International
MUON Collider
Collaboration

MuCol

Funded by
the European Union

Muon colliders

Fabrice Balli, CEA Saclay

IRN Terascale @ IP2I Lyon
13-15 November 2024

DE LA RECHERCHE À L'INDUSTRIE
cea

Apéritif: recent history of muon colliders

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

Bright muon beams and muon colliders

D. Schulte, M. Palmer, 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 and A.Yamamoto,

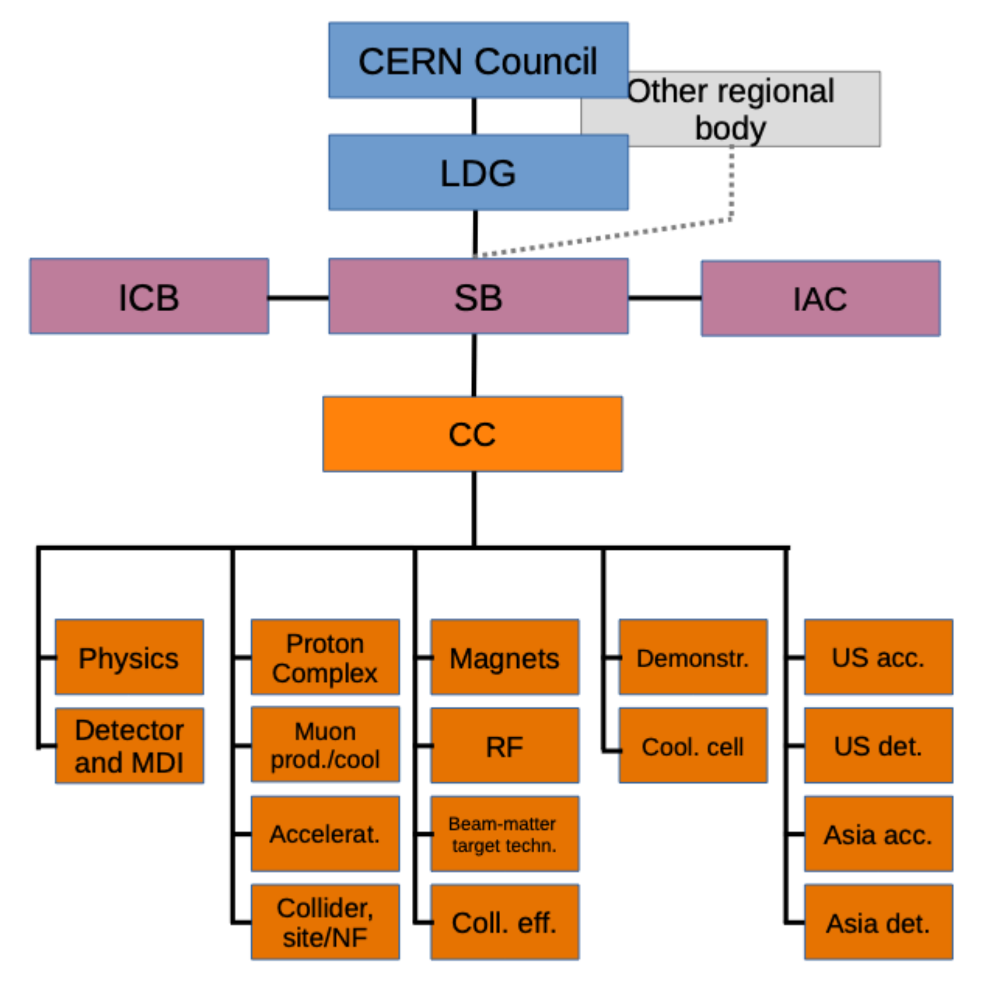
- Strong basis thanks to very advanced MAP studies in the US (2011-2014, studies and hardware), abruptly interrupted by DoE in 2014
- Revived interest in Europe in the last years
- Mention of muon colliders in European Strategy document and in CERN Medium-Term Plan (MTP)
    - **New budget line** 2M CHF/year in 2021, increased to **3M CHF/year over 2023-2026**, + 1.8 MCHF over 2025-2027

- Considered as an **alternative option for future accelerators at CERN** in case there is no FCC
- **International muon collider collaboration (IMCC) strongly established** with several working groups and also **European funding (Mucol project)**

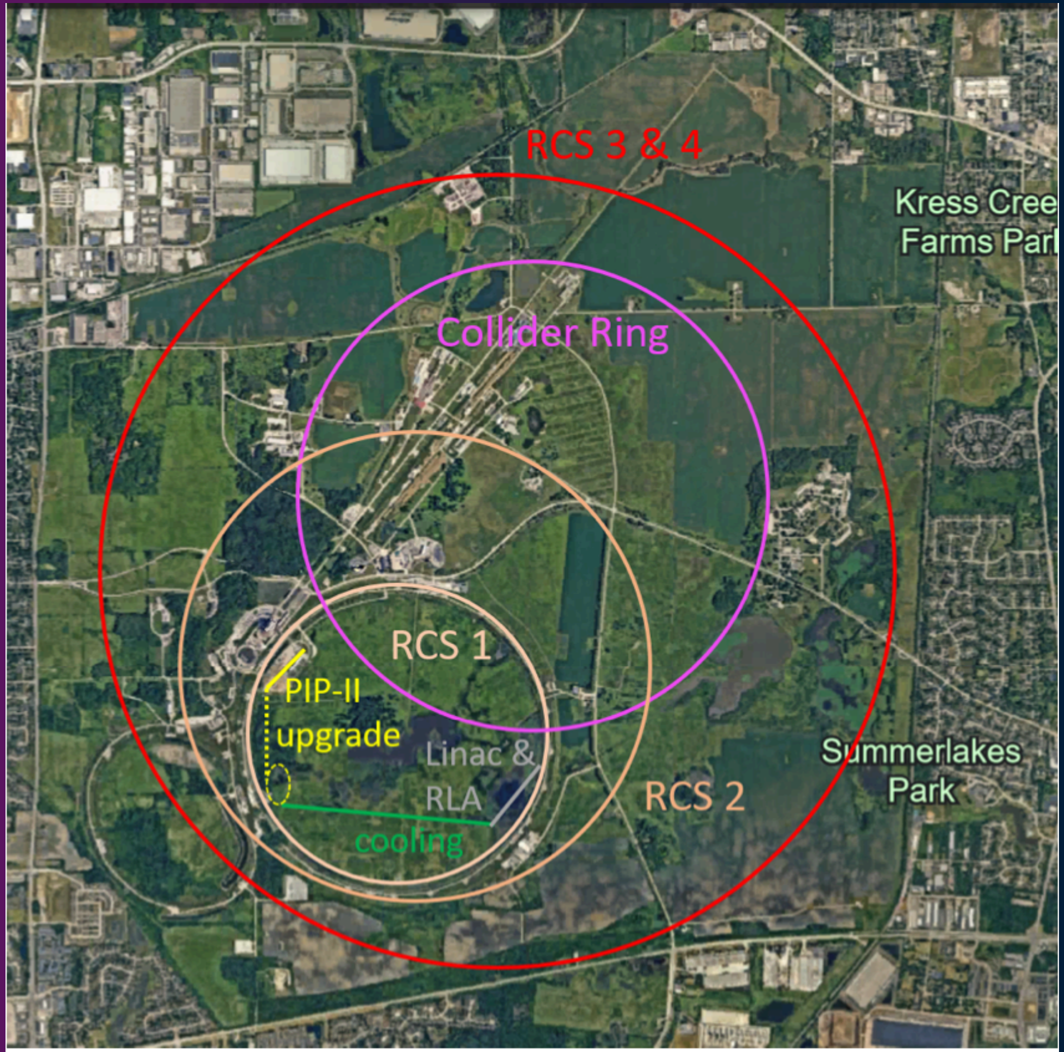
IMCC

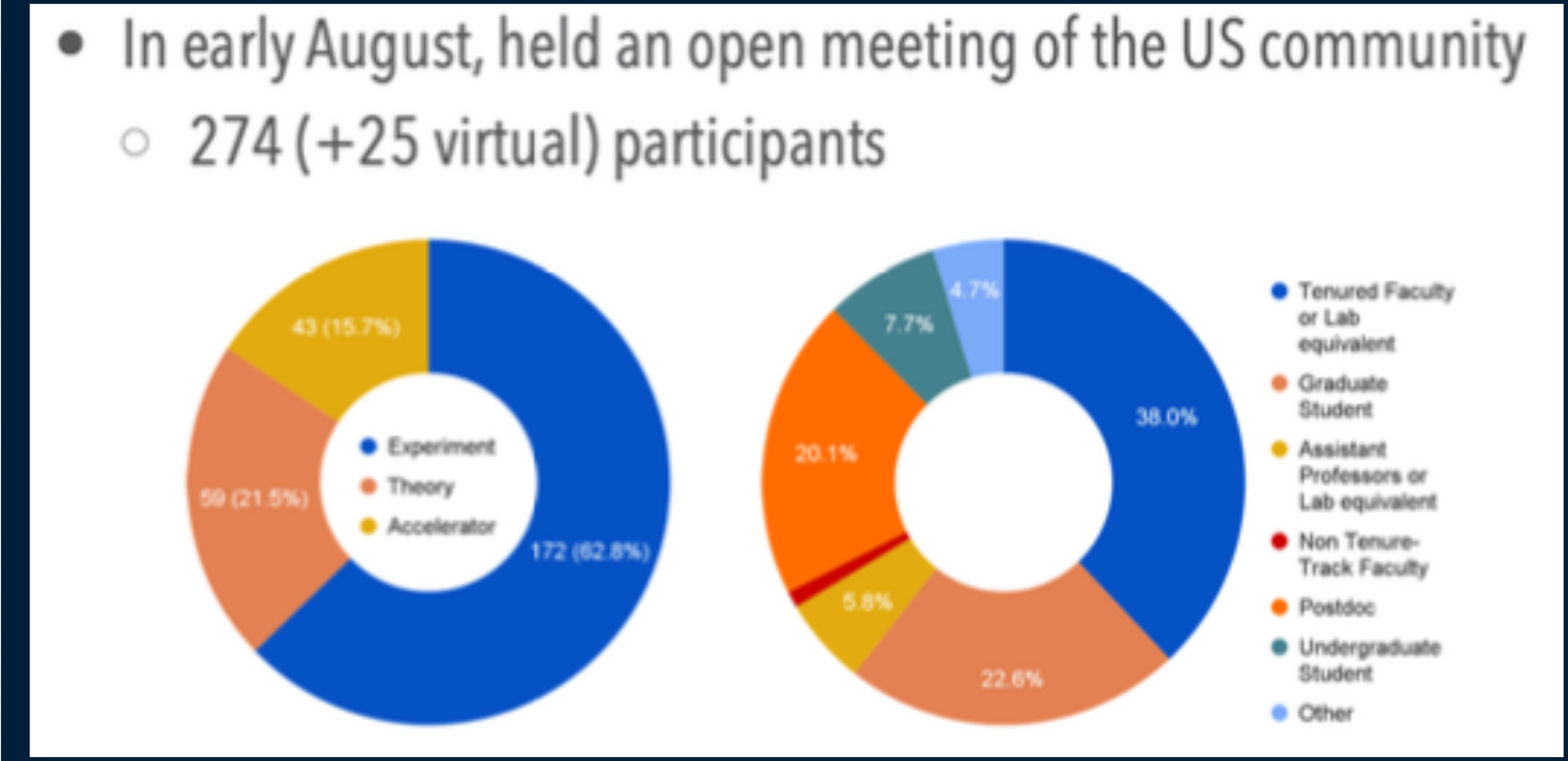
- Can be joined by signing Memorandum of Cooperation (58 signed)
- Main goals:
  - Assess and develop the muon collider concept for a O(10 TeV) facility
    - Muon collider promises **sustainable approach** to the energy frontier
    - Technology and design advances in past years
    - **Reviews in Europe and US found no unsurmountable obstacle**
  - Identify potential sites to implement the collider
  - Develop initial muon collider stage that **can start operation around 2050**
  - Develop an R&D roadmap toward the collider

IEIO	**CERN**	IT	**INFN**	SE	**ESS**	US	**Iowa State University**
FR	**CEA-IRFU**		**INFN, Univ., Polit. Torino**		**University of Uppsala**		**University of Iowa**
	CNRS-LNCMI		**INFN, Univ. Milano Biocca**	NL	**University of Twente**		**Wisconsin-Madison**
	Mines St-Etienne		**INFN, Univ. Padova**	FI	**Tampere University**		***University of Pittsburgh***
DE	DESY		**INFN, Univ. Pavia**	LAT	**Riga Technical University**		**Old Dominion**
	Technical University of Darmstadt		**INFN, Univ. Bologna**	CH	**PSI**		**Chicago University**
	University of Rostock		**INFN Trieste**		**University of Geneva**		**Florida State University**
	KIT		**INFN, Univ. Bari**		EPFL		**RICE University**
UK	**RAL**		**INFN, Univ. Roma 1**	BE	**Univ. Louvain**		**Tennessee University**
	UK Research and Innovation		***ENEA***	AU	**HEPHY**		***MIT Plasma science center***
	University of Lancaster		**INFN Frascati**		***TU Wien***		**Pittsburgh PAC**
	University of Southampton		**INFN, Univ. Ferrara**	ES	**I3M**		Yale
	University of Strathclyde		**INFN, Univ. Roma 3**		***CIEMAT***		***Princeton***
	University of Sussex		INFN Legnaro		**ICMAB**		***Stony Brook***
	Imperial College London		**INFN, Univ. Milano Bicocca**	China	***Sun Yat-sen University***		Stanford/SLAC
	Royal Holloway		**INFN Genova**		**IHEP**		...
	University of Huddersfield		**INFN Laboratori del Sud**		**Peking University**	DoE labs	FNAL
	University of Oxford		INFN Napoli		**Inst. Of Mod. Physics, CAS**		LBNL
	University of Warwick	Mal	**Univ. of Malta**	KO	**Kyungpook National University**		JLAB
	University of Durham	EST	**Tartu University**		**Yonsei University**		BNL
	University of Birmingham	PT	**LIP**		***Seoul National University***	Brazil	***CNPEM***



US plans

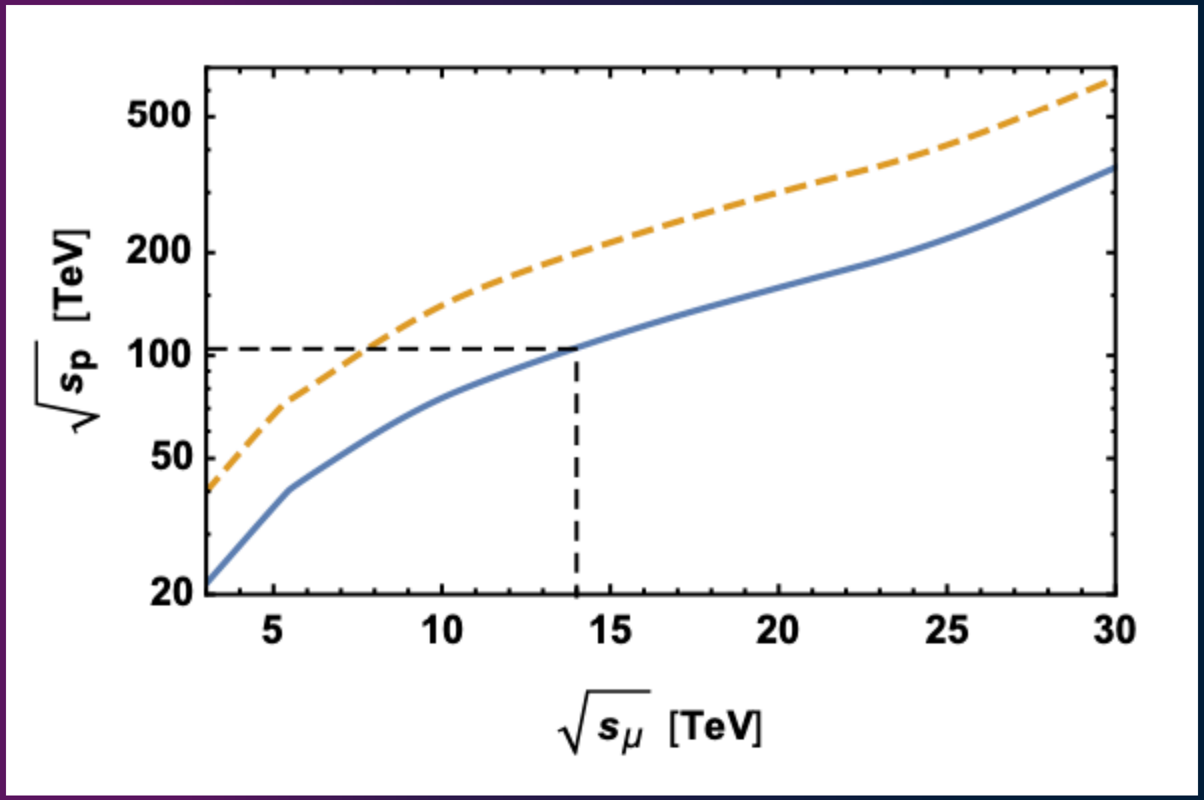


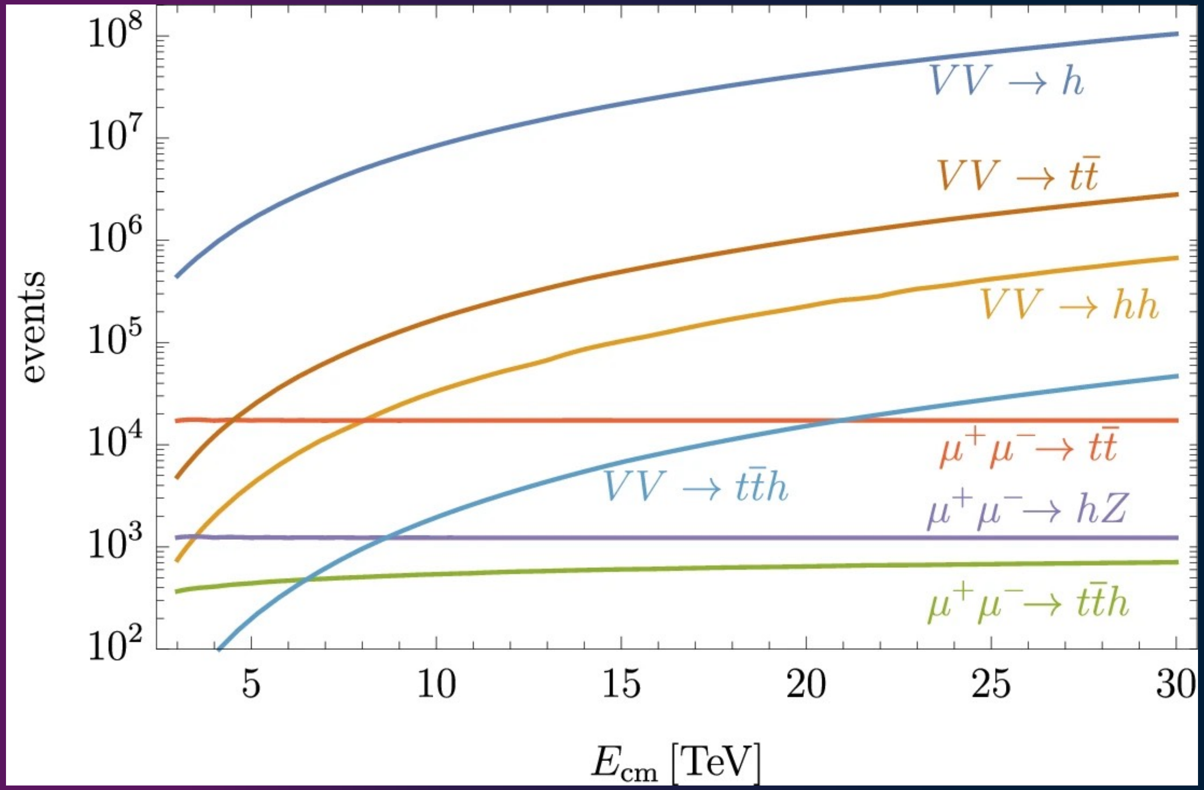


- In early August, held an open meeting of the US community
  - ○ 274 (+25 virtual) participants

- Muon colliders explicitly mentioned in P5 report end of last year
- US Muon Collider Inauguration Meeting beginning of August at FNAL showed a strong interest (again) !
  - Full integration of IMCC with US planned and started
  - CERN-DoE agreement in preparation

Physics case in a nutshell





- Well known fact : hard interactions in lepton colliders benefit from the full beam energy (contrary to hadron colliders where proton constituents interact)
- ~10 TeV muon collider competes with 100 TeV pp collider in this respect
- VBF: primary production mechanism for most processes (muon colliders at high energy **qualify as Higgs factories**)
    - Allows to “scan” centre of mass energies
    - High cross-section for most processes
    - Muon collider is a W/Z/gamma collider
- Sensitivity to BSM physics
- More studies still need to be performed to assess the full physics potential
    - Lots of room for contributions

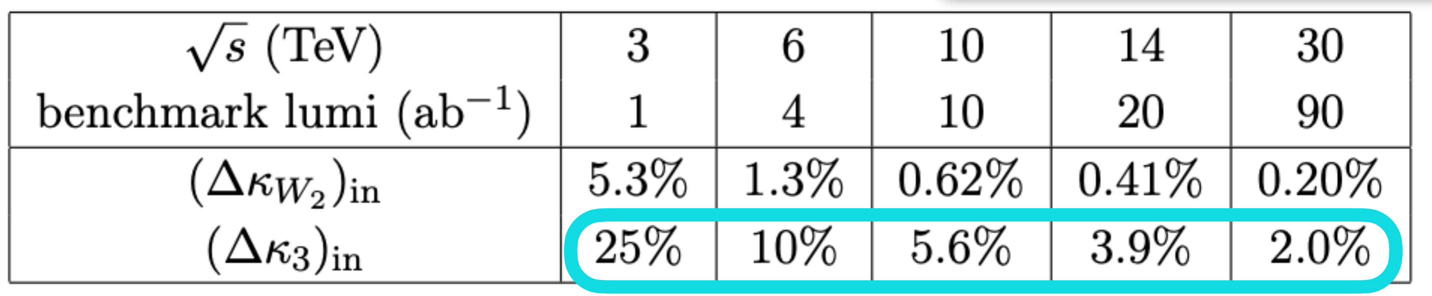
Physics case: Higgs

- Bread and butter of muon colliders

ECM (TeV)	1,5	3	10	30
N(Higgs) / 10^7 s	37,500	200,000	10^7	10^8

- In comparison, 250 GeV Higgs factories (FCC-ee/ILC/CEPC) produce ≈ 10^6 Higgses
- Higgs couplings determined with similar or better precision in the multi TeV regime
- Can measure trilinear coupling with a precision <5% through di-Higgs measurements

arXiv:2008.12204



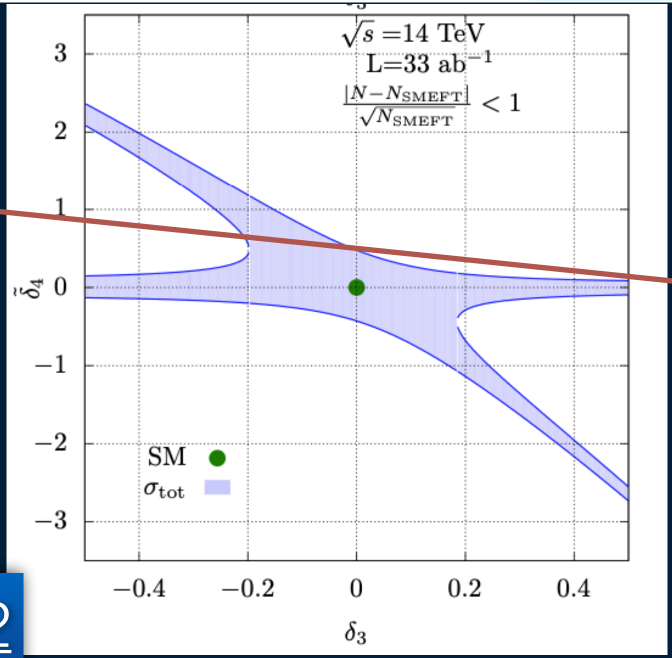
$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$(\Delta\kappa_{W_2})_{\text{in}}$	5.3%	1.3%	0.62%	0.41%	0.20%
$(\Delta\kappa_3)_{\text{in}}$	25%	10%	5.6%	3.9%	2.0%

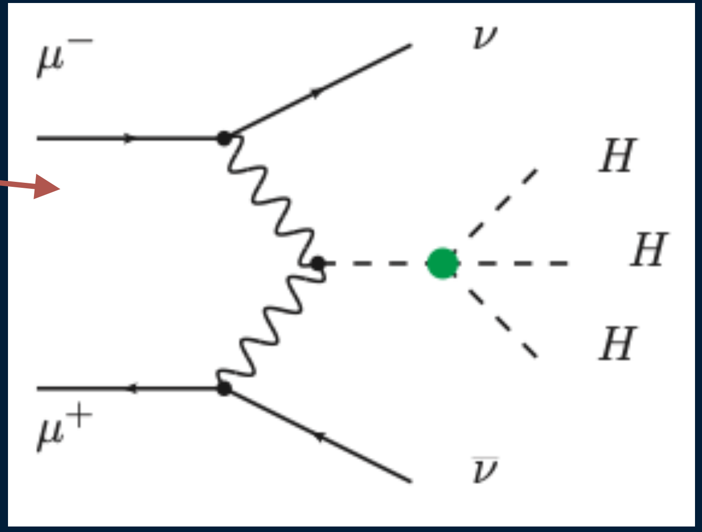
- **The only machine giving access to quartic coupling** via triple Higgs production

$$V(H) = \frac{1}{2}m_H^2 H^2 + \boxed{\lambda_3} v H^3 + \frac{1}{4}\boxed{\lambda_4} H^4,$$

BSM:

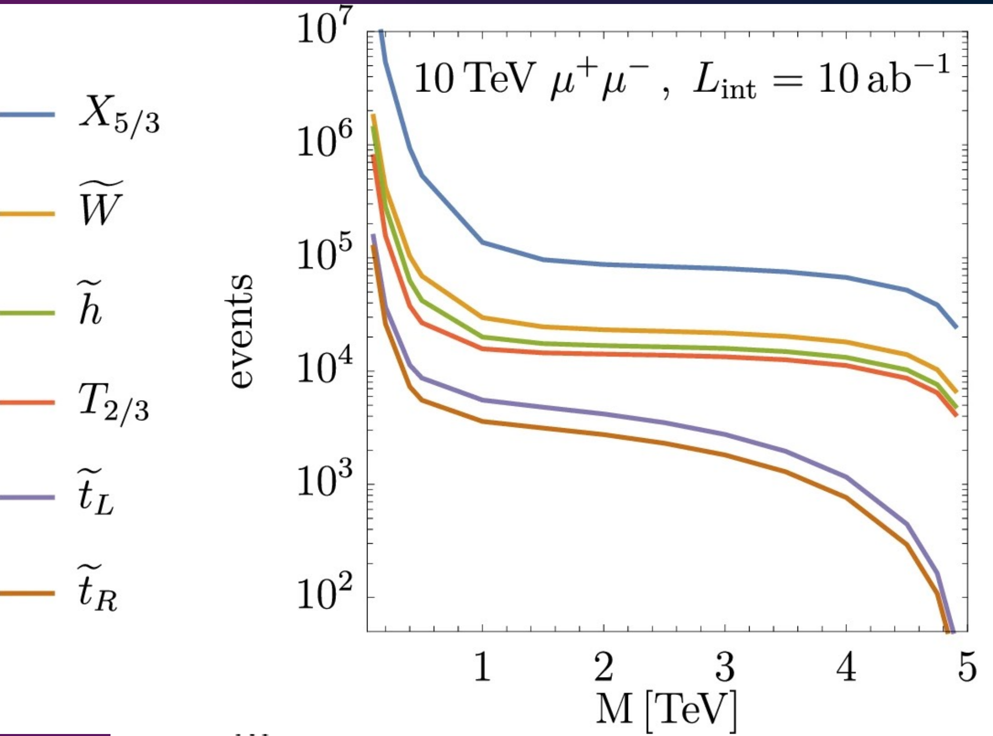
$$\lambda_3 = \lambda_{SM}(1+\delta_3)$$
$$\lambda_4 = \lambda_{SM}(1+\delta_4)$$

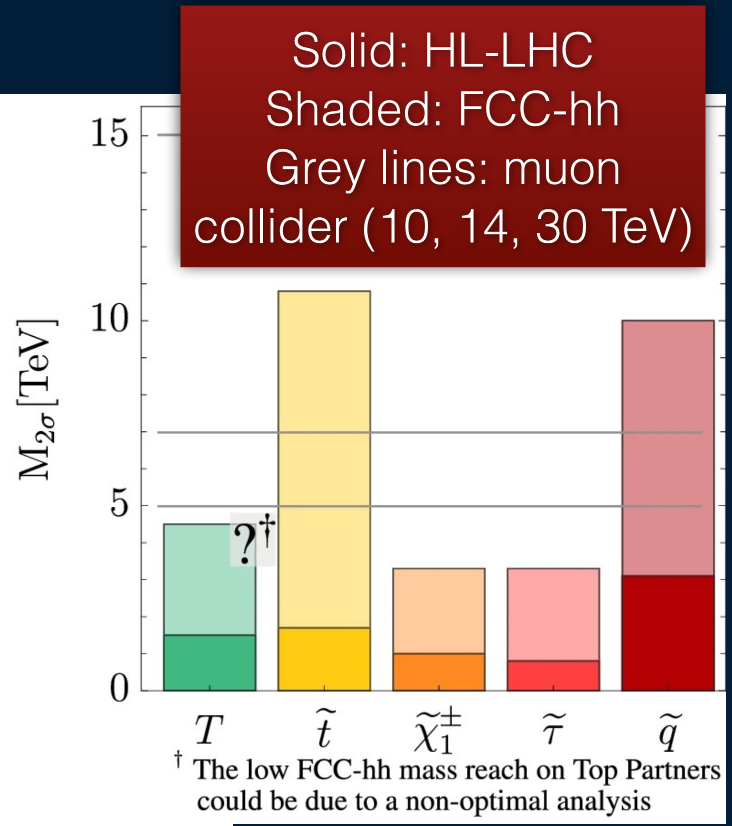




arXiv:2003.13628v2

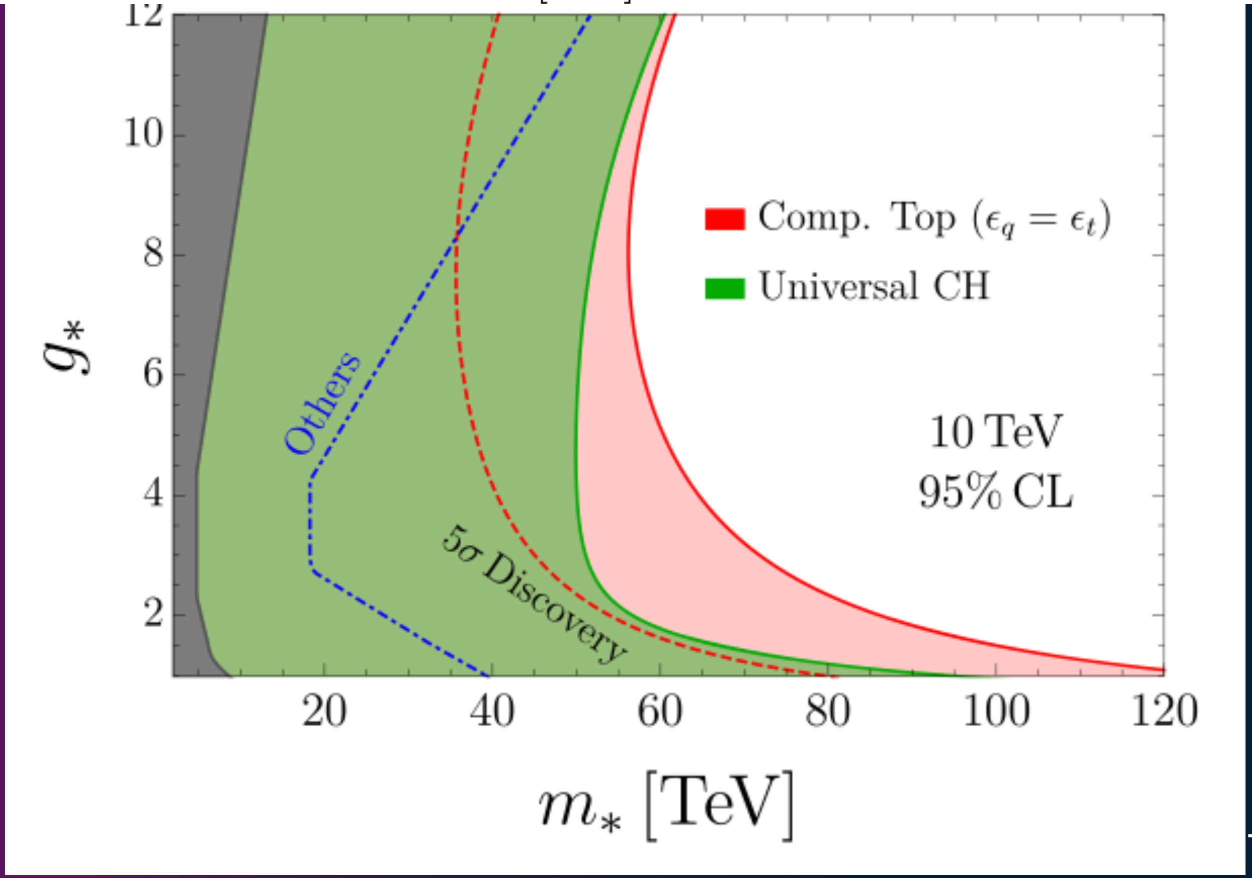
Physics case: BSM




Solid: HL-LHC
Shaded: FCC-hh
Grey lines: muon collider (10, 14, 30 TeV)

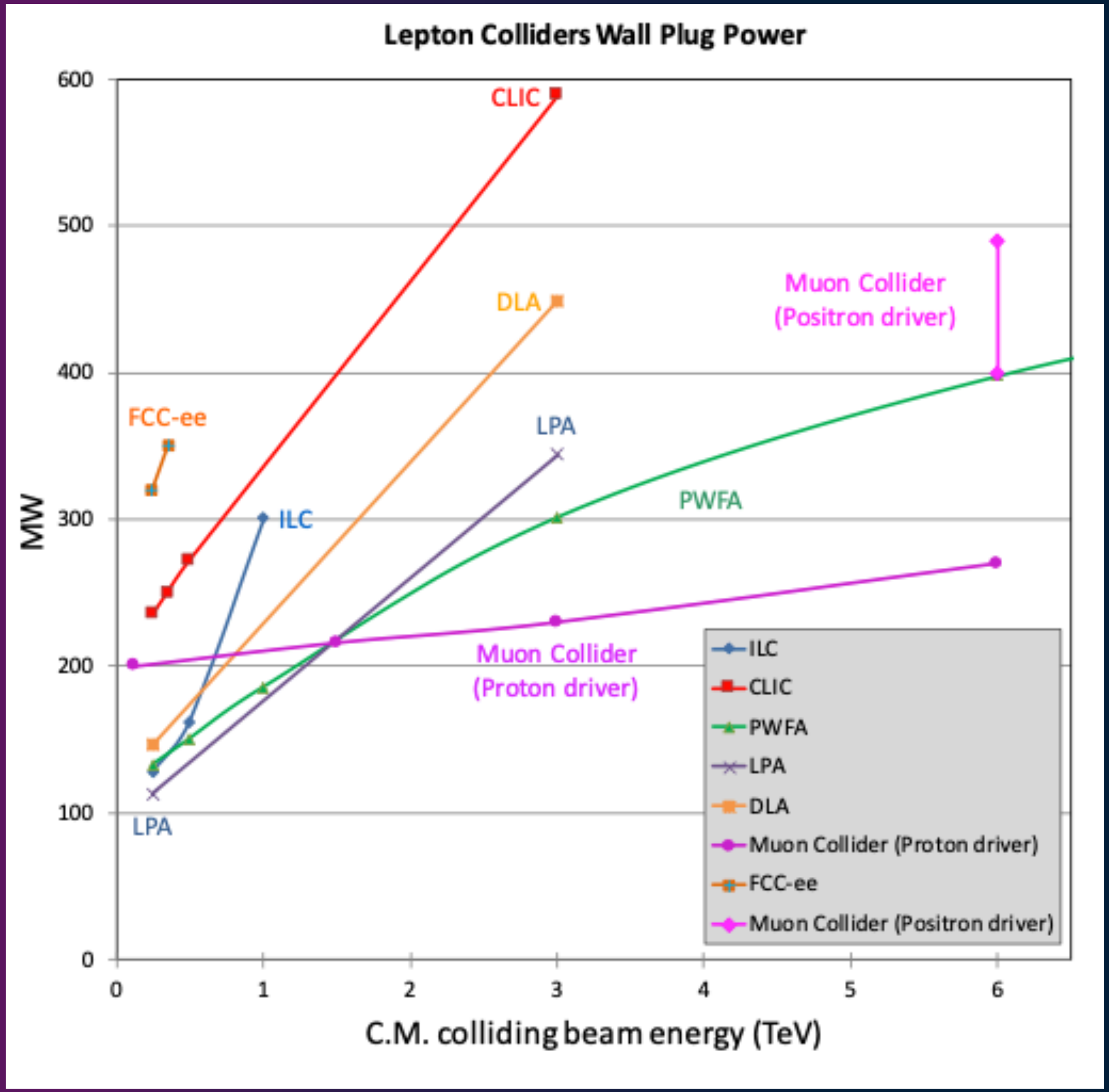
† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

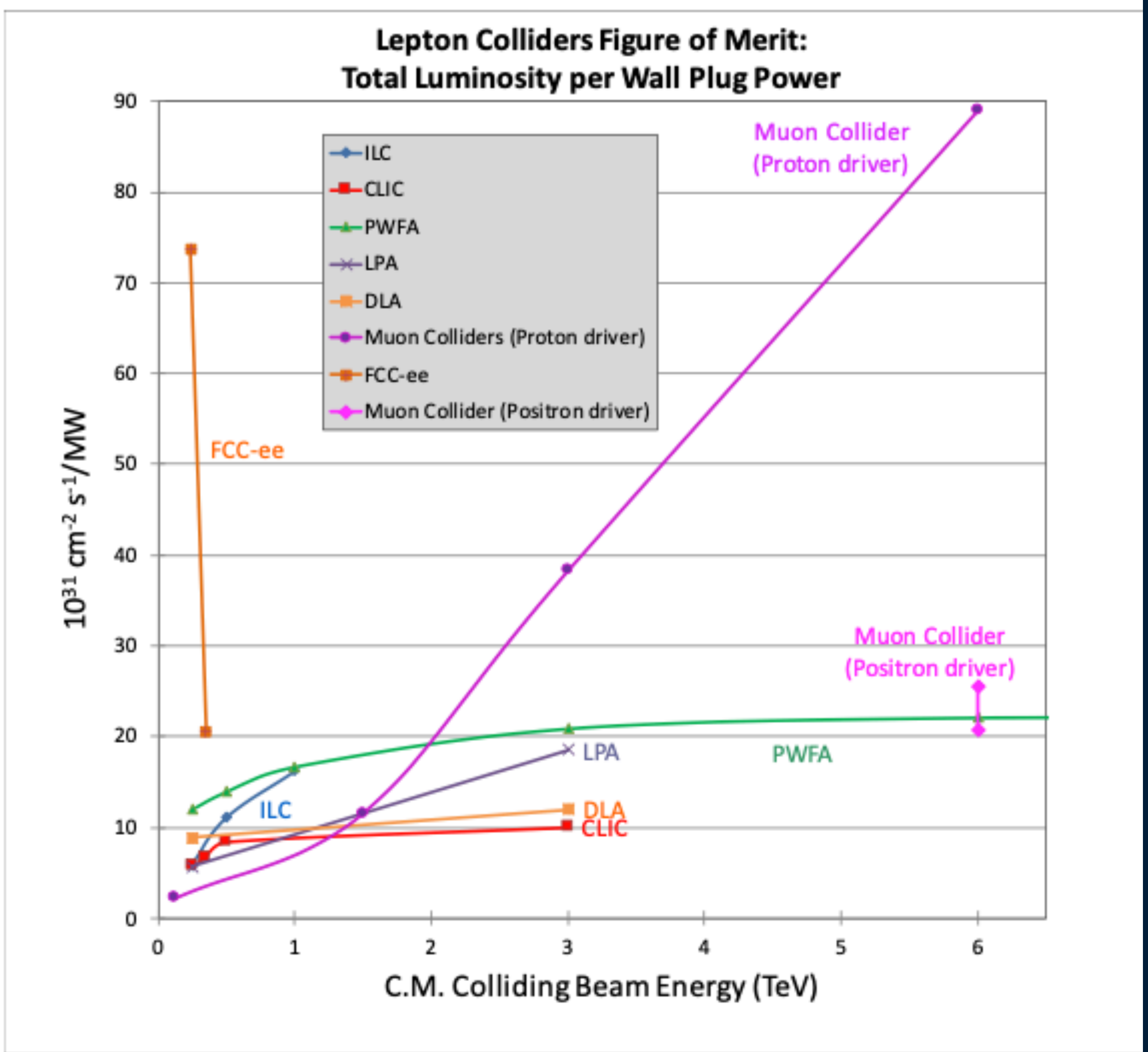
- Outstanding physics reach for pair production of new particles, mass reach being the kinematic limit of the collider



- Best possible mass/coupling reach in case of a Composite Higgs scenario (‘Others’ dotted line includes all other future projects)
  - Due to falling parton luminosities of 100 TeV *pp* collider, or to tiny effect of high scale new physics at 100 GeV (e+e-)

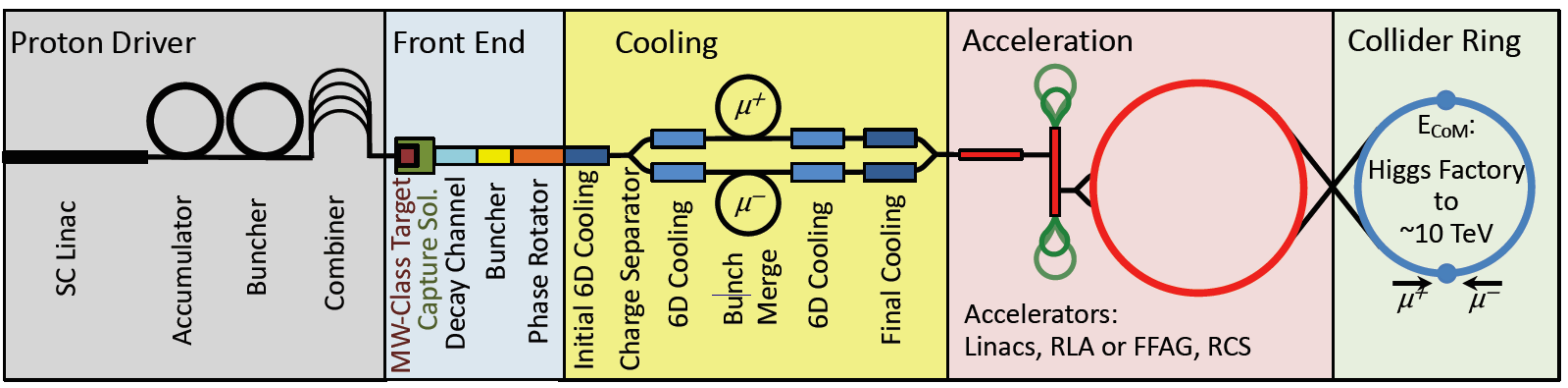
Sustainability: Luminosity per wall plug power





- Very attractive option for very high energy : in particular linear e+e- is limited by the wall plug power
- —> Focus on high energy scenarios : 3, 10, 14 TeV (maybe 30)
- **Low-energy staging at the top threshold** is in principle very appealing: the collider ring would be tens of meters and all the acceleration components would be quite cheap and easy to build

Muon production and acceleration chain: overview



Short, intense proton bunch

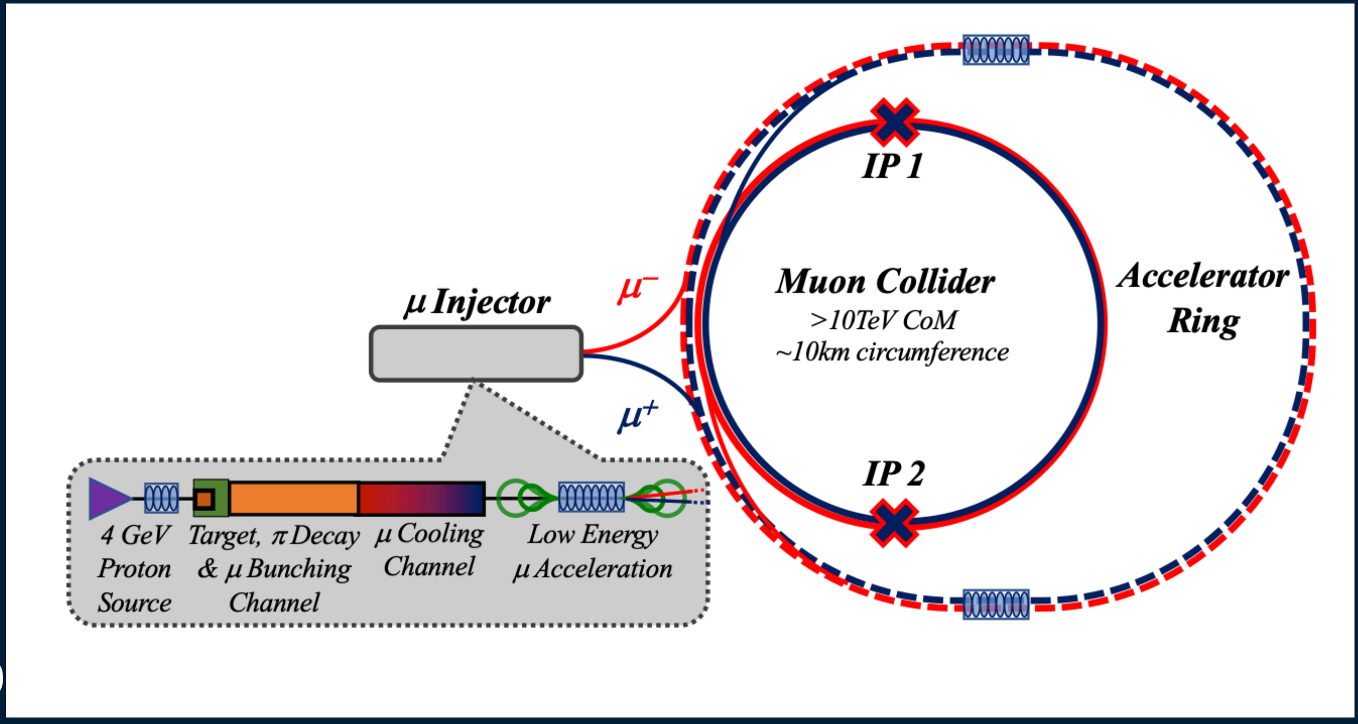
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

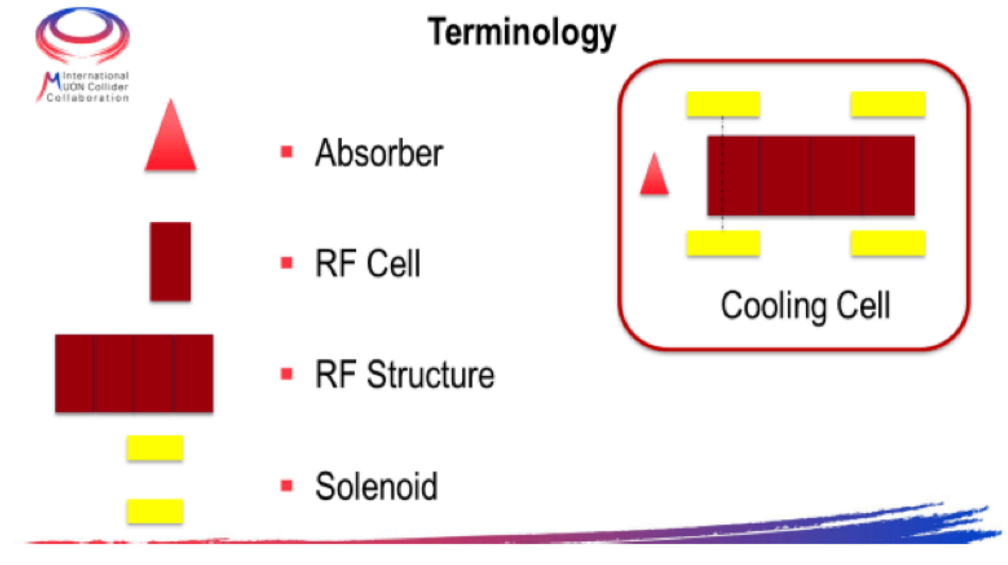
Protons produce pions which decay into muons muons are then captured

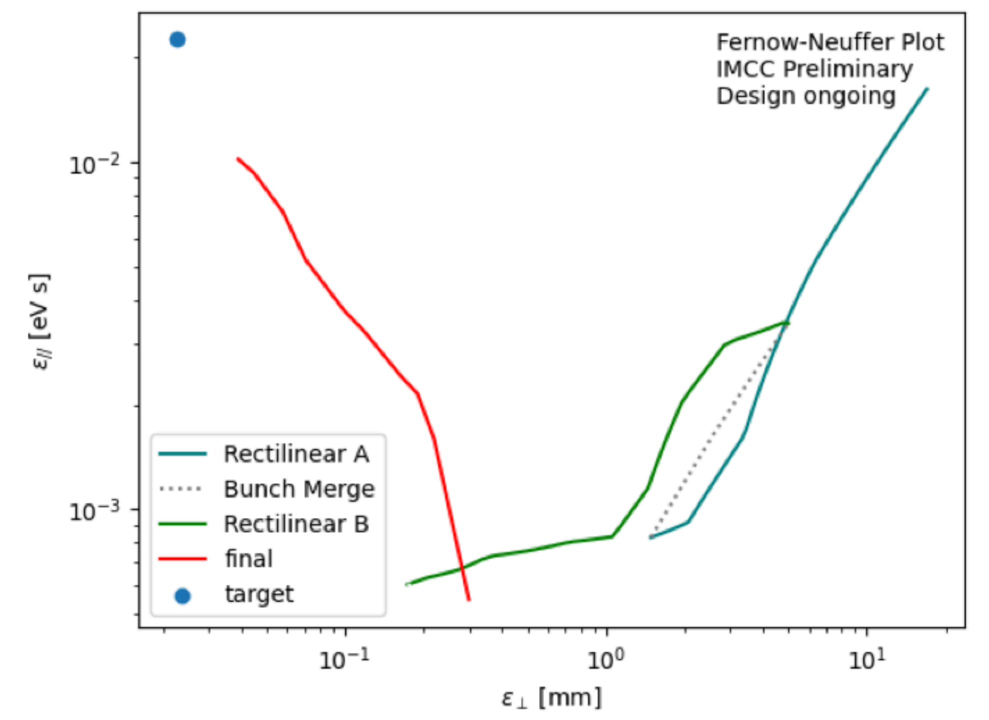
Need to do it quickly as muons decay !
Lifetime is $\tau = \gamma \times 2.2\ \mu s$



Muon Ionisation Cooling

- During the US MAP-era a complete design of a Muon Collider cooling system was developed, was further improved by the IMCC
- Comprises a series of solenoids, which focus the beam onto energy absorbers to reduce the momentum
- Momentum is restored longitudinally using RF cavities
- Rectilinear A initially reduces the beam emittance sufficiently and the many initial bunches can be merged into one single bunch.
- Then cooled down using Rectilinear B, followed by a sequence of high field solenoids operated ultimately with a low momentum (non-relativistic) beam.
- Needs for solenoids as strong as possible for the last phase (> 30 T)
  - Strong R&D on HTS superconductor solenoids





Several sites at CERN and FNAL can host a future demonstrator

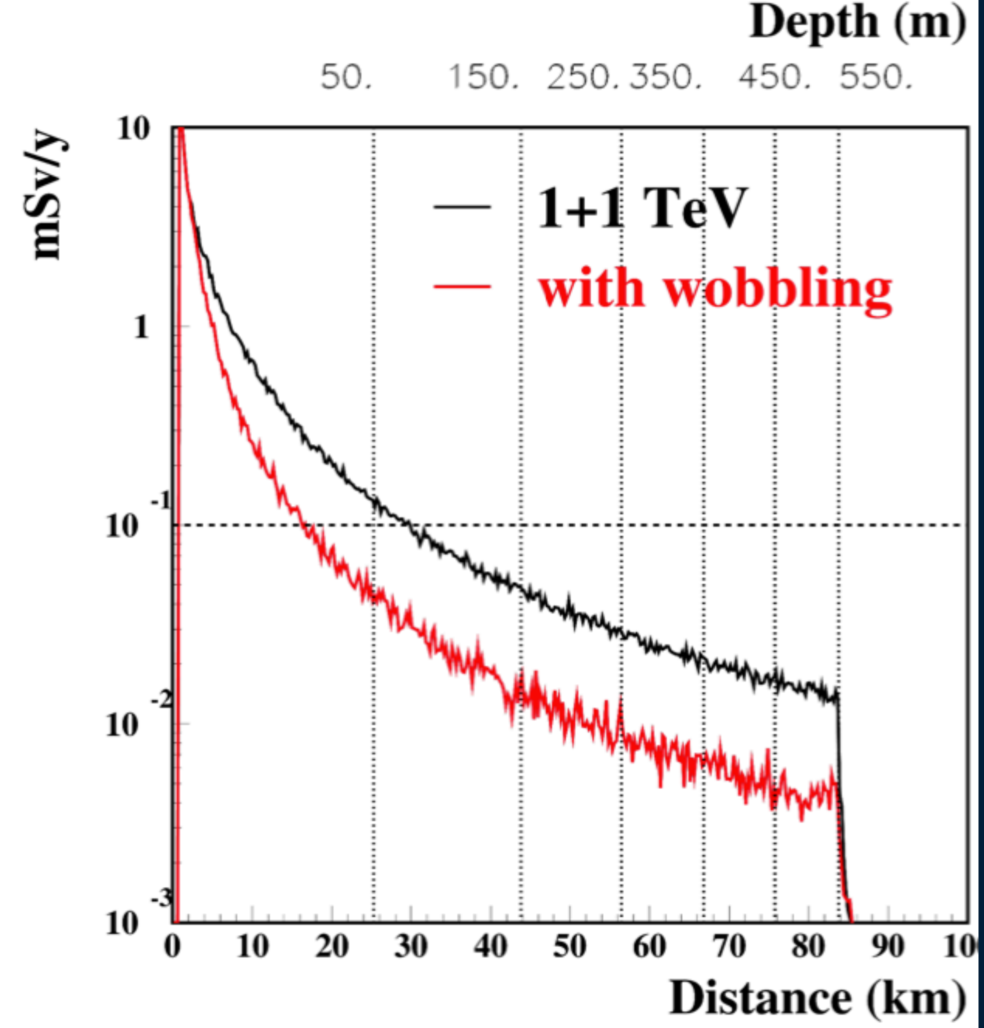
Neutrino radiation

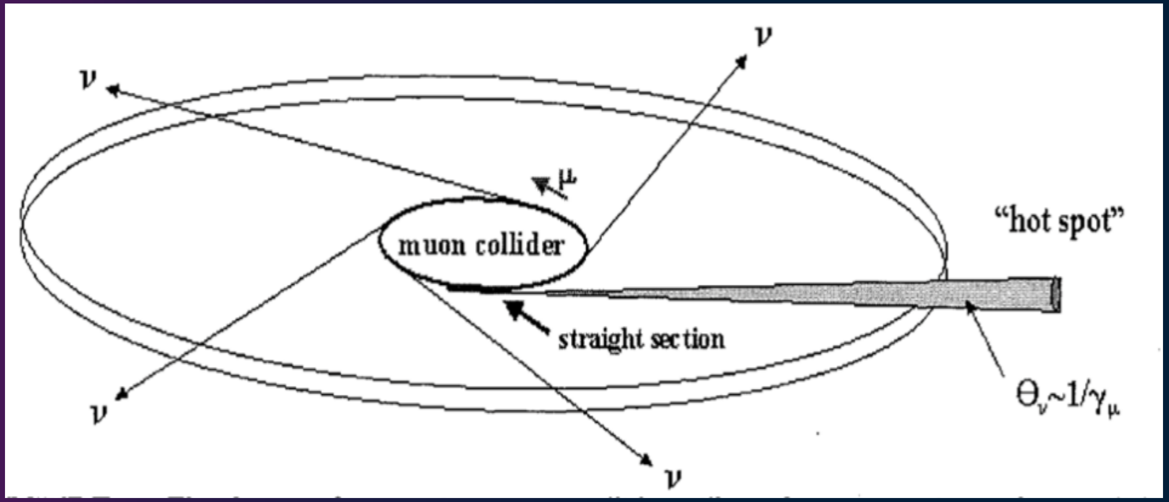
- Neutrinos are emitted along the beam line and emerge at the surface
  - regenerate muons in the last 100's of m before exiting Earth
- Dose from muons at Earth's surface (mS/year) ~ $1.5\frac{N_\mu E_\mu^3}{R^2}$
- Aiming for a negligible dose
- Becomes problematic beyond ~10 TeV (grows as E^3)
- Solutions need to be investigated
  - beam wobbling in the z direction
  - Adjustement on collider location and inclination with Geoprofile

R : distance between ring and exit point~36 km

$N\mu$: number of muons per 10^{13} second

$E\mu$: muon beam energy in TeV

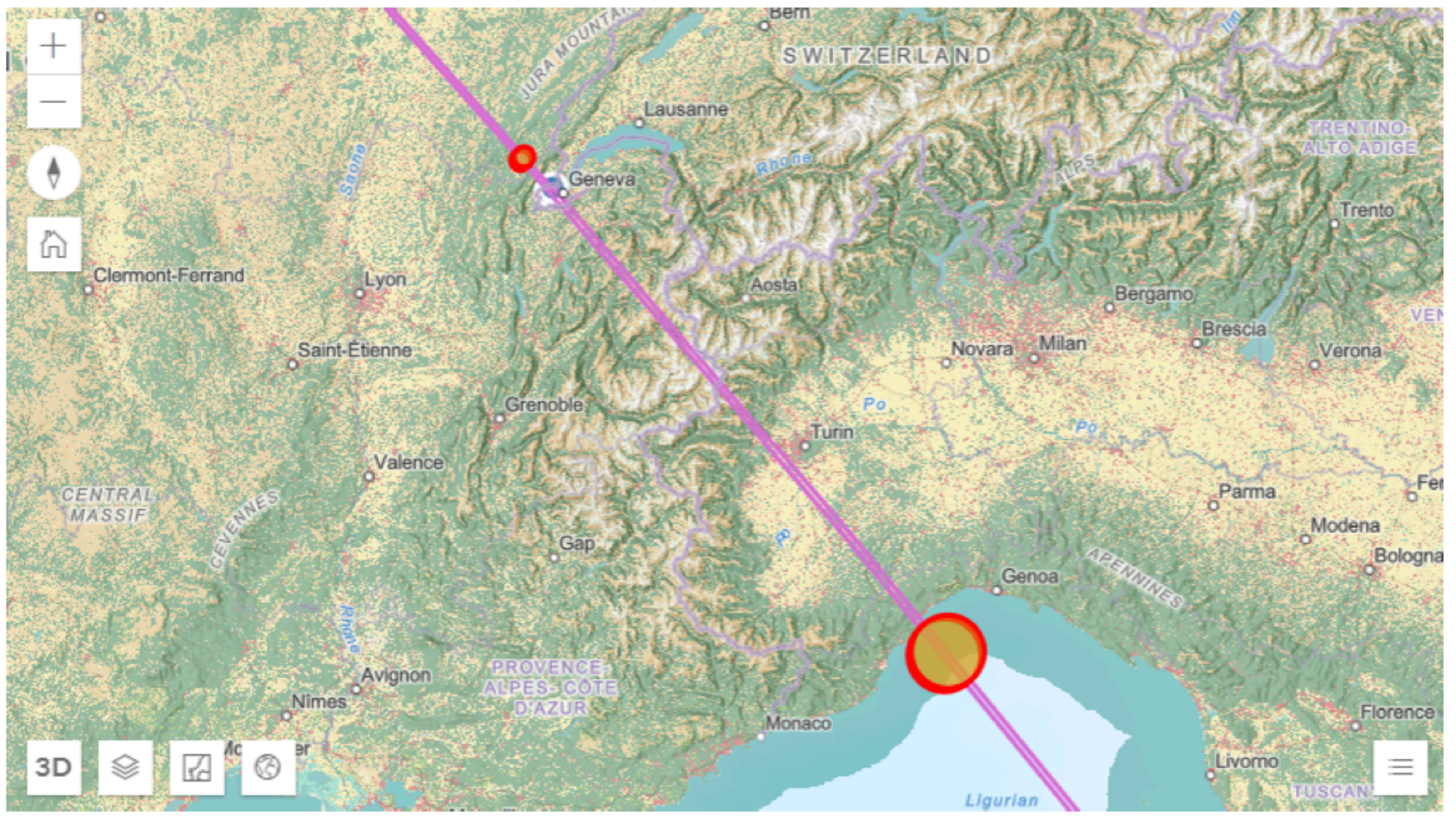


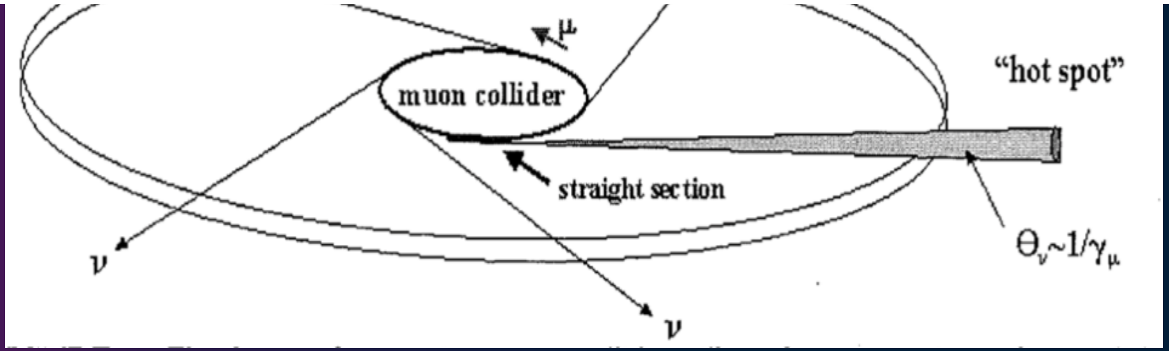


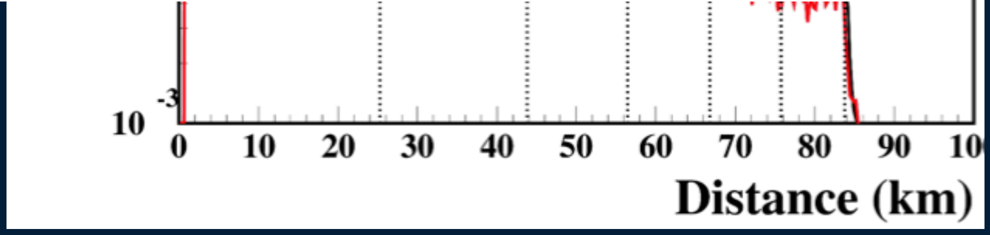
Neutrino radiation

R : distance between ring and exit

- Neutr
  surfa
  - re
- Dose
- Aimin
- Beco
- Soluti
  - b
  - A

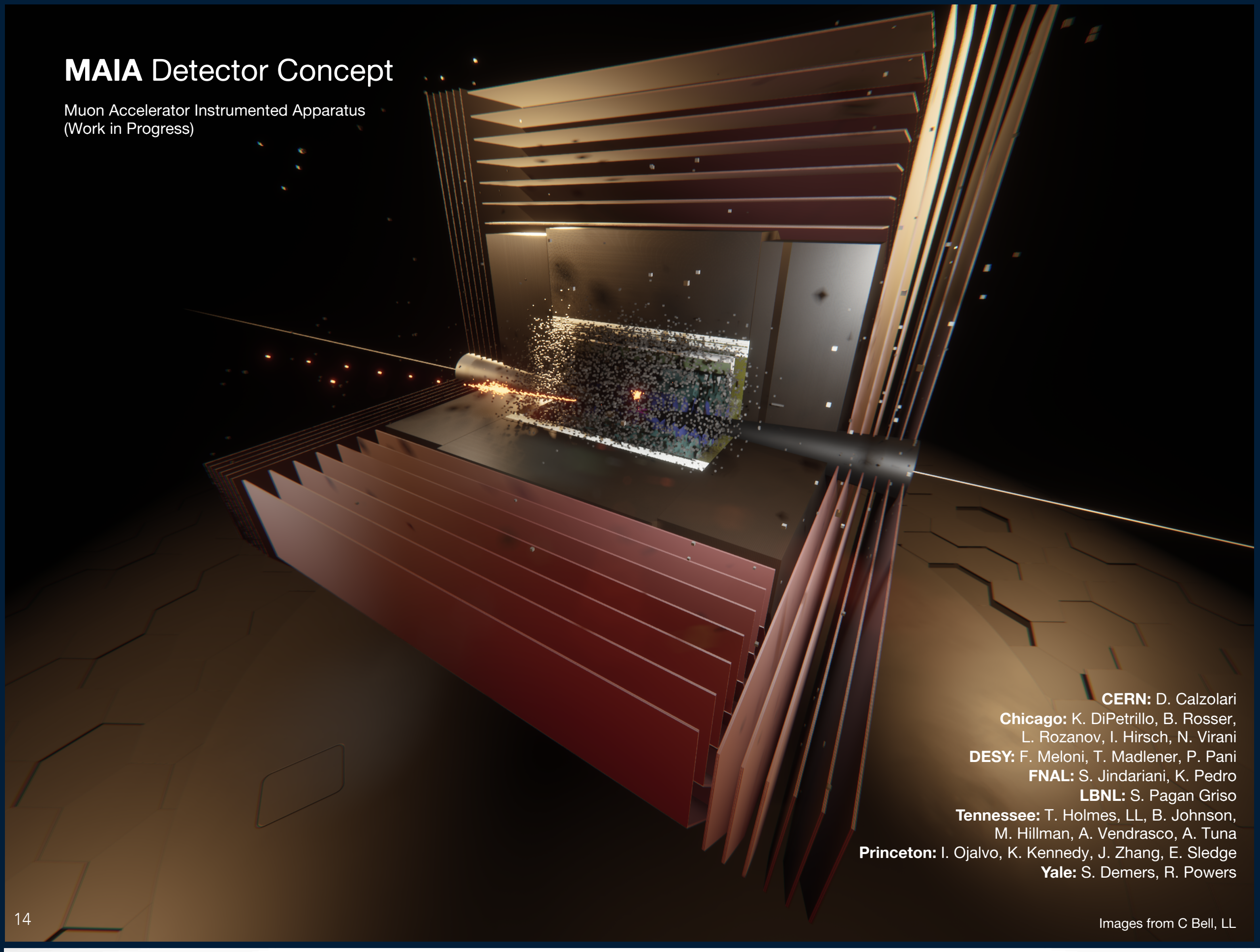






Quick detector overview

- Two different baselines, but sharing the same genealogy, derived from CLIC and adapted to the muon collider conditions:
    - MUSIC (Muon Smasher for Interesting Collisions)
        - High field solenoid between ECal and HCal (2.4m radius, 4-5T)
    - MAIA (Muon Accelerator Instrumented Apparatus)
        - Solenoid before calorimeters (1.7m, 5T)
- High occupancy (10x HL-LHC)
- Total ionizing dose/year is comparable to HL-LHC and orders of magnitude less than FCC-hh
- Extensive studies ongoing, with software based on key4hep



MAIA Detector Concept

Muon Accelerator Instrumented Apparatus
(Work in Progress)

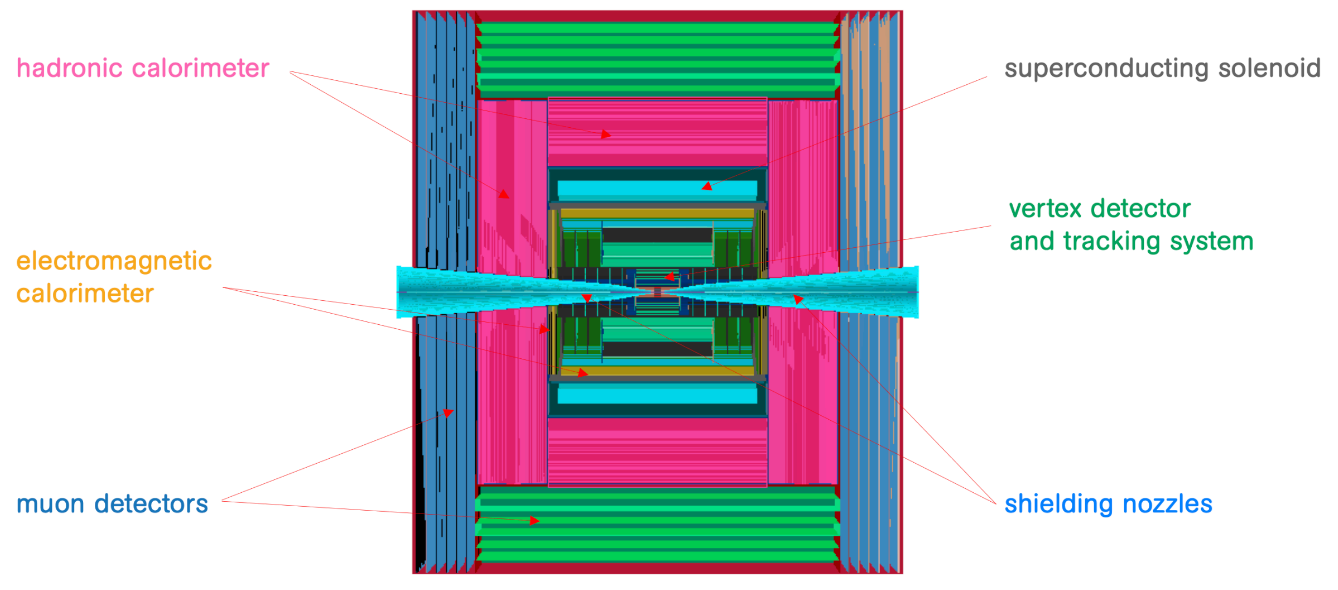
CERN: D. Calzolari
Chicago: K. DiPetrillo, B. Rosser, L. Rozanov, I. Hirsch, N. Virani
DESY: F. Meloni, T. Madlener, P. Pani
FNAL: S. Jindariani, K. Pedro
LBNL: S. Pagan Griso
Tennessee: T. Holmes, LL, B. Johnson, M. Hillman, A. Vendrasco, A. Tuna
Princeton: I. Ojalvo, K. Kennedy, J. Zhang, E. Sledge
Yale: S. Demers, R. Powers

14

Images from C Bell, LL

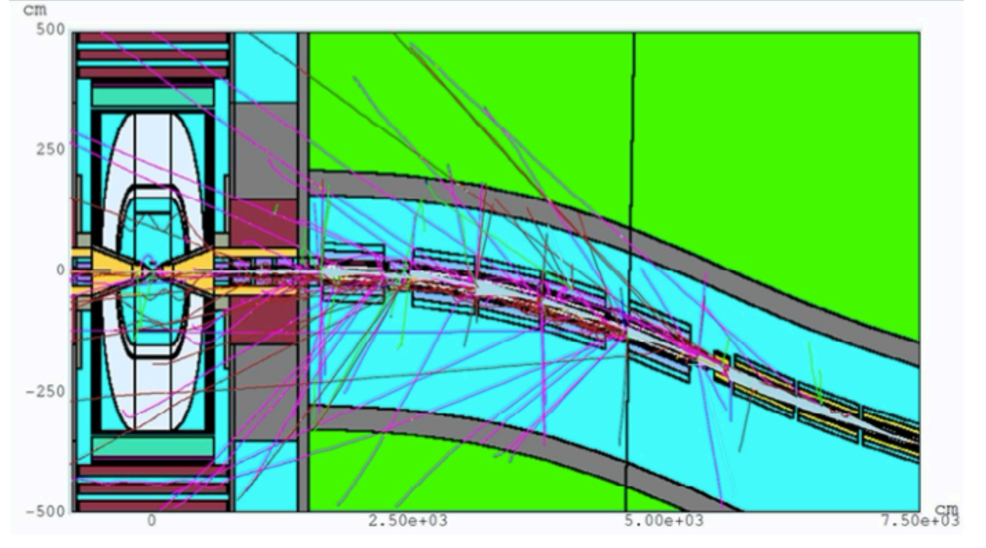
MUSIC Detector Concept

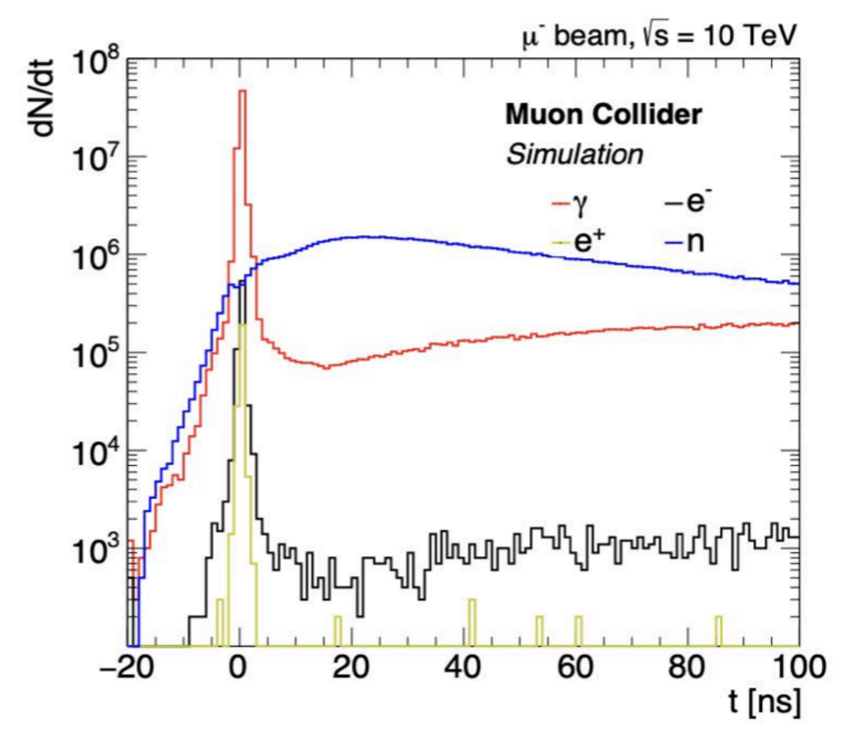
Muon Smasher for Interesting Collisions

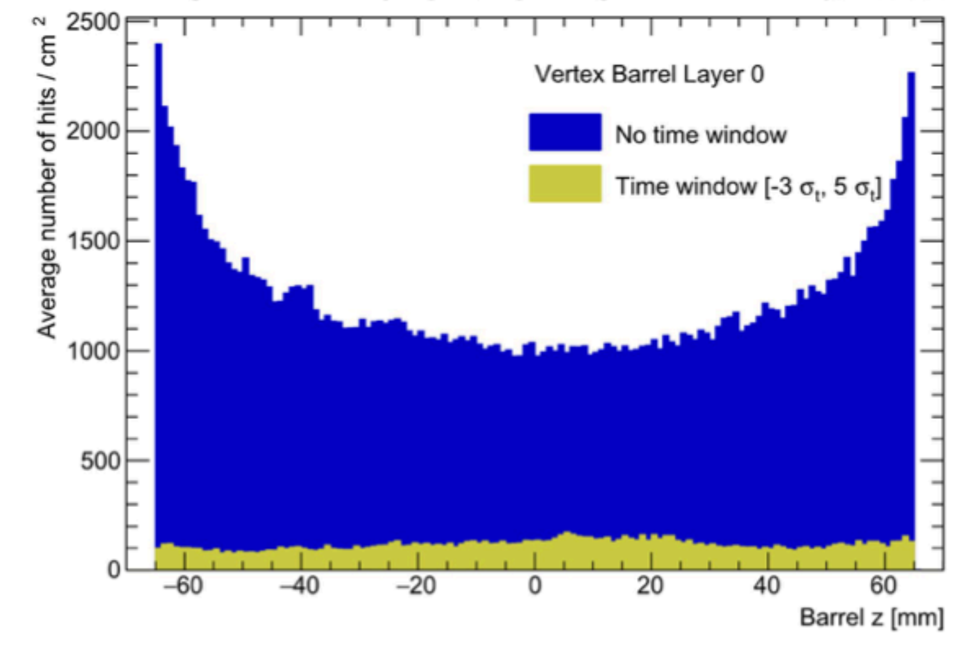


Beam-induced background (BIB)

- BIB is critical for
  - Magnets (need shielding)
  - Detector : performance depends on the rate of background particles arriving to each subdetector
- Full simulation of BIB at 10 TeV with FLUKA
- Rate is ~$2x10^3$ e/meter/ns, however collimated within an average angle of 10^{-3} rad
  - Electromagnetic showers induced by electrons and photons interacting with the machine components generate hadrons, secondary muons and electrons and photons
- Two tungsten nozzles play a crucial role in background mitigation inside the detector
- Tracking crucial to reject BIB with a timing resolution ~30ps for the innermost layers
- Hbb study proves that this background is manageable
- Further studies ongoing

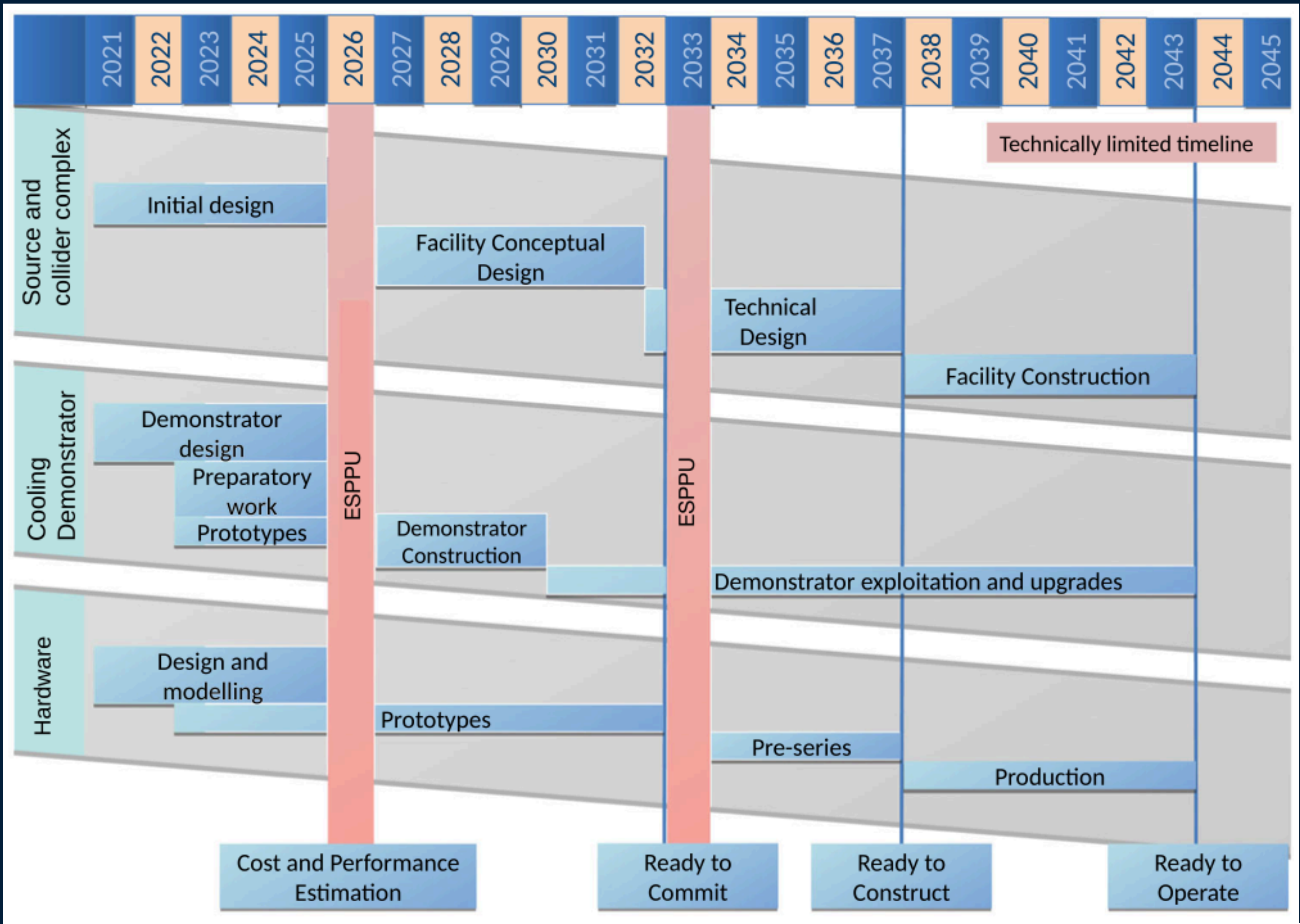






Digestif: concluding remarks

- The muon-collider is a very attractive possibility for the very high energy, even in terms of timeline
  - Compelling physics case!
- A precise study of having it as the next collider, *e.g.* reusing the LHC accelerator chain, is ongoing
- There are plenty of interesting studies to be performed on the machine, detector and physics sides, and combined optimisations
  - Strong synergy with neutrino factories (not mentioned in this talk)
  - Synergies with other domains: neutron spallation, nuclear fusion, etc.
- Collaboration very mature, extending to the US
- Muon test facility hosted at CERN or FNAL to have a demonstrator for ionization cooling is under serious discussion (https://indico.fnal.gov/event/64984/)
- Thanks for your attention !



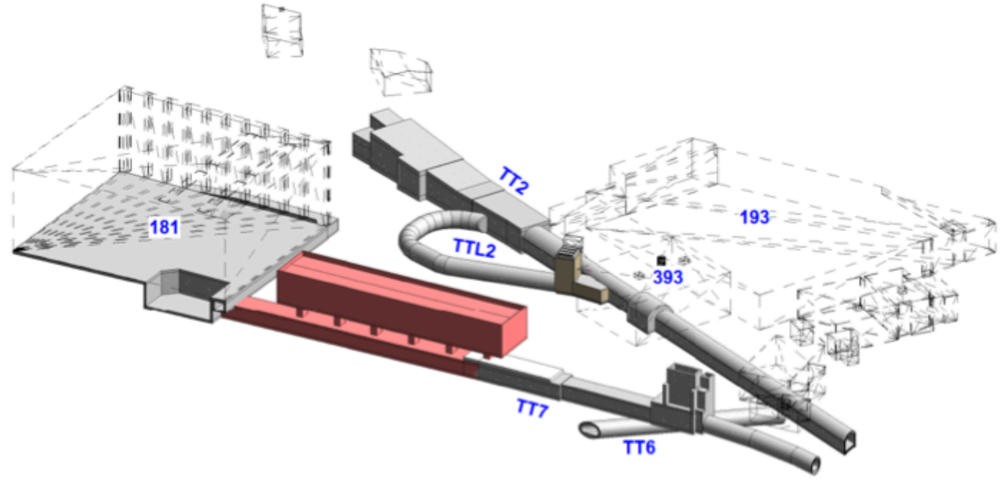


Fig. 6.18: General layout of the proposed test facility at TT7 area.

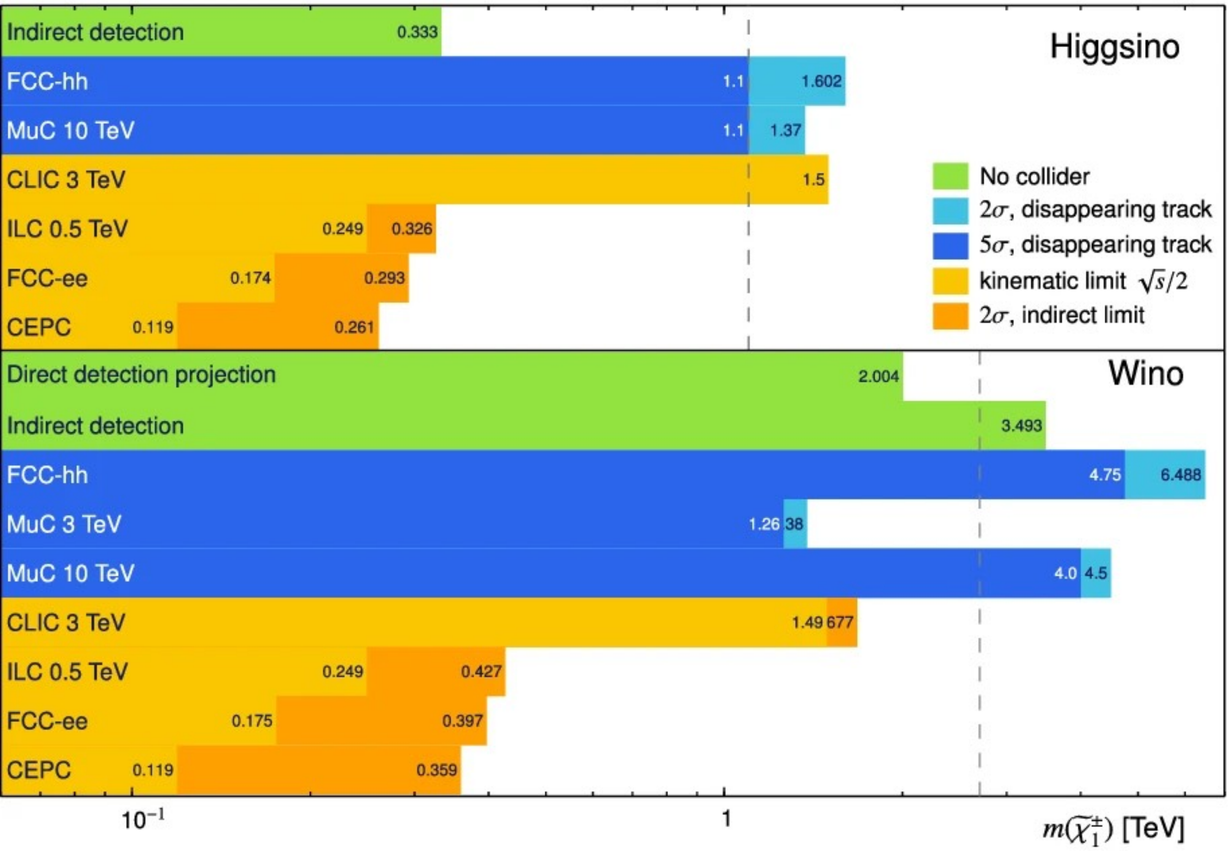
References

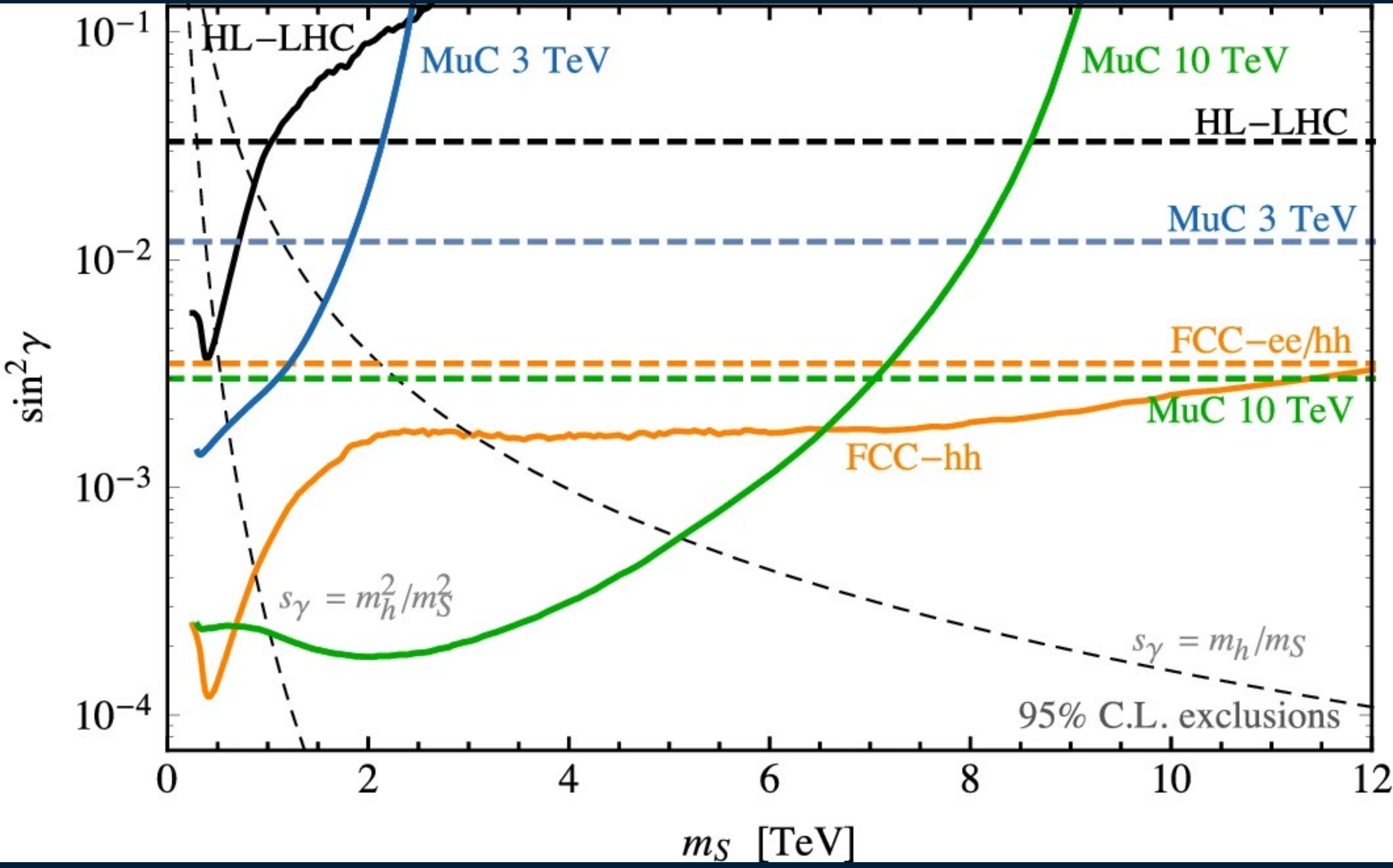
- Interim report for the International Muon Collider Collaboration (IMCC) - https://arxiv.org/abs/2407.12450
- Towards a muon collider - https://link.springer.com/article/10.1140/epjc/s10052-023-11889-x

- Electroweak Couplings of the Higgs Boson at a Multi-TeV Muon Collider - https://arxiv.org/abs/2008.12204
- The collider landscape: which collider for establishing the SM instability? - https://arxiv.org/abs/2203.17197

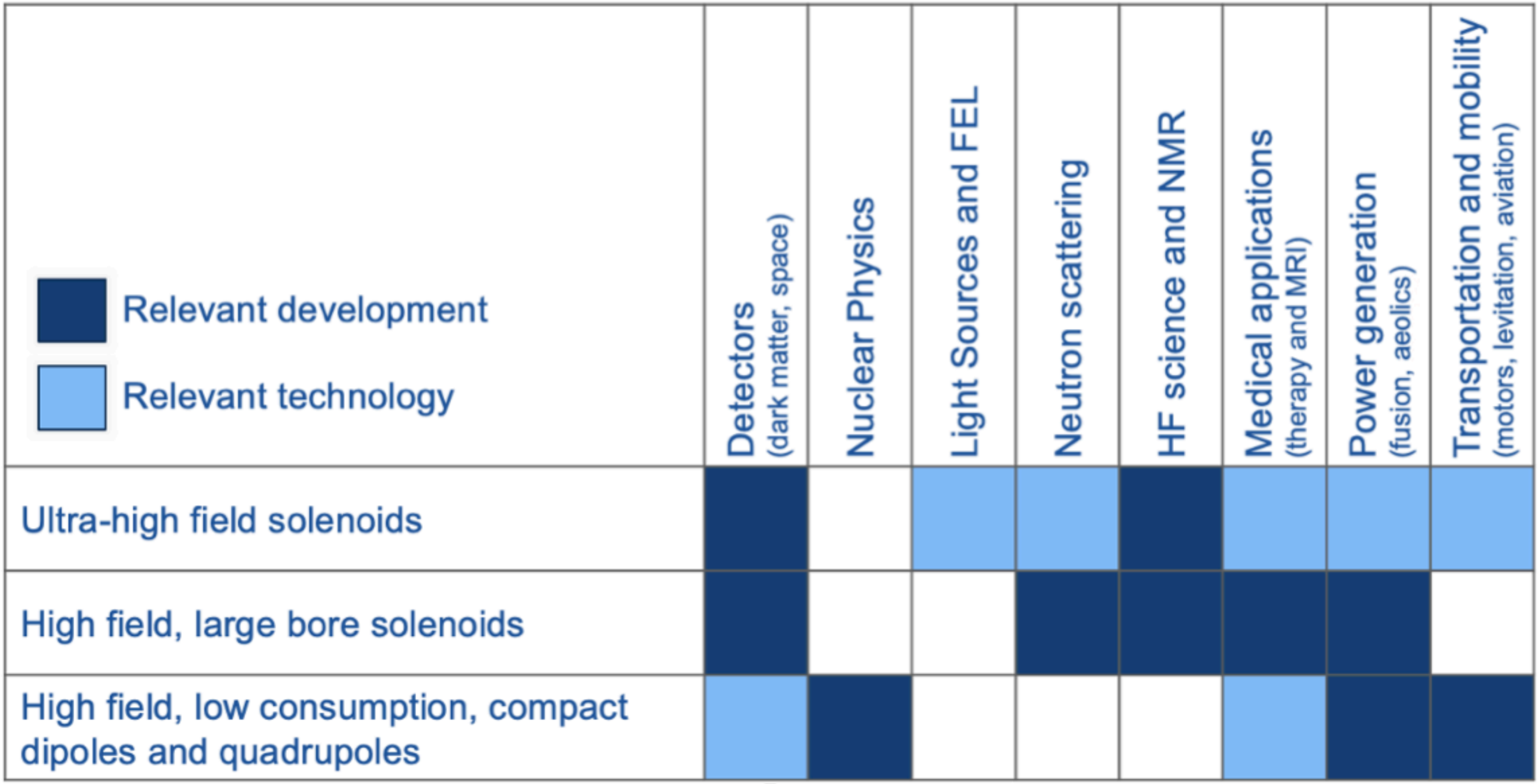
Backup

Higgsino/Wino reach





Synergies with other domains



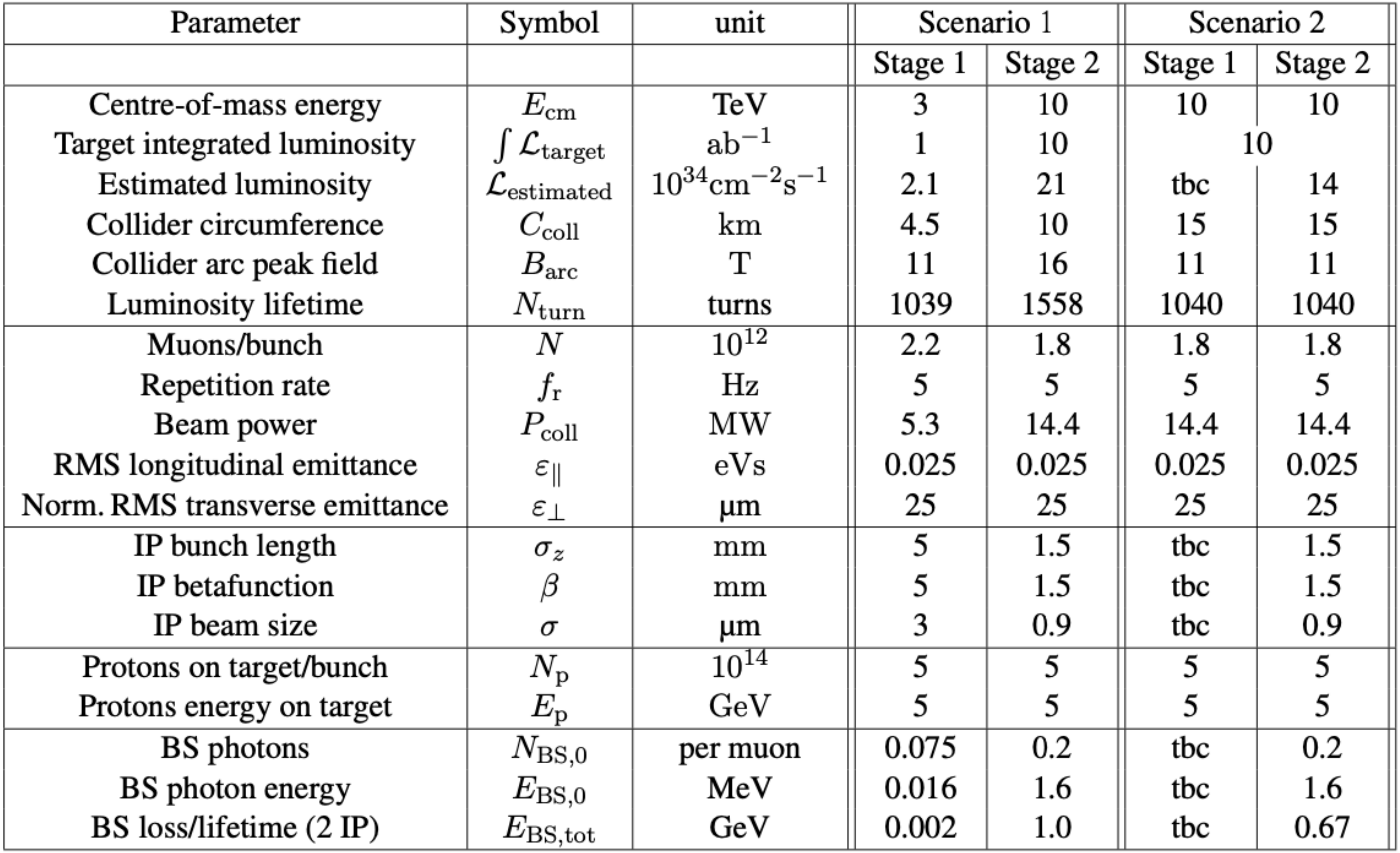
■ Relevant development

▨ Relevant technology

	Detectors (dark matter, space)	Nuclear Physics	Light Sources and FEL	Neutron scattering	HF science and NMR	Medical applications (therapy and MRI)	Power generation (fusion, aeolics)	Transportation and mobility (motors, levitation, aviation)
Ultra-high field solenoids	■		▨	▨	■	▨	▨	▨
High field, large bore solenoids	■			■	■	■	■	
High field, low consumption, compact dipoles and quadrupoles	▨	■				▨	■	■

Fig. 7.2: Matrix of relevance of the developments required for a Muon Collider (rows) to other fields of science and societal applications (columns). The color shading indicates whether the developments can have direct application to other fields (dark shading) or whether the technology development is relevant, but application to other fields may require further development (light shading).

Tentative target beam parameters



Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{\text{target}}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{\text{estimated}}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	2.1	21	tbc	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5	5	5
Protons energy on target	E_{p}	GeV	5	5	5	5
BS photons	$N_{\text{BS},0}$	per muon	0.075	0.2	tbc	0.2
BS photon energy	$E_{\text{BS},0}$	MeV	0.016	1.6	tbc	1.6
BS loss/lifetime (2 IP)	$E_{\text{BS,tot}}$	GeV	0.002	1.0	tbc	0.67

Cooling magnets

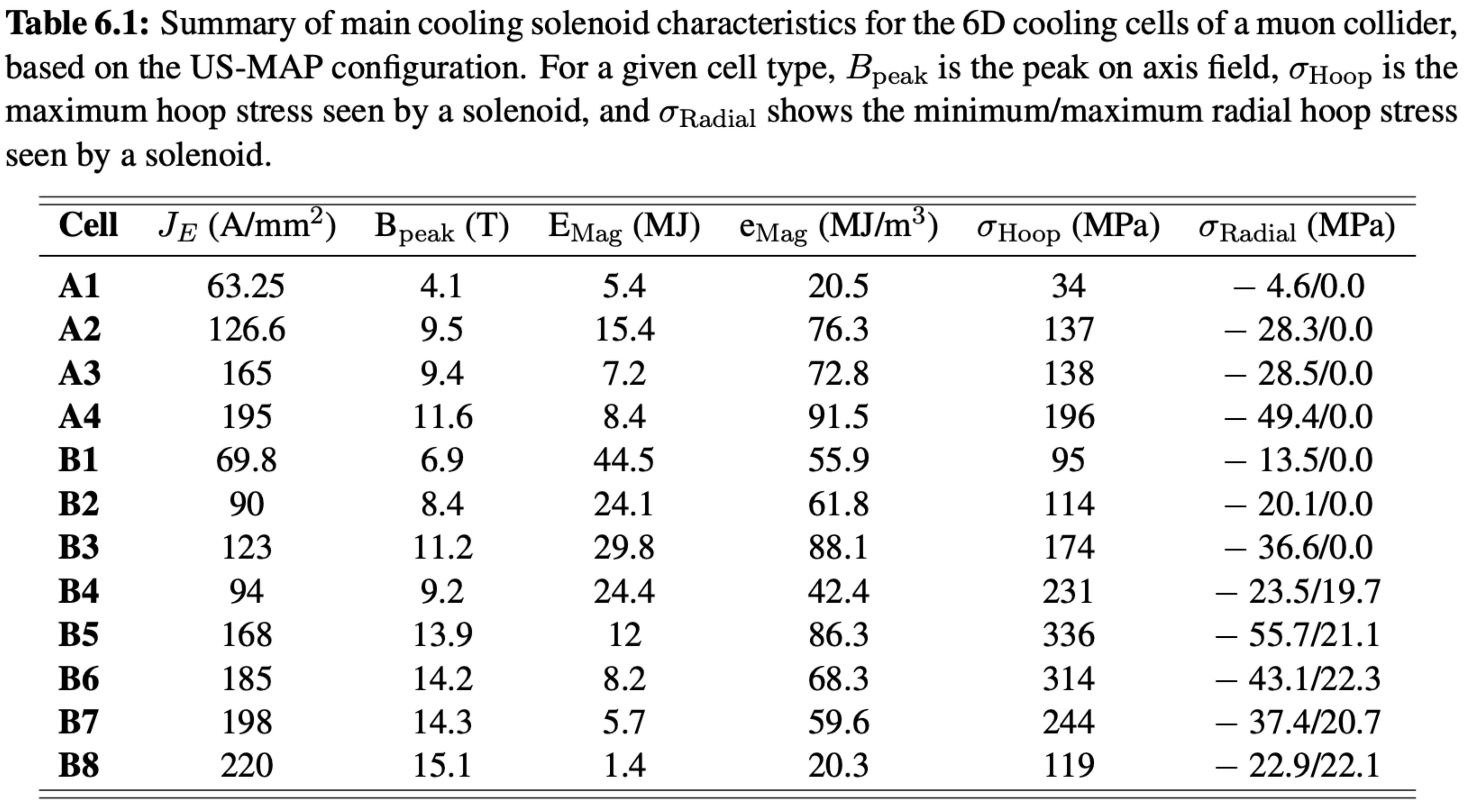


Table 6.1: Summary of main cooling solenoid characteristics for the 6D cooling cells of a muon collider, based on the US-MAP configuration. For a given cell type, B_{peak} is the peak on axis field, σ_{Hoop} is the maximum hoop stress seen by a solenoid, and σ_{Radial} shows the minimum/maximum radial hoop stress seen by a solenoid.

Cell	J_E (A/mm^2)	B_{peak} (T)	E_{Mag} (MJ)	e_{Mag} (MJ/m^3)	σ_{Hoop} (MPa)	σ_{Radial} (MPa)
A1	63.25	4.1	5.4	20.5	34	– 4.6/0.0
A2	126.6	9.5	15.4	76.3	137	– 28.3/0.0
A3	165	9.4	7.2	72.8	138	– 28.5/0.0
A4	195	11.6	8.4	91.5	196	– 49.4/0.0
B1	69.8	6.9	44.5	55.9	95	– 13.5/0.0
B2	90	8.4	24.1	61.8	114	– 20.1/0.0
B3	123	11.2	29.8	88.1	174	– 36.6/0.0
B4	94	9.2	24.4	42.4	231	– 23.5/19.7
B5	168	13.9	12	86.3	336	– 55.7/21.1
B6	185	14.2	8.2	68.3	314	– 43.1/22.3
B7	198	14.3	5.7	59.6	244	– 37.4/20.7
B8	220	15.1	1.4	20.3	119	– 22.9/22.1