IMCC Cross-Pollination Talks

Muon Collider Theory

Cari Cesarotti

MIT CTP

IMCC Annual Meeting

DESY, Hamburg - May 12

Outline

Part I

What physics questions do we want to answer with collider physics?

Part II

What does theory need from the accelerator and collier community?

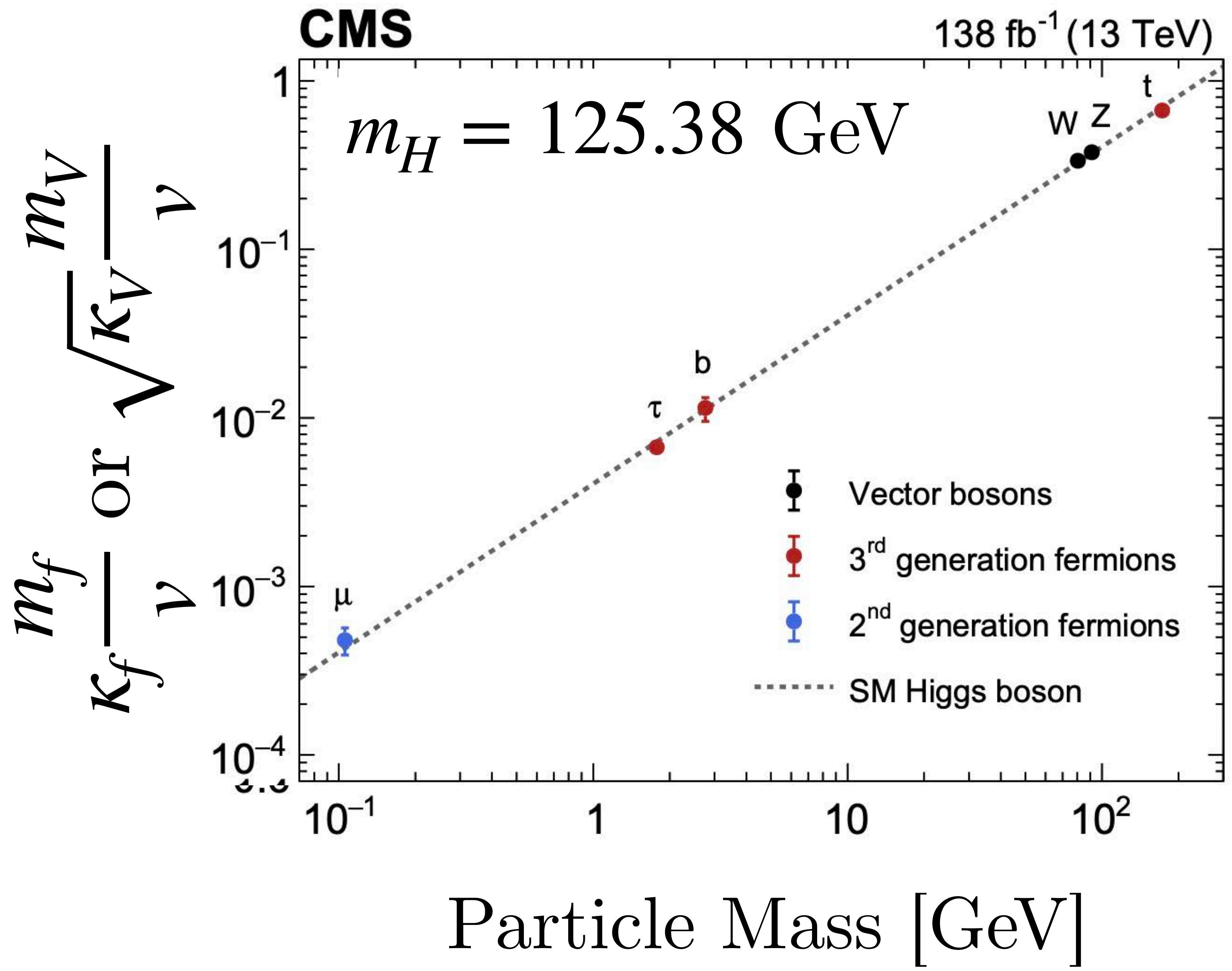
PART I

An overview of the theory program

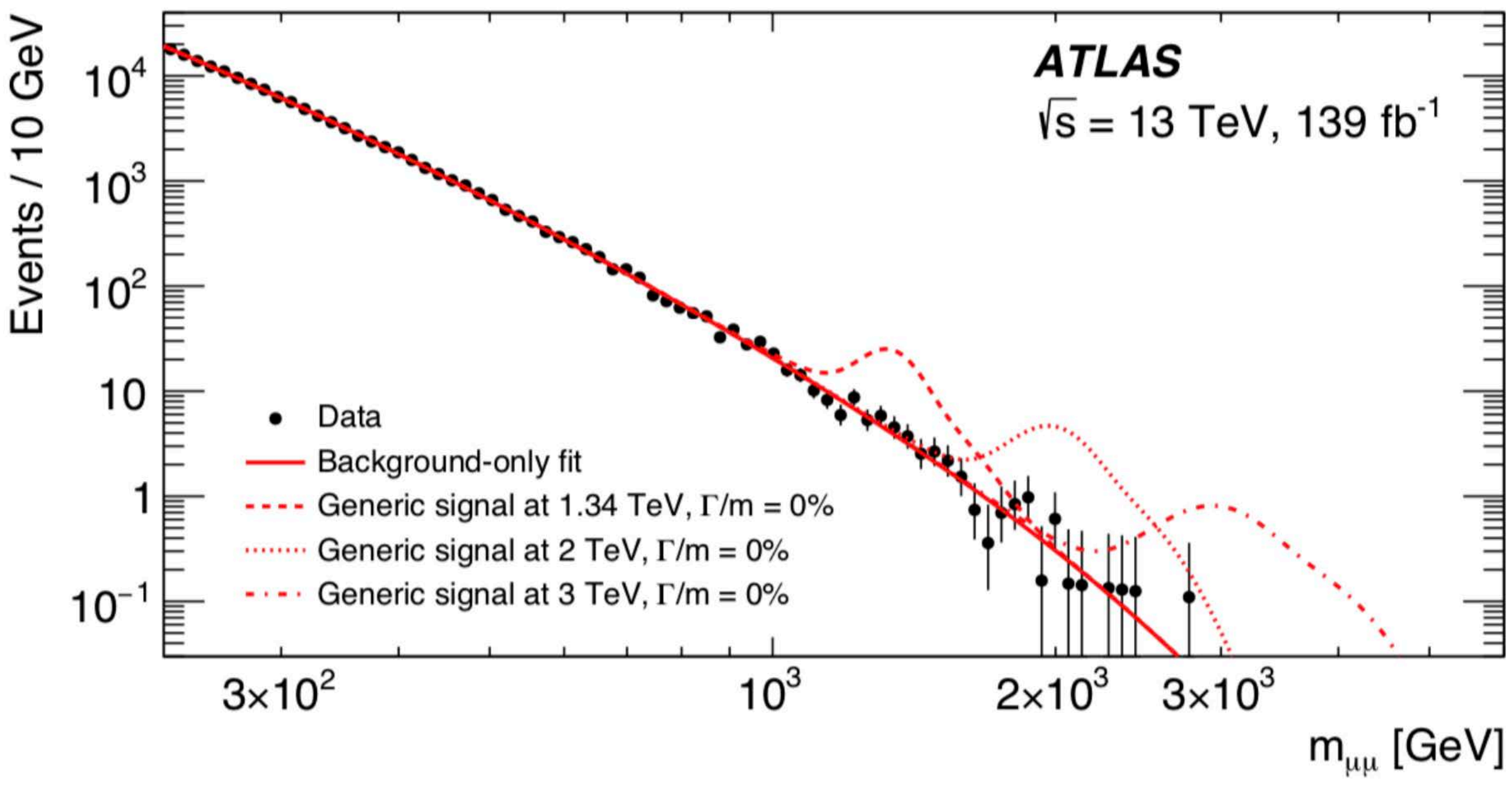
Open Questions in Particle Physics

LHC discovered the Higgs and has shown amazing confirmation of the SM...

Higgs physics



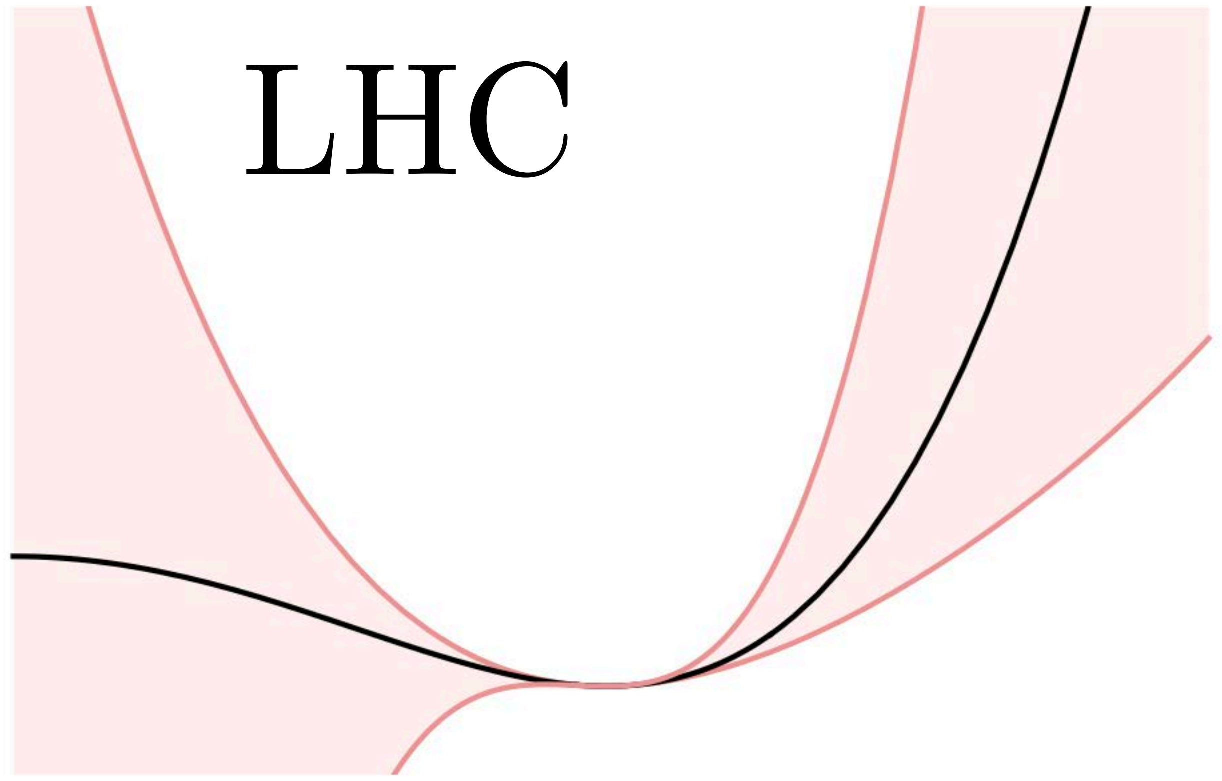
New Resonances Search

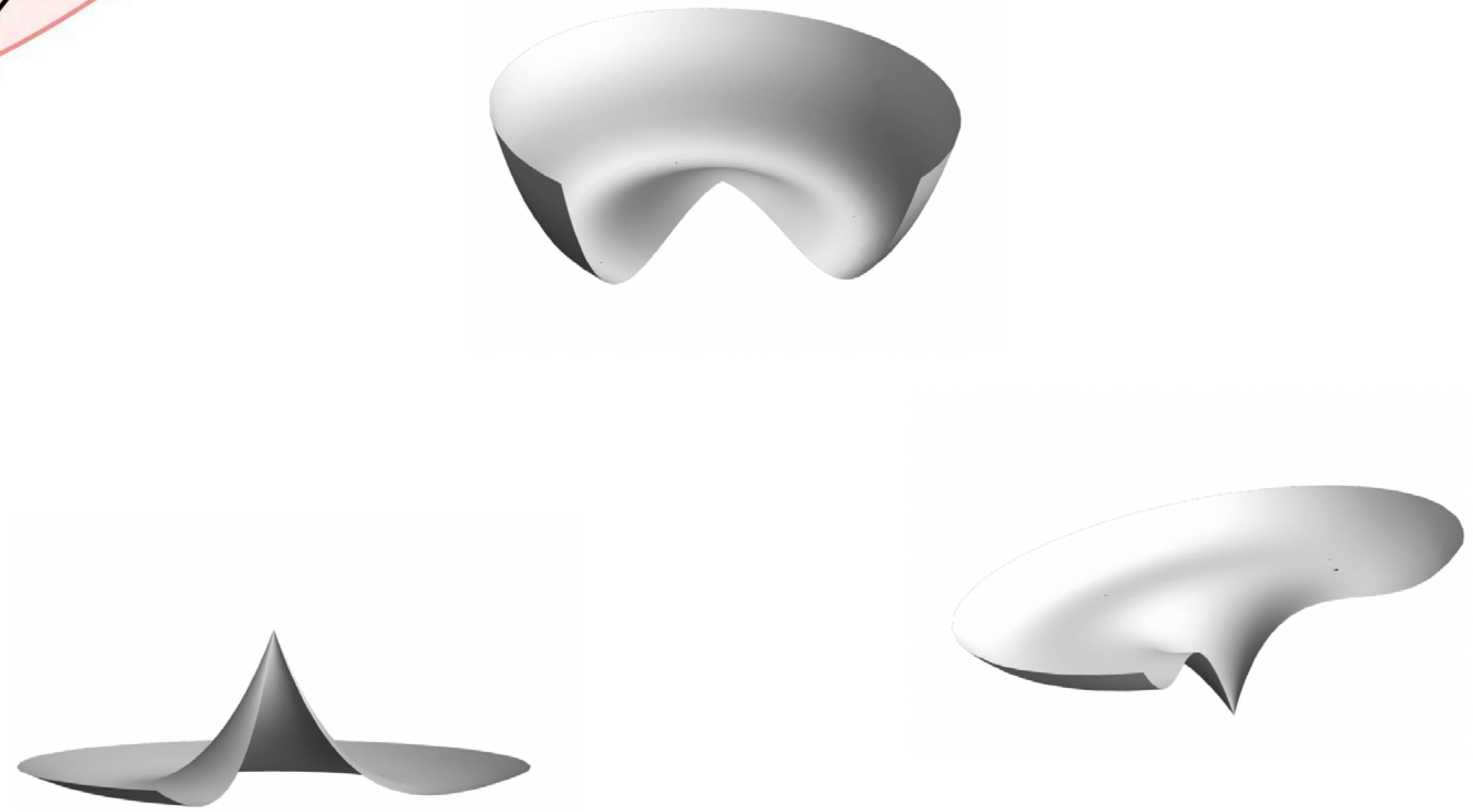


Open Questions in Particle Physics

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

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





Open Questions in Particle Physics

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

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

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

Open Questions in Particle Physics

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

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

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

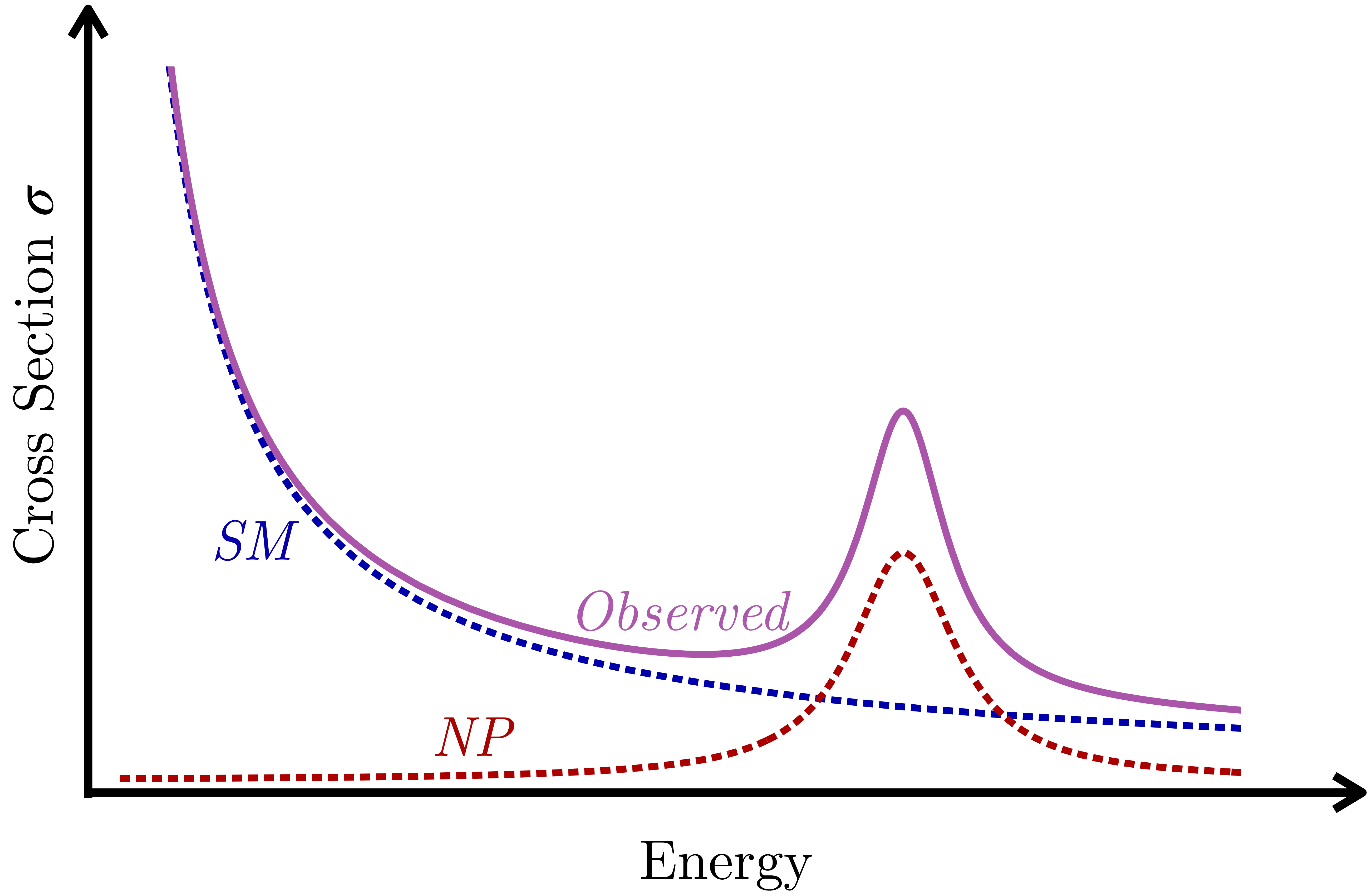
Unifying principle: *we need data at high energies*

Colliders are the best technology we have for this

THEORY & MACHINES

Two avenues for progress:

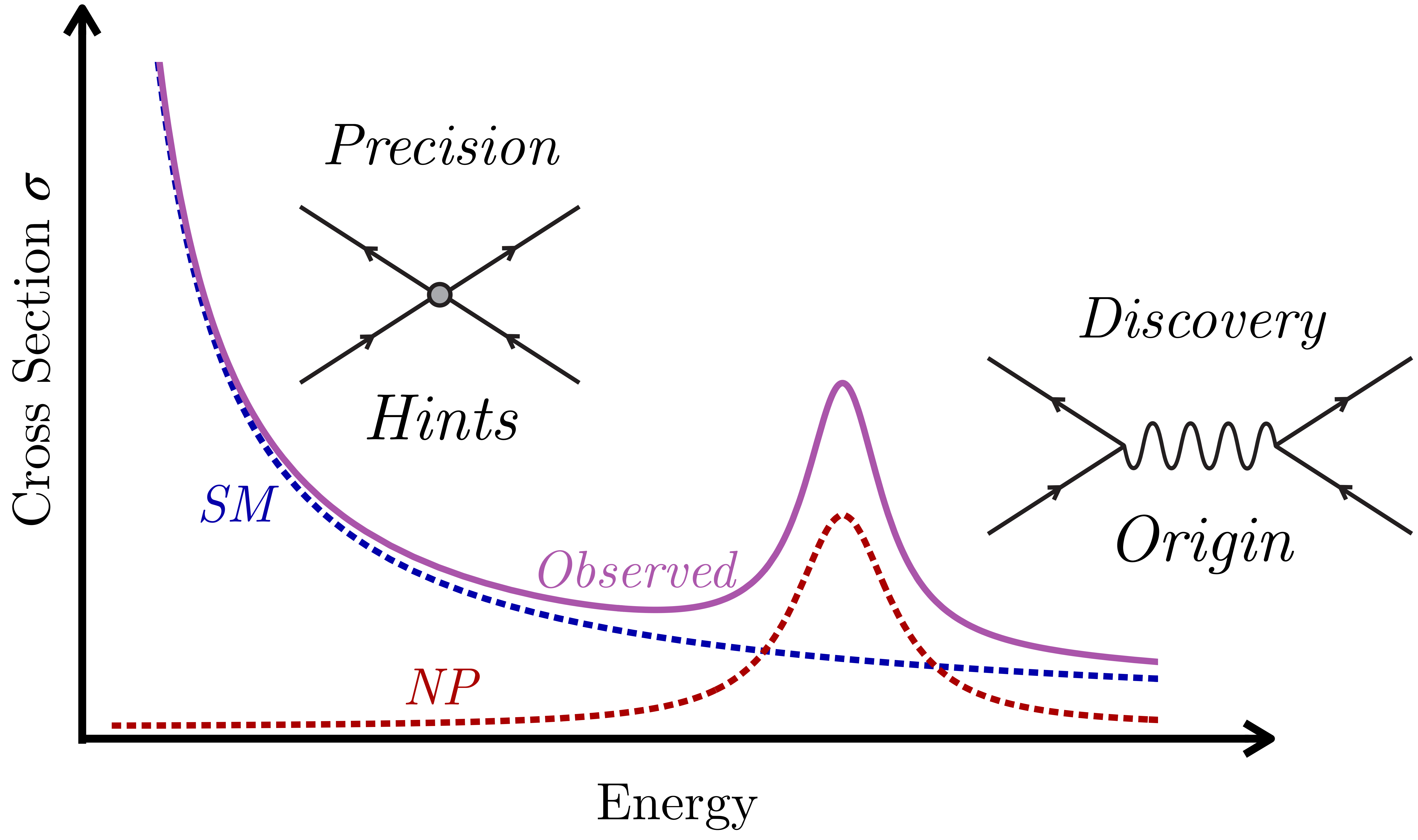
Precision or *Discovery* machines



THEORY & MACHINES

Two avenues for progress:

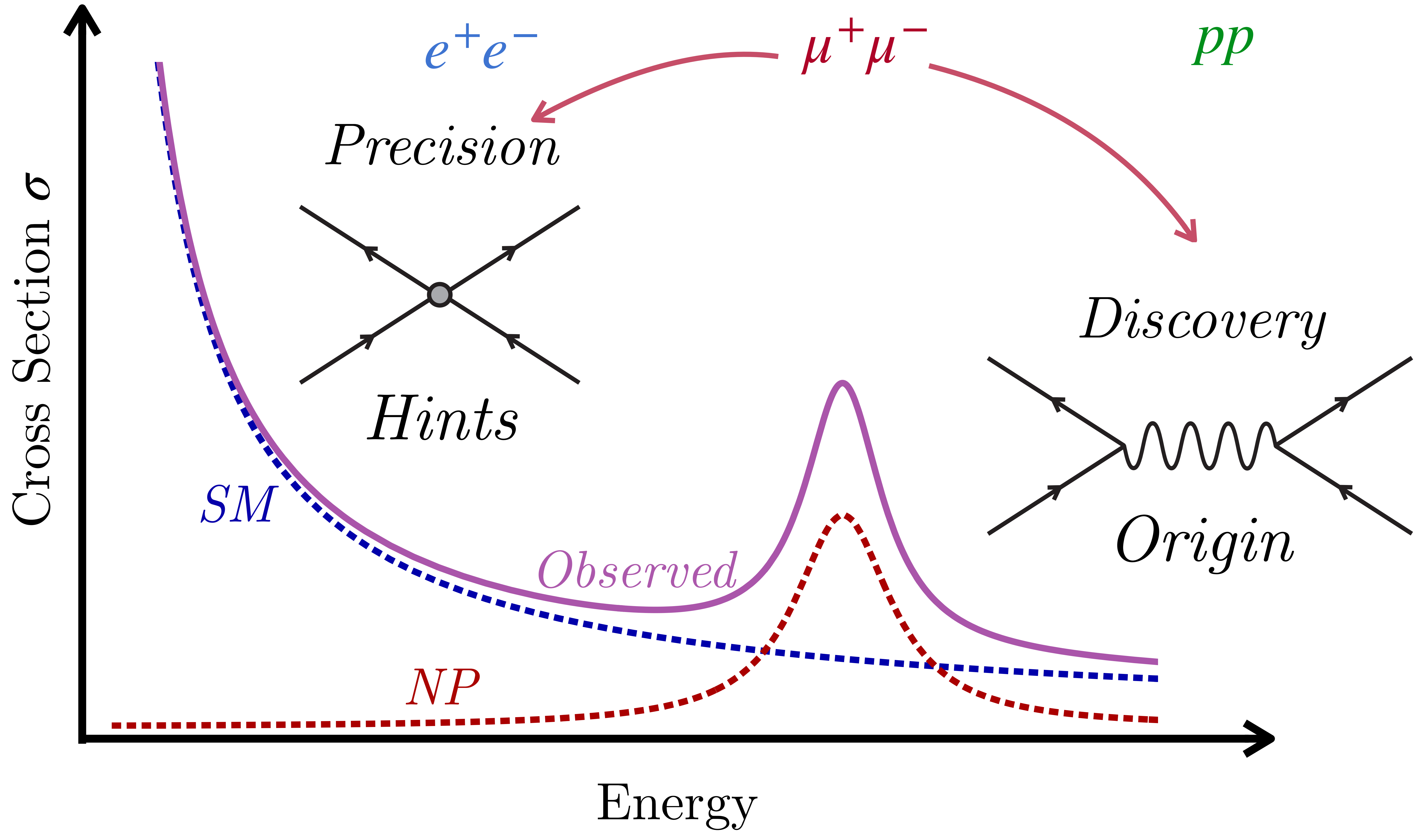
Precision or *Discovery* machines



Theory & Machines

Two avenues for progress:

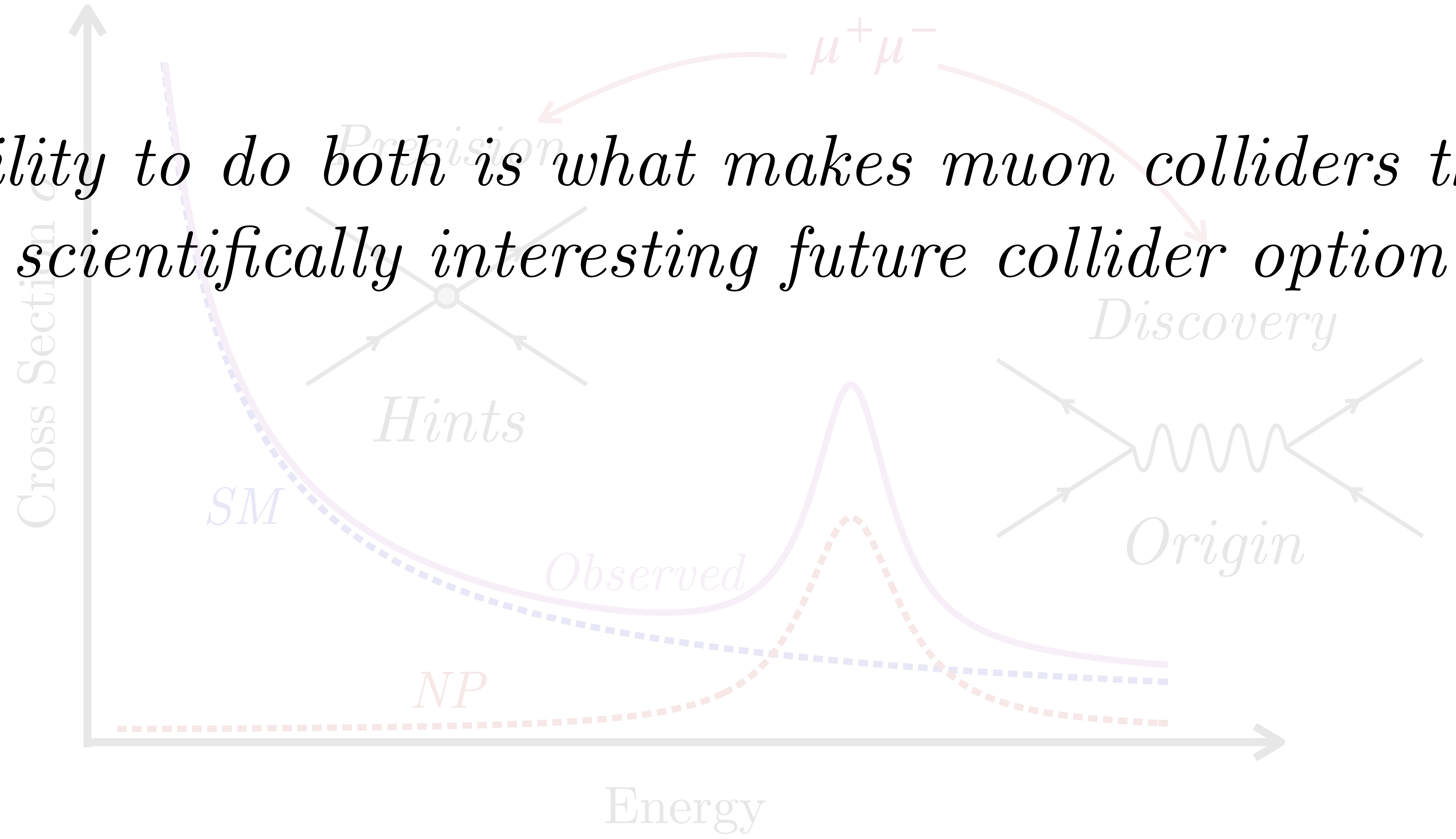
Precision and *Discovery* machines



Theory & Machines

Two avenues for progress:

Precision and *Discovery* machines

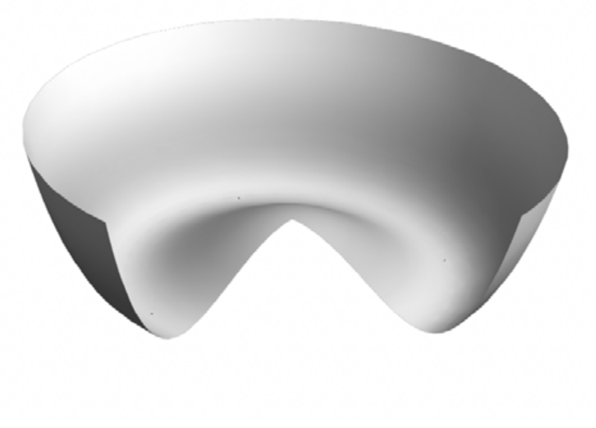


The ability to do both is what makes muon colliders the most scientifically interesting future collider option

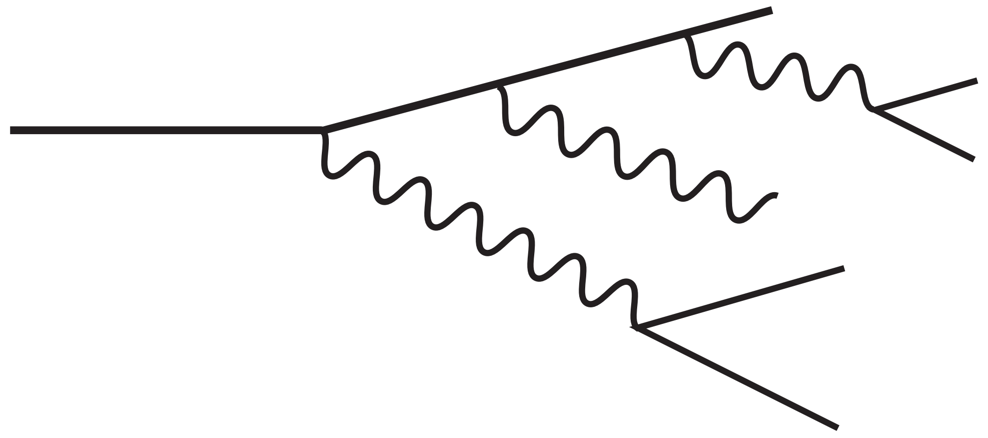
Physics Program at MuC

Standard Model (SM) Deliverables (cost justification?)

Higgs



Electroweak @ High Energy

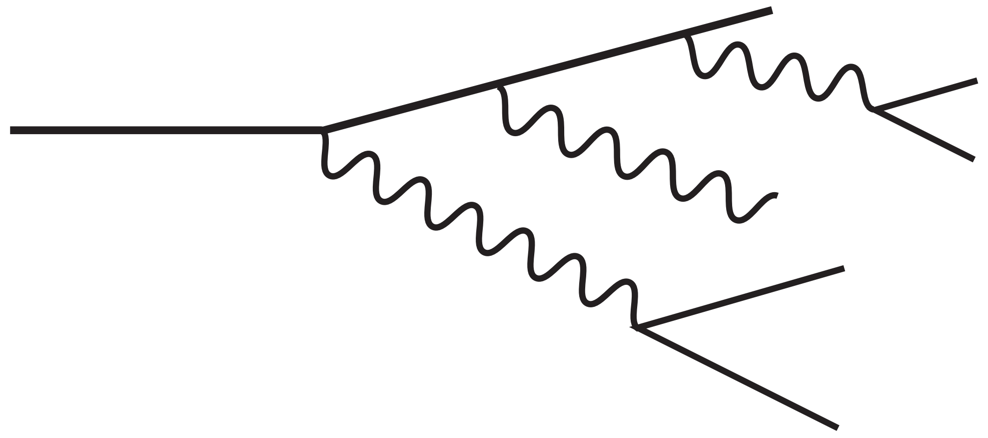


Physics Program at MuC

Standard Model (SM) Deliverables (cost justification?)

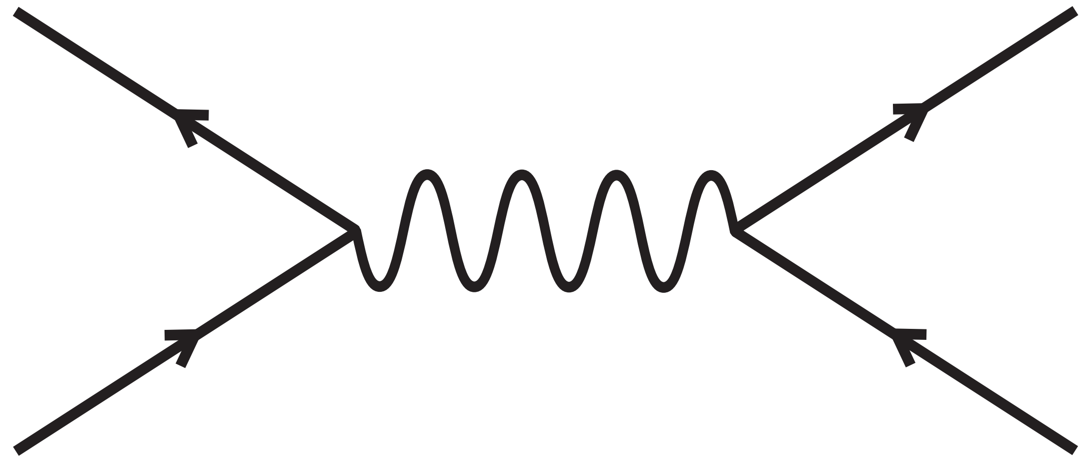
Higgs

Electroweak @ High Energy

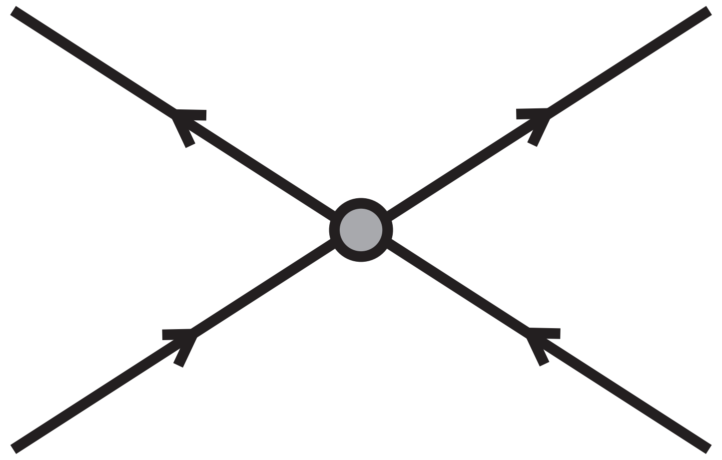


Beyond the Standard Model (BSM) Exploration

Direct

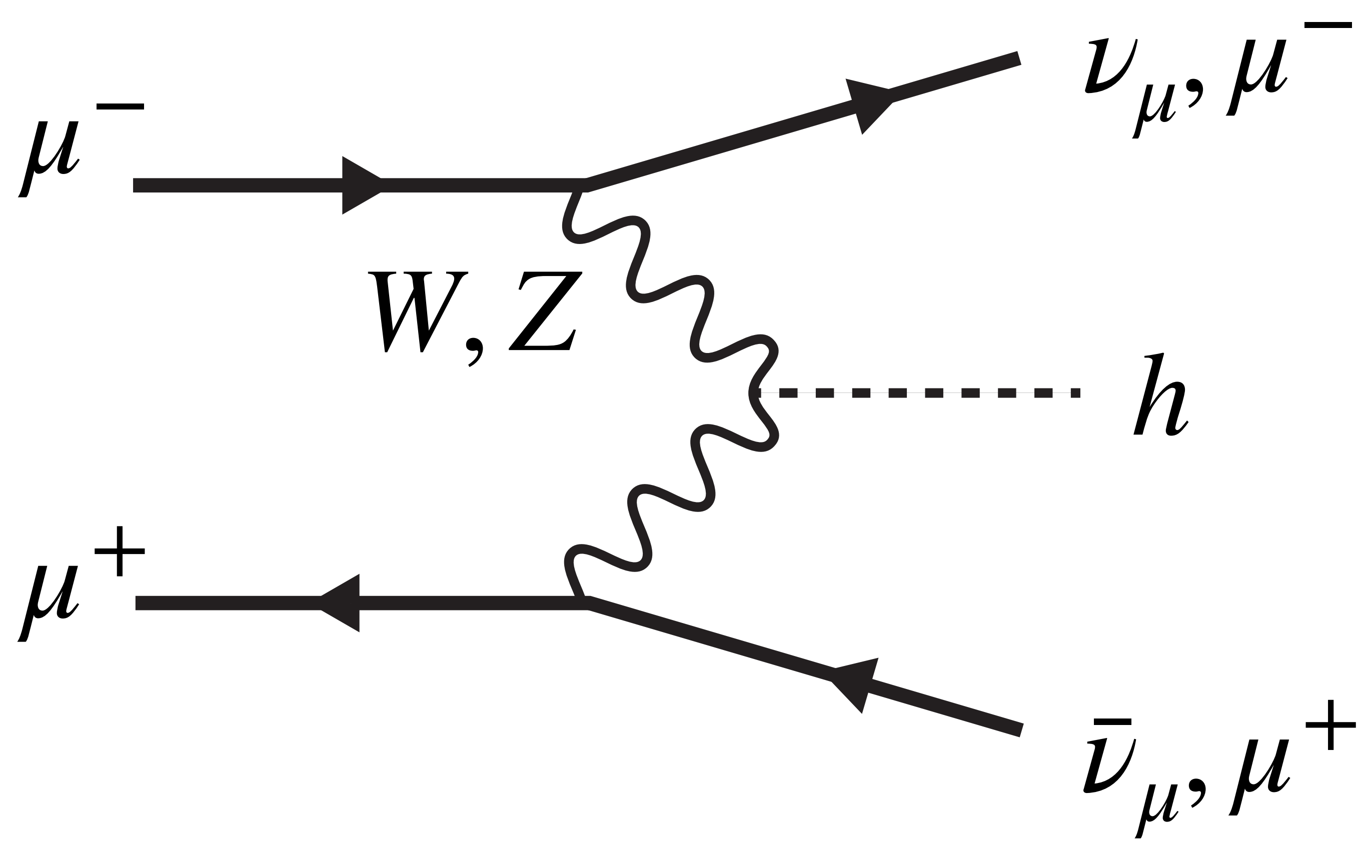


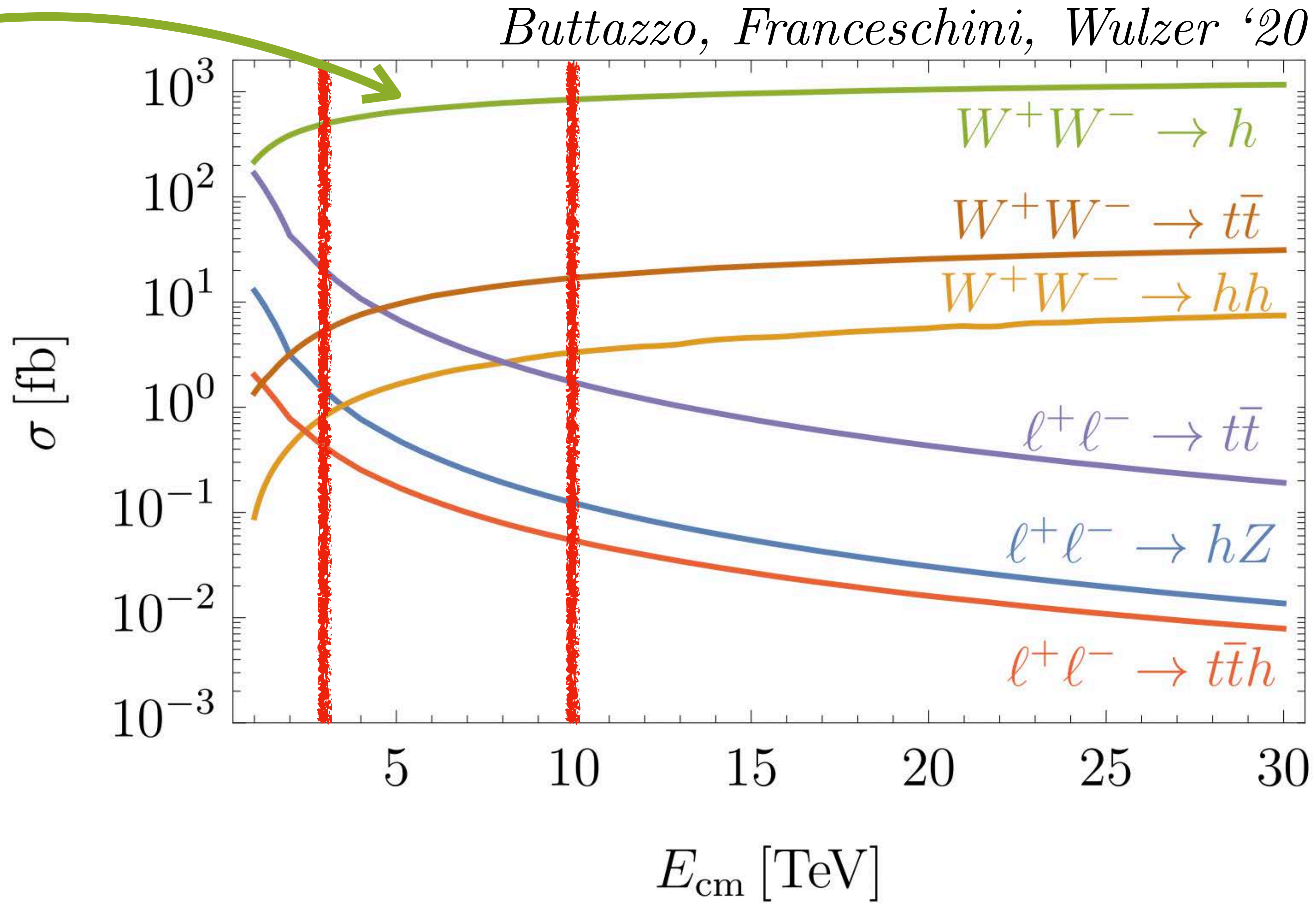
Indirect



Higgs Physics at MuC

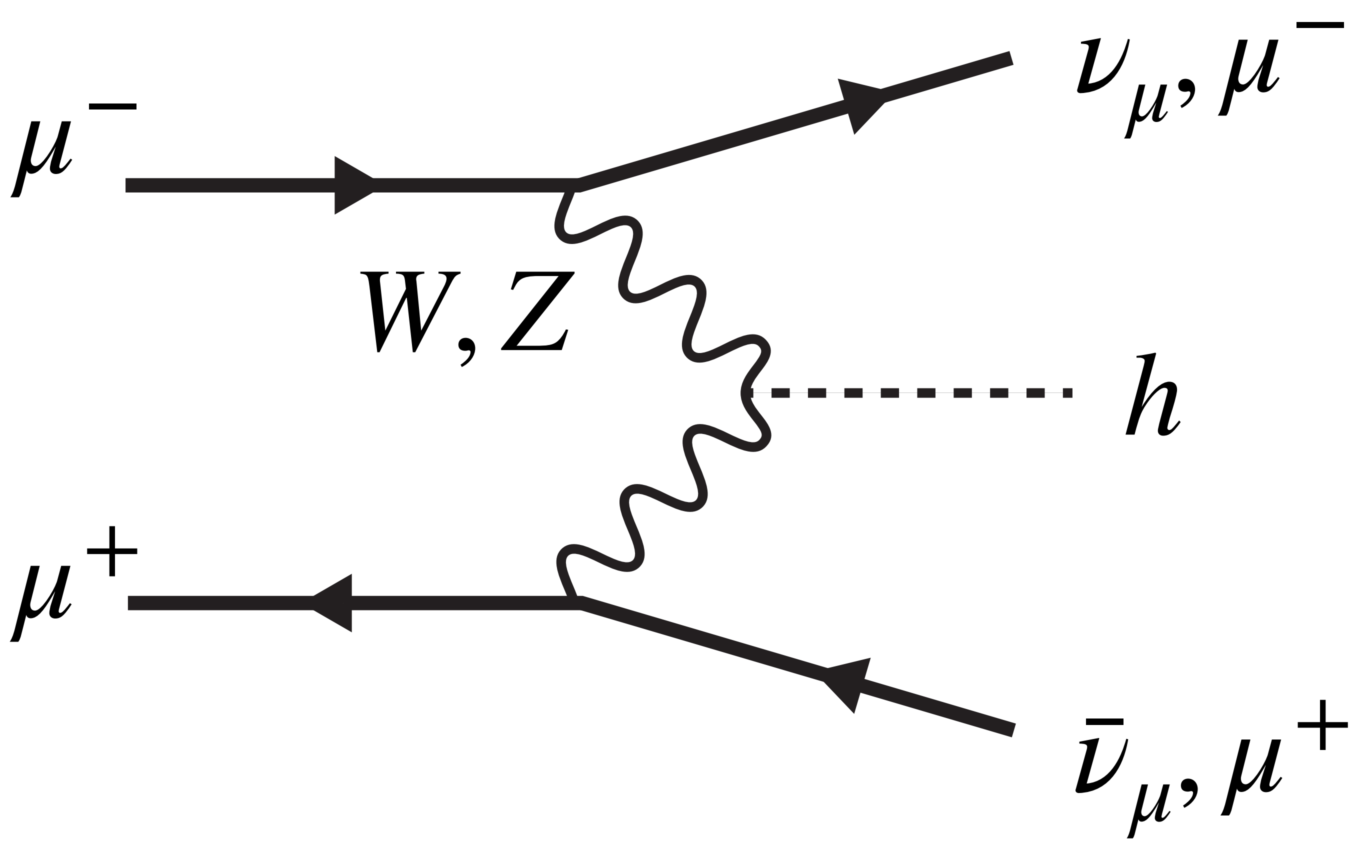
At MuC, more energy means *more Higgs*



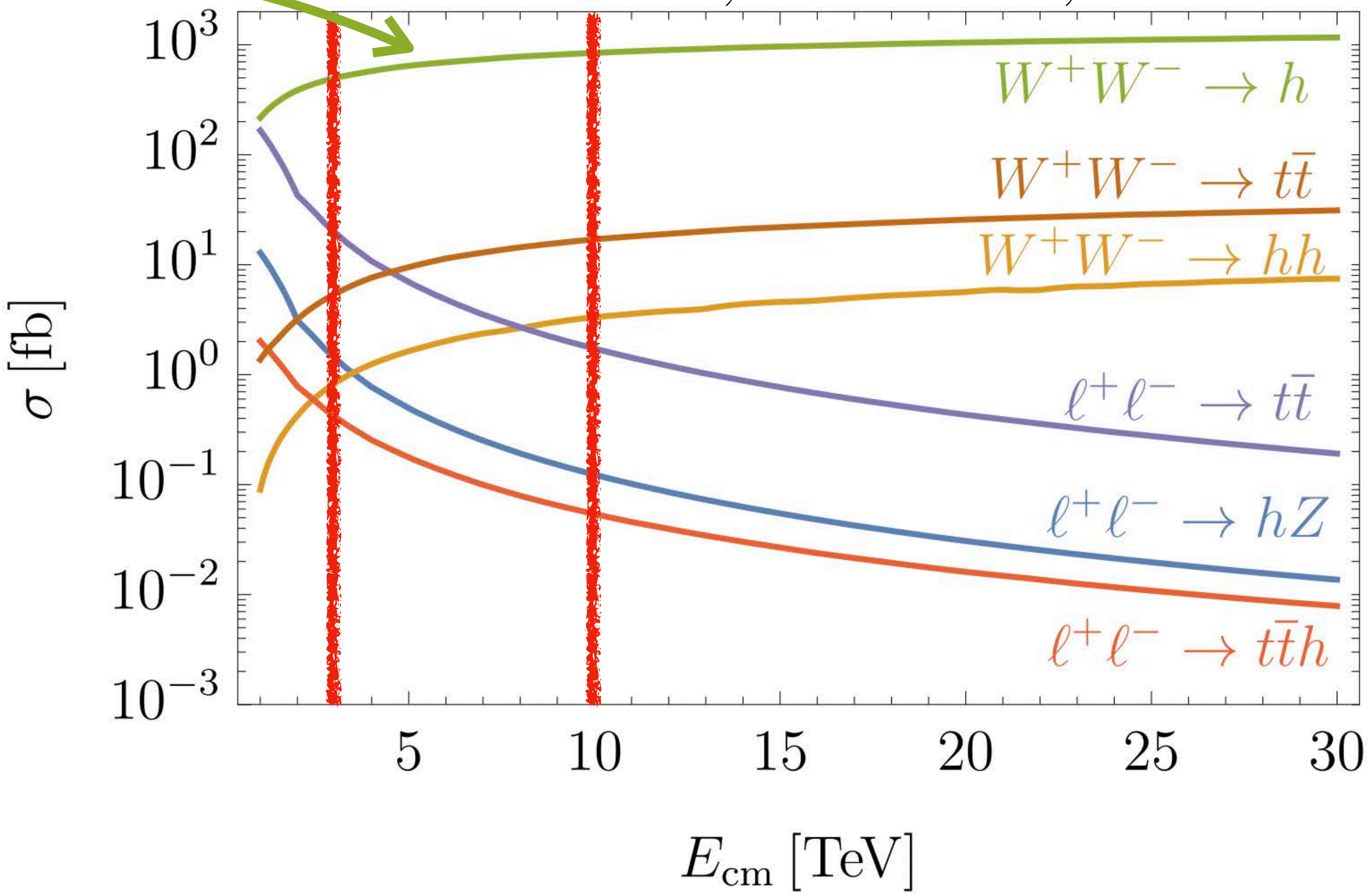


Higgs Physics at MuC

At MuC, more energy means *more Higgs*



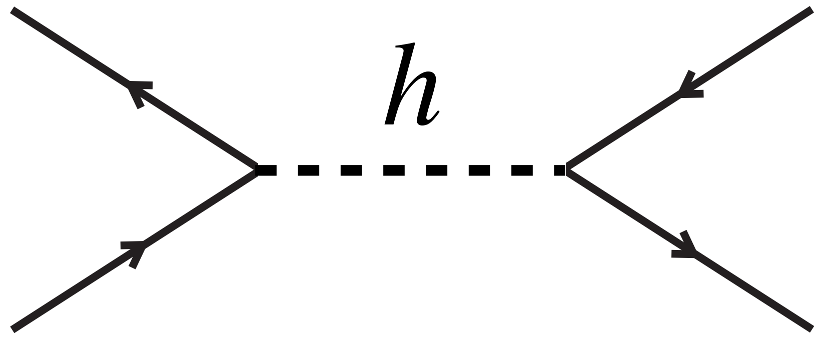
Buttazzo, Franceschini, Wulzer '20



Threshold (s-channel) too small

—muons are light!

$\sqrt{s} = m_h$



Nothing *special* about 10 TeV,

just *a lot* of Higgs ($\sim 10^6$)

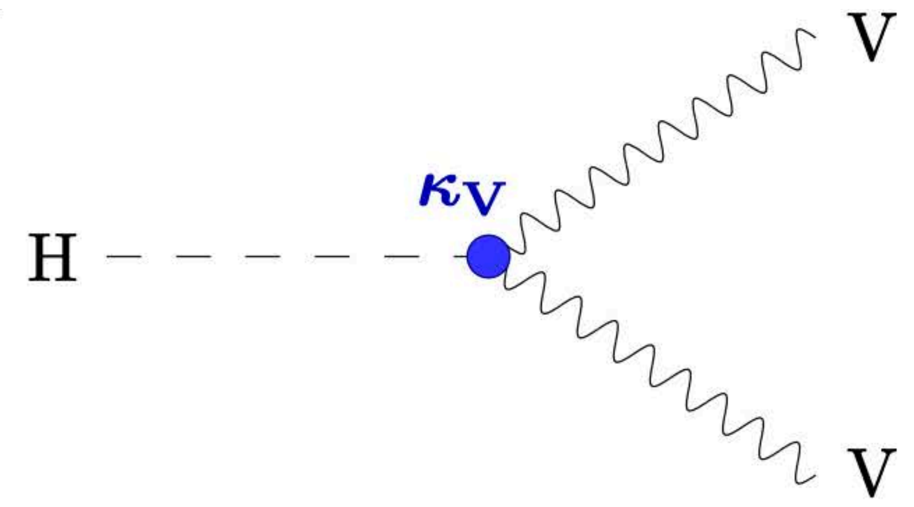
Higgs Physics at MuC

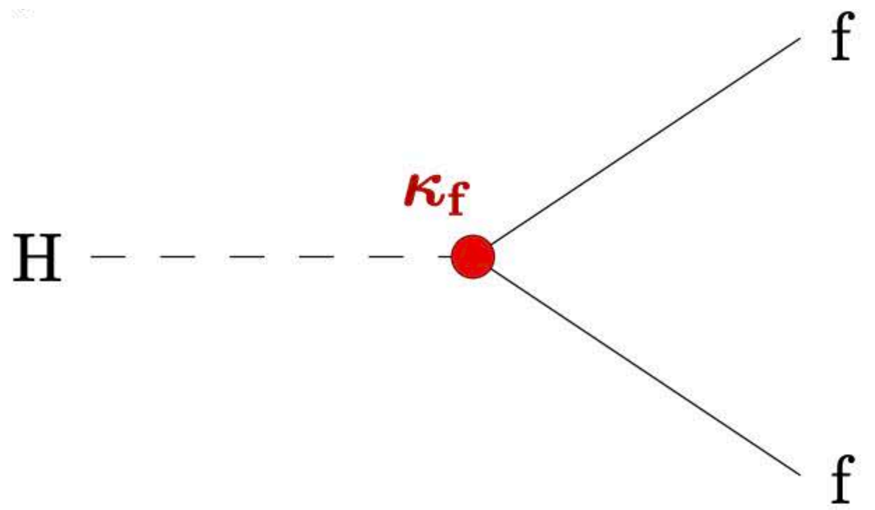
With a *Higgs Factory*, we can improve measurements on couplings

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

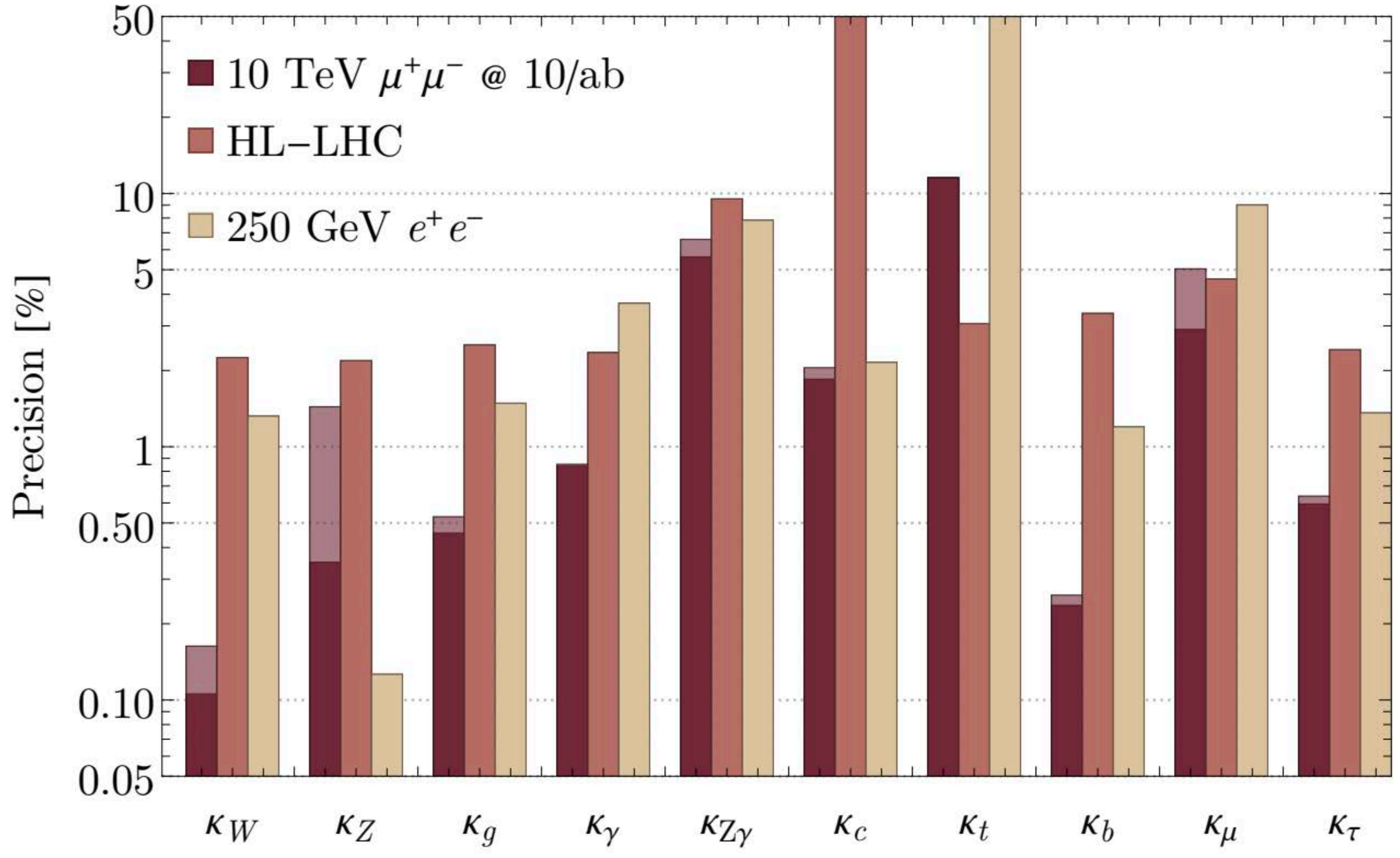
κ Framework

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

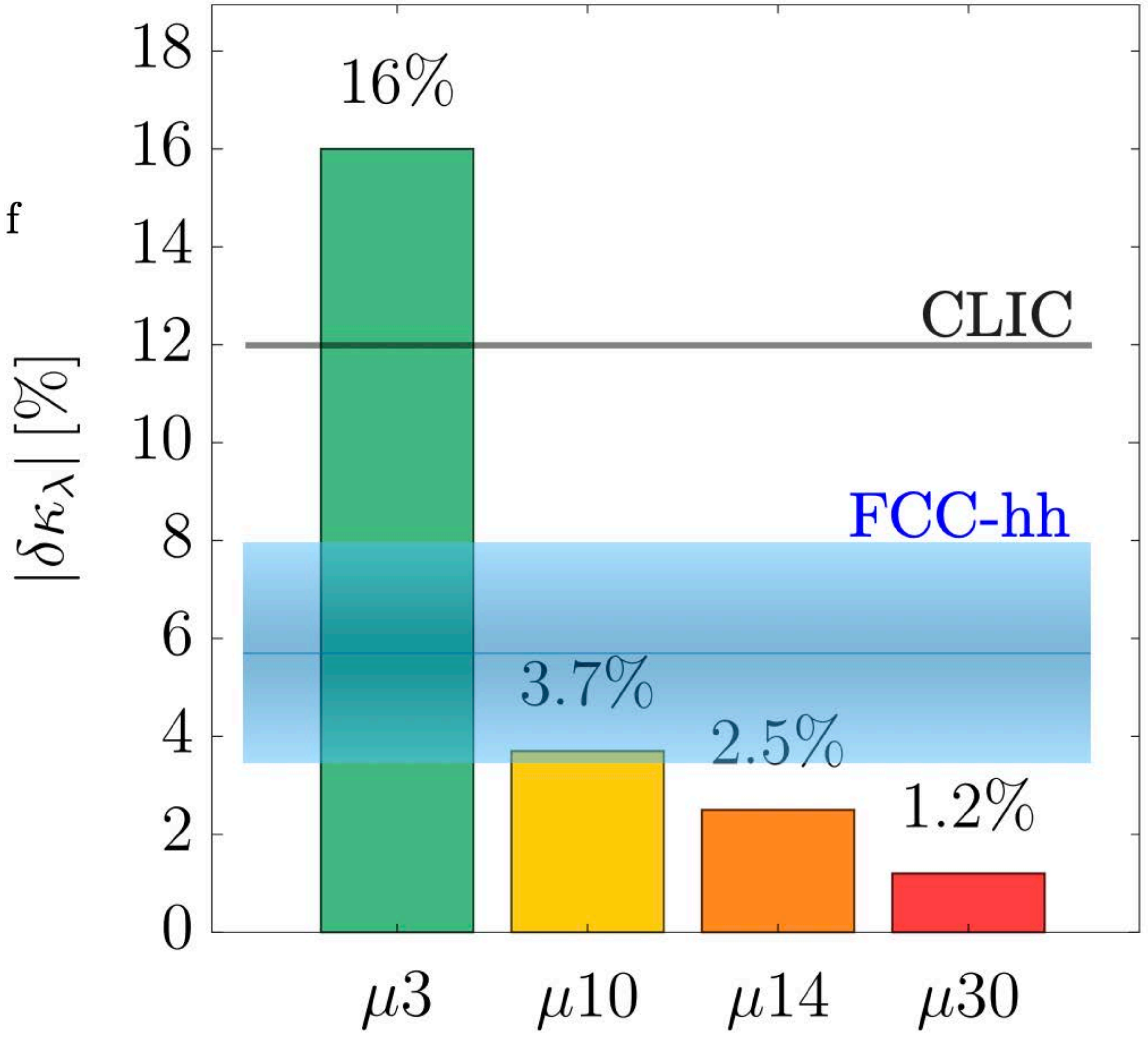




Forslund & Meade '23



Towards a Muon Collider '23



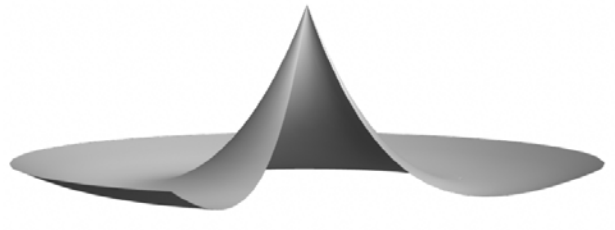
Higgs Physics at MuC

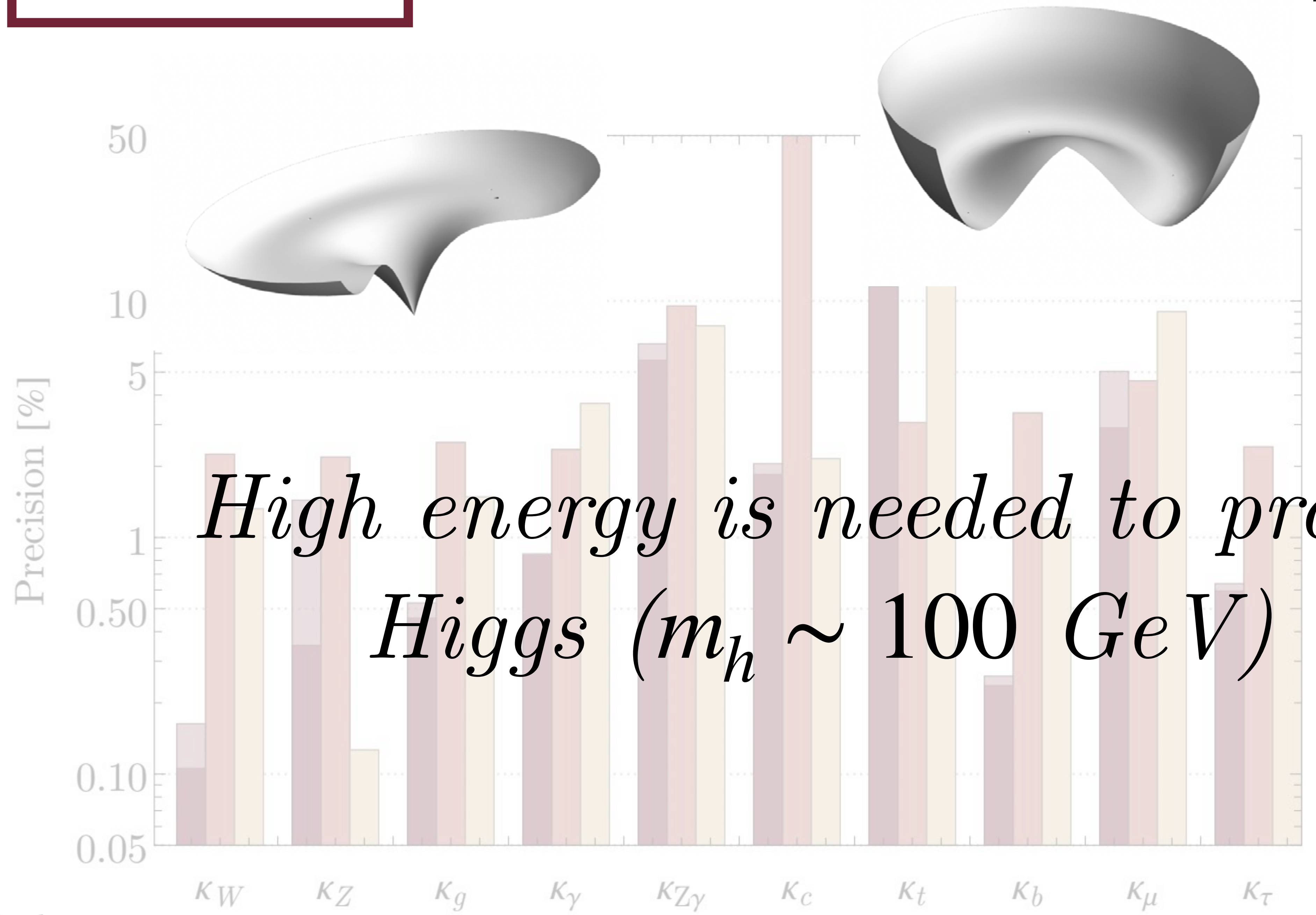
With a *Higgs Factory*, we can improve measurements on couplings

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

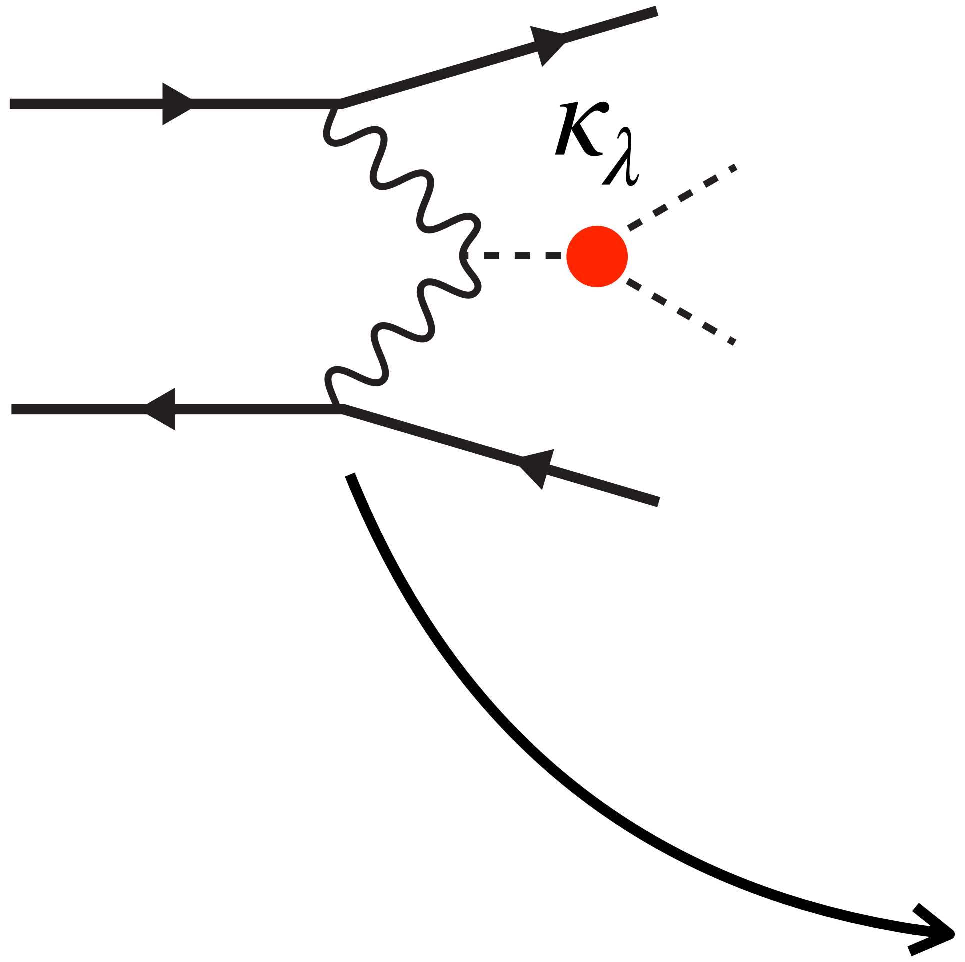
κ Framework

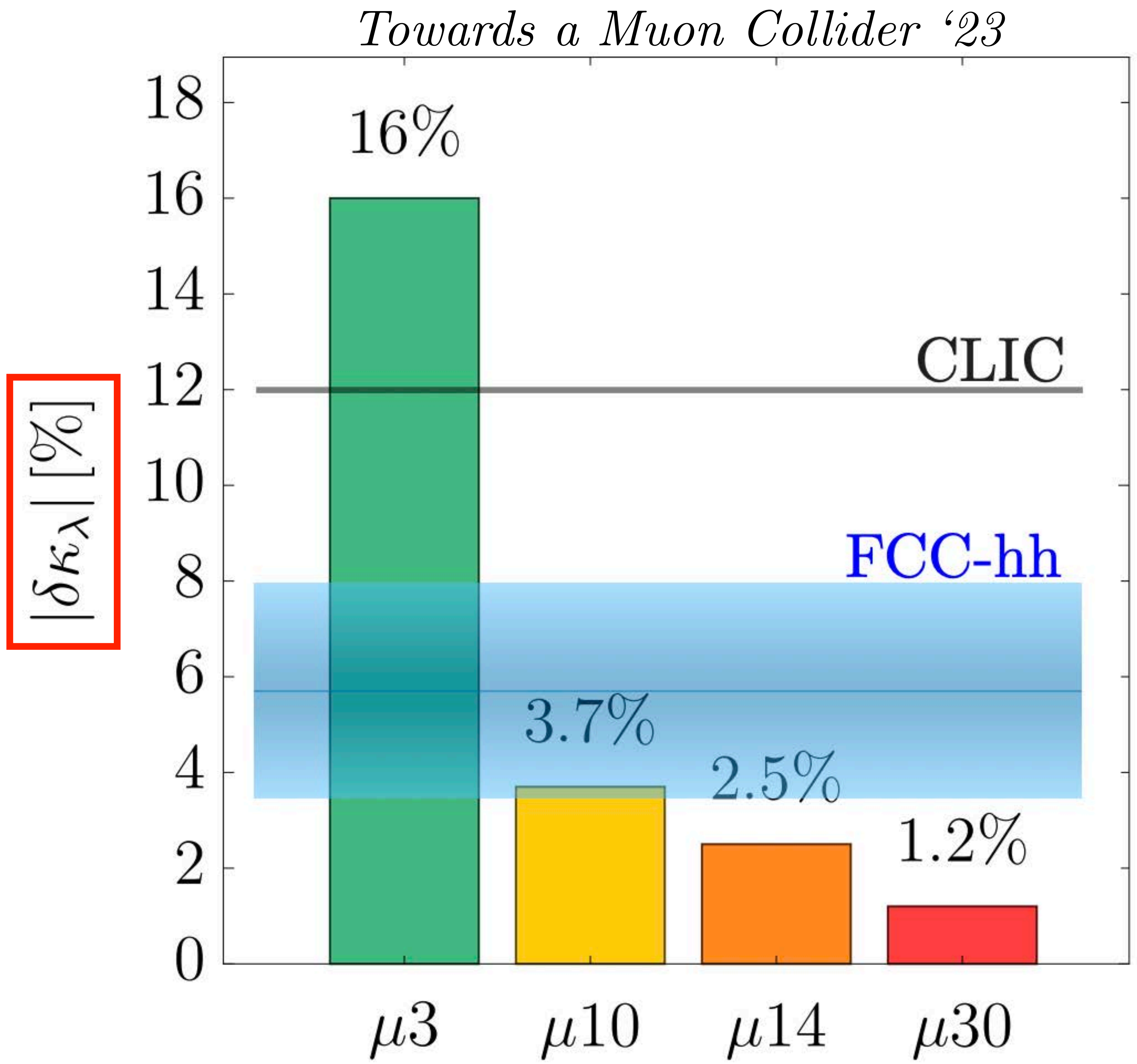
$$\kappa_X \sim \frac{\mathcal{O}_X^{obs}}{\mathcal{O}_X^{SM}}$$





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





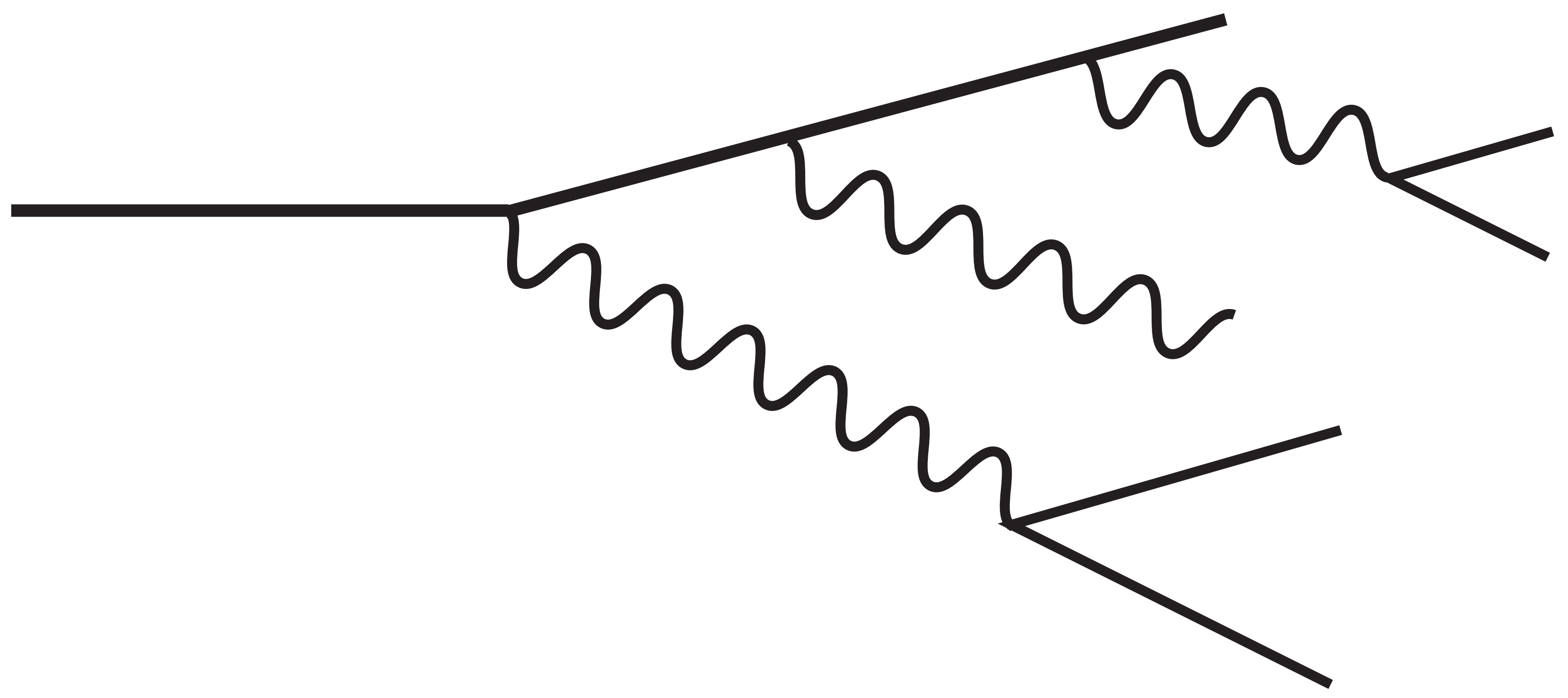
EW Physics at MuC

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

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



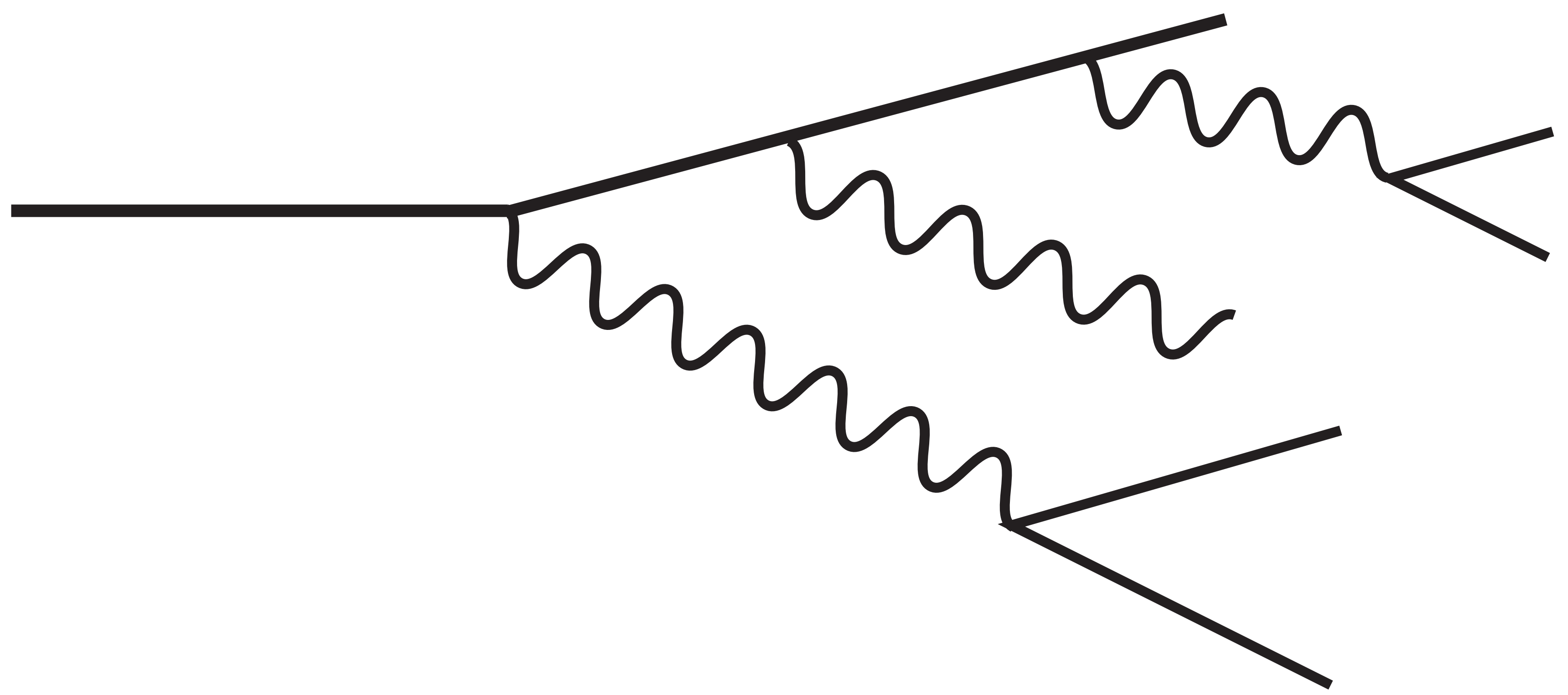
EW Physics at MuC

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

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



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

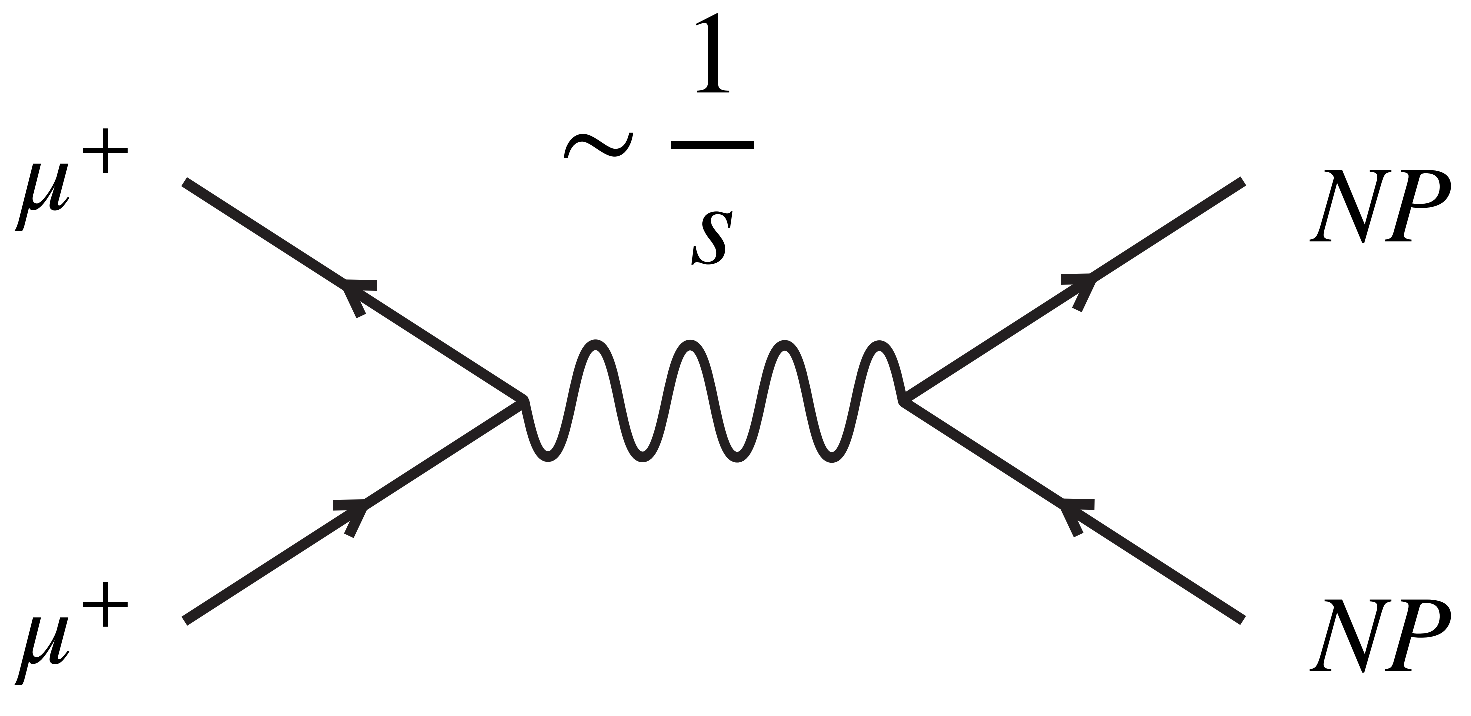
How do we understand loop corrections to EW processes? (Ma, Pagani, Zero '24)

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

...

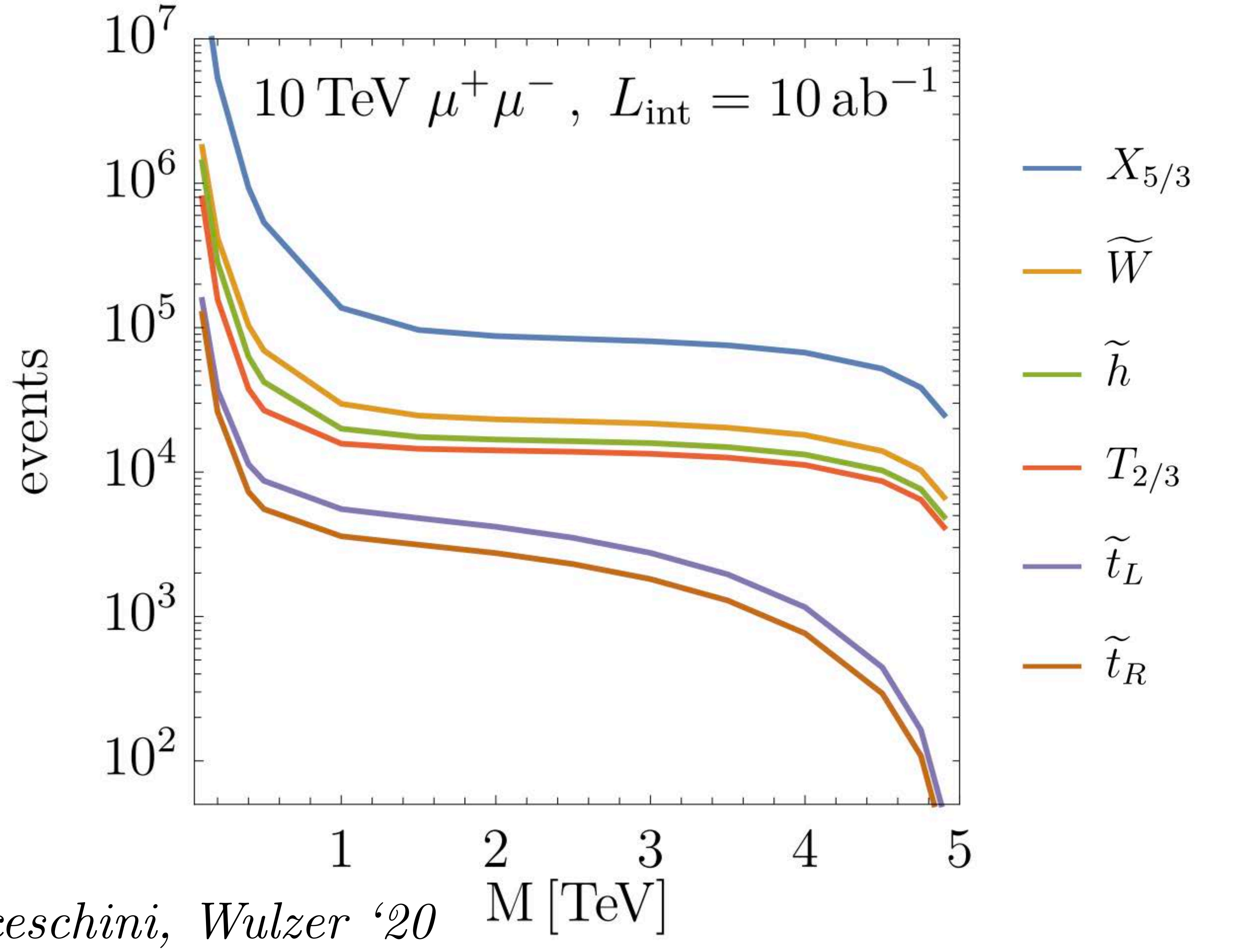
BSM Direct Searches

We assume we can directly produce on-shell new particles



Reach is often kinematic:

$$m_{\rm NP} \lesssim \sqrt{s} \qquad \rightarrow \mathscr{L} \sim \frac{N_\mu}{\text{bunch}} \times E^2$$



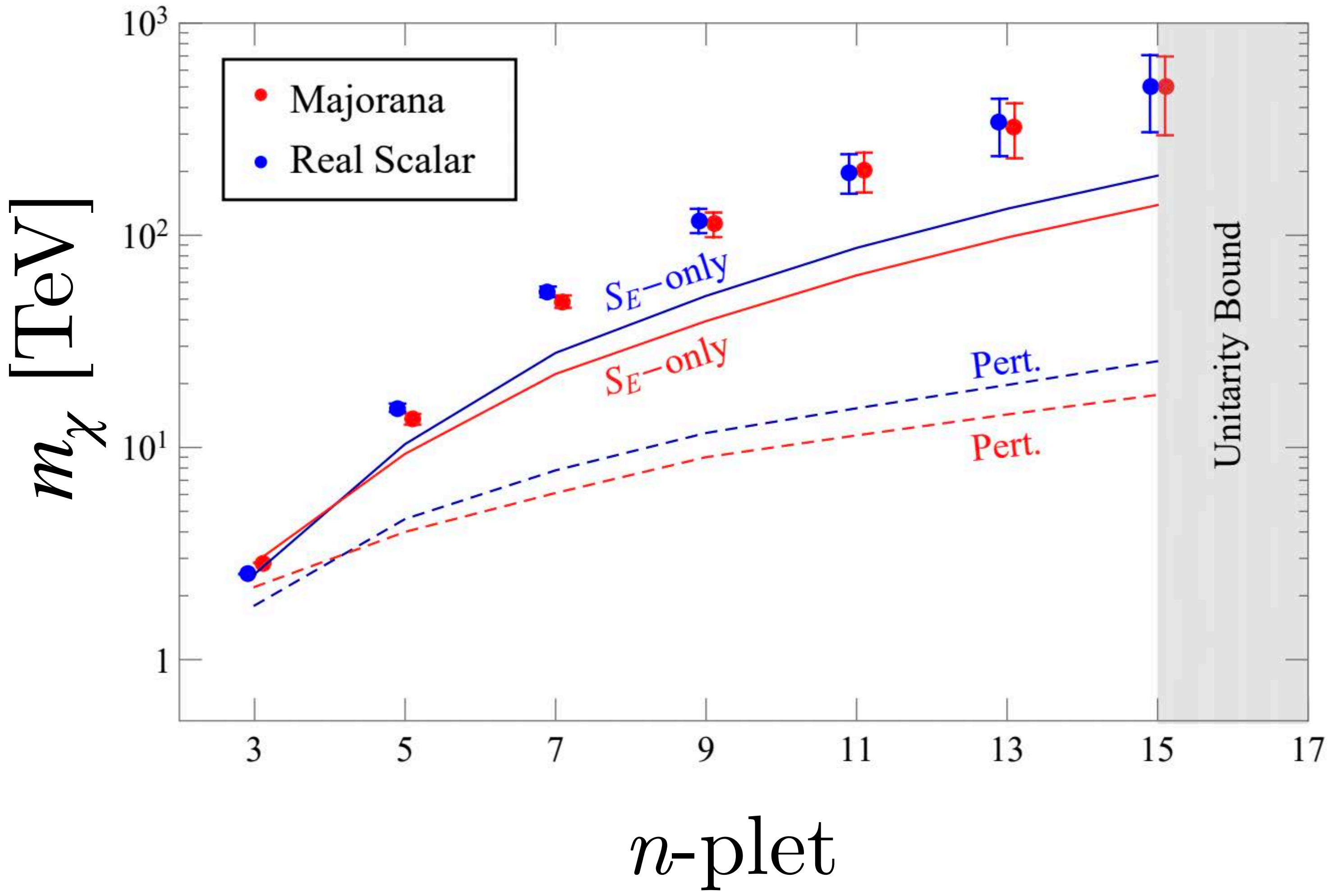
High-energy is the key to empirical evidence for a UV theory of the SM

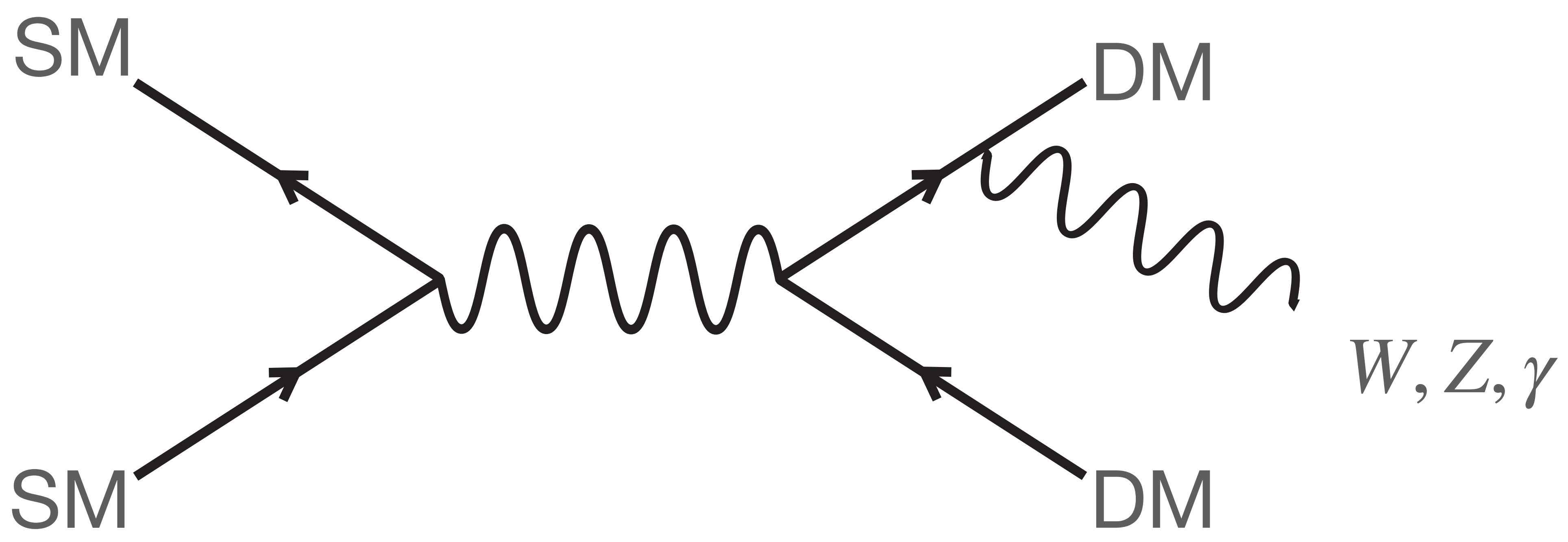
Buttazzo, Franceschini, Wulzer '20

BSM Direct Searches

We assume we can directly produce on-shell new particles

Example: Thermal Dark Matter





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

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

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

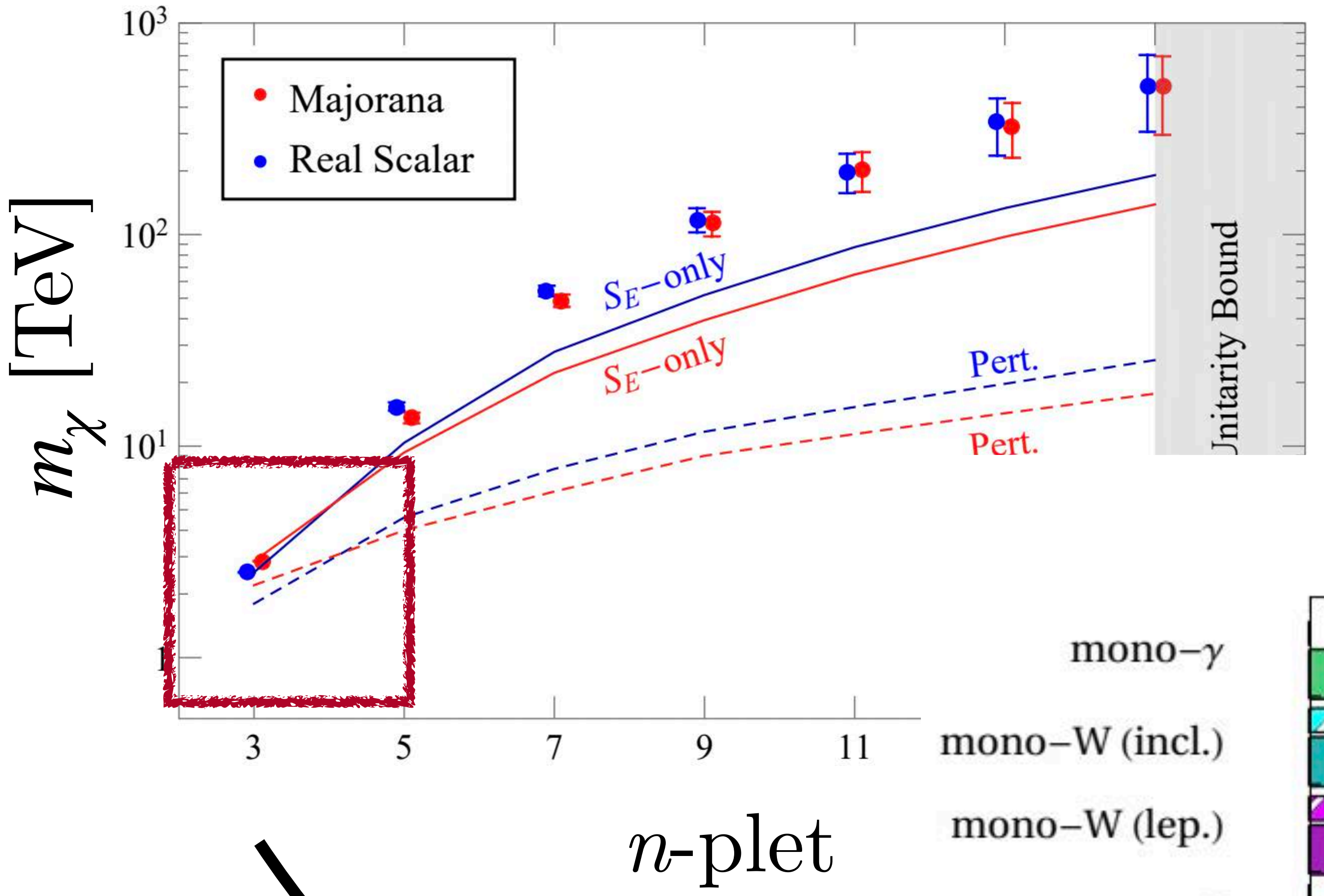
Cesarotti, Krnjaic '24

Han, Liu, Wang, Wang '20

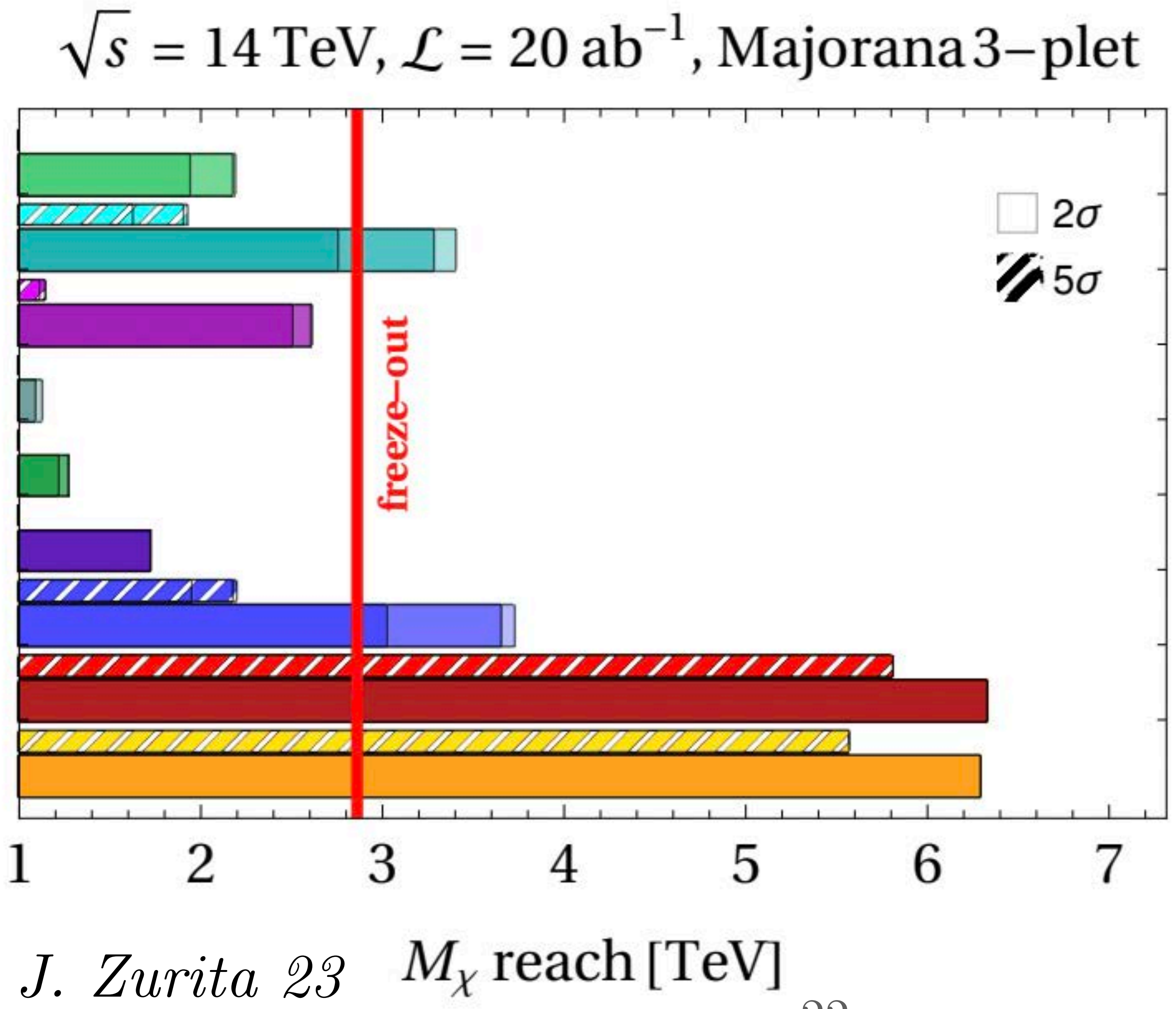
BSM Direct Searches

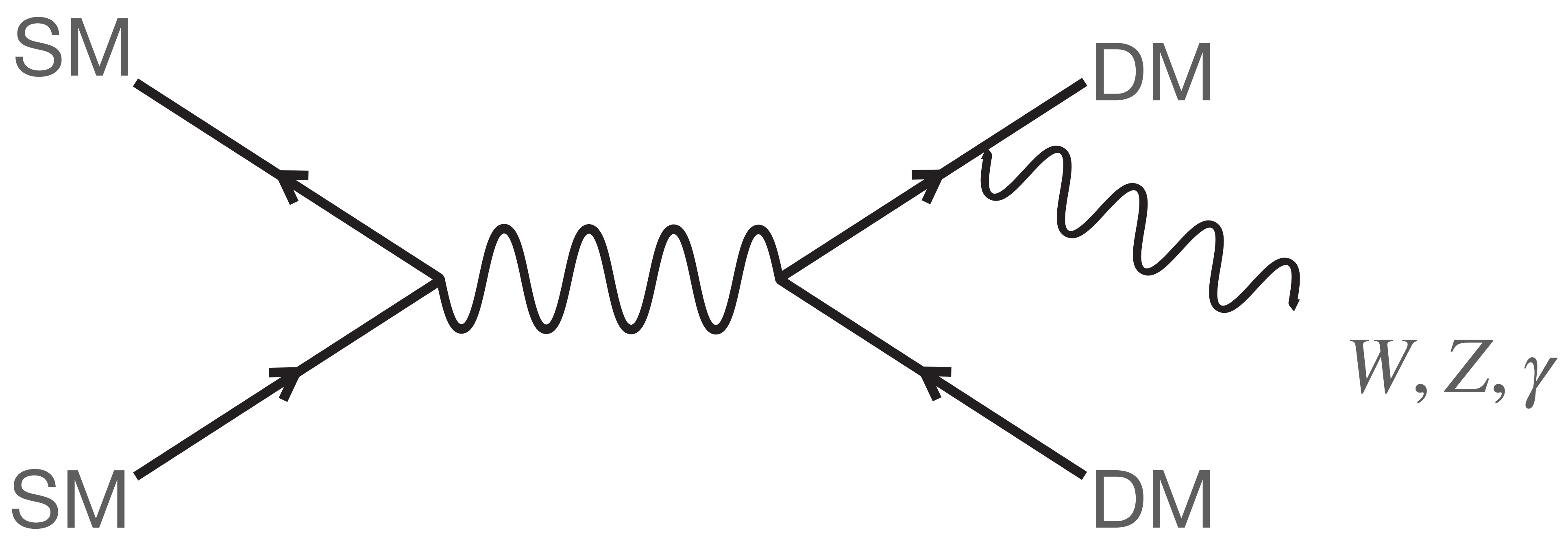
We assume we can directly produce on-shell new particles

Example: Thermal Dark Matter



SU(2) 3-plet





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

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

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

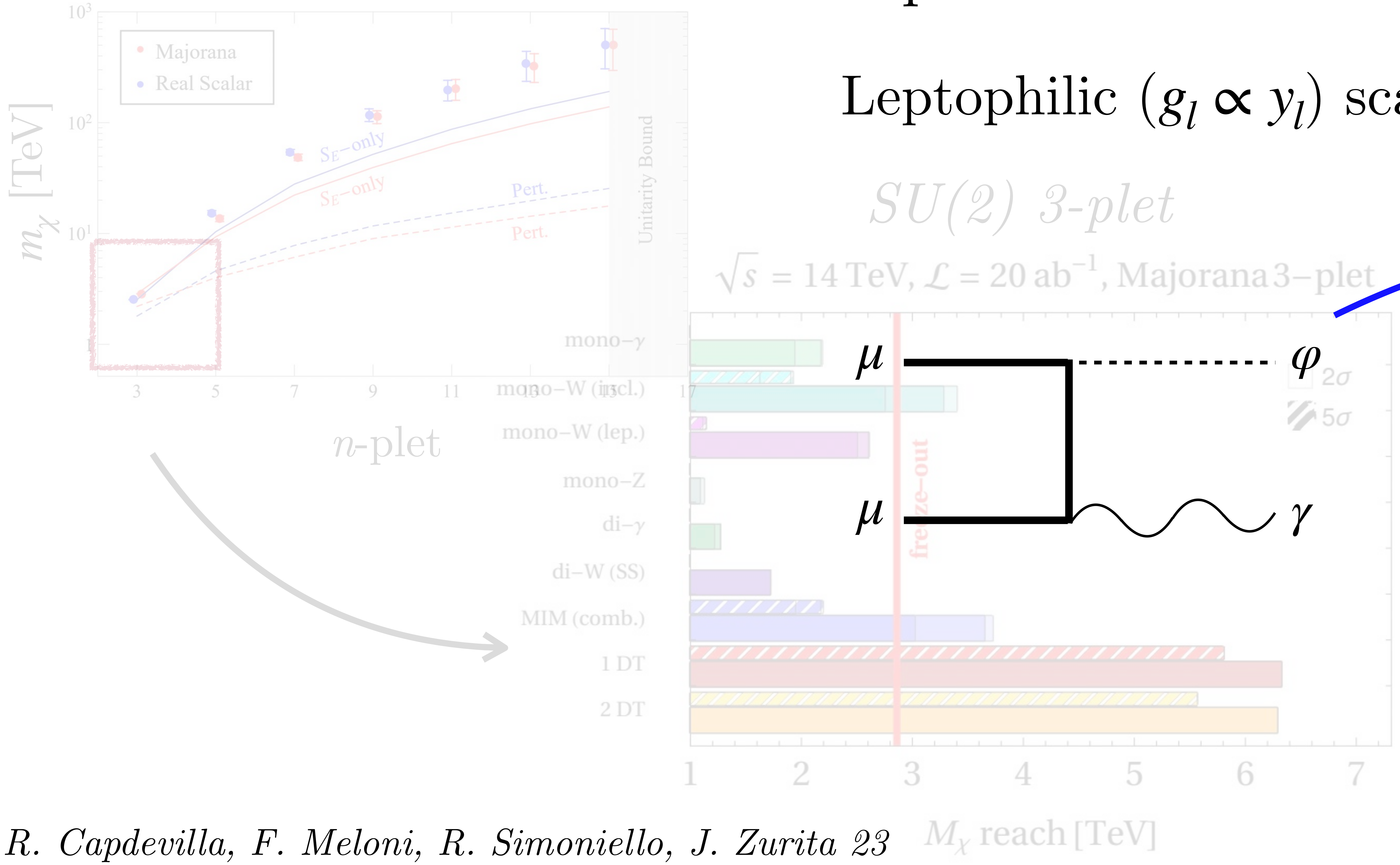
Cesarotti, Krnjaic '24

Han, Liu, Wang, Wang '20

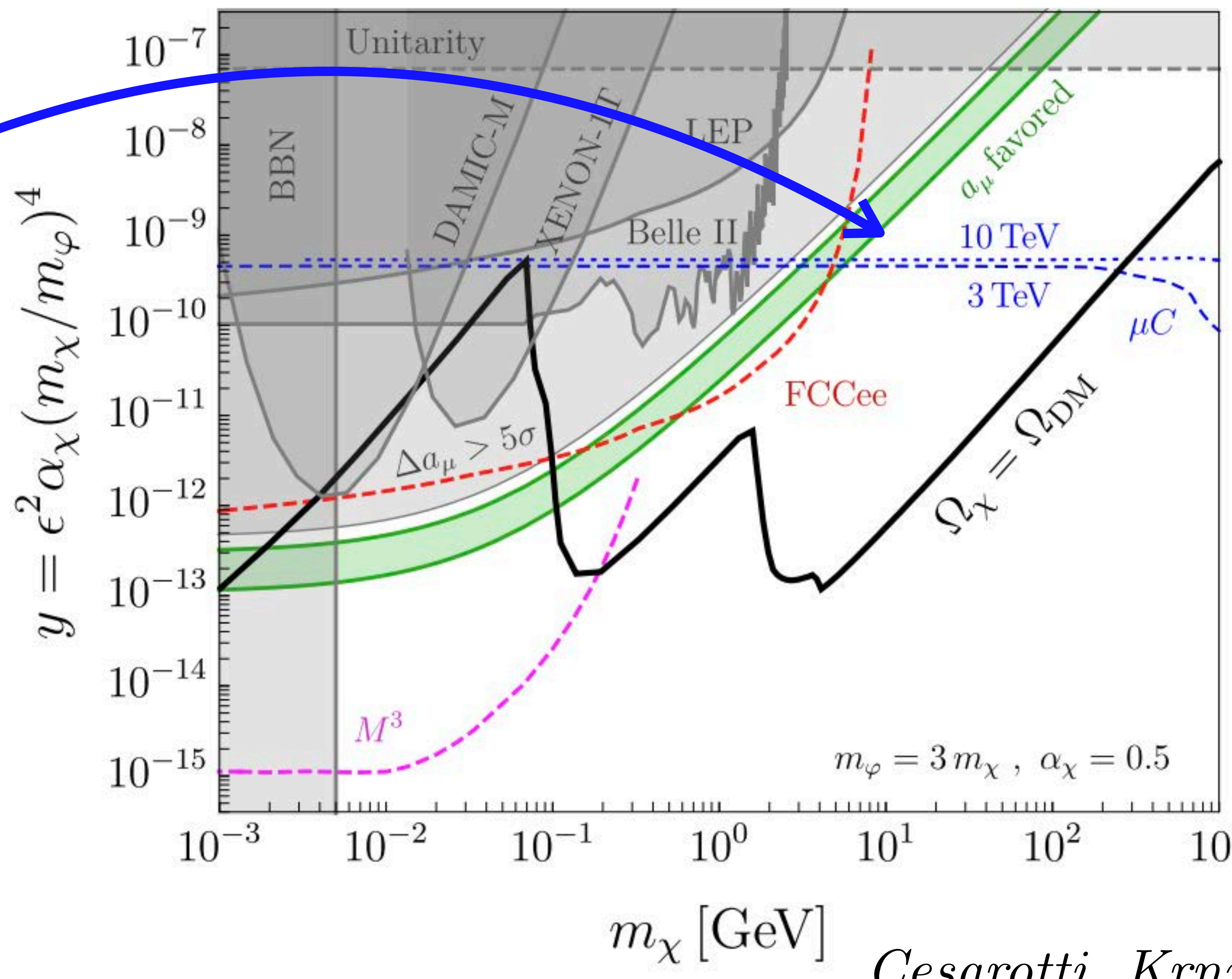
BSM Direct Searches

We assume we can directly produce on-shell new particles

Example: Thermal Dark Matter



Leptophilic ($g_l \propto y_l$) scalar portal DM—also ideal at MuC



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

Cesarotti, Krnjaic '24

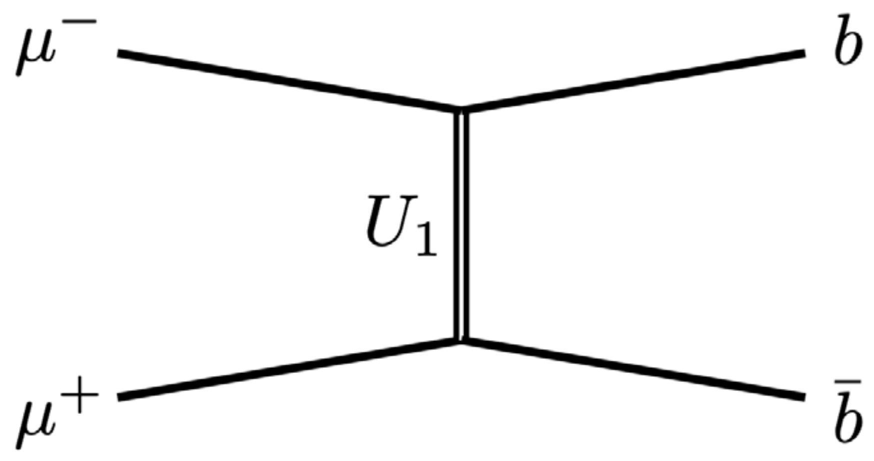
Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

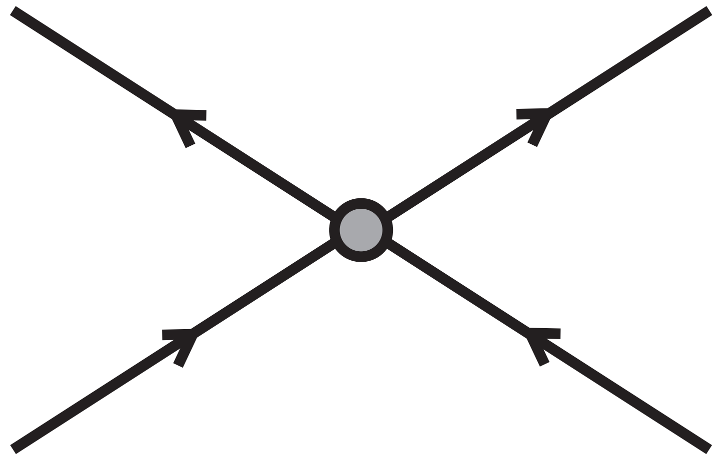
Han, Liu, Wang, Wang '20

BSM Indirect Searches

BSM particles are *not* in final state, only effects are observed

Can probe beyond $m_{NP} > \sqrt{s}$... but *not uniquely constraining*

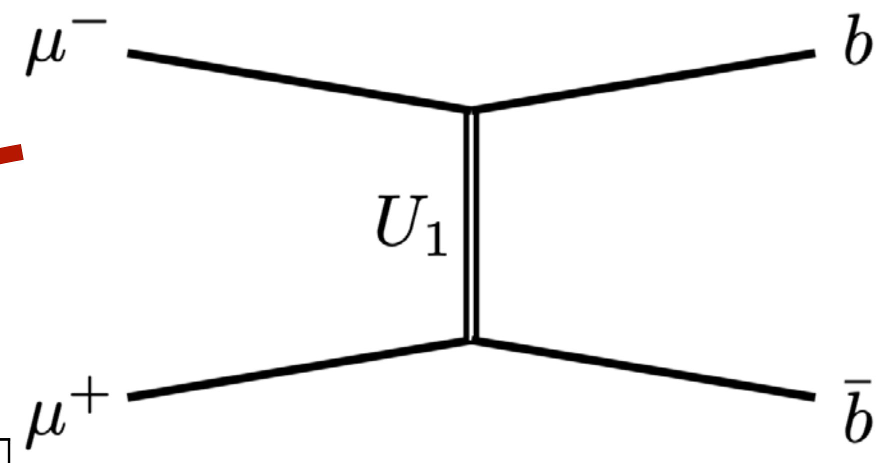


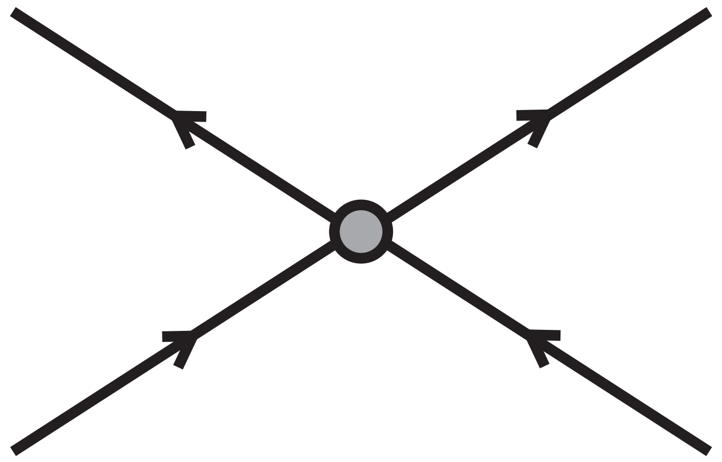


BSM Indirect Searches

BSM particles are *not* in final state, only effects are observed

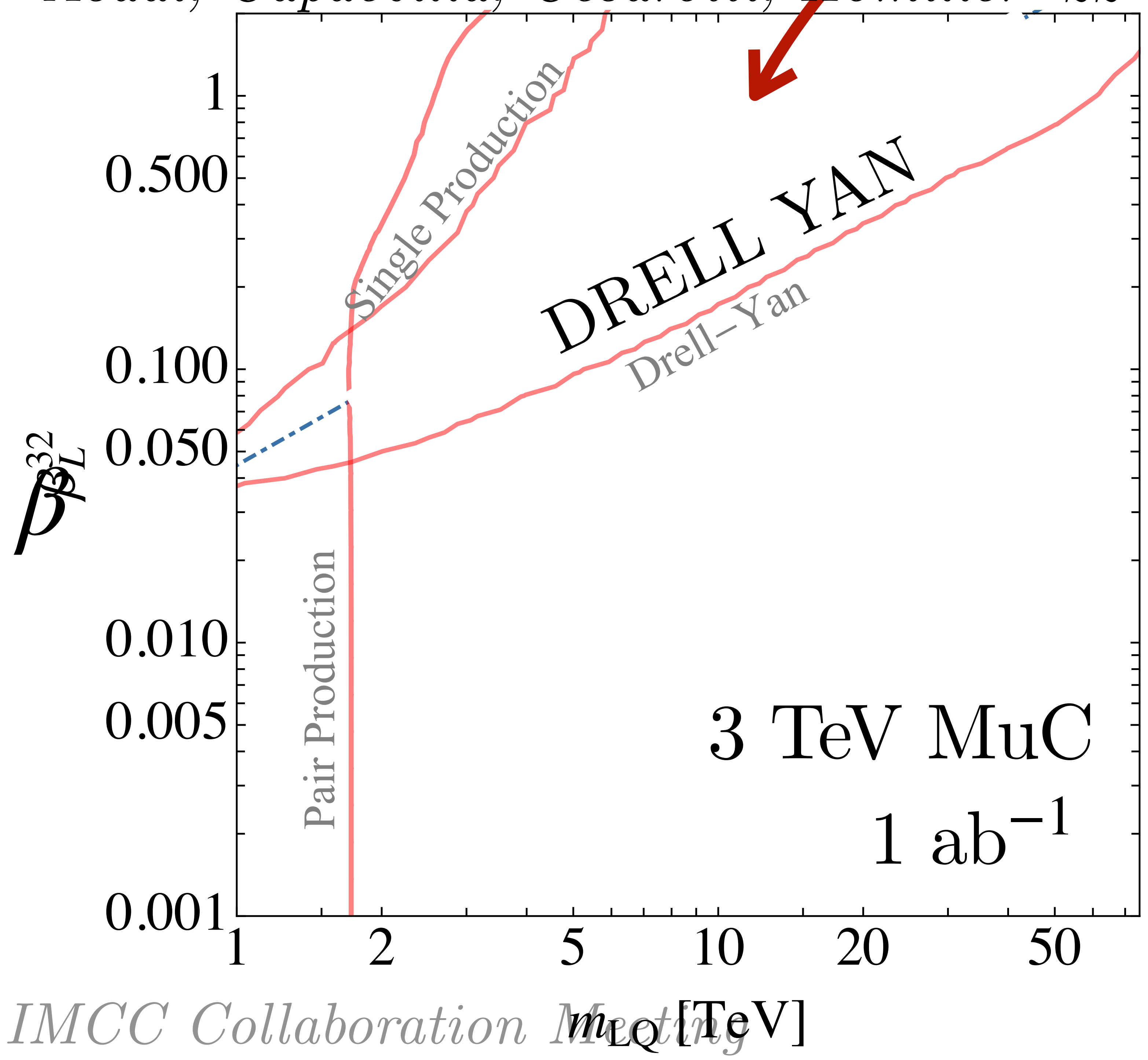
Can probe beyond $m_{NP} > \sqrt{s}$... but *not uniquely constraining*





Ex.: *Leptoquarks*

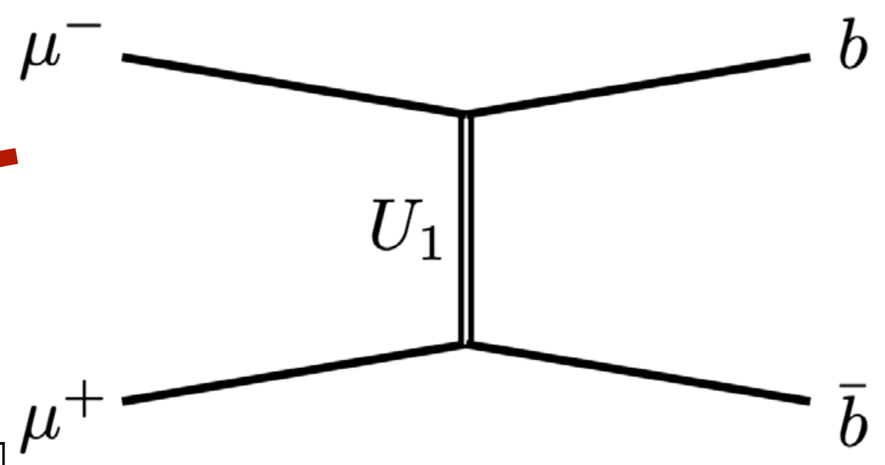
Asadi, Capdevilla, Cesarotti, Homiller '22

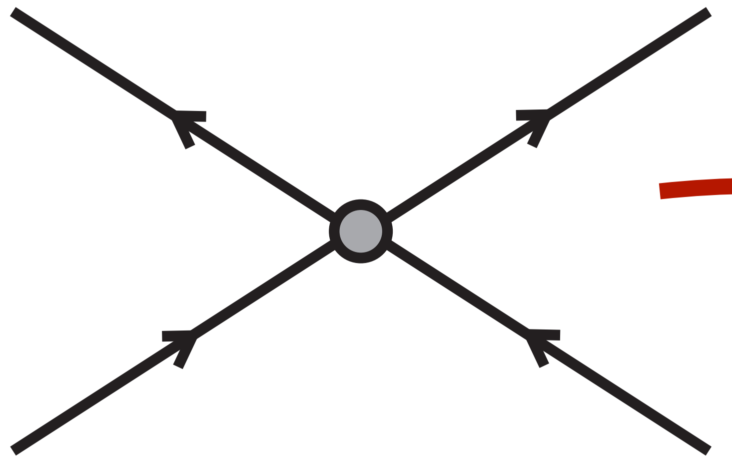


BSM Indirect Searches

BSM particles are *not* in final state, only effects are observed

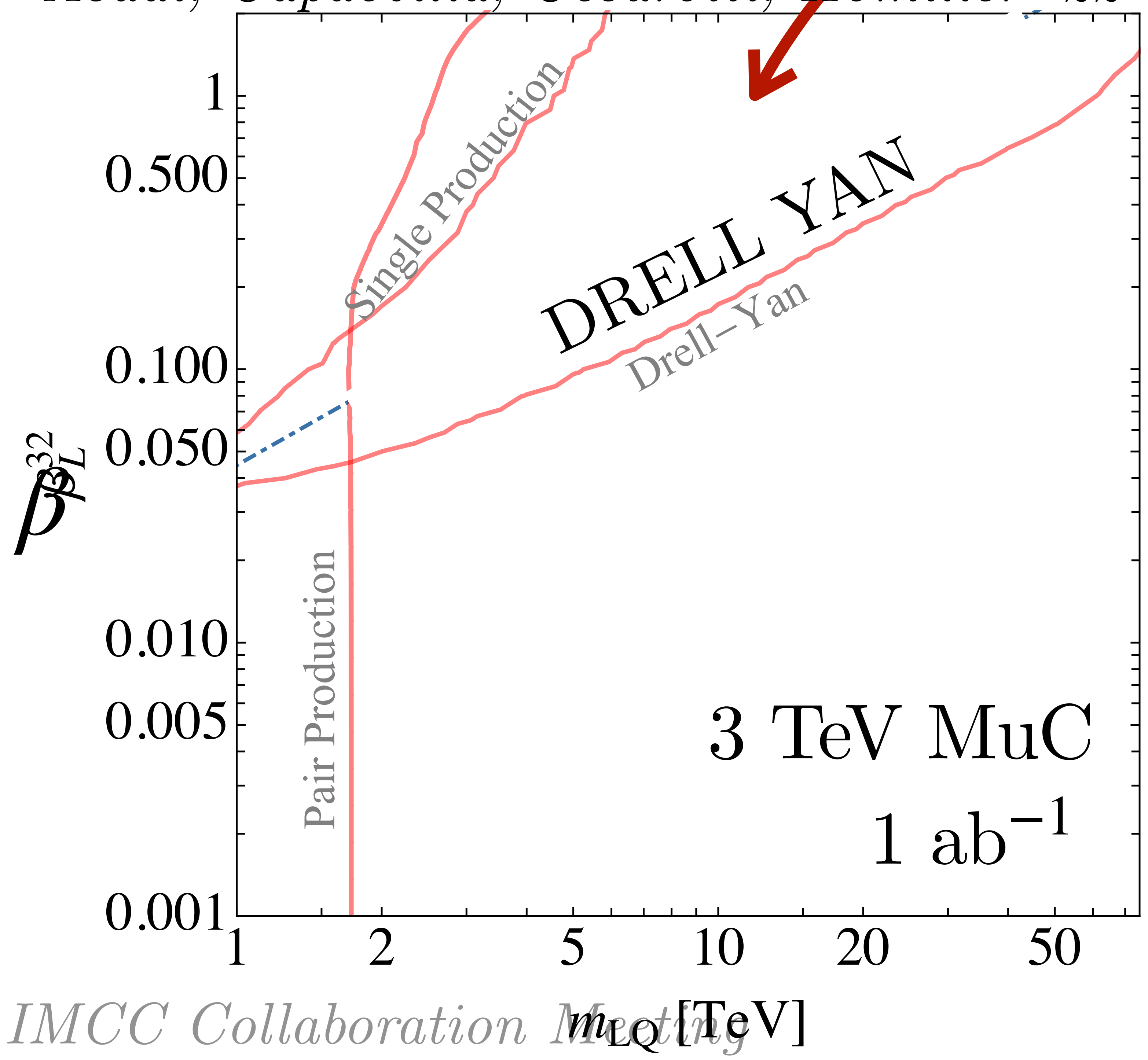
Can probe beyond $m_{NP} > \sqrt{s}$... but *not uniquely constraining*



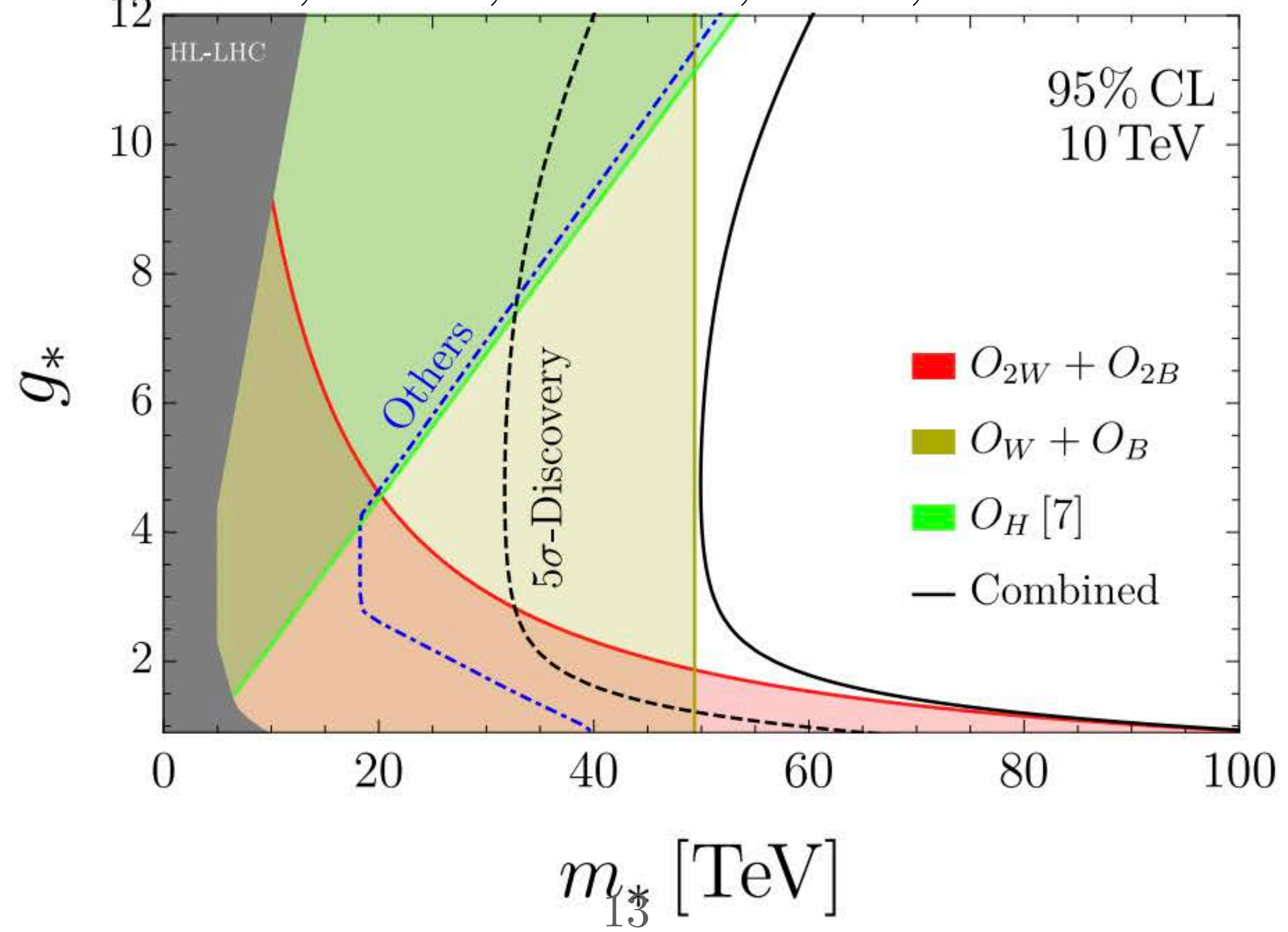


Ex.: *Leptoquarks*

Asadi, Capdevilla, Cesarotti, Homiller '22



Chen, Gliotti, 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 (Summary)

Standard Model (SM) Deliverables (cost justification?)

Higgs | Electroweak @ High Energy

Well defined questions,
operation targets for answers

Beyond the Standard Model (BSM) Exploration

Direct | Indirect

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

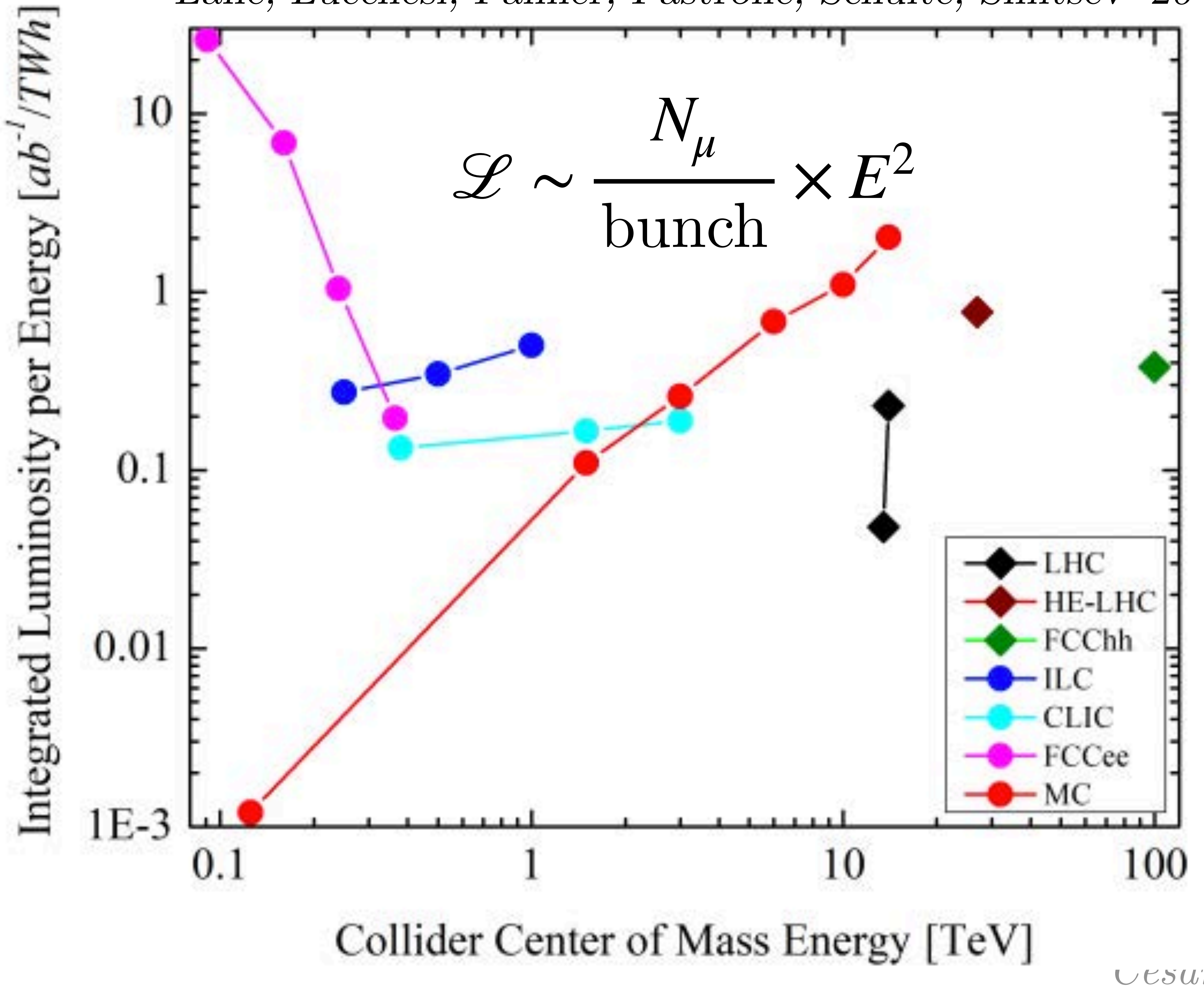
PART II

Accelerator-Experiment-Theory cross talk

Theory Needs

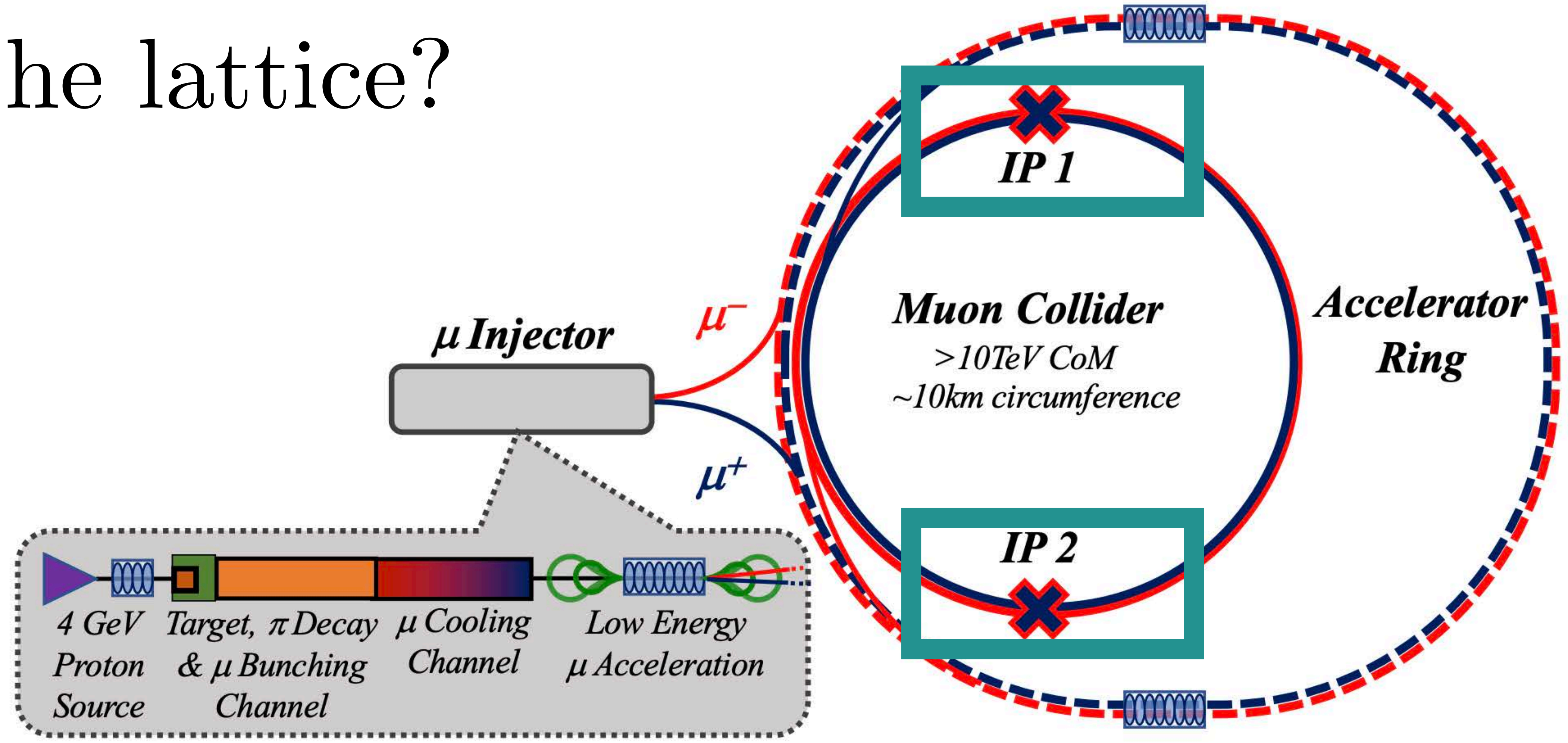
- High energy!
- Energy squared luminosity scaling
- Disappearing track capabilities
- Mitigation of BIB (also simulation?)
- Forward tagging of muons?

Lane, Lucchesi, Palmer, Pastrone, Schulte, Shiltsev '20



Input for theory

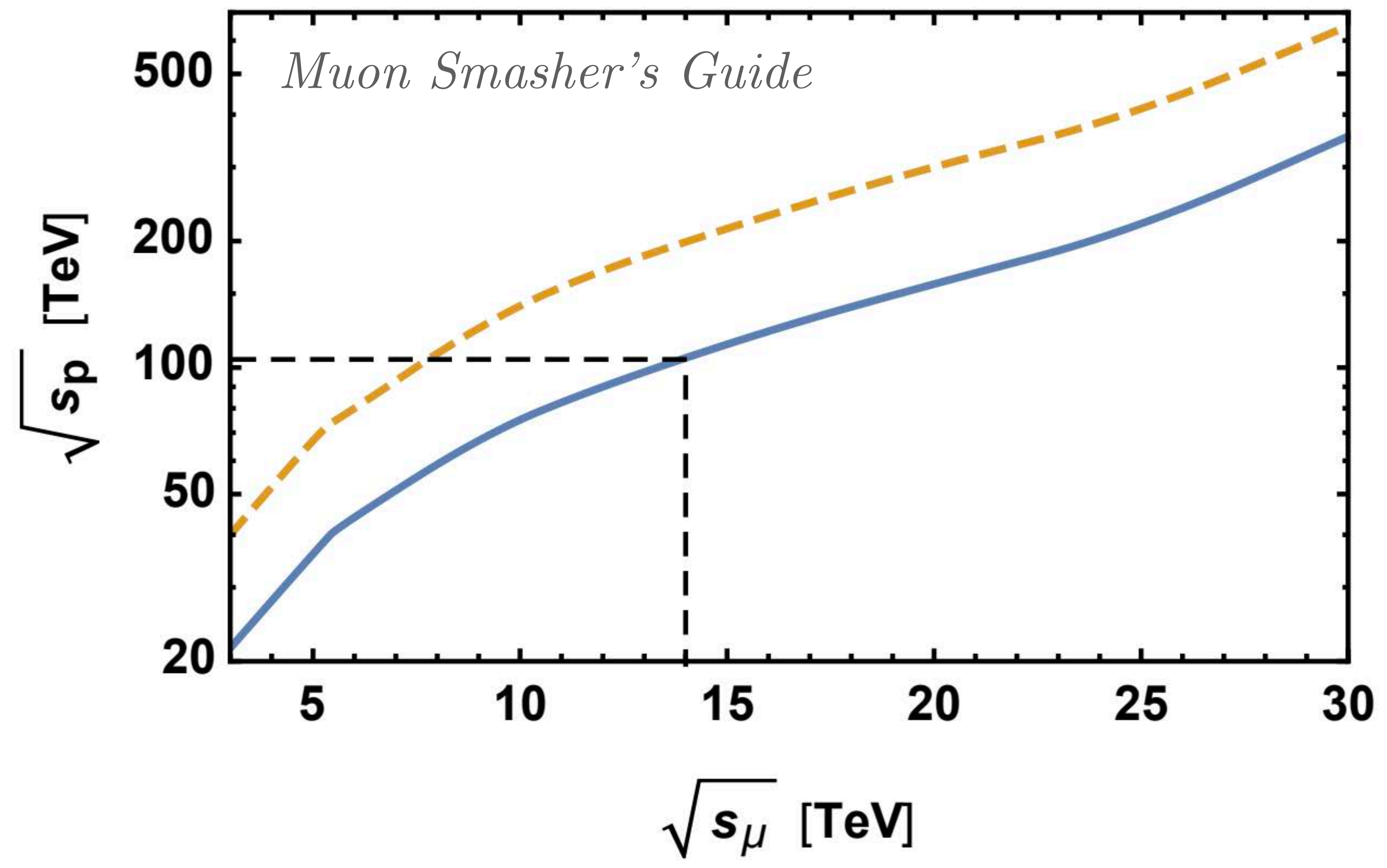
- What $\sqrt{s}$ can we realistically achieve?
- What resolution and reconstruction efficiencies?
- What flavor tagging efficiencies?
- How big is the fiducial detection region?
- What will be the straight sections on the lattice?
- What about this low-luminosity run?
  - $\sqrt{s} \sim 10$ TeV, $\mathscr{L} \sim 1$ ab^{-1}

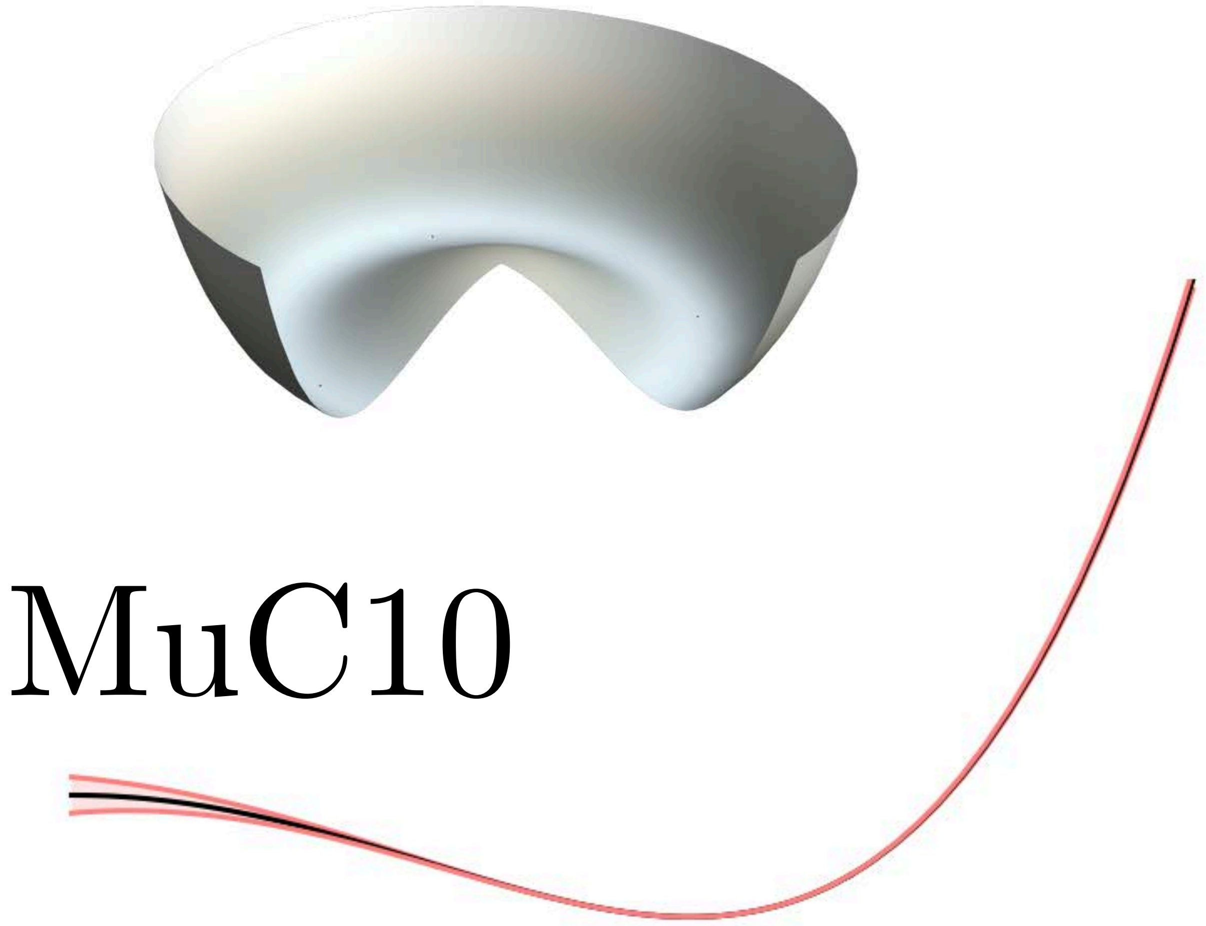


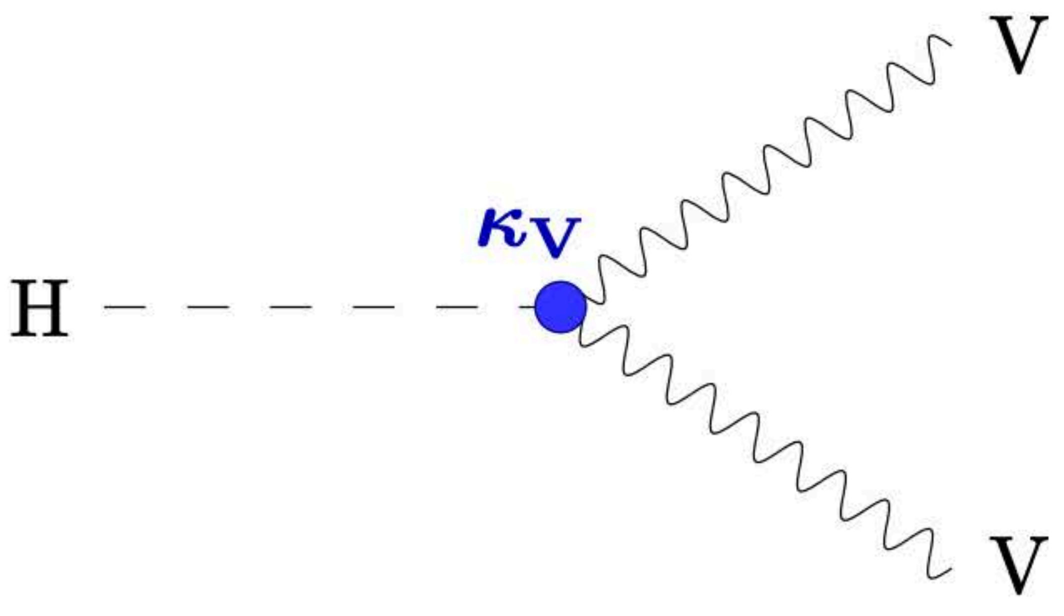
What do you need from Theory?

- A motivated theory that points to a definitive energy scale
- Scans through run parameters? (e.g. various efficiencies, acceptance, etc)
- Physics targets for performance goals? (e.g. flavor tagging, forward muons)

Muon Smasher's Guide '19



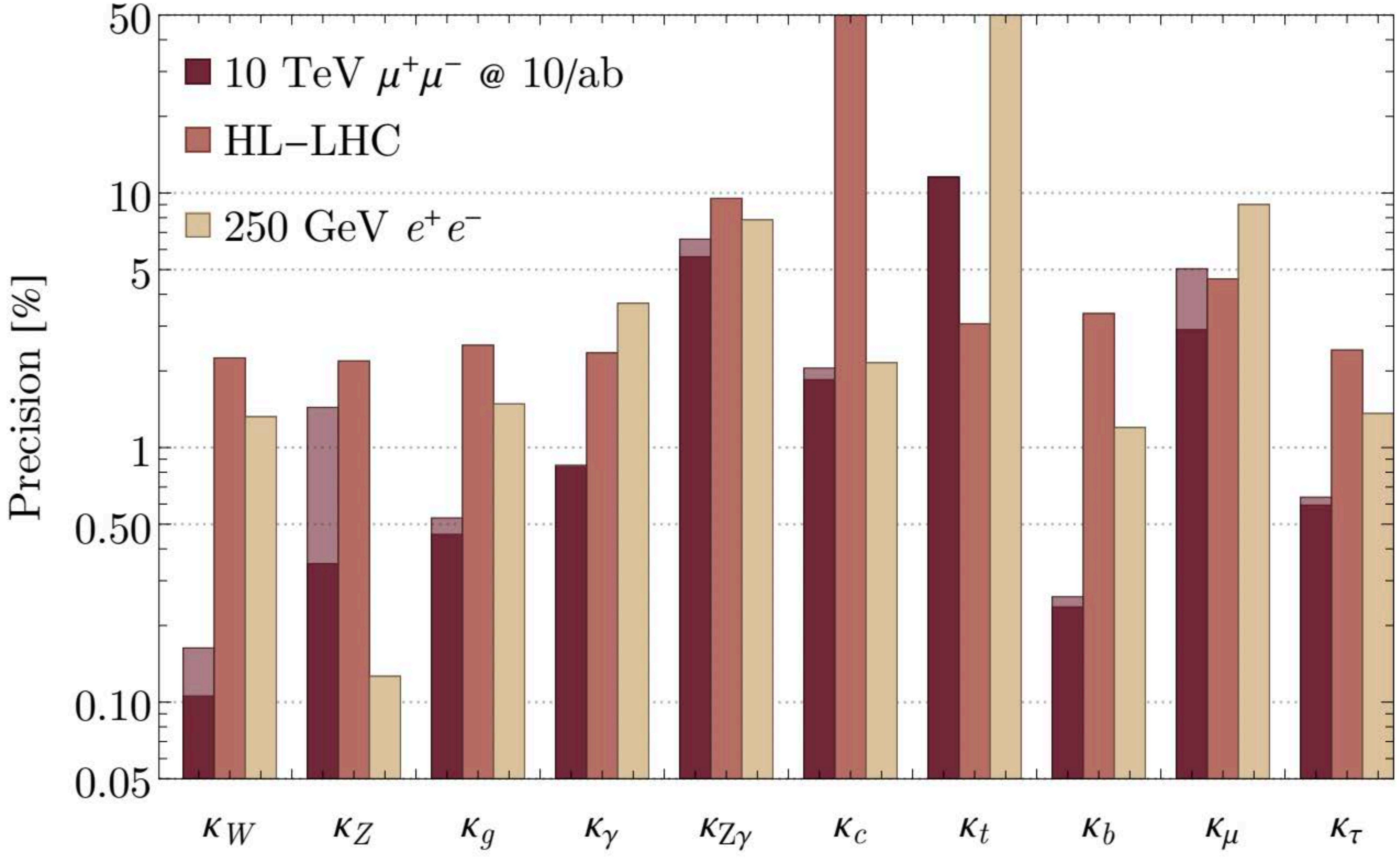


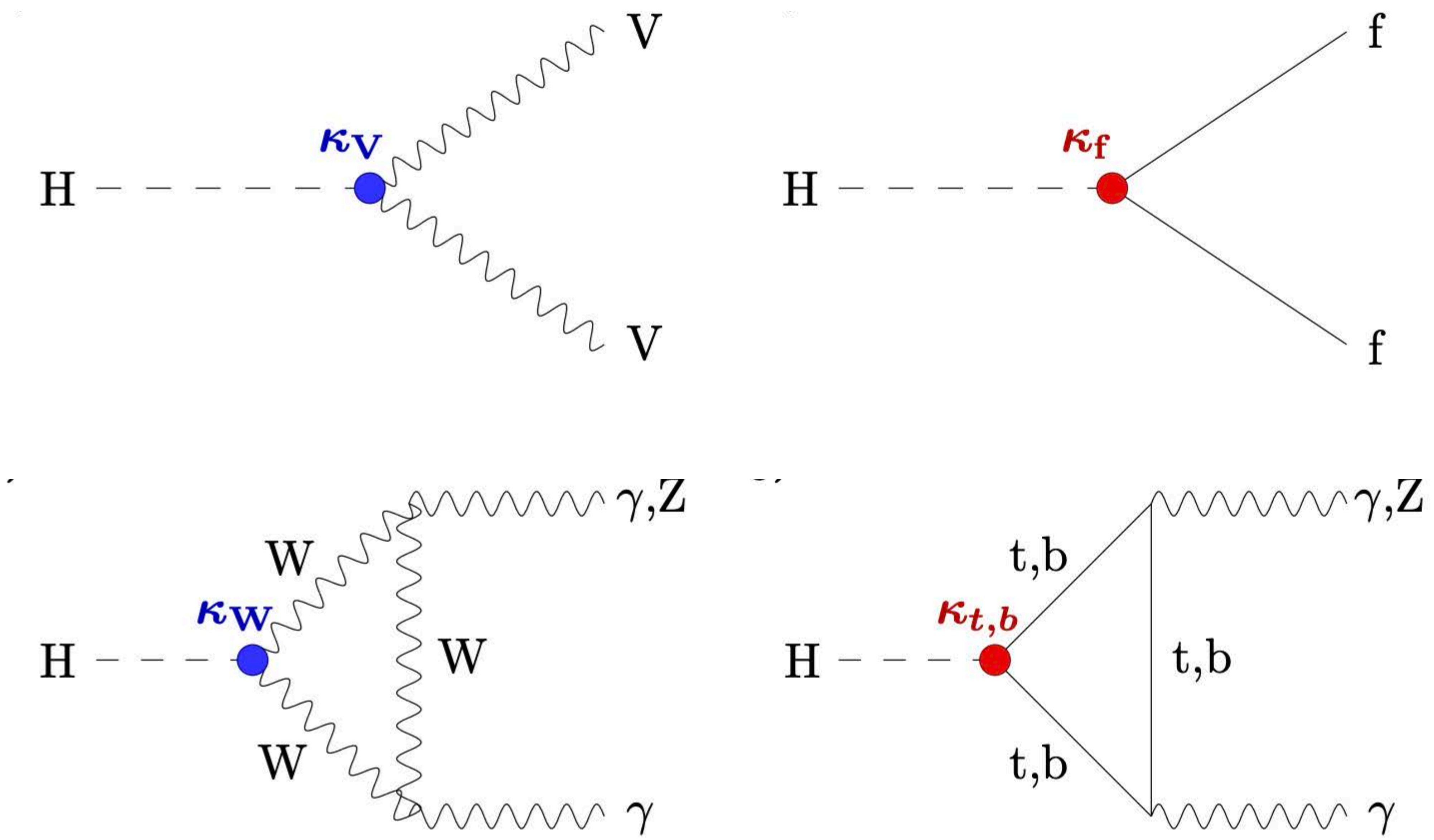


Backup Slides

Higgs Couplings

Forslund & Meade '23

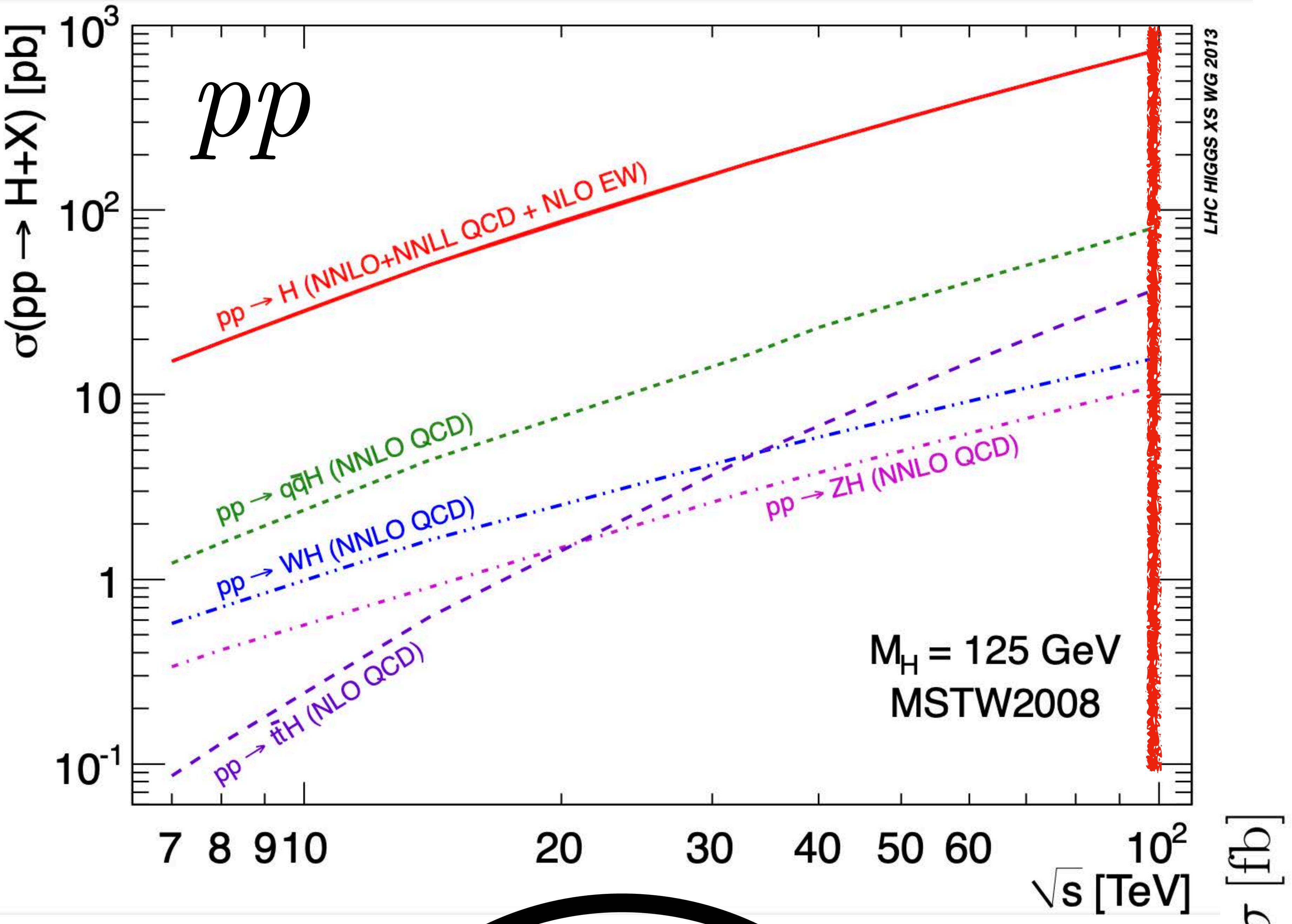


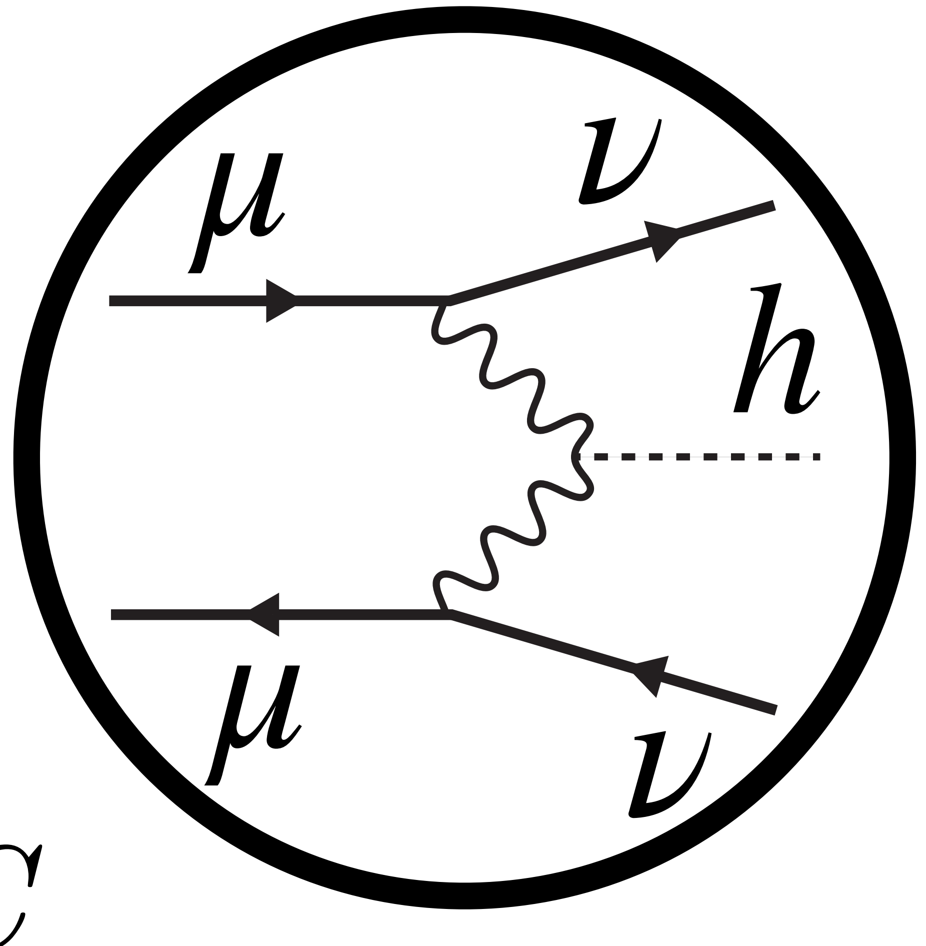


Reach of $\mathcal{O}(10^6)$ Higgs can be up to an order of magnitude more precise than HL-LHC

Higgs Production

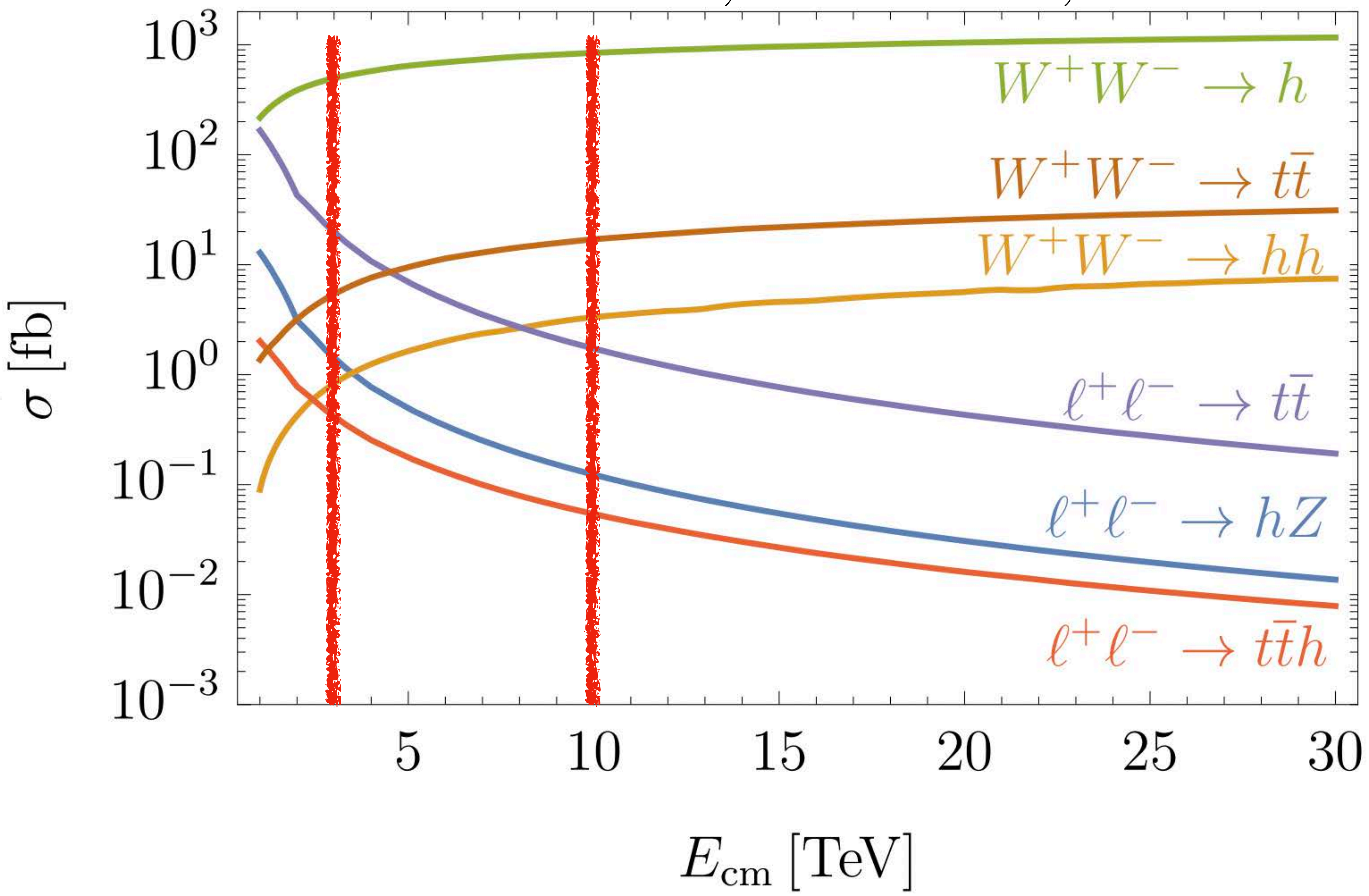
LHC Higgs WG





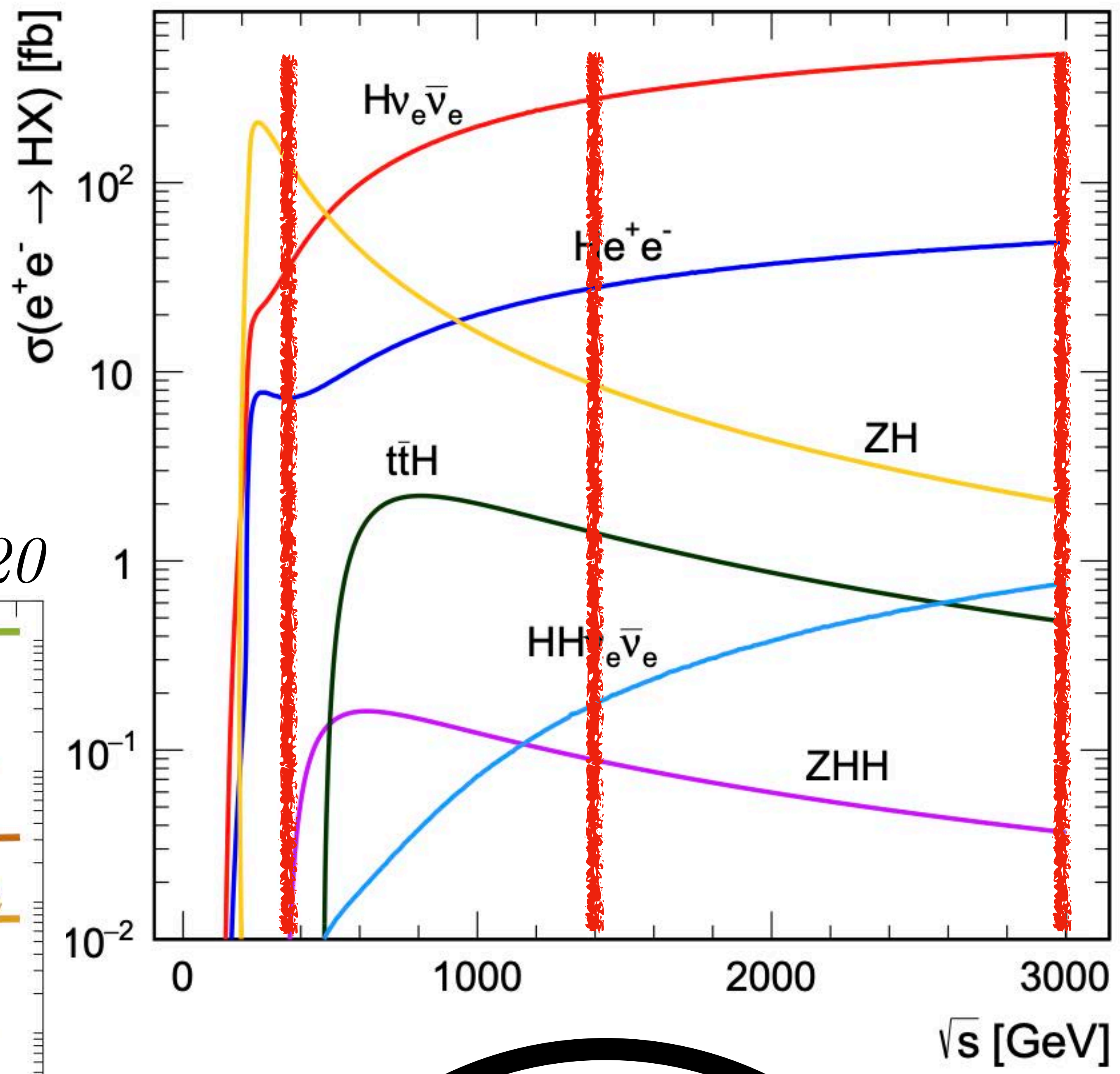
MuC

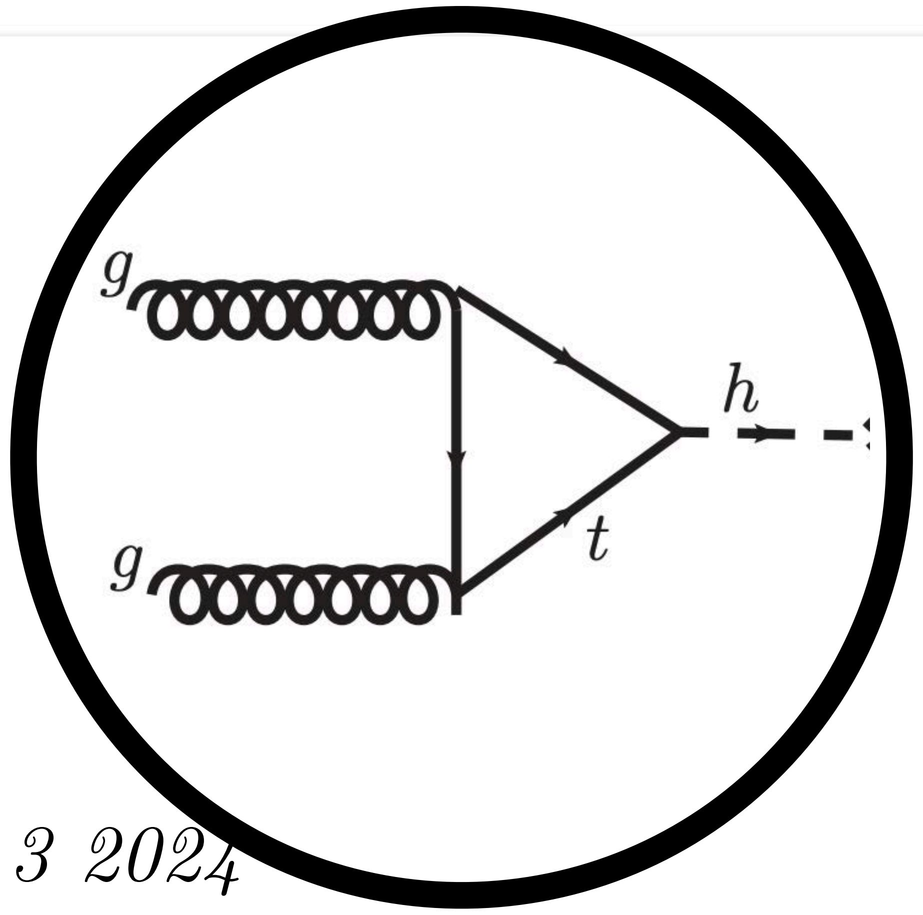
Buttazzo, Franceschini, Wulzer '20

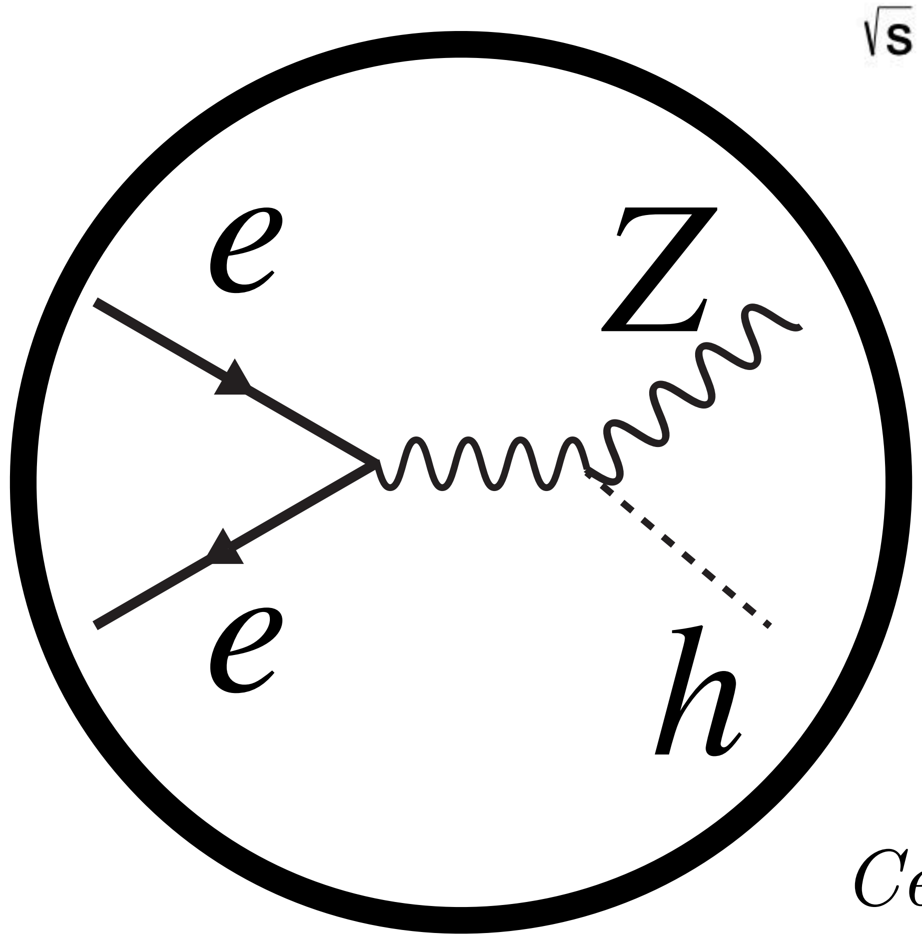


CLiC Summary Report

e^+e^-







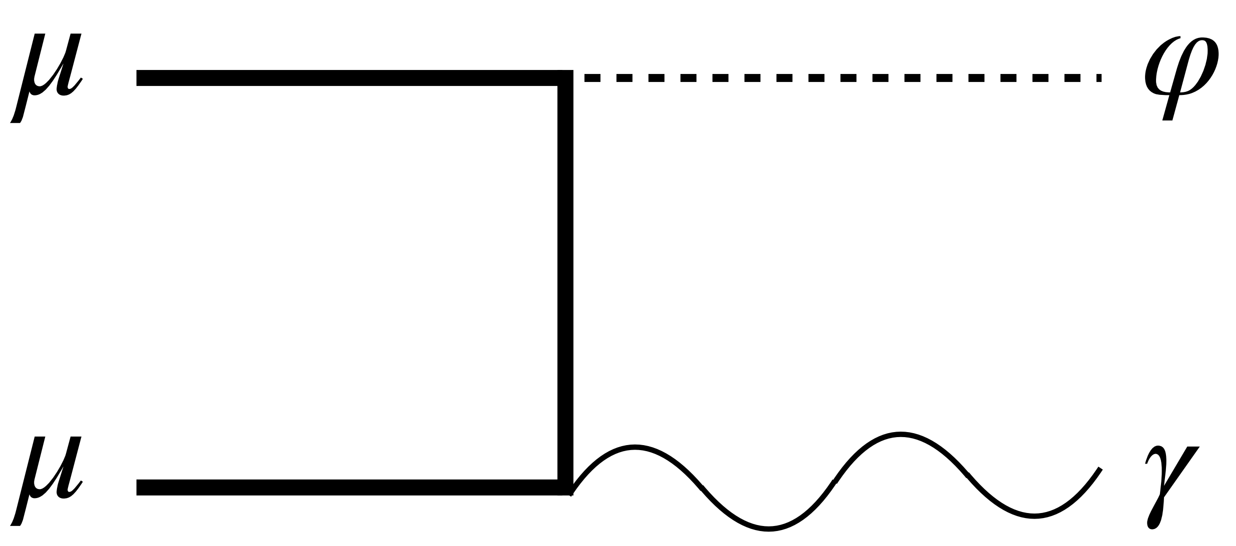
DM at MuC: Leptophilic DM

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

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

Mono-X Search

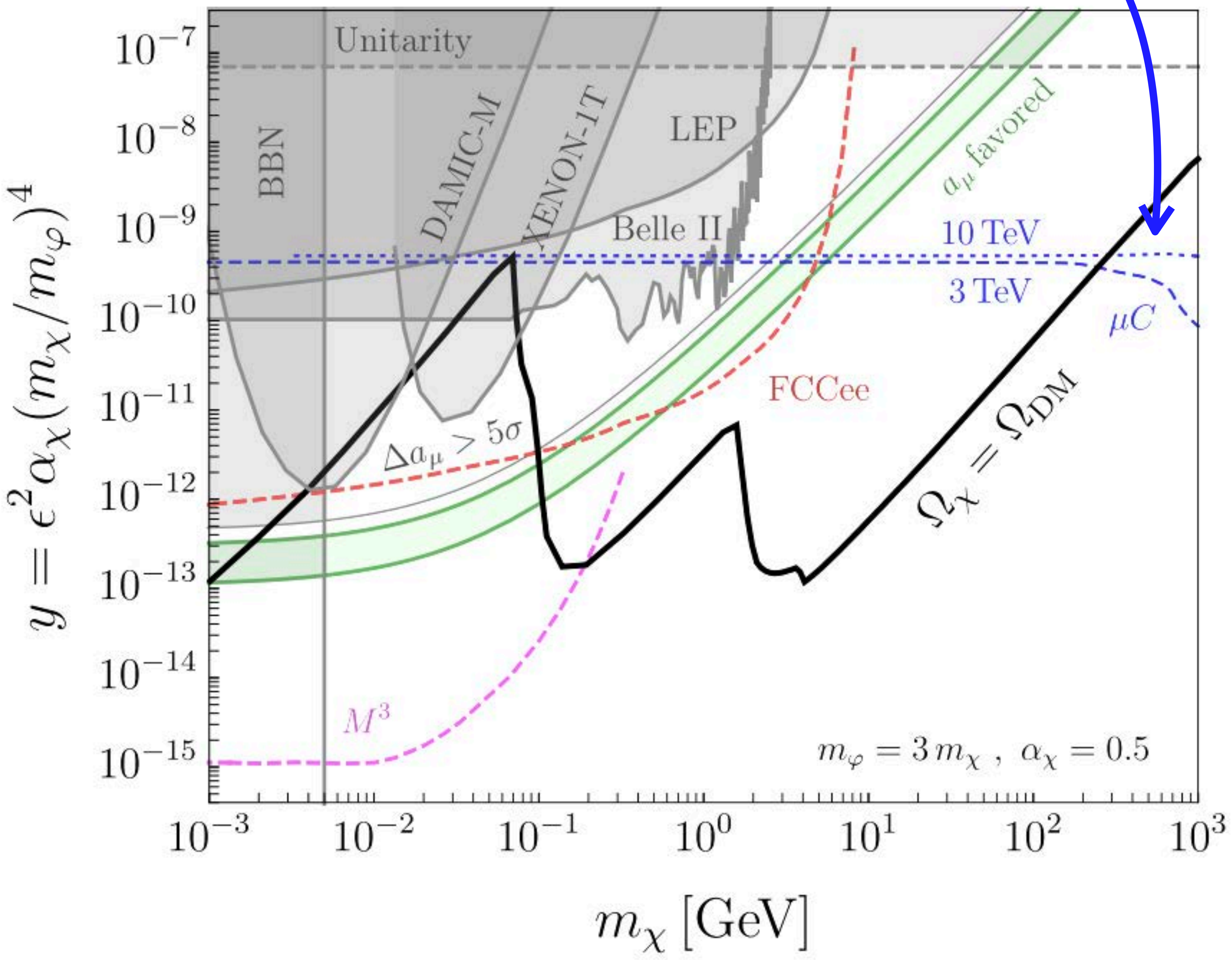
$$\mu^+\mu^- \to \varphi\gamma = \gamma\cancel{E}$$



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

Background:

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

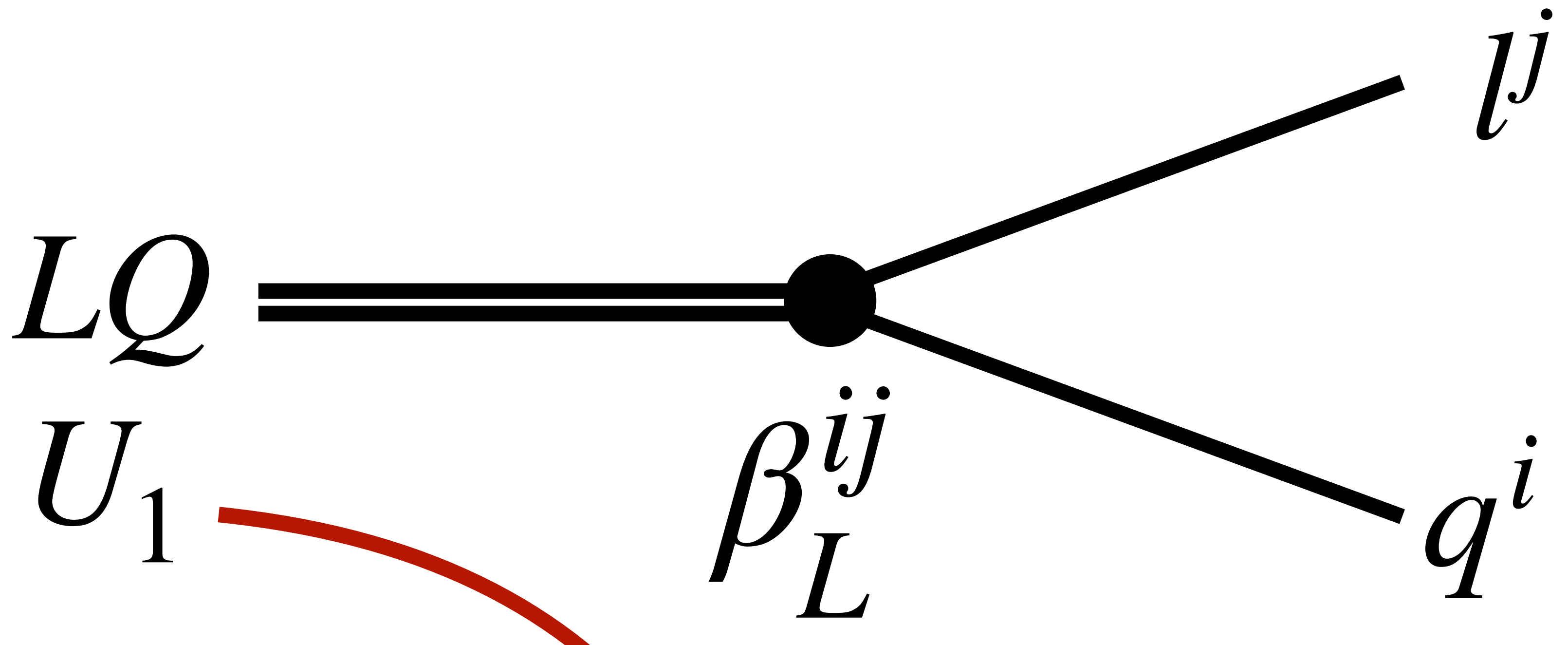


BSM at MuC: Leptoquarks

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

Consider a BSM benchmark model: the *leptoquark*

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



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

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

Broad class of NP model

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

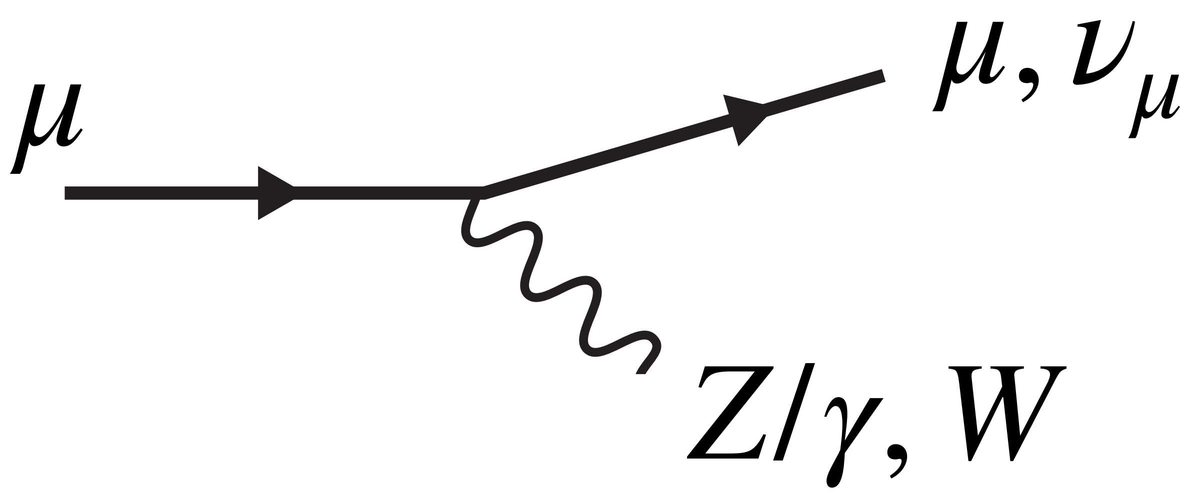
BSM at MuC: Leptoquarks

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

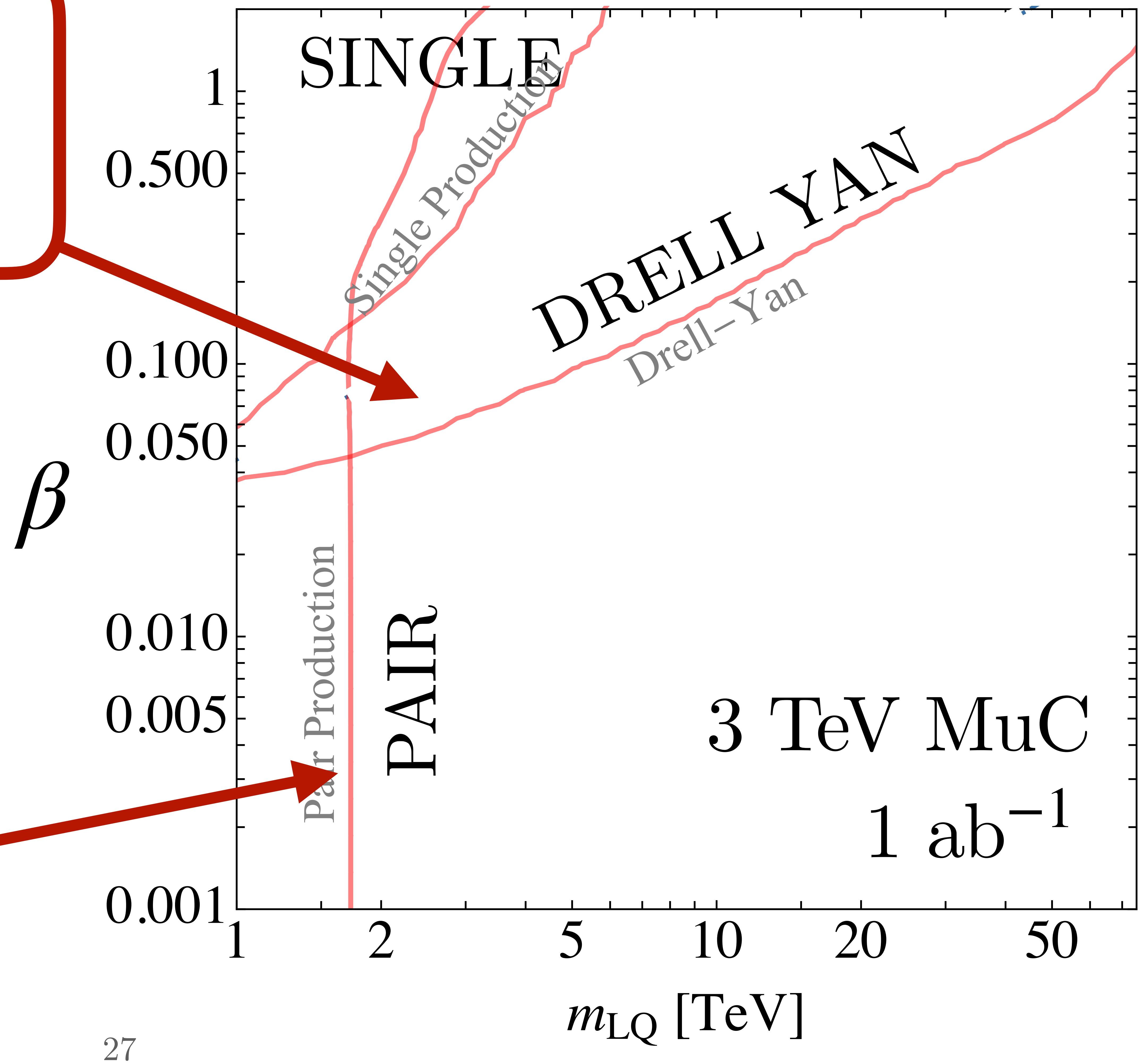
For benchmark choice of couplings, 5σ reach at 3 TeV MuC

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

Muon colliders are also *gauge boson* colliders



Muons have PDFs too!



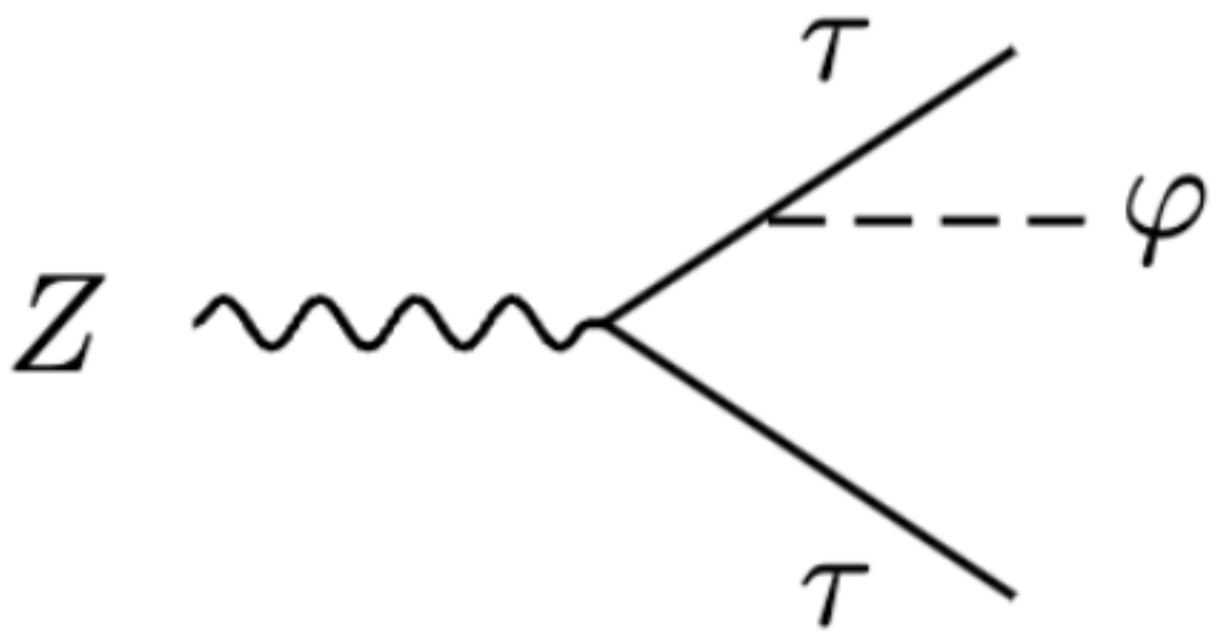
DM AT EE COLLIDER: LEPTOPHILIC DM

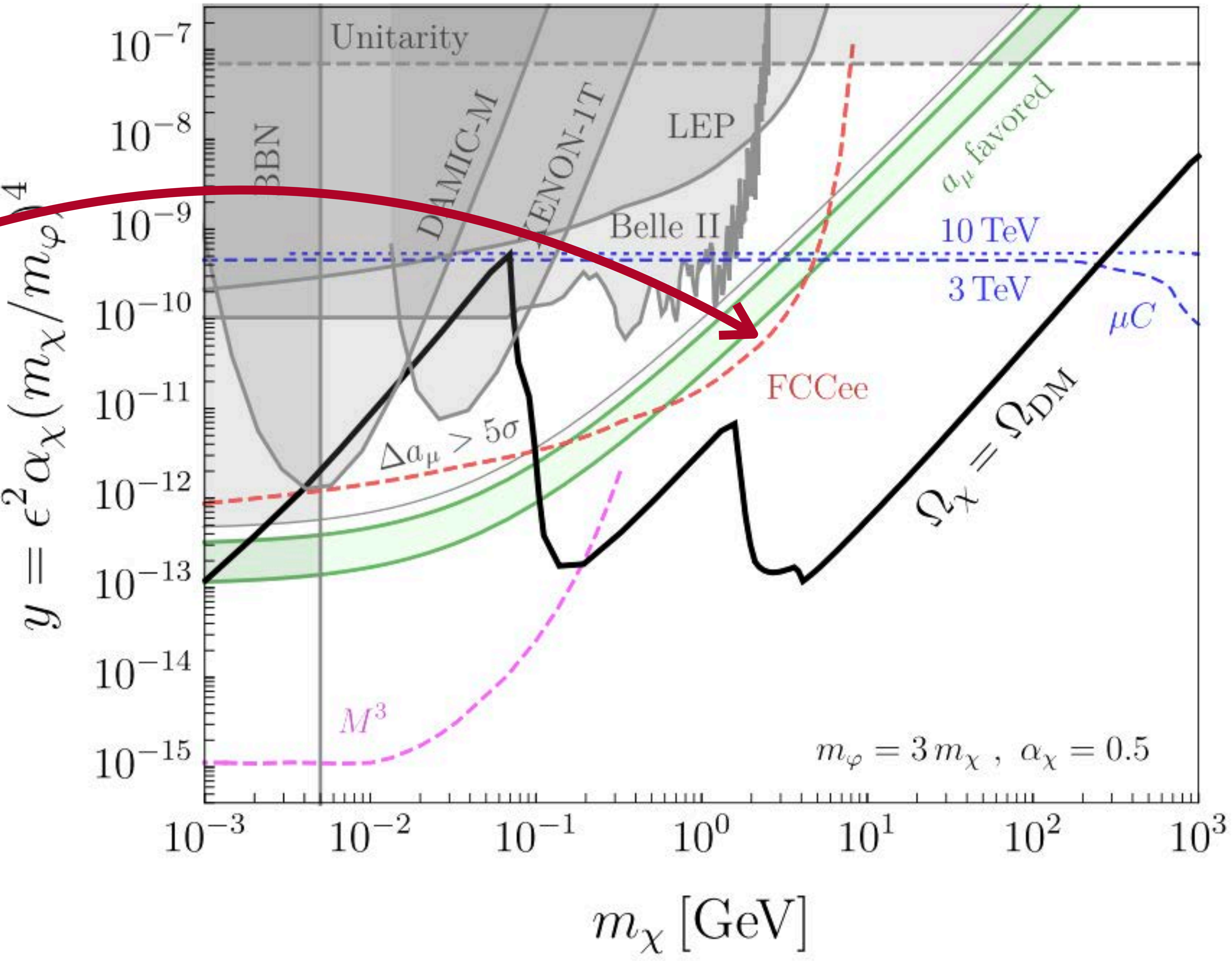
***CC**, Krnjaic,'24*

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*