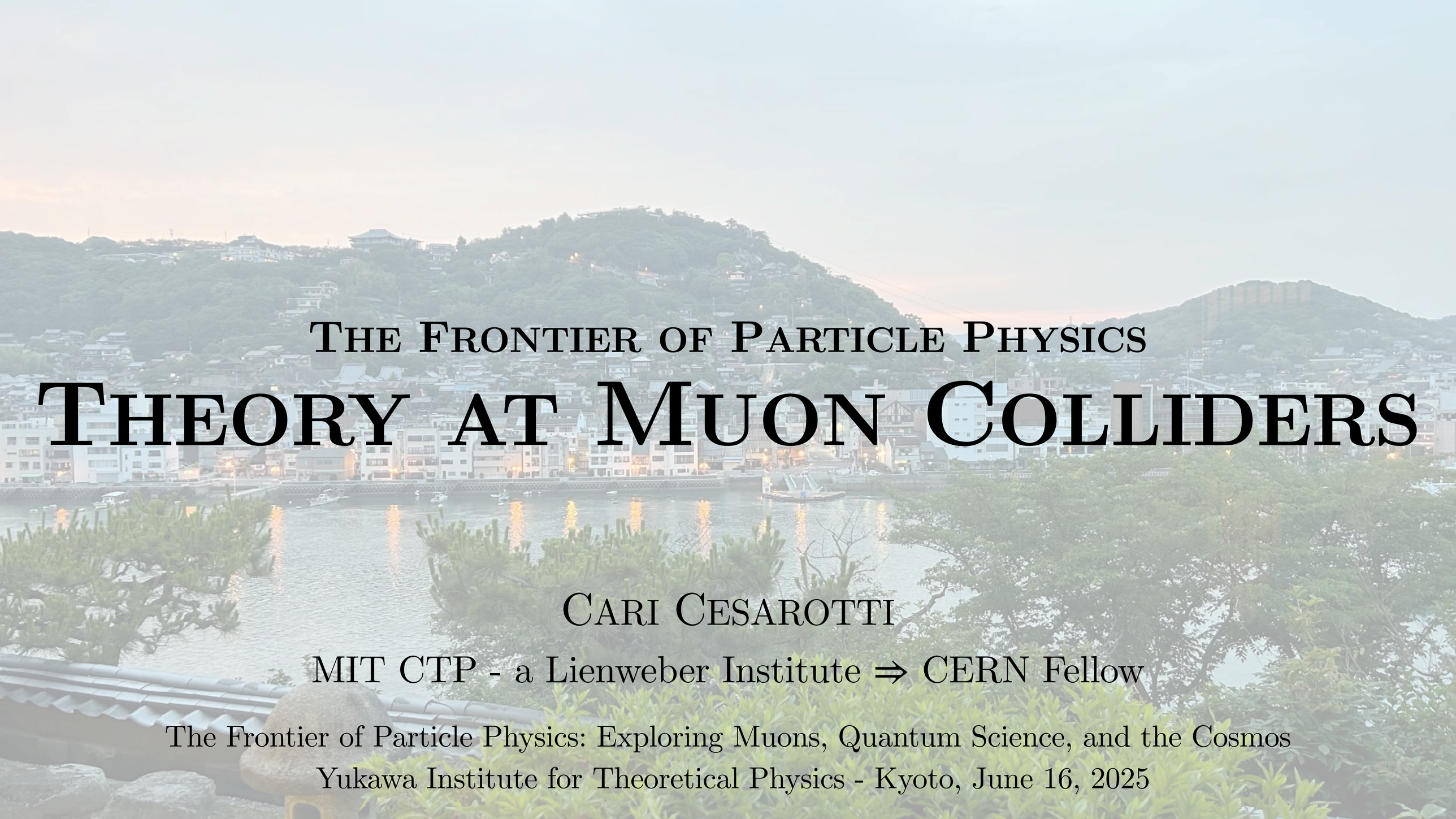


The Frontier of Particle Physics

Theory at Muon Colliders

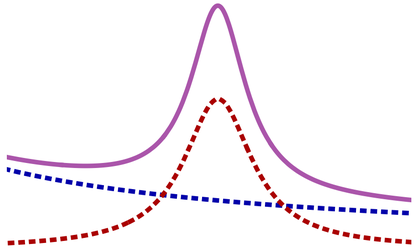
Cari Cesarotti

MIT CTP - a Lienweber Institute ⇒ CERN Fellow

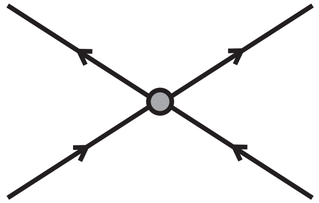
The Frontier of Particle Physics: Exploring Muons, Quantum Science, and the Cosmos

Yukawa Institute for Theoretical Physics - Kyoto, June 16, 2025

Outline



Why collide particles at all?



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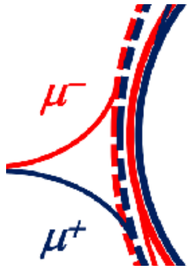
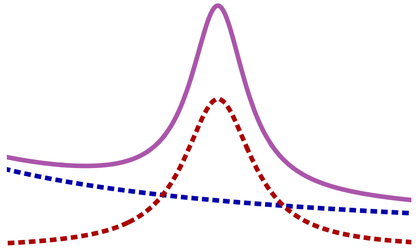


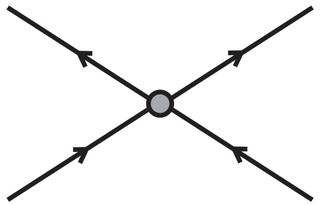
What needs R&D to collide muons?

Outline



Why collide particles at all?

High-energy environments uncover new phenomena



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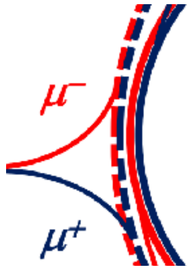
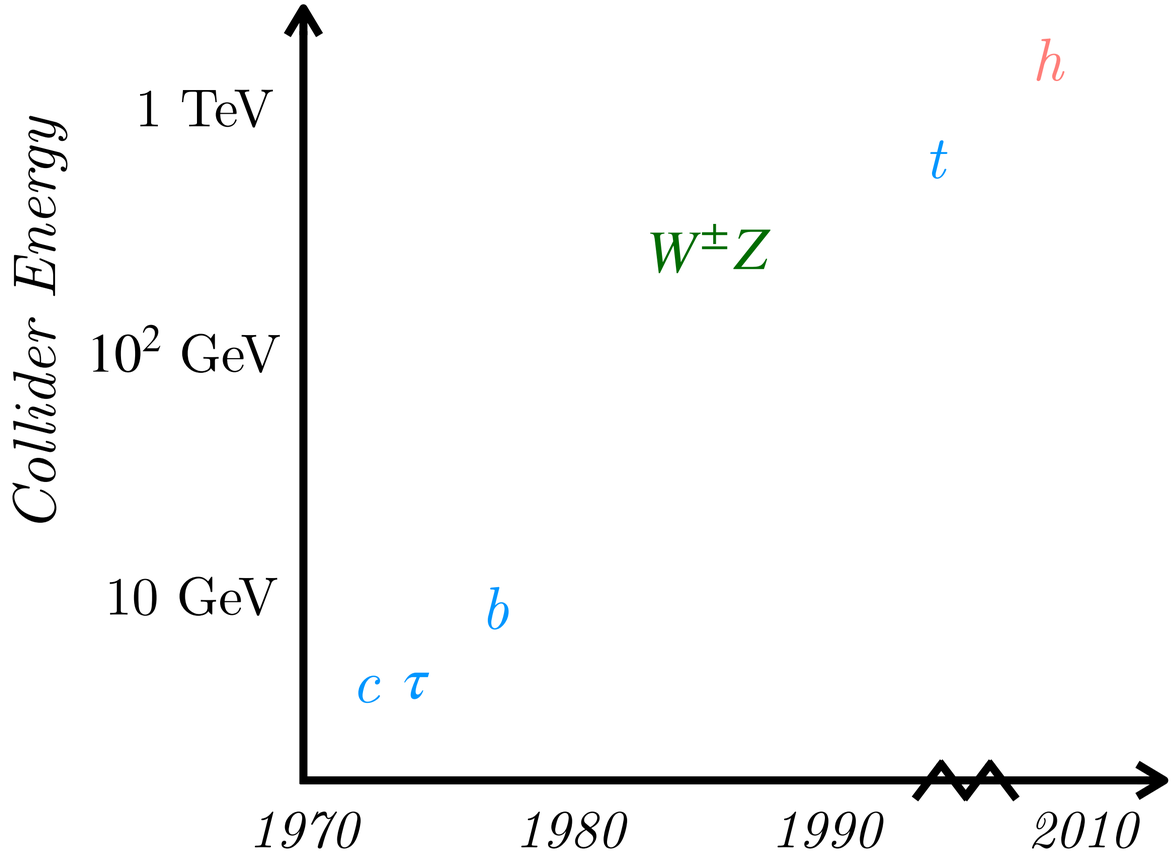


What needs R&D to collide muons?

Open Questions in Particle Physics

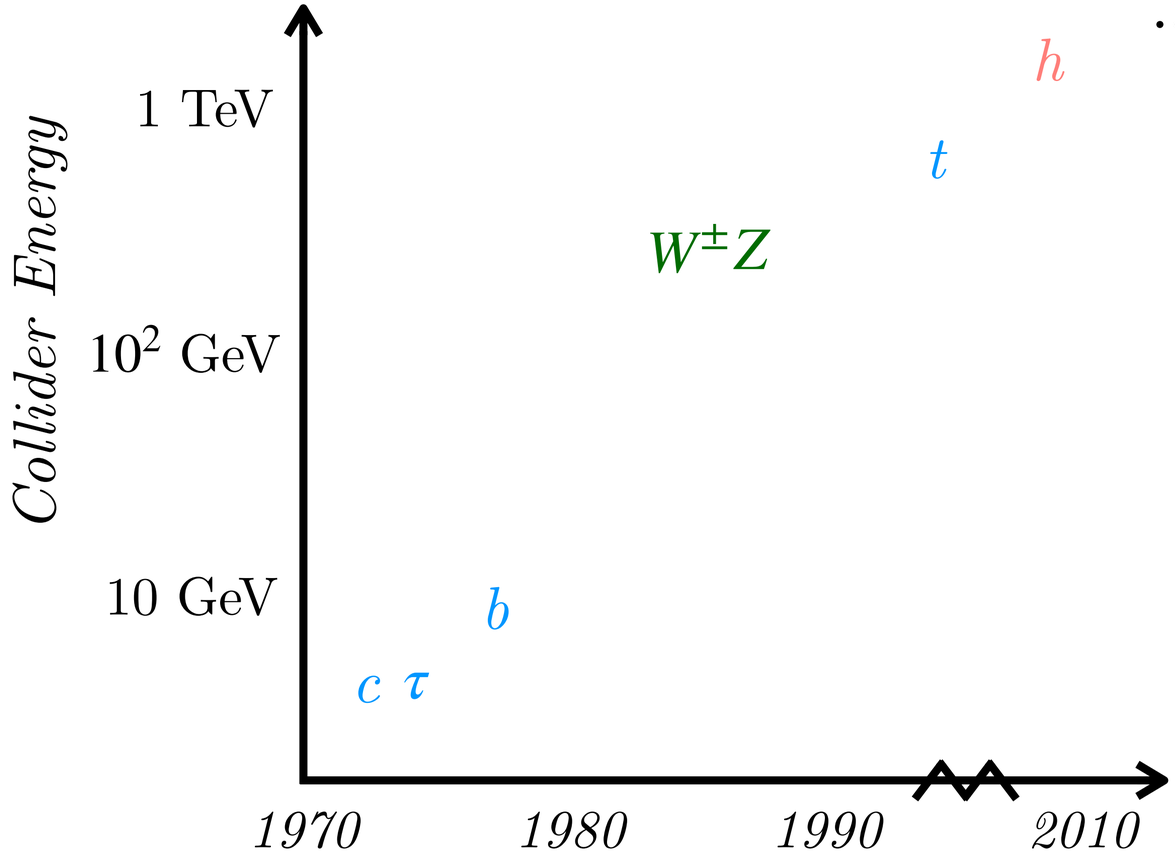
Higher energies at colliders have always revealed insights on fundamental degrees of freedom...

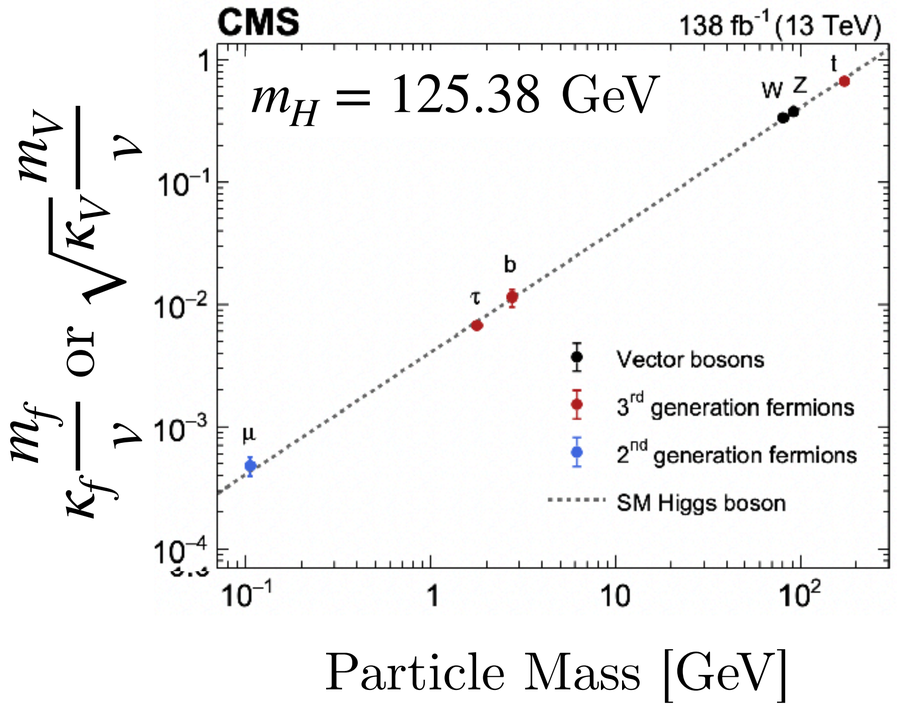


Open Questions in Particle Physics

Higher energies at colliders have always revealed insights on fundamental degrees of freedom...

...mostly confirming the Standard Model (SM)



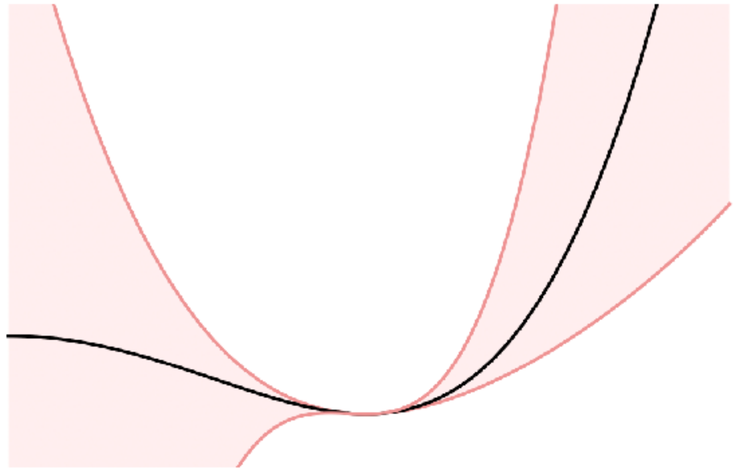


Open Questions in Particle Physics

Additionally, the SM is a *model* without principled explanations of high-energy behavior

Many open questions remain...

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



LHC

Open Questions in Particle Physics

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Many open questions remain...
...and even more exist *beyond* the SM (BSM)

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

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- ...
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- ...

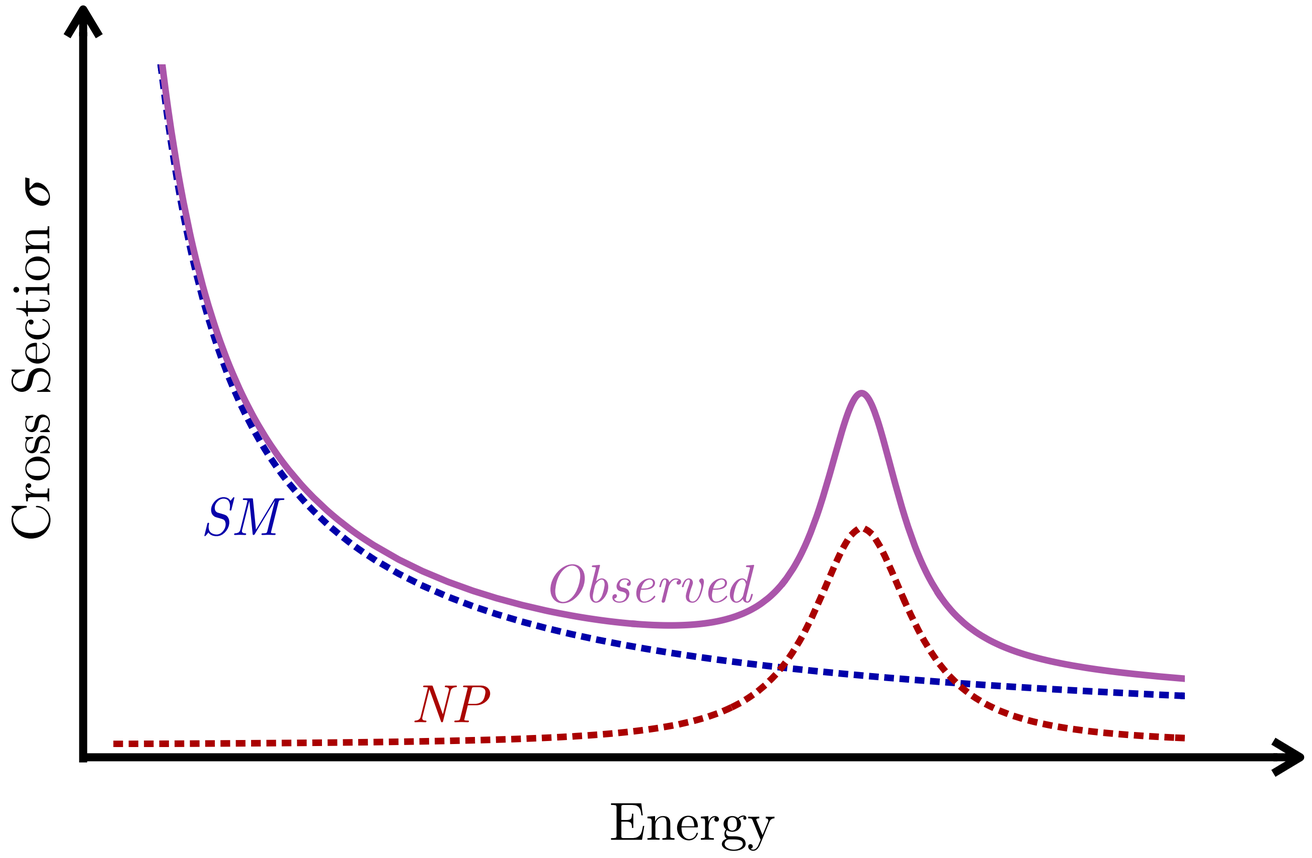
Unifying principle: *we need data at high energies*

Colliders are the best technology we have for this

Theory & Machines

Two avenues for progress:

Precision or *Discovery* machines



Theory & Machines

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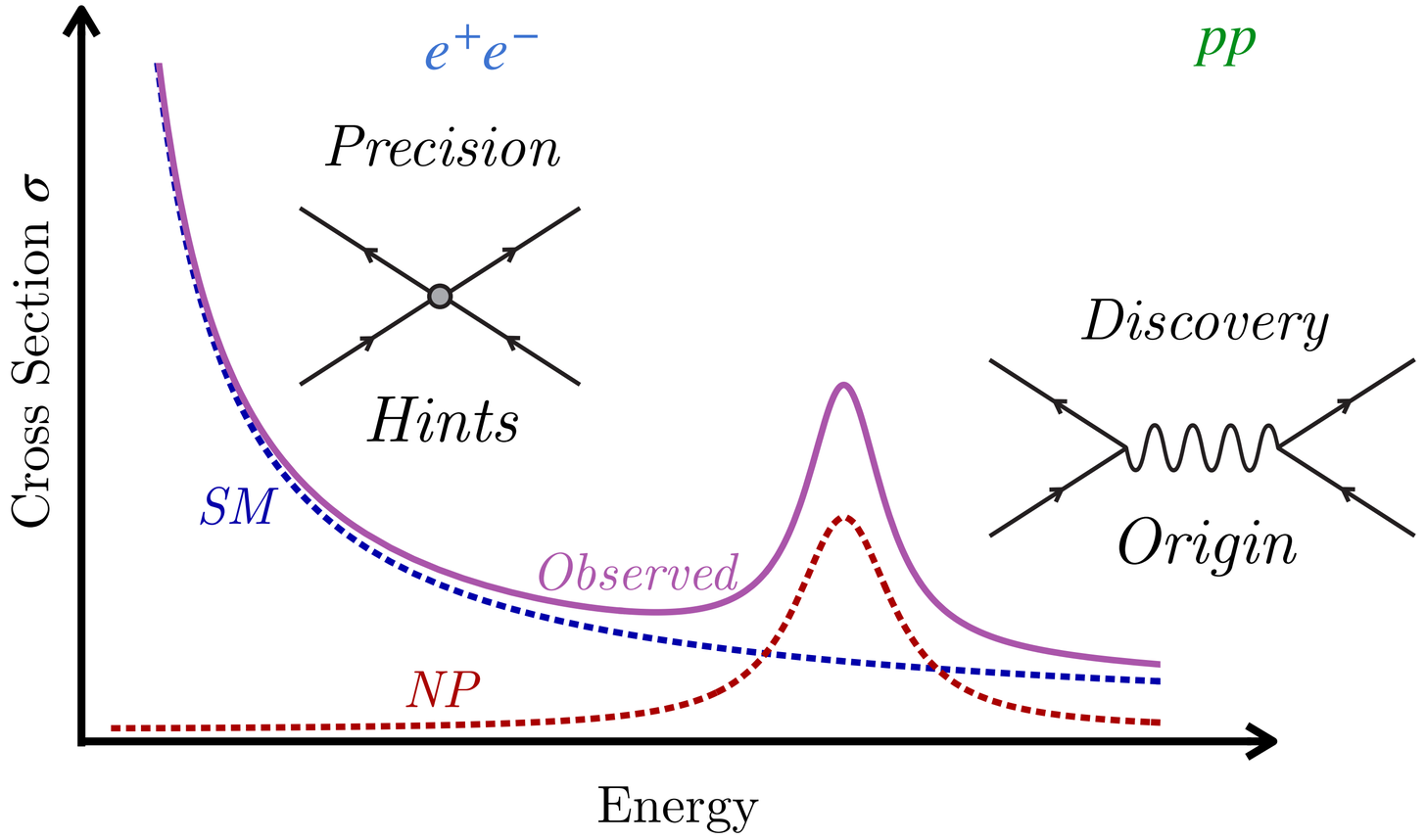

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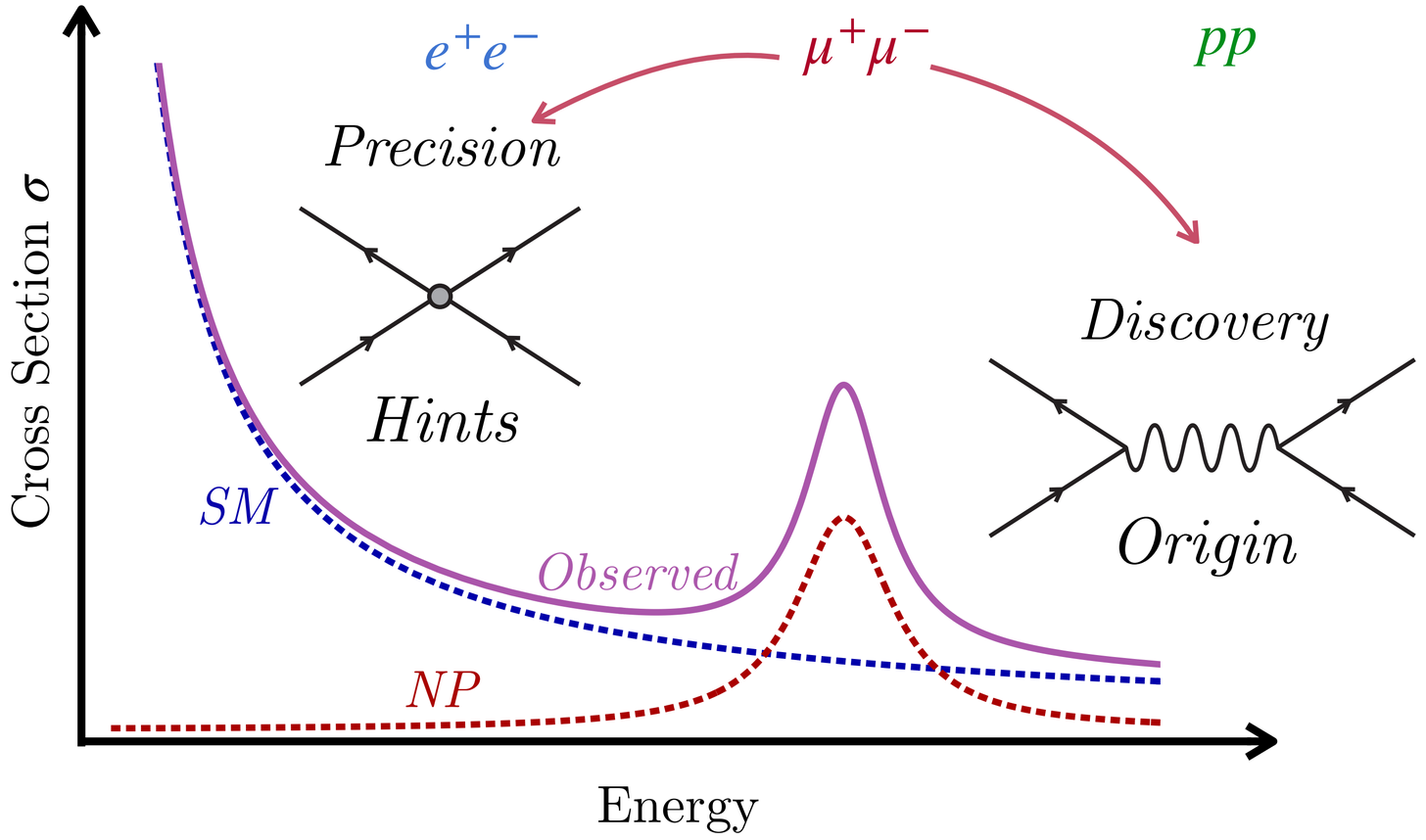

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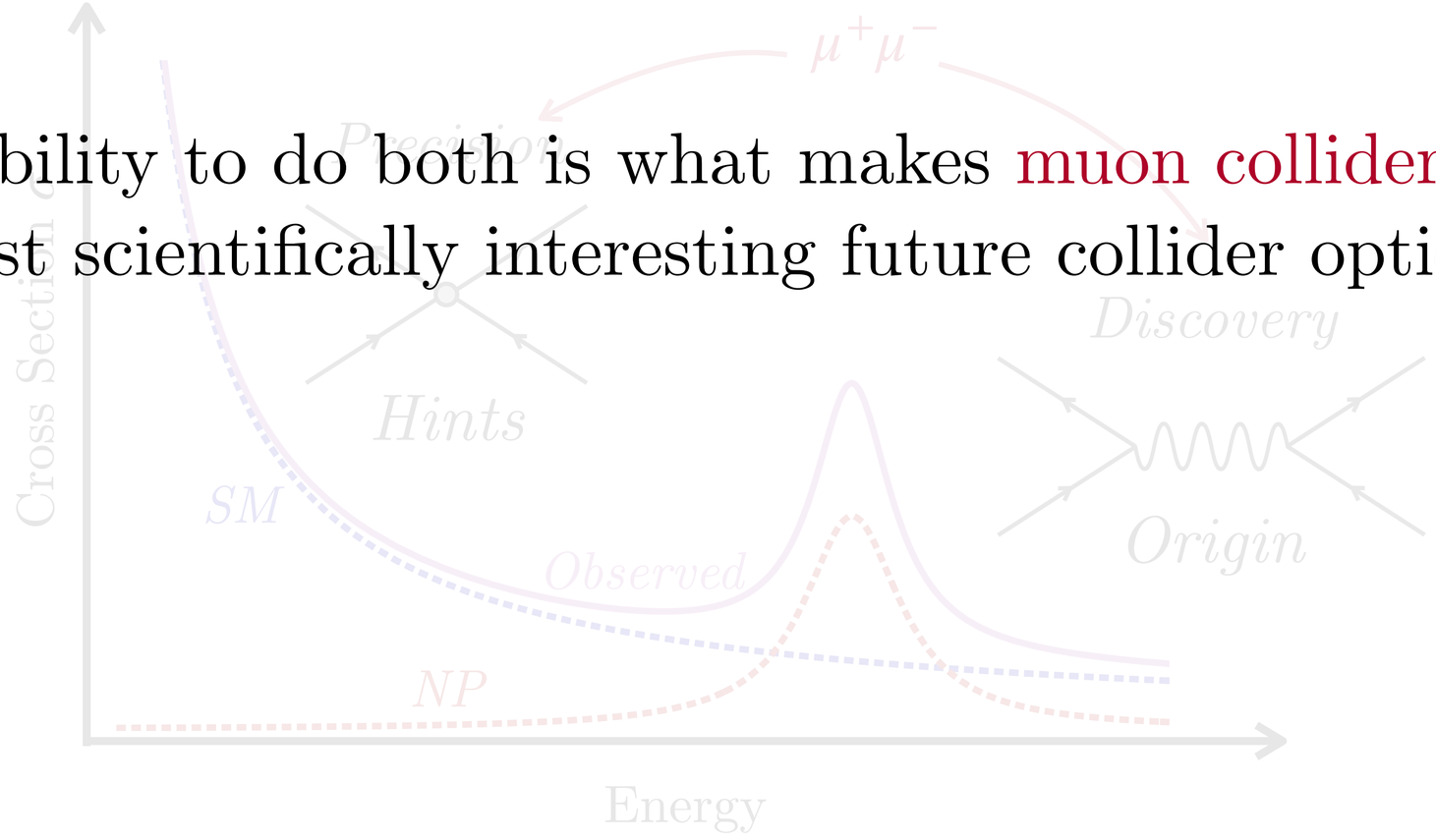
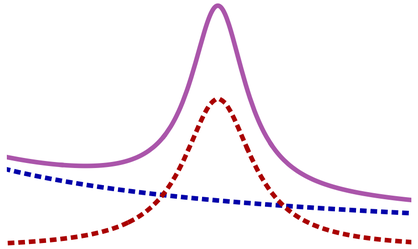


The ability to do both is what makes muon colliders the most scientifically interesting future collider option

Outline



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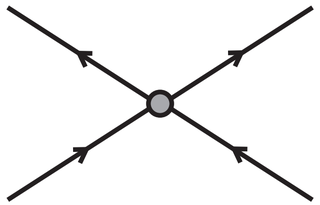
High-energy environments uncover new phenomena



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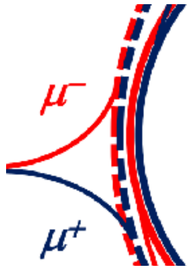

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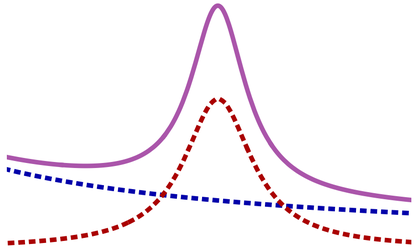

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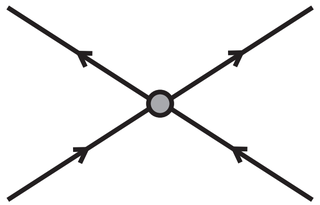
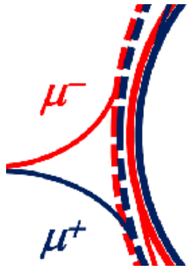


Why collide muons?

Reach higher energies and flavor-dependent couplings



What needs R&D to collide muons?

Comparison of Future Colliders

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

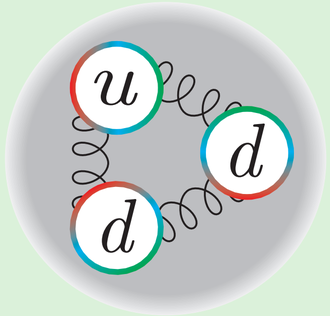
Circular | *Linear*

Comparison of Future Colliders

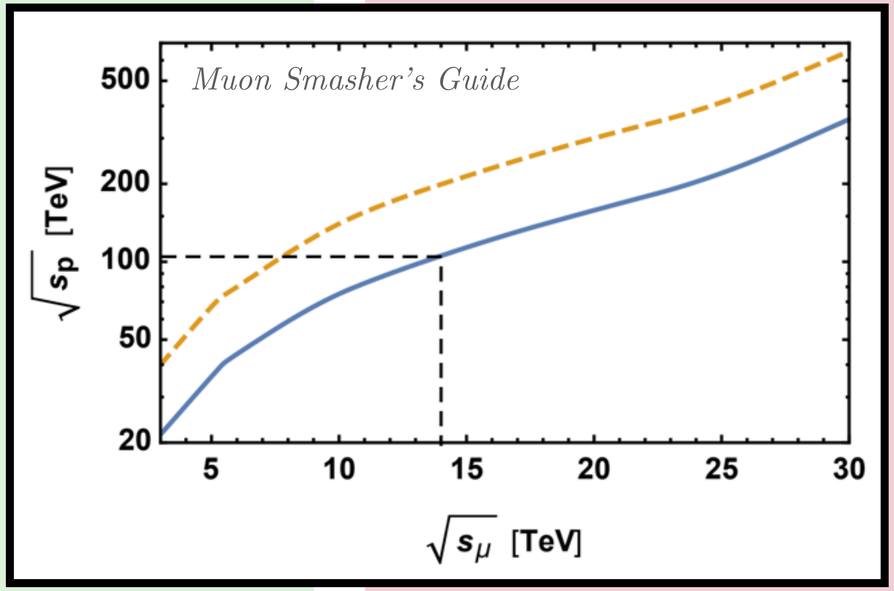
pp | $\mu^+\mu^-$ | e^+e^- *Circular* | e^+e^- *Linear*

Composite

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

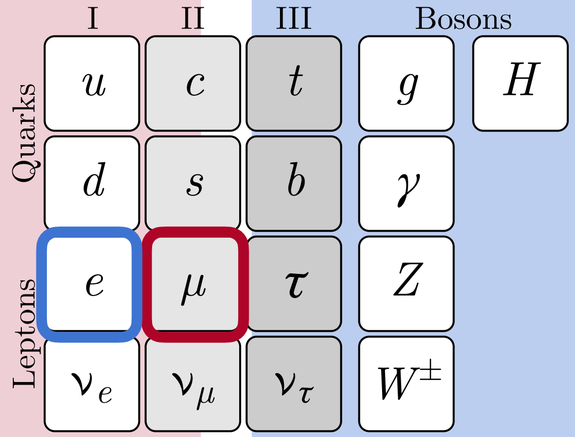


Muon Smasher's Guide '19



Fundamental

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



Comparison of Future Colliders

pp	$\mu^+\mu^-$	e^+e^-	
		Circular	*Linear*
$\mathcal{O}(100)$ TeV	$\mathcal{O}(1-10)$ TeV	$\mathcal{O}(300)$ GeV	$\lesssim 3$ TeV

Synchrotron Radiation

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

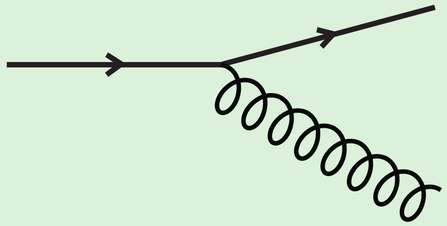
$$P_\mu / P_e \sim 10^{-9}$$

Comparison of Future Colliders

pp

$\mathcal{O}(100)$ TeV

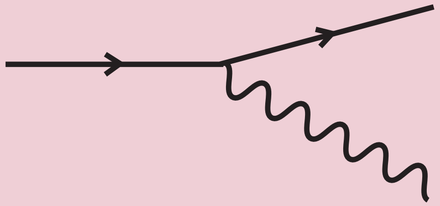
QCD



$\mu^+\mu^-$

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

Electroweak



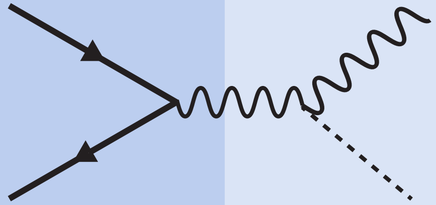
e^+e^-

Circular *Linear*

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs

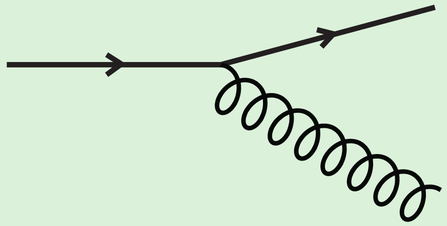


Comparison of Future Colliders

pp

$\mathcal{O}(100)$ TeV

QCD

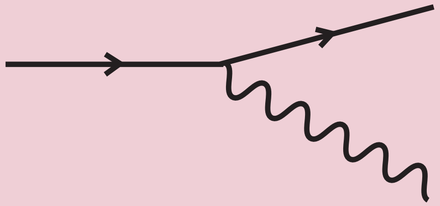


Pro
High energy, known

$\mu^+\mu^-$

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

Electroweak



Pro
High energy & precision

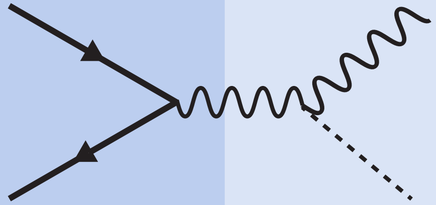
e^+e^-

Circular *Linear*

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs



Pro
Precision, known, upgrades

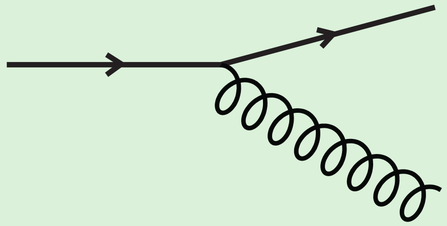
CC ∈ Accettura et al, Towards a Muon Collider '23 · CC ∈ IMCC, Interim Report '24

Comparison of Future Colliders

pp

$\mathcal{O}(100)$ TeV

QCD



Pro

High energy, known

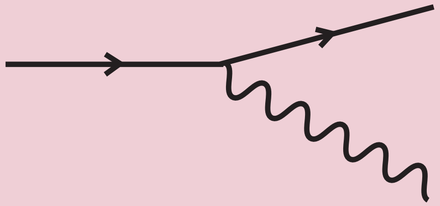
Con

Far future, new technology

$\mu^+\mu^-$

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

Electroweak



Pro

High energy & precision

Con

Undemonstrated technology

(Muons decay, muon cooling)

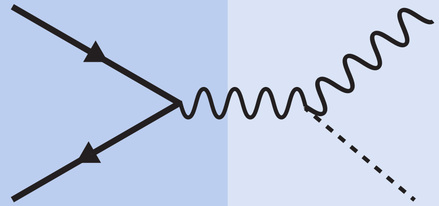
e^+e^-

Circular *Linear*

$\mathcal{O}(300)$ GeV

$\lesssim 3$ TeV

Precision Higgs



Pro

Precision, known, upgrades

Con

Low Energy, *Funding Uncertain*

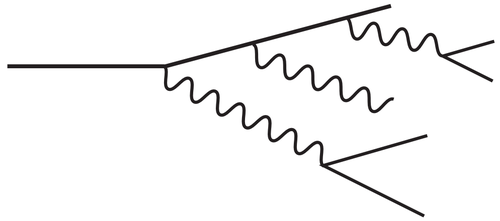
Max 3 TeV

Physics Program at MuC

SM Deliverables: questions *we know need answers*

Higgs

Electroweak @ High Energy



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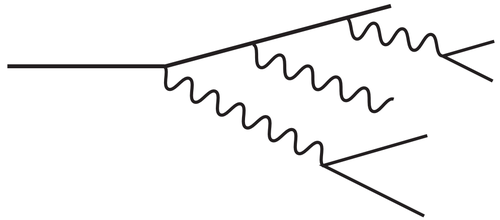
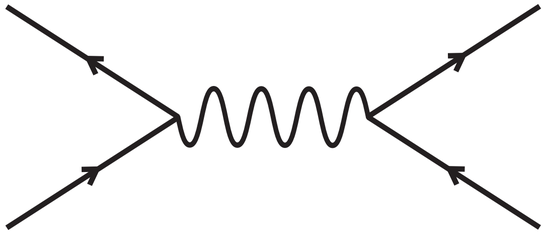
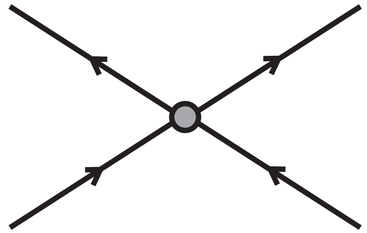


BSM Exploration: questions that *necessitate empirical input*

Direct



Indirect



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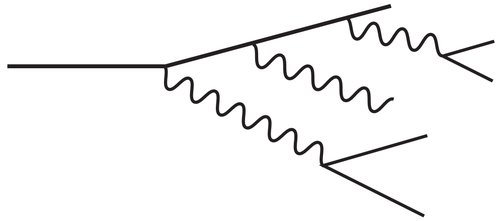


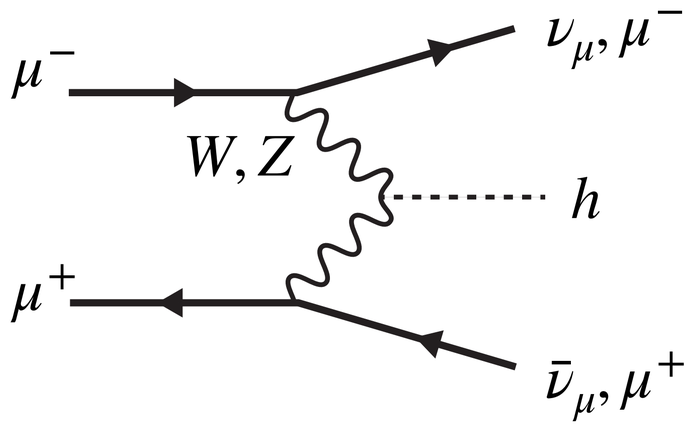
BSM Exploration: questions that *necessitate empirical input*

Direct

Indirect

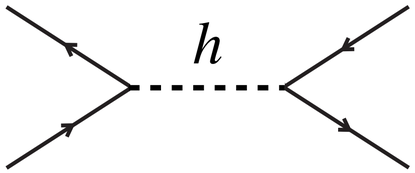
Higgs Physics at MuC

Vector Boson Fusion (VBF) production scales with log of energy



Threshold (s-channel) too small

$$\sqrt{s} = m_h$$

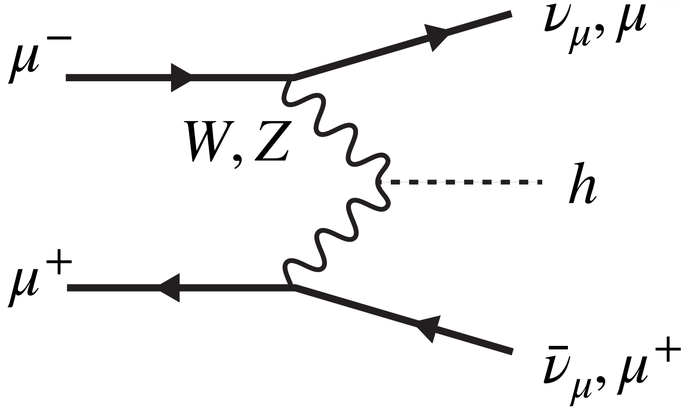


$$\sim \left(\frac{m_\mu}{v}\right)^2$$

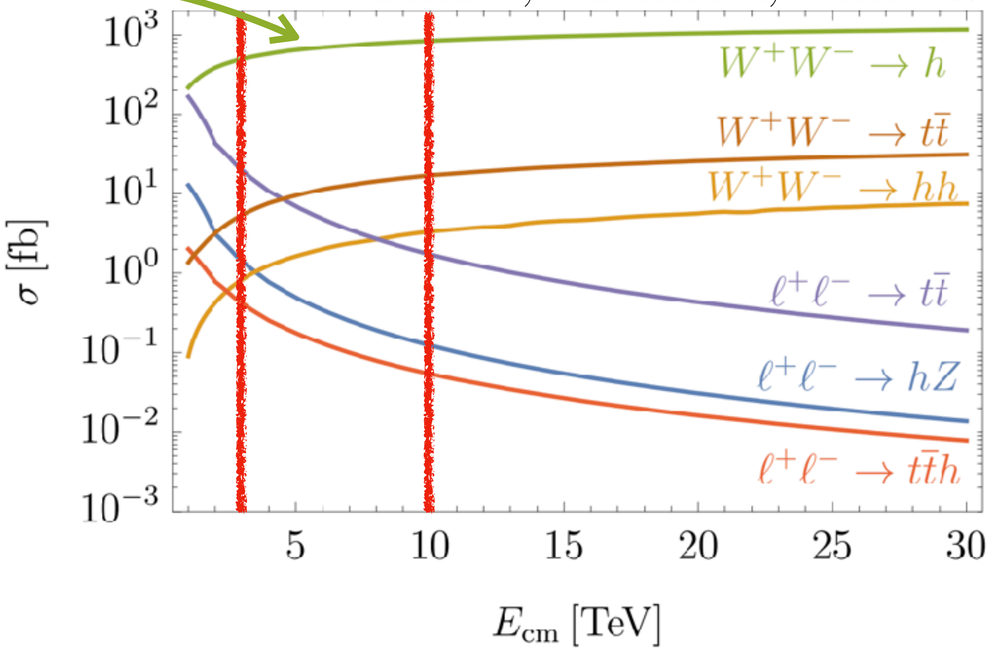
Higgs Physics at MuC

Vector Boson Fusion (VBF) production scales with log of energy

MuC at 10 TeV *is* a Higgs Factory ($\mathcal{O}(10^7)$ h produced)



Buttazzo, Franceschini, Wulzer '20



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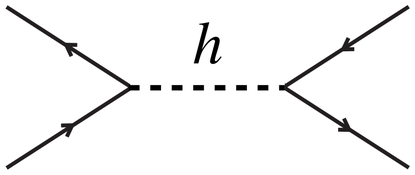
$\sqrt{s} = m_h$  $\sim \left(\frac{m_\mu}{v}\right)^2$

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

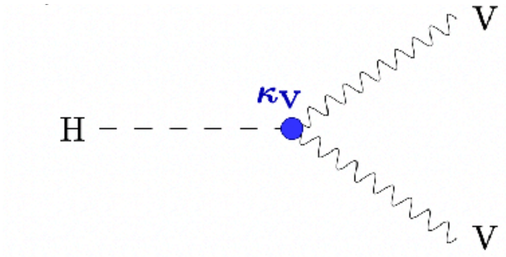
Higgs Physics at MuC

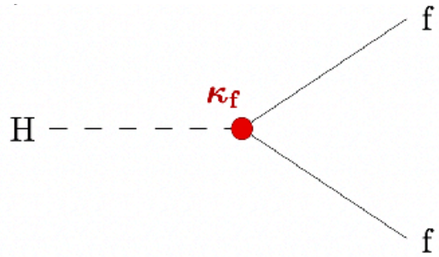
With a Higgs Factory, we can improve measurements on couplings

...and test for deviations → signatures of new dynamics

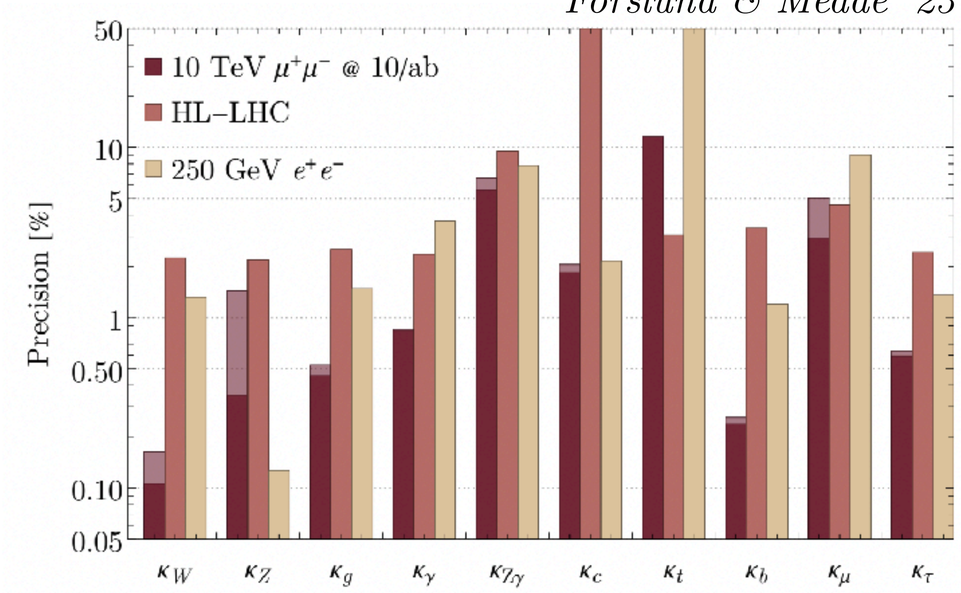
κ Framework

$$\kappa_X \sim \frac{\mathcal{O}_X^{obs}}{\mathcal{O}_X^{SM}}$$

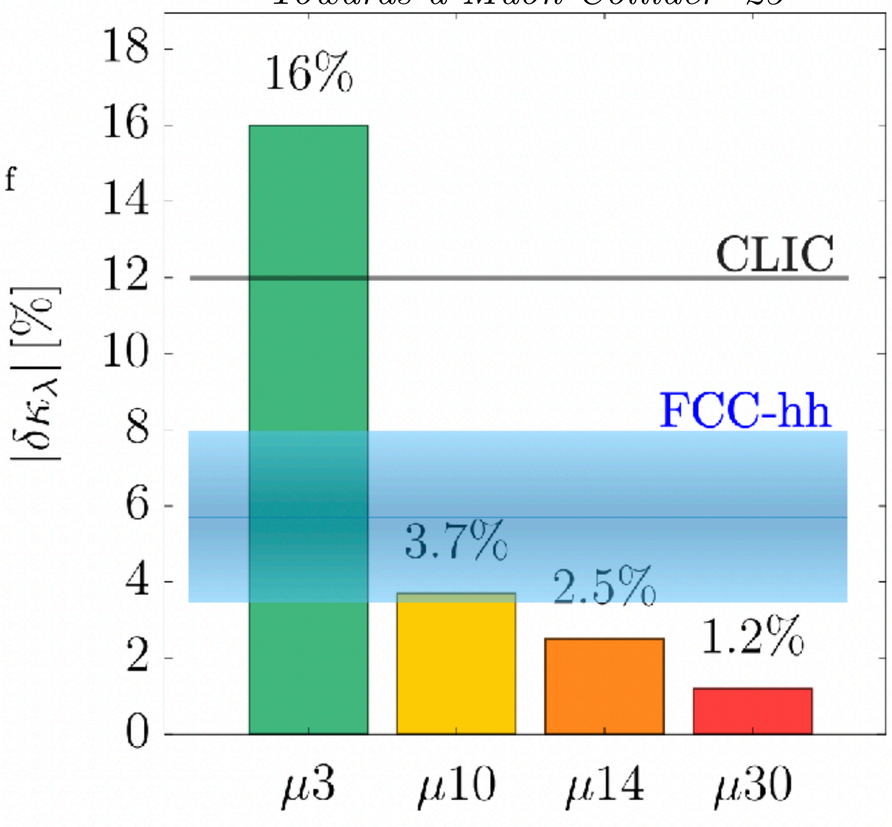




Forslund & Meade '23



Towards a Muon Collider '23



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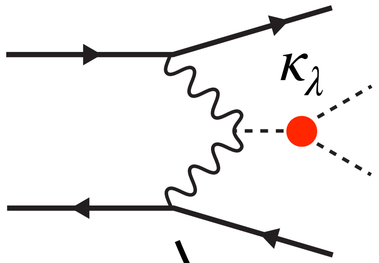
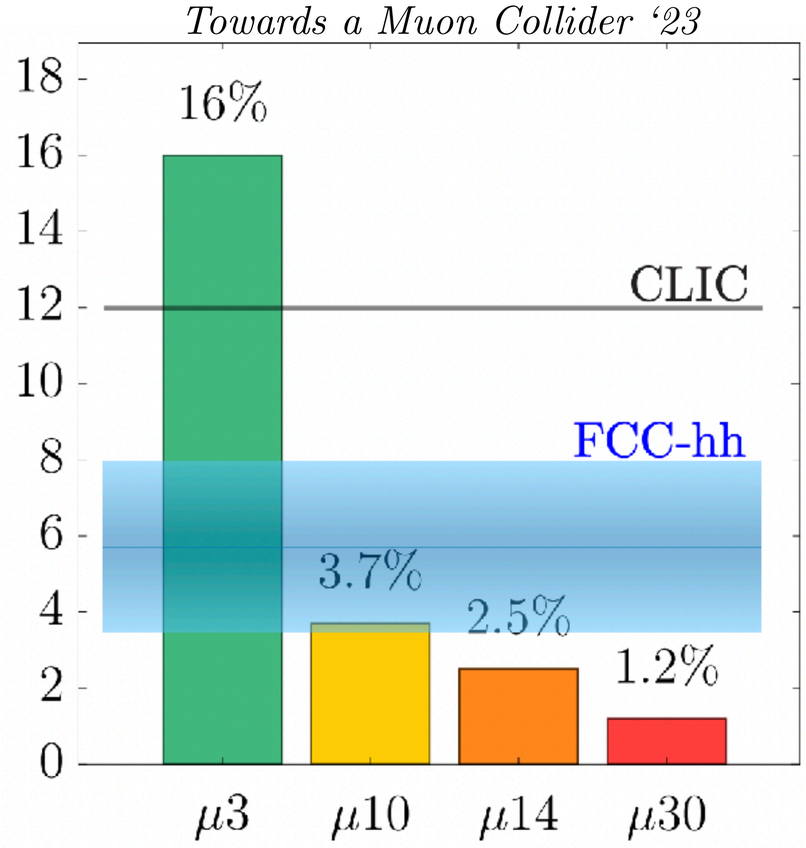


High energy is needed to produce several Higgs ($m_h \sim 100$ GeV) on-shell!

$|\delta\kappa_\lambda|$ [%]



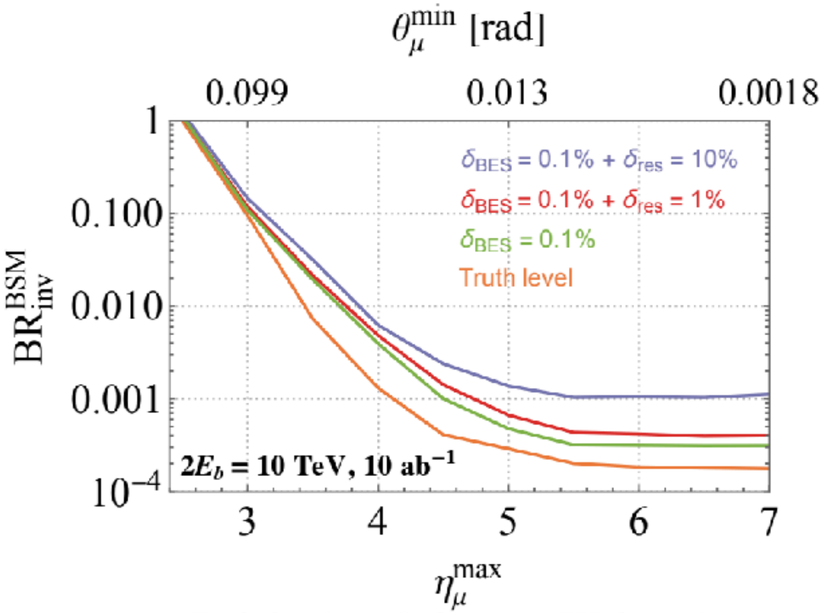
Higgs (& BSM) Physics at MuC

Example: Improving measure of Higgs to invisible measurement

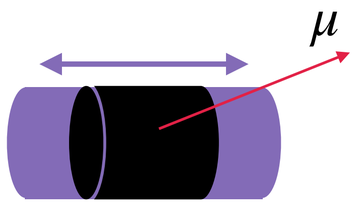
SM Prediction: $h \to ZZ^* \to 4\nu$

Can further validate SM

Motivates detector design



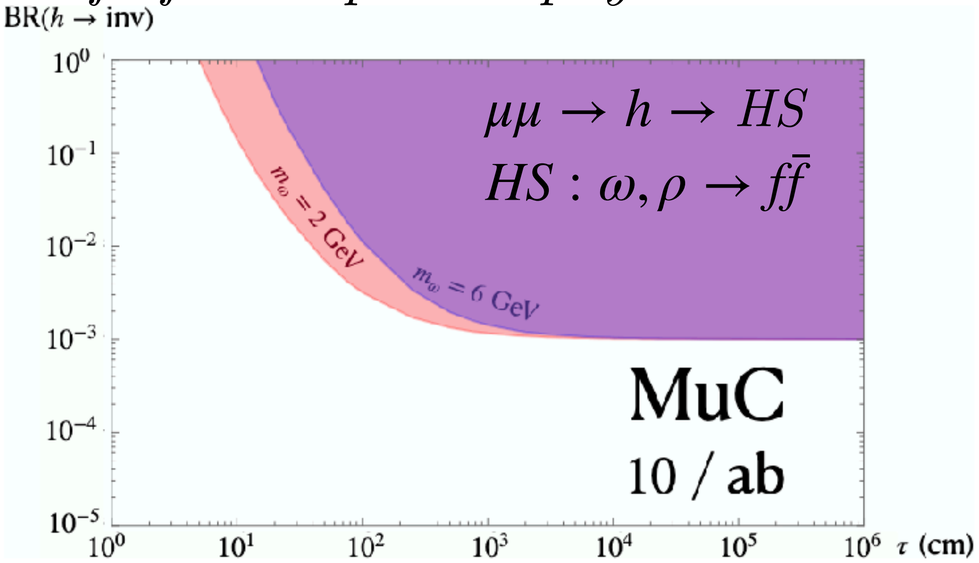
Ruhdorfer, Salvioni, Wulzer '23



Max η

Set benchmarks on exotic scenarios

Proof-of-concept new physics sensitivity



***CC**, Musk, Williams (WIP)*

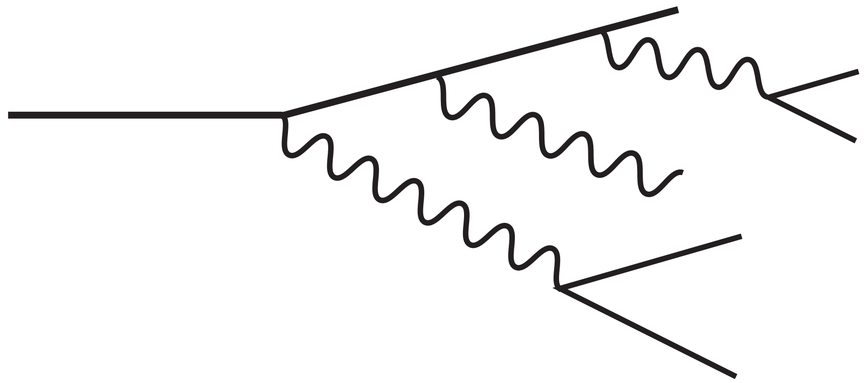
EW Physics at MuC

Electroweak radiation at high energy is very different than at low energy:

When $E_V \gg m_V$, gauge bosons can radiate like photons (?)

Emission probability

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



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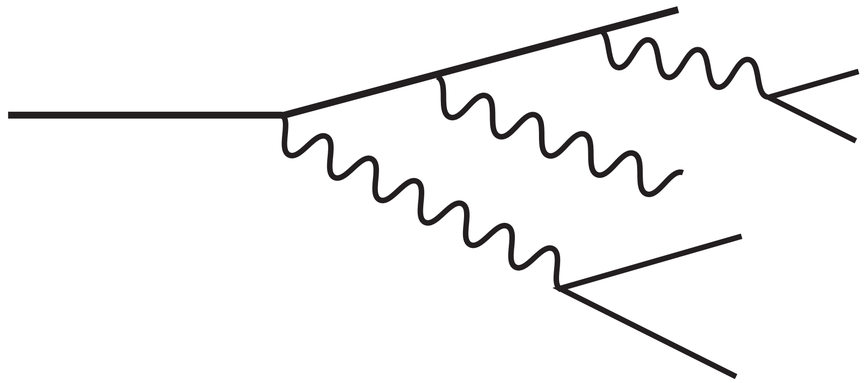

At sufficiently high energy, gauge bosons are massless? (Capdevilla, Han '24)

How do we understand loop corrections to EW processes? (Ma, Pagani, Zero '24)

How do we dress a lepton with Z and W PDFs? (Garosi, Marzocca, Trifinopoulos '23)

...

Physics Program at MuC

SM Deliverables: questions *we know need answers*

Higgs

Electroweak @ High Energy

High-energy studies of EW phenomena

BSM Exploration: questions that *necessitate empirical input*

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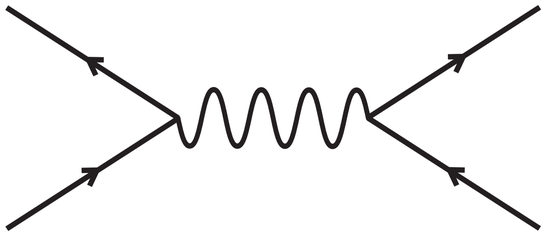
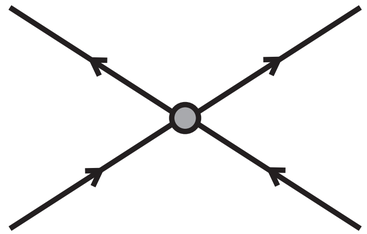
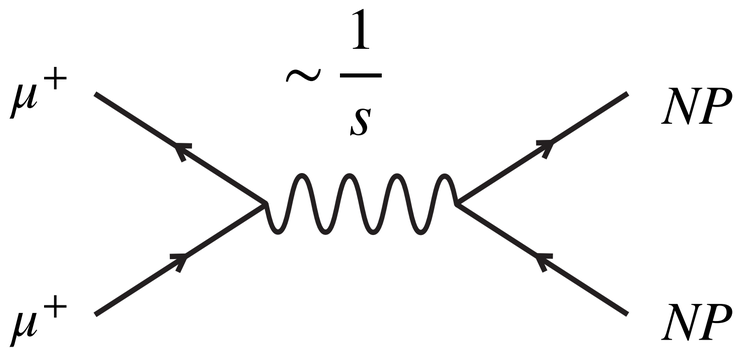


Indirect



BSM Direct Searches

We assume we can directly produce on-shell new particles



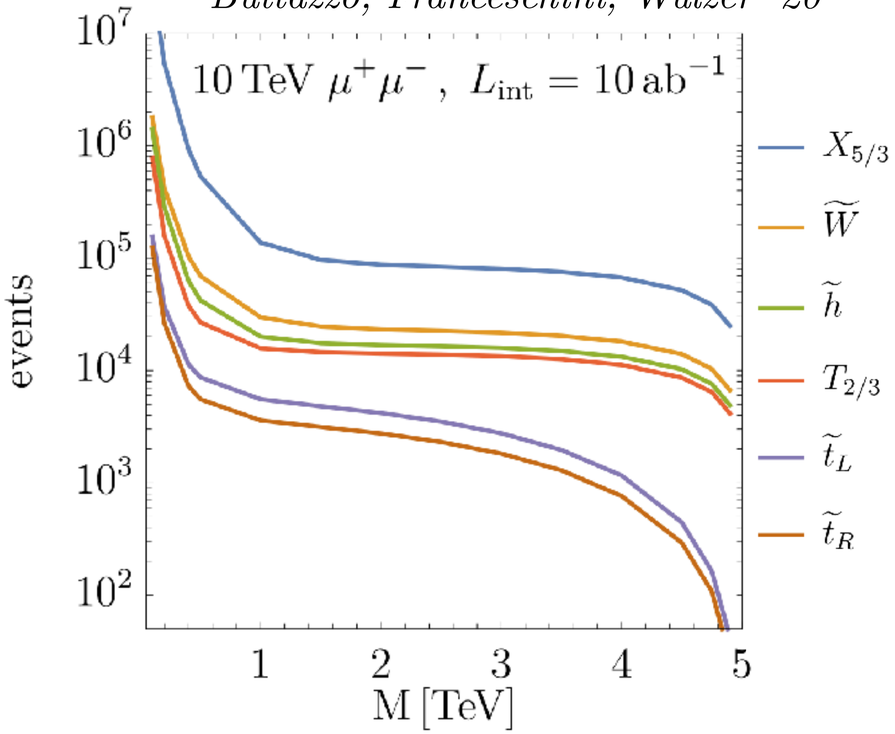
$$m_{\rm NP} \lesssim \sqrt{s}$$

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

High-energy is the key to empirical evidence for a UV theory of the SM

Reach is often kinematic:

Buttazzo, Franceschini, Wulzer '20



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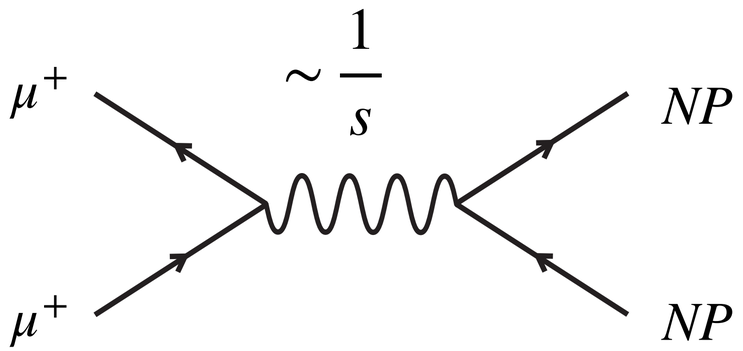

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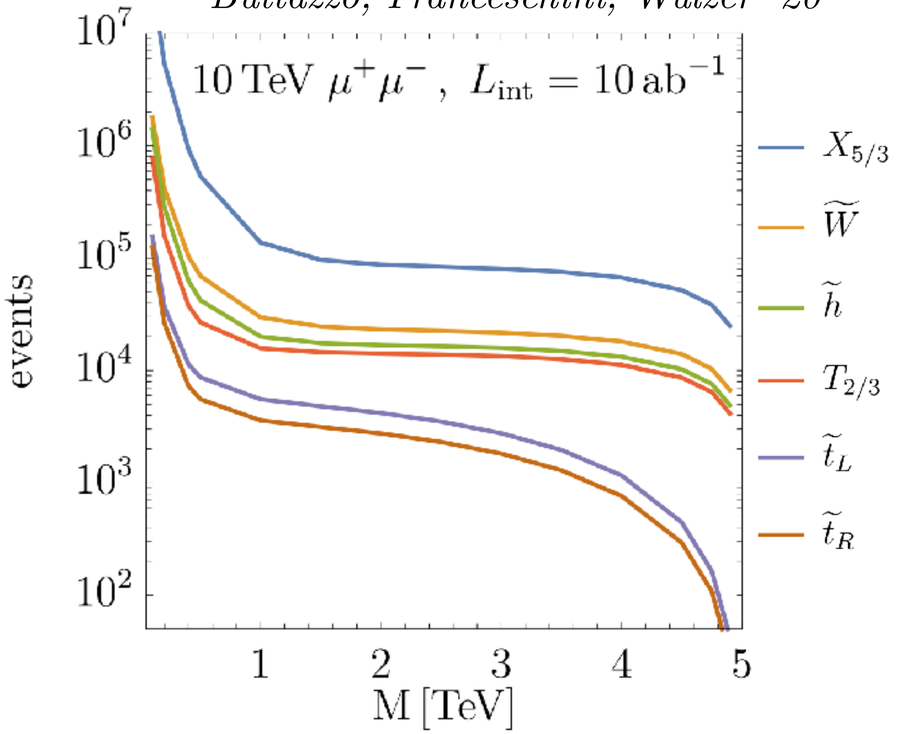

We should be exploratory but not unmotivated in BSM searches

BSM Direct Searches

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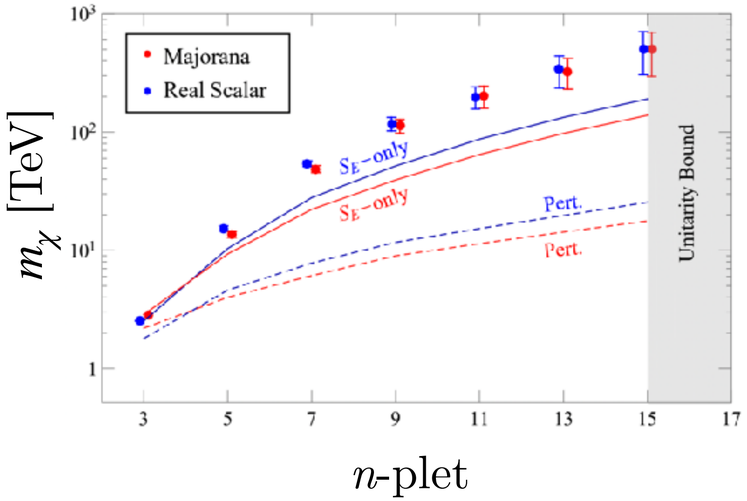
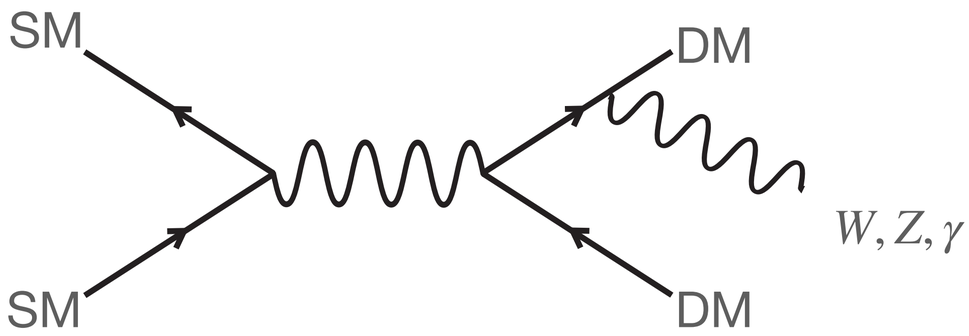
Example: Thermal Dark Matter





WIMP is motivated, EW coupling, and heavy—*ideal* at MuC!

Han, Liu, Wang, Wang '20

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

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

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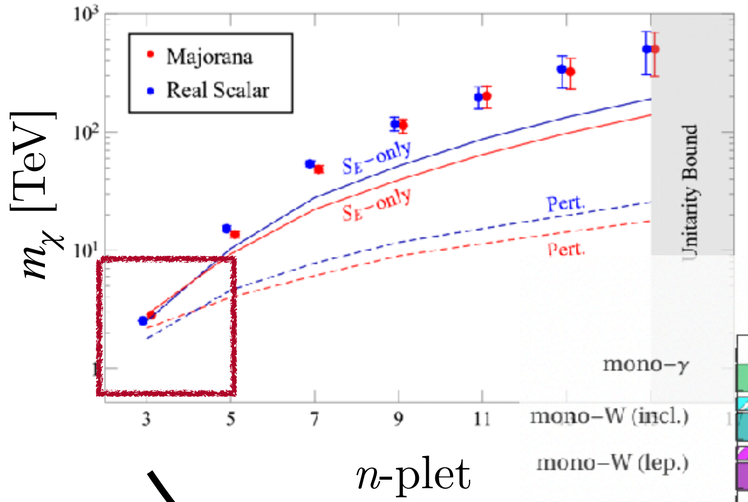
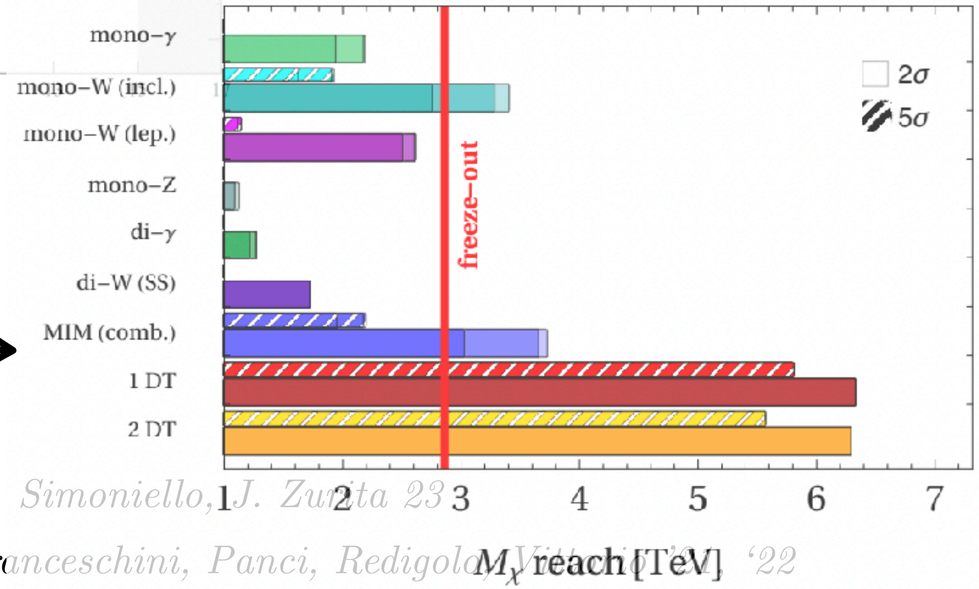
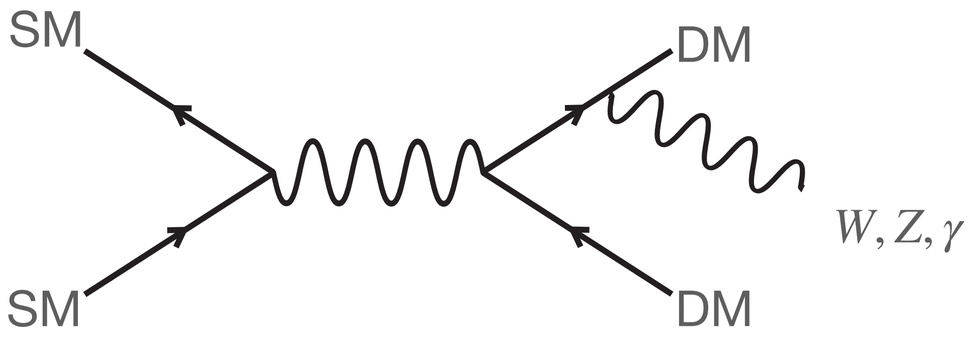


SU(2) 3-plet





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BSM Direct Searches

We assume we can directly produce on-shell new particles

Example: Leptophilic Thermal Dark Matter

Fermionic DM model with a scalar portal that couples *leptophilically*

χ is DM

φ is portal

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

(proportional to Yukawa couplings)

D'Ambrosio, Giudice, Isidori, Strumia '02

BSM Direct Searches

We assume we can directly produce on-shell new particles

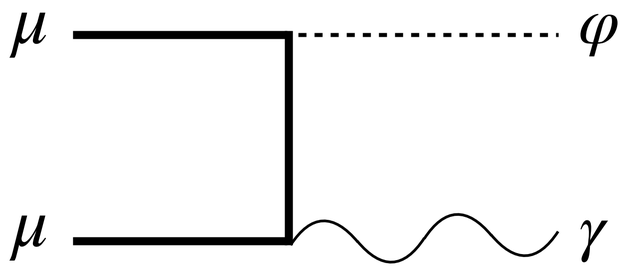
Example: Leptophilic Thermal Dark Matter

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

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

Mono-X Search

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



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

Background:

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

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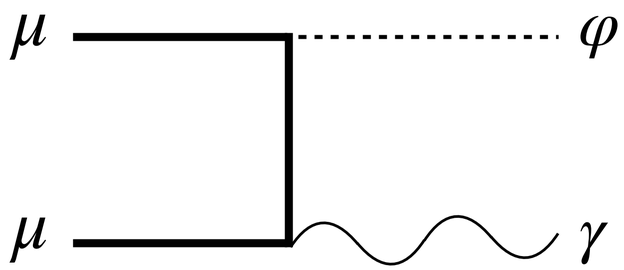

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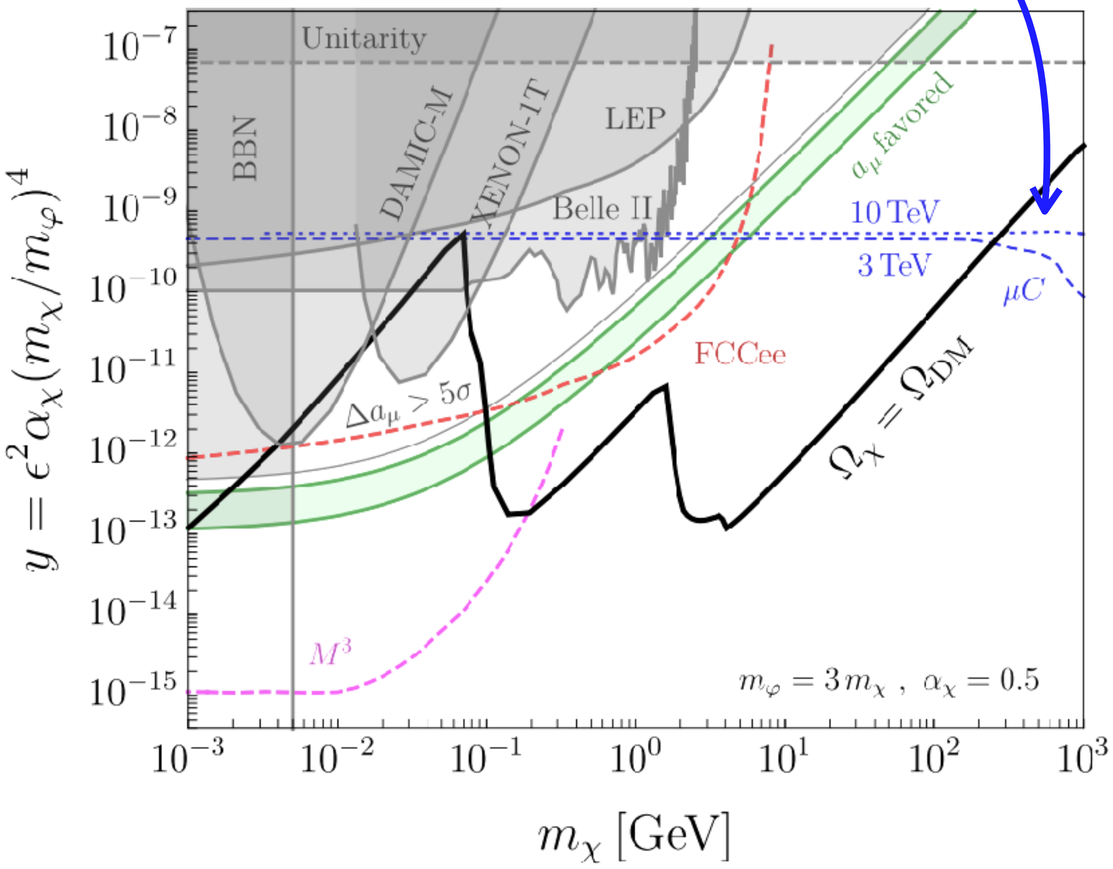
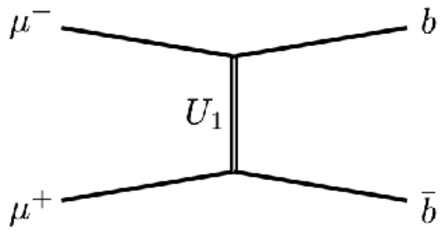
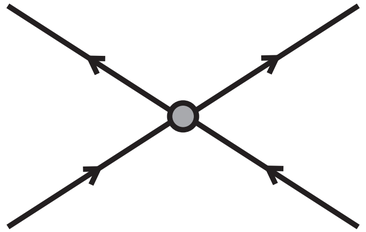


BSM Indirect Searches

To go beyond energy reach, we can indirectly probe new particles

Example: Interference at tree- and loop- level





BSM Indirect Searches

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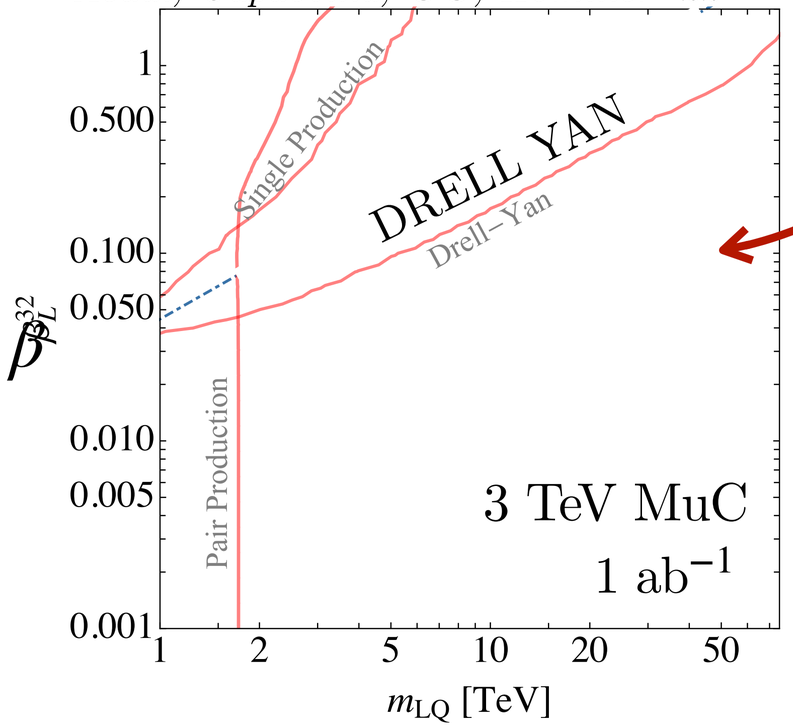
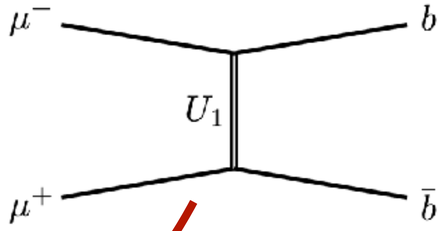
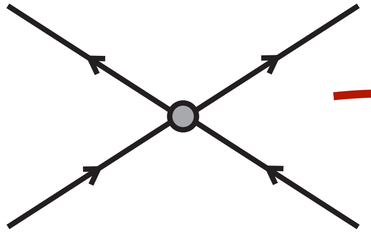
Example: Interference at tree- and loop- level

$U(1)$ *Leptoquarks*

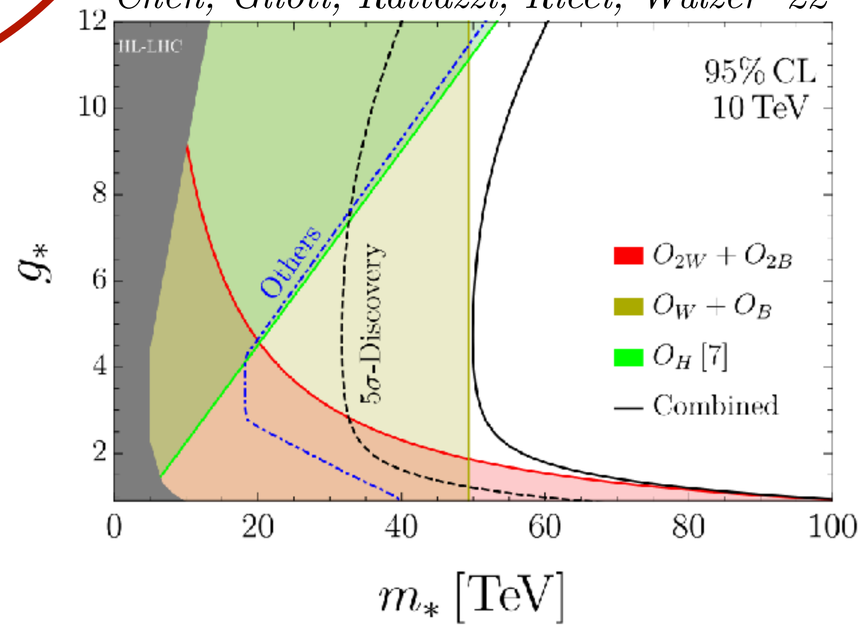
Asadi, Capdevilla, ***CC****, Homiller '22*







Chen, Glioti, Rattazzi, Ricci, Wulzer '22



$$O_{2W} = (D_\mu W^{\mu\nu,a})^2$$

$$O_{2B} = (\partial_\mu B^{\mu\nu})^2$$

$$O_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$$

$$O_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu}$$

Measuring precisely $\mathcal{O}$ can tell us about high-energy dynamics

Physics Program at MuC

SM Deliverables: questions *we know need answers*

Higgs

Electroweak @ High Energy

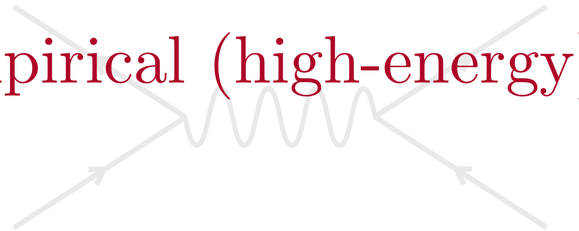
High-energy studies of EW phenomena

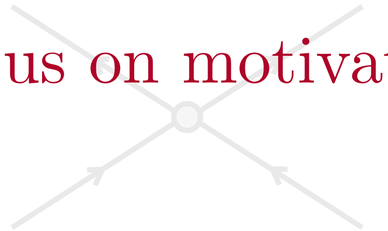
BSM Exploration: questions that *necessitate empirical input*

Direct

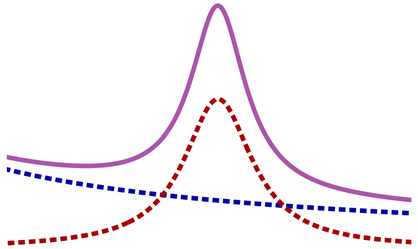
Indirect

Need empirical (high-energy) evidence to put us on motivated direction



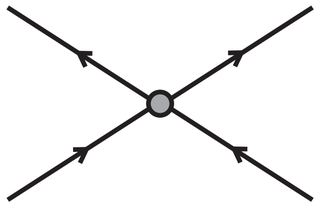


Outline



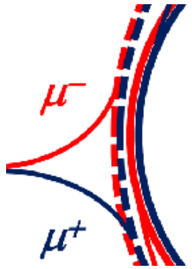
Why collide particles at all?

High-energy environments uncover new phenomena



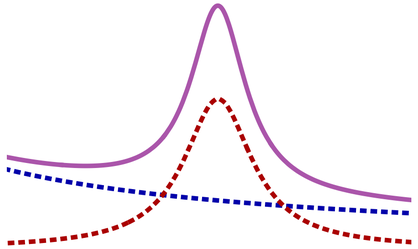
Why collide muons?

Reach higher energies and flavor-dependent couplings



What needs R&D to collide muons?

Outline



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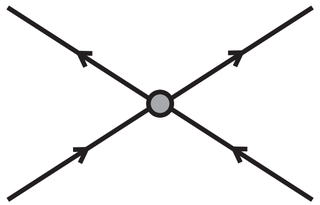

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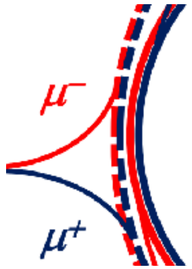


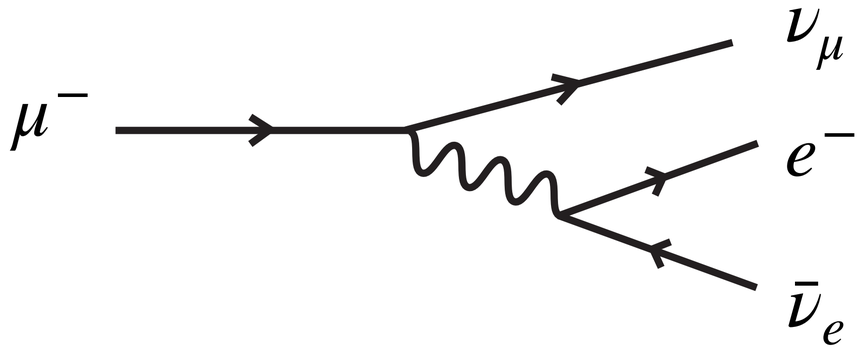
What needs R&D to collide muons?

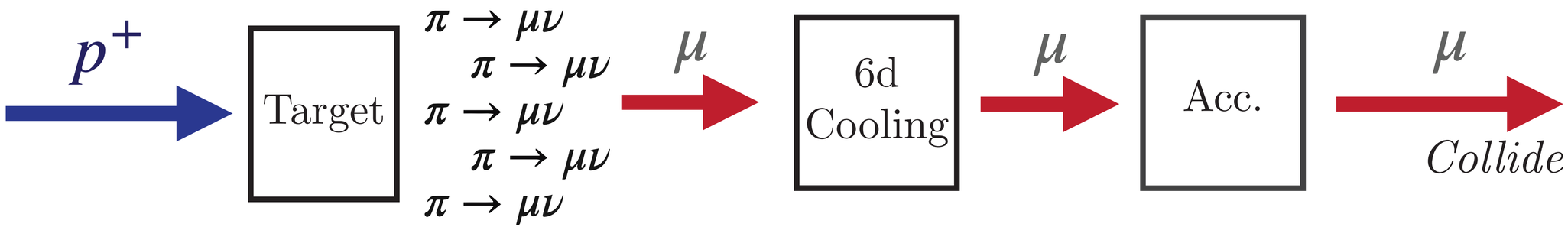
Focusing particles that decay

Challenges of MuC

Muons Decay

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





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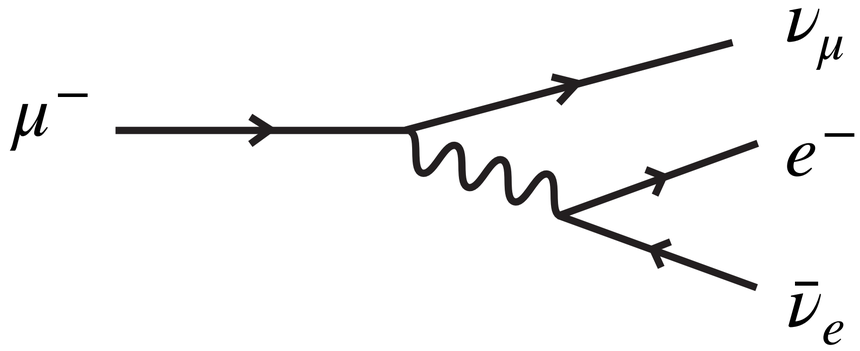
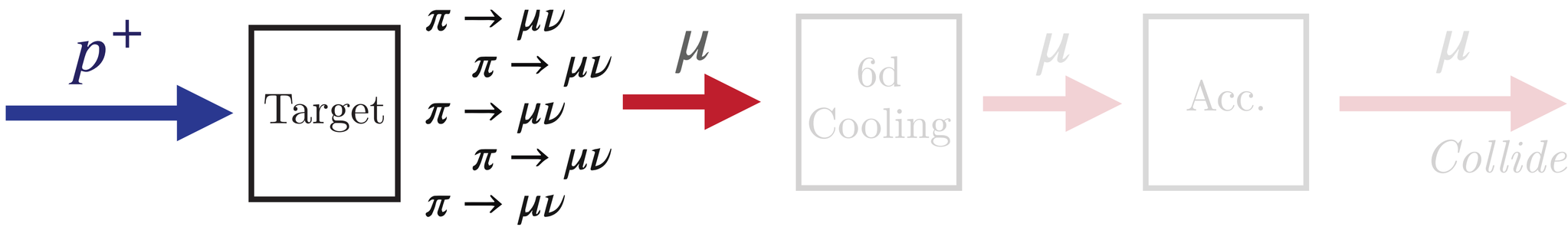


Production as tertiary beam

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



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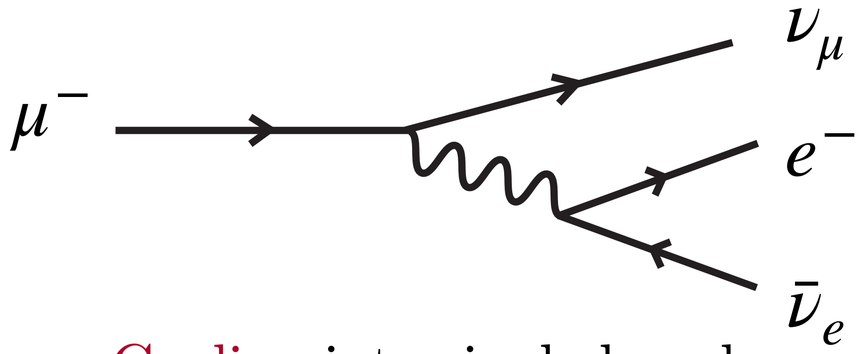

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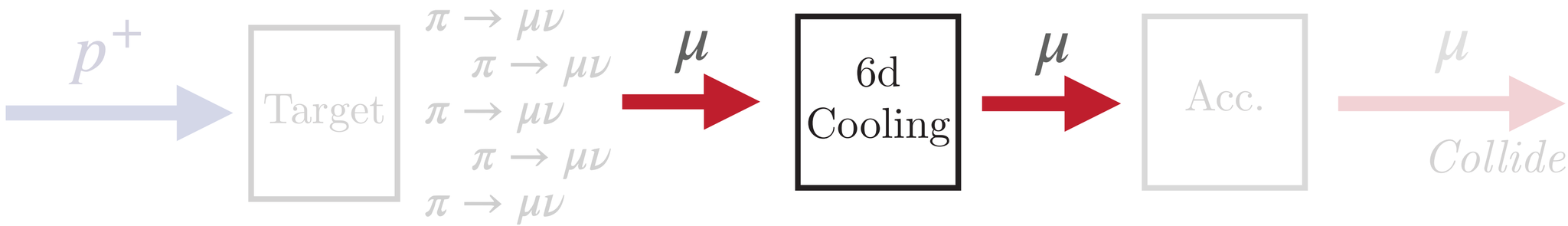
$0.9^{120} \sim 10^{-6}$



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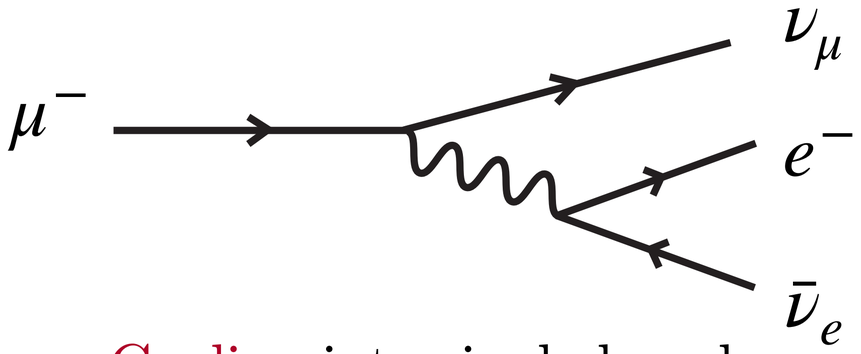

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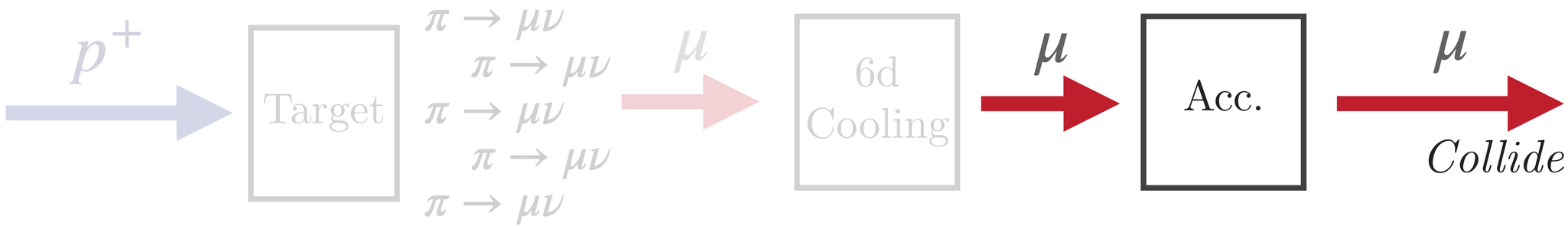
Acceleration and collision

Too quick to ramp up magnets



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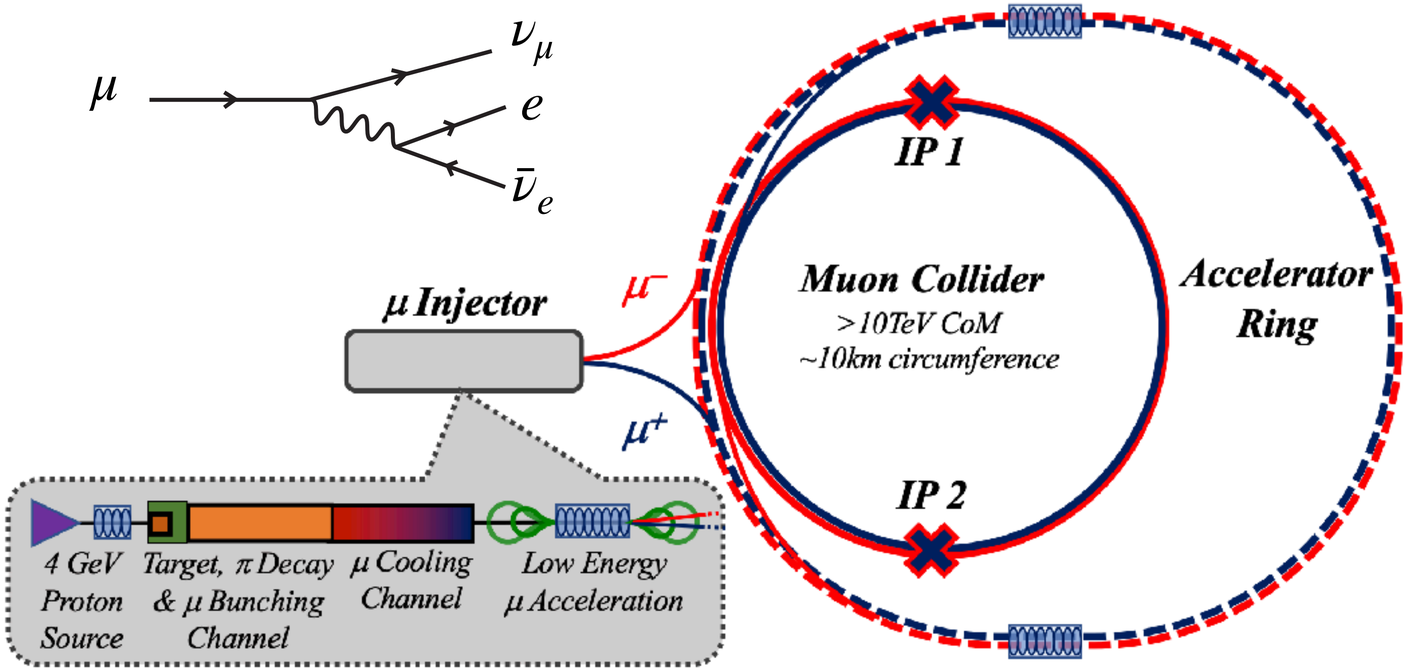
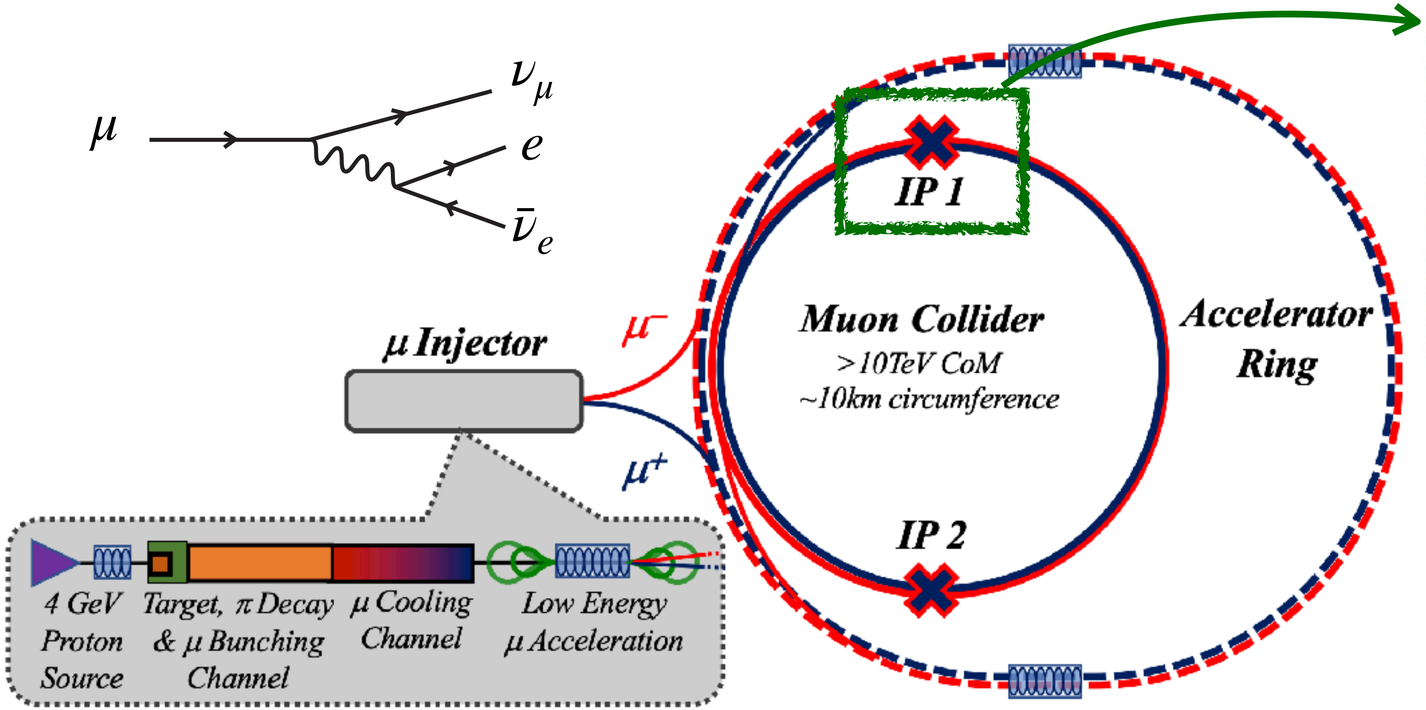


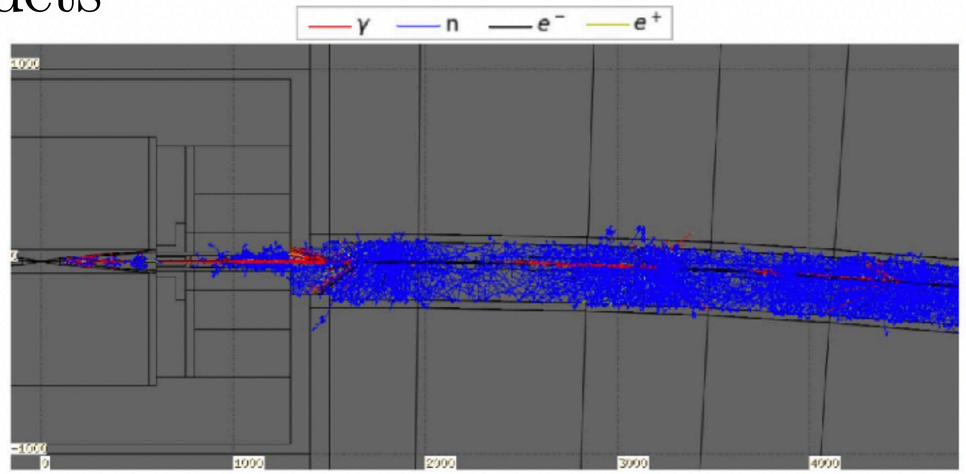
Challenges of MuC

Muons Decay

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

Beam-induced background from decay products





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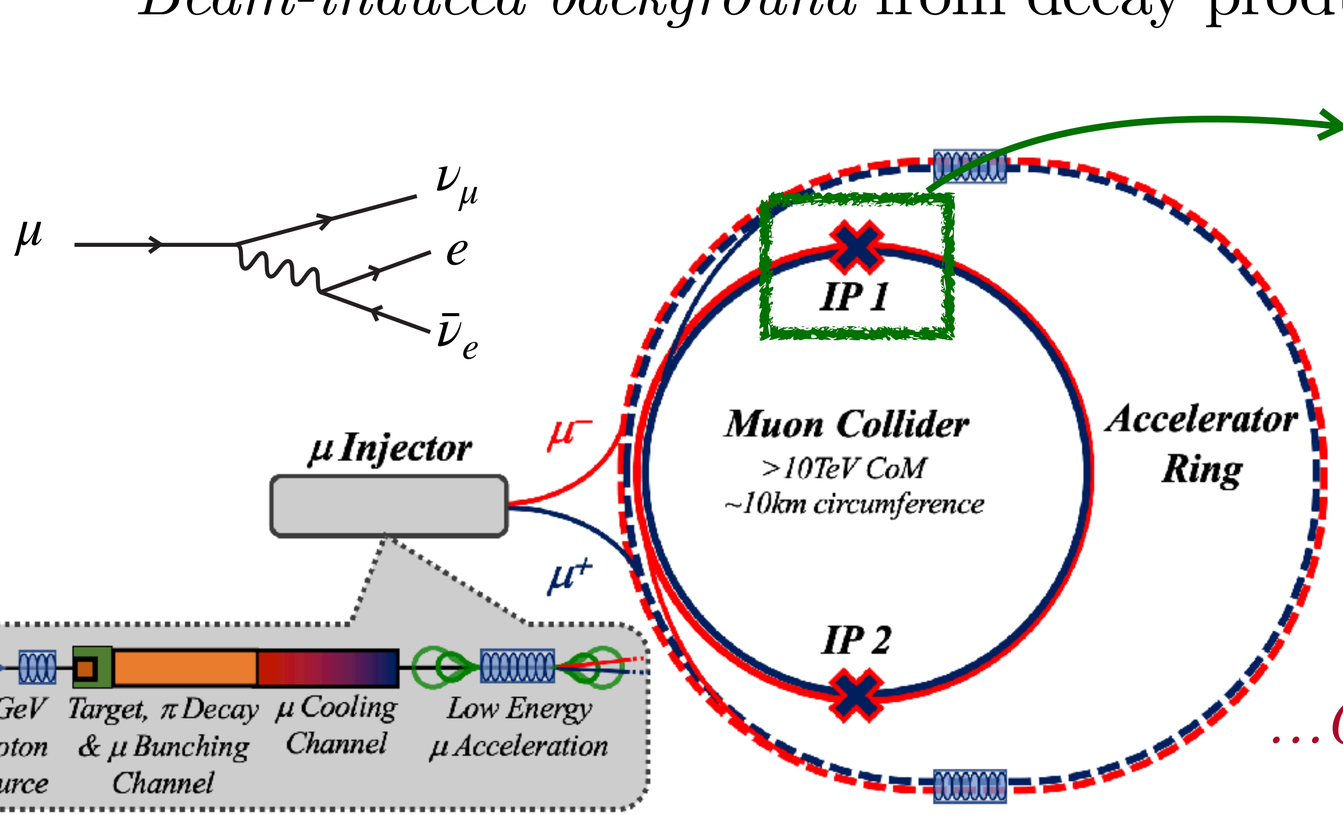
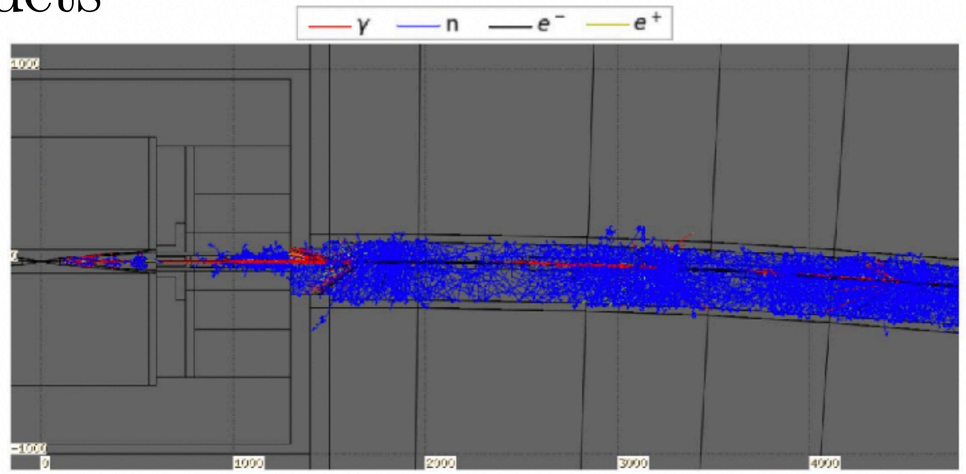
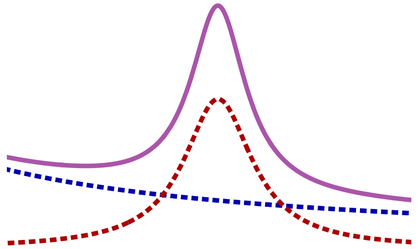




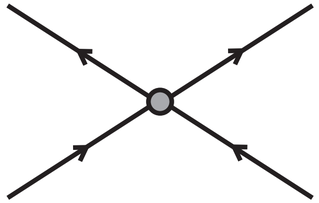
…Opportunity for forward detectors and neutrino synergies!

Outline



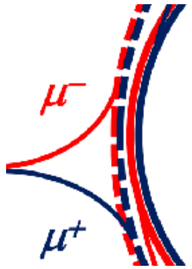
Why collide particles at all?

High-energy environments uncover new phenomena



Why collide muons?

Reach higher energies and flavor-dependent couplings

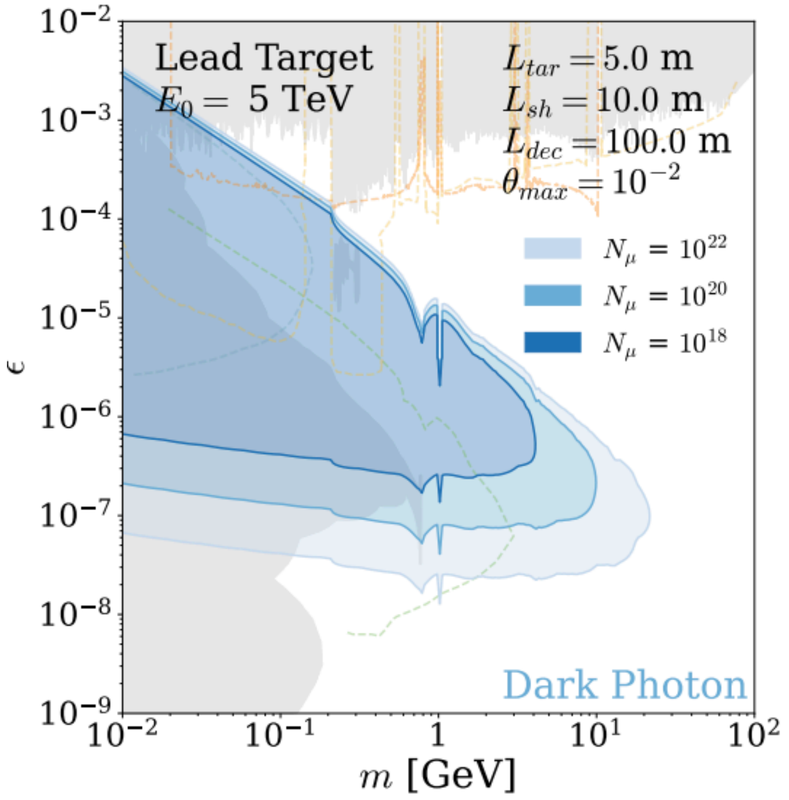


What needs R&D to collide muons?

Focusing particles that decay

Points for Discussion

- What else can we do with a muon beam?
- What can we do with neutrinos?
- What technologies have we not considered?
- What energy is most interesting to achieve?
- What are the most important questions we need to answer in particle physics?
- ...



Outlook

Muons are the best opportunity to reach the 10 TeV frontier, *soon*

We need to balance exploratory studies with motivated searches

Design is flexible — needs input from theorists!

Scientific input will be the primary motivator for this collider:

We must understand *now* what a future machine should achieve

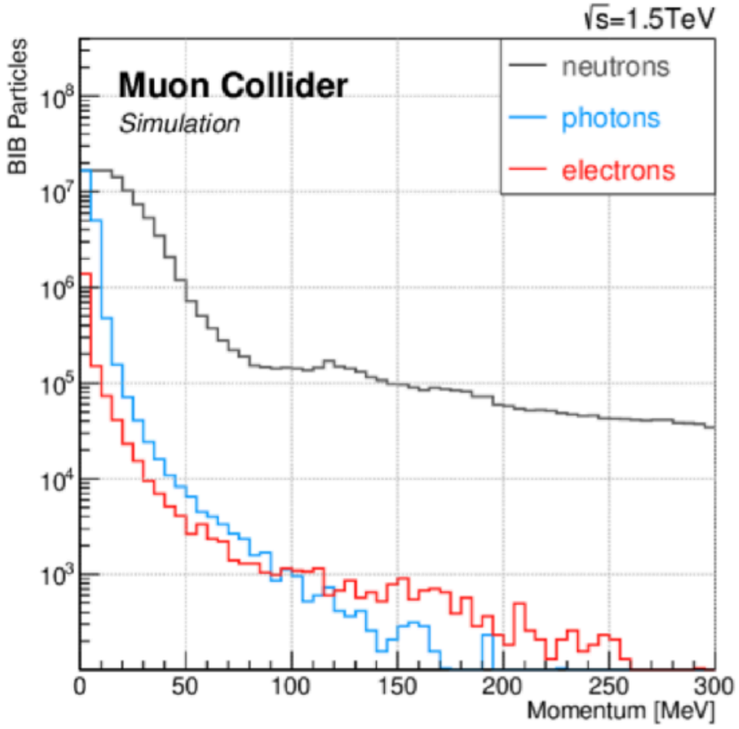
Backup Slides

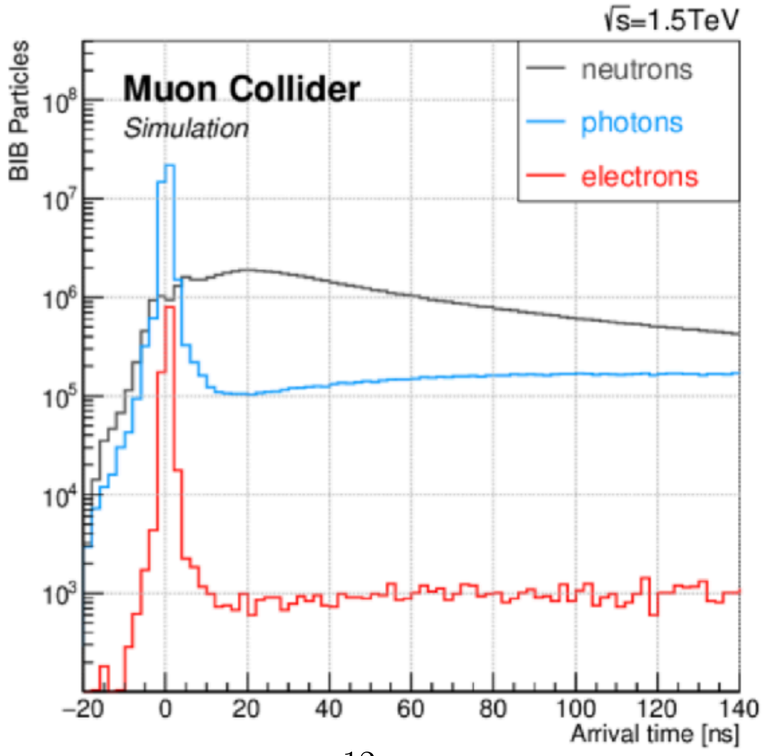
Challenges of MuC

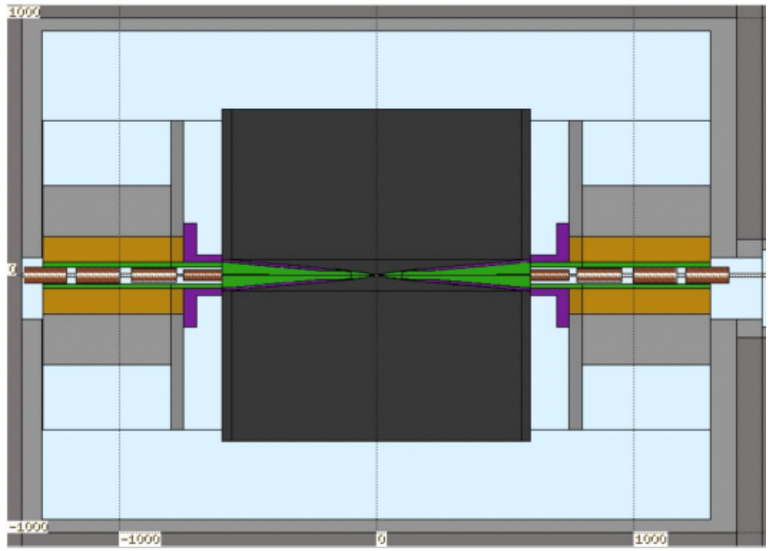
Muons Decay

Beam-induced background from decay products

Mitigated with timing, kinematics, and shielding





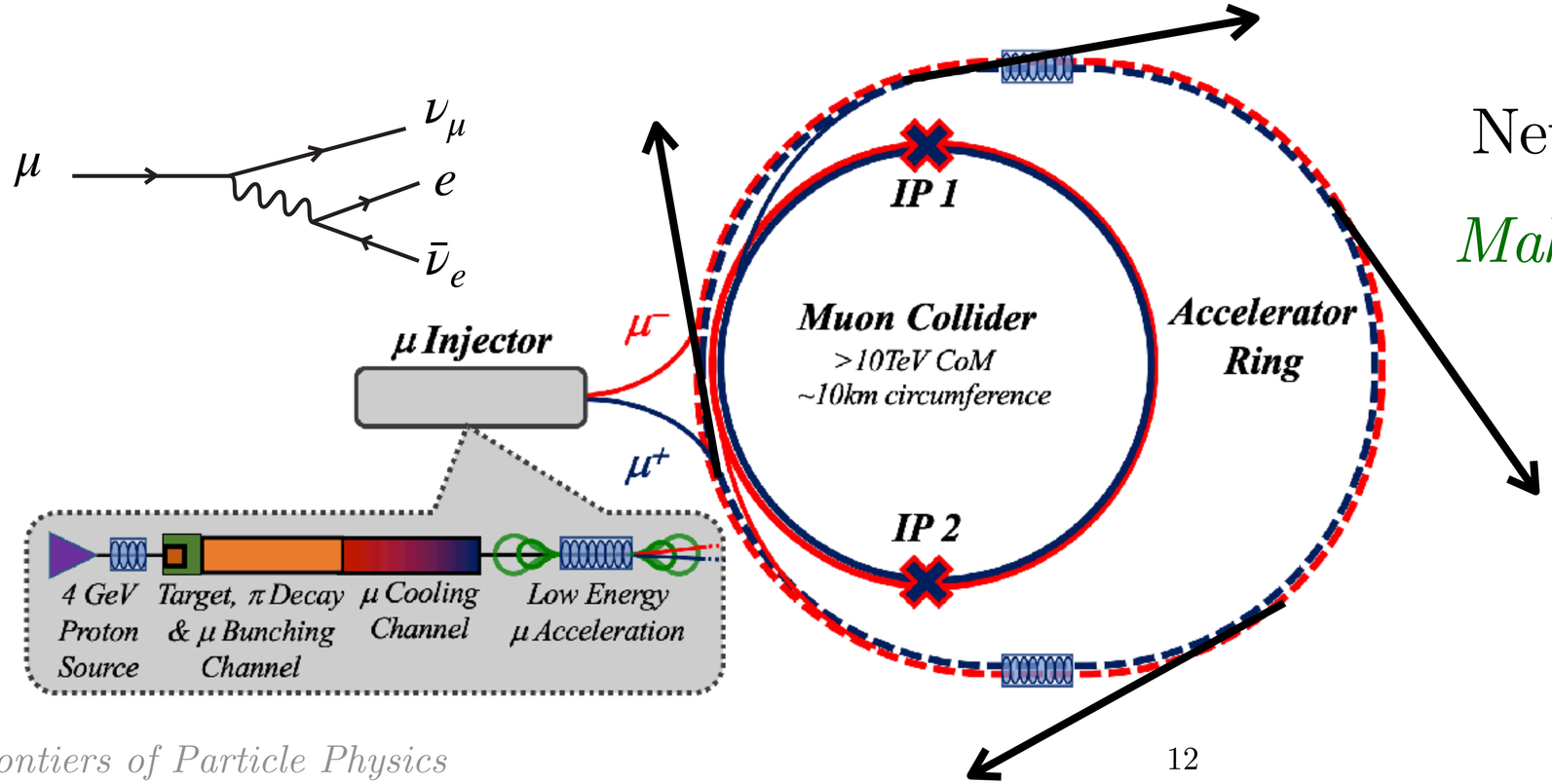


Challenges of MuC

Muons Decay

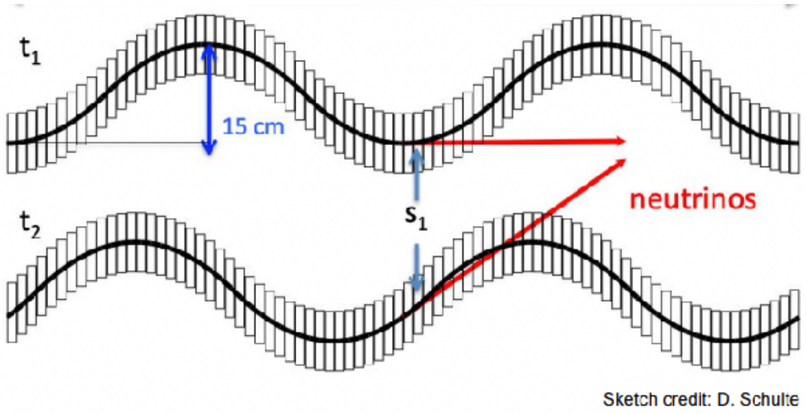
Beam-induced background from decay products

Mitigated with timing, kinematics, and shielding



Neutrinos interact at high energy

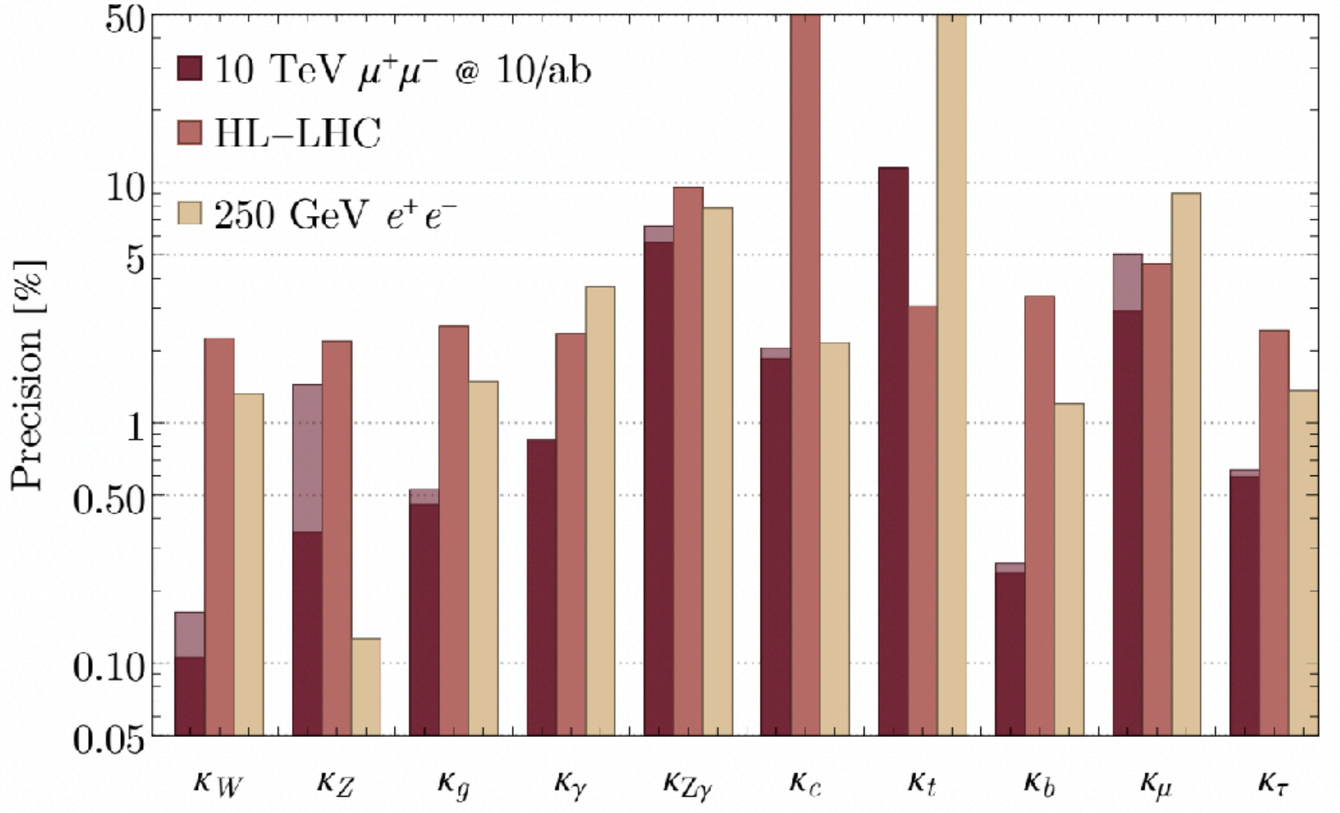
Make ring deep & diffuse the beam

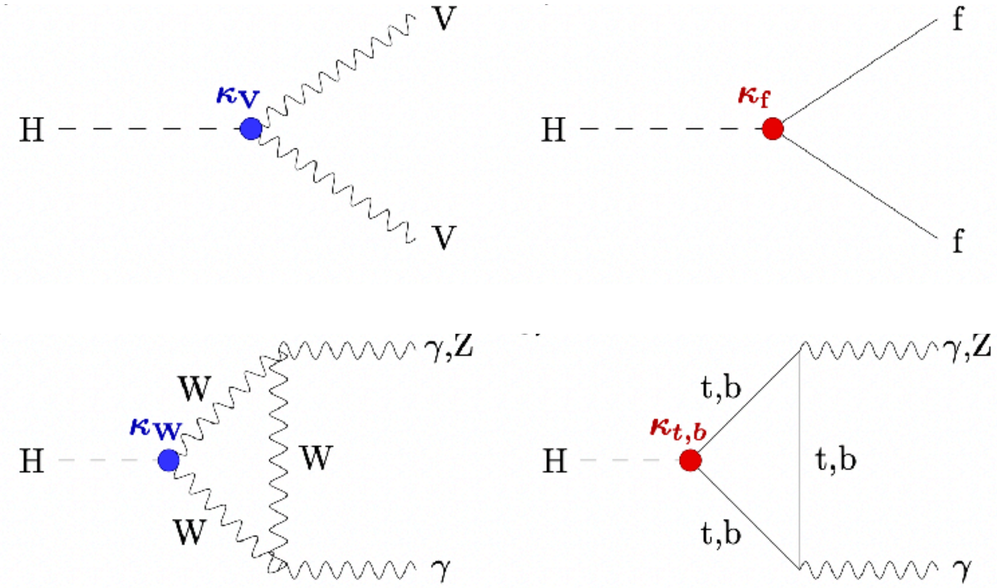


Sketch credit: D. Schulte

Higgs Couplings

Forslund & Meade '23

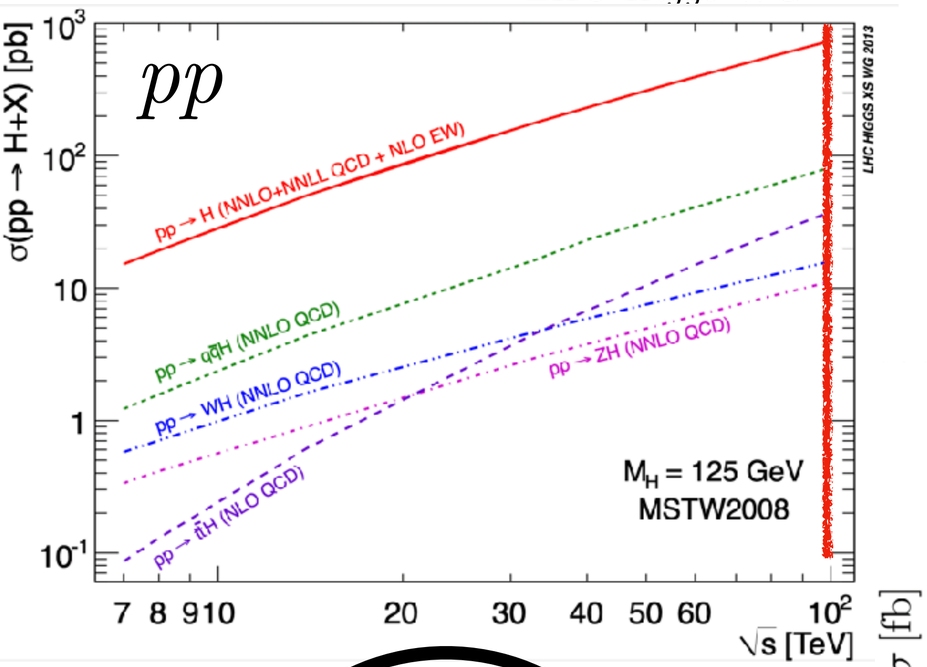


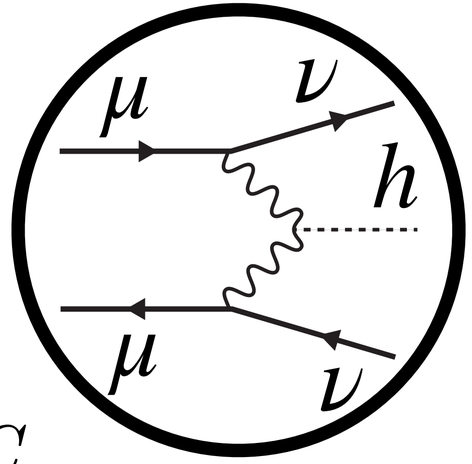


Reach of $\mathcal{O}(10^6)$ Higgs can be up to an order of magnitude more precise than HL-LHC

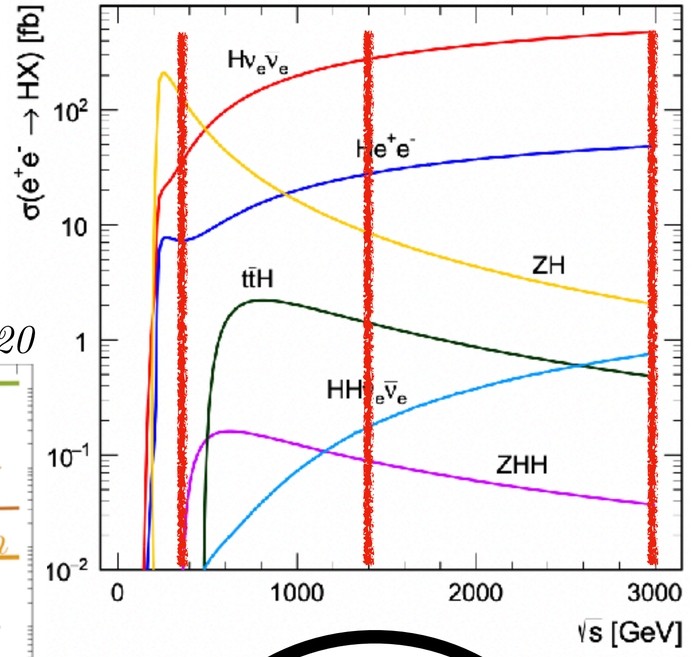
Higgs Production

LHC Higgs WG



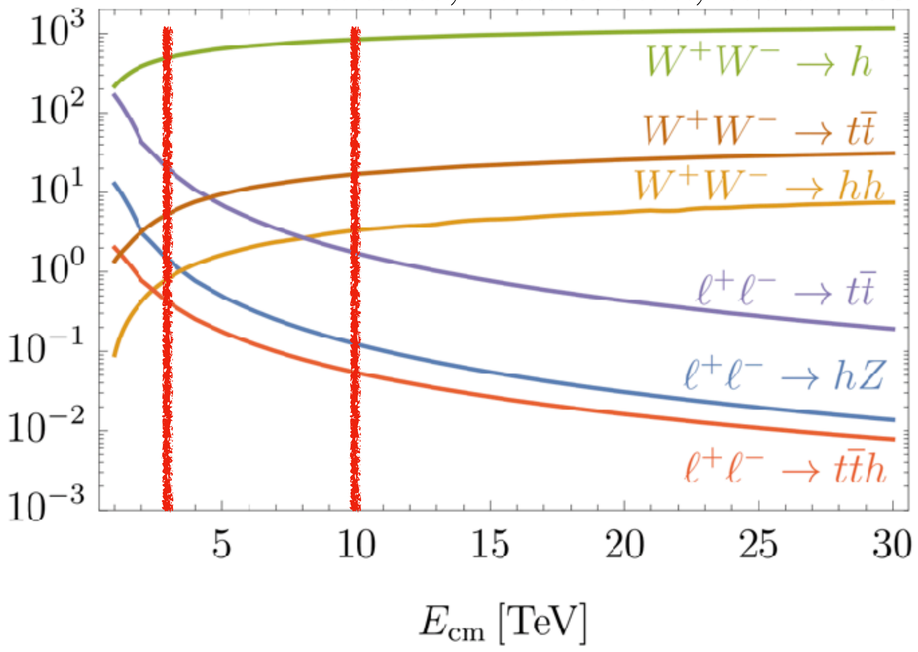


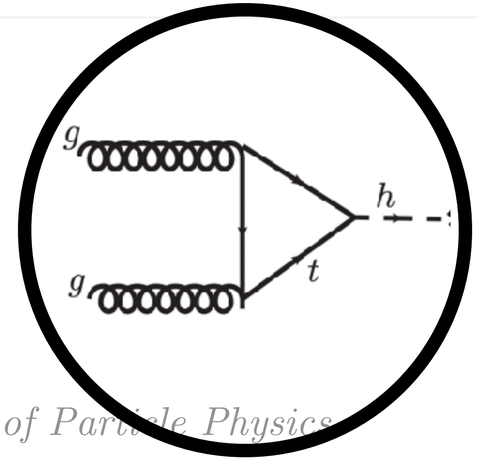
CLiC Summary Report e^+e^-

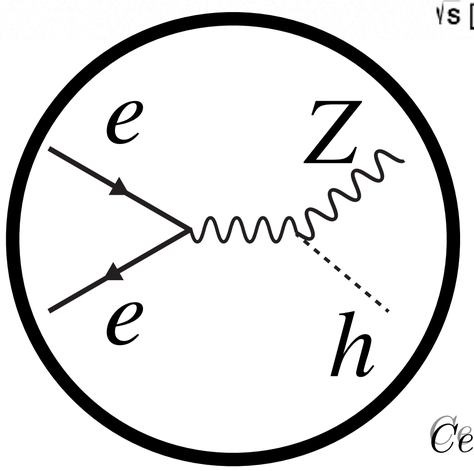


MuC

Buttazzo, Franceschini, Wulzer '20







DM at MuC: Leptophilic DM

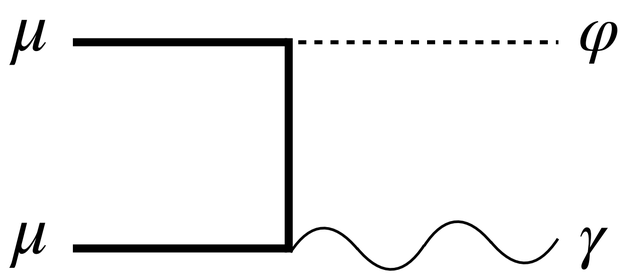
Muon Decay

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

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

Mono-X Search

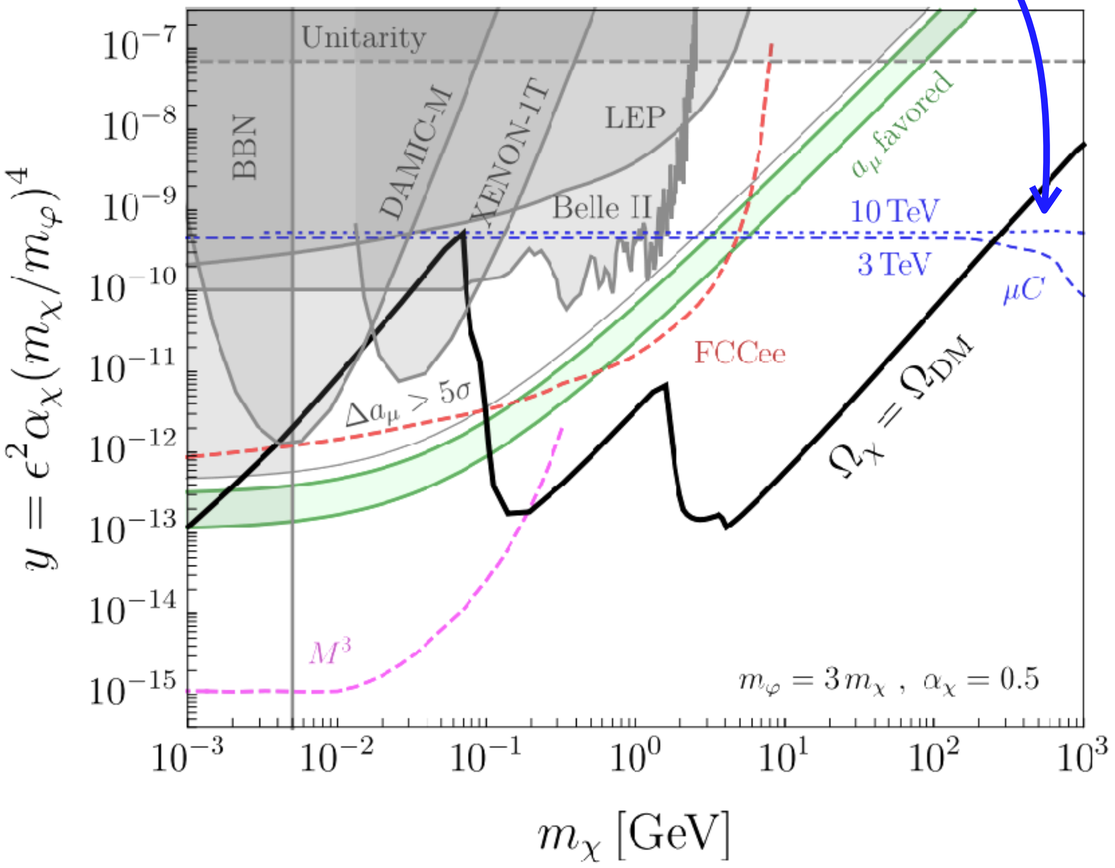
$$\mu^+\mu^- \to \varphi\gamma = \gamma \not{E}$$



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

Background:

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



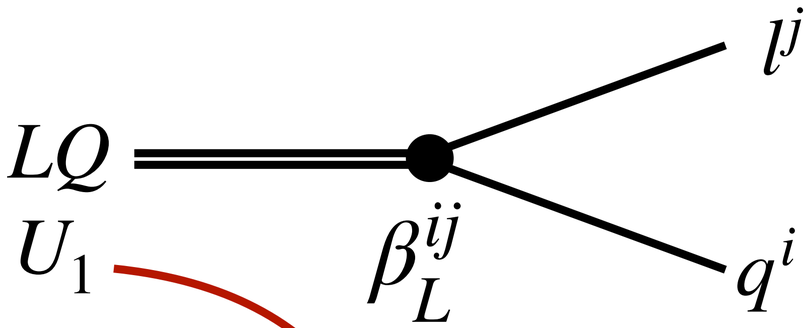
BSM at MUC: Leptoquarks

Muons: decay

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

Consider a BSM benchmark model: the *leptoquark*

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



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

Broad class of NP model

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

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

BSM at MuC: Leptoquarks

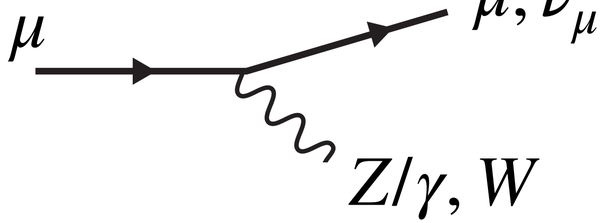
*Asadi, Capdevilla, **CC**, Homiller, '21*

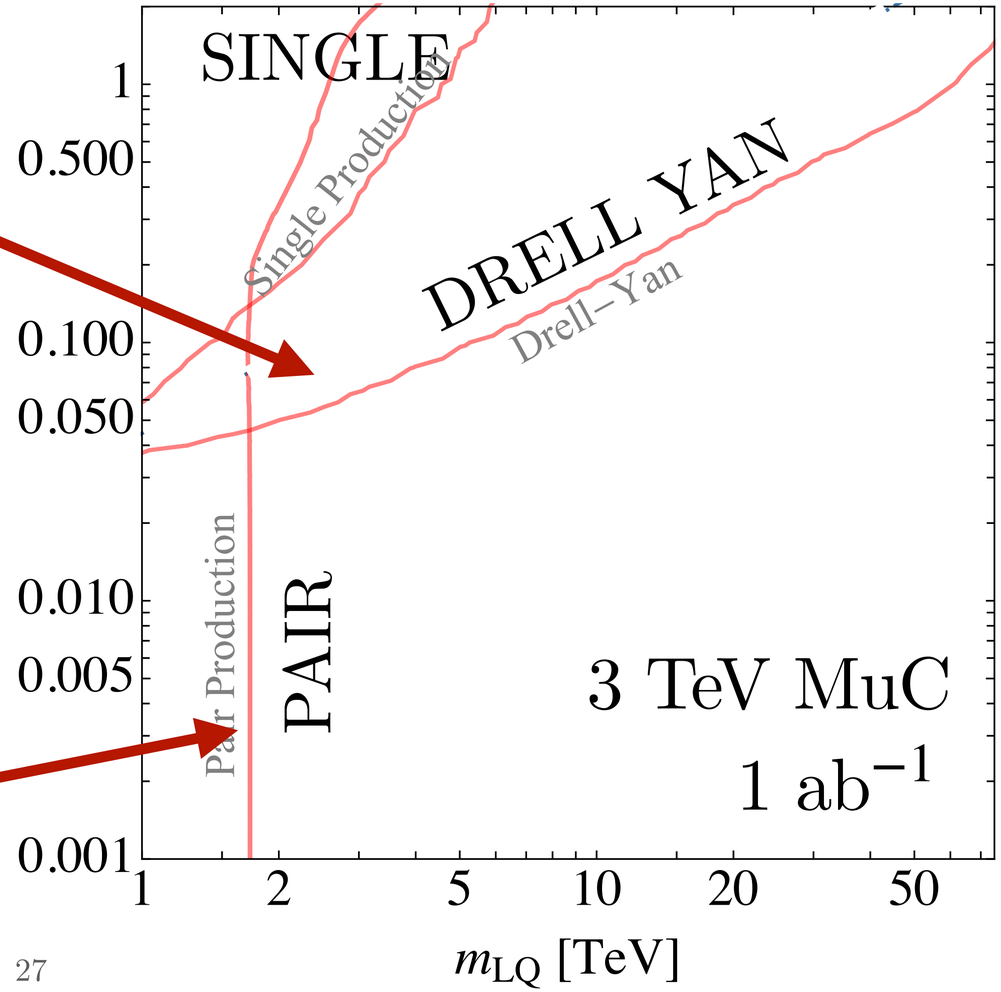
For benchmark choice of couplings, 5σ reach at 3 TeV MuC

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

Muons have PDFs too!

Muon colliders are also *gauge boson* colliders





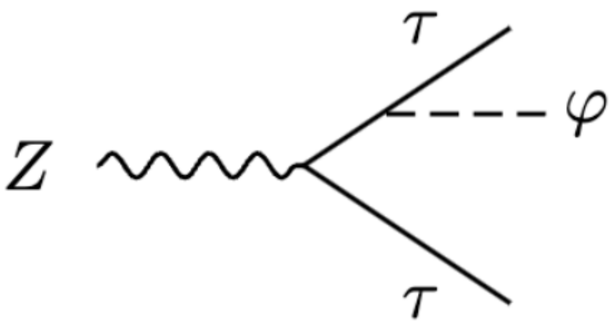
DM at EE Collider: Leptophilic DM

***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*