Benchmark questions on muon collider physics

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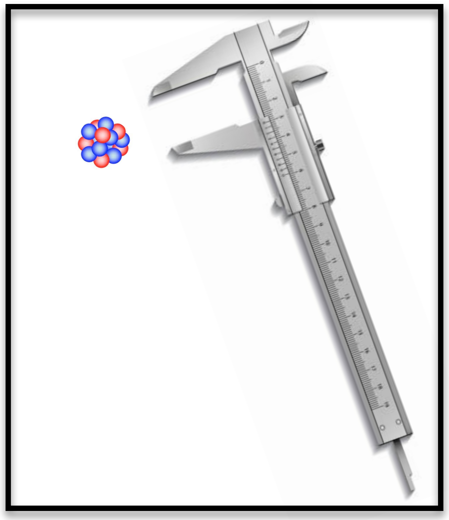
Mostly based on the best review ever on muon colliders:

Towards a Muon Collider

Published as EPJC review

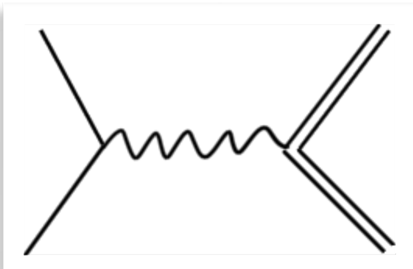
Wide spectrum of physics opportunities

Energy

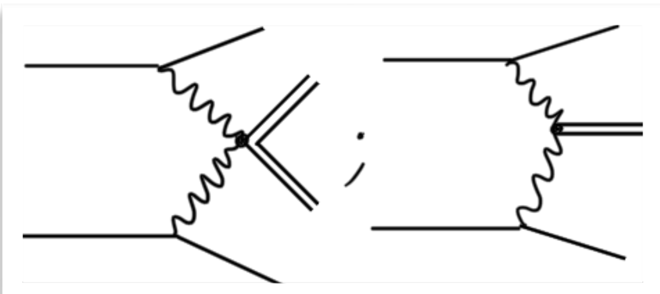


Precision

Wide spectrum of physics opportunities



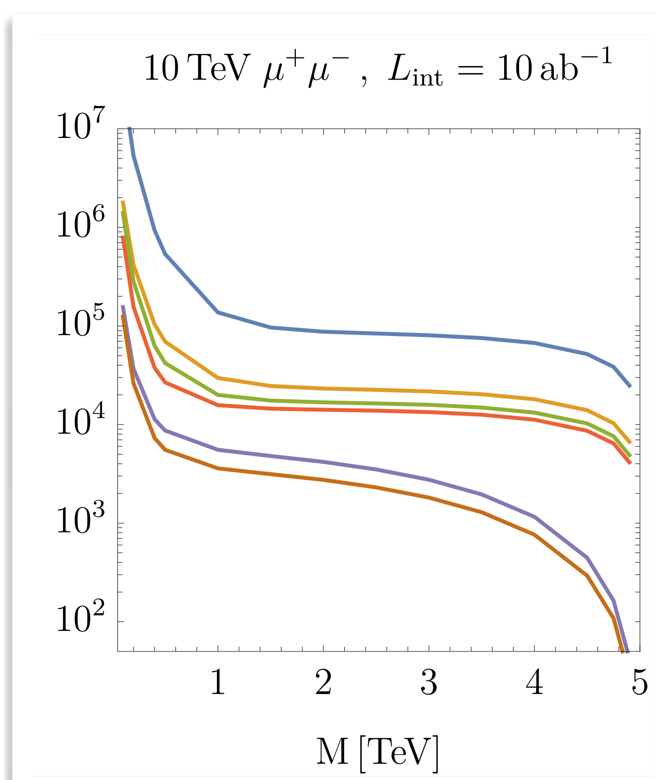
μμ annihilation: production of **EW-charged particles** up to $E_{cm}/2$
These searches can, for instance, advance probes of (un)-Natural EWSB by one or two orders of magnitude

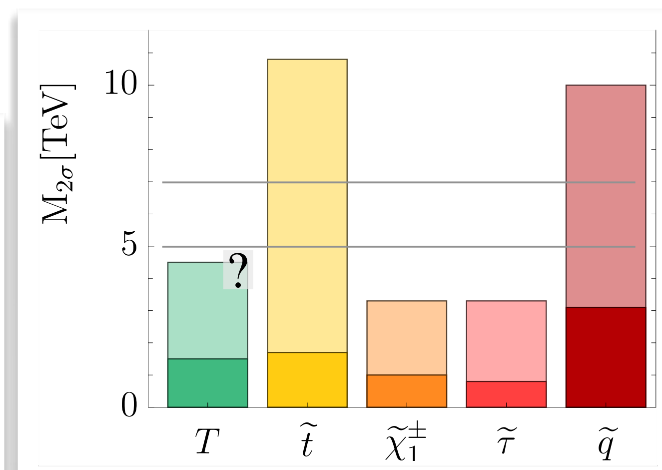


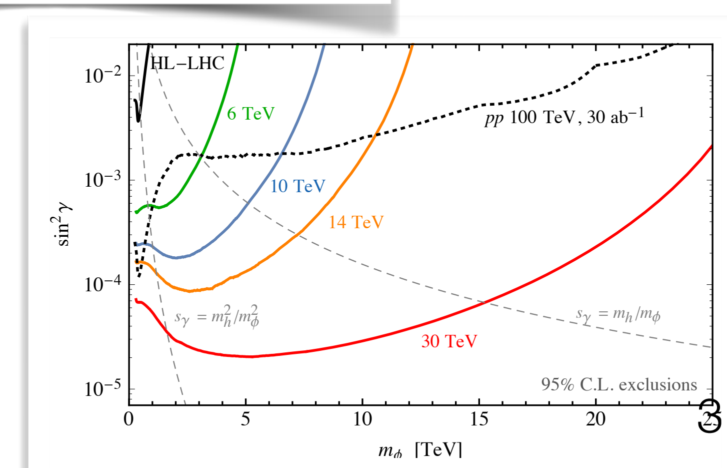
Vector Bosons Fusion: sensitive to EW-neutral **Higgs-Portal** particles

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

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



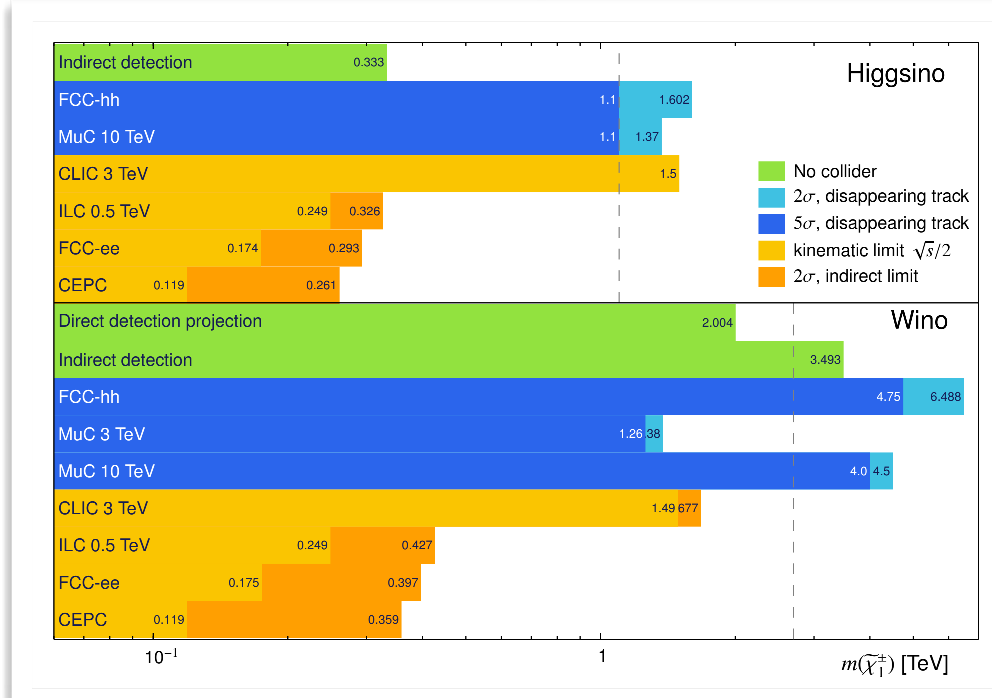


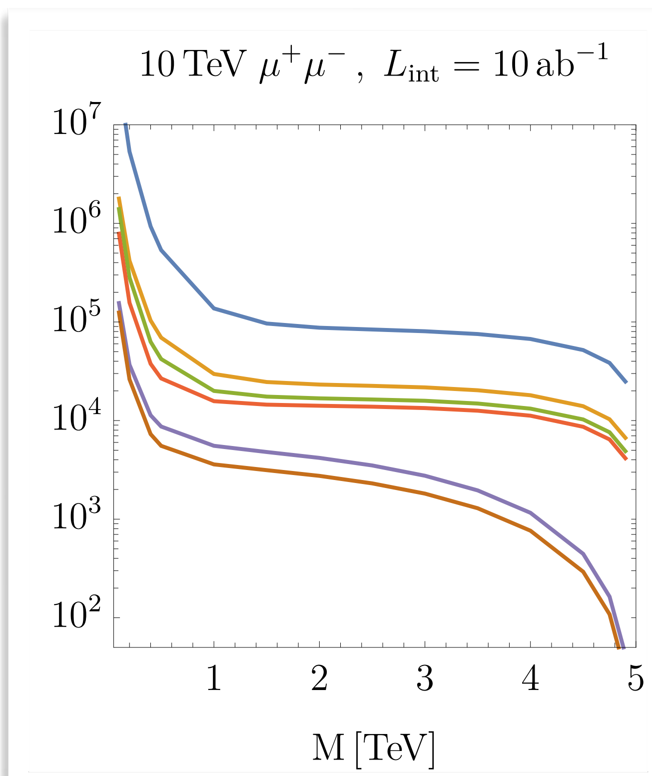


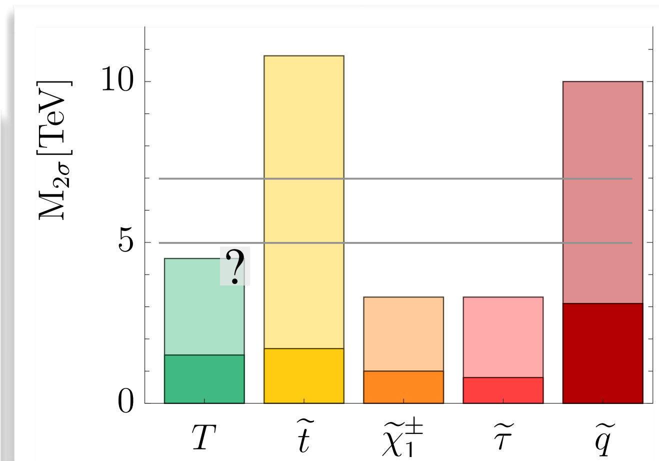
Wide spectrum of physics opportunities

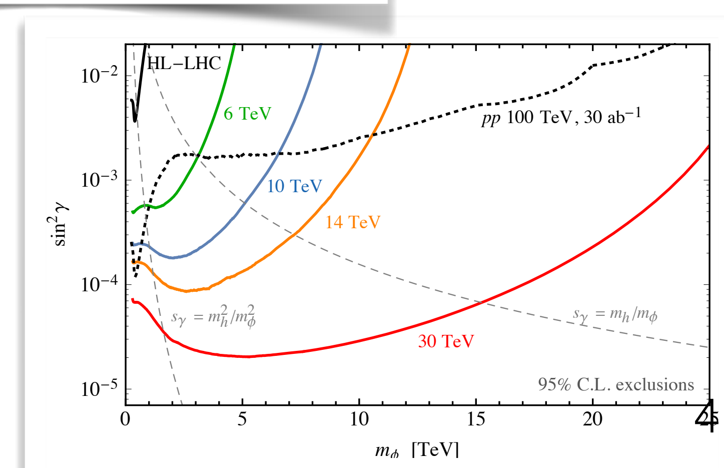
WIMP or WIMP-like DM search program:

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



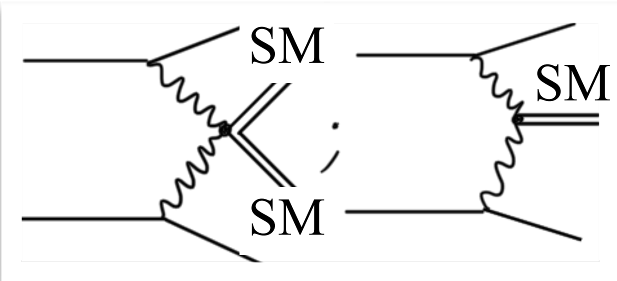




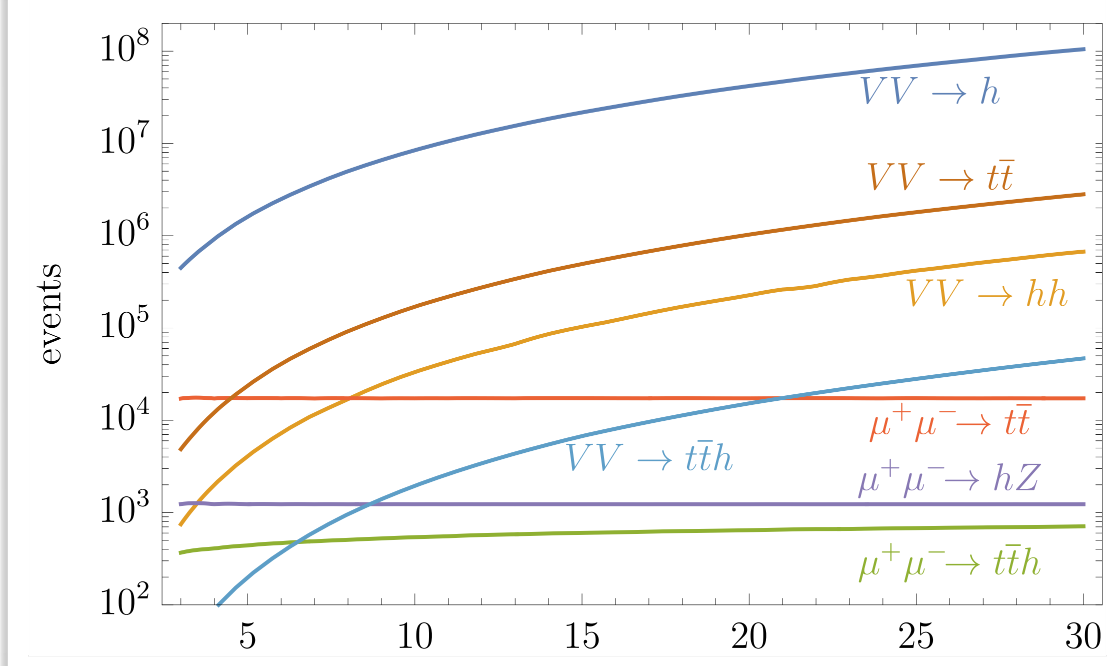


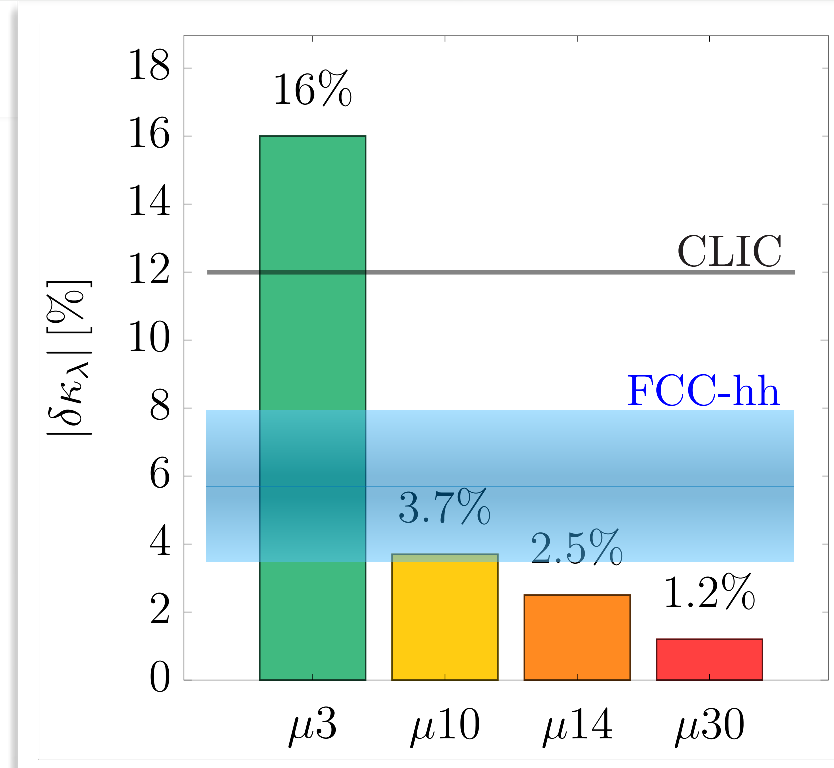
Wide spectrum of physics opportunities

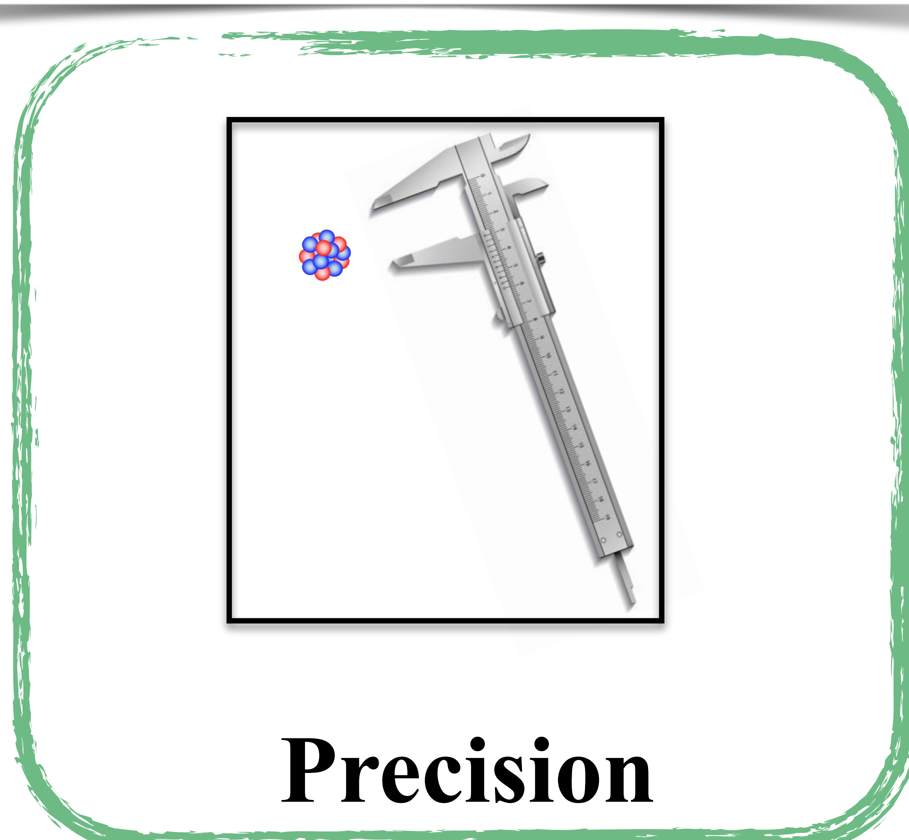
Huge rate, from VBS/VBF, for EW-scale processes



[reason is Lumi $\propto E^2$, not the log]







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* No input used for μ collider

Wide spectrum of physics opportunities

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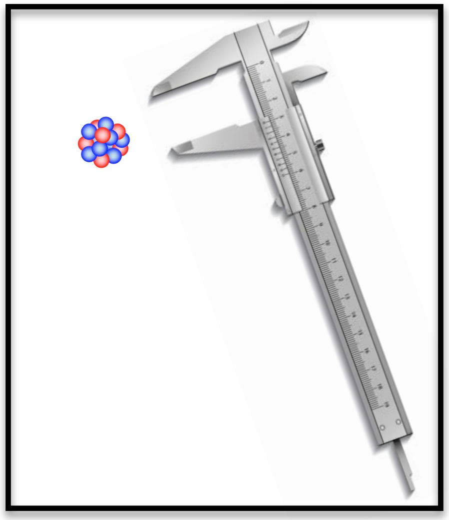

Precision

Wide spectrum of physics opportunities

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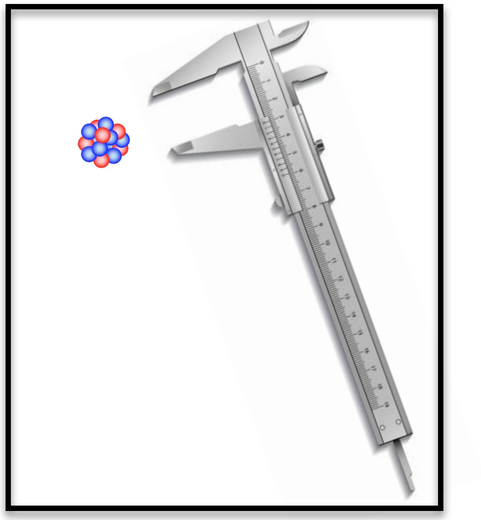

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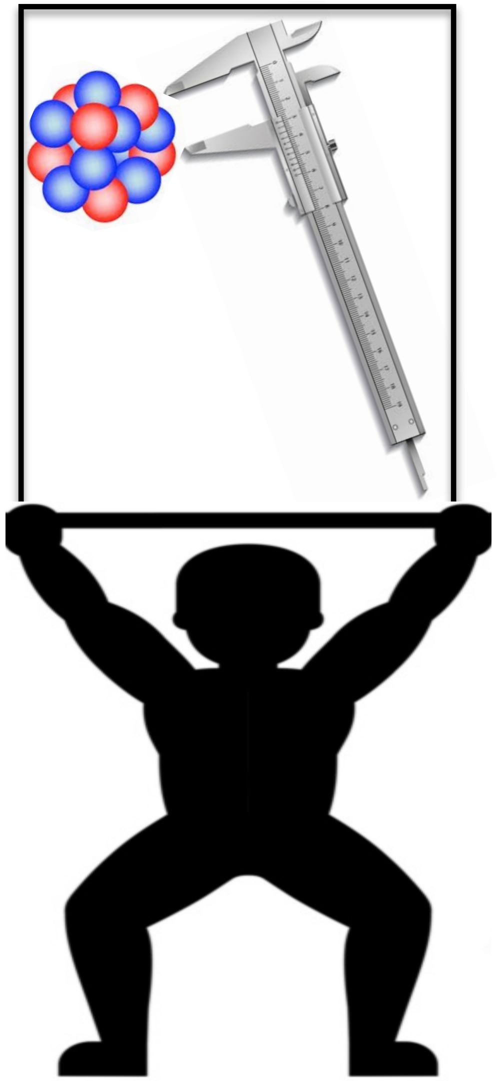
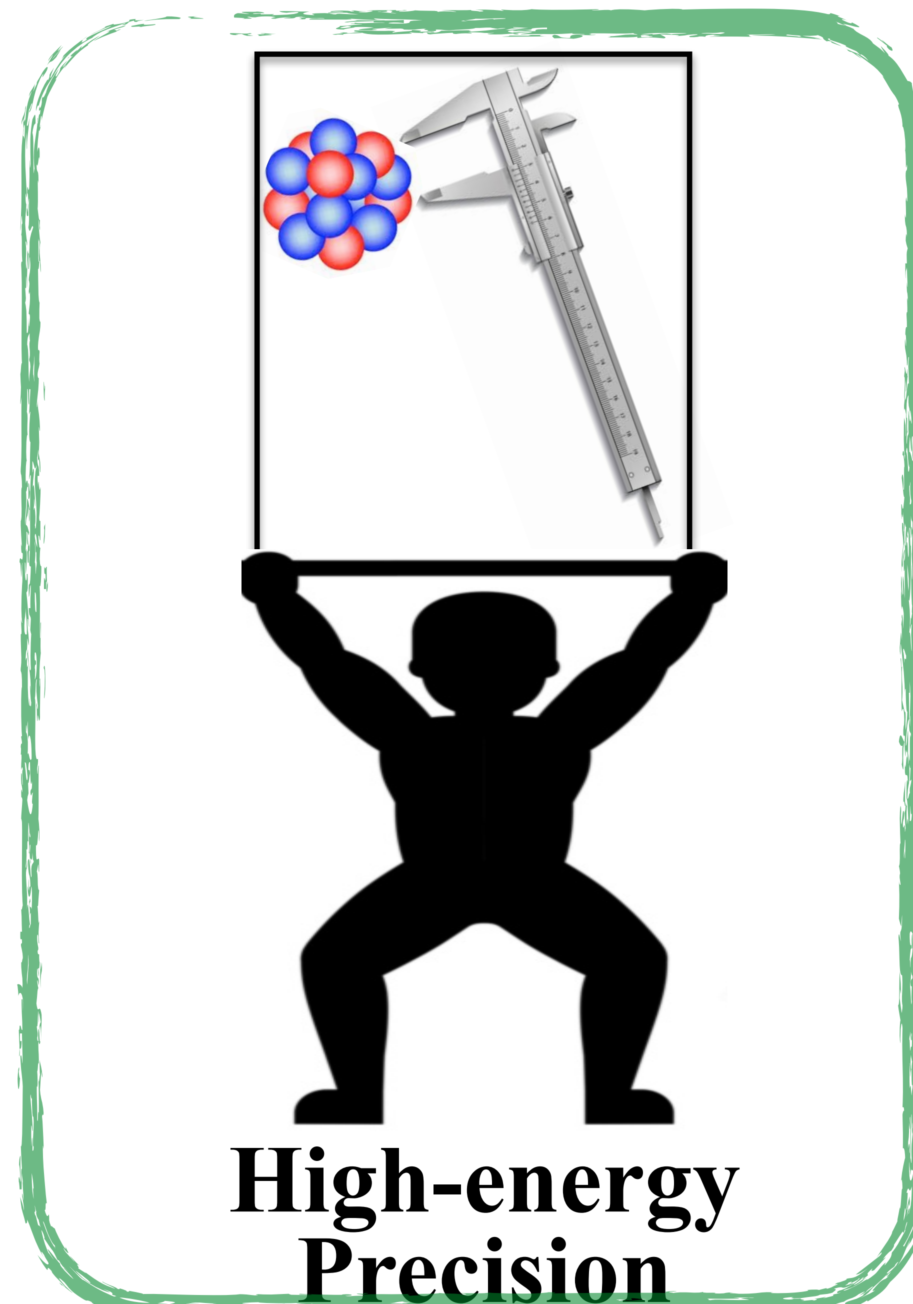


High-energy Precision

Wide spectrum of 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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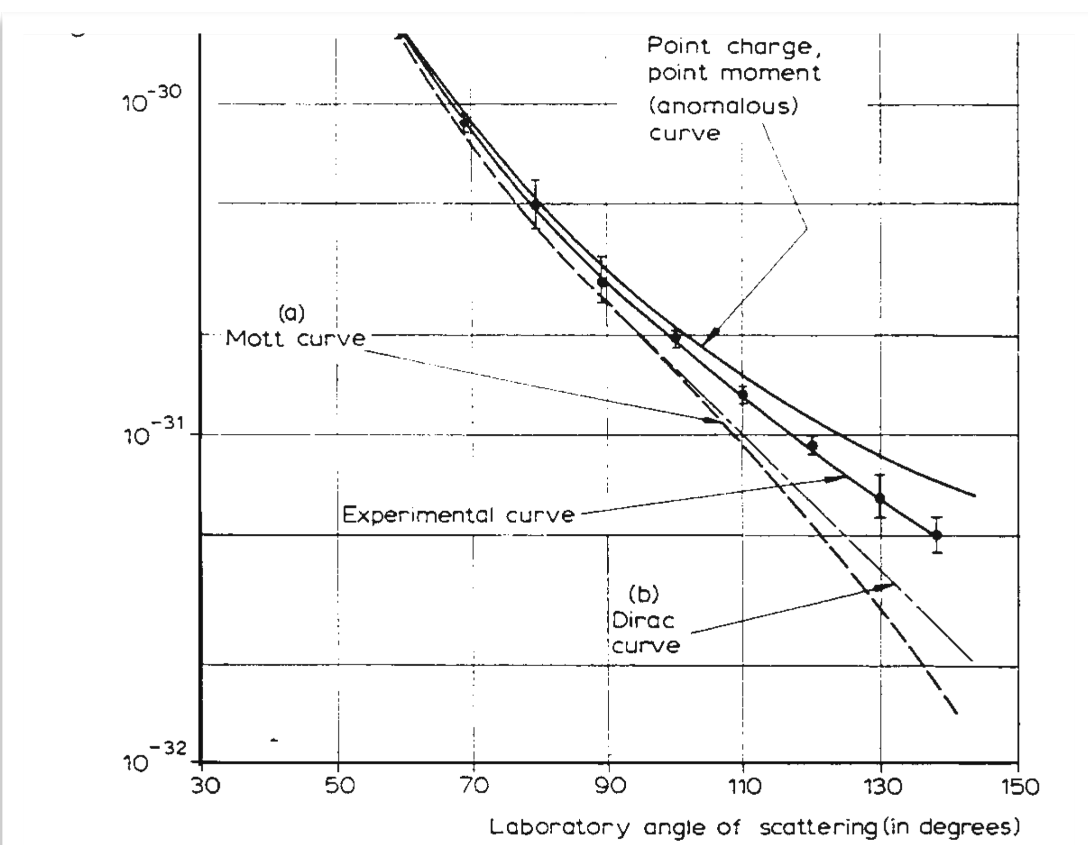
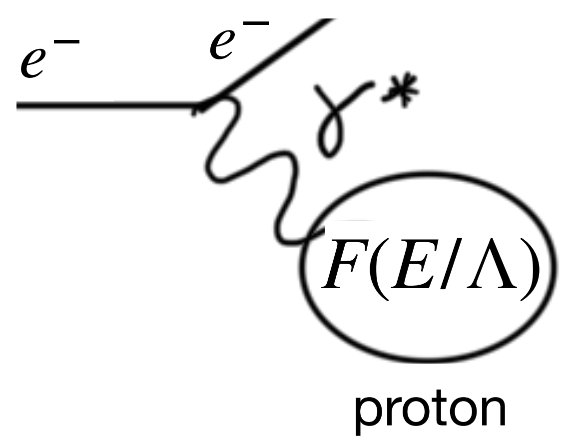
Proton compositeness discovery:

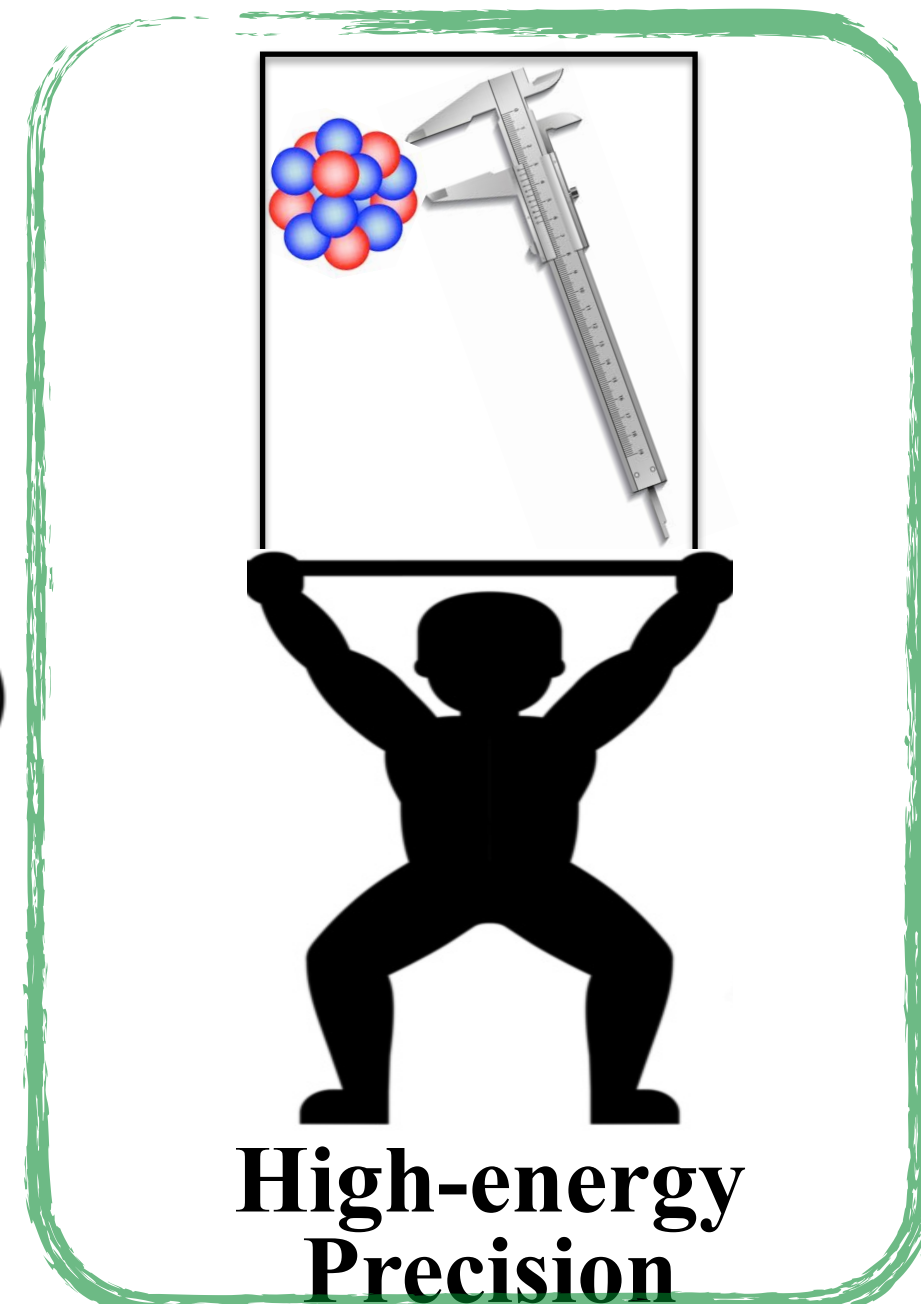
- Order 10% departure from point-like prediction.
- Visible form-factor effects required **large energy**

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



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





Wide spectrum of physics opportunities

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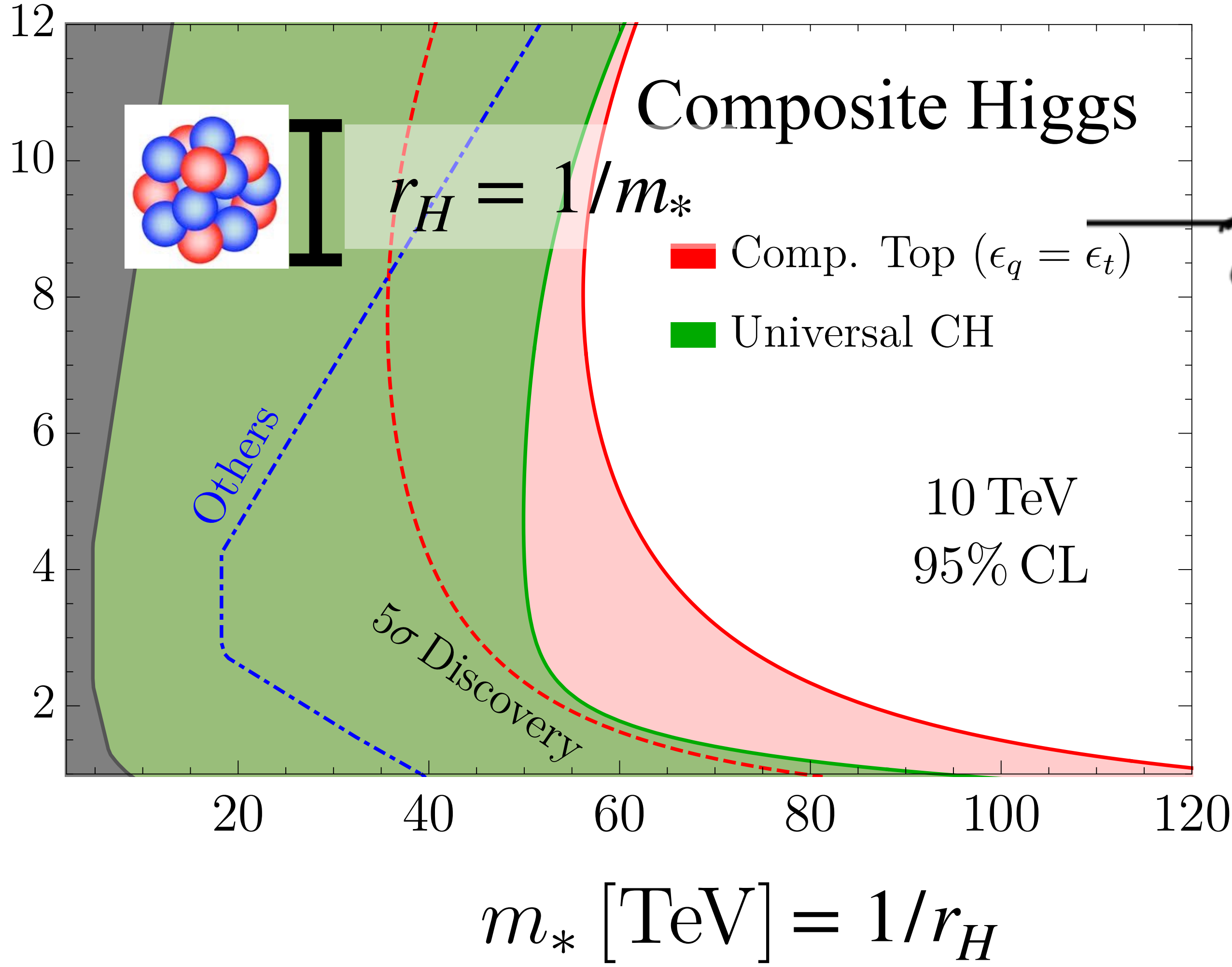
Neutral Currents

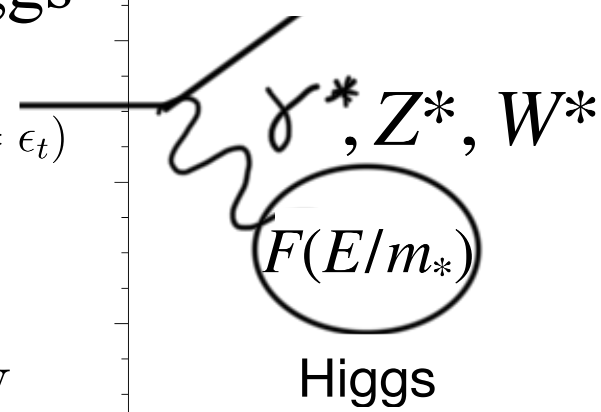
Proton Compositeness

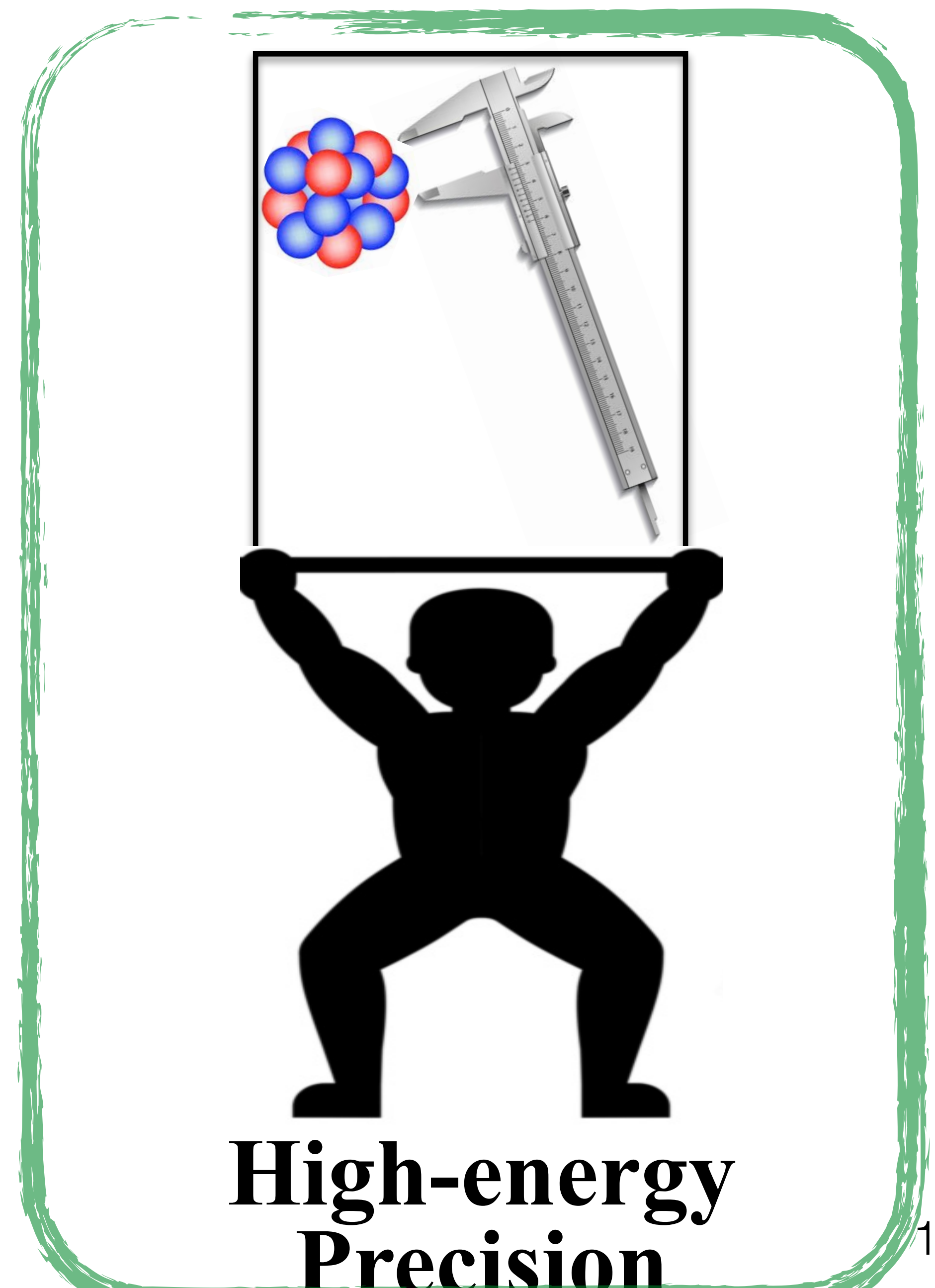
Higgs compositeness ?

Might happen just the same, with **larger energy**

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







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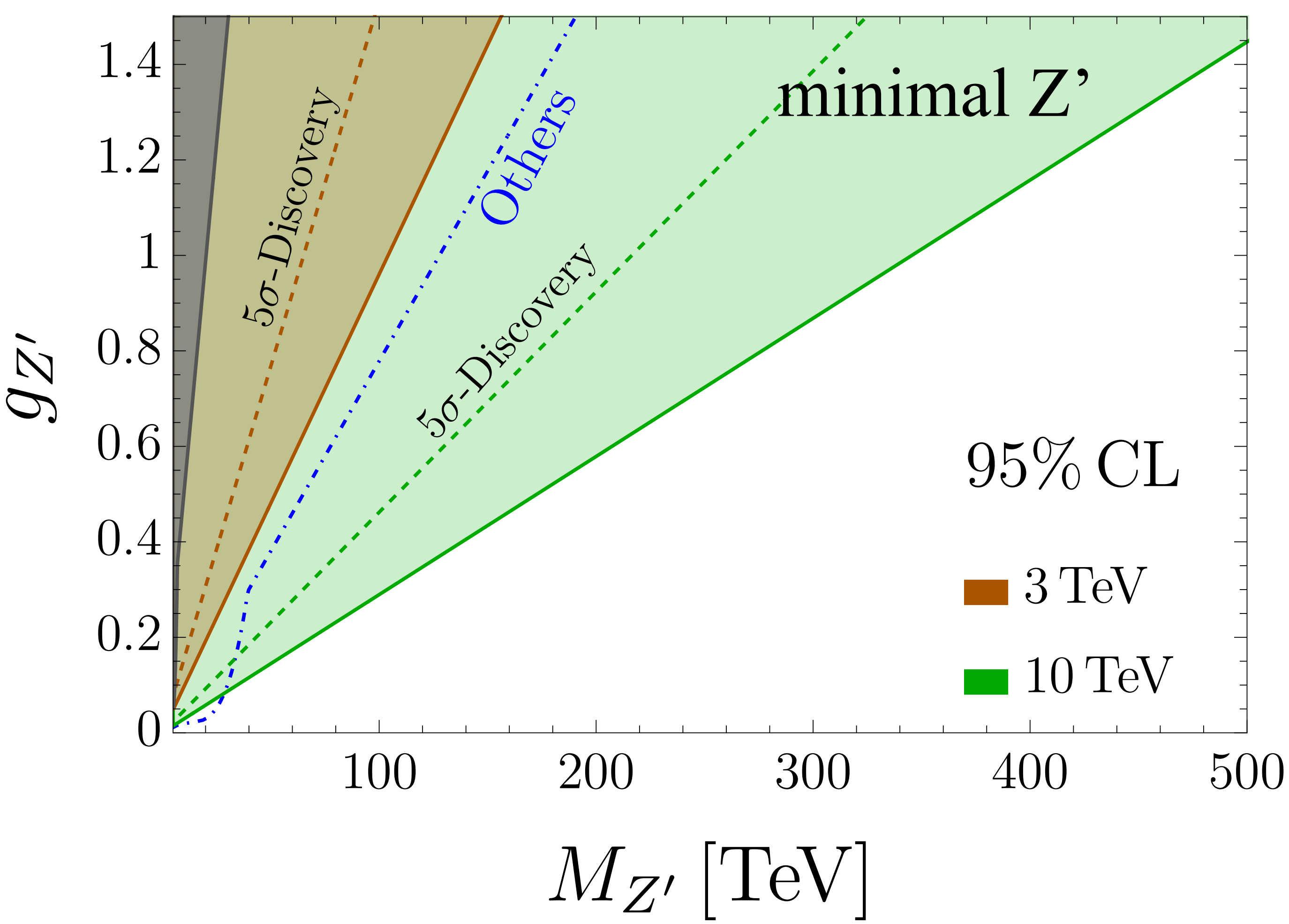
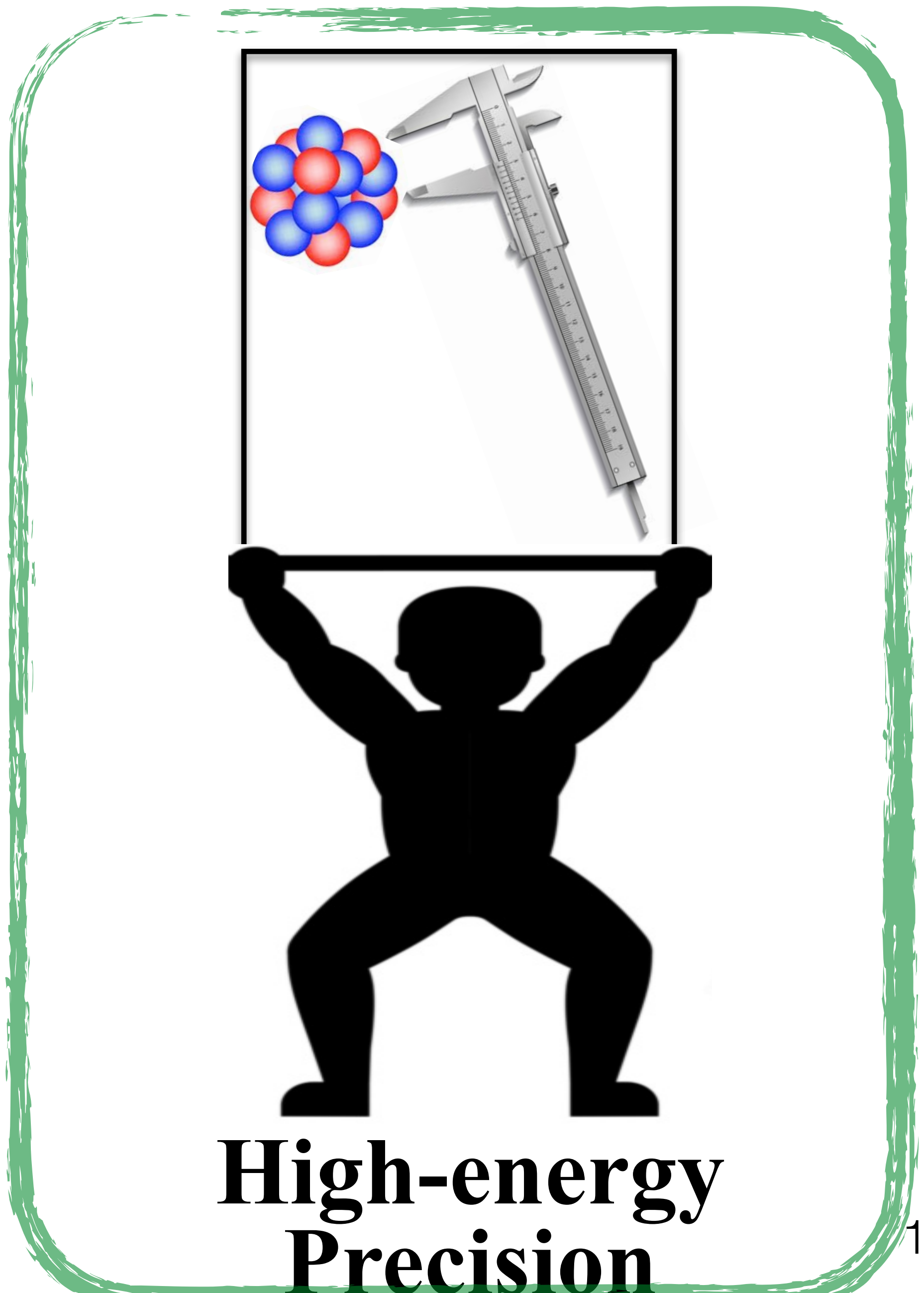
A new Z' force carrier?

- New Neutral Currents





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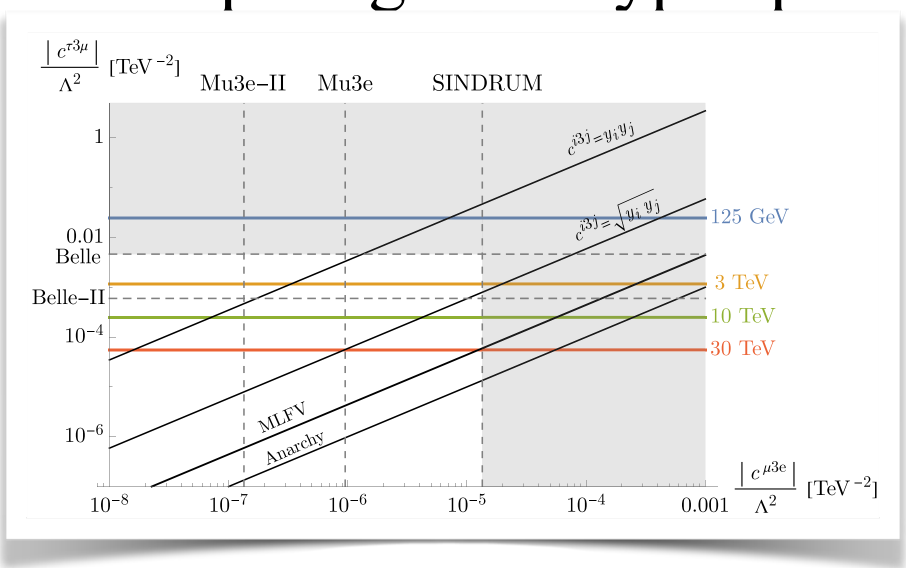
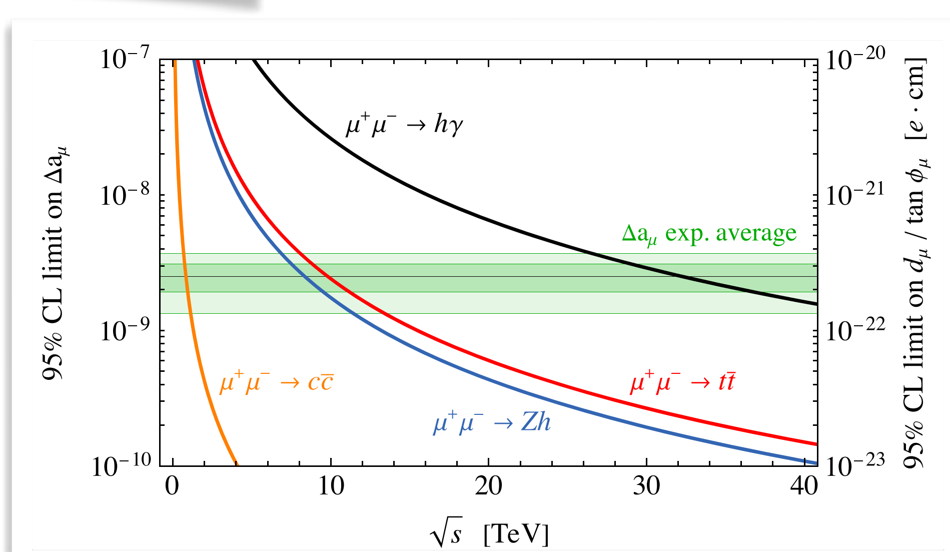
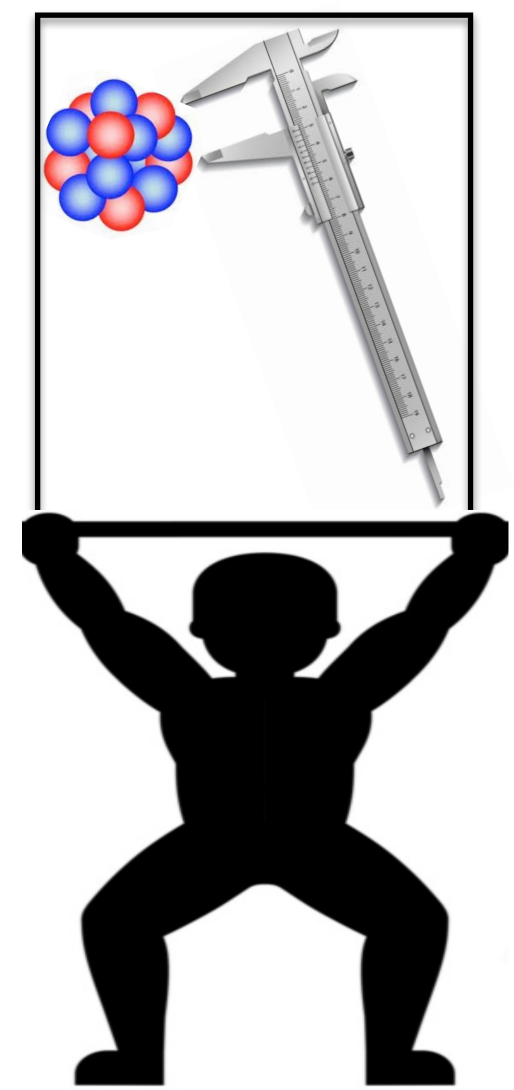
Rare phenomena from very heavy physics

- Competing with hyper-precise low-en



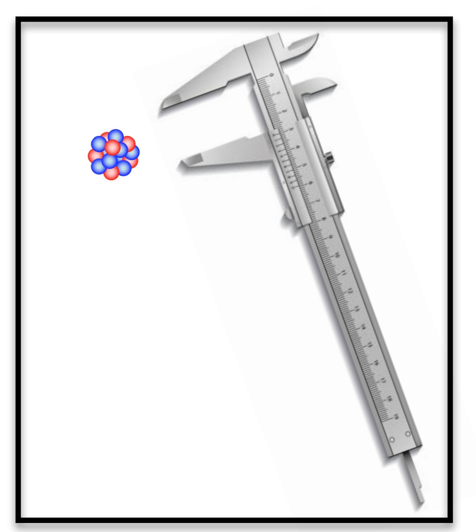




High-energy Precision

Wide spectrum of physics opportunities

Energy



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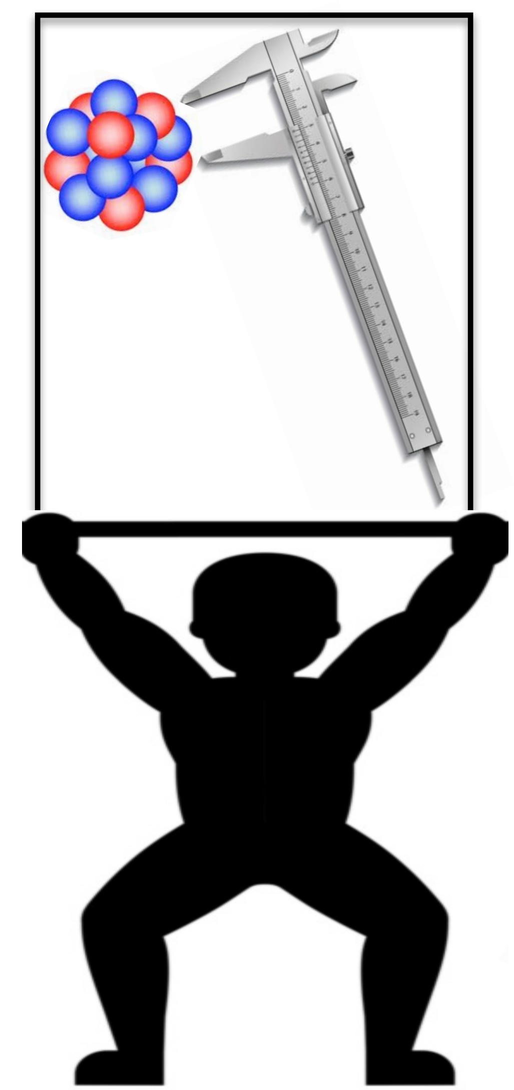
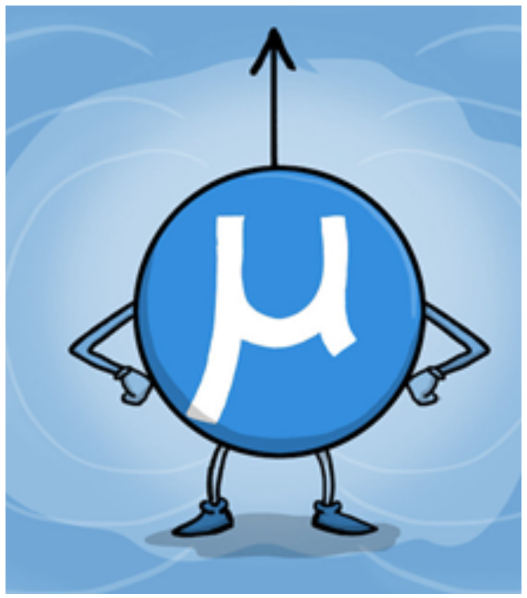


High-energy Precision

Wide spectrum of physics opportunities

Muons!!



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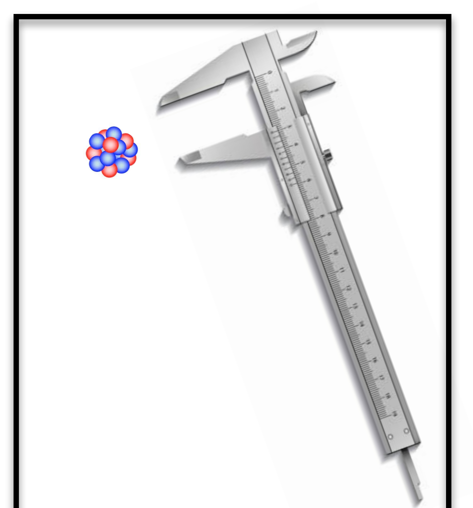

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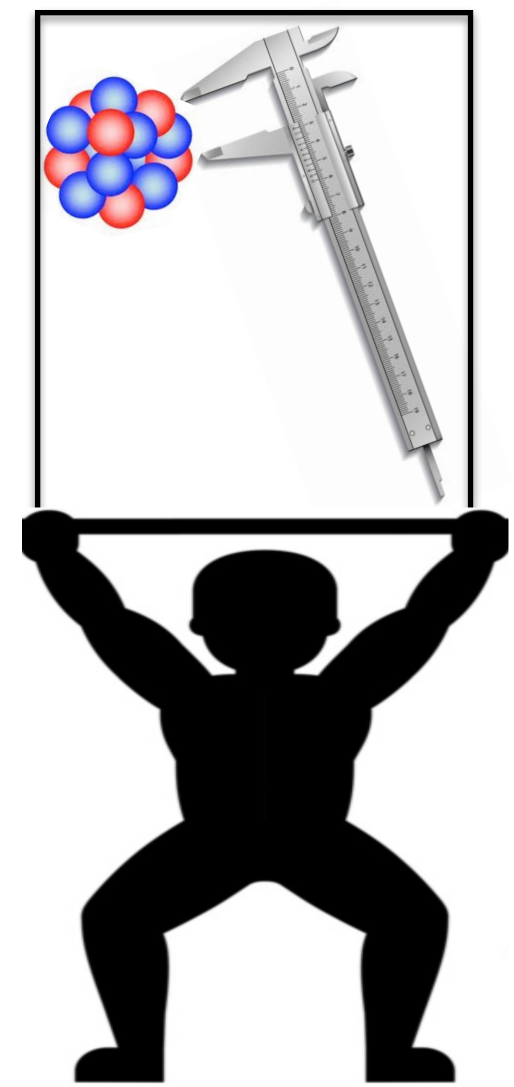

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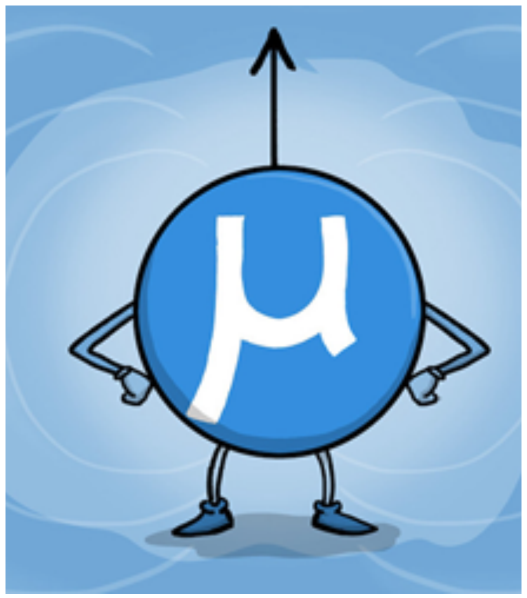

Muons colliding for first time

Self-evident potential of exploration.

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

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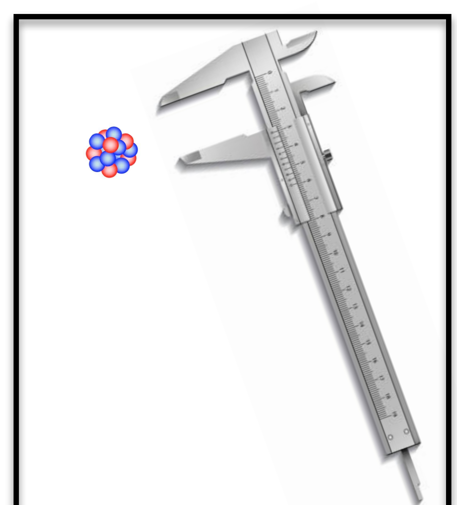

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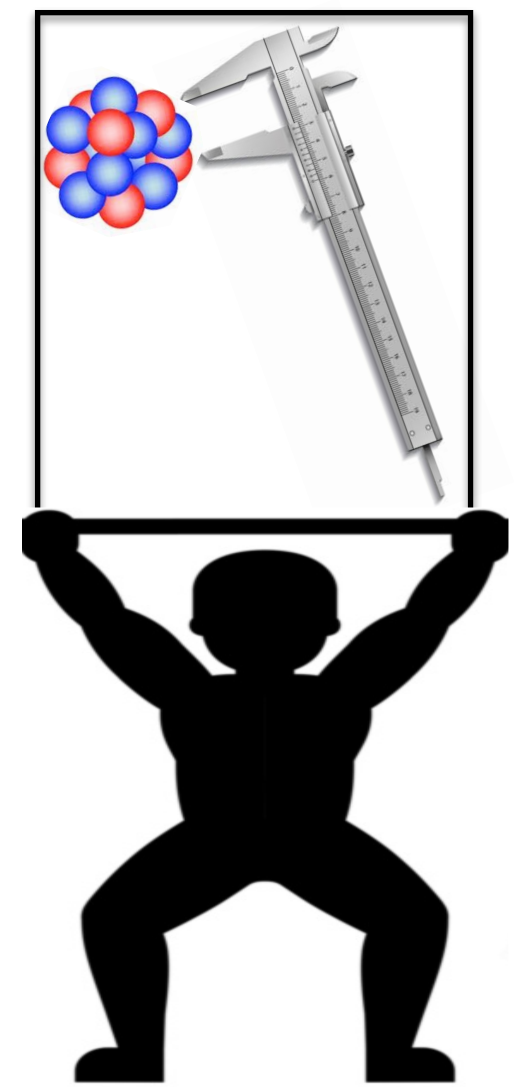

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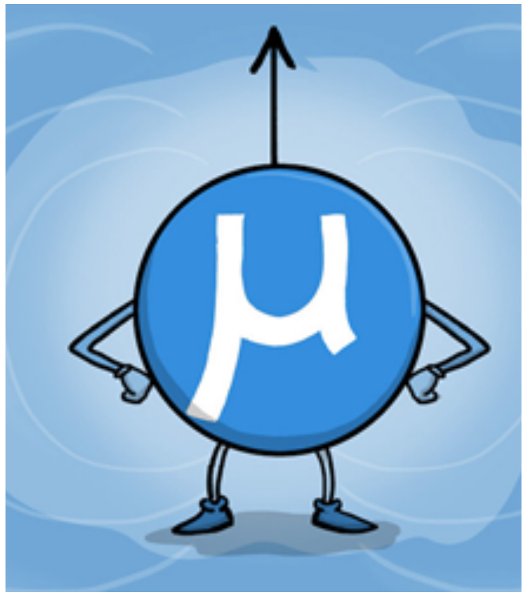

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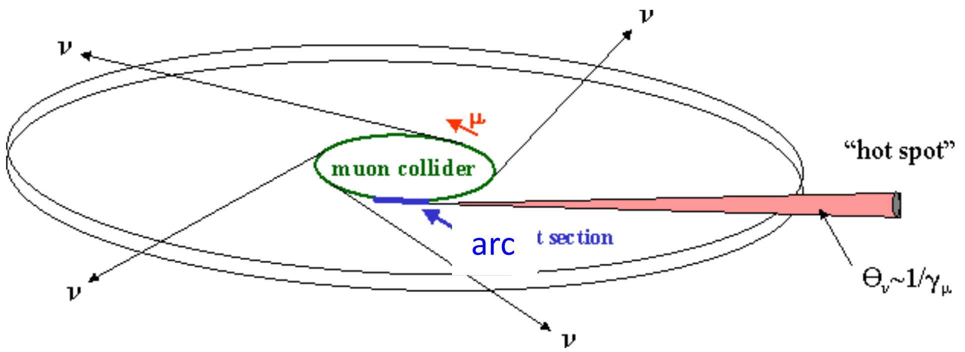
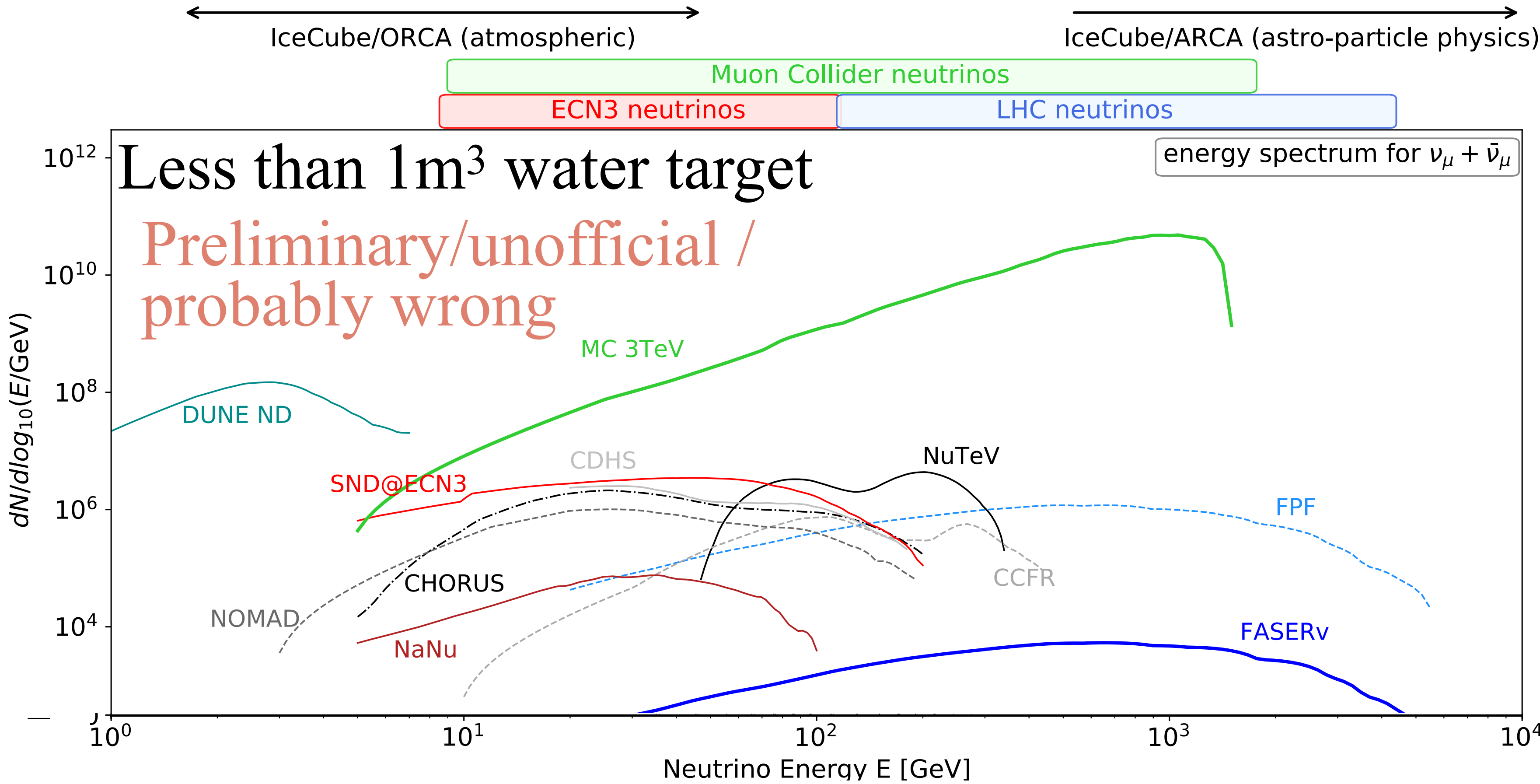
Muons decay to neutrinos:

Collimated, perfectly known, TeV-energy neutrino beams!





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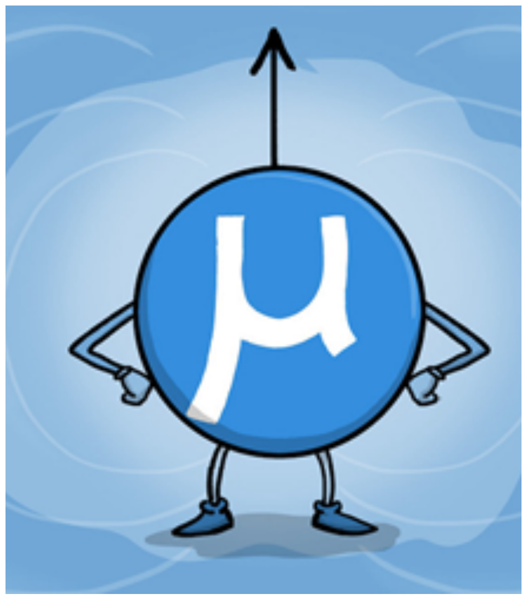

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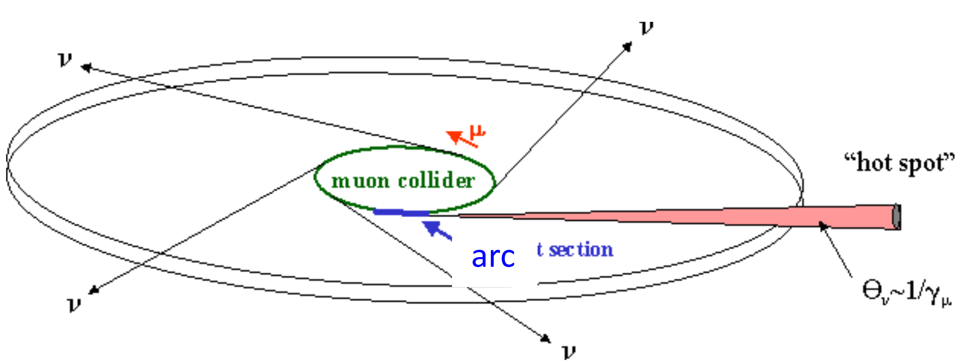
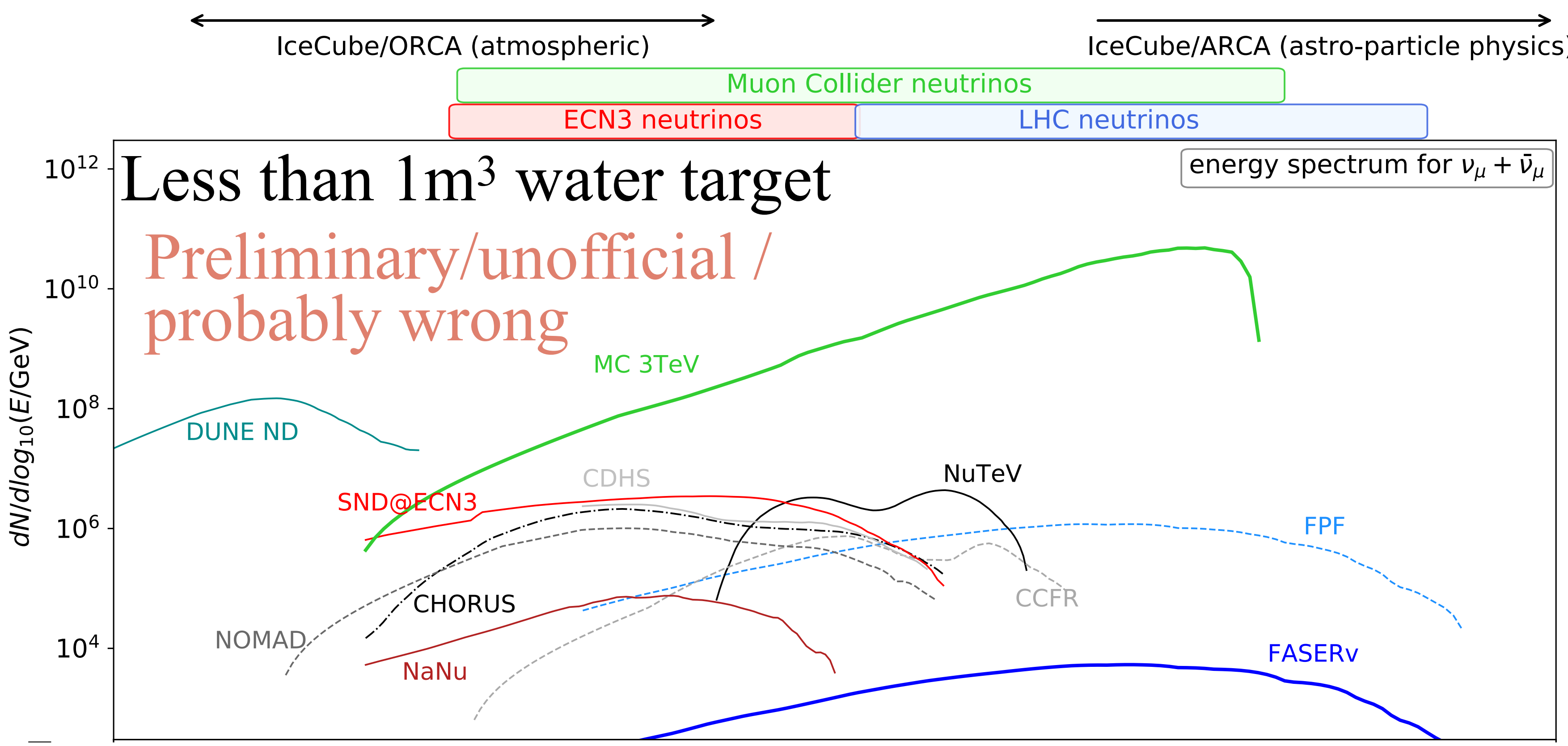




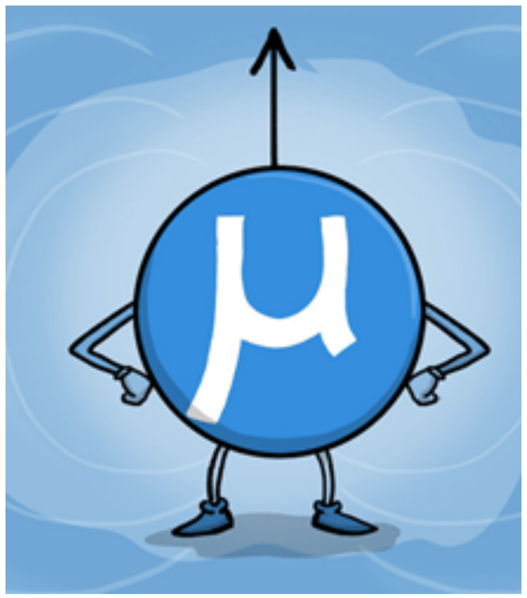
Which experiments with neutrino beam?

Statistics could enable ground-breaking PDF program

What about neutrino physics? Which BSM opportunities?

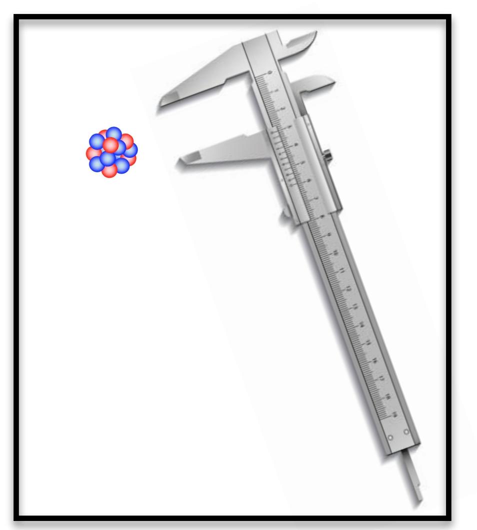
Wide spectrum of physics opportunities

Muons!!



Benchmark questions to organise exploration of this vast landscape of opportunities

Energy



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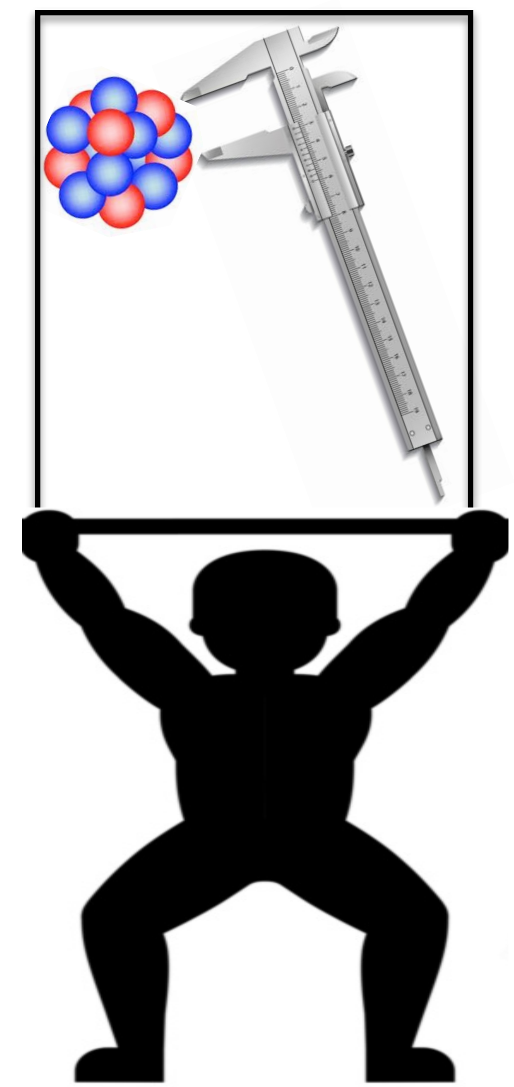

High-energy Precision

Benchmarks I: Consolidate Physics Case

Improving confidence or outline challenges on projections

With reasonably defined detector performance requirements, to inform design

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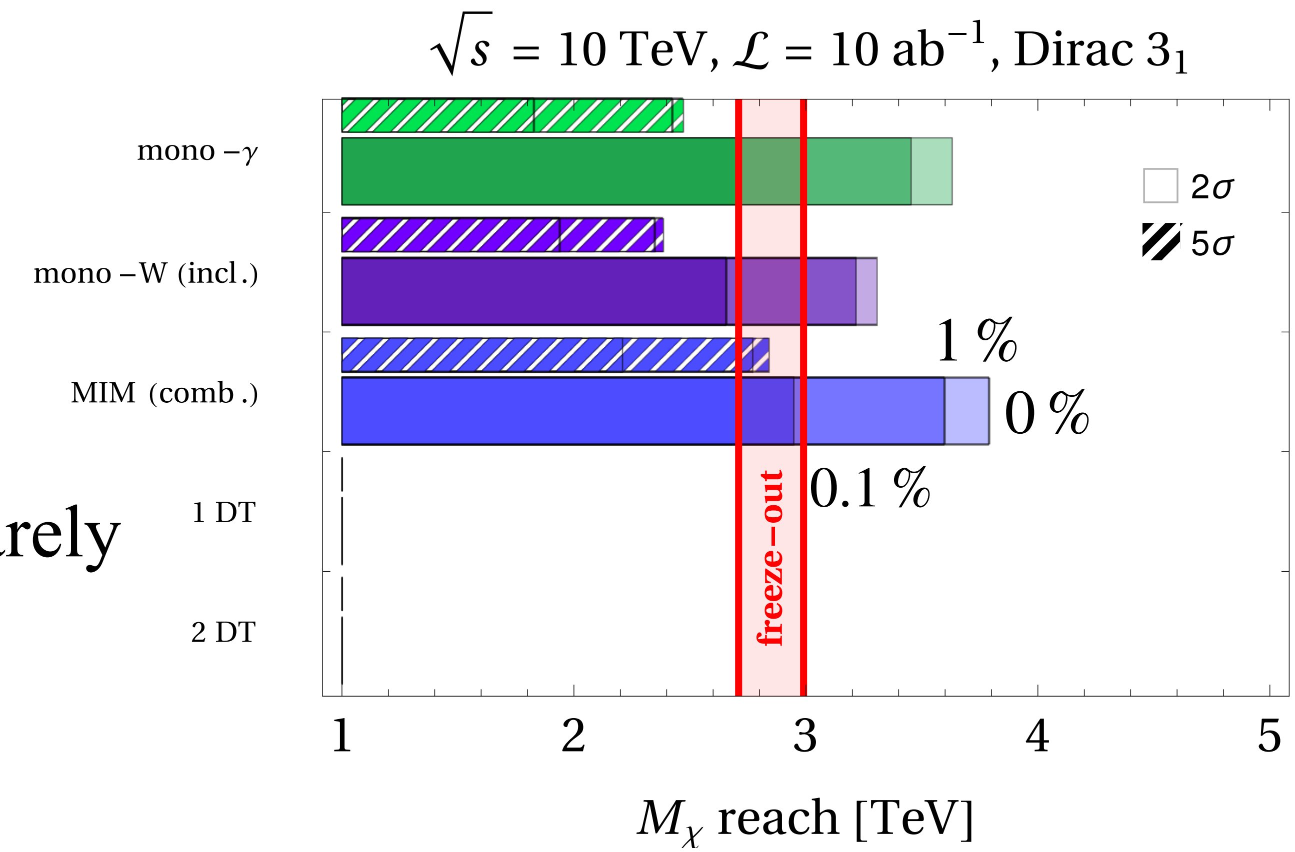
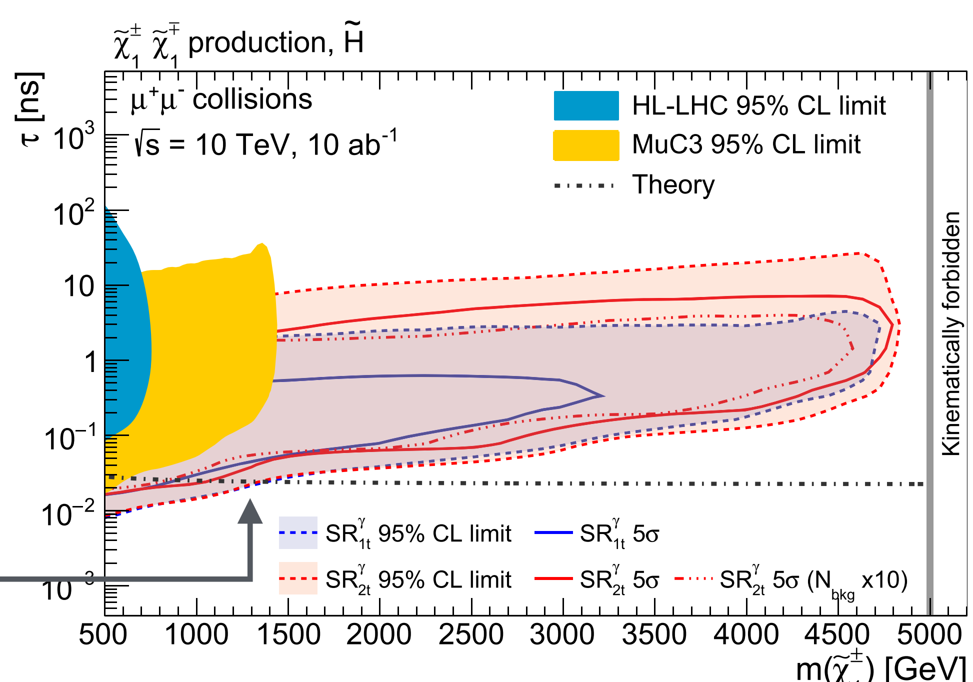
Dark Matter physics case

- Mono-X searches for small non-resonant signal on large background distribution.
- Systematics at ‰ can spoil termal target. Investigation needed.



- Thermal Higgsino in disappearing track barely visible at 10 TeV. Can we improve?
  At 3TeV, we produce it but not (yet) see it.



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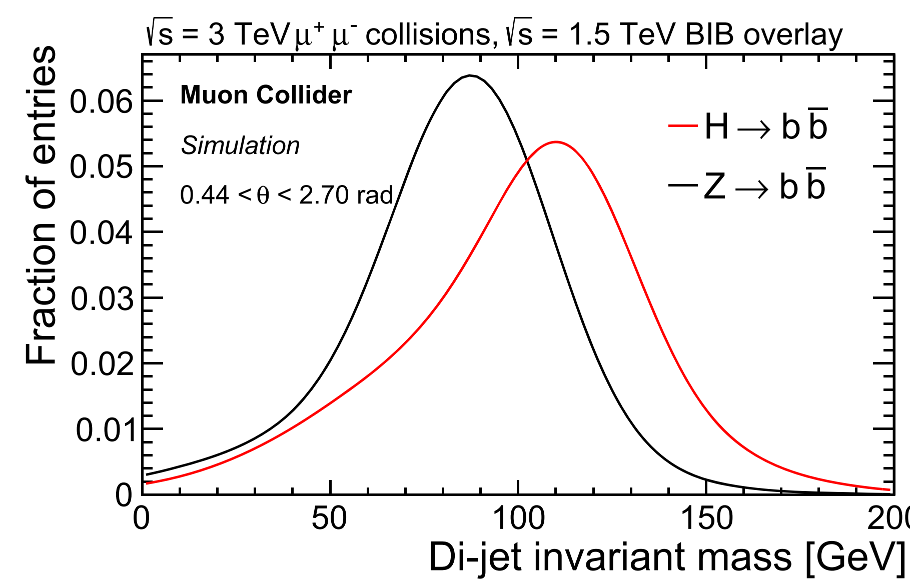
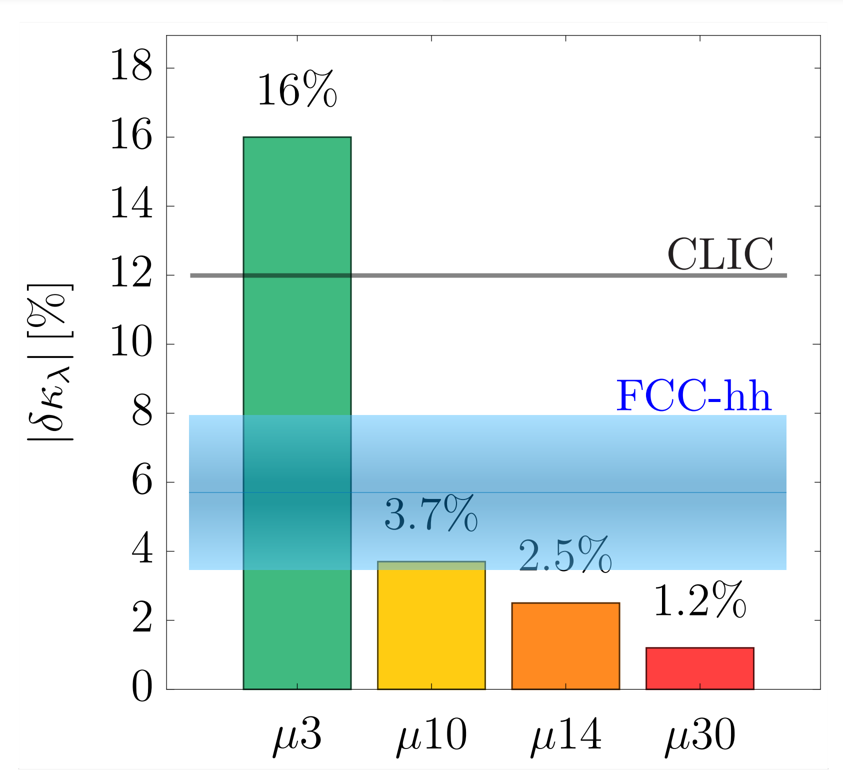
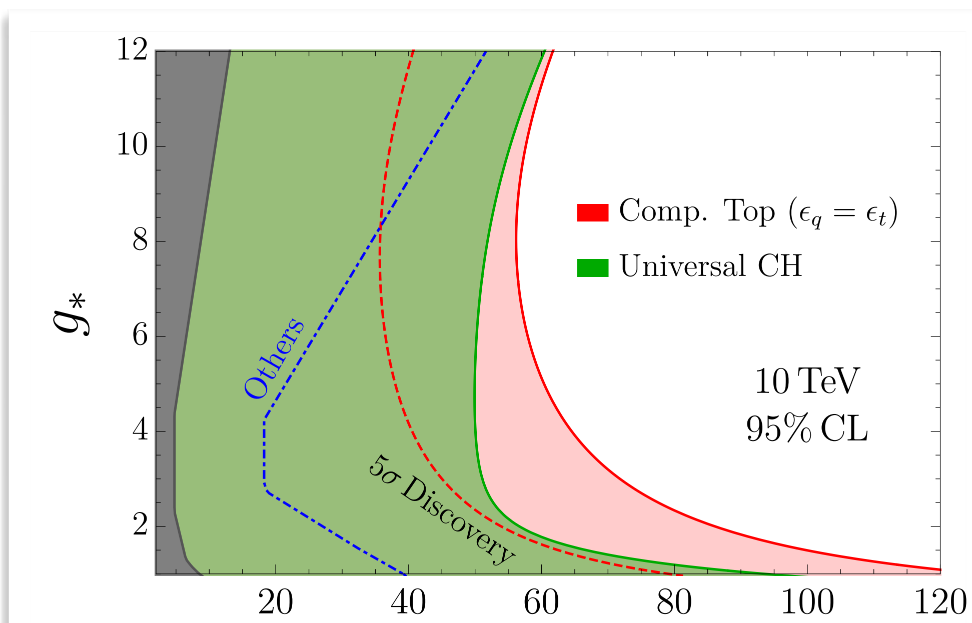
Higgs physics case

- Detector requirements for relevant measurements: single/double/compositeness
- Outline case for Higgs tagging/discrimination beyond state of art







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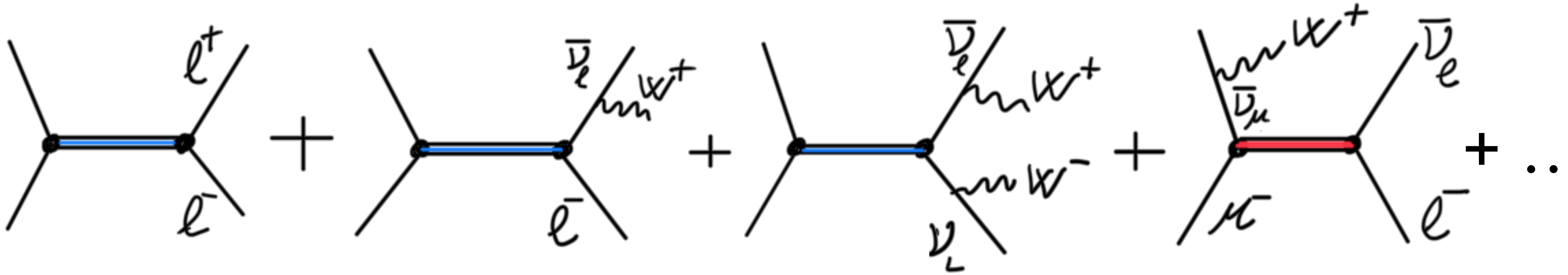
Improving confidence or outline challenges on projections

With reasonably defined detector performance requirements, to inform design

“Simple” resonances?

- A 10 TeV di-lepton resonance will look like this:



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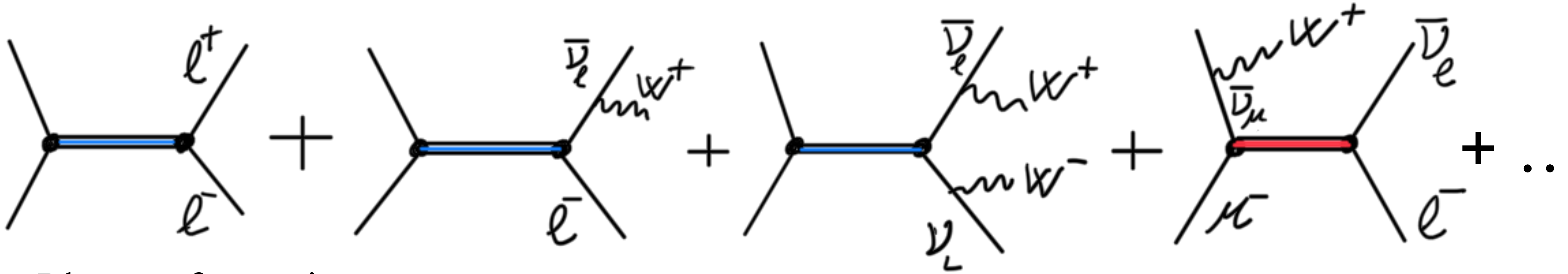


- Plenty of questions:
  Will we resolve the vector bosons?
  Need new concept of electroweak jets?
  Can we tell if decays to lepton or neutrino?
  Can we tell if is neutral or charged resonance?

- Nobody looked into that!

Benchmarks I: Consolidate Physics Case

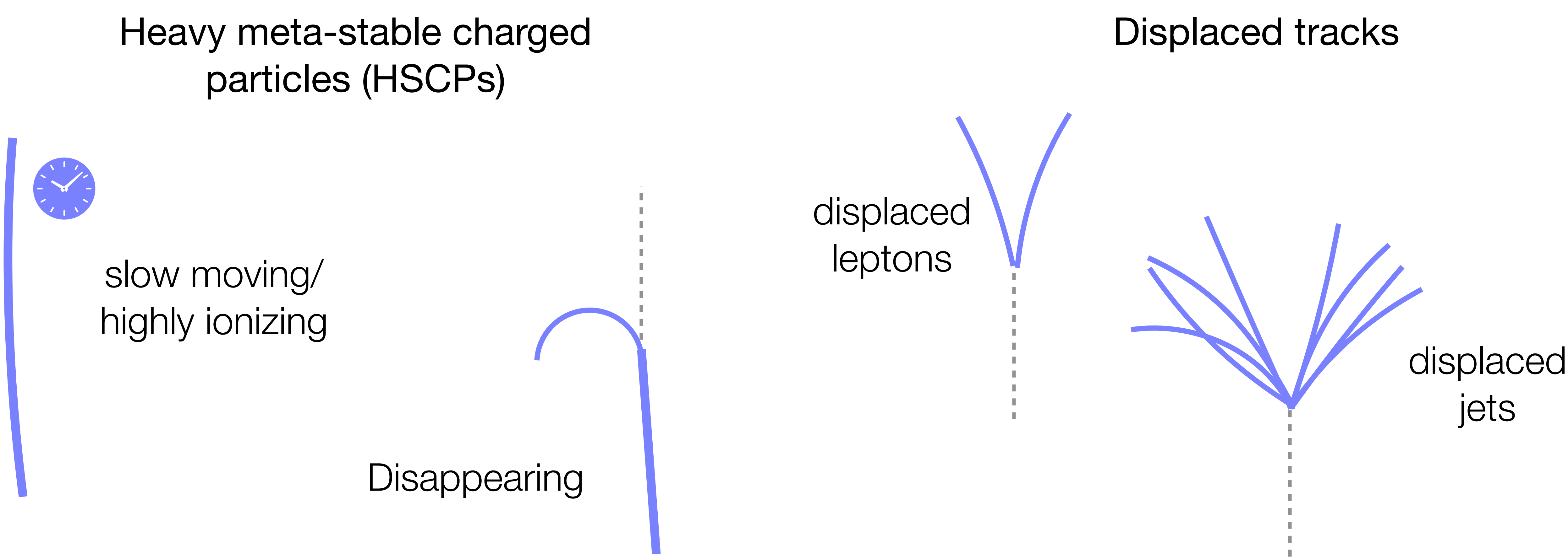
Improving confidence or outline challenges on projections

With reasonably defined detector performance requirements, to inform design

BSM particles survey

See Rodolfo's talk

Long-lived particles offer broad spectrum of signatures



Benchmarks II: Calculation 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.

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

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- KLN Theorem non-applicable.
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→ **Practical need** of computing EW Radiation effects
- Enhanced by $\log^{(2)} E^2/m_{\rm EW}^2$

EW theory is Weakly-Coupled
The IR cutoff is physical

→ **First-Principle** predictions **must** be possible
- For arbitrary multiplicity final state

Benchmarks II: Calculation 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

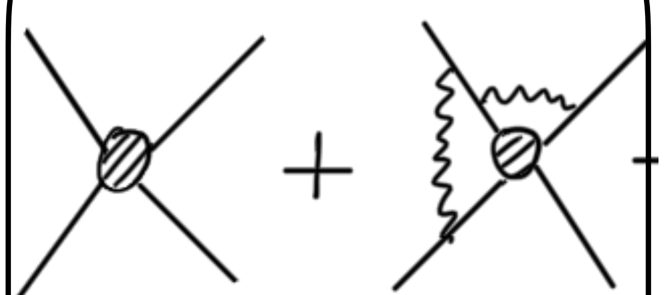
Scale separation entails enhancement of Radiation effect.

Quantitatively, resummation is needed.

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

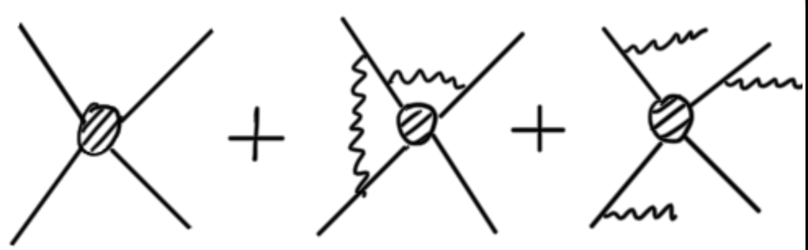
→ 10 TeV MuC

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.

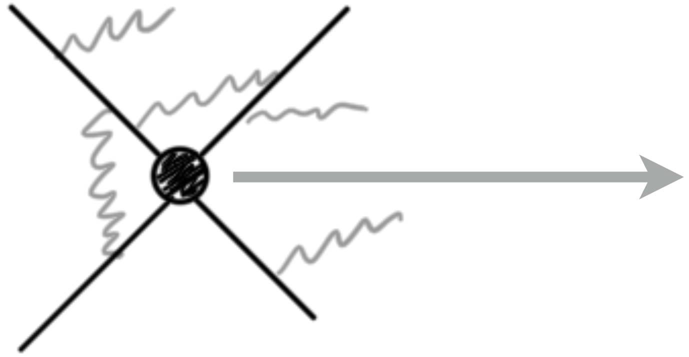
Process	N (Ex)	N (S-I)
e^+e^-	6794	9088
$e\nu_e$	—	2305
$\mu^+\mu^-$	206402	254388
$\mu\nu_\mu$	—	93010
$\tau^+\tau^-$	6794	9088
$\tau\nu_\tau$	—	2305
jj (Nt)	19205	25725
jj (Ch)	—	5653
$c\bar{c}$	9656	12775
cj	—	5653
$b\bar{b}$	4573	6273
$t\bar{t}$	9771	11891
bt	—	5713
Z_0h	680	858
$W_0^+W_0^-$	1200	1456
$W_T^+W_T^-$	2775	5027
$W^\pm h$	—	506
$W_0^\pm Z_0$	—	399
$W_T^\pm Z_T$	—	2345

= charged

Benchmarks II: Calculation Challenges

Benchmark predictions we must learn how to make:

- Direct 2→2 annihilation:



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

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

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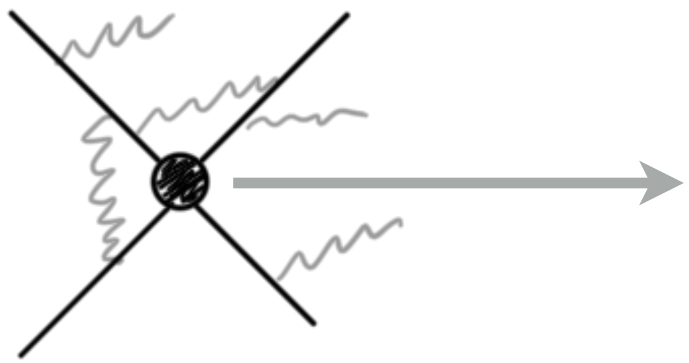

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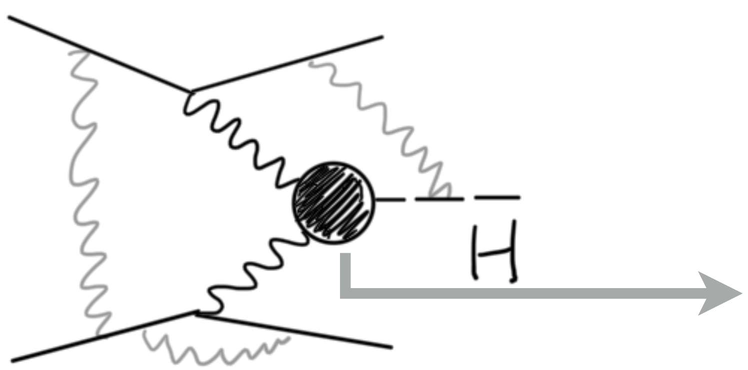
- EW-scale VBS: single Higgs production:



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

same scale of radiation emission as of scattering

Benchmarks III: A SM physics case?

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.**

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Can we convincingly argue for future colliders with SM alone?

- With BSM exploration only icing on the cake?
- MuC physics is so new. We could succeed.

Benchmarks III: A SM physics case?

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

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

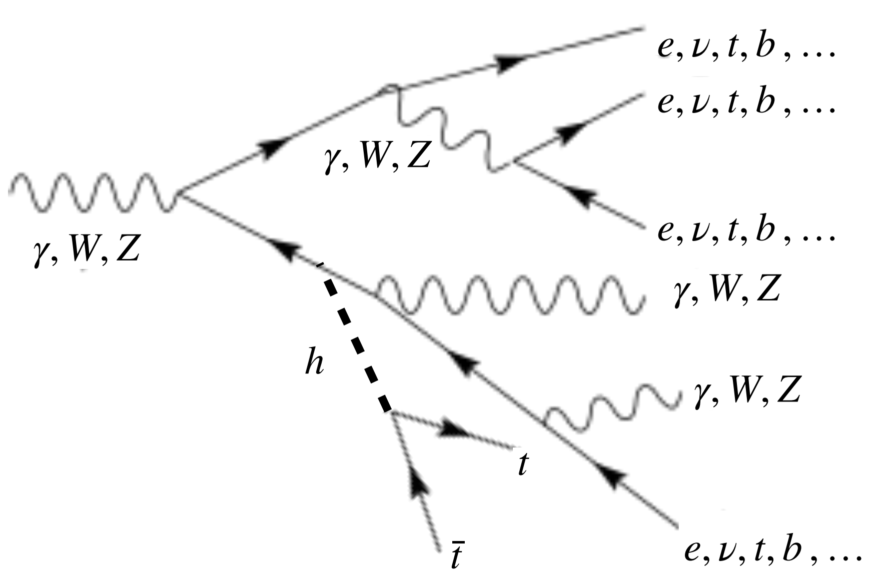
Plenty of cool things will happen:

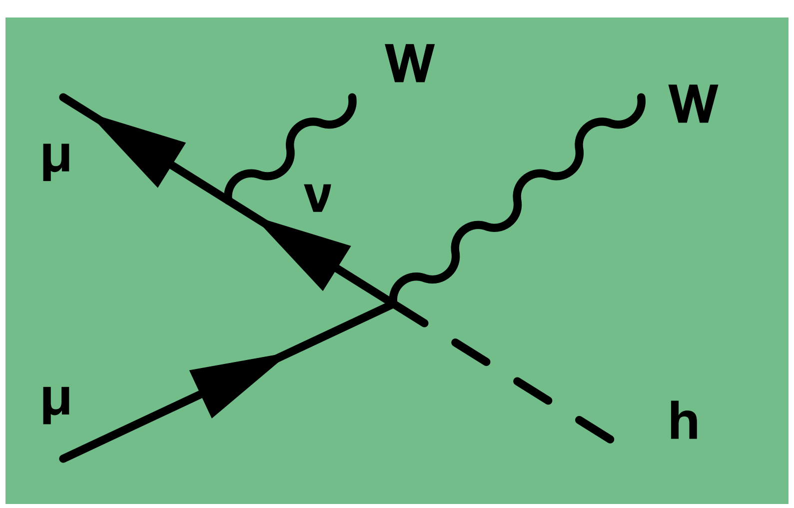
Electroweak Restoration. The $SU(2) \times U(1)$ group emerging, finally!

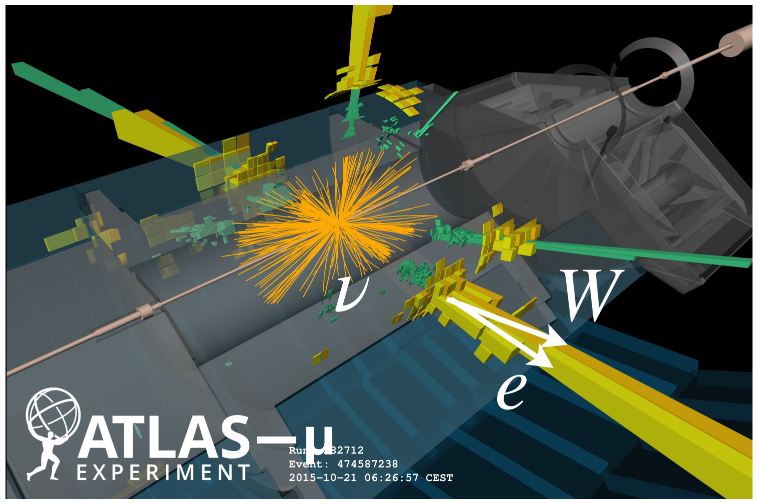
Electroweak Radiation in nearly massless broken gauge theory.
Never observed, never computed (and we don't know how!)

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







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How to translate this into **SM** physics benchmarks?

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