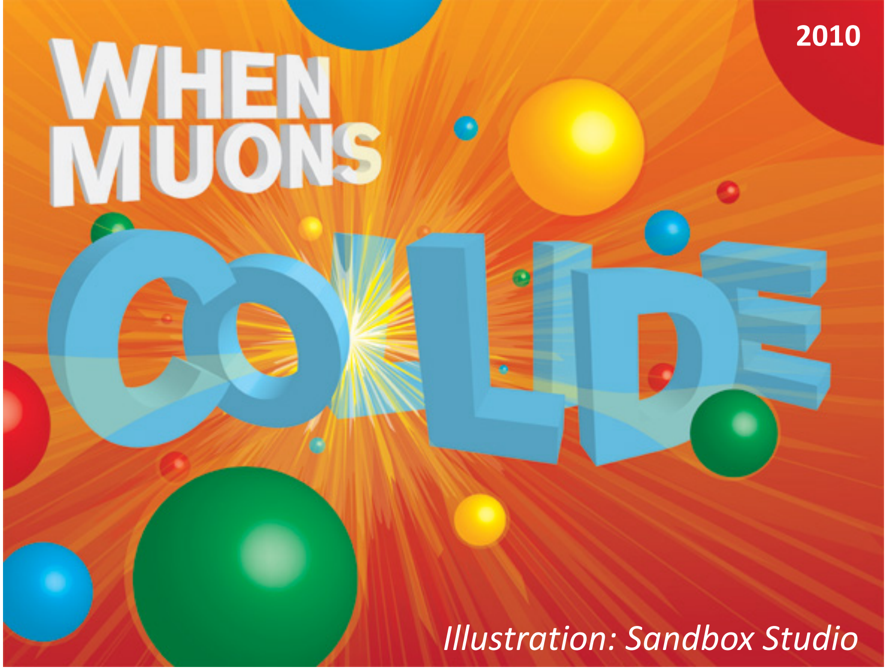
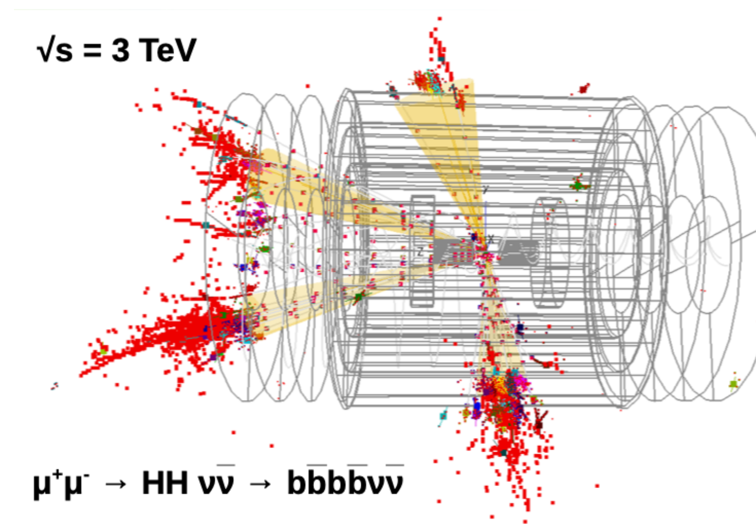


www.symmetrymagazine.org

PITT PACC Workshop
November 30th, 2020

Muon Collider: are we ready?

Nadia Pastrone
INFN TORINO



D. Lucchesi et al.

Wonders

- Muon is a fundamental particle ~ 200 times heavier than electron:
  - no synchrotron radiation (limit of circular e^+e^- colliders)
  - no beamstrahlung at collision (limit of linear e^+e^- colliders)

➔ A multi-pass circular collider can be designed to reach the multi-TeV energies:
  - compact acceleration system and collider
  - cost effective construction & operation

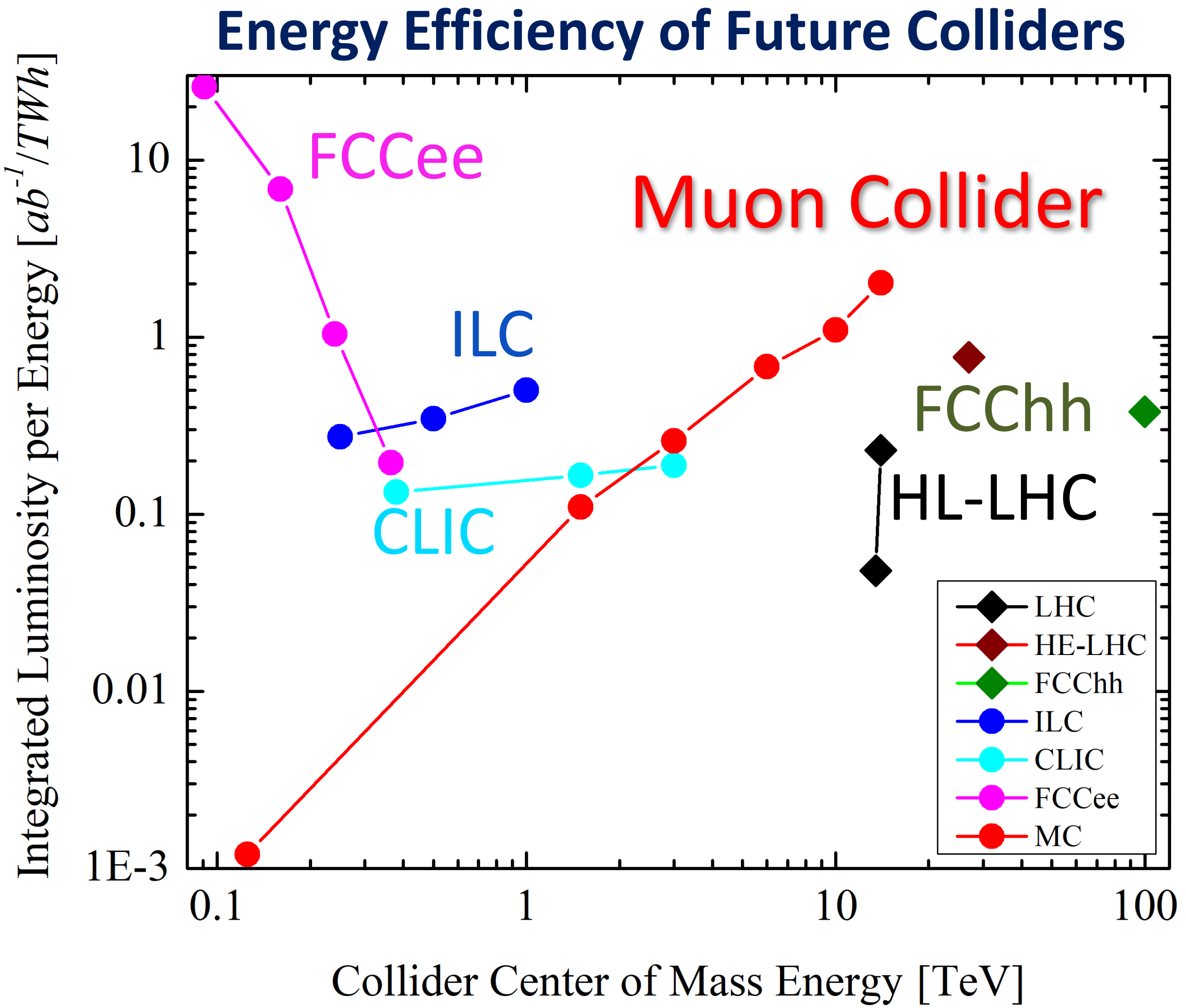
- Unique opportunity for lepton colliders @ $\sqrt{s} > 1$ TeV
- Possible reuse of existing facilities and infrastructure (i.e. LHC tunnel) in Europe

It is an idea over 50 years old that can become feasible only now
thanks to the – present and near future – technology achievements

- High luminosity possible at reasonable beam power and wall plug power needs

Figure of merit

arXiv:2007.15684 [physics.acc-ph]



Challenges

- Muons decay with lifetime at rest 2.2 μs demanding:
  - fast production, fast novel cooling, fast acceleration and collision
  - machine protection/shielding
  - Machine Detector Interface (MDI) at experiment collision point

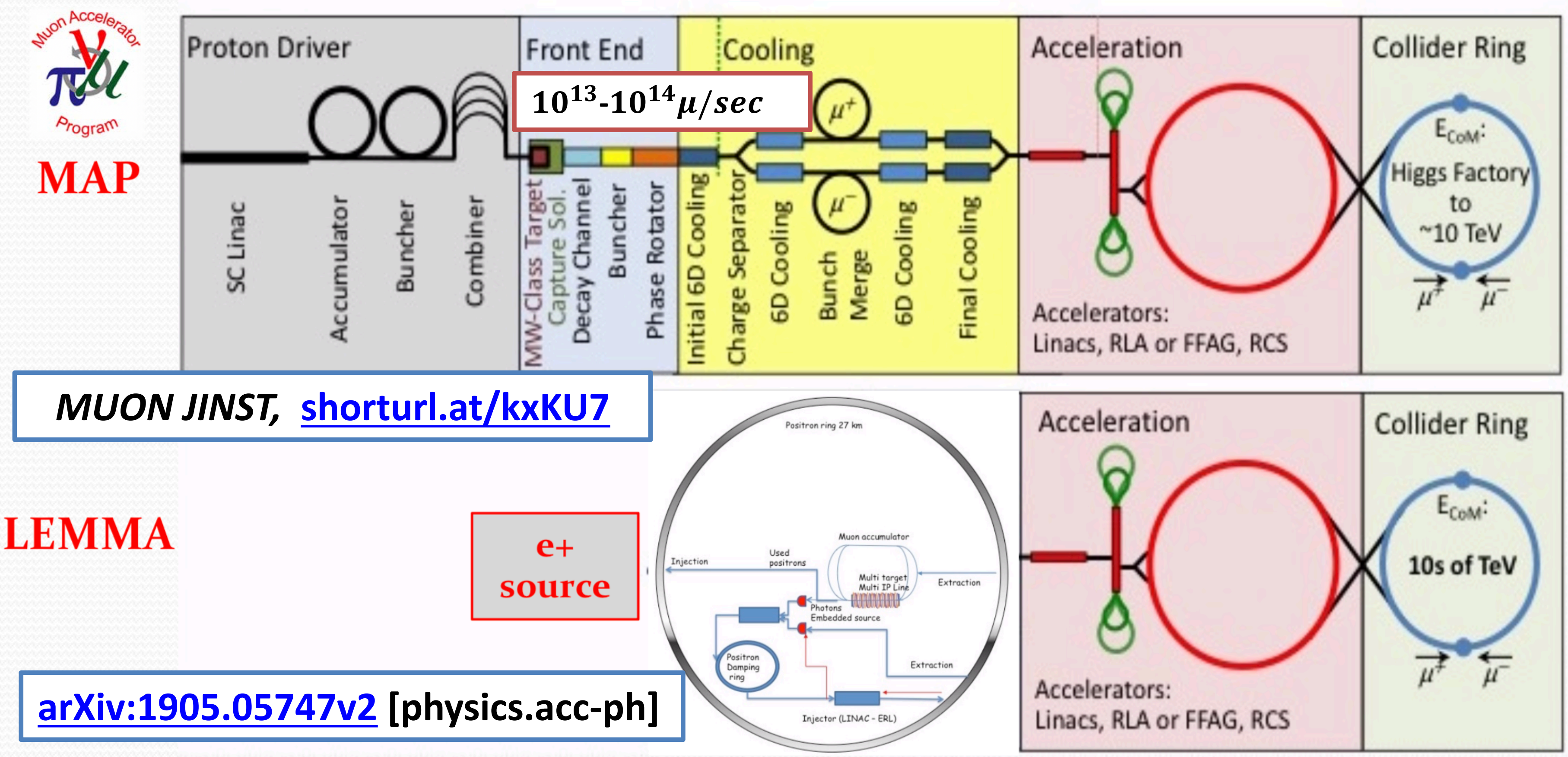
- New experiment design to prove physics reach with Beam Induced Beackground

- Intense neutrino beams may cause radiation hazard ➔ could limit ultimate energy

- High intensity beams at collision require well collimated low emittance source:
  - Proton driven ➔ demands innovative 6D ionization cooling
  - Positron driven – not yet mature ➔ requires new production studies and ideas

Great opportunities to develop novel ideas and technologies

proton (MAP) vs positron (LEMMA) driven Muon Source



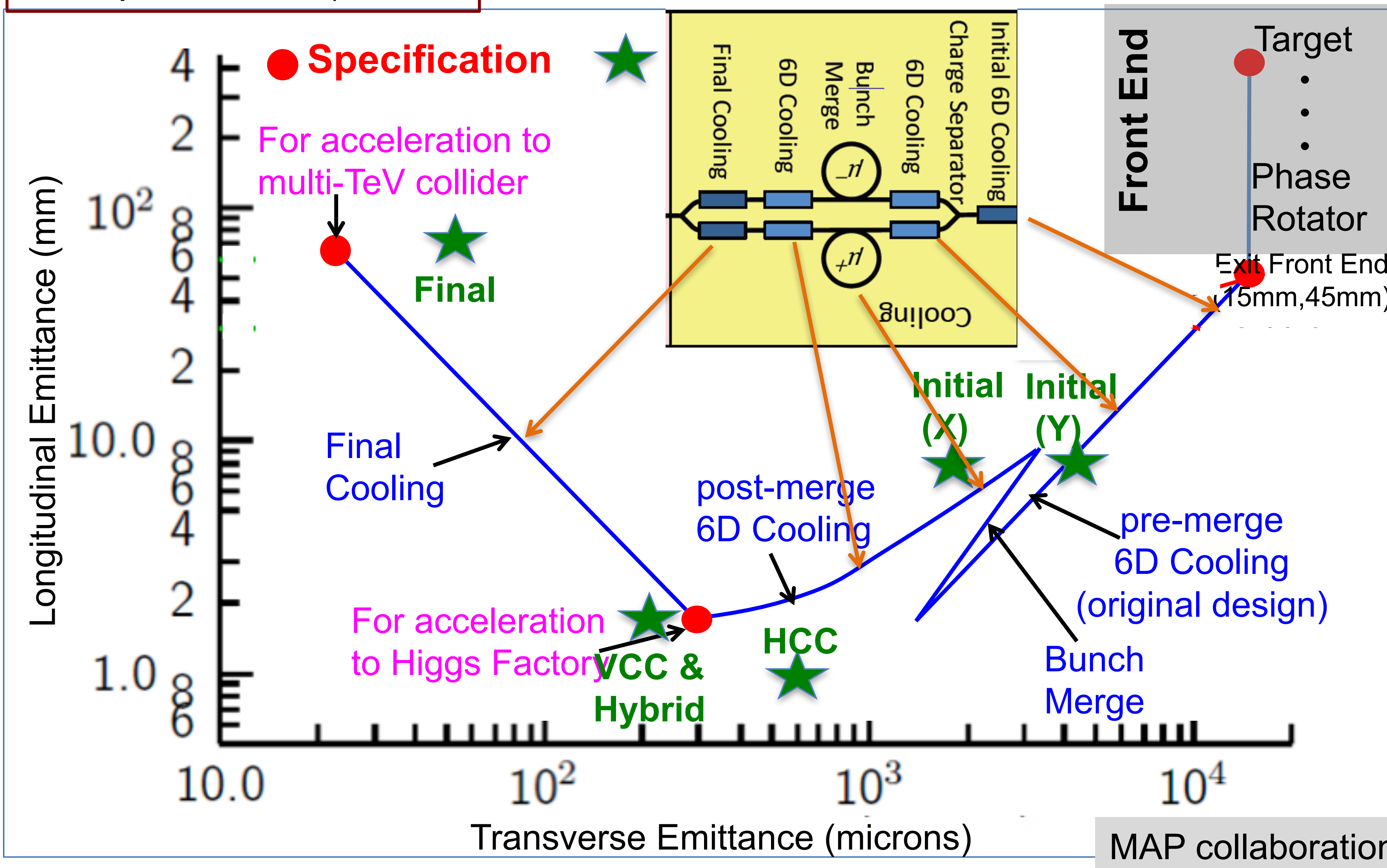
MUON JINST, shorturl.at/kxKU7

arXiv:1905.05747v2 [physics.acc-ph]

➔ **need consolidation** to overcome technical limitations to reach higher muon intensities

Cooling: Emittance Path

Highest field HTS
Phase space beam manipulations



Muon Collider Luminosity Scaling

Fundamental limitation
Requires emittance preservation and advanced lattice design

Applies to MAP scheme

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

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

Luminosity per power naturally increases with energy
Provided all technical limits can be solved
Constant current for required luminosity increase
Better scaling than linear colliders

Tentative Target Parameters

Based on extrapolation of MAP parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
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

The study should verify that these parameters can be met

$$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$$

↓

@ 3 TeV ~ 1 ab^{-1} 5 years

@ 10 TeV ~ 10 ab^{-1} 5 years

@ 14 TeV ~ 20 ab^{-1} 5 years

Towards the highest possible energy

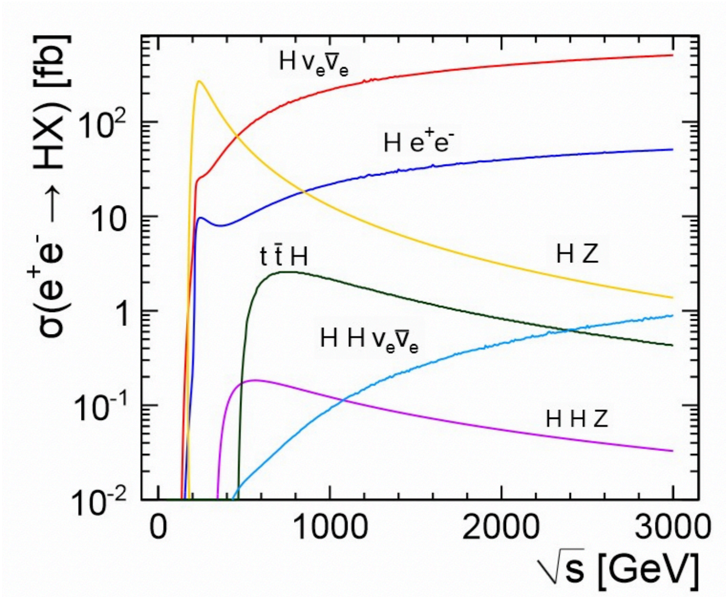
- **Overwhelming physics potential:**
  - Discovery searches ➔ high energy at pointlike level ➔ new perspectives!
    (pair production of heavy particles up to M ~ ½ $\sqrt{s_{\mu\mu}}$)
  - Precision measures ➔ Higgs physics
  - Many new directions for BSM

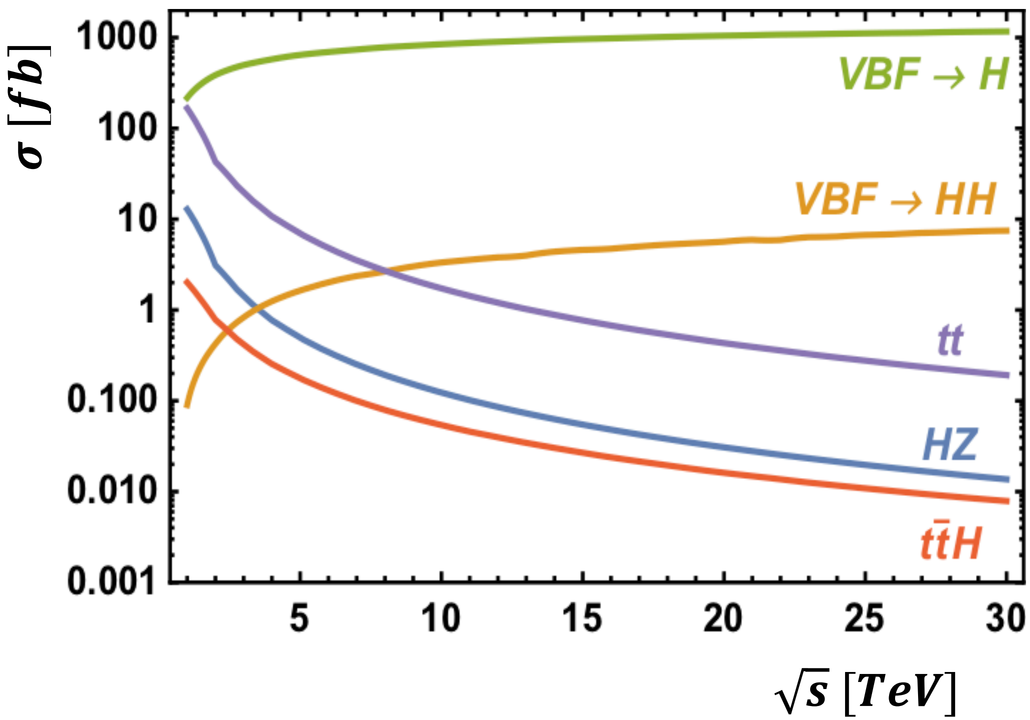
- Focus on two energy ranges:
  - **1-3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, requires more advanced technology: enters uncharted territory

➔ **Physics benchmarks steer machine parameters and experiment design**

- **Challenging Machine Design**:
  - Key issues/risks
  - R&D plan and synergies

Higgs production at Lepton Collider





Motivation: Higgs potential

M. Chiesa et al. arXiv:2003.13628 [hep-ph]

determine the Higgs potential by measuring trilinear and quadrilinear self coupling

$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Trilinear coupling k_3

$\sqrt{s}$=10 TeV $\mathcal{L} \sim 2 \cdot 10^{35} cm^{-2} s^{-1}$

20 ab^{-1} ➔ $k_3$sensitivity ~ 3%

Best sensitivity ~ 5% FCC combined
arXiv:1905.03764 **[hep-ph]**

Quadrilinear coupling k_4

$\sqrt{s}$=14 TeV $\mathcal{L} \sim 3 \cdot 10^{35} cm^{-2} s^{-1}$

~30 ab^{-1} ➔ $k_4$sensitivity few 10%

significantly better than what is currently expected to be attainable at the FCC-hh with a similar luminosity
arXiv:1905.03764 **[hep-ph]**

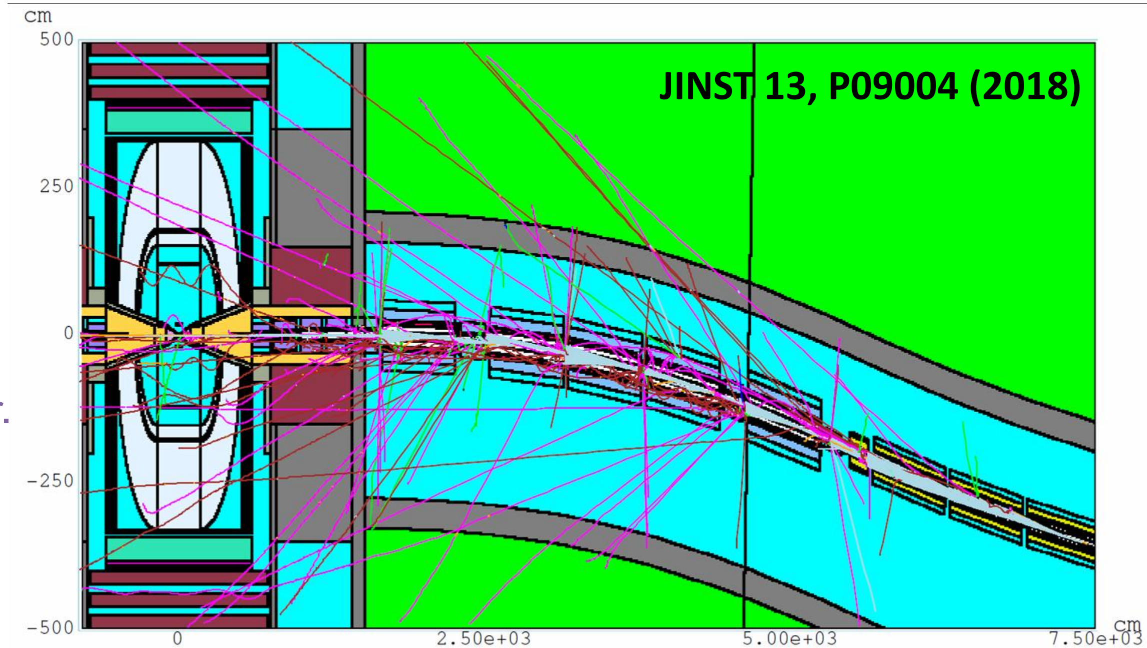
This just looking at the Higgs sector!
Top and new physics sectors also to be scrutinized

Full simulation: beam induced background

Nikolai Mokhov et al. - MARS15

MAP developed realistic simulation of beam-induced backgrounds in the detector:
- implemented a model of the tunnel ±200 m from the interaction point, with realistic geometry, materials distribution, machine lattice elements and magnetic fields, the experimental hall and the machine-detector interface (MDI)
- secondary and tertiary particles from muon decay are simulated with MARS15 then transported to the detector borders

In particular, the two tungsten nozzles, cladded with a 5-cm layer of borated polyethylene, play a crucial role in background mitigation inside the detector.



For each collider energy the machine elements, the MDI and interaction region have to be properly designed and optimized

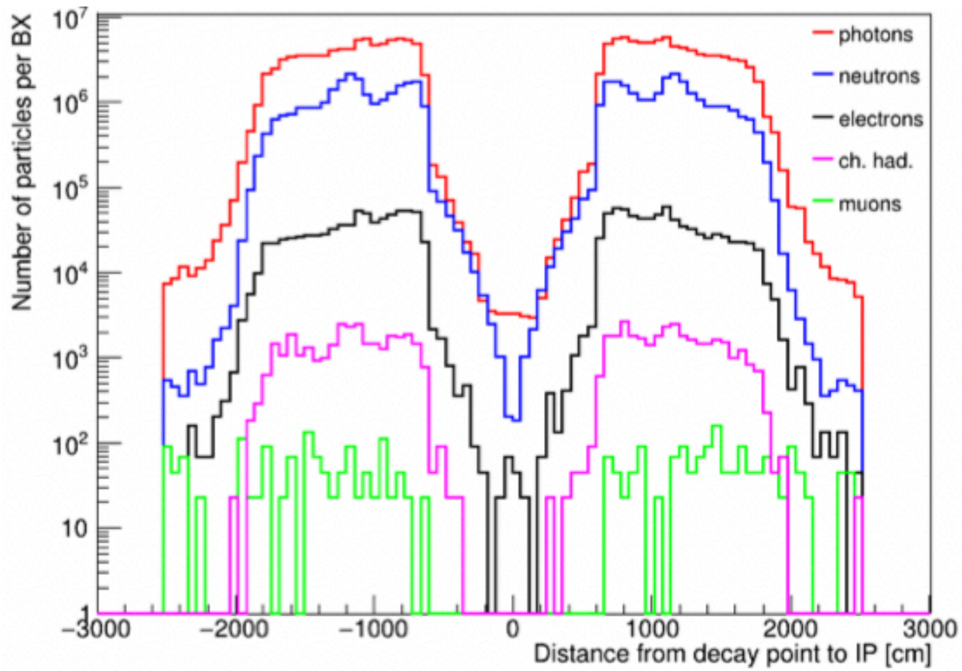
Beam Induced background @ 1.5 TeV

Nikolai Mokhov et al. - MARS15

***JINST* 15 (2020) 05, P05001**

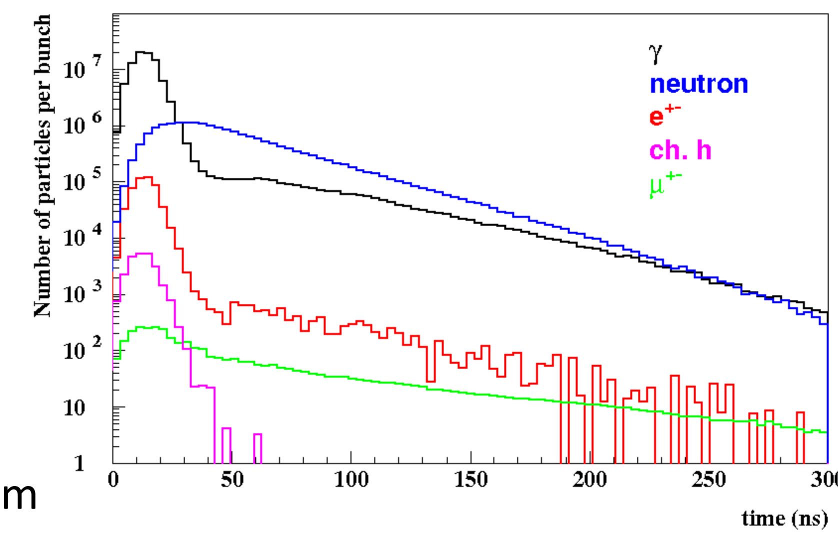
Beam muons decay products interact with machine elements and cause a continuous flux of secondary and tertiary particles (mainly γ, n, e±, h±) that eventually reach the detector

The amount and characteristics of the beam-induced background (BIB) depend on the collider energy and the machine optics and lattice elements



muon beams of **0.75 TeV** with **2×10^12^ muons/bunch**

➔ **4×10⁵ muon decays/m** in single bunch crossing



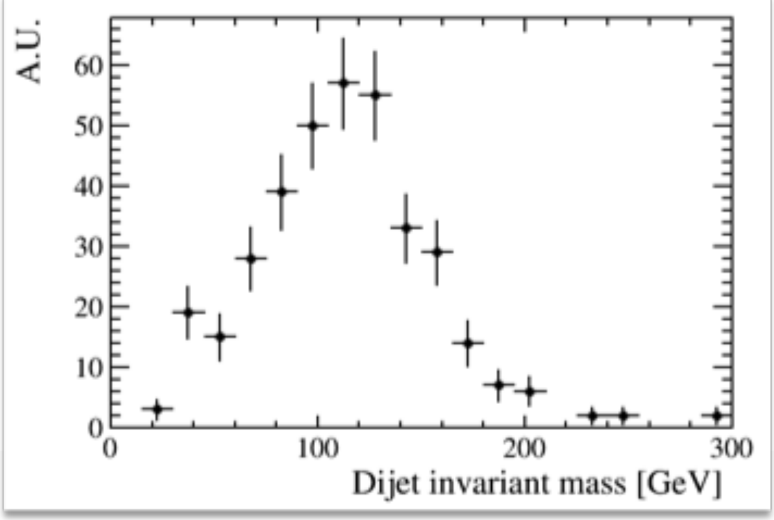
Secondary and tertiary particles have low momentum and different arrival time in the Interaction Point

H→bb @ 1.5 TeV

JINST 15 (2020) 05, P05001

D. Lucchesi et al.

$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated



Higgs $b\bar{b}$ Couplings Results

- The instantaneous luminosity, $\mathcal{L}$, at different √s is taken from MAP.
- The acceptance, A, the number of signal events, N, and background, B, are determined with simulation.

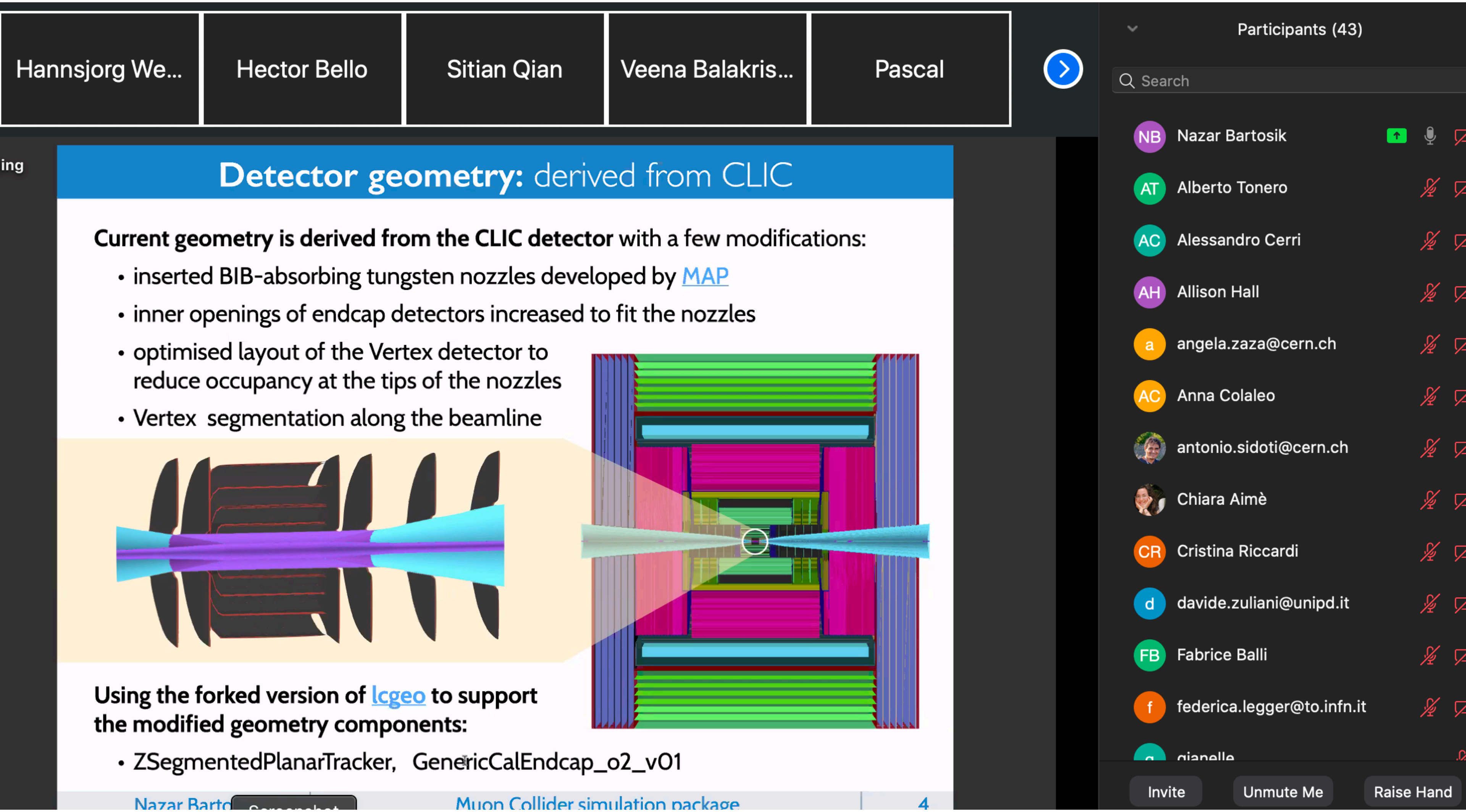
$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

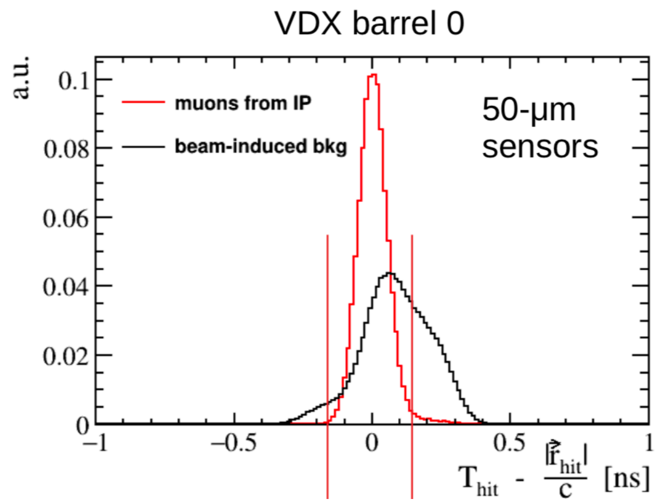
CLIC numbers are obtained with a model-independent multi-parameter fit performed in three stages, taking into account data obtained at the three different energies.

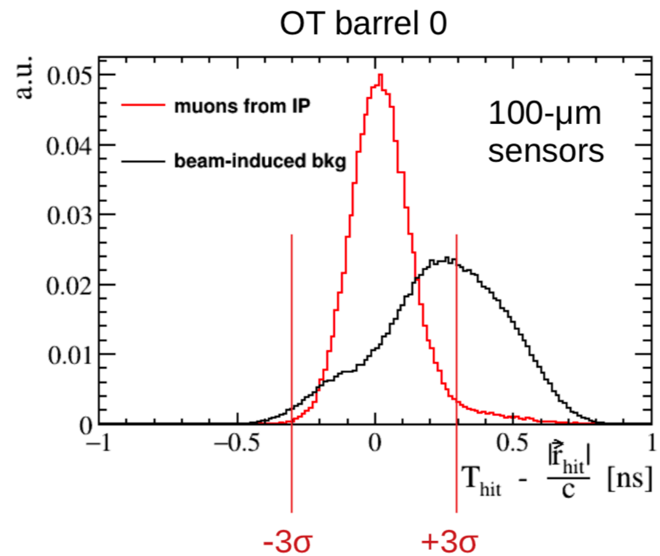
Results published on JINTST as Detector and Physics Performance at a Muon Collider

Experiment design to be improved



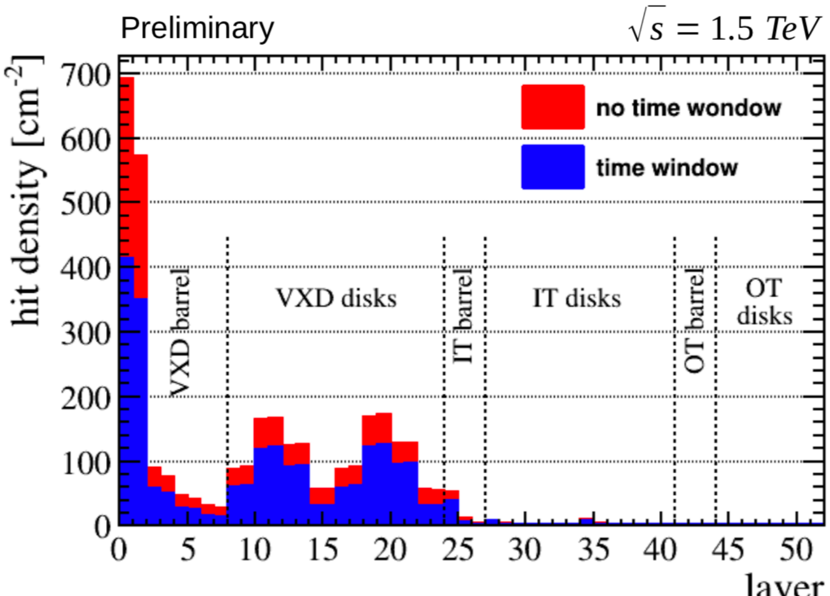
Tracking requirements ➔ R&D needs





- ±150ps window at 50ps time resolution in the Vertex detector allows to strongly reduce the occupancy (by ~30%)

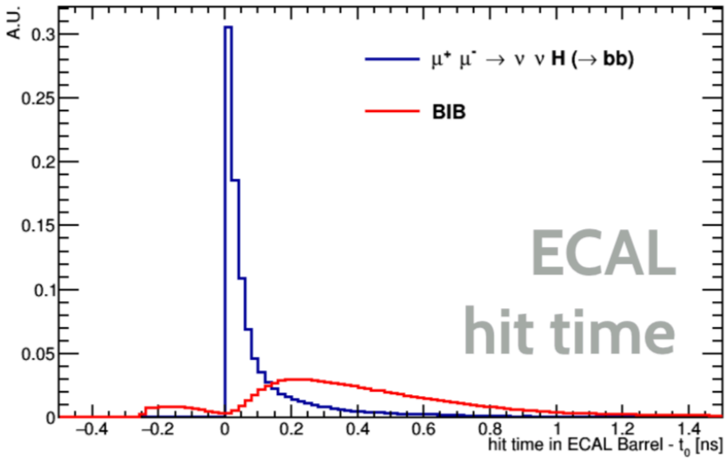
- Handles to reject spurious hits from BIB:
  - applying a time window to readout only hits compatible with particles originating from interaction region;
  - exploiting energy deposited in the tracker sensors (under development);
  - correlating hits on double-layer sensors (under development).

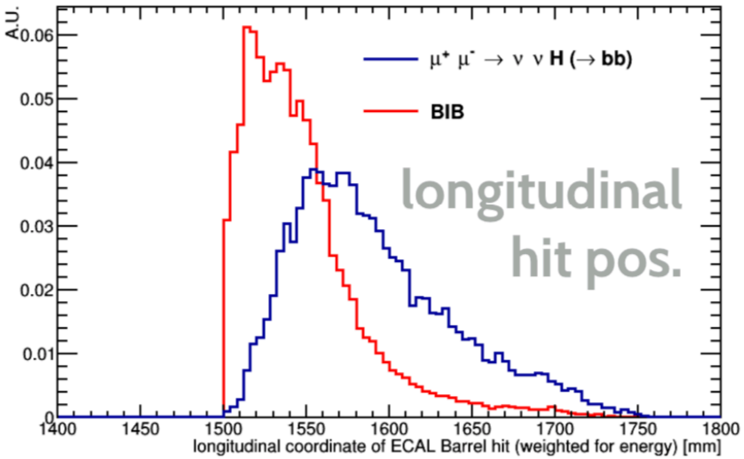


State of the art fast tracking sensors can push this even further: σ_t~10ps

Calorimeter optimization

Timing and longitudinal shower distribution provide a handle on BIB in ECAL





Various BIB mitigation approaches for ECAL can be studied

- possibly adding a preshower for absorbing the initial part of BIB in ECAL
- subtraction of BIB depositions using the hit time+depth information

Hadronic showers have longer development time → timing not critical

- the most straightforward approach: evaluate the average BIB energy deposition and consider only energy deposits above the BIB level

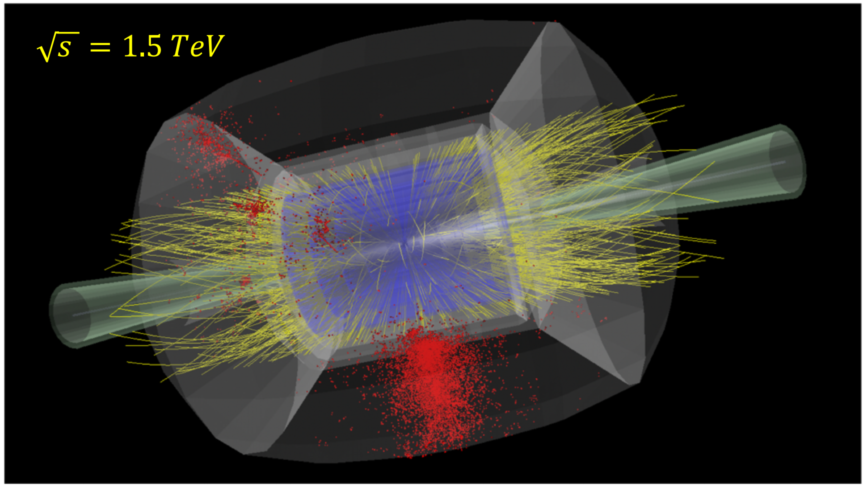
Physics and Detector

Physics at 10+ TeV is in uncharted territor ➔ need important effort

- Physics case and potential under study, also in comparison to other options

- Need to include realistic assumptions about the detector performance:
  - use synergies with technologies that will be developed for other detectors
  - identify additional needs for muon collider ➔ R&D

- Main detector challenge in machine detector interface (MDI)
  - @ 14 TeV: 40,000 muons decay per m and bunch crossing
  - @ 3 TeV: 200,000 muons per m and bunch crossing



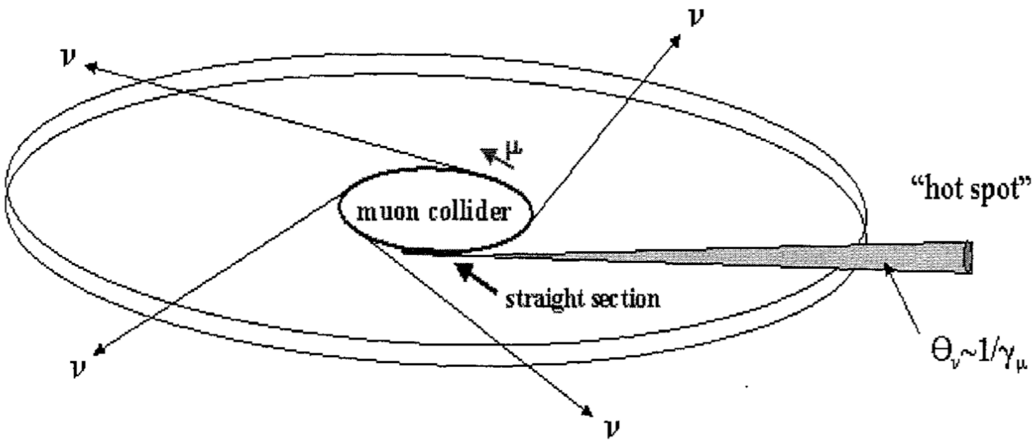
Detector must be designed for robustness

- effective masking
- high granularity
- fast timing
- clever algorithms

Detailed design of machine is required

Challenge: Neutrino Radiation Hazard

Neutrinos from decaying muons can produce showers just when they exit the earth



Potential mitigation by

- Site choice
- Having a dynamic beam orbit so it points in different directions at each turn in the arcs
    - Or at least paint the beam in the the straights to dilute radiation

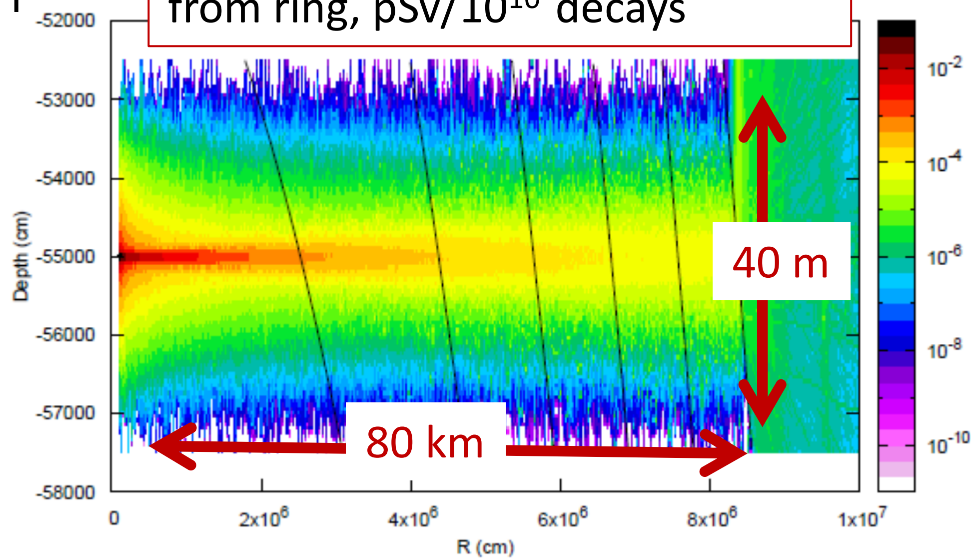
More important at higher energies (scaling E^3)

US study concluded: 6 TeV parameters are OK

Reasonable goal 0.1 mSv/ year, to be verified

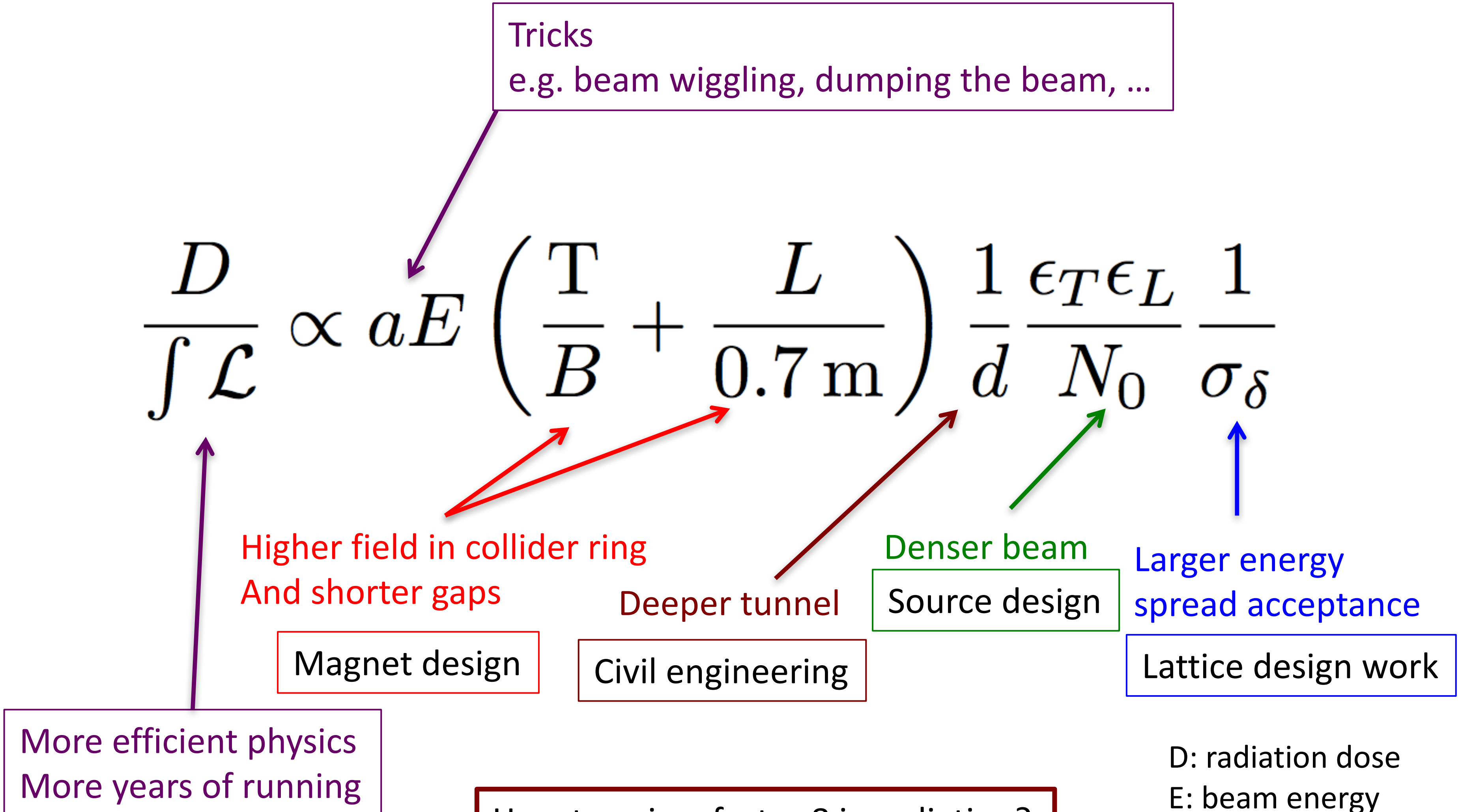
On-going simulations and studies for mitigation with existing/future tunnels

Dose from 1 TeV $\mu^\pm$ vs distance from ring, pSv/10^{10} decays



Mitigation Approaches

$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\,\frac{\epsilon_T \epsilon_L}{N_0}\,\frac{1}{\sigma_\delta}$$

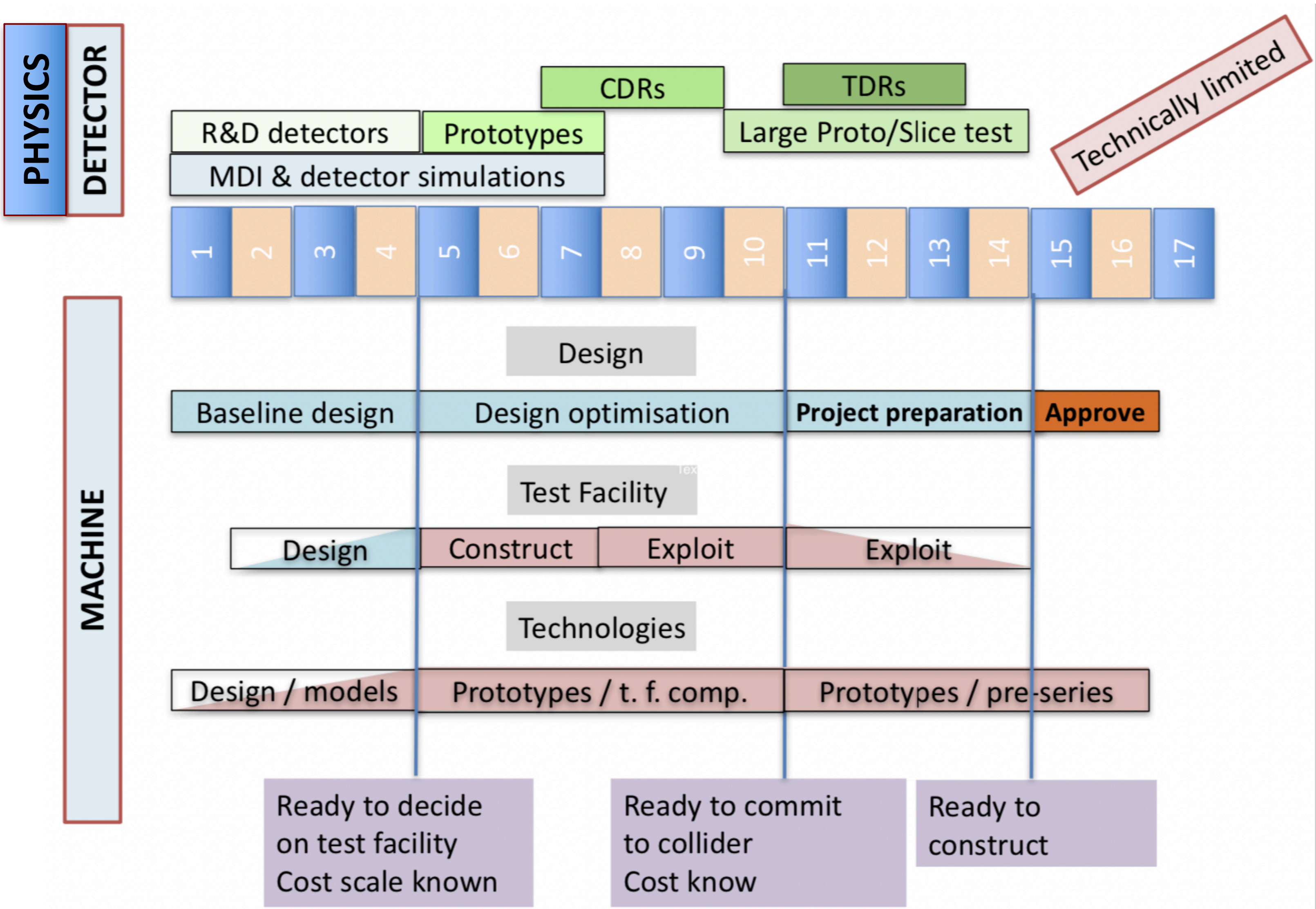


How to gain a factor 8 in radiation?
Seems hard but not impossible

D: radiation dose
E: beam energy
B: Magnetic field
d: depth underground

Technically Limited Potential Timeline

Physics Briefing Book arXiv:1910.11775v2 [hep-ex]



Synergies in EU,USA…. more to find

- Many LoI submitted to SnowMass 2021
  ➔ now under discussion towards Contributed Papers due by July 2021

- **Roadmap R&D Accelerators** coordinated by CERN Lab Directors Group
- **Roadmap R&D Detectors** coordinated by ECFA
  (tracking, calorimetry, electronics, on detector processing, new ideas)

- **Medium term plan** at CERN 2021-2025 - dedicated budget line -
  per year 5 FTE staff, 6 fellows, 4 students, 1 associate, 5 x 2 MCHF

- **New approved EU INFRA-INNOV project: I.FAST** on accelerator R&D
  - **MUST** – MUon colliders STrategy network *(INFN, CERN, CEA, CNRS, KIT, PSI, UKRI)*
- **New approved EU RISE project: aMUSE** (with activities @ FNAL Muon Campus)
  - Donatella Lucchesi (Univ. PD) for Muon Collider with US Laboratories FNAL, BNL
- **New approved EU INFRA-INNOV project: AIDAinnova** on detector R&D

Critical key issues

- **Advanced detector concepts and technologies**, requiring excellent timing, granularity and resolution, able to reject the background induced by the muon beams
- **Advanced accelerator design** and beam dynamics for high luminosity and power efficiency
- **Robust targets and shielding** for muon production and cooling as well as collider and detector component shielding and possibly beam collimation
- **High field, robust and cost-effective superconducting magnets** for the muon production, cooling, acceleration and collision. High-temperature super-conductors are an ideal option
- **High-gradient and robust normal-conducting RF** to minimise muon losses during cooling.
- High rate **positron production** source and high current positron ring (LEMMA)
- **Fast ramping normal-conducting, superferric or superconducting magnets** that can be used in a rapid cycling synchrotron to accelerate the muons and efficient power converters
- **Efficient, high-gradient superconducting RF** to minimise power consumption and muon losses during acceleration
- **Efficient cryogenics systems** to minimise the power consumption of the superconducting components and minimise the impact of beam losses
- Other accelerator technologies including high-performance, compact **vacuum systems** to minimise magnet aperture and cost as well as fast, robust, **high-resolution instrumentation**

Synergies

- Important synergies exist for the key muon collider technologies
  - Magnet development for hadron colliders
    - e.g. link to high-temperature superconducting magnet development
  - Superconducting RF cavities for hadron colliders and ILC
  - Normal-conducting structures for CLIC
  - Cooling for hadron colliders
  - Material, target, shielding, …
  - Instrumentation, vacuum, ...

- Synergies for physics and experiment will also be exploited
  - Physics studies
  - Simulation tools
  - …

Thanks for the attention!

extras

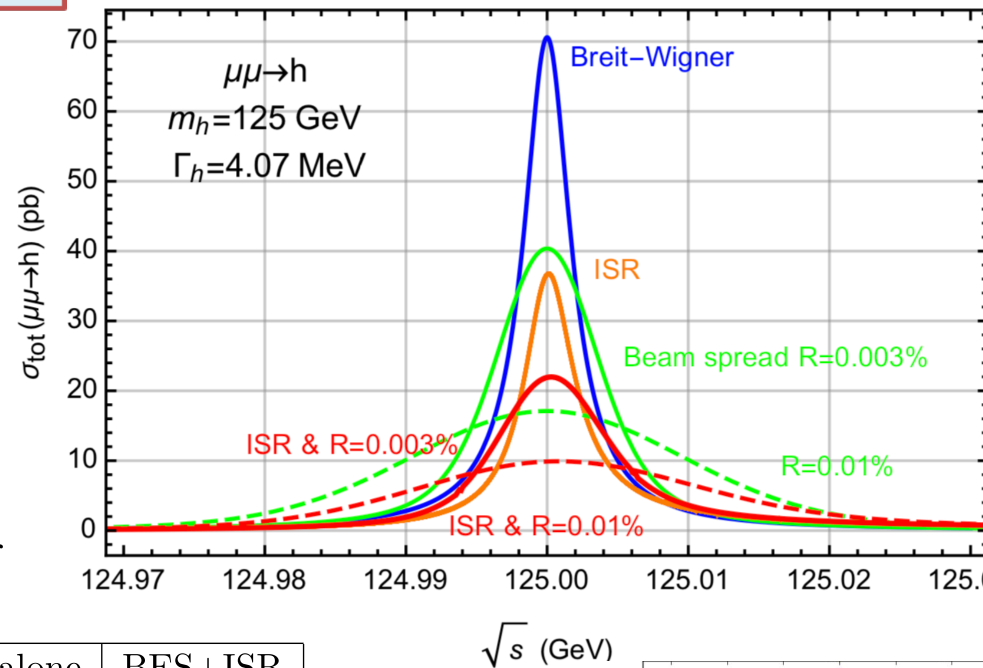
Lepton Colliders: μ vs e @ $\sqrt{s}$=125 GeV

Back on the envelope calculation:

$$\sigma(\mu^+\mu^- \to H) = \left(\frac{m_\mu}{m_e}\right)^2 \times\sigma(e^+e^- \to H) = \left(\frac{105.7MeV}{0.511\,MeV}\right)^2 \times\sigma(e^+e^- \to H)$$

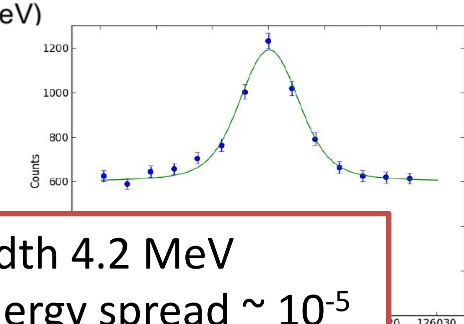
$$\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)$$

More precise determination
by M. Greco et al. arXiv:1607.03210v2



R: percentage beam energy resolution, key parameter

σ(BW)	ISR alone	R (%)	BES alone	BES+ISR
$\mu^+\mu^-$: 71 **pb**	37	0.01	17	10
		0.003	41	22
e^+e^-: 1.7 **fb**	0.50	0.04	0.12	0.048
		0.01	0.41	0.15



Higgs width 4.2 MeV
Beam energy spread ~ 10^{-5}

A long story… up to now and here!

- The **muon collider idea** was first introduced in **early 1980's** *[A. N. Skrinsky, D. Neuffer et al.,]*
- Idea further developed by a **series of world-wide collaborations**
- **US Muon Accelerator Program – MAP,** created in **2011,** was terminated in **2014**
  *MAP developed a **proton driver scheme** and addressed the feasibility of novel technologies required for Muon Colliders and Neutrino Factories* ***"Muon Accelerator for Particle Physics," JINST,***
  https://iopscience.iop.org/journal/1748-0221/page/extraproc46
- **LEMMA (Low EMittance Muon Accelerator)** proposed in **2013** *[M. Antonelli e P. Raimondi]*
  *a new end-to-end design of a **positron driven scheme** presently under study by INFN-LNF et al.*
  to overcome technical issues of initial concept ➔ arXiv:1905.05747
- **CERN-WG on Muon Colliders:** September 2017- June 2020
- Padova Aries2 Workshop on Muon Colliders – July 2018
- **Input document** submitted to ESPPU: "Muon Colliders" arXiv:1901.06150 December 2018 (*)
- Various workshop/meeting to prepare for Granada (2019) and during ESPPU

FINDINGS and RECCOMENDATIONS (*):
Set-up an international collaboration to promote muon colliders
And **organize the effort on the development of both accelerators and detectors**
and to define the road-map towards a CDR by the next Strategy update….
Carry out the R&D program toward the muon collider

EU Strategy → International Design Study

European Strategy Update – June 19, 2020:

3 High-priority future initiatives

High-priority future initiatives [..]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*;

European Large National Laboratories Directors Group (LDG) – July 2

LDG chaired by Lenny Rivkin

Agree to start building the collaboration for international muon collider design study

Accept the proposal of organisation

Accept the goals for the first phase

Daniel Schulte ad interim project leader

Strengthening cooperation and ensuring effective use complementary capabilities

Core team: N. Pastrone, L. Rivkin, D.Schulte

International Muon Collider Collaboration kick-off virtual meeting - July 3

(>250 participants) https://indico.cern.ch/event/930508/

Target Parameter Examples

M. Palmer: https://map.fnal.gov/

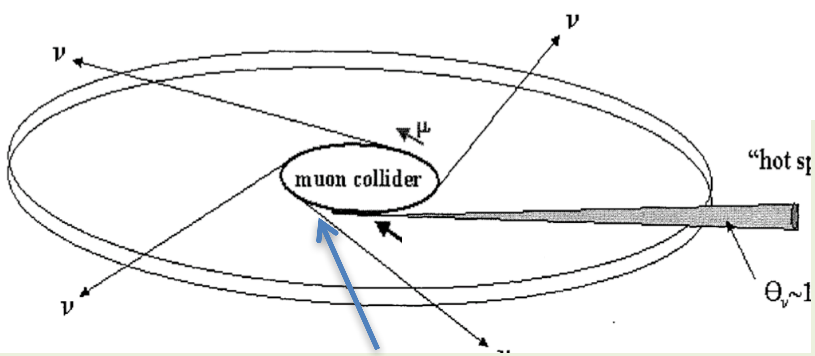
Muon Collider Parameters

		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Even at 6 TeV above target luminosity with reasonable power consumption
But have to confirm power consumption estimates

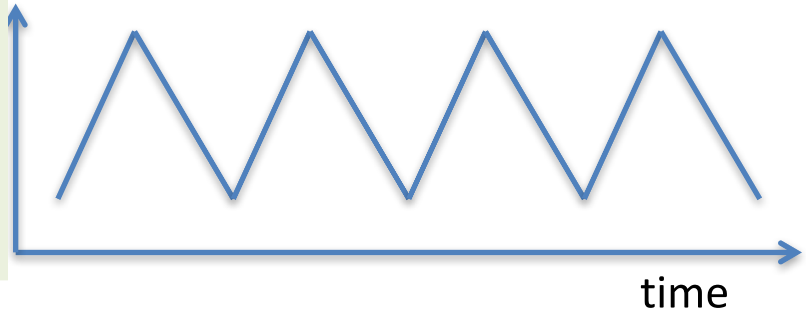
Example Neutrino Radiation Mitigation

Mitigation by varying beam orbit in collider is limited and costly (more space in magnets needed)

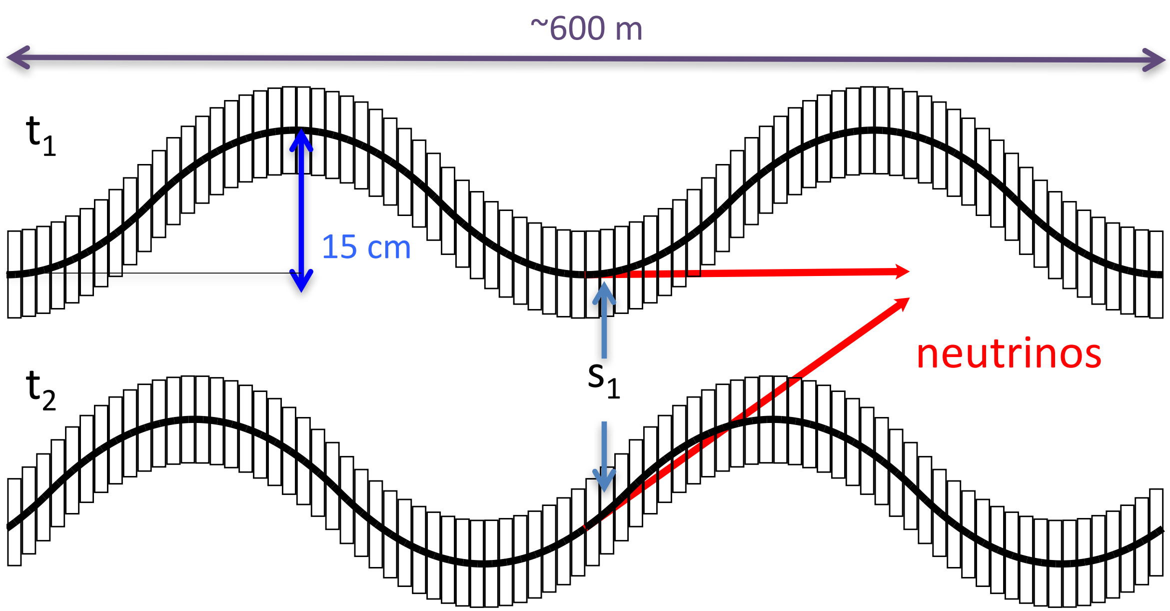


Relevant length of arc at s_1 is O(10 cm)

Vary vertical beam angle at s_1 in time



Move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

O(100) larger than decay cone
⇒ gain O(100) in radiation

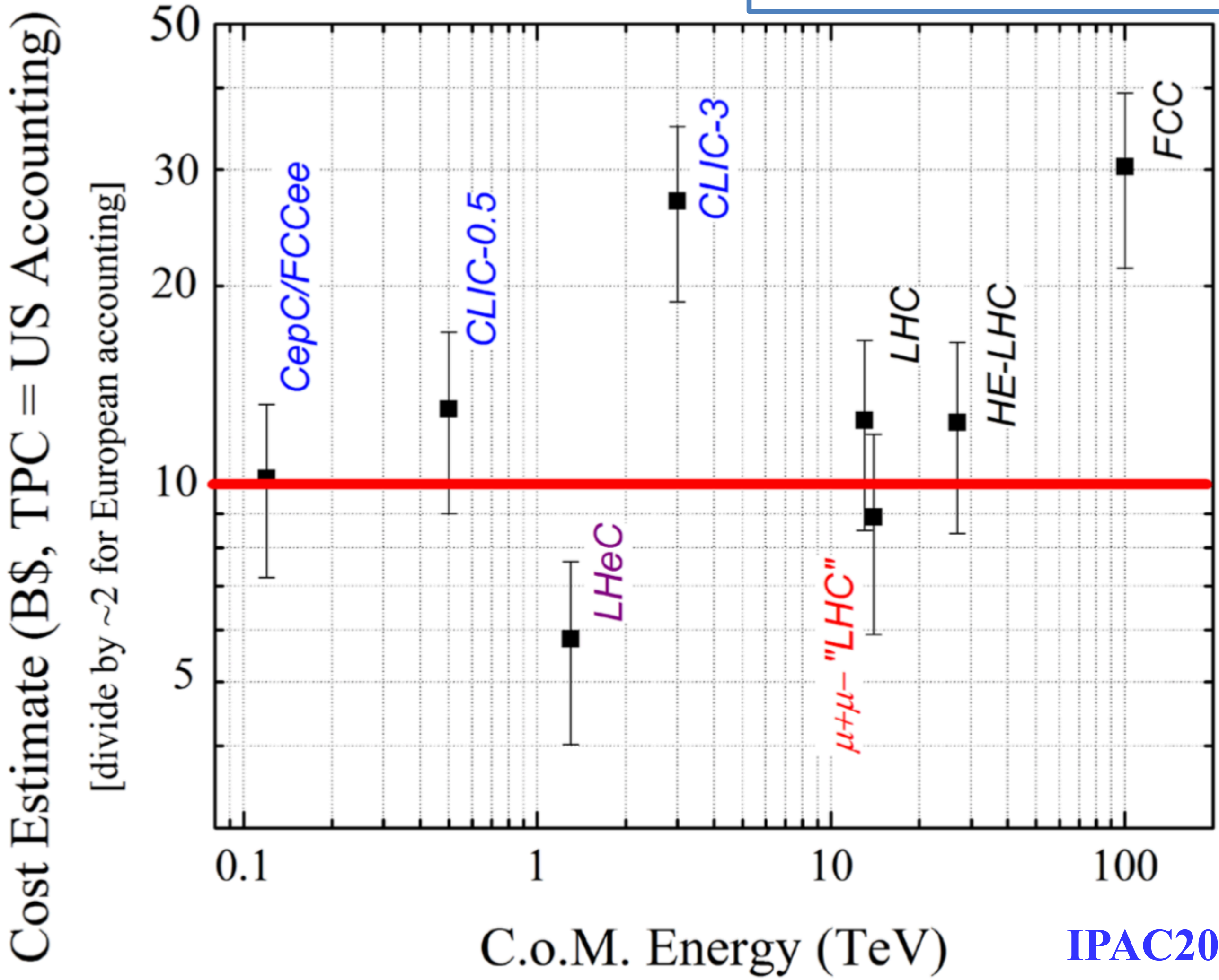
In straights, additional improvement in horizontal

Need to study impact on beam and operation, e.g. dispersion control

Cost estimate

NB: all $$ - "US Accounting" (divide by 2-2.4 at CERN)

Vladimir SHILTSEV,David NEUFFER (Fermilab)



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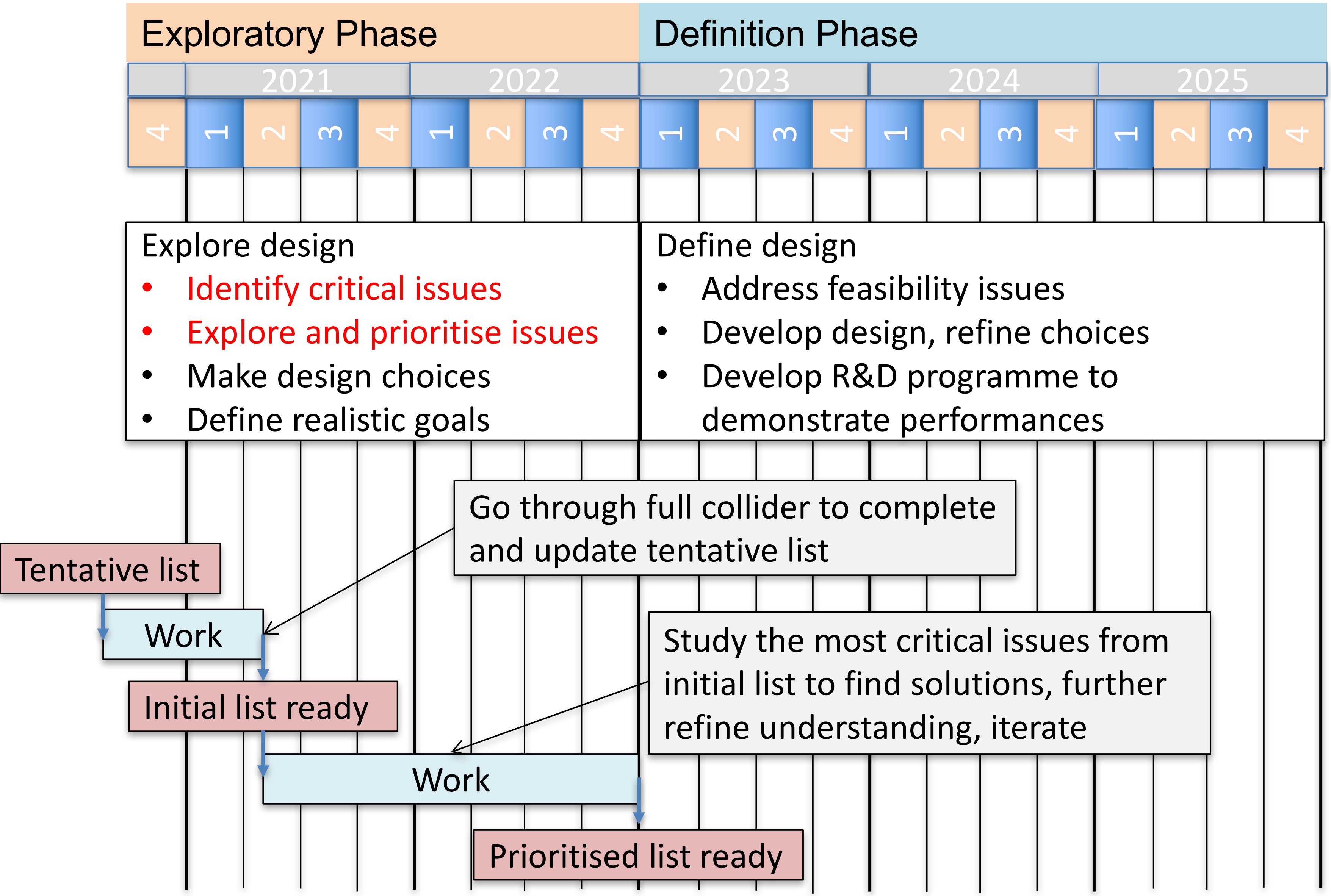
Tentative Roadmap



Physics at high energy

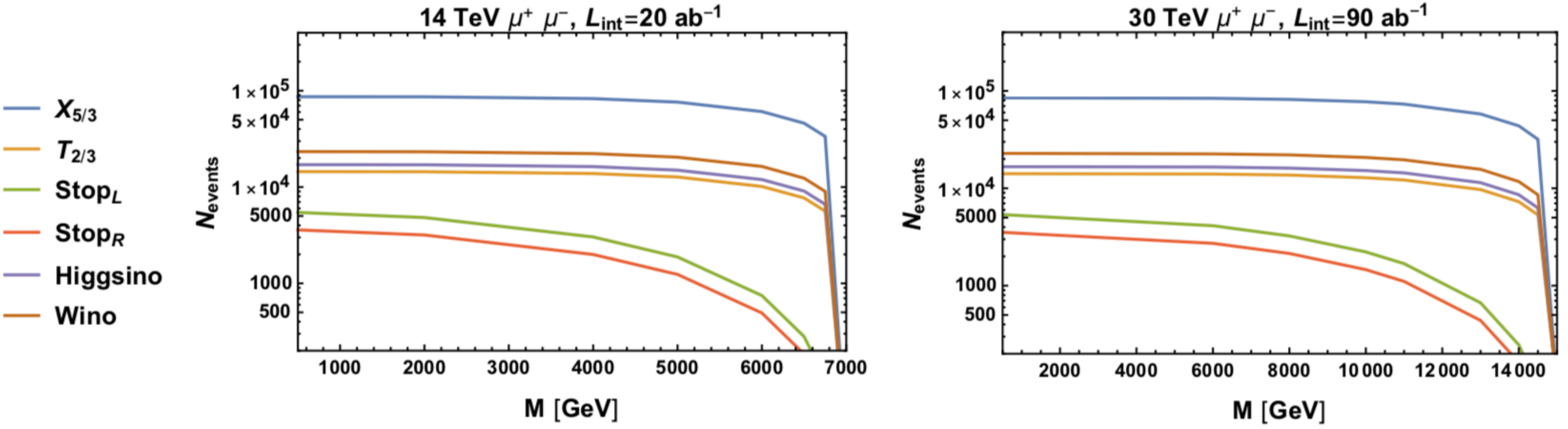
Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly

Direct Reach

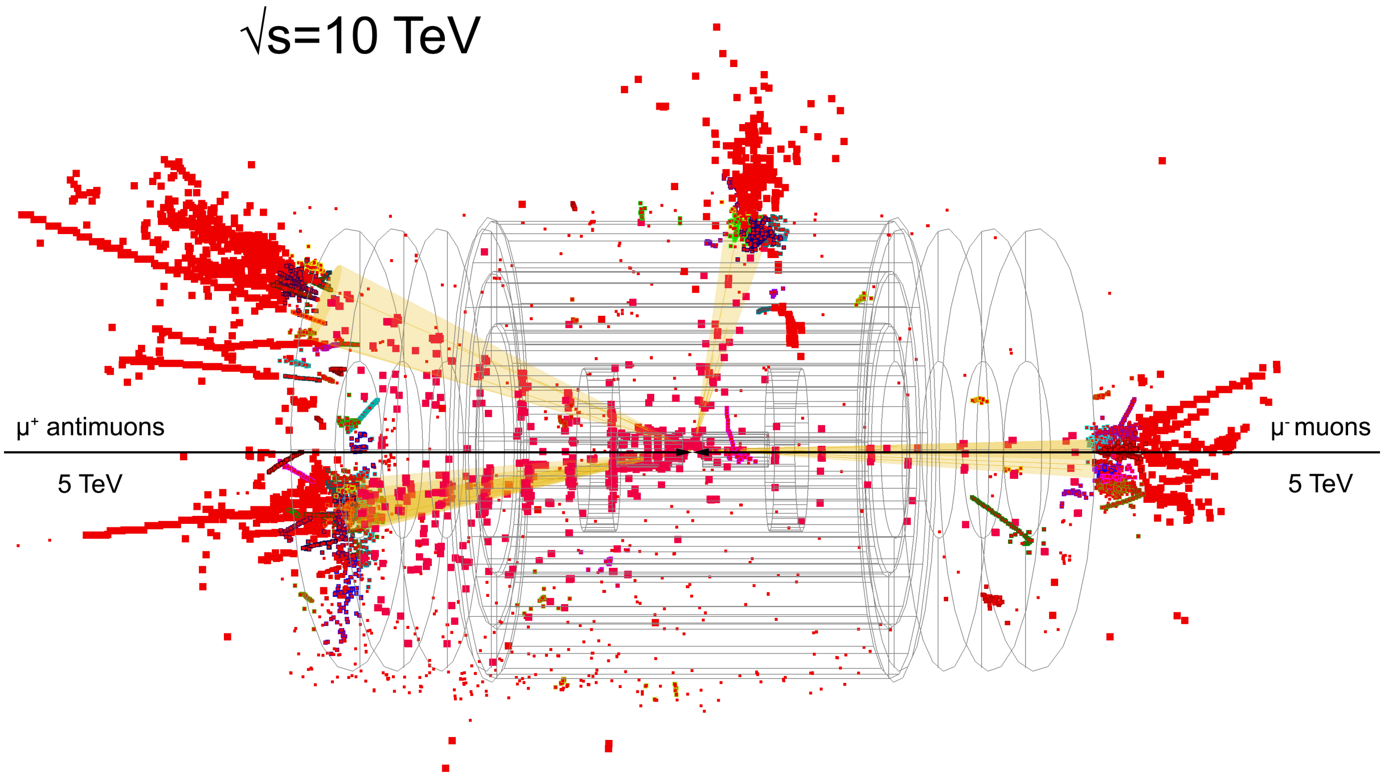
Andrea Wulzer

Discover **Generic EW** particles **up to mass threshold**

exotic (e.g., displaced) **or difficult** (e.g., compressed) decays to be studied

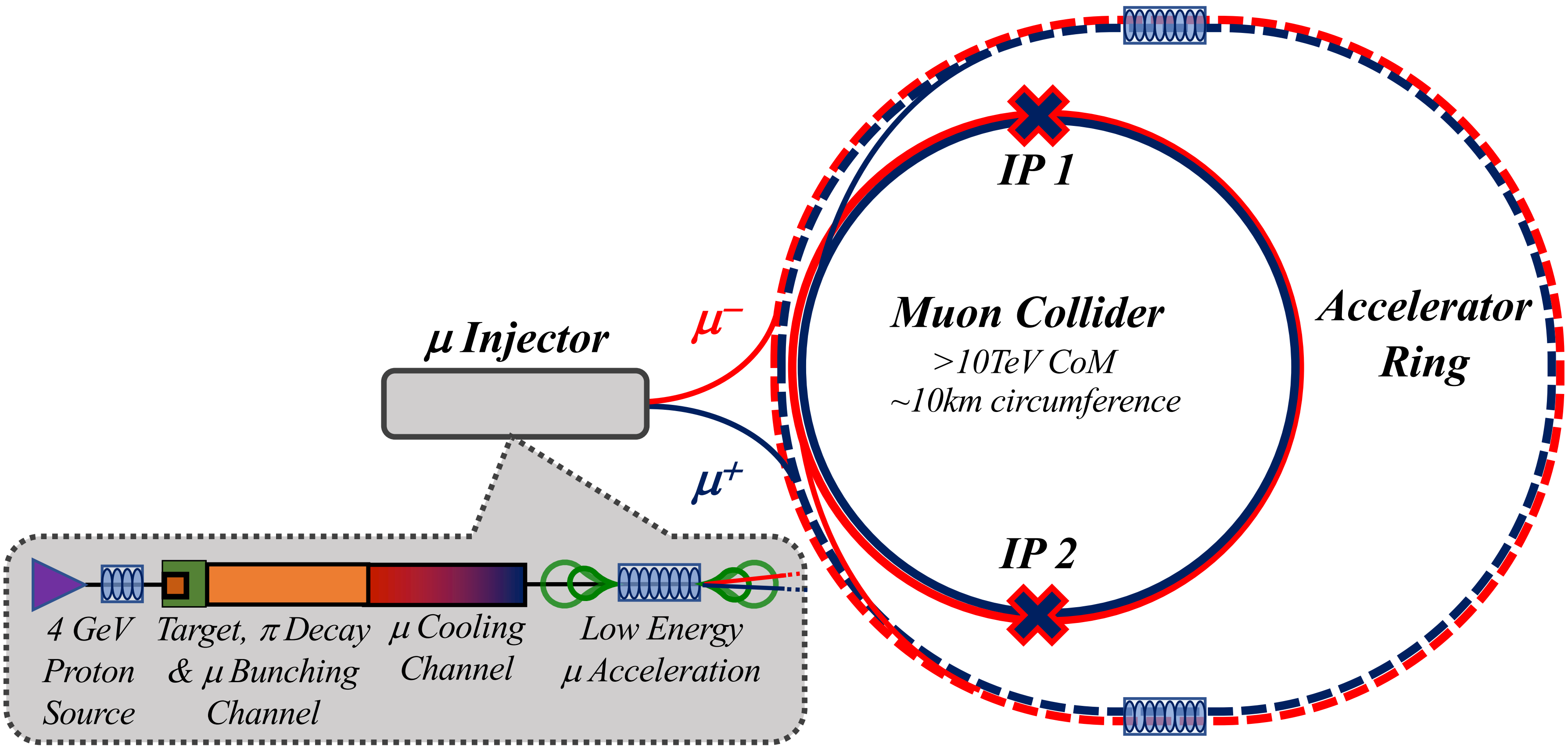


10 TeV $HH\nu\bar{\nu}$ event – no Beam Induced Background



$\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$

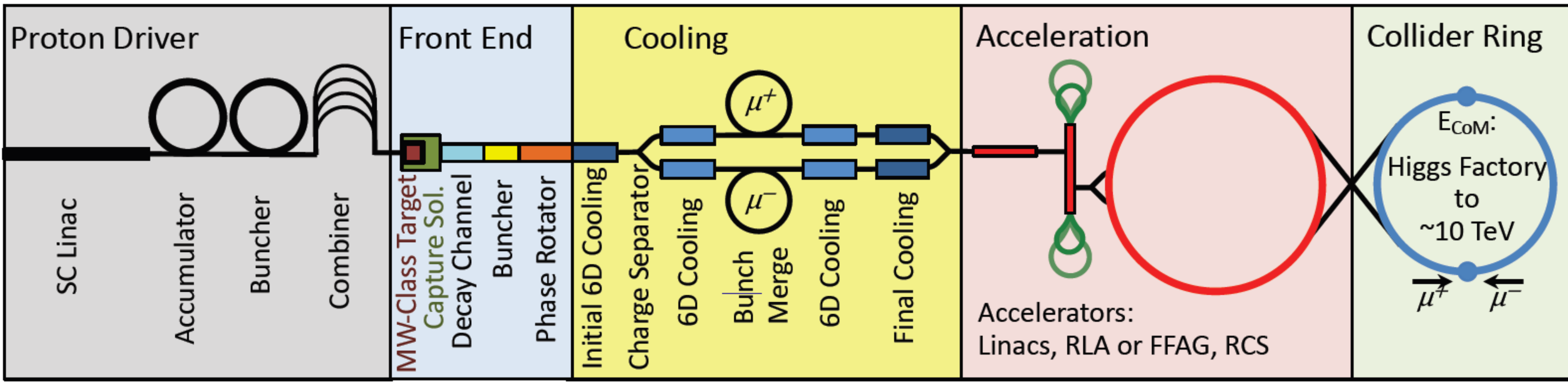
Sketch of the facility



Proton-driven Muon Collider Concept

US Muon Accelerator Program – MAP, launched in **2011,** wound down in **2014**

*MAP developed a **proton driver scheme** and addressed the feasibility of the novel technologies required for Muon Colliders and Neutrino Factories*



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled

Acceleration to collision energy

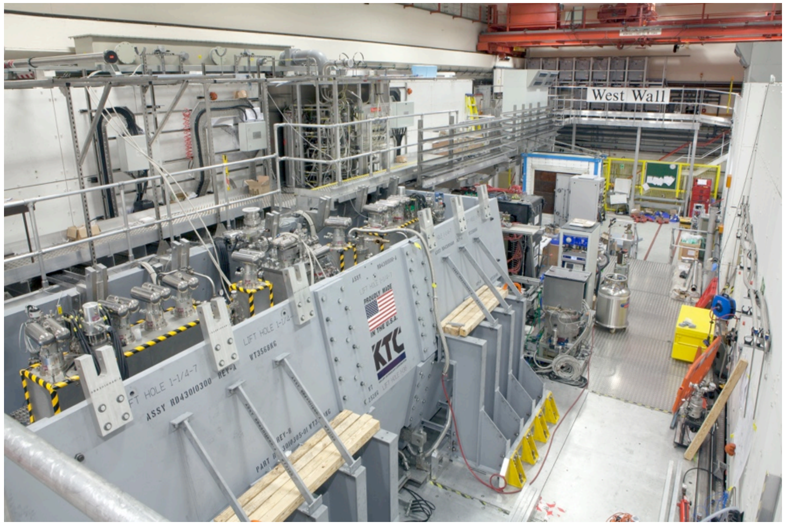
Collision

Pions decay into muons that can be captured

"Muon Accelerator for Particle Physics," JINST,
https://iopscience.iop.org/journal/1748-0221/page/extraproc46

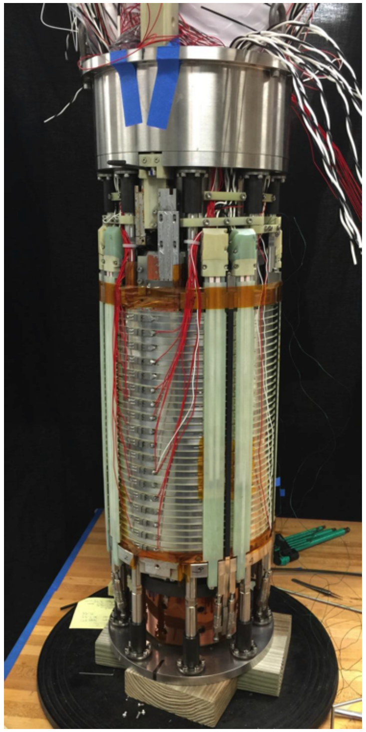
MAP R&D - design Status

MICE (UK)



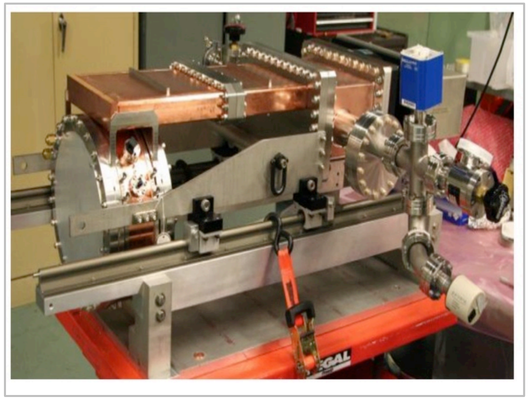
Key systems designed for 3 TeV in US
A number of key components has been developed
Cooling test performed according to theory

FNAL
HTS cables



NHFML
32 T solenoid with low-temperature HTS

MuCool: >50 MV/m in 5 T field



FNAL
12 T/s HTS - 0.6 T max

LEMMA: *LowEMittanceMuonAccelerator*

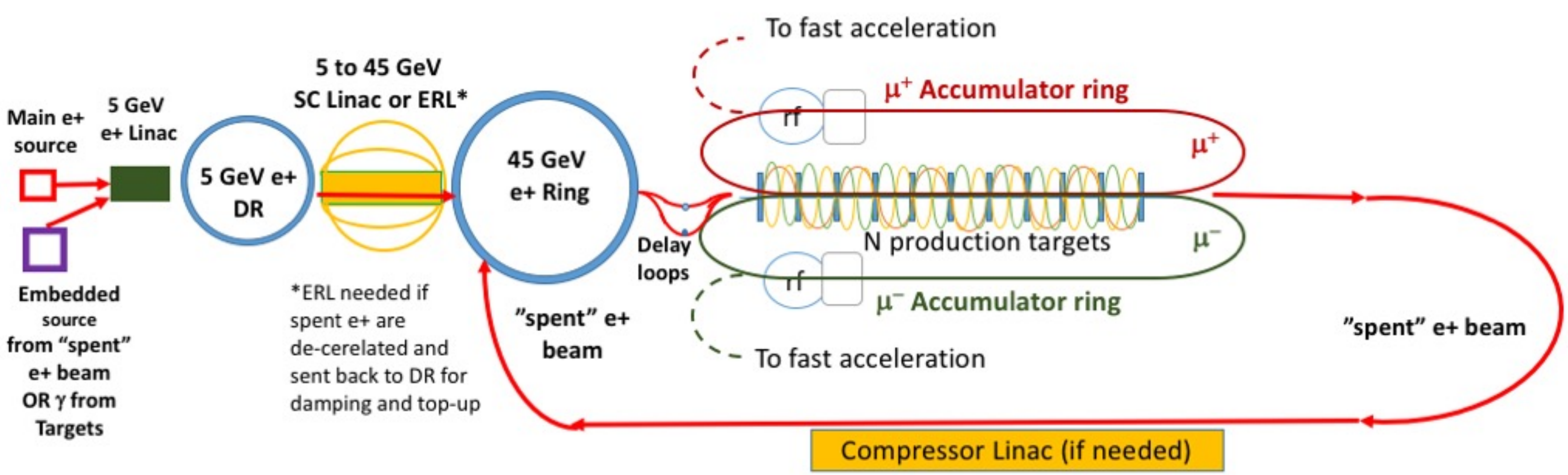
M. Antonelli and P. Raimondi, Snowmass Report (2013) - INFN-13-22/LNF Note

- Based on muons production from a 45 GeV positron beam annihilating with the electrons of a target close to threshold for pair creation
  - ➔ generating muon beams with low enough transverse emittance for a high energy collider
  - ➔ muon pair boost for post-production capture and emittance minimization, drastically reducing the source transverse emittance and, coupled with a collider nano-beam scheme
  - ➔ should allow reaching for the luminosity with a lower bunch intensity
- **Scheme under study**:
  - ➔ positron bunches extracted to impinge on multiple targets in a dedicated straight section
  - ➔ muons are then collected in two Accumulation Rings (AR) and stored until the muon bunch has a suitable number of particles.

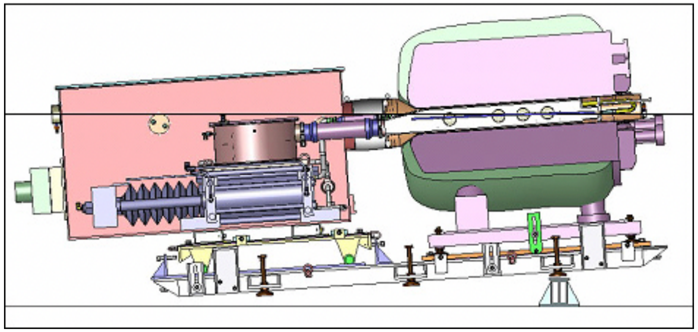
This scheme aims at releasing the impact of the average power on the targets and also reducing the number of positron needed from the source

LEMMA new scheme in brief

- Positron for first fill produced by Main **e$^+$ source** (MPS) and accelerated to 5 GeV for damping in a 5 GeV **Damping Ring** (DR)
- Acceleration to 45 GeV in SC Linac or ERL and storage of 1000 e$^+$ bunches in **Positron Ring** (PR)
- **Extraction of e$^+$ bunches** to one or more muon production lines, while produced **muons are accumulated in two AR** and a muon bunch is "built" by several passages through the targets, to be then delivered to the **fast acceleration chain**
- Re-injection and damping in the PR @45 GeV of the spent e$^+$ beam to save on the number of needed e$^+$, the MPS and a possible γ-embedded source will provide the refilling of lost e$^+$ Other option: send e$^+$ back to DR (through decelerating ERL) for damping and top-up

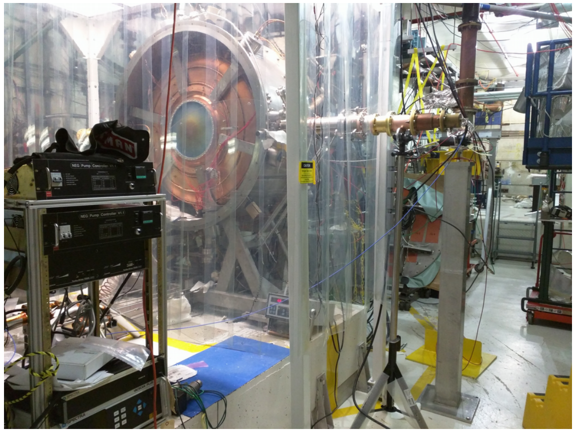


International R&D program



MERIT - CERN

Demonstrated principle of liquid Mercury jet target

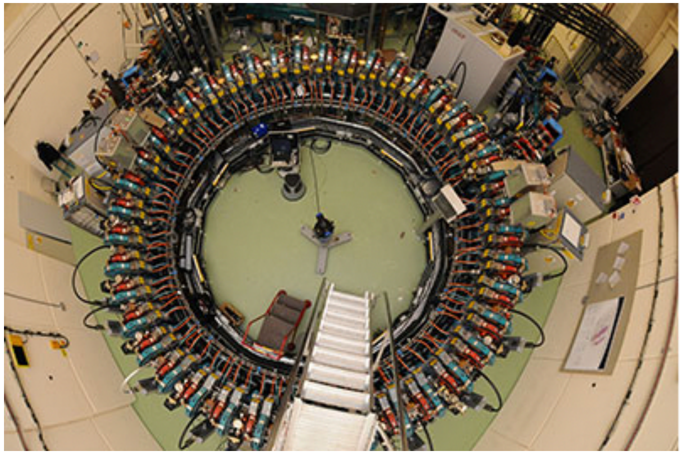


MuCool Test Area - FNAL

Demonstrated operation of RF cavities in strong B fields

EMMA - STFC Daresbury Laboratory

Showed rapid acceleration in non-scaling FFA



MICE - RAL

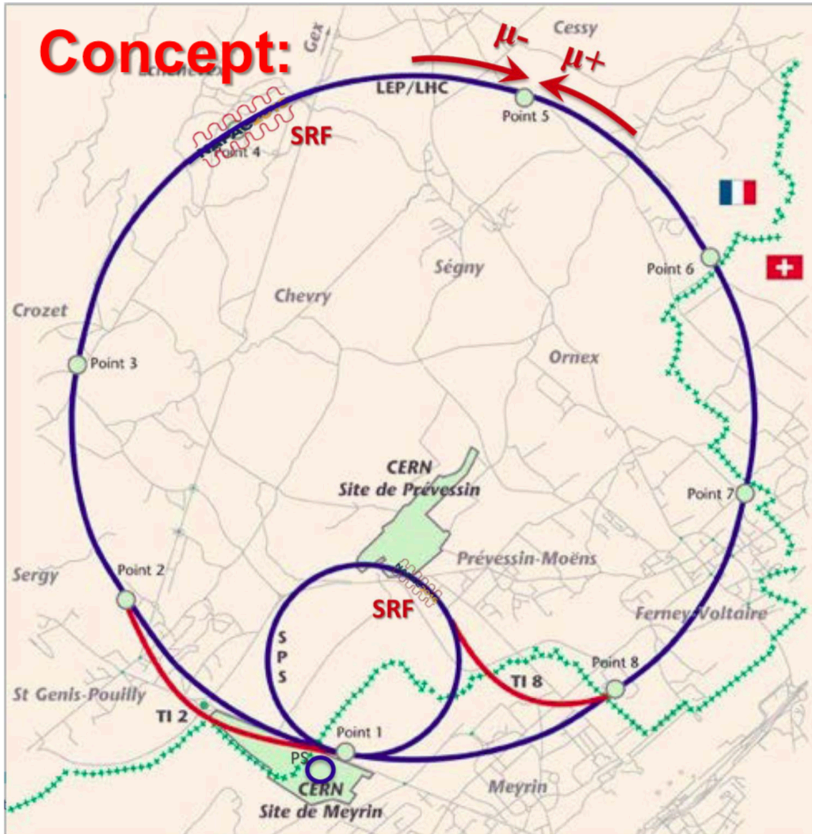
Demonstrate ionization cooling principle

Increase inherent beam brightness

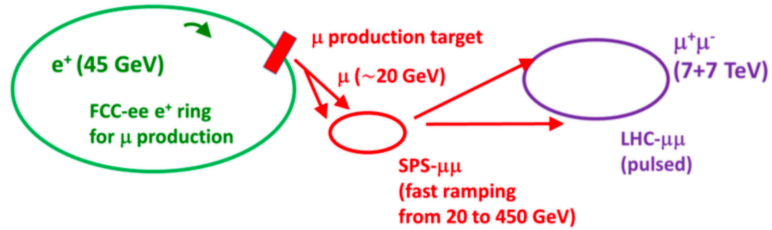
→ number of particles in the beam core

“Amplitude”

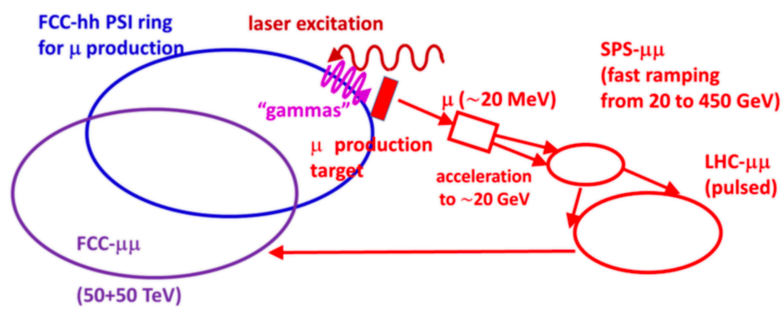
Dream or possibility?



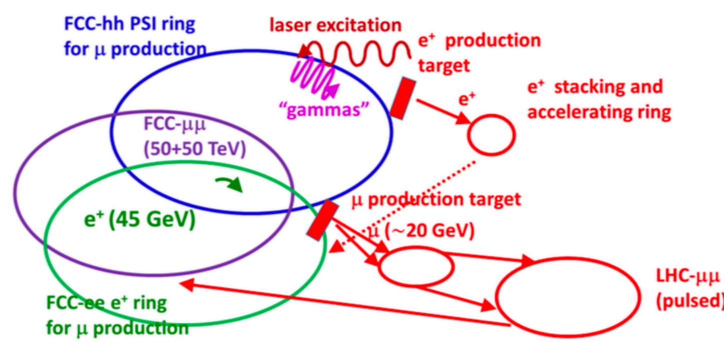
14 TeV μ collider LHC-μμ with FCC-ee $\mu^\pm$ production



100 TeV μ collider FCC-μμ with FCC-hh PSI $\mu^\pm$ production



100 TeV μ collider FCC-μμ with FCC-hh PSI e^+
& FCC-ee $\mu^\pm$ production



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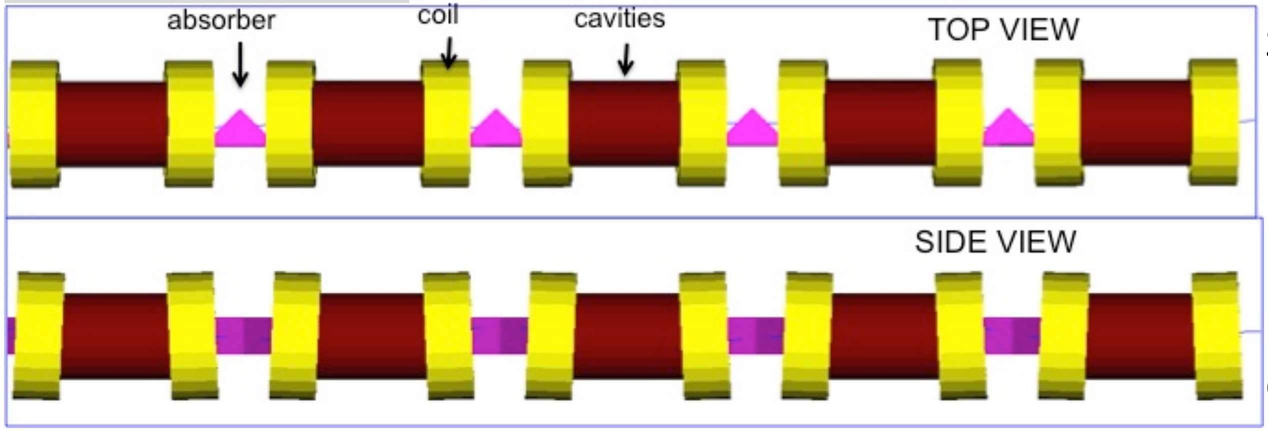
Cooling Concept

MAP collaboration

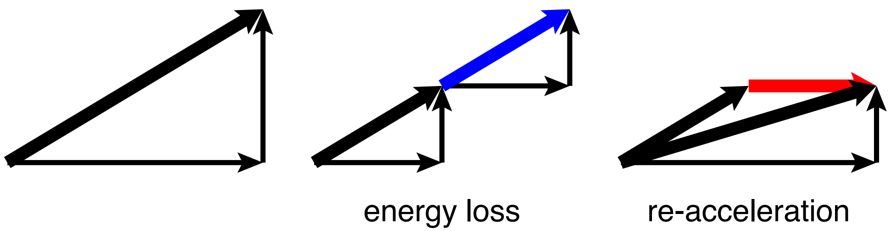


Superconducting solenoids

High-field normal conducting RF

Liquid hydrogen targets

Compact design



$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Tentative Considerations on Baseline

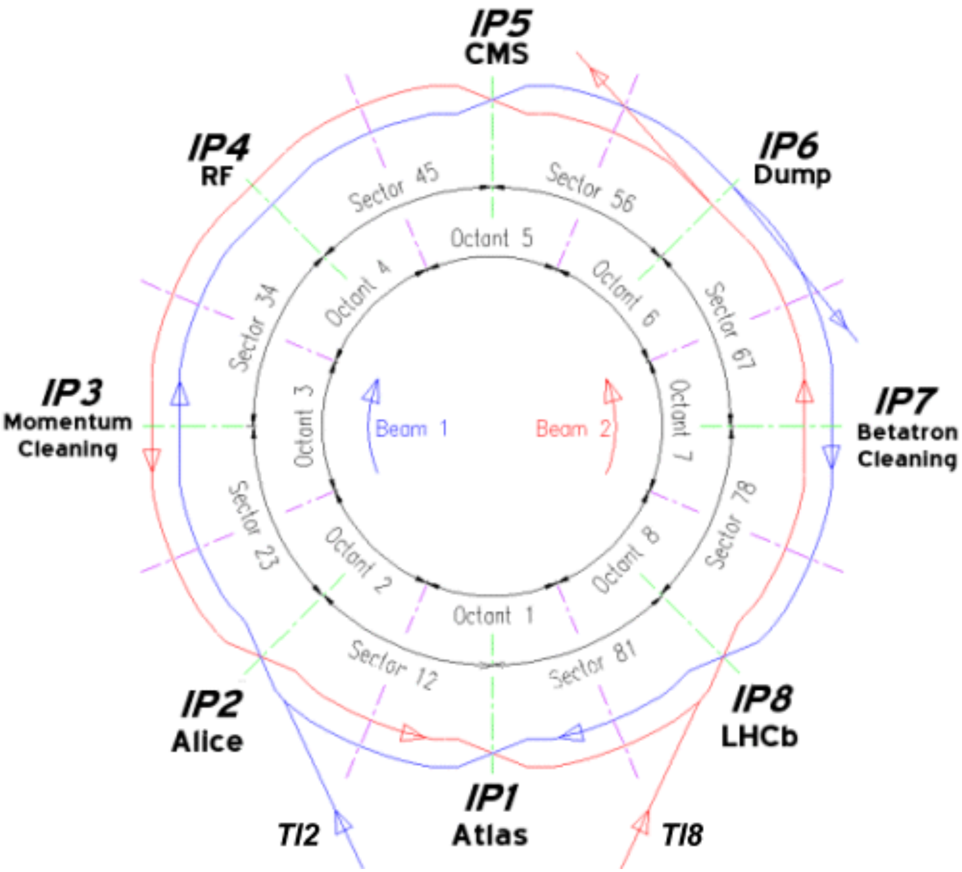
- **Focus on first stage with energy of O(1.5 + 1.5 = 3 TeV)**
  - To come after higgs factory and matching highest CLIC energy
  - Using the high-energy strength of muon colliders
  - Realistic design for implementation at CERN, with cost power and risk scale
  - If successful, feasibility demonstration for CDR

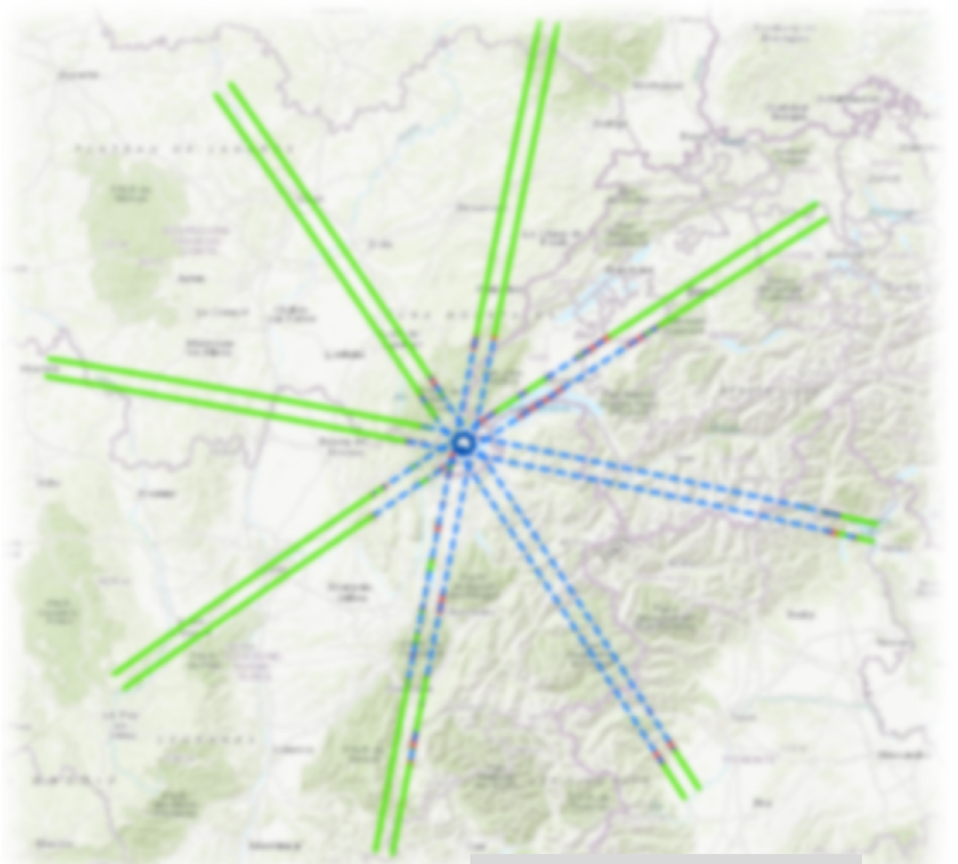
- **Explore 14 TeV as further step**
  - To match FCC-hh discovery potential
  - Mainly exploration of parameters to guide choices
  - Provide evidence for feasibility, maybe cost frame

- **Some exploration of lower energies / Higgs factory**
  - Scaling from higher energies
  - Not a main focus, except if other projects do not cover lower energies

- Open for input

Effective Depth of LHC





J. Osborn, Y. Robert, …

Minimum distance is 17 km, corresponds to effective depth of d = 23 m
Second shortest is 25 km (d = 50 m), longest is 263 km (d = 5430 m)

Review Conclusion

We think we can answer the following questions

- **Can muon colliders at this moment be considered for the next project?**
    - Enormous progress in the proton driven scheme and new ideas emerged
    - But at this moment not mature enough for a proposal

- **Is it worthwhile to do muon collider R&D?**
    - Yes, it promises the potential to go to very high energy
    - It may be the best option for very high lepton collider energies, beyond 3 TeV
    - It has strong synergies with other projects, e.g. magnet and RF development
    - Has synergies with other physics experiments
    - Should not miss this opportunity

- **What needs to be done?**
    - Muon production and cooling is key => A new test facility is required.
    - A conceptual design of the collider has to be made
    - Many components need R&D, e.g. fast ramping magnets, background in the detector
    - Site-dependent studies to understand if existing infrastructure can be used
        - limitations of existing tunnels, e.g. radiation issues
        - optimum use of existing accelerators, e.g. as proton source

Note: Total Power Consumption

Power consumption estimates are based on a table calculated by R. Palmer
- Leaves out a number of components, e.g. magnets
- Quote: “These numbers are preliminary, with large uncertainties”

J.-P. Delahaye added a constant value

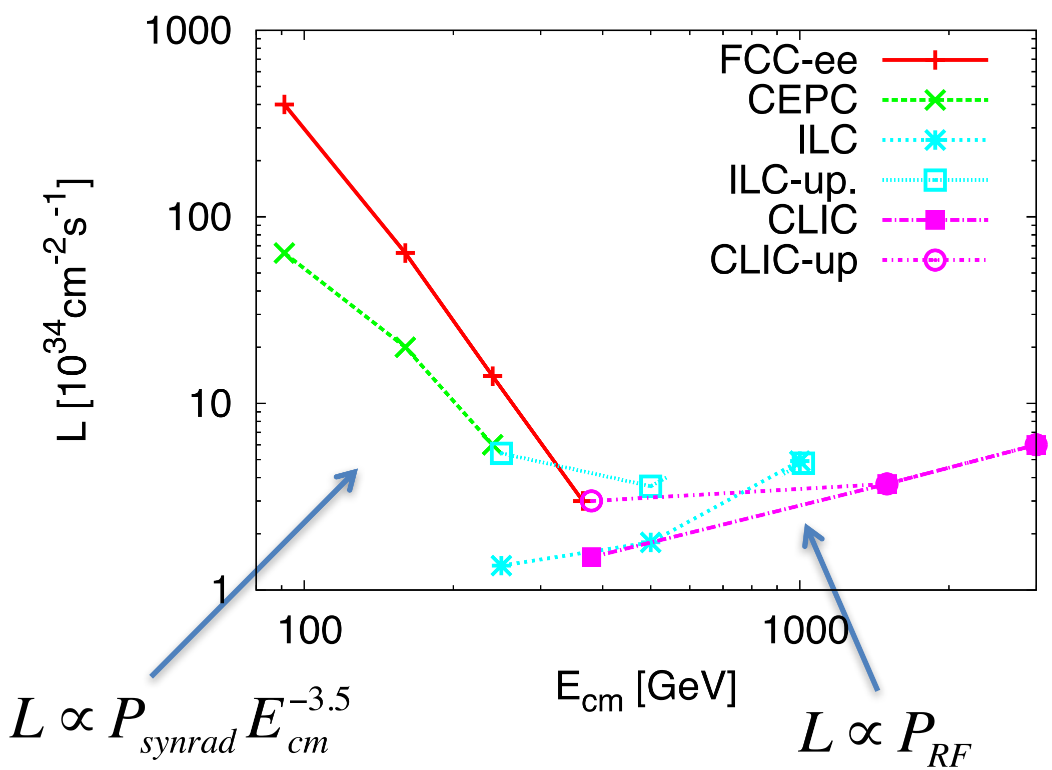
Table 2. Estimated collider wall power requirements for 1.5 TeV center of mass; this does not include detectors, buildings, air conditioning, etc. ‘PS’ refers to Power Supplies, ‘4 K’ and ‘20 K’ refer to cryogenic power to cool elements to these temperatures.

	Length	Static	Dynamic	—	—	—	Total
		4° K	rf	PS	4° K	20° K	
	m	MW	MW	MW	MW	MW	MW
Proton driver (SC linac)							(20)
Target and taper	16			15.0	0.4		15.4
Decay and phase rot	95	0.1	0.8		4.5		5.4
Charge separation	14						
6D cooling before merging	222	0.6	7.2		6.8	6.1	20.7
Merging	115	0.2	1.4				1.6
6D cooling after merging	428	0.7	2.8			2.6	6.1
Final 4D cooling	78	0.1	1.5			0.1	1.7
NC rf acceleration	104	0.1	4.1				4.2
SC rf linac	140	0.1	3.4				3.5
SC rf RLAs	10,400	9.1	19.5				28.6
SC rf RCSs	12,566	11.3	11.8				23.1
Collider ring	2600	2.3		3.0	10		15.3
Total	26	24.6	52.5	18.0	21.7	8.8	145.6

Need to have conceptual start-to-end design to estimate power correctly
Efficiency of wall plug to beam is not very different from CLIC

Proposed Lepton Colliders (Granada)

Luminosity per facility



CLIC can reach 3 TeV

- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy

But is it affordable?

R&D required towards higher energies (or improvement of 3 TeV)
- Reduction of cost per GeV (improved NC acceleration, novel acceleration technologies
- Improved power consumption (higher RF to beam efficiency, higher beam quality)

Few Preliminary Results

A. Wulzer et al.

Higgs 3-linear coupling: **δκλ=(5%, 3.8%, 1.6%) for E = (10, 14, 30) TeV**

[2008.12204; 2005.10289; Buttazzo, Franceschini, Wulzer, to appear]

[FCC reach is from 3.5 to 8.1% depending on systematics assumptions]

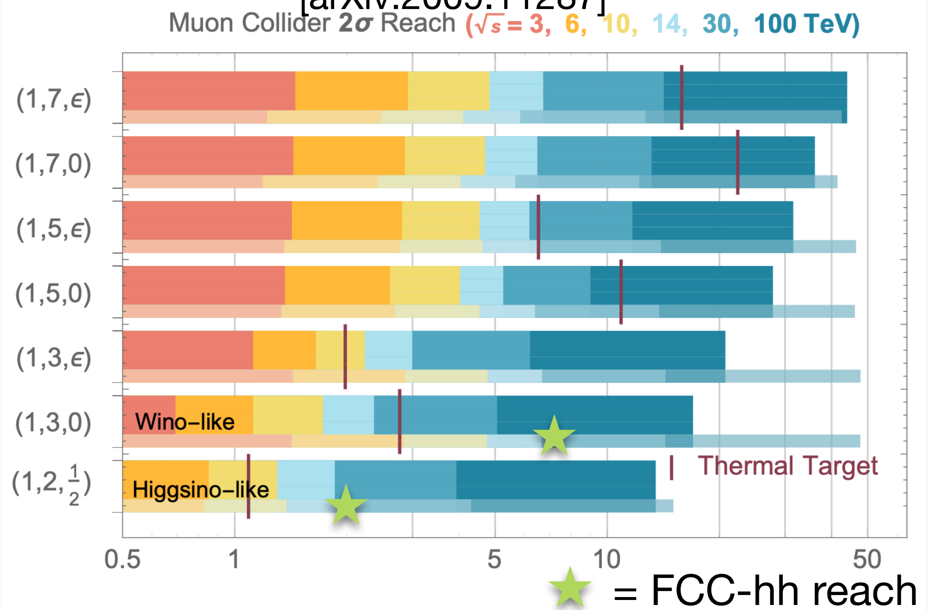
Higgs compositeness scale: **(38, 53, 115) TeV for E = (10, 14, 30) TeV**

[Buttazzo, Franceschini, Wulzer, to appear]

[other F.C.: from 20 to 40 TeV depending on model]

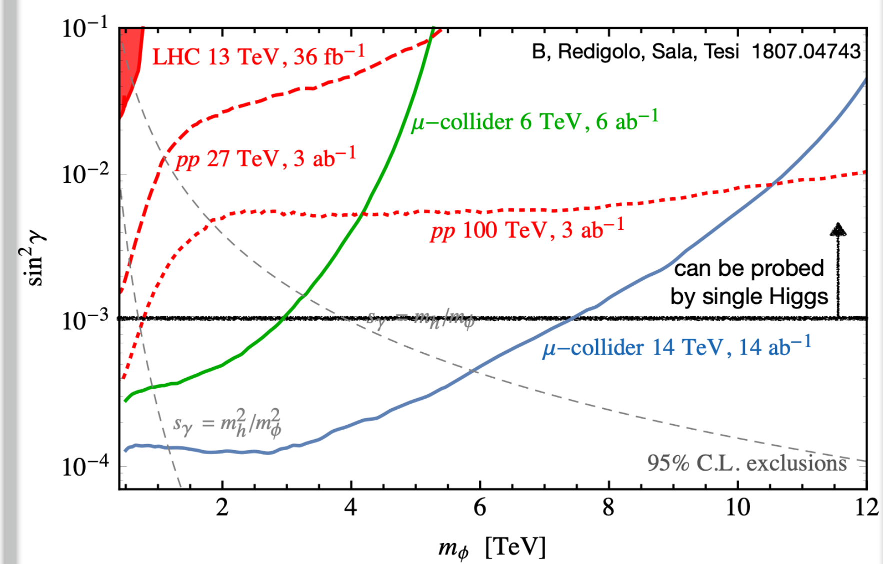
WIMP DM

[arXiv:2009.11287]



= FCC-hh reach

Scalar Singlet



MAP Budget/Effort Overview

Mark Palmer

- Overview of FY12-FY17
  - Full program in FY12-14 (funding includes fully burdened labor)
  - Ramp-down with focus on MICE completion during FY15-17

	FY12	FY13	FY14	FY15	FY16	FY17
US Funding (M$)	12.0	11.8	12.7	9.0	6.0	1.0

Snapshot of Effort Distribution During "full" program operation in FY13

- 23 Institutions Participating
- ~45 FTEs

Reduced scope of effort