Physics of a Future Muon Collider

Aspen Center for Physics

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An important caveat...

A muon collider is **not** at the same level of development as the HL-LHC or an e^+e^- machine

The proposals are for **R&D** to see if the technology is *feasible* not to start construction

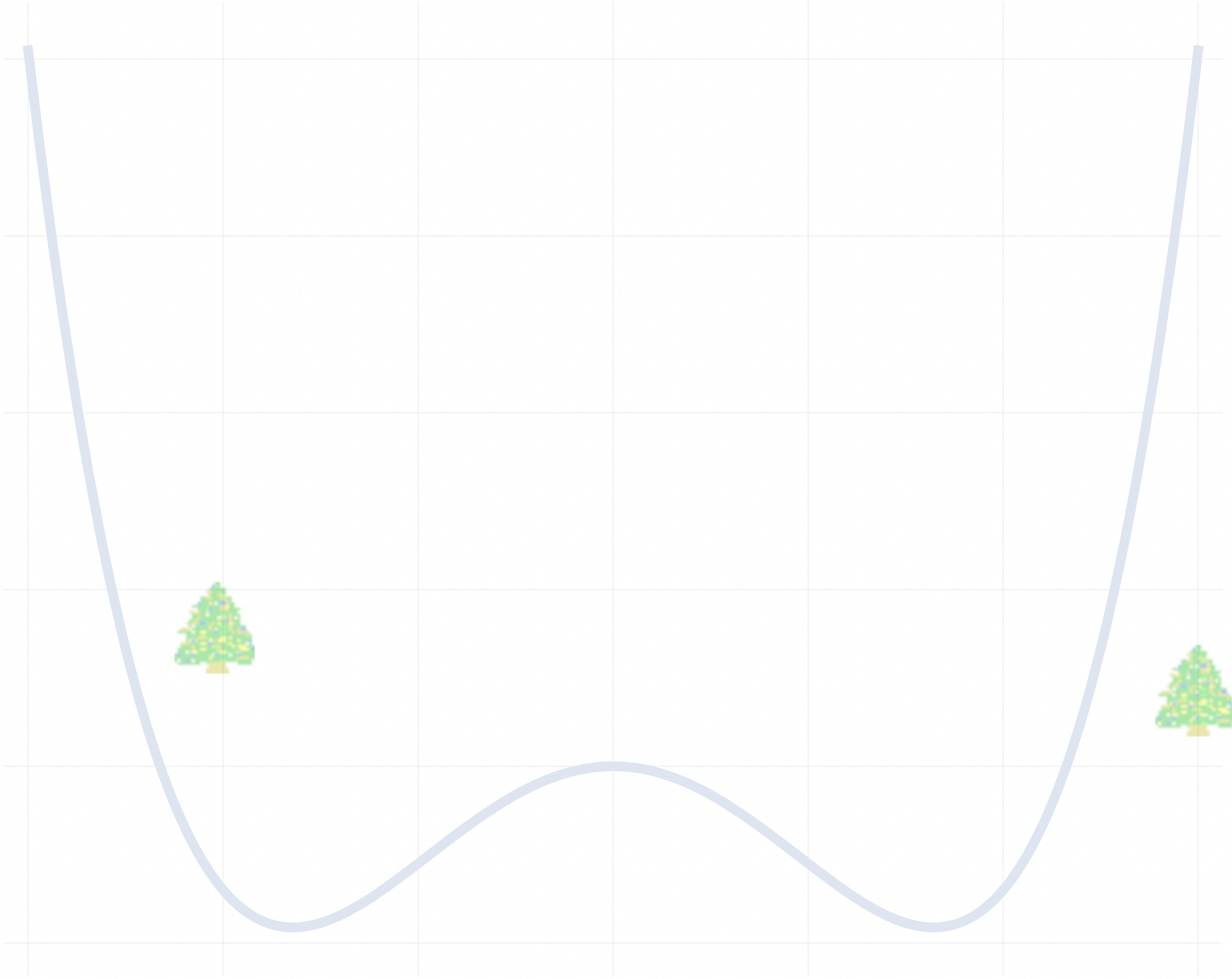
In an ideal world, multiple colliders could exist!

Why do we need another collider?

Colliders and Particle Physics

Many open questions remain in the

SM & beyond



COLLIDERS AND PARTICLE PHYSICS

Many open questions remain in the

SM & beyond

- Higgs boson?
- EWSB?
- EW Sector?
- BAU?
- Origin of Flavor?

Colliders and Particle Physics

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- Dark matter?
- Above 10 TeV?
- Hidden Sectors?
- Anomalies?

Colliders and Particle Physics

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Need empirical input

Why Are MuC Worth The Investment

We need an experimental program that does the most "new stuff"

PRECISION

DISCOVERY

Why Are MuC Worth The Investment

We need an experimental program that does the most "new stuff"

PRECISION	DISCOVERY
Clean Signatures	High Energy
High Statistics	On-shell Production
Hints	*Origin*
e^+e^-	hh

Why Are MuC Worth The Investment

We need an experimental program that does the most "new stuff"

PRECISION		DISCOVERY
Clean Signatures		High Energy
High Statistics	MuC	On-shell Production
Hints		*Origin*
e^+e^-		hh

MuC can be a **precision** and **discovery** machine

Comparison of Colliders

pp

$\mu^+\mu^-$

e^+e^-

Comparison of Colliders

pp

Composite

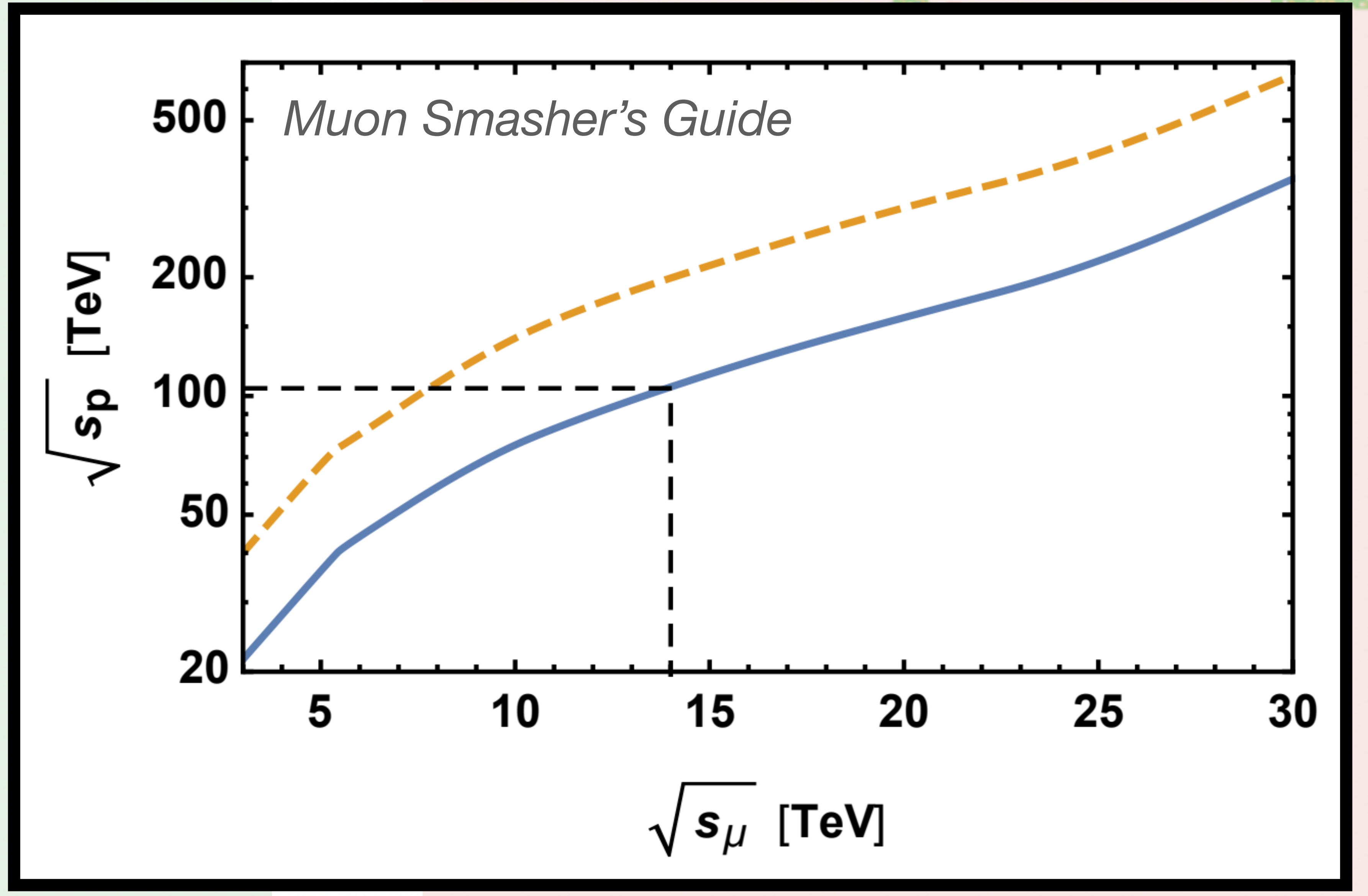
$\sqrt{\hat{s}} \ll \sqrt{s}$ *

$\mu^+\mu^-$

Fundamental

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

e^+e^-



Comparison of Colliders

pp

Composite

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

$\mu^+\mu^-$

Fundamental

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

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

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

$\mathcal{O})(1 - 100?)$ TeV

e^+e^-

$\mathcal{O}(100 - 300)$ GeV

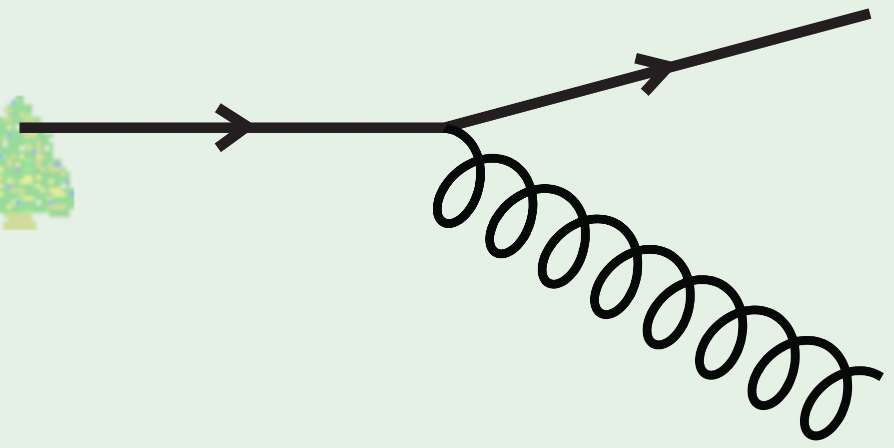
Comparison of Colliders

pp

Composite

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

QCD



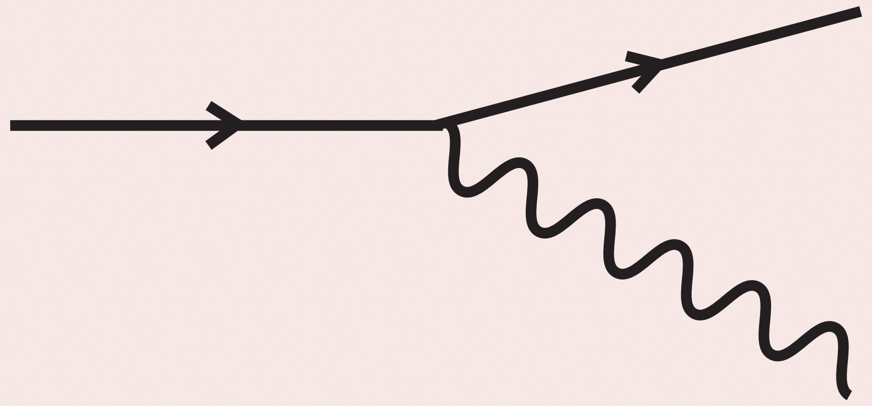
$\mu^+\mu^-$

Fundamental

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

$\mathcal{O})(1 - 100?)$ TeV

Electroweak



e^+e^-

$\mathcal{O}(100 - 300)$ GeV

Comparison of Colliders

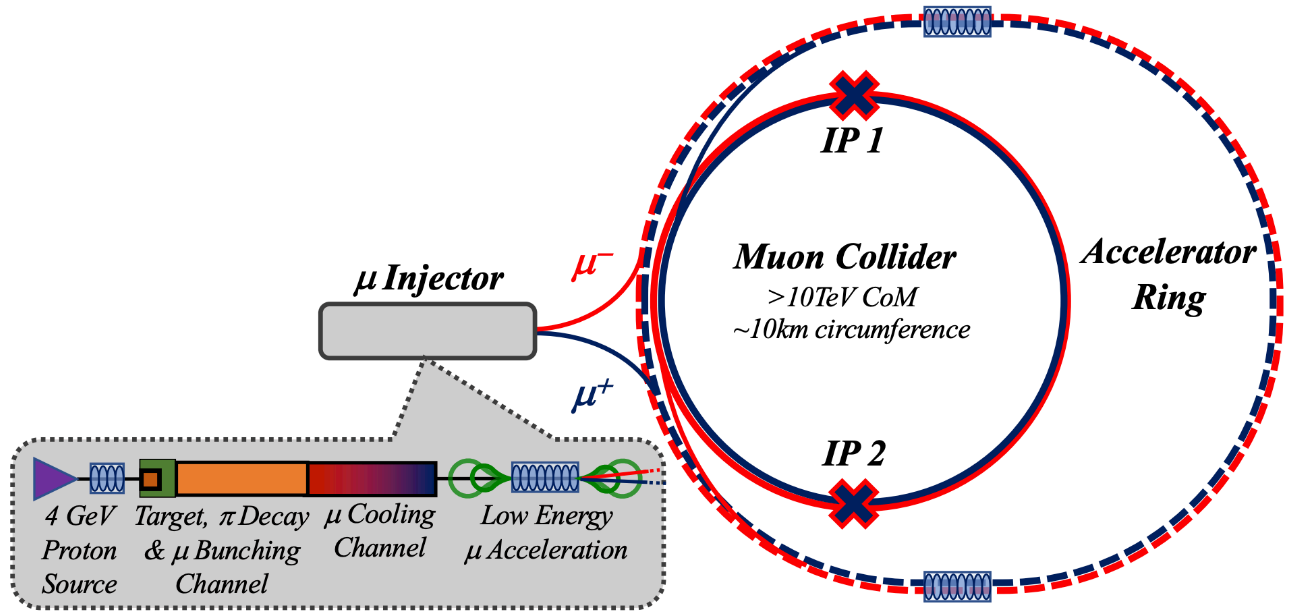
pp

FCC-hh
100 km

$\sqrt{s}$ = 100 TeV

$\mu^+\mu^-$

MuC
10 km



$\sqrt{s}$ = 10 TeV

e^+e^-

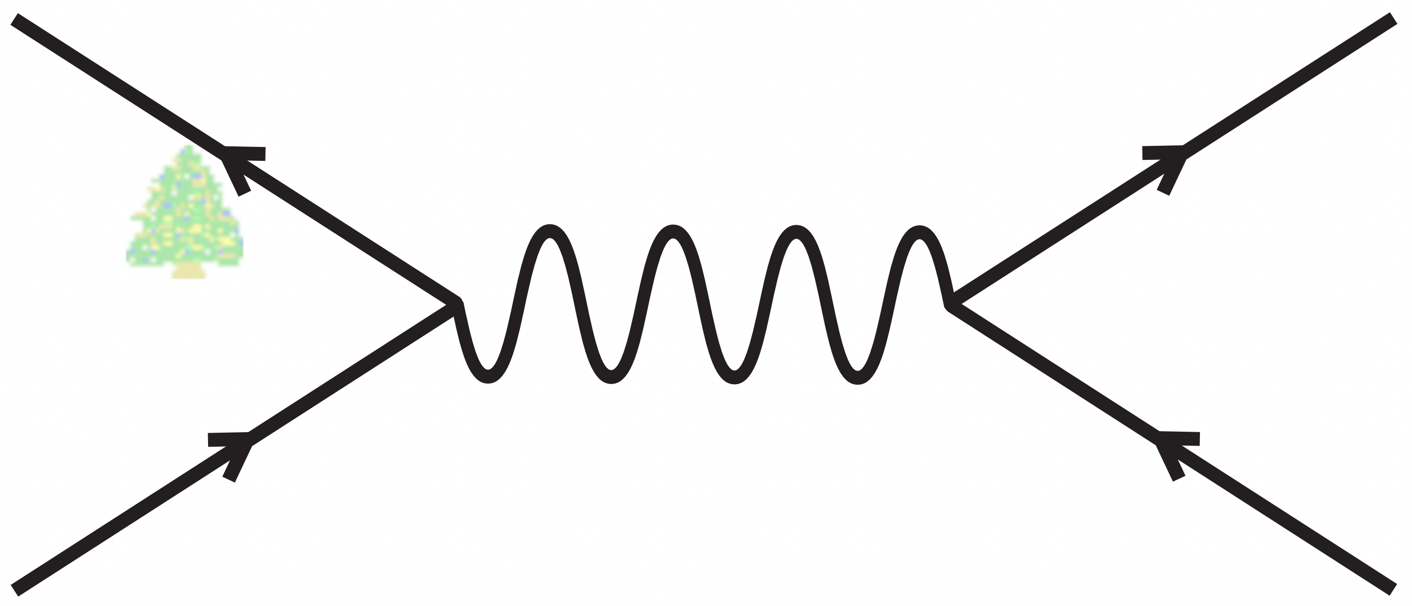
FCC-ee
100 km

$\sqrt{s} \sim 240$ GeV

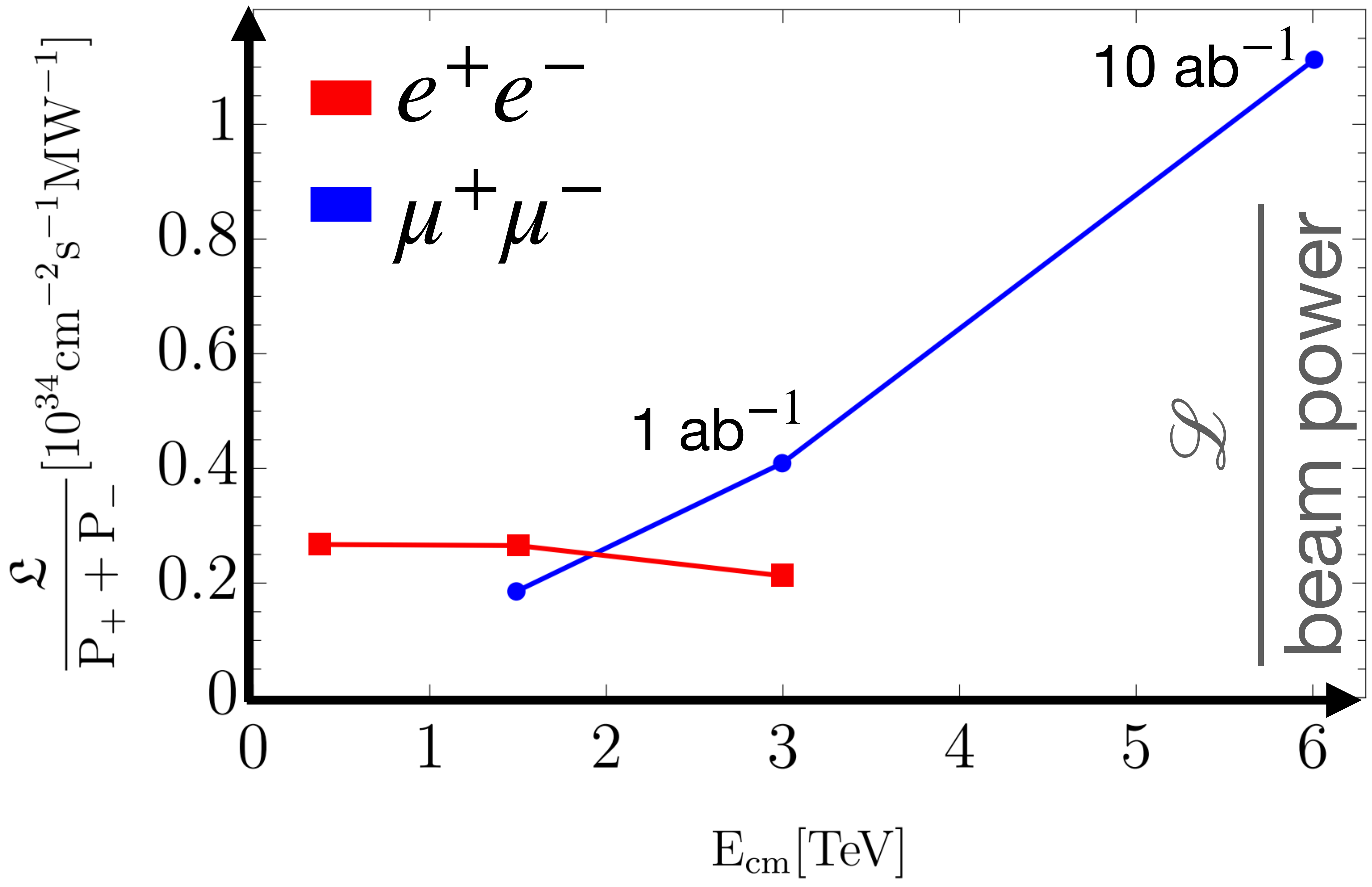
Comparison of Lepton Colliders

The higher the energy, the larger the luminosity

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



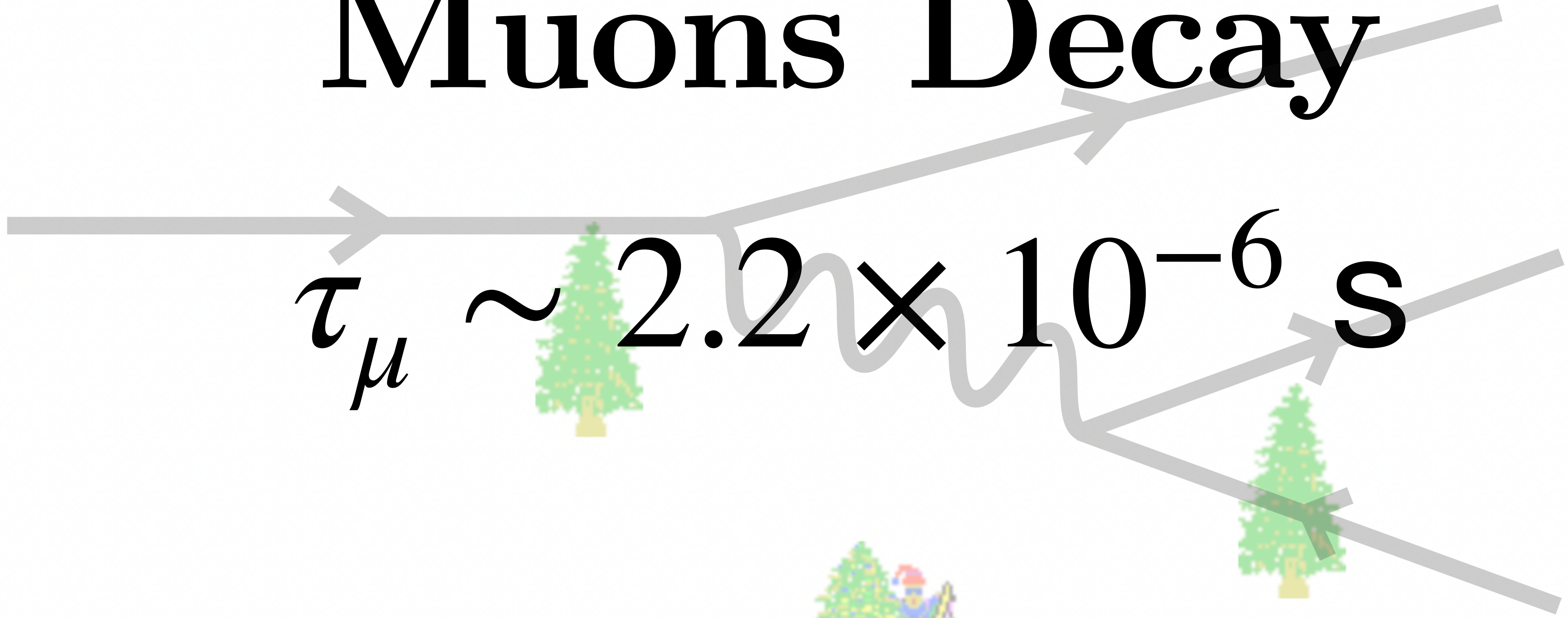
$$\sim \frac{1}{s}$$



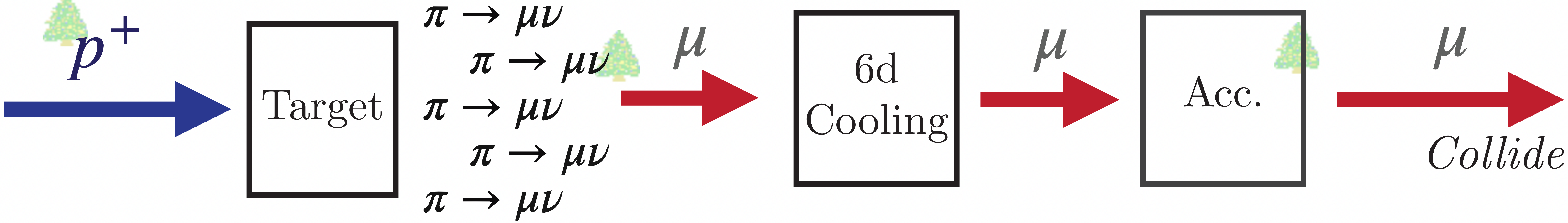
What are the biggest challenges?

Challenges of MuC

Muons Decay



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



Challenges of MuC

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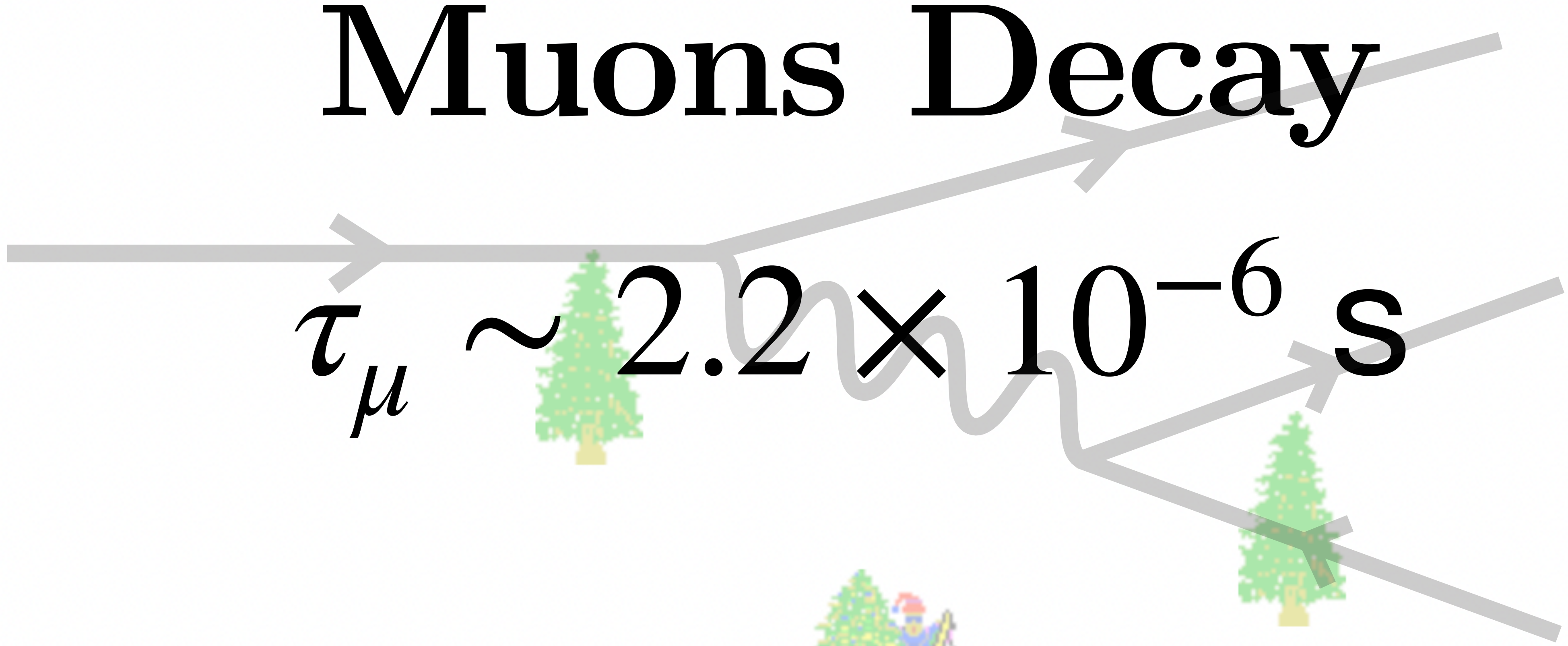

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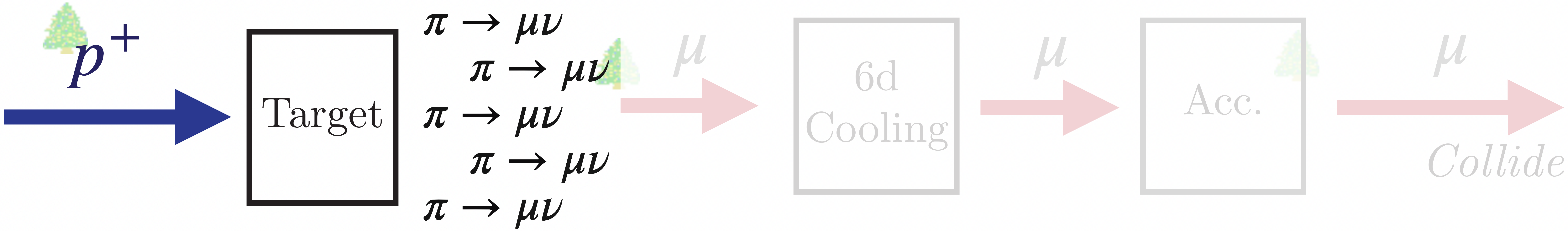
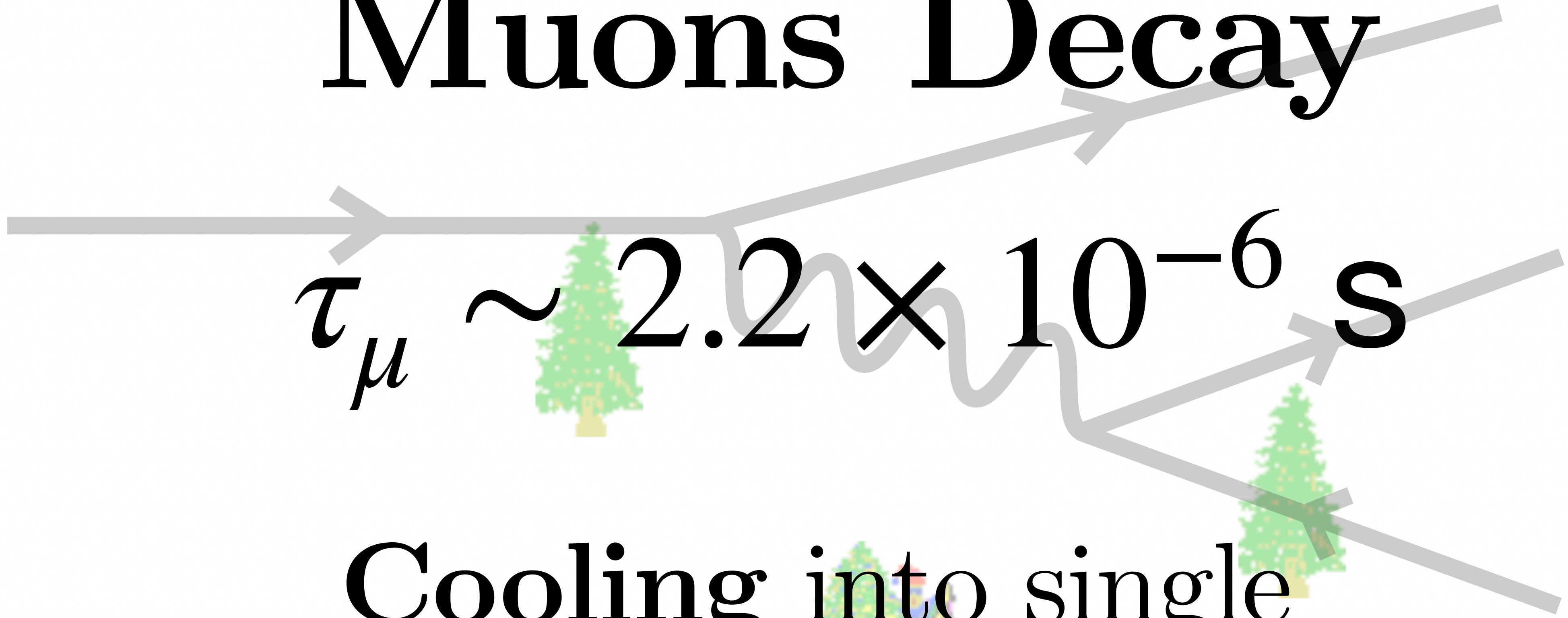
Production as tertiary beam

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



Challenges of MuC

Muons Decay



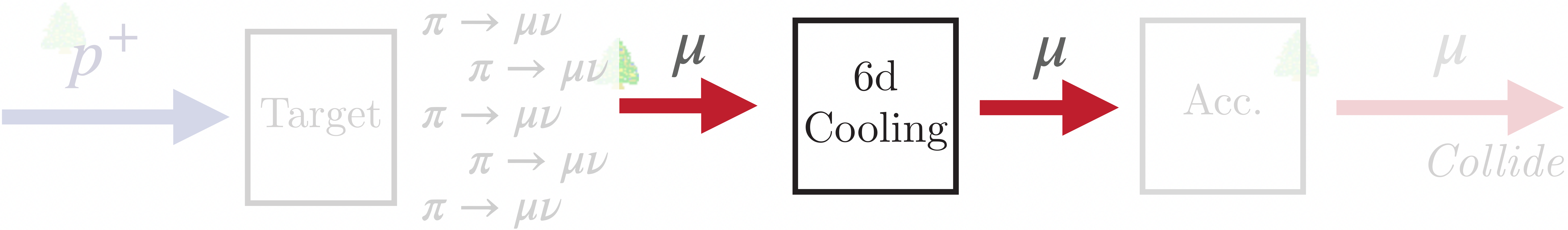
$\tau_\mu \sim 2.2 \times 10^{-6}$ s

Production as tertiary beam

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

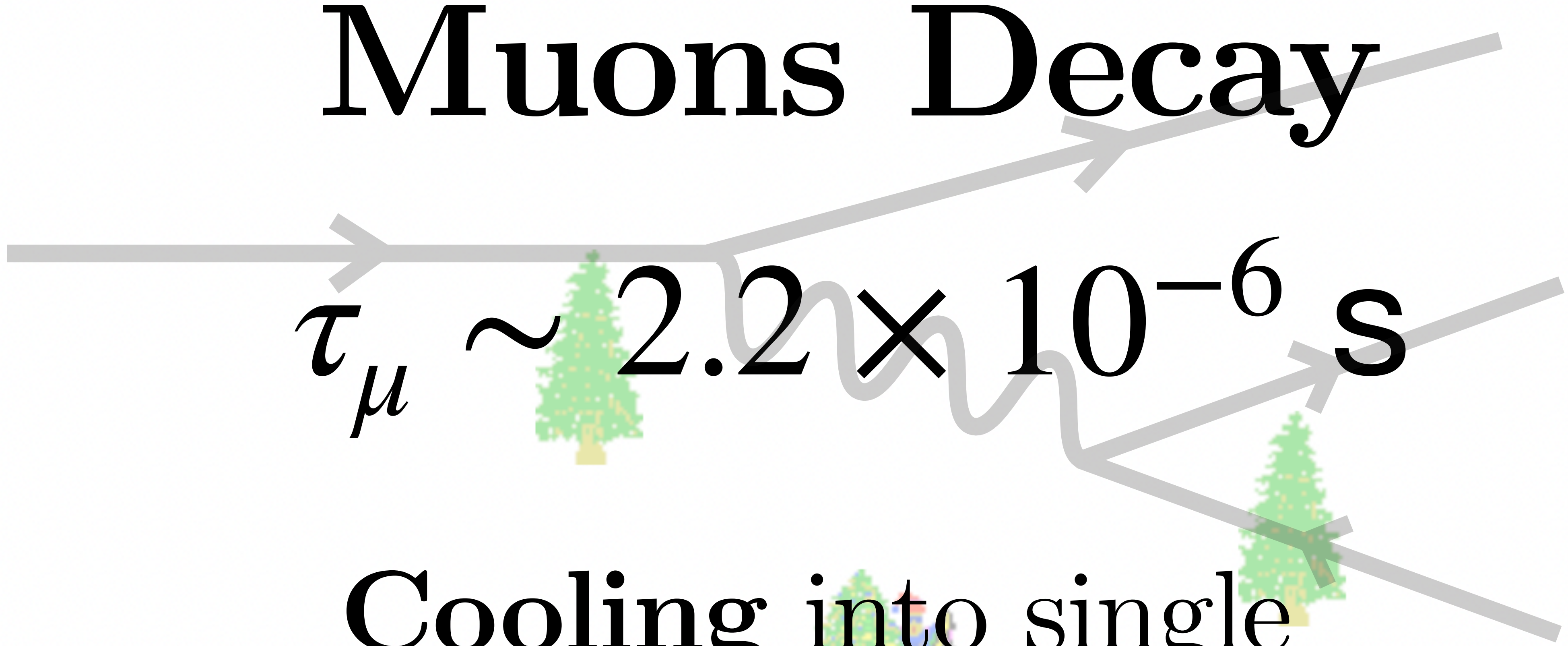
Cooling into single collimated bunch

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



Challenges of MuC

Muons Decay



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Production as tertiary beam

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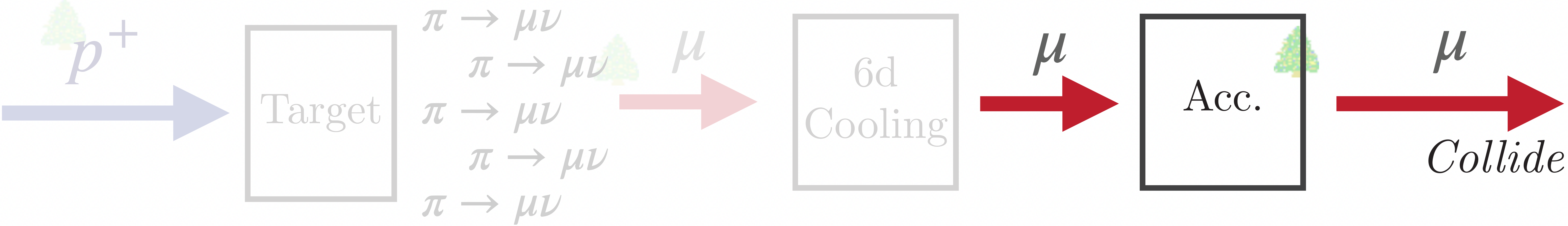
Acceleration and collision

Too quick to ramp up magnets



Challenges of MuC

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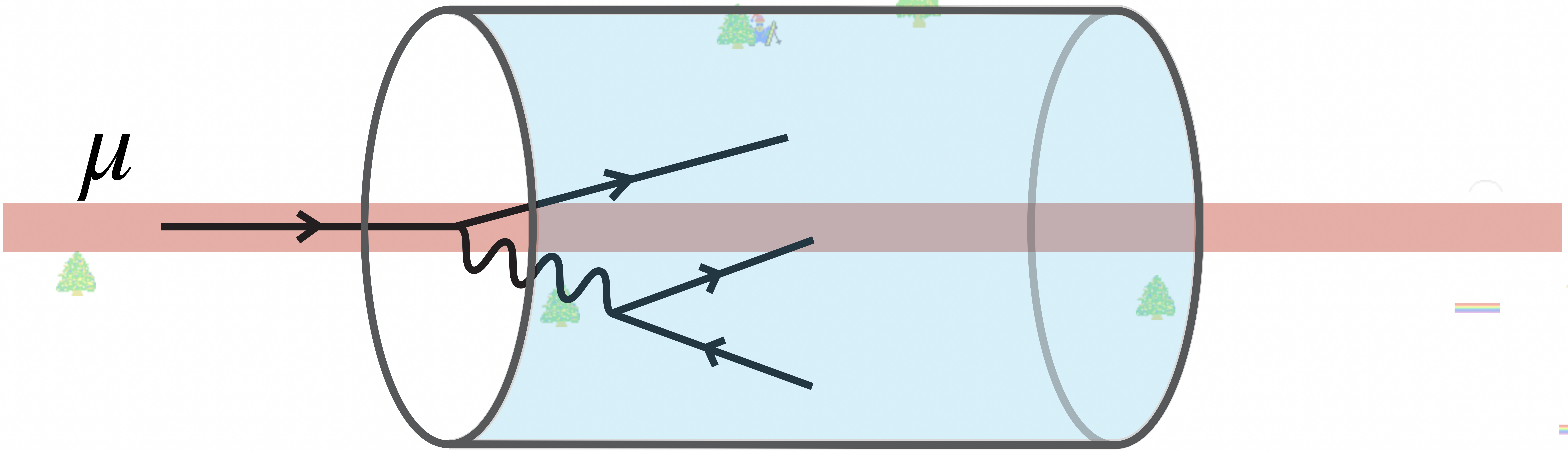


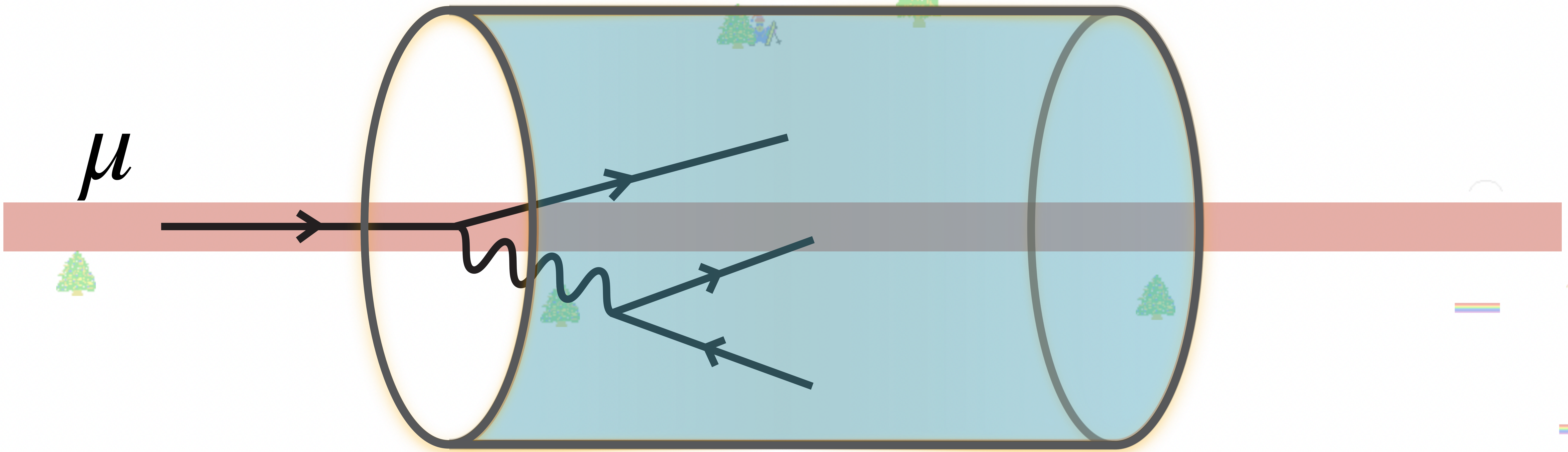
Challenges of MuC

Muons Decay

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

Beam Induced Background (BIB)

Timing, energy cuts, acceptance



Challenges of MuC

Muons Decay

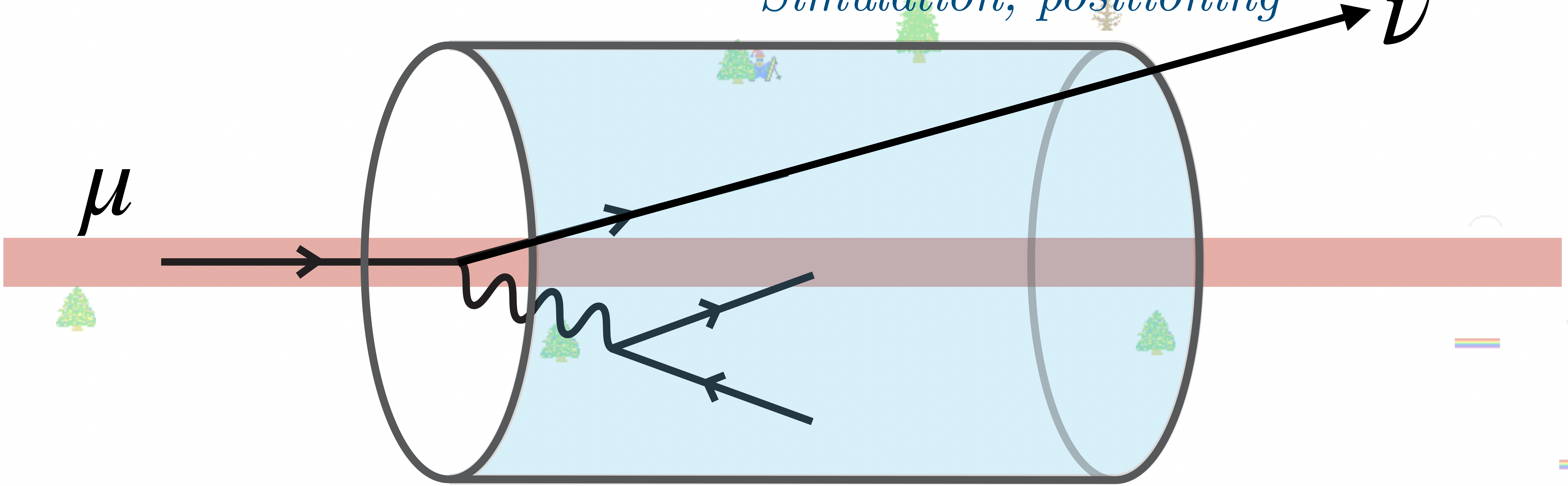
$\tau_\mu \sim 2.2 \times 10^{-6}$ **s**

Beam Induced Background (BIB)

Timing, energy cuts, acceptance

Neutrino Radiation

Simulation, positioning



Two Paths Forward with a MuC

Energy Staging

Intensity Staging

Two Paths Forward with a MuC

Energy Staging

3, 10, 30?, 100 TeV?

Intensity Staging

Start with smaller magnets, bigger ring

$$\mathscr{L} \to \mathscr{L} \times 10^{-1}$$

Two Paths Forward with a MuC

Energy Staging

3, 10, 30?, 100 TeV?

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Start with smaller magnets, bigger ring

$$\mathscr{L} \to \mathscr{L} \times 10^{-1}$$

This early in the process, we cannot make fully informed decisions about what run configurations we will have

What is the physics reach?

Physics Program at MuC

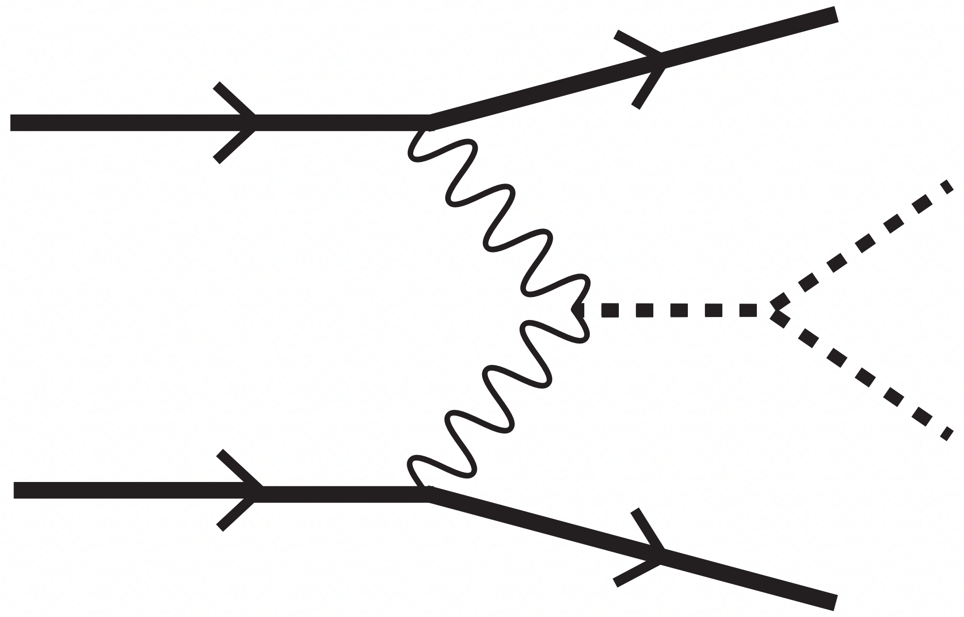
Electroweak Precision

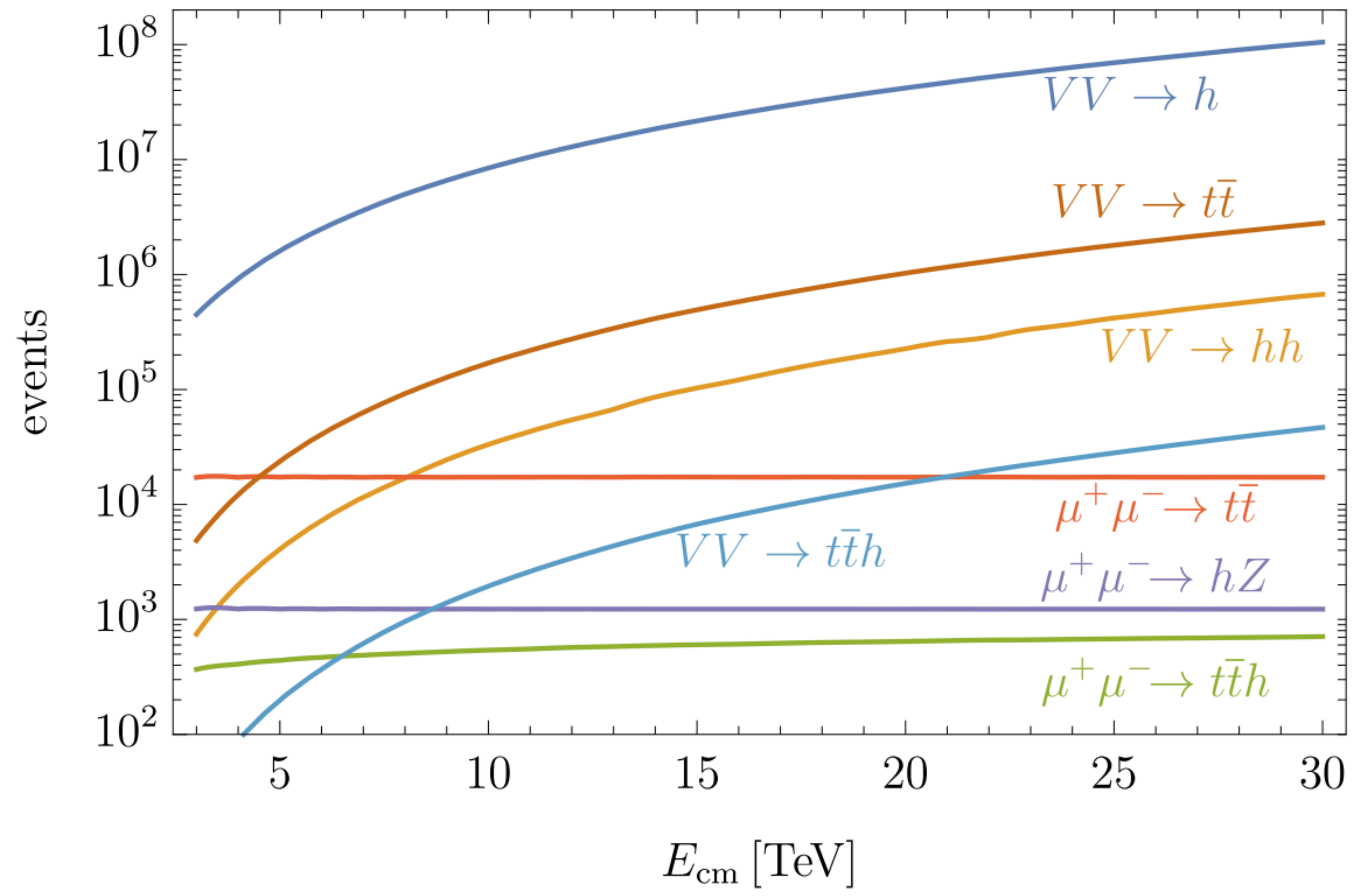
Direct & Indirect Heavy States

Physics Program at MuC

Electroweak Precision

Higgs EWSB VBF



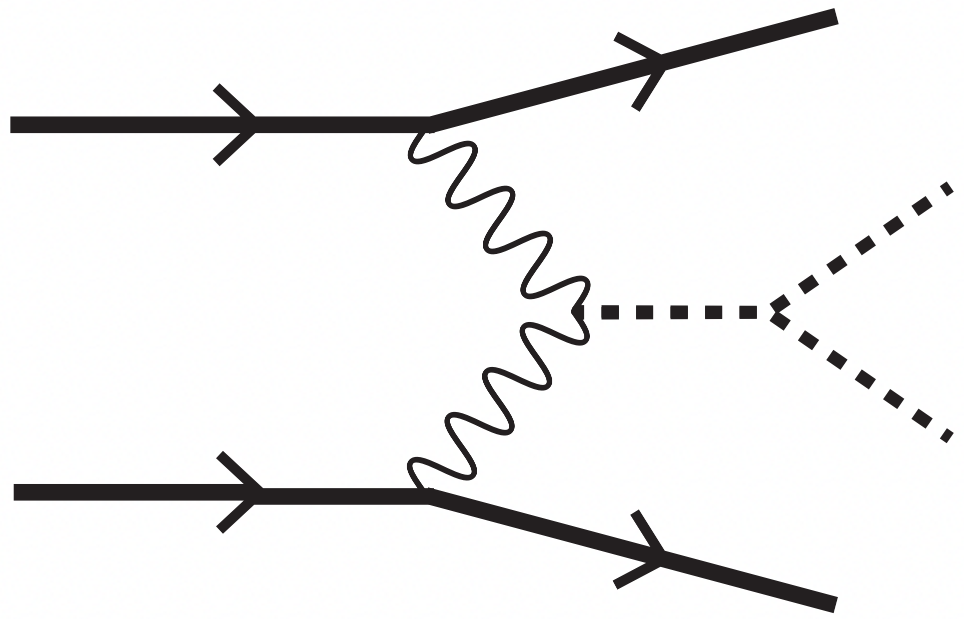


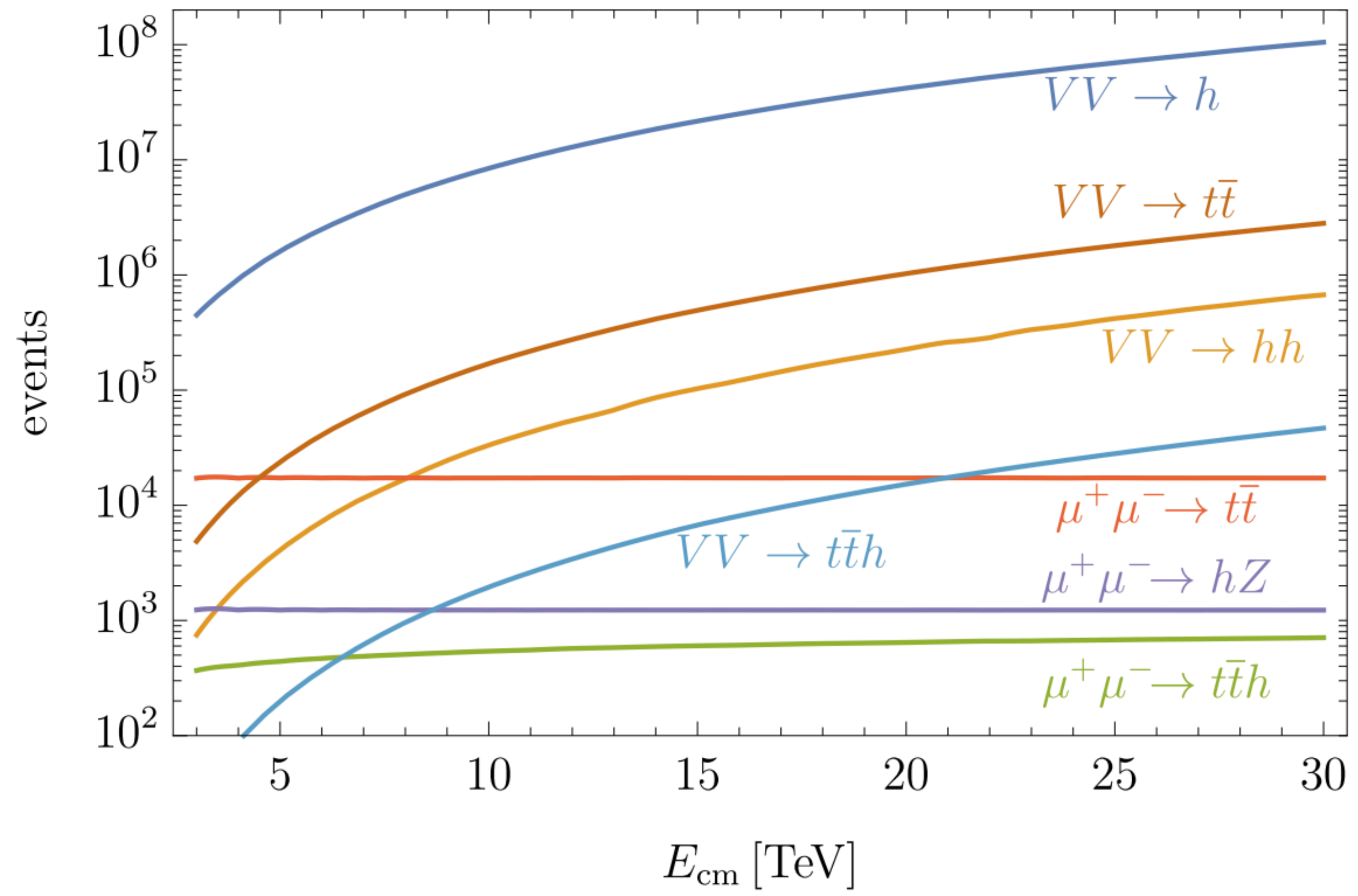
Direct & Indirect Heavy States

Physics Program at MuC

Electroweak Precision

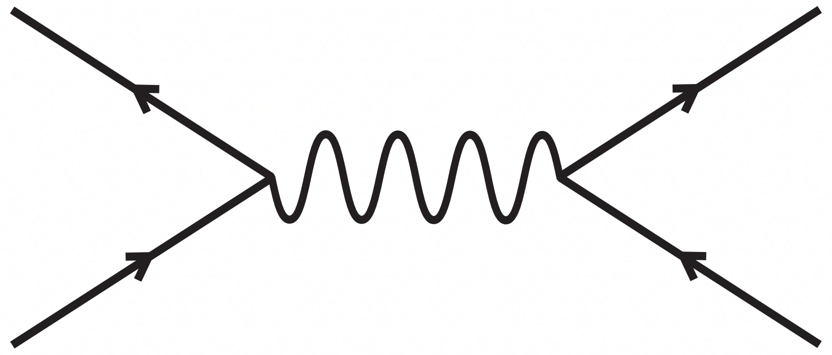
Higgs EWSB VBF





Direct & Indirect Heavy States

New Physics Pair Production



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

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

Heavy Flavor Couplings

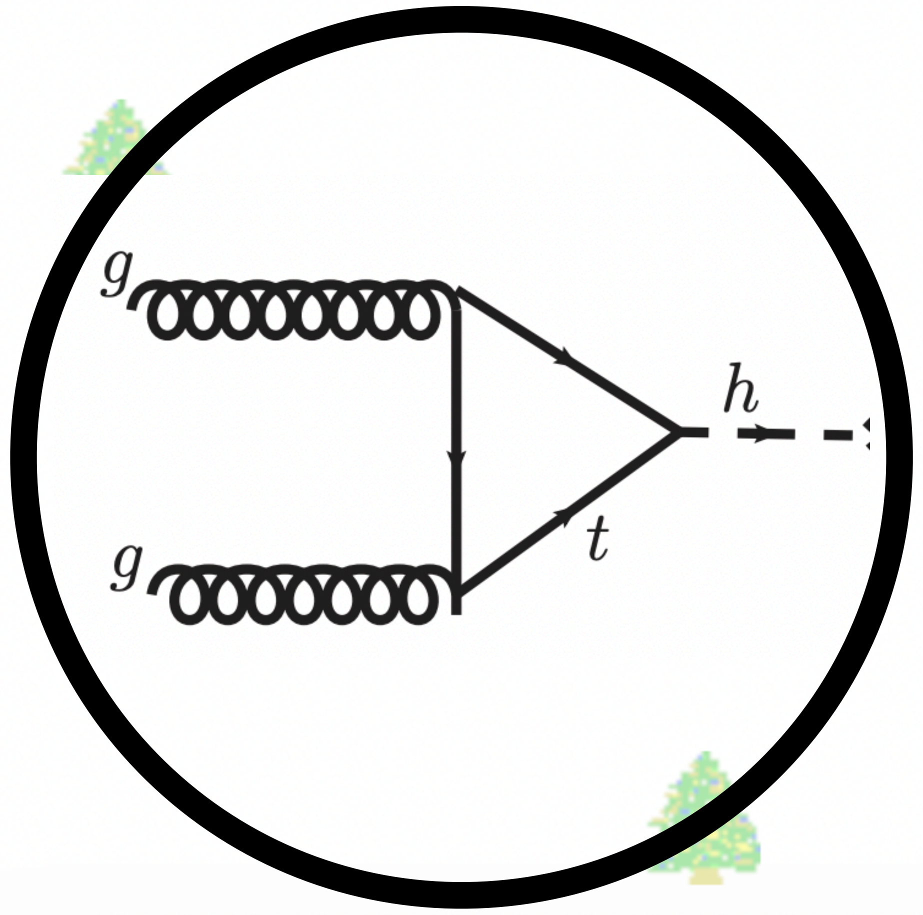
EFTs

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

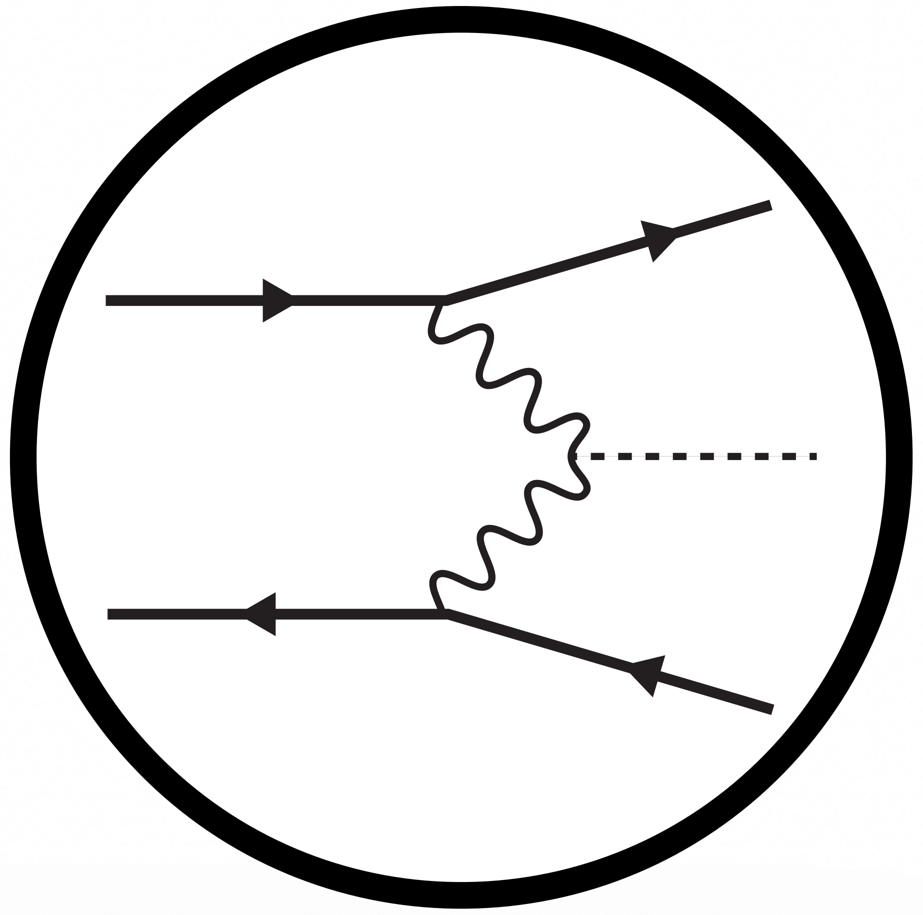
Higgs Studies

Higgs Production

pp Collider

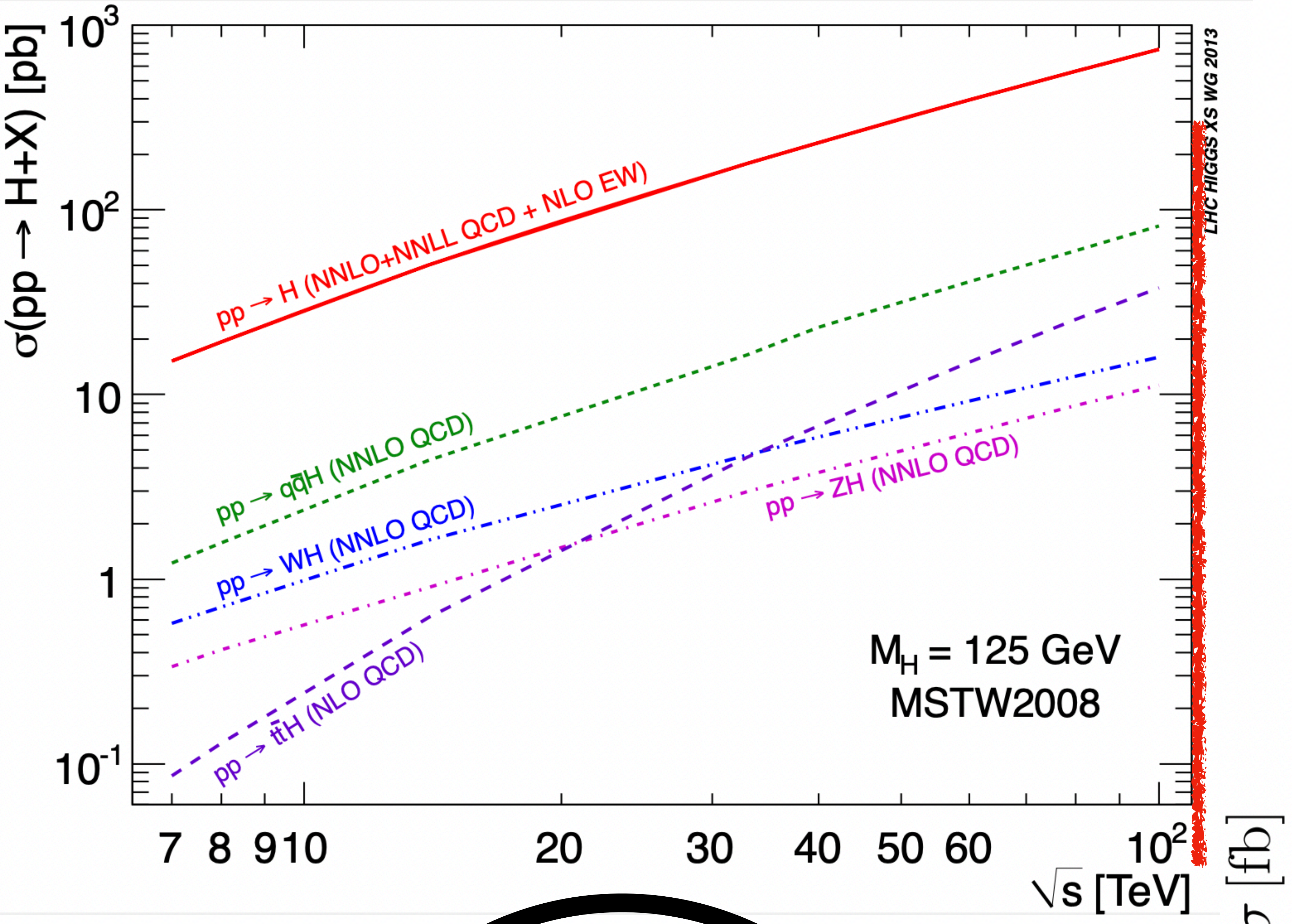


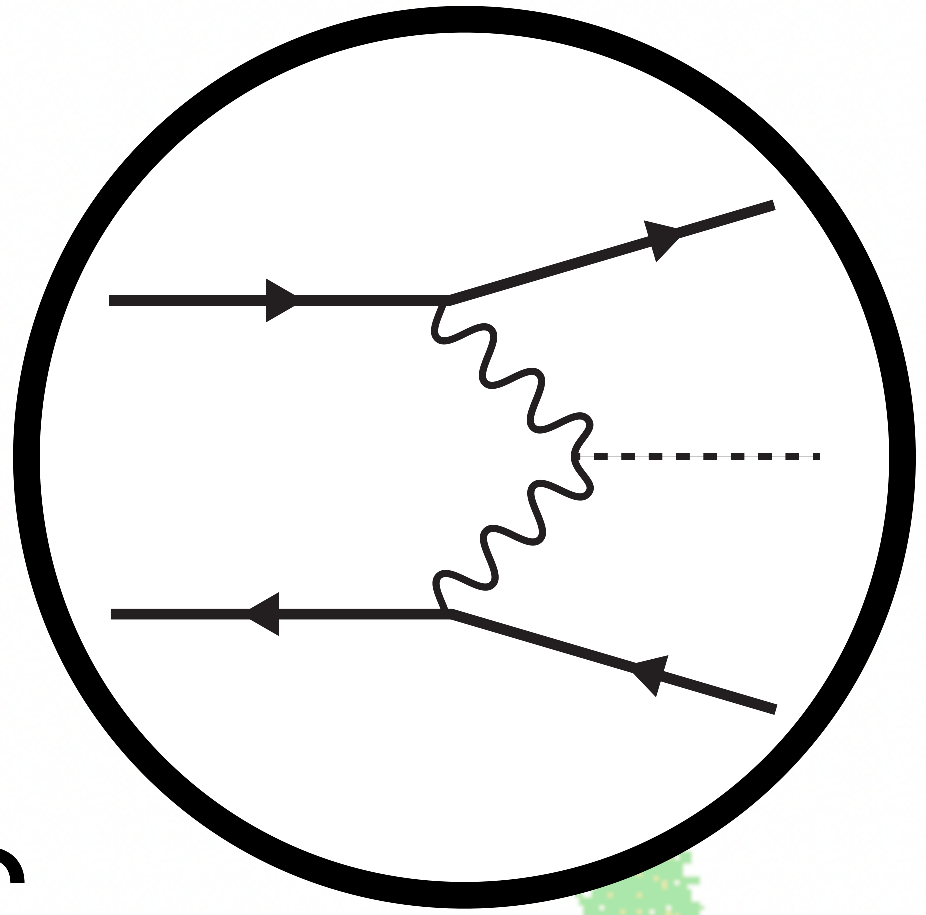
l^+l^- Collider

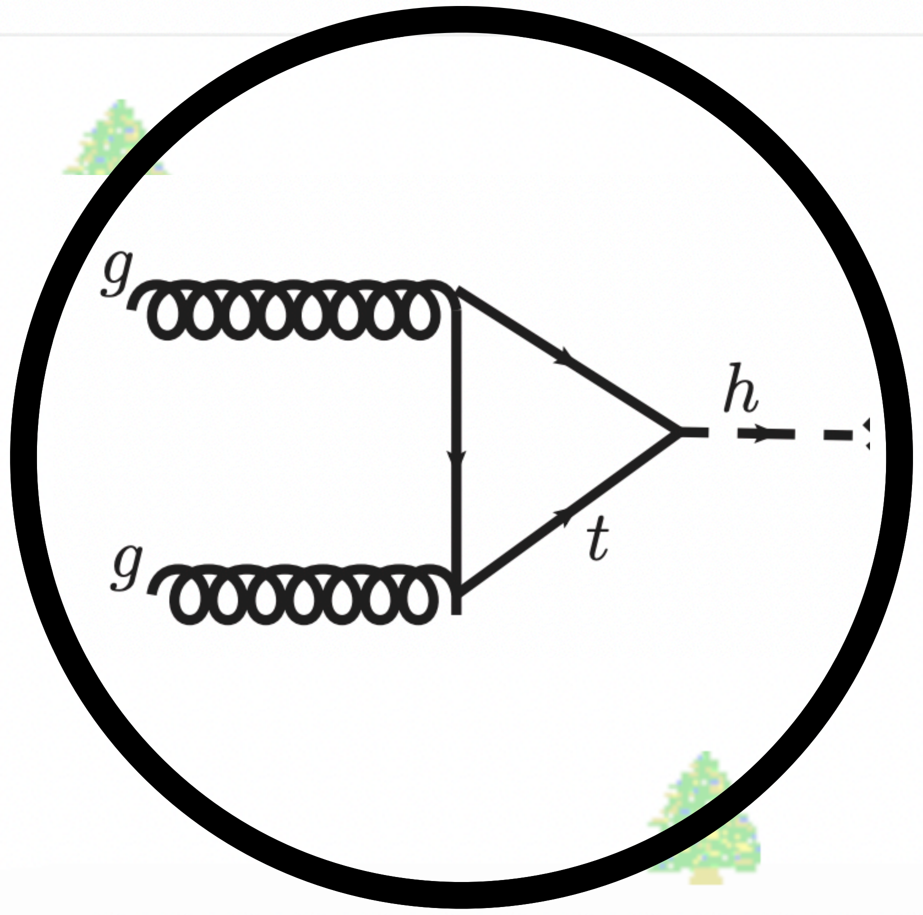


Higgs Production

LHC HIGGS WG







MuC

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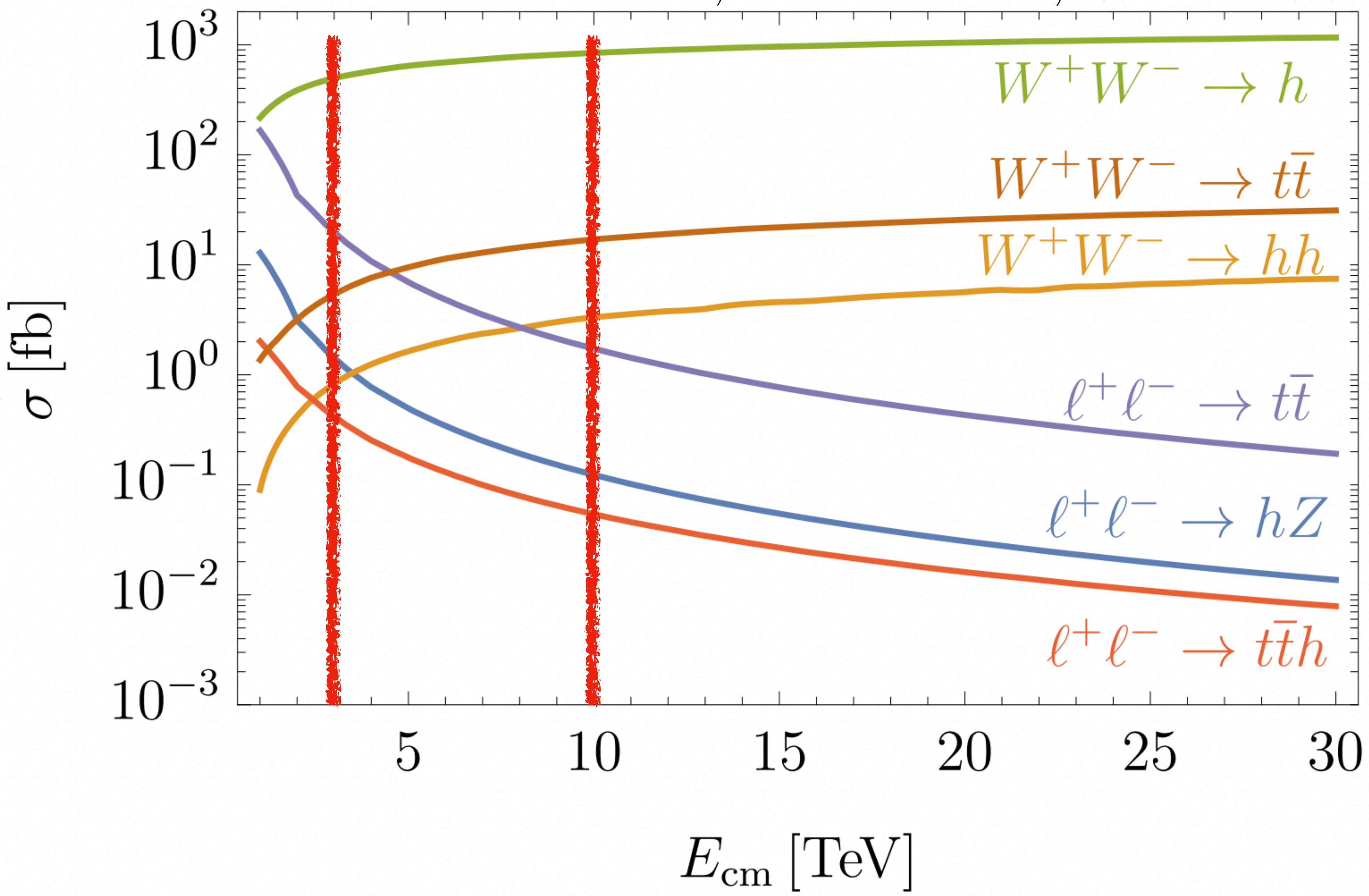
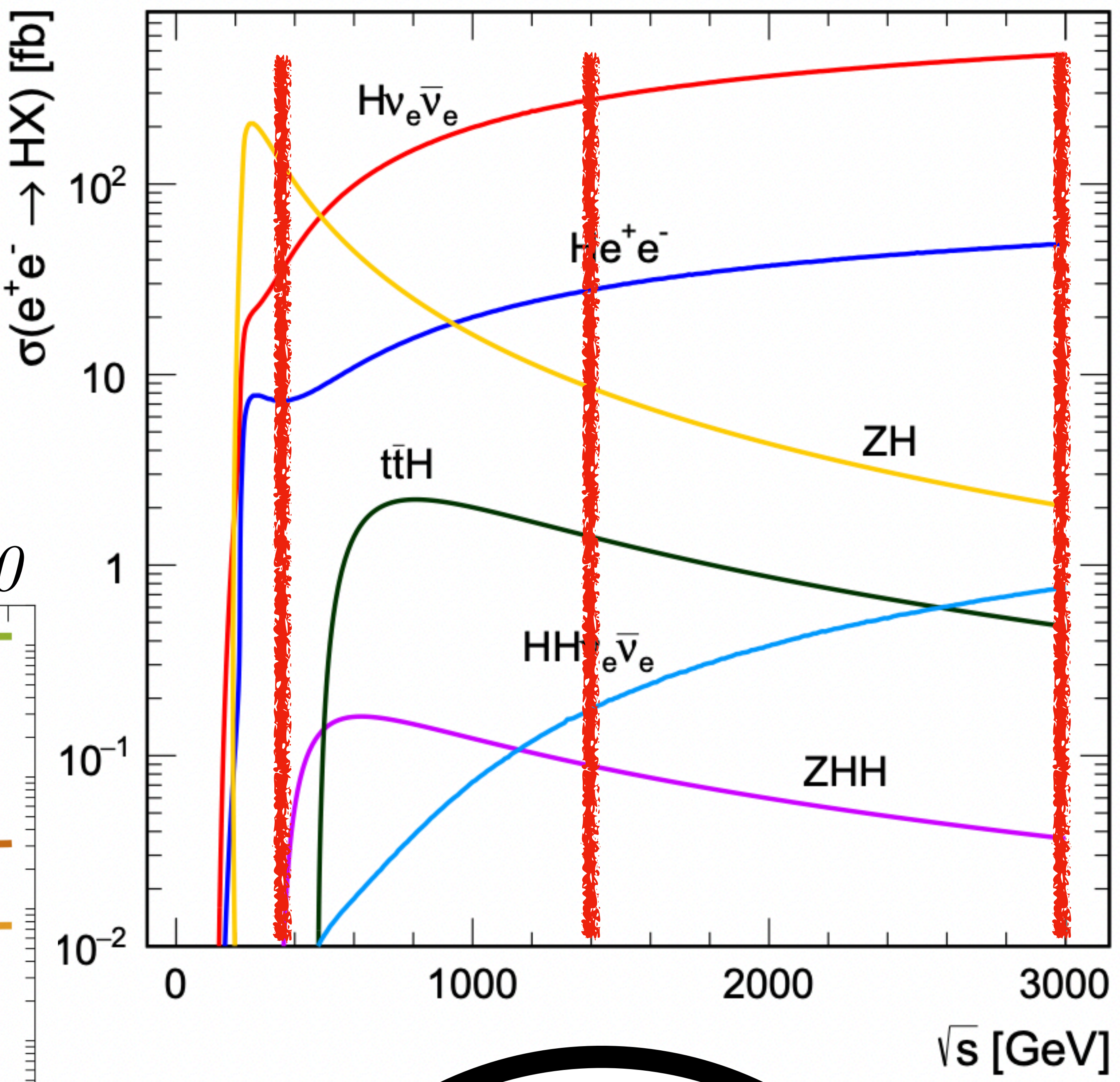
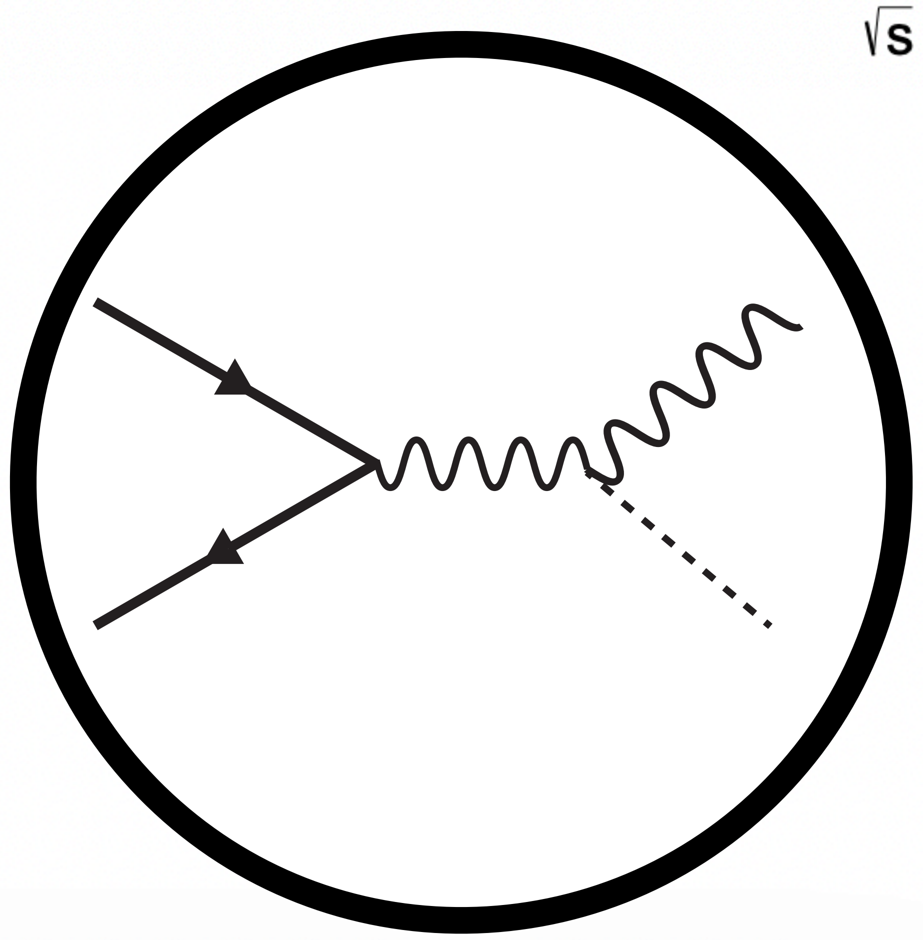


CLIC '18

e^+e^-



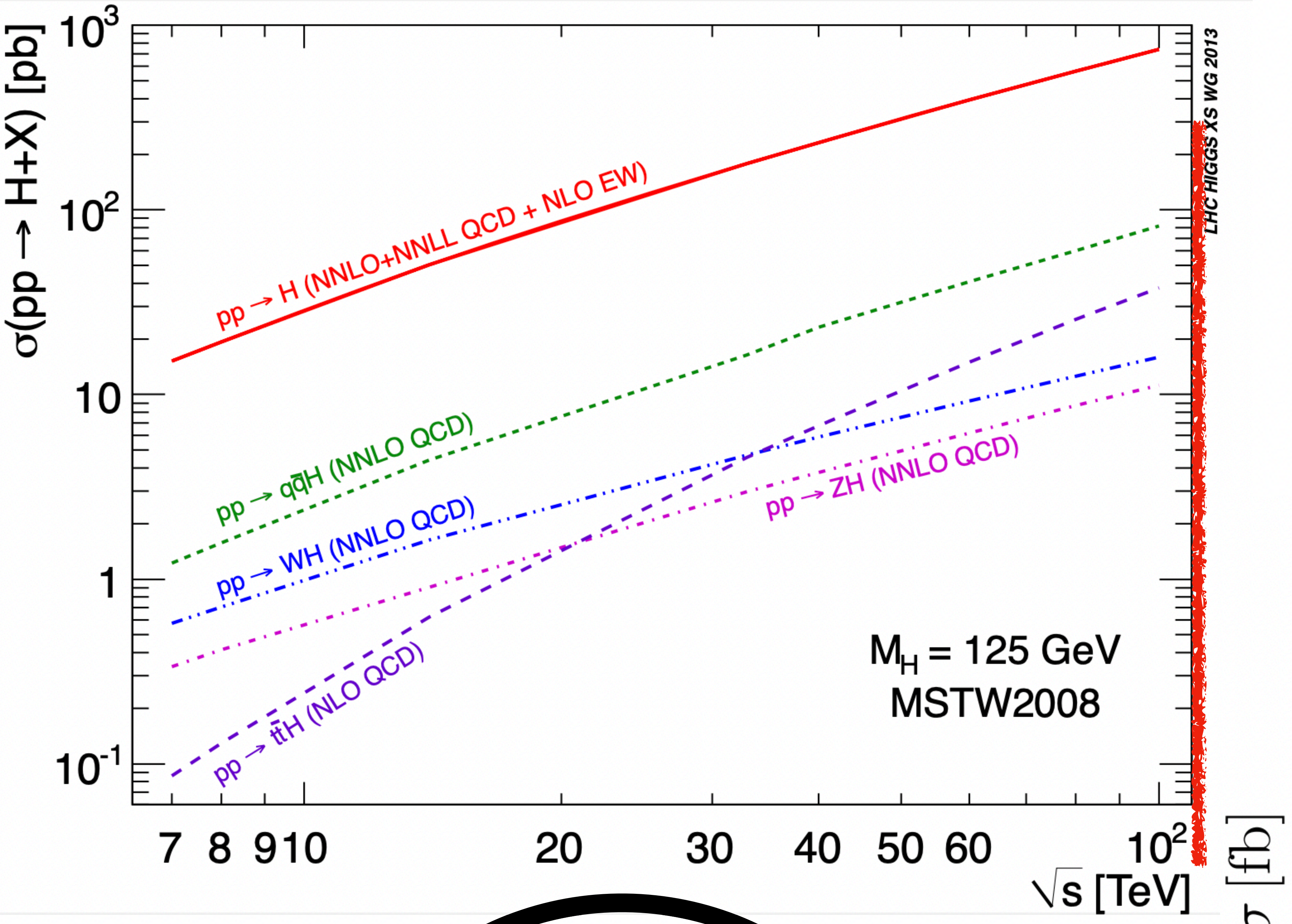


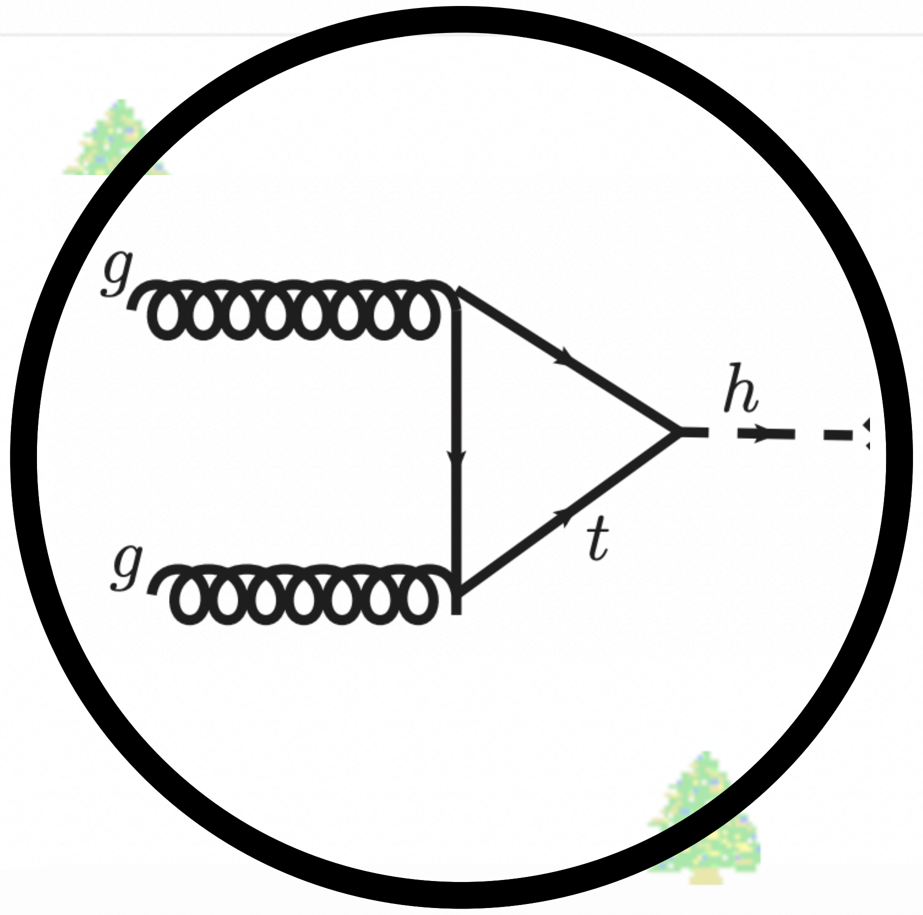
HIGGS PRODUCTION

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

Higgs Produced

LHC HIGGS WG





MuC

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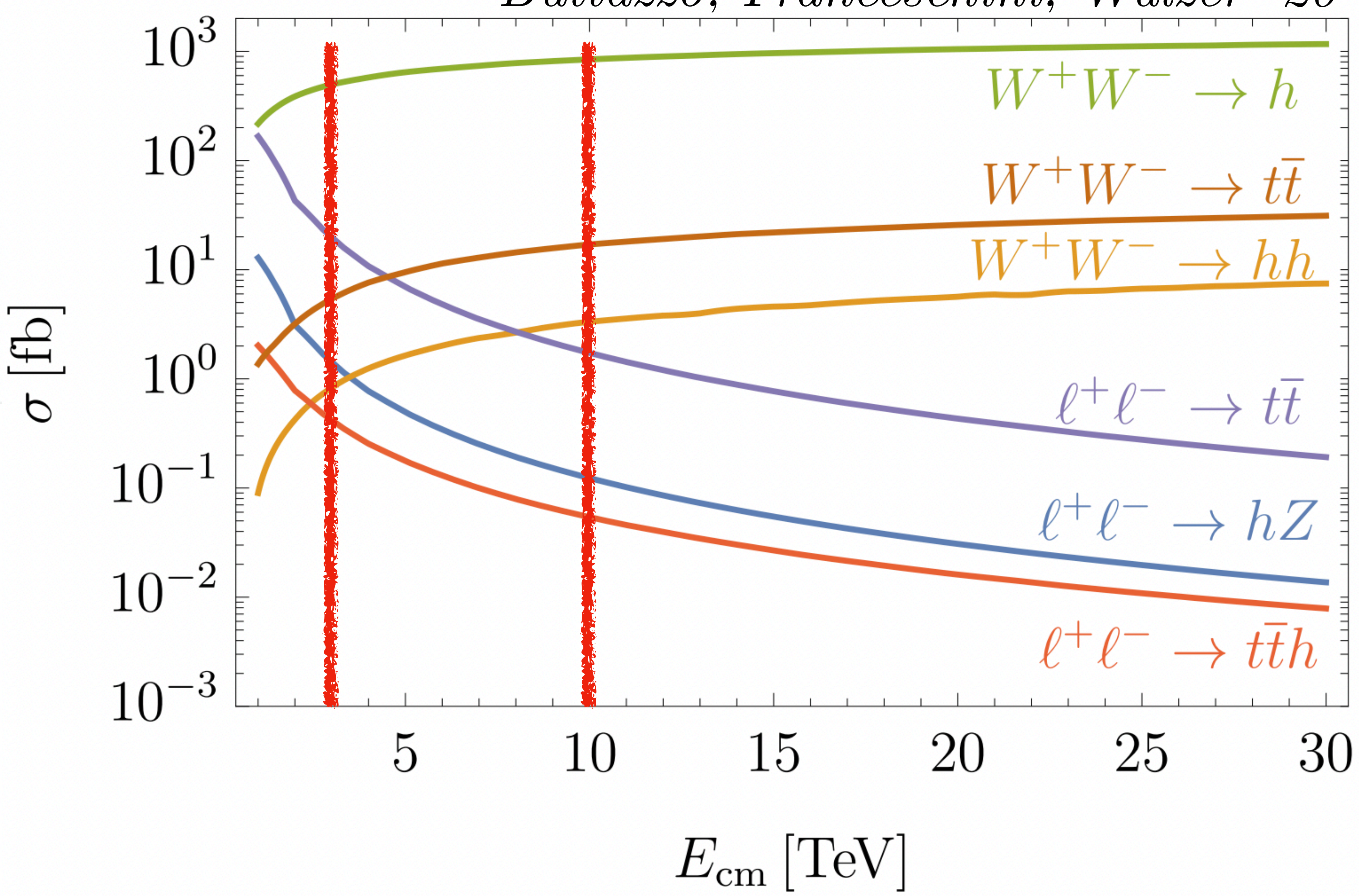
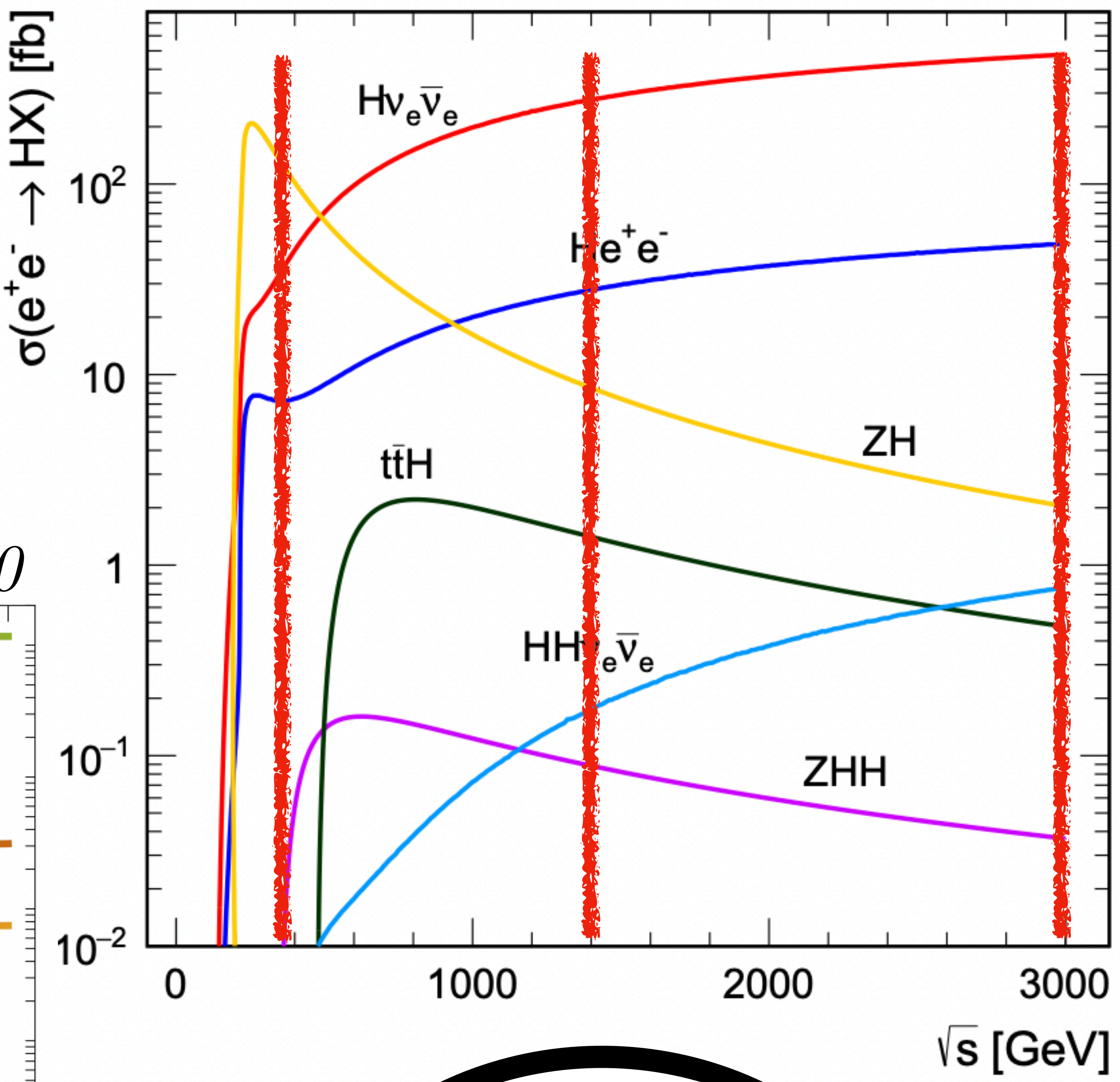
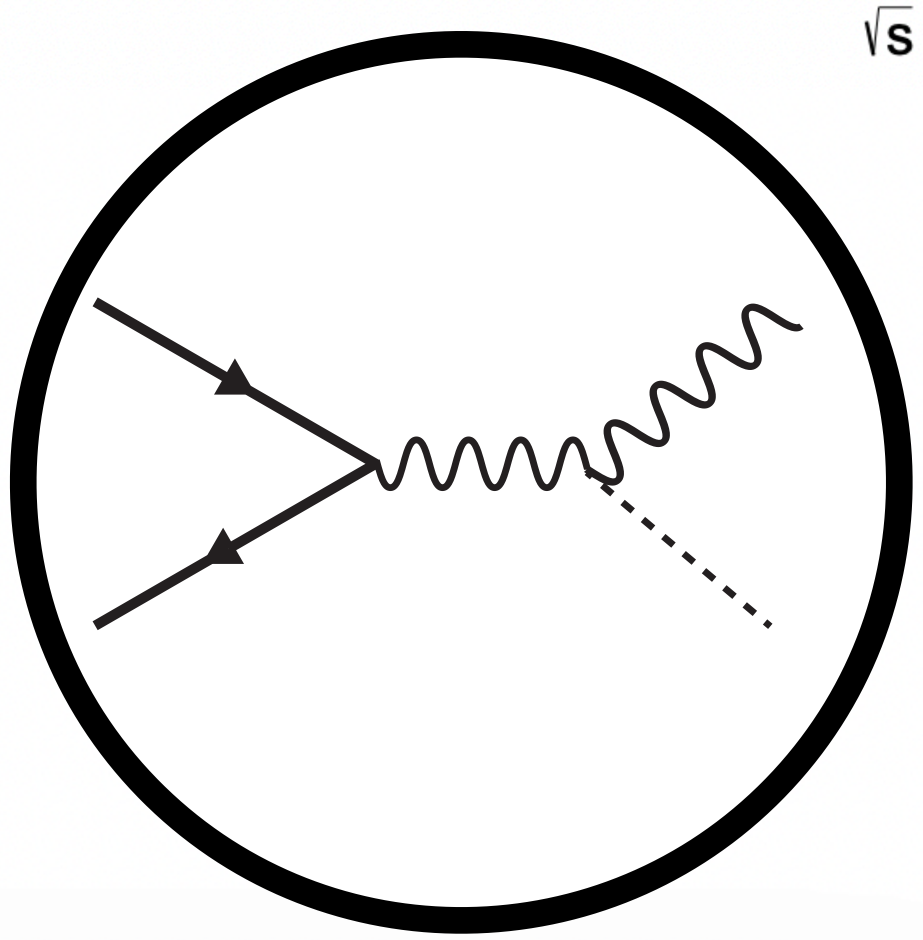


e^+e^-

CLIC '18





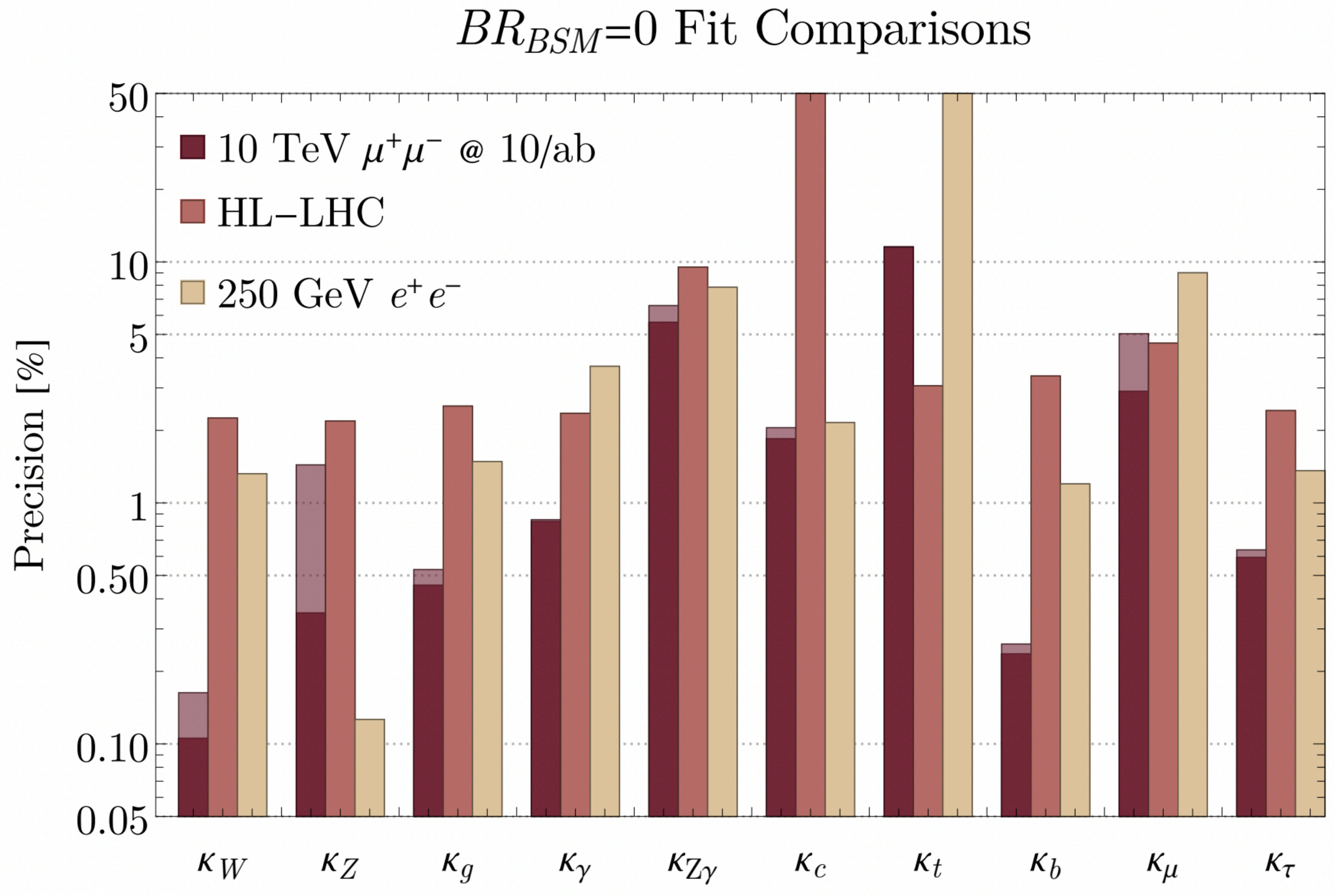
HIGGS PRODUCTION

Consider precision in κ framework

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

1905.03764 2308.02633

κ-0 fit	HL-LHC	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ 10000
κ_W [%]	1.7	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31

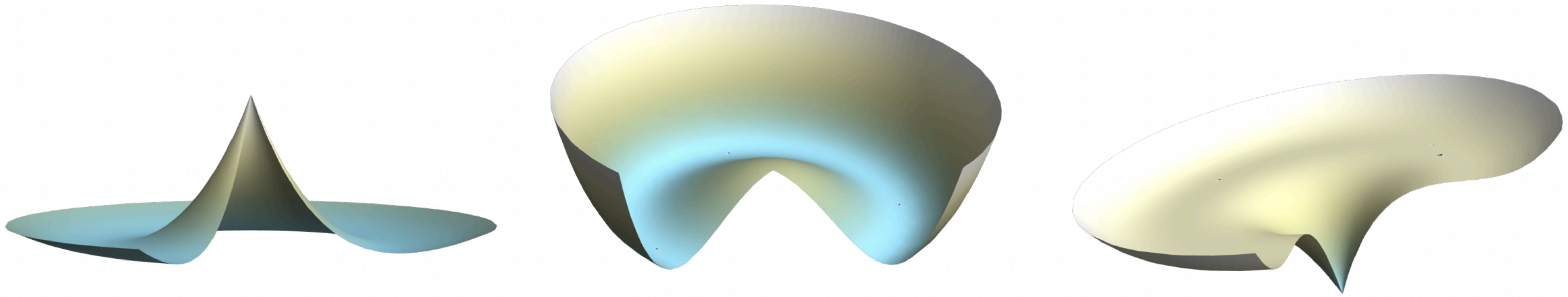


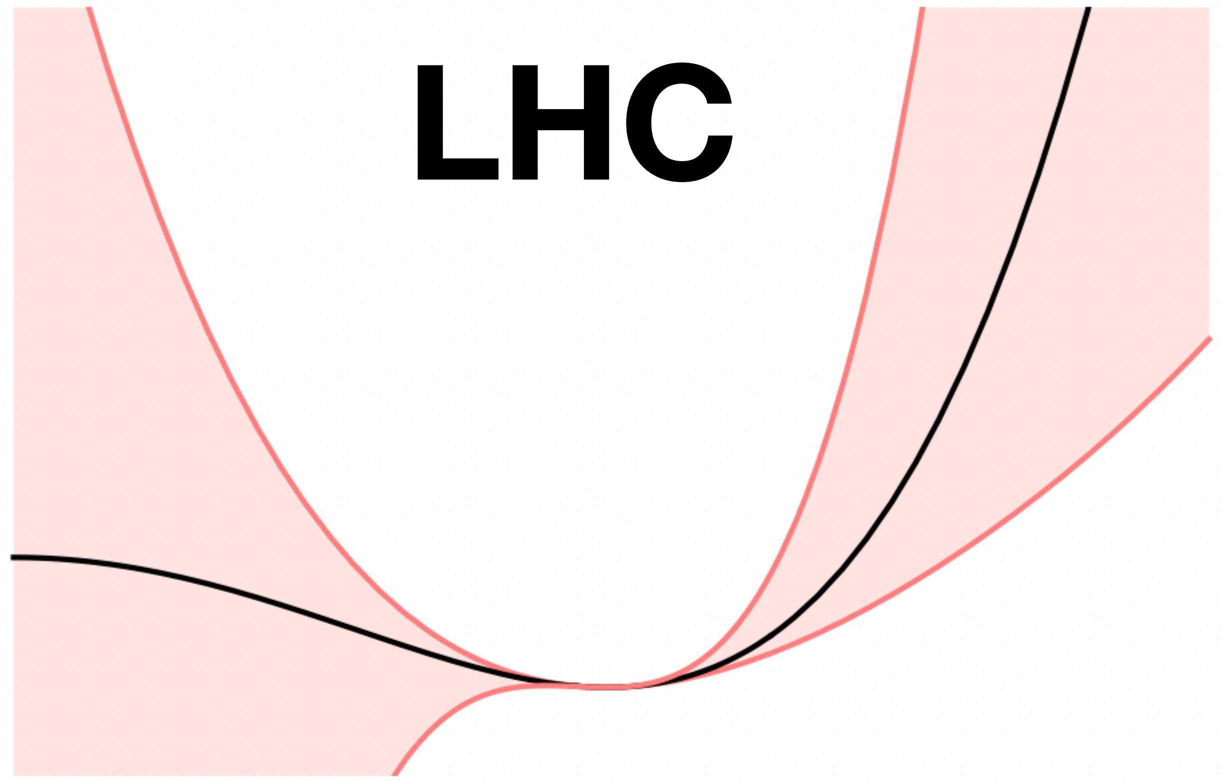
Scenario	BR_{inv}
kappa-0	fixed at 0

Meade & Forslund 23

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

Higgs Potential





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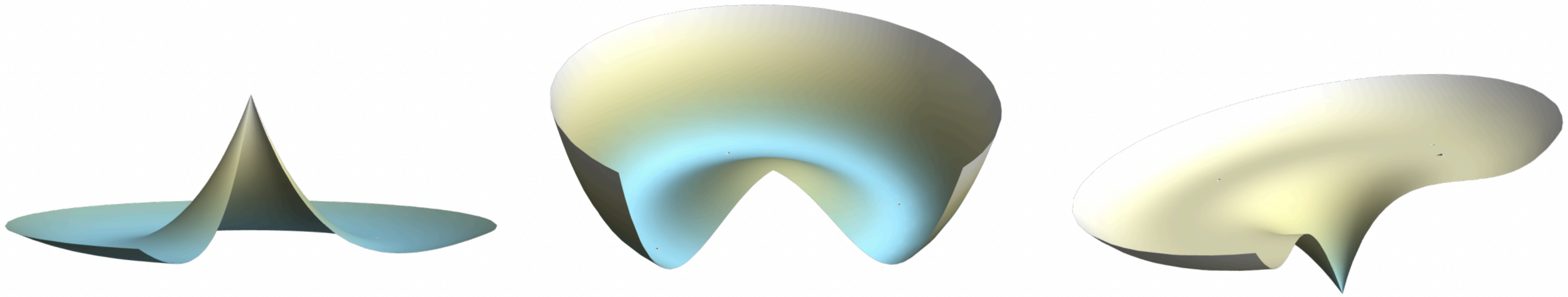
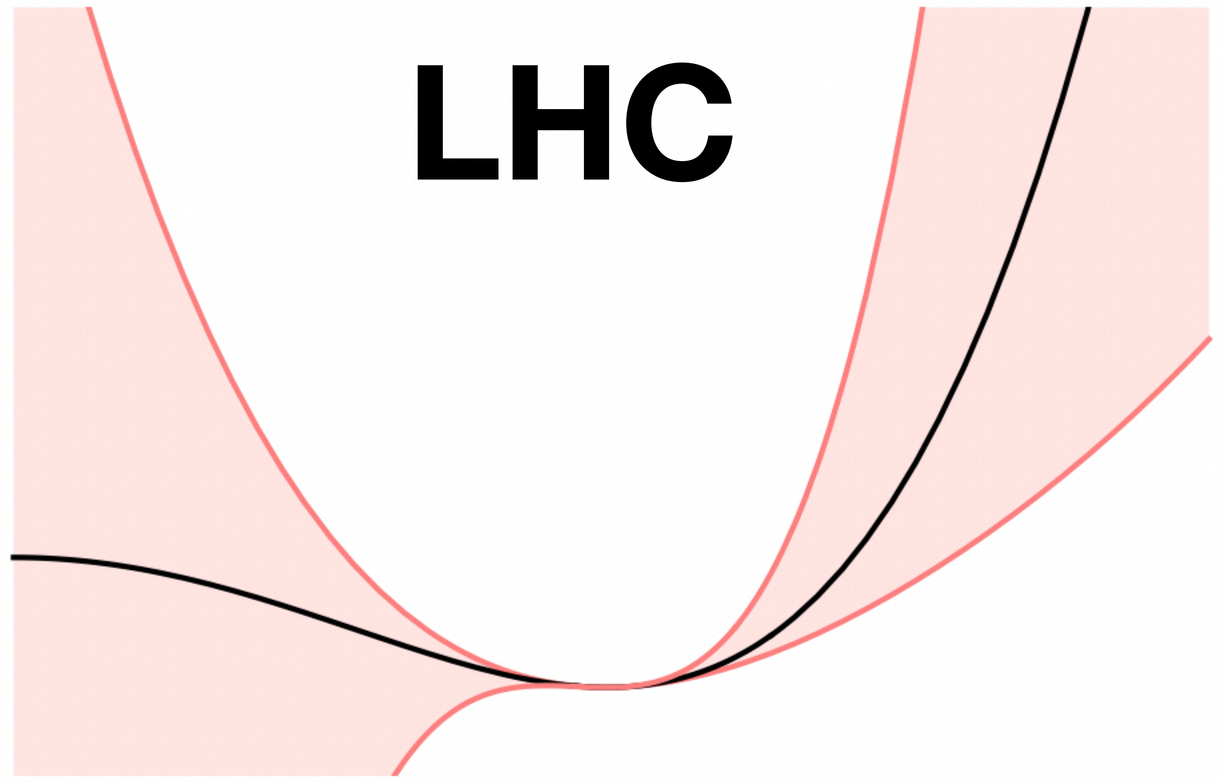
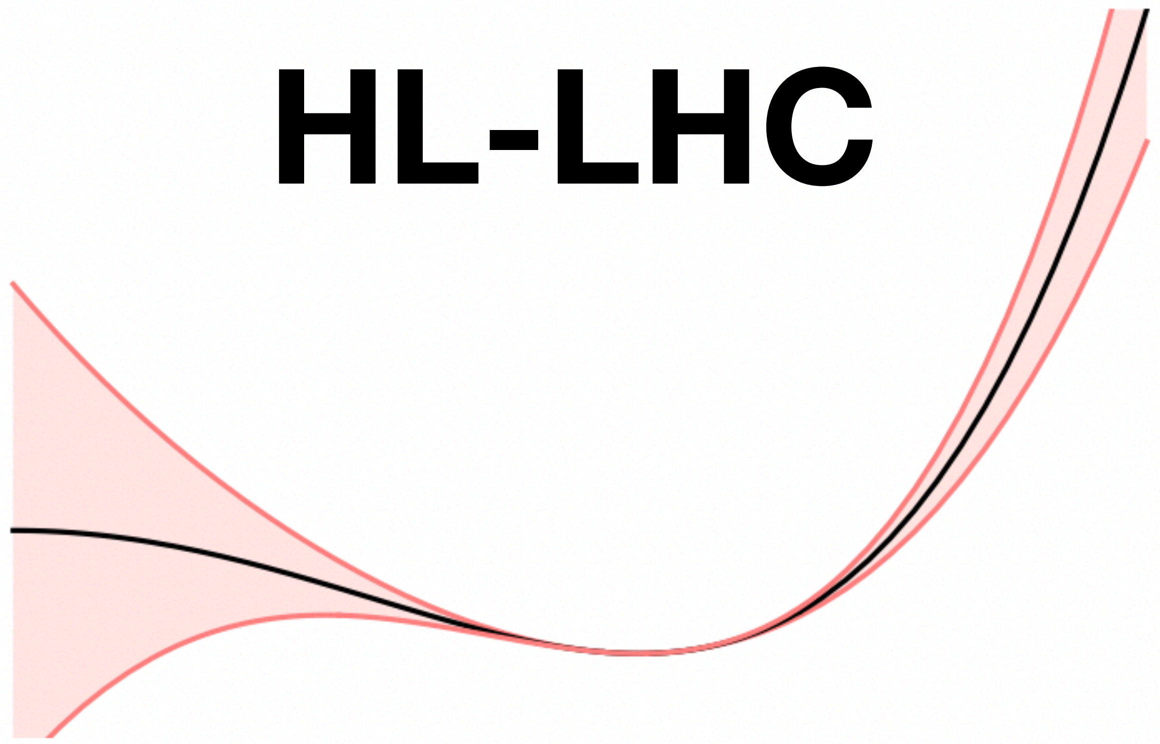
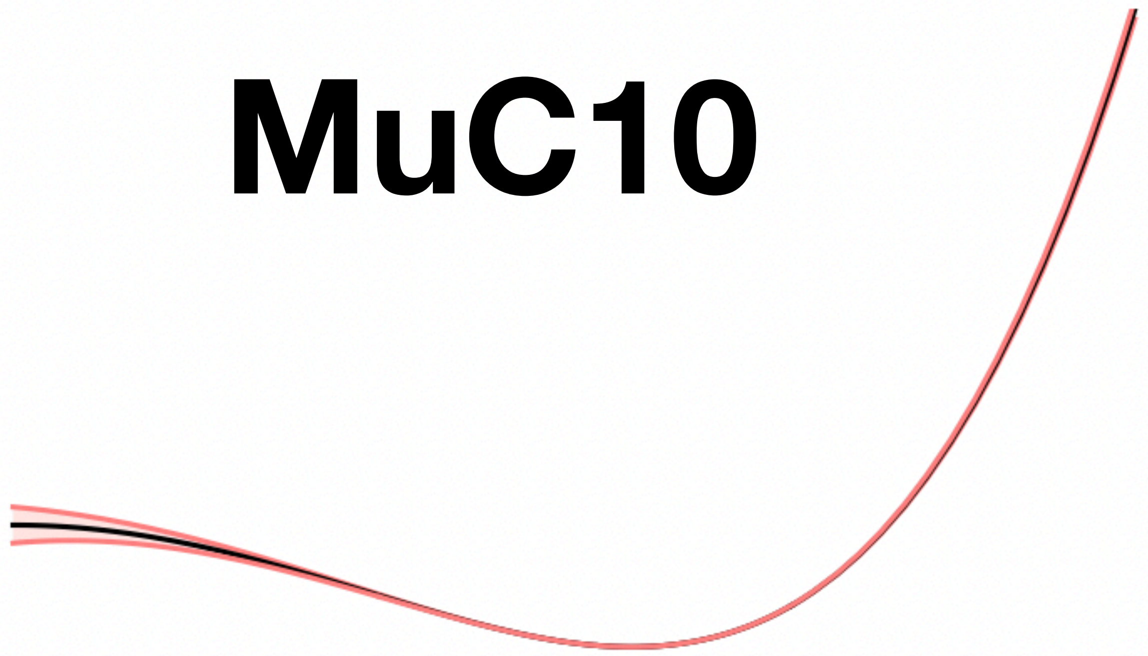
Higgs Potential









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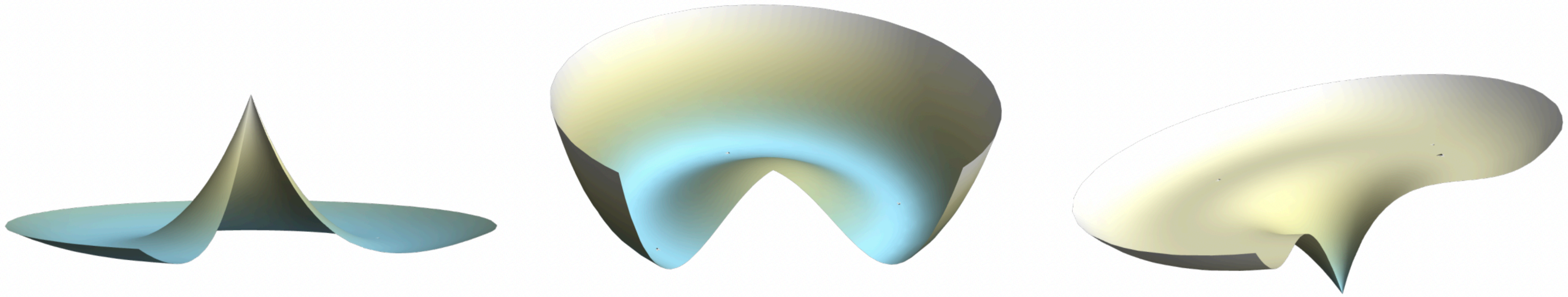
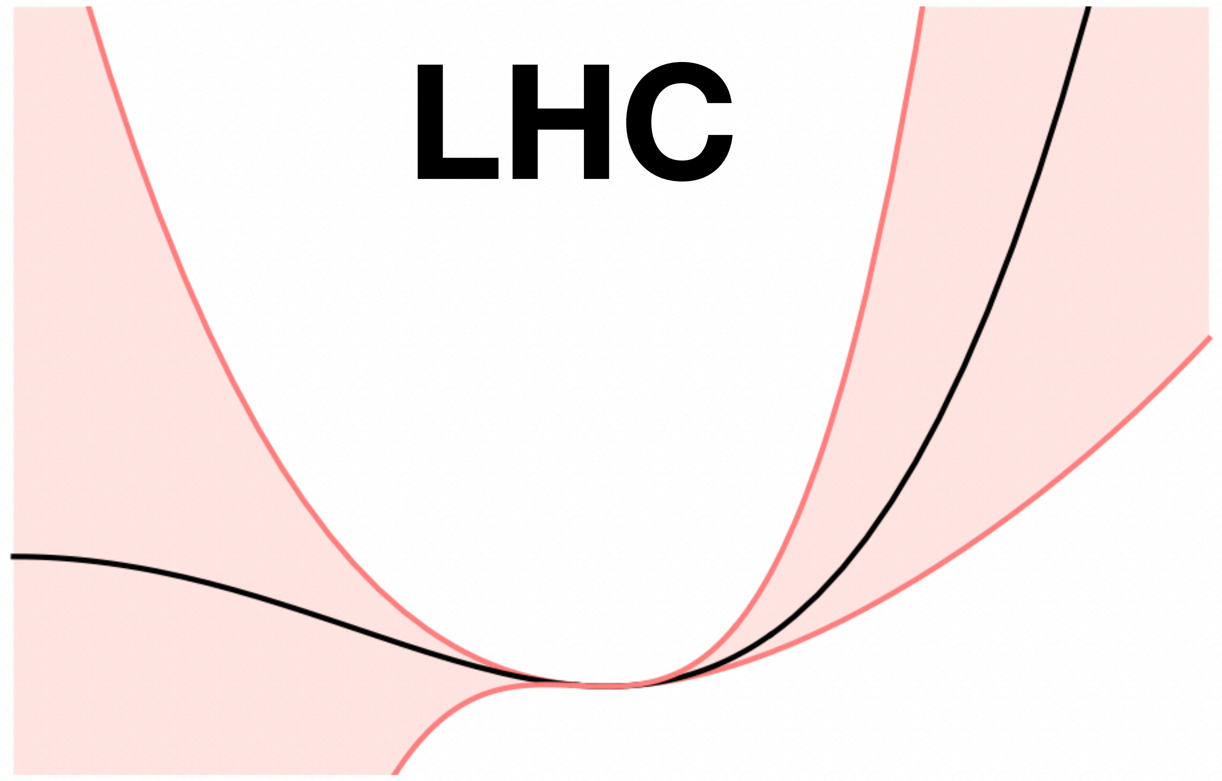
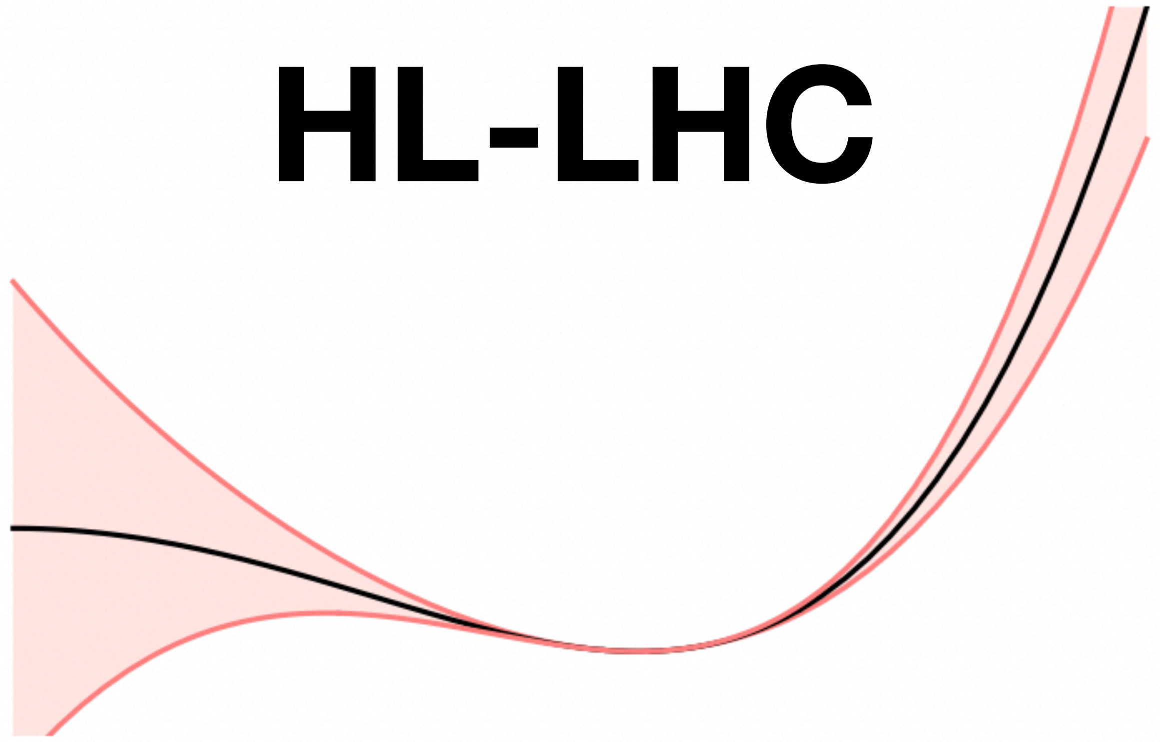
Higgs Potential

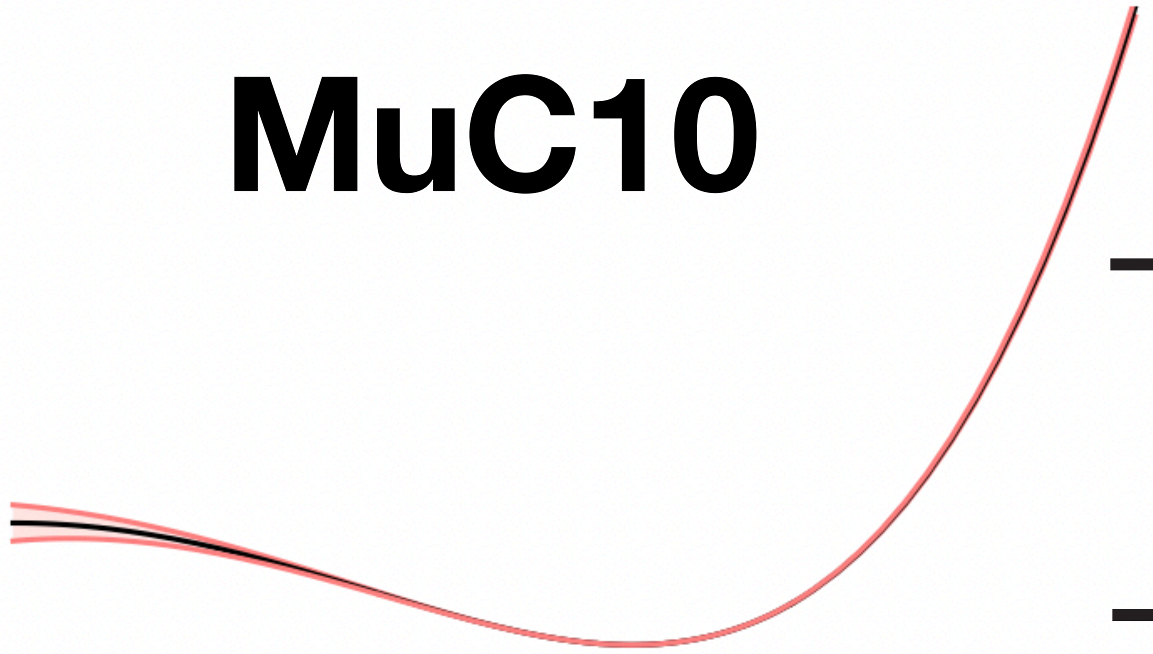




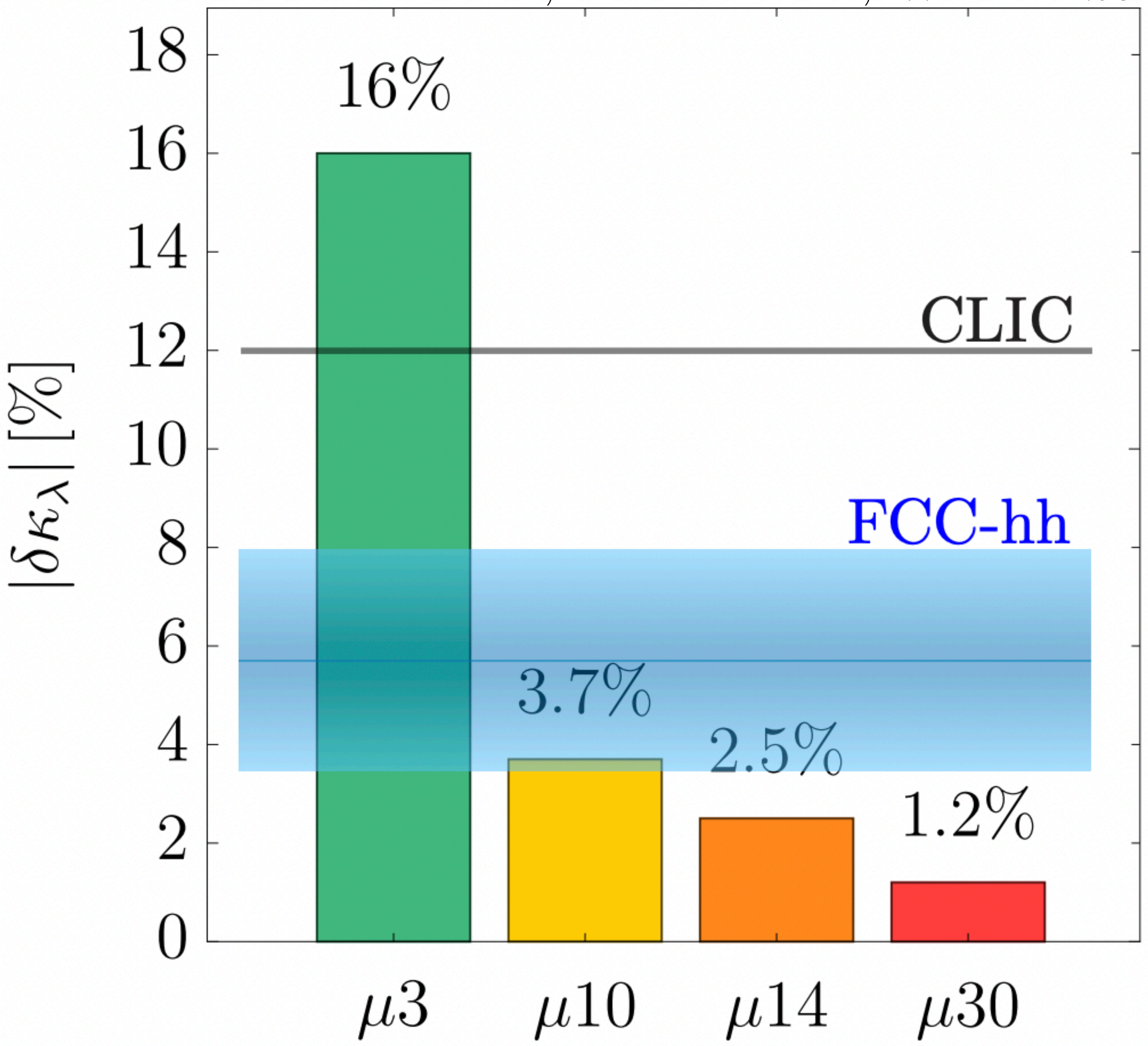
HL-LHC

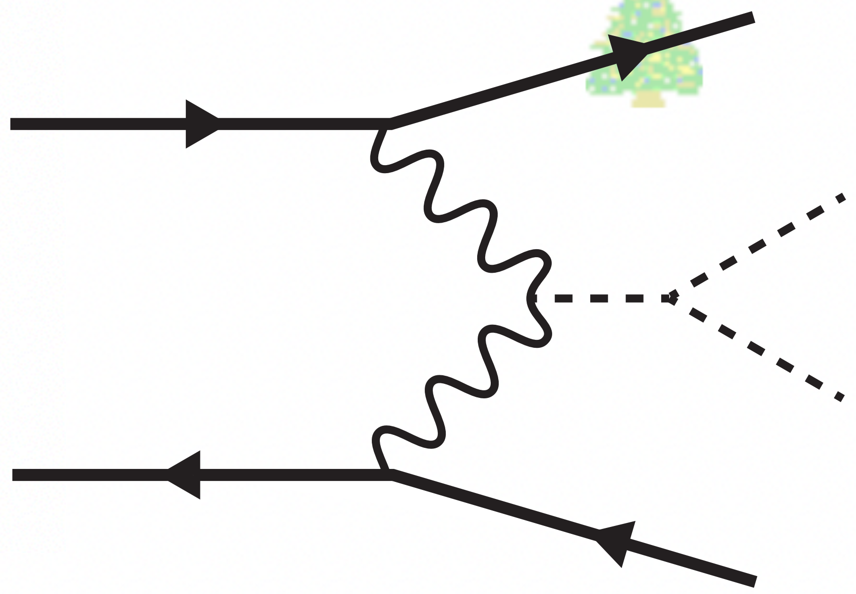


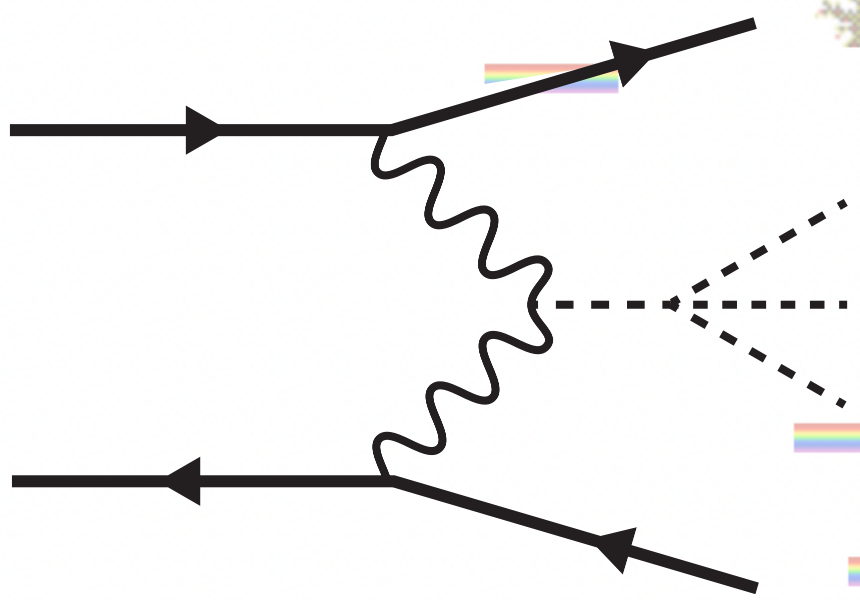
MuC10



Buttazzo, Franceschini, Wulzer '20





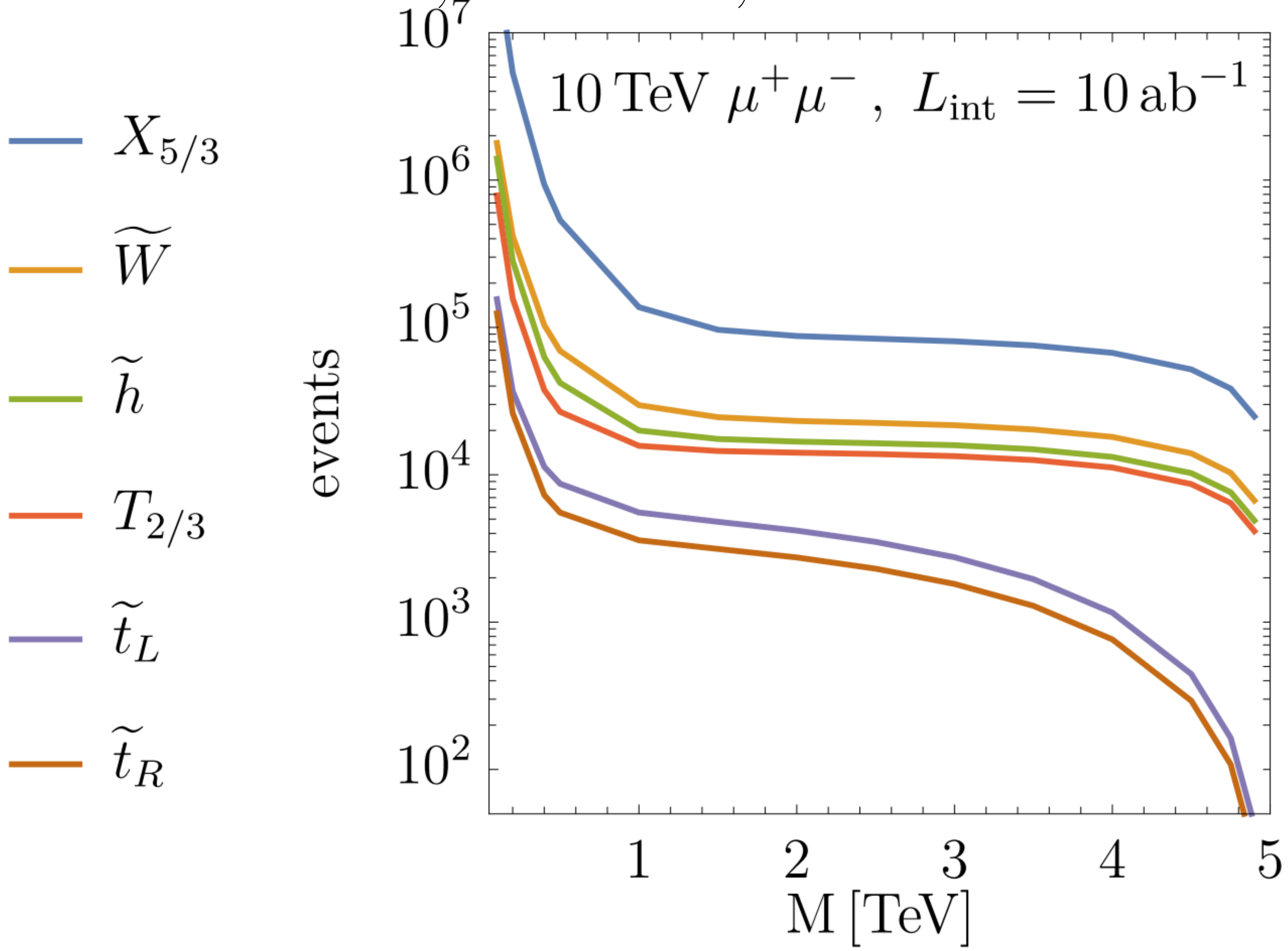


Examples of Direct Production of Heavy New Physics

Physics Reach of MuC: Heavy States

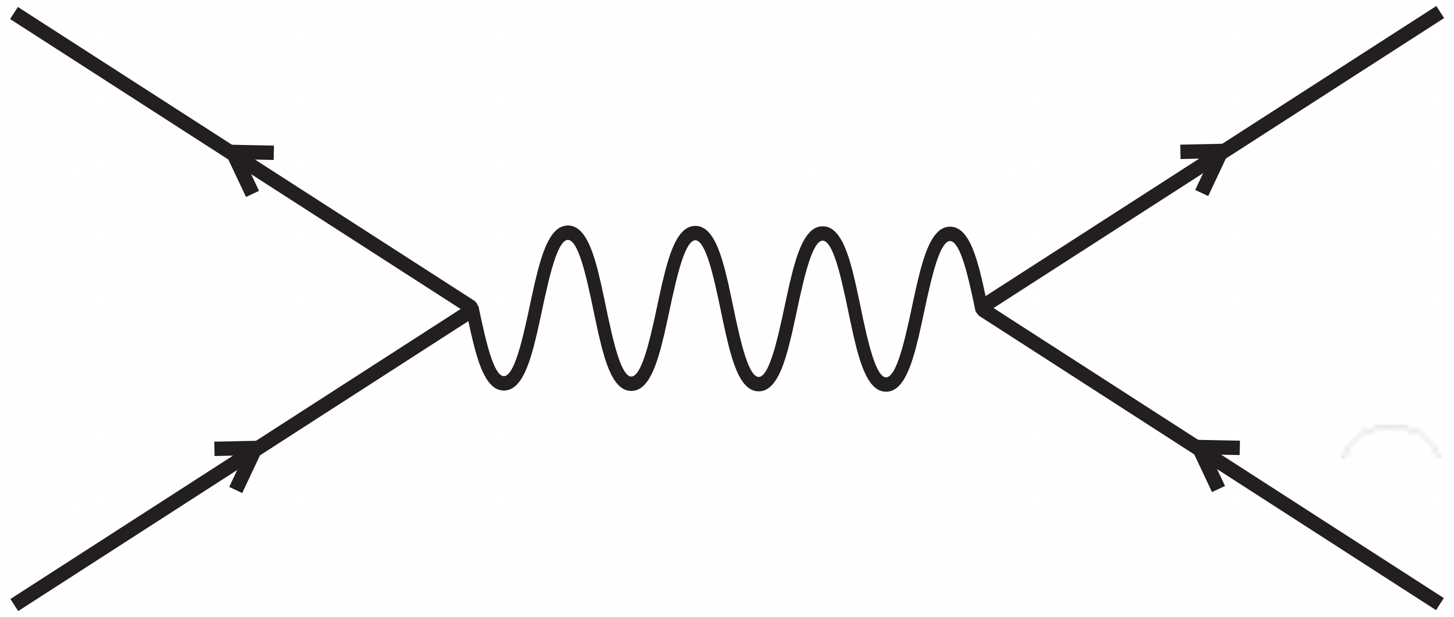
Generic Direct Production

Buttazzo, Franceschini, Wulzer 20



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

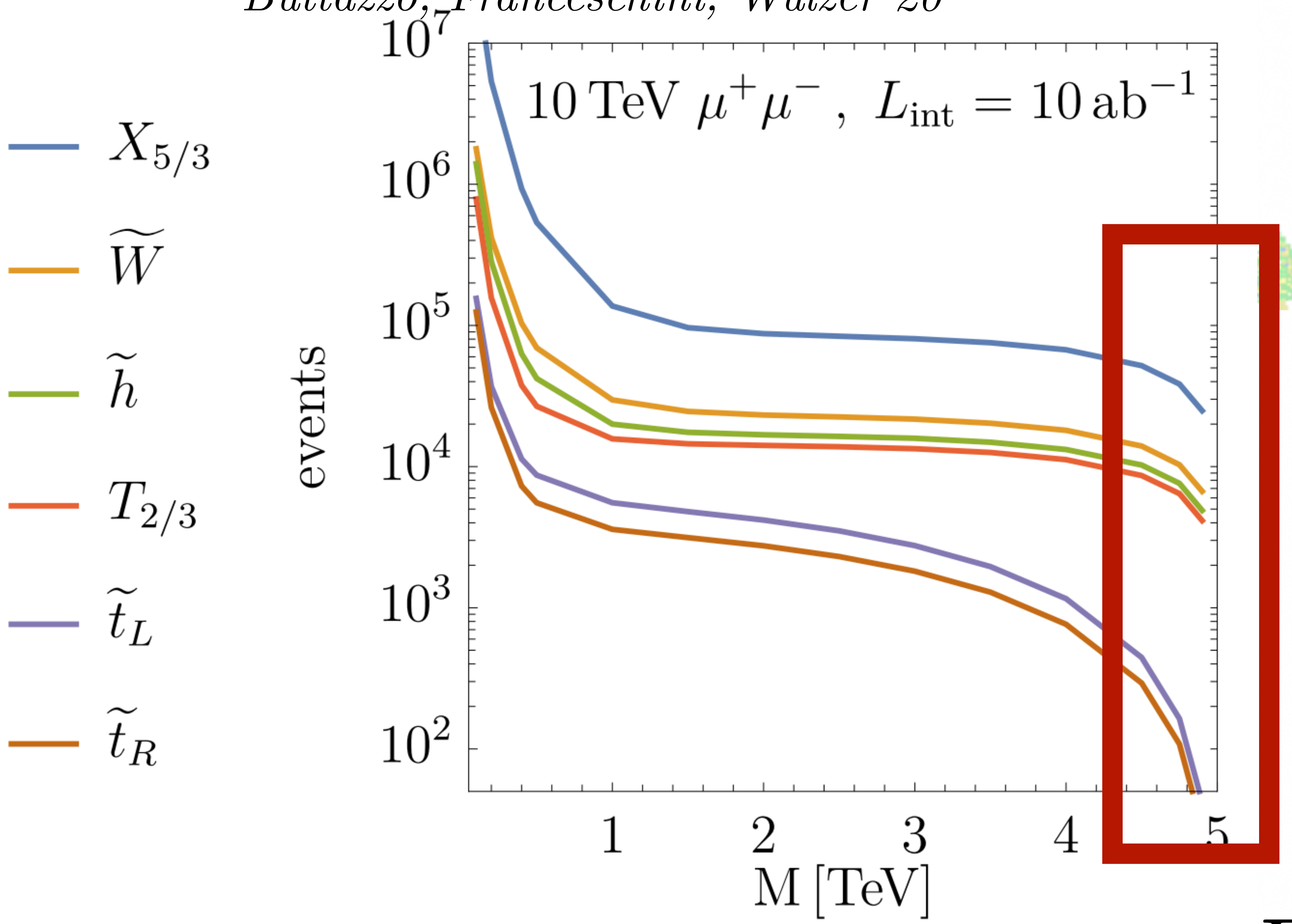
$$\mathscr{L} \sim \frac{N_\mu}{\text{bunch}} \times E^2$$



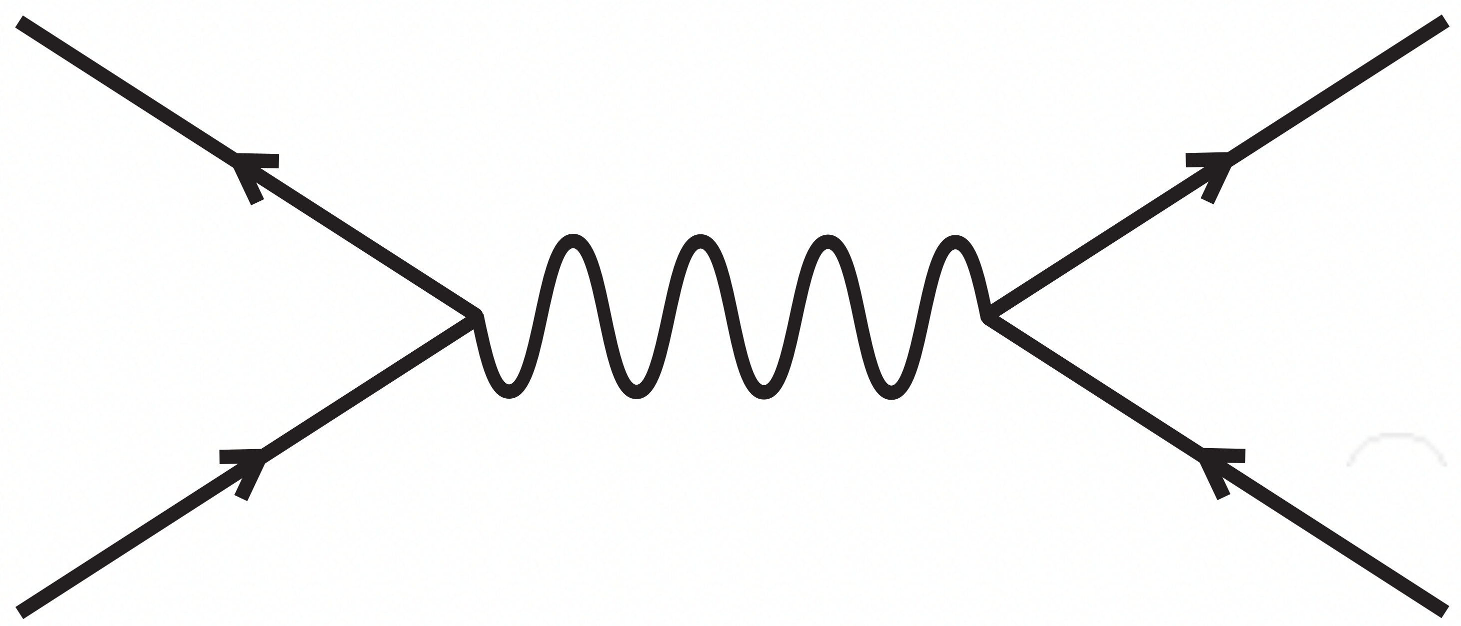
Physics Reach of MuC: Heavy States

Generic Direct Production

Buttazzo, Franceschini, Wulzer 20



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

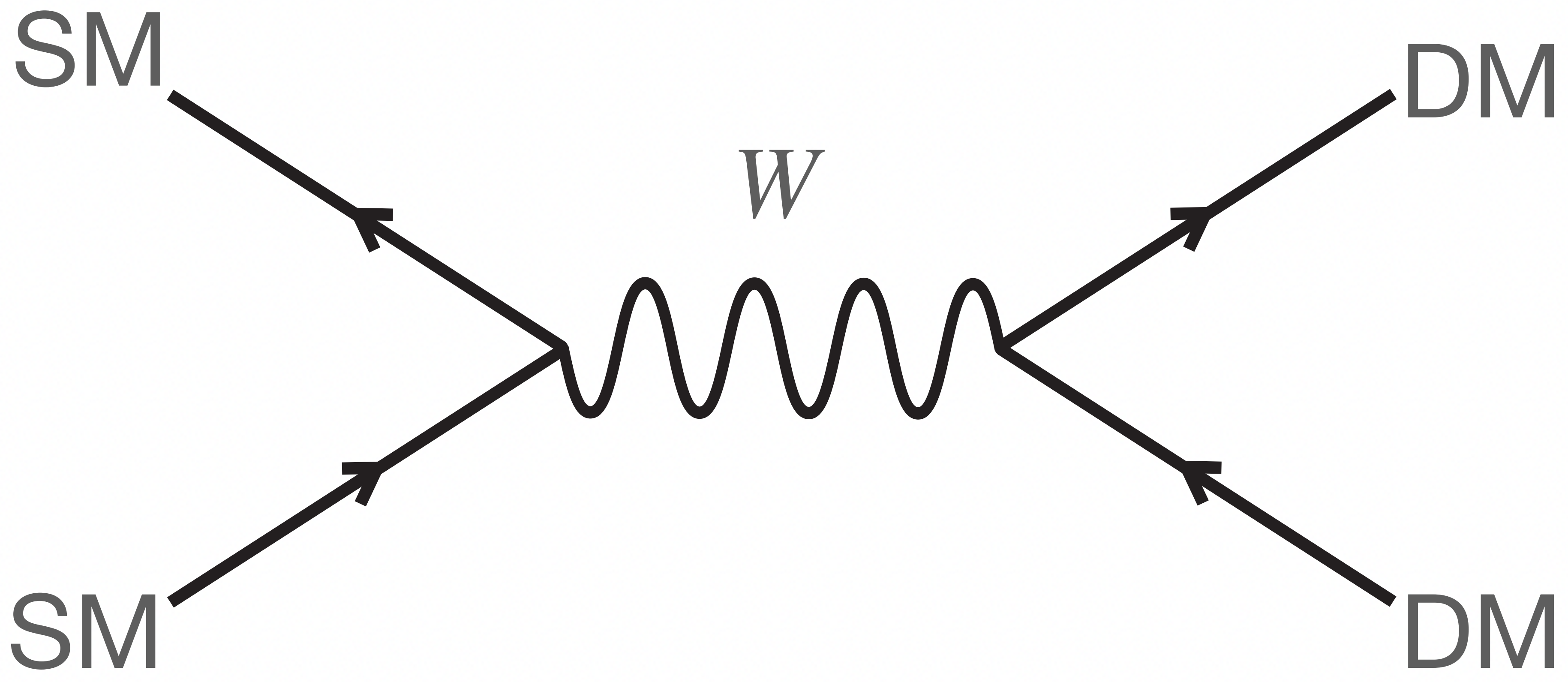


Reach up to kinematic threshold

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

Physics Reach of MuC: WIMPs

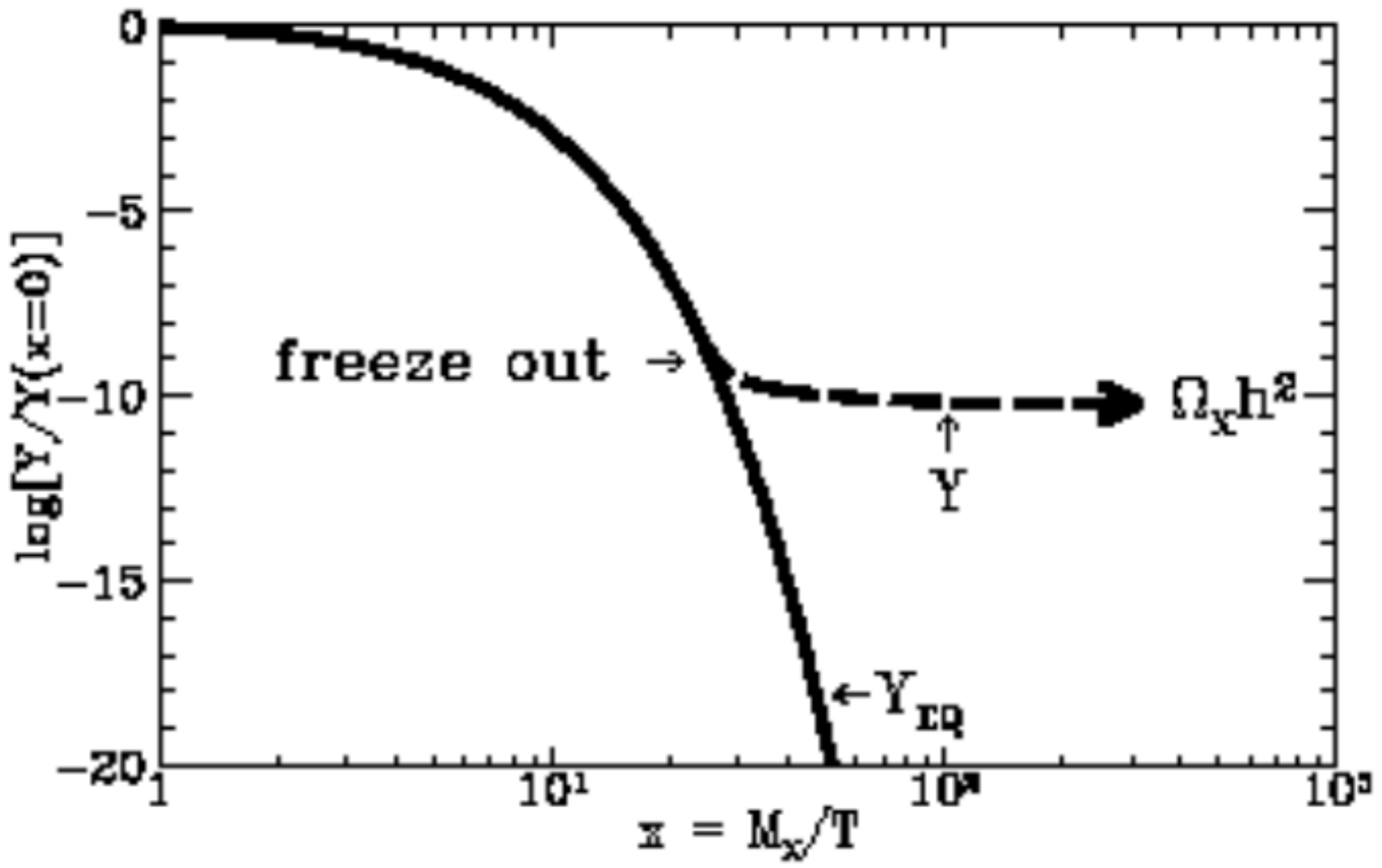
For dark matter models coupling to EW bosons, MuC is an ideal place for searches



Electroweak n-plet $\left\{ \begin{array}{l} \vdots \\ \chi^+, \chi^- \\ \chi^0 \end{array} \right.$

Mass fixed by freeze-out abundance

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



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

Physics Reach of MuC: WIMPs

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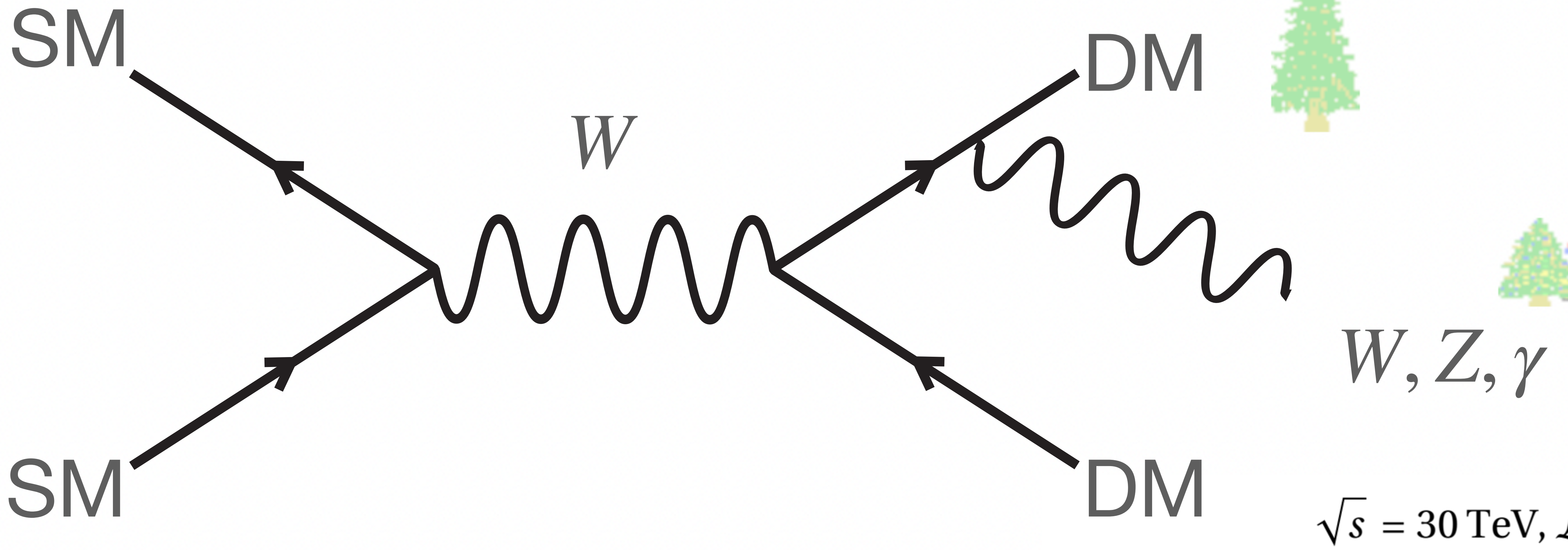
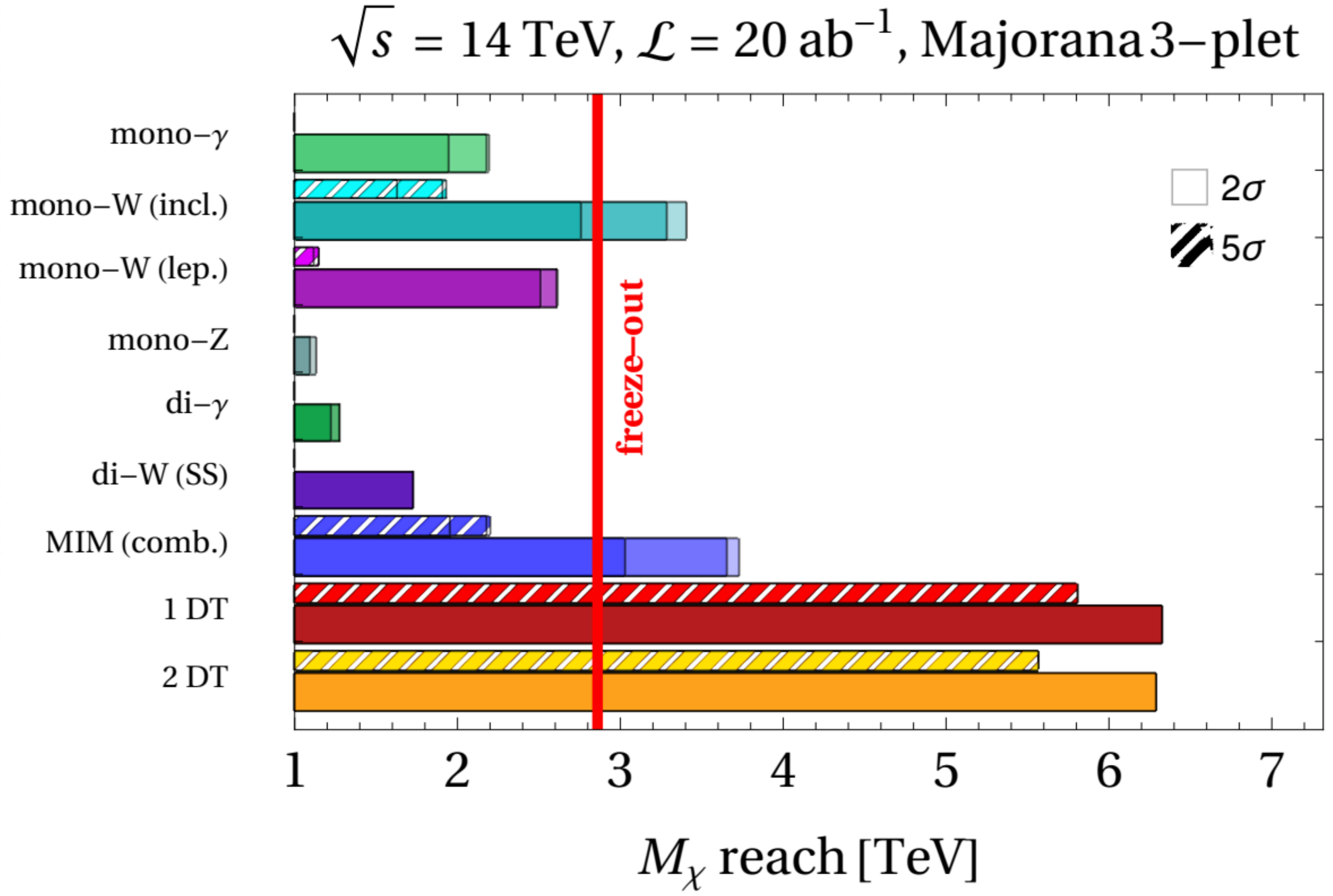
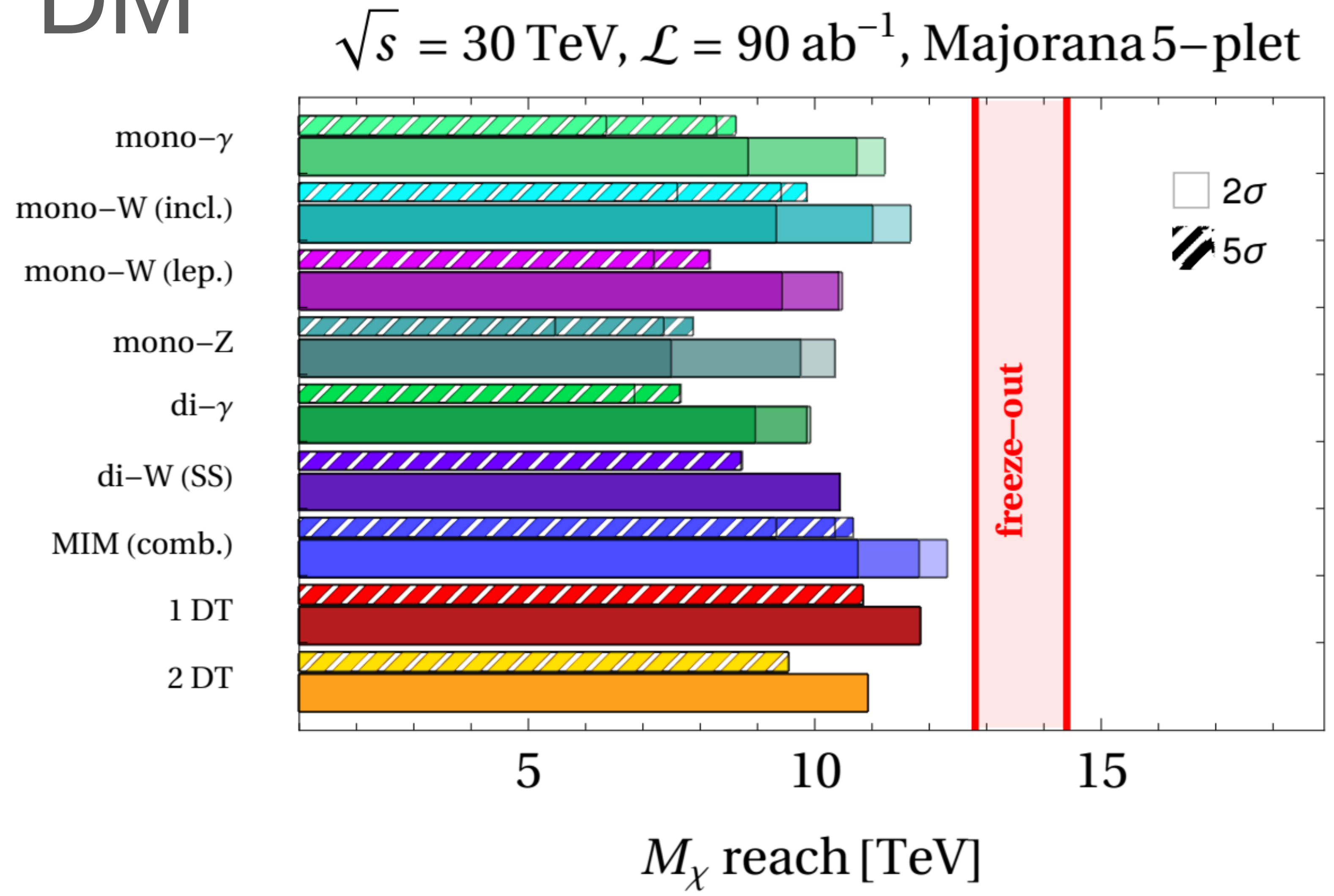


$$\mu^+\mu^- \to \chi\bar{\chi} + X$$





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Examples of Indirect Production of Heavy New Physics

Physics Reach of MuC: Indirect

EFT Approach for Energy $\leftrightarrow$ Precision

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

Physics Reach of MuC: Indirect

EFT Approach for Energy $\leftrightarrow$ Precision

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

Say you can measure something to 1% precision

$g \sim 1$

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

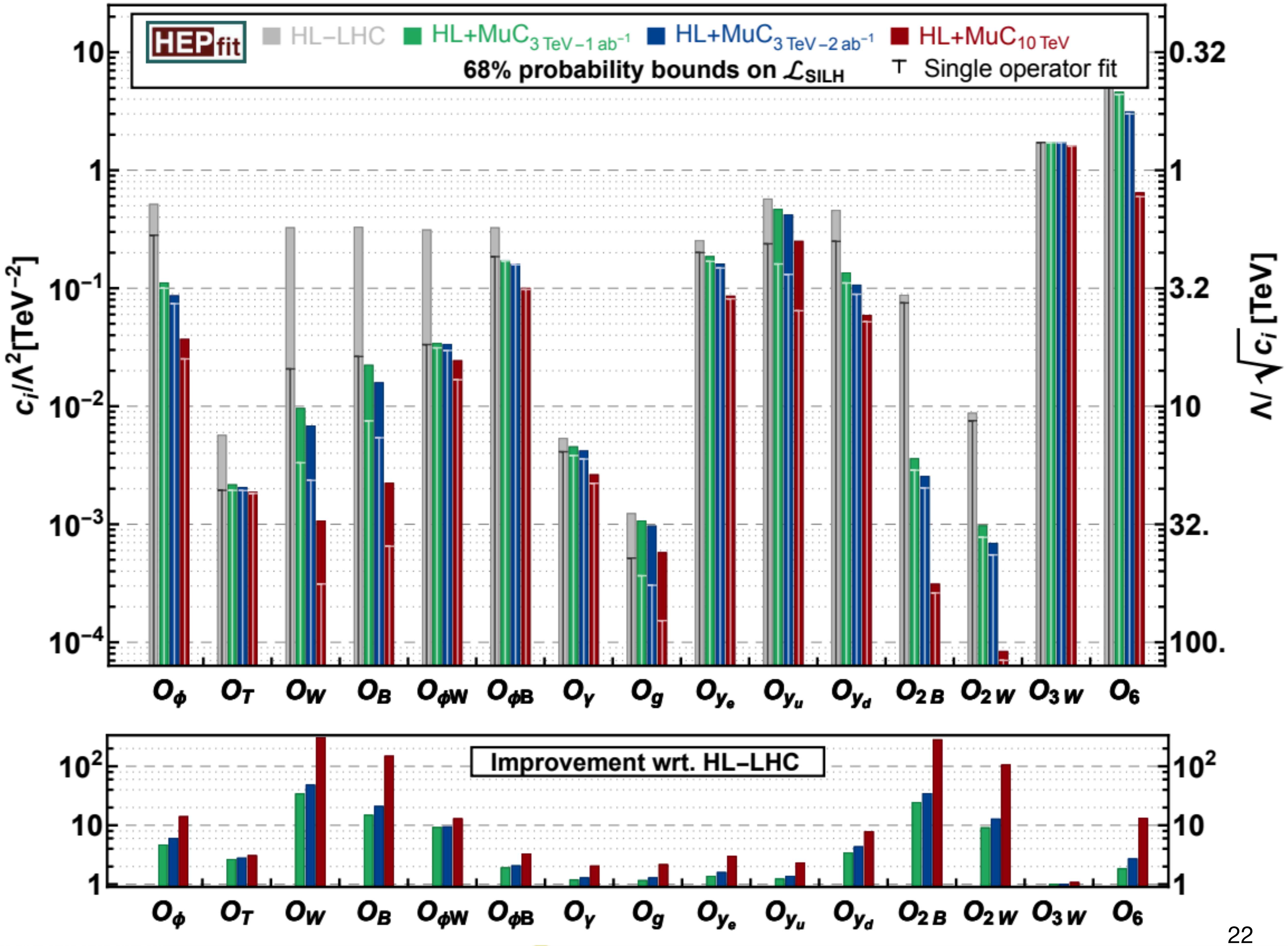
$E \sim 10$ TeV

$\Lambda \sim 100$ TeV

Can still be probing new physics at much higher scales!

Physics Reach of MuC: Indirect

EFT Approach for Energy ↔ Precision



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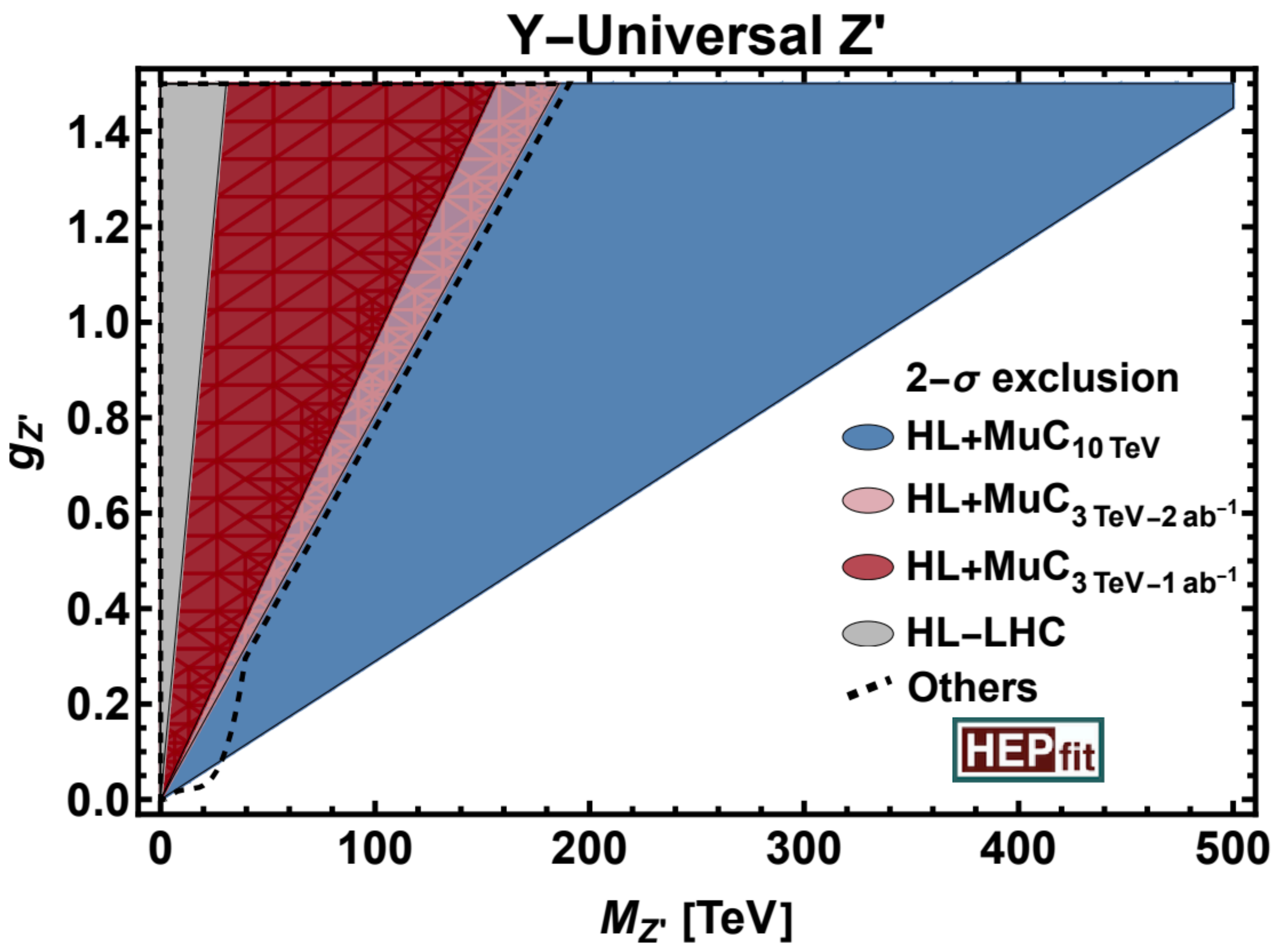

Any thing else we could do with a muon collider?

Any thing else we could do with a muon collider?

Yes! See Zahra's Talk Today

Final Thoughts 🌶️

- A muon collider is a technology concept, not a fully on-shell experiment ready to build
- The run parameters of a MuC should be flexible depending on the status of other colliders
- We can explore new physics at the 10 TeV scale *soon* and in a clean environment

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- (🌶️🌶️) What makes a MuC special is our ability to sprint to the 10+ TeV frontier. *Why* should we do luminosity staging?

FINAL THOUGHTS 🌶️

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- (🌶️🌶️) What makes a MuC special is our ability to sprint to the 10+ TeV frontier. *Why* should we do luminosity staging?

THANKS!

Backups

Challenges of MuC

	Recent Improvements
Cooling	MICE, Simulation, Timescales
Magnets	20 T Dipoles 30 T Solenoids 10^3 T/s Ramping
Community Interest	IMCC + US R&D
“Need *N* Miracles”	“No Showstoppers Identified”

ESPPU + P5 $\Longrightarrow$ Time is **now**!

Demonstrator Facilities & Beam Dump

Before construction (or approval) of a full collider
we need to demonstrate technologies

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

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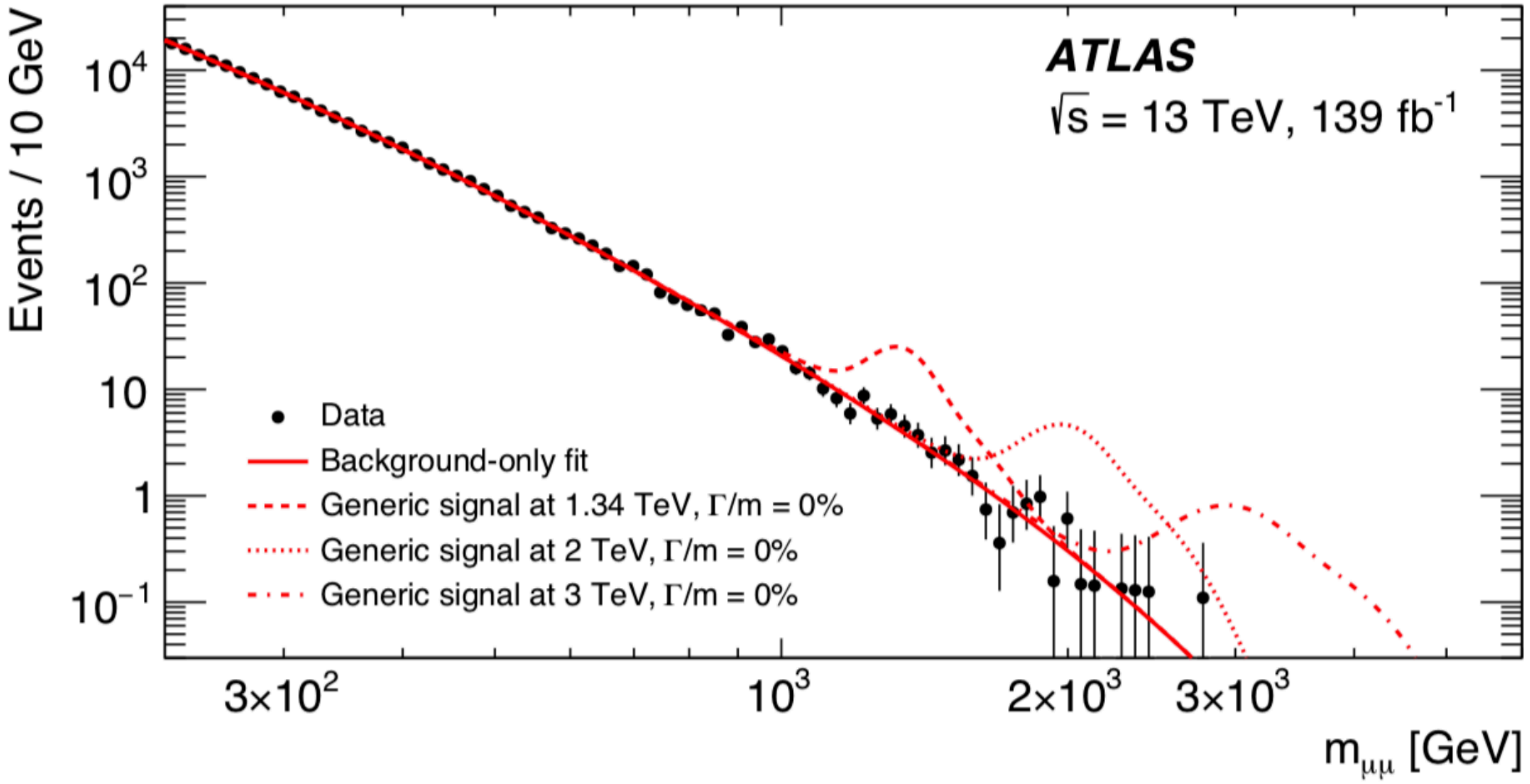
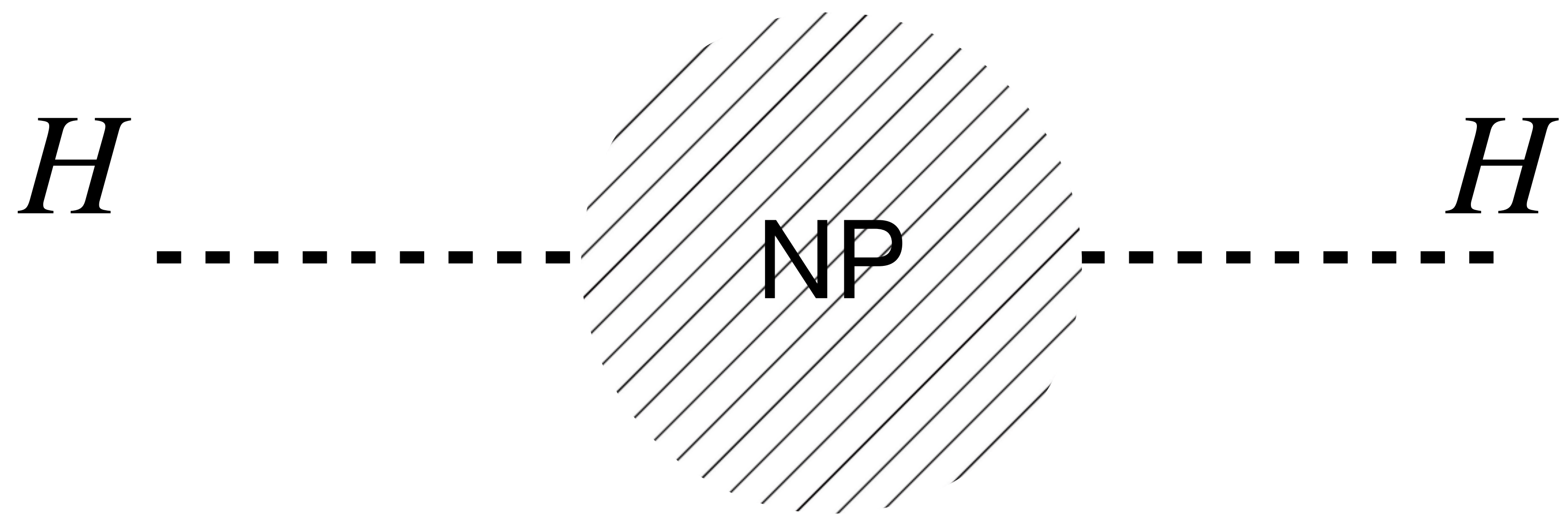


Beyond typical LHC $\sqrt{\hat{s}}$



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

New Physics showing up to affect EW Physics?

Slide Credit: D. Buttazzo

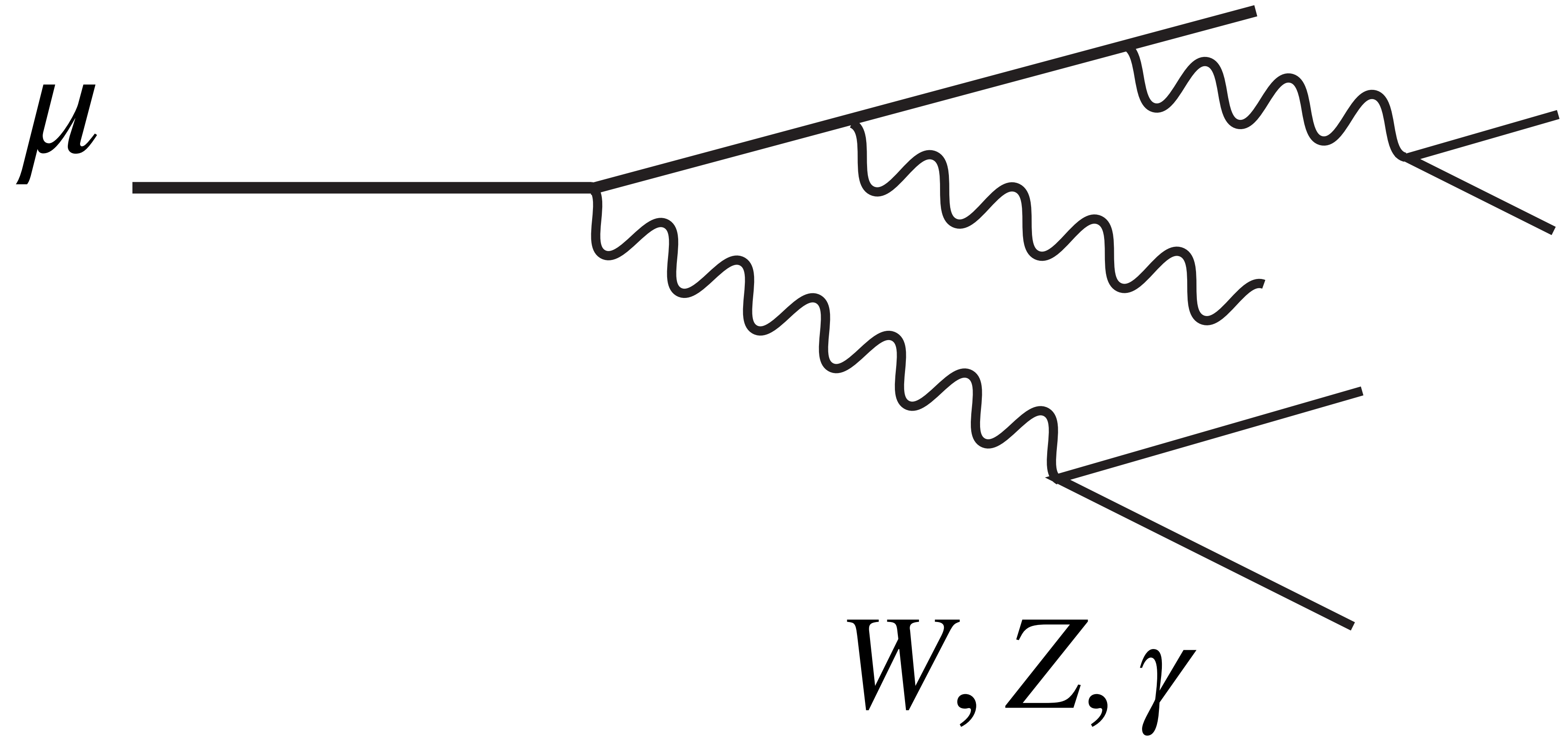
Muon Collider Staging

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 $\sqrt{\hat{s}}$

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 2202.10509

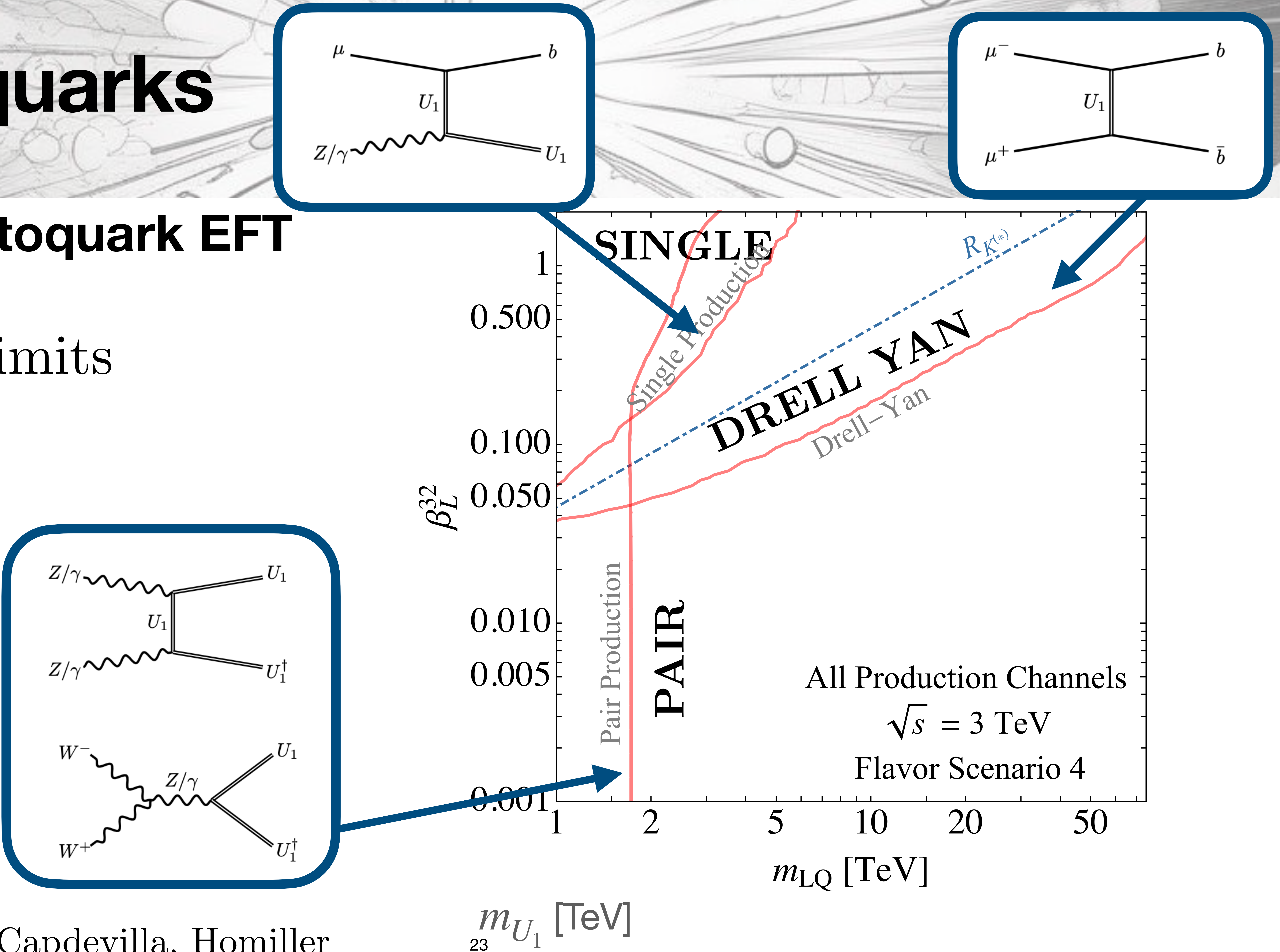
Ex: Leptoquarks

Minimal U_1 Leptoquark EFT

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

5σ confidence limits

3 TeV μC



2104.05720 **CC**, Asadi, Capdevilla, Homiller

Ex: Leptoquarks

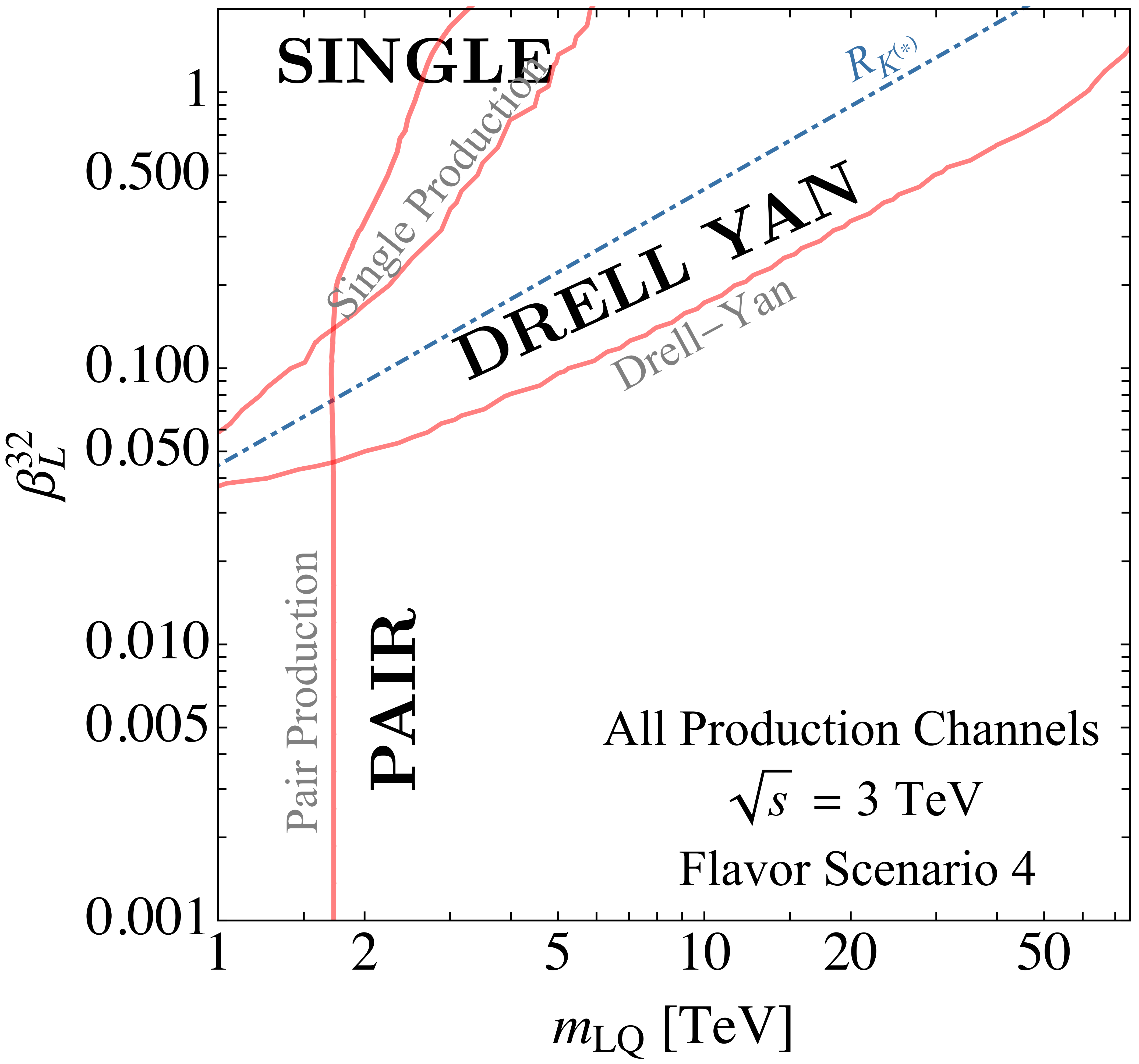
Minimal U_1 Leptoquark EFT

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

5σ confidence limits

3 TeV μC

$\left(\beta_L^{22}, \beta_L^{23}, \beta_L^{33}\right) = (\beta_L^{32}, 0.1, 1)$



m_{U_1} [TeV]

2104.05720 **CC**, Asadi, Capdevilla, Homiller

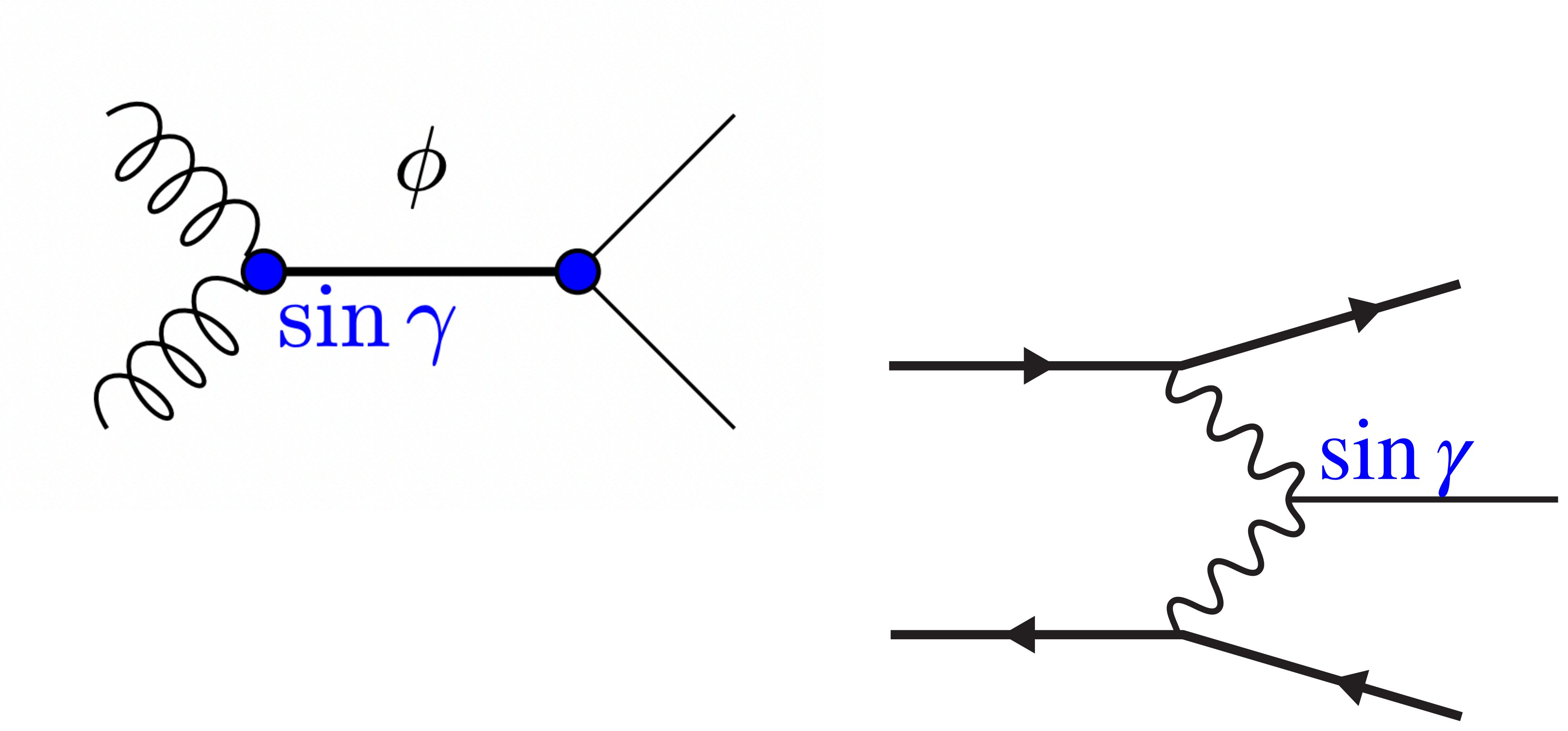
Ex: New Physics with Higgs Mixing

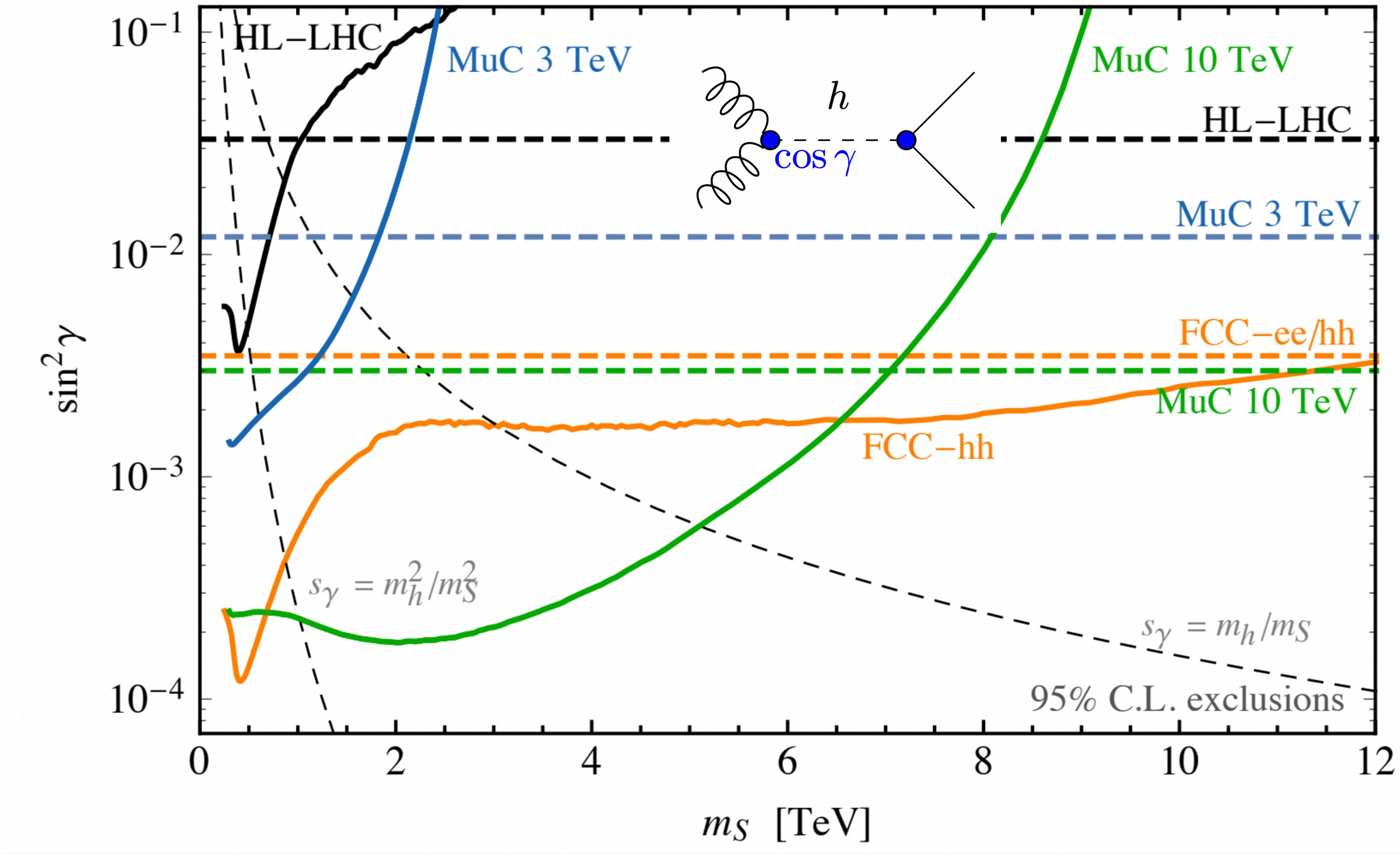
Benchmark model: New singlet *S* mixes with Higgs

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

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

$$\phi \rightarrow hh, ZZ, WW$$





Buttazzo, Redigolo, Sala, Tesi 1807.04743

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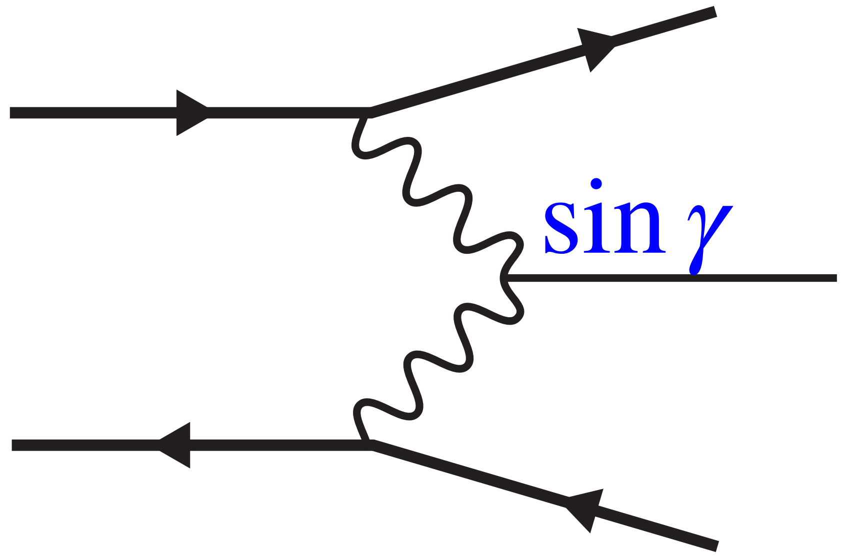
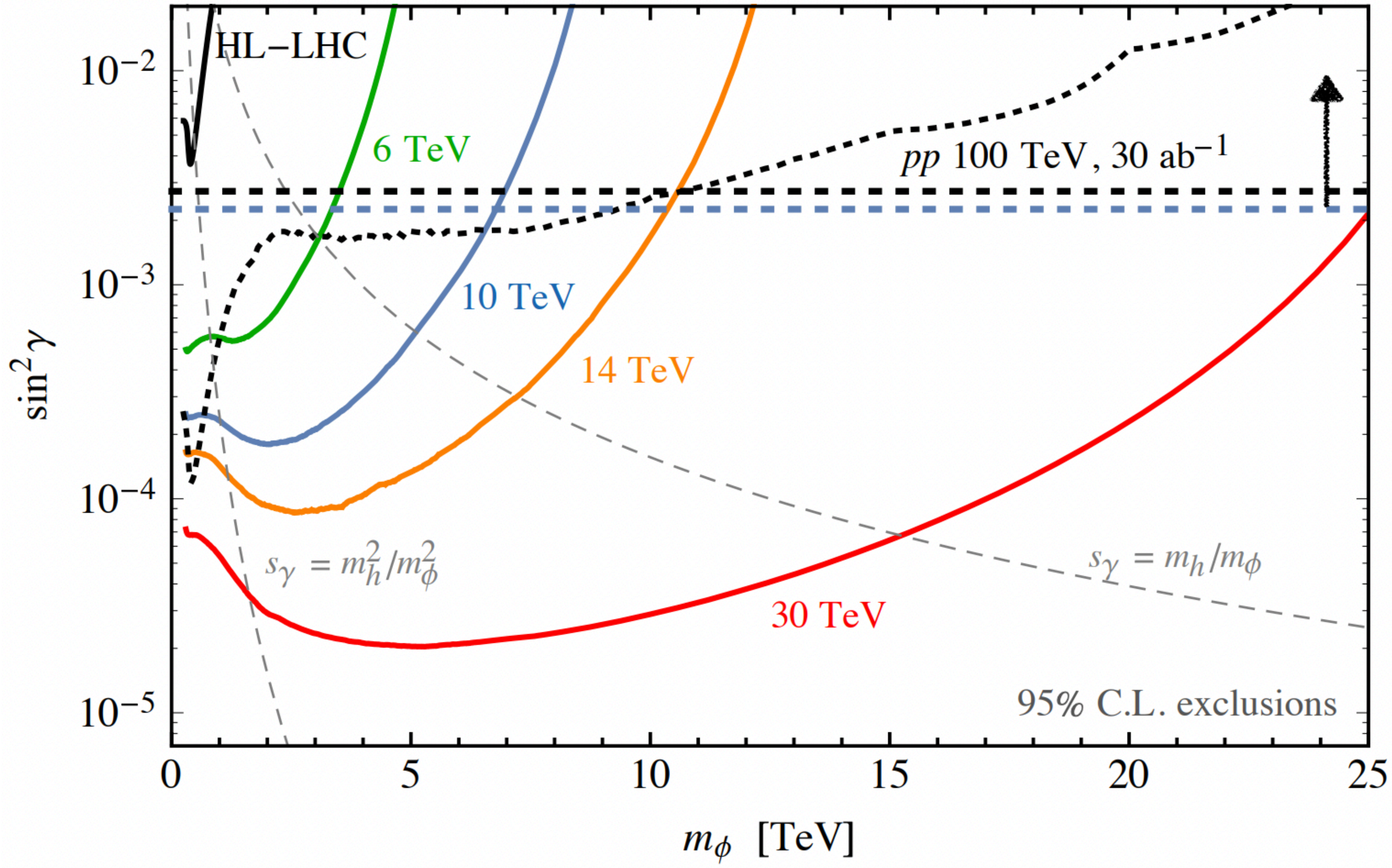




Buttazzo, Redigolo, Sala, Tesi 1807.04743

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 $\sqrt{\hat{s}}$
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?

Demonstrators & Beam Dumps

More processing means **fewer** muons

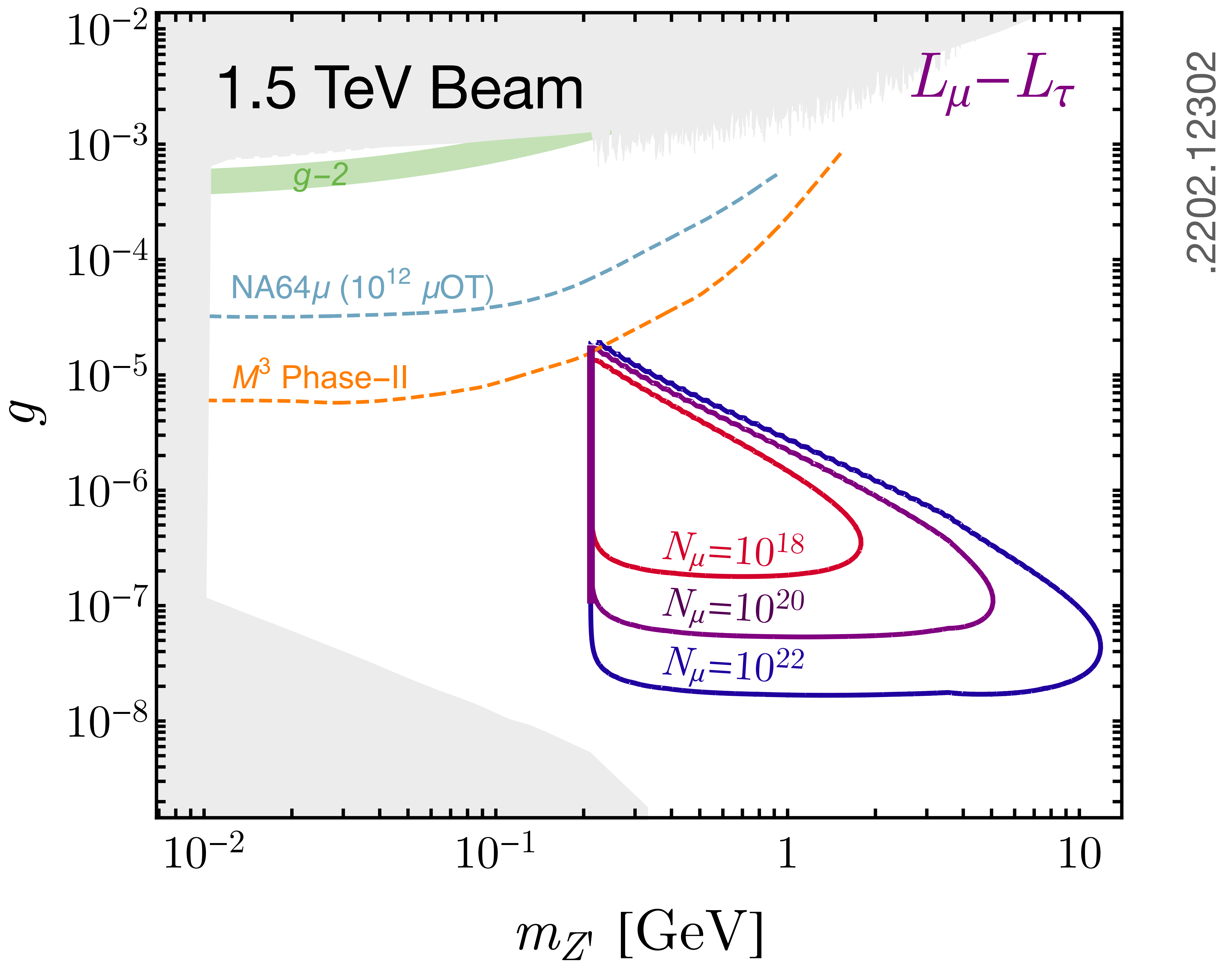
…but should run *synergistically*

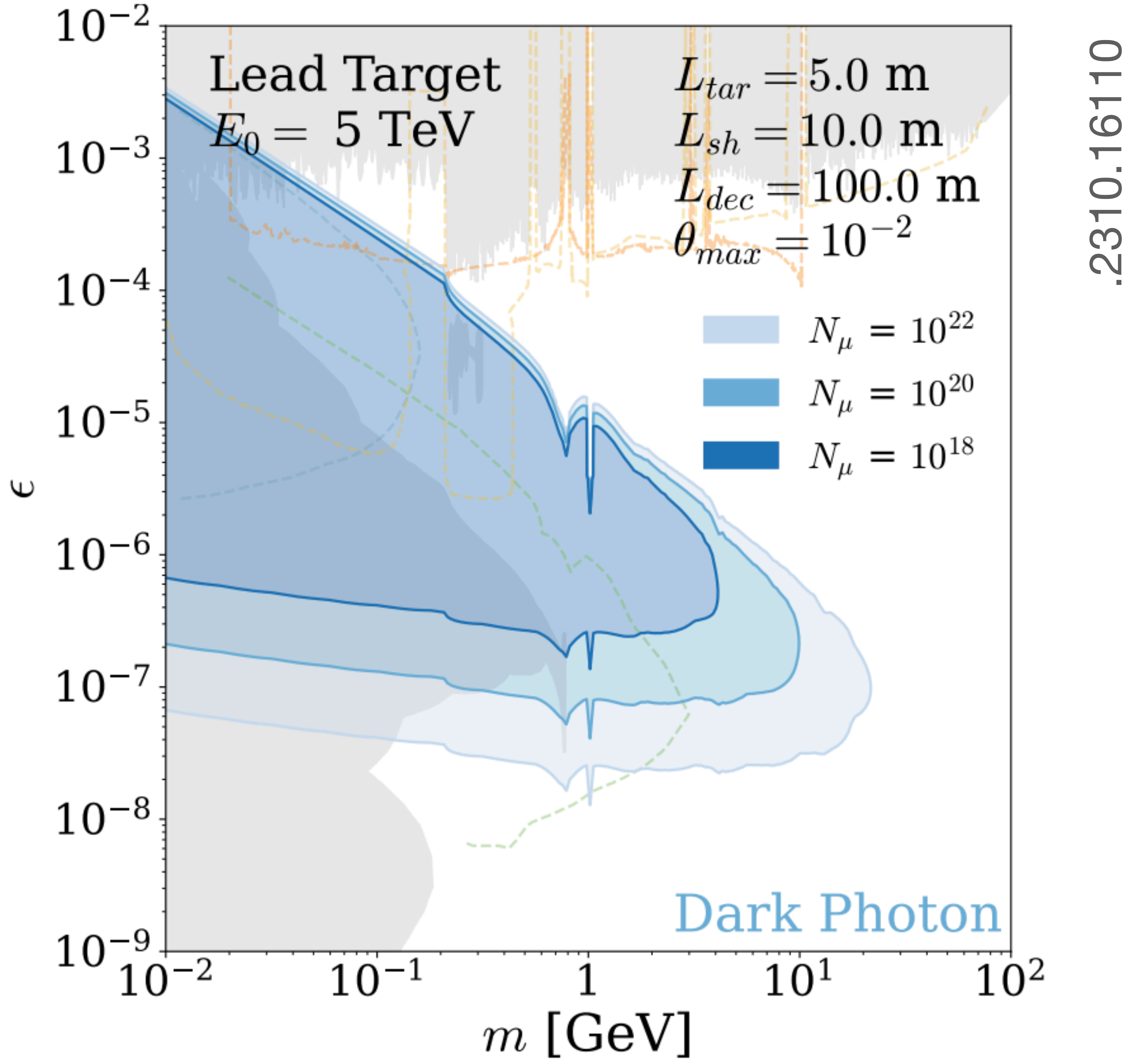
Muon Collider Beam Dump

2050ish

3, 10 TeV MuC

Dark Photon



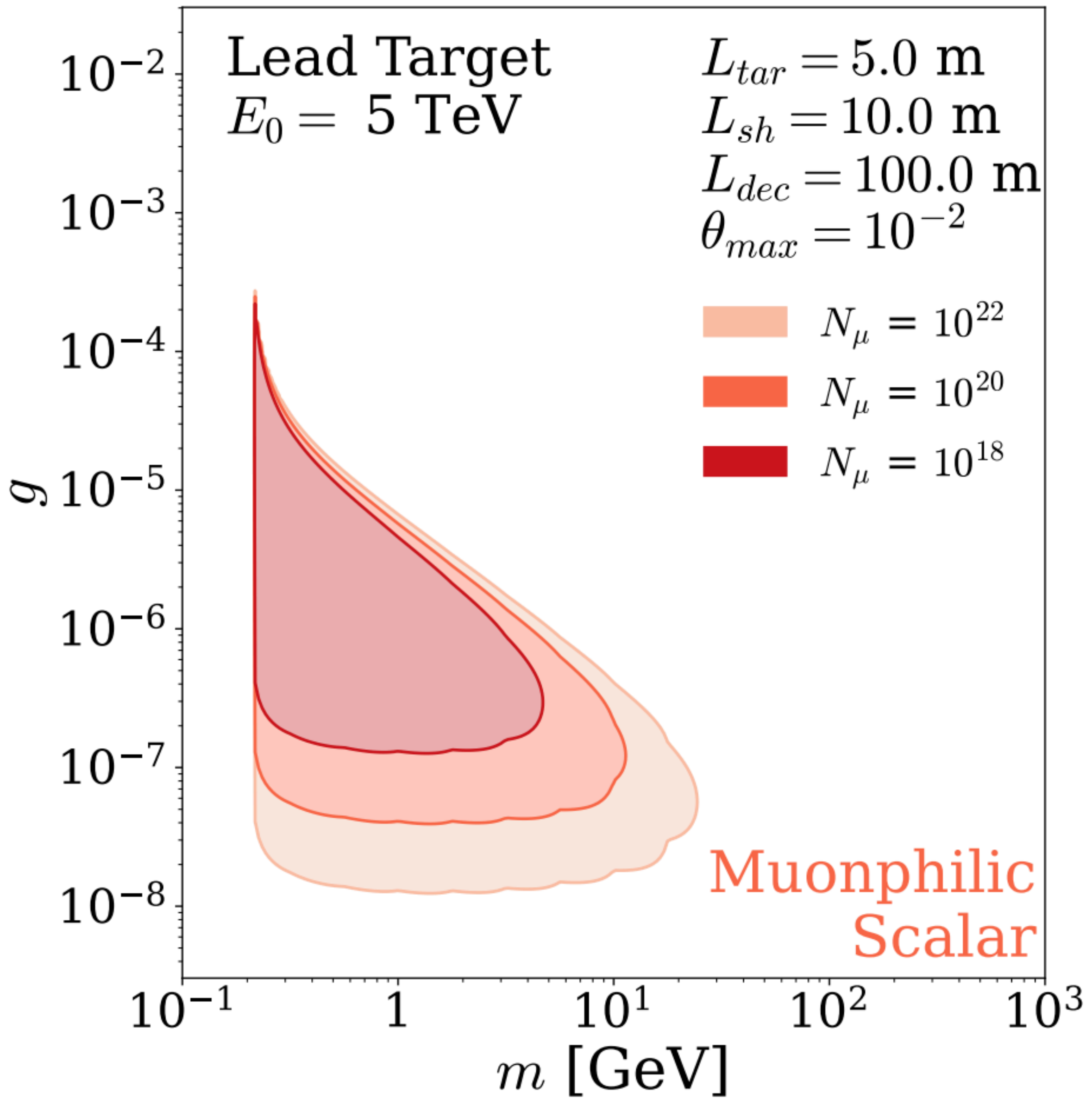


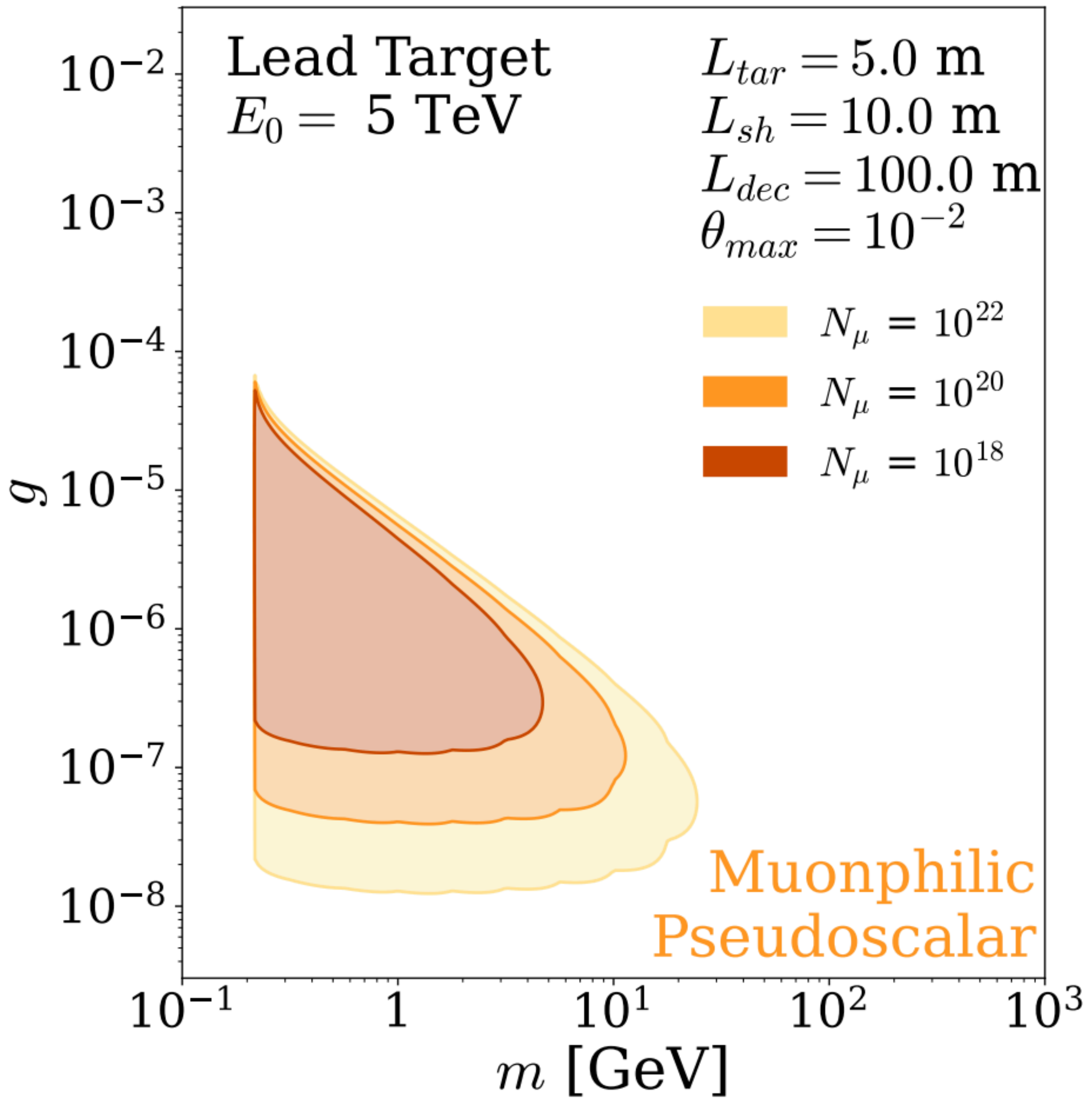
CC, Homiller, Mishra, Reece 2202.12302, **CC**, Gambhir 2310.16110

Muon Collider Beam Dump

2050ish

3, 10 TeV MuC





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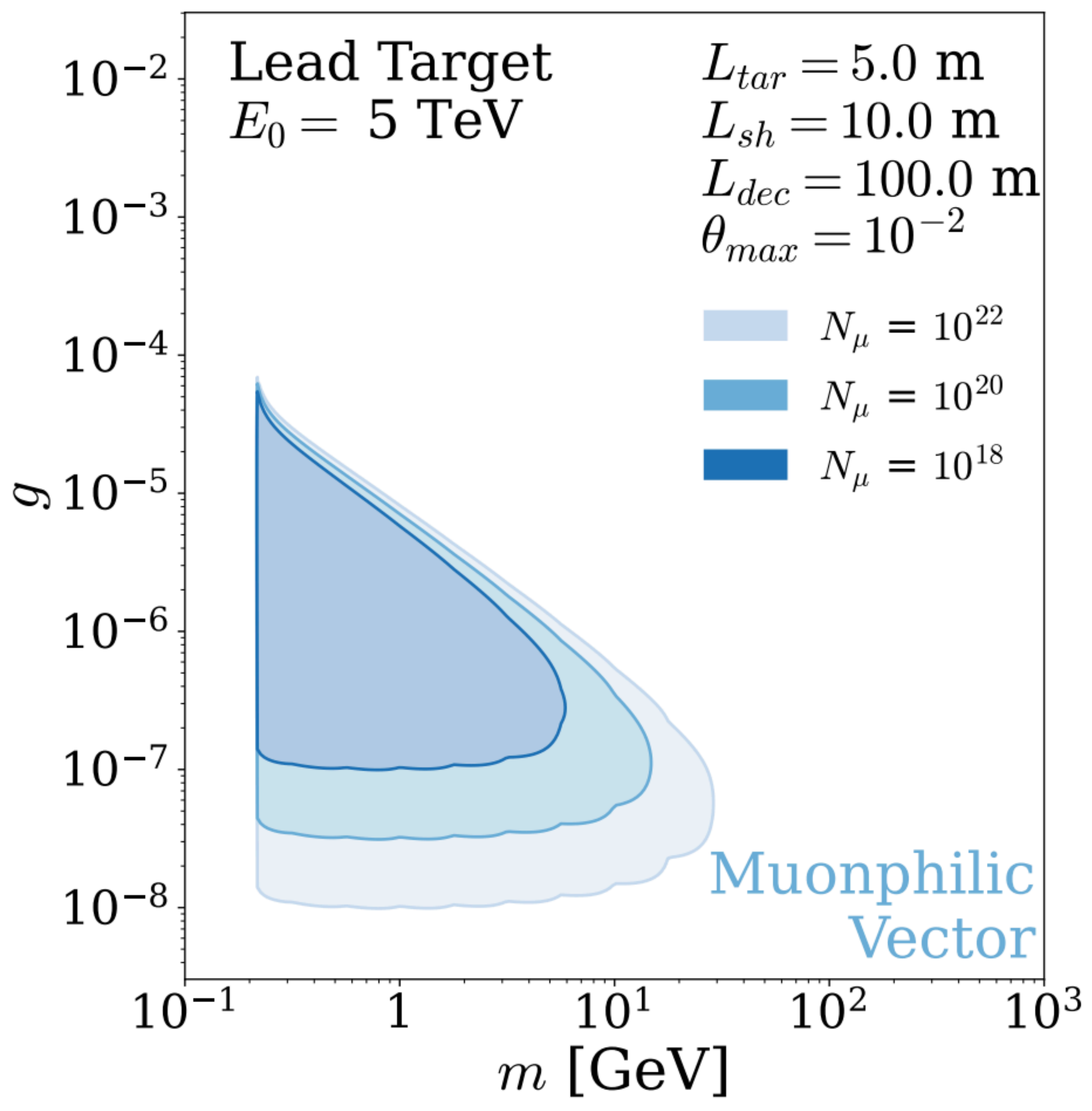
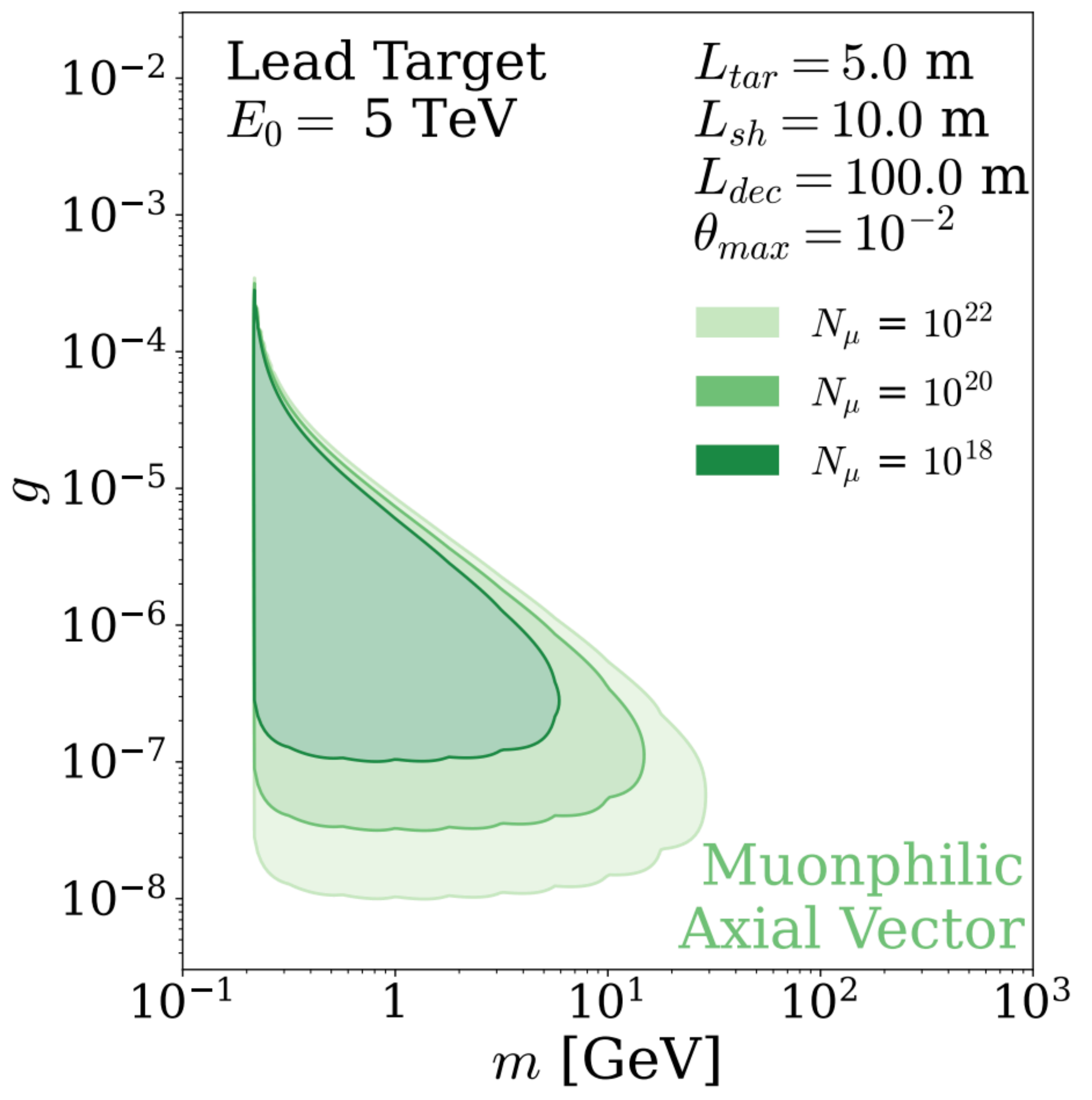
Muonphilic couplings





$$\mathcal{L}_{\text{int}} \supset \frac{1}{2}\partial_\mu \phi^2 - \frac{1}{2} m_\phi^2 \phi^2 + i g_\psi \mathcal{O}_{\bar{\psi}\psi\phi}$$

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Demonstrator Facility Beam Dump

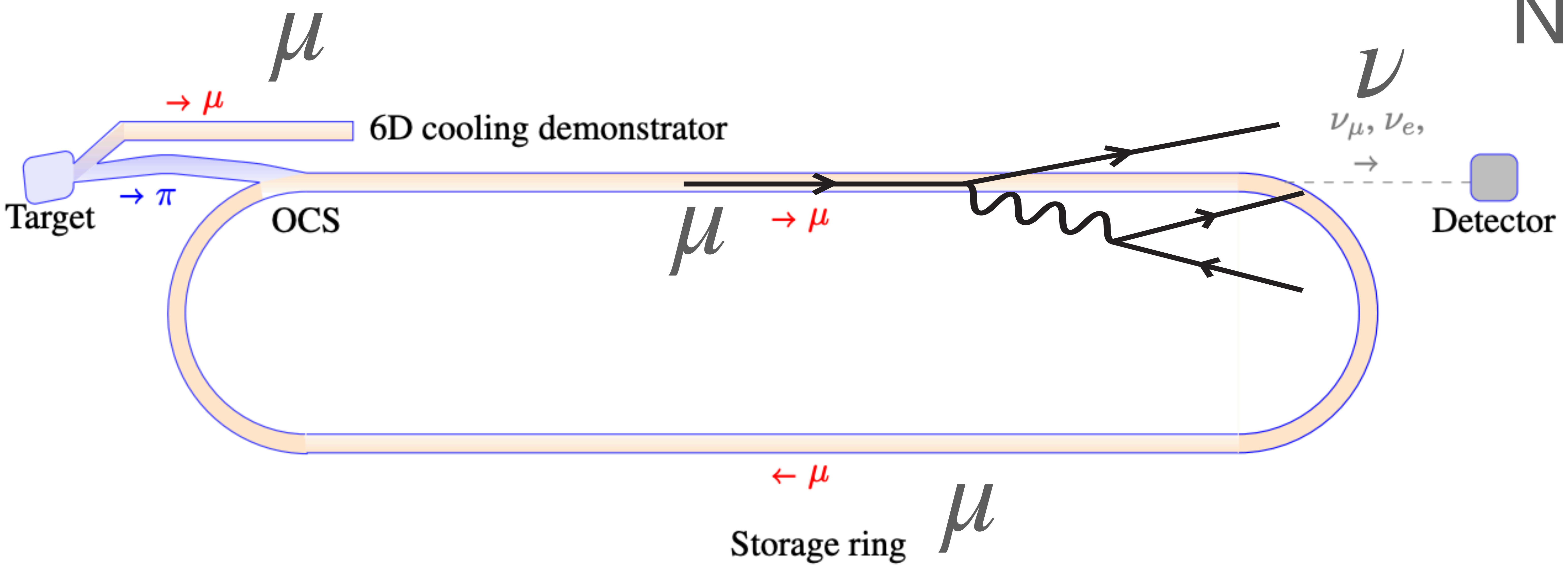
.2310.16110

Mild Acceleration: Cooling & Synergies

Higgs Threshold MuC

3, 10 TeV MuC

Motivation: Neutrino Facilities?



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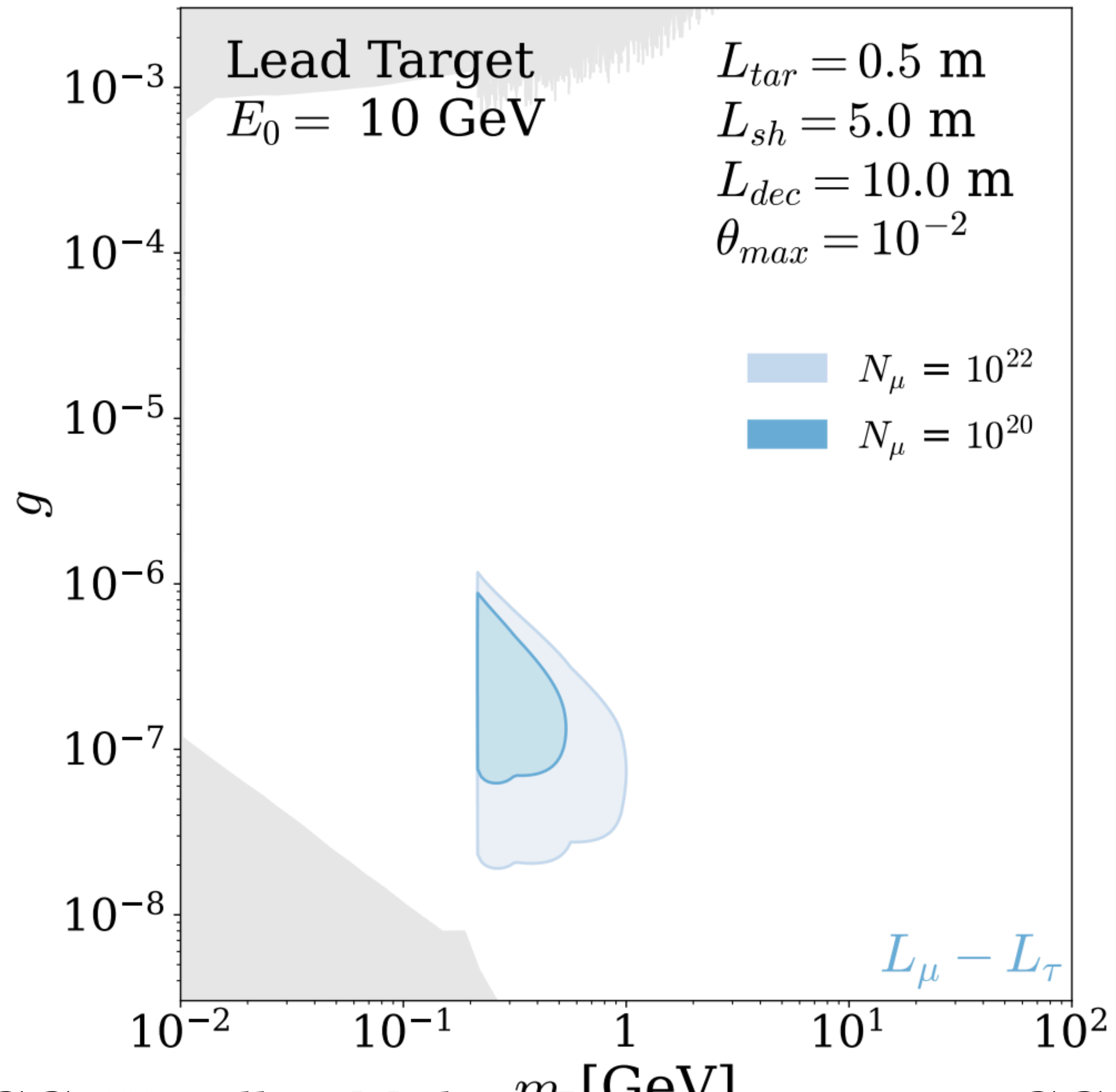
Demonstrator Facility Beam Dump

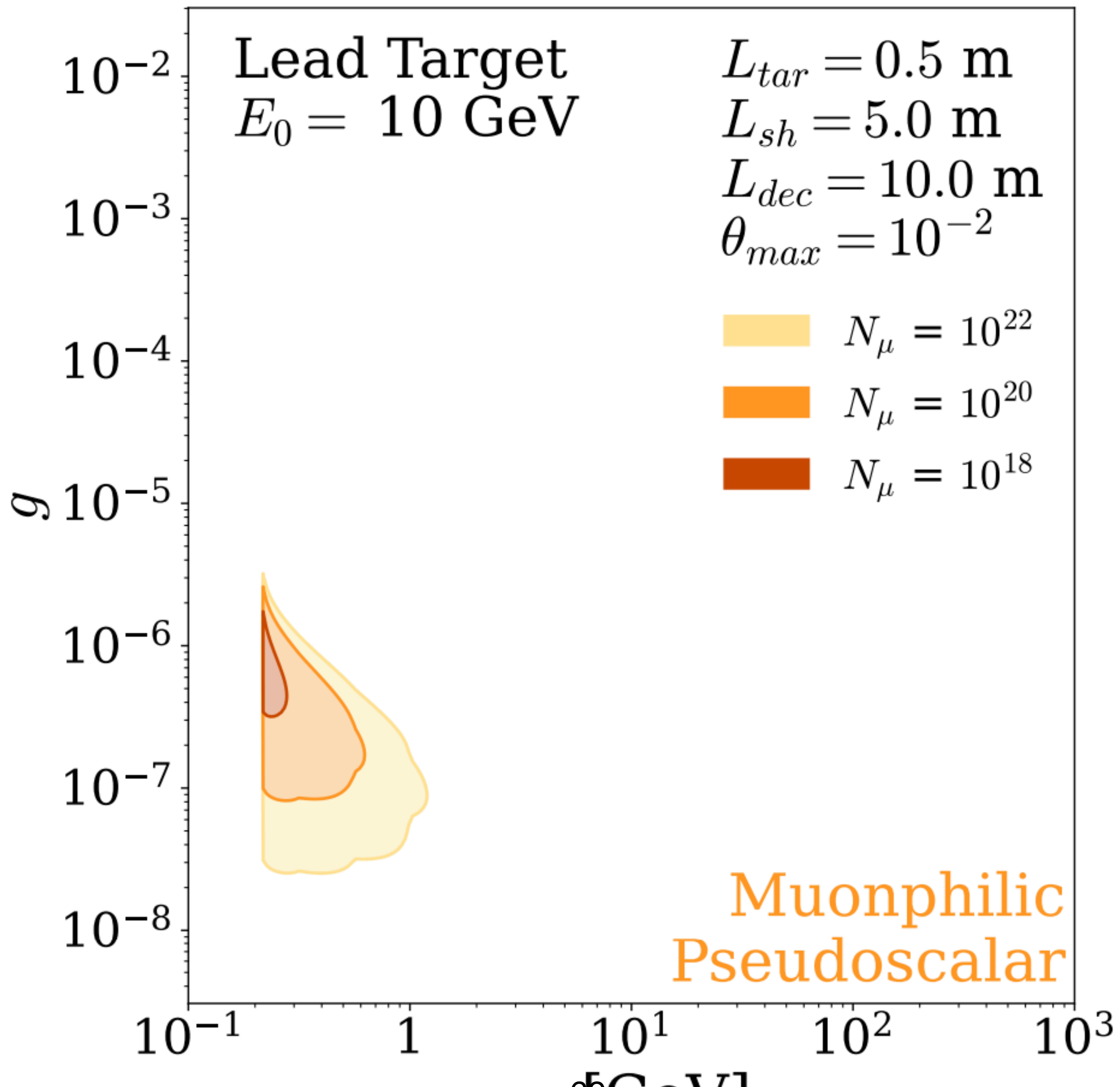
Late 2030s? | 2040ish | 2050ish

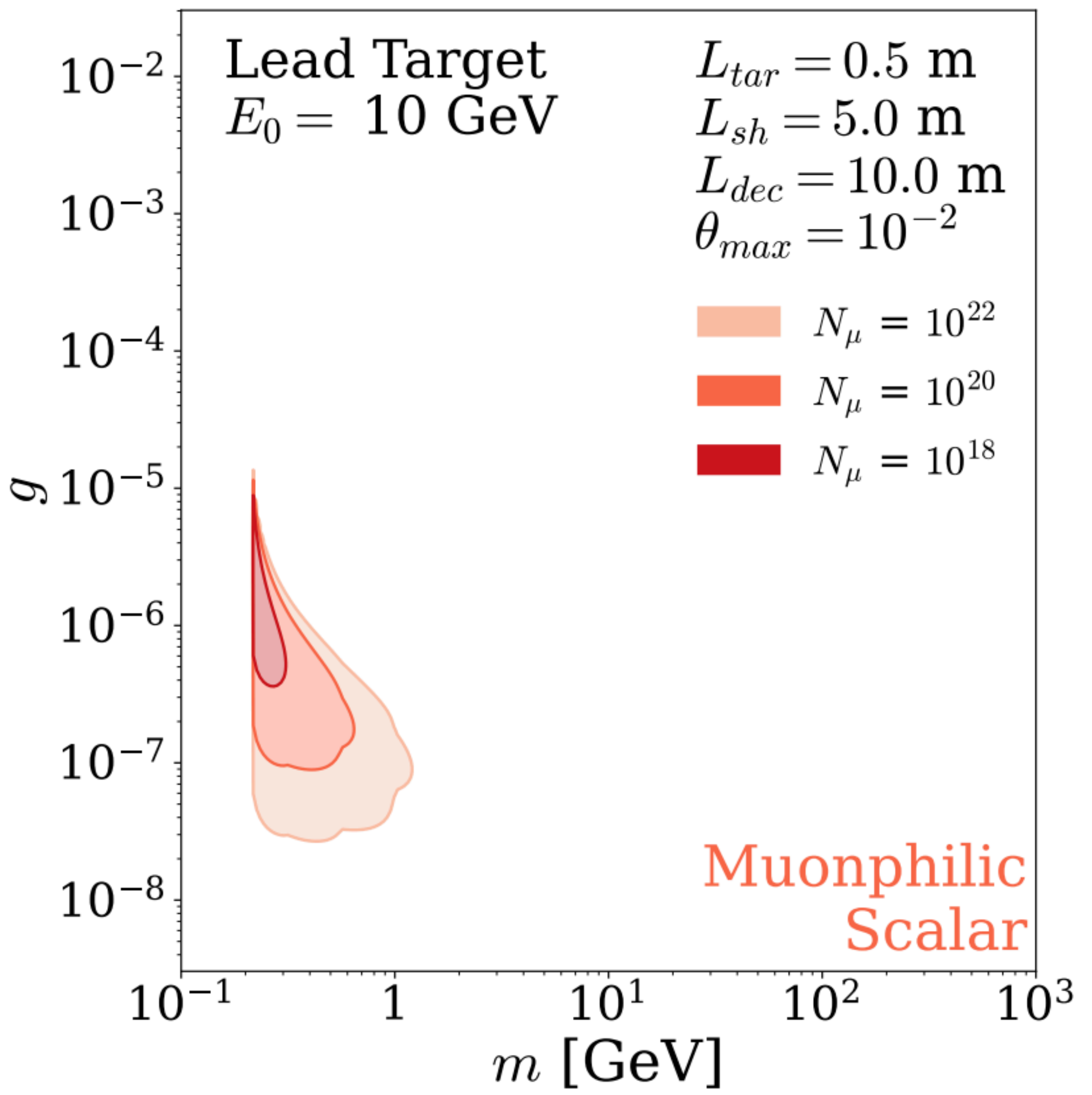
Mild Acceleration: Cooling & Synergies

Higgs Threshold MuC

3, 10 TeV MuC







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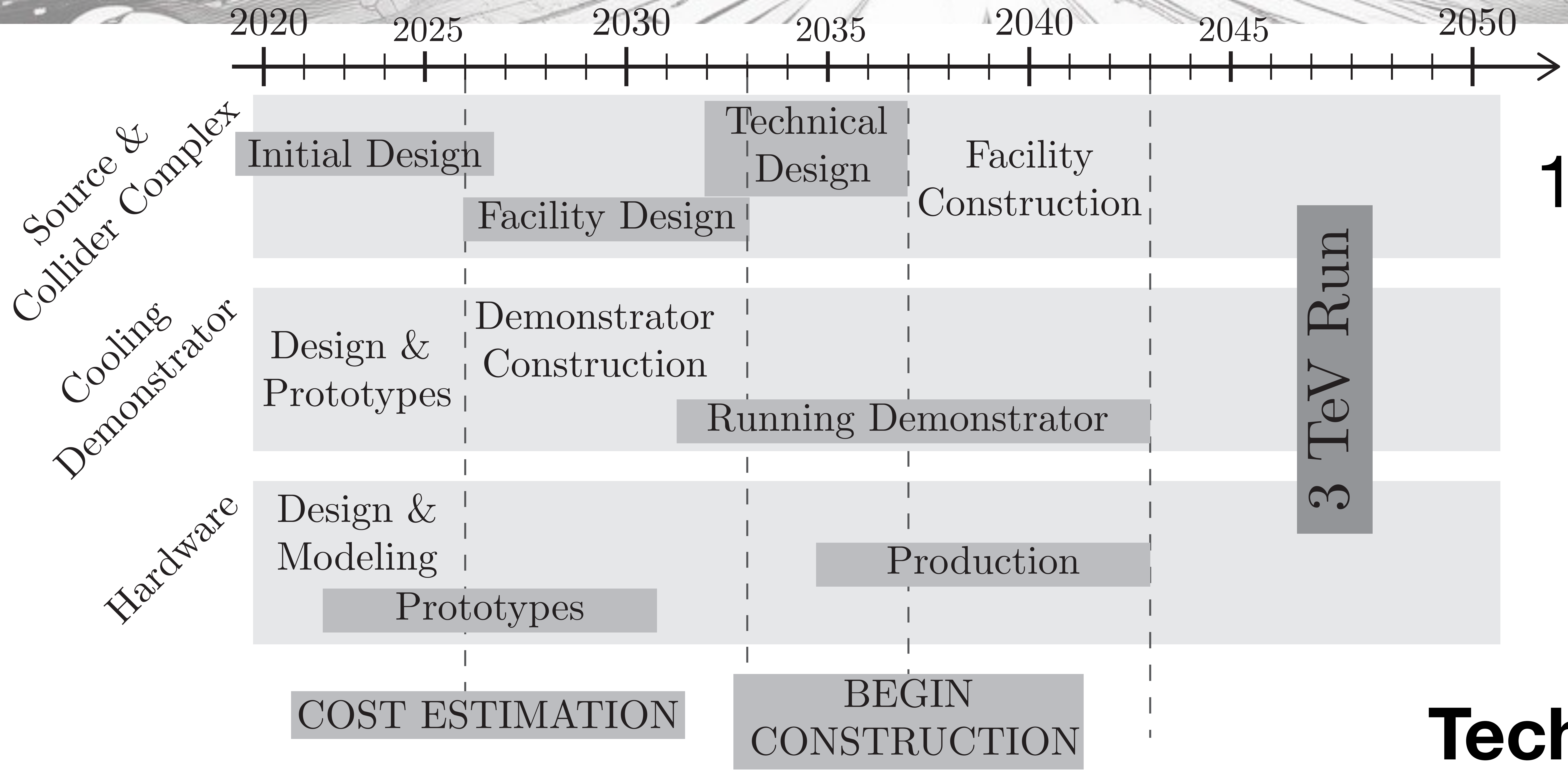
Muon Collider Timescales



2055:
10 TeV Run?

Technically Limited Timeline*

Future Collider Timescales