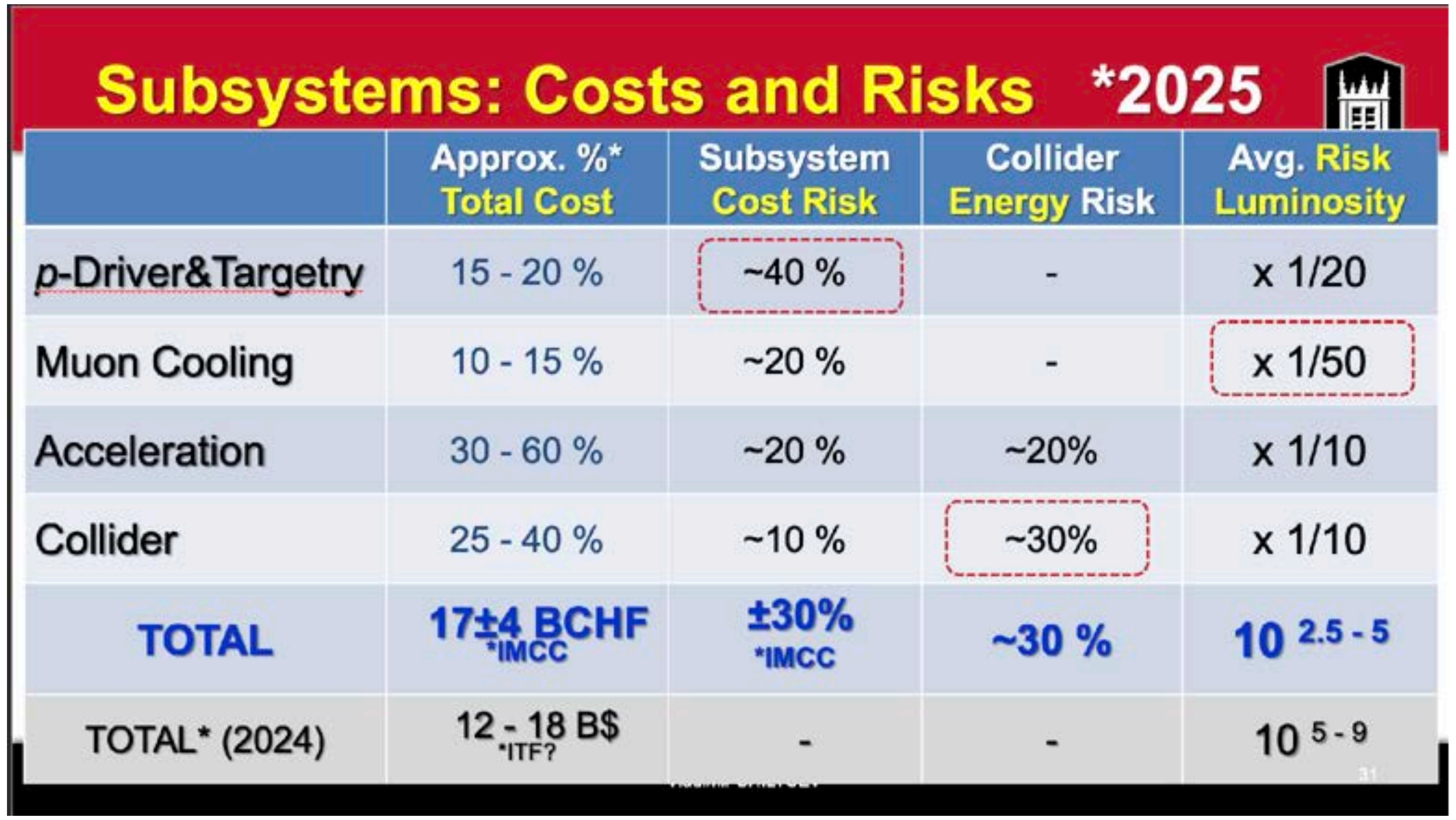


Subsystems: Costs and Risks *2024

	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

→



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

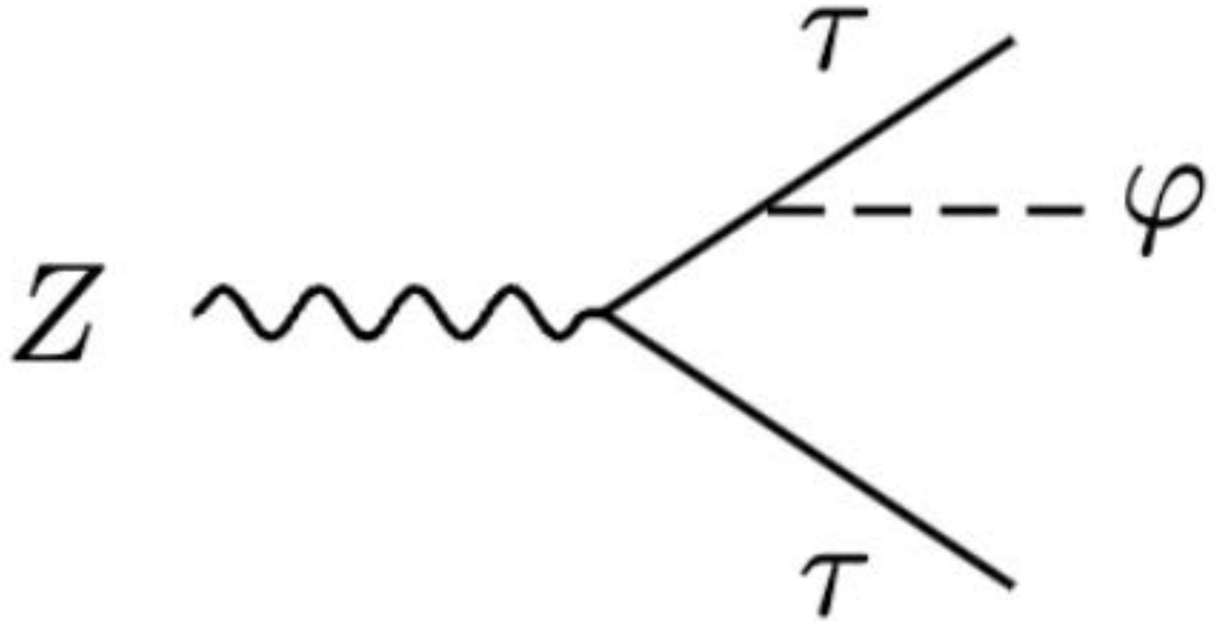
DM AT EE COLLIDER: LEPTOPHILIC DM

***CC**, Krnjaic,'24*

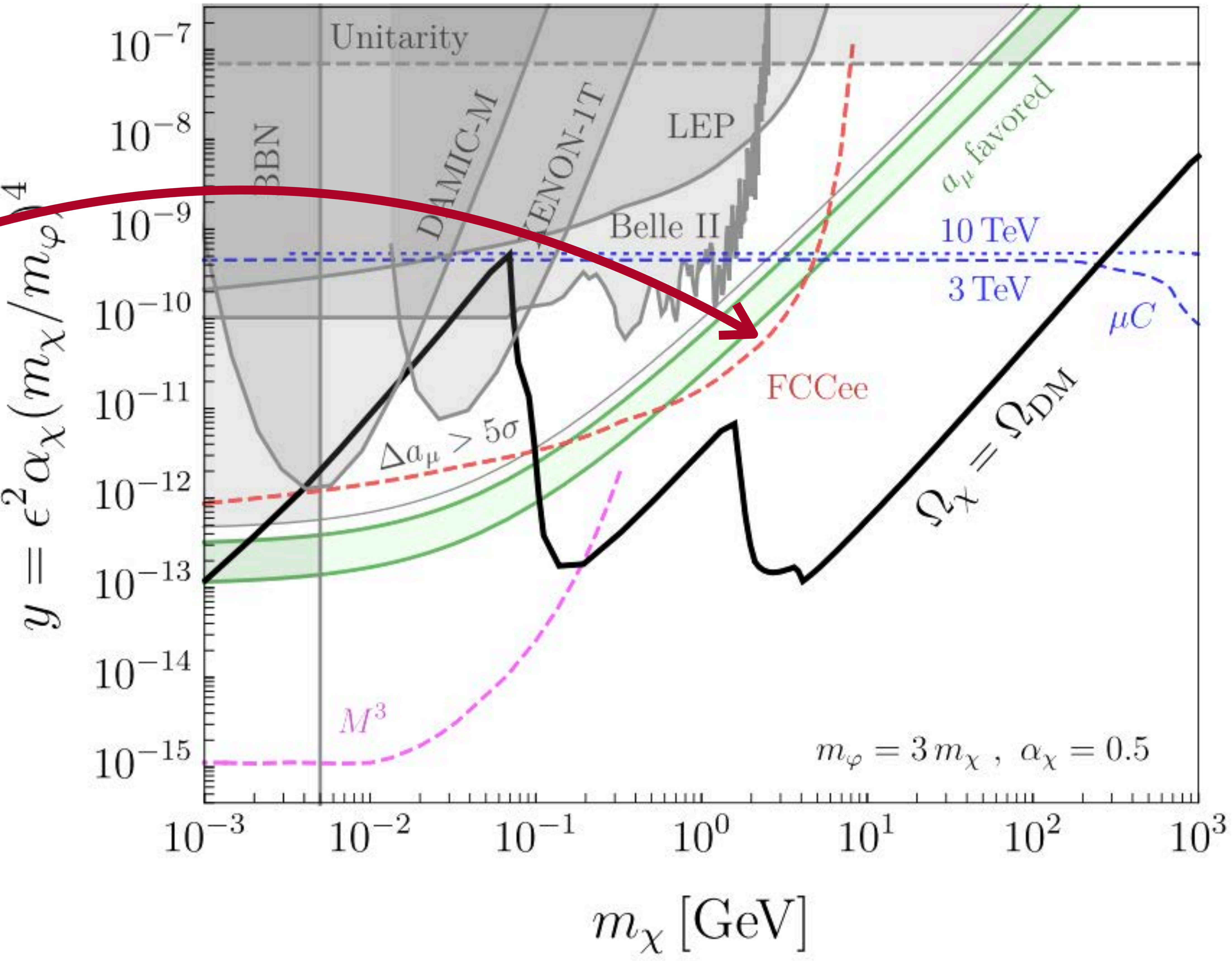
The improved sensitivity at *precision electron machine* is because of the huge statistics at the Z-pole (5×10^{12} Z bosons!)

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

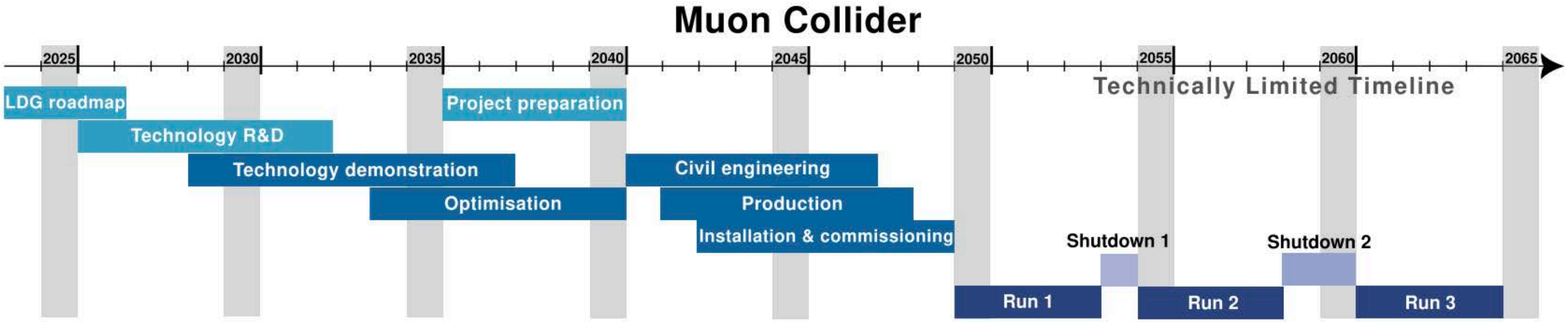
Bound set by uncertainty in BR



FUTURE MACHINES ARE *COMPLEMENTARY*



MUON COLLIDER TIMESCALES



MUON COLLIDER STAGING

Staging options are important to ensure a muon collider can collect data even if upgrades need more time for R&D

3 TeV

10 TeV

30 TeV

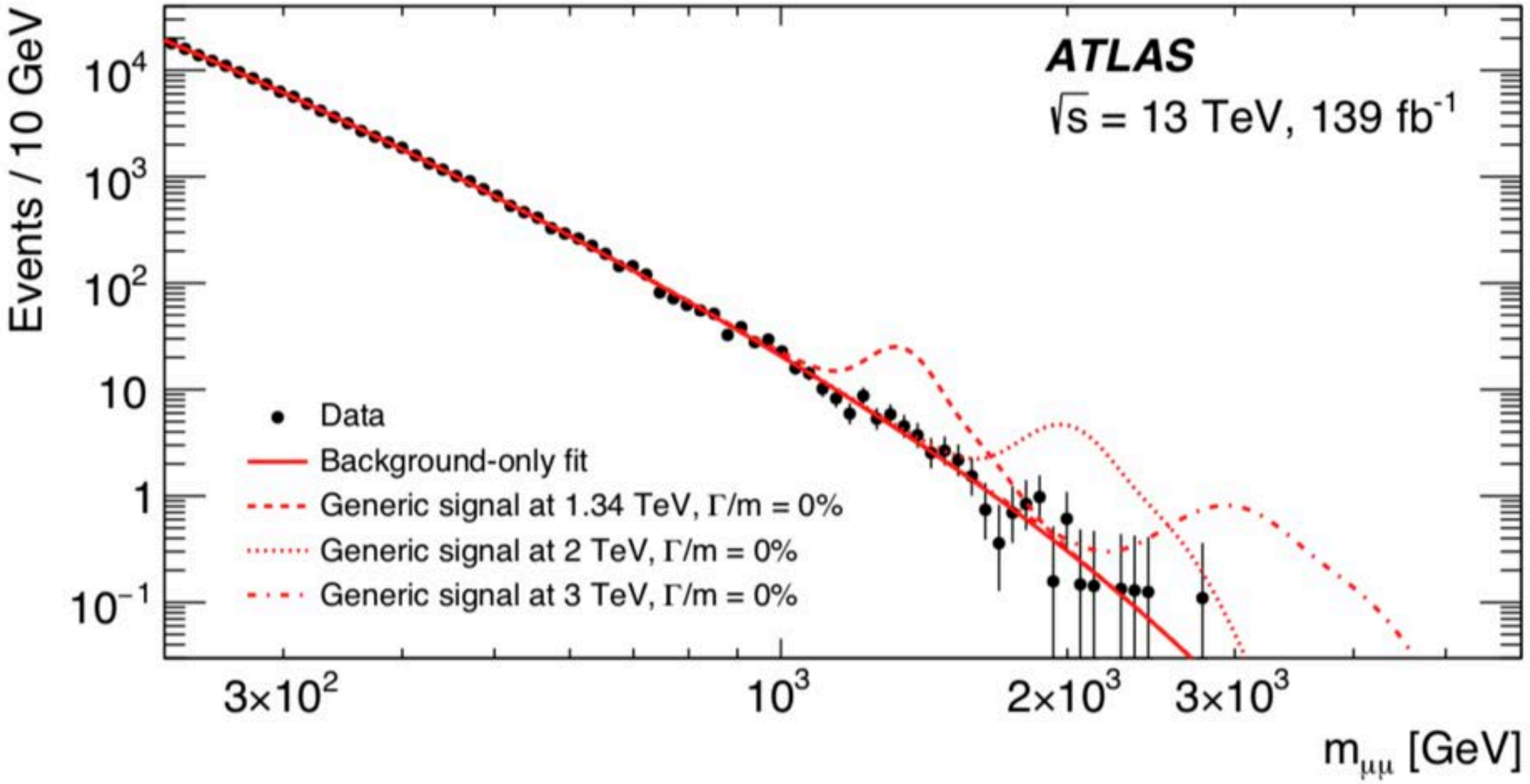
100 TeV

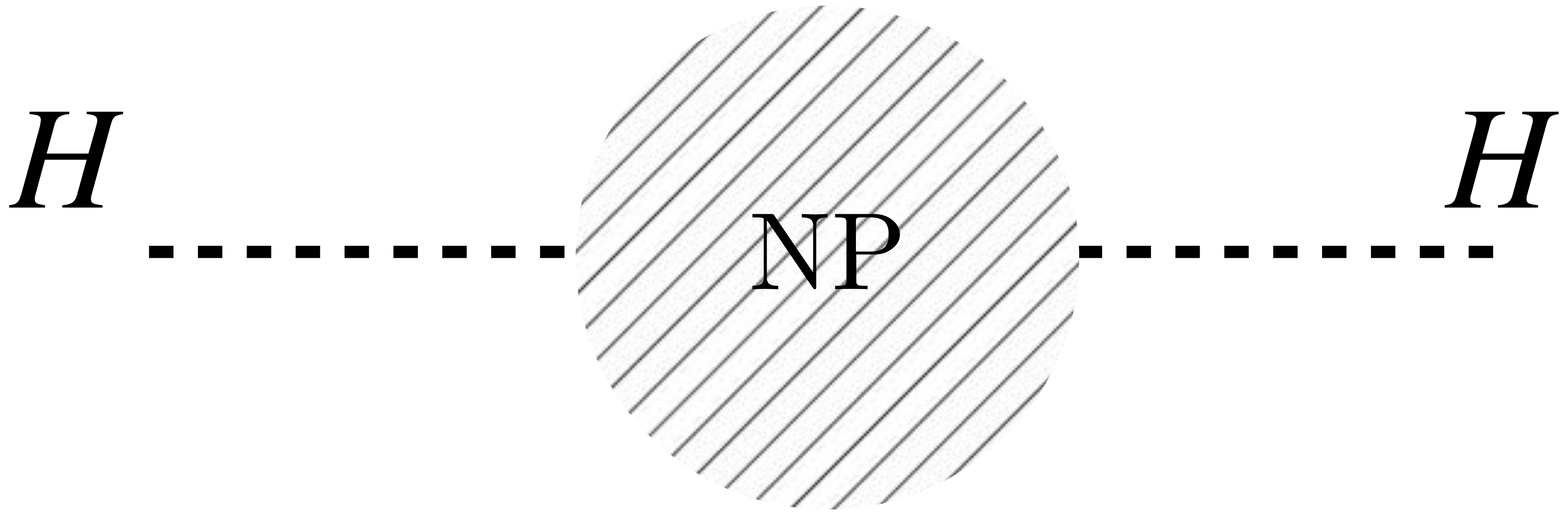
Muon Collider Staging

Staging options are important to ensure a muon collider can collect data even if upgrades need more time for R&D

$(1\ \mathrm{ab}^{-1})$ 3 TeV

Beyond typical LHC $\sqrt{\hat{s}}$





$$\delta m_H^2 \sim \frac{g^2}{16\pi^2} M_{NP}^2 \lesssim g^2 v^2$$

New Physics showing up to affect EW Physics?

MUON COLLIDER STAGING

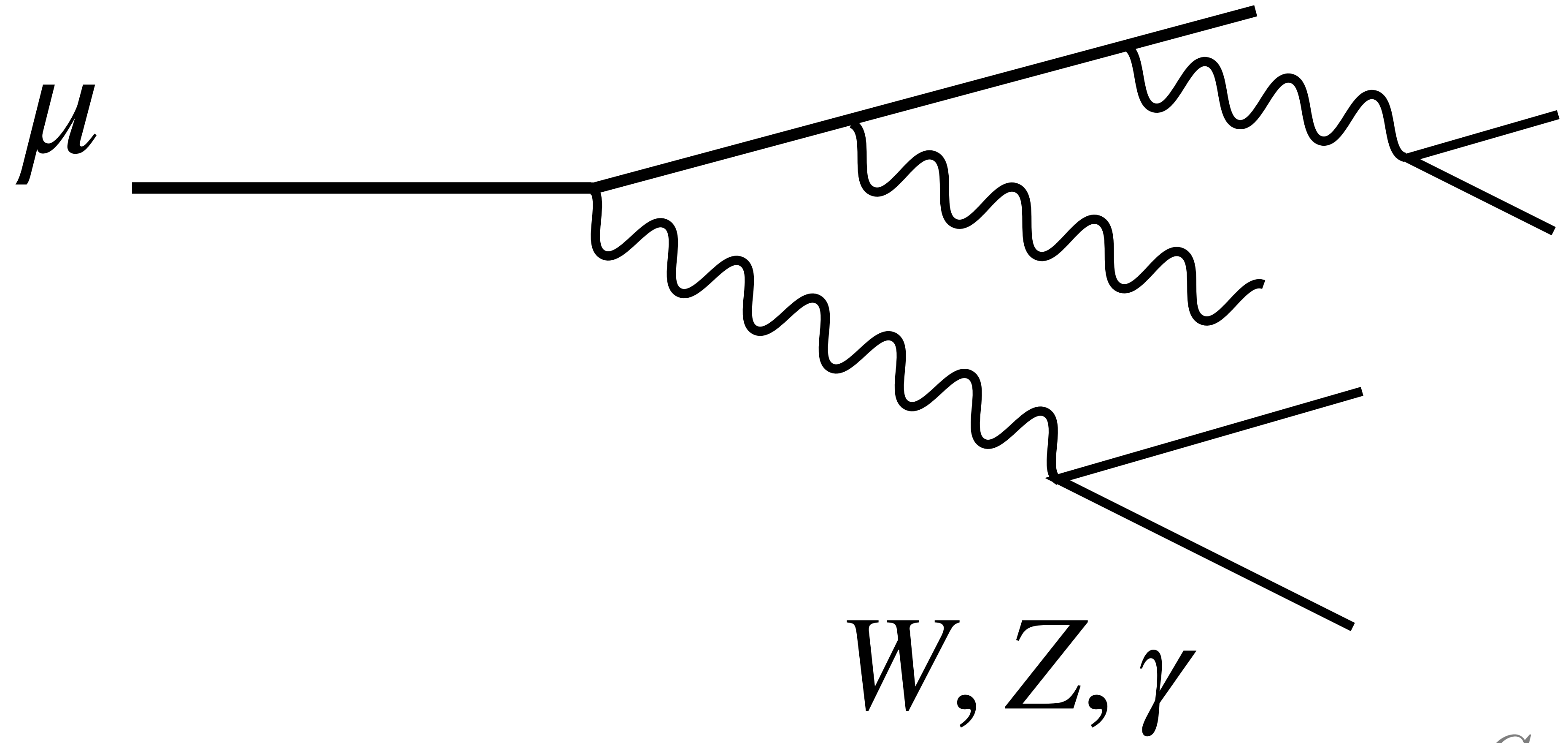
Staging options are important to ensure a muon collider can collect data even if upgrades need more time for R&D

$(1\ \mathrm{ab}^{-1})$ 3 TeV Beyond typical LHC $\sqrt{\hat{s}}$

$(10\ \mathrm{ab}^{-1})$ 10 TeV See new SM phenomena (e.g. EW jets)

$$\frac{\alpha}{4\pi}\log^2\left(\frac{E^2}{m_W^2}\right)\times \text{Casimir} \sim 1 \text{ for E } \sim 10 \text{ TeV}$$

Chen, Glioti, Rattazzi, Ricci, Wulzer '22



MUON COLLIDER STAGING

Staging options are important to ensure a muon collider can collect data even if upgrades need more time for R&D

($1\ \mathrm{ab}^{-1}$)	3 TeV	Beyond typical LHC $\sqrt{\hat{s}}$
($10\ \mathrm{ab}^{-1}$)	10 TeV	See new SM phenomena (e.g. EW jets)
	30 TeV	Reach Thermal Target DM Candidates
		Dramatically new Energy Frontier
	100 TeV	Limits of reasonable projections?

MUON COLLIDER STAGING

Staging options are important to ensure a muon collider can collect data even if upgrades need more time for R&D

3 TeV

Beyond typical LHC $\sqrt{\hat{s}}$

($1\ \text{ab}^{-1}$) 10 TeV

Another option:

Increase energy, reduce luminosity

(*Important in context of global collider program*)

30 TeV

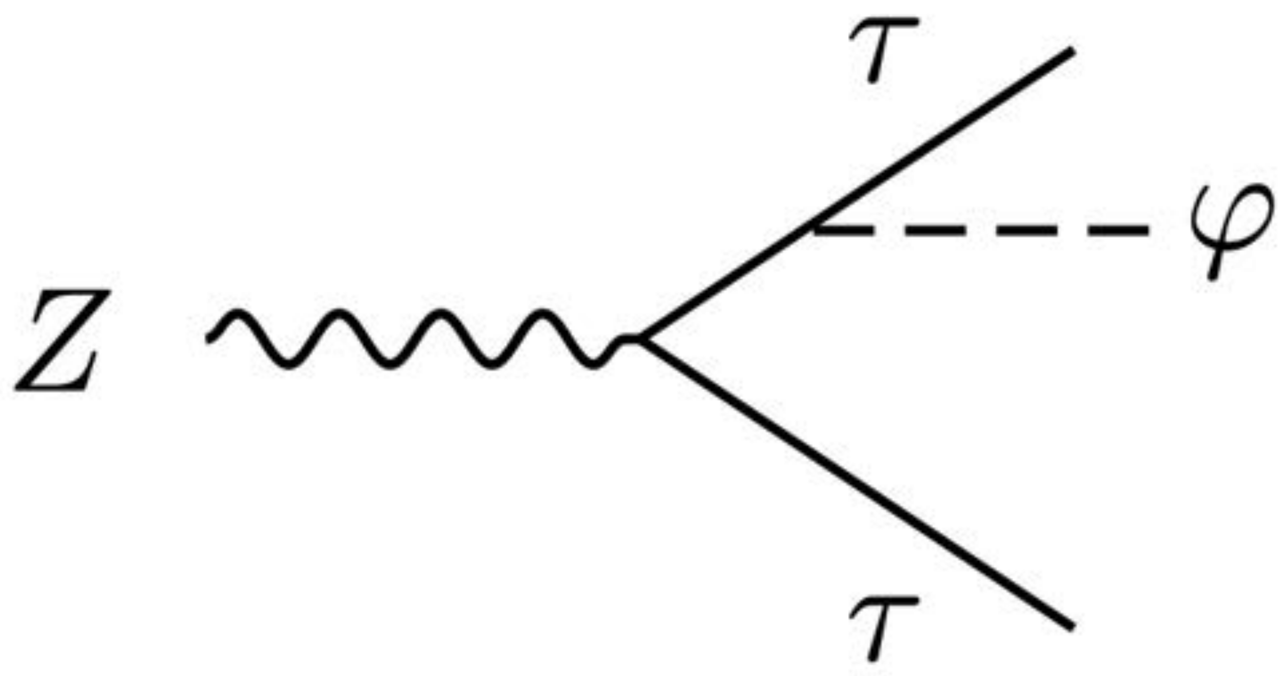
100 TeV

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

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

Bound set by uncertainty in BR

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

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

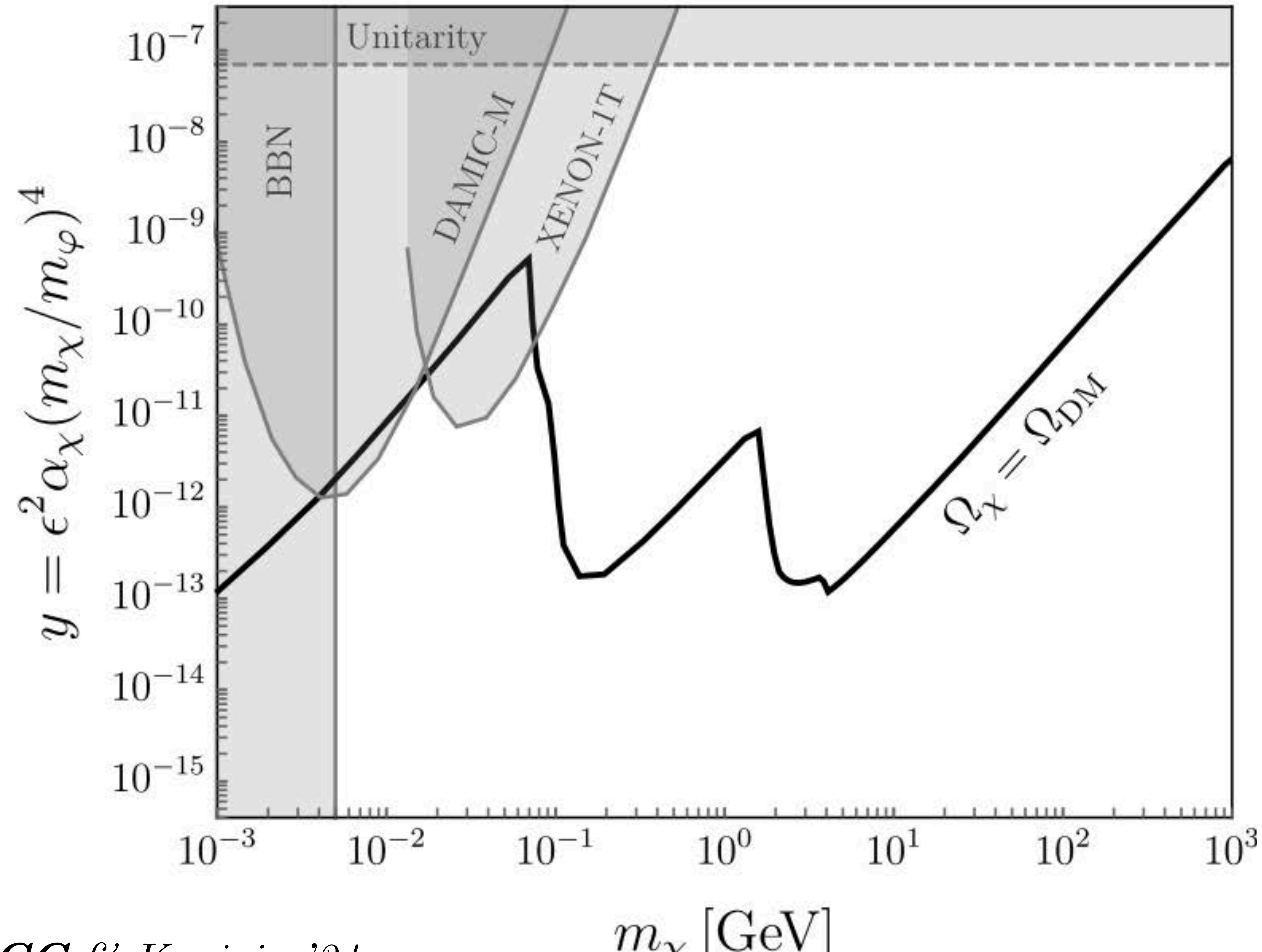
FCCee Tera-Z: $(10^{12}\ Z\text{'s})$

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

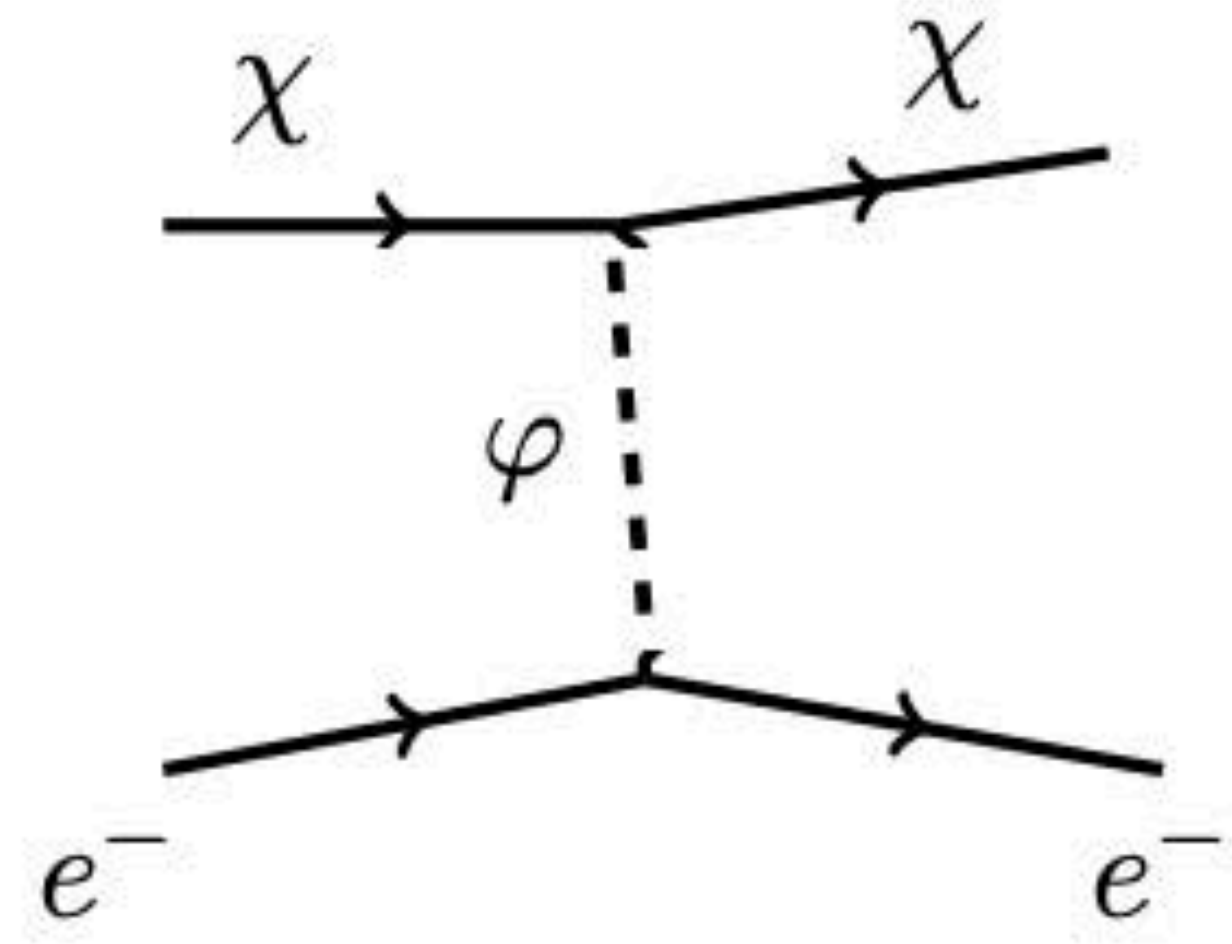
Assume primary improvements come from statistics

OTHER BOUNDS

Direct Detection



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

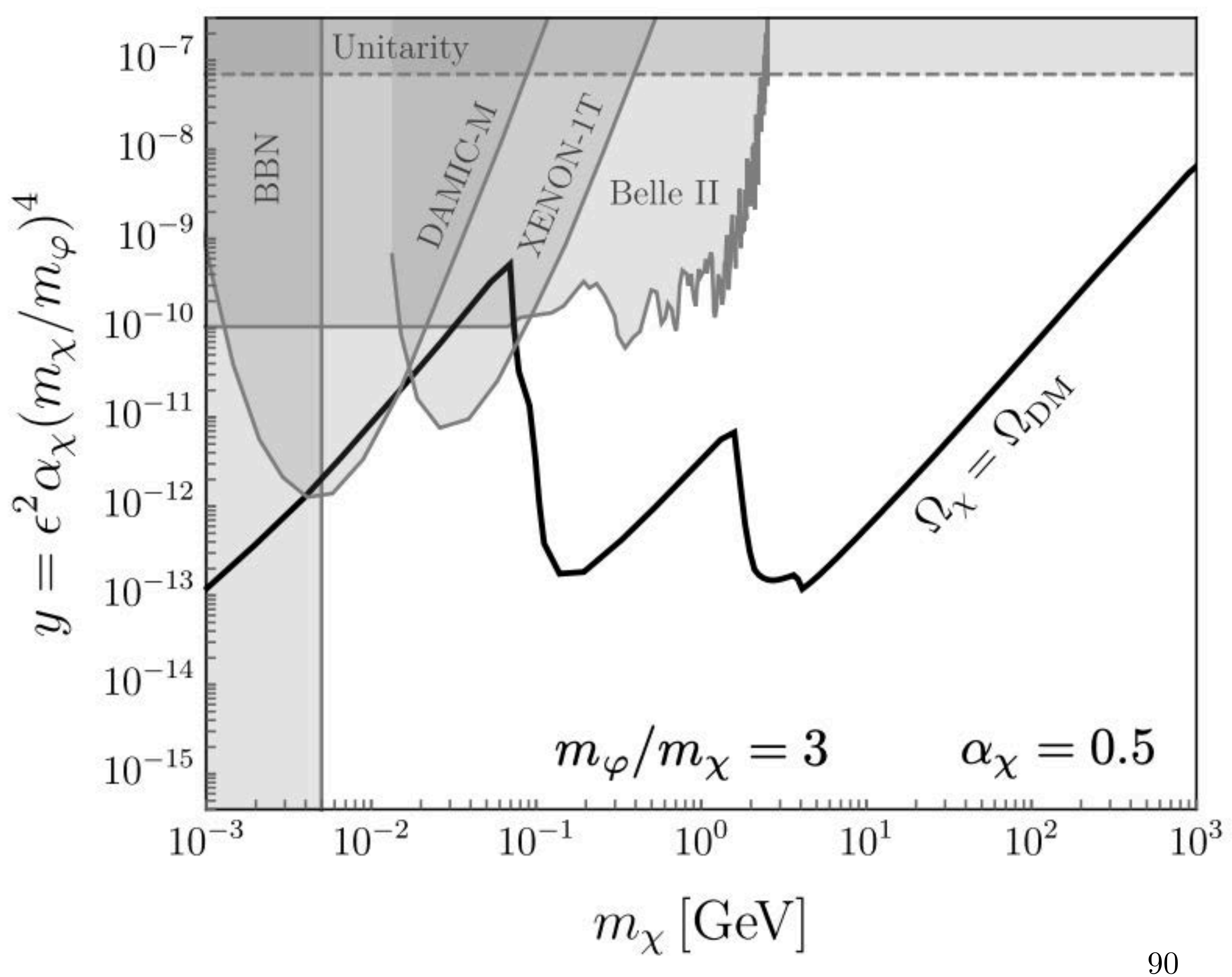


DAMIC-M 2302.02372
XENON-IT 2112.12116

***CC** & Krnjaic '24*

OTHER BOUNDS

B Factories



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

ve a lot of experiments

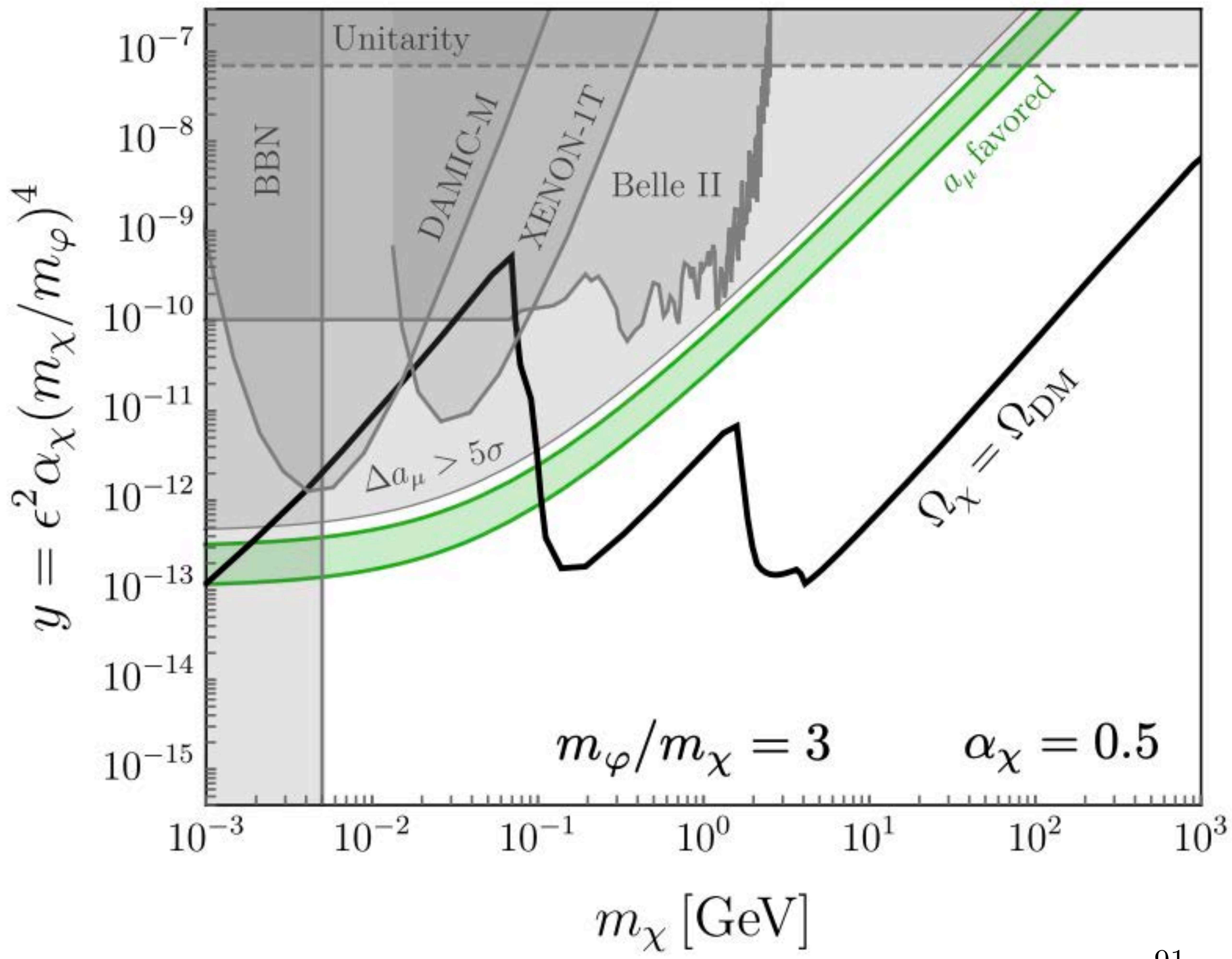
$$e^+e^- \to \mu^+\mu^-\varphi$$

(Dimuon + missing energy)

Belle II Collaboration 2212.03066

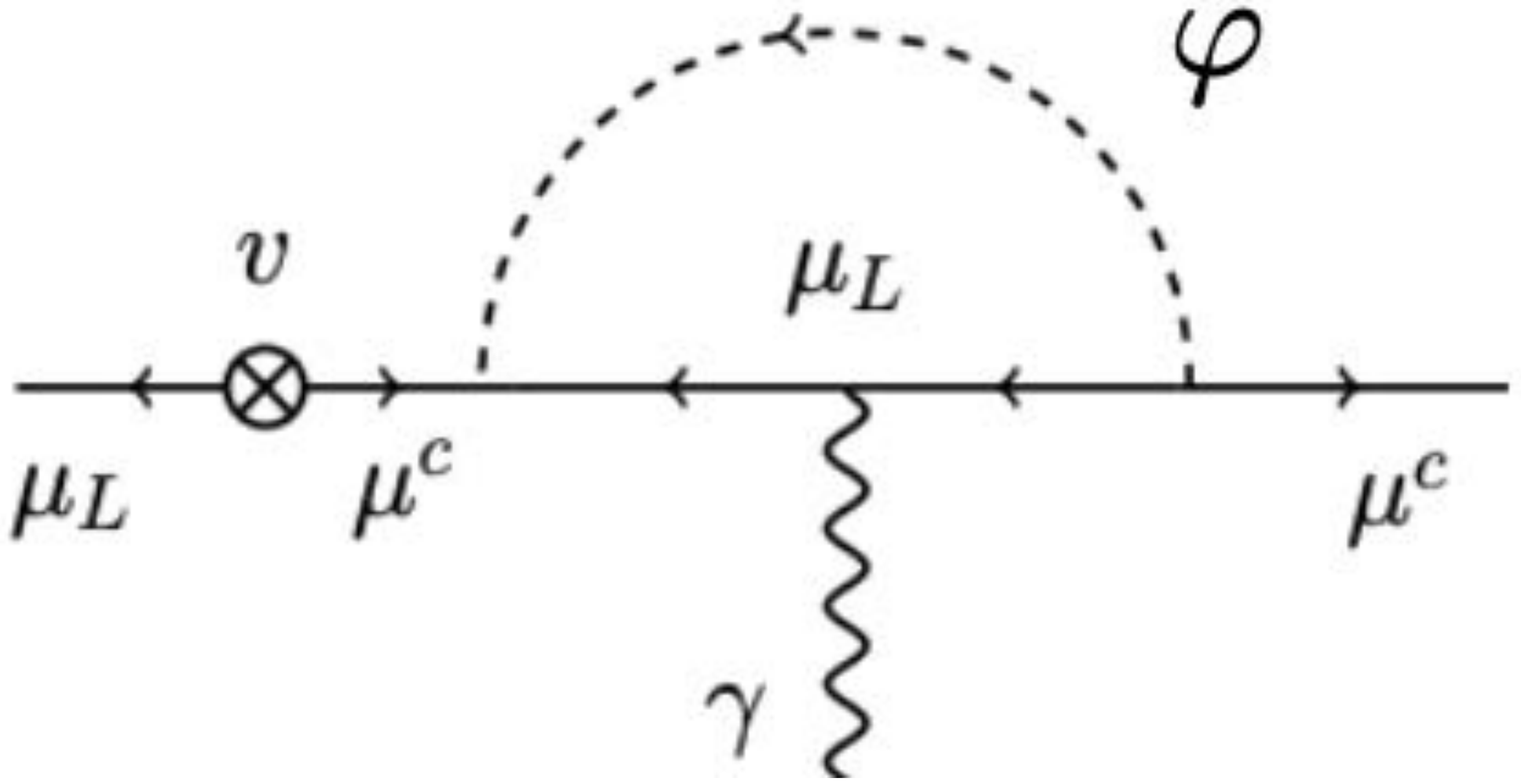
OTHER BOUNDS

Muon g-2



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

.d serve a lot of experiments



Muon *g-2* 2311.08282

DEMONSTRATORS & BEAM DUMPS

Protons from Booster

100%

High-Z Target

HADRONS

Uncooled Muons

Beam Dump

1.5%

Cooling

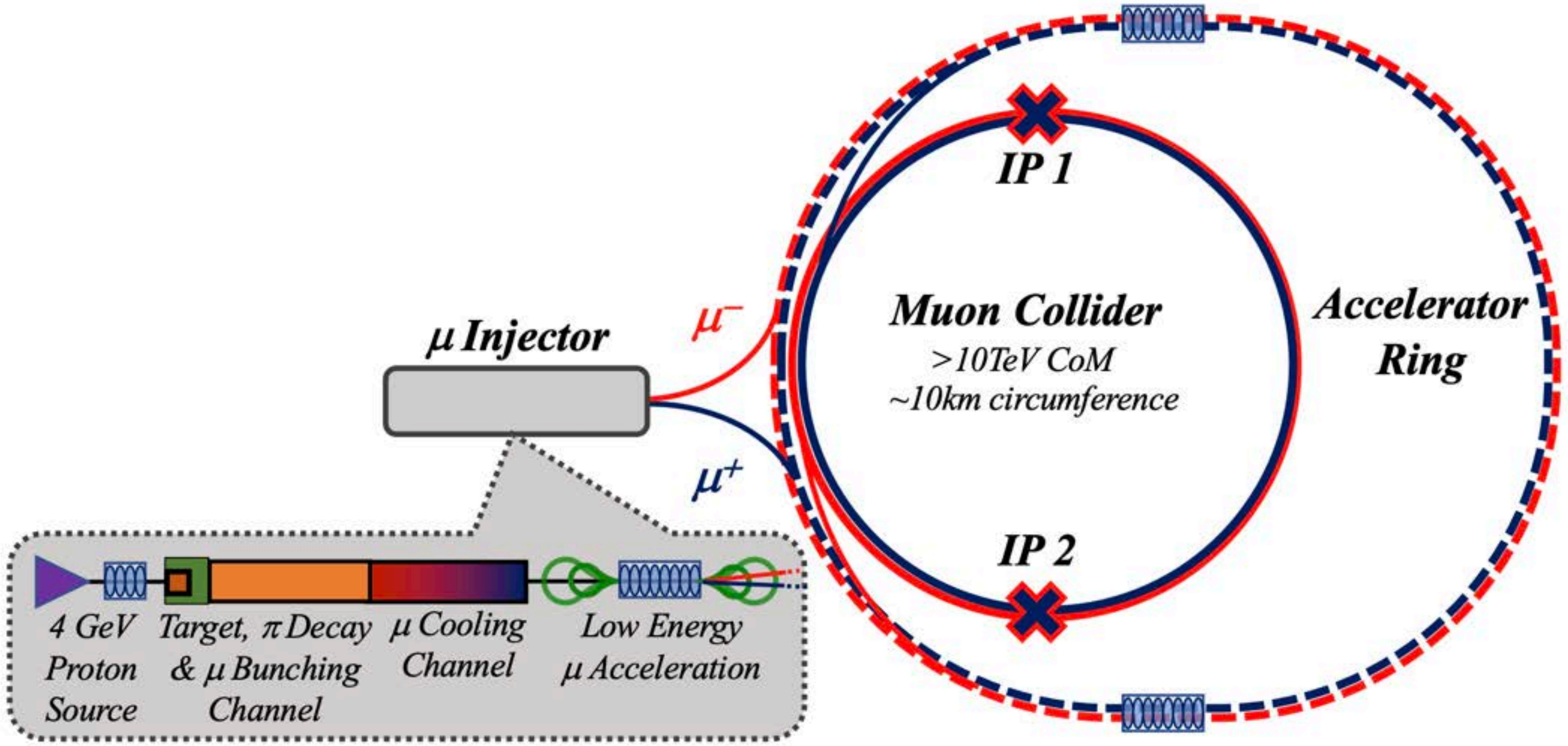
Beam Dump

0.15%

Accelerator

Beam Dump

<0.1%



$10^{18} - 10^{20}$ μ on target

Ex: General Indirect Production

What are most relevant physics scenarios?

EFT Approach for Energy ↔ Precision

$$\mathscr{L} \supset \frac{g^2}{\Lambda^2}\mathcal{O}^6 + \dots$$

Say you can measure something to 1% precision

$$g \sim 1$$

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} = 0.01 \approx \frac{E^2}{\Lambda^2}$$

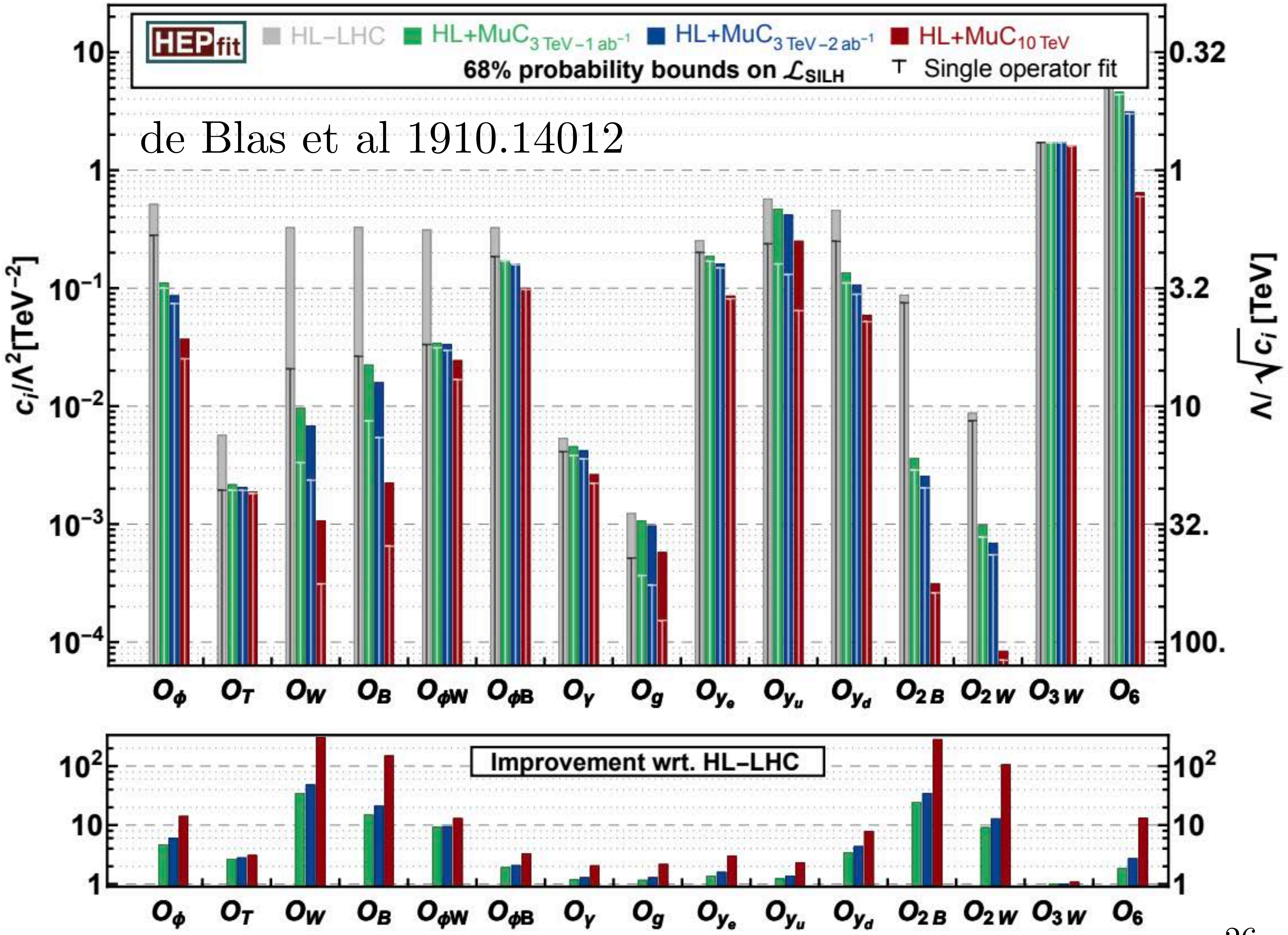
$E \sim 10$ TeV

$\Lambda \sim 100$ TeV

Can still be probing new physics at much higher scales!

PHYSICS REACH OF MUC

EFT APPROACH FOR ENERGY ↔ PRECISION



de Blas et al 1910.14012

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