Implications for a future physics program

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On behalf of the
International MUON Collider Collaboration

Community Report on Accelerators Roadmap
Jul. 12, 2023

For references, and much more, see here

Towards a Muon Collider

Accepted as EPJC review

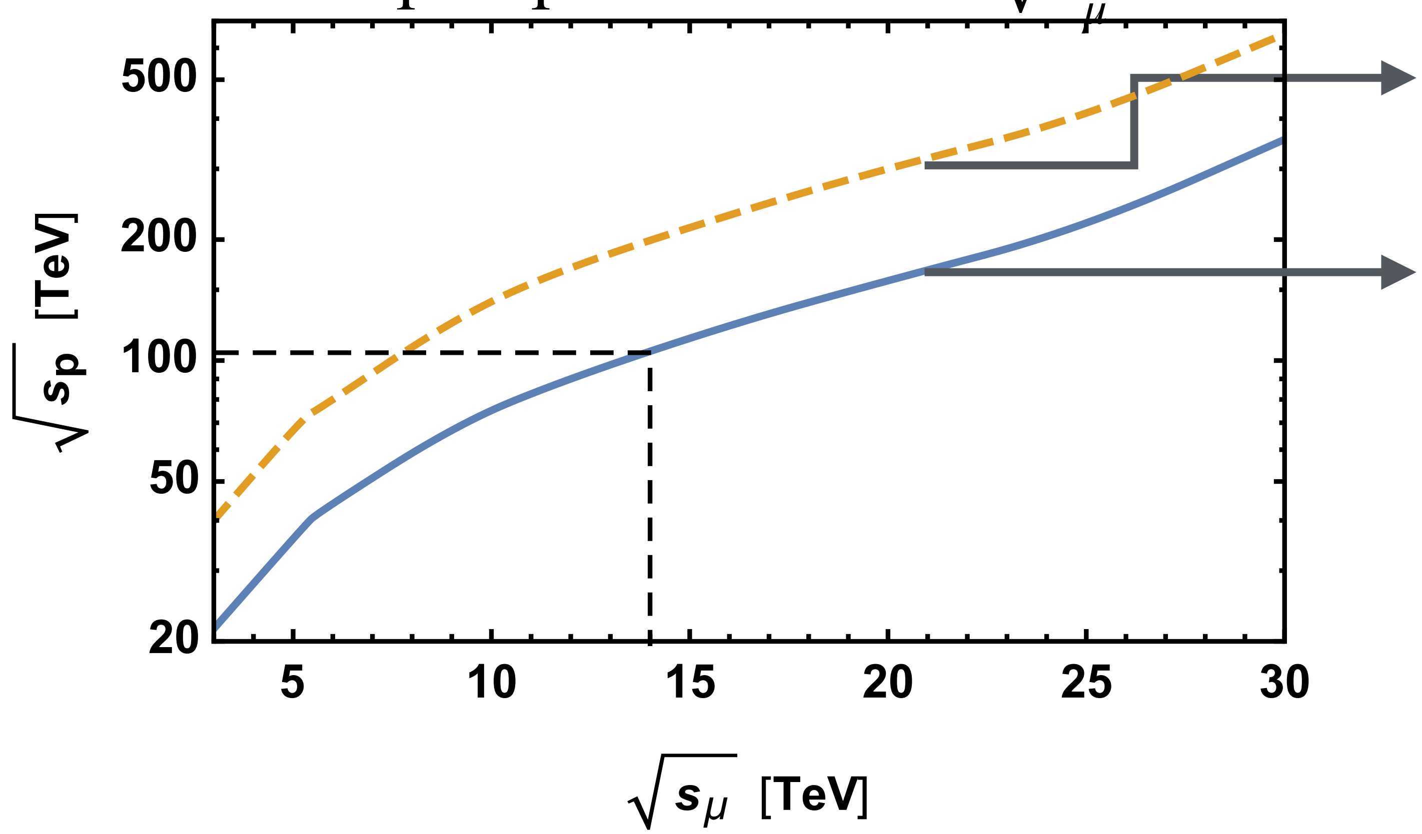
Why Building a Muon Collider

Leptons are the ideal probes of short-distance physics:

- **Electroweak** is dominant interaction, and EW+Higgs is main future target
- All the energy is stored in the colliding partons
- No energy "waste" due to parton distribution functions
- High-energy physics probed with much smaller collider energy

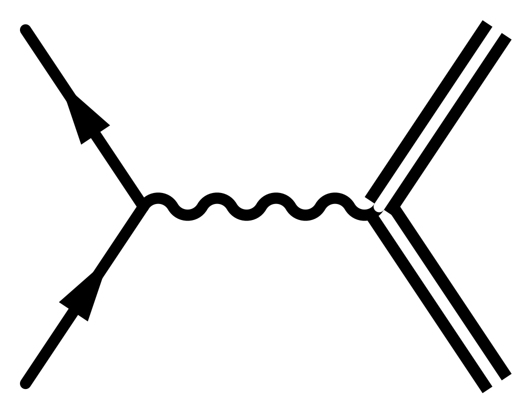
pp $\sqrt{s}$ at which $\sigma_{pp} = \sigma_{\mu\mu}$

for pair prod. with $M \sim \sqrt{s_\mu}$



Estimate for EWK-only charged particles

Estimate for EWK+QCD-charged particles



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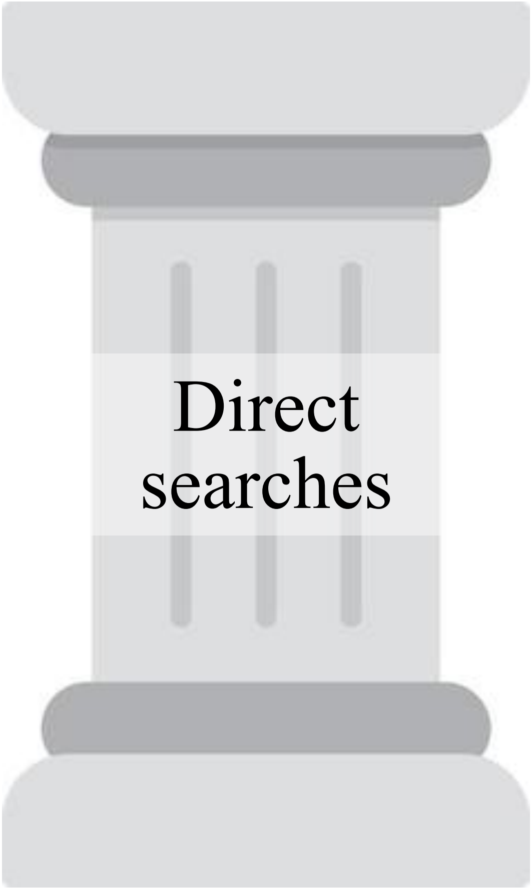
Electrons radiate too much, while **muons** don’t

International
MUON Collider
Collaboration

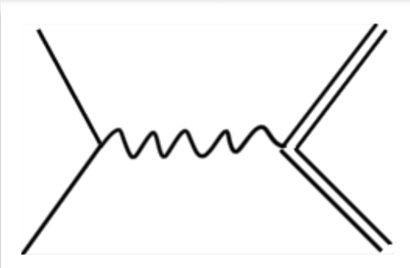
Muon Collider Physics Pillars

The muon collider combines pp and ee advantages:

- High available energy for new heavy particles production

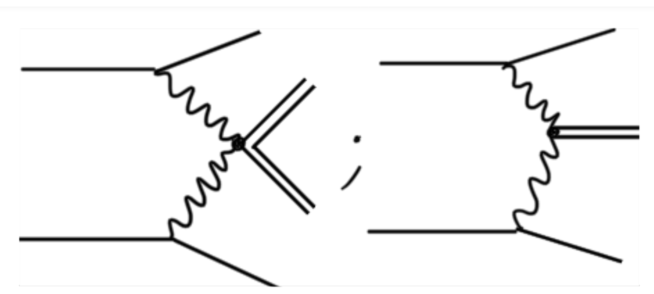


Direct searches



μμ annihilation: copious production of **EW-charged particles** up to $E_{cm}/2$

These searches can, for instance, advance probes of (un)-Natural EWSB by one or two orders of magnitude



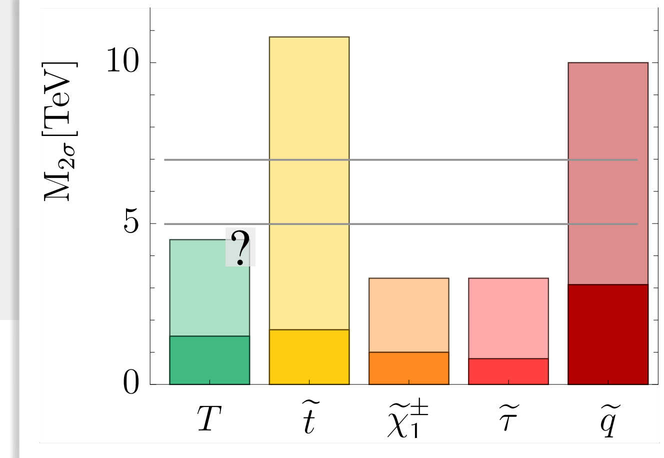
Vector Bosons Fusion: sensitive to EW-neutral **Higgs-Portal** particles

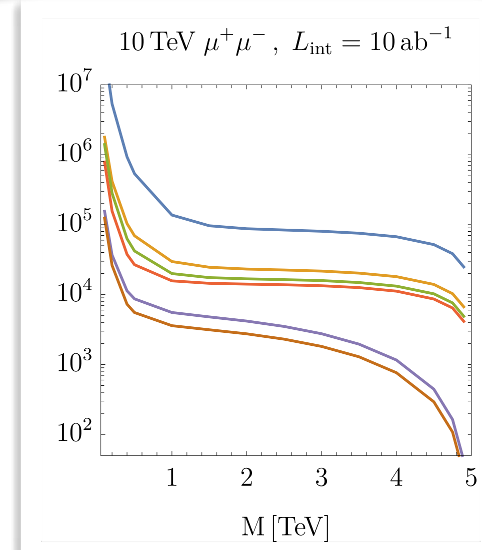
$|H|^2 \cdot X^2$; or $|H|^2 \cdot X$

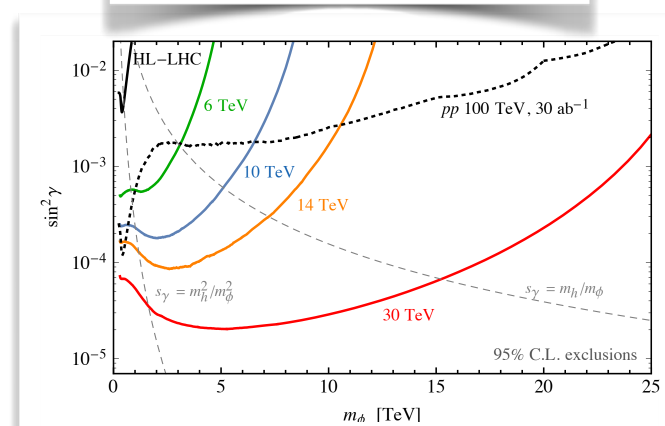
This will, for instance, probe conclusively extended Higgs sectors that produces strong first-order EW phase transition in the early Universe

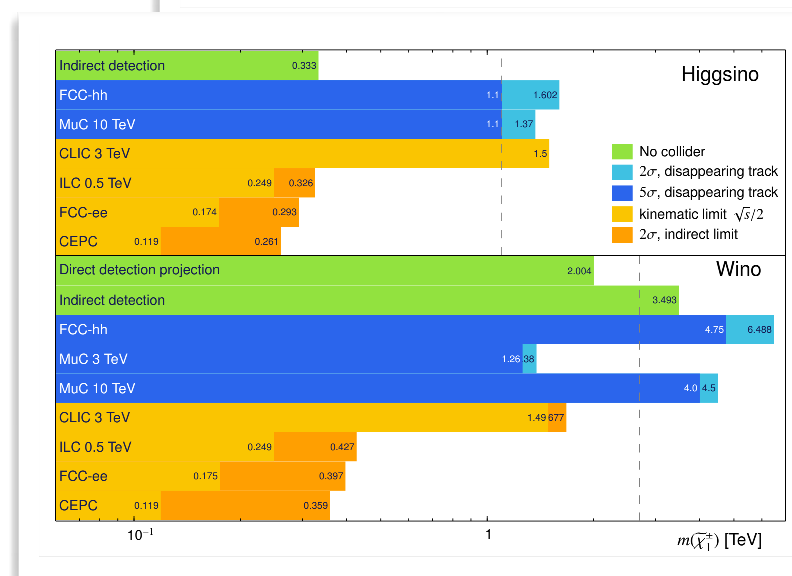
Amazing **WIMP or WIMP-like DM** search program:

- Disappearing tracks
- Mono-X
- Higgs-portal DM in VBF
- **Thermal Wino and Higgsino discovery**









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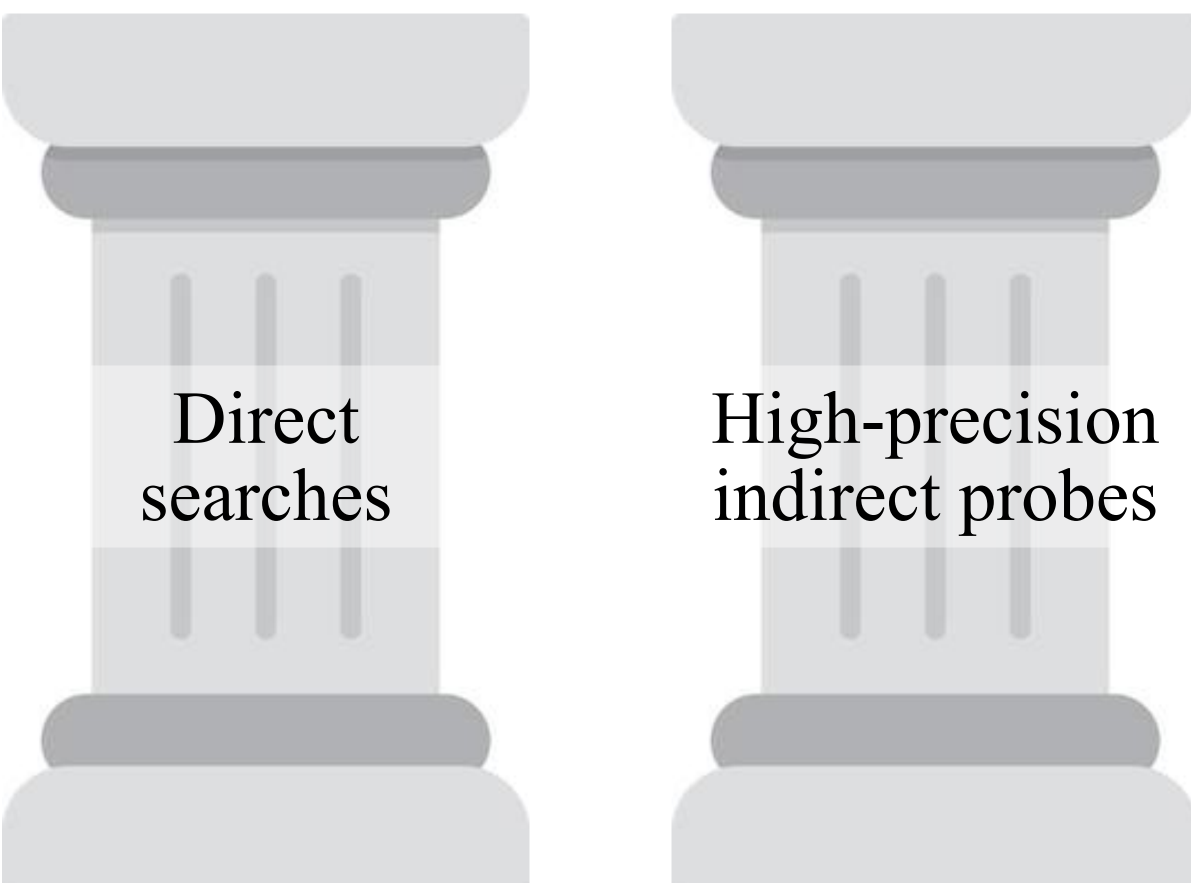
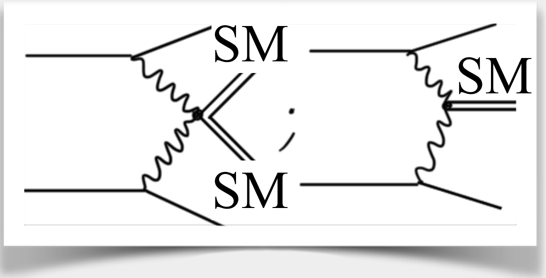
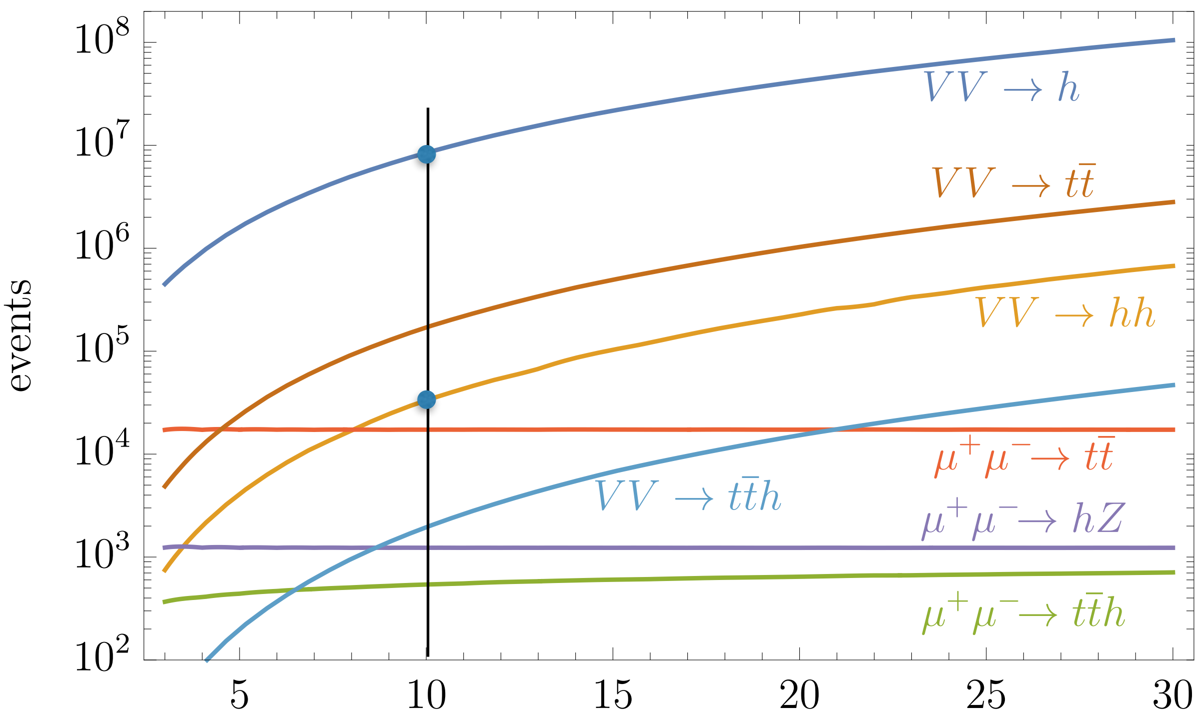


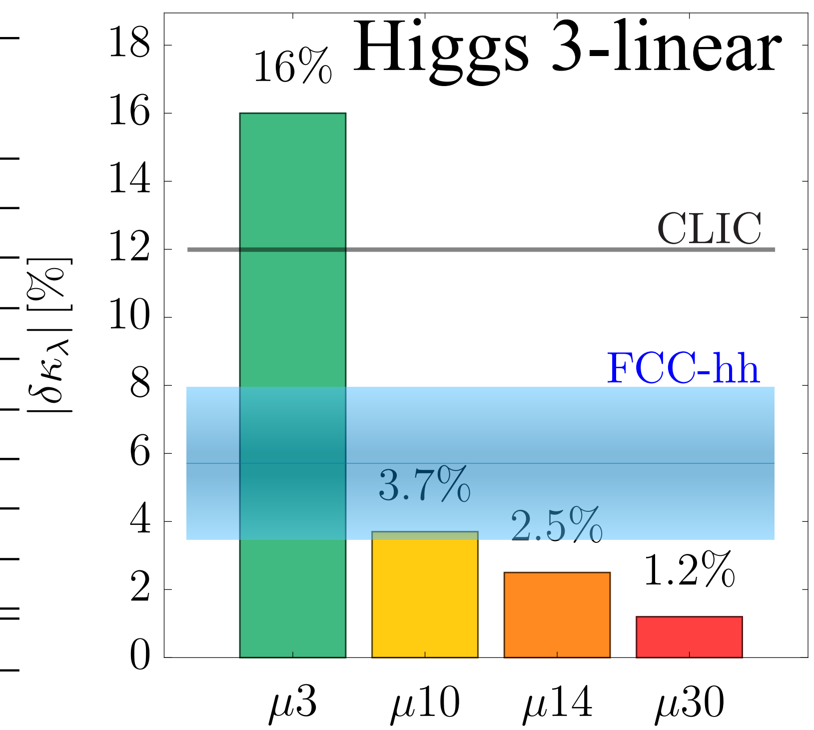


High-precision indirect probes

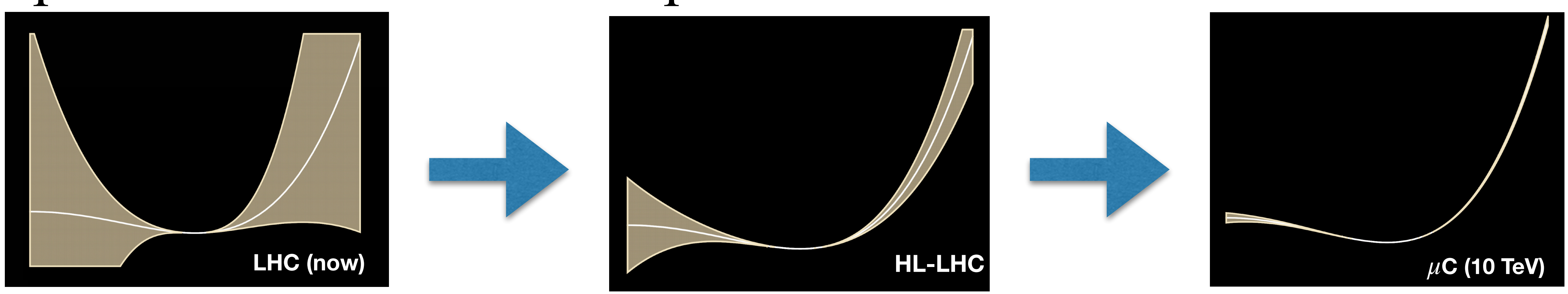


	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

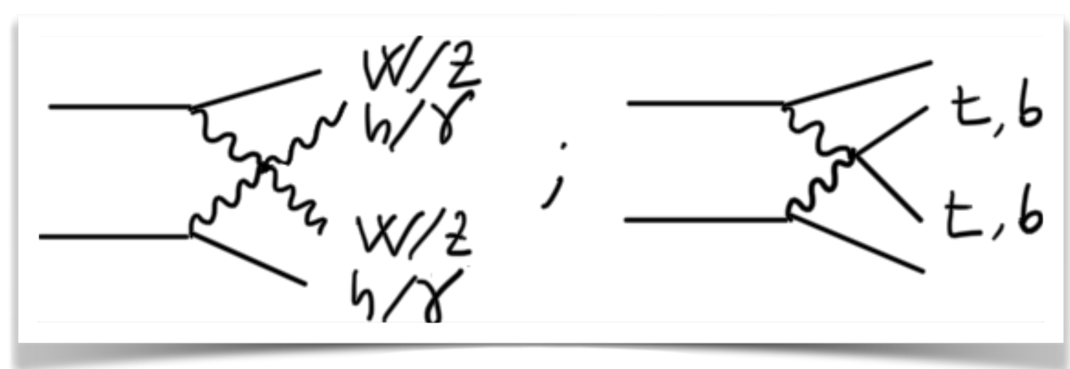


A pictorial view of 3-linear precision:



Many unexplored opportunities

[e.g., VV scattering]



Muon Collider Physics Pillars

The muon collider combines pp and ee advantages:

- High available energy for new heavy particles production
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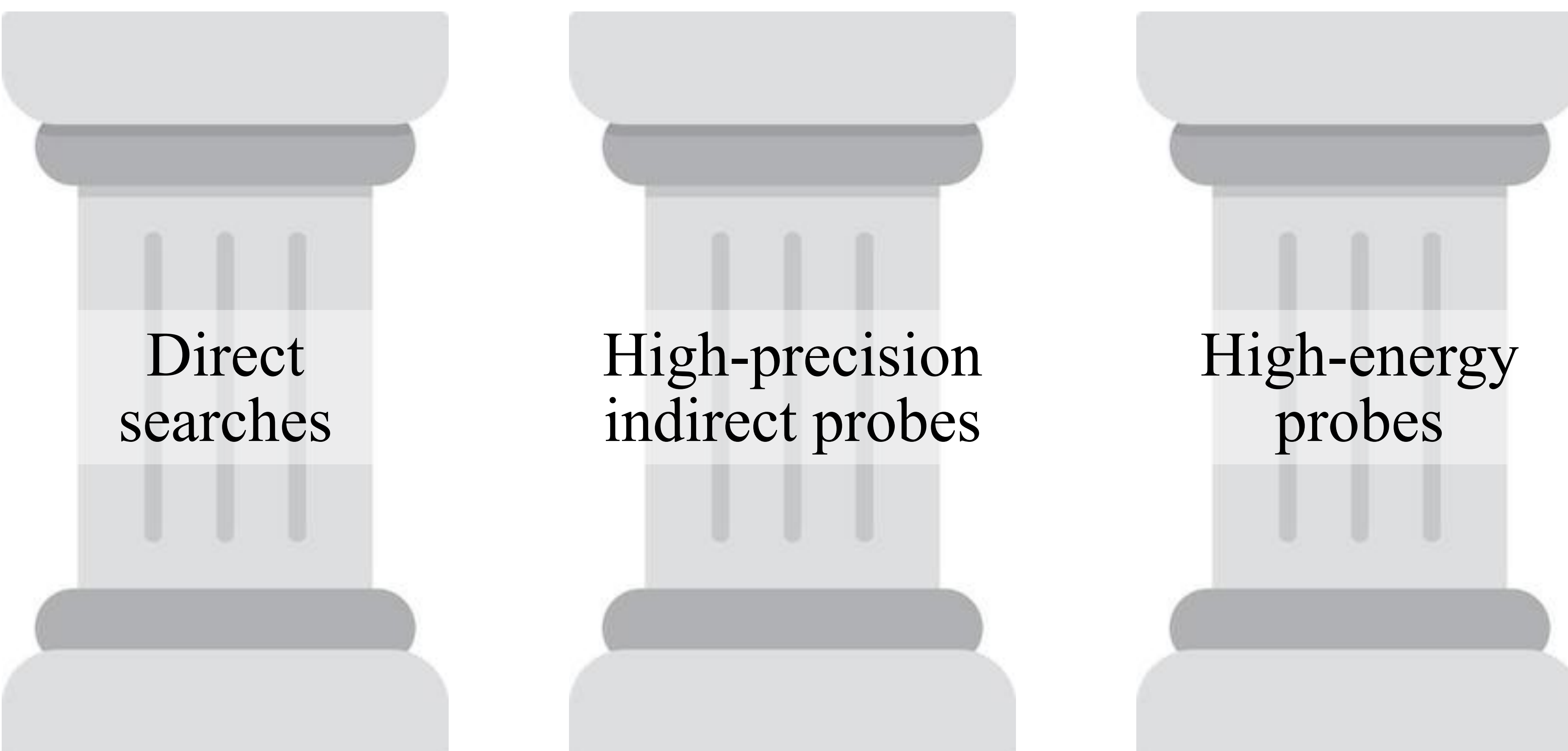
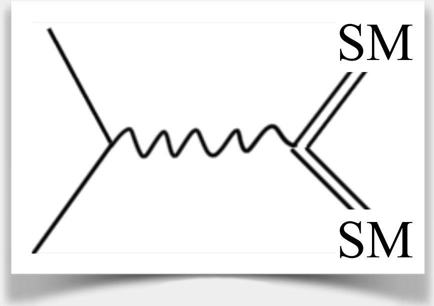
Furthermore:

- Can measure processes of very high energy





High-energy probes

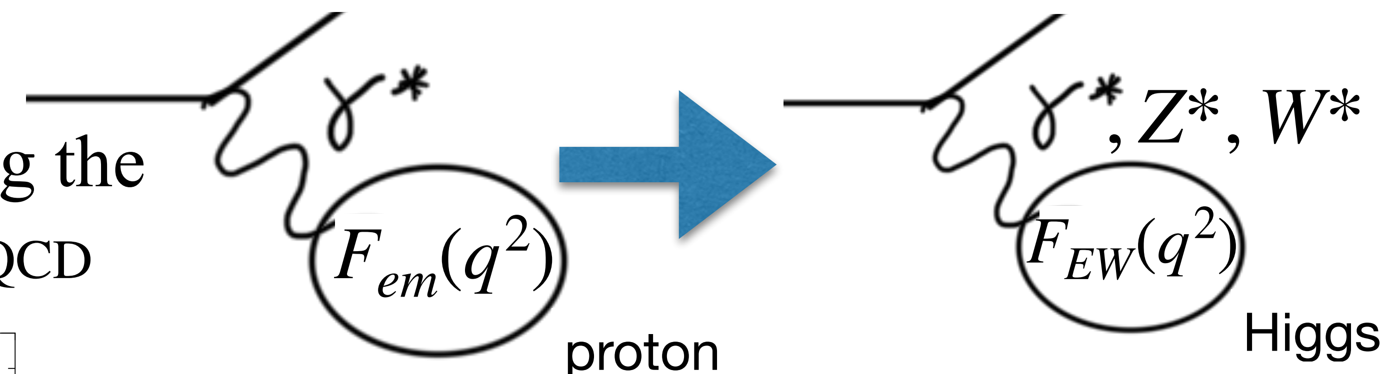
As simple as this:

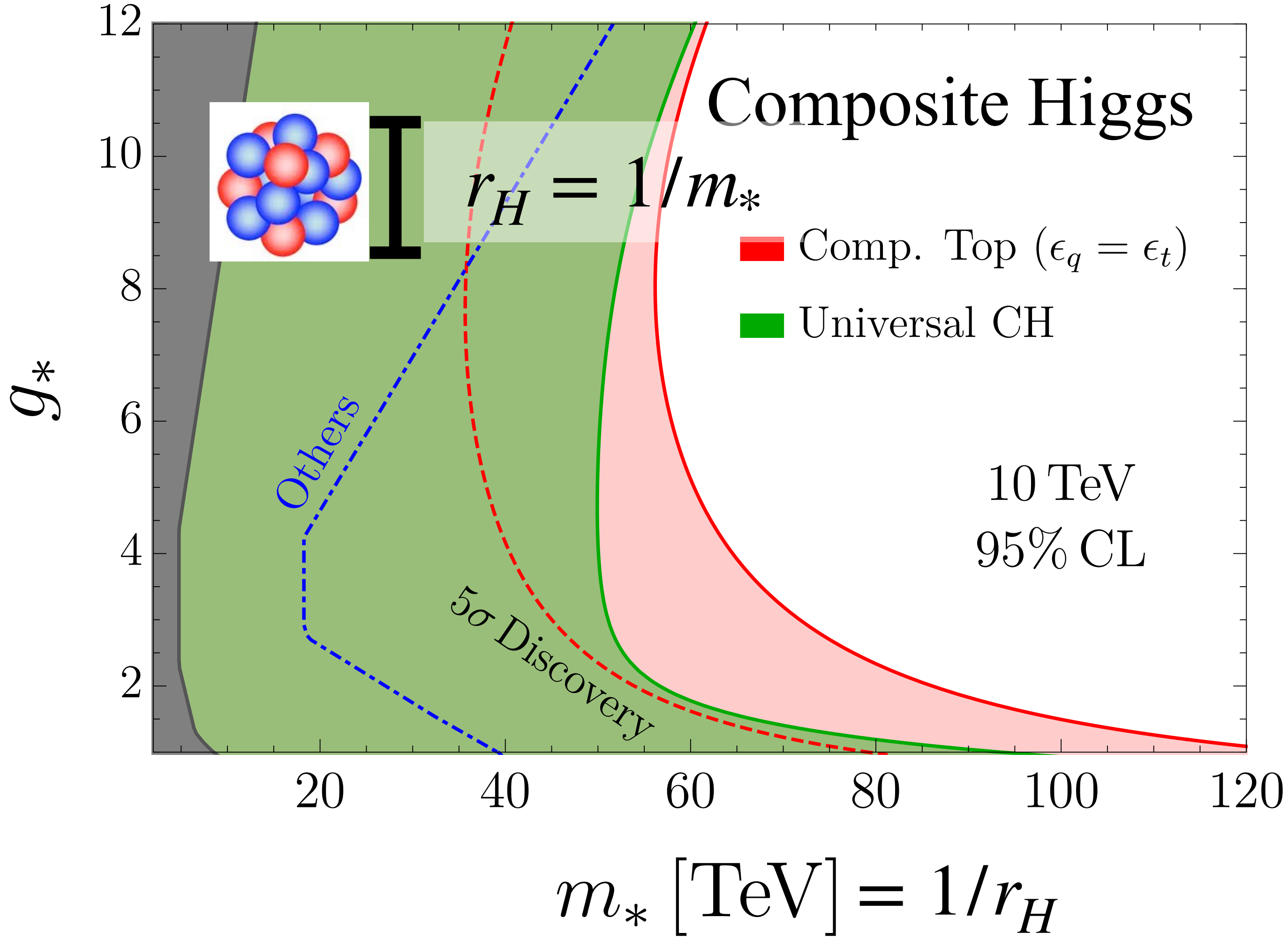
$$\frac{\Delta\sigma(E)}{\sigma_{SM}(E)} \propto \frac{E^2}{\Lambda^2_{BSM}} \overset{\text{[say, }\Lambda_{BSM}=100\text{ TeV]}}{=}$$

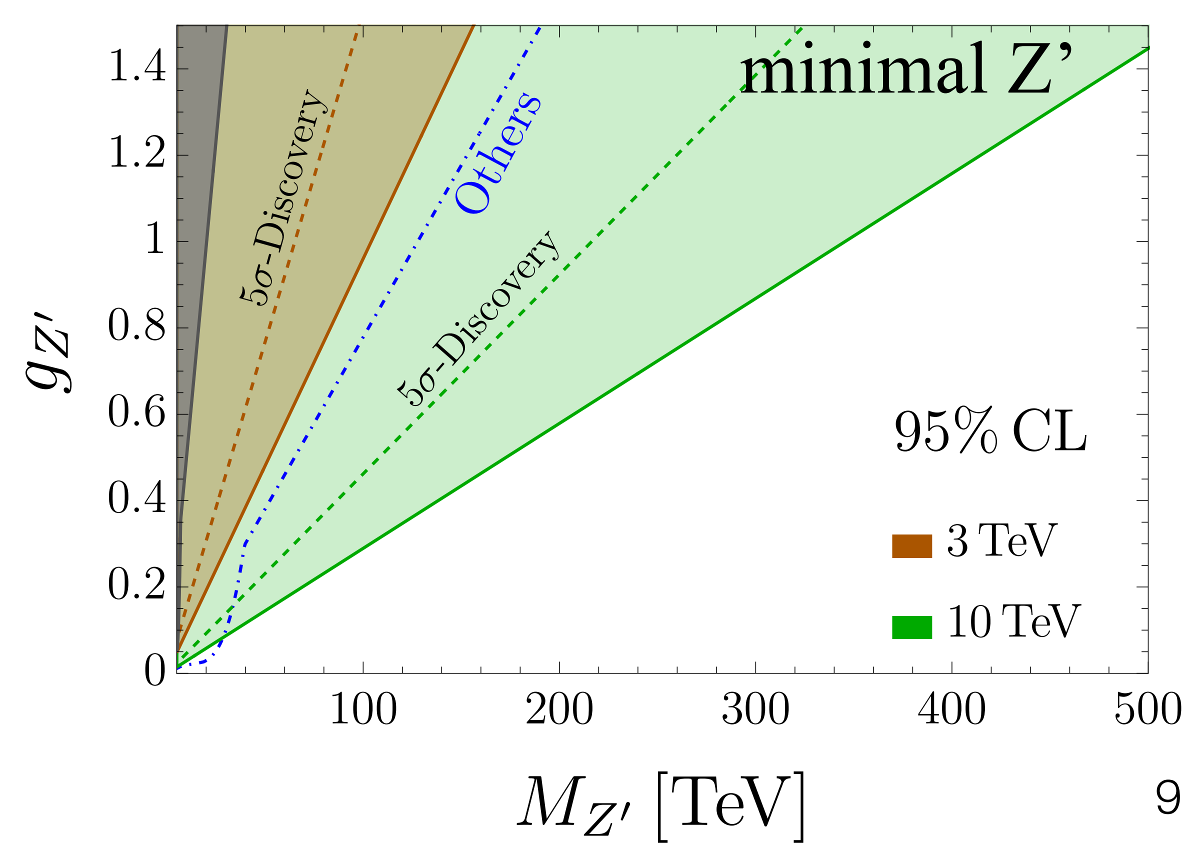
- $\mathbf{10^{-6}}$ at EW [FCC-ee] energies
- $\mathbf{10^{-2}}$ at **muon collider** energies

Or even simpler:

Proton compositeness discovered probing the proton with $E \sim 100$ MeV $\lesssim 1/r_p \sim \Lambda_{QCD}$







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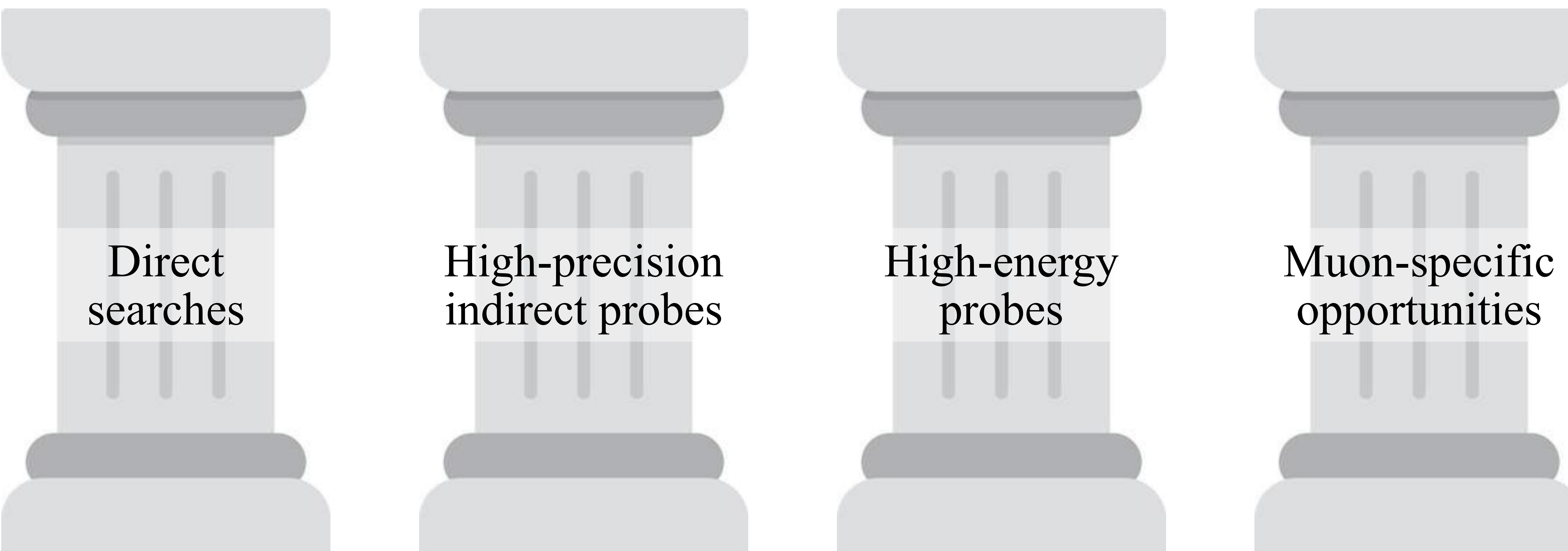
The muon collider combines pp and ee advantages:

- High available energy for new heavy particles production
- High available statistics for precise measurements (and no QCD bck)

Furthermore:

- Can measure processes of very high energy
- Collides muons, for the first time



The SM Physics Case

[Under constructions. Thanks to N.Craig, I.Low, M.Luty and G.Sterman for discussions]

What is a **SM physics case?**

We tend to considers our daily work (in spite of loving it!) an uninteresting technicality towards the (unspecified) Big Thing.

Other communities are more successful, enthusiastic and appealing because they value their "everyday work" as physicists.

We must learn to spell out the excitement of predicting and observing **new phenomena, in SM.**

The SM Physics Case

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The muon collider will **probe a new regime of EW force:**

$$\mathbf{E \gg m_W}$$

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The muon collider will **probe a new regime of EW force:**

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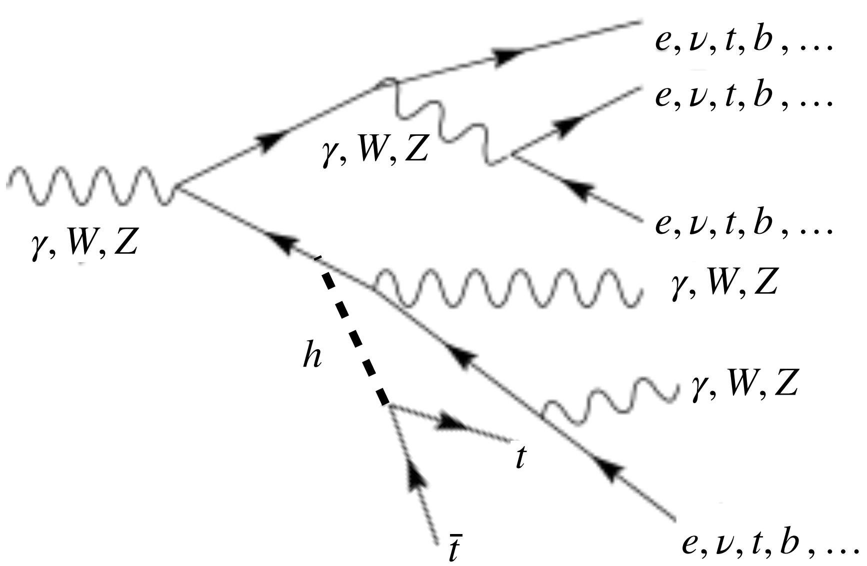
Plenty of cool things will happen:

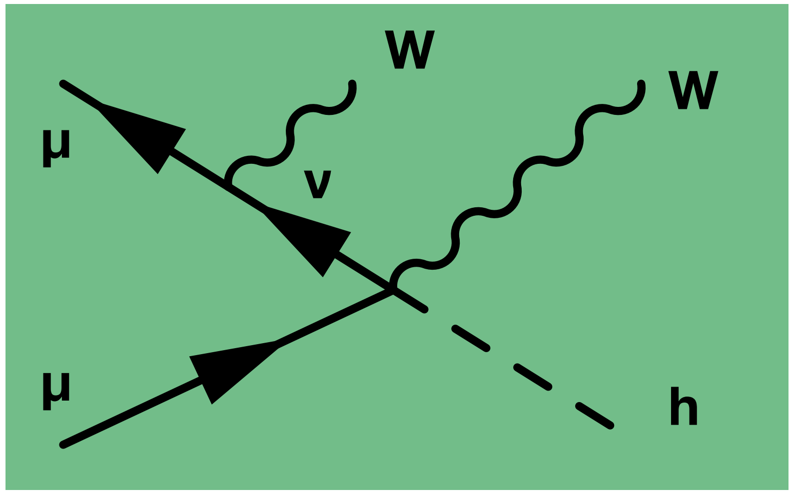
Electroweak Restoration. The $SU(2) \times U(1)$ group emerging, finally!

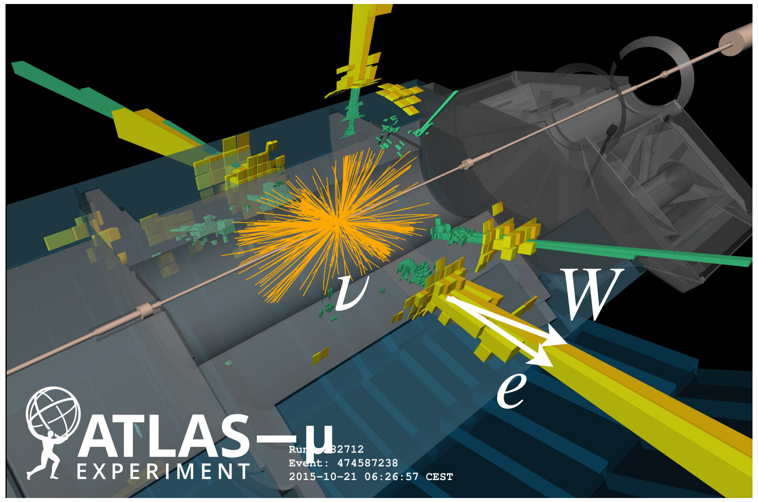
Electroweak Radiation in nearly massless broken gauge theory.
Never observed, never computed (and we don't know how!)

The **partonic content of the muon**: EW bosons, neutrinos, gluons, tops, …
Copious **scattering of 5 TeV neutrinos!**

The **particle content of partons:** e.g., find Higgs in tops, or in W's, etc
Neutrino jets will be observed, and many more cool things

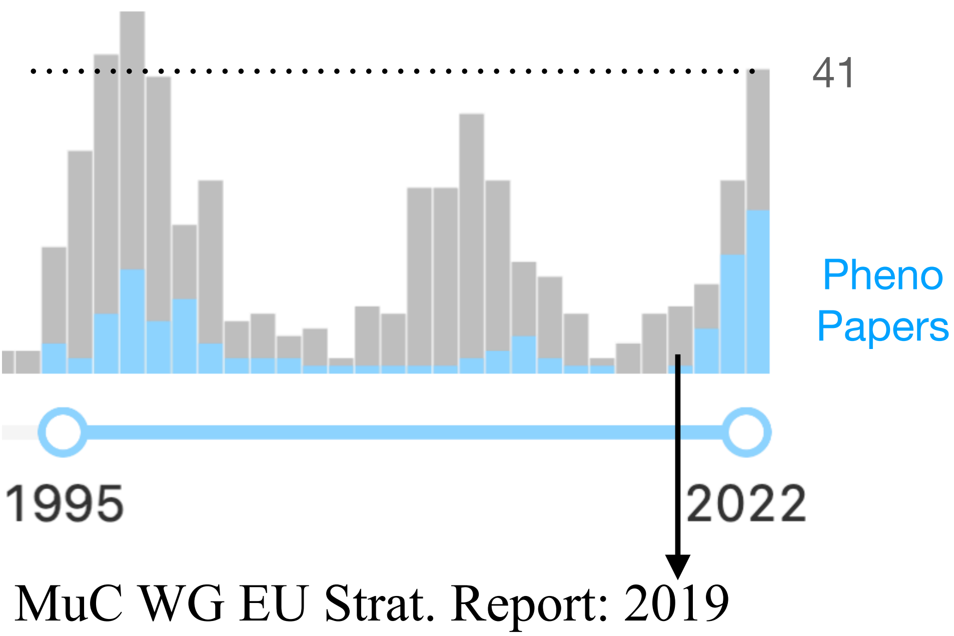






Why Working on the Muon Collider

A **new interest** on muon colliders, **not** a **renewed** one



"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. [...] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. [...] Multi-TeV muon colliders will have the benefit of excellent signal to background [...] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential."

From Snowmass EF report. Based on 2 IMCC + 1 MuC Forum reports. 15 editors, ~150 authors total. Work from ~100 papers in 3 past years

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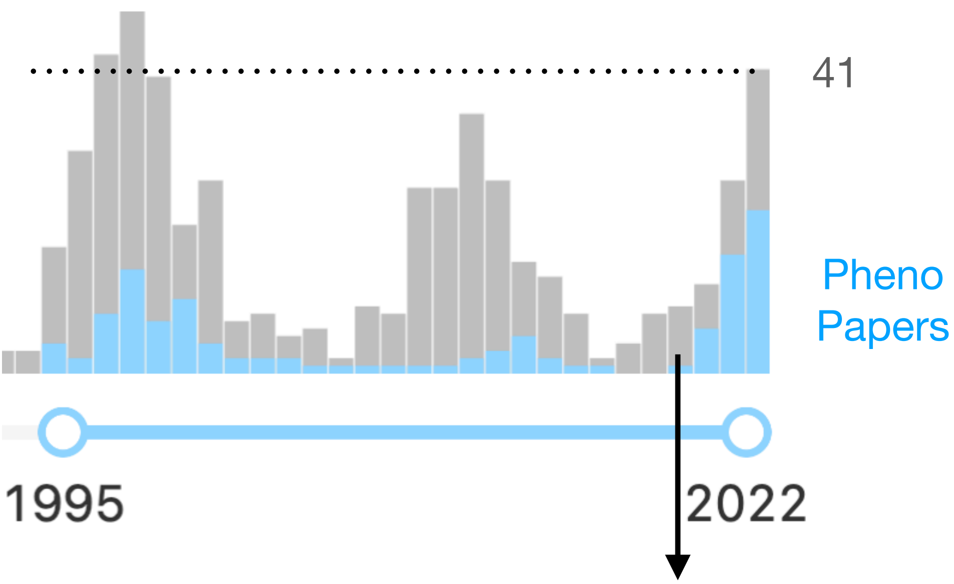

MuC WG EU Strat. Report: 2019

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Workshop at KITP:

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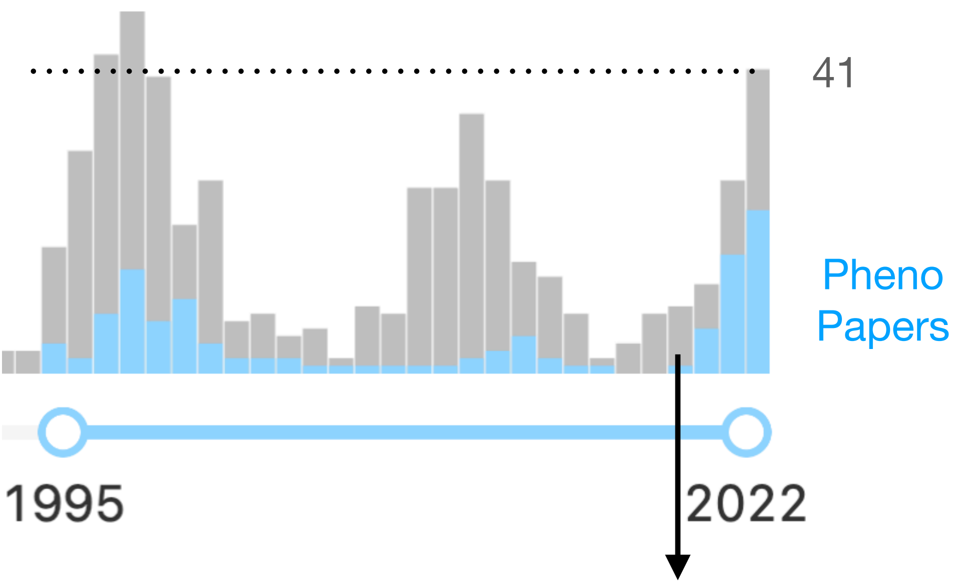

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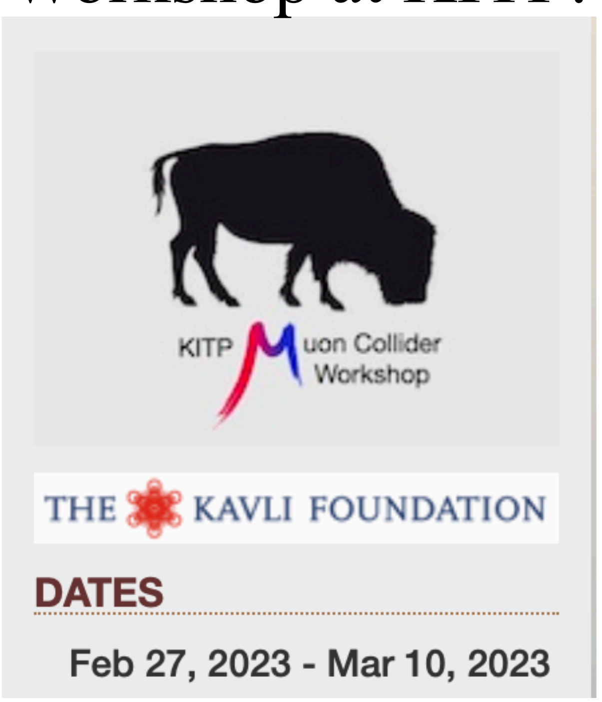

An enthusiastic community:

Why Working on the Muon Collider

Why this enthusiasm?

1. Before LHC, thinking about other future colliders was less urgent
2. After LHC, need of perspective for ambitious jump ahead in energy exploration. Studies for F.C. such as FCC and CLIC prepared the ground.
3. We sharply identified 10+TeV as the final goal. Shorter-term physics opportunities are intermediate steps towards 10+TeV realisation.
4. MuC is very new! Both from Facility and from Physics point of view. People like working on MuC, because there is interesting work to do!

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An excerpt from the To Do list:

- Monte Carlo in novel phase-space
- EW-PDF and Z-γ interference
- Per-mil accuracy in single-Higgs?
- EW showering
- EW radiation resummation for O(1) modelling. Next move to precision!
- EW jet definition and observability
- Hadronic VB/Higgs/top reconstruction
- BSM particle discovery and characterisation potential
- VV Scattering phenomenology

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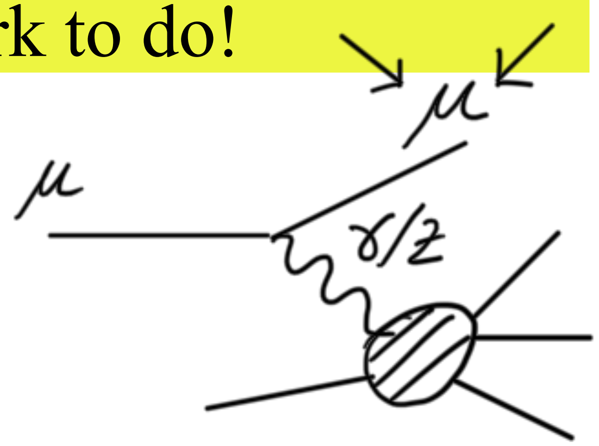
More items in the To Do list:



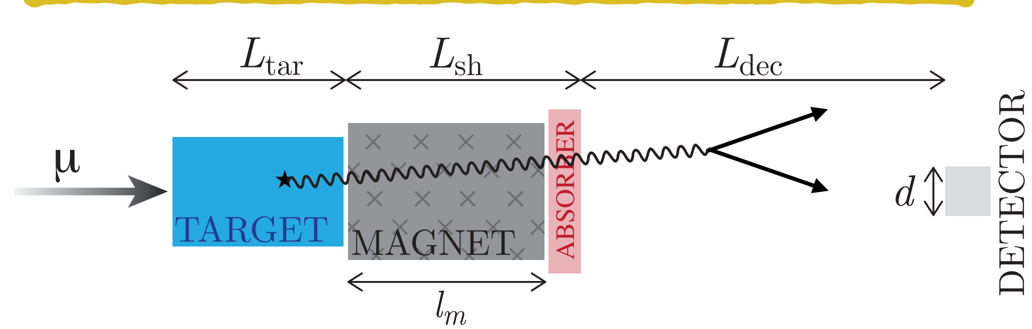
Probing LLPs in new experimental conditions

Exploiting a foward muon detector

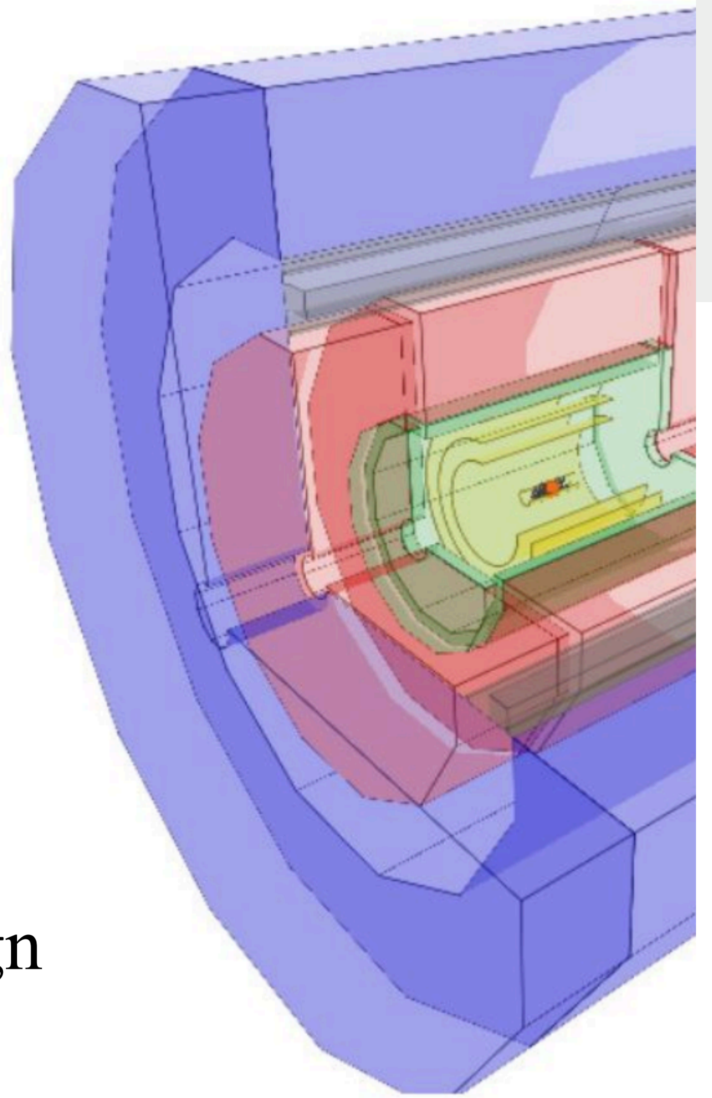
FASERν-type physics and detector for ν beam from μ decay

Facility and demonstrator exploitation, e.g. beam dump

Physics synergies and Physics Along the Way [talk by Chris]



Experiment Design



Design detector for precision at multi-TeV scale

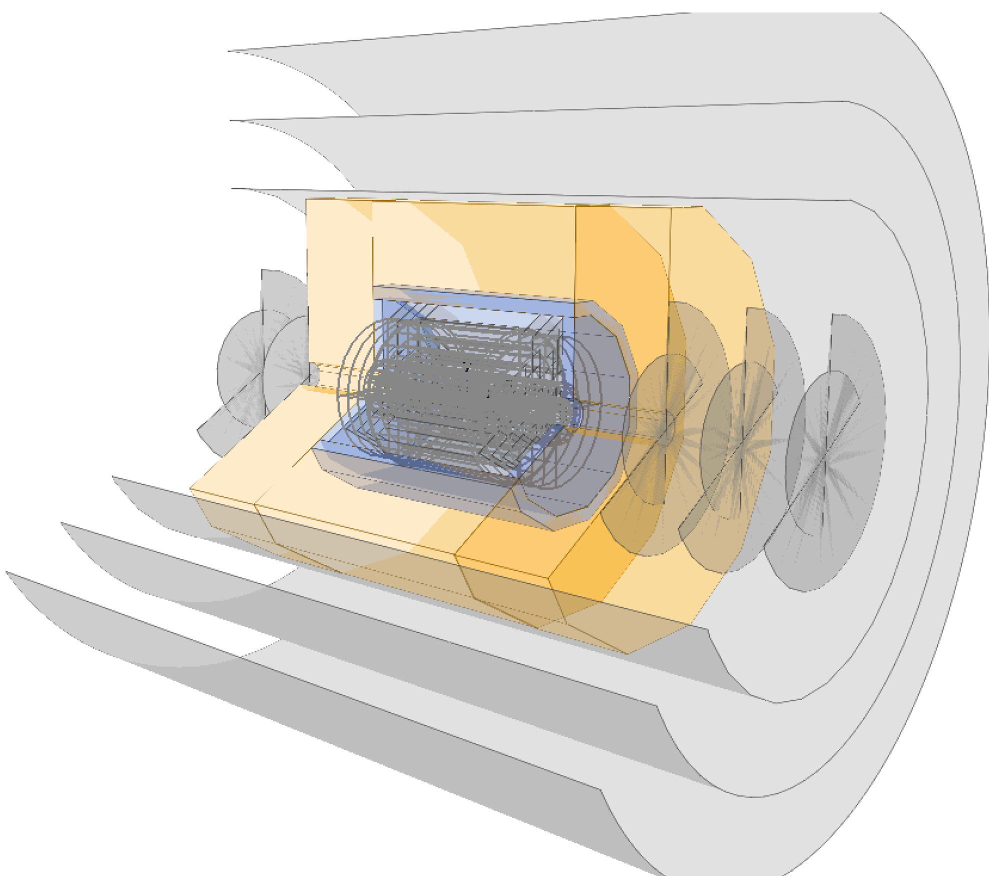
- Extract physics from GeV- and from TeV-energy particles
- Built-in sensitivity to “unconventional” signatures

The BIB is under control. See EPJC Review

- Demonstrated LHC-level performances with CLIC-like design
- Sensitivity to Higgs production
- Disappearing tracks detection

Exciting opportunities ahead

- Explore new detector concepts
- Identify and pursue key R&D requirements for technology development in next 20 years
- New challenges → new techniques that could be ported back to HL-LHC and F.C.
- Tackle the gigantic physics program of the MuC!



Conclusions

MuC is great option for the future of high-energy physics:

- Direct access to what most of us want to study: EW and Higgs
- **Energy and Precision** at once. And, **Precision at High Energy**
- $E \gg m_W$ is a theoretically and experimentally unexplored regime of QFT

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MuC is great option for the **present** of high-energy physics:

- **The first collider of its species.** All is new, for ACC, PH, TH, EXP!
- MuC physics requires and enables innovative research of self-standing relevance
  This work must start today:

*"We are not **waiting** for the muon collider, we are **working** on it"* *F. Maltoni*

A lot of cool LHC physics was done decades before the LHC started
And LHC physics was built on decades of previous proton collider experience!
Twenty years is barely enough to be ready!

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New enthusiasm on muon collider physics:

- In spite of (actually, because of!) the risk of failure
- Scientists like working on what is new and difficult
- **Opportunity, not threat(!) for collider physics at large**

Thank You