Why building a muon collider

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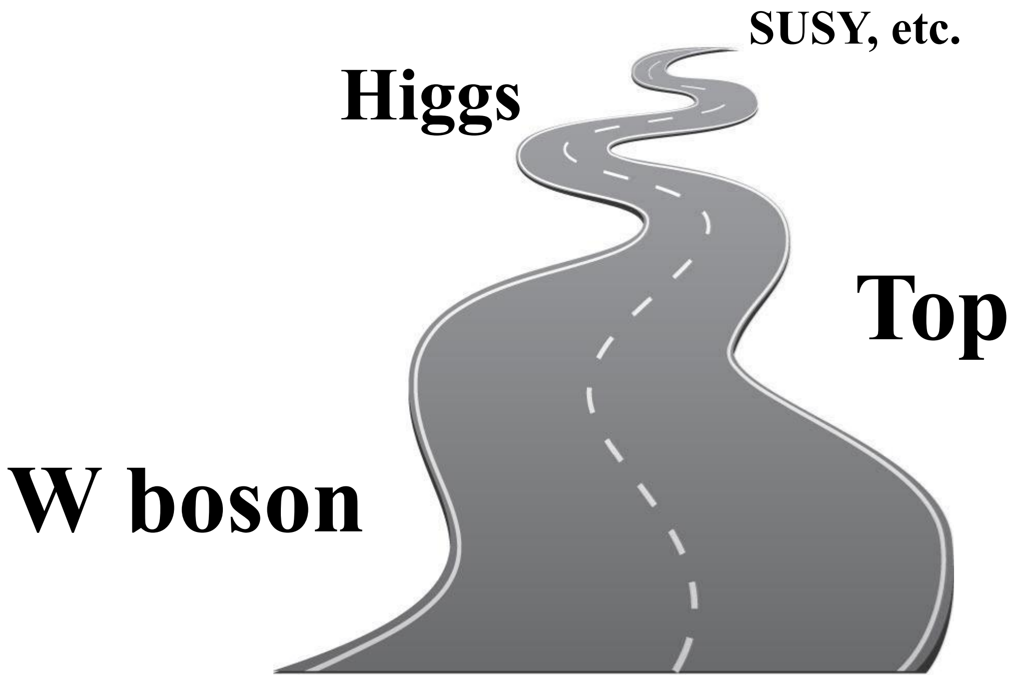
ICREA @ IFAE

Institut de Física d'Altes Energies

The High Energy Physics Landscape

HEP Yesterday | **LHC** → | **HEP Today**



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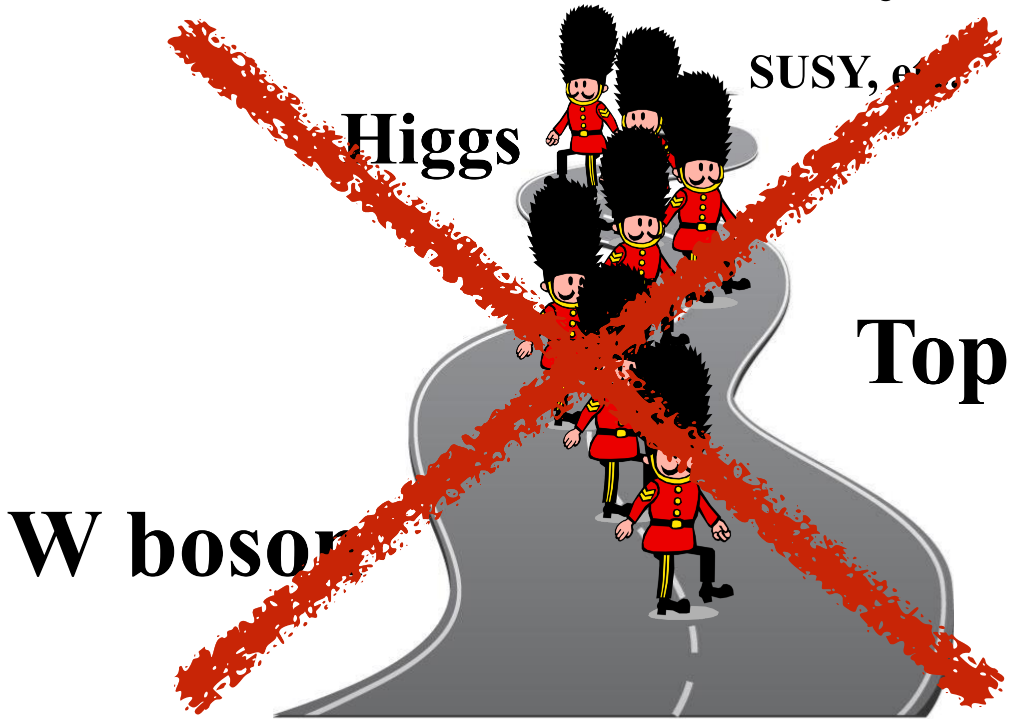

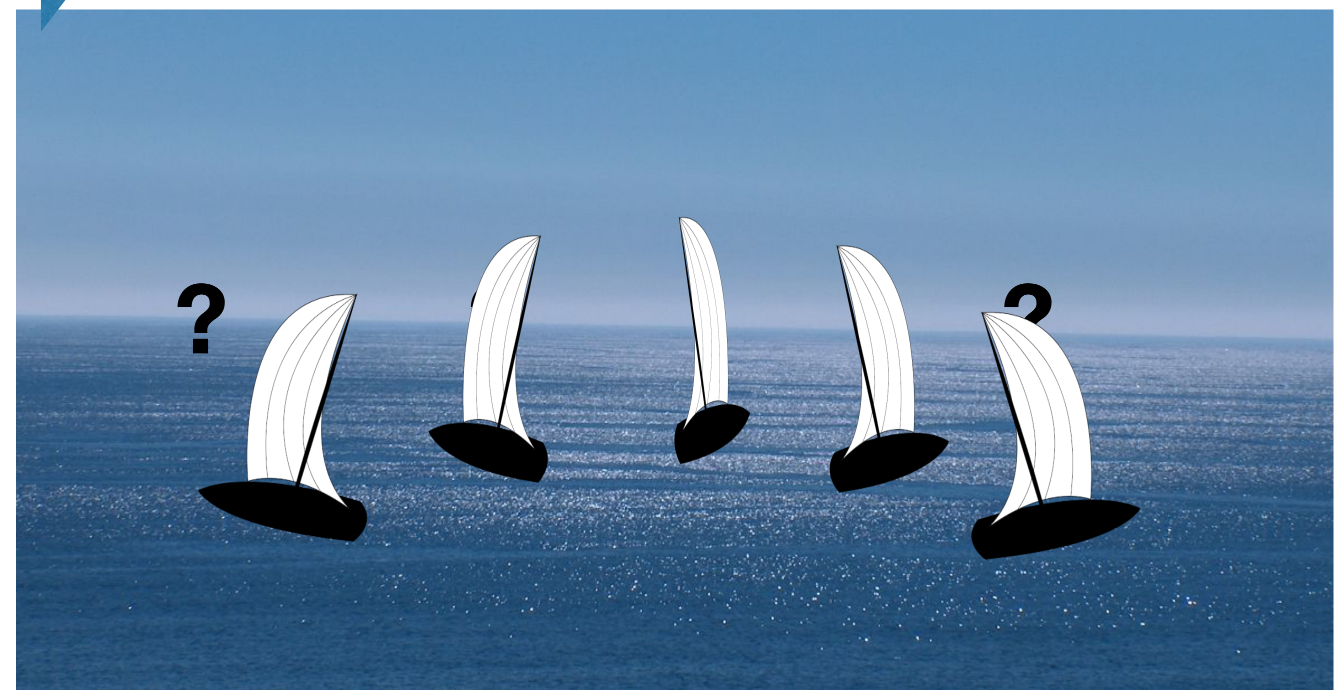

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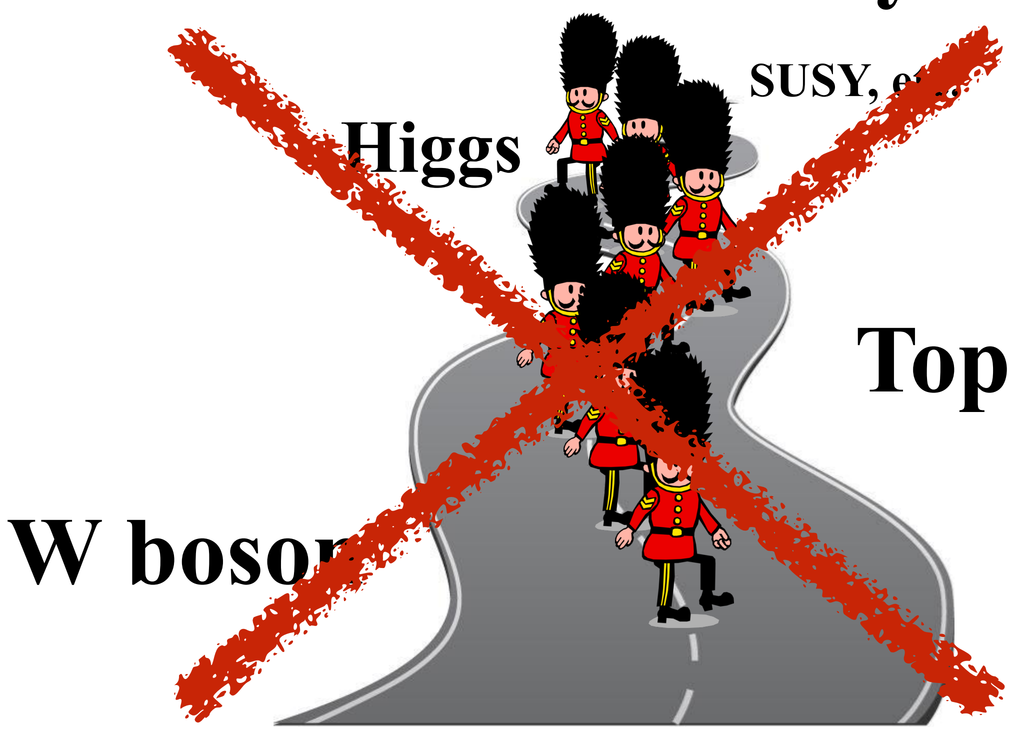

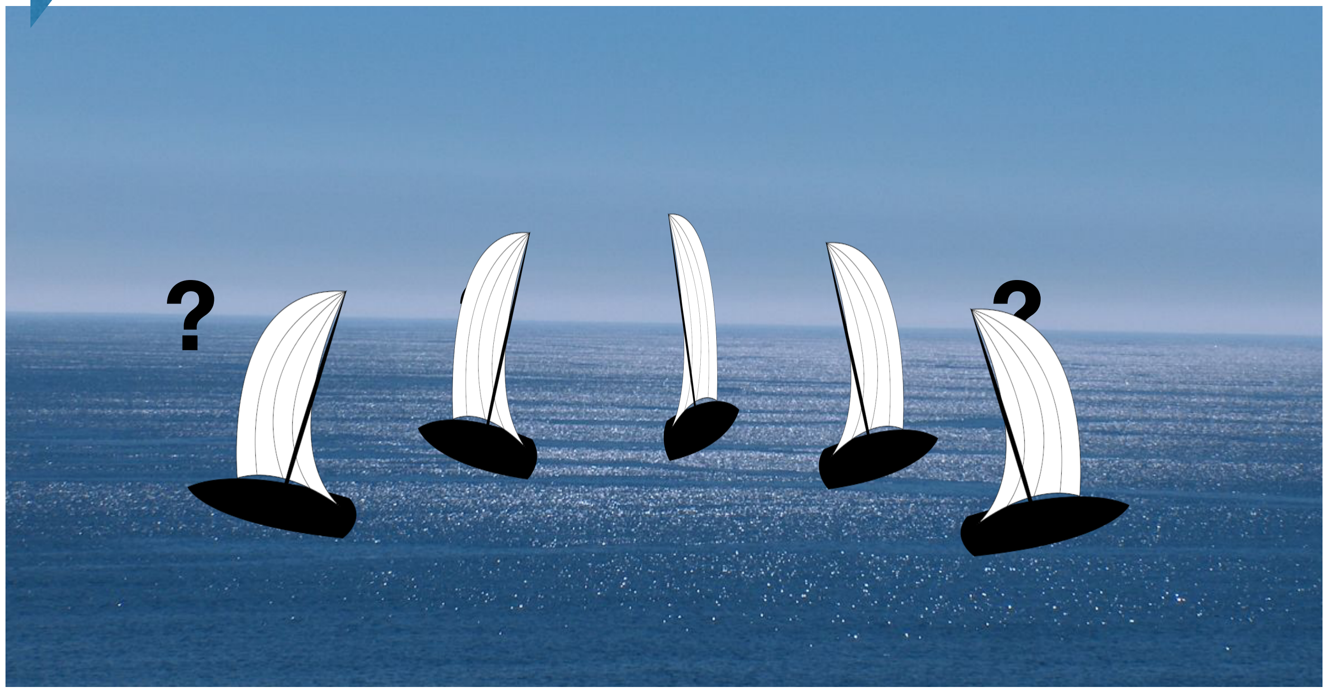

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This is why we started speaking about **Frontiers**

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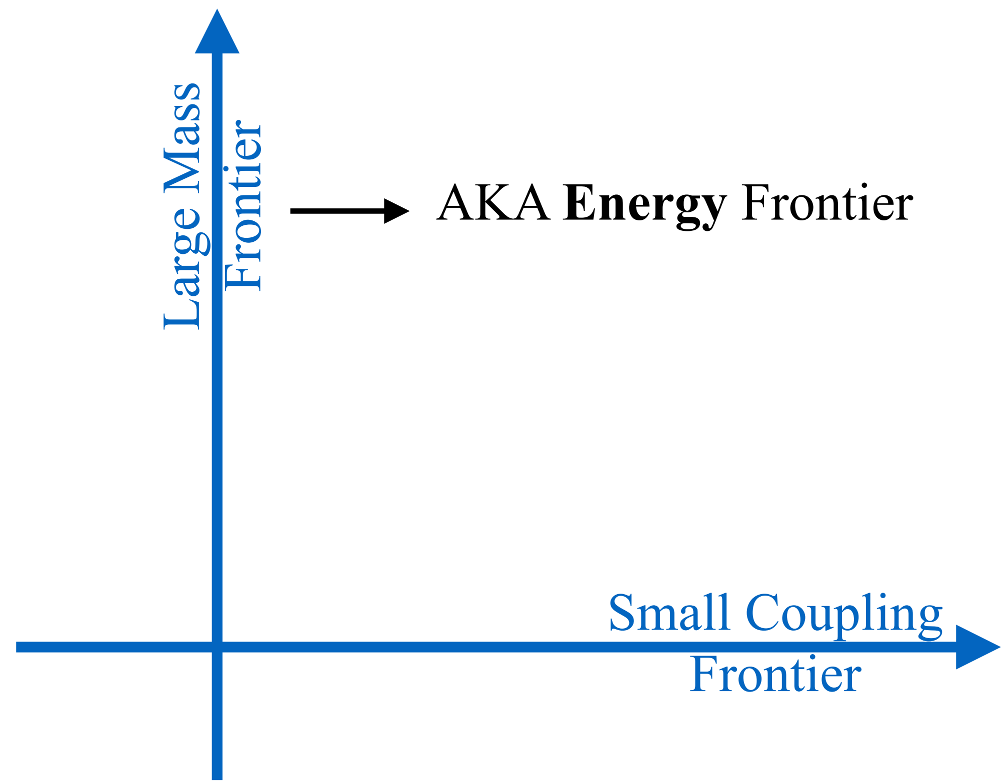
The High Energy Physics Landscape

Our **Frontiers are the directions** in which (i.e., reasons why) New Physics might hide



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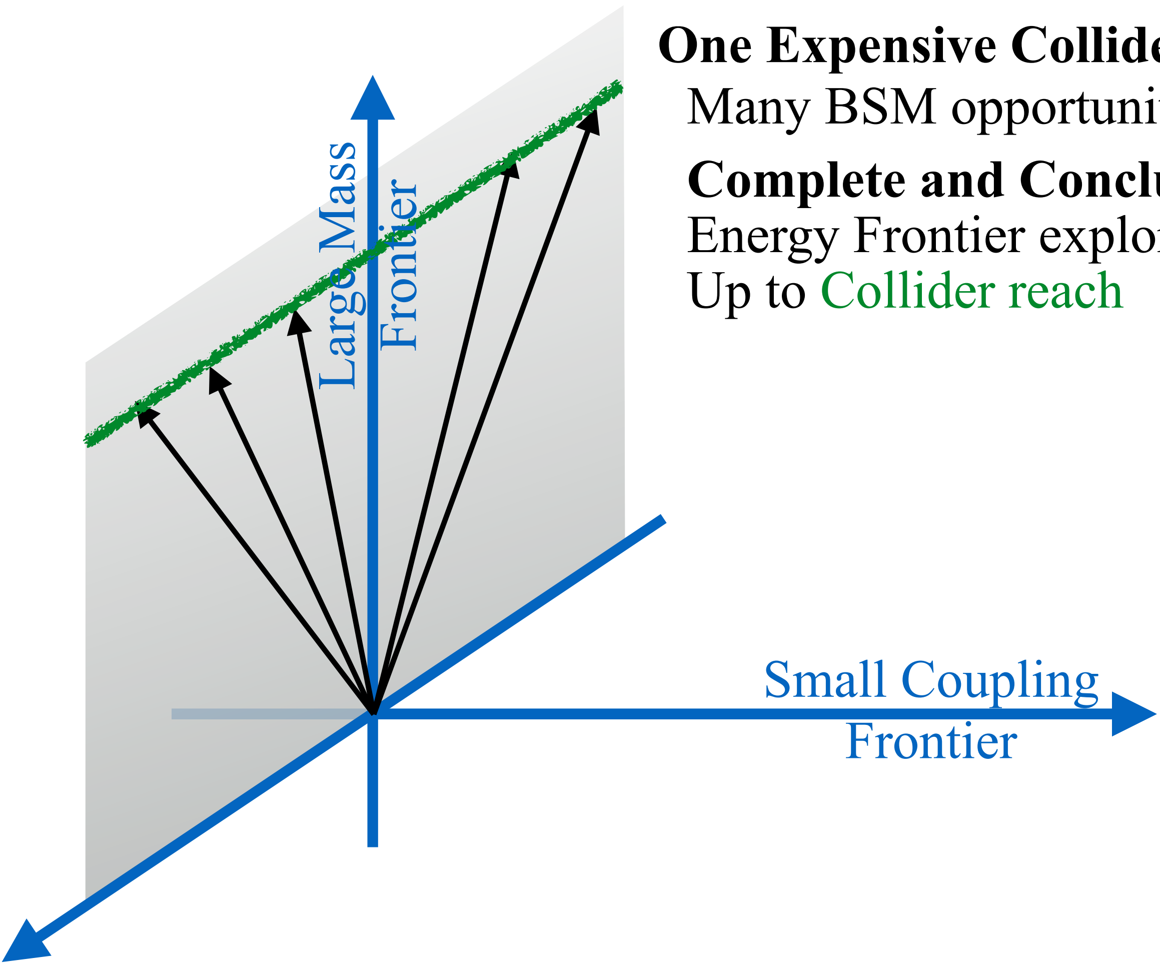
Only one drawback: they are **Expensive**.

Why Colliders?

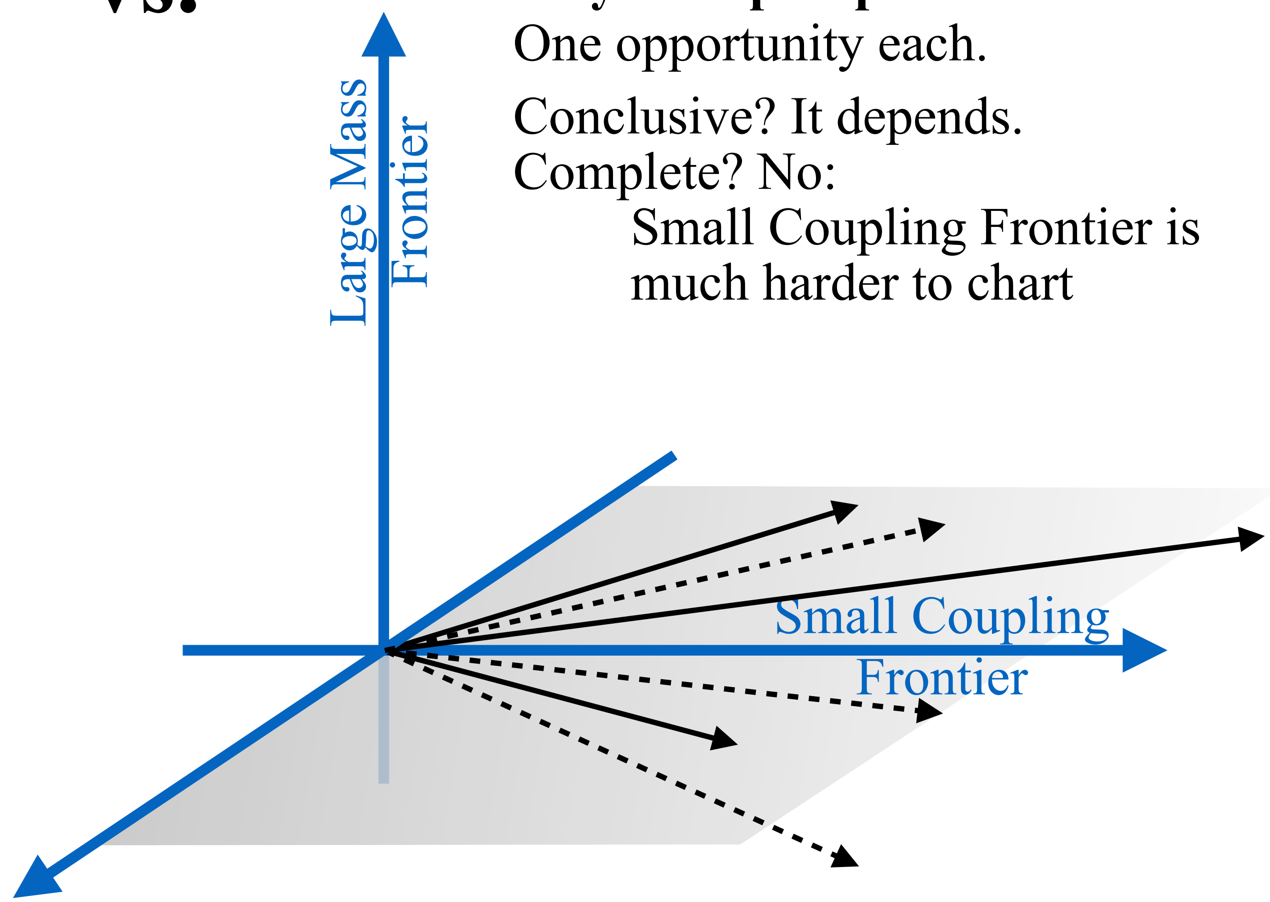
Expensive? Yes, no doubt, but …



One Expensive Collider
Many BSM opportunities

Complete and Conclusive
Energy Frontier exploration.
Up to Collider reach

vs.



Many Cheap Experiments
One opportunity each.

Conclusive? It depends.
Complete? No:
Small Coupling Frontier is much harder to chart

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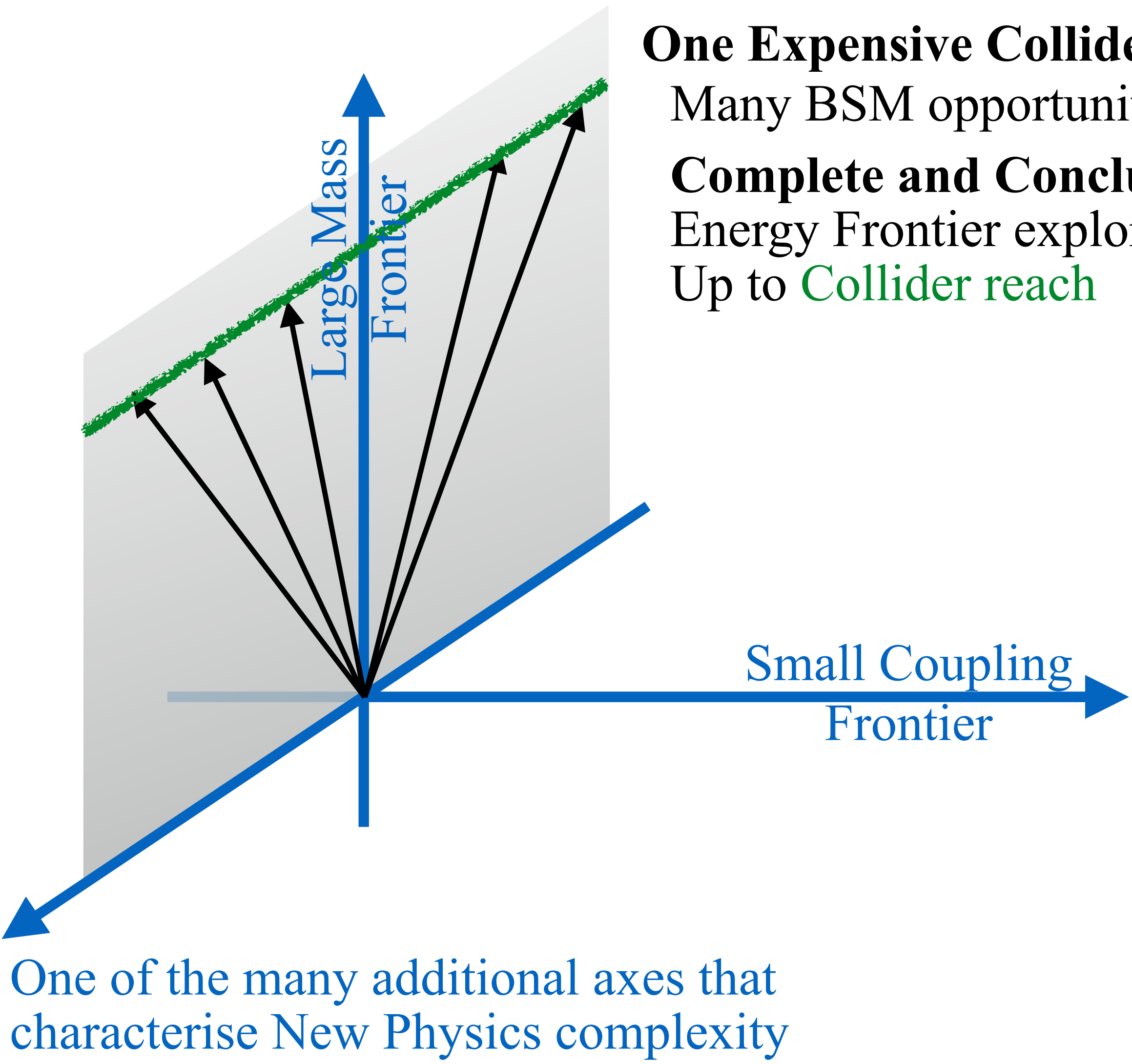

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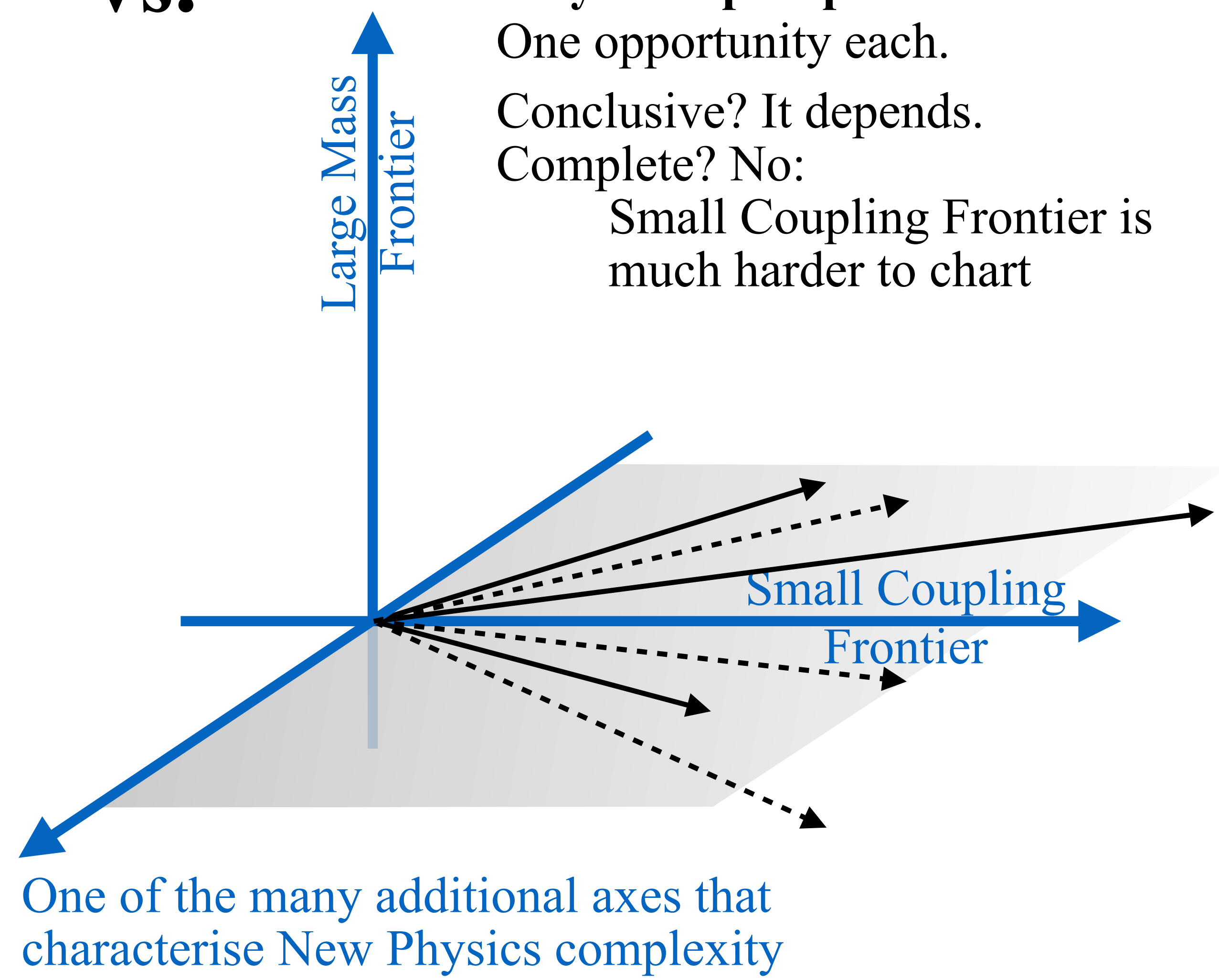

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Still, no doubt that next big project, to have a chance, must be ambitious enough to make **great jump ahead** in exploration of **multiple directions**

[even better if constructed with **revolutionary technology**]

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High-energy physics probed with much smaller collider energy

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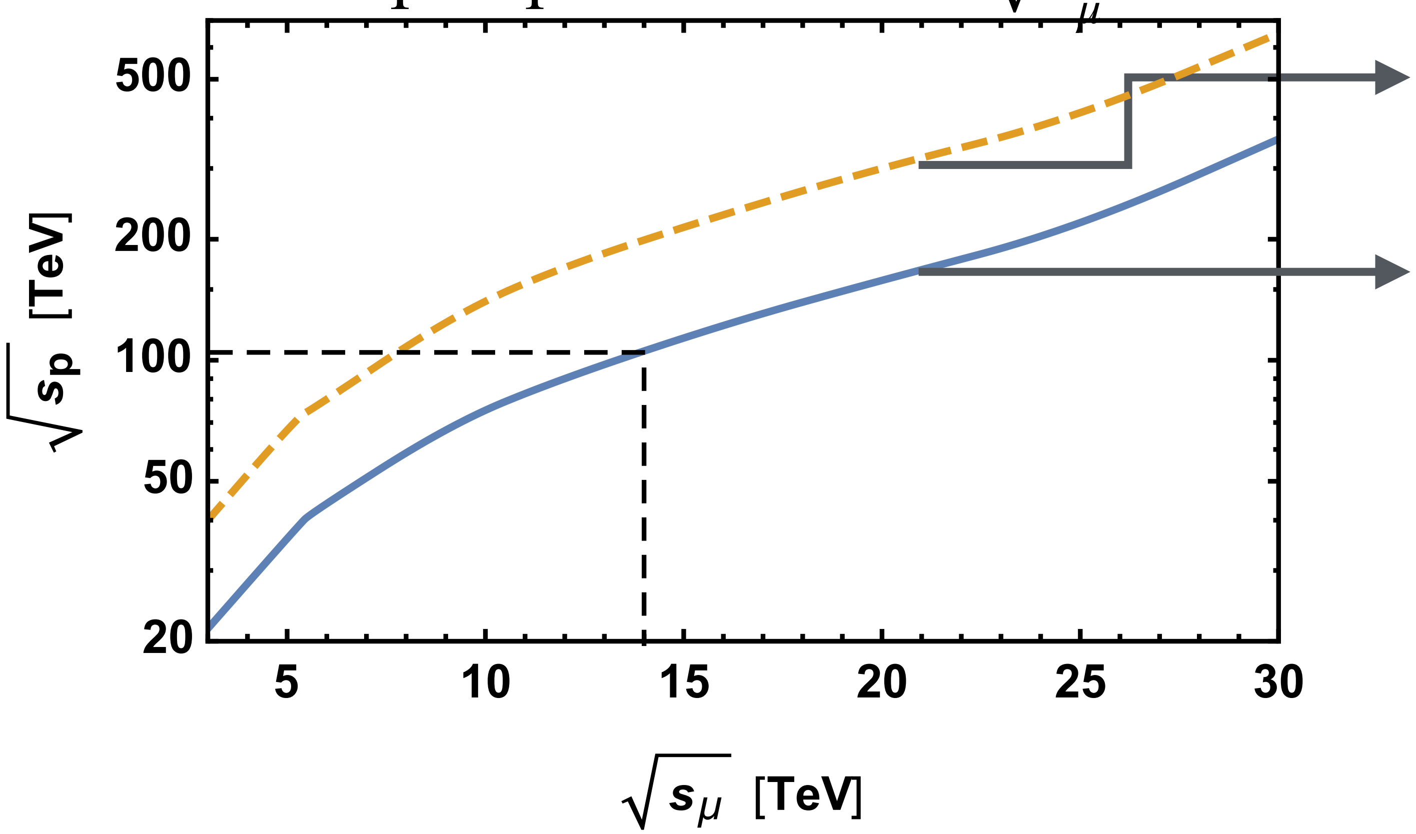
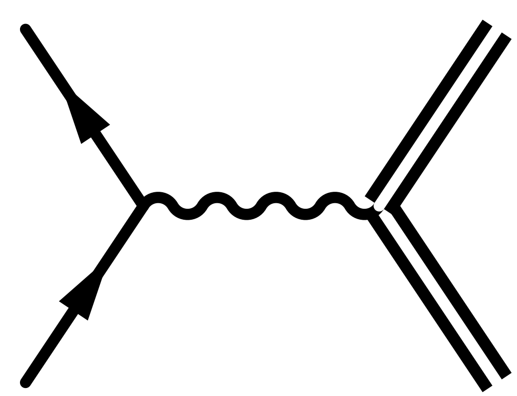
pp $\sqrt{s}$ at which $\sigma_{pp} = \sigma_{\mu\mu}$
for pair prod. with $M \sim \sqrt{s_\mu}$



Estimate for EWK-only charged particles

Estimate for EWK&QCD charged particles



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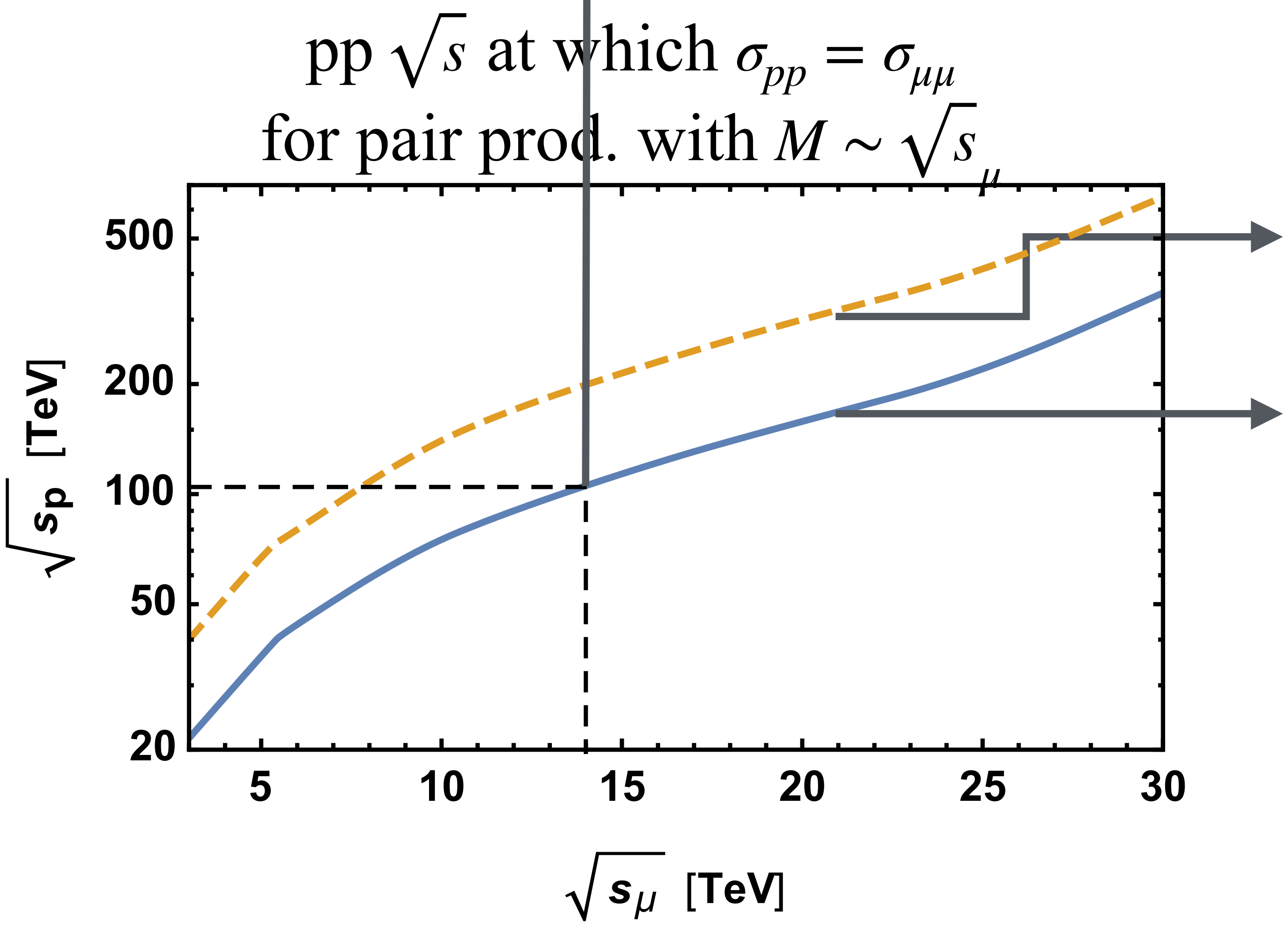

For reference:
14 TeV μ-collider ~ FCC@100 TeV

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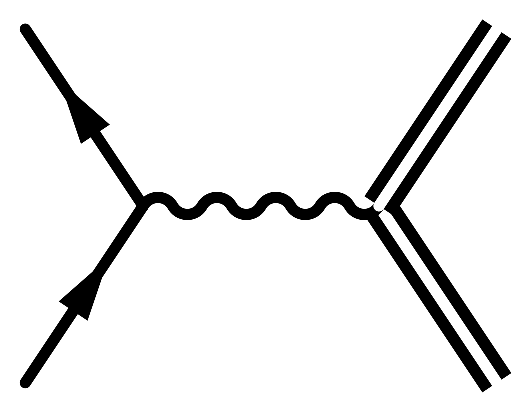

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[cannot accelerate them in rings above few 100 GeV]
[linear colliders limited to few TeV by size and power]

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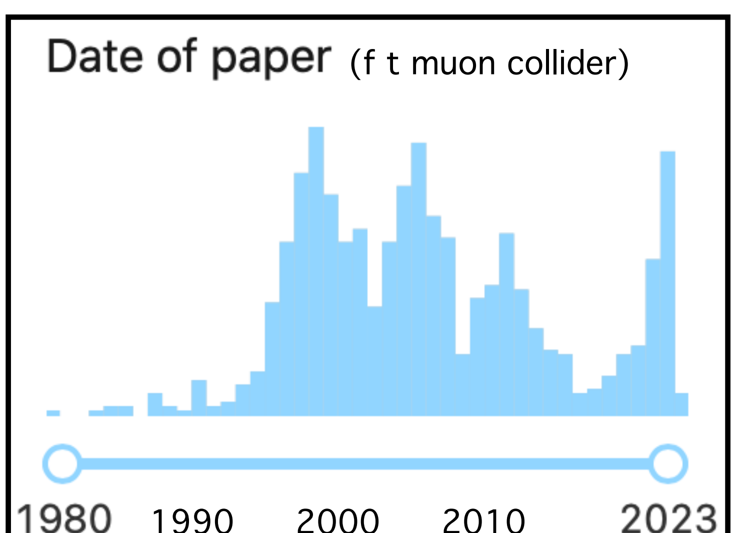
Muon Colliders

1980
First ideas

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

2020 Update of EU Strategy
outcome: set up collaboration



International
UON Collider
Collaboration
muoncollider.web.cern.ch

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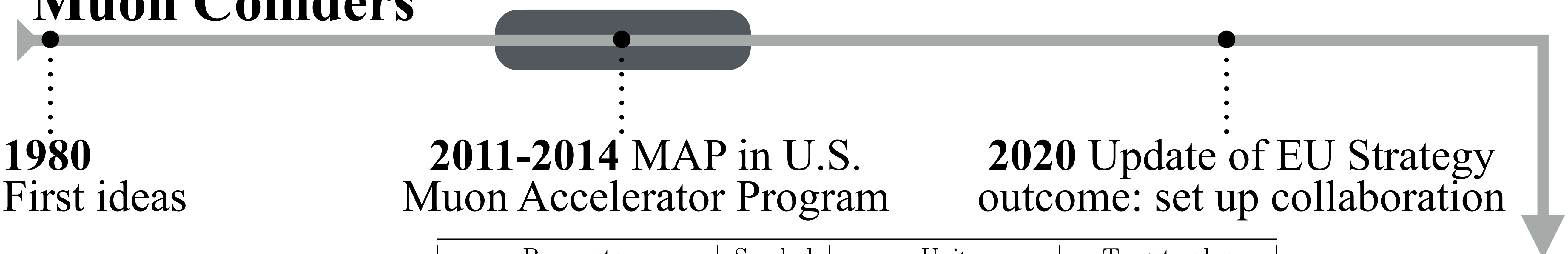

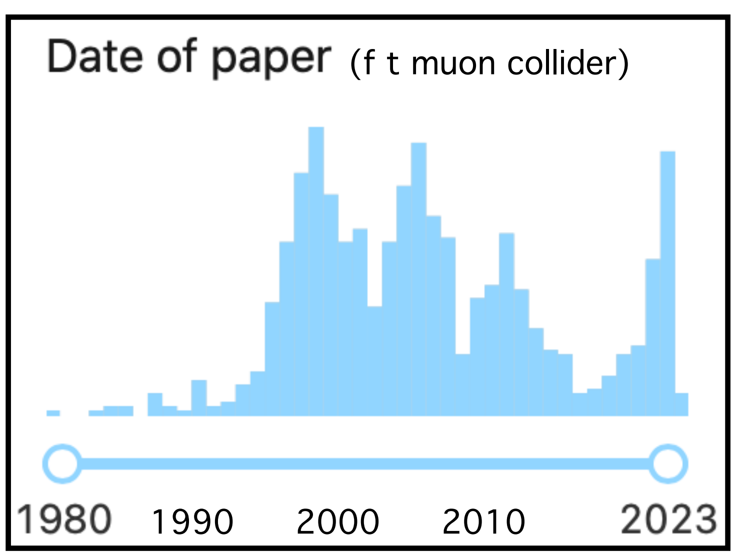

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14

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

Natural quadratic lumi scaling at MuC

International
MUON Collider
Collaboration

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Muon Collider Physics Pillars

The muon collider combines pp and ee advantages:

- High available energy for new heavy particles production

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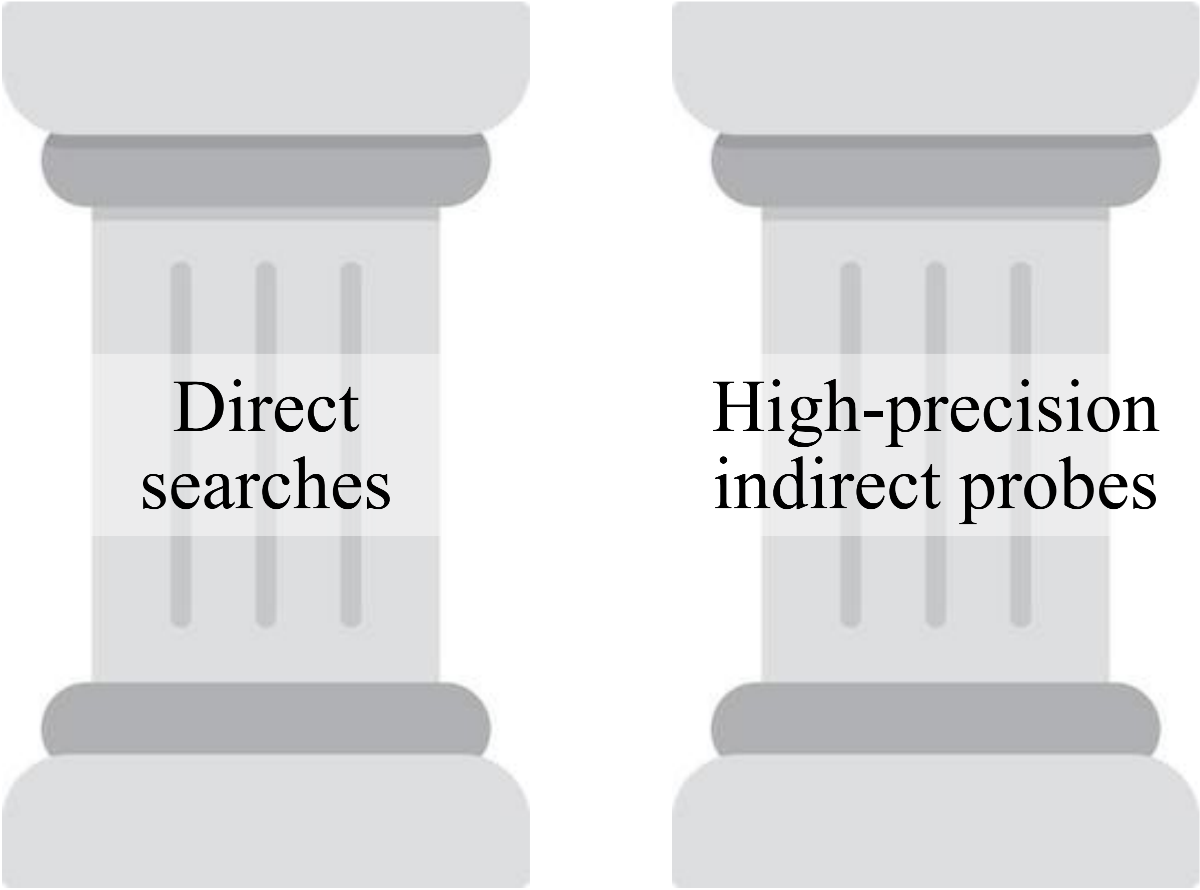

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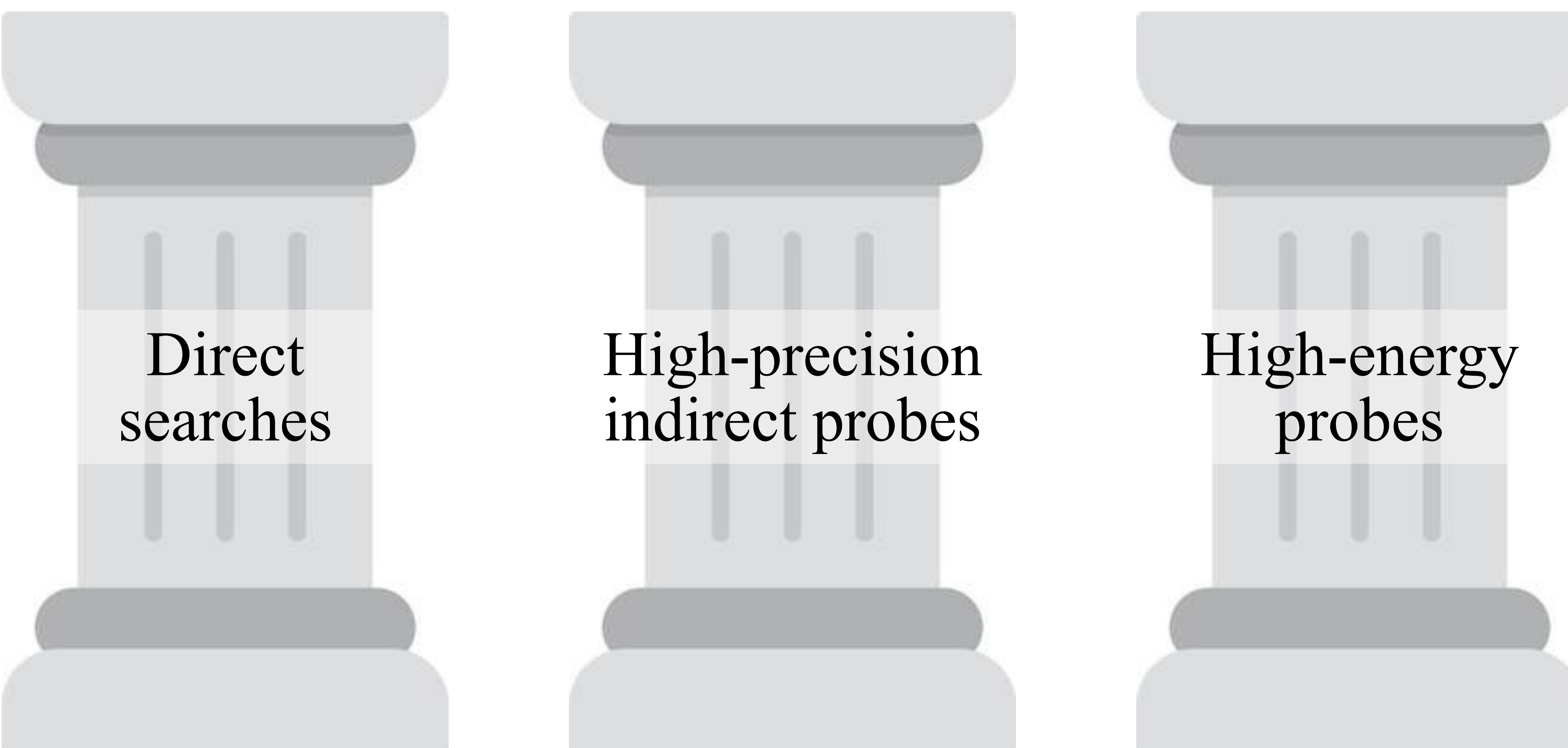
Furthermore:

- Can measure processes of very high energy



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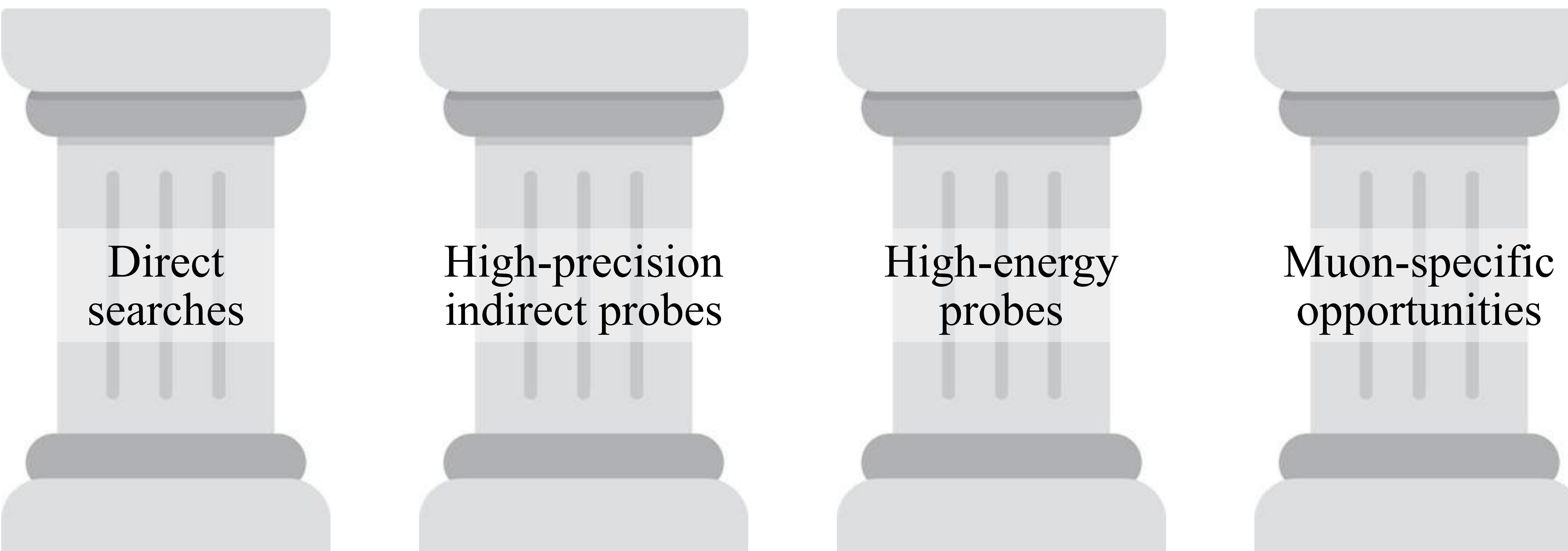
The muon collider combines pp and ee advantages:

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

Furthermore:

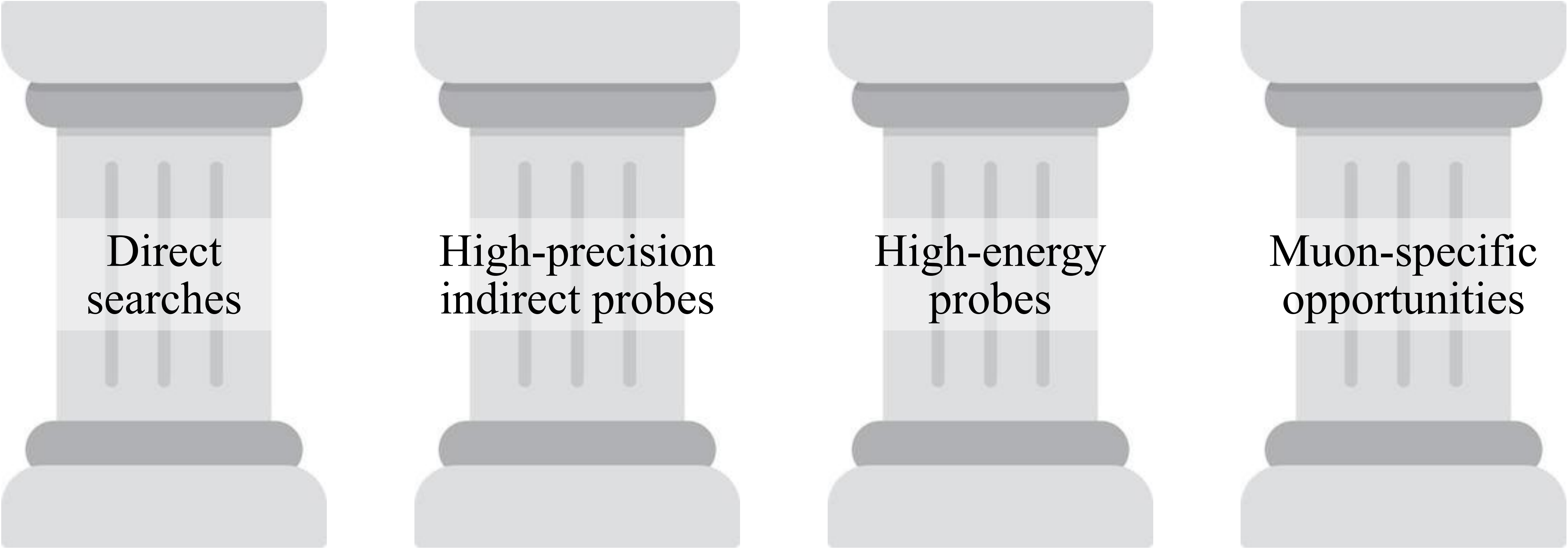
- Can measure processes of very high energy
- Collides muons, for the first time



Muon Collider Physics Pillars

More than a review, what follows is a ToDo list.
Based on work of the (very) few past years.
Read more here:

Muon Collider Physics Summary
The physics case of a 3 TeV muon collider stage
Muon Collider Forum Report
Towards a muon collider (to appear)



Direct searches

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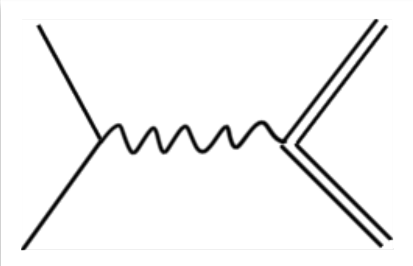
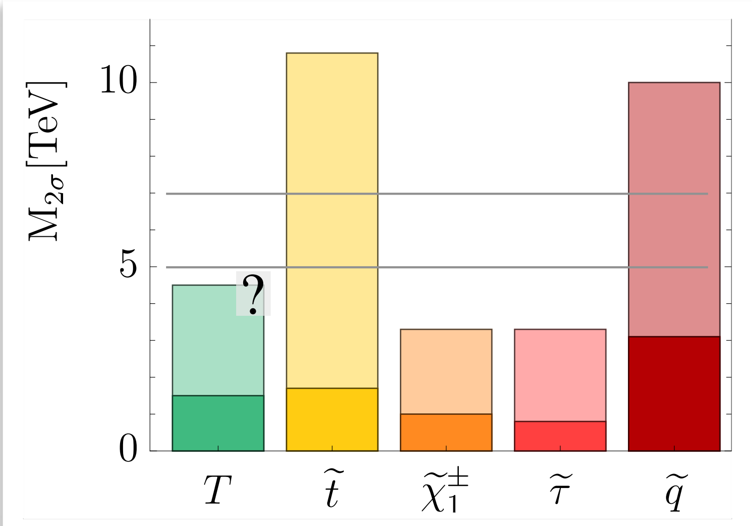
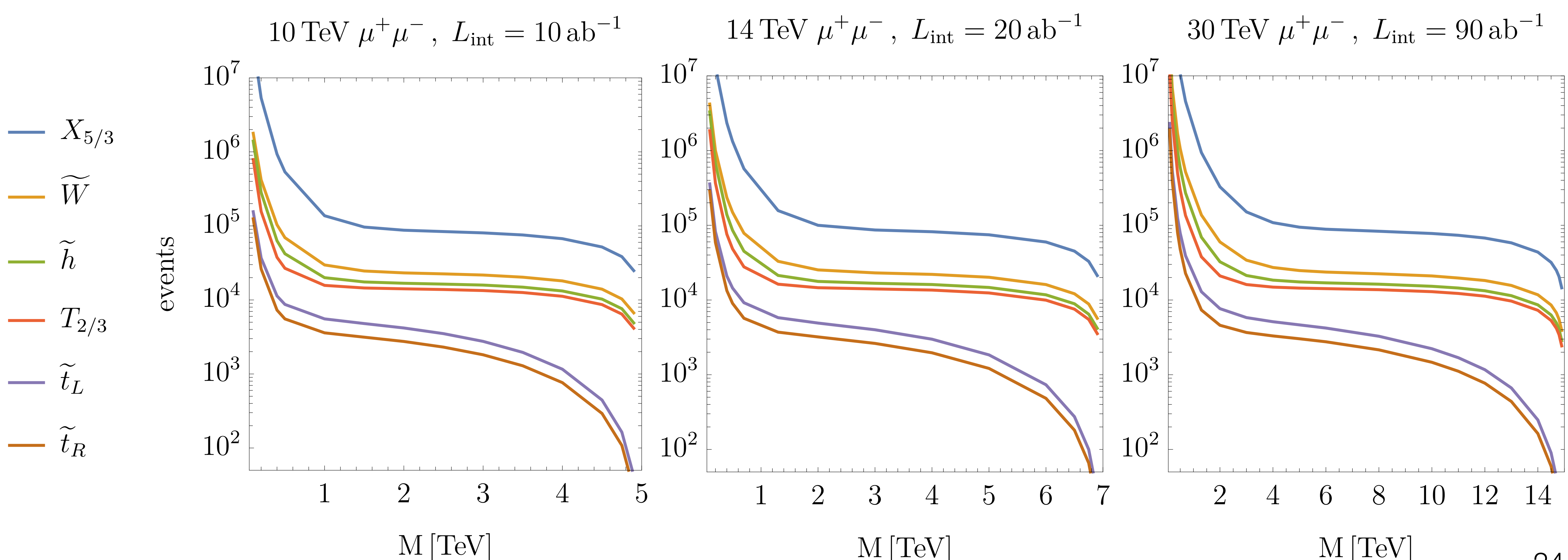


μμ annihilation: copious production of **EW-charged particles** up to $E_{cm}/2$



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



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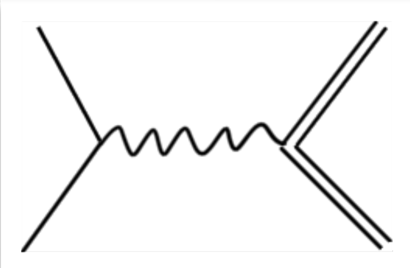

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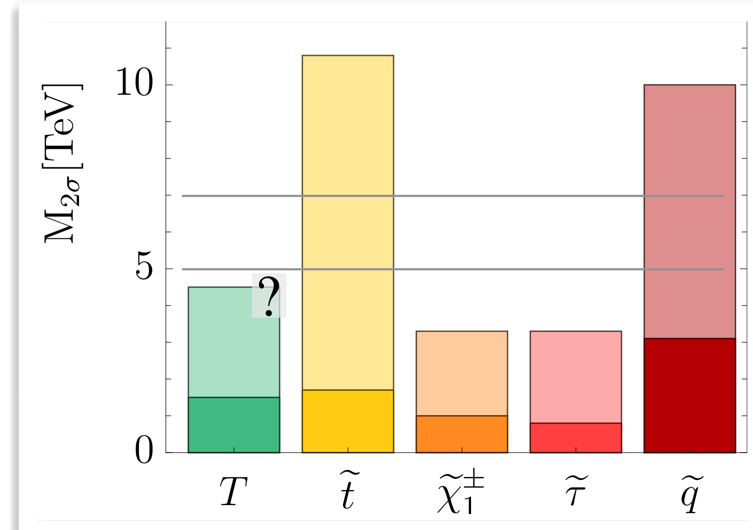

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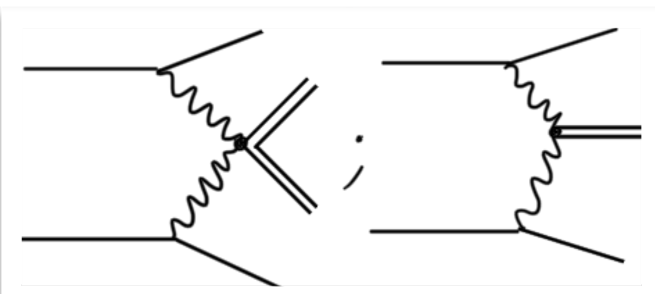
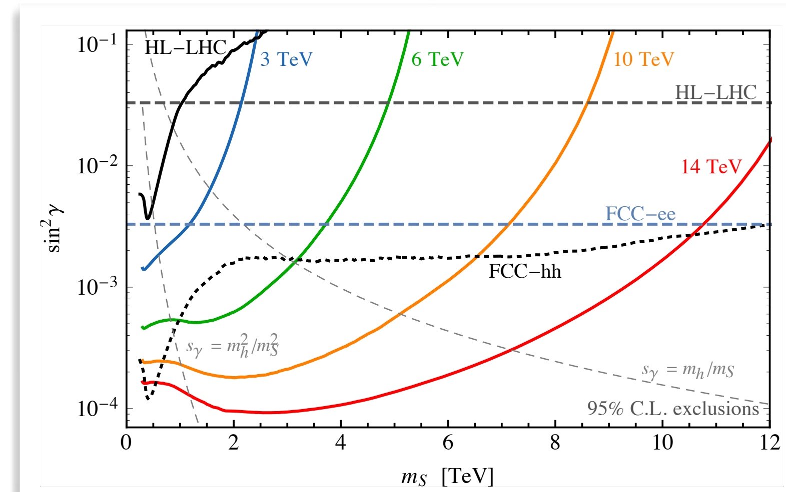
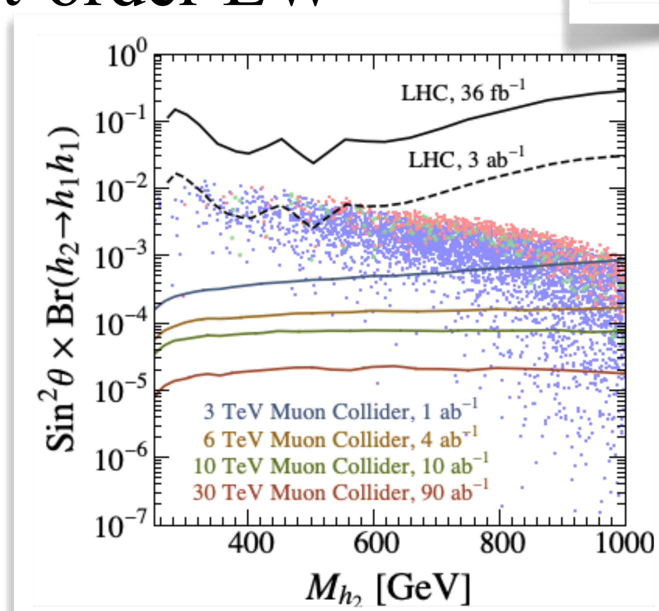


Vector Bosons Fusion: sensitive to EW-neutral **Higgs-Portal** particles

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



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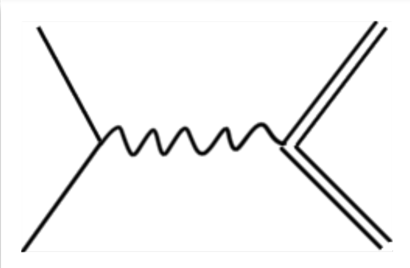

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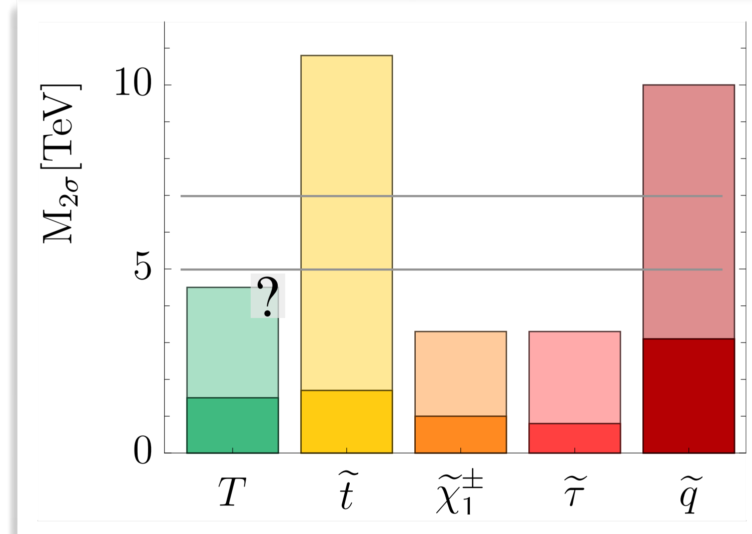

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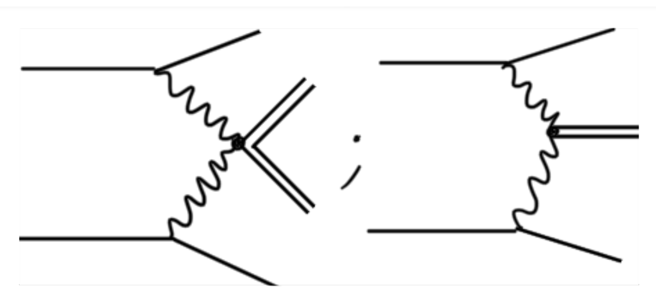

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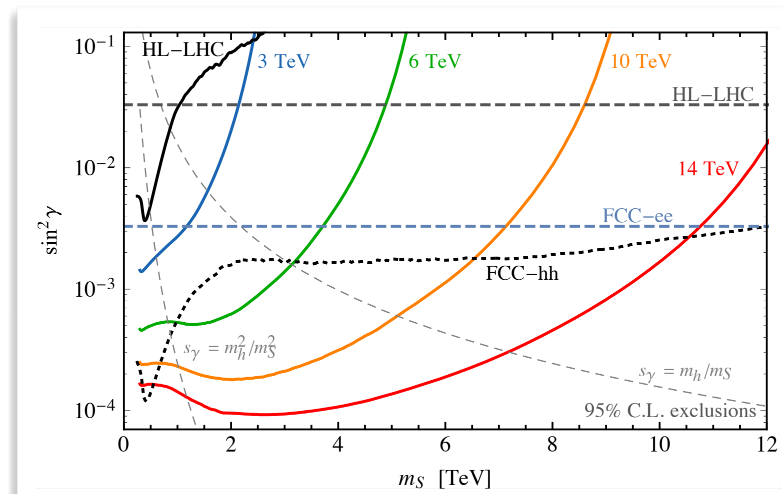

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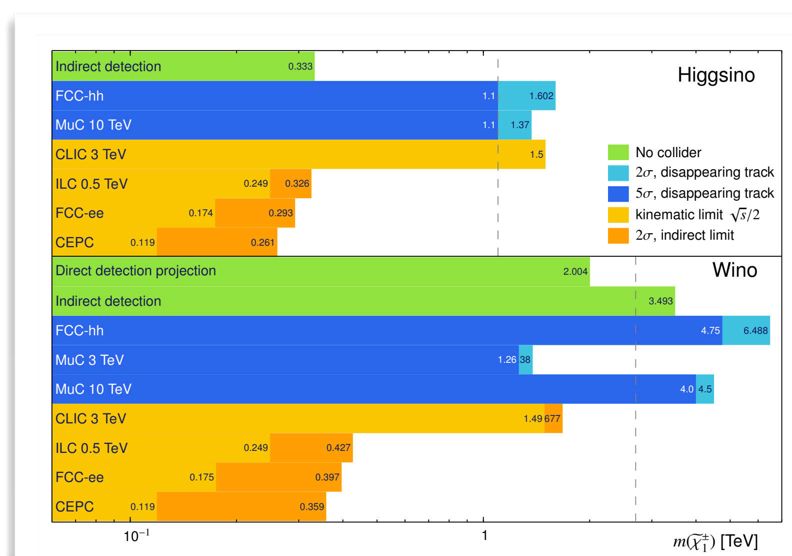
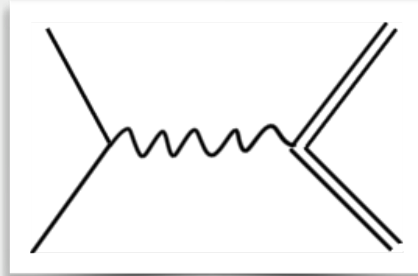
One target is **WIMP Dark Matter**, to be probed:

- in mono-X searches
- by disappearing tracks
- indirectly! (also above coll. threshold)





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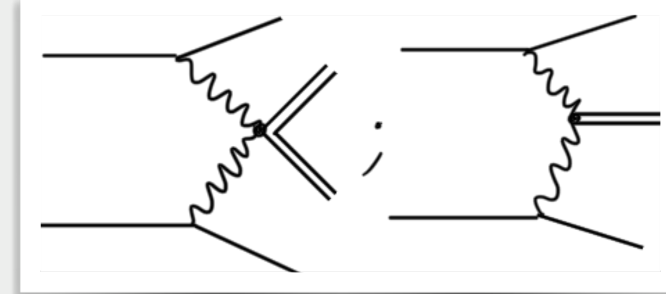
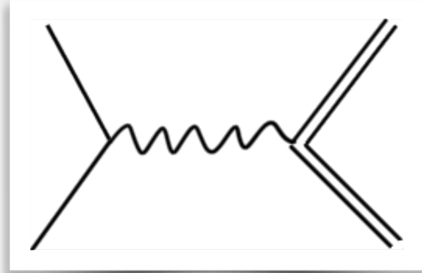


Much work is needed!:

Concrete **BSM** scenarios and **models** feature many particles, and many signatures. Detailed study will enable:

- Comparative assessment of different Direct strategies and their complementarity, as well as Direct vs Indirect
- Study muon collider discovery and characterisation perspectives
- Sound comparison with FCC: not signature- but model-based



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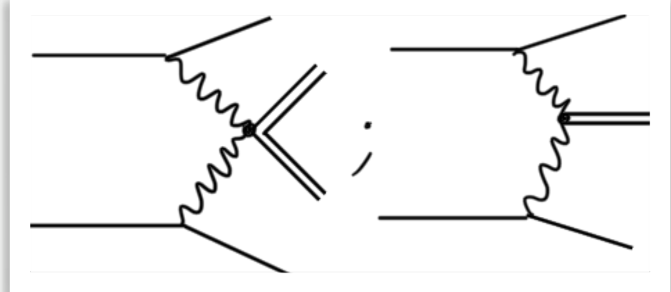

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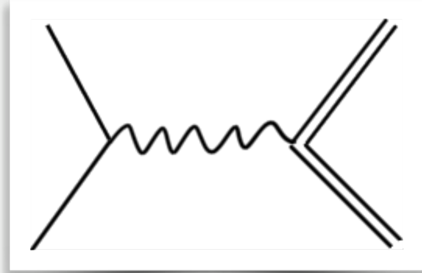
Comprehensive and **realistic** signature survey, fertile ground for studies like:

- Boosted hadronic objects, studied for FCC-hh as well, but our problem is not QCD
- 10TeV MuC detector specification requirement



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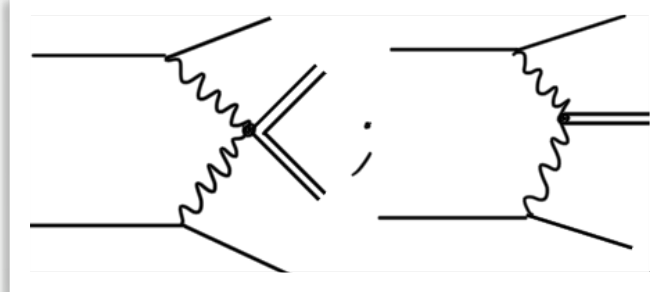

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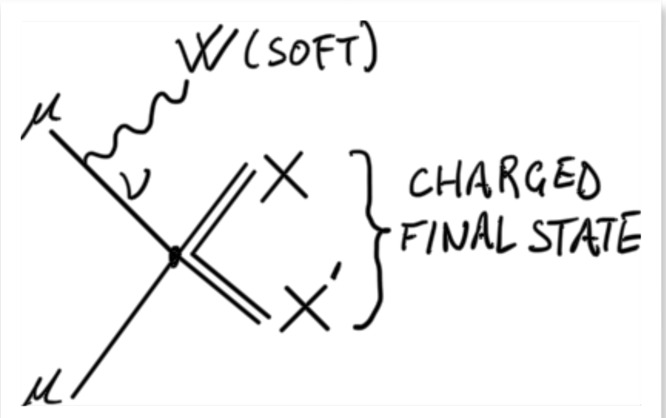
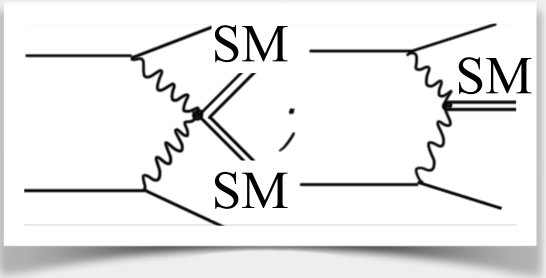
Simulations/predictions challenges:

- Problematic Monte Carlo convergence in VBS/VBF
- Order-one **EW radiation effects**. Leading to novel signatures!
- Relevance and implementation of EW showering



High-precision indirect probes



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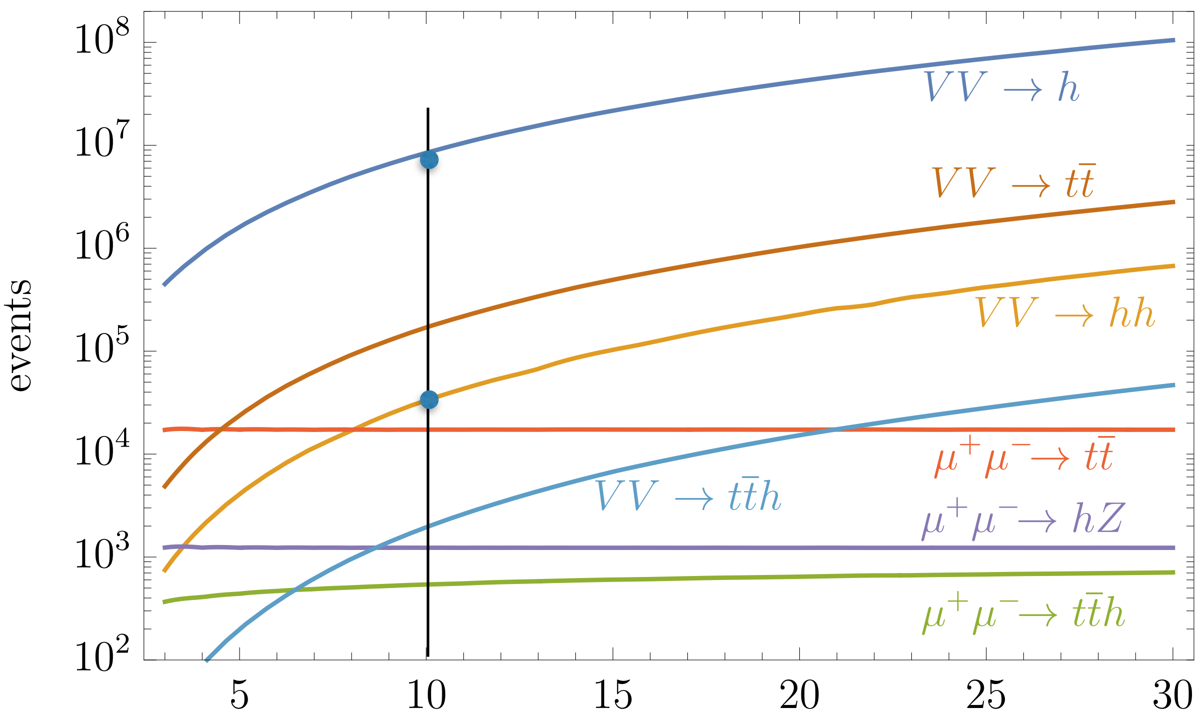
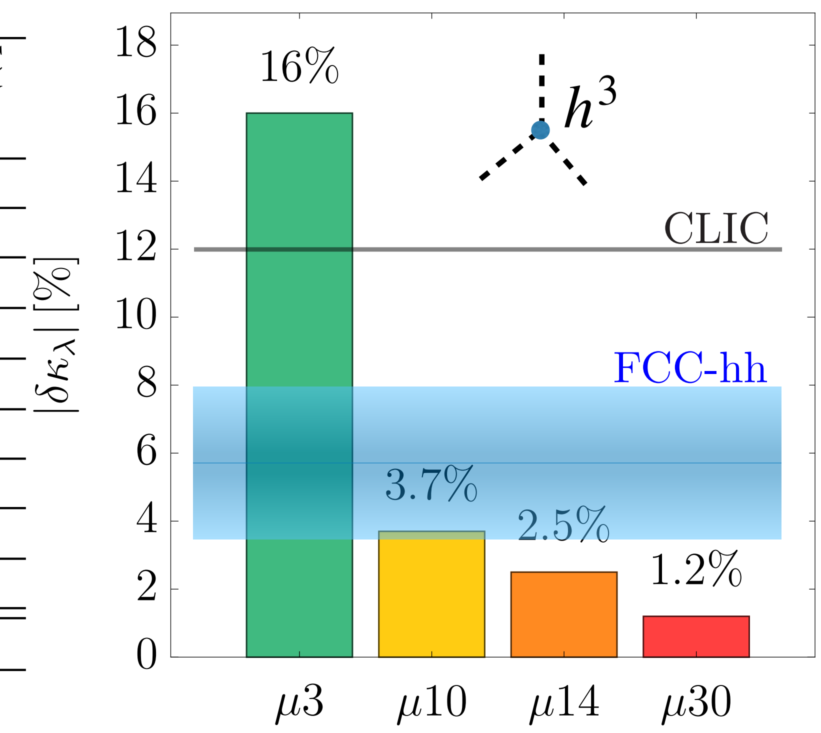
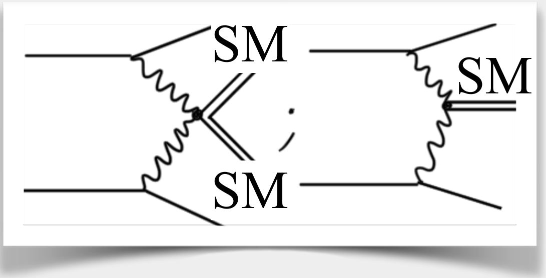


	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV $+\,ee$
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider





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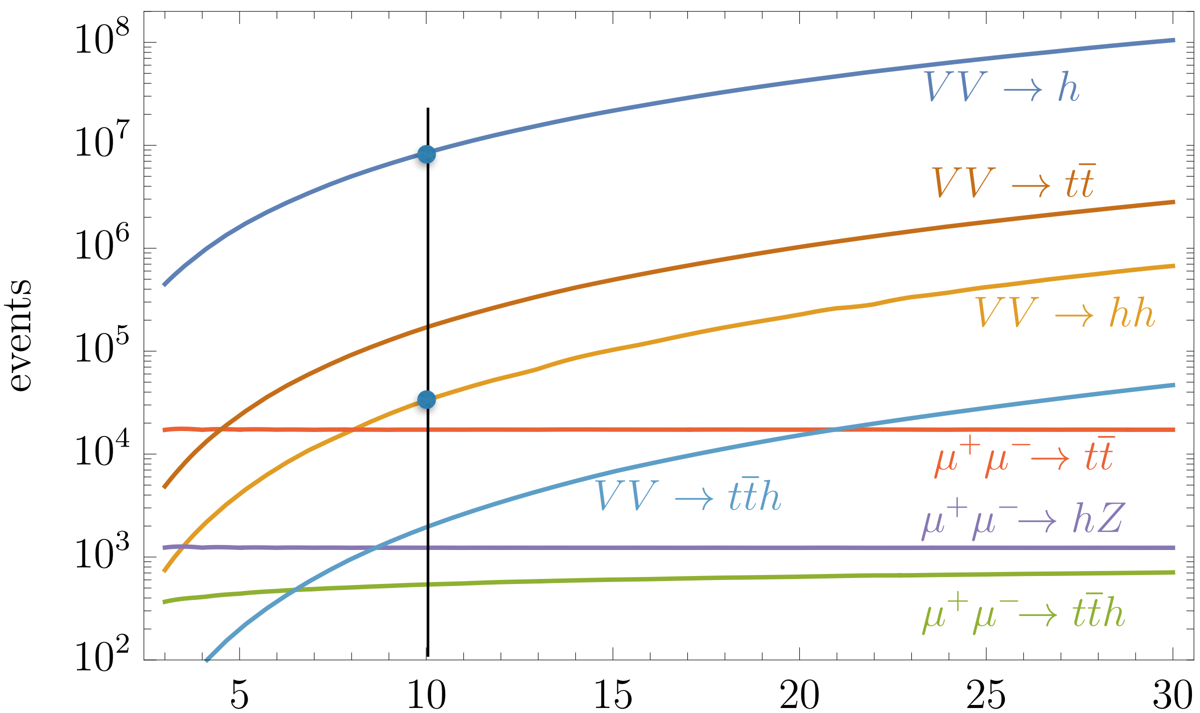
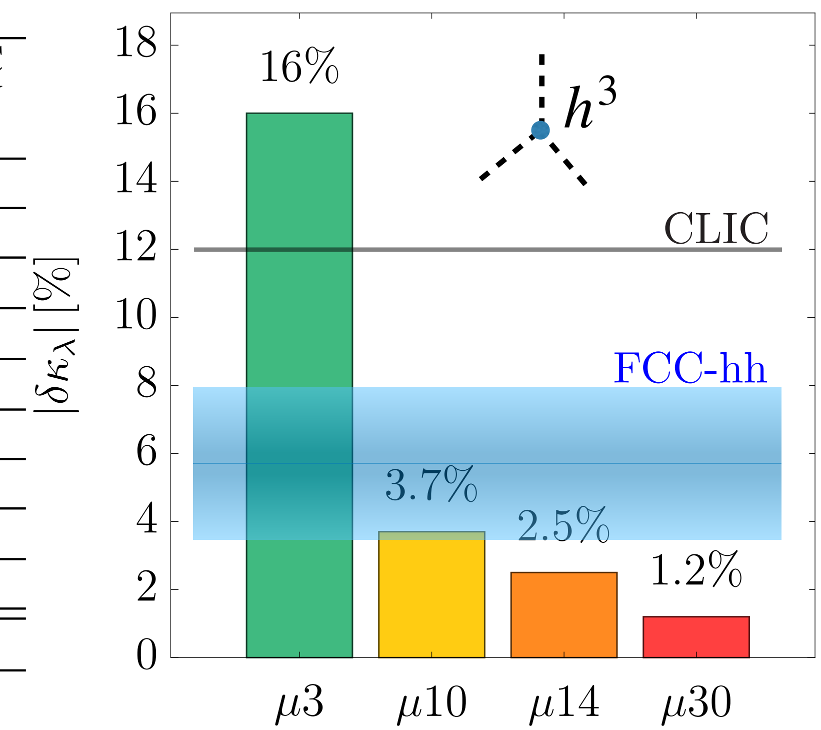


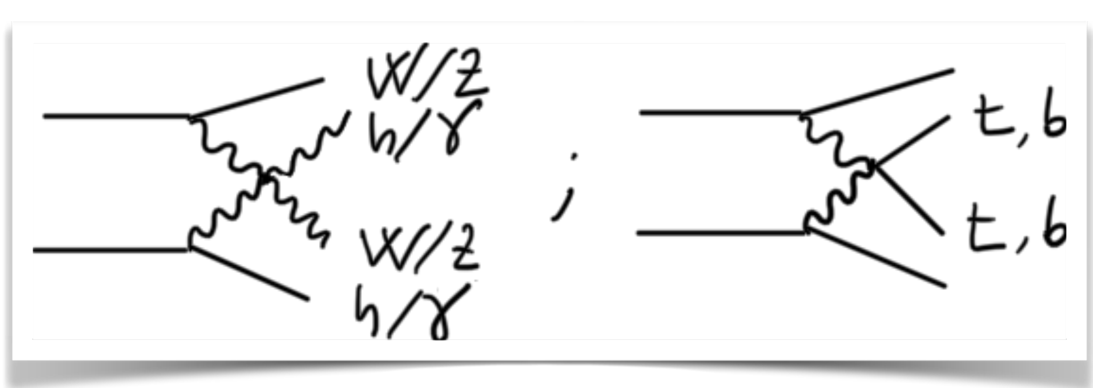
	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

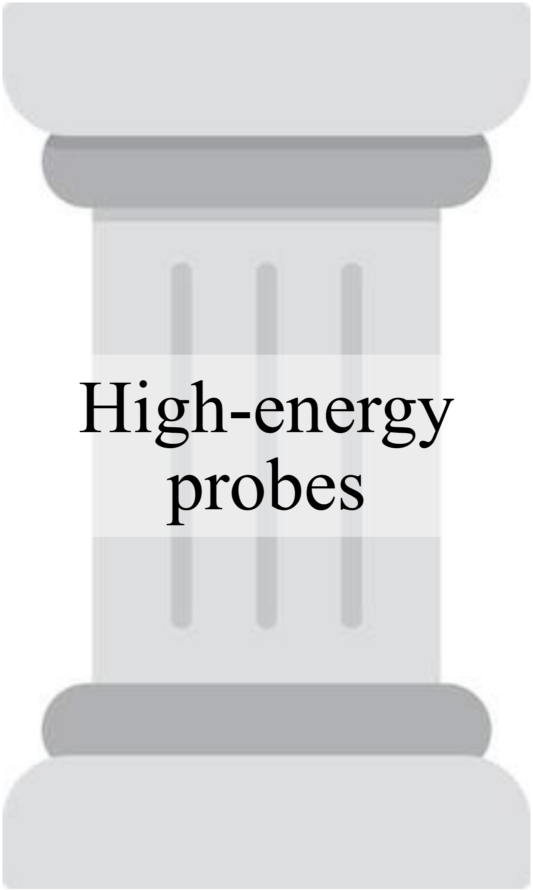


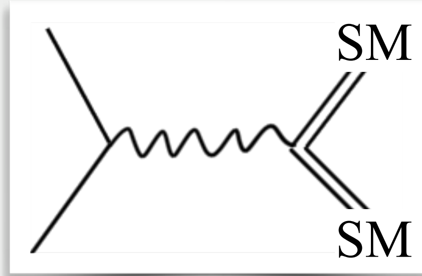
Precision To-Do List:

- Will per-mille class measurements for Higgs physics be possible?
- And per-mille level predictions?
- Furthermore, Higgs couplings is one over many ways to probe the SM EFT. Vector Boson Scattering defines a rich set of processes, much desired at LHC but challenging because of QCD. MuC will do much better and at higher energy.



High-energy probes





High-energy probes

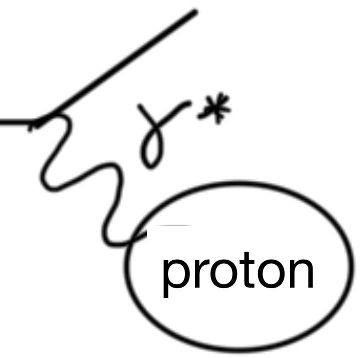
As simple as this:

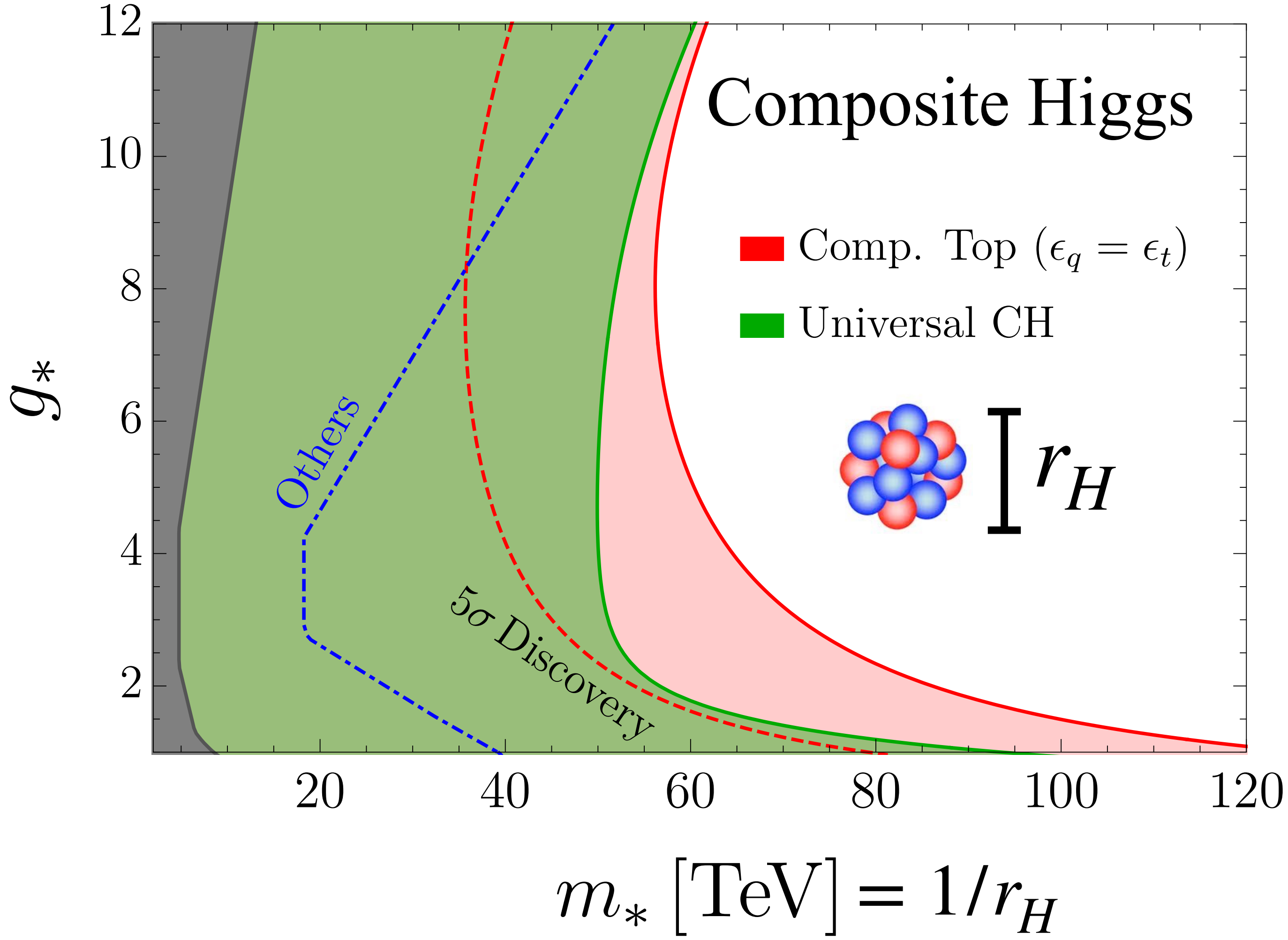
$$\frac{\Delta\sigma(E)}{\sigma_{\rm SM}(E)} \propto \frac{E^2}{\Lambda_{\rm BSM}^2} \overset{[\text{say, } \Lambda_{\rm BSM} = 100\ \text{TeV}]}{=}$$

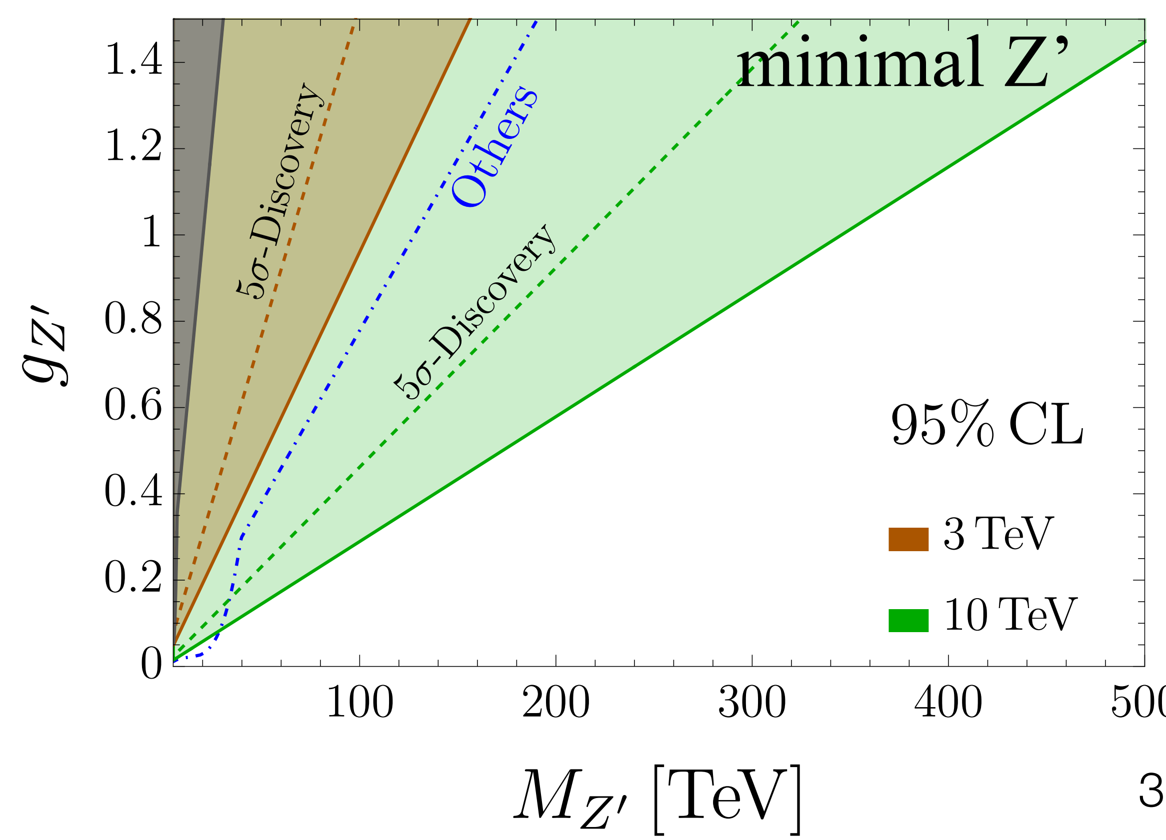
- **10^{-6}** at EW [FCC-ee] energies
- **10^{-2}** at **muon collider** energies

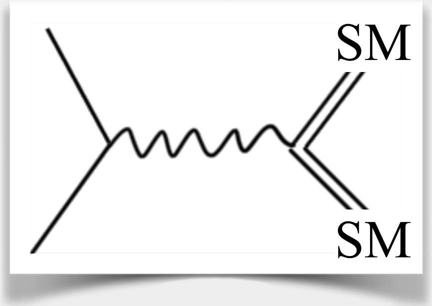
Or even simpler:

Proton compositeness could be discovered only by probing it with $E \lesssim 1/r_p \sim \Lambda_{\rm QCD}$









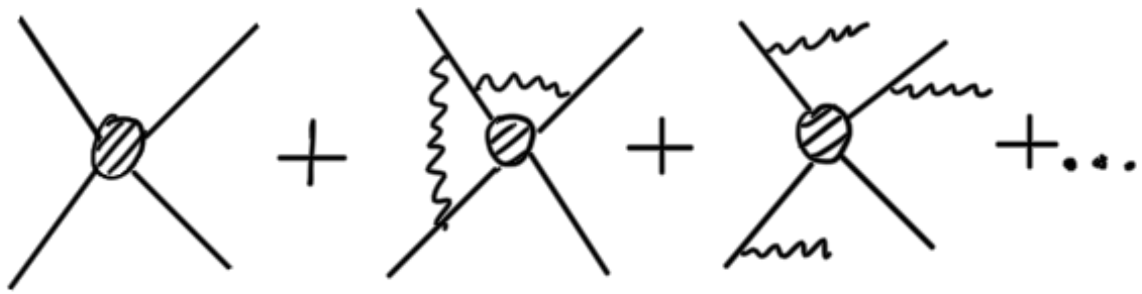
High-energy probes

EW radiation poses a major challenge to theoretical predictions:

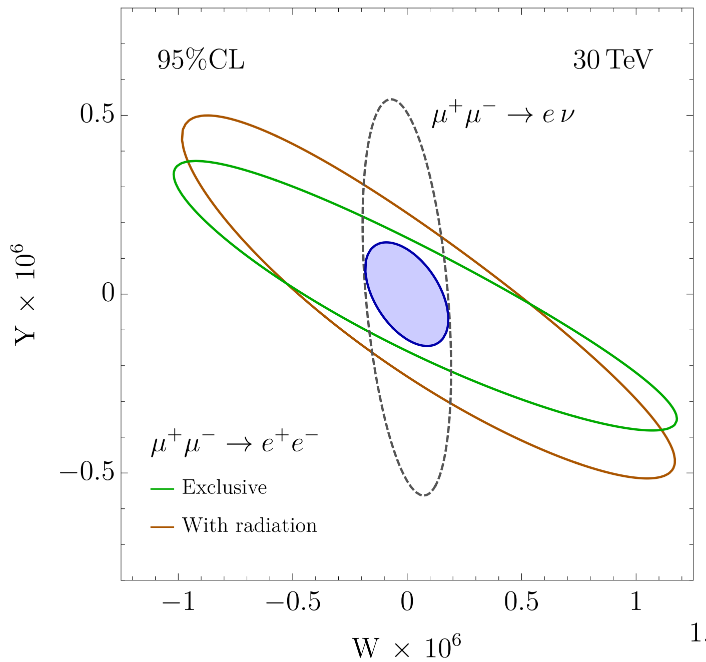
Order-one effects: need **resummation**.

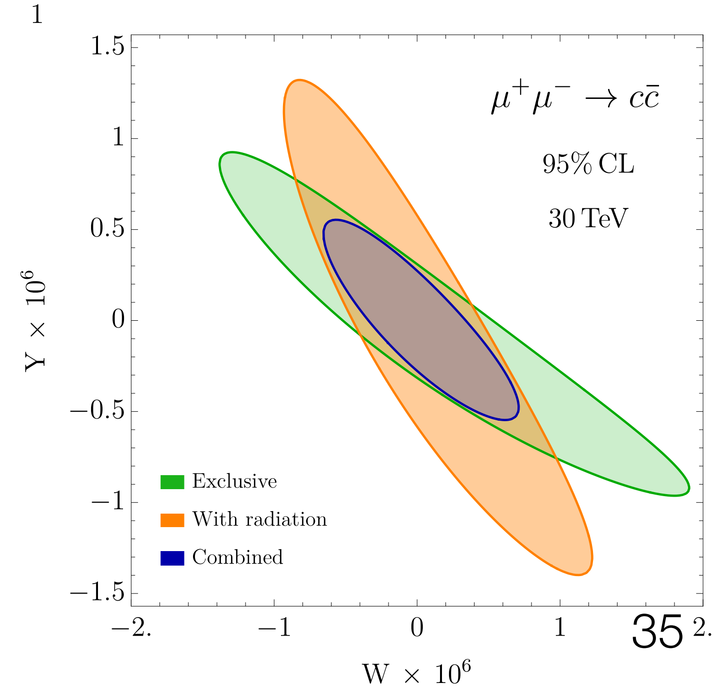
Unavoidable: no "safe" observables unlike QCD/QED.

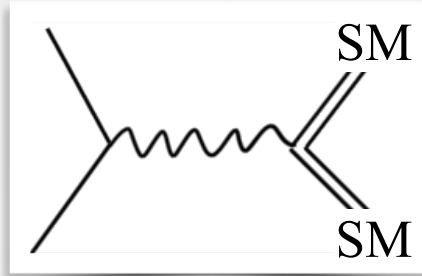
Helpful: real emission pattern brings information on new physics!



	DL	$e^{\mathrm{DL}}-1$	$\mathrm{SL}(\frac{\pi}{2})$
$\ell_L \to \ell'_L$	-0.82	-0.56	0.33
$\ell_L \to q_L$	-0.78	-0.54	0.34
$\ell_L \to e_R$	-0.56	-0.43	0.17
$\ell_L \to u_R$	-0.48	-0.38	0.15
$\ell_L \to d_R$	-0.43	-0.35	0.13
$\ell_R \to \ell'_L$	-0.56	-0.43	0.17
$\ell_R \to q_L$	-0.53	-0.41	0.16
$\ell_R \to \ell'_R$	-0.30	-0.26	0.09
$\ell_R \to u_R$	-0.22	-0.20	0.07
$\ell_R \to d_R$	-0.17	-0.16	0.05







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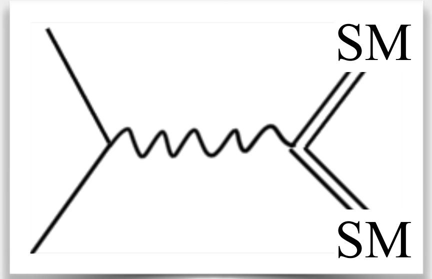
- Soft-Collinear Effective Theory (SCET) promising tool.
- Interplay with EW PDF, and with principled approach to EW showering



High-energy probes

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Challenge for phenomenology as well:

- How real radiation impacts booted objects tagging/reconstruction?
- VB recombination? EW jets? …?

Muon-specific opportunities

Muon-specific opportunities

Strong focus so far on B and g-2 anomalies:

Both related with muons

MuC is (obviously) a superior device for assessing their origin.

But the point here is anomaly-independent:

New physics can hide in muons, because we never checked!

This is why B and g-2 anomalies can be explained by still untested models

Muons more strongly coupled than electrons to EWSB

To be re-considered when anomaly status settles

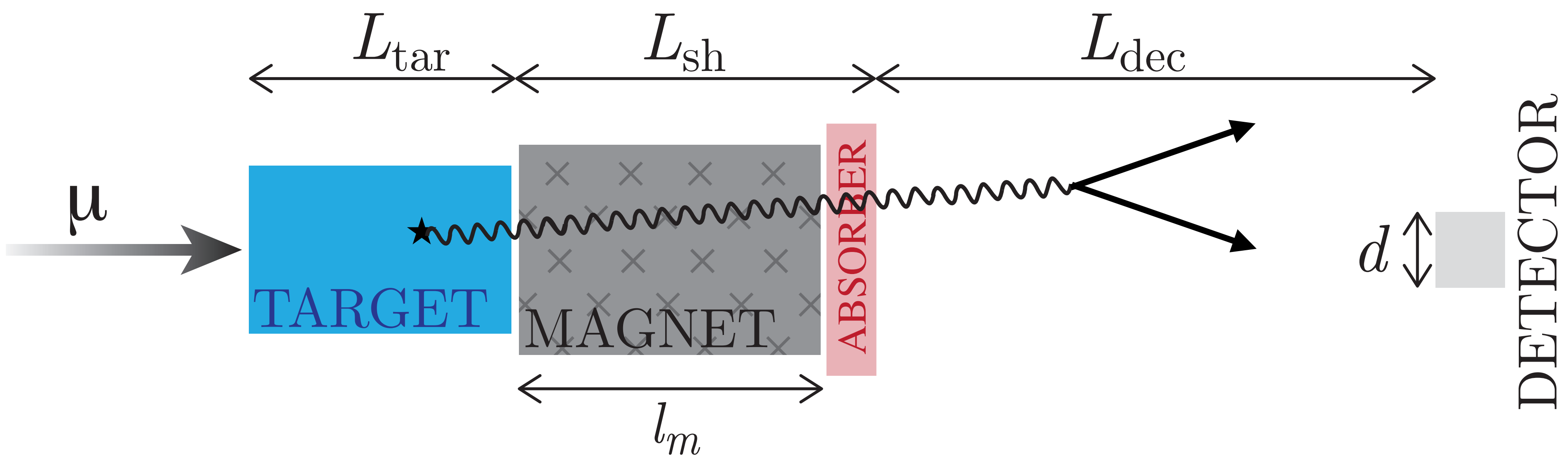
Lattice results and g-2 ongoing work

LHCb recently “restored” LFU

More To-Do List items

Muon beam dump?:

Spent muons could be sent to target-magnet-detector searching for decaying Dark-Photon or similar signatures.



The high-energy neutrinos physics case:

Collimated precisely-known neutrino beam.

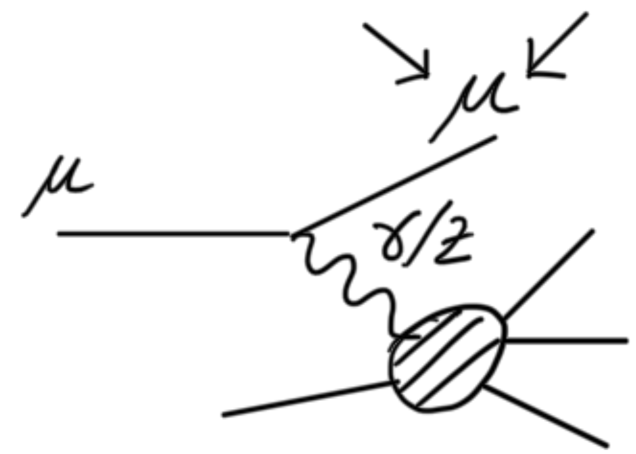
Neutrino cross-section measurements and FASERν-like physics

More To-Do List items

A forward muon detector:

Fraction-of-degree muons from VBF or VBS.
Tagging the occurrence of neutral VBF(S)
possible only at the MuC.

Implications for BSM VV to DM, Higgs physics,
plus expectedly for all precision studies in VBF(S).



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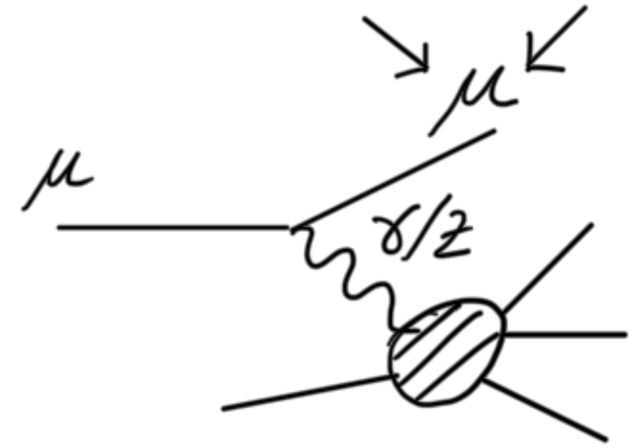
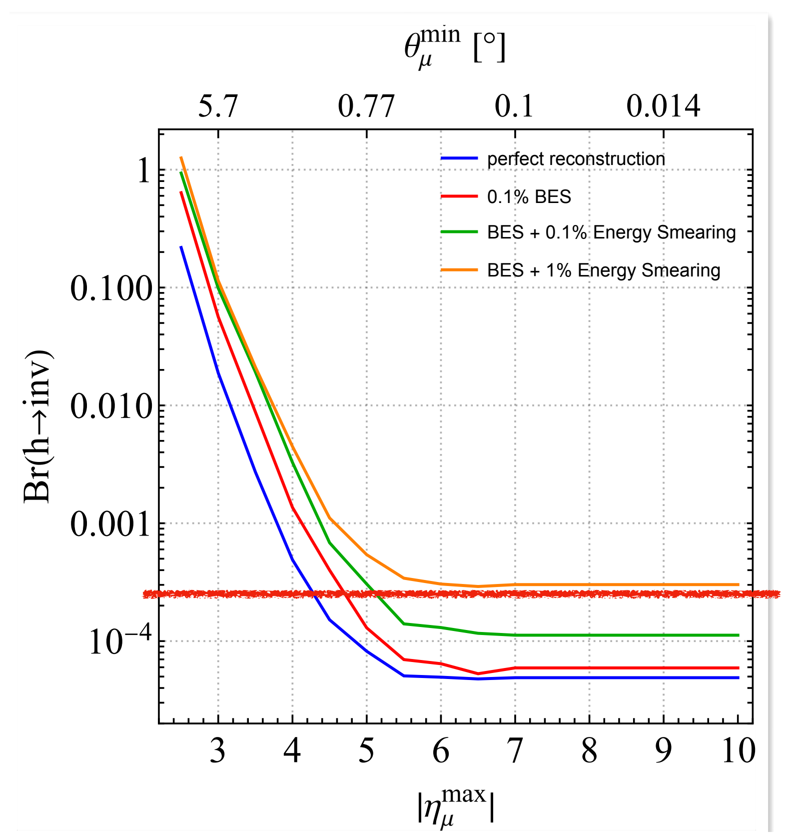


Implications for BSM VV to DM, Higgs physics, plus expectedly for all precision studies in VBF(S).

Muon momentum measurement would further help.
Assessing required precision.

- Sensitivity to BR($h \to$ inv) with all effects combined



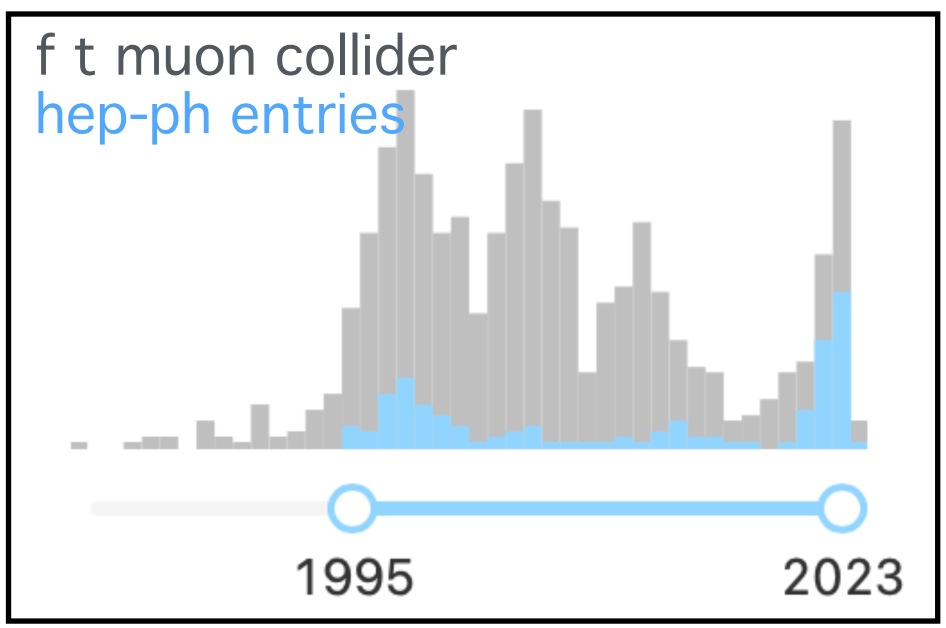
1. Perfect 4-momentum reconstruction
2. 0.1% BES
3. 0.1% BES + 0.1% energy uncertaint
4. 0.1% BES + 1% energy uncertainty

FCC-hh projection: $2.5 \cdot 10^{-4}$

Muon Collider Plans

New interest on MuC has 2 reasons:

Well-perceived need for perspective of big jump ahead in energy (F.C. studies).
Realised that MuC offers such perspective.
Challenges to energy extension of ee and pp colliders make innovation urgent.



"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar or better 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 snowmass21 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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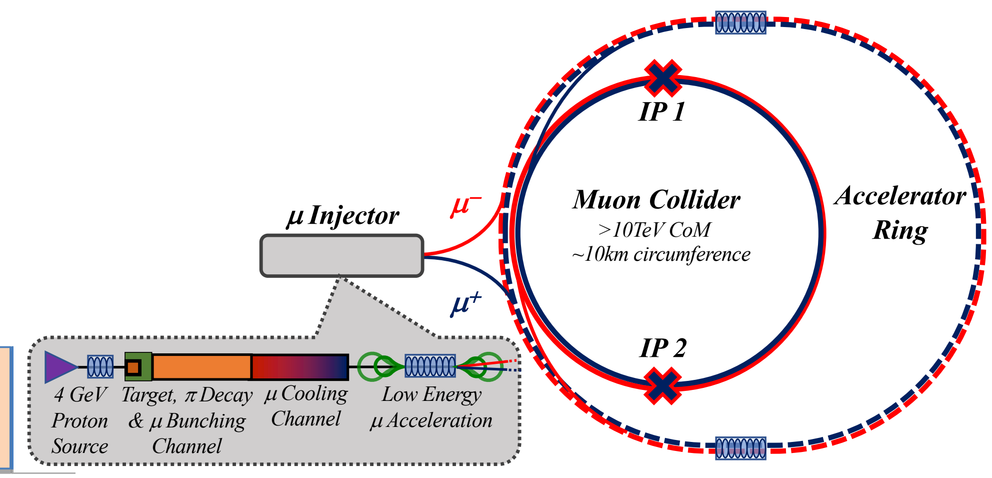
MuC design and technology advances during and after MAP.
E.g., MICE demonstrated cooling; MUCOOL demonstrated RF in high B-field;
30 T magnets for final cooling demonstrated.

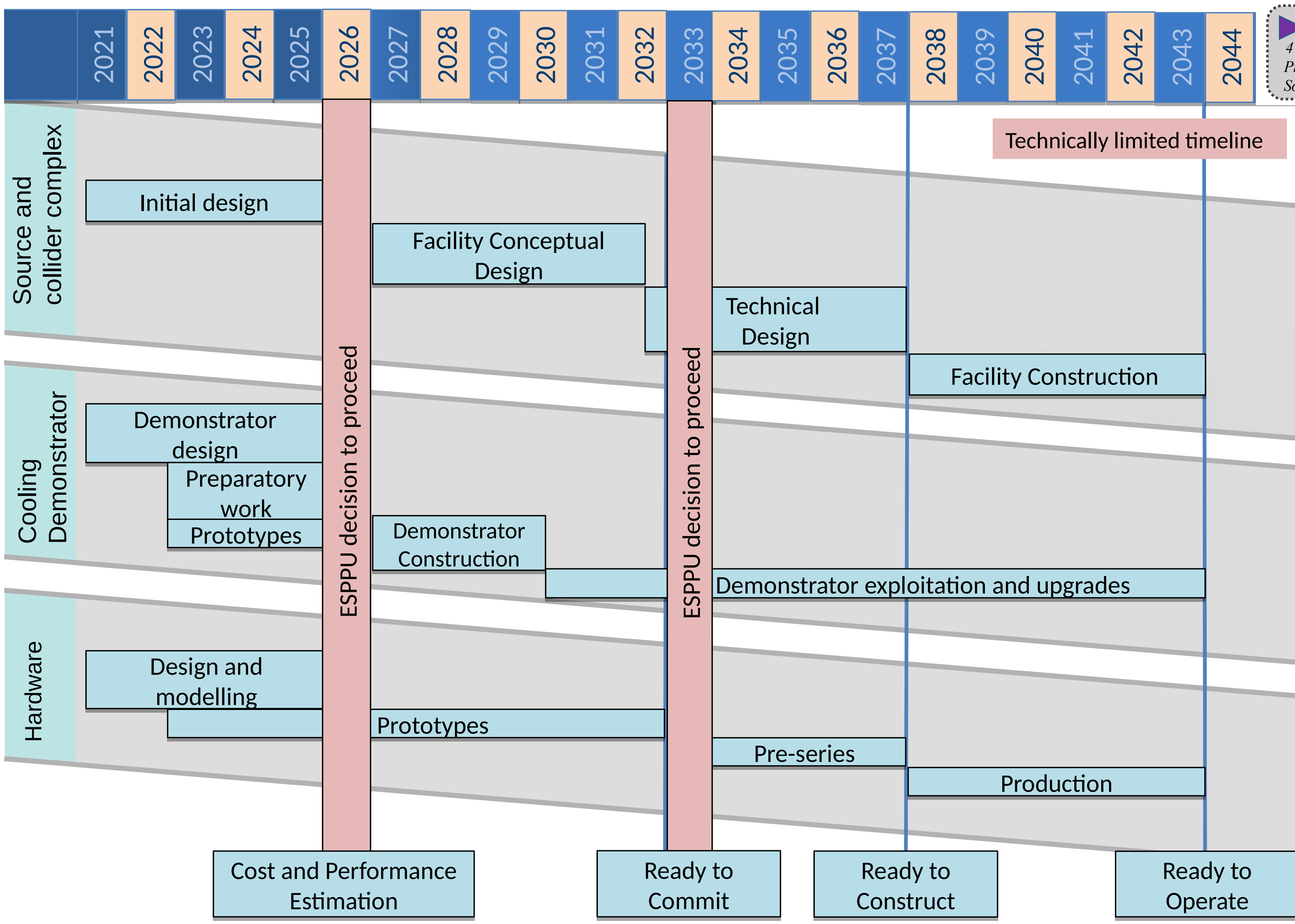
MuC now part of European Roadmap for Accelerator R&D.
No showstopper identified. **Timeline** for R&D being implemented by IMCC

Muon Collider Plans

Technically limited timeline:

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



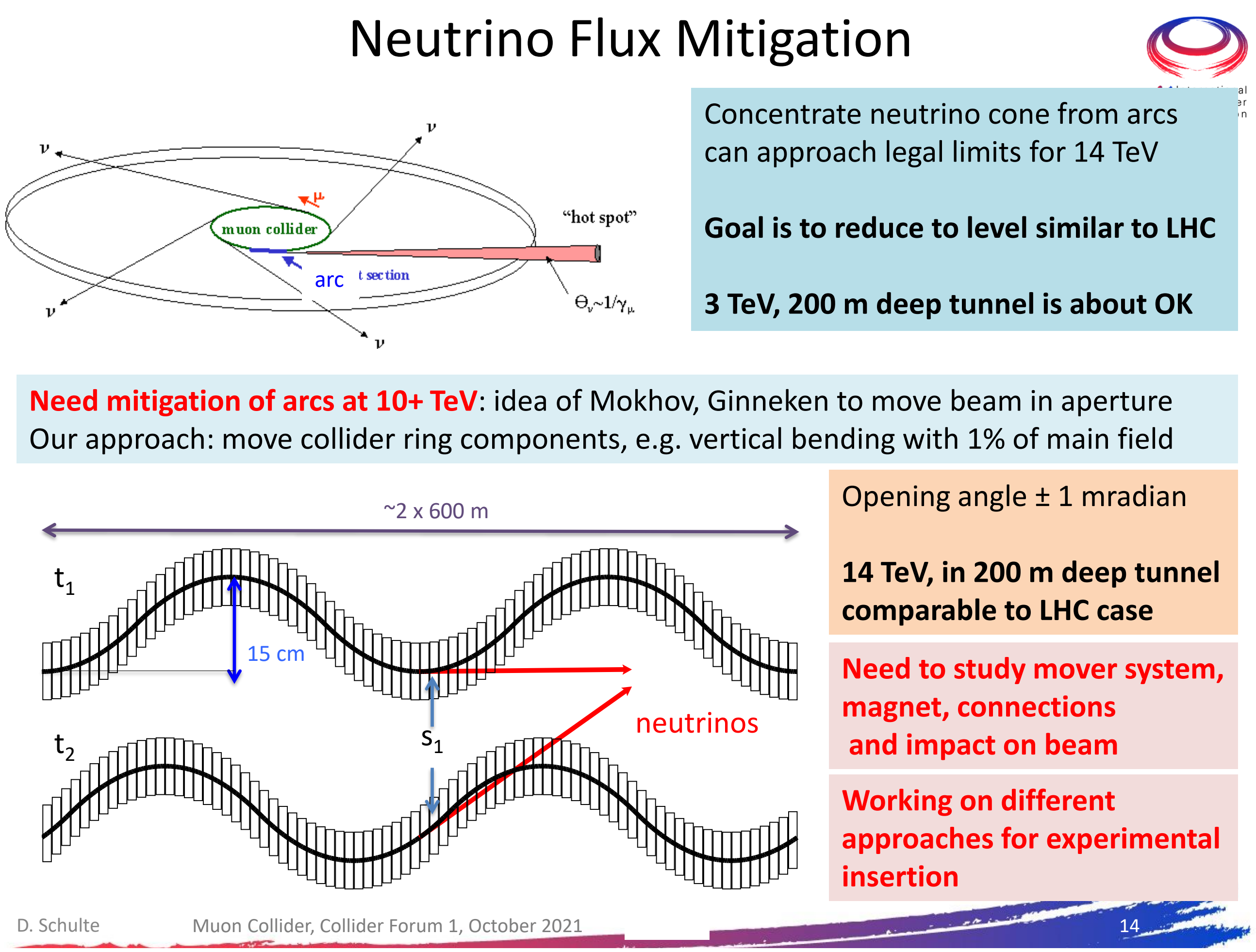


International MUON Collider Collaboration

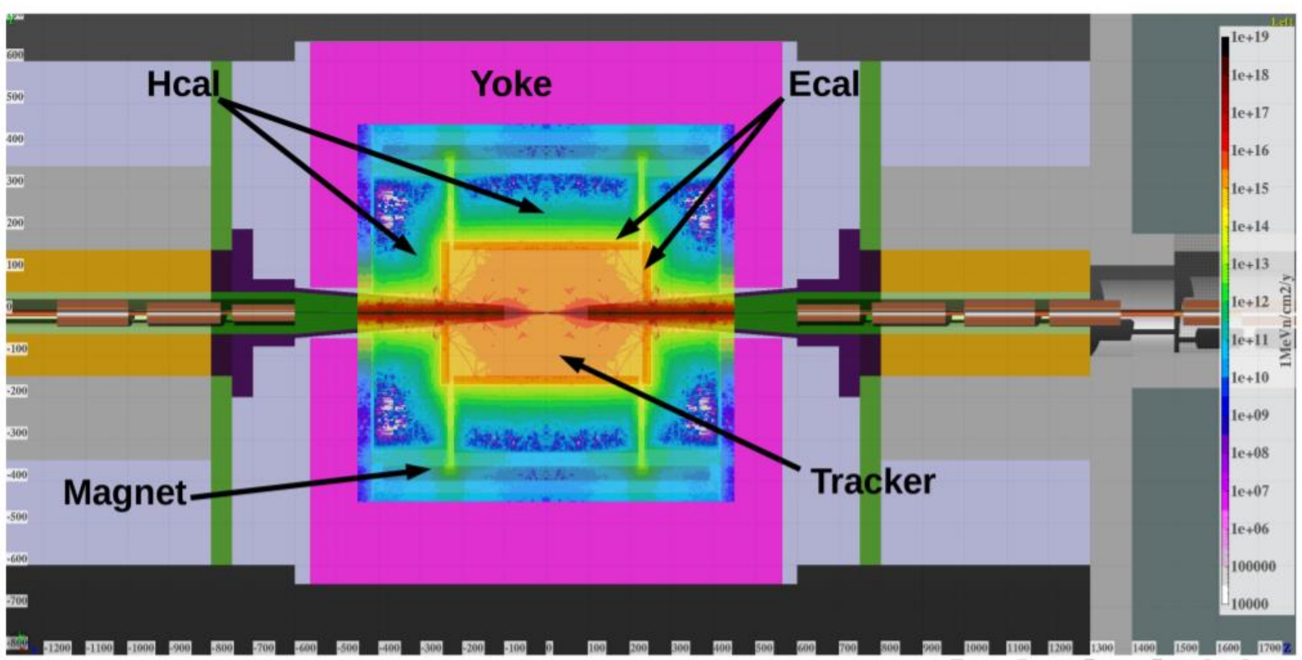
Muon Collider Plans

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



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



FLUKA @ 1.5 TeV

Conclusions

MuC could be best option for continuation of the HEP journey

R&D has initiated. Design consolidation will be soon completed.

Why working on muon collider physics?

It is **Important:** 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 will **advance particle physics today**, on top of paving the way toward a muon collider further in the future.

Conclusions

The Very High Energy Muon Collider is a Dream

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And, often, Dreams DO become Reality!

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Thank You !