RD Muon Collider

MuCol EU Design Study

Gruppi **INFN** *in* ***RD_MUCOL @ CSN1*** **121 persone/30.2 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

Fabio Maltoni — Bologna 7 Nov 2024

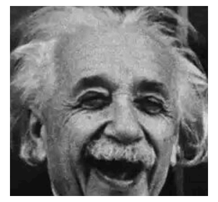
With key inputs by Nadia Pastrone and Marco Breschi

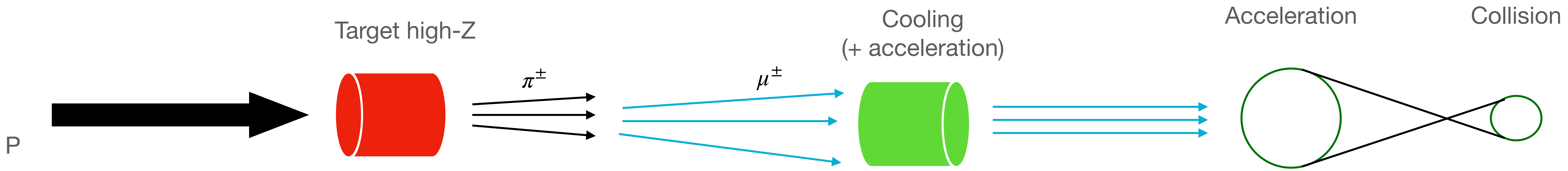
The crazy idea of a multi-TeV muon collider

1. m_μ = 105 MeV $\Rightarrow P_\mu = \left(\frac{m_e}{m_\mu}\right)^4 P_e \Rightarrow$ up to 10-14 TeV syncrotron radiation is not a problem 🙂

2. $\tau_\mu = 2.2 \cdot 10^{-6} s \Rightarrow$ it decays very fast

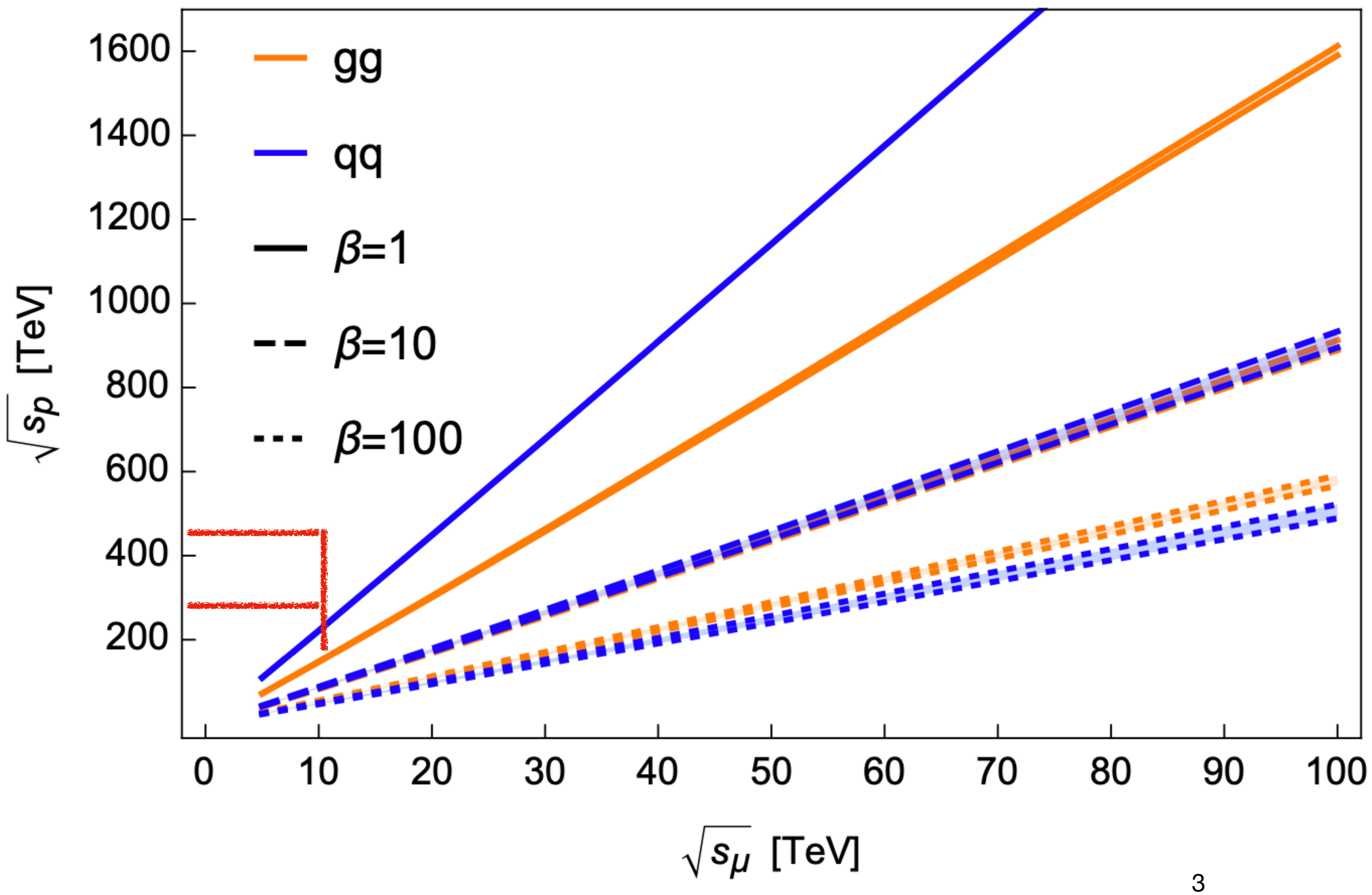
3. $\gamma = 10^4 \Rightarrow t_\mu = 2.2 \cdot 10^{-2} s \Rightarrow 6.6 \cdot 10^3\,\mathrm{Km} = 660$ turns





Muon collider physics

The essentials #0 : physics potential



muC@10 TeV ~ pp@70 TeV

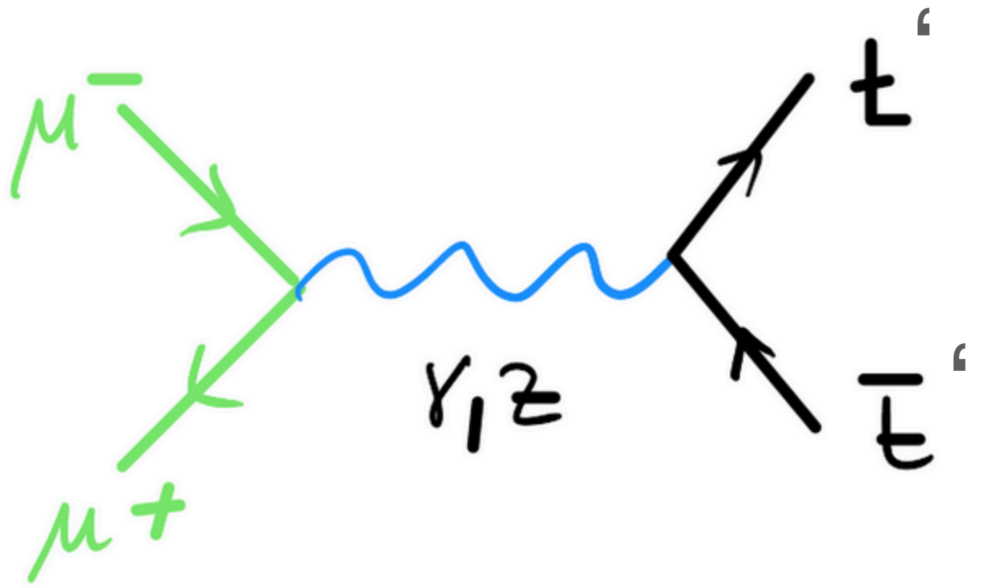
Simple/Naive/Rough estimate based on parton-parton luminosity for a generic $2 \to 2$ scattering.

$$EW : \beta \sim 1$$

$$QCD : \beta \sim (\alpha_S/\alpha)^2 \sim 100$$

Muon collider physics
The essentials #1 : two colliders in one

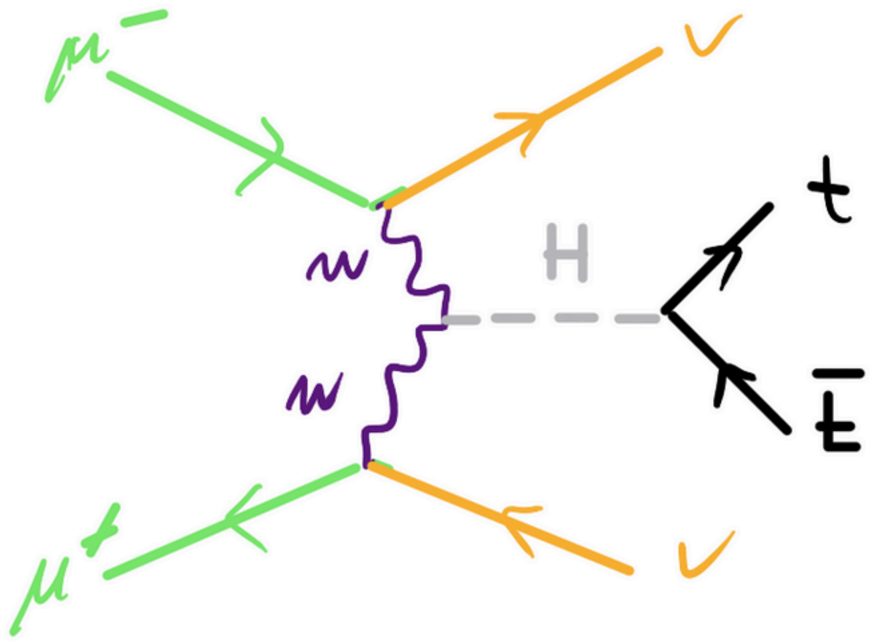
O(10) TeV muon collider energy allows to have two colliders in one:



$$\sigma_s \sim \frac{1}{s}$$

⟷

$$\sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$



Energetic final states
(either heavy or very boosted)

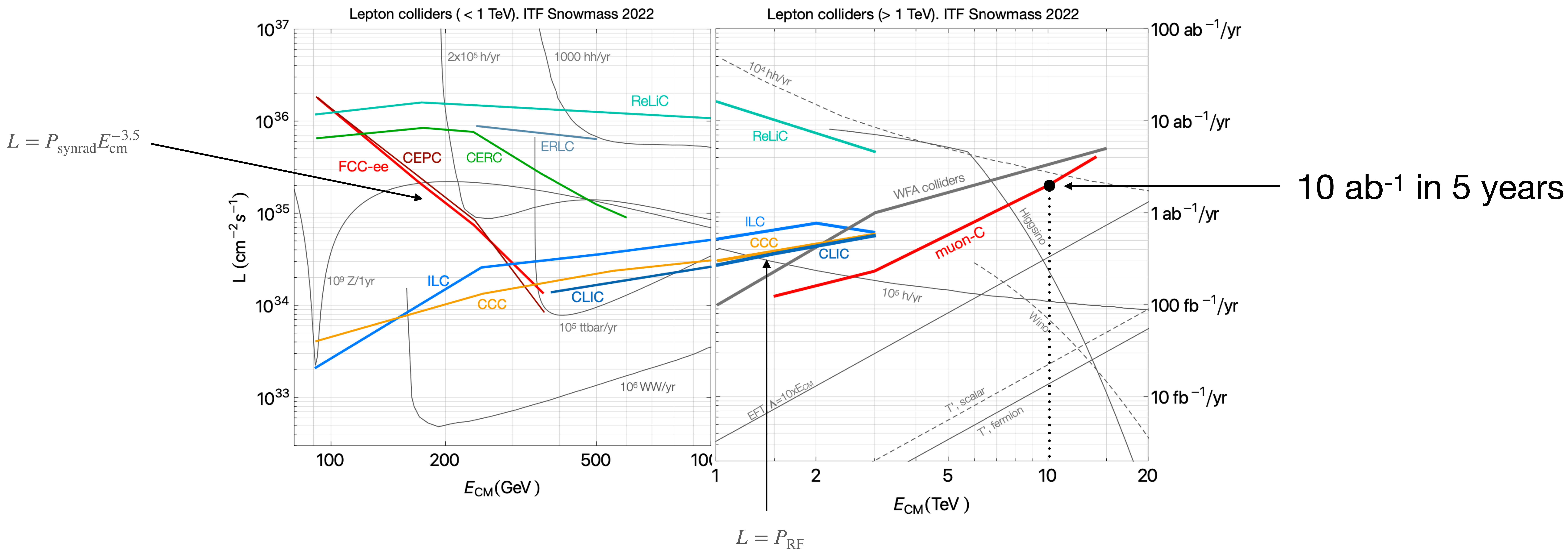
Large production rates,
SM coupling measurements
Discovery light and weakly interacting

A completely new regime opening for a multi-TeV muon collider

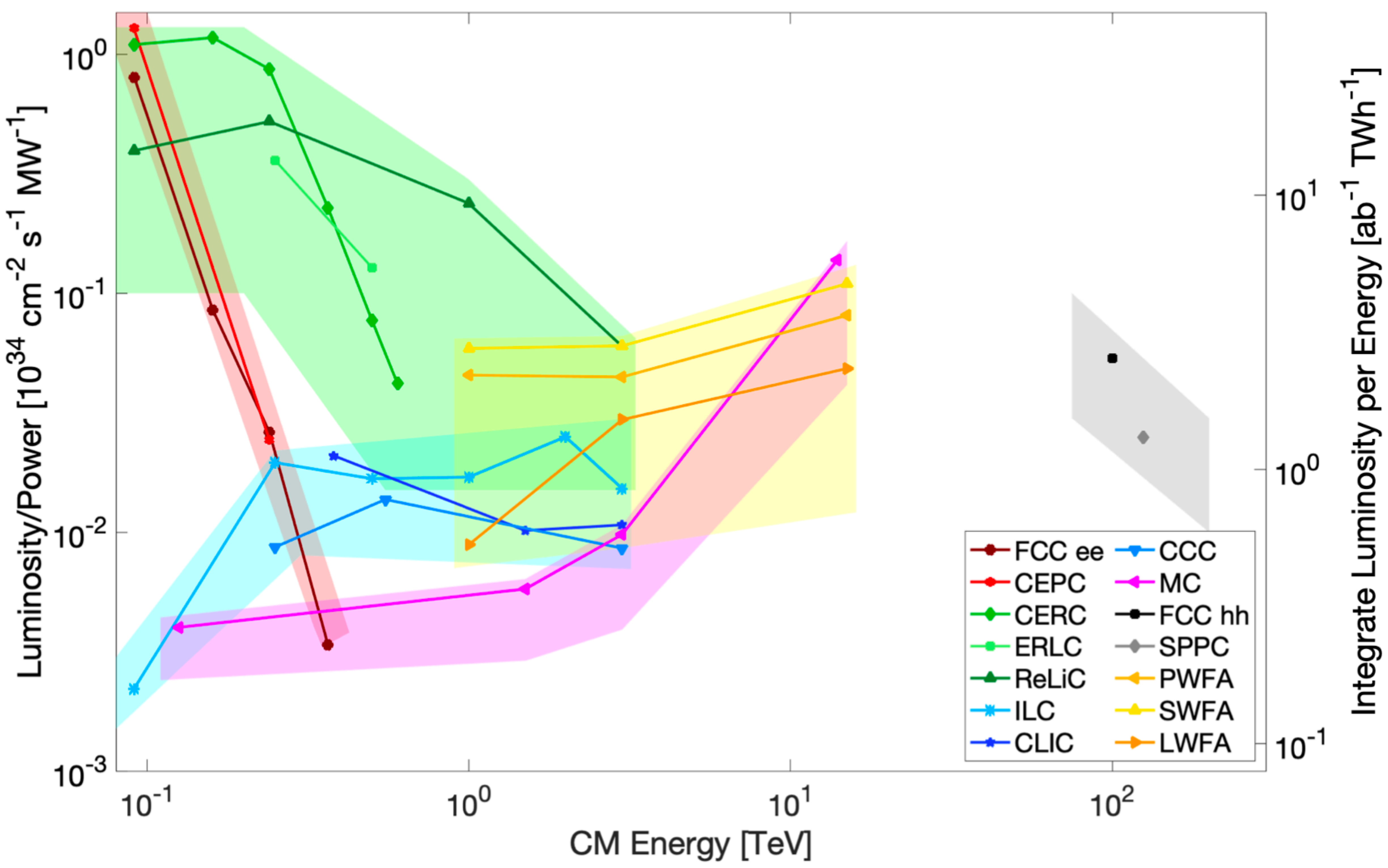
Different physics being probed in the two channels

Muon collider physics

The essentials #2 : luminosity with energy



Muon collider physics
The essentials #3 : the green side

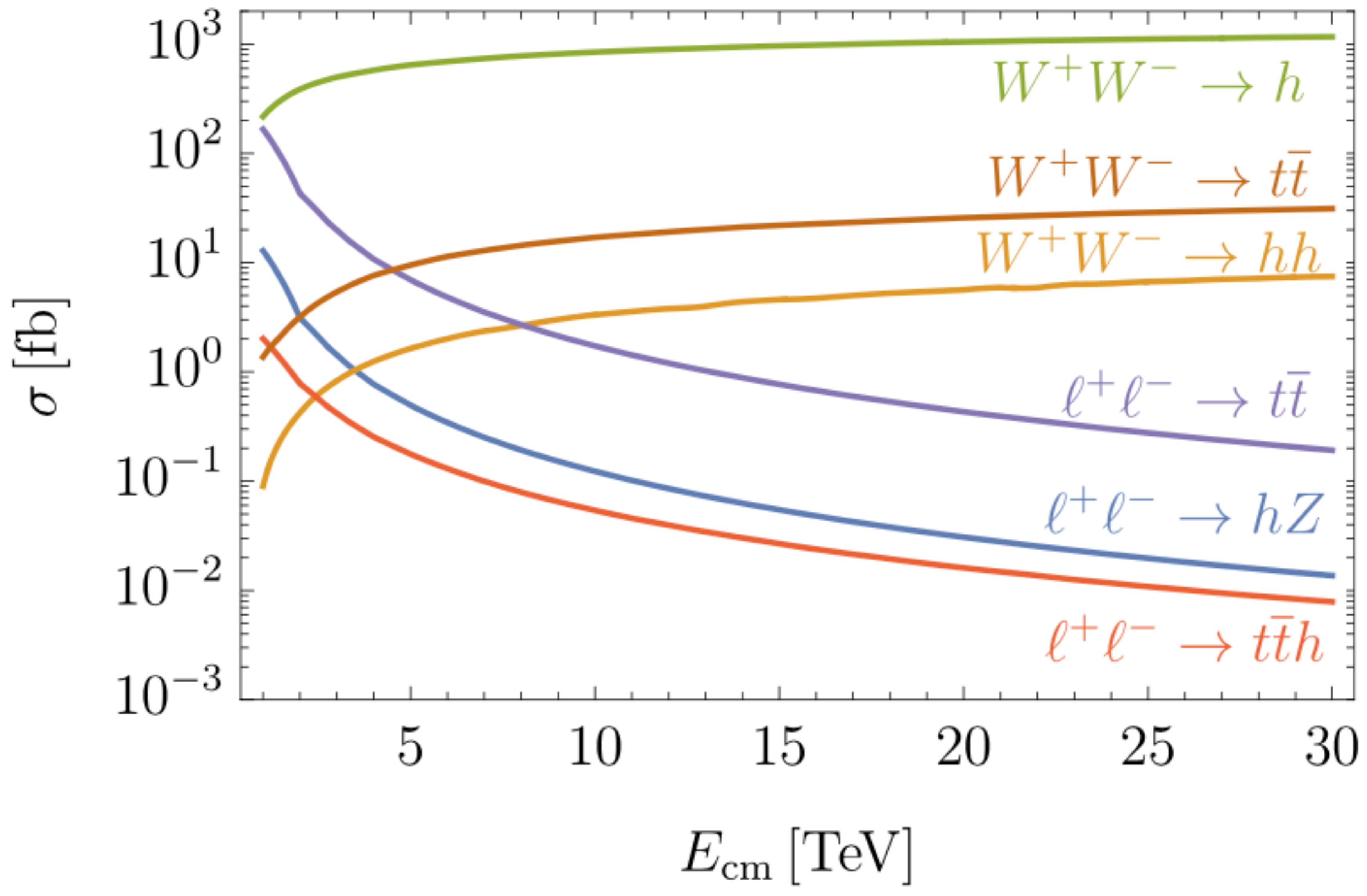


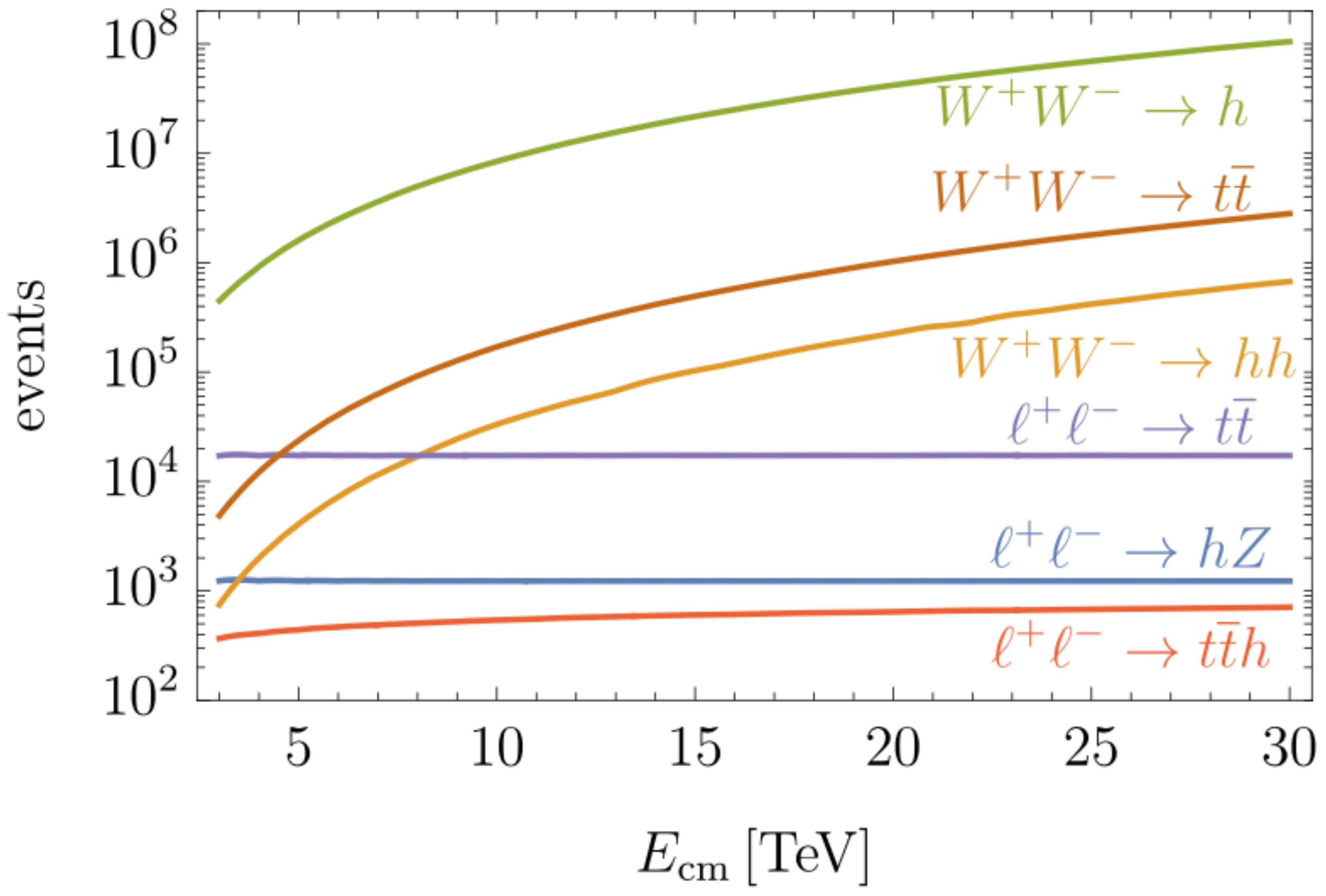
[Buttazzo, Franceschini, Wulzer 2012.11555]

Muon collider physics

The essentials #4 : luminosity with energy

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}}\right)^2 2\cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

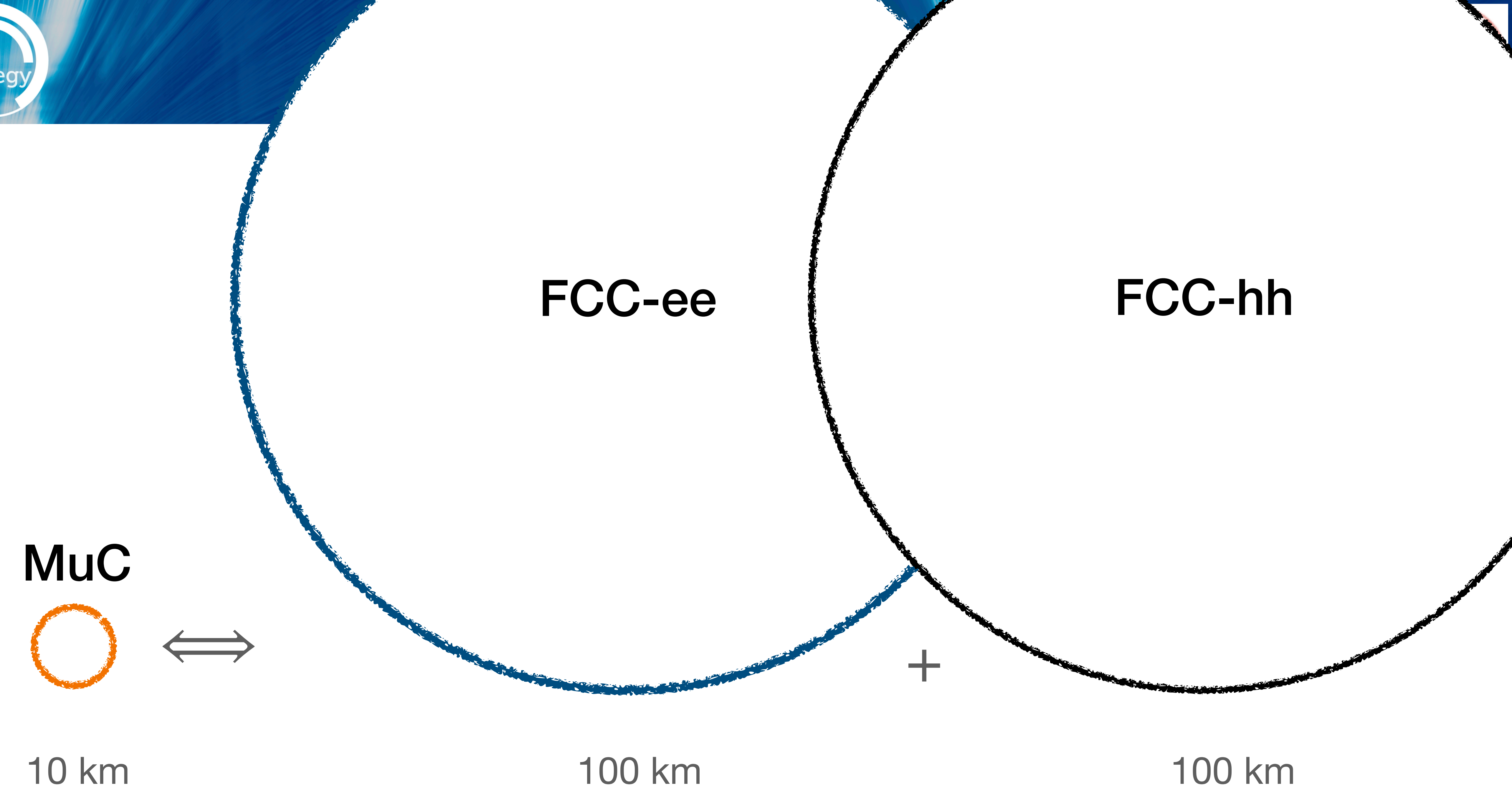




$$\widehat{\mathcal{L}} = 10\,\text{ab}^{-1}\left(\frac{E_{\rm cm}}{10\,\text{TeV}}\right)^2$$

Muon collider physics
The essentials #5: compactness

1] O(10) TeV Energy small hybrid collider:



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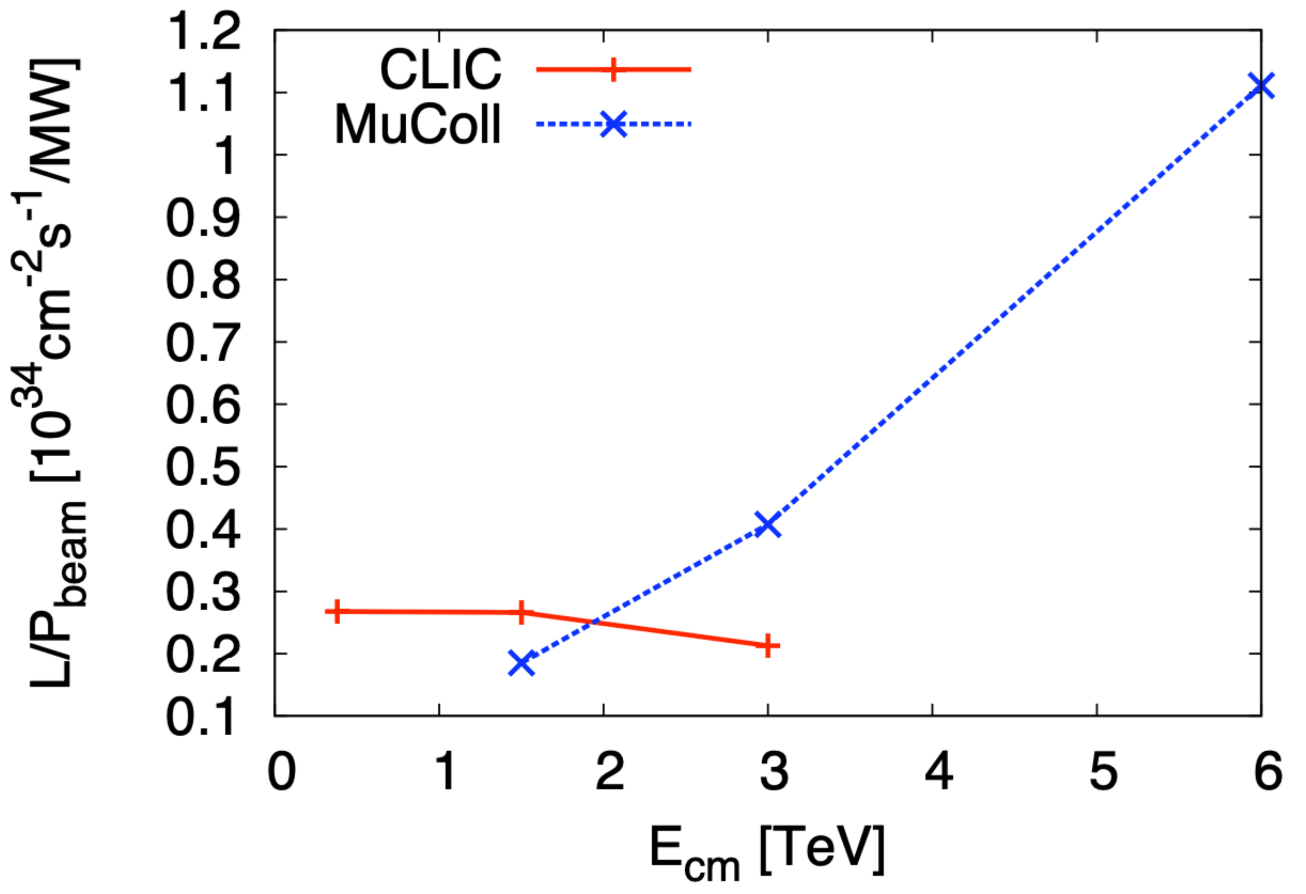
2] Luminosity growing with energy:



⇒MuC is an STCC = Space-Time-Compact Collider

⇒ Goal of the tens:

10 TeV , 10 iab, 10 x smaller and O(10) x faster than the FCC

A muon collider
The project

Strong interest in **high-energy, high-luminosity lepton collider**

- combines **precision physics** and **discovery reach**
- application of hadron collider technology to a lepton collider

Muon collider promises **sustainable** approach to the **energy frontier**
- limited power consumption, cost and land use -> **site evaluation and reuse of existing tunnels**

Technology and **design advances** in past years

- reviews of the muon collider concept in Europe and US found **no insurmountable obstacle**
- **identified required R&D**, documented in accelerator R&D Roadmap
- first parameters' report submitted October 2023

Aim at **10+ TeV** and potential initial stage at **3 TeV**
NEW OPTION: initial 10 TeV stage at reduced luminosity
Interim report https://arxiv.org/abs/2407.12450

Strong support by P5 Report @ December 2023

Presently not considered by CERN as a possible near-term project.
R&D is being financed in a very mild way.

Chart g: Muon collider studies

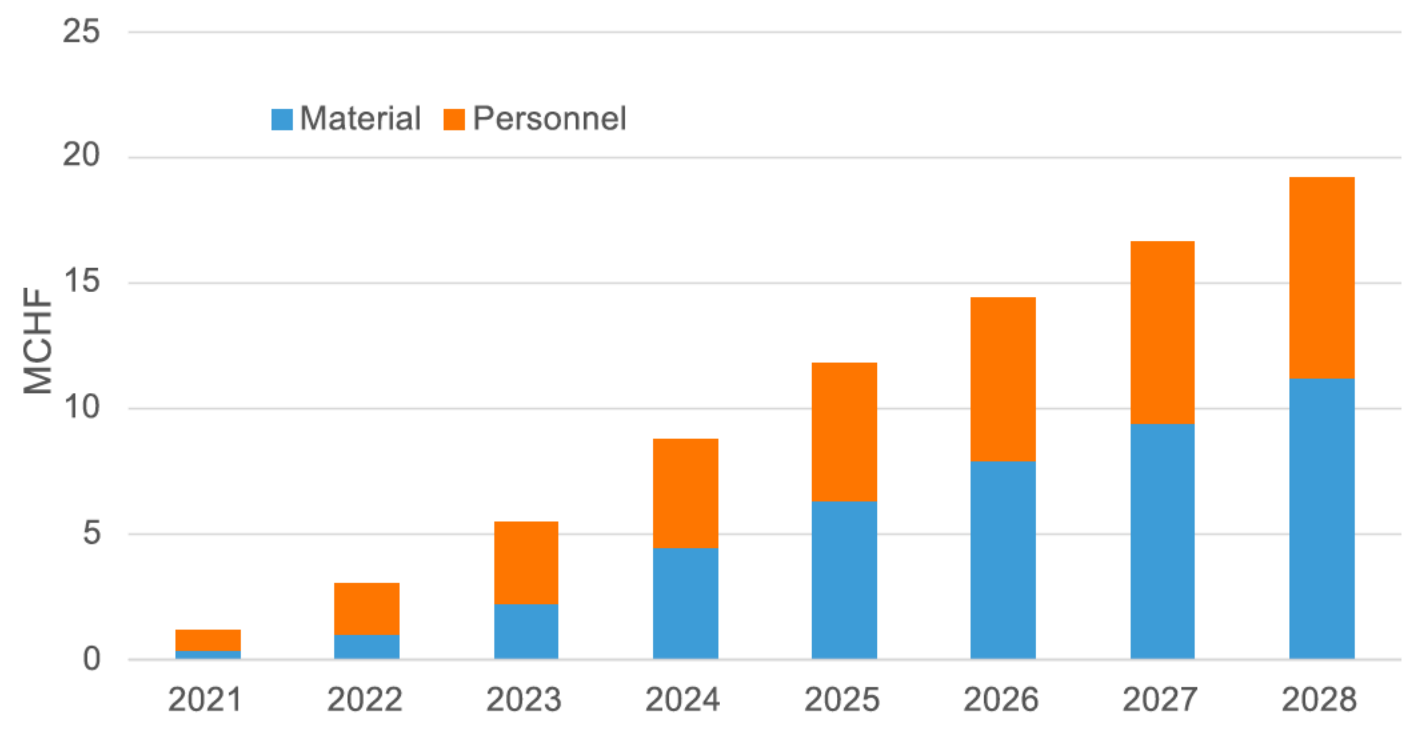
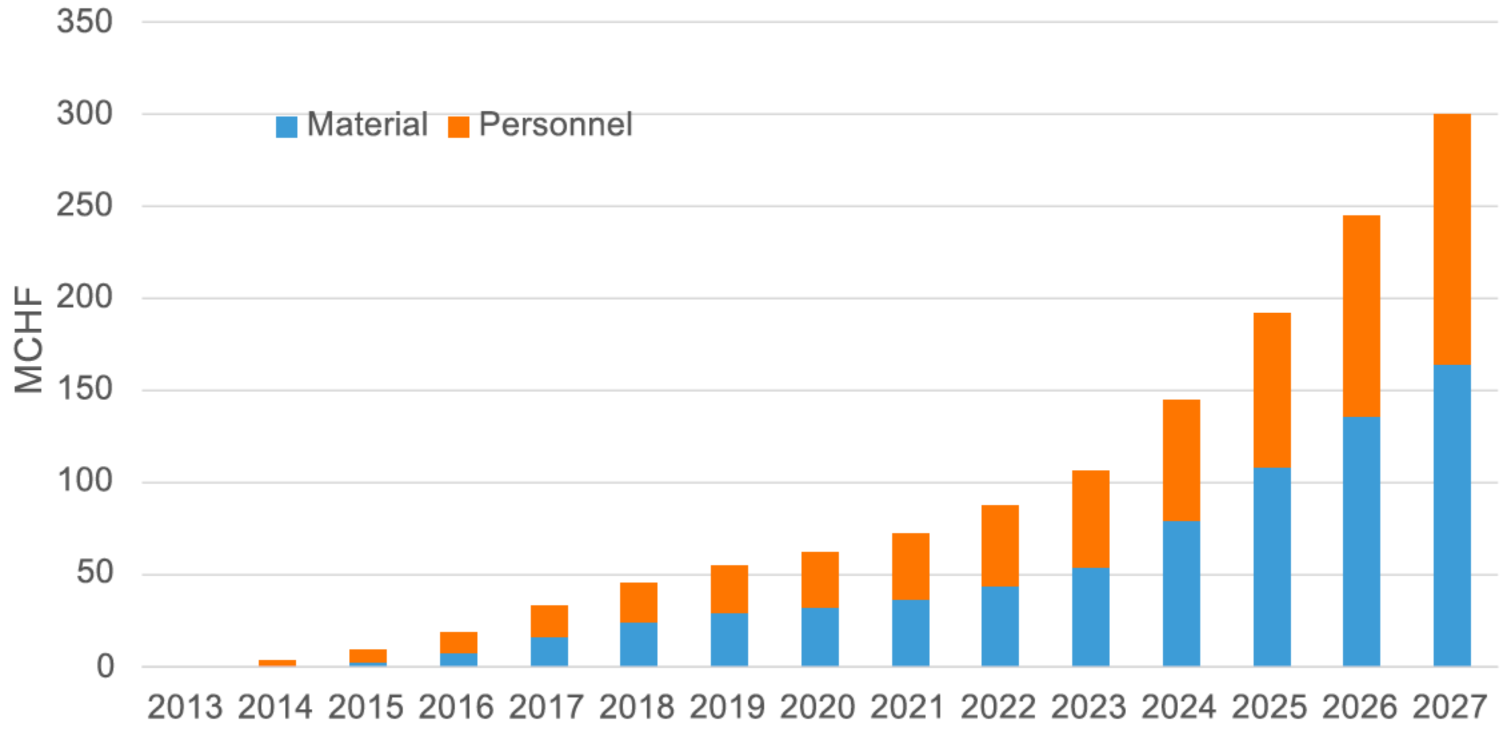


Chart f: Future Circular Collider studies



Muon collider physics

Activities in Bologna

People:

FM (20%),
Davide Pagani (20%)
1 INFN post-doc (100% just finished)
Master students

Science:

Physics case

- Accurate predictions
- Monte Carlo generators

MuColl collaboration:

FM is co-editor of the physics case input to the strategy

EW corrections and Heavy Boson Radiation at a high-energy muon collider
Yang Ma (INFN, Bologna), Davide Pagani (INFN, Bologna), Marco Zaro (INFN, Milan)
e-Print: 2409.09129 [hep-ph]

Interim report for the International Muon Collider Collaboration (IMCC)
International Muon Collider Collaboration • C. Accettura (CERN) et al.
Published in: CERN Yellow Rep.Monogr. 2 (2024)

Probing Higgs-muon interactions at a multi-TeV muon collider
Eugenia Celada (Bologna U. and Manchester U.), Tao Han (Pittsburgh U.), Wolfgang Kilian (Siegen U.), Nils Kreher (Siegen U.), Yang Ma (INFN, Bologna) et al.
Published in: JHEP 08 (2024), 021

Towards a muon collider
Carlotta Accettura (CERN), Dean Adams (Rutherford), Rohit Agarwal (UC, Berkeley (main)), Claudia Ahdida (CERN), Chiara Aimè (Pavia U. and INFN, Pavia) et al.
e-Print: 2303.08533 [physics.acc-ph]
Published in: Eur.Phys.J.C 83 (2023) 9, 864, Eur.Phys.J.C 84 (2024) 1, 36 (erratum)

Muon Collider Forum report
K.M. Black (U. Wisconsin, Madison (main)), S. Jindariani (Fermilab), D. Li (LBNL, Berkeley), F. Maltoni (Louvain U., CP3 and INFN, Bologna and U. Bologna, DIFA), P. Meade (YIT
e-Print: 2209.01318 [hep-ex]
Published in: JINST 19 (2024) 02, T02015

Simulated Detector Performance at the Muon Collider
Muon Collider Collaboration • N. Bartosik (INFN, Turin) et al.
e-Print: 2203.07964 [hep-ex]

A Muon Collider Facility for Physics Discovery
Muon Collider Collaboration • D. Stratakis (Fermilab) et al.
e-Print: 2203.08033 [physics.acc-ph]

Promising Technologies and R&D Directions for the Future Muon Collider Detectors
Muon Collider Collaboration • S. Jindariani (Fermilab) et al.
e-Print: 2203.07224 [physics.ins-det]

Muon Collider Physics Summary
Chiara Aime (Pavia U. and INFN, Pavia), Aram Apyan (Brandeis U.), Mohammed Attia Mahmoud Mohammed (Fayoum U.), Nazar Bartosik (INFN, Turin), Fabian Batsch (CERN) et al
e-Print: 2203.07256 [hep-ph]

The physics case of a 3 TeV muon collider stage
Muon Collider Collaboration • Jorge de Blas (Granada U., Theor. Phys. Astrophys.) et al.
e-Print: 2203.07261 [hep-ph]

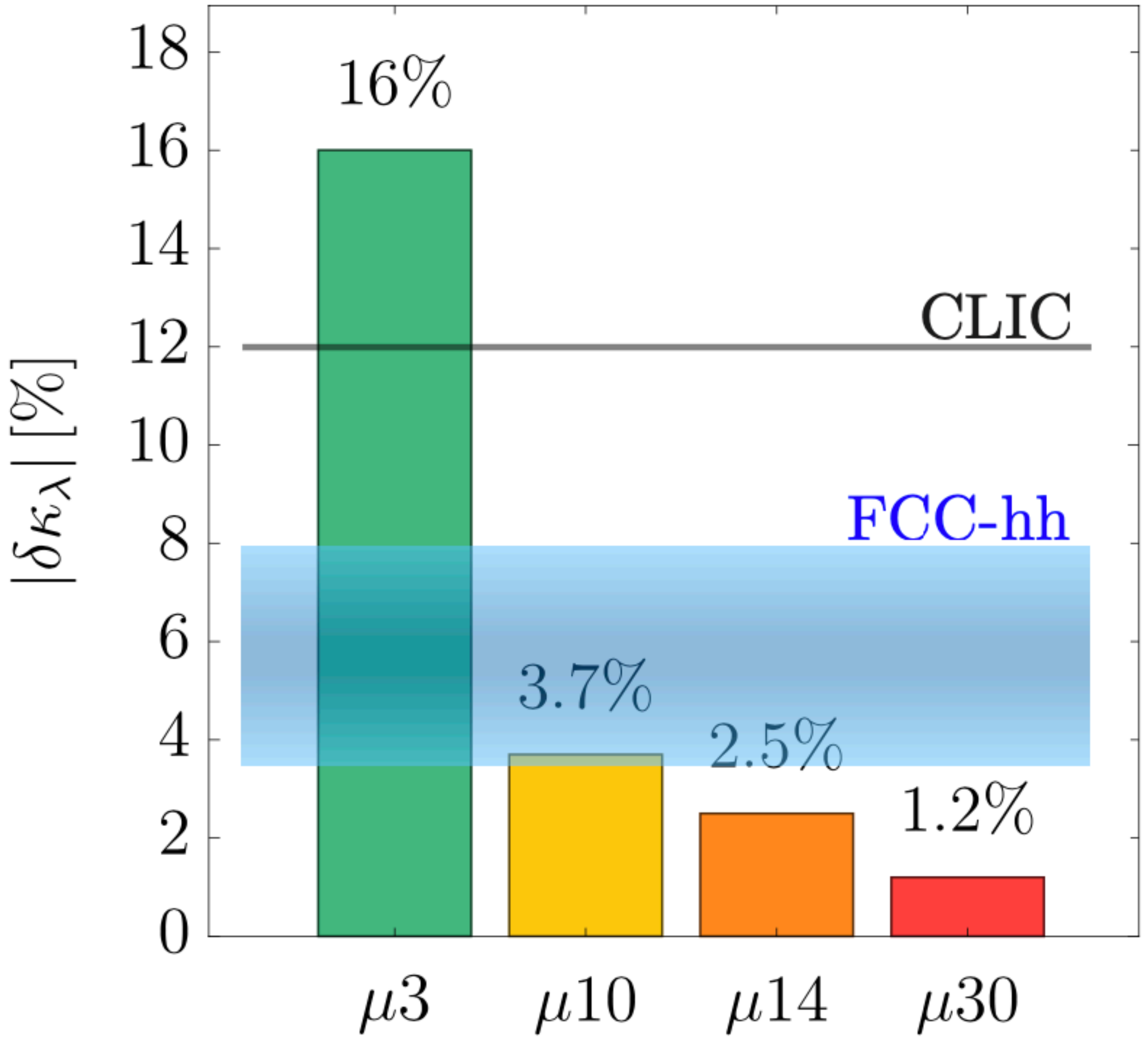
The Effective Vector Boson Approximation in high-energy muon collisions
Richard Ruiz (Cracow, INP), Antonio Costantini (Louvain U., CP3), Fabio Maltoni (Louvain U., CP3 and Bologna U. and INFN, Bologna), Olivier Mattelaer (Louvain U., CP3)
Published in: JHEP 06 (2022), 114

Vector boson fusion at multi-TeV muon colliders
Antonio Costantini (INFN, Bologna), Federico De Lillo (Louvain U., CP3), Fabio Maltoni (Louvain U., CP3 and Bologna U. and INFN, Bologna), Luca Mantani (Louvain U., CP3 and I
Published in: JHEP 09 (2020), 080

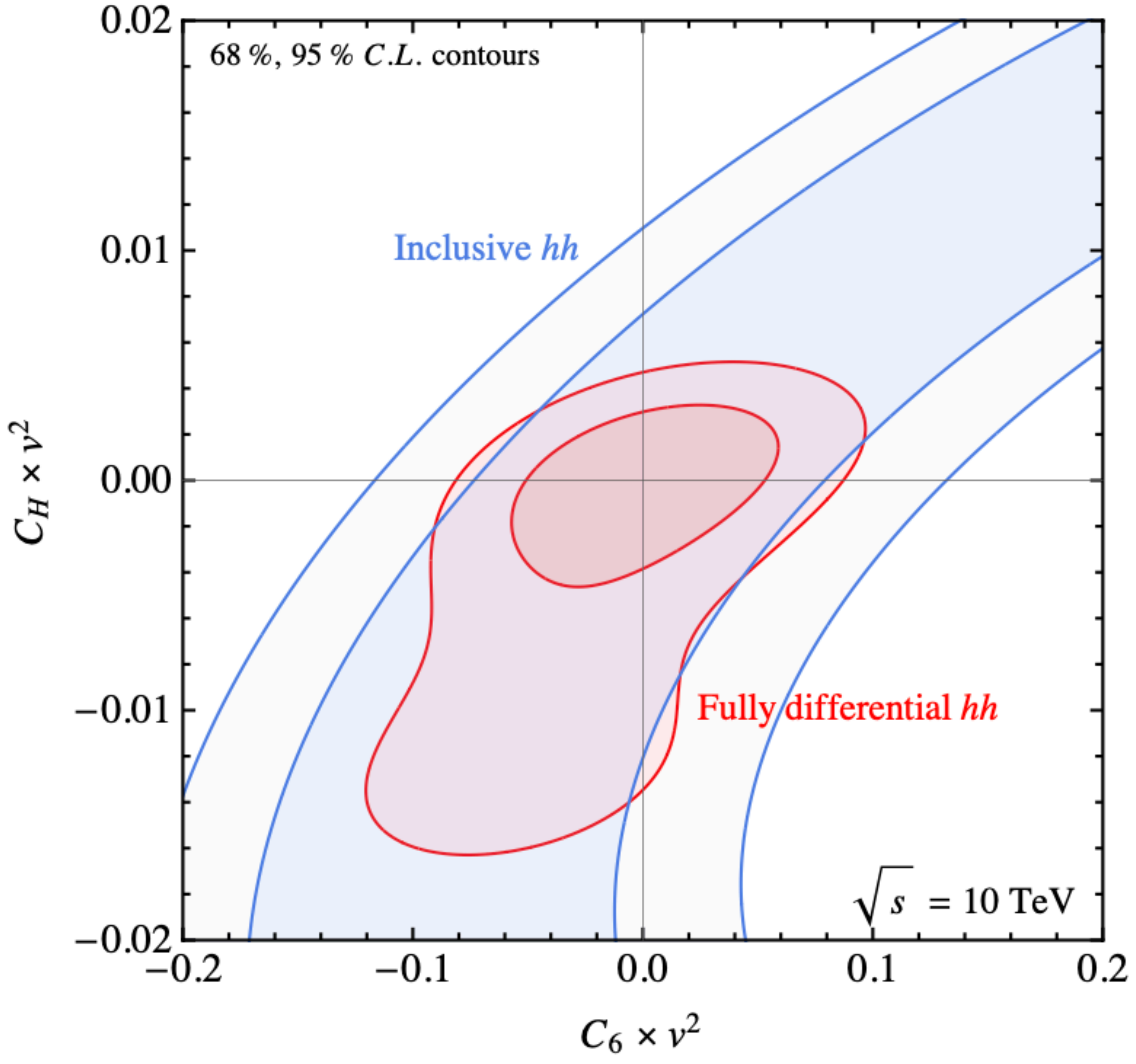
Measuring the quartic Higgs self-coupling at a multi-TeV muon collider
Mauro Chiesa (Annecy, LAPTH), Fabio Maltoni (Louvain U., CP3 and U. Bologna, DIFA and INFN, Bologna), Luca Mantani (Louvain U., CP3 and U. Heidelberg, ITP), Barbara Mele
Published in: JHEP 09 (2020), 098

Higgs precision physics

The shape of the H potential: HH production



arXiv:2203.07256v1



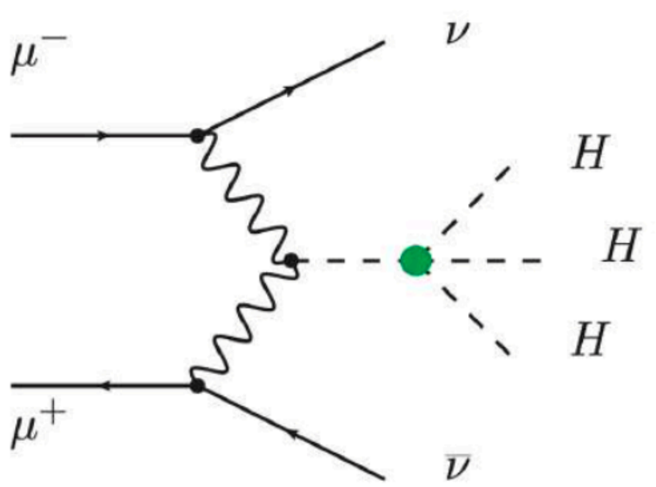
[Buttazzo et al. 2012.11555]

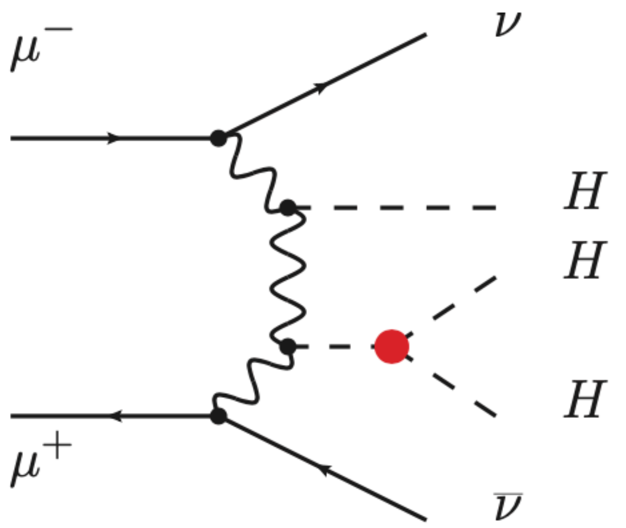
Reach on the trilinear coupling (and more) extremely competitive.

Higgs precision physics

The shape of the H potential : HHH production

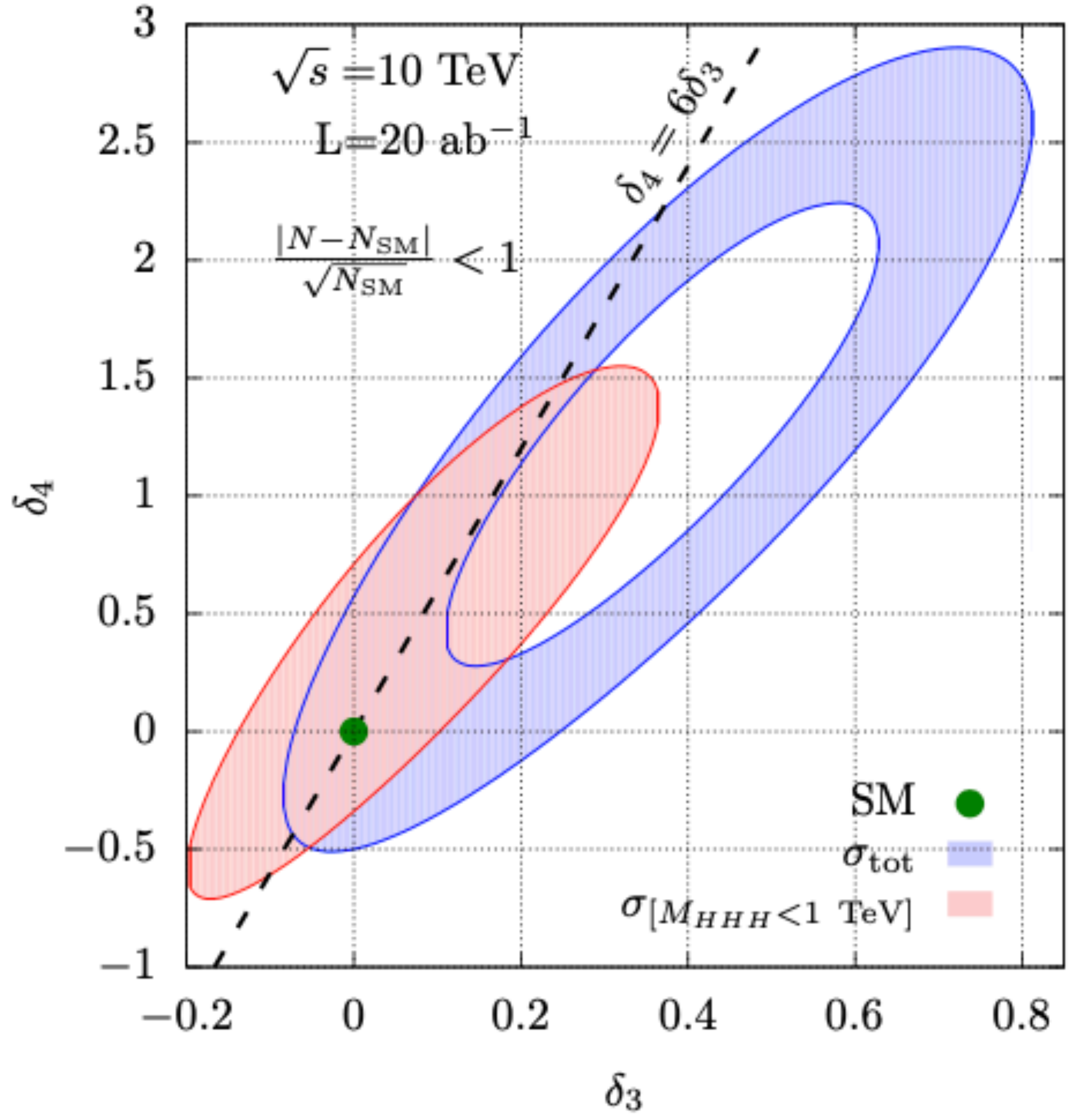
3 Higgs final state





Quadrilinear determination extremely challenging at any collider, due to limited sensitivity.

$$\text{ILC} \sim [-10, 10]$$
$$\text{CLIC} \sim [-5, 5]$$
$$\text{FCC} \sim [-2, 4]$$

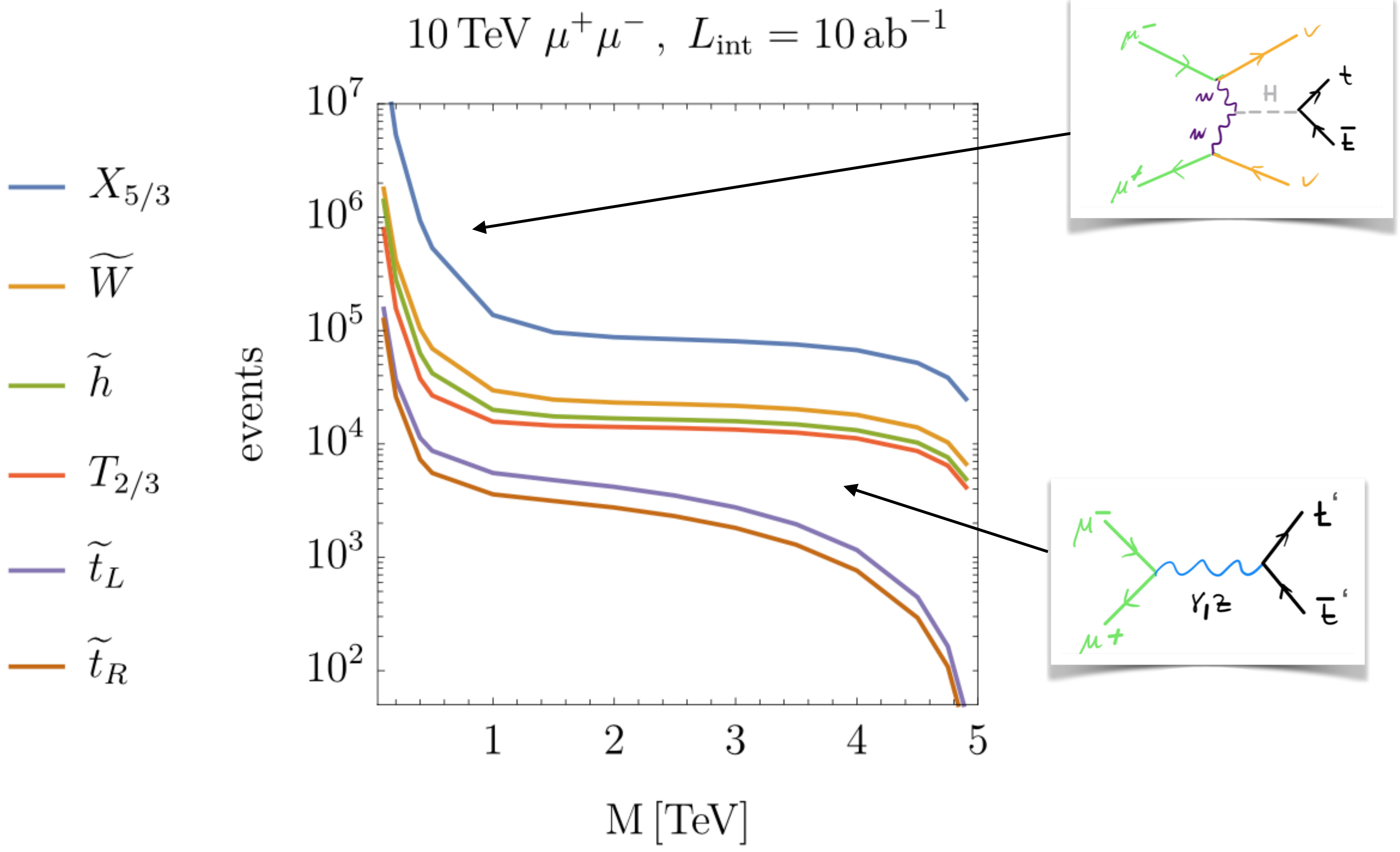


[Chiesa et al. 2003.13268]

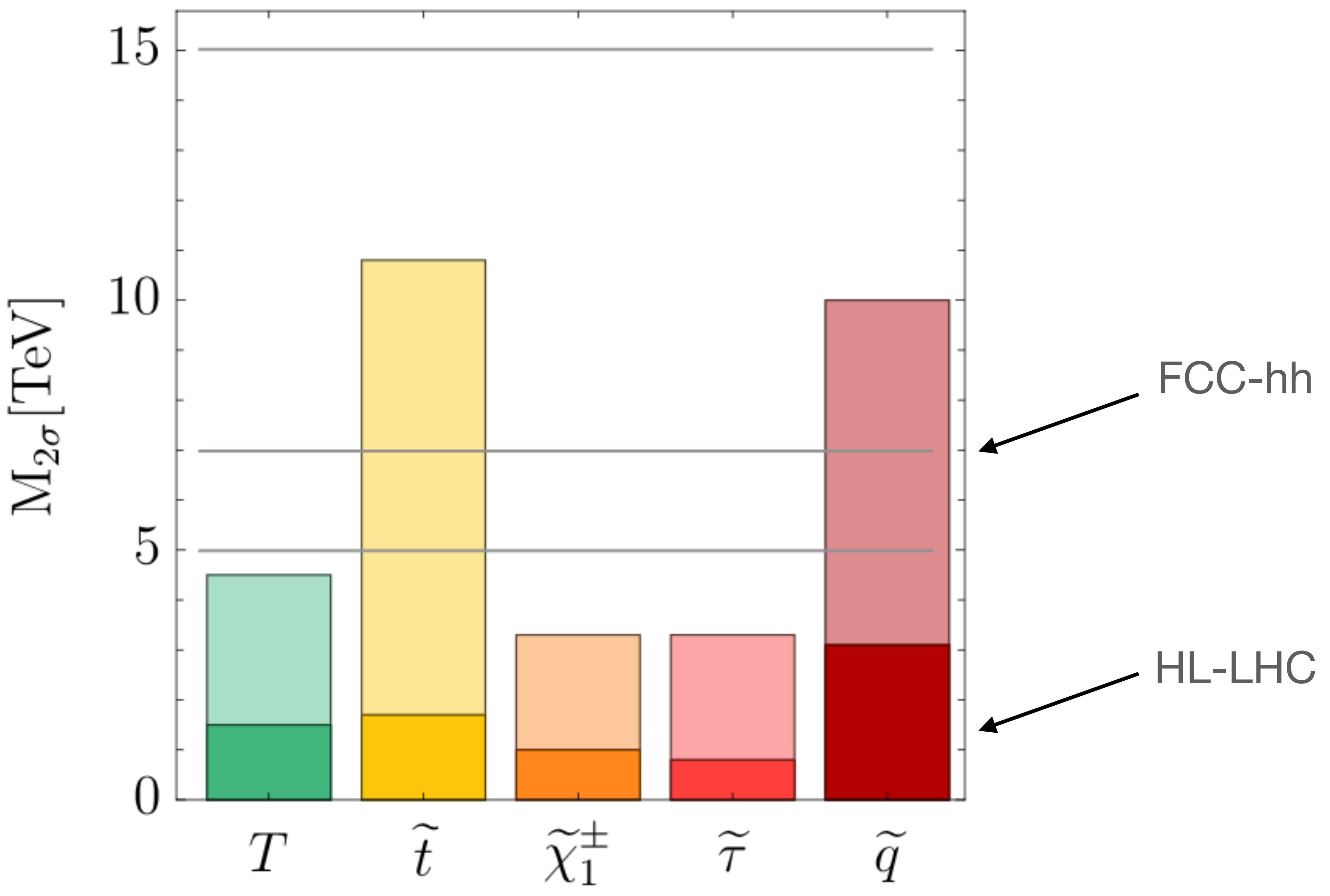
Very preliminary study points to the possibility of setting competitive bounds at a muon collider.

$$10\ \text{TeV} \quad \delta_4 \sim [-0.4, 0.7]$$

Direct reach
s-channel pair production



A few months of run could be sufficient for a discovery.



Matching Higgs precision:

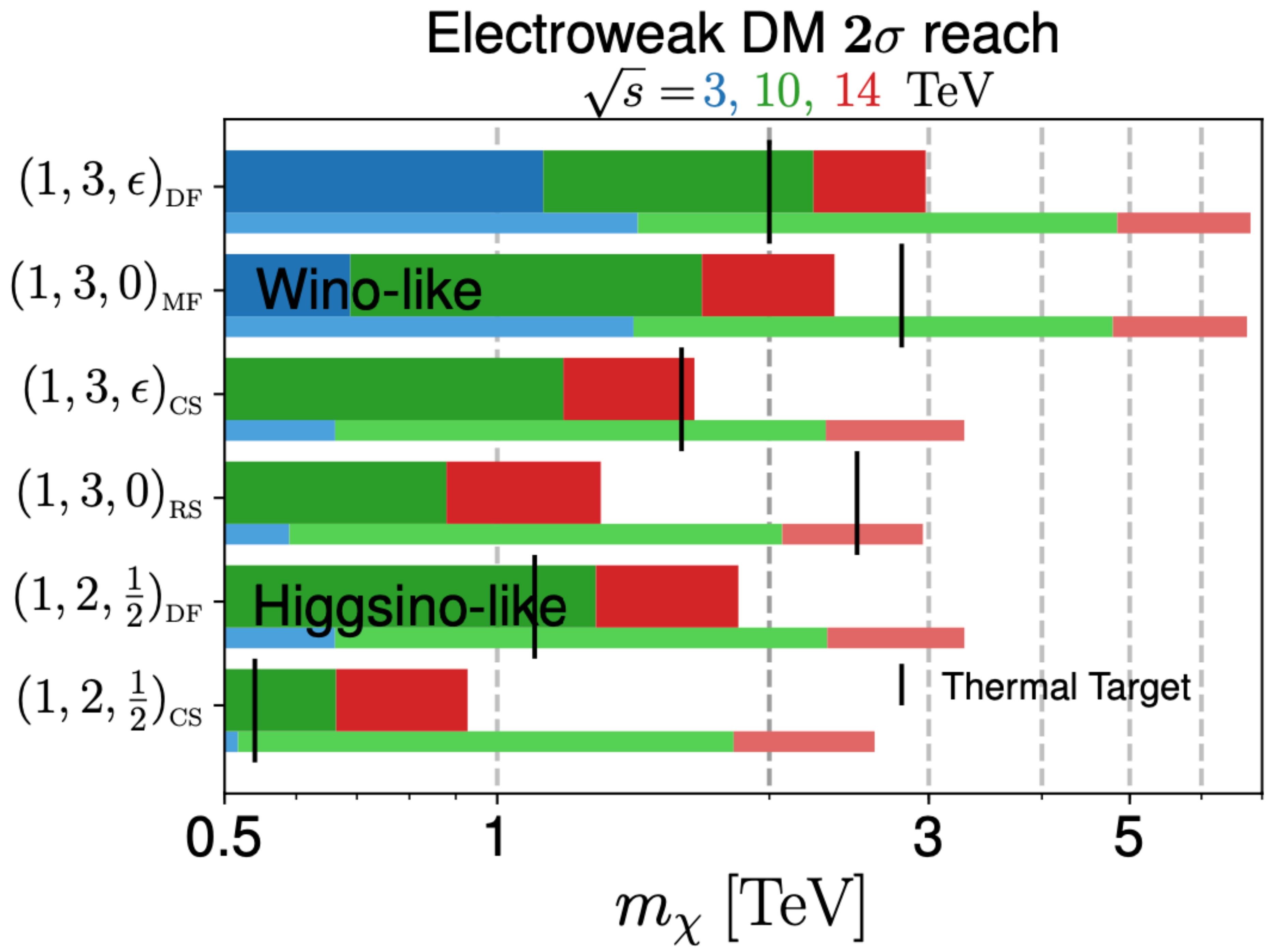
$$\delta\kappa_g = \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

$$m_{\tilde{t}} \gtrsim 1.5\,\text{TeV}\sqrt{\frac{0.67\%}{\delta\kappa_g^{\max}}}.$$

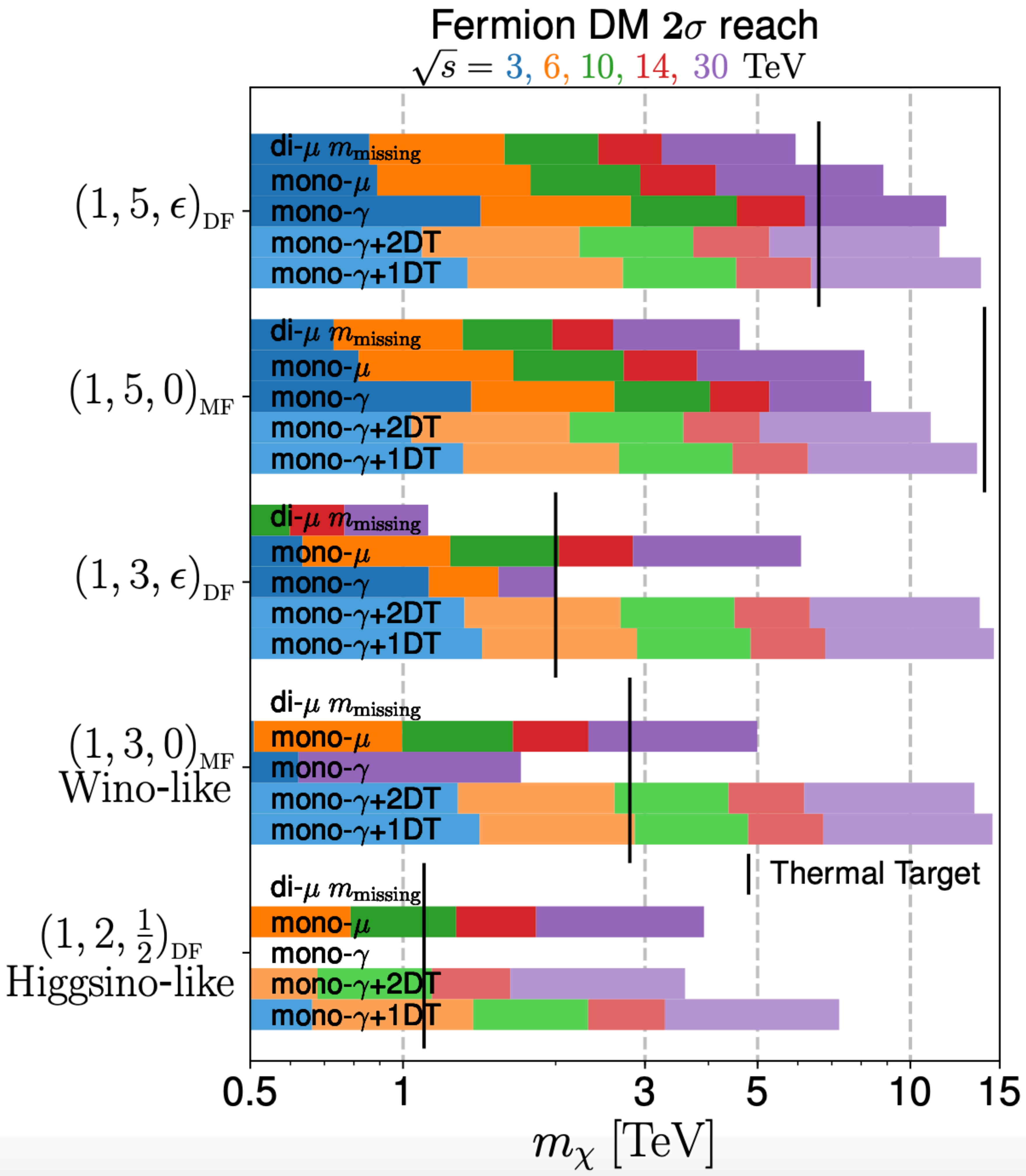
Direct reach

Minimal DM

arXiv:2209.01318 Muon Collider Forum Report



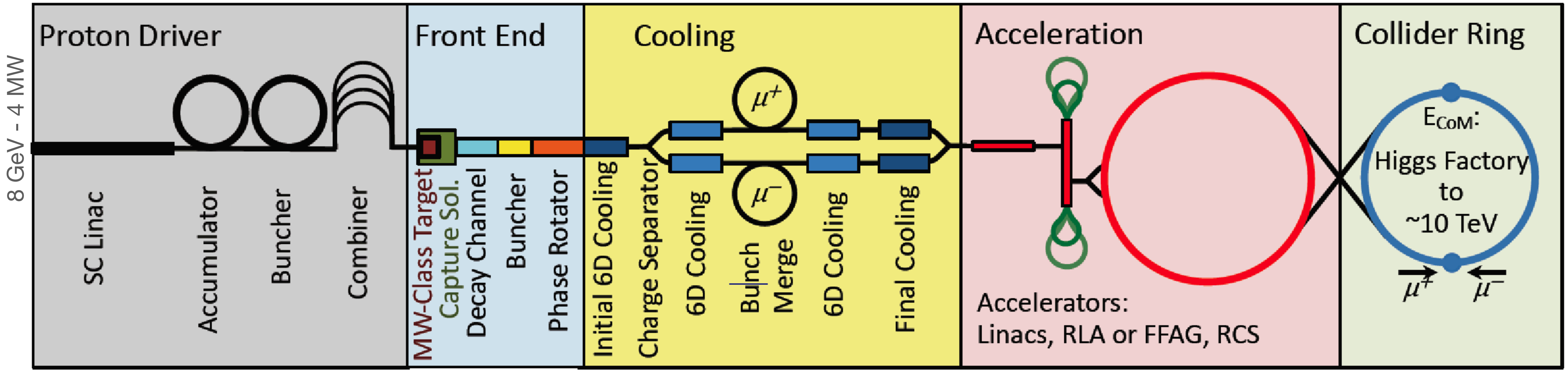
2σ exclusion of DM masses with horizontal (thick) bars for combined channels and various muon collider running scenarios by the different color codes. The thin bars are the estimation of the mono-photon plus one disappearing track search. The vertical bars indicate the thermal mass targets for the corresponding WIMP DM.



2σ exclusion of fermion DM masses with horizontal bars for individual search channels and muon collider energies by the different colors. The vertical bars indicate the thermal mass targets

Muon collider technology

New generation of accelerator technologies.
No known showstoppers. Need to be demonstrated.



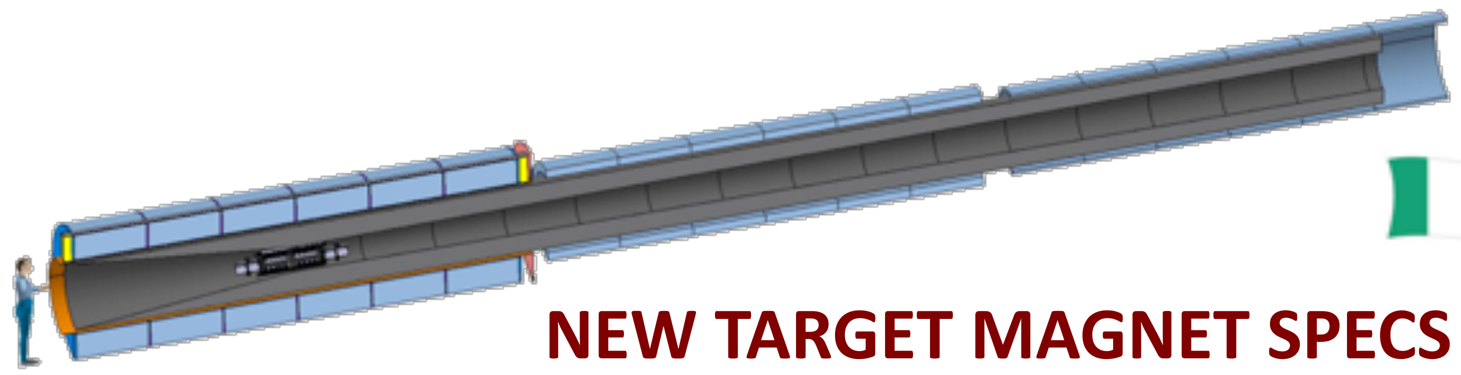
Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

Ionisation cooling of muon in matter

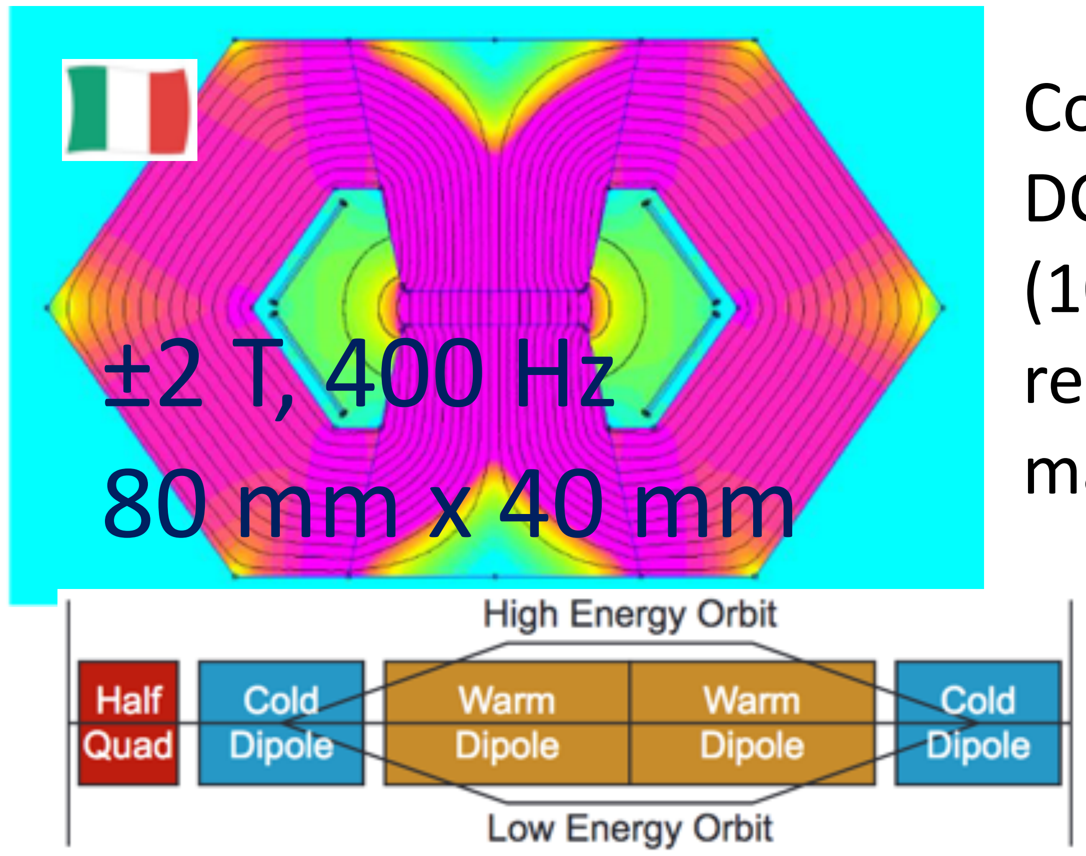
Acceleration to collision energy

Collision



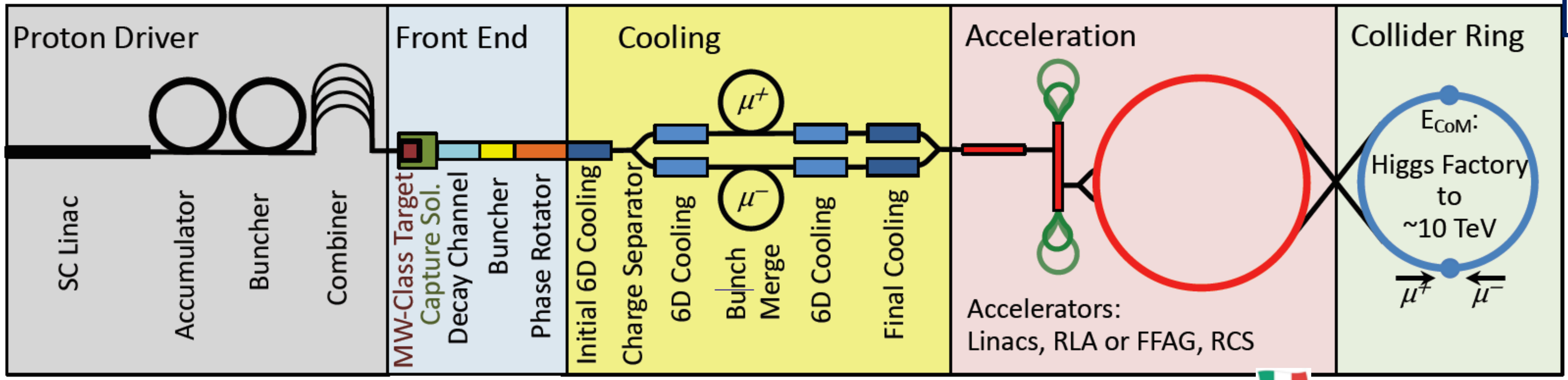
NEW TARGET MAGNET SPECS
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy

High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads

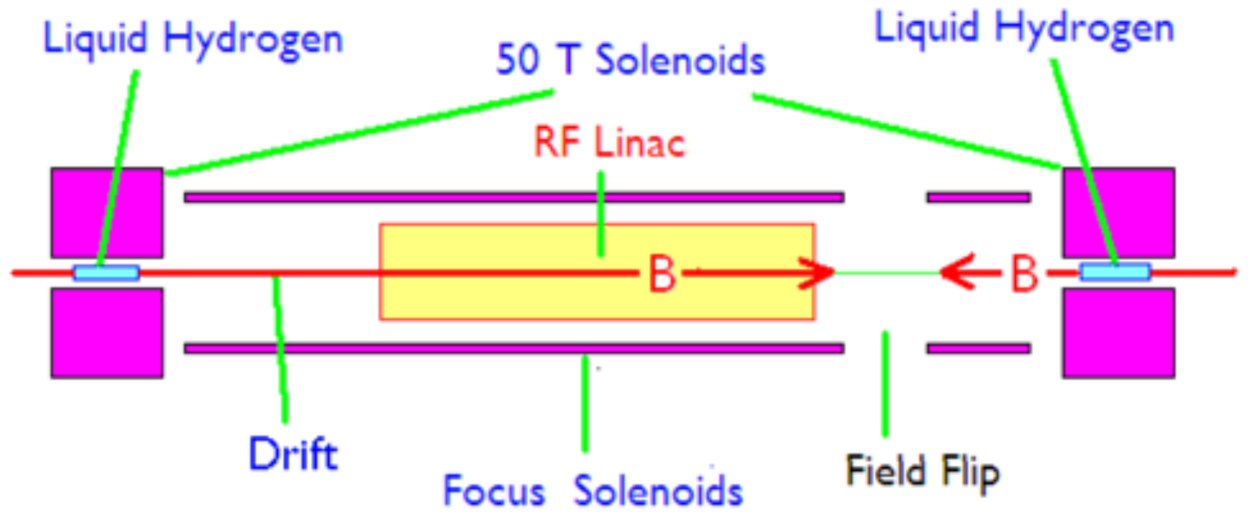


Combination of DC SC magnets (10 T) and AC resistive magnets (± 2T)

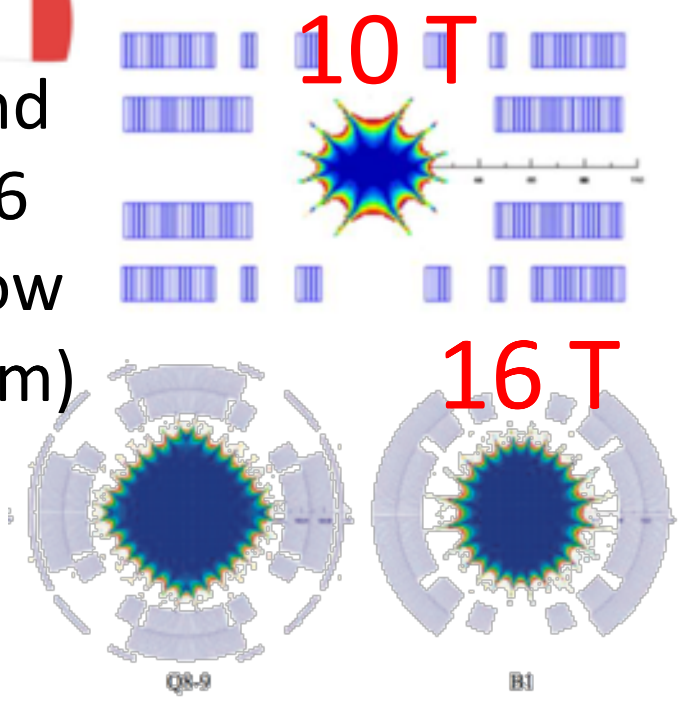
L. Rossi, M. Statera et al.
MI-LASA
B. Caiffi, A. Bersani et al.
Genova
M. Breschi et al.
Bologna



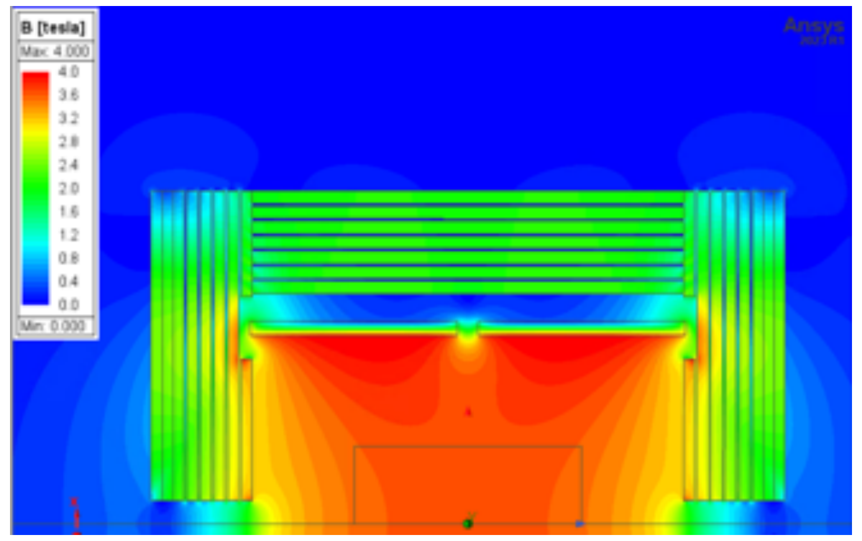
Ultra-high-field solenoids (40…60 T) to achieve desired muon beam cooling



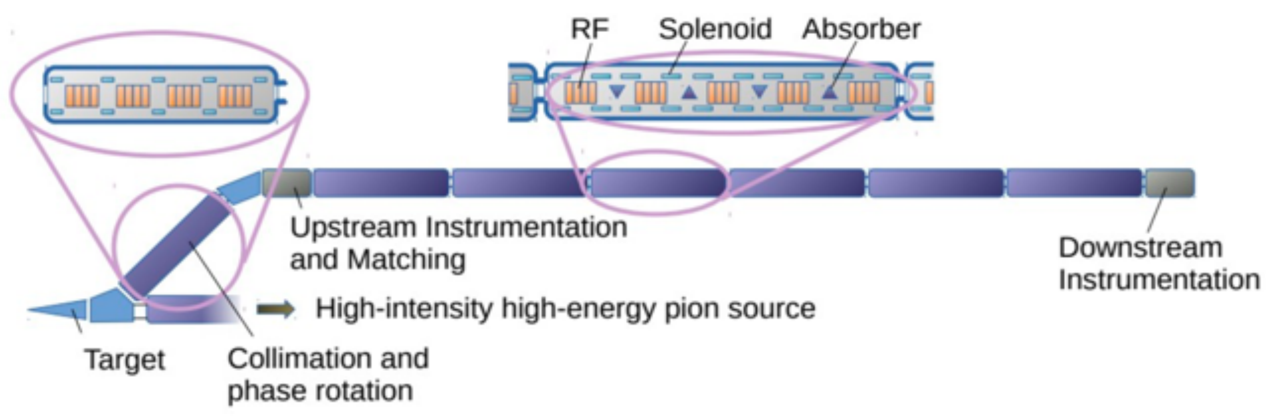
Open midplane or large dipoles and quadrupoles in the range of 10…16 T, bore in excess of 150 mm to allow for shielding against heat (500 W/m) and radiation loads



Detector Magnet
to be designed for 10TeV



Demonstrator Facility: a crucial step forward!

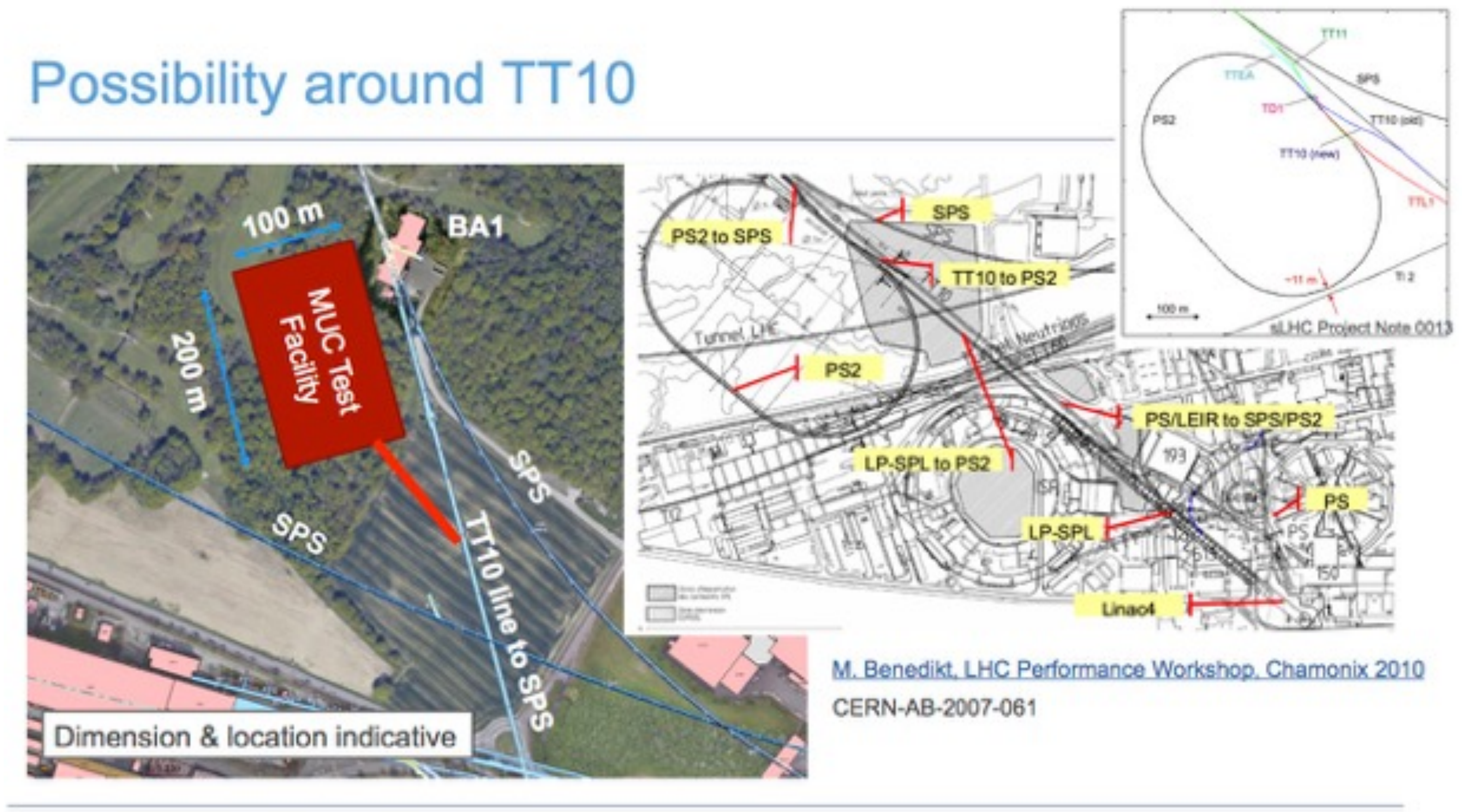


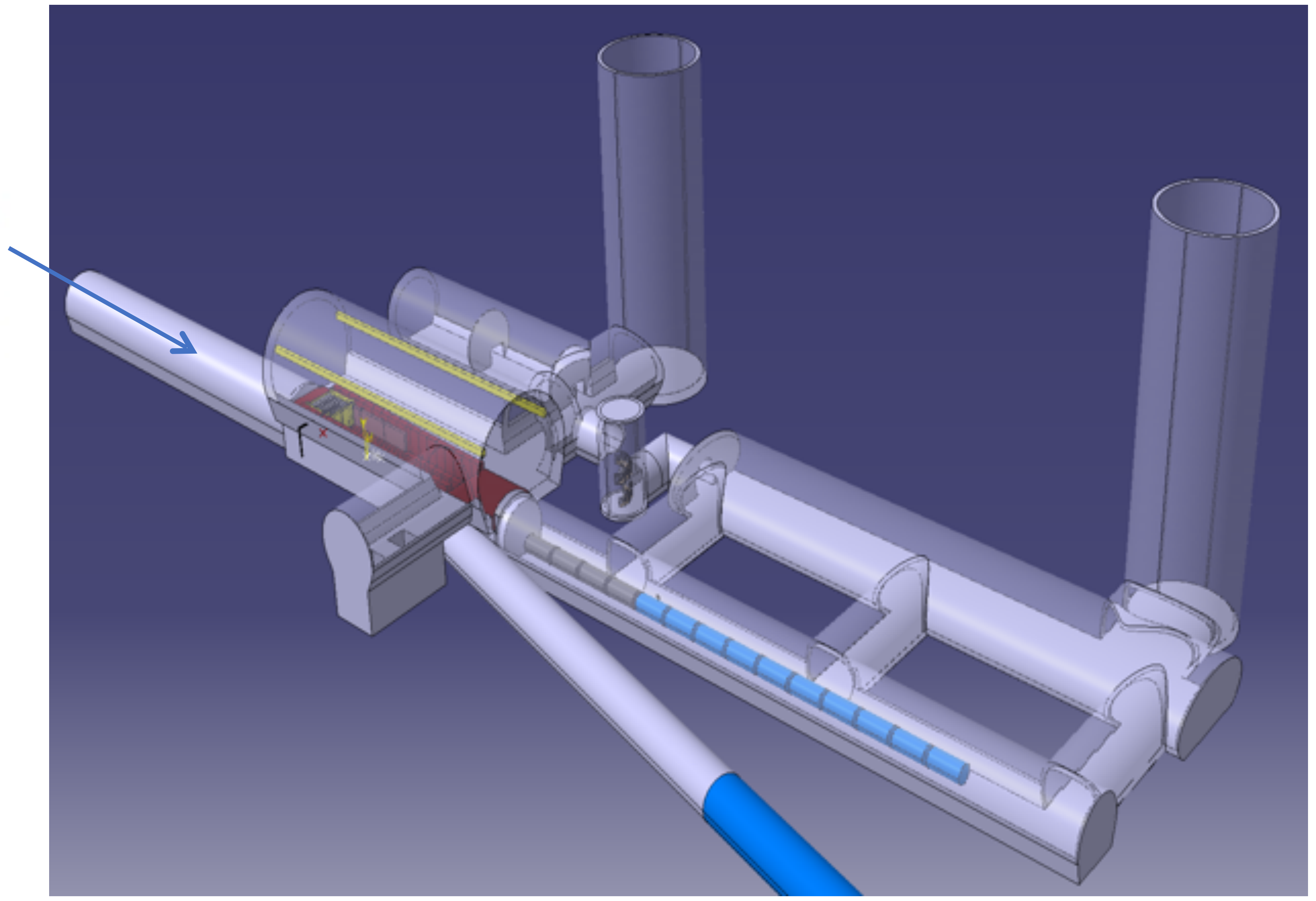
Planning **demonstrator** facility with muon production target and cooling stations

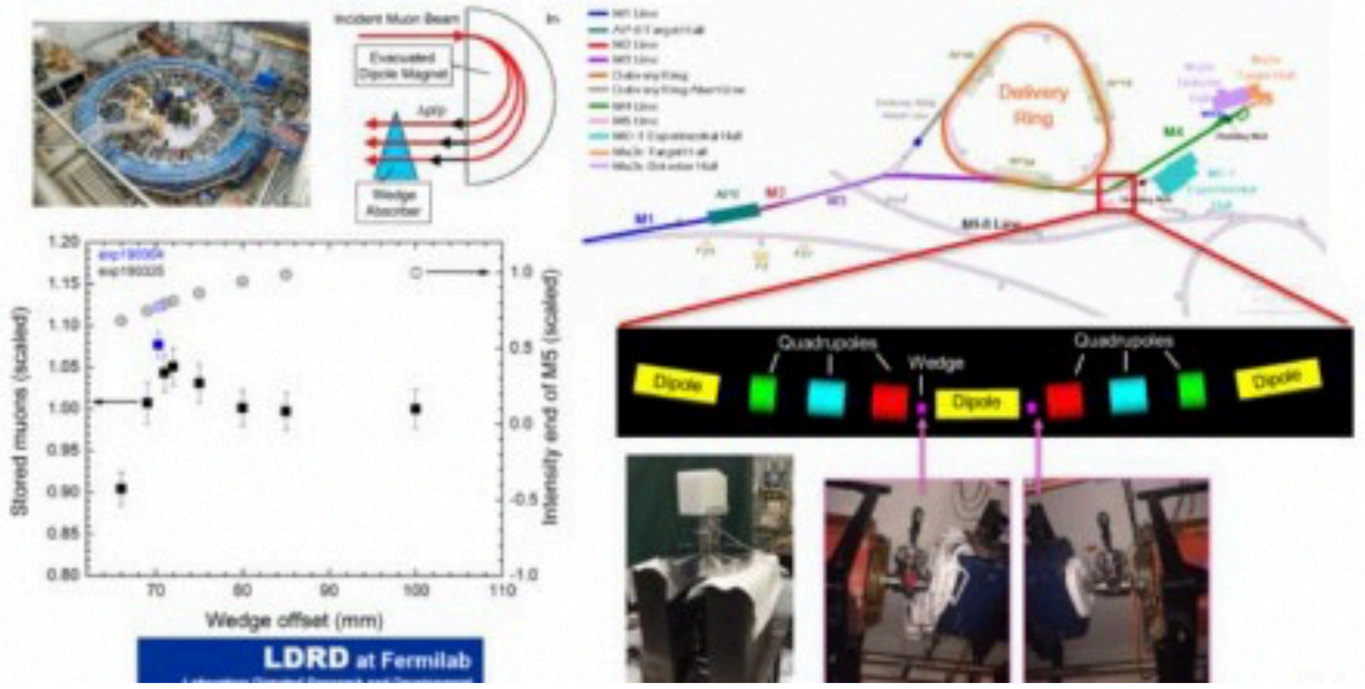
@ CERN

Suitable **site exists** on CERN land and can use **PS proton beam**

- could combine with **NuStorm** or other option







@ FNAL

International Muon Collider Collaboration: Demonstrator Workshop

@ FNAL October 30 – November 1, 2024

Muon collider technology
Activities in Bologna

People:
Marco Breschi

Science:

1. Design of **fast-ramped resistive dipoles** for the rapid cycling synchrotron (RCS) accelerator
2. Advances in the modeling of the **H-type magnet**
3. Design of **fast-ramped resistive quadrupoles** for the RCS accelerator

MuColl collaboration:
Member of EU MUcoll project

1. Design of fast-ramped resistive dipoles

- Magnet specifications:

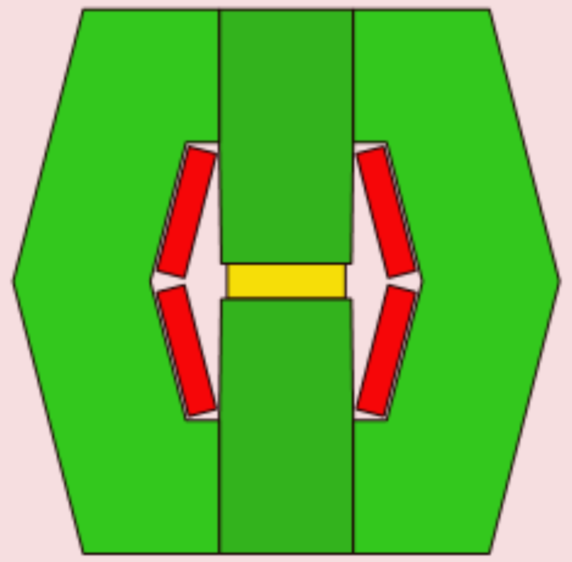
  1) Magnetic field in the aperture 1.8 T

  2) Good field region (30 mm * 100 mm)

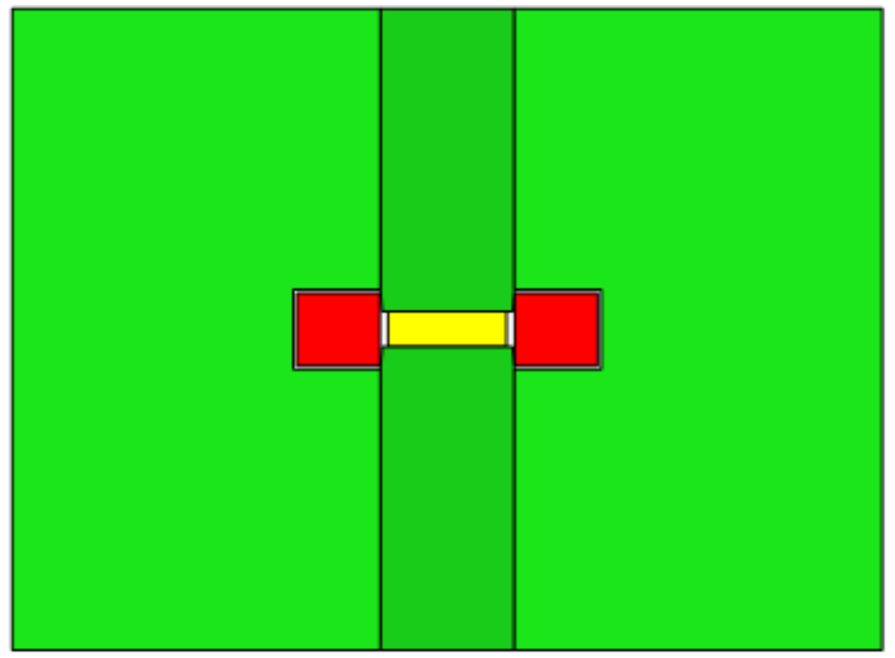
  3) 1 ms ramp from –1.8 to + 1.8 T

- Various magnet configurations available in the literature were analyzed with a FEM model and a design optimization procedure
- Comparison made in terms of stored magnetic energy (relevant for the power supply system), electrodynamic losses (relevant for operation and environmental costs) and field quality

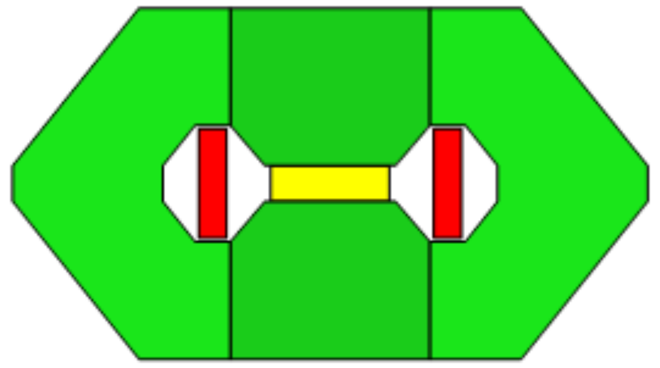
1. Design of fast-ramped resistive dipoles



HG (J=10 A/mm²): Emag = 5.71 [kJ/m]

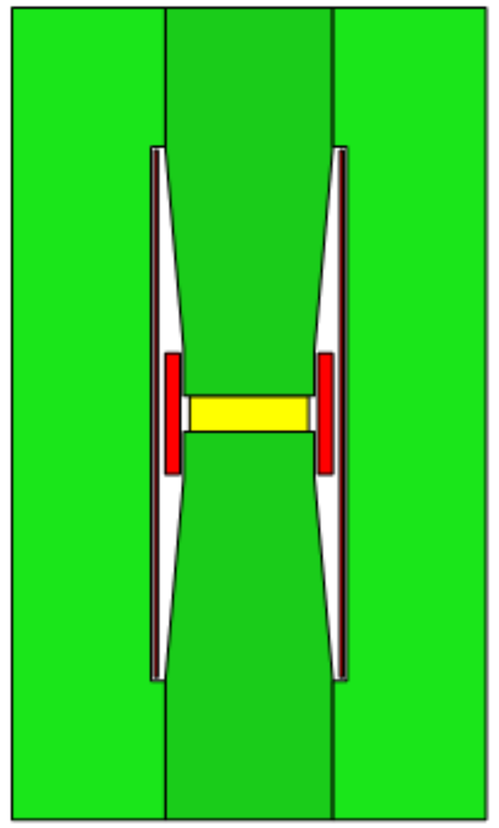


WF1: (J=10 A/mm² Emag = 5.37 [kJ/m]

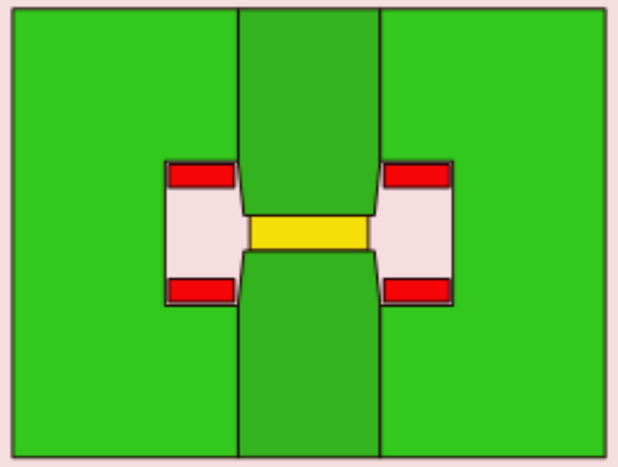


WF1M: (J=20 A/mm² Emag = 6.05 [kJ/m]

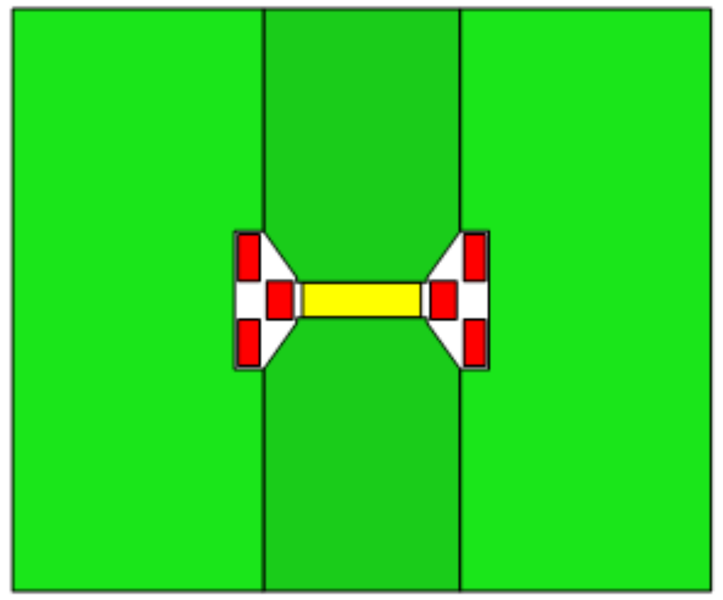
- Selected configurations (low energy and losses)



WF2: (J=20 A/mm² Emag = 5.44 [kJ/m]



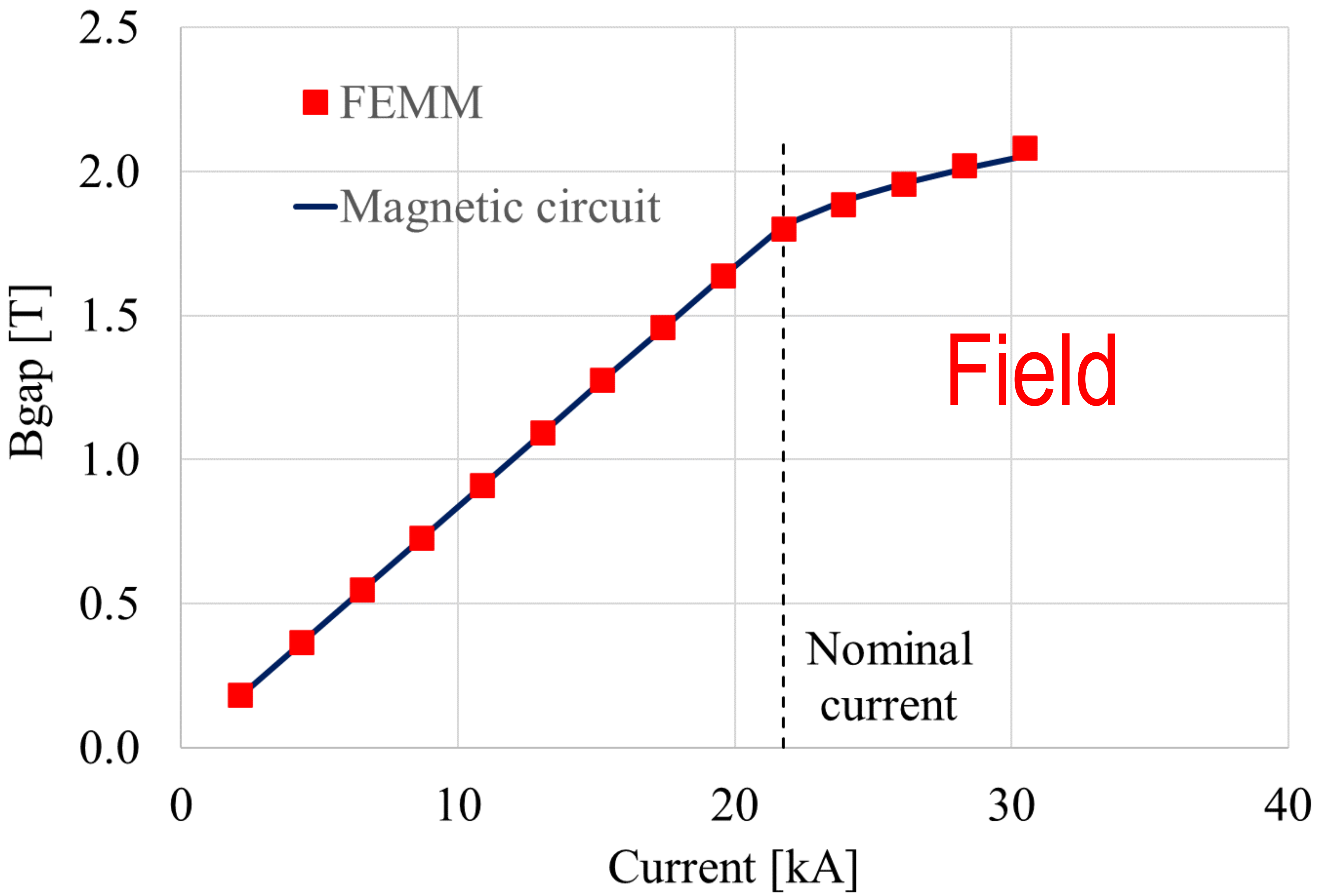
HM: (J=20 A/mm² Emag = 5.74 [kJ/m]

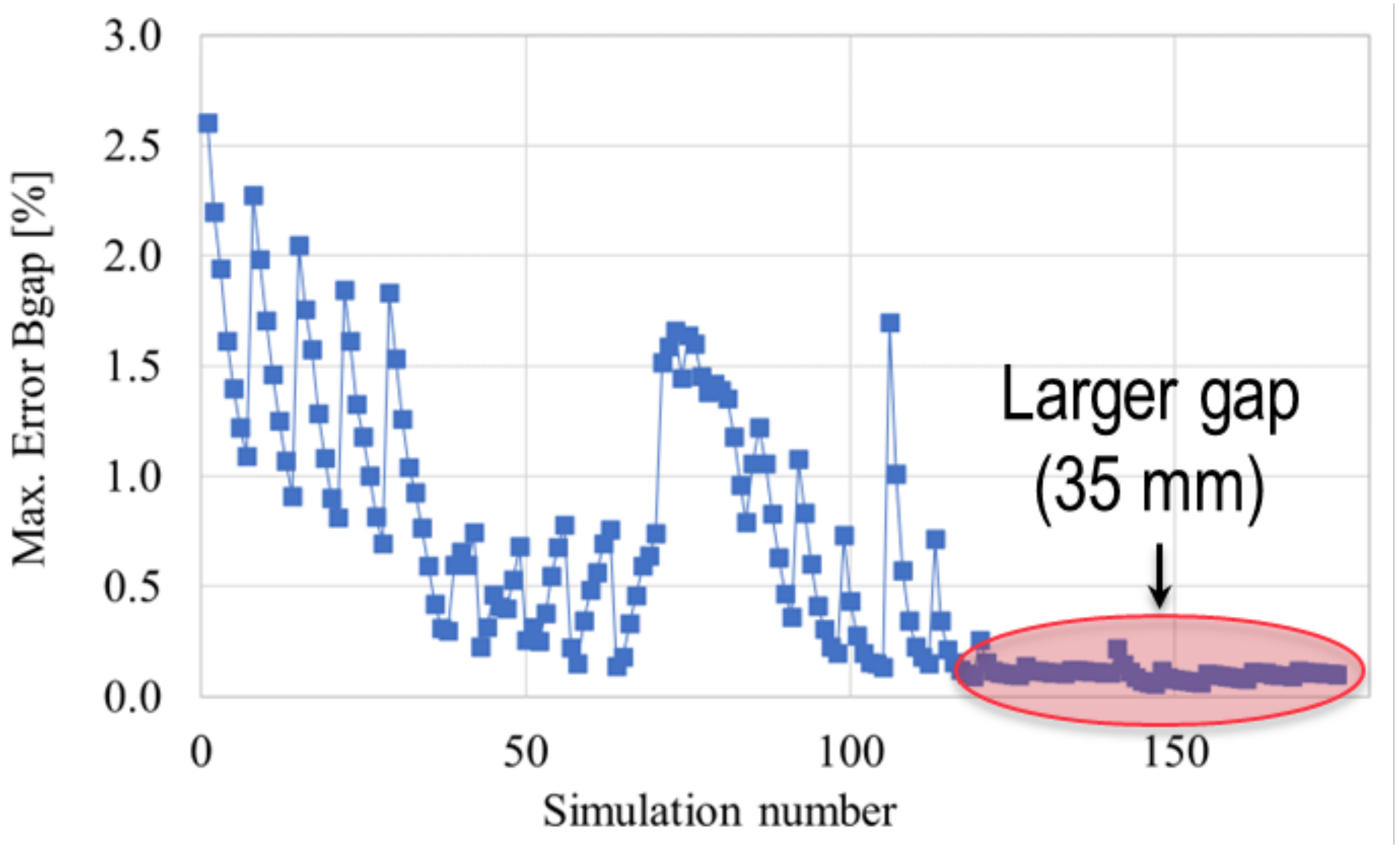


WF3: (J=20 A/mm² Emag = 5.36 [kJ/m]

2. Magnetic circuit model of the H-type magnet

- The field in the gap, total flux linked to the winding and losses were computed with both the magnetic circuit and the 2D FEM model.
- A good agreement was found for 175 different configurations with different geometric parameters.

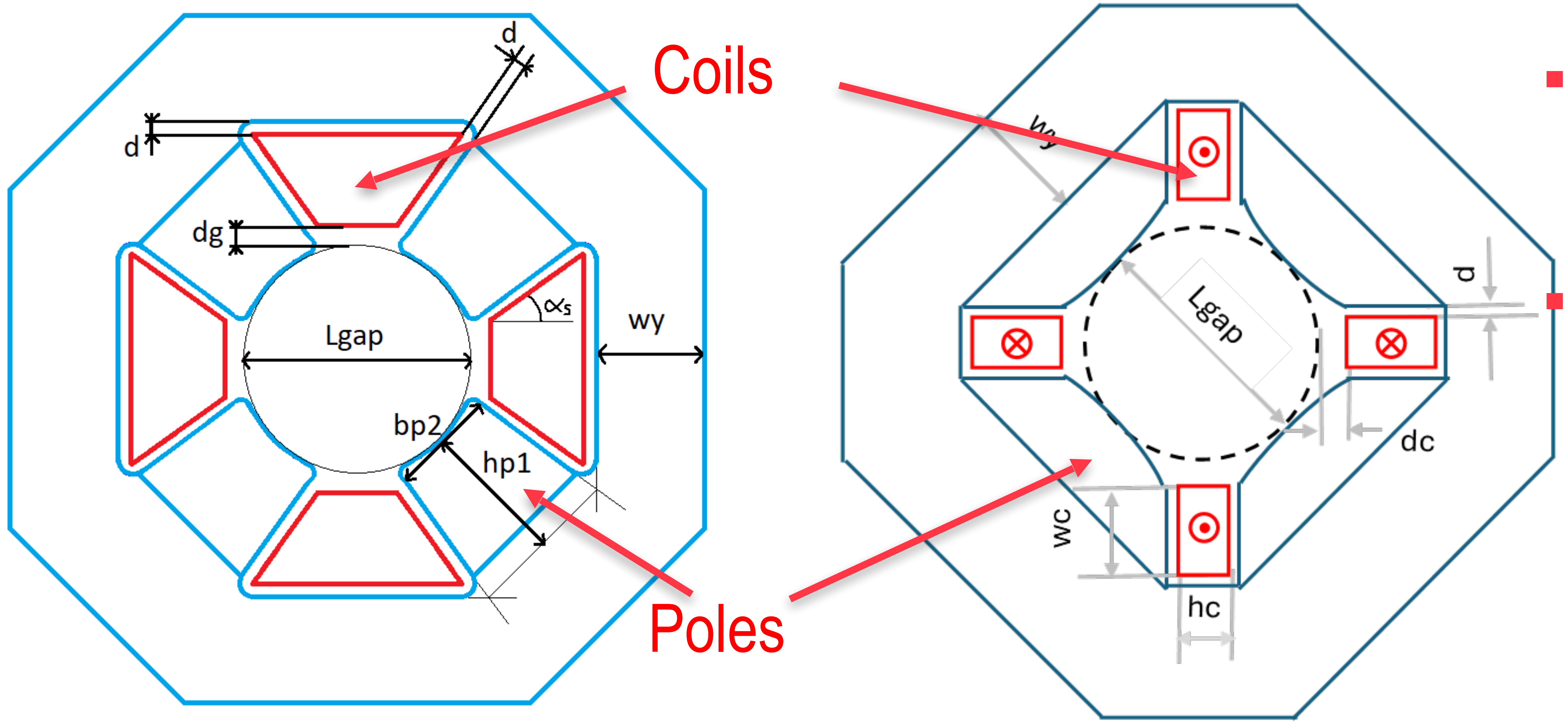




3. Design of fast-ramped resistive quadrupoles

- An optimization procedure was applied to the design of the quadrupole magnets of the RCS accelerators

E = 163 J/m (Lgap = 40 mm) E = 247 J/m



Trapezoidal coils Rectangular coils

- Both configurations analyzed reach the specified gradient (30 T/m), with a good field quality (to be improved)
- The lowest magnetic energy is found for the trapezoidal coil configuration

Conclusions

- A multi-TeV muon collider is a tantalising proposal.
- The EW physics case of 10 TeV machine is outstanding. The reach of TeV beams of muons to be fully explored.
- US are very interested in R&D. INFN has order 30 FTE working on Physics/Detectors/ Accelertor. Now it is the time to build a demonstrator.
- Bologna contributions so far in the physics potential and magnet design.

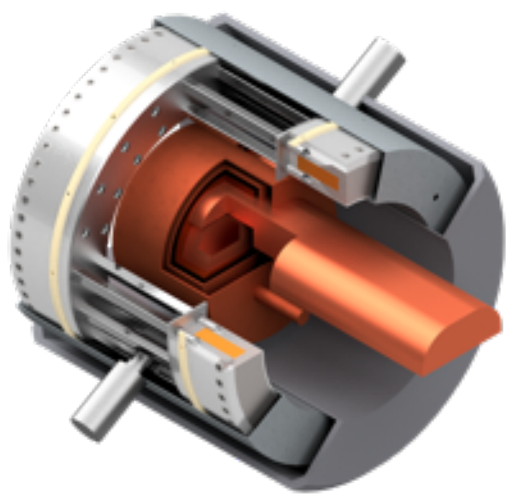
European Strategy Update
European Strategy Update

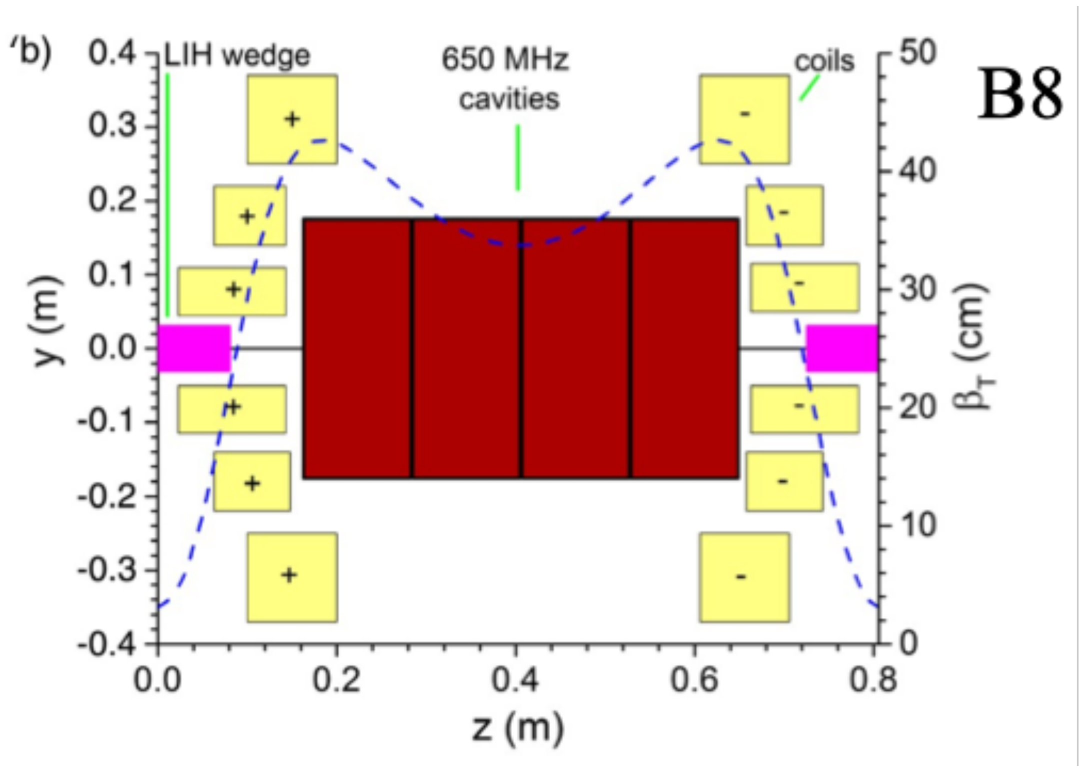
Developments

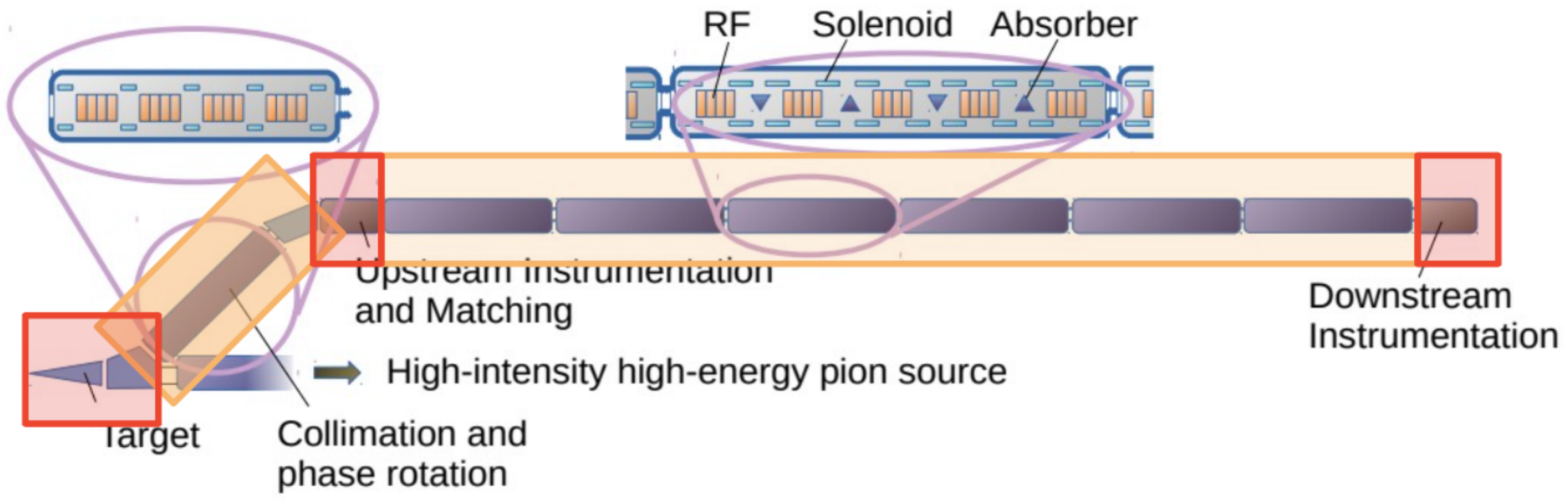
Muon cooling technology
- **RF test stand** to test cavities in magnetic field
- **Muon cooling cell** test infrastructure
- **Demonstrator**
  - Muon beam production and cooling in several cells

Magnet technology
- HTS solenoids
- Collider ring magnets with Nb3Sn or HTS

Detector technology and design
- Can do the important physics with near-term technology
- But available time will allow to improve further and exploit AI, MI and new technologies





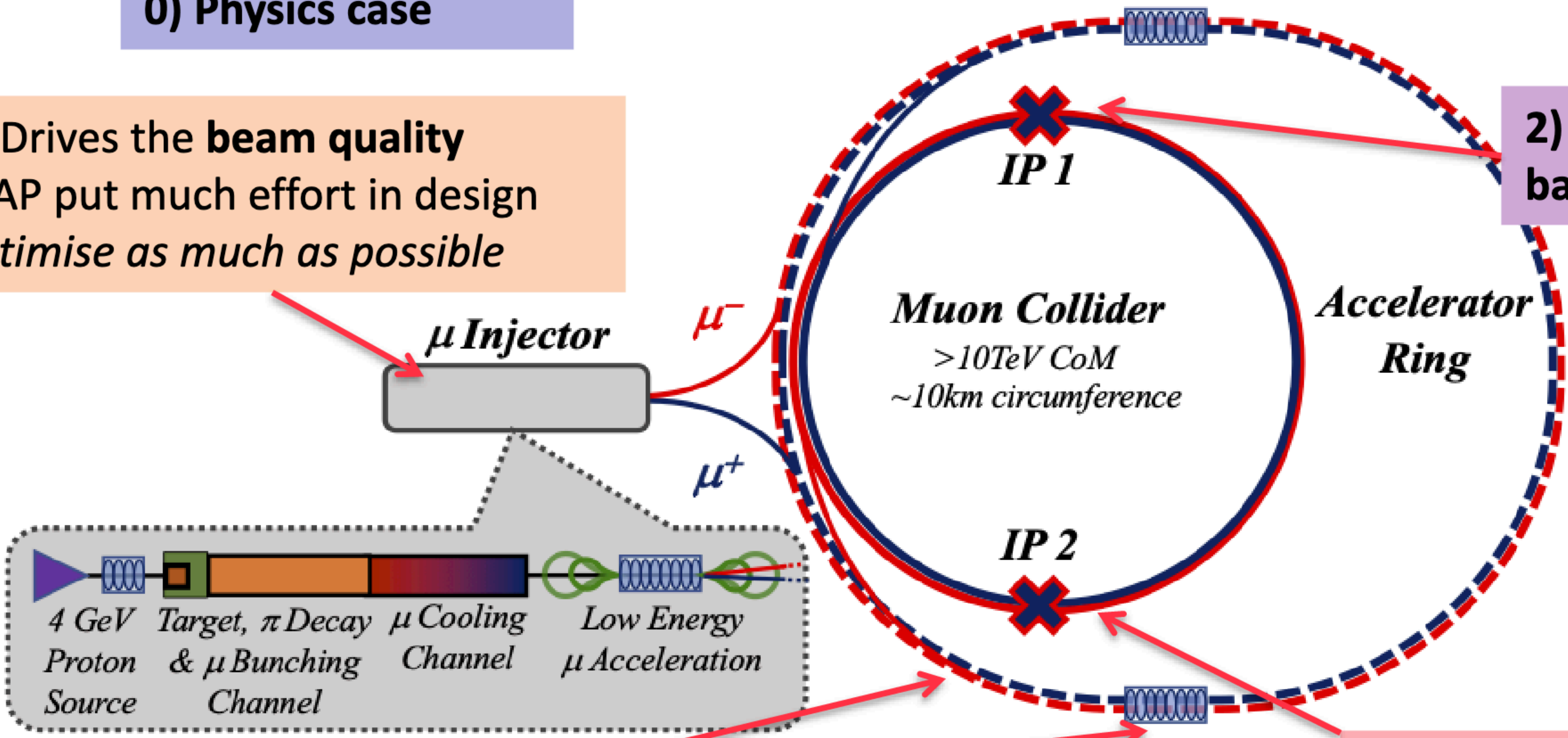


Key Challenges

0) Physics case

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

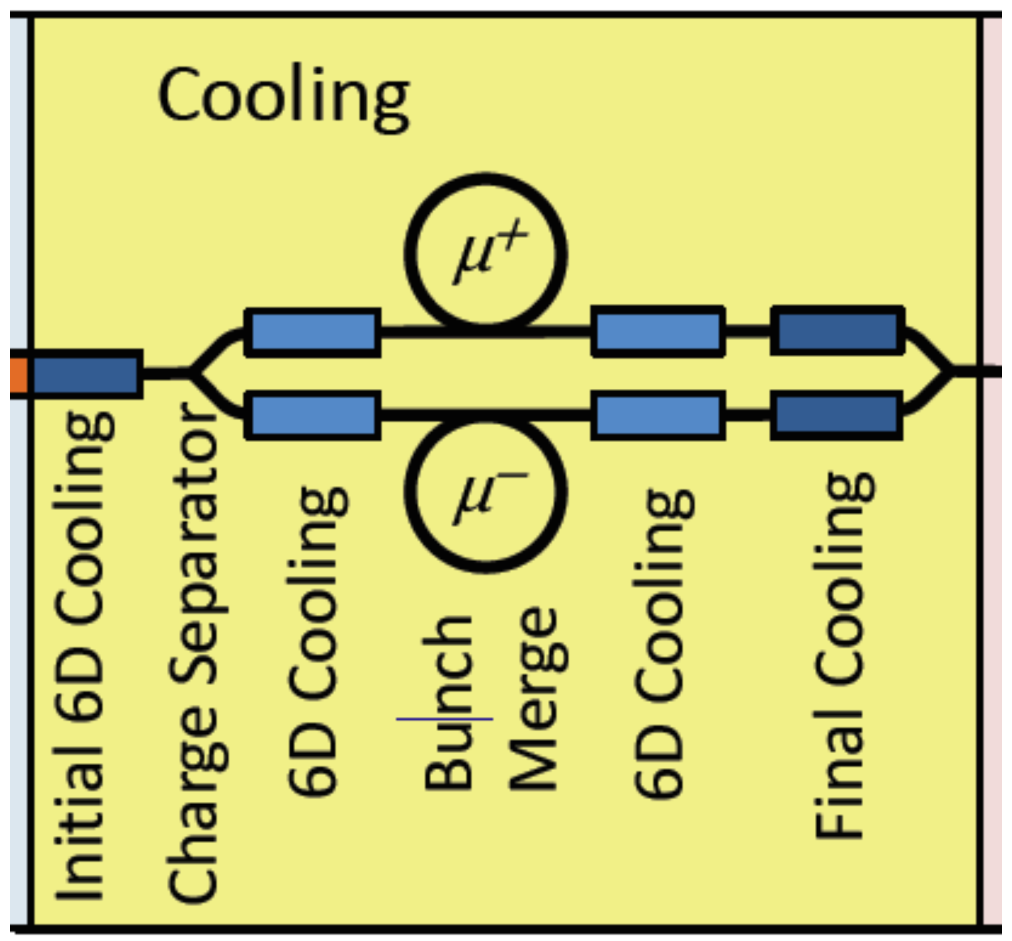
2) Beam-induced background

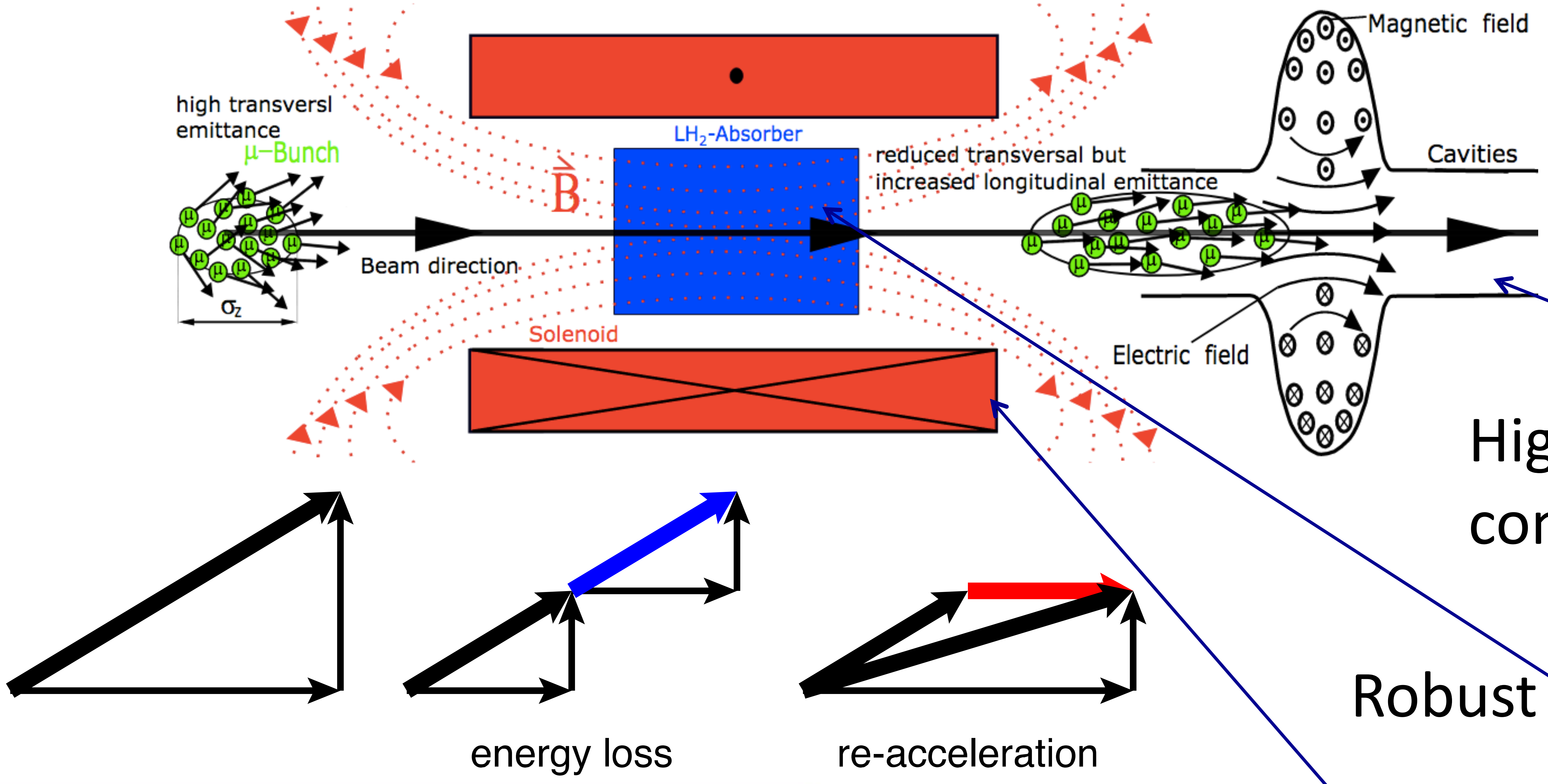


1) Dense neutrino flux
mitigated by mover system and site selection

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

Muon Cooling Principle

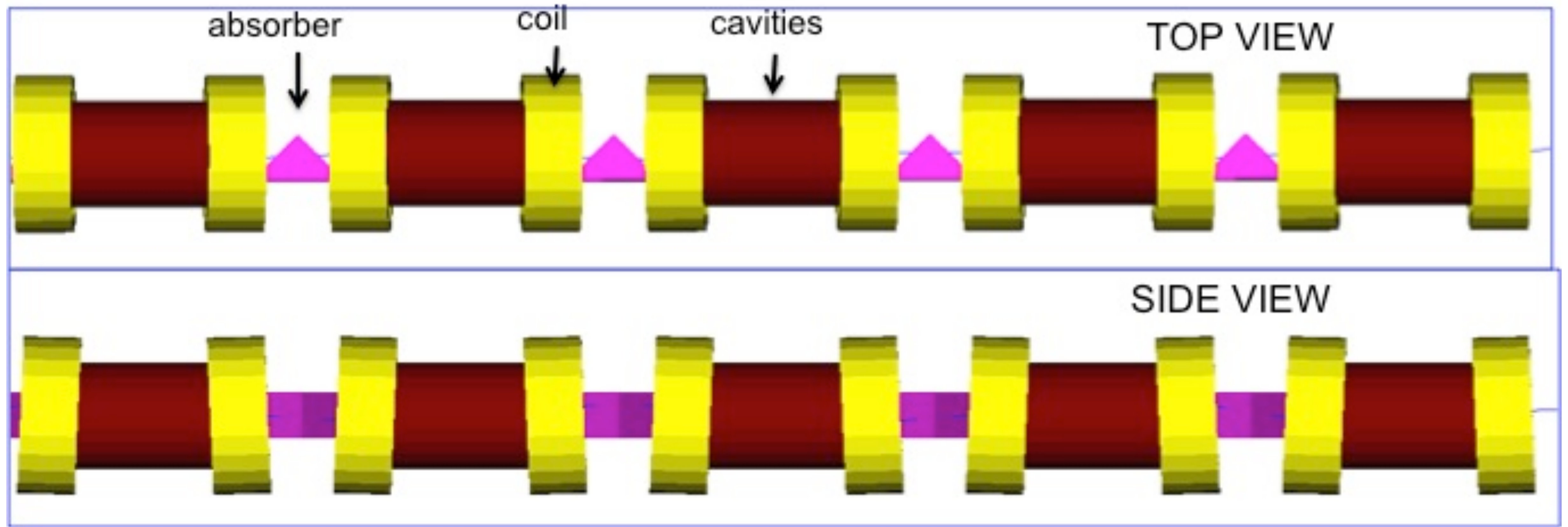




High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid



Principle has been demonstrated in MICE
Nature vol. 578, p. 53-59 (2020)