Towards a Muon Collider

Andrea Wulzer

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Institut de Física
d'Altes Energies

For extensive overview, see the **IMCC** **<u>EPJC Report</u>**

Towards a Muon Collider

… and updates in the **IMCC** **<u>Interim Report</u>**

… and the Strategy Report **<u>The Muon Collider</u>**

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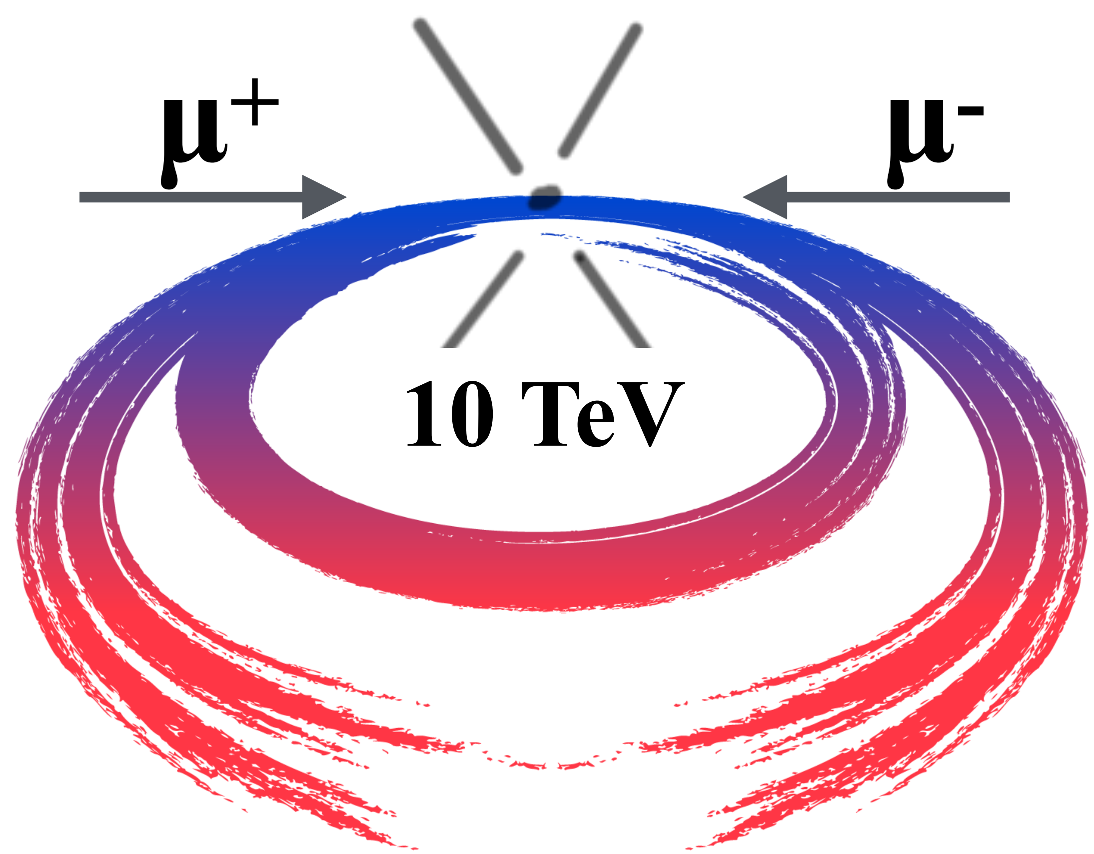


What is Particle Physics?

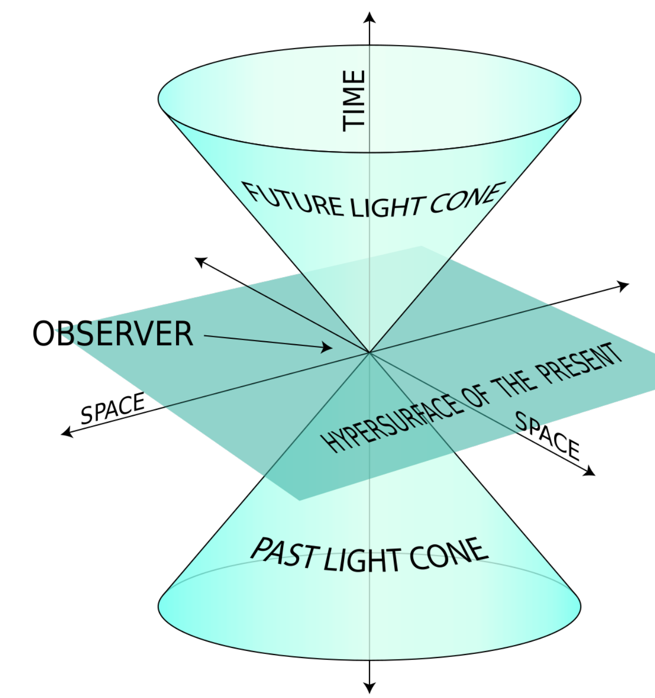
What's **inside?**

It is the quest for the most **simple**, **universal** laws that rule the occurrence of **any Natural phenomenon**

i.e., for the smallest building blocks (**particles**) and their mutual influence (**forces**)

We now understand **forces** as quantum exchange of **particles**. The two concepts are unified, and described by **fields**.

The BIG achievements of Particle Physics



We discovered a satisfactory notion of **causality**
From Special Relativity

Understood that **particles do not have a position:**
Detectors have $\longrightarrow$ **Field** Observables $\mathcal{O}(t, \vec{x})$

Microcausality Principle and QFT

Incorporates and **supersedes** both QM and SR

The BIG achievements of Particle Physics

We worked out **one single theory** that accounts for (almost) **all phenomena** that ever or will ever occur in the Universe!!

This theory is close to accomplish the Particle Physics dream.

But we are not yet there

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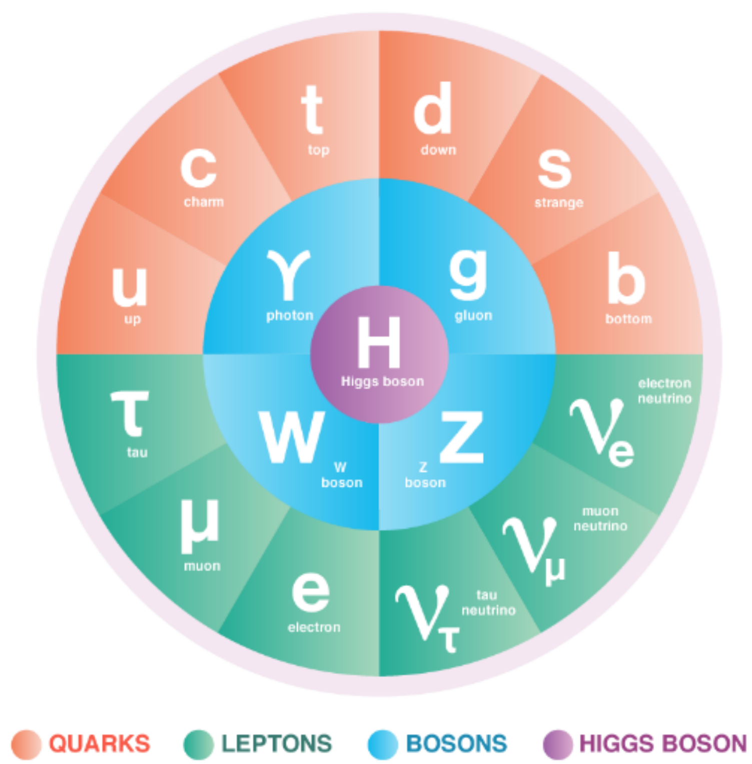
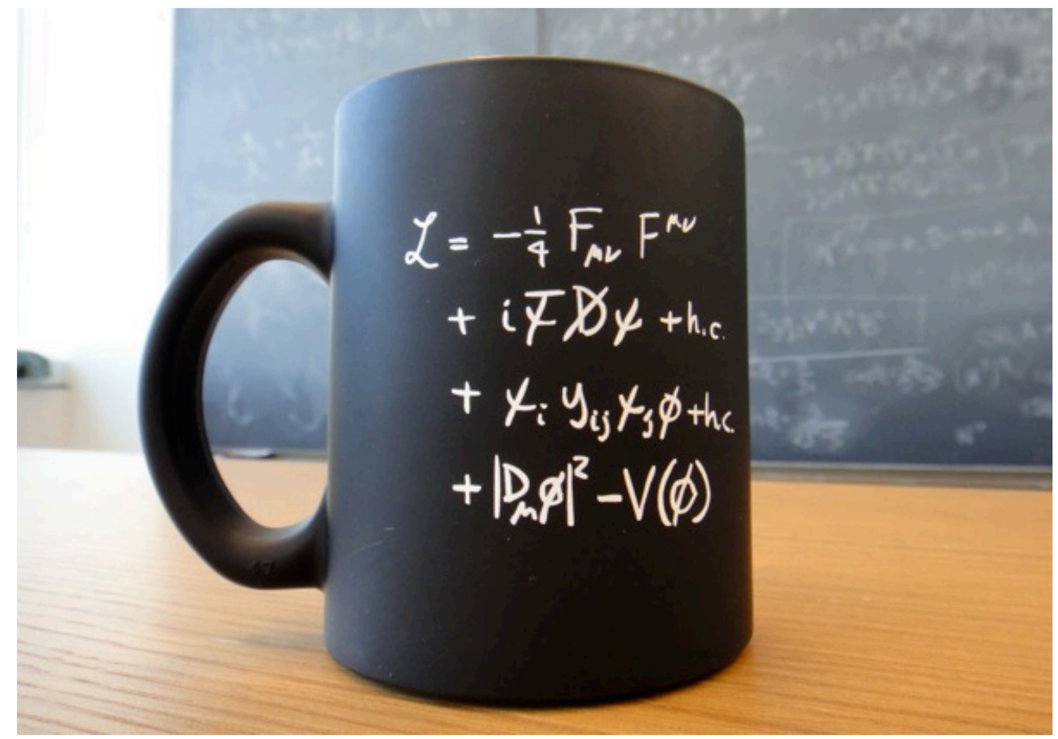


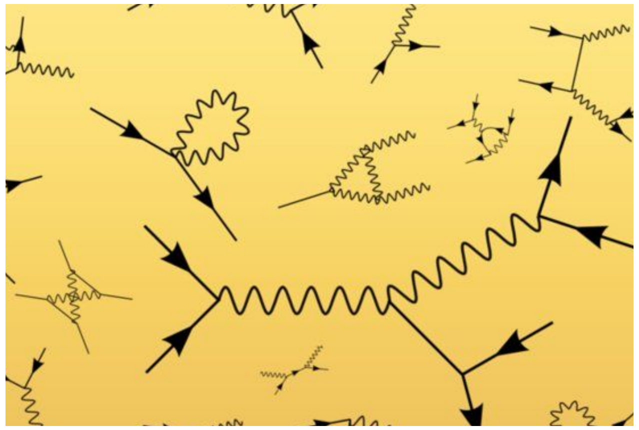


This monumental achievement of mankind is:

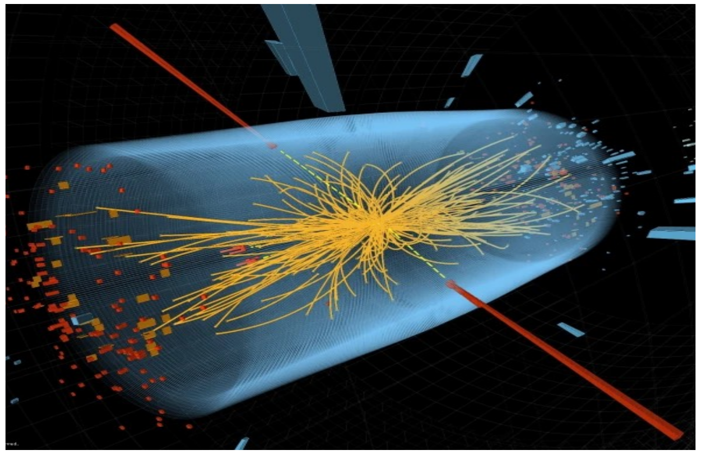
The Standard Model

It would definitely deserve a better name

The Standard Model is not enough

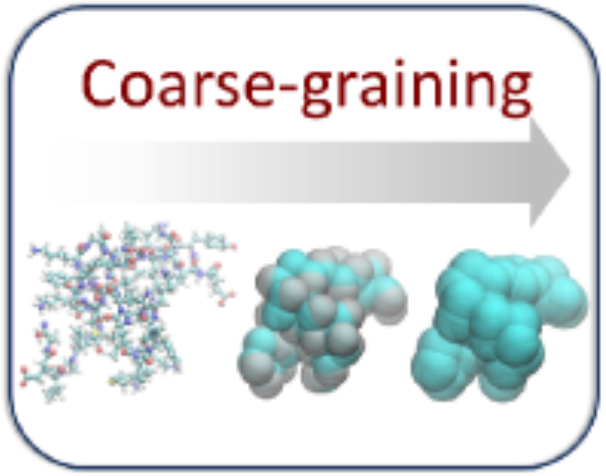


Built by a **practical implementation** of QFT principles
Surely not the final one, as it **fails with Gravity**
A new theory breakthrough is waiting for us



Its particle/field content is merely **dictated by experiments**
New experiments are needed to tell if there are more particles
And we believe there are: for instance dark matter

Creating heavy particle requires energy: $E = m\,c^2$



"Practical QFT" does not explain why only some type of interactions are observed.
The **Wilsonian explanation** is **disproven** if the Higgs boson is a **fundamental particle** as in the SM:

We must check if it truly is fundamental

We need energetic particles

What's **inside?**

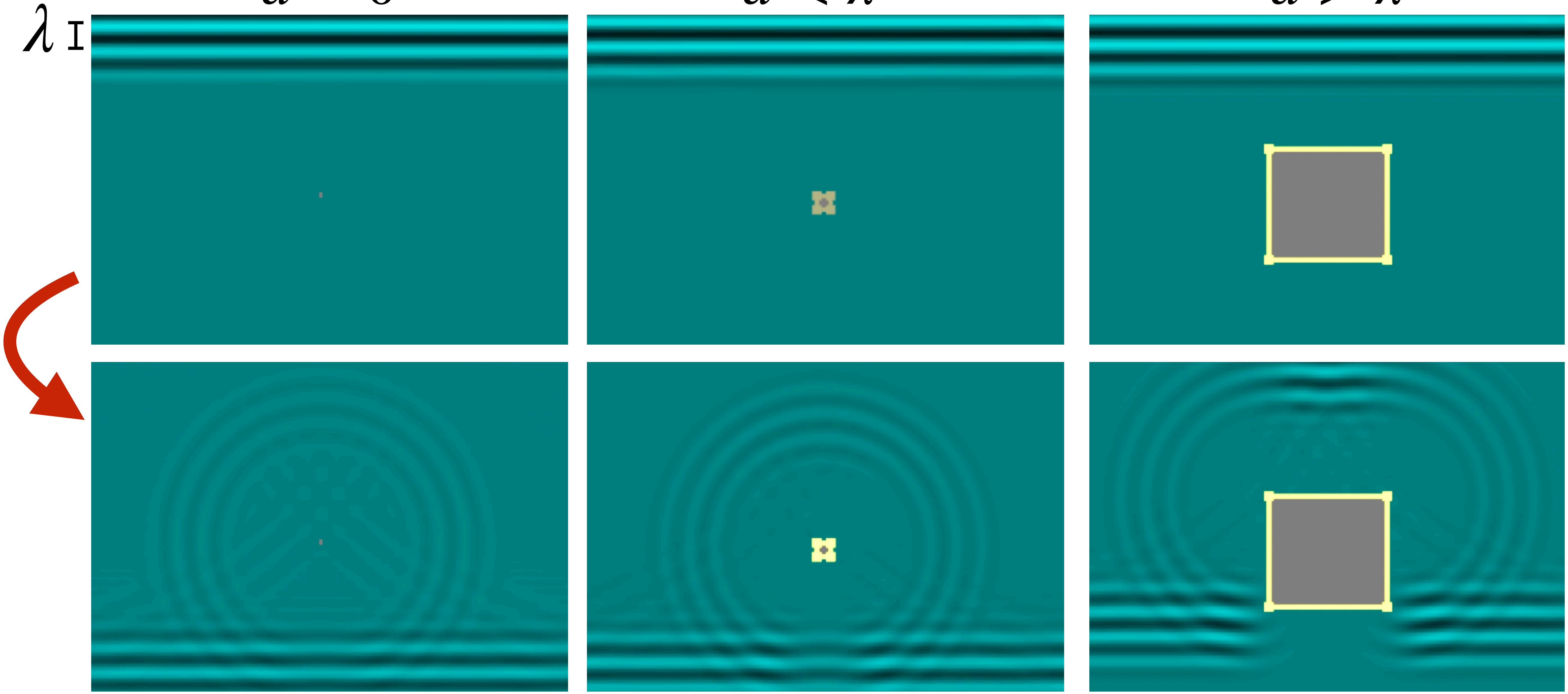
We need large energy in order to probe short distances:

d = the length scale we want to resolve

$\lambda = 1/E$ = the wavelength of the wave we use

Detecting "d" requires: $\lambda < d$

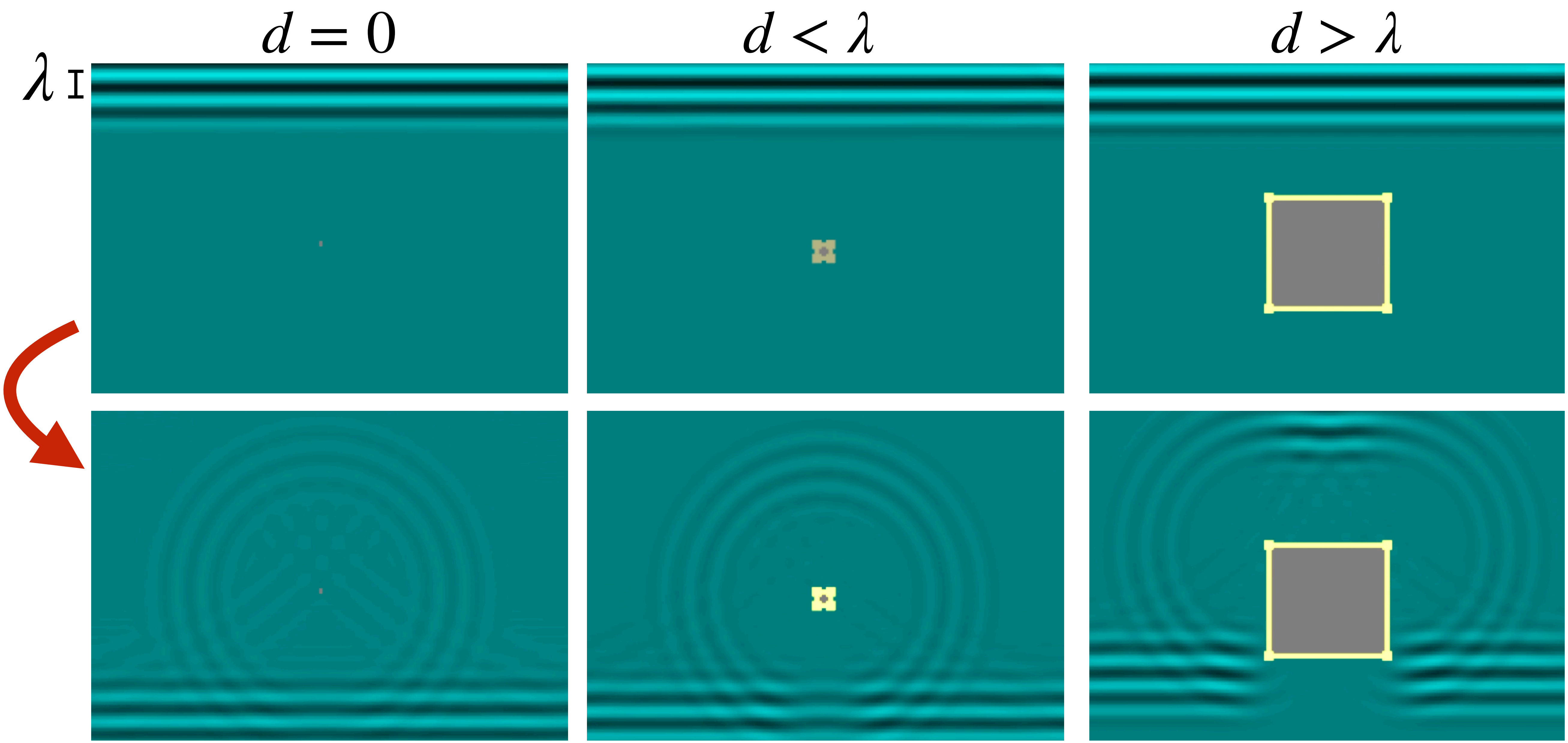
$d = 0$ | $d < \lambda$ | $d > \lambda$



We need energetic particles

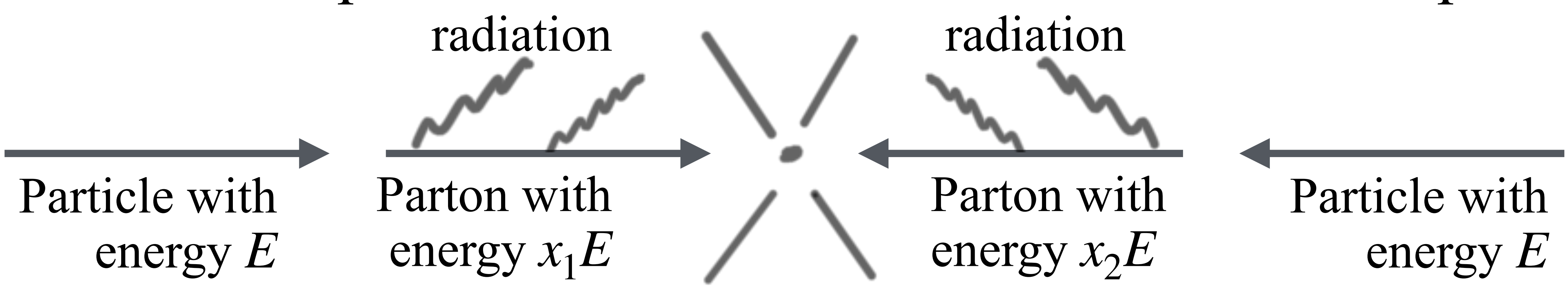
What’s **inside?**

10 TeV is the next energy frontier

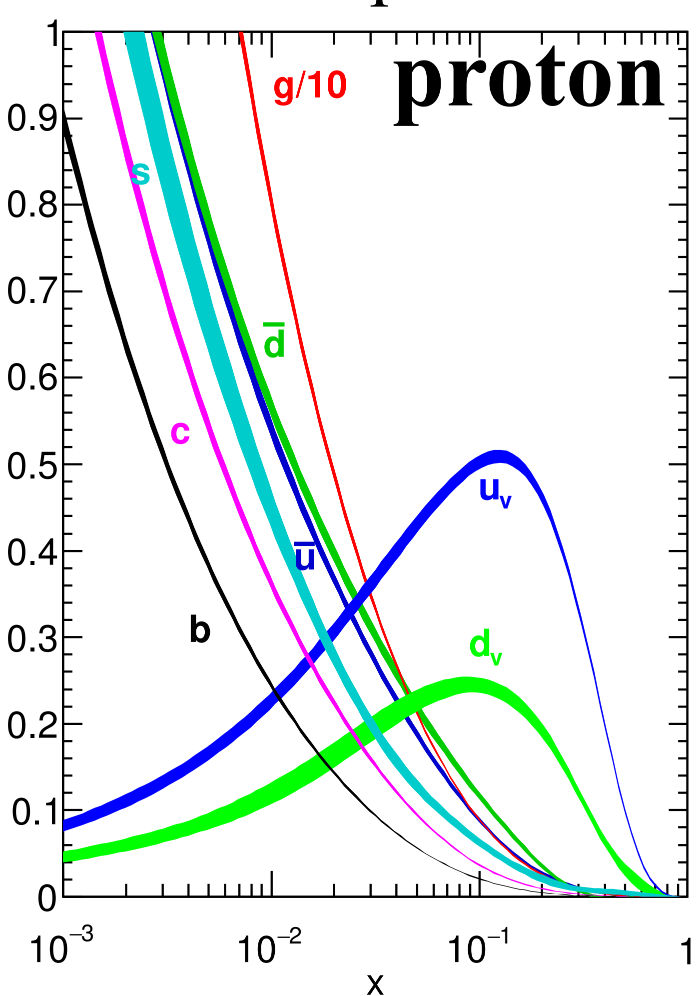


We need energetic **partons**

Pure state of a particle becomes a statistical ensemble of partons!



Distribution of partons in



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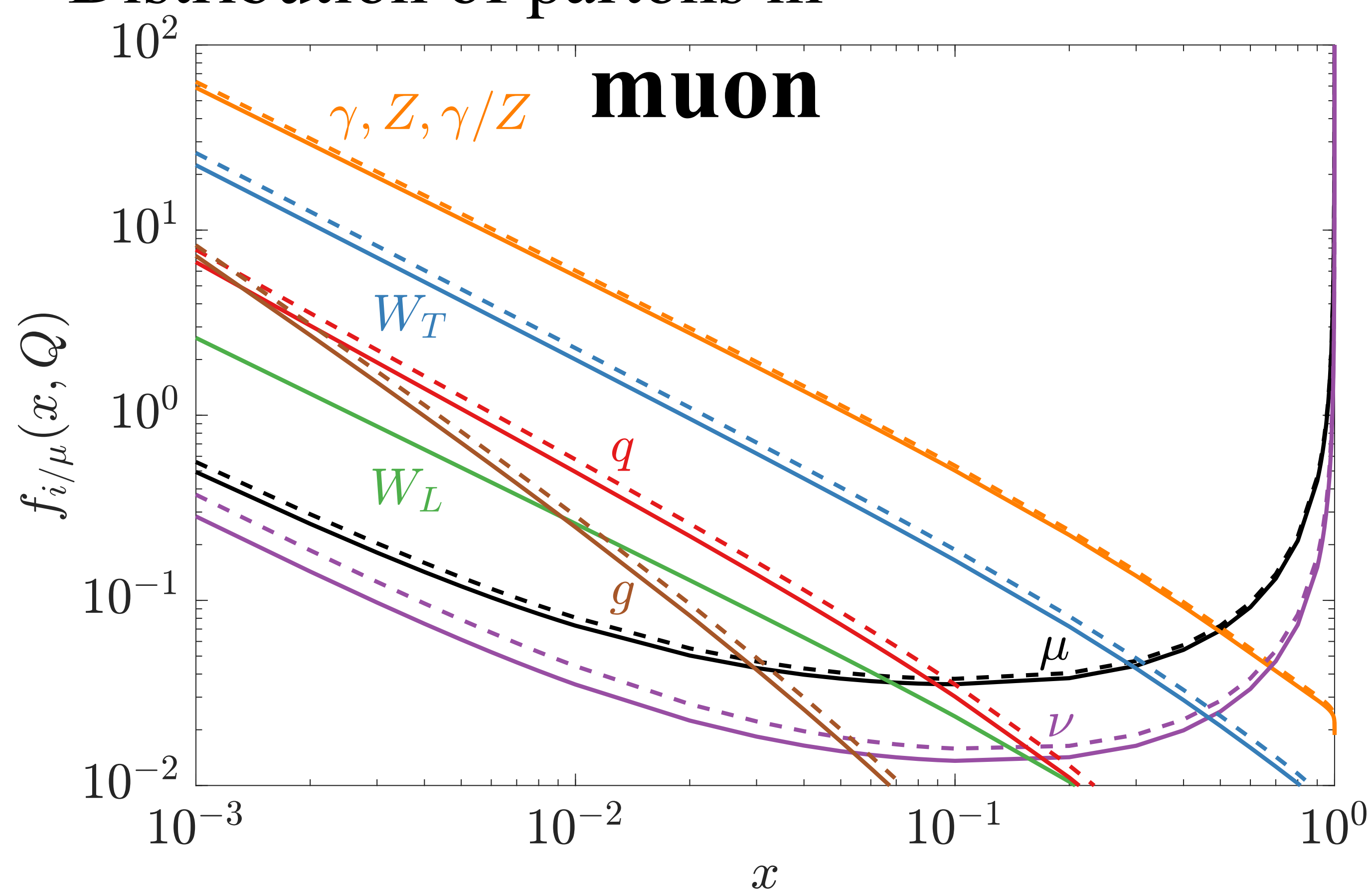

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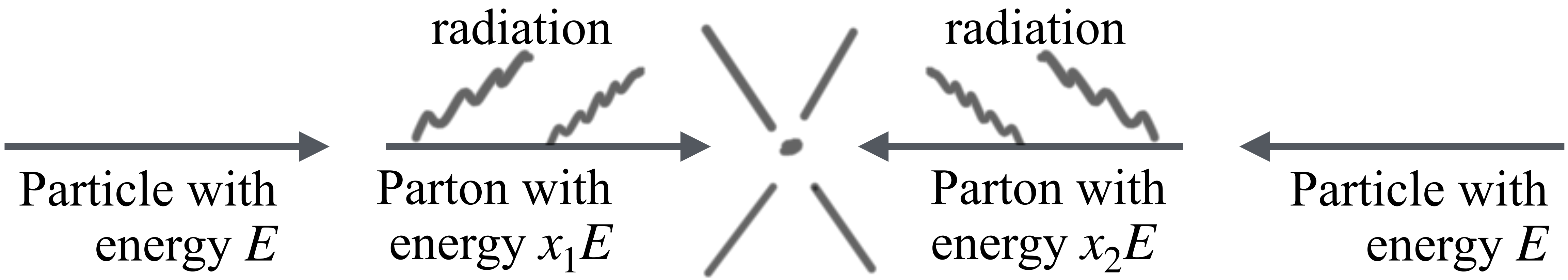

Muon collider probes partons energy as high as the beam energy
Most energy is "wasted" at proton colliders instead

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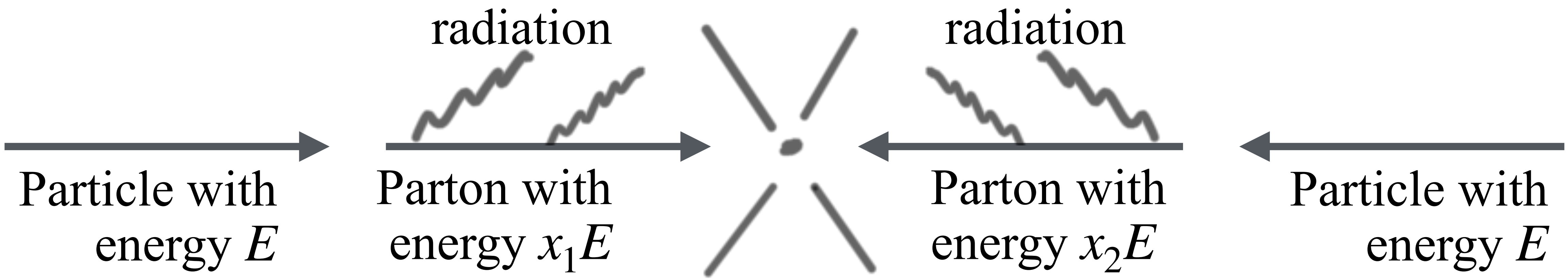

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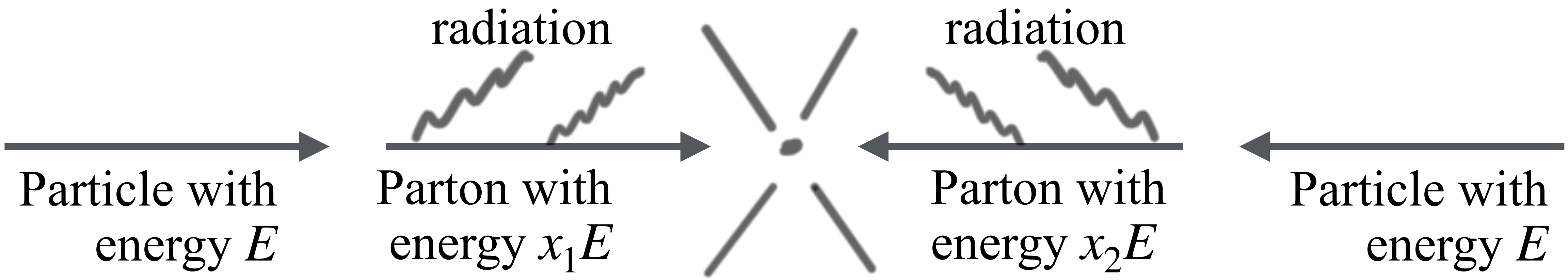
A **10 TeV muon** collider reaches
the 10 TeV energy frontier

100 TeV energy needed for **protons**
instead in order to reach 10 TeV

We need energetic **partons**

Pure state of a particle becomes a statistical ensemble of partons!



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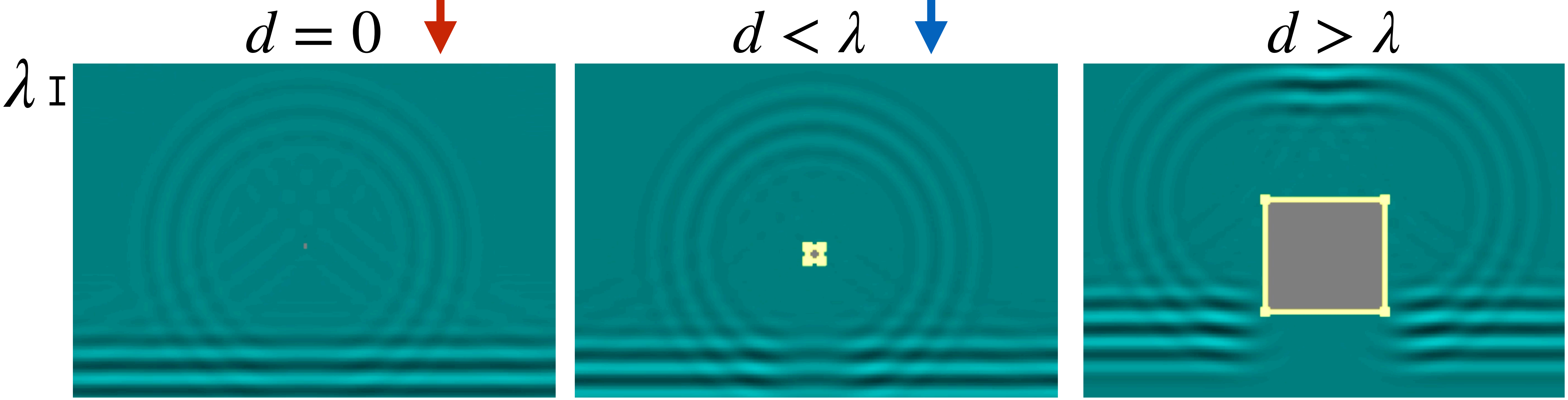
P5-certified

We need **precision** as well

If you look **precisely** enough, **this** is different from **that**



We need **precision** as well

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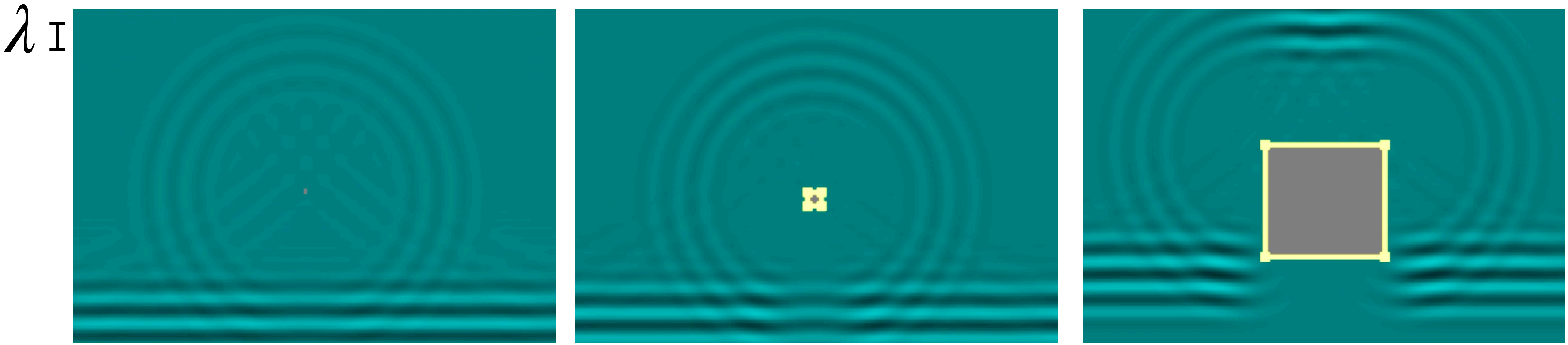
$d = 0$ $\qquad$ $d < \lambda$ $\qquad$ $d > \lambda$



The precision of **proton** colliders is limited long-distance phenomena that are difficult to model: **QCD backgrounds**

The **muon** collider is **energetic** and **precise** at once

Muon Colliders Status

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

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

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

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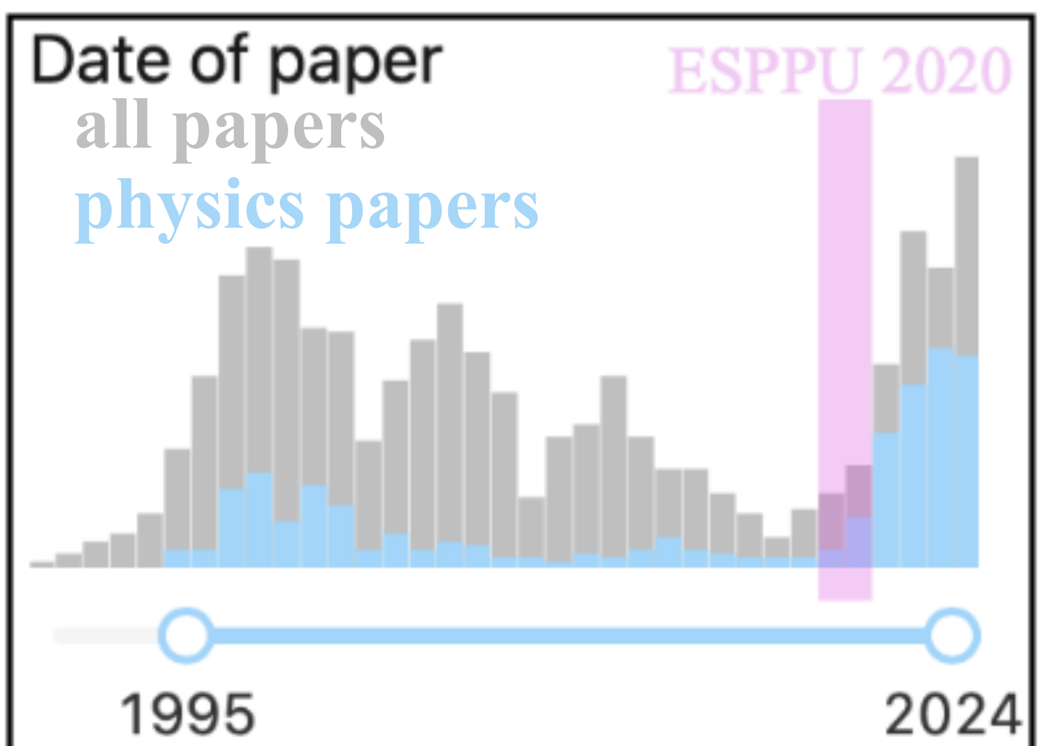

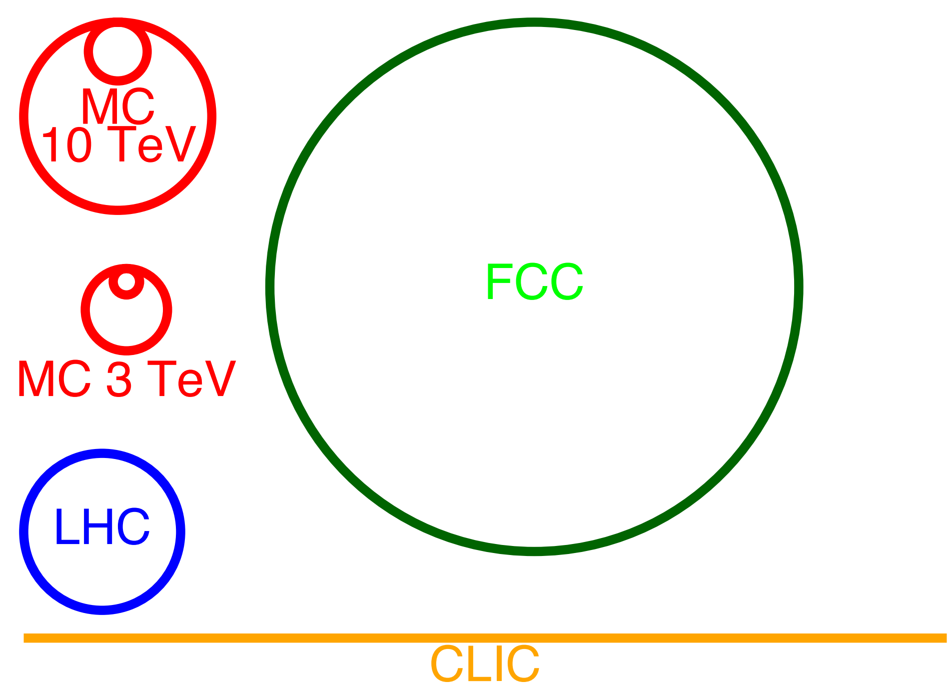

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2023 P5 outcome:
"The Muon Shot"

Resurrection of collider ambitions in USA!

*Although we do not know if a muon collider is ultimately feasible, the road toward it leads to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D **towards a muon collider.** At the end of the path is an unparalleled global facility on **US soil**.*

This is our Muon Shot.

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2026 ESPPU

?

As per ESPPU 2020 and LDG mandate, IMCC provided ESPPU 2026 with an evaluation report, aimed at:

Assessing MuC potential (no showstopper identified)

Detailing R&D path plan (including technical **demonstrator(s)**)

We are few years away from establishing MuC feasibility!

Muon Collider Physics Targets

Most complete and recent overview: **The Muon Collider**

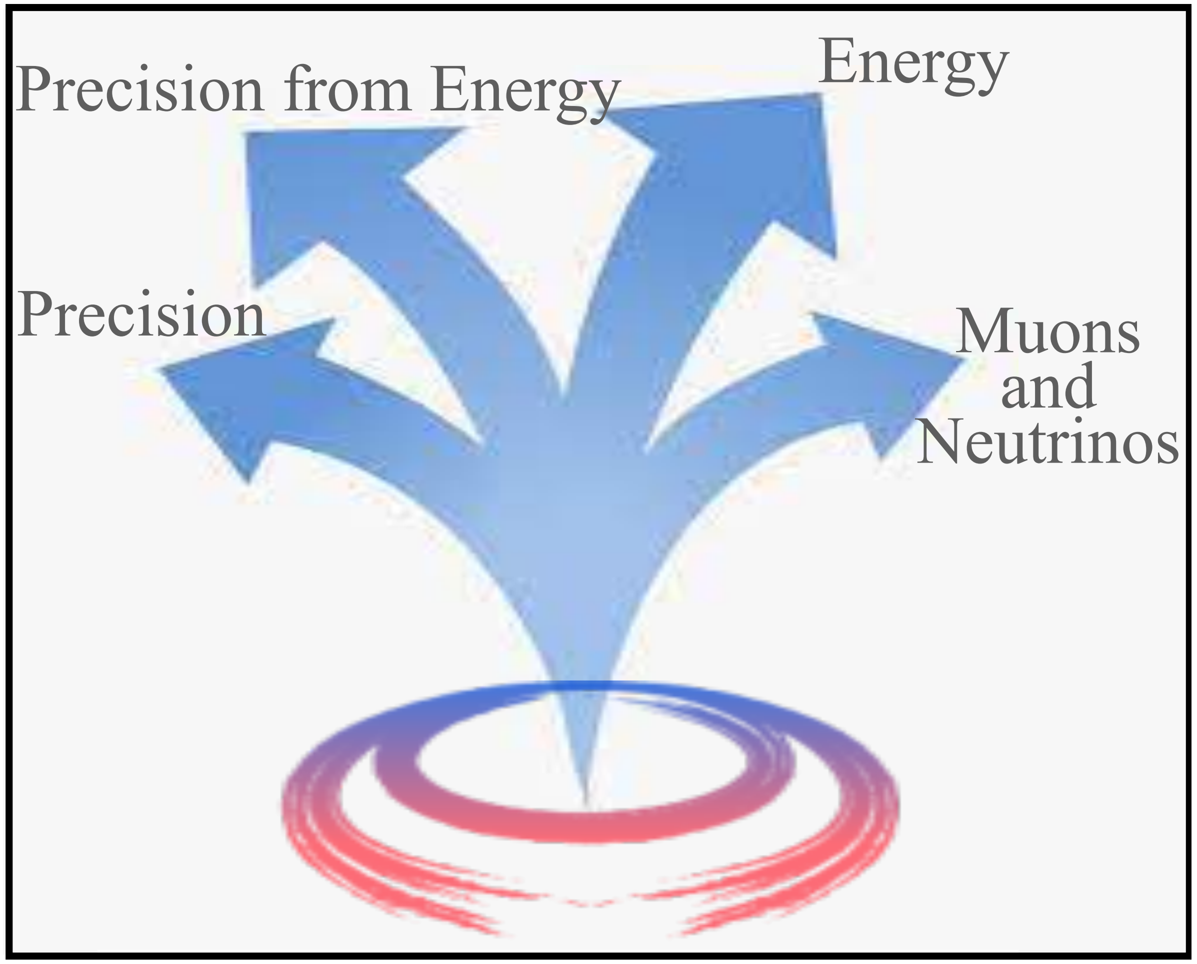
In short:

—***discover new particles*** *with presently inaccessible mass, including WIMP dark matter candidate*

—*discover cracks in the SM by the* ***precise study of the Higgs boson****, including the precise direct measurement of triple Higgs coupling.*

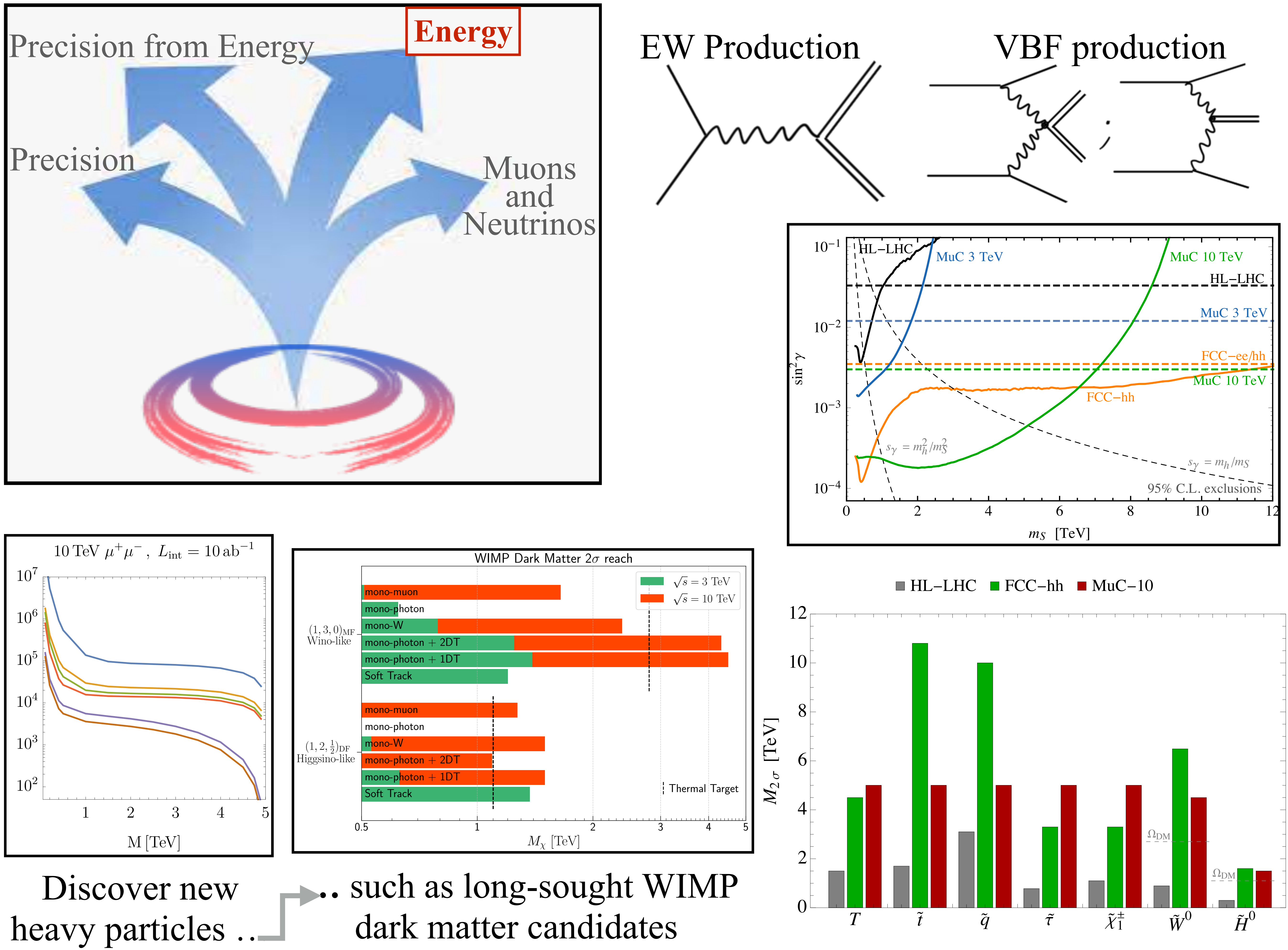
—***uniquely*** *pursue the quantum imprint of new phenomena in novel observables by* ***combining precision with energy****.*

—*give* ***unique access*** *to new* ***physics coupled to muons*** *and delivers* ***beams of neutrinos with unprecedented properties*** *from the muons decay.*

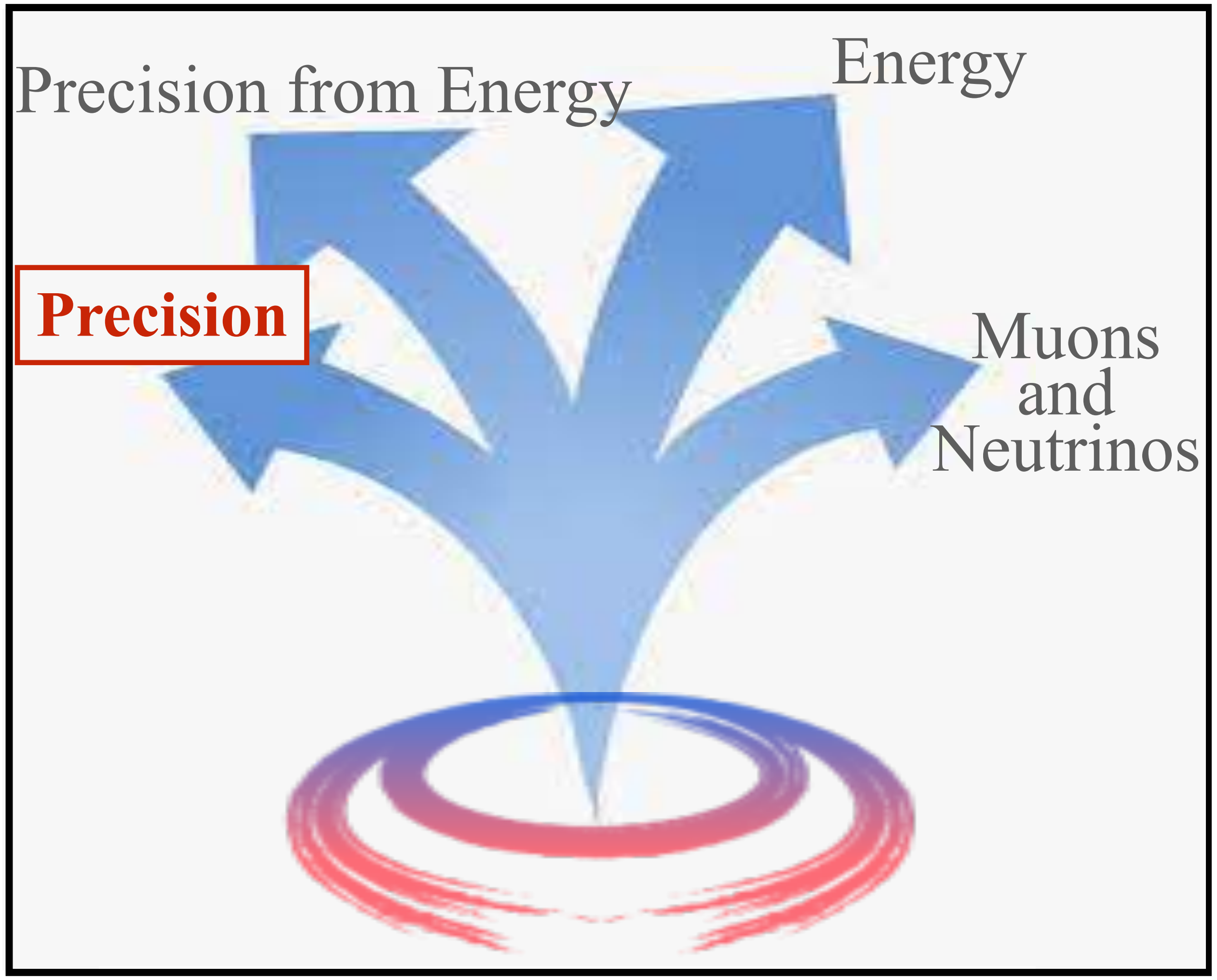


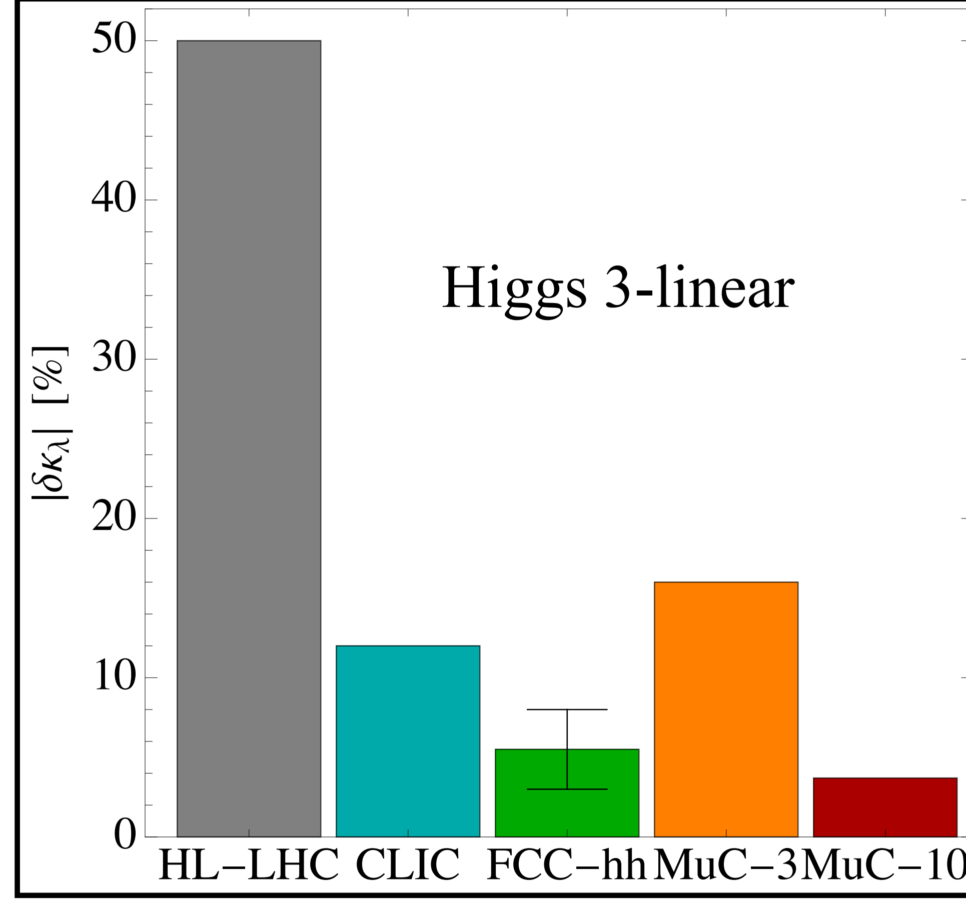
But also:

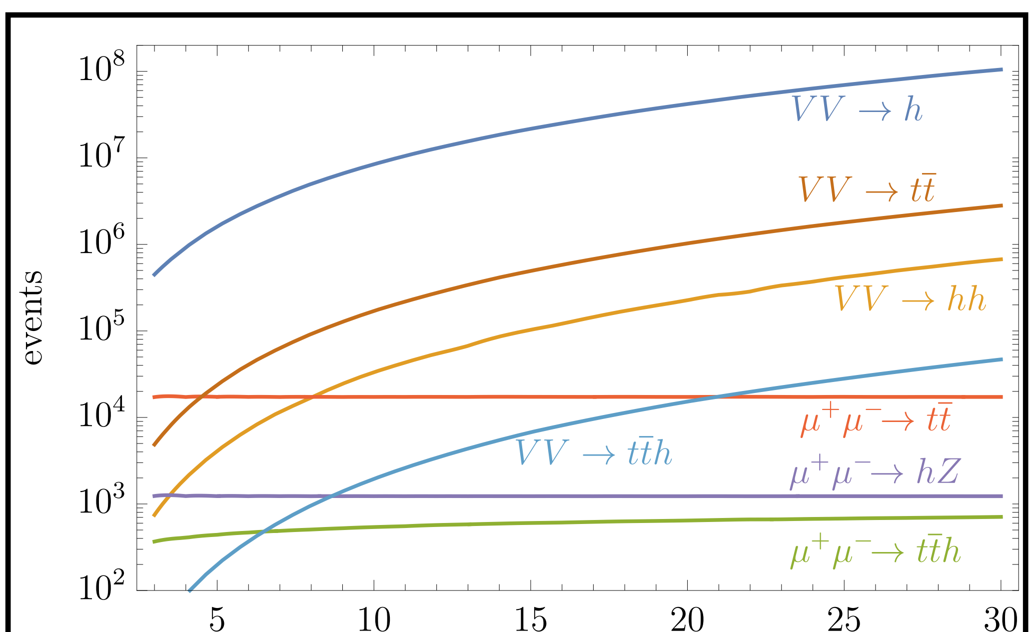
—***unique probe of EW+Higgs in novel high-energy regime.***
The SM is a great physics case!

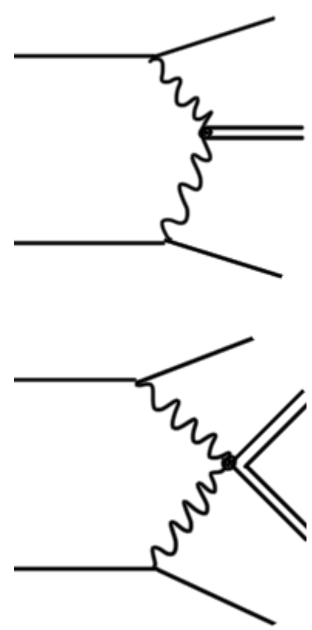


Energy
Precision from Energy
Precision
Muons
and
Neutrinos
EW Production
VBF production
HL−LHC
MuC 3 TeV
MuC 10 TeV
FCC−ee/hh
FCC−hh
95% C.L. exclusions
$\sin^2\gamma$
m_S [TeV]
$s_\gamma = m_h^2/m_S^2$
$s_\gamma = m_h/m_S$
10 TeV $\mu^+\mu^-$, $L_{\rm int} = 10\,{\rm ab}^{-1}$
M [TeV]
WIMP Dark Matter 2σ reach
$\sqrt{s} = 3$ TeV
$\sqrt{s} = 10$ TeV
$(1,3,0)_{\rm MF}$ Wino-like
$(1,2,\frac{1}{2})_{\rm DF}$ Higgsino-like
mono-muon
mono-photon
mono-W
mono-photon + 2DT
mono-photon + 1DT
Soft Track
Thermal Target
M_χ [TeV]
HL−LHC
FCC−hh
MuC−10
$M_{2\sigma}$ [TeV]
$\Omega_{\rm DM}$
T $\tilde{t}$ $\tilde{q}$ $\tilde{\tau}$ $\tilde{\chi}_1^\pm$ $\tilde{W}^0$ $\tilde{H}^0$
Discover new heavy particles ...
... such as long-sought WIMP dark matter candidates



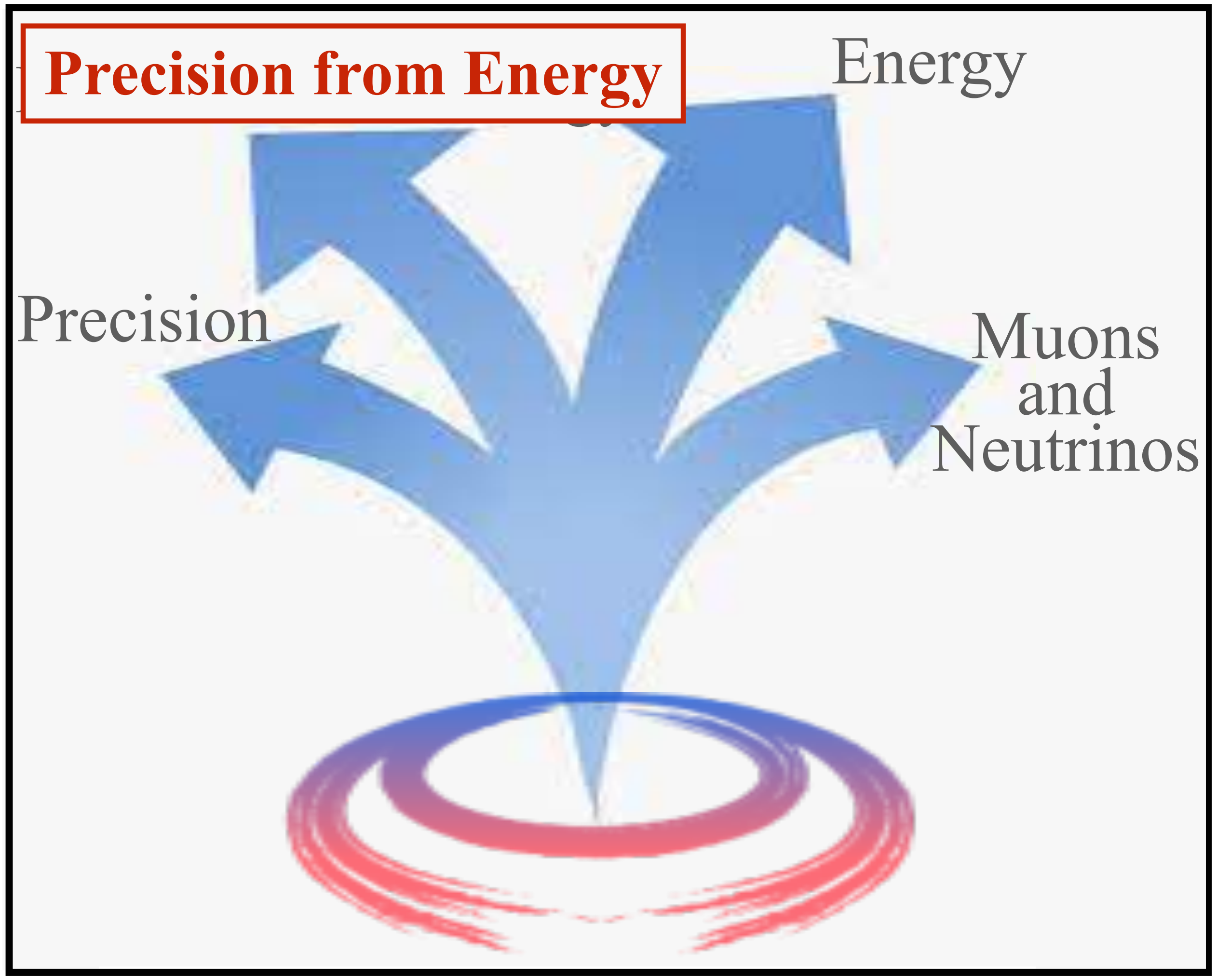


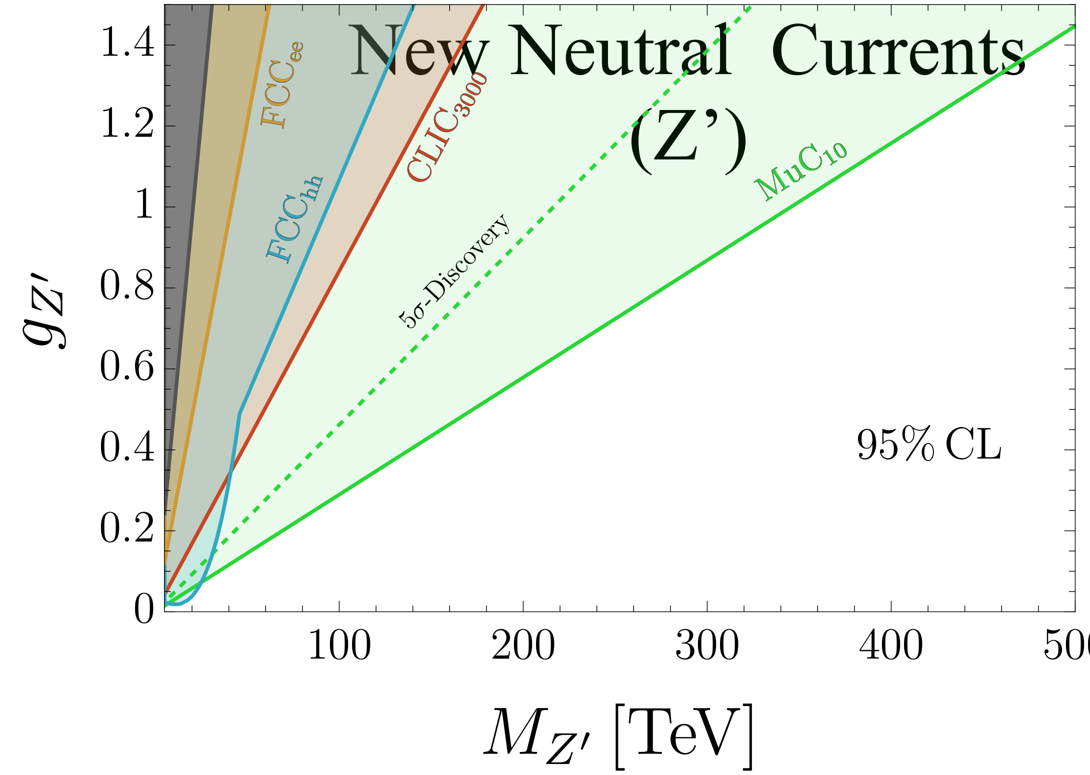


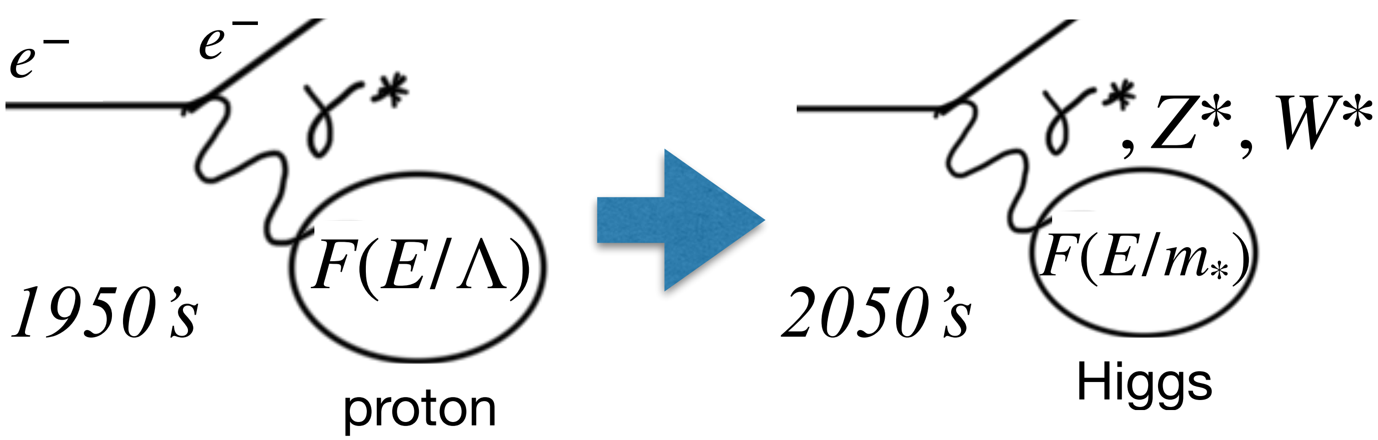


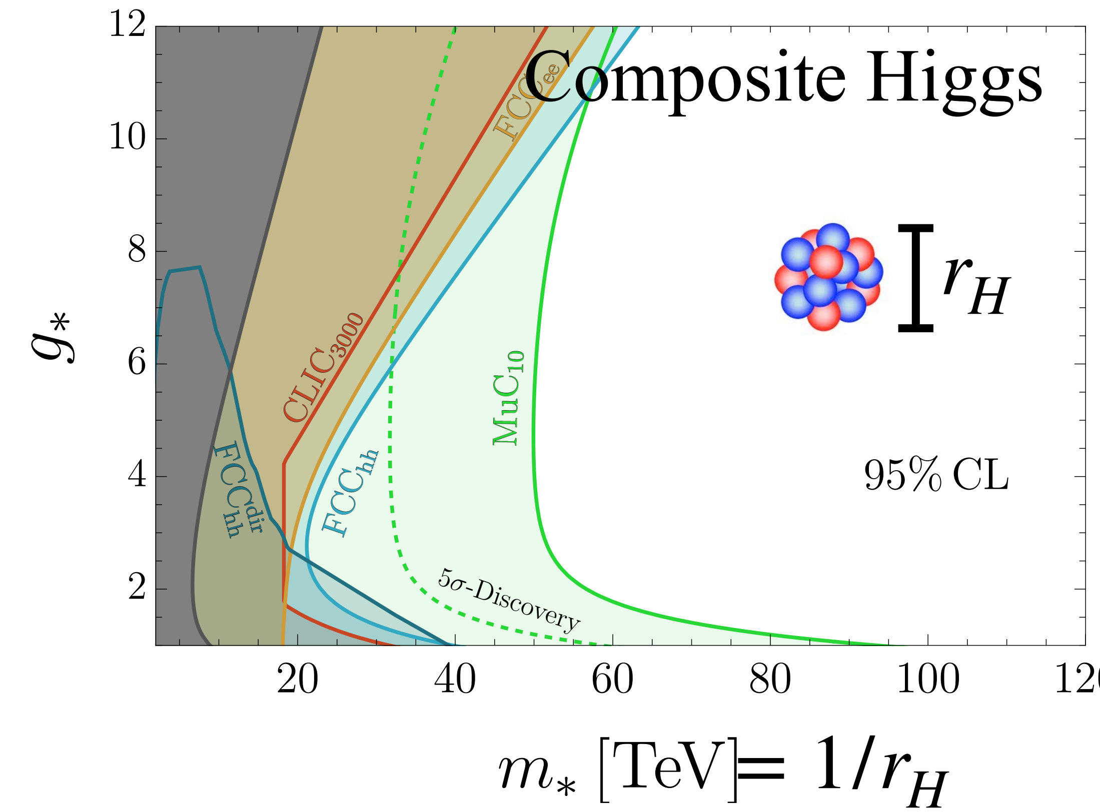
κ[%]	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.2	0.1
κ_g	2.3	0.5	0.5
κ_γ	1.9	0.7	0.7
$\kappa_{Z\gamma}$	10	5.2	3.9
κ_c	-	1.9	0.9
κ_b	3.6	0.4	0.4
κ_μ	4.6	2.4	2.2
κ_τ	1.9	0.5	0.3

10 M Higgs bosons produced → Permille-level precision on Higgs couplings





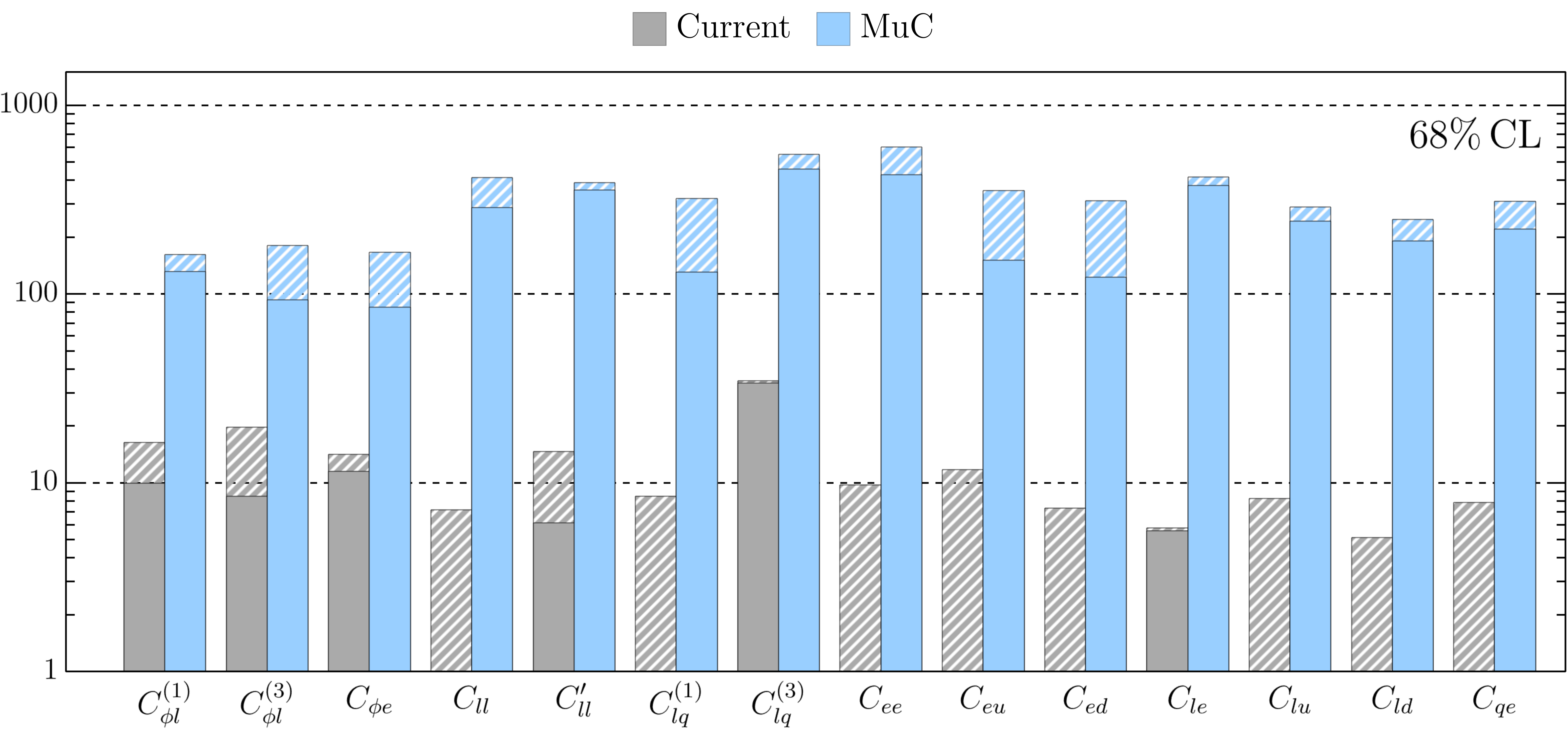




Higher-energy observables are more sensitive to heavy physics:

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

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



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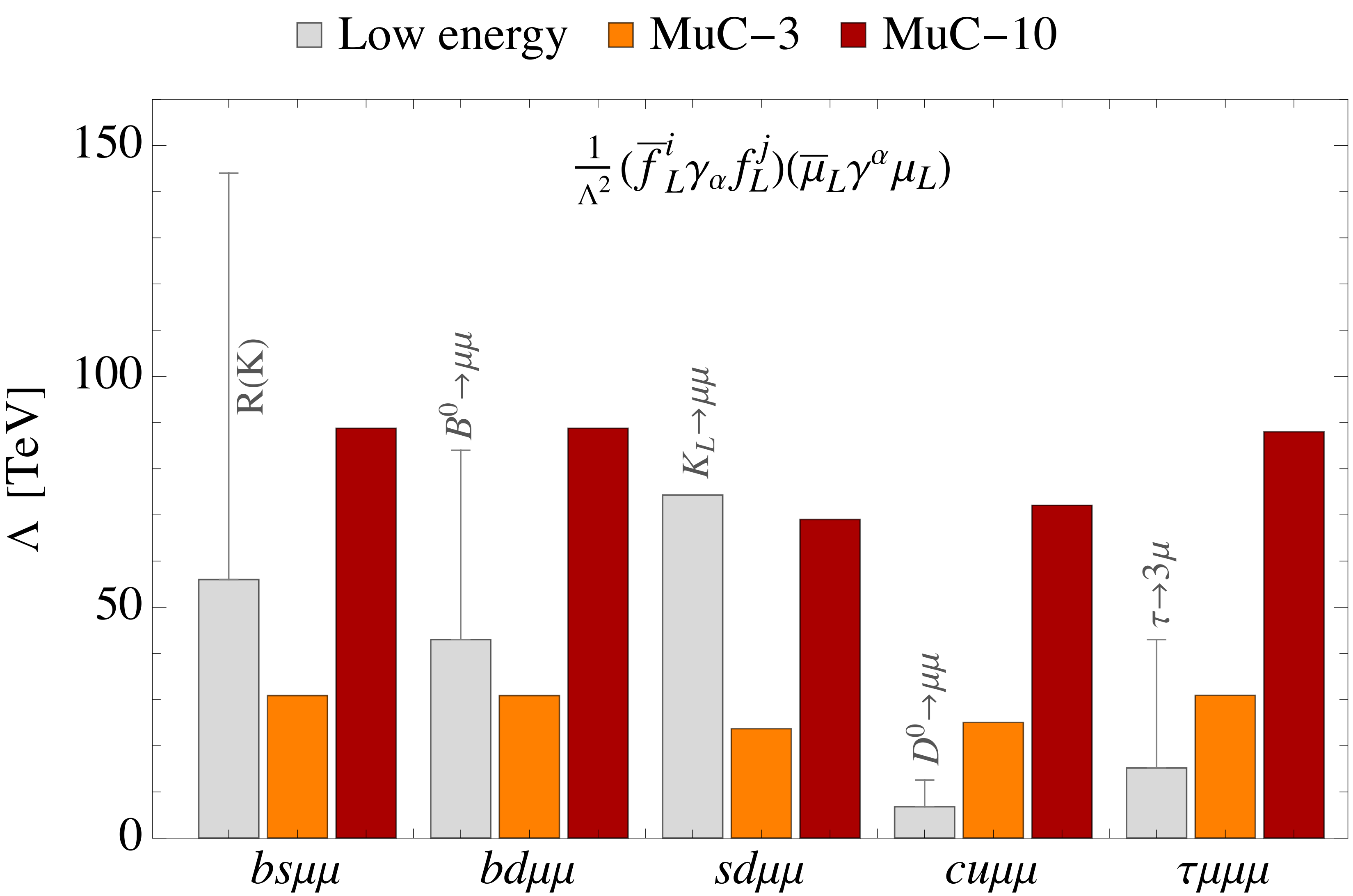
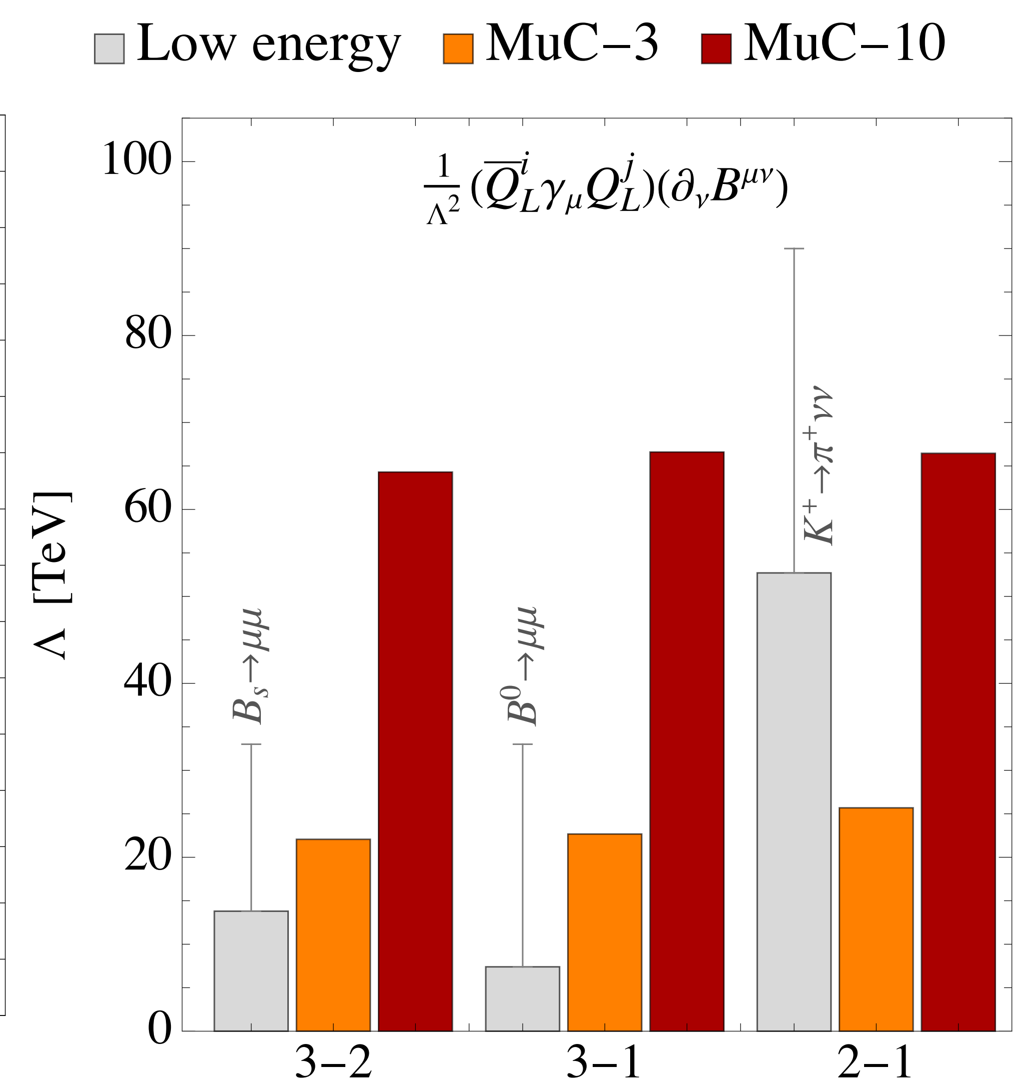
10^{-6} at EW [FCC-ee] energies

10^{-2} at **muon collider** energies

Flavour Physics at the Energy Frontier





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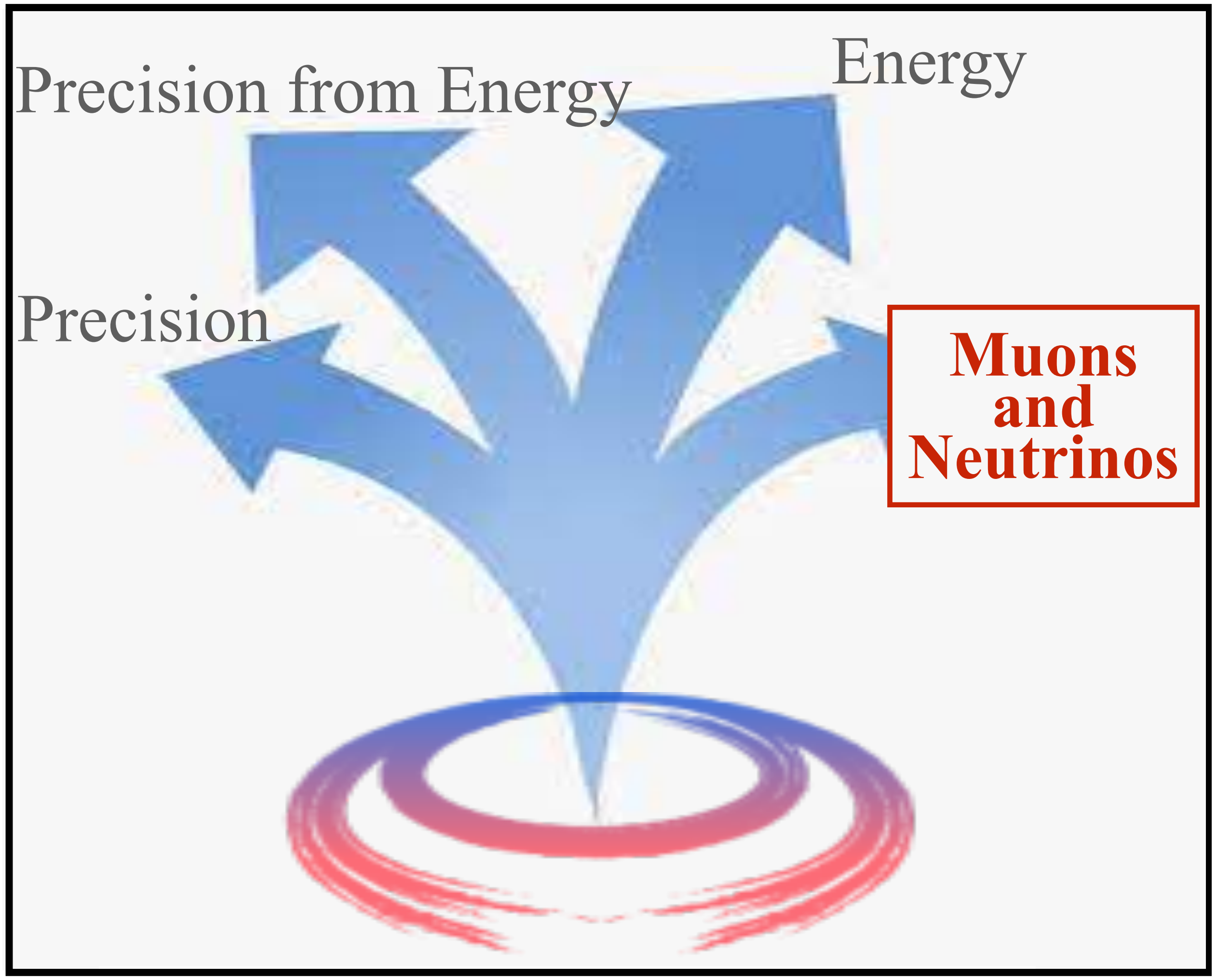
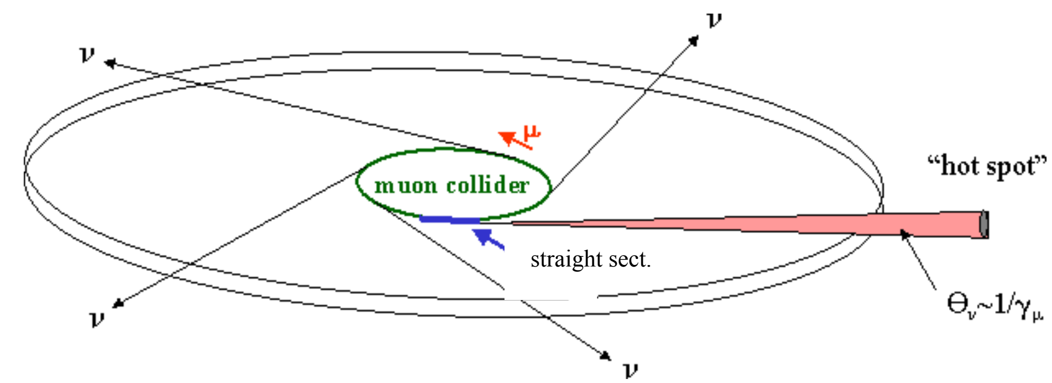
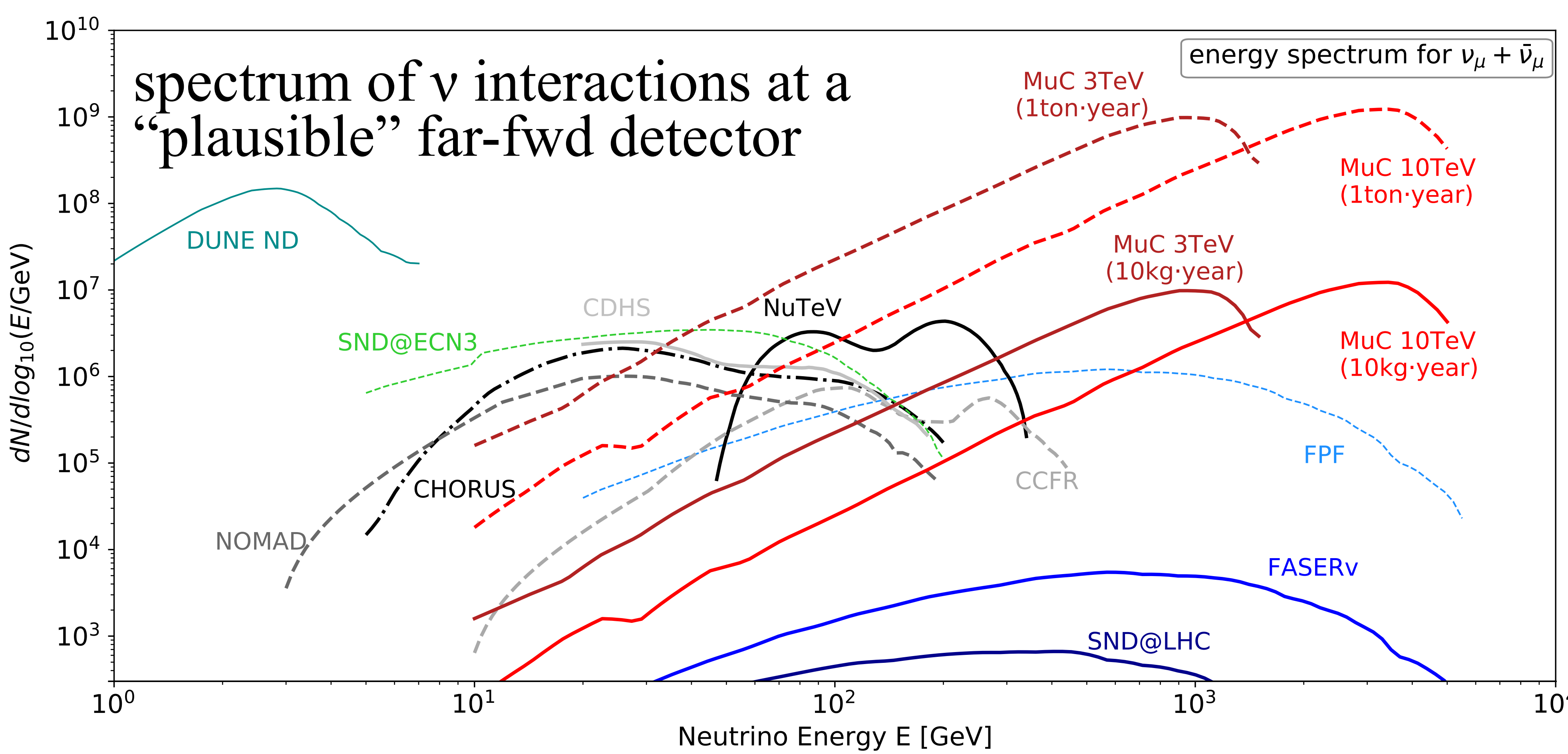
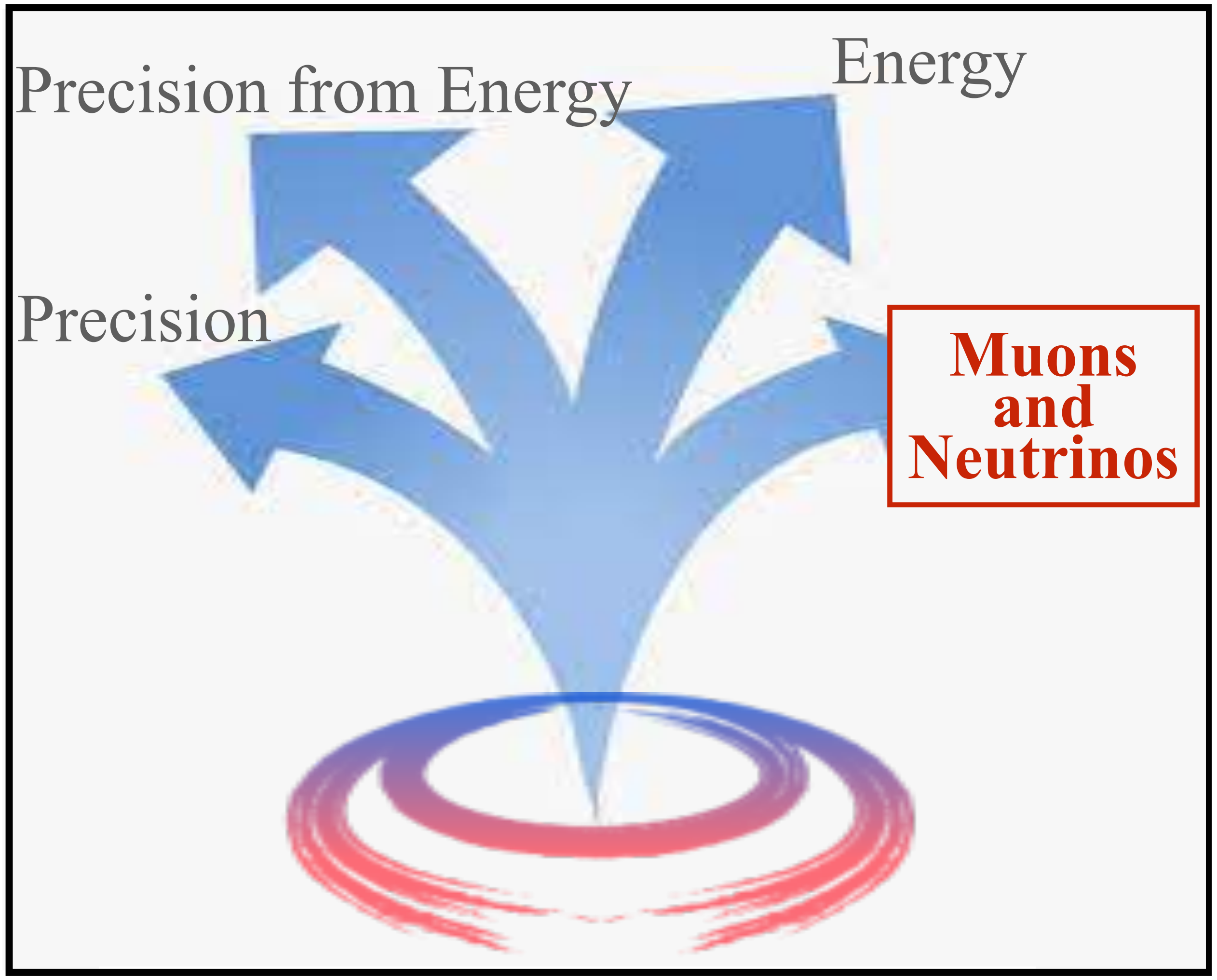




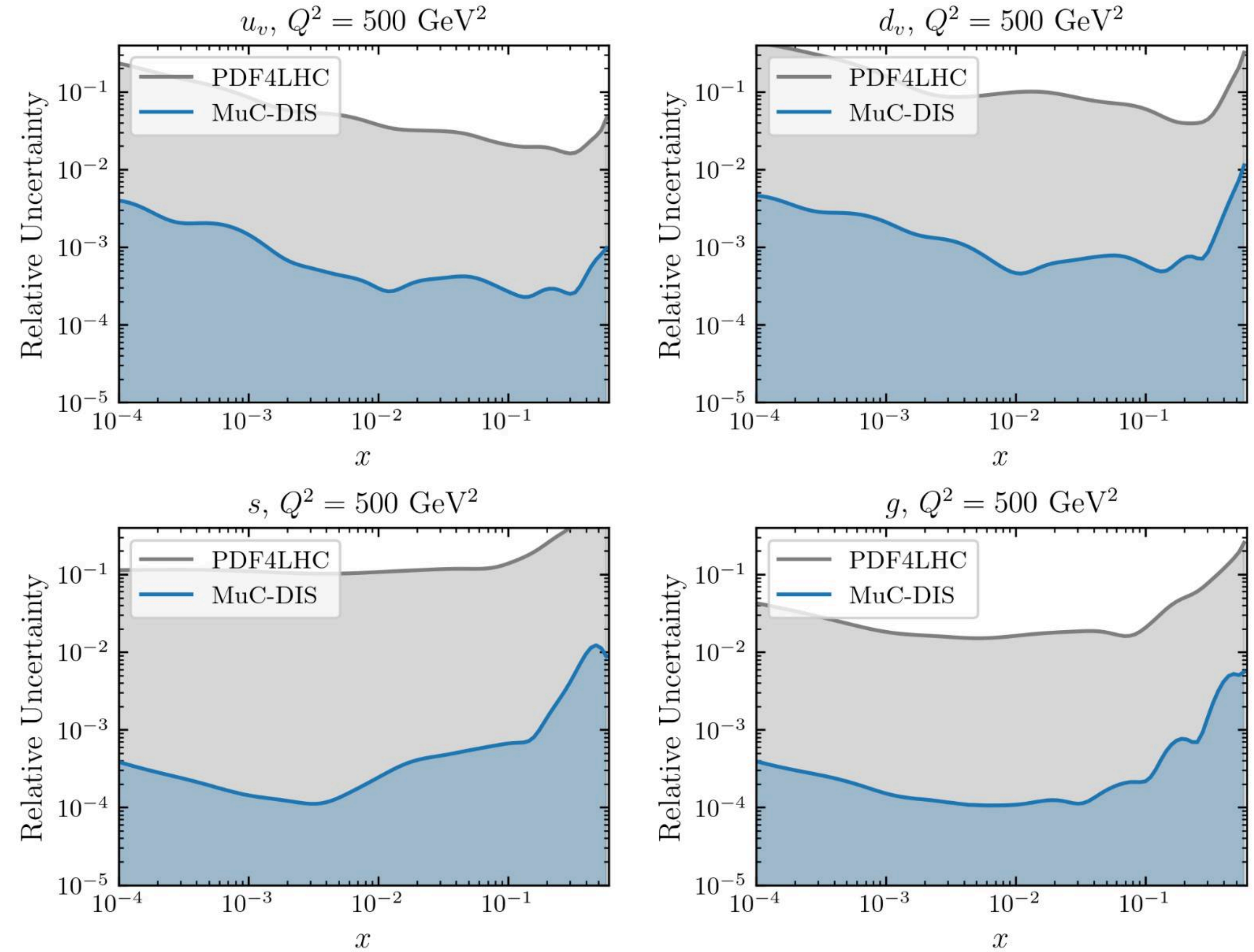
Muons decay to neutrinos:

Collimated, perfectly known,
TeV-energy neutrino beam

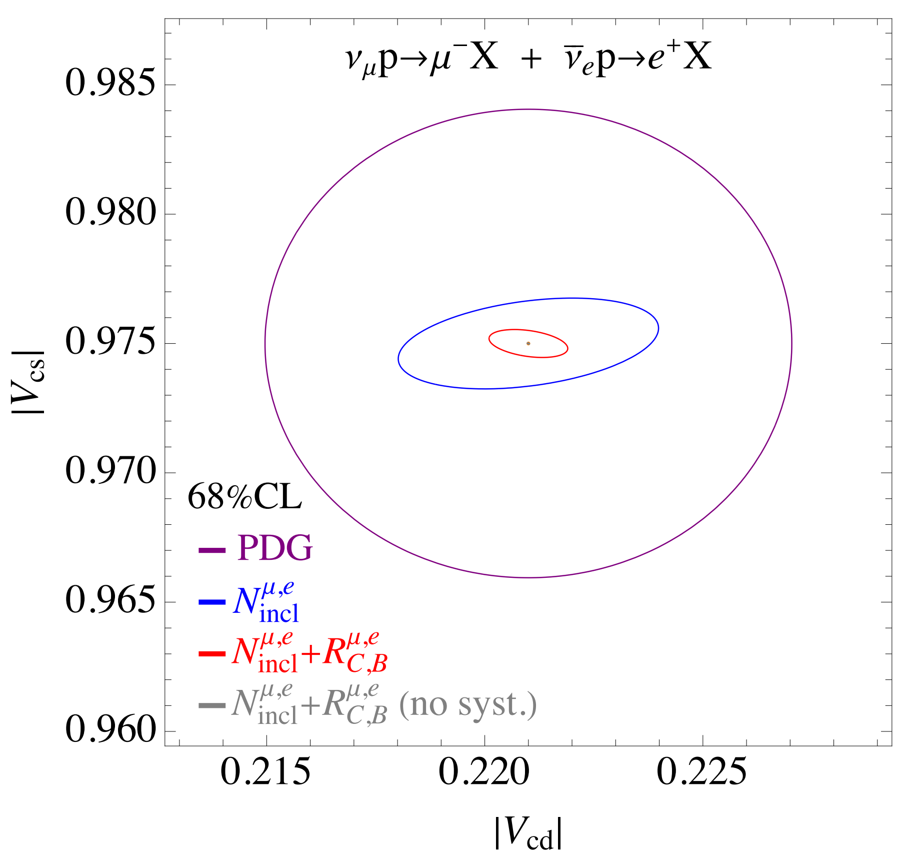


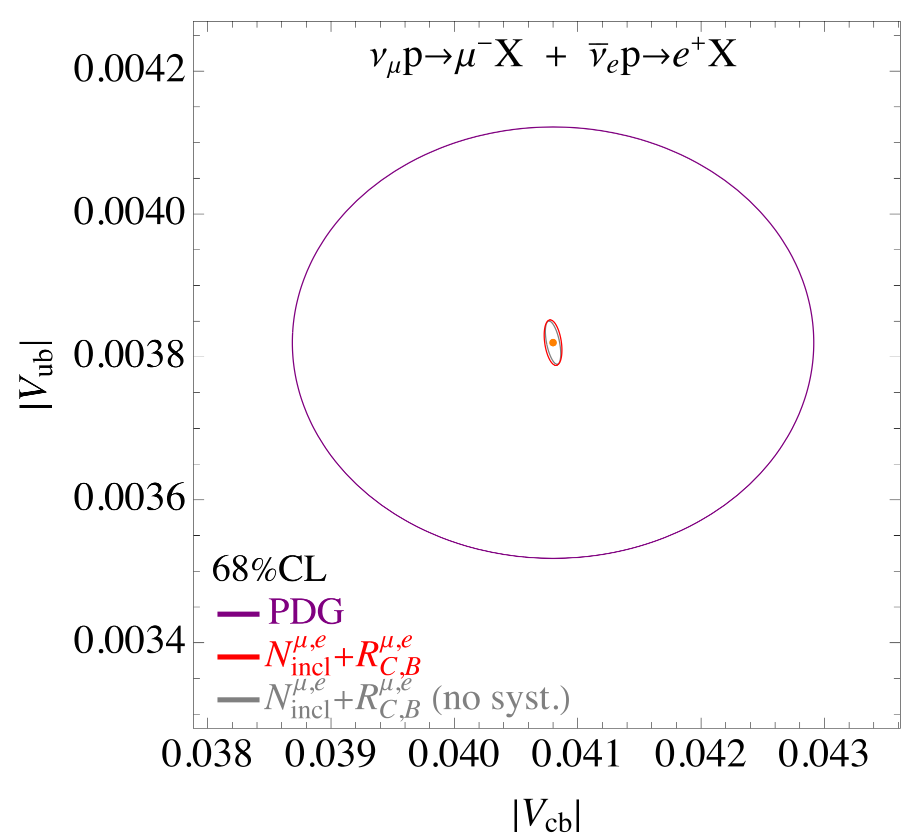


The "ultimate" PDF fit

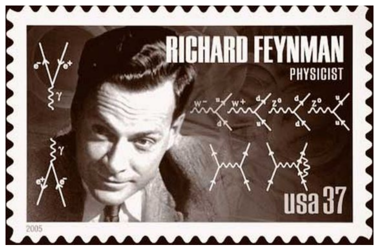


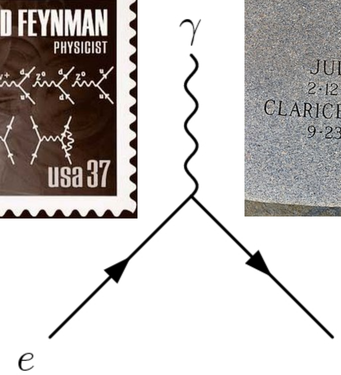
CKM elements determination

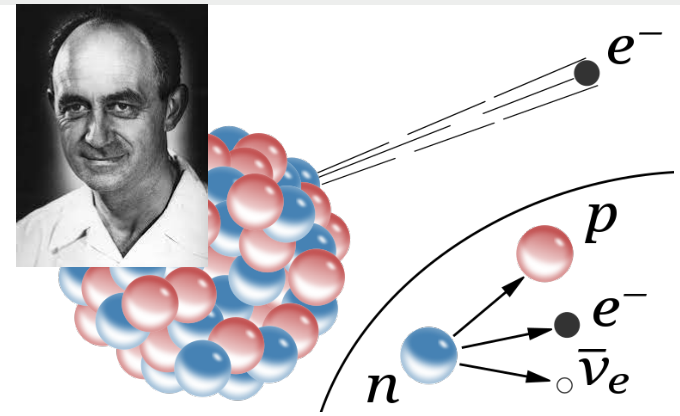




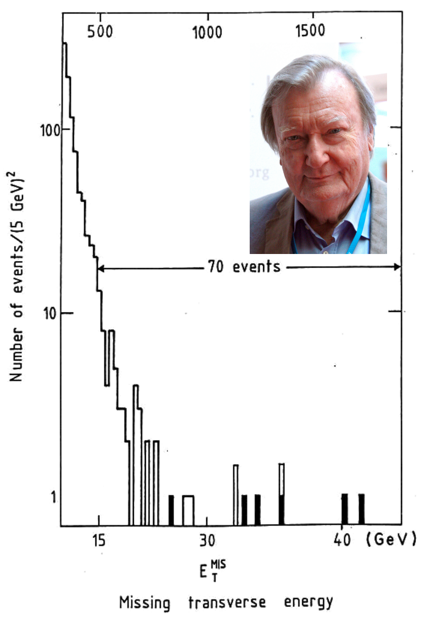
Muon Collider Physics: a SM view

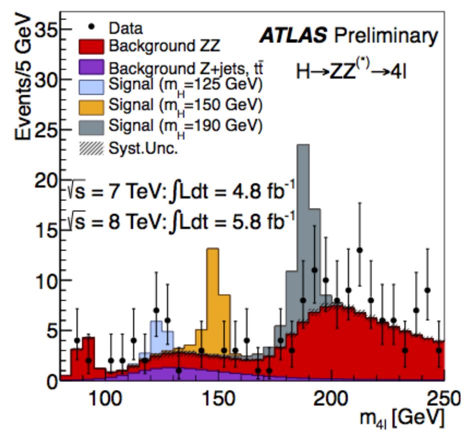


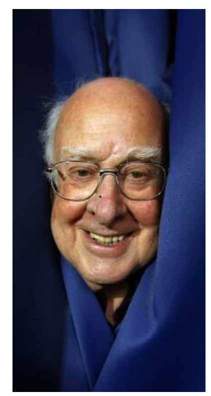


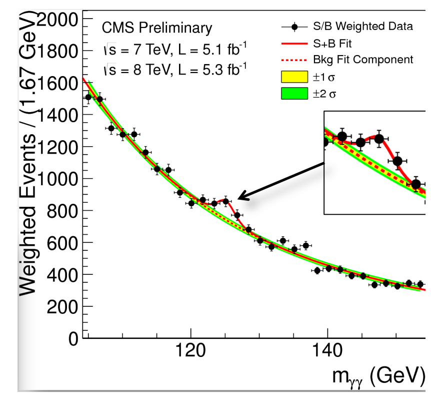


$E \ll m_W$









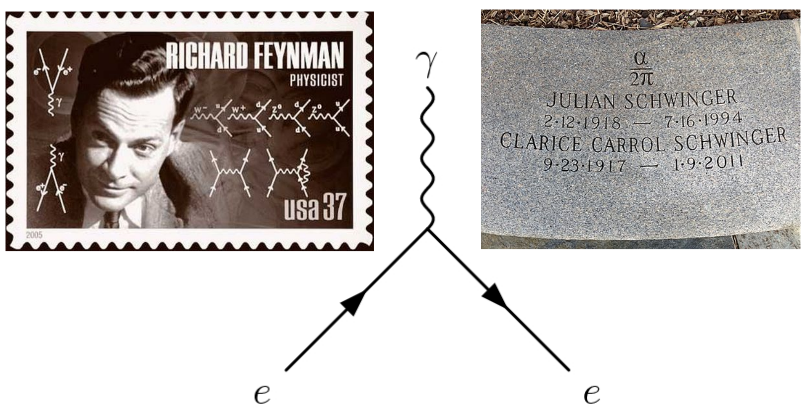
$E \gtrsim m_W$

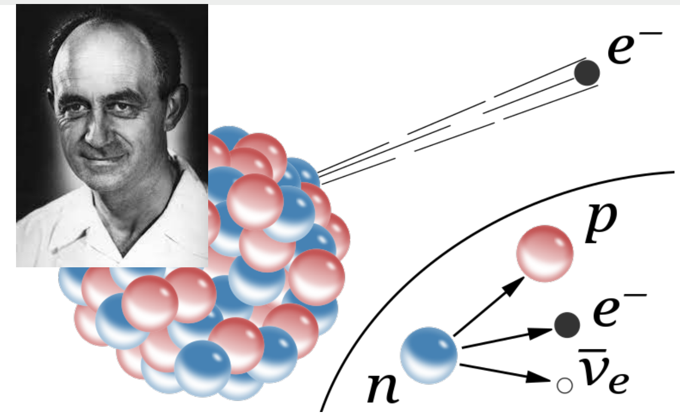
The Higgs particle shows up **here**

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

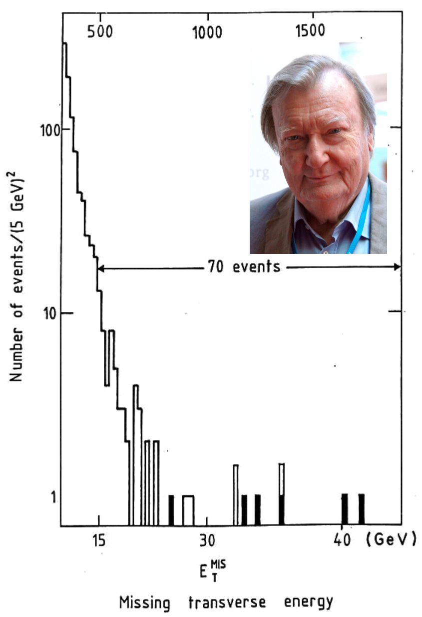
$E \gg m_W$

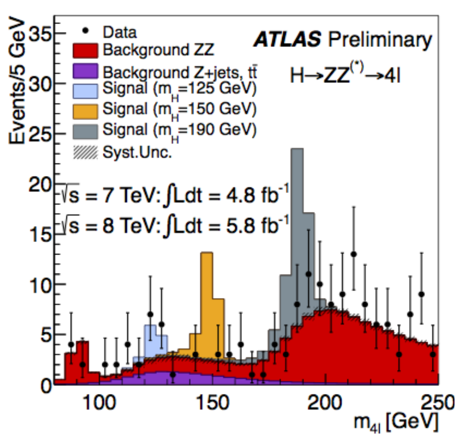
Muon Collider Physics: a SM view

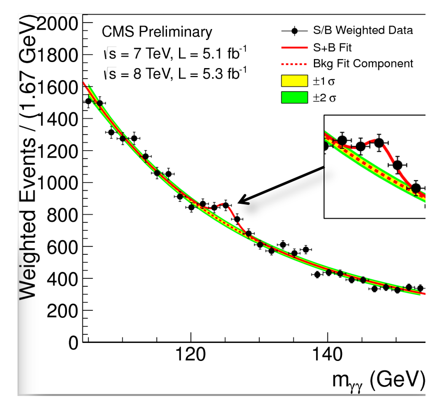




$$E \ll m_W$$







$$E \gtrsim m_W$$

The Higgs particle shows up **here**

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

Most direct theory implications are at high En.

$$E \gg m_W$$

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

Muon Collider Physics: a SM view

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

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

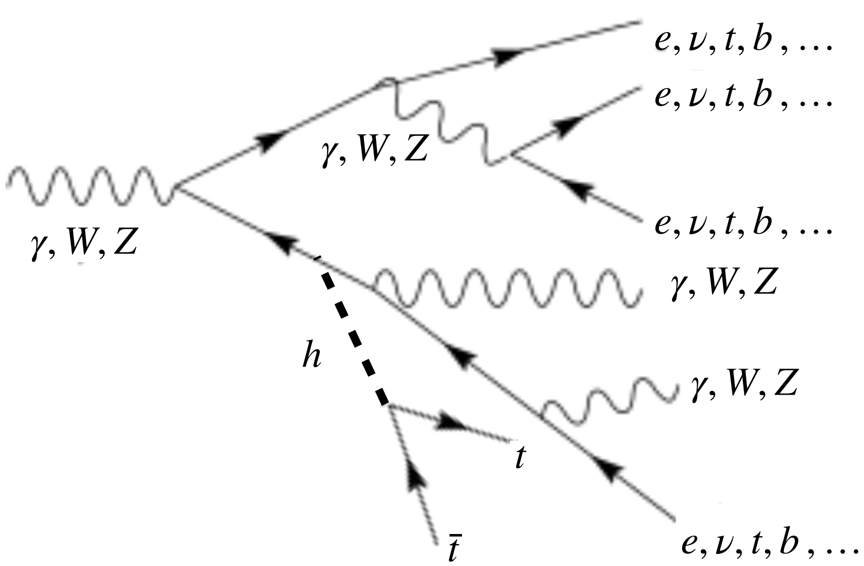
Plenty of cool things will happen:

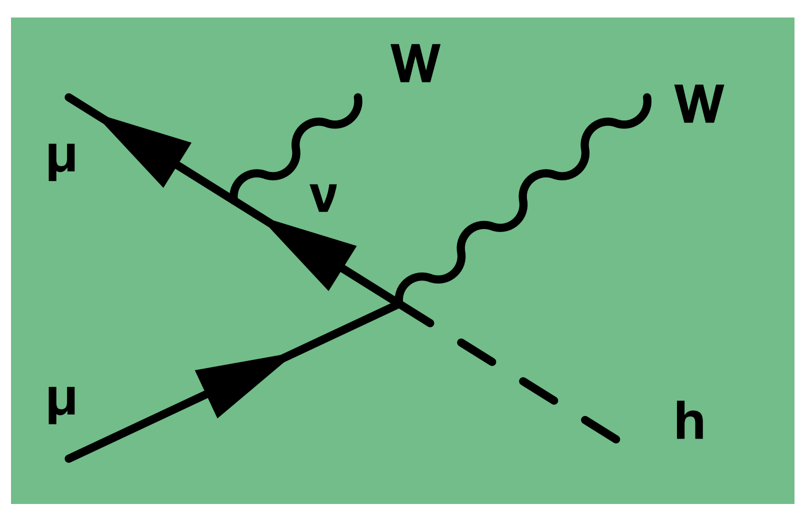
Electroweak Restoration. The $SU(2) \times U(1)$ group emerging, finally!

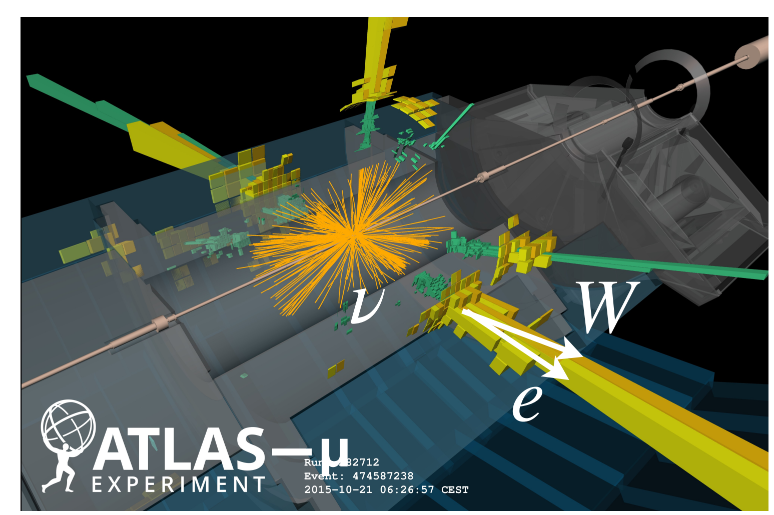
Electroweak Radiation in nearly massless broken gauge theory.
Never observed, never computed (and we don't know how!)

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







Theory Challenges

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

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

Large muon collider energy

Small IR cutoff scale

Scale separation entails enhancement of Radiation effect.

Like QCD ($E \gg \Lambda_{\rm QCD}$) 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 $\log^{(2)} E^2/m_{\rm EW}^2$

EW theory is Weakly-Coupled

The IR cutoff is physical

First-Principle predictions **must** be possible

For arbitrary multiplicity final state

Principal Challenges — Key R&D
[More in backup]

Environmental impact:
- MuC is smaller and less power-consuming than other options
- Requires mitigation of the effect of neutrinos from muon decay
  Beam movers plus adequate orientation make **environmental impact negligible**
- Possible infrastructure reuse would strongly impact full lifecycle assessment

Detector and MDI:
- **BIB from muon decay is manageable.**
  First detector design and full sim results already available and more will come
- Timing resolution and radiation hardness for components R&D

Muons production and cooling:
- Proton beam and target design; R&D of 20T HTS solenoid in synergy with fusion
- Prototyping cooling cell (RF in MF could be built soon)
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Accelerator and collider:
- RCS and collider ring are being designed
- Non-available 16 T would still allow 10 TeV with less luminosity

Take-home messages

The muon collider is a **high-energy electroweak** (lepton) **collider**

- Unique direct access to the simplicity of the **Standard Model** in new h.e. regime
- Unique promise for conclusive **Beyond the Standard Model** physics exploration.
- Combines **energy** with **precision** gaining more than the union of the two.

Unique physics opportunities

- Explore 10 TeV scale
- **New strategies** to address old questions:
  - Higgs characterisation in VBF
  - Energy&Accuracy
  - Lepton and quark flavour at high-energy
- **New questions from new strategies:**
  - EW+Higgs physics in novel regime
  - Neutrino beam

Take-home messages

Coordinated MuC R&D effort is progressing:

- Led by **Europe** after extraordinarily quick expertise ramp-up
- Key US competences will re-enter after P5 recommendation implementation

IMCC proposes detailed R&D path

- A cooling **demonstrator facility.**
- Many smaller-scale technology demonstrators.
- Few years away from establishing muon collider feasibility!

Take-home messages

Why working on the MuC? — Because is **new**!

- **The first collider of its species!**
- Challenges/opportunities in **all areas** of accelerator physics
- Plus, technology **synergies**
- Opportunity also for **Physics, Experiment, Detector:**
  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!

New enthusiasm on muon colliders:

- In spite of (actually, because of!) the risk of failure
- Scientists like working on what is new and difficult
- **Opportunity—see P5 outcome—for collider physics at large**

Thank You

Backup

Principal Challenges — Key R&D

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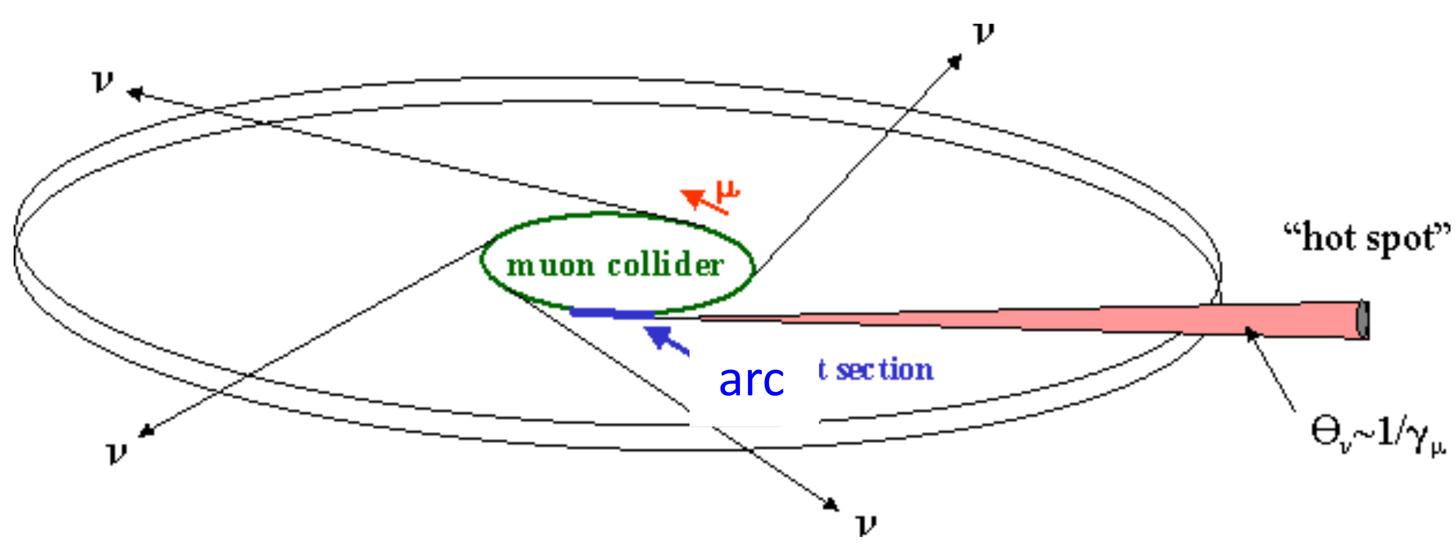
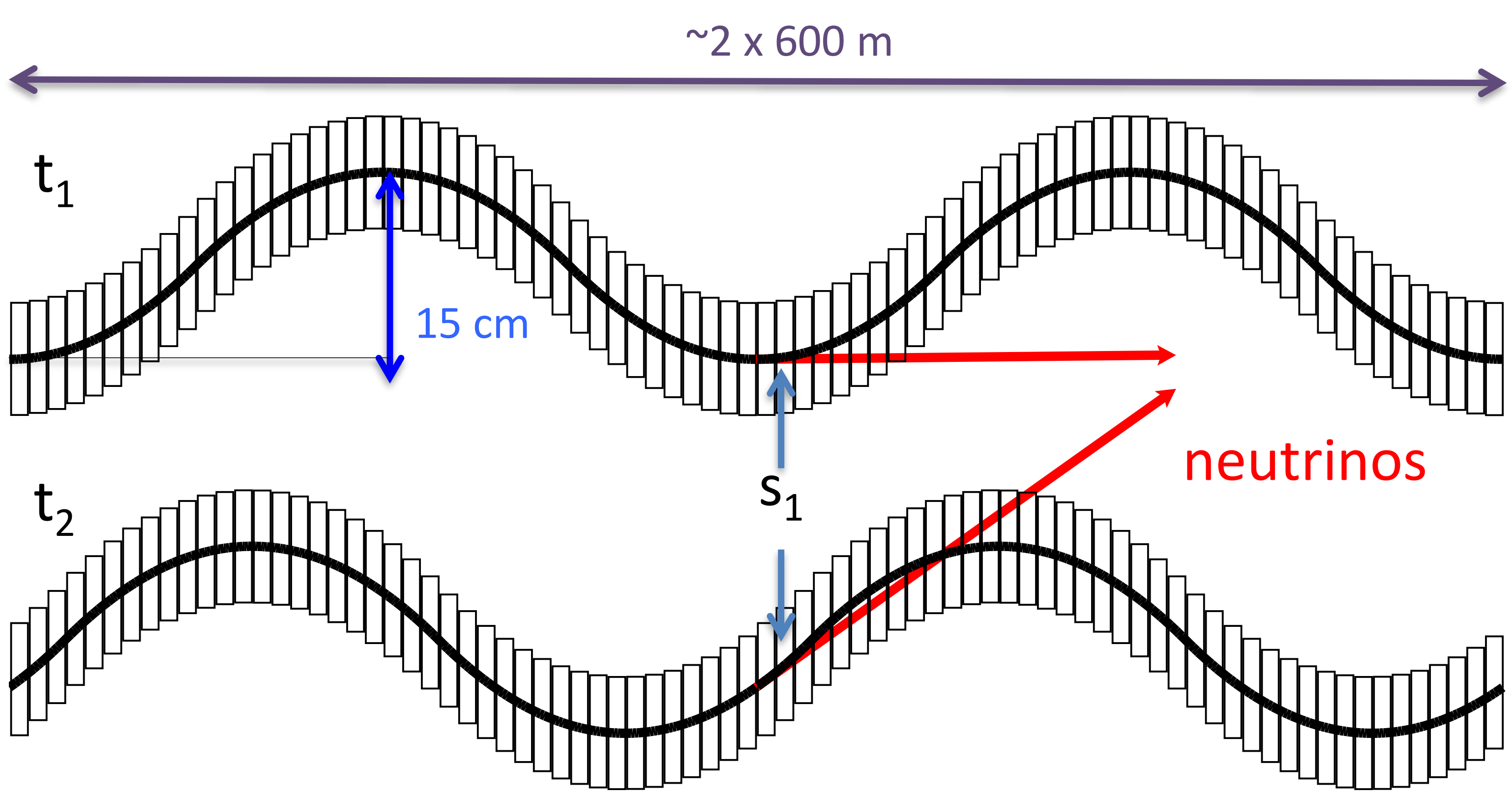
Radiation dose from neutrinos



Legal limit: 1 mSv/year

IMCC goal: **below threshold for legal procedure** < 10**μ**Sv/year

LHC achieved: < 5 μSv/year



With opening angle of 1 mrad:

14 TeV MuC as safe as LHC

Need to engineer mover system and study impact on beams

Principal Challenges — Key R&D

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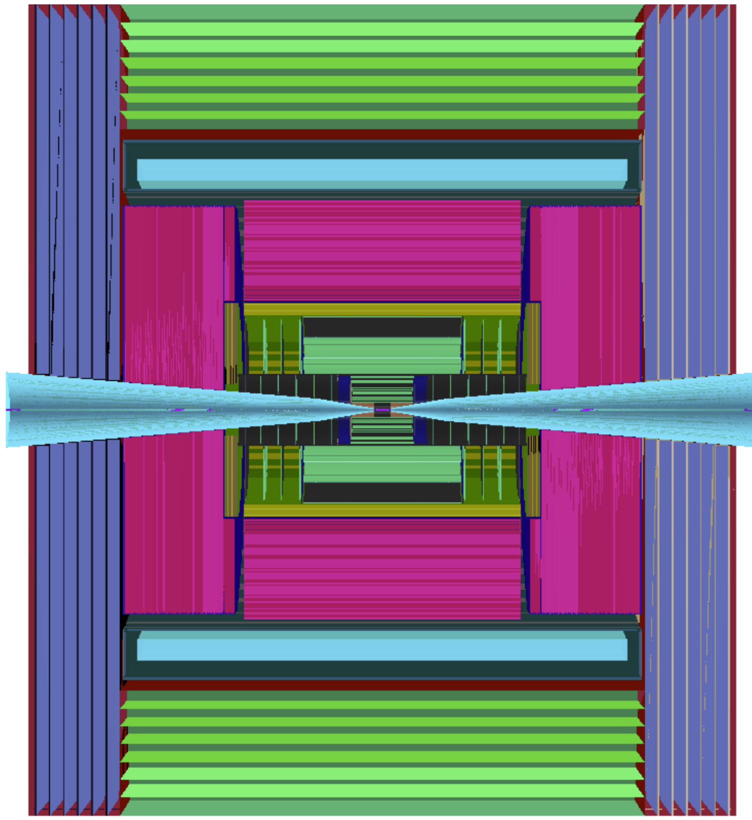
Experiment Design



Design detector for precision at multi-TeV scale

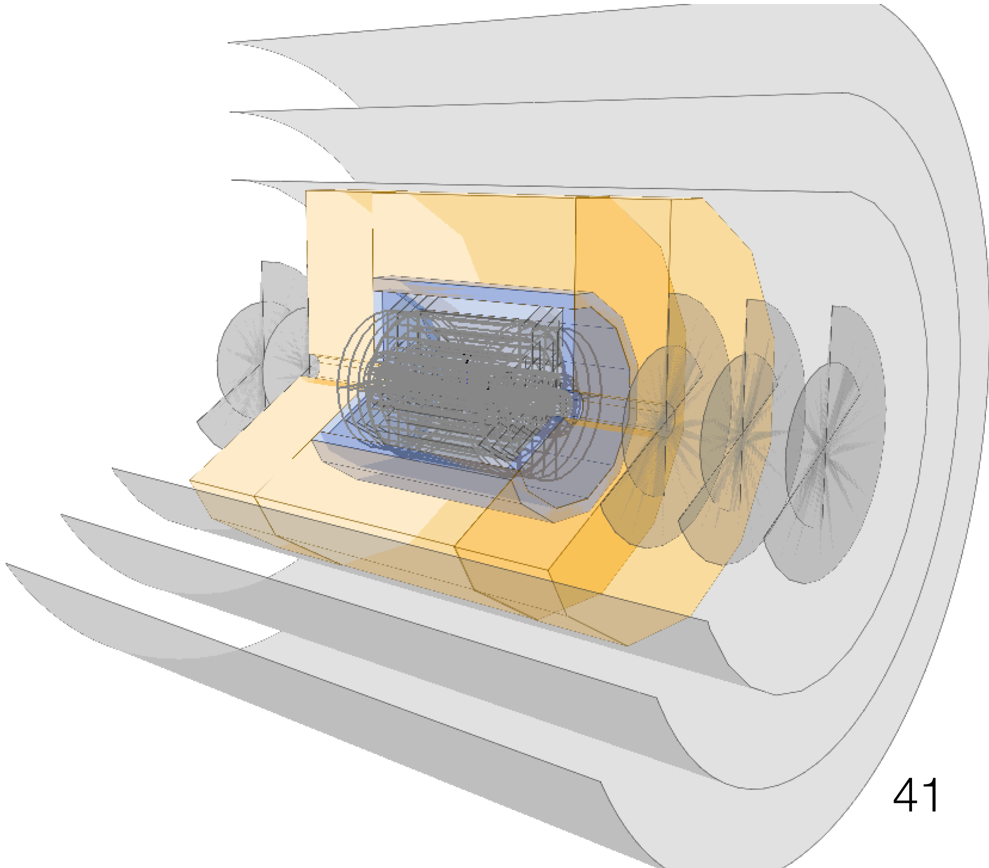
- Extract physics from GeV- and from TeV-energy particles
- Built-in sensitivity to “unconventional” signatures

The BIB is under control. See EPJC Review

- Demonstrated LHC-level performances with CLIC-like design
- Sensitivity to Higgs production
- Disappearing/short tracks detection
  → Thermal Higgsino & 3 TeV MuC!

Exciting opportunities ahead

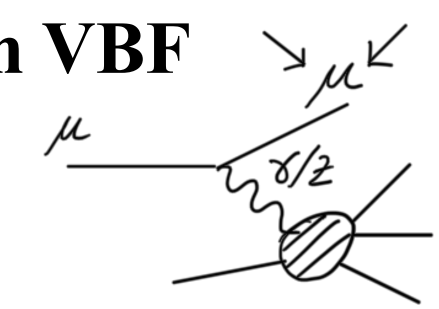
- Explore new detector concepts
- Identify and pursue key R&D requirements for technology development in next 20 years
- New challenges → new techniques that could be ported back to HL-LHC and F.C.
- Tackle the gigantic physics program of the MuC!



Target Detector performances

Requirement	**Baseline**		**Aspirational**
	$\sqrt{s} = 3$ **TeV**	$\sqrt{s} = 10$ **TeV**	
Angular acceptance	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4$
Minimum tracking distance [cm]	~ 3	~ 3	< 3
Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.5/\sqrt{E}$	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	100	10
Timing resolution (muon system) [ps]	~ 50 for $\lvert\eta\rvert > 2.5$	~ 50 for $\lvert\eta\rvert > 2.5$	< 50 for $\lvert\eta\rvert > 2.5$
Flavour tagging	b vs c	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

Note **unique** muon collider **opportunity to tag very forward muons from VBF**
→ Invisible or untagged Higgs (absolute coupling)
→ Angular correlations for Higgs CP, VBS characterisation, etc
→ Higgs-portal DM and other BSM



Physics targets for optimisation: Higgs precision; heavy resonances; disappearing tracks
Timing for BIB suppression, but also low-β particles tagging

Principal Challenges — Key R&D

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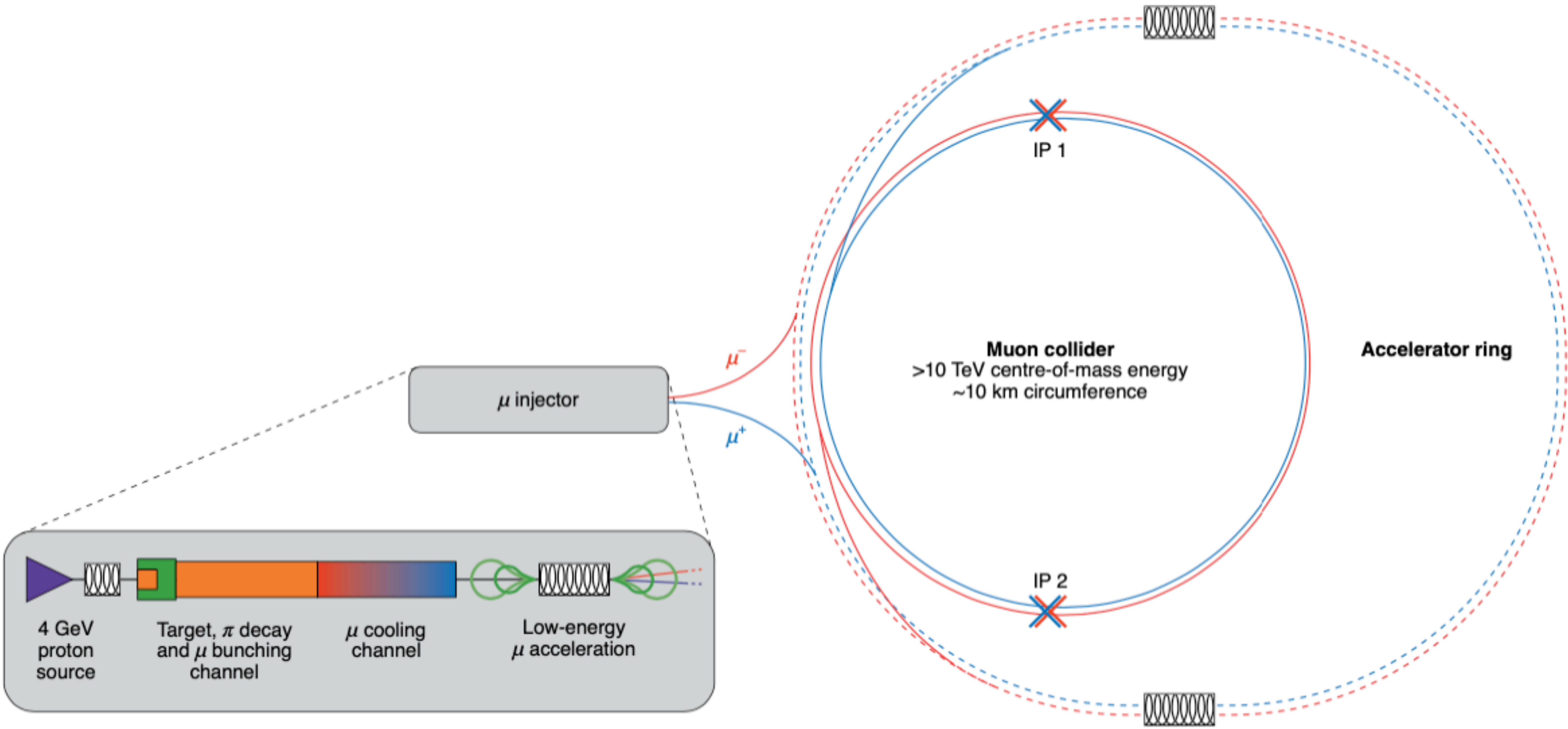
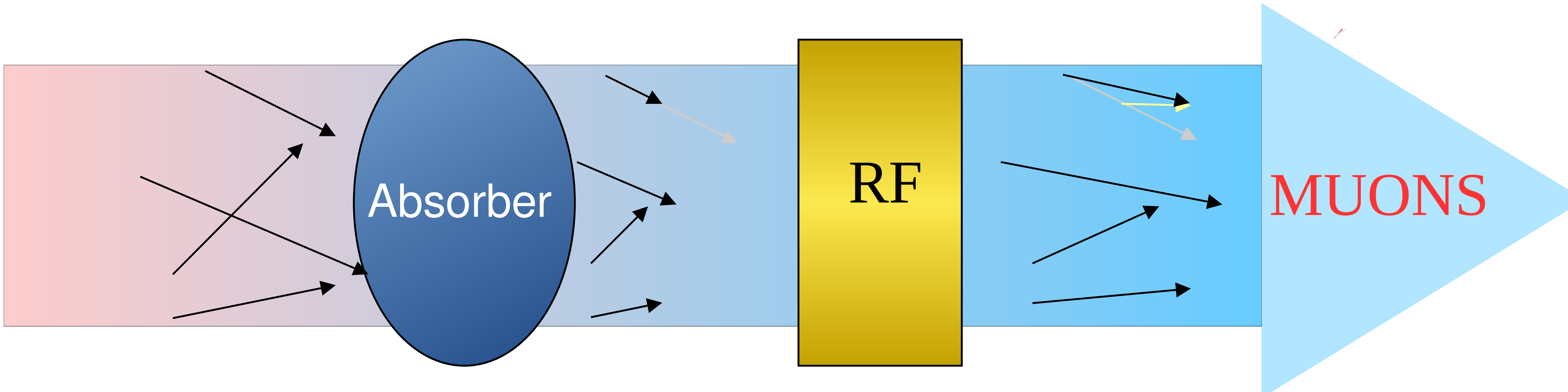
Muon Collider Facility

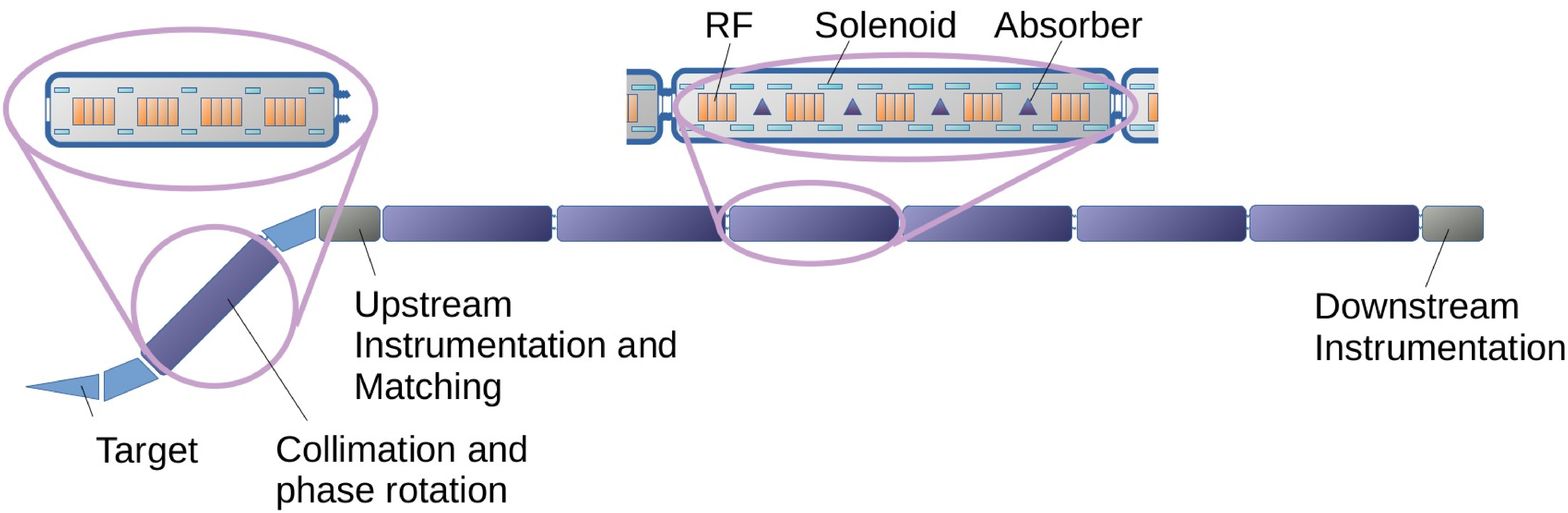


Ionisation Cooling



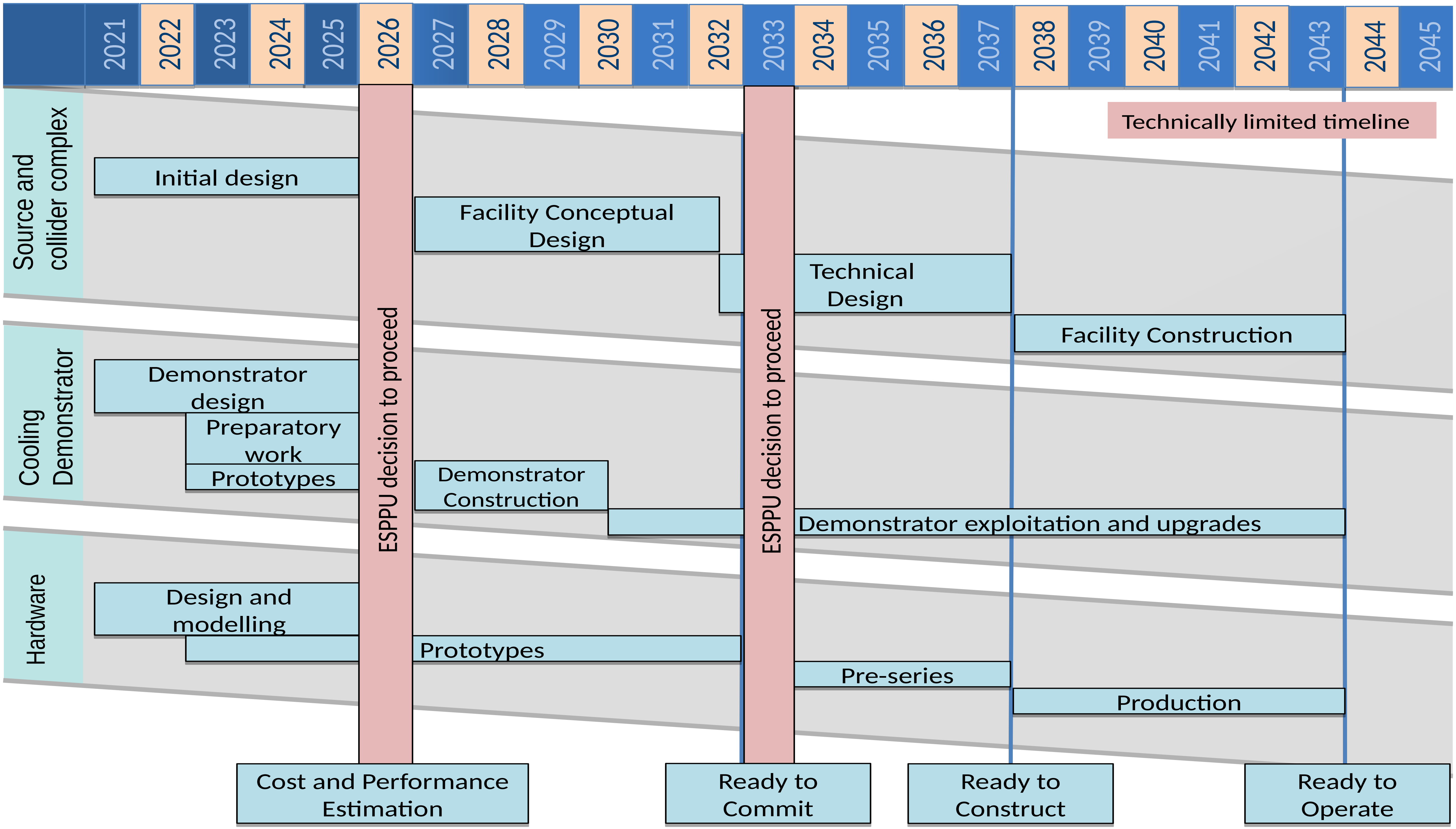
- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Demonstrated by the Muon Ionisation Cooling Experiment

Cooling Demonstrator



- Build on MICE
  - Longitudinal and transverse cooling
  - Re-acceleration
  - Chaining together multiple cells
  - Routine operation

Technically limited timeline [Stay tuned for consolidated timeline release]



Particle Physics Community

International MUON Collider Collaboration

- Huge “grass roots” interest from the particle and accelerator physics community

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
Mal	**Univ. of Malta**
BE	***Louvain***

UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**

US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
CH	**PSI**
	University of Geneva
	EPFL

KO	**KEU**
	Yonsei University
India	***CHEP***
IT	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
US	FNAL
	LBL
	JLAB
	Chicago
	Tenessee

IMCC Organisation

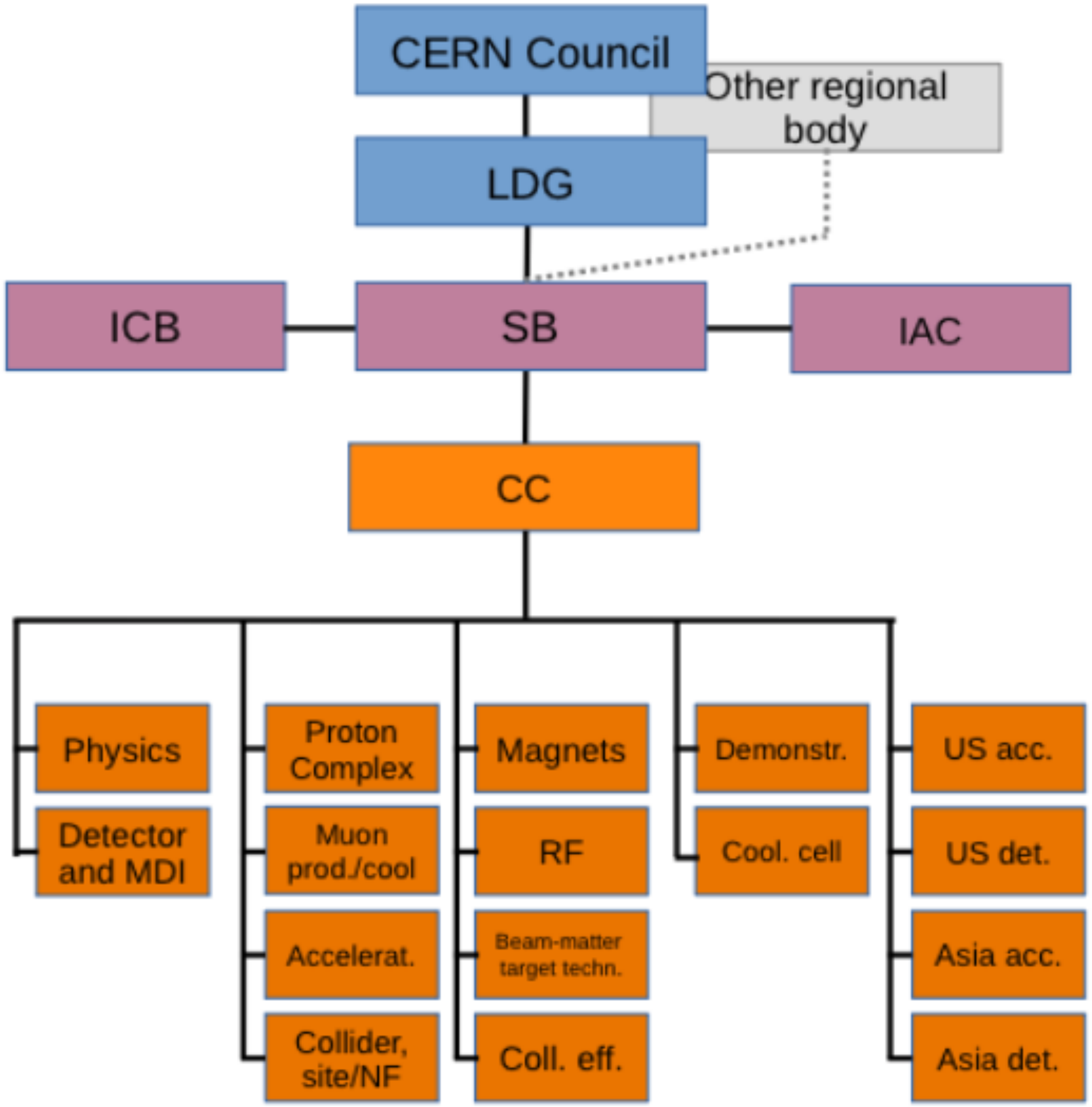
Collaboration Board (ICB)
- Elected chair: **Nadia Pastrone**
- **50 full members, 60+ total**

Steering Board (ISB)
- Chair **Steinar Stapnes**
- CERN members: Mike Lamont, Gianluigi Arduini
- ICB members: Dave Newbold (STFC), Pierre Vedrine (CEA), N. Pastrone (INFN), Beate Heinemann (DESY), successor of Mats Lindroos† (ESS)
- Study members: SL and deputies

Advisory Committee

Coordination committee (CC)
- Study Leader: **Daniel Schulte**
- Deputies: Andrea Wulzer, Donatella Lucchesi, Chris Rogers

Will integrated the US also in the leadership



Theory Challenges

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

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

Large muon collider energy

Small IR cutoff scale

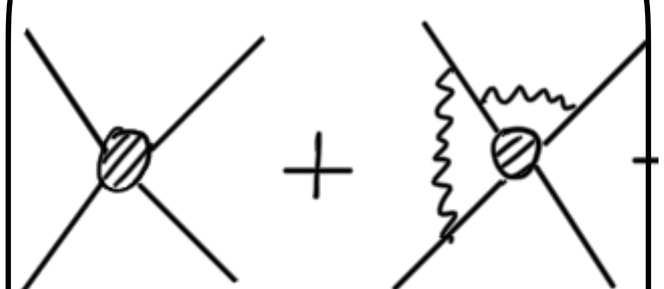
Scale separation entails enhancement of Radiation effect.

Quantitatively, resummation is needed.

10 TeV MuC

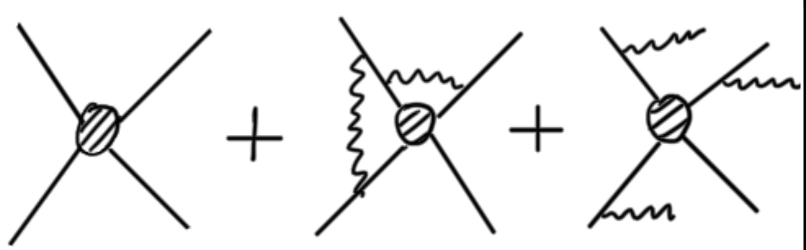
$$\exp\left[-g^2/16\pi^2 \log^2(E_{\rm cm}^2/m_{\rm w}^2) \times {\rm Casimir}\right] \approx \exp[-1]$$

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.

= charged

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

Technically limited timeline