Muon Colliders

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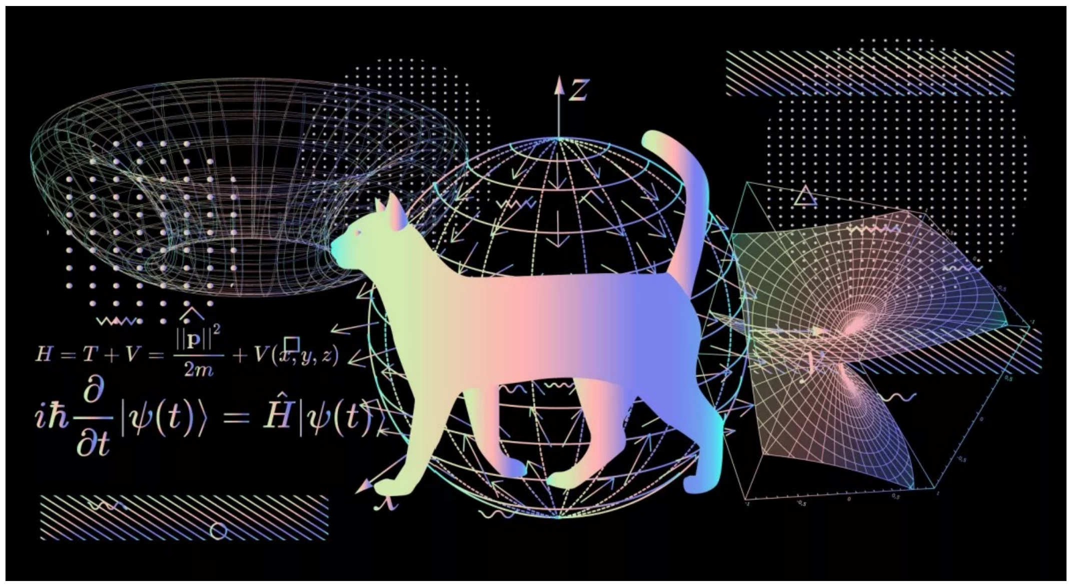
Institut de Física d'Altes Energies

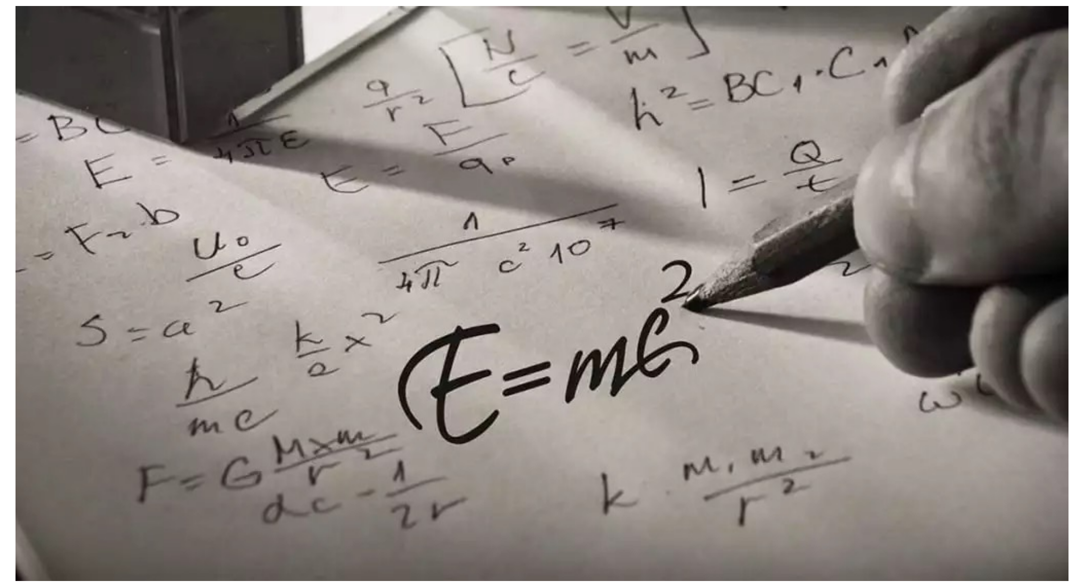
On behalf of

International MUON Collider Collaboration

High Energy Physics Landscape

Quantum Mechanics + **Special Relativity**





¿ = ? **Quantum Field Theory**

¿ = ? **The Standard Model**

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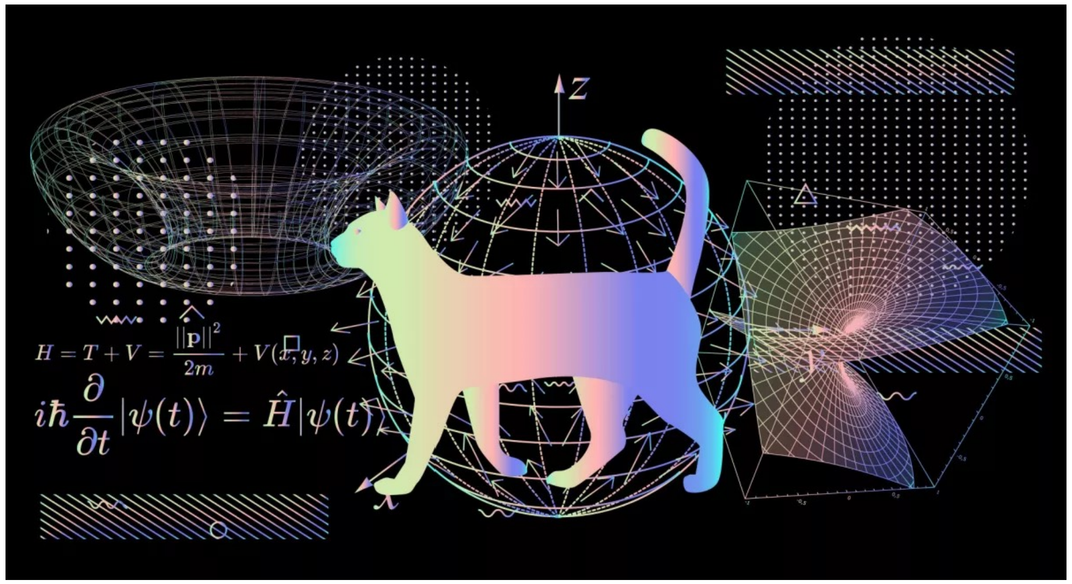

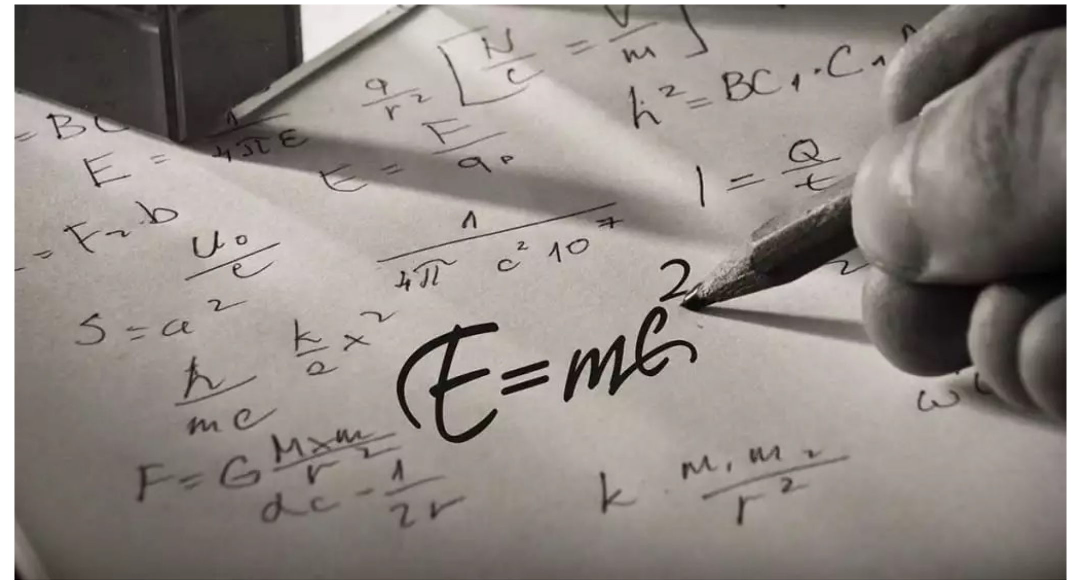

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No, of course. The SM merely **accommodates** all fields we have observed and the corresponding particles. And, it seems, not all of them, like Dark Matter.

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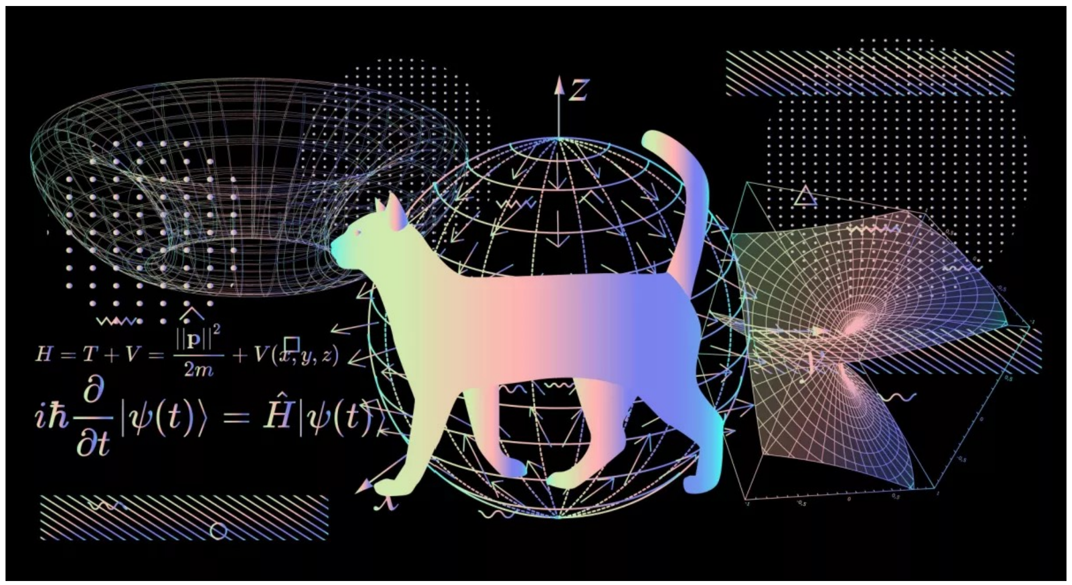

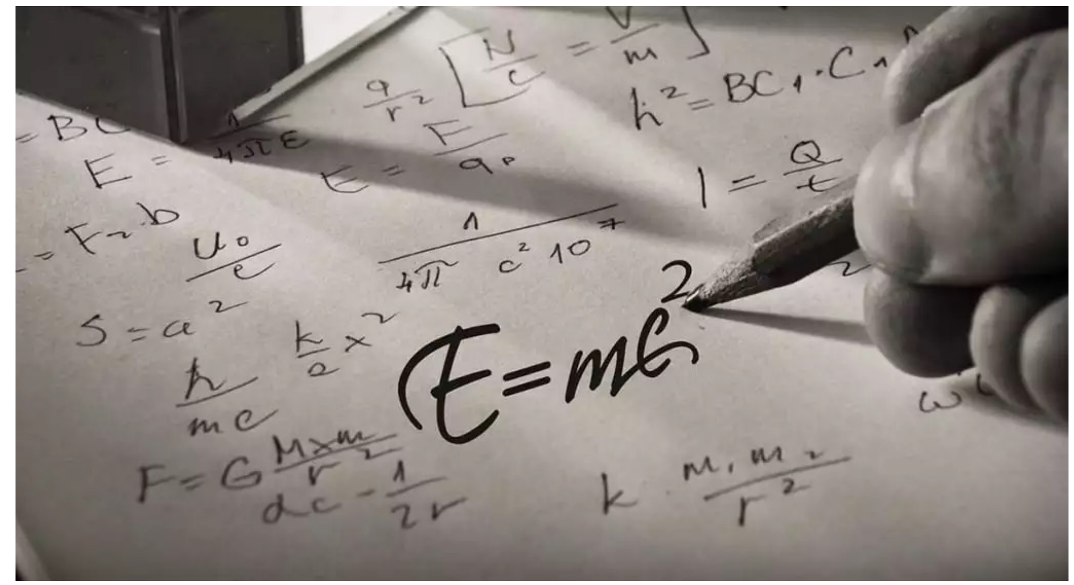

¿ = ? Quant

Our present knowledge of fundamental (or not) particles emerges from past observations.
The existence or non-existence of other particles can thus be only established by future observations

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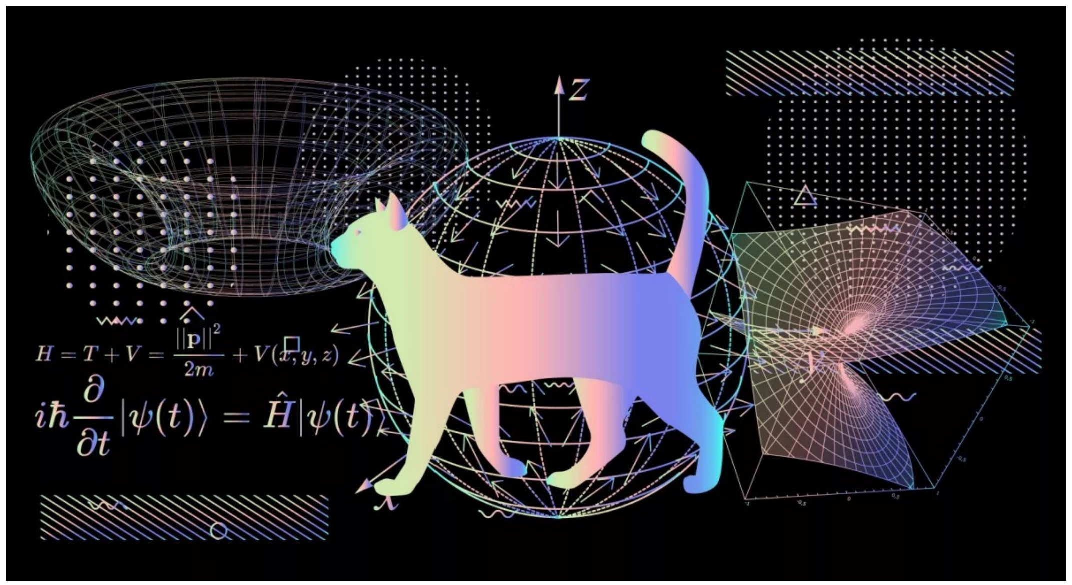

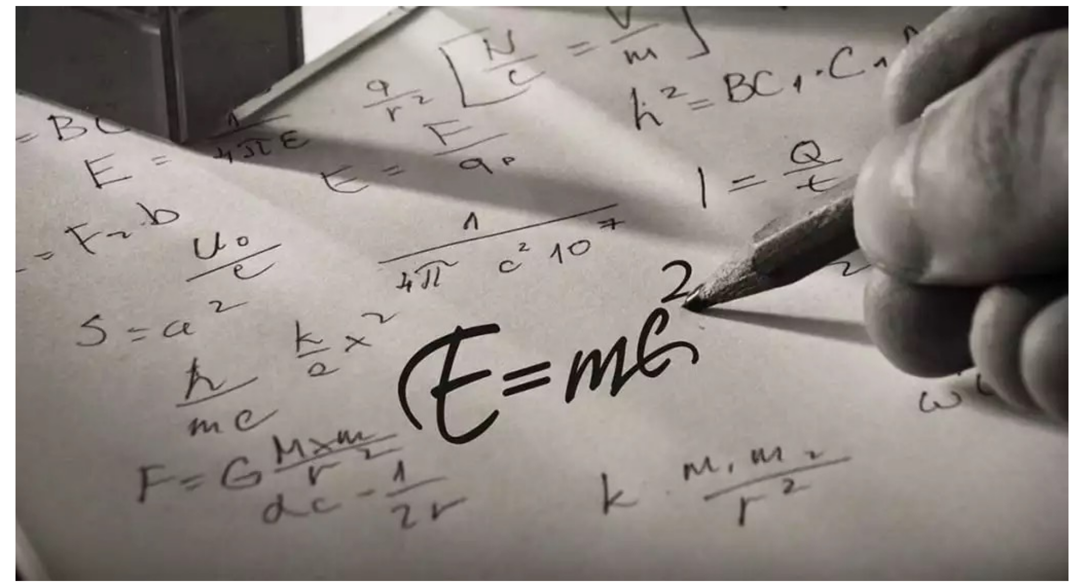

¿ = ? Quantum Field Theory

No! Quantum fields with local Lagrangian and gauge theories are **one implementation** of QM+SR principles (definitely incomplete, as it fails with Gravity). Its success surely stem from an even deeper unknown underlying principle.

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High Energy Physics Landscape

The Higgs is revolutionary!

One more direct experimental confirmation of the QFT implementation of QM+SR principles (and indirectly of the principles).

The **first manifestation of** a new class of theories: **massive gauge theories**

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Higgs is not a superconductor
There is no Higgs "medium"

Spin-one relativistic particles and their high-energy description are as unique of hep as it sounds

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A special m.g.t.: perturbatively **extends to high, untested, energies**

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Testing new SM predictions is a prime target

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Could be the first **elementary scalar**.
Disproves Wilsonian explanation of QFT emergent as EFT.

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We must check!!

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Higgs Physics questions for future colliders:

Is it the Standard Model Higgs Particle?

- Single-Higgs couplings
- Trilinear Higgs coupling

What is it made of?

- Composite Higgs

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Is it the Standard Model Higgs Theory?

- High-energy EW (with Higgs) Physics

Why Muons?

Leptons are the ideal probes of short-distance physics:

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
No QCD background, to study EW+Higgs

Electrons radiate too much

[cannot accelerate them in rings above few 100 GeV]
[linear colliders limited to few TeV by size and power]

Muon Colliders

1980
First ideas

2011-2014 MAP in U.S.
Muon Accelerator Program

2020 Update of EU Strategy
outcome: set up collaboration

International
MUON Collider
Collaboration

muoncollider.web.cern.ch

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2023 P5 outcome: “The Muon Shot”

?

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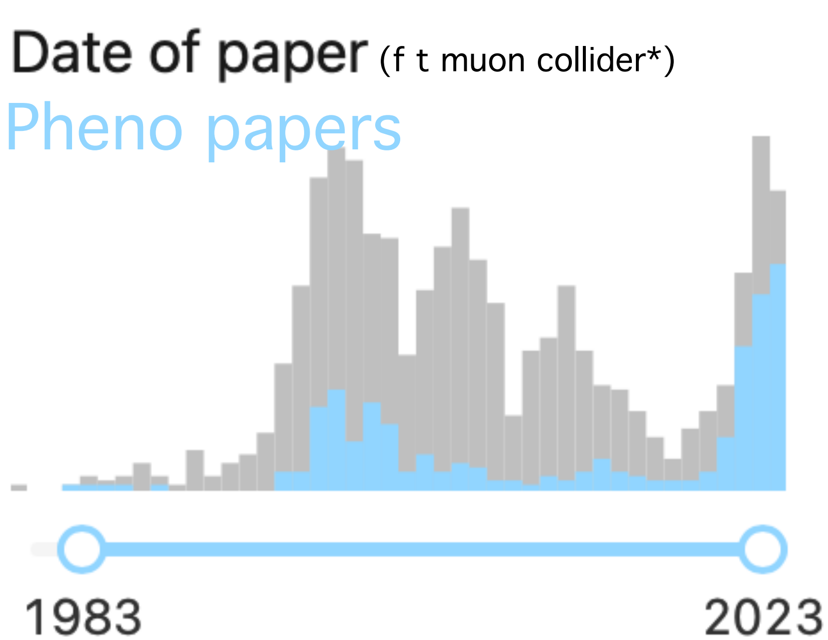
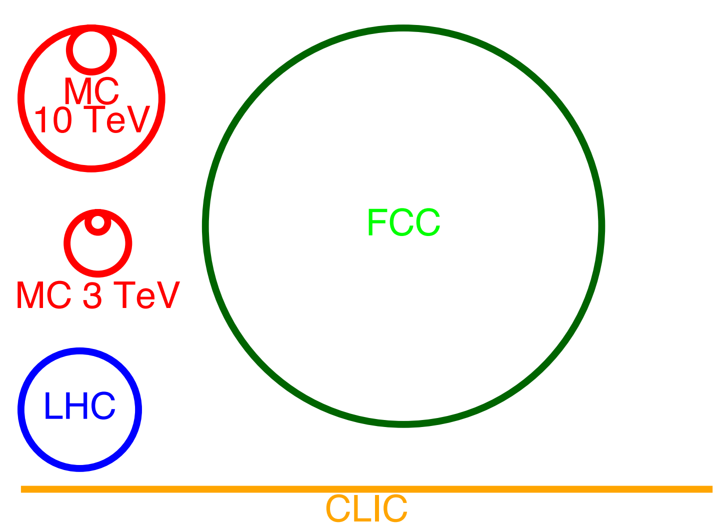
Muon Colliders

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	$E_{\rm cm}$	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1\times10^{34}\,{\rm cm}^{-2}\,{\rm s}^{-1}$	1.8	20	40
Collider circumference	$C_{\rm coll}$	km	4.5	10	14

5 yrs run, 1 IP: $\mathfrak{L}_{\rm int} = 10\,{\rm ab}^{-1}\left(\frac{E_{\rm cm}}{10\,{\rm TeV}}\right)^2$

Unprecedented enthusiasm:





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Physics Opportunities

The muon collider combines pp and ee advantages:

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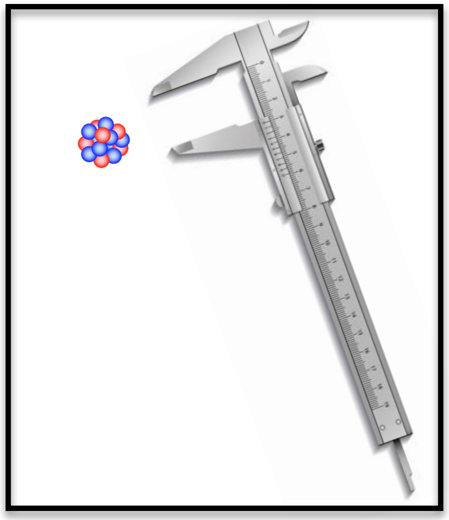
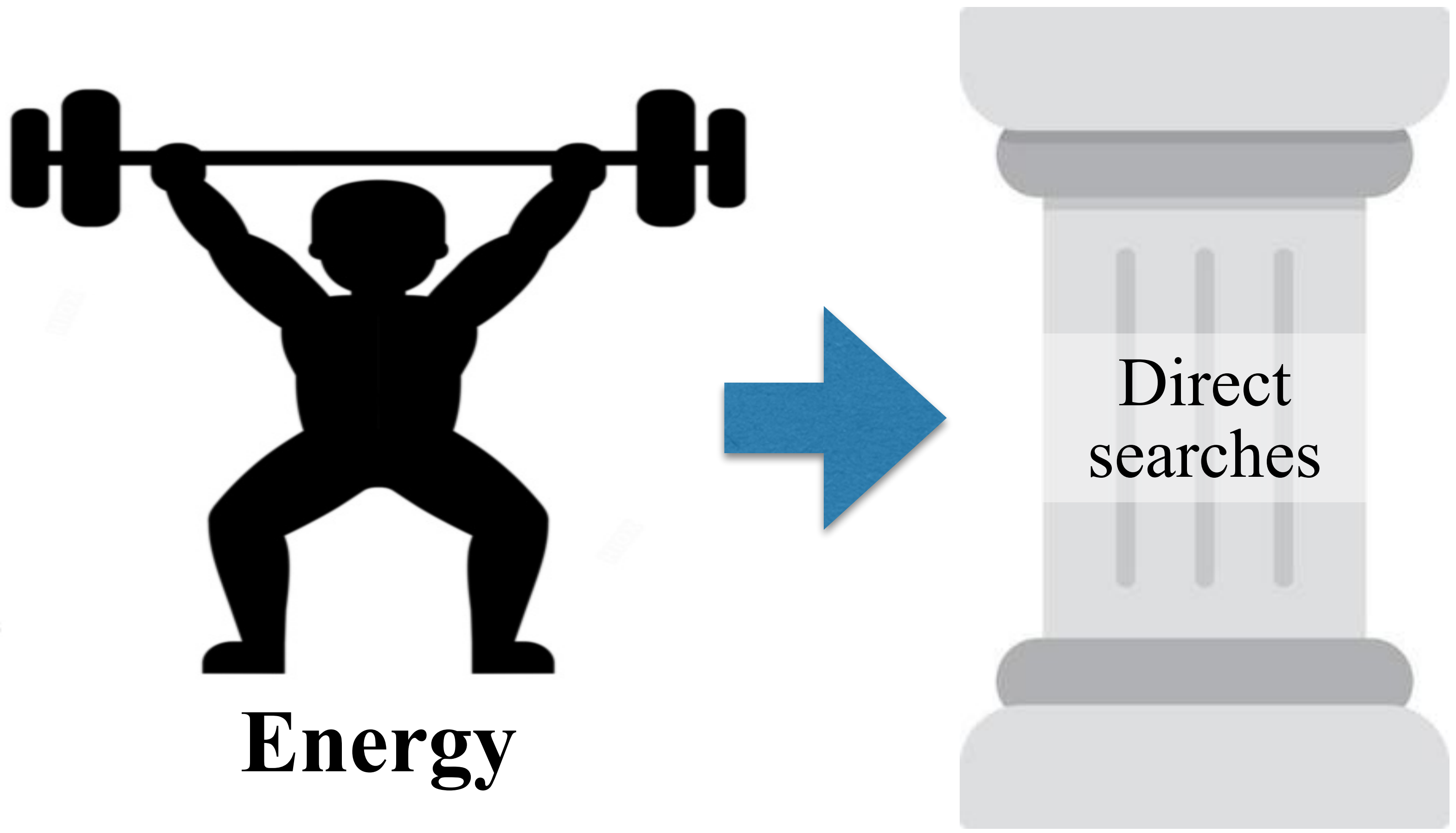


Precision

Direct searches



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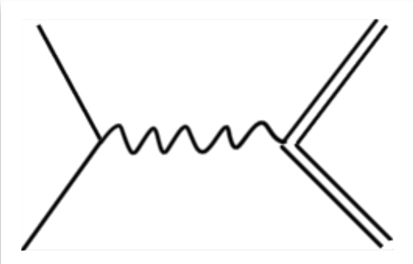
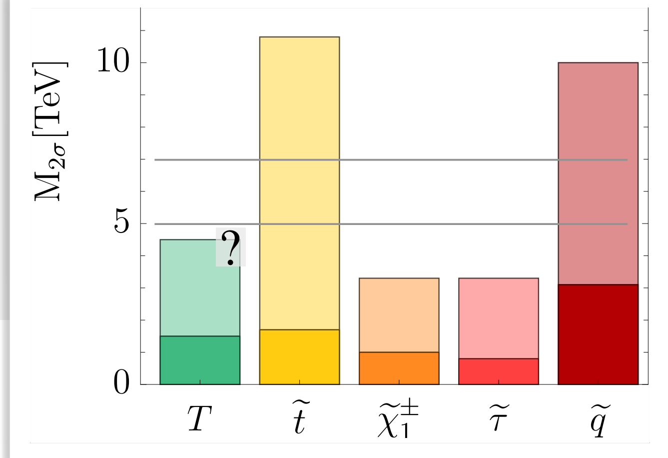
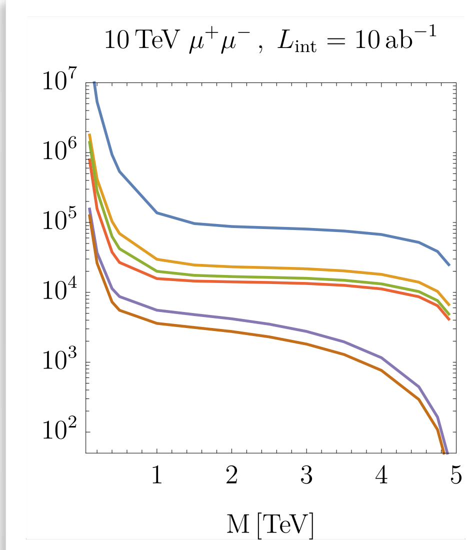
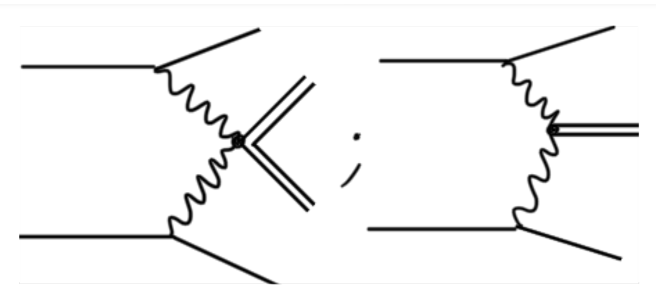


μμ annihilation: copious production of **EW-charged particles** up to $E_{cm}/2$



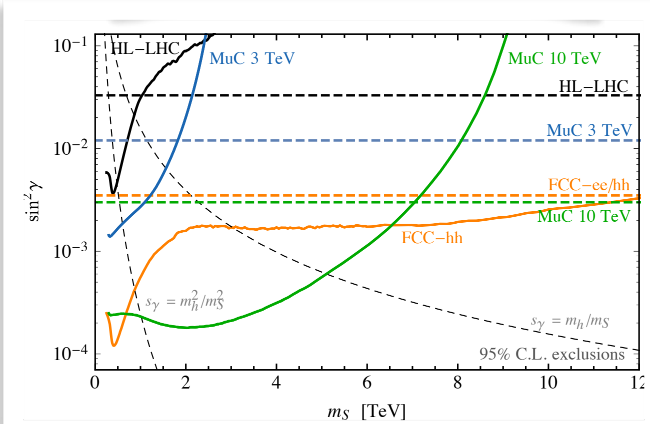
These searches can, for instance, advance probes of (un)-Natural EWSB by one or two orders of magnitude





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

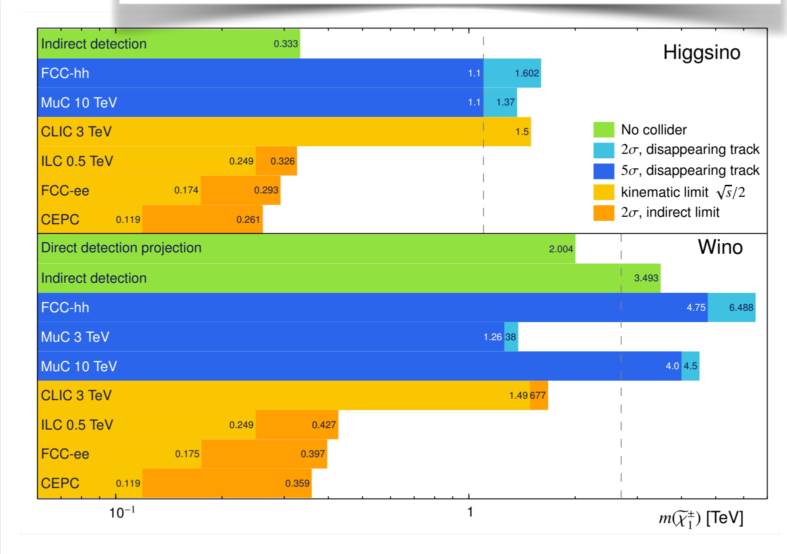
$|H|^2 \cdot X^2$; or $|H|^2 \cdot X$



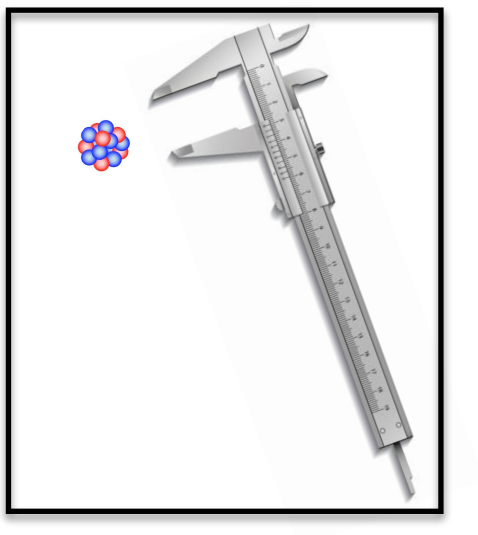
This will, for instance, probe conclusively extended Higgs sectors that produces strong first-order EW phase transition in the early Universe

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

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



High-precision indirect probes



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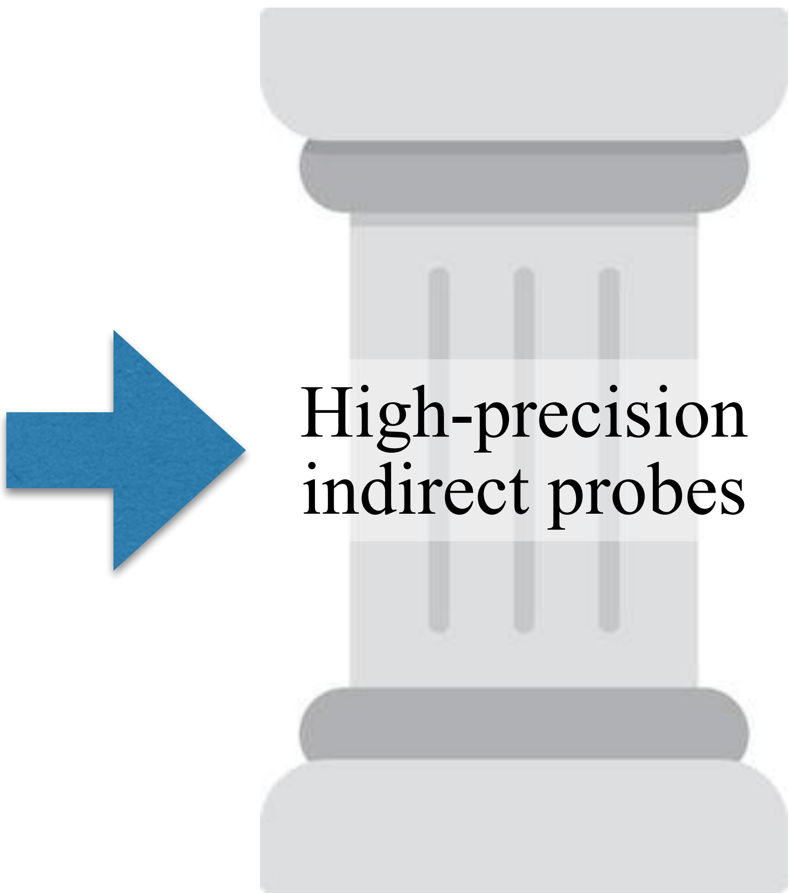

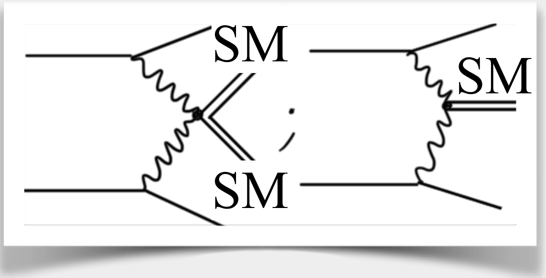

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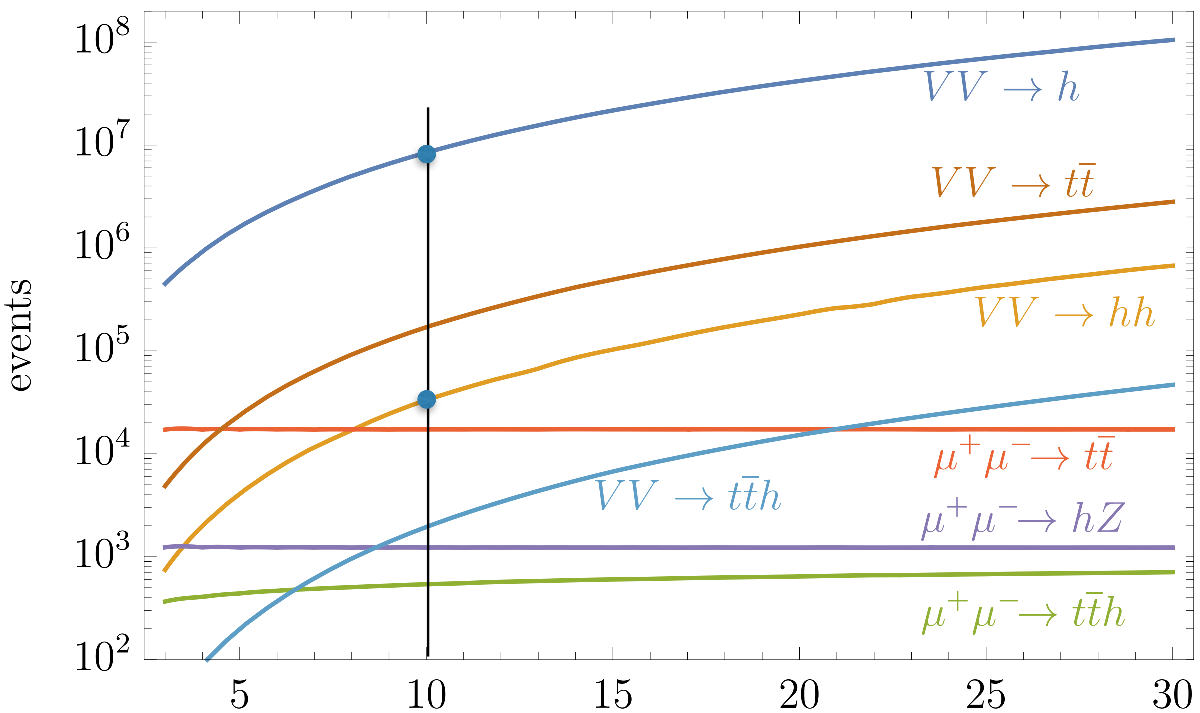
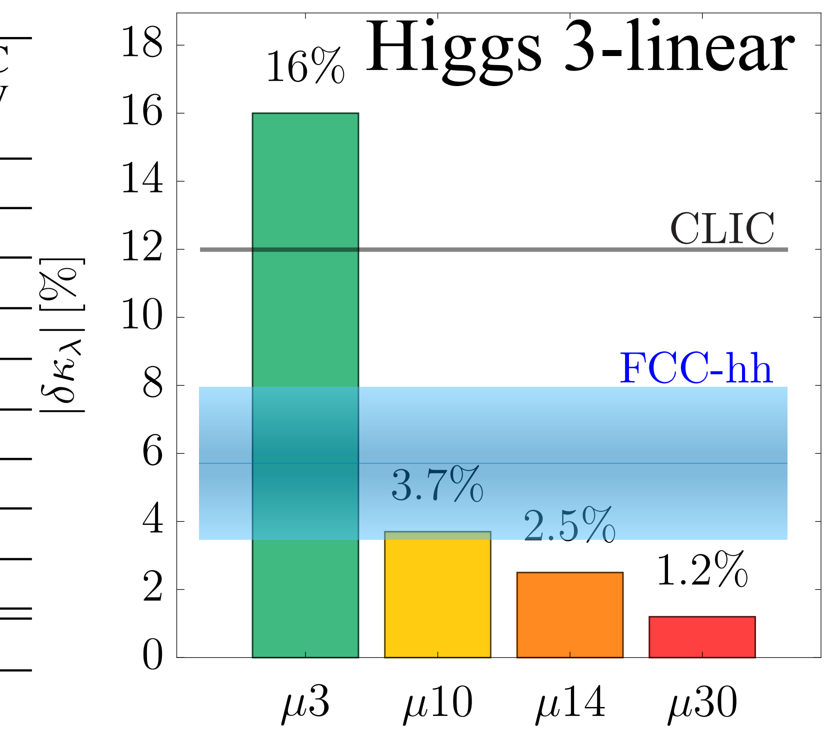
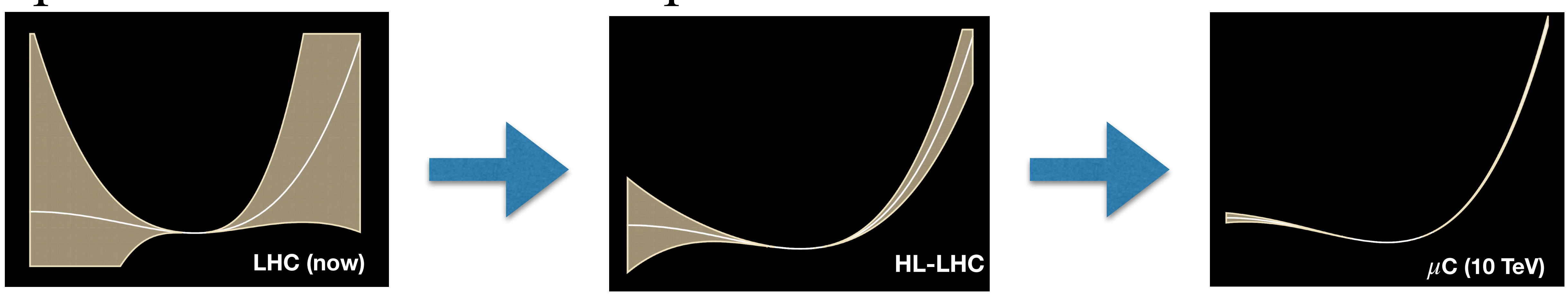


	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

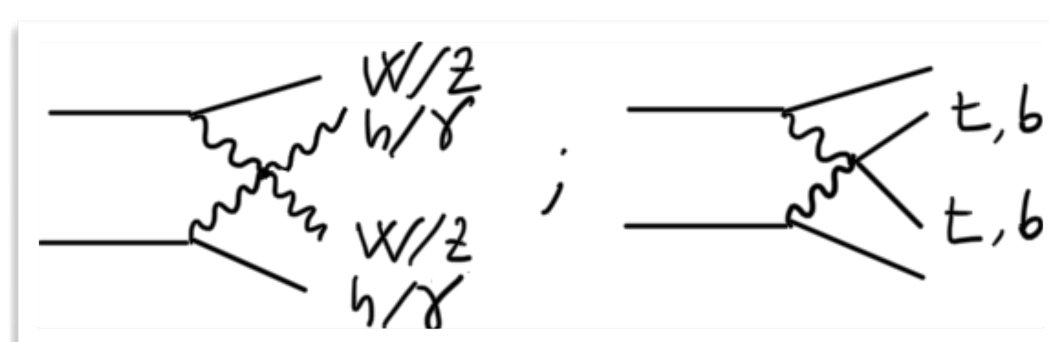


A pictorial view of 3-linear precision:



Many unexplored opportunities

[e.g., VV scattering]

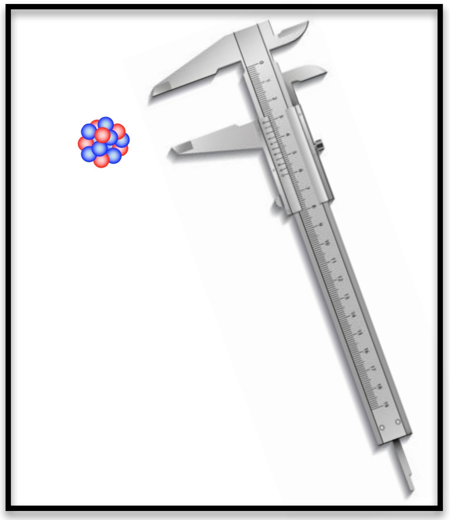


Physics Opportunities

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)

Energy



Precision

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Furthermore:

- Can measure processes of very high energy

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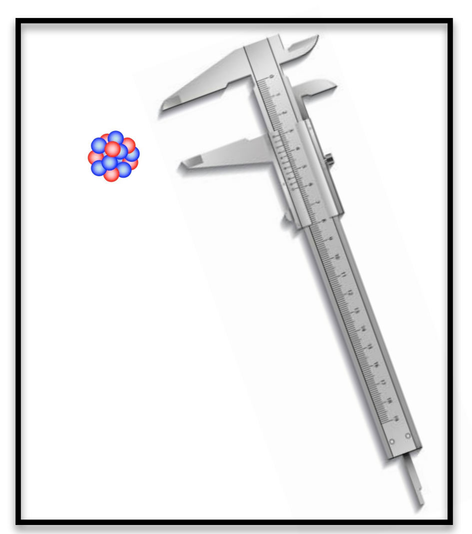

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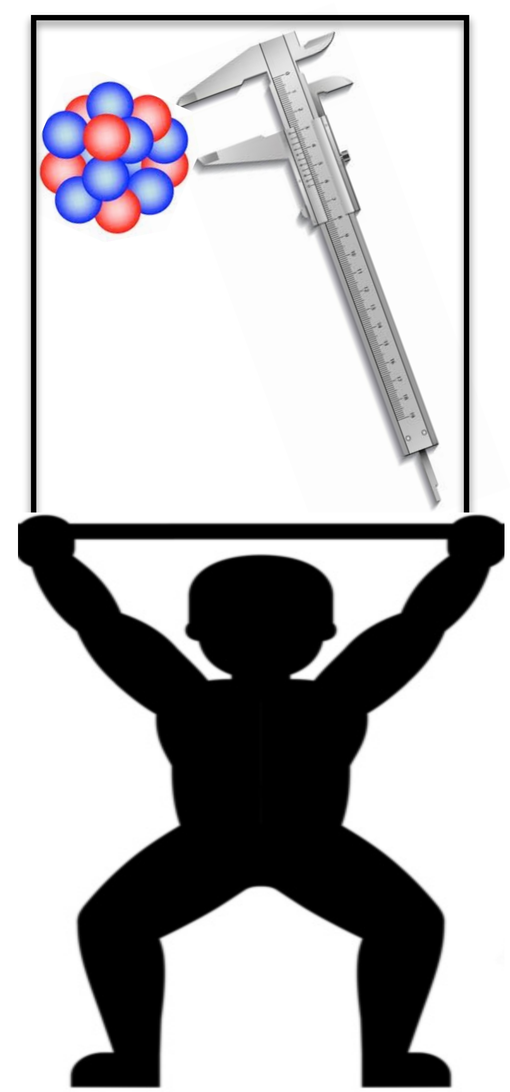
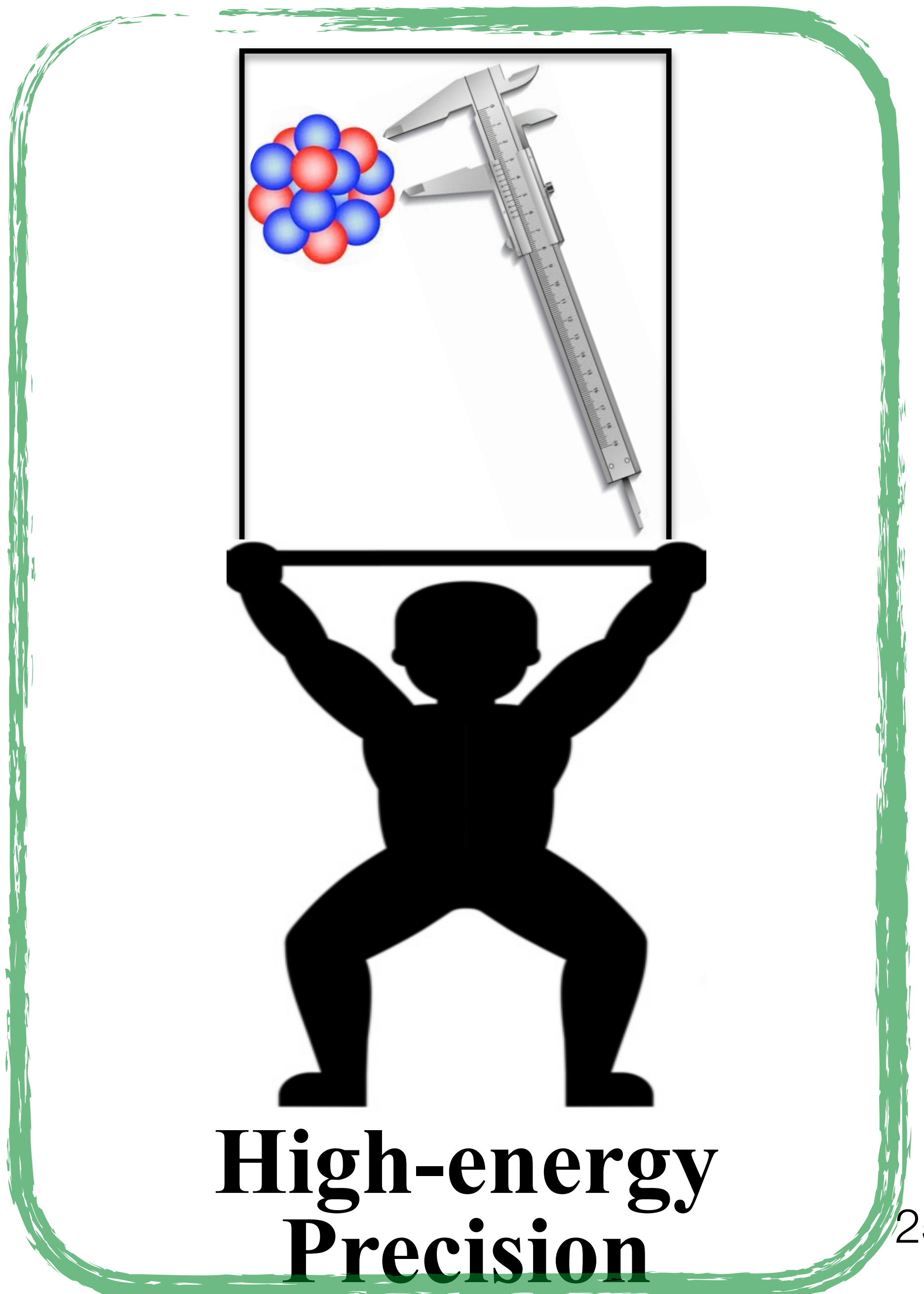


High-energy Precision

Physics Opportunities

Many discoveries came neither from new particle detection, nor from extreme precision, **but needed energy**. E.g.:

- Neutral Currents
- Proton Compositeness



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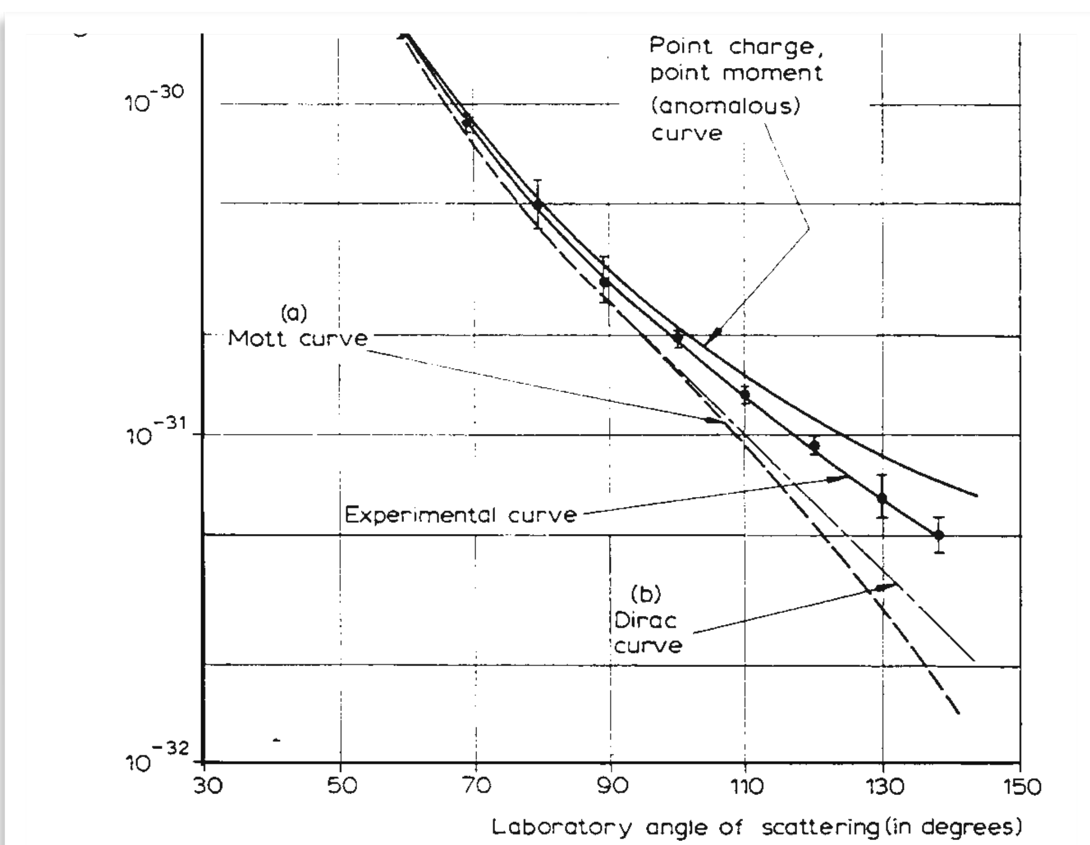
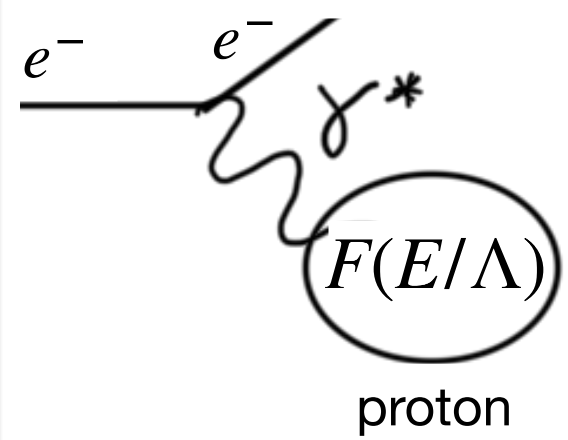
Proton compositeness discovery:

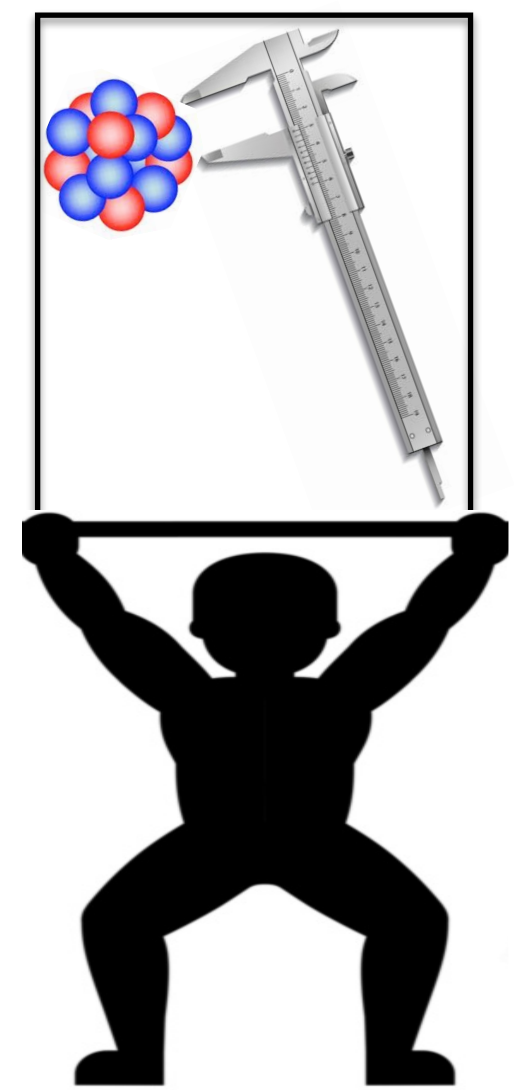
- Order 10% departure from point-like prediction.
- Visible form-factor effects required **large energy**

$$E \nearrow \Lambda \sim 1/r_p$$



Electron scattering from the proton at an incident energy of 188 MeV.





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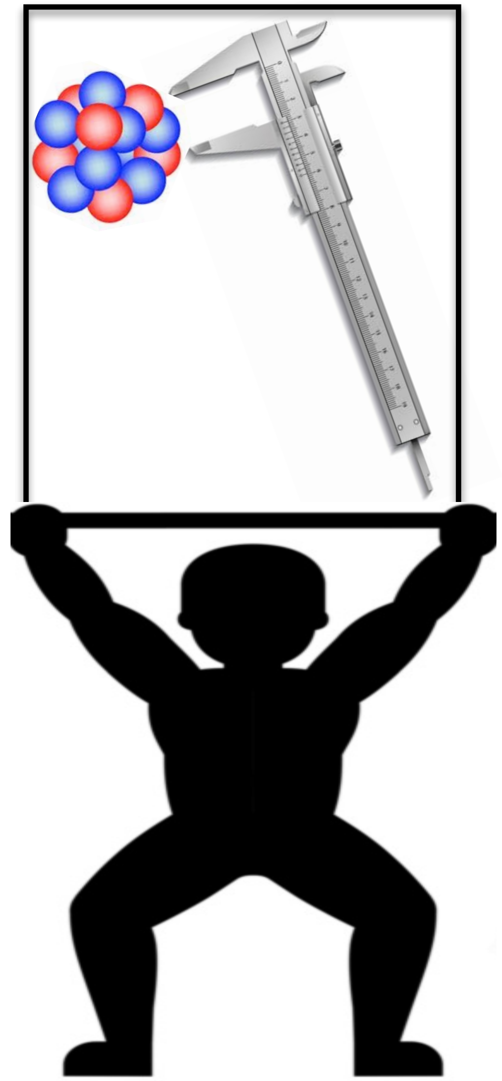
High-energy probes



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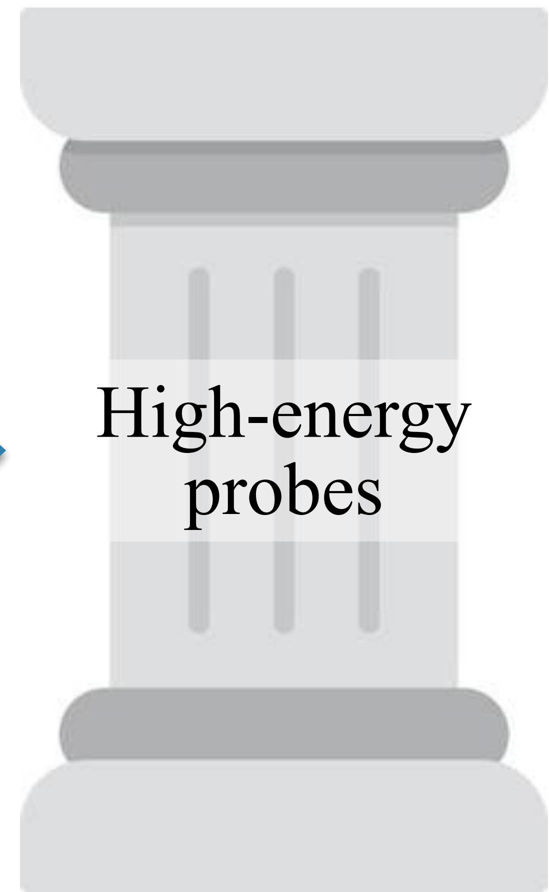
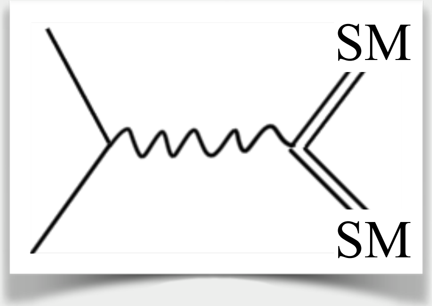




High-energy probes

As simple as this:

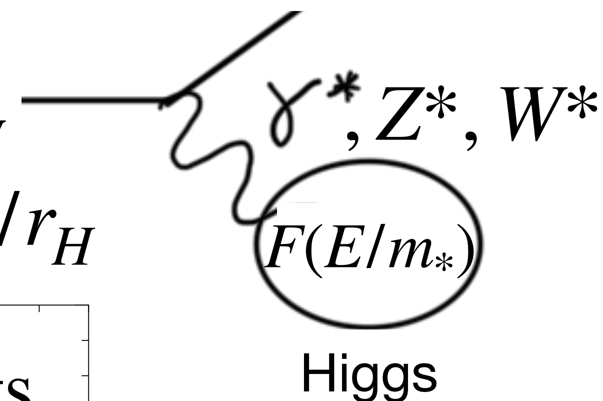
$$\frac{\Delta\sigma(E)}{\sigma_{SM}(E)} \propto \frac{E^2}{\Lambda^2_{BSM}} \overset{\text{[say, } \Lambda_{BSM} = 100 \text{ TeV]}}{=}$$

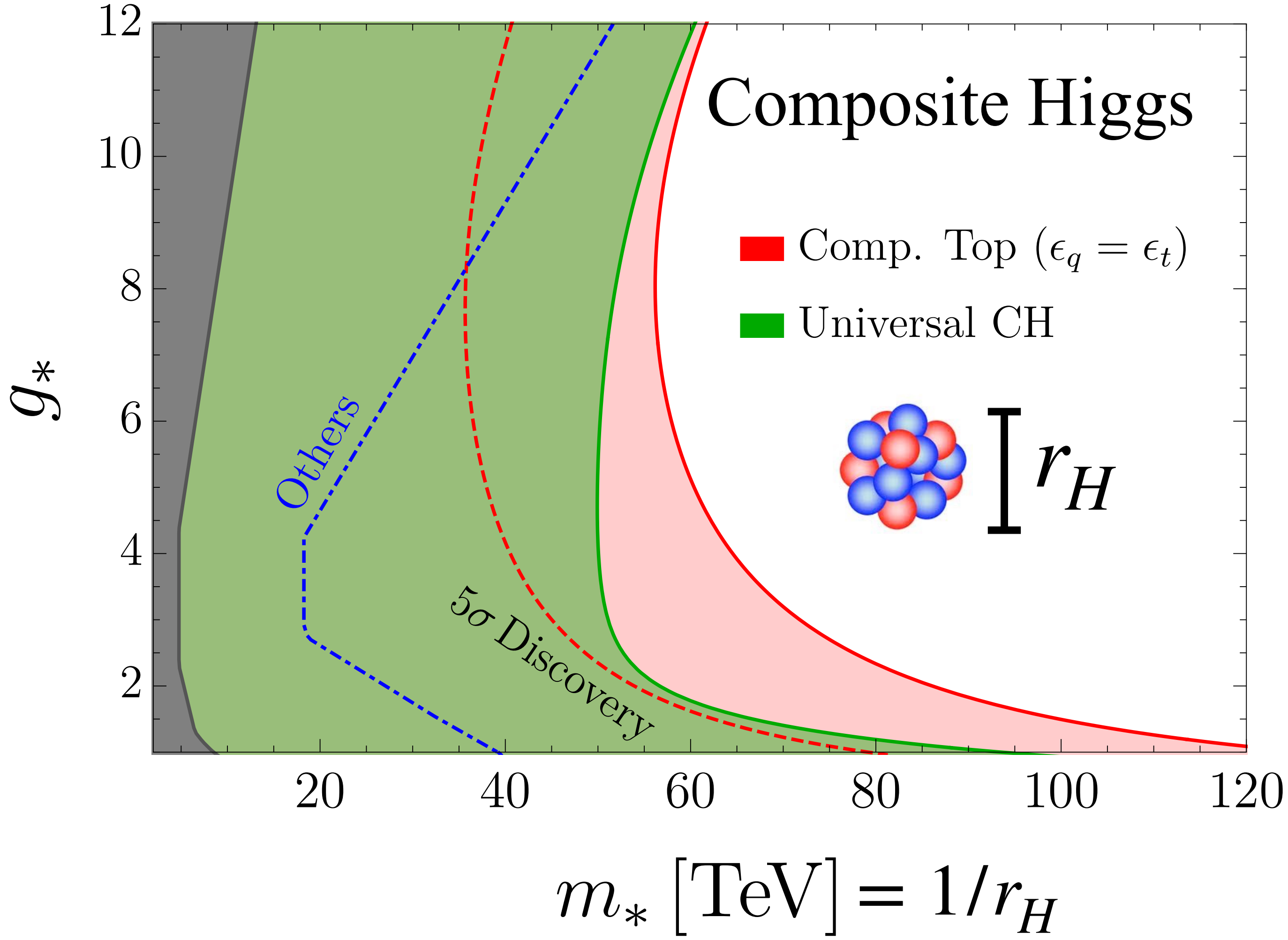
- $\mathbf{10^{-6}}$ at EW [FCC-ee] energies
- $\mathbf{10^{-2}}$ at **muon collider** energies

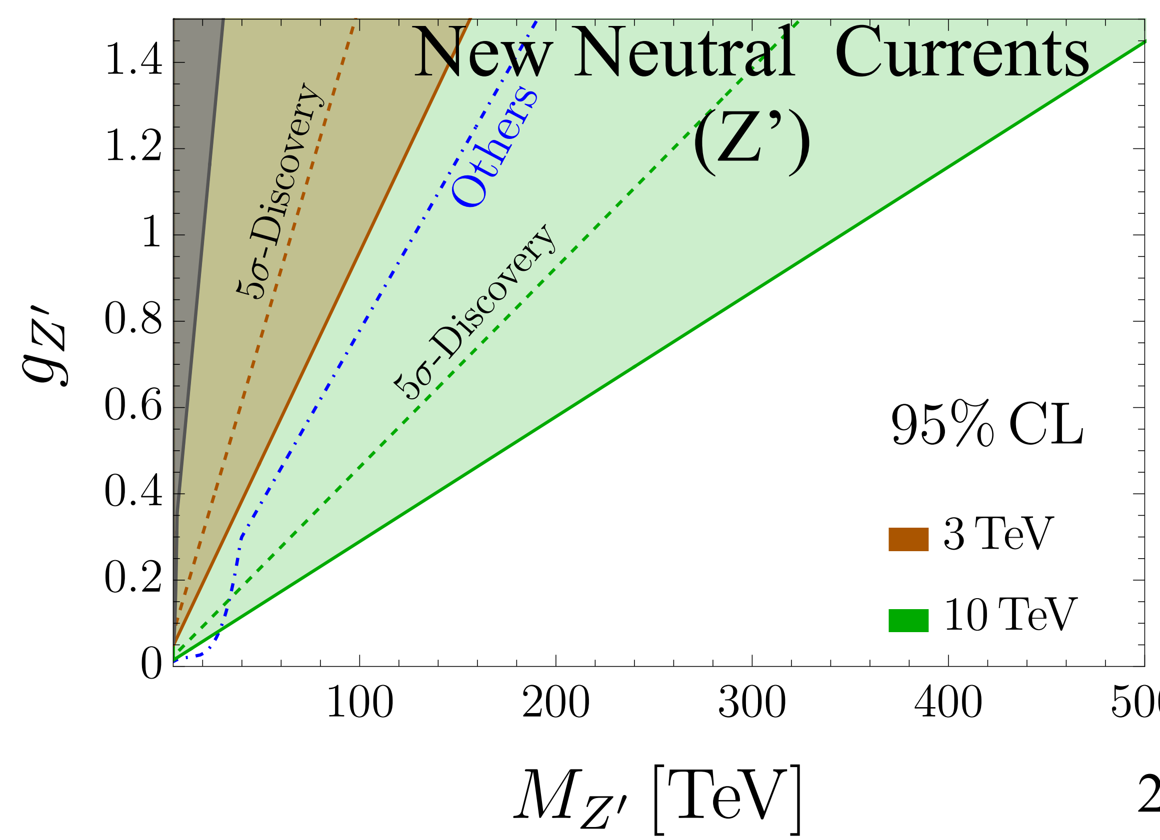
Or even simpler:

Same as proton, with **larger energy**

$E \nearrow m_* \sim 1/r_H$

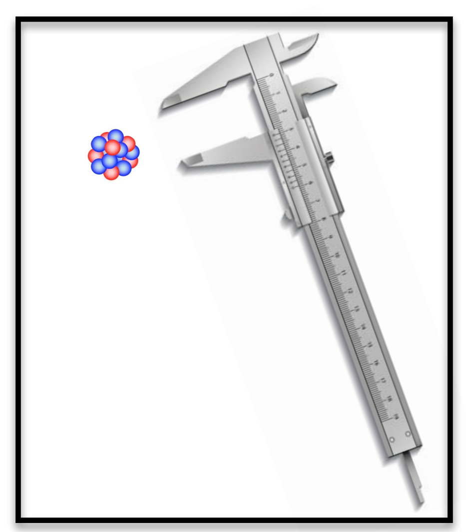






Physics Opportunities

Energy



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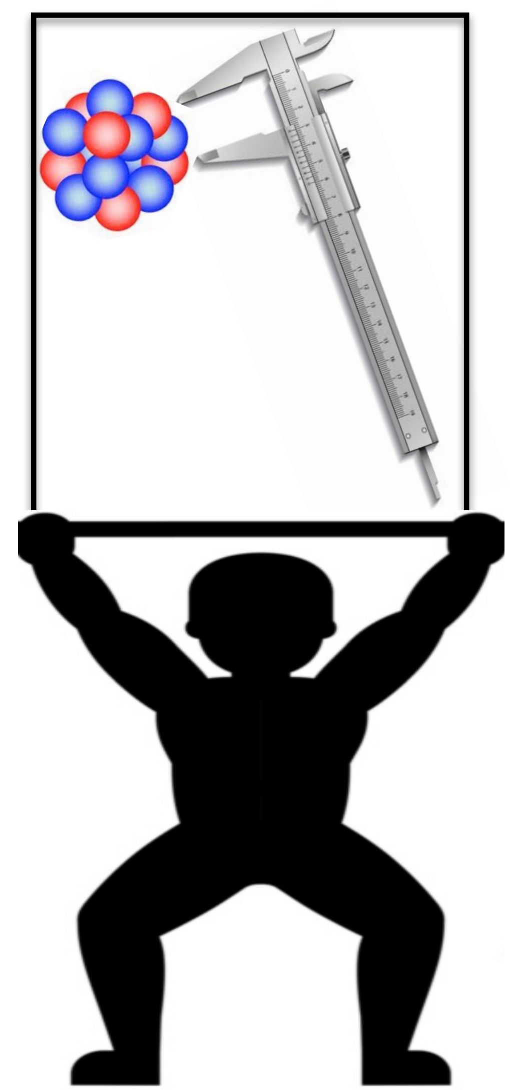
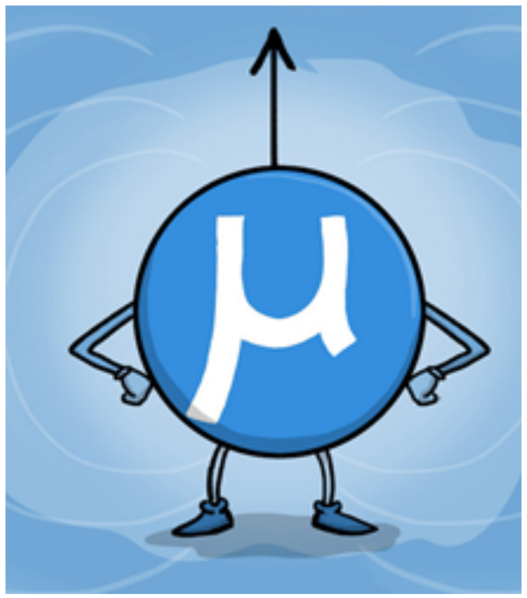


High-energy Precision

Physics Opportunities

Muons!!



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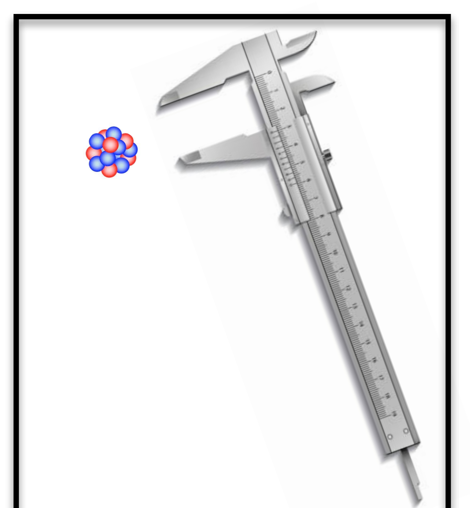

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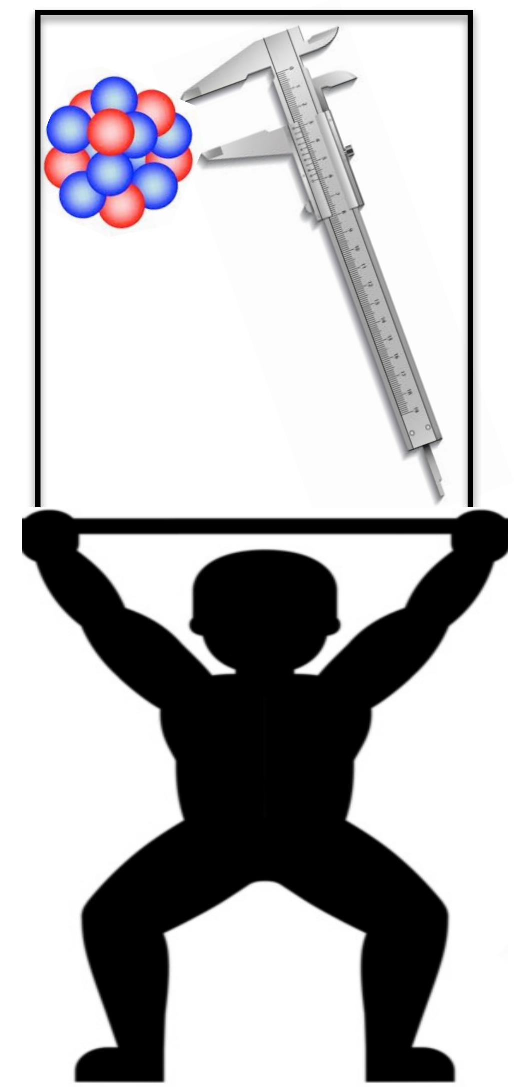

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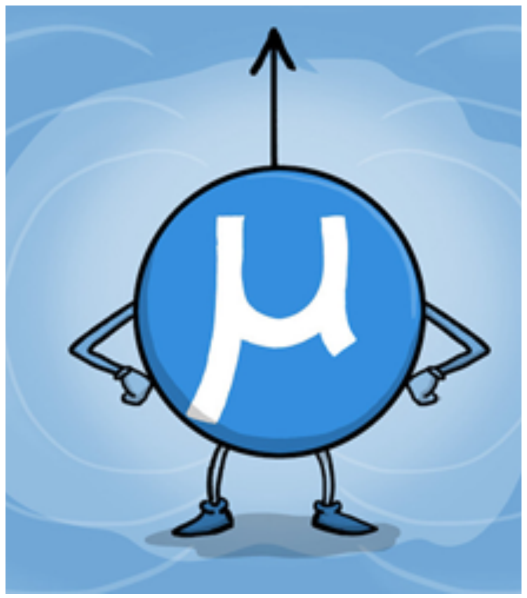
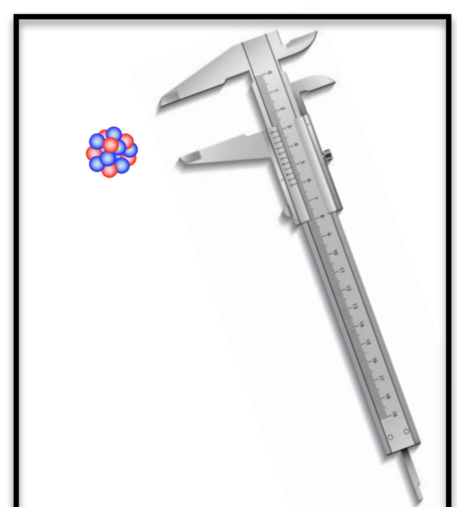


Muons colliding for first time

Self-evident potential of exploration.

Novelty and **challenge** for accelerator physics, technology, and detector, **make such long-term project plausible!**

Energy



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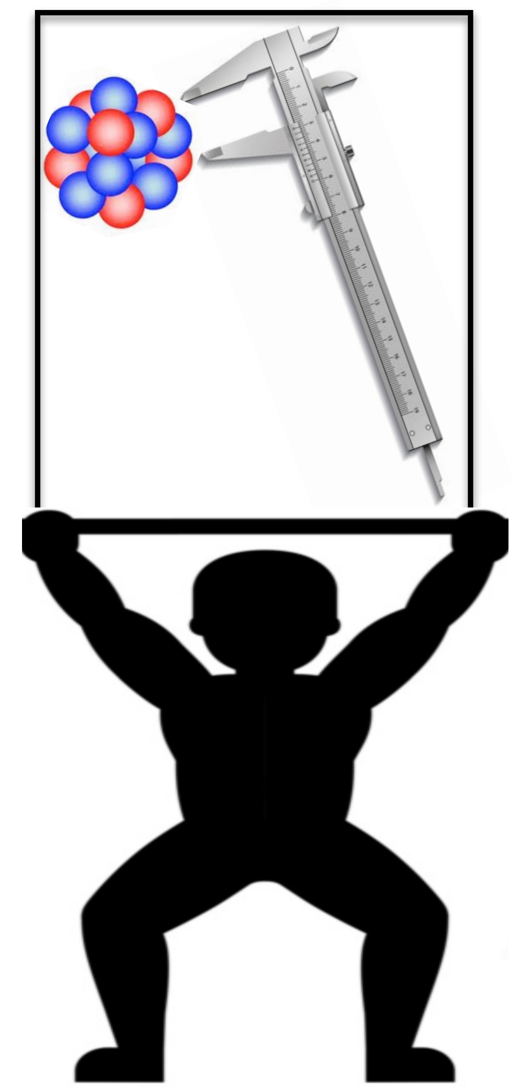

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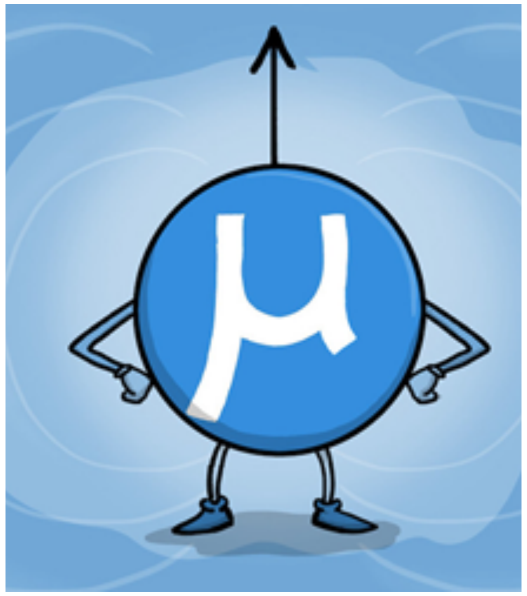

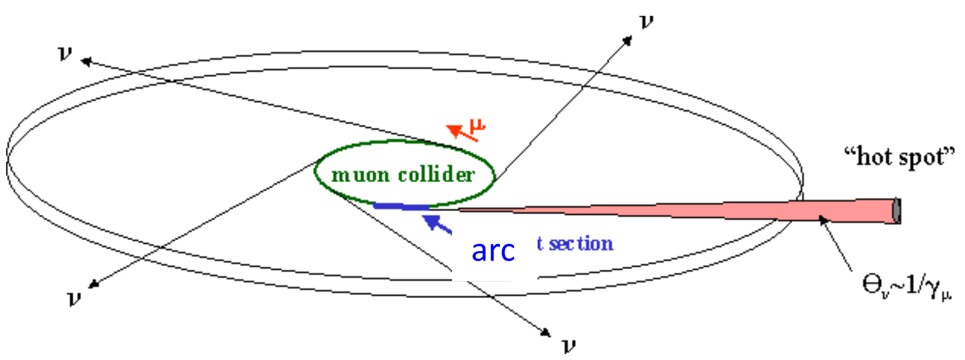

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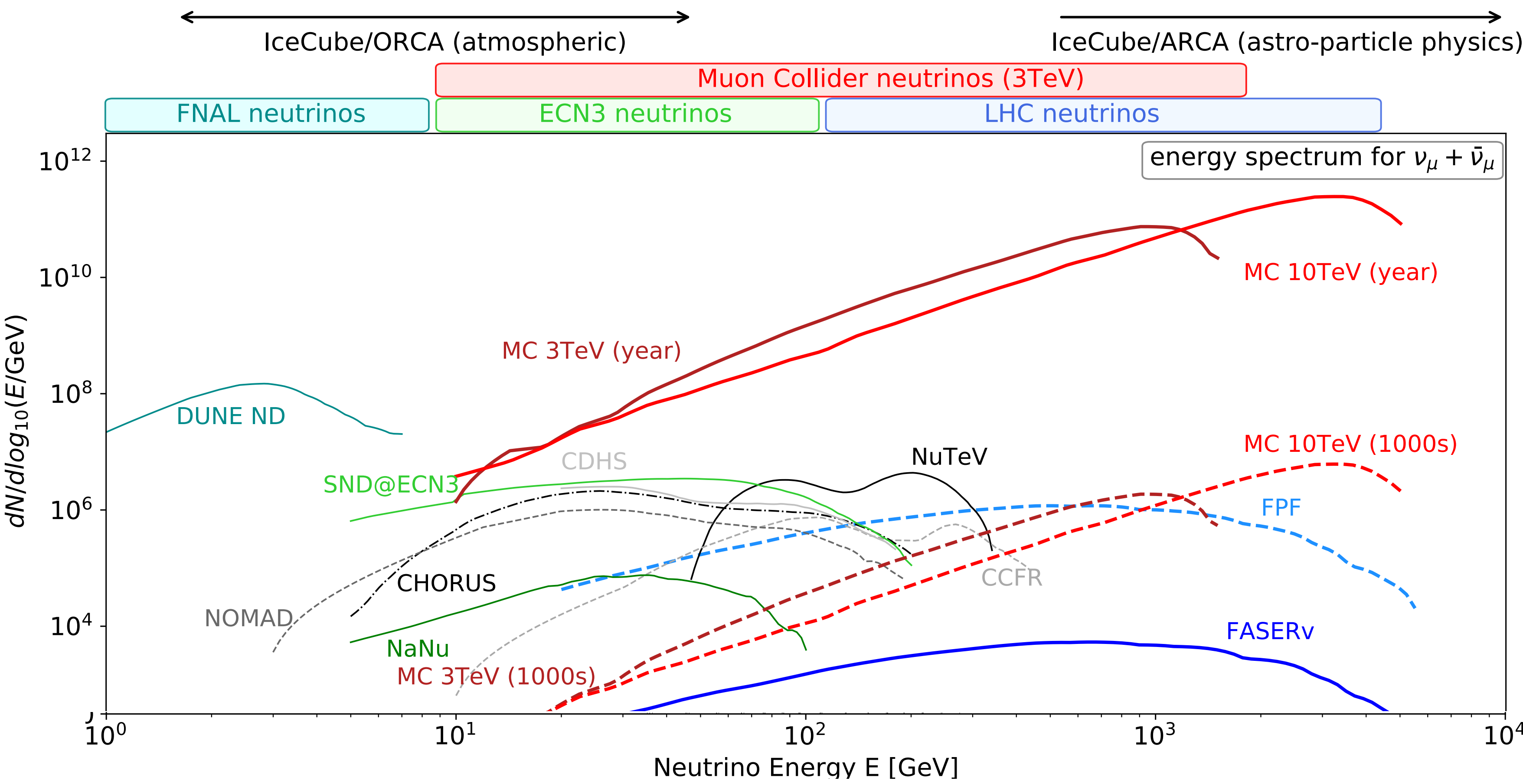
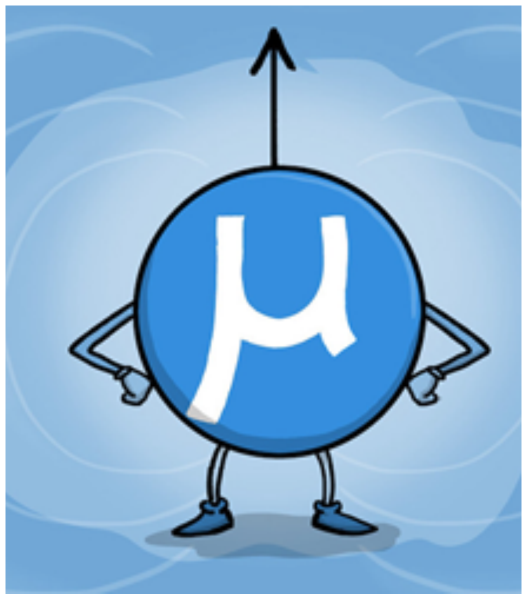
Muons decay to neutrinos:

Collimated, perfectly known, TeV-energy neutrino beams!



Physics Opportunities

Muons!!



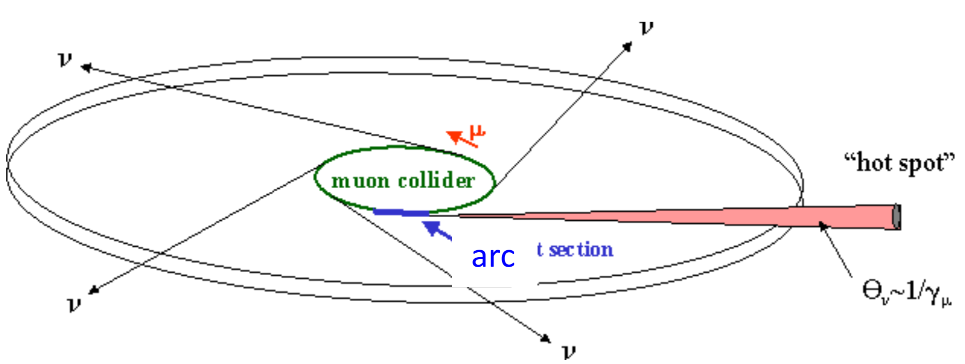
Muons colliding for first time

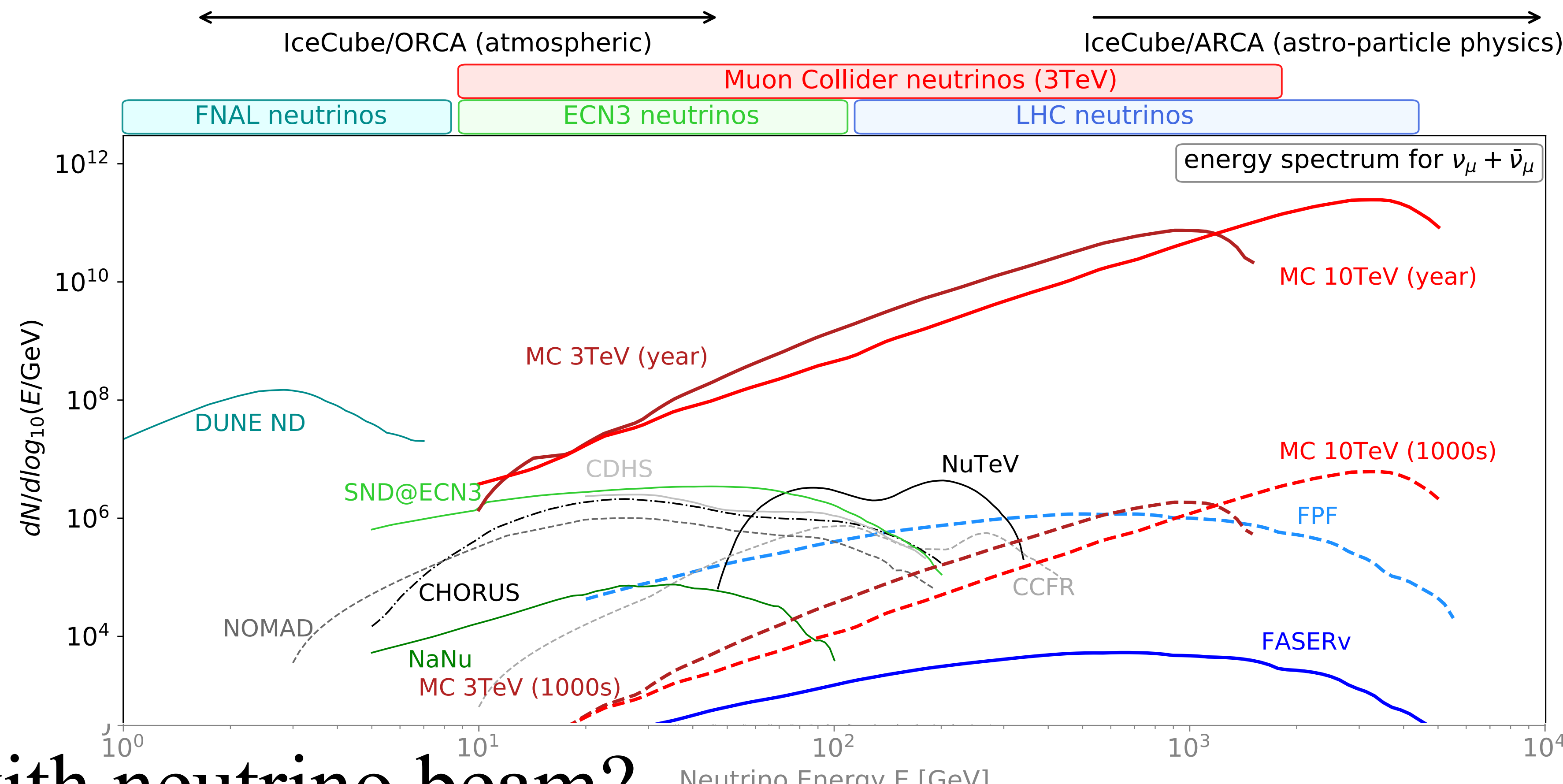
Self-evident potential of exploration.

Novelty and **challenge** for accelerator physics, technology, and detector, **make such long-term project plausible!**

Muons decay to neutrinos:

Collimated, perfectly known, TeV-energy neutrino beams!



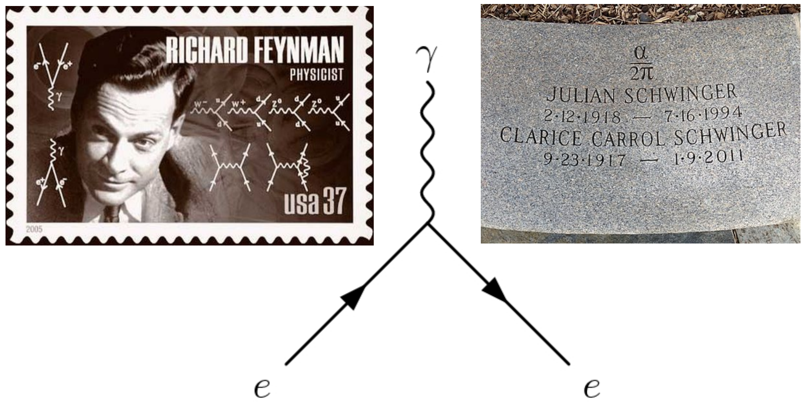


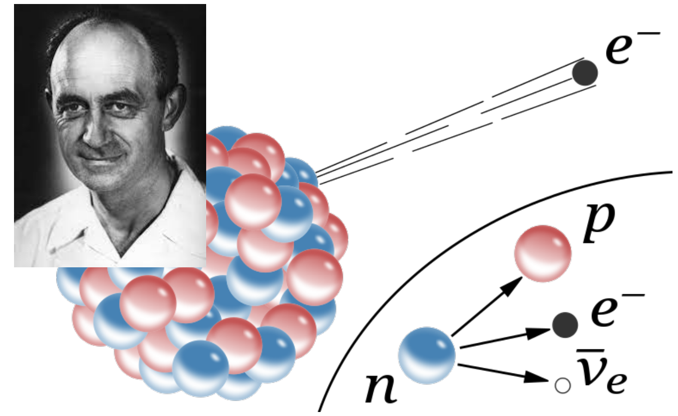
Which experiments with neutrino beam?

Statistics could enable ground-breaking PDF program

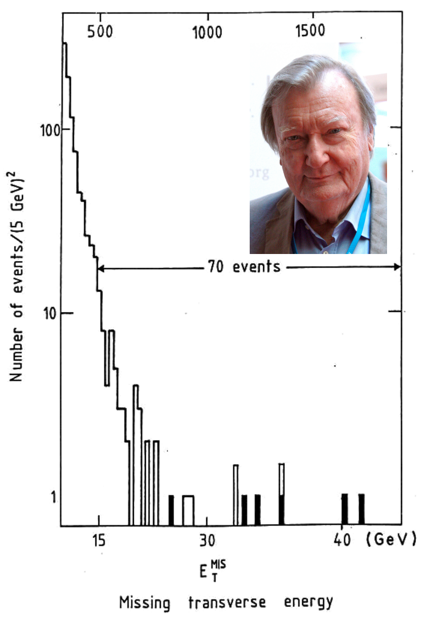
What about neutrino physics? Which BSM opportunities?

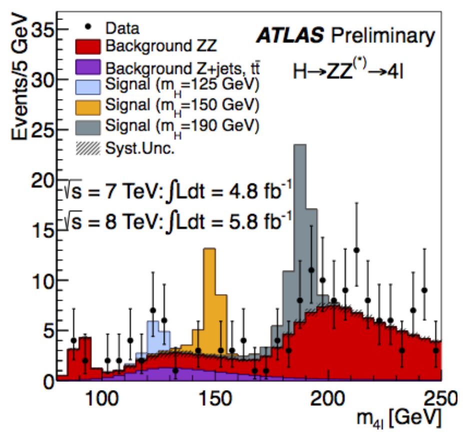
The Standard Model Higgs **Theory** ?

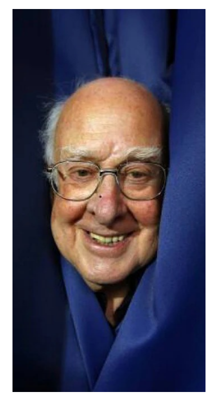


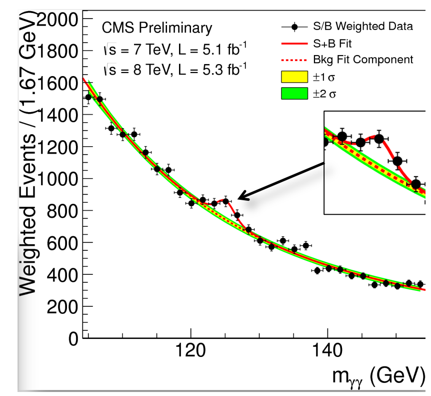


$E \ll m_W$





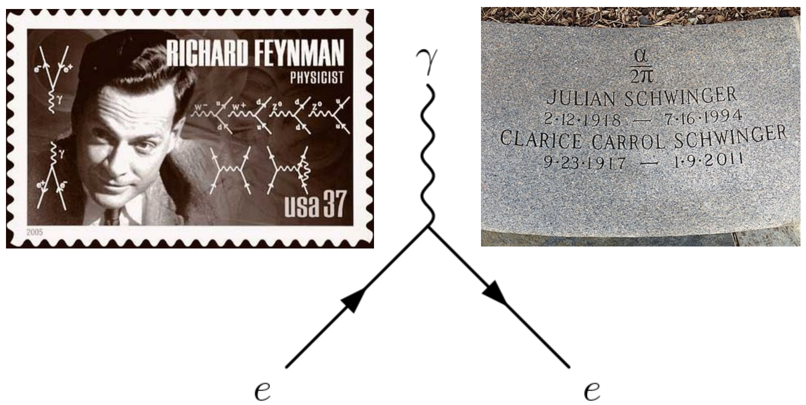


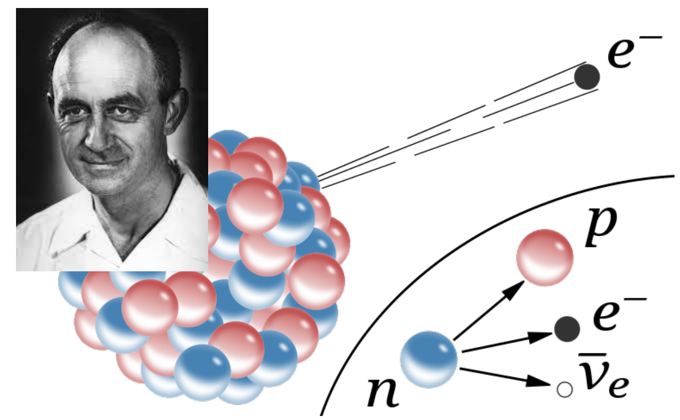


$E \gtrsim m_W$

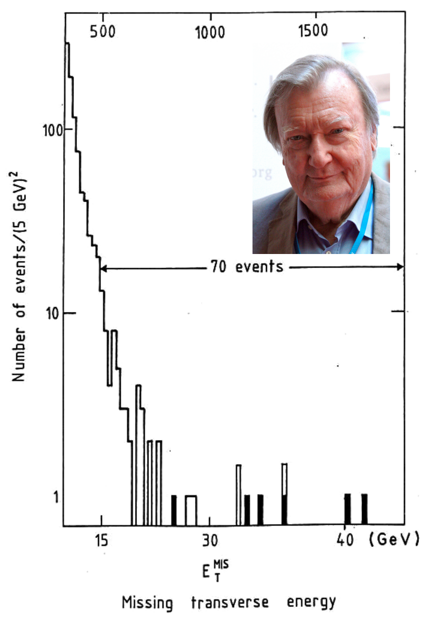
$E \gg m_W$

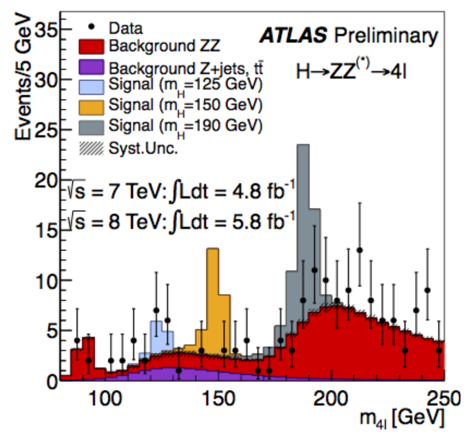
The Standard Model Higgs **Theory** ?

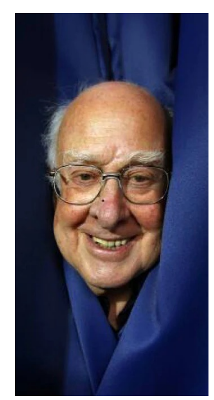


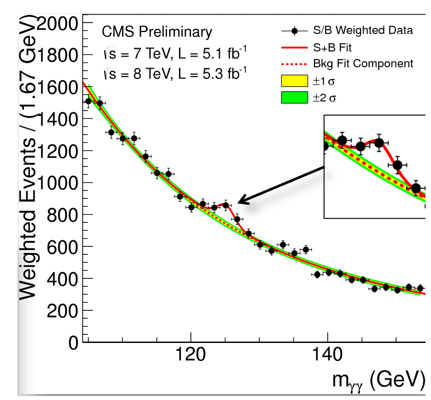


$E \ll m_W$









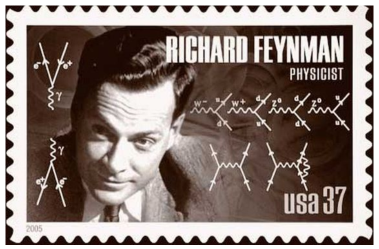
$E \gtrsim m_W$

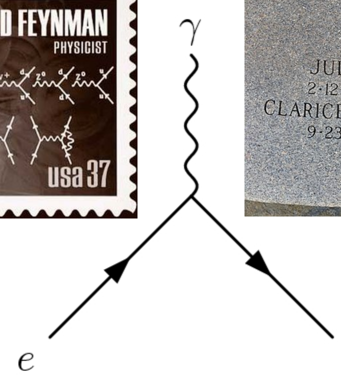
The Higgs particle shows up **here**

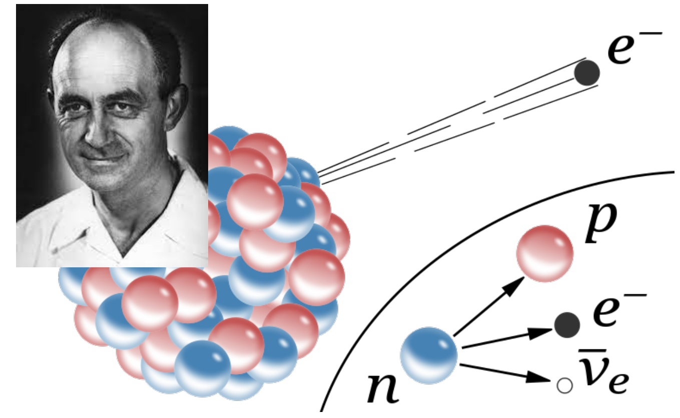
but theory needs it in order to go **there**

$E \gg m_W$

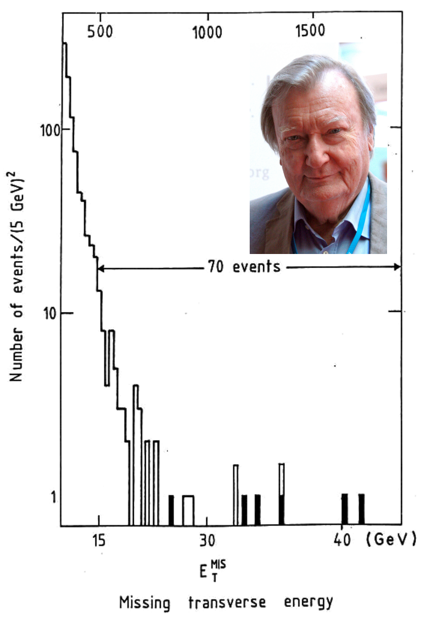
The Standard Model Higgs **Theory** ?

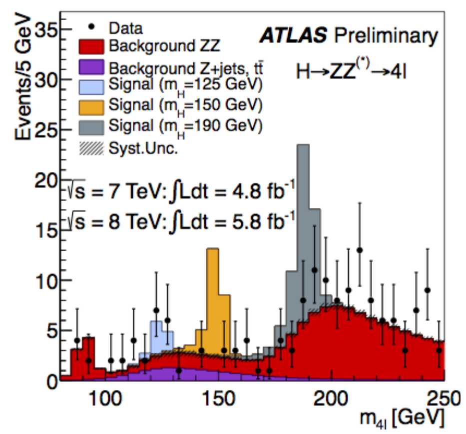


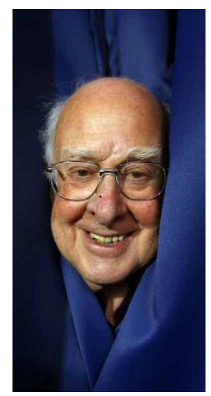
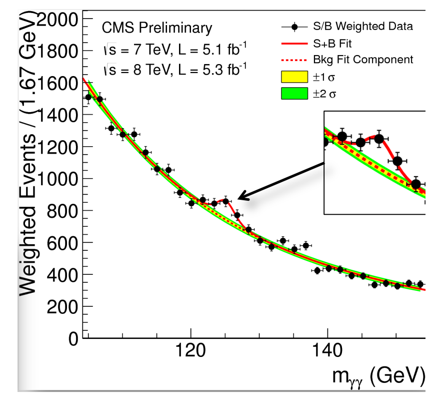




$E \ll m_W$





$E \gtrsim m_W$

The Higgs particle shows up **here**

but theory needs it in order to go **there**

Most direct theory implications are at high En.

The role of the Higgs as part of the microscopic description of the EW force must be verified by **high energy** experiments

$E \gg m_W$

The SM Physics Case

The muon collider will **probe a new regime of EW (+H) force:**

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

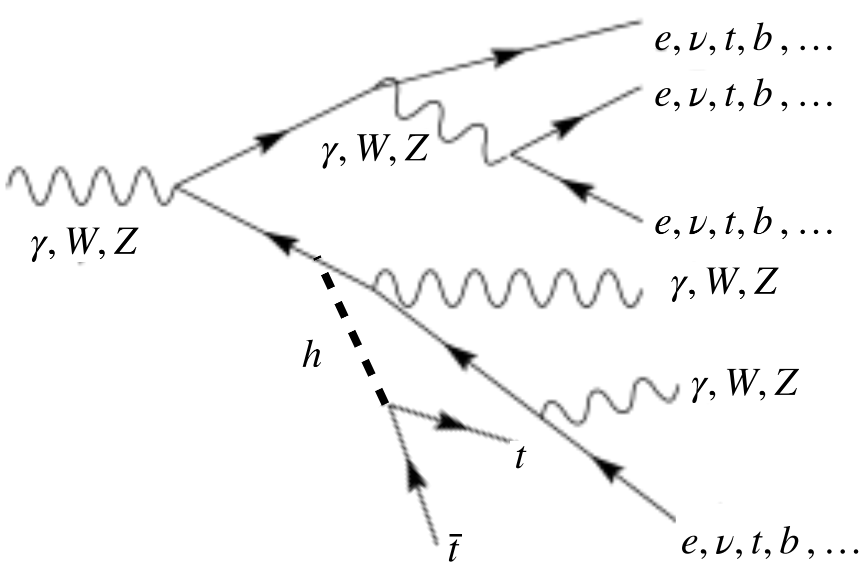
Plenty of cool things will happen:

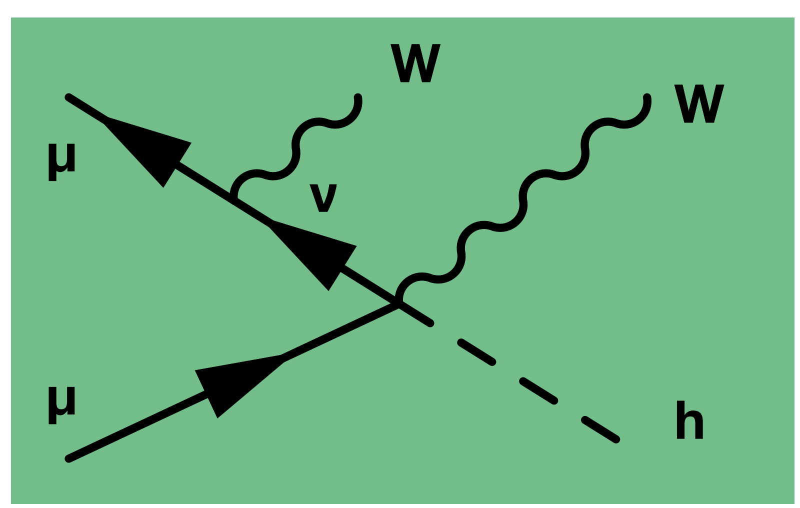
Electroweak Restoration. The $SU(2) \times U(1)$ group emerging, finally!

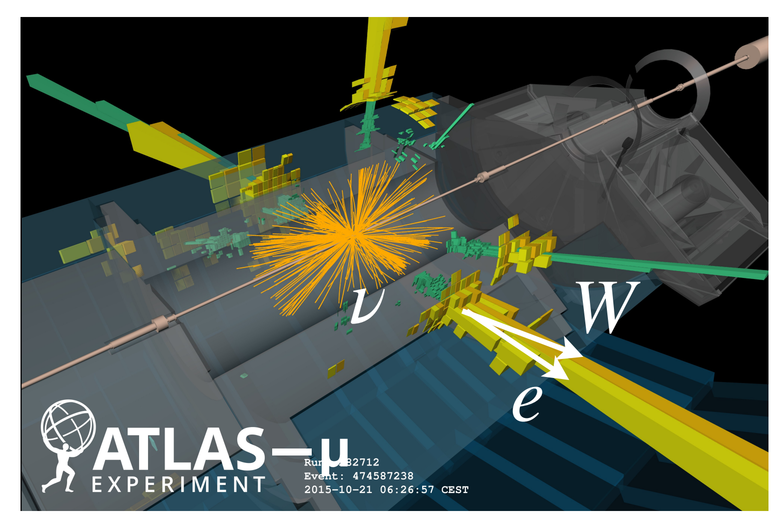
Electroweak Radiation in nearly massless broken gauge theory.
Never observed, never computed (and we don't know how!)

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

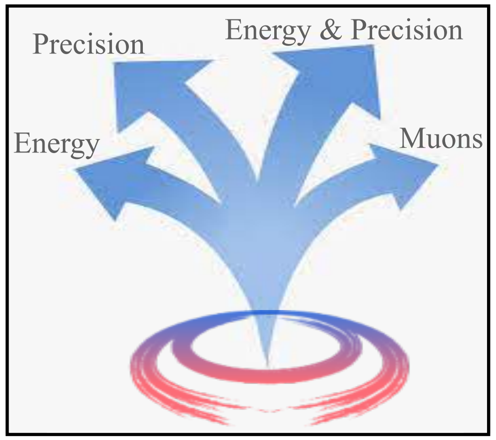
The **particle content of partons:** e.g., find Higgs in tops, or in W's, etc
Neutrino jets will be observed, and many more cool things







Conclusions



Why dreaming of a muon collider?

Explore energy frontier comprehensively by a variety of strategies

Why **working** on muon collider physics?

It is **Useful:** we must **consolidate** the potential, define **new targets**, **motivate** and **inform** Accelerator design.

It is **Fun:** novel BSM possibilities wait to be explored, as well as novel **challenges for predictions**, object reconstruction, BIB mitigation, etc.

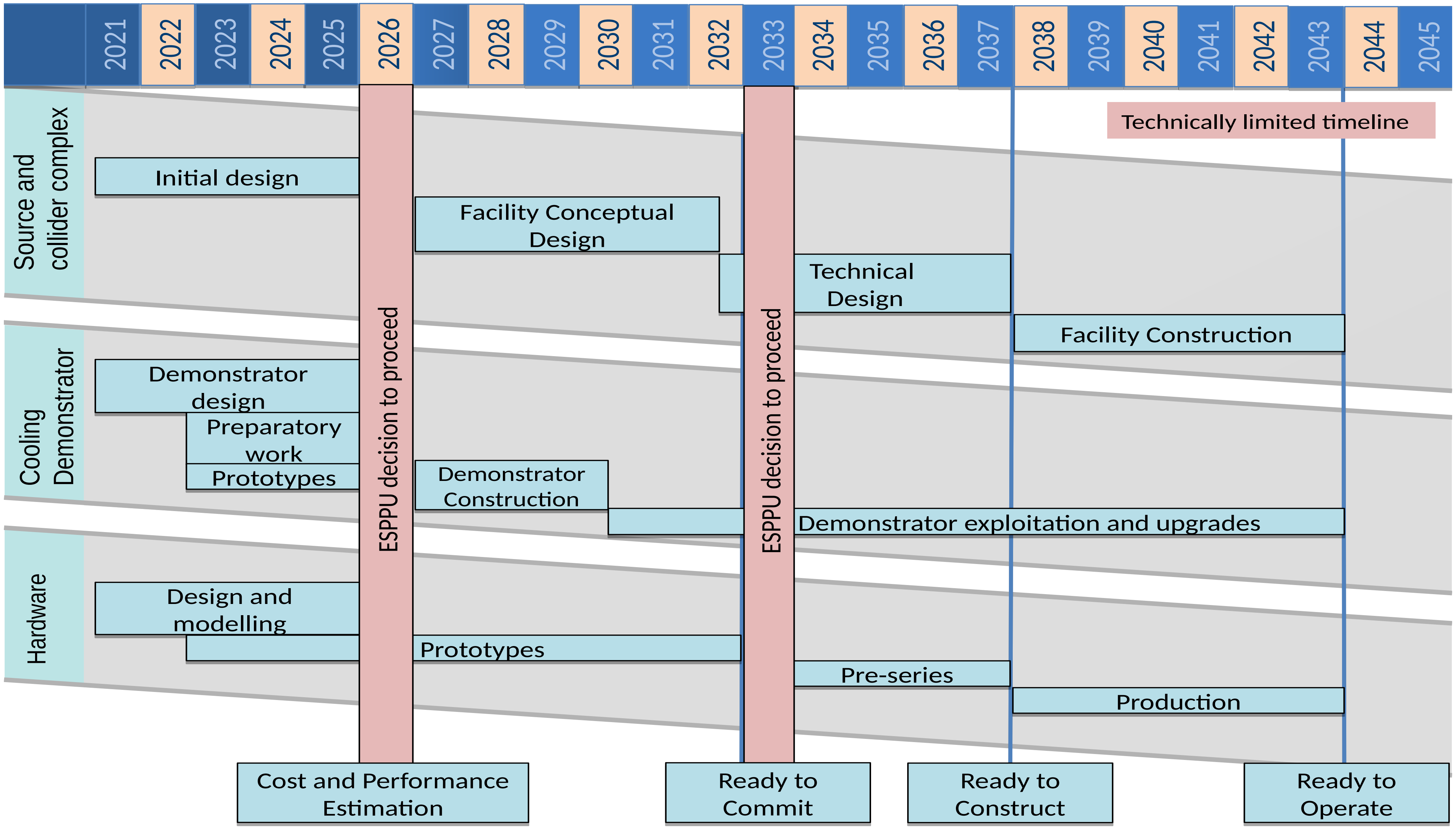
The novelty of the theme and the lack of established solution enables and require innovative research that **is advancing and revitalising particle physics today**, on top of paving the way towards a muon collider

Conclusions

Technically limited timeline [Stay tuned for consolidated timeline release]

Soon we will know if concept mature for CDR
Demonstrator program will initiate right after.

MuC R&D program is as ambitious as it sound: a brand new accelerator concept
Tremendous opportunity that we cannot (and will not) miss!



Conclusions

Thank You !

Backup

Theory Challenges

EW theory is weakly coupled, but observables are not IR safe

$$E_{\text{cm}} \gg m_W$$

Large muon collider energy ← E_{cm}; m_W → Small IR cutoff scale

Scale separation entails enhancement of Radiation effect.

Like QCD ($E \gg \Lambda_{\text{QCD}}$) and QED ($E \gg m_\gamma = 0$), **but:**

EW symmetry is broken:

EW color is observable ($W \neq Z$).
KLN Theorem non-applicable.
(inclusive observables not safe)

→ **Practical need** of computing EW Radiation effects

Enhanced by $\log^{(2)} E^2/m_{\text{EW}}^2$

EW theory is Weakly-Coupled
The IR cutoff is physical

→ **First-Principle** predictions **must** be possible

For arbitrary multiplicity final state

Theory Challenges

EW theory is weakly coupled, but observables are not IR safe

$$E_{\rm cm} \gg m_W$$

Large muon collider energy ← $E_{\rm cm}$; m_W → Small IR cutoff scale

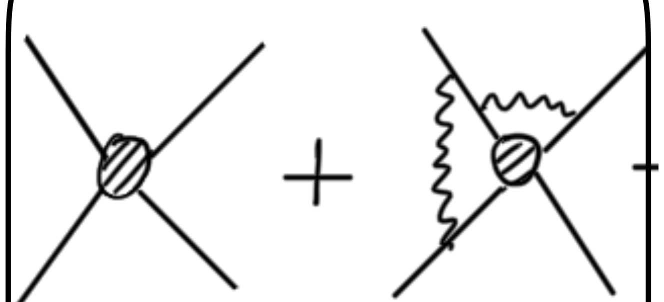
Scale separation entails enhancement of Radiation effect.

Quantitatively, resummation is needed.

$$\exp\left[-g^2/16\pi^2 \log^2(E_{\rm cm}^2/m_{\rm w}^2)\times {\rm Casimir}\right] \approx \exp[-1]$$

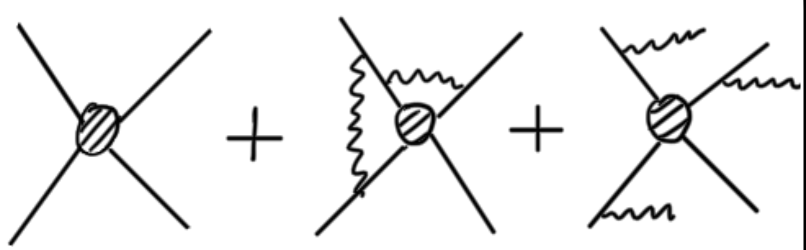
→ 10 TeV MuC

Exclusive X-S



Two hard bodies with **definite EW color**.
Veto on EW bosons.

Semi-Inclusive X-S



Two hard bodies of **definite EW color**.
EW bosons allowed.

Process	N (Ex)	N (S-I)
e^+e^-	6794	9088
$e\nu_e$	—	2305
$\mu^+\mu^-$	206402	254388
$\mu\nu_\mu$	—	93010
$\tau^+\tau^-$	6794	9088
$\tau\nu_\tau$	—	2305
jj (Nt)	19205	25725
jj (Ch)	—	5653
$c\bar{c}$	9656	12775
cj	—	5653

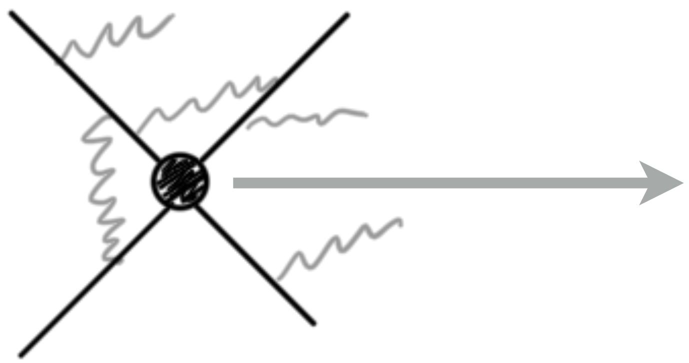
= charged

$b\bar{b}$	4573	6273
$t\bar{t}$	9771	11891
bt	—	5713
$Z_0 h$	680	858
$W_0^+W_0^-$	1200	1456
$W_T^+W_T^-$	2775	5027
$W^\pm h$	—	506
$W_0^\pm Z_0$	—	399
$W_T^\pm Z_T$	—	2345

Theory Challenges

Benchmark predictions we must learn how to make:

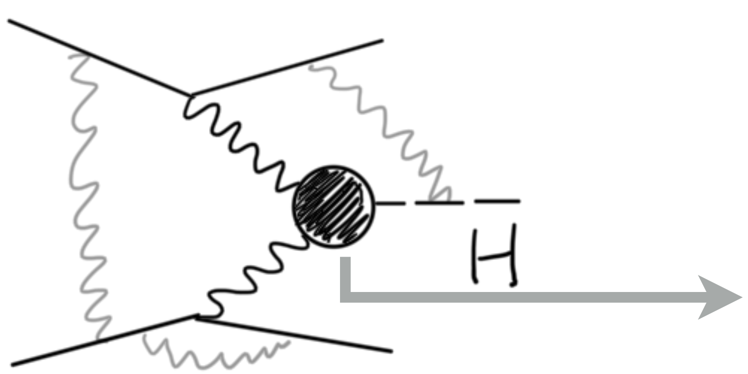
- Direct 2→2 annihilation:



$$\sqrt{\hat{s}} = E_{\mathrm{cm}} \gg m_{\mathrm{w}}$$

need X-S calculations and modelling of radiation (showering)

- EW-scale VBS: single Higgs production:



$$\sqrt{\hat{s}} = m_{\mathrm{h}} \simeq m_{\mathrm{w}}$$

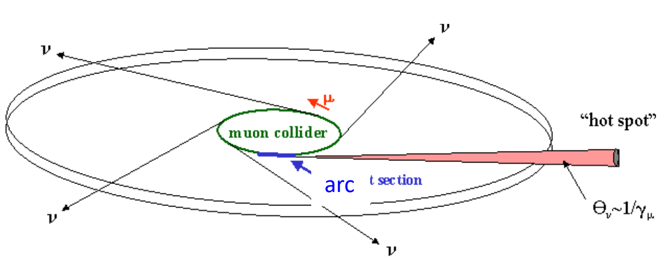
same scale of radiation emission as of scattering

Muon Collider Plans

Principal Challenges:

Demonstrate neutrino flux mitigation system
Full design of collider and acceleration
Integration of muon production and cooling stages
Optimise collider/MDI for the suppression of BIB from muon decay

Neutrino Flux Mitigation

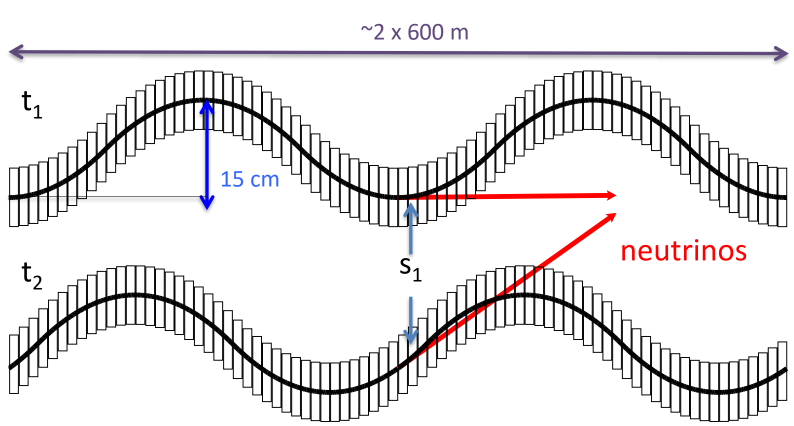


Concentrate neutrino cone from arcs can approach legal limits for 14 TeV

Goal is to reduce to level similar to LHC

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV: idea of Mokhov, Ginneken to move beam in aperture
Our approach: move collider ring components, e.g. vertical bending with 1% of main field



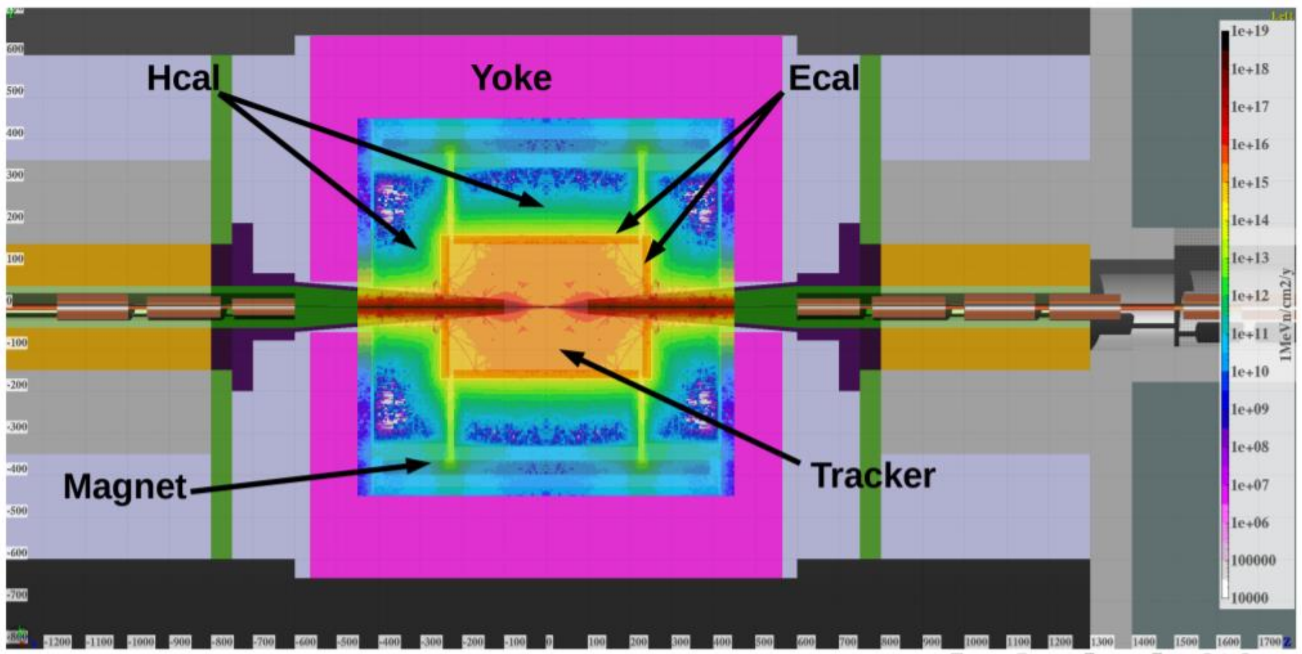
Opening angle ± 1 mradian

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

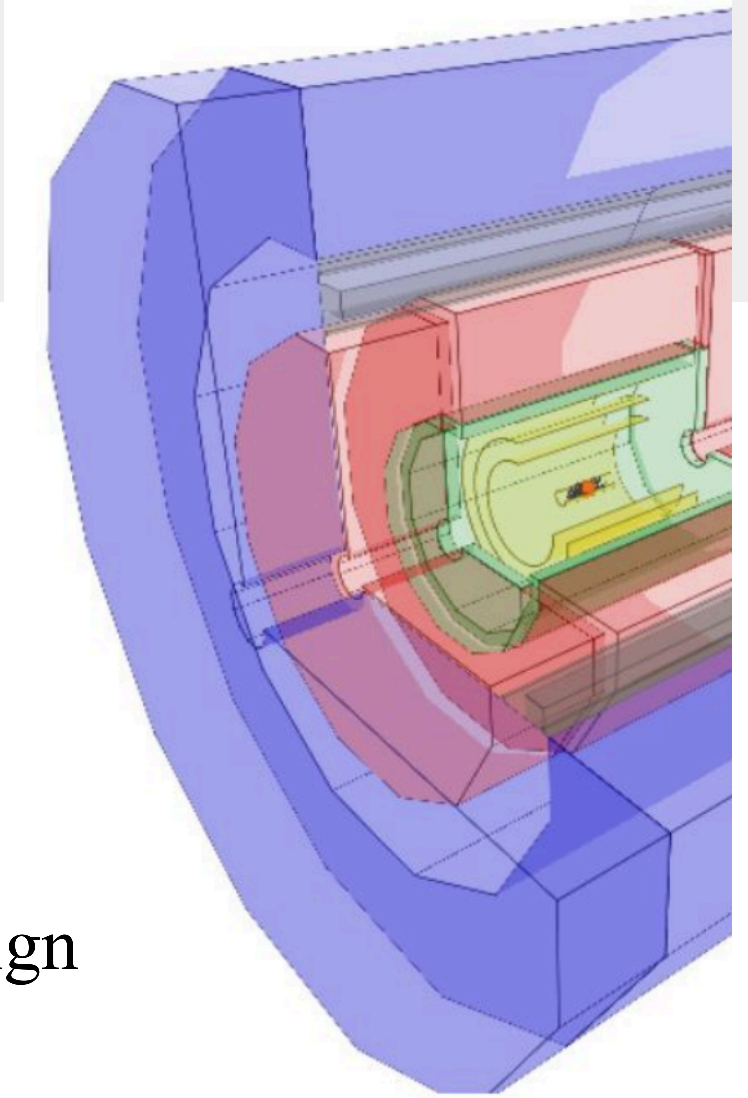
Working on different approaches for experimental insertion

MuC features a novel type of BIB.
Detector and reconstruction design studies are crucial even at this early stage.



FLUKA @ 1.5 TeV

Experiment Design



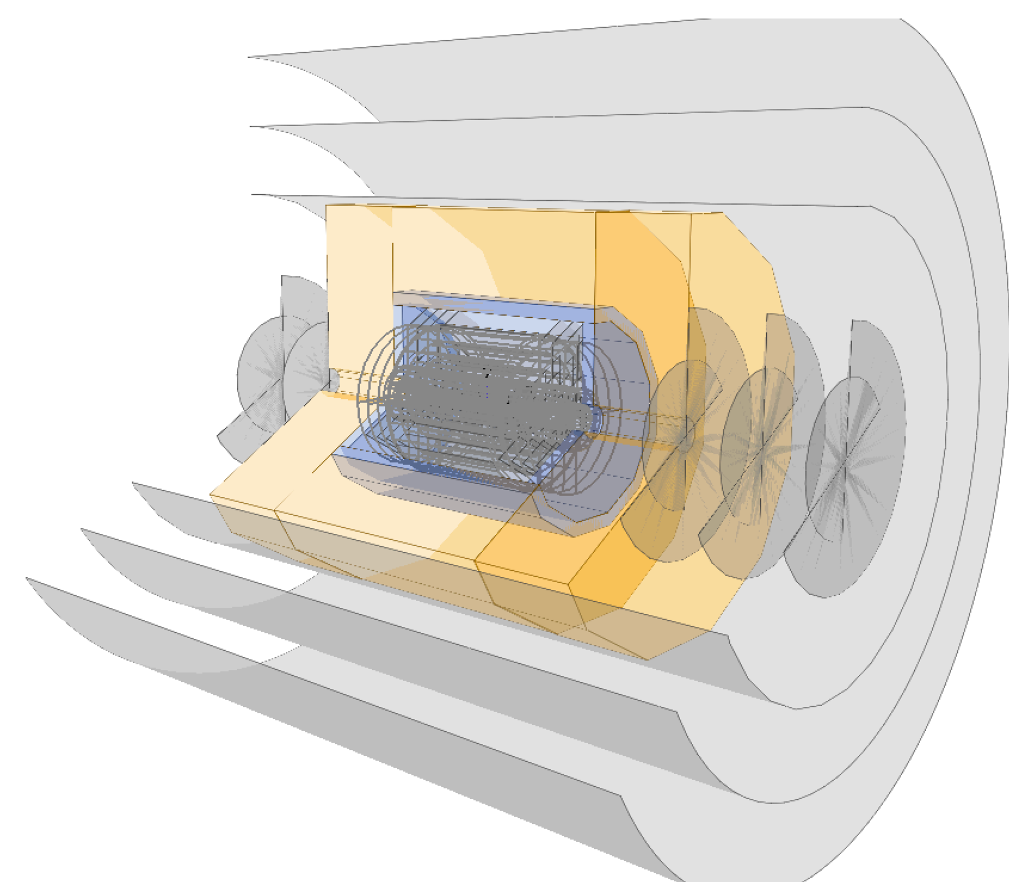
Design detector for precision at multi-TeV scale

- 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!