Multi-TeV Muon Collider Design Study

towards the European Strategy for Particle Physics Update @ 2025-26

International MUON Collider Collaboration

Direct searches	High-rate measurements	High-energy probes	Muon physics
Pair production, Resonances, VBF, Dark Matter, …	Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, …	Di-boson, di-fermion, tri-boson, EFT, compositeness, …	Lepton Flavor Universality, b → sμμ, muon g-2, …

***INFN** groups in **RD_MUCOL @ CSN1**:* ~ 120 people/25 FTE

RD_MUCOL @ CSN1 – ESPP_A_MUCOL @ GE – UE-MUCOL – UE-I.FAST

BA BO FE GE MI MIB LNF LNL LNS NA PD PI PV RM1 RM3 TO TS

Physics, Detector R&D, MDI, Crystals/Targets, Accelerator Activities

iFAST — AIDA innova — EURO-LABS (European Laboratories for Accelerator Based Sciences) — aMUSE — IRIS (Innovative Research Infrastructure on applied Superconductivity) — MuCol

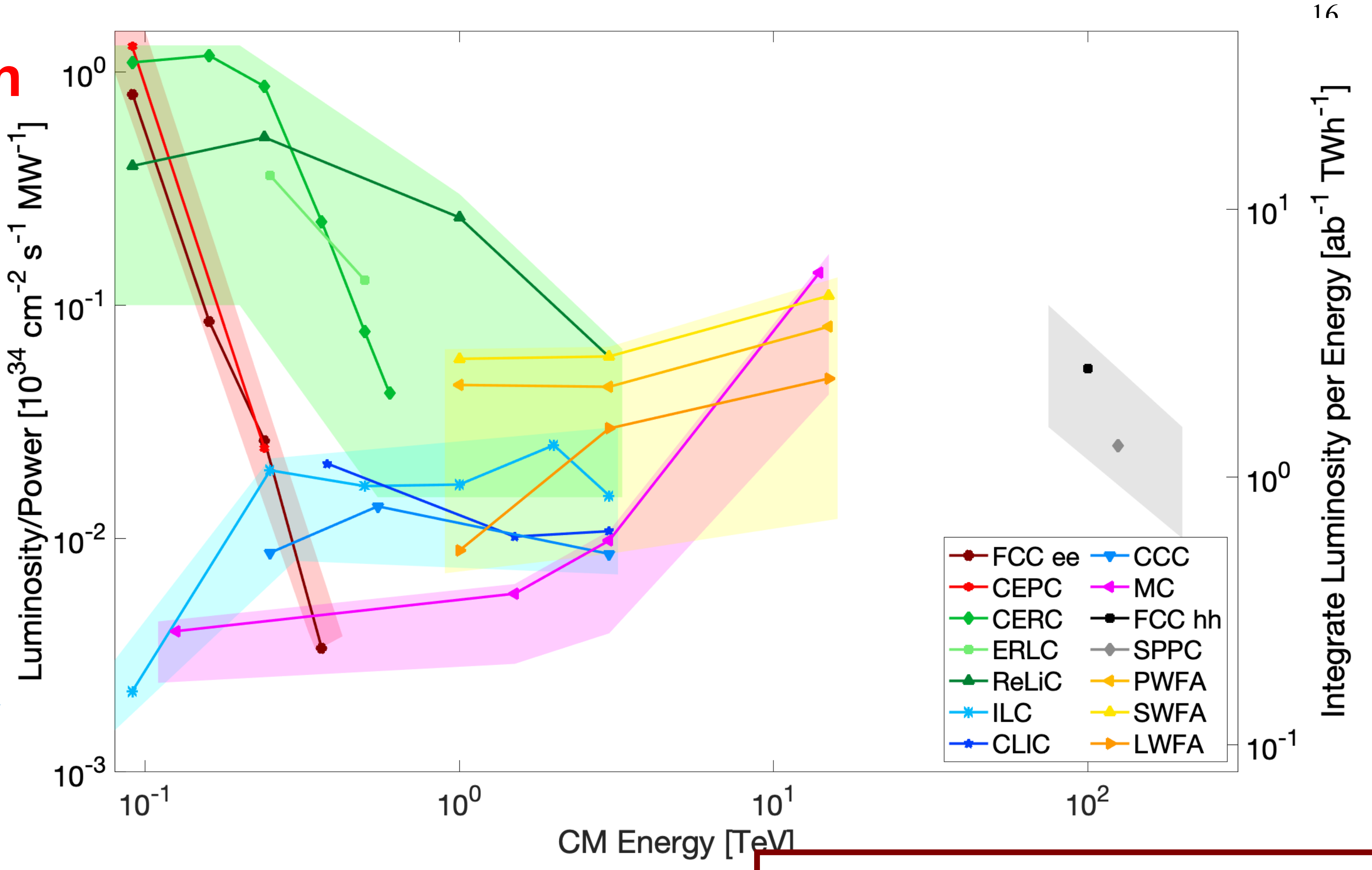
HORIZON-INFRA-2022-DEV-01-01

Energy efficiency of present and future colliders

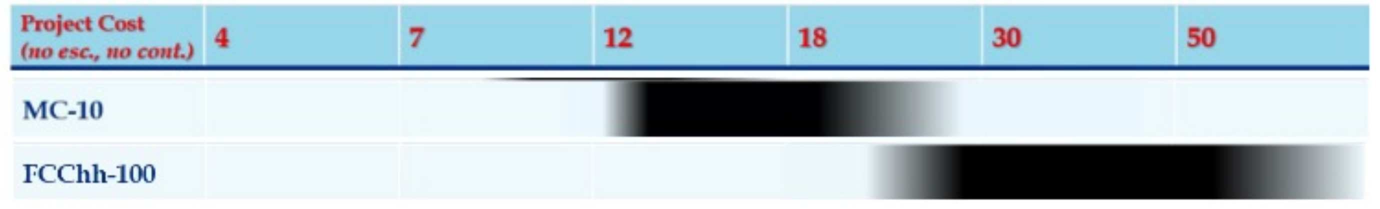
Thomas Roser et al., Report of the Snowmass 2021 Collider Implementation Task Force, Aug 2022

Luminosity per power consumption

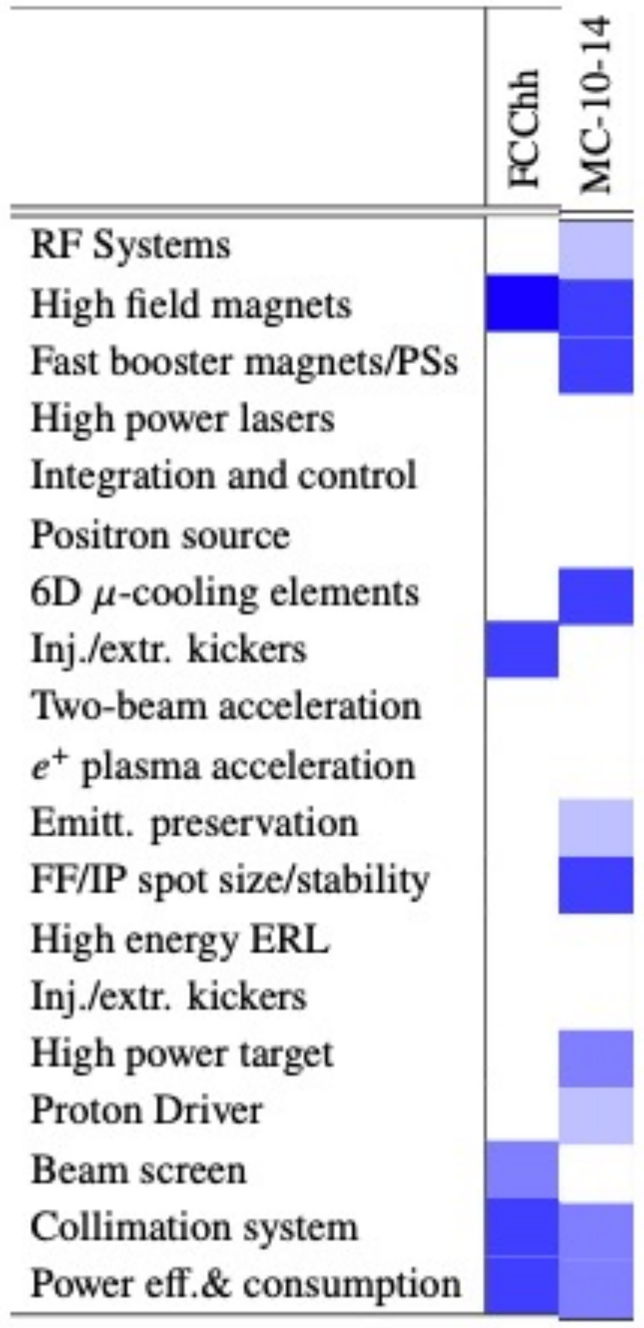
- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Luminosity is per IP and integrated luminosity assumes 10^7 sec/year
- Data points are provided to the ITF by proponents of the respective machine
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



Options @ 10 TeV Scale



Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
MC (14 TeV)	~300	27 km	III	III
FCC-hh (100 TeV)	~560	91 km	II	III



The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh) is approximately a factor of seven lower than that of a lepton collider operating at the same energy per beam

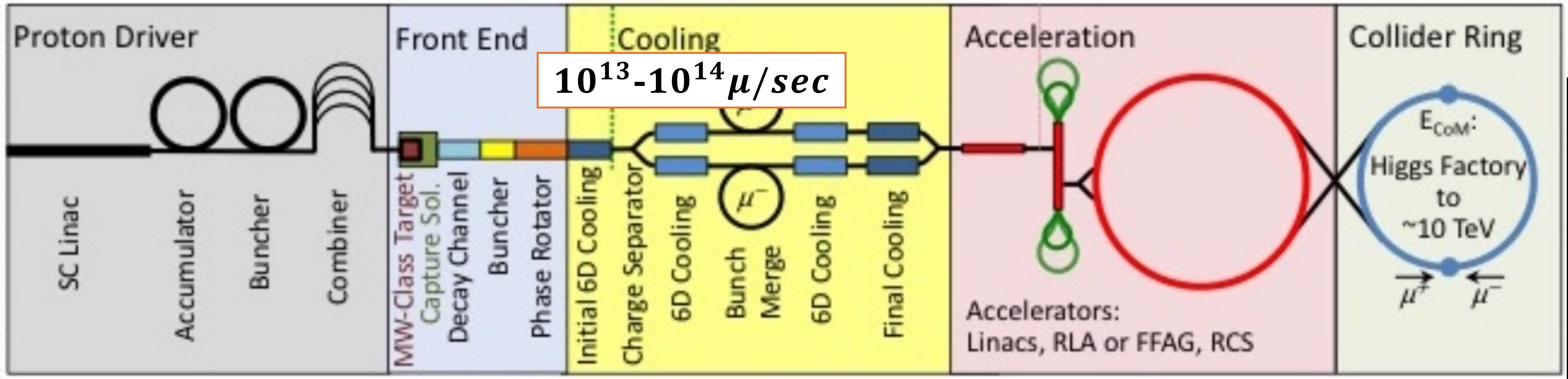
P5 report & Muon Collider & key messages

…
Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities 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.**

proton (MAP) vs positron driven muon source

Fully driven by muon lifetime

MAP

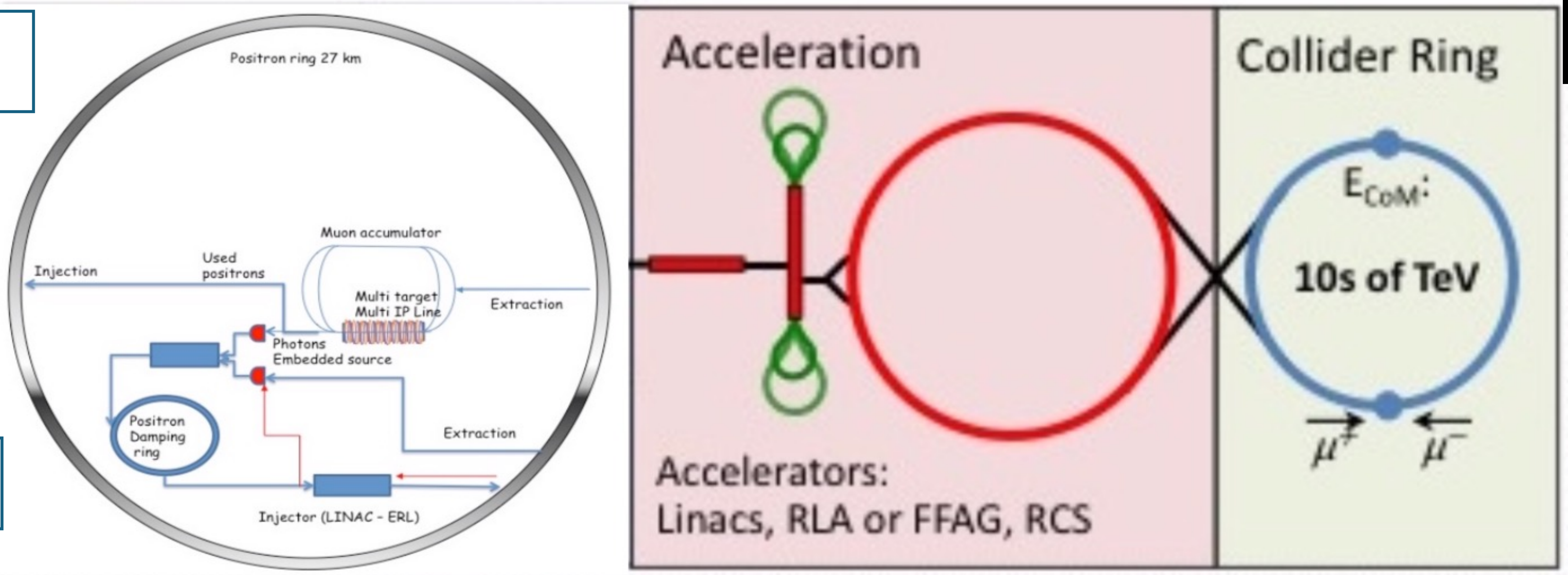


10^{13}-10^{14} μ/sec

[MUON JINST collection]

LEMMA

e+ source



[arXiv:1905.05747v2] **[physics.acc-ph]**

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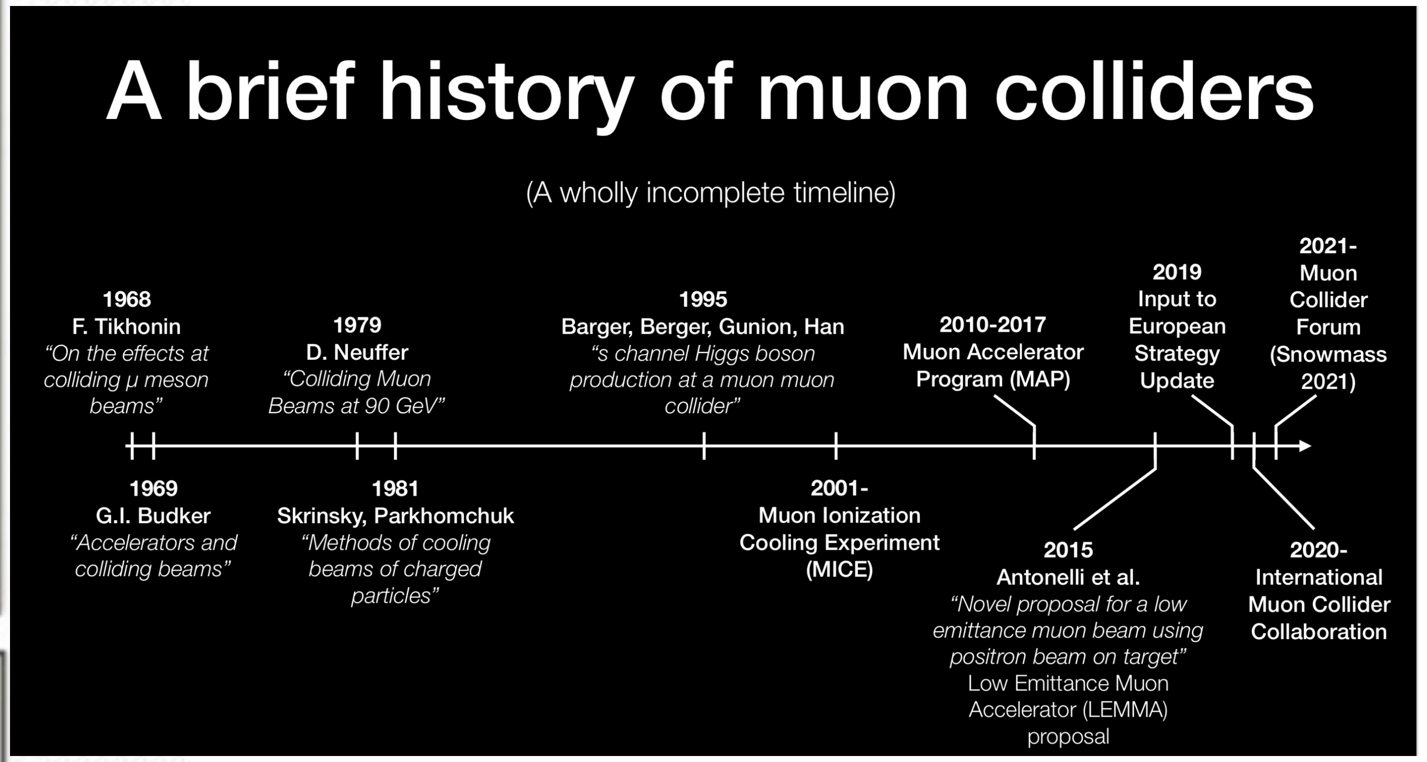


Muon Collider Working Group

*Jean Pierre Delahaye (CERN), Marcella Diemoz (INFN-IT), Ken Long (Imperial College-UK), Bruno Mansoulie (IRFU-FR), **Nadia Pastrone** (INFN-IT) **(chair)**, Lenny Rivkin (EPFL & PSI-CH), Daniel Schulte (CERN), Alexander Skrinsky (BINP-RU), Andrea Wulzer (EPFL & CERN-CH)*

High-priority future initiatives [..]

19 June 2020

[10.17181/CERN.JSC6.W89E]

In addition to the high field magnets the **accelerator R&D roadmap** could contain:

[..] an **international design study** for a **muon collider**, as it represents a **unique opportunity** to achieve a ***multi-TeV energy domain*** *beyond the reach of* e^+e^- *colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The **biggest challenge** remains to produce an intense beam of cooled muons, but *novel ideas are being explored.*

Accelerator R&D Roadmap - implementation

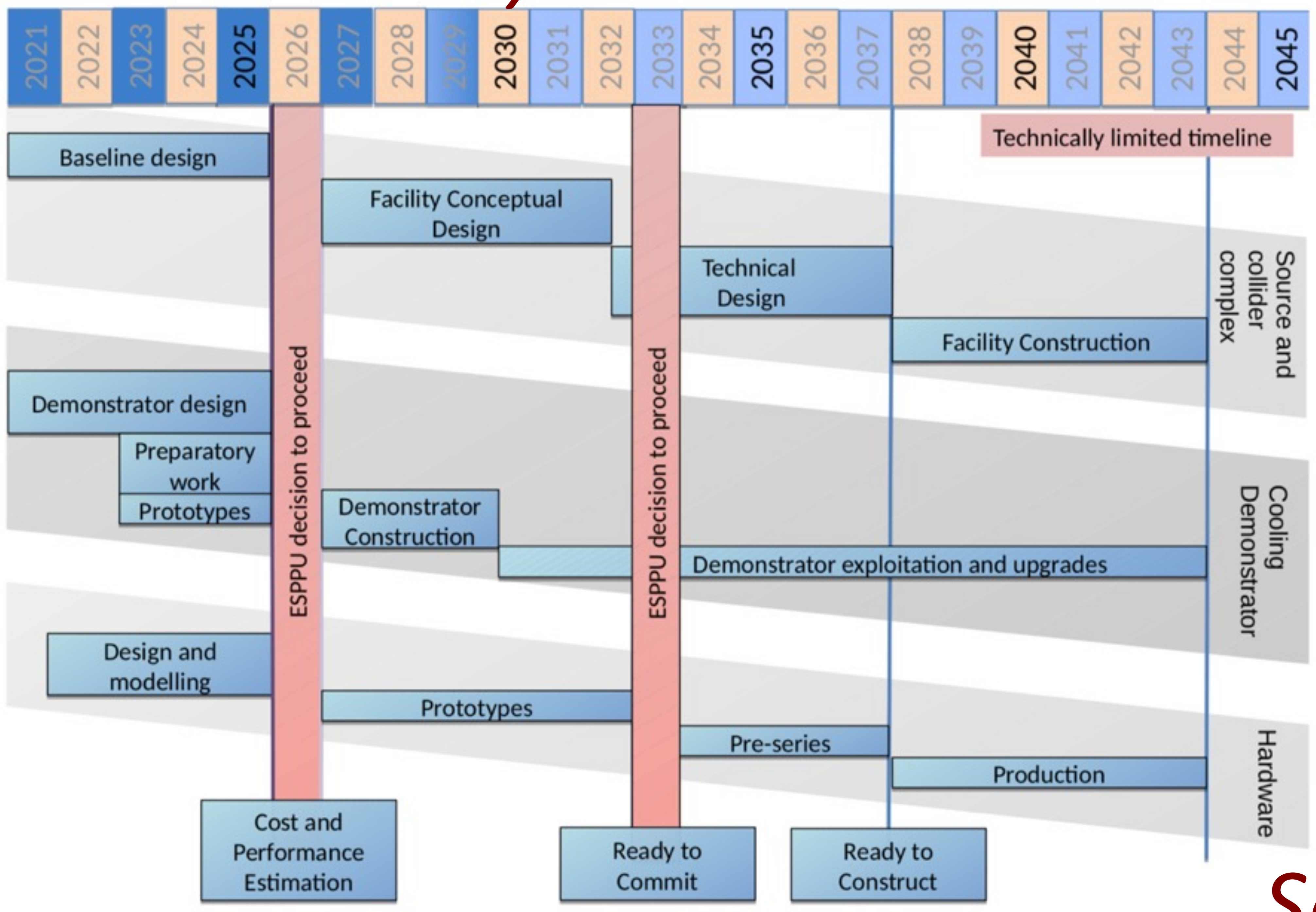
Bright Muon Beams and Muon Colliders

Panel members: **D. Schulte**,(Chair), M. Palmer (Co-Chair), T. Arndt, A. Chancé, J. P. Delahaye, A.Faus-Golfe, S.Gilardoni, P.Lebrun, K.Long, E.Métral, **N.Pastrone**, L.Quettier, T.Raubenheimer, C.Rogers, M.Seidel, D.Stratakis, A.Yamamoto
Associated members: A. Grudiev, R. Losito, **D. Lucchesi**

International MUON Collider Collaboration

presented to CERN Council in December 2021
published https://arxiv.org/abs/2201.07895

Technically limited timeline



Development path to deliver a 3 TeV muon collider after HL-LHC

Roadmap Plan

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

MDI

Dipoles/solenoids
High field
(Nb3Sn, HTS?)

RF cavities
SC e NC

Cooling cell
Demonstrator

Scenarios

Aspirational		Minimal	
[FTEy]	[kCHF]	[FTEy]	[kCHF]
445.9	11875	193	2445

~70 Meu/5 years

Project Organization

Study Leader: **Daniel Schulte**

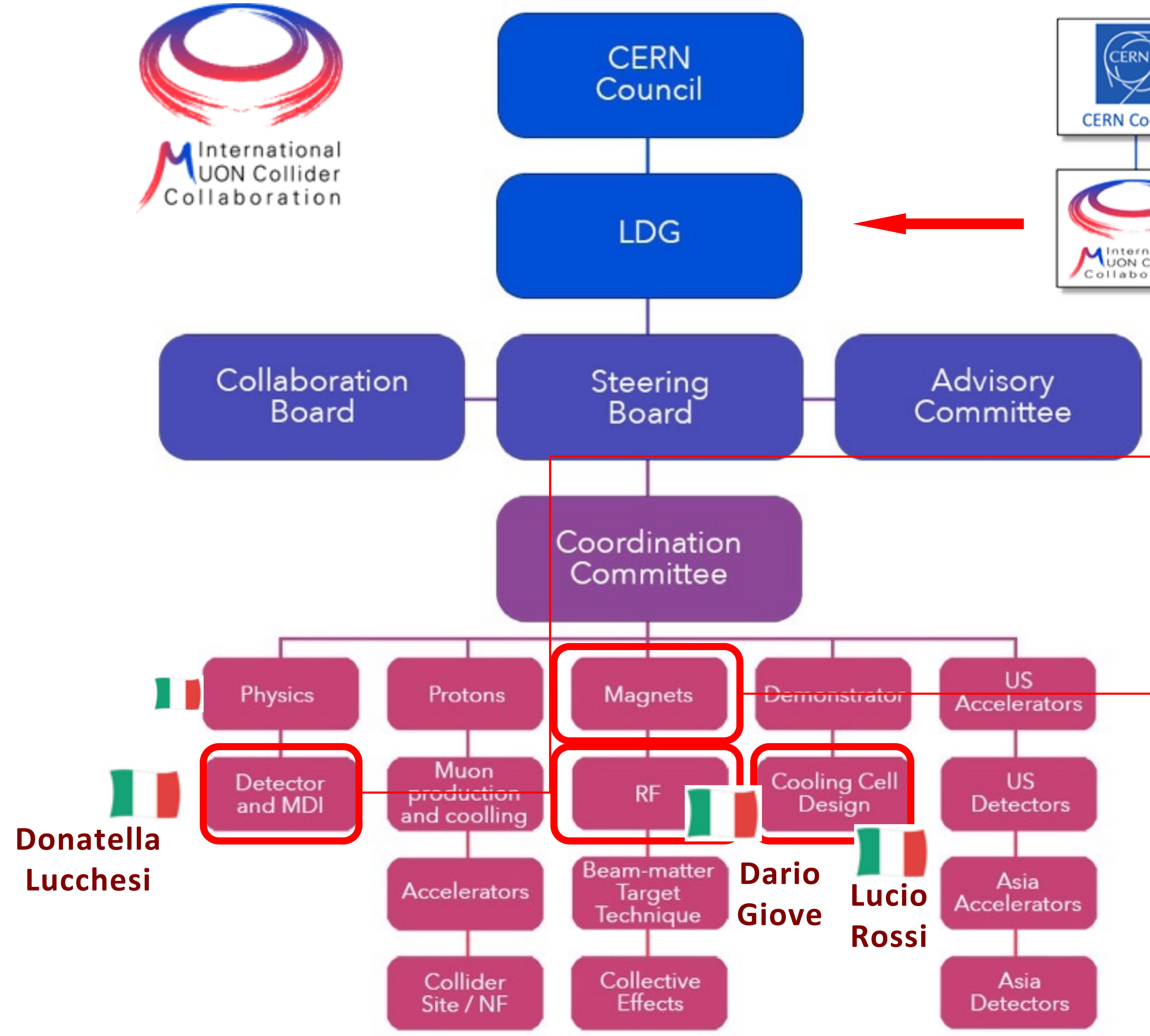
Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**

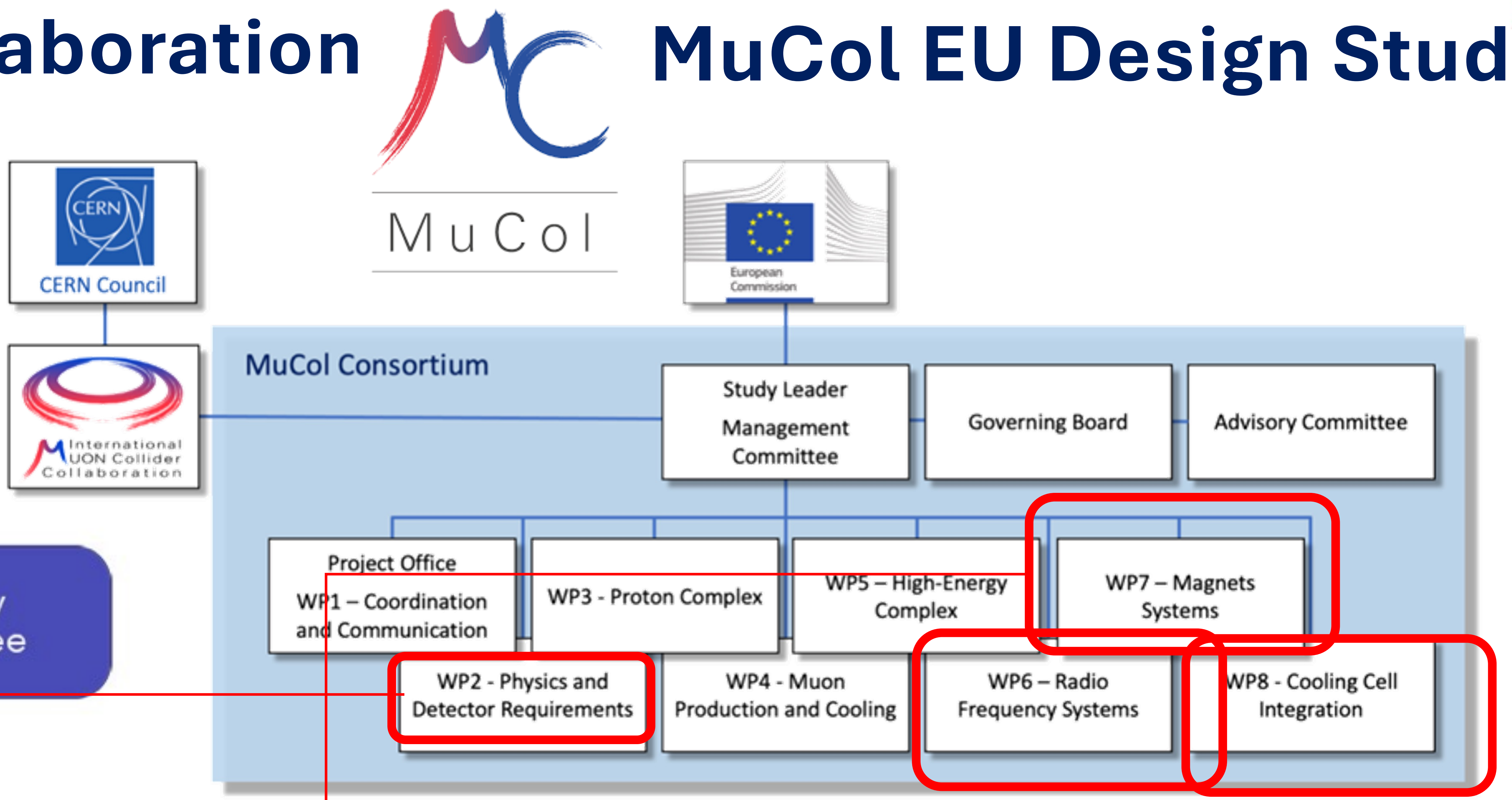
After the ESPPU recommendation in June 2020:
Laboratory Directors' Group (LDG)
initiated the Muon Collider Collaboration July 2, 2020

Collaboration Board (ICB) elected chair **Nadia Pastrone**

International Muon Collider Collaboration

MuCol EU Design Study





INFN is deeply involved and play the role of main responsibility or at least deputy responsibility on the outlines WP:

- WP6 RadioFrequency Systems
- WP7 Magnets Systems
- WP8 Cooling cell Integration
- WP2 Physics&Detector – MDI

19 countries: CERN, IT, US, UK, FR, DE, CH, ES.. CHINA, KOREA, INDIA…. Interest from Japan **80 institutes ++**

International Muon Collider Collaboration @ CERN

International
MUON Collider
Collaboration

Objective

In time for the next European Strategy for Particle Physics Update, the Design Study based at CERN since 2020 aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

It will **provide a baseline concept**, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.

It will also **identify an R&D path to demonstrate the feasibility of the collider**.

Scope

Focus on the high-energy frontier and two energy ranges:

– **3 TeV** with technology ready for construction in 10-20 years

– **10+ TeV** with more advanced technology, **the reason to choose muon colliders**

NEW OPTION: initial 10 TeV stage at reduced luminosity

- Develop initial stage to start operation by 2050: lower energy or luminosity
- Identify potential sites
- Explore synergies with other facilities' options (neutrino/higgs factory)
- Define **R&D path**

Reviews of the muon collider concept in Europe and US found no insurmountable obstacle

First ECFA-INFN ECR Meeting

MuCol

Istituto Nazionale di Fisica Nucleare

Università degli Studi di Padova

International Muon Collider Collaboration

The Muon Collider project

DAVIDE ZULIANI[1,2], ON BEHALF OF IMCC

Co-funded by the European Union

LNF, FRASCATI - 03/07/2024

[1]INFN PADOVA, [2]INFN TRIESTE, [3]UNIVERSITÀ DI PADOVA

*FOR INFO: DAVIDE.ZULIANI@CERN.CH

What to do after LHC?

And most importantly, why?

CREDITS: R. FRANCESCHINI

Open Questions on the "big picture" on fundamental physics circa 2020

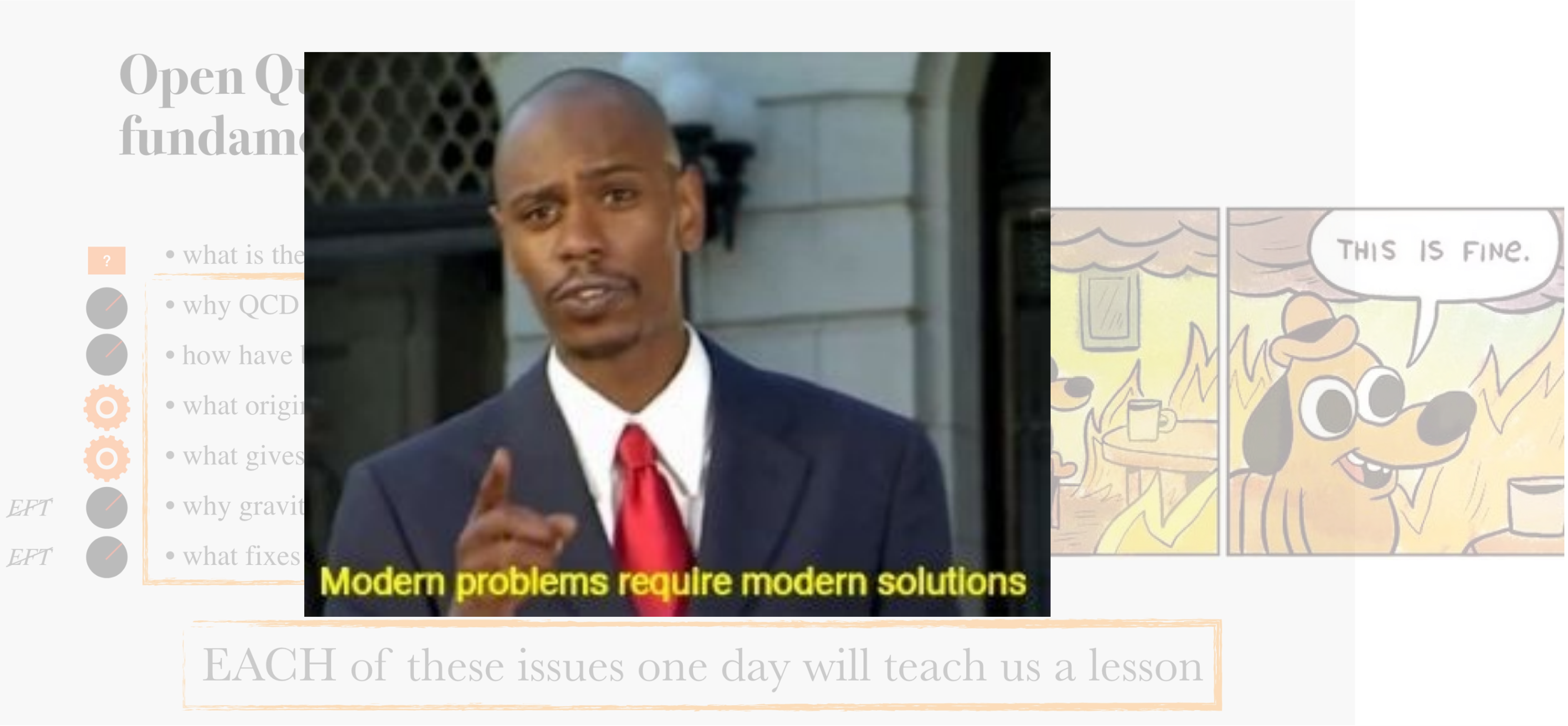
- ? what is the dark matter in the Universe?
- why QCD does not violate CP?
- how have baryons originated in the early Universe?
- what originates flavor mixing and fermions masses?
- what gives mass to neutrinos?
- ~~EFT~~ why gravity and weak interactions are so different?
- ~~EFT~~ what fixes the cosmological constant?

EACH of these issues one day will teach us a lesson

What to do after LHC?

And most importantly, why?

CREDITS: R. FRANCESCHINI

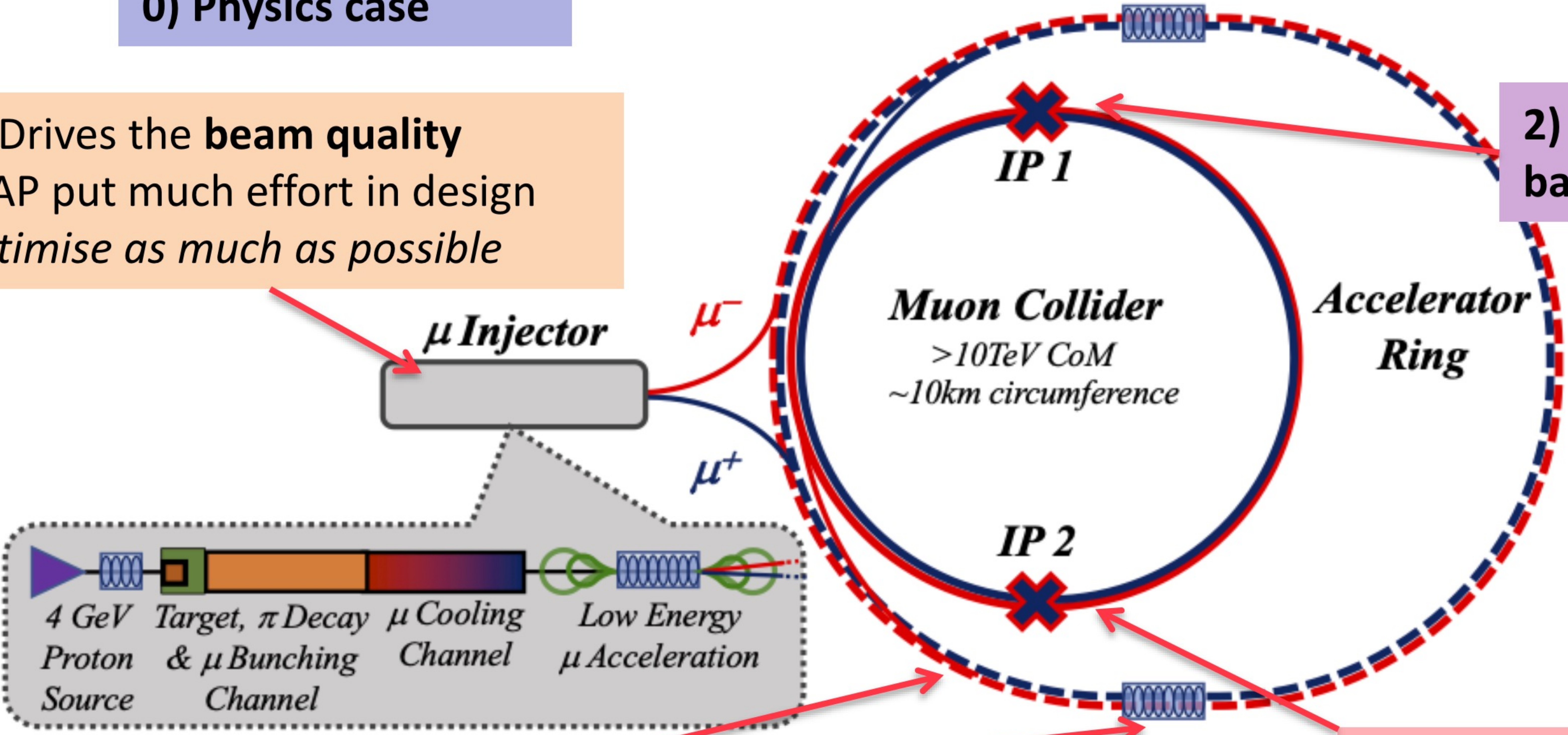


The Muon Collider machine

The “Dream Machine”

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible



2) Beam-induced background

1) **Dense neutrino flux**
mitigated by mover system
and site selection

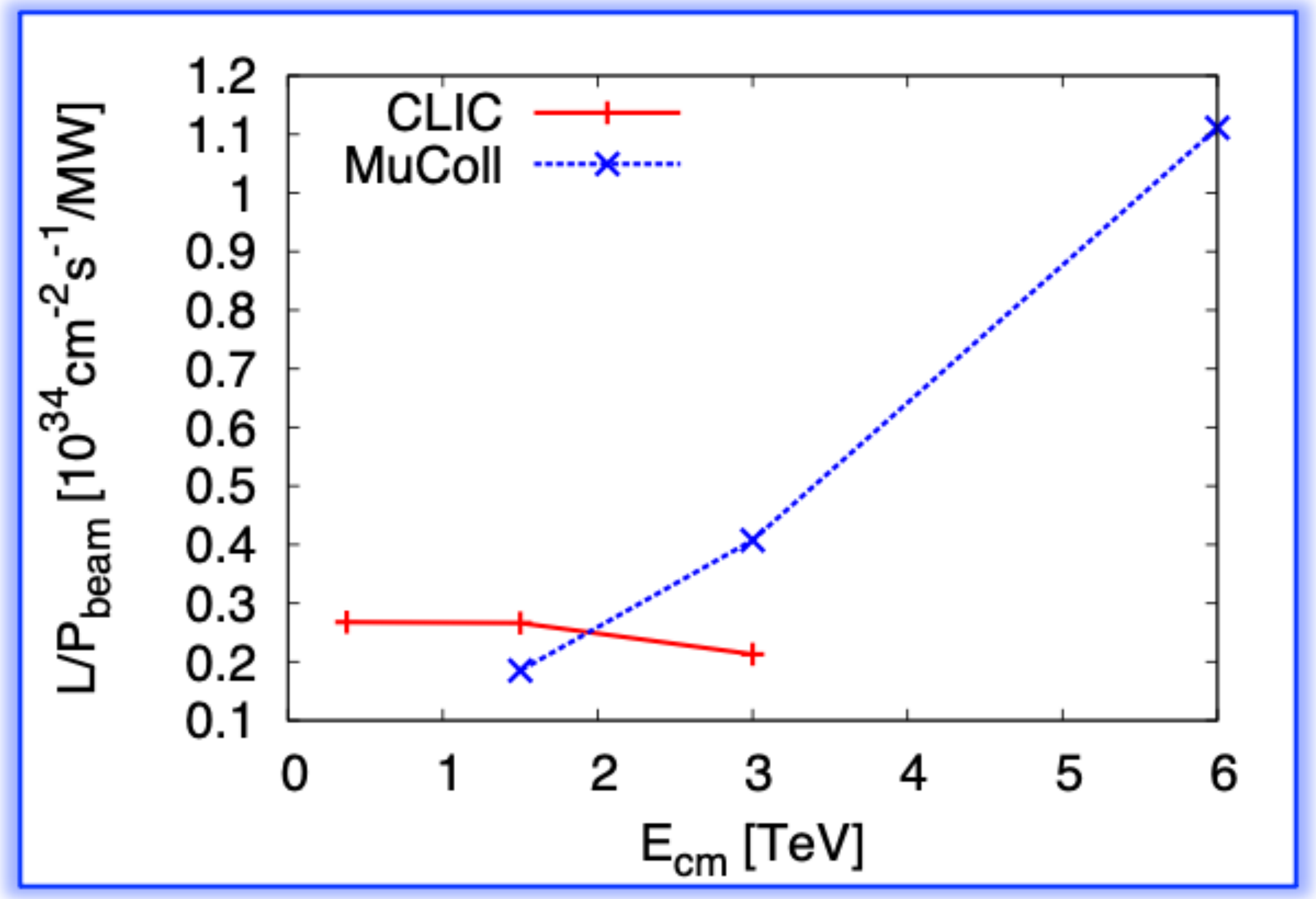
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

CREDITS: D. SCHULTE

Pros of a Muon Collider

Yay!

$$P^{sync} \sim \frac{\alpha}{R^2}\left(\frac{E}{m}\right)^4$$ ➡ Possible to accelerate to very high energy

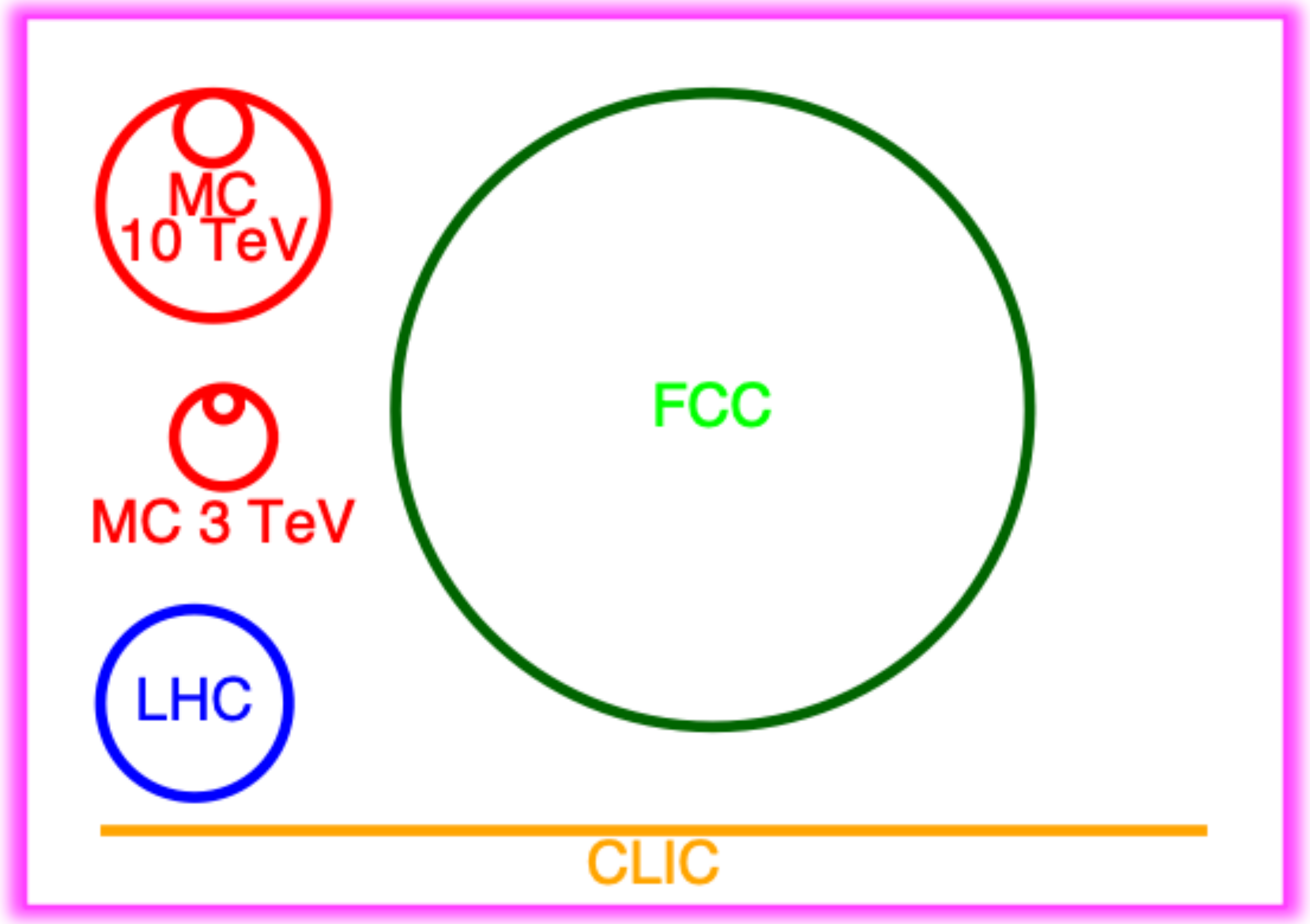


High center of mass energy & high luminosity & power efficient: luminosity increase per beam power

C. Accettura et al. "Towards a muon collider"

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	1×10^{34} cm^{-2} s^{-1}	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Total beam power	$P_- + P_+$	MW	5.3	14	20
Longitudinal emittance	ε_l	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_\perp$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.1
IP beta-function	$\beta^*_\perp$	mm	5	1.5	1.1
IP beam size	$\sigma_\perp$	µm	3	0.9	0.6

Compact: cost effective & sustainable

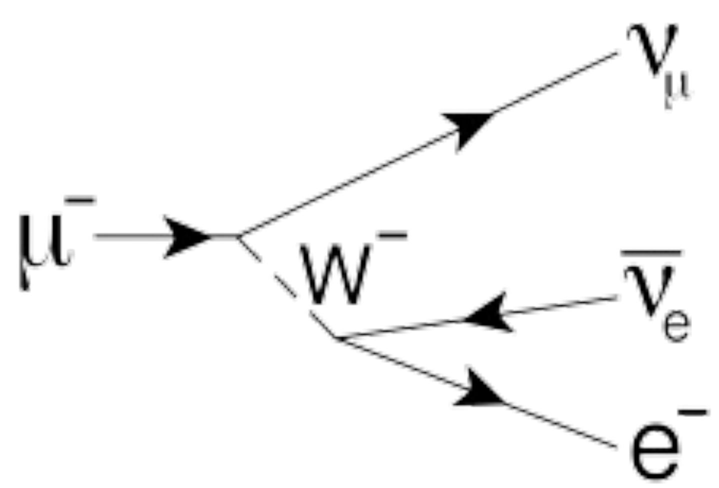


CREDITS: D. LUCCHESI

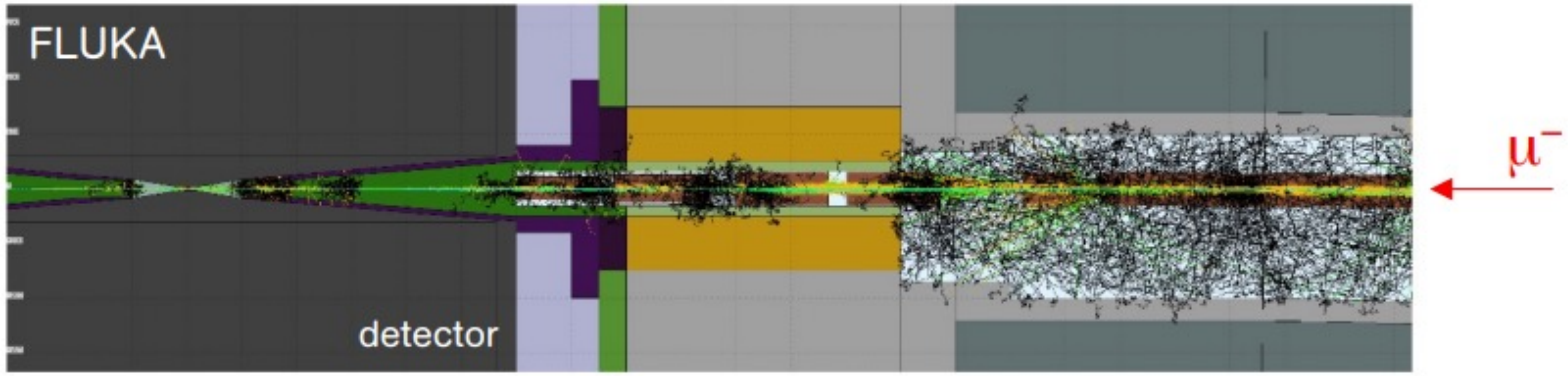
Integrated luminosity:
$\sqrt{s} = 3$ TeV 1 ab^{-1} 5 years one experiment
$\sqrt{s} = 10$ TeV 10 ab^{-1} 5 years one experiment

Cons of a Muon Collider

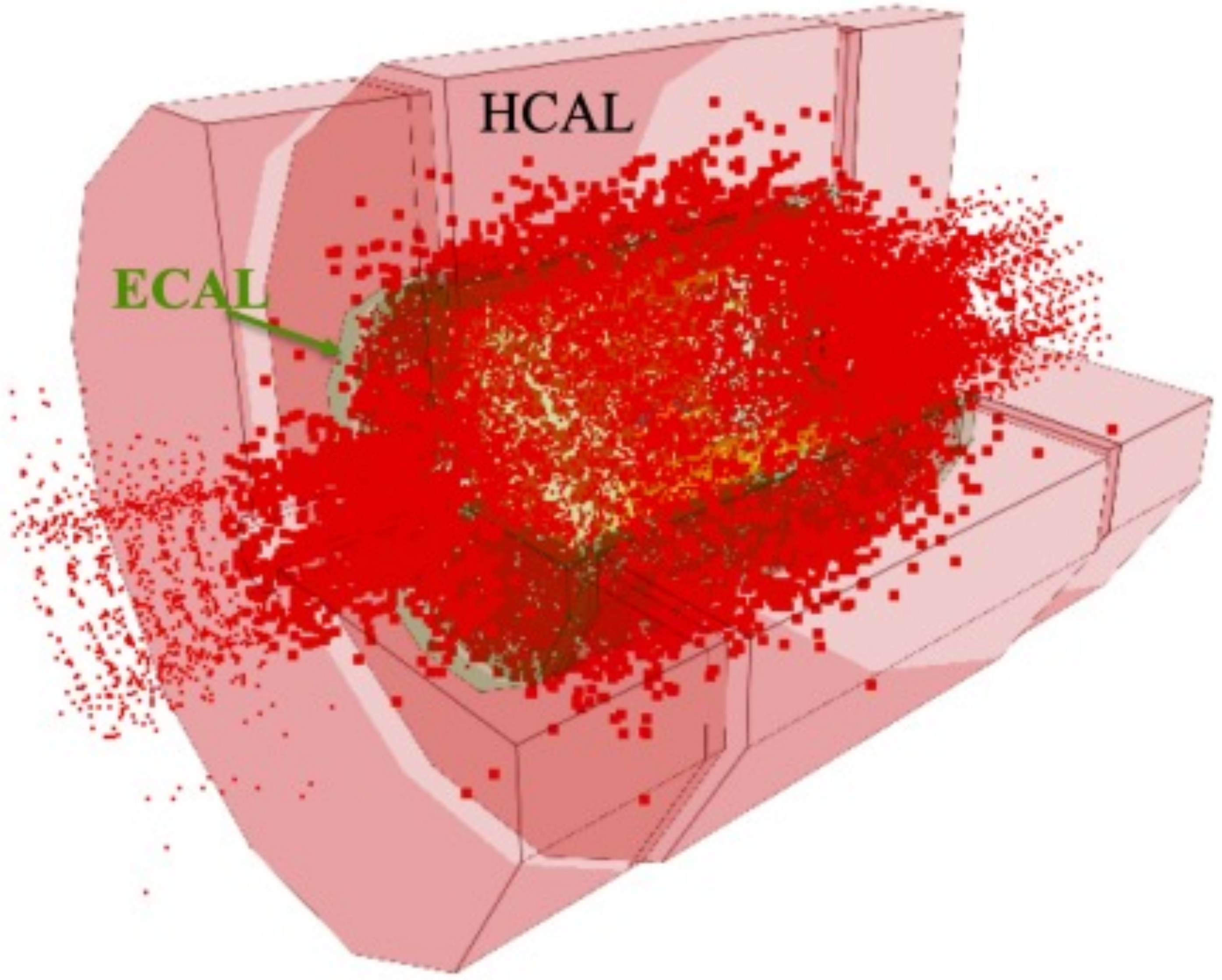
Life is not user-friendly

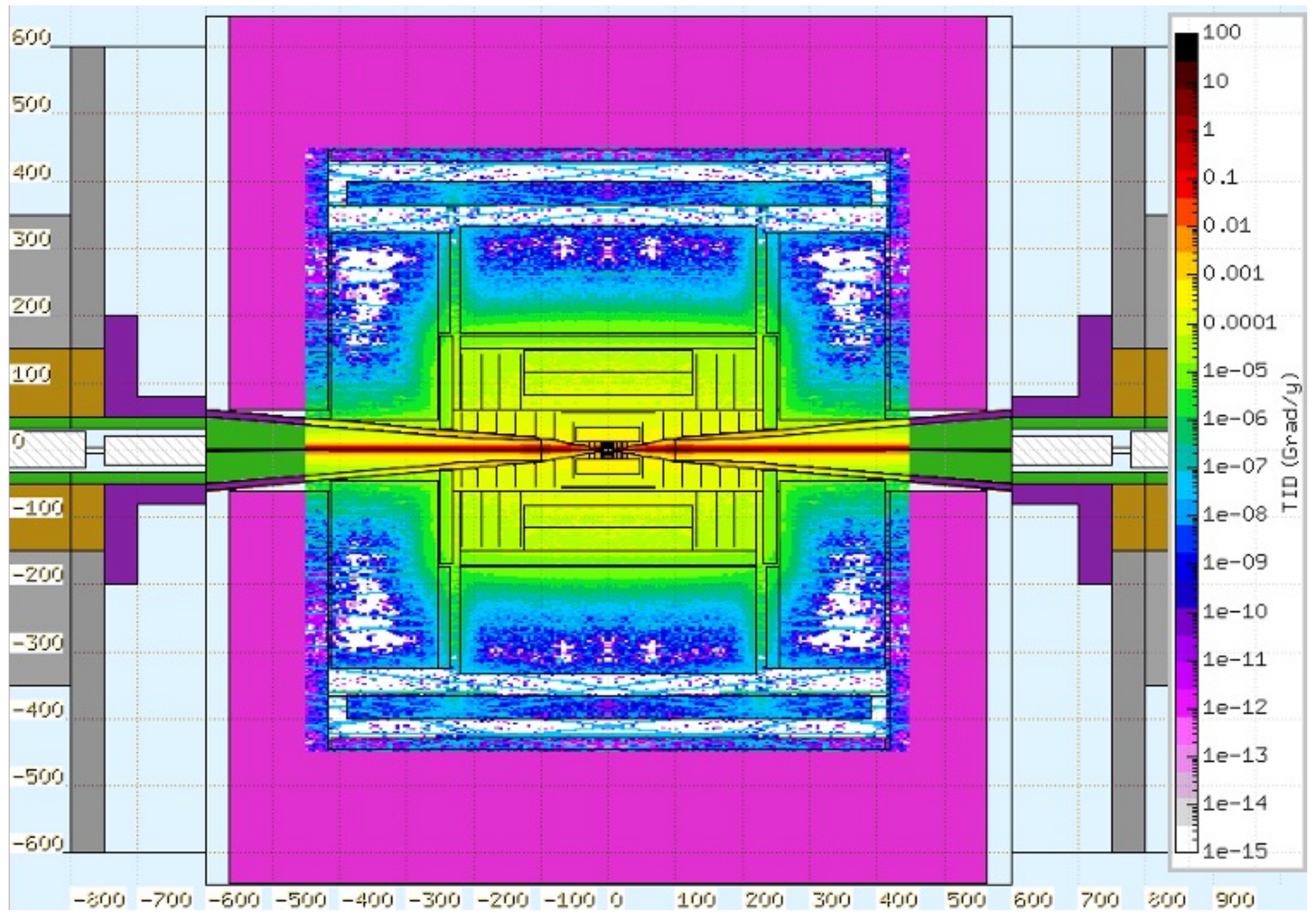


$\tau = 2.2\ \mu s$



- Muons decay :(
  - Decay products interact with machine, producing huge flux of particles
- Result:
  - Huge flux of particles interacting with detector:
    BEAM-INDUCED BACKGROUND





CREDITS: N. BARTOSIK, F. COLLAMATI, N. MOKHOV

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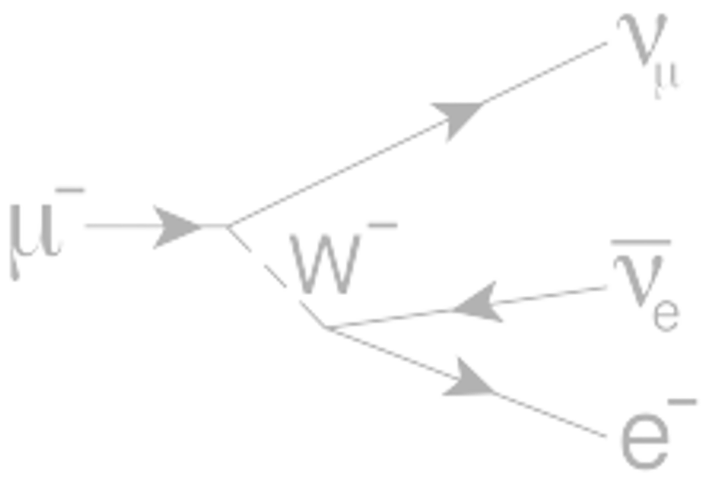

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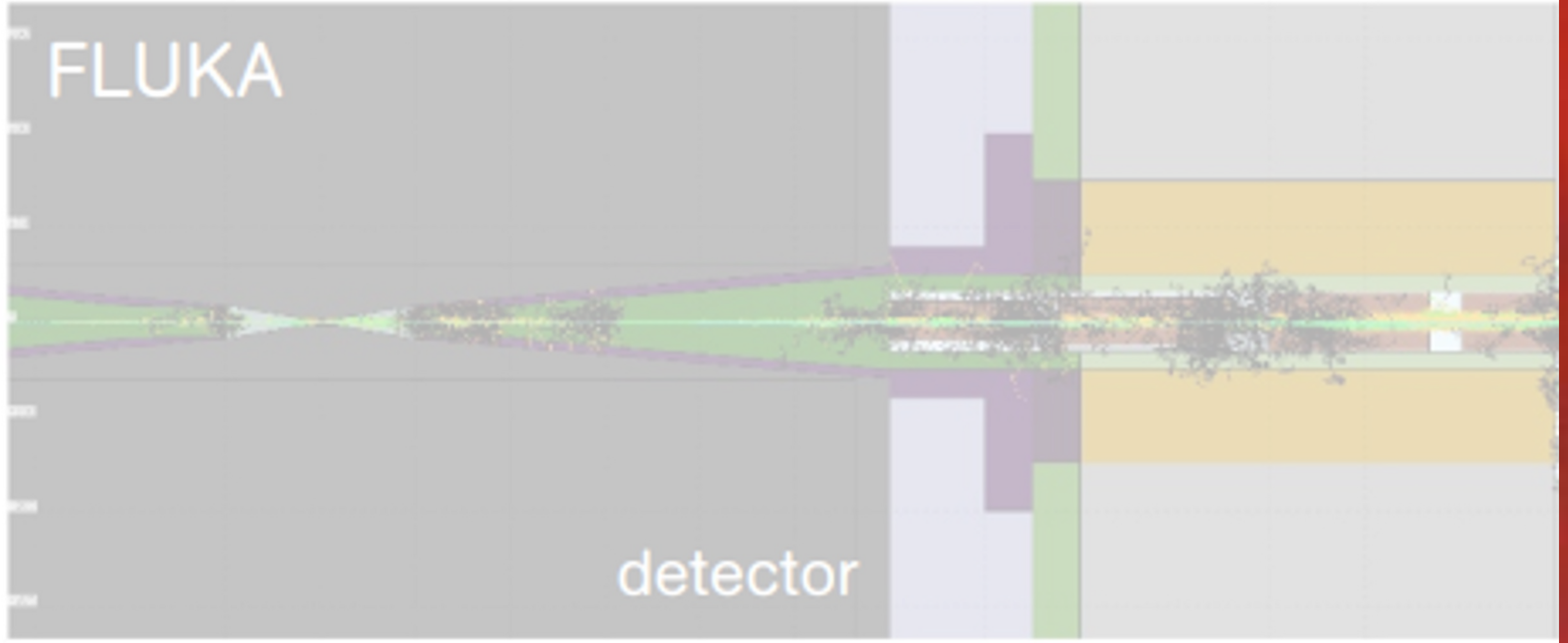

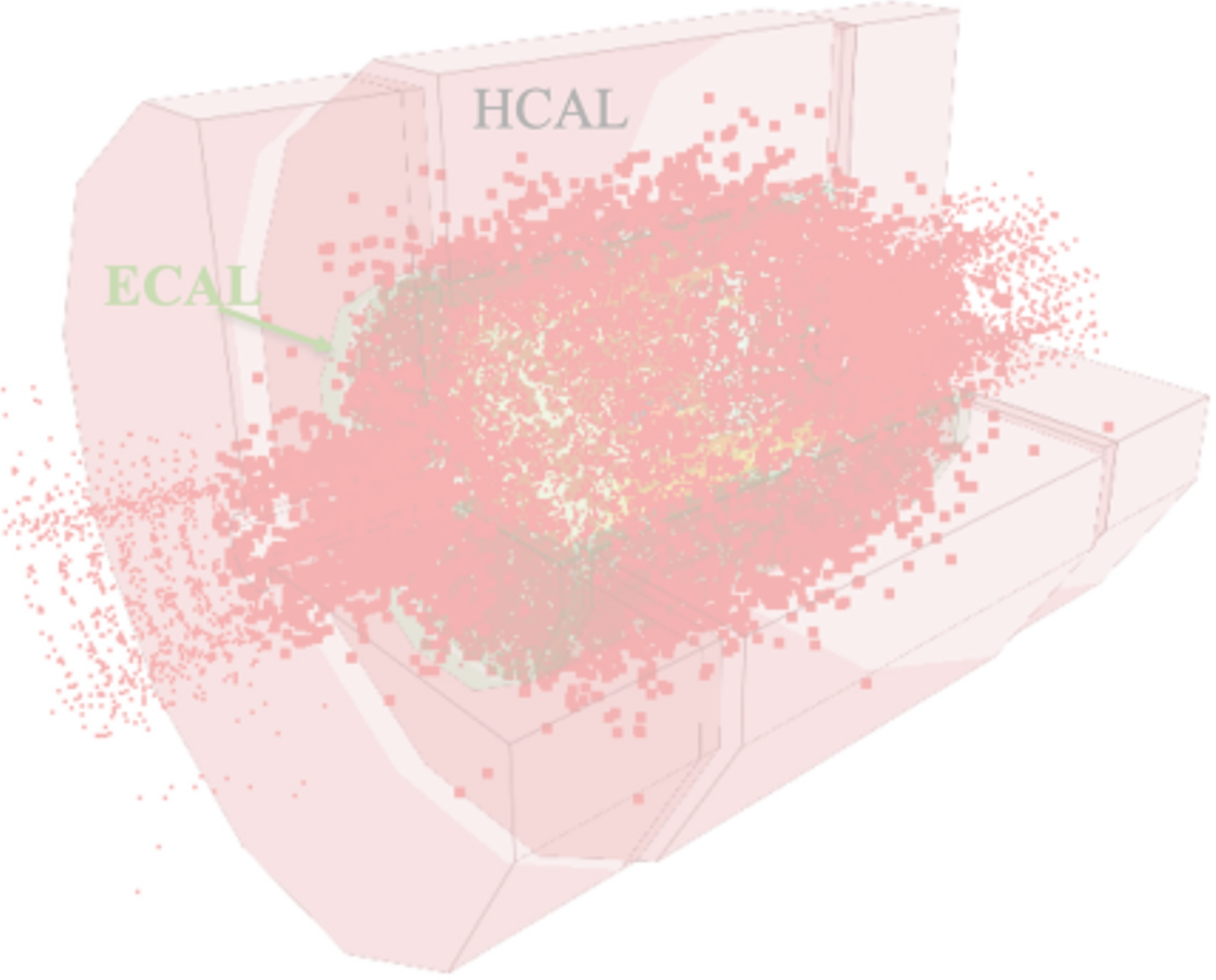

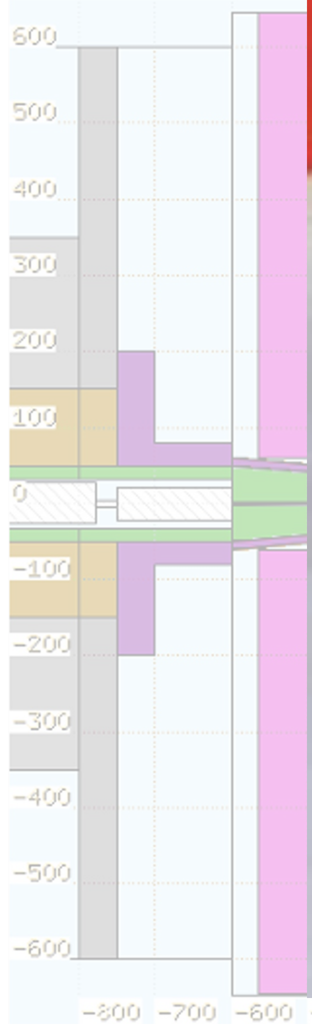

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Decay products interact with machine, producing huge flux of particles

esult:

Huge flux of particles interacting with detector:
BEAM-INDUCED BACKGROUND

Cons of a Muon Collider

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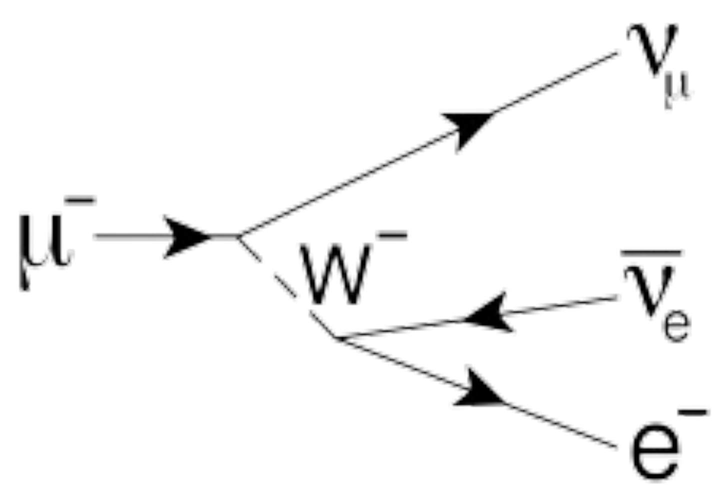
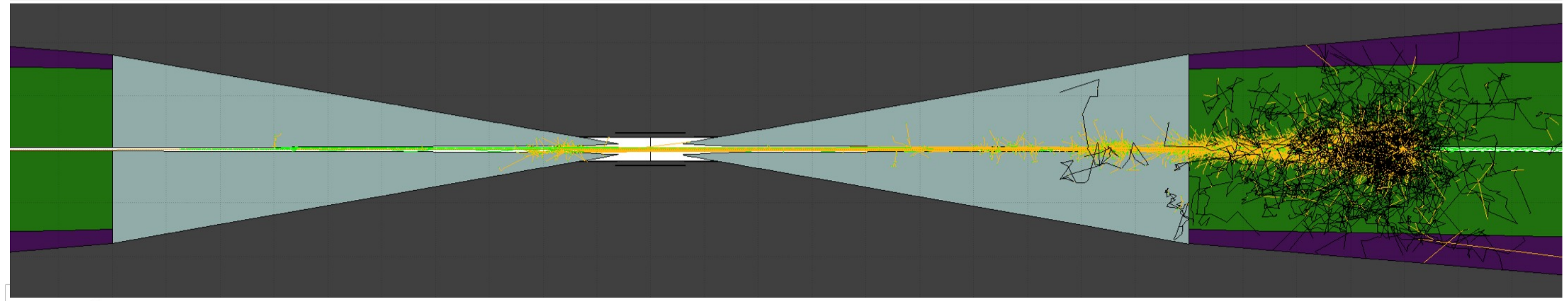


τ = 2.2 μs



- Muons decay :(
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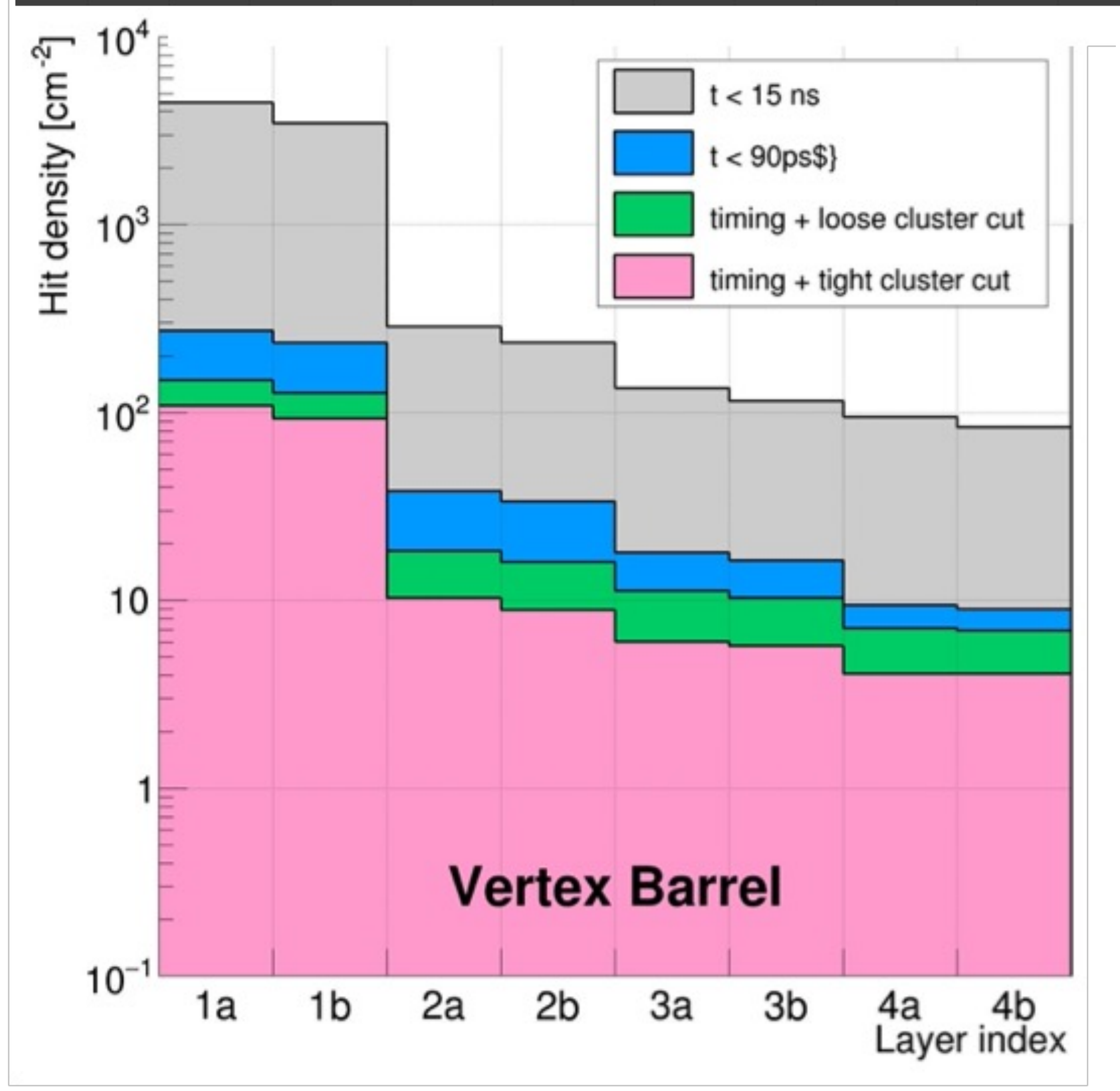
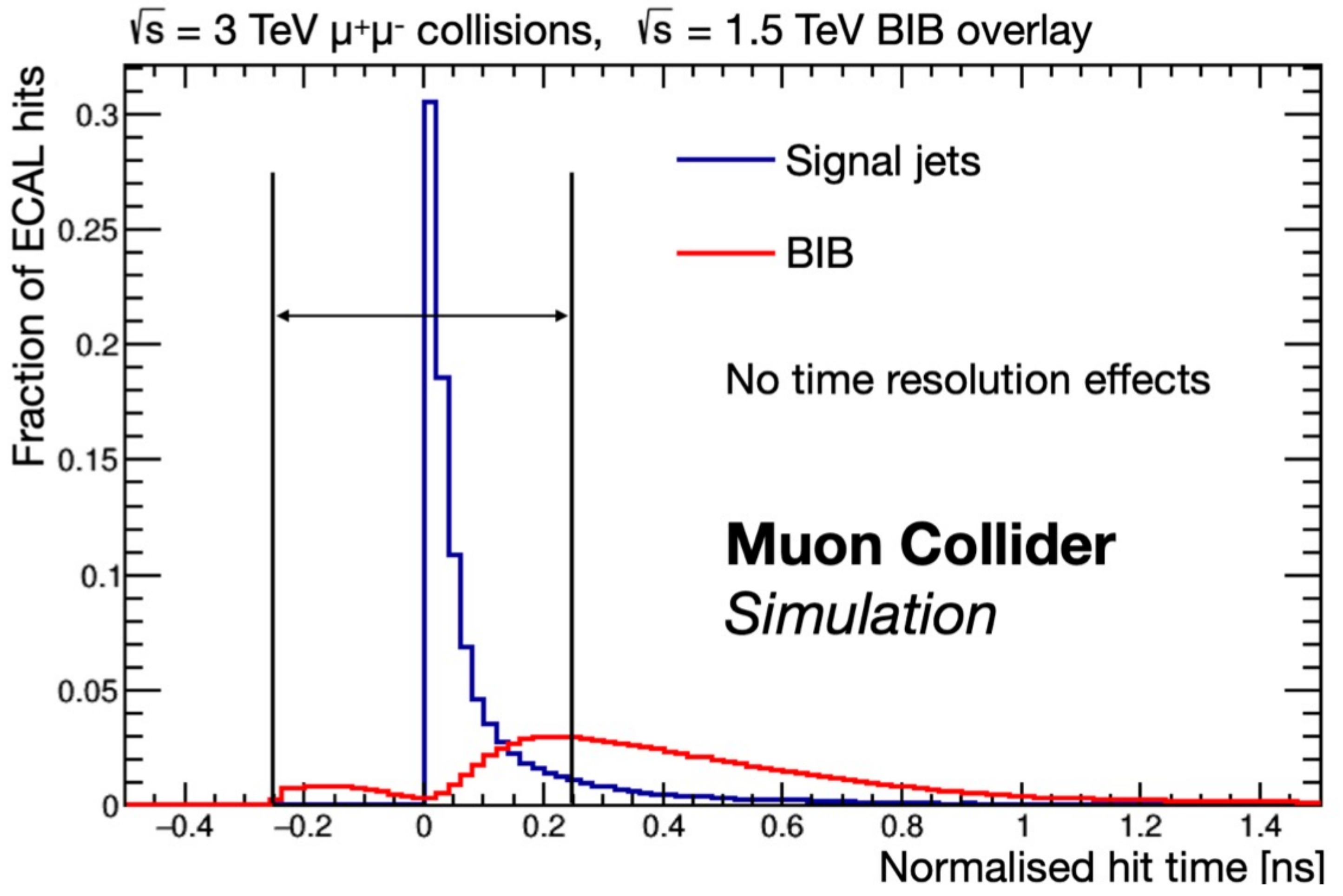




CREDITS: C. SELLGREN, S.P. GRISO, L. SESTINI

- Result:
  - Huge flux of particles interacting with detector:
    BEAM-INDUCED BACKGROUND
- Need to use **innovative techniques** to mitigate this effect
  - Hardware: **tungsten nozzles**
  - Software: **efficient algorithms**

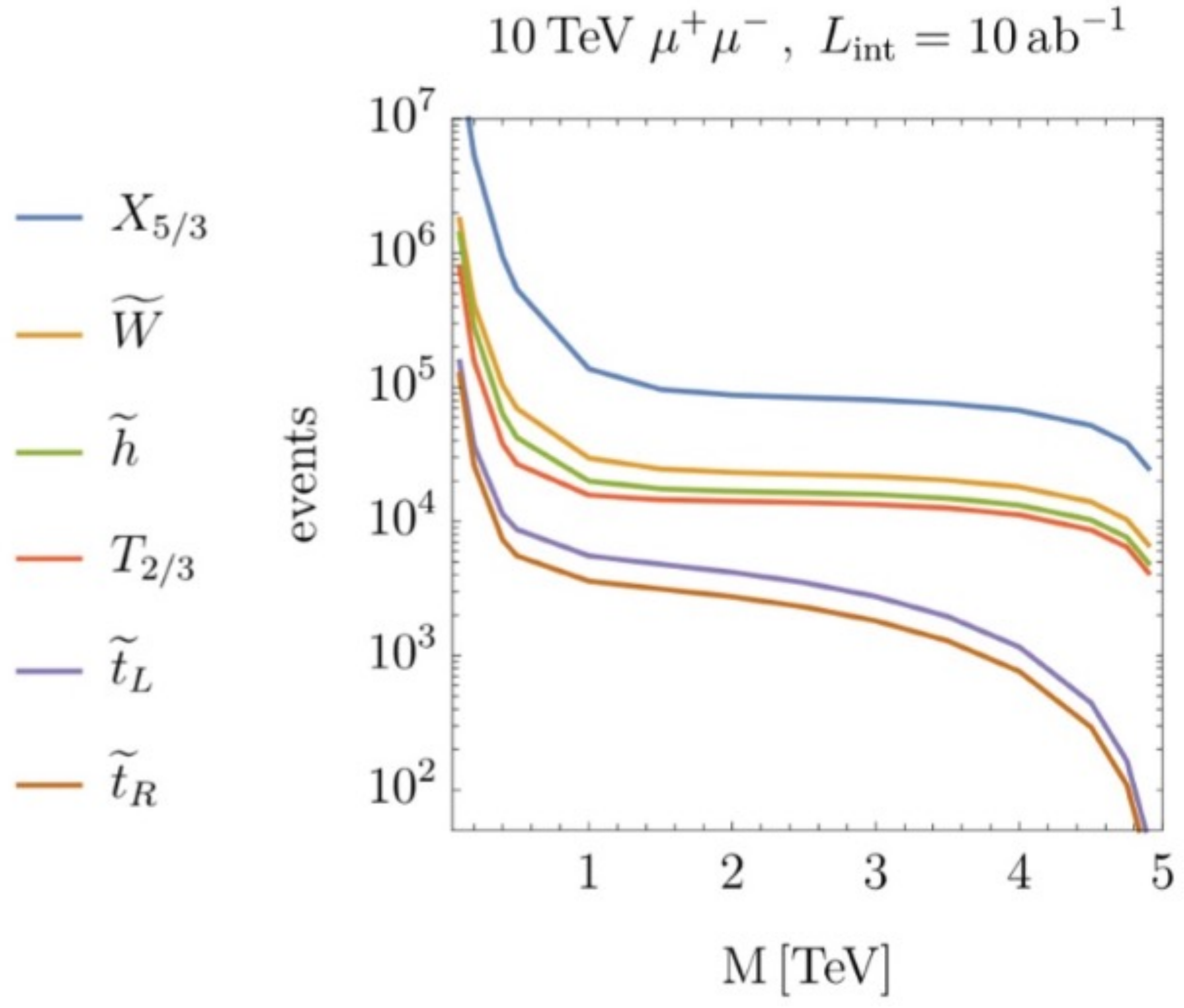
Physics @ Muon Collider

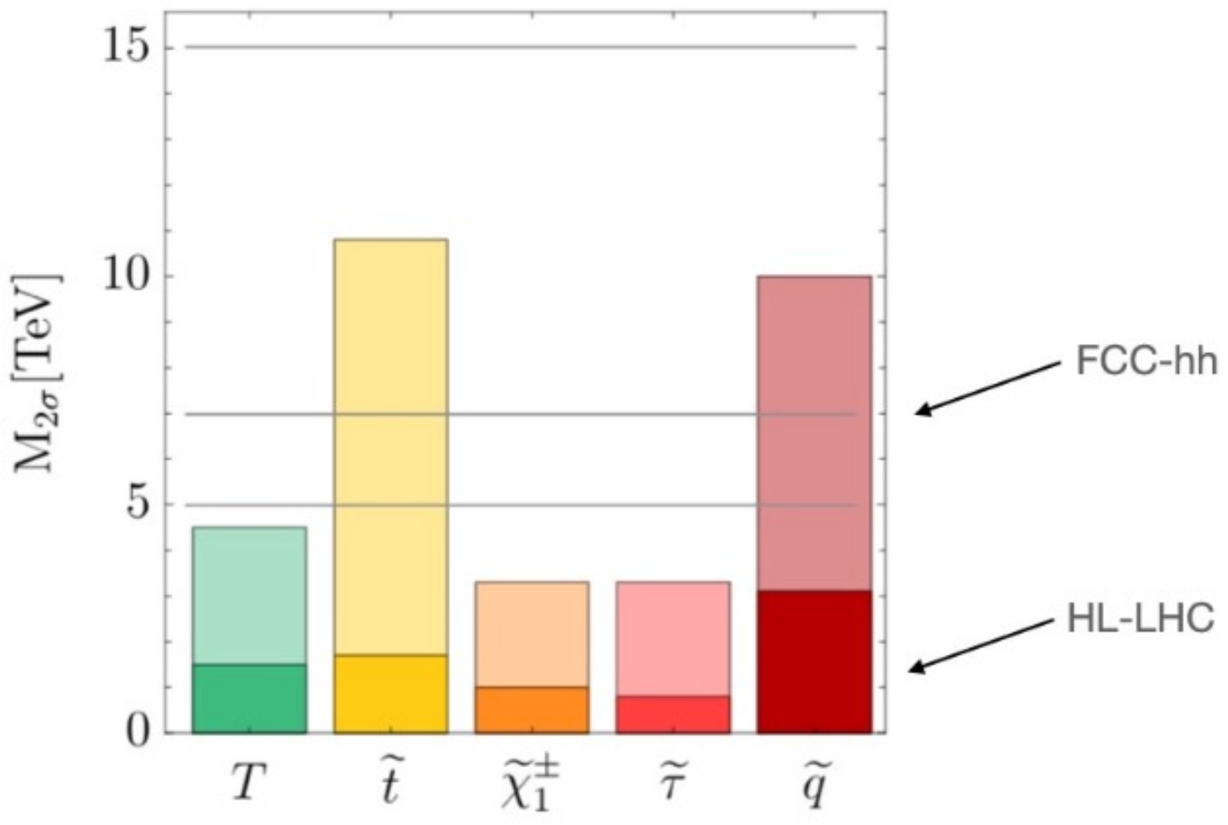
All in one

CREDITS: D. BUTTAZZO, P. MEADE

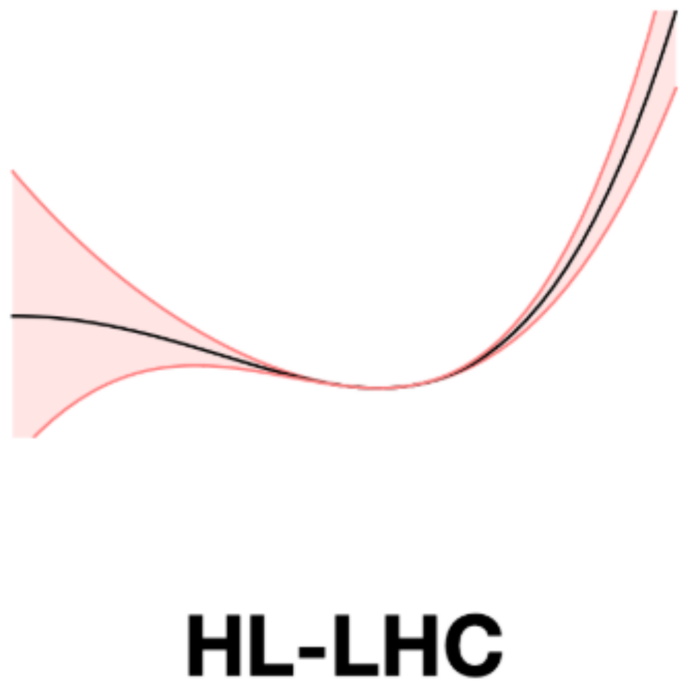
Direct searches	High-rate SM measurements	High-energy SM measurements
high energy to search for heavy new particles	high statistics for precise measurements	high energy to look for NP in SM processes

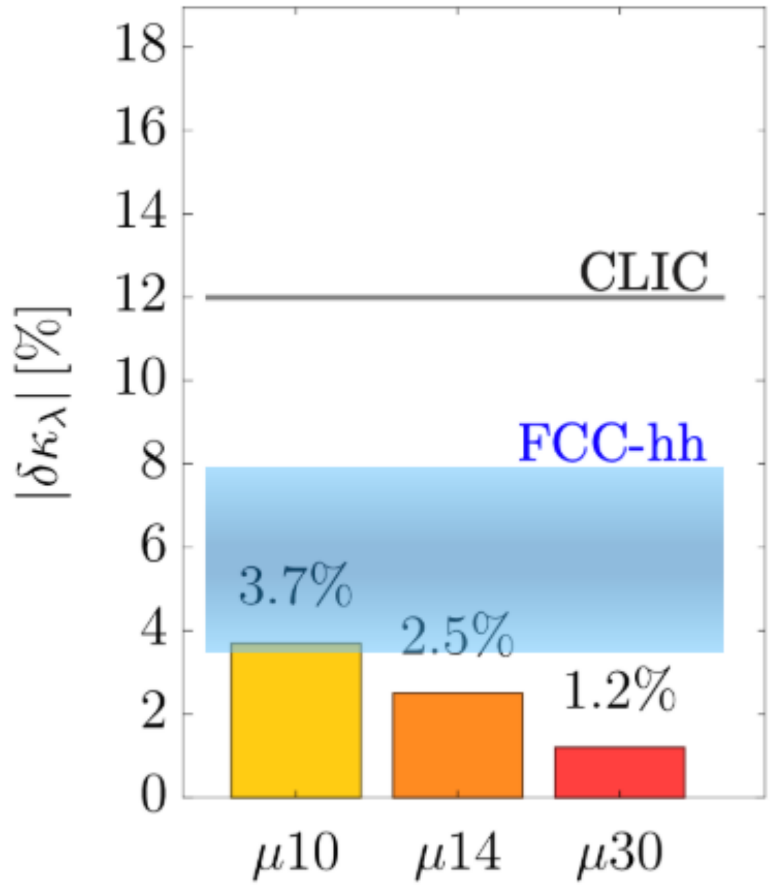
Discovery potential

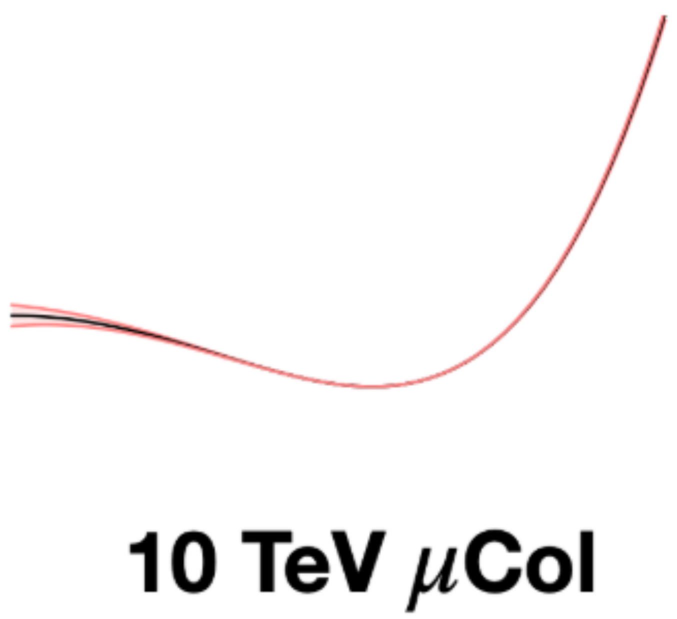




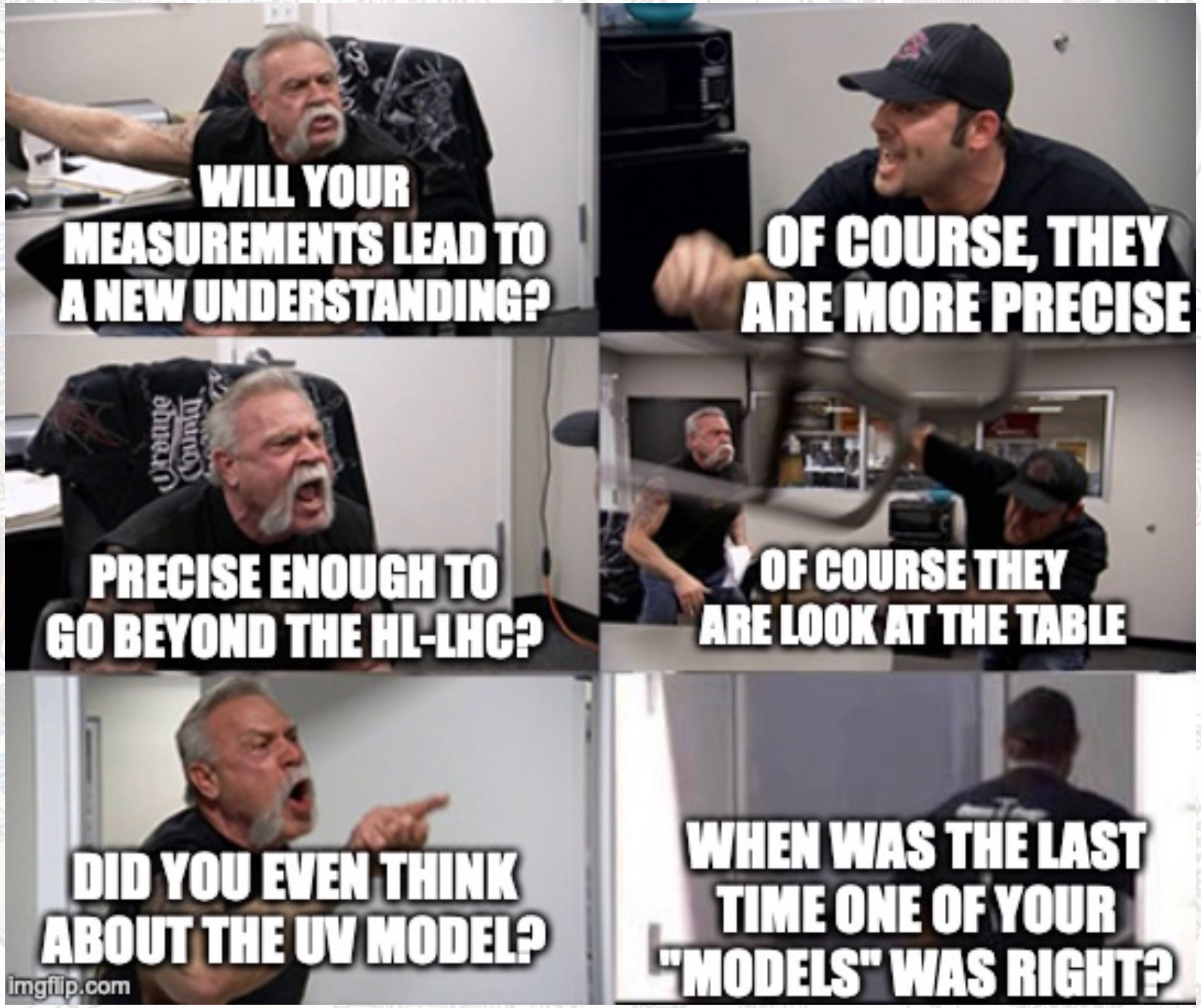
Precision measurements







A typical quiet conversation between a theorist and an experimentalist



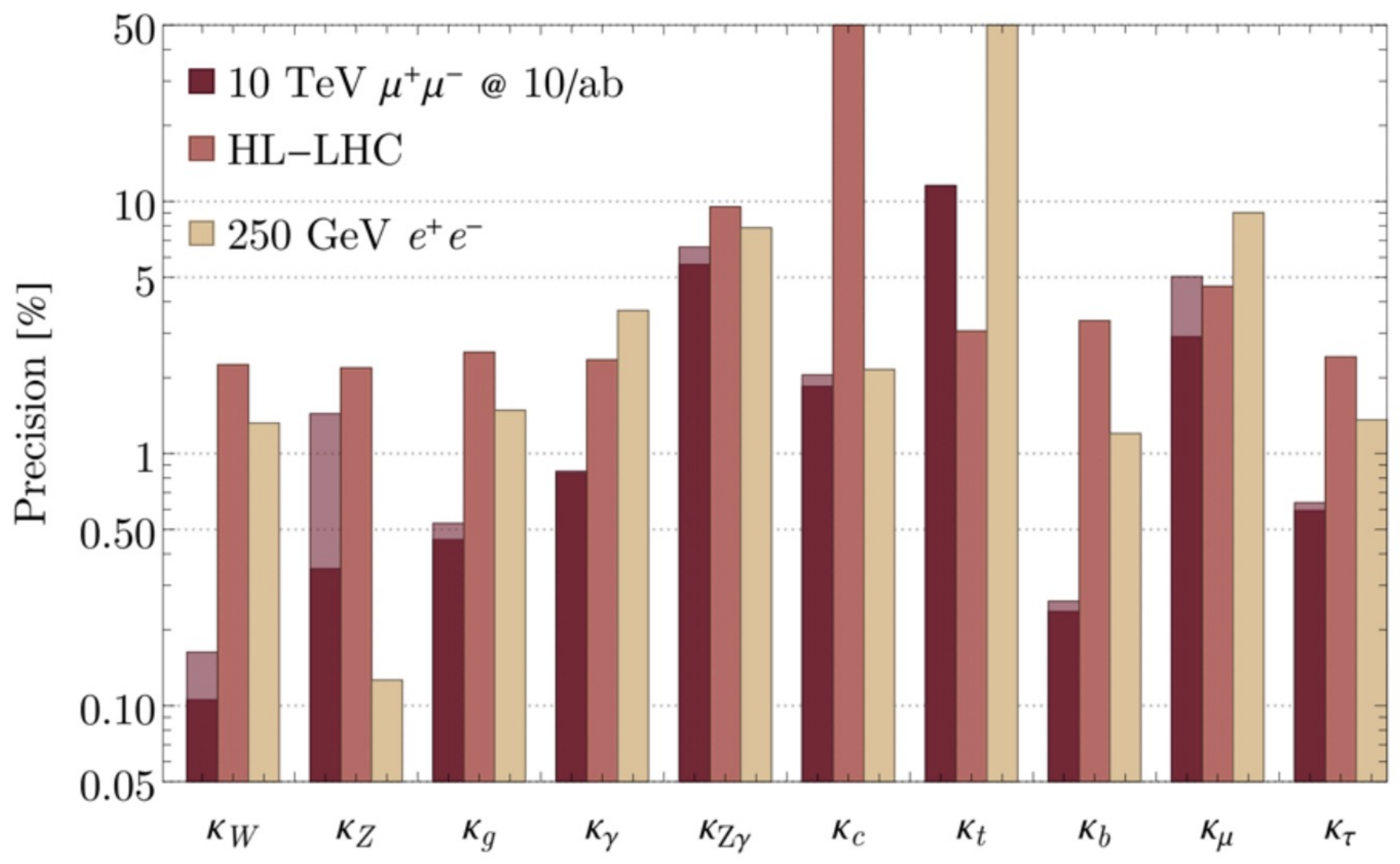
TAKEN FROM P. MEADE

Ok, let's say that I'm interested in working on the Muon Collider... what can I do?

Beware: quite some bias towards experimental activities

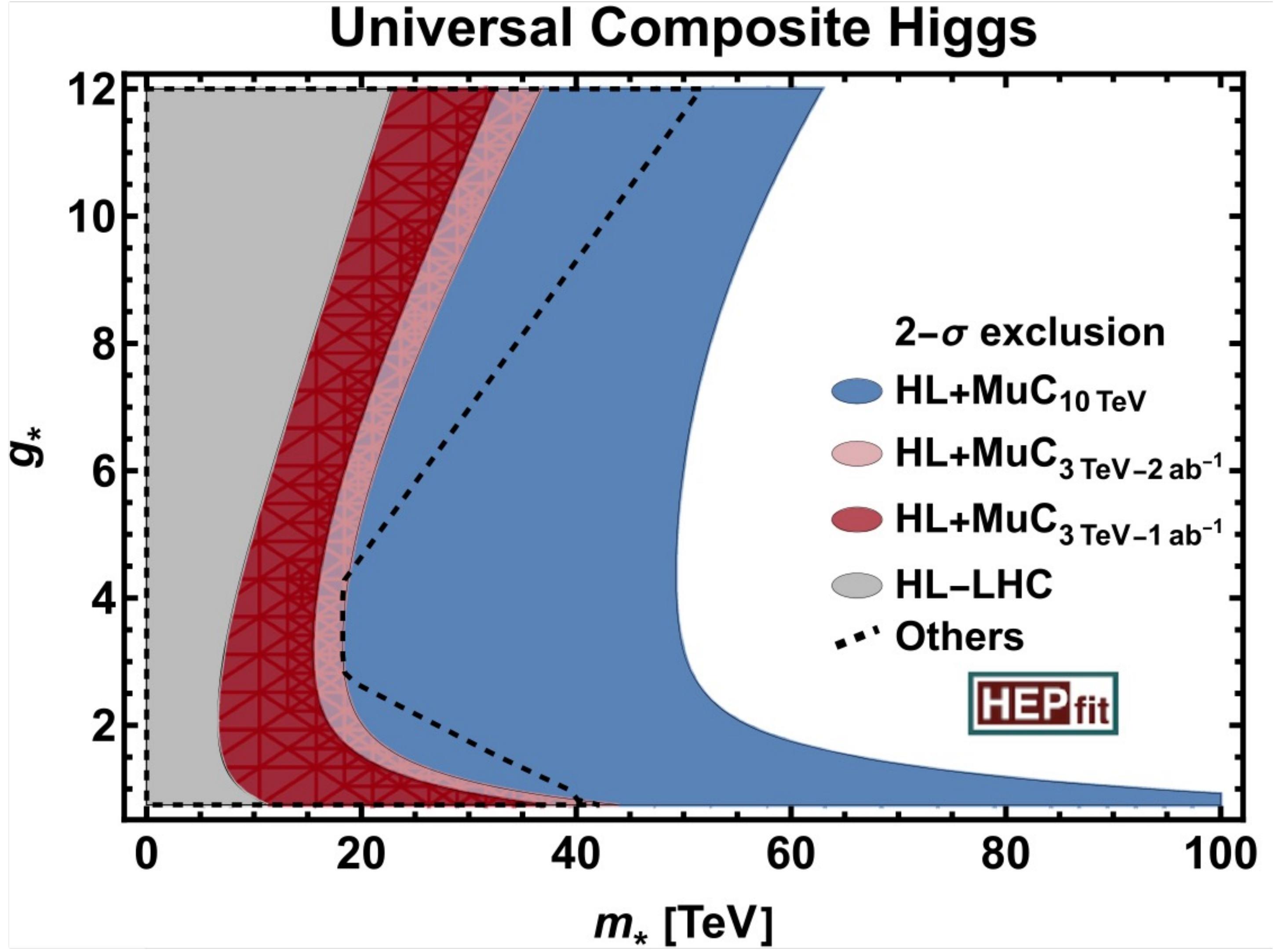
Muon Collider: theory

Higgs potential



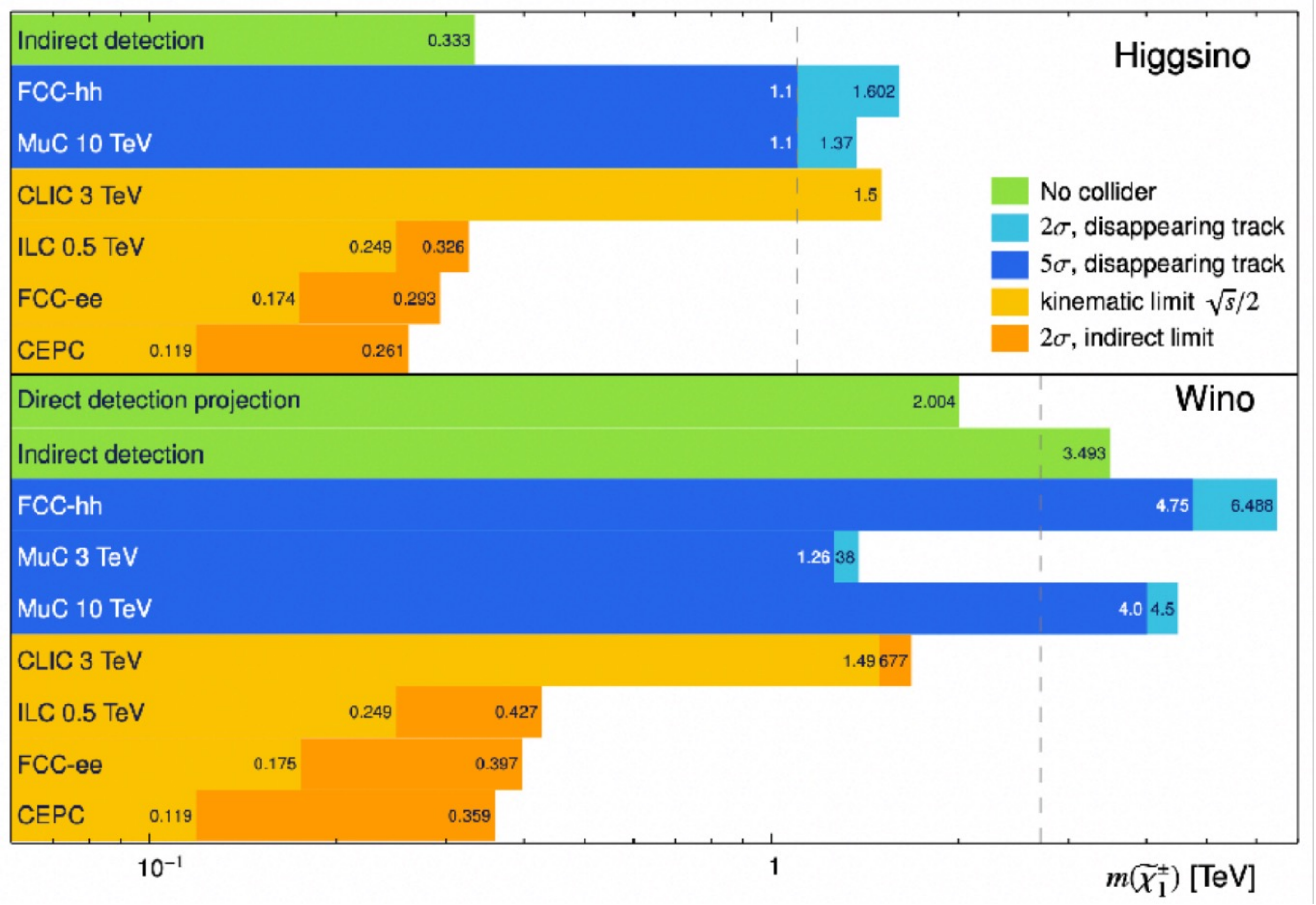
- Possibility to reach $\mathcal{O}(1\%)$ precisions in couplings
- Access to Higgs self-couplings

Higgs compositeness



- Is the Higgs an elementary particle?
- The higher the energy, the better the probe

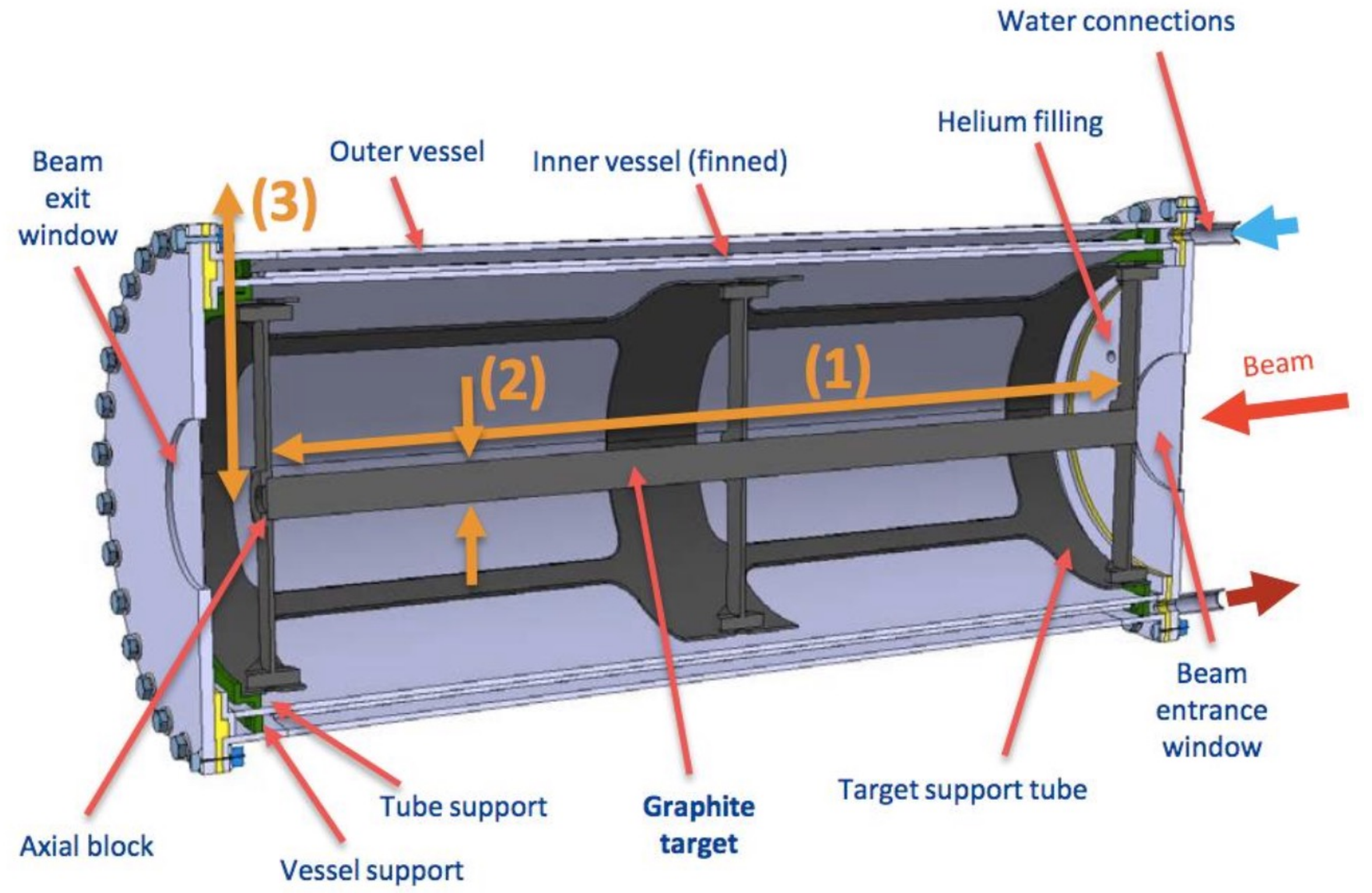
SUSY and DM



- Different scenarios can be probed
- Again, going to higher energies is a game changer

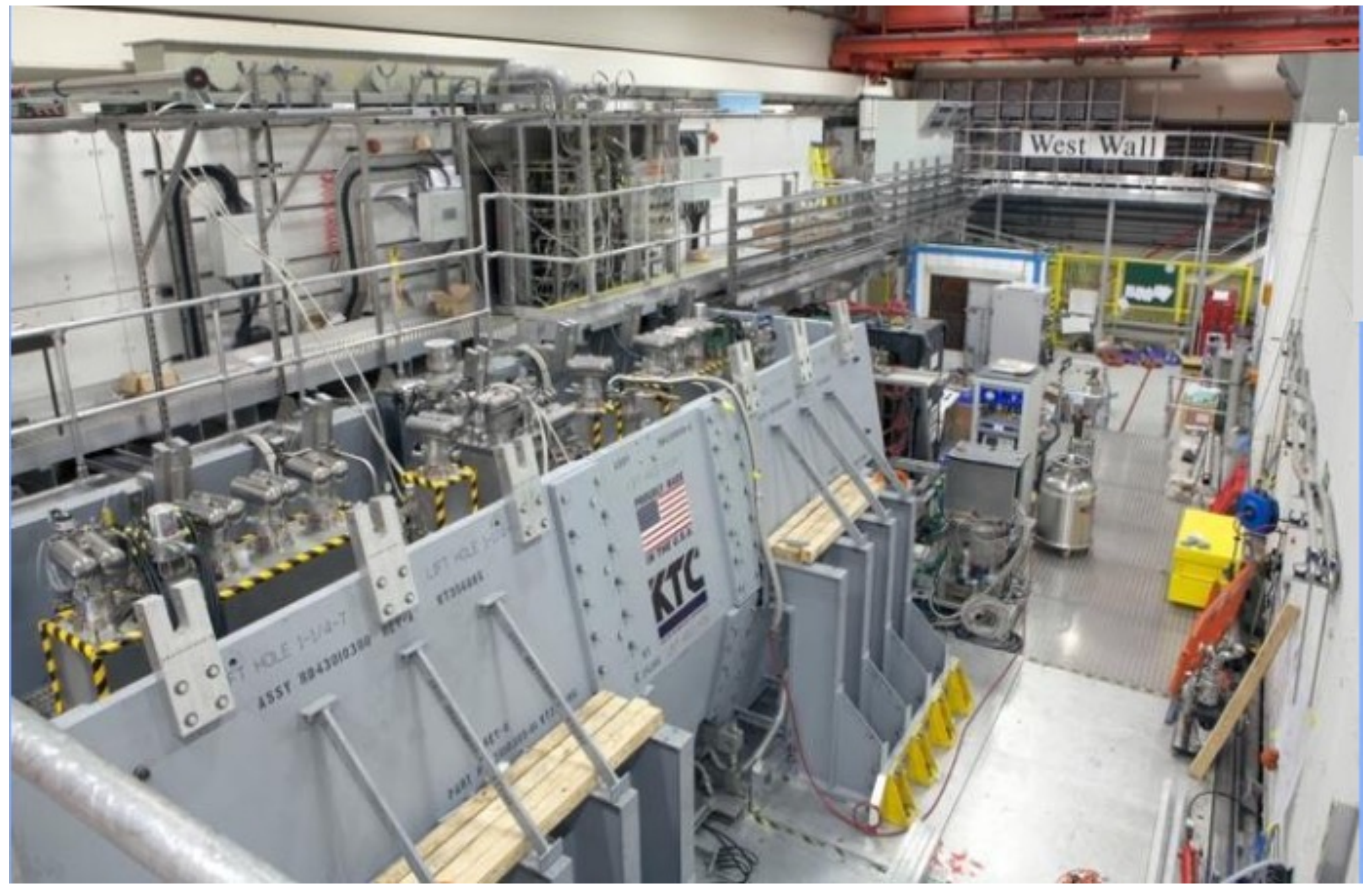
Muon Collider: machine

Target



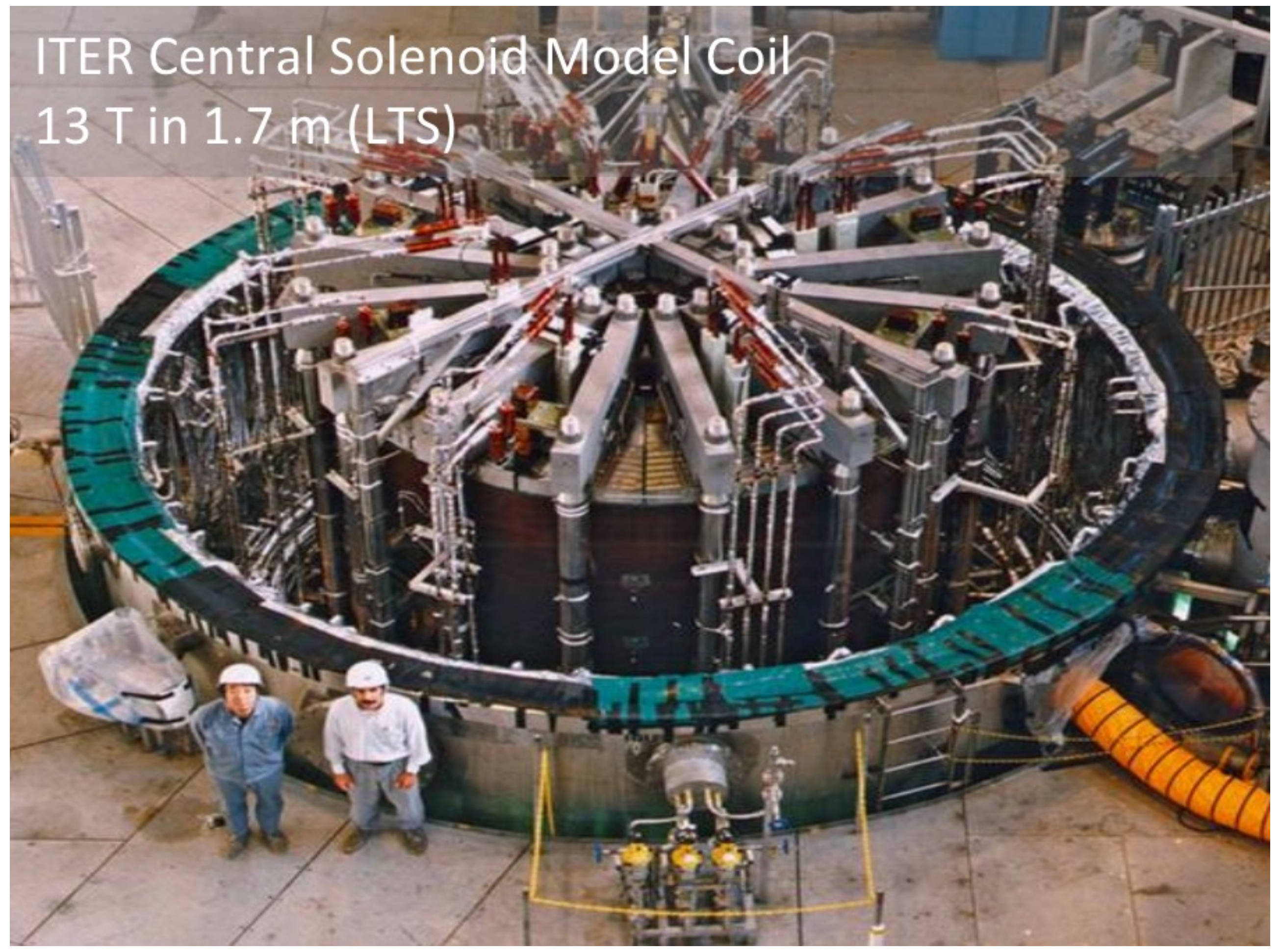
- 5 GeV proton beam, 2 MW power at hand
- Need to properly design target, solenoid and magnet shielding

Cooling



- Principle of muon cooling demonstrated
- Integration/optimisation of overall cooling design
- Integrating improved technology

Magnets

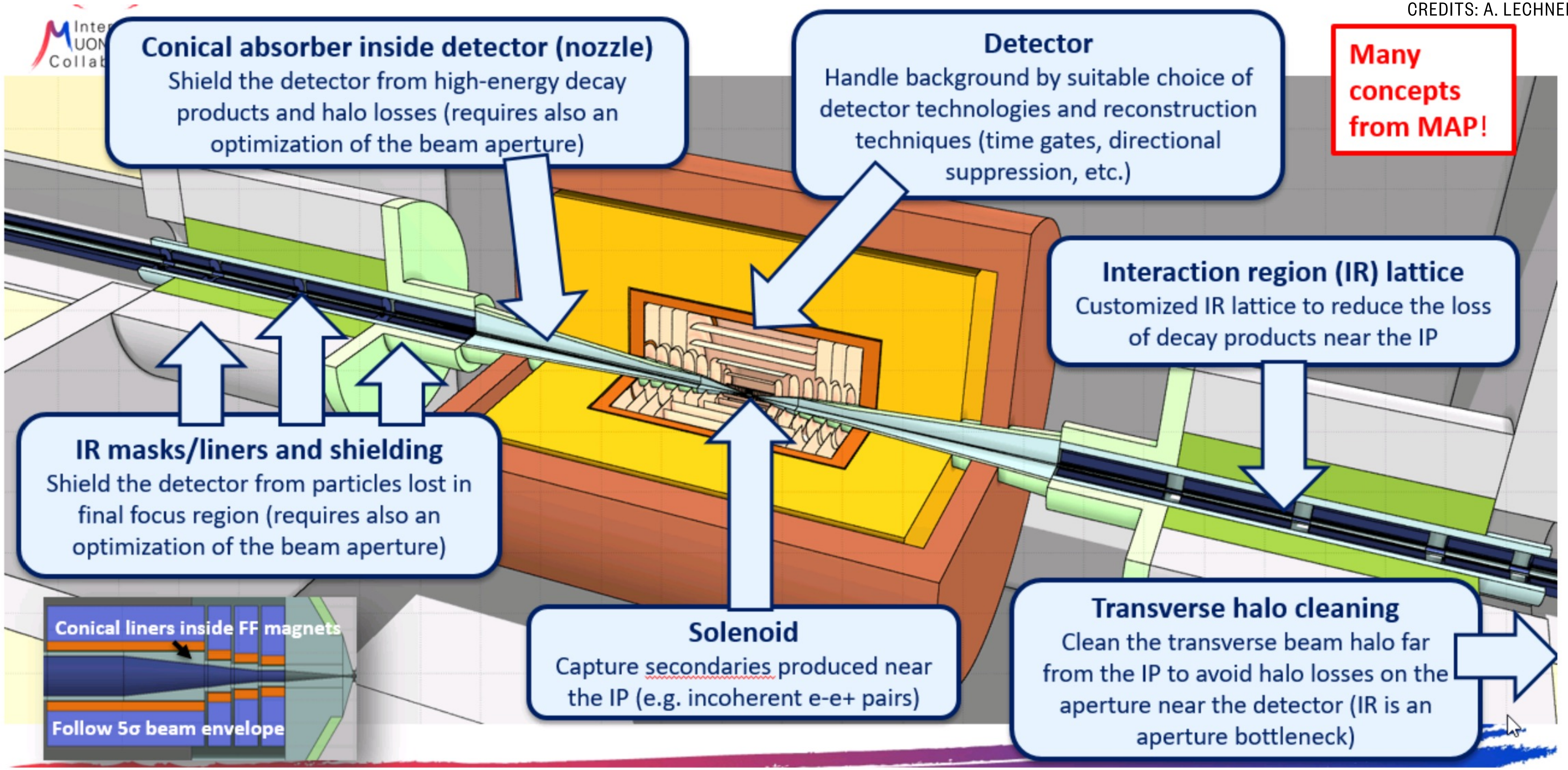


- Target solenoid: 20 T, 20 K
- Started HTS solenoid development for high fields
- Synergies with fusion reactors, …

Muon Collider: MDI

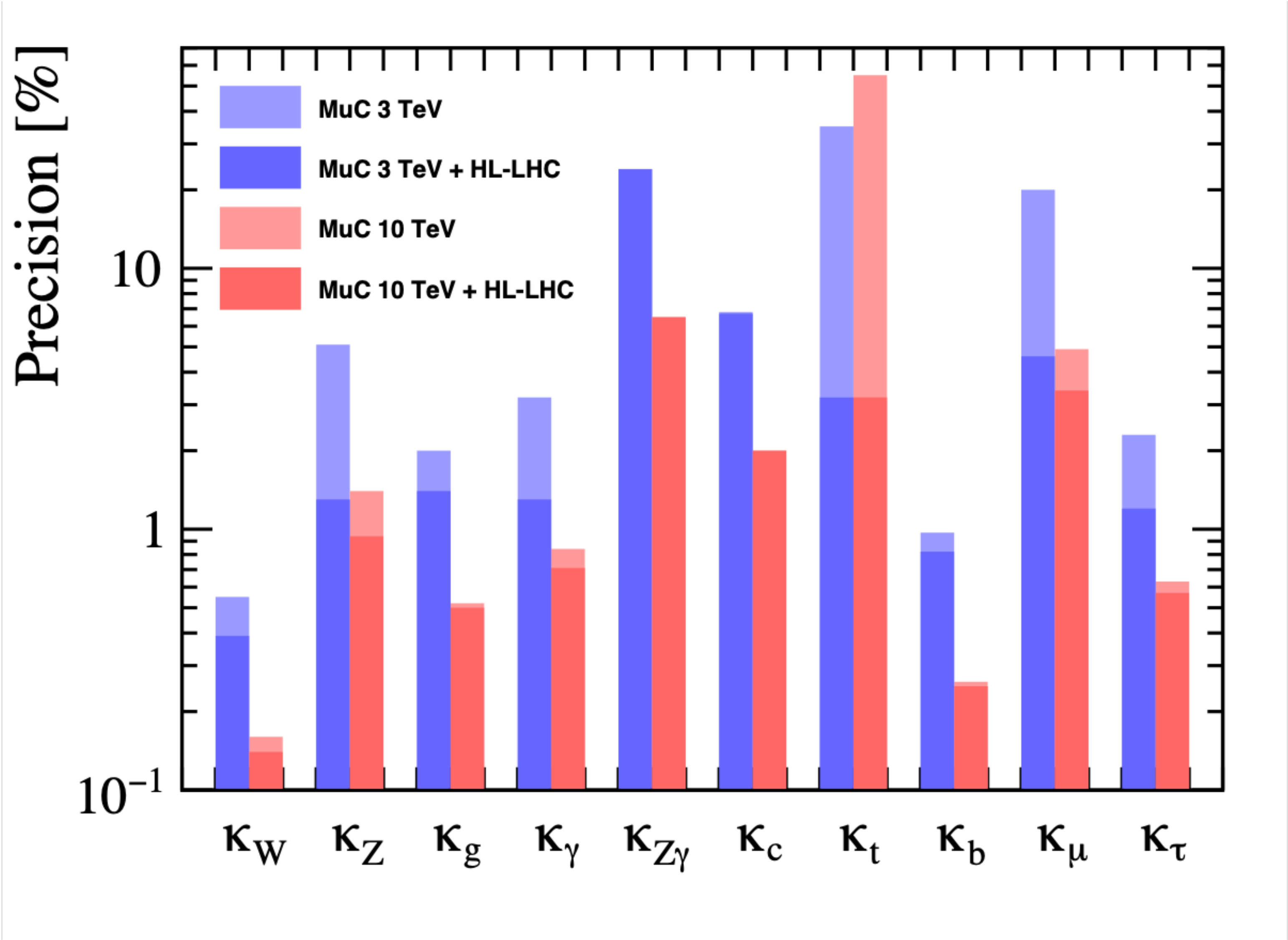
BIB, nozzles optimisation, incoherent pair production, ...

CREDITS: A. LECHNER, D. CALZOLARI



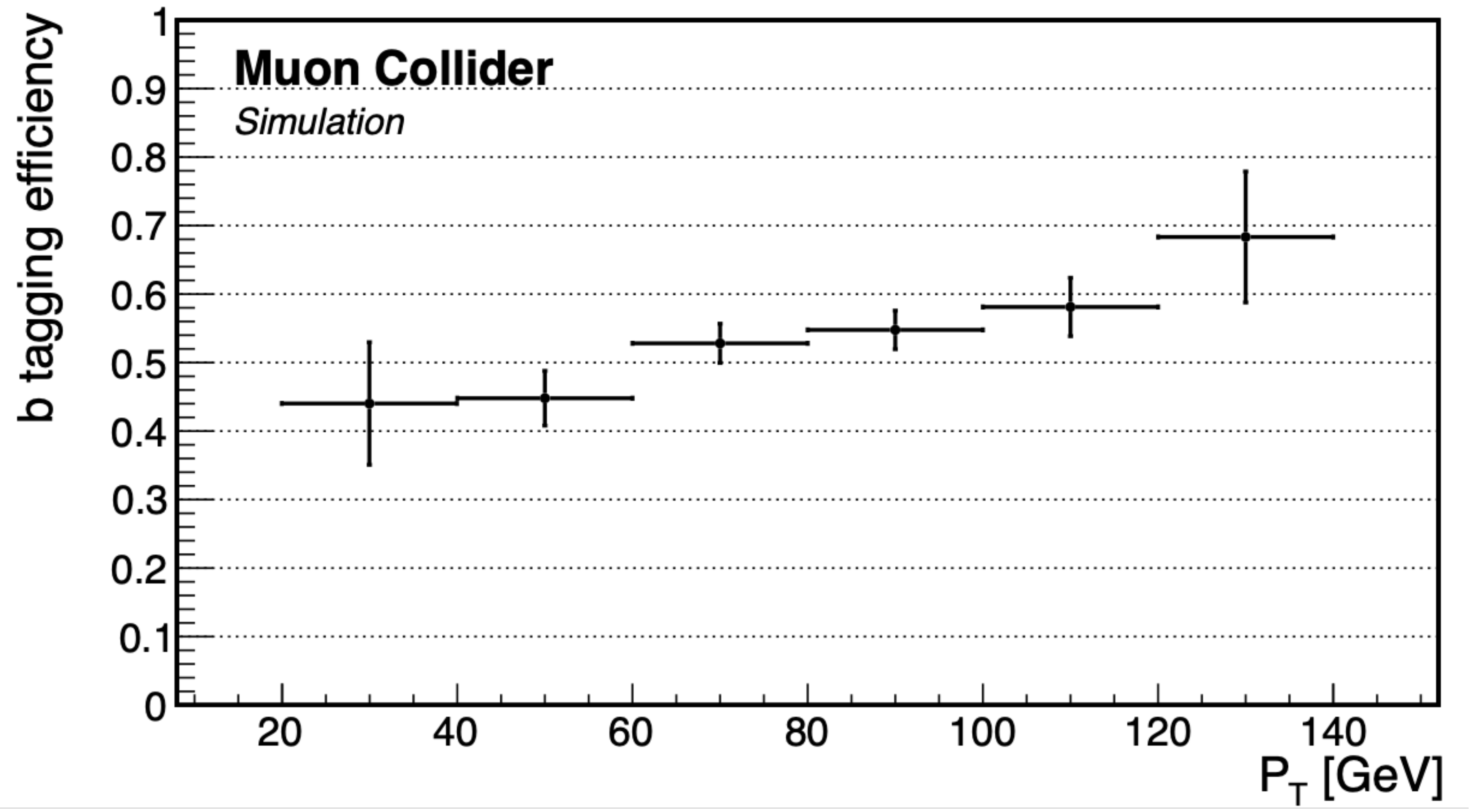
Muon Collider: detector

Physics analyses



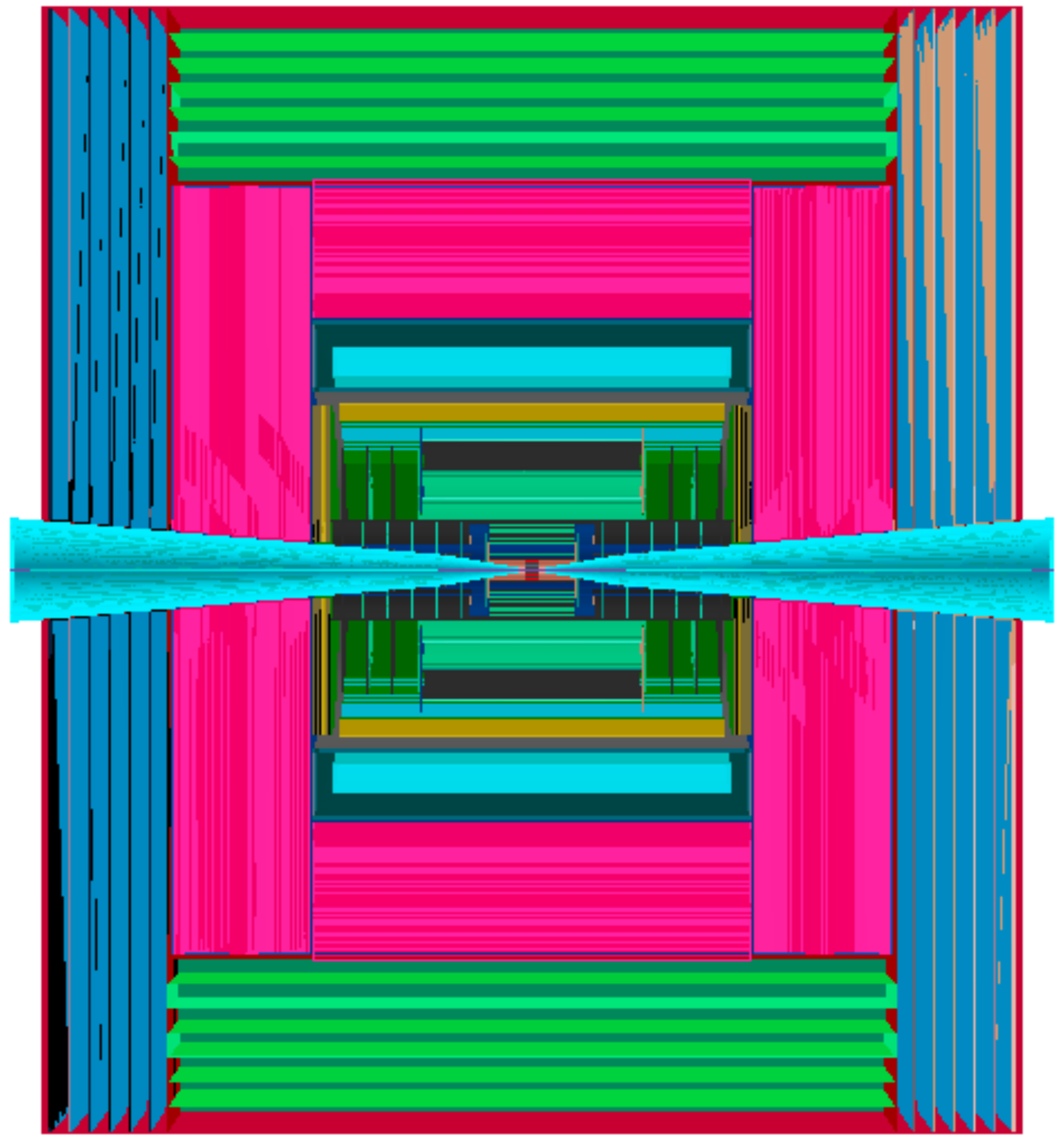
- Evaluate "real" impact of BIB on detector
- Test theoretical expectations with full simulation and reconstruction algorithms

Algorithm optimization



- Optimize algorithms:
  - Object reconstruction
  - Jet tagging
  - …
- Usage of innovative techniques (mainly ML)

Detector configuration

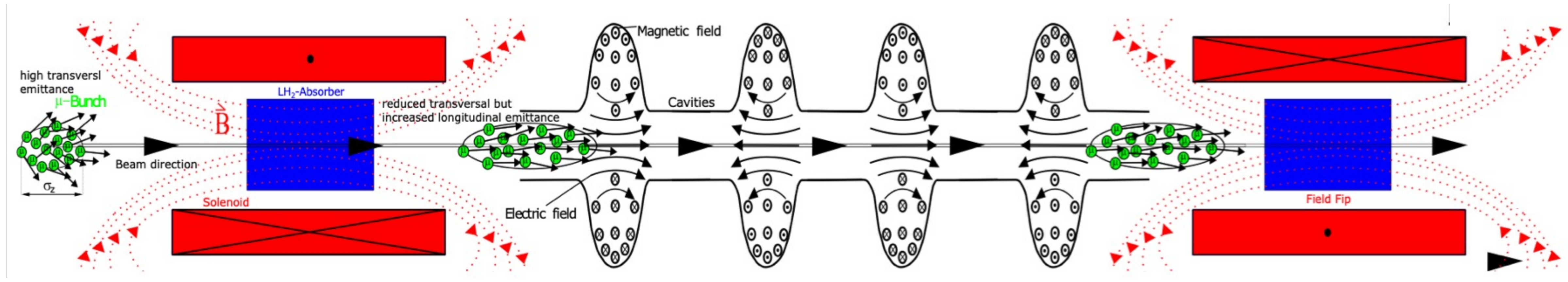


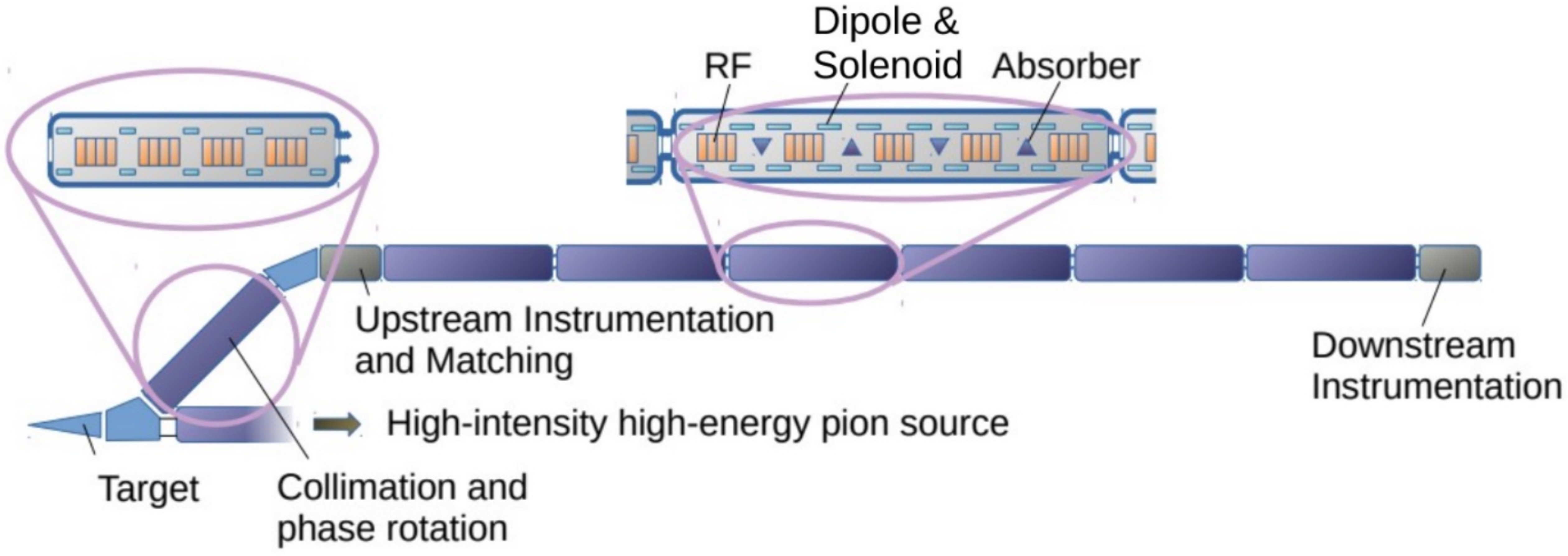
- Detector optimisation for 10 TeV configuration
- Test-beams!!
- Practically, you can build your own detector

Bonus: building a demonstrator

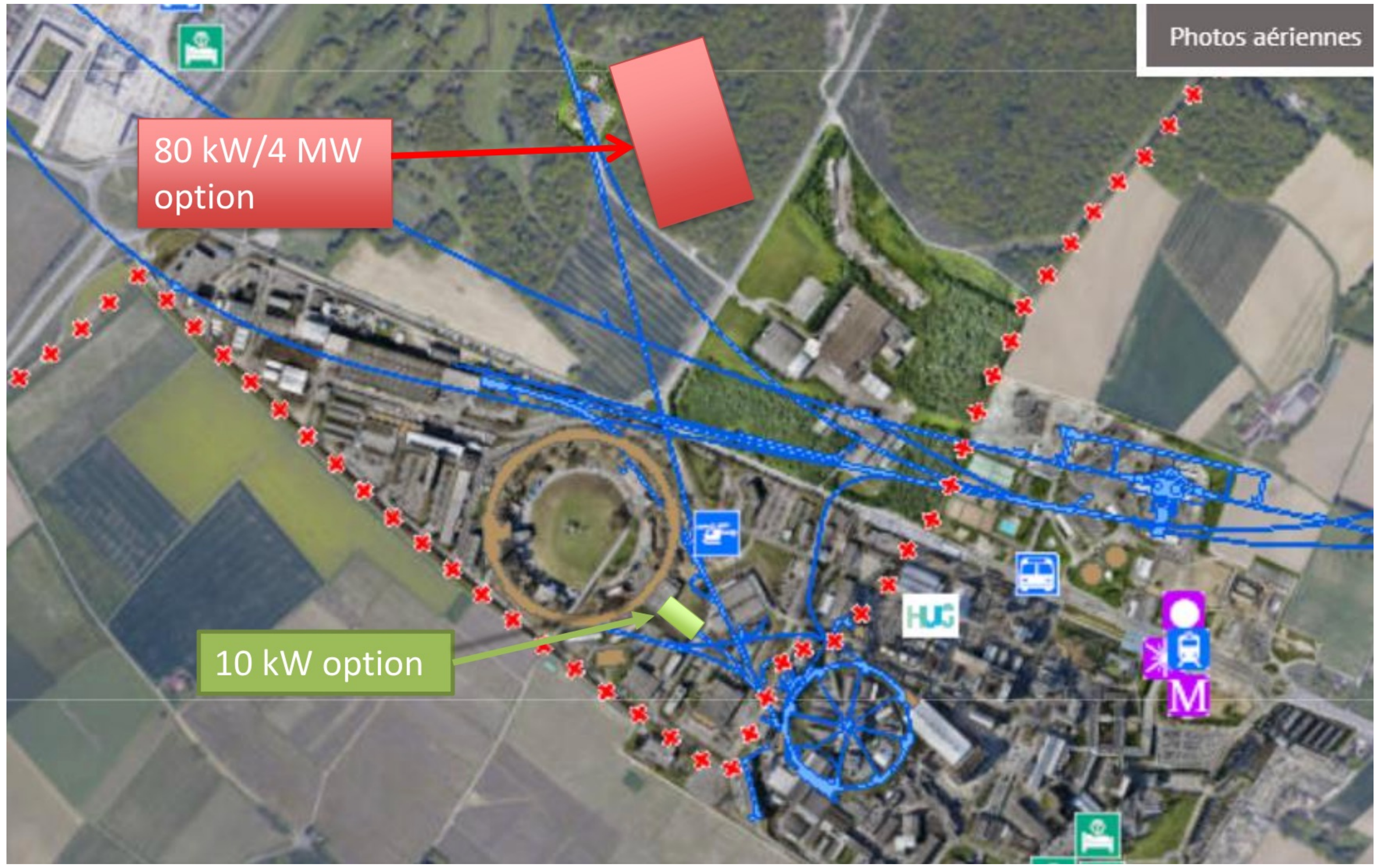
Better safe than sorry

- The MICE collaboration demonstrated the muon cooling
  - Proof-of-principle, need demonstration of 6D cooling (including re-acceleration)
- Currently designing a **demonstrator**
  - Possibly operative in 10 years





CREDITS: C. ROGERS



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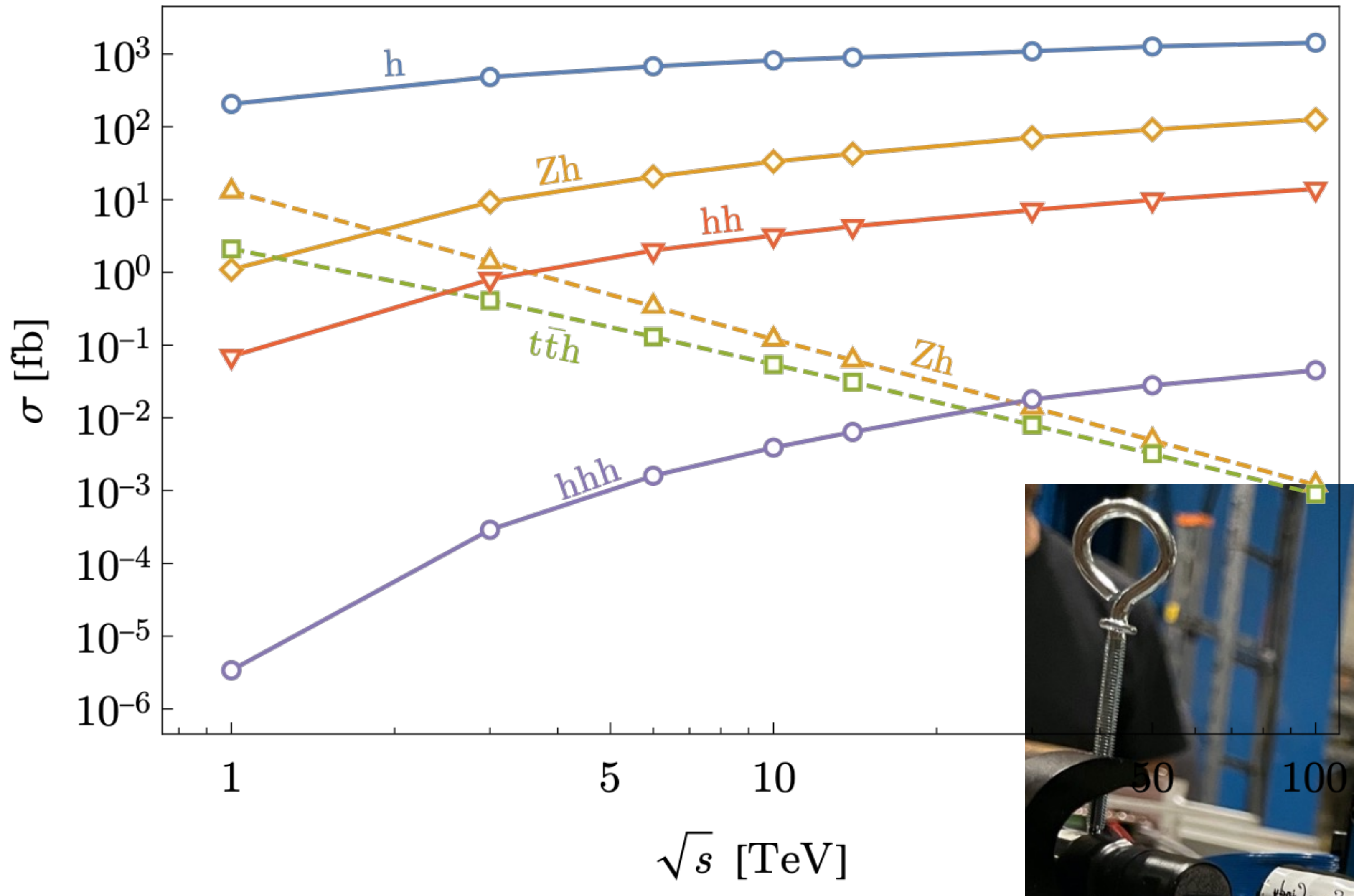
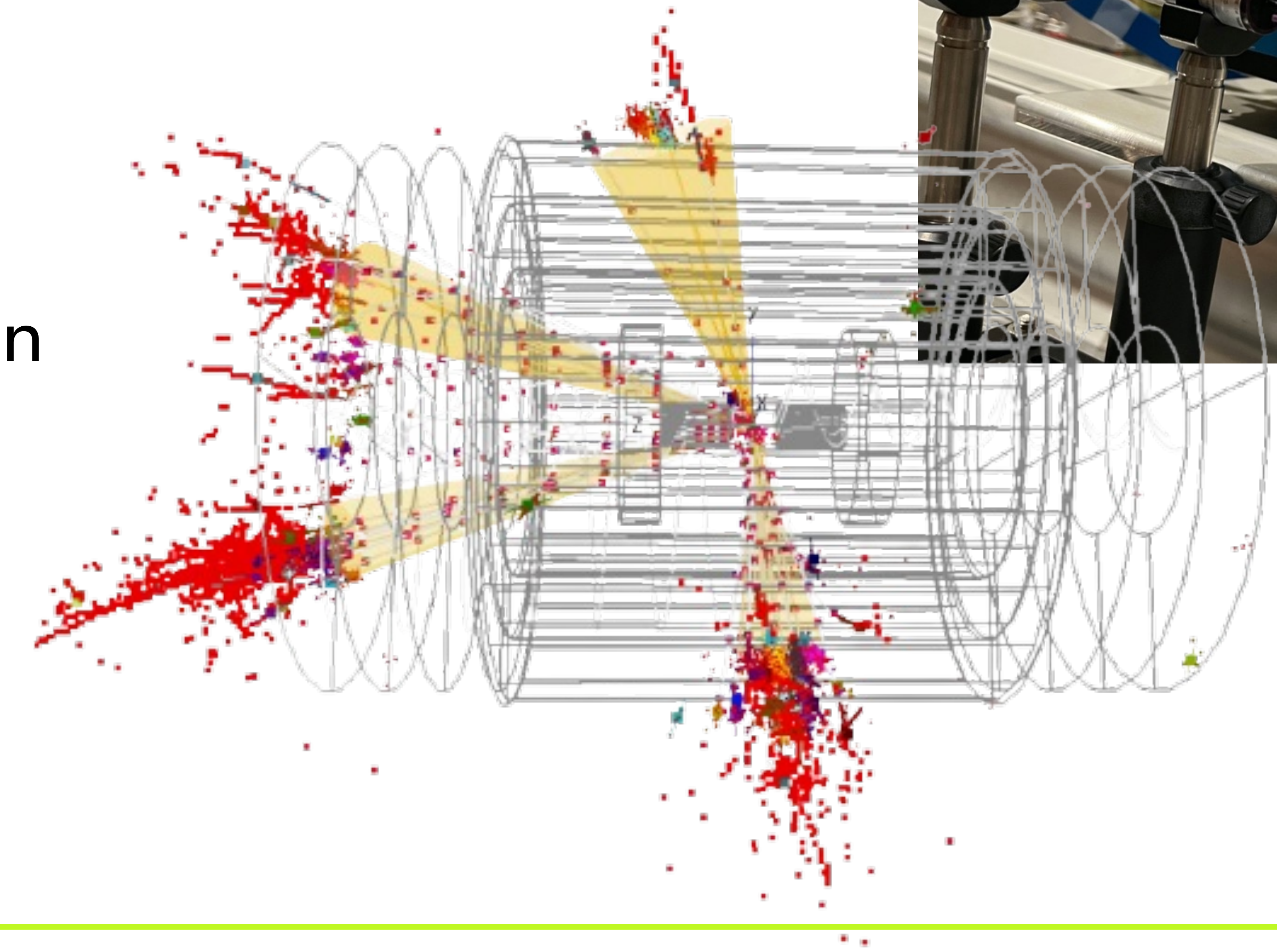
A bit of advertisement

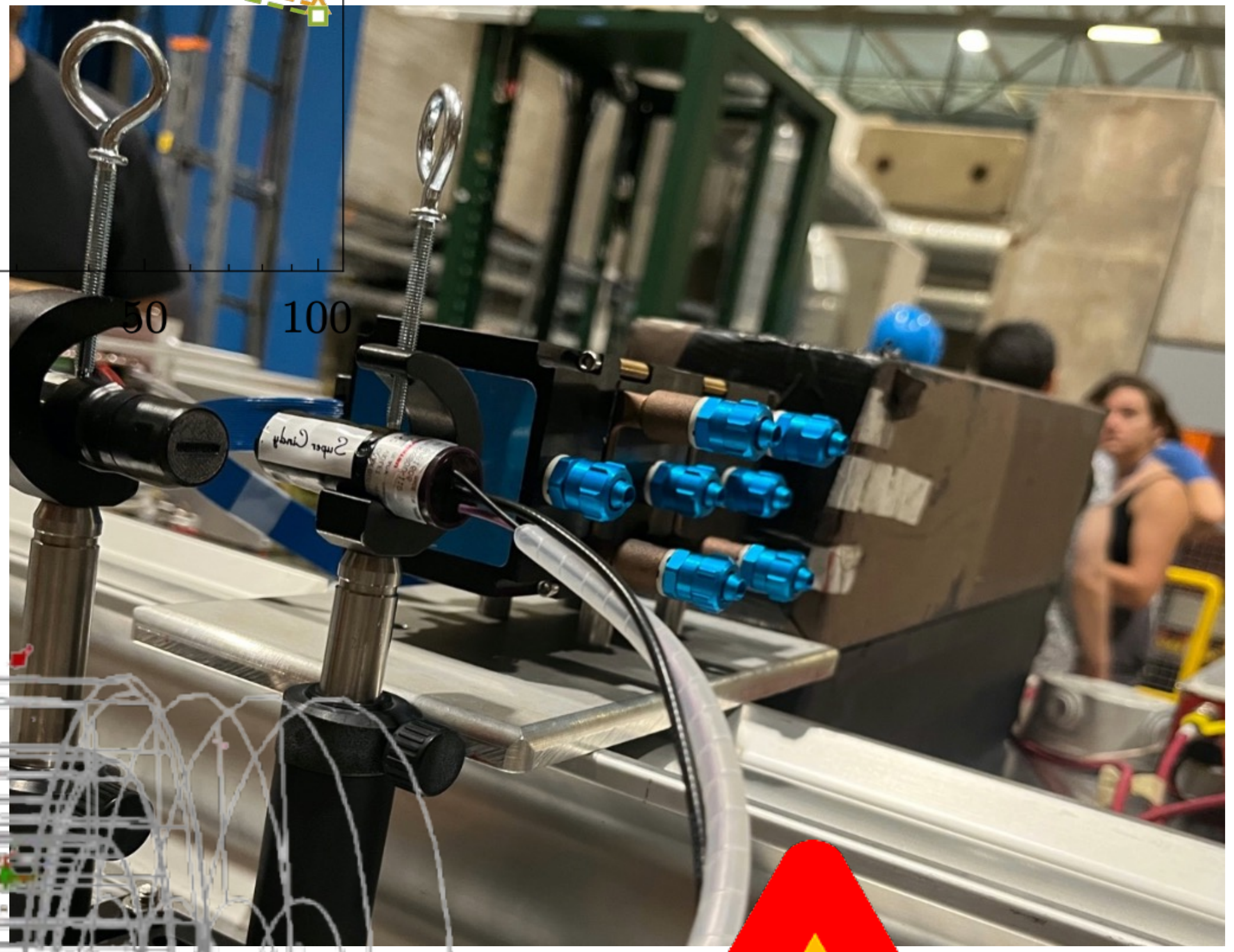
Conclusions

Take-home message

- The Muon Collider is a **fascinating and new project**, where you basically can:
  - Elaborate theories on Higgs physics and extension of SM
  - Actively participate in building and testing prototypes
  - Study muon collisions and their impact on the detector (BIB mitigation)
  - Optimize detector for 10 TeV configuration







You just need to join us :)

Thank you for your attention!

Backup slides

Muon collider parameters

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Note: currently focus on 10 TeV, also explore 3 TeV

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5	1.07	
ε	µm	25	25	25	
$\sigma_{x,y}$	µm	3.0	0.9	0.63	

CREDITS: D. SCHULTE