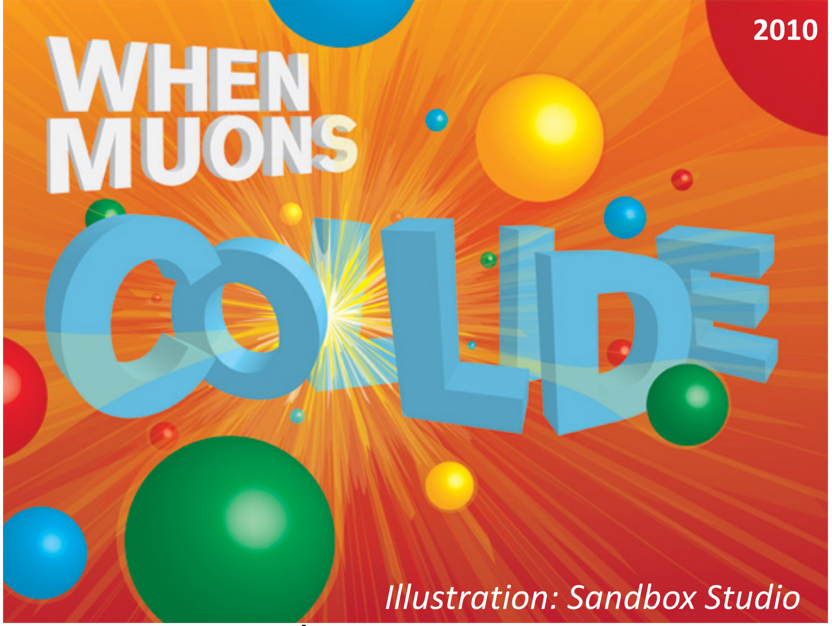


www.symmetrymagazine.org

PAUL SCHERRER INSTITUT

PSI

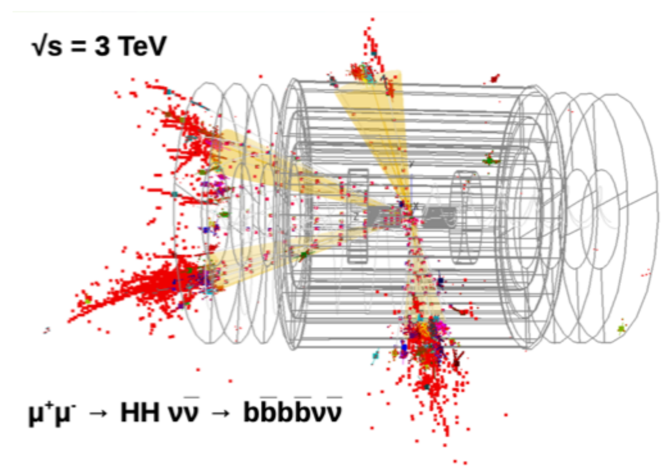
PSI/LTP Thursday Colloquium

May 6, 2021

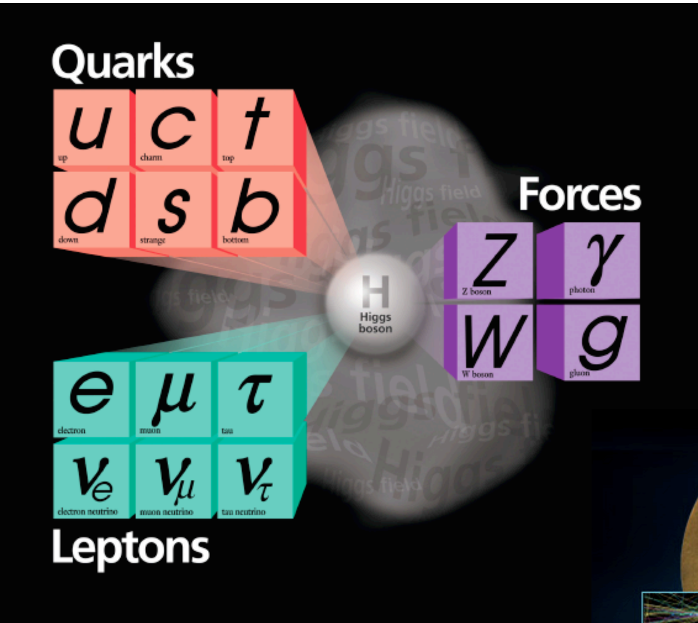
Muon Colliders: a challenging opportunity

Nadia Pastrone

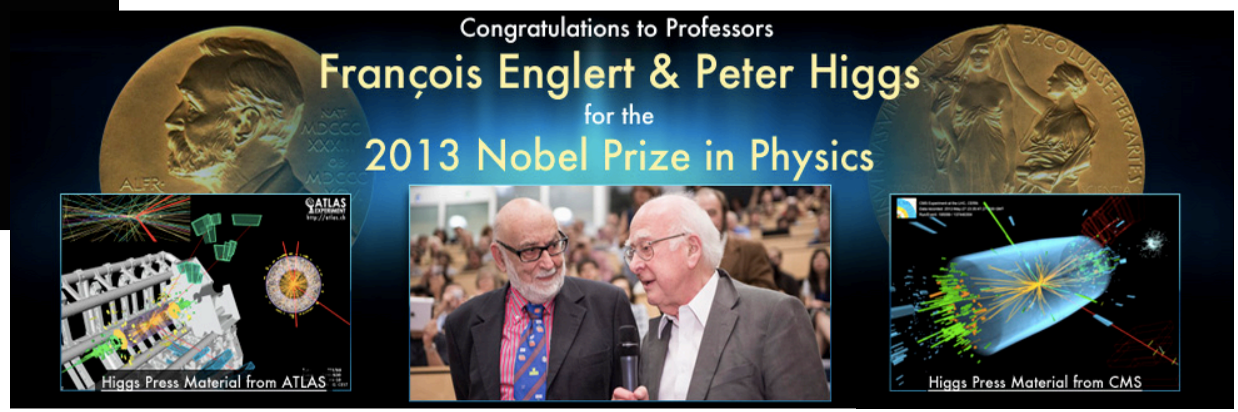
INFN TORINO



Standard Model of Particle Physics



- **Extremely precise measurements and confirmation of Standard Model (SM)**
- **No signal of Beyond Standard Model evidence or SUSY**



"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

- **Precision measurements of Higgs boson production and couplings @ LHC and HL-LHC**

Many open questions

- **Data driven:**
  - What is the nature of DM?
  - What's the origin of neutrino masses?
  - What's the origin of the matter-antimatter asymmetry?
  - What is the Dark energy?

  ...

- **Theory driven:**
  - What kind of unification may exist?
  - What is the origin of flavour?
  - Is there a deeper reason for gauge symmetry?

  .....

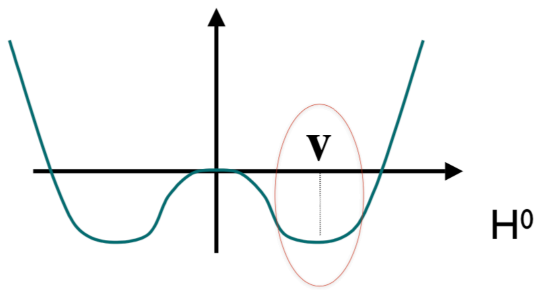
For none of the open questions, the path to an answer is unambiguously defined

However, the questions emerging in stronger and stronger terms from the LHC, appear to single out a unique well defined direction to explore ....

Is it the SM Higgs? Is it the only one?

Why is there EWSB? What sets the scale?

Question to the future colliders



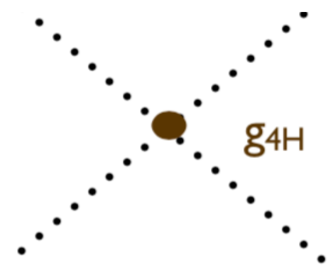
$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

$$v = (\sqrt{2}G_F)^{-1/2} \sim 246\ \text{GeV}$$

$$\mu = m_H \qquad \lambda = \frac{m_H^2}{2v^2}$$

$$g_{3H} \Rightarrow 4\lambda v = \frac{2m_H^2}{v}$$



$$g_{4H} \Rightarrow \lambda = \frac{m_H^2}{2v^2}$$

The relations between Higgs self-couplings, m_H and v
entirely depend on the functional form of the Higgs potential
Their measurement is an important test of the SM nature of the Higgs mechanism

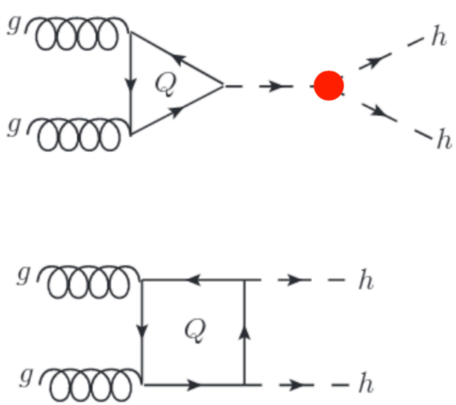
Double Higgs production

[Higgs Boson Studies at Future Particle Colliders]

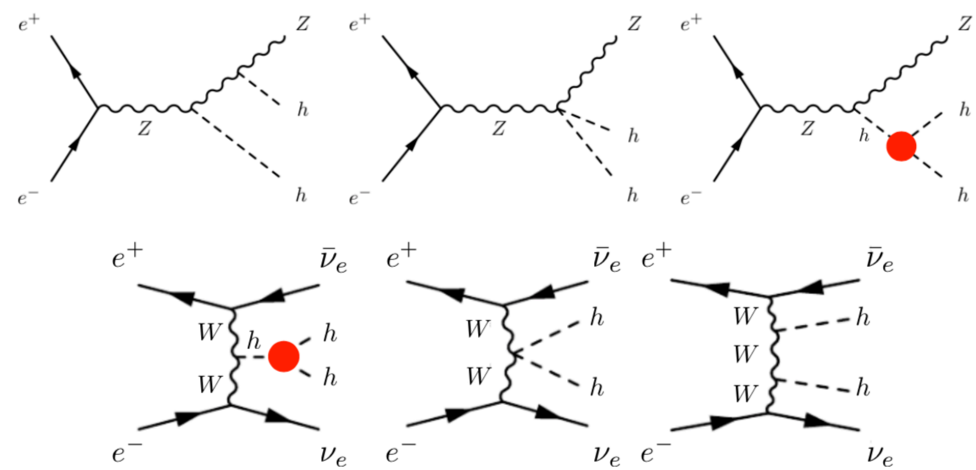
The *measurement* of the Higgs potential is a high priority goal on the physics programme of all future colliders

$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4 \quad \text{with} \quad \lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$

Hadron collider



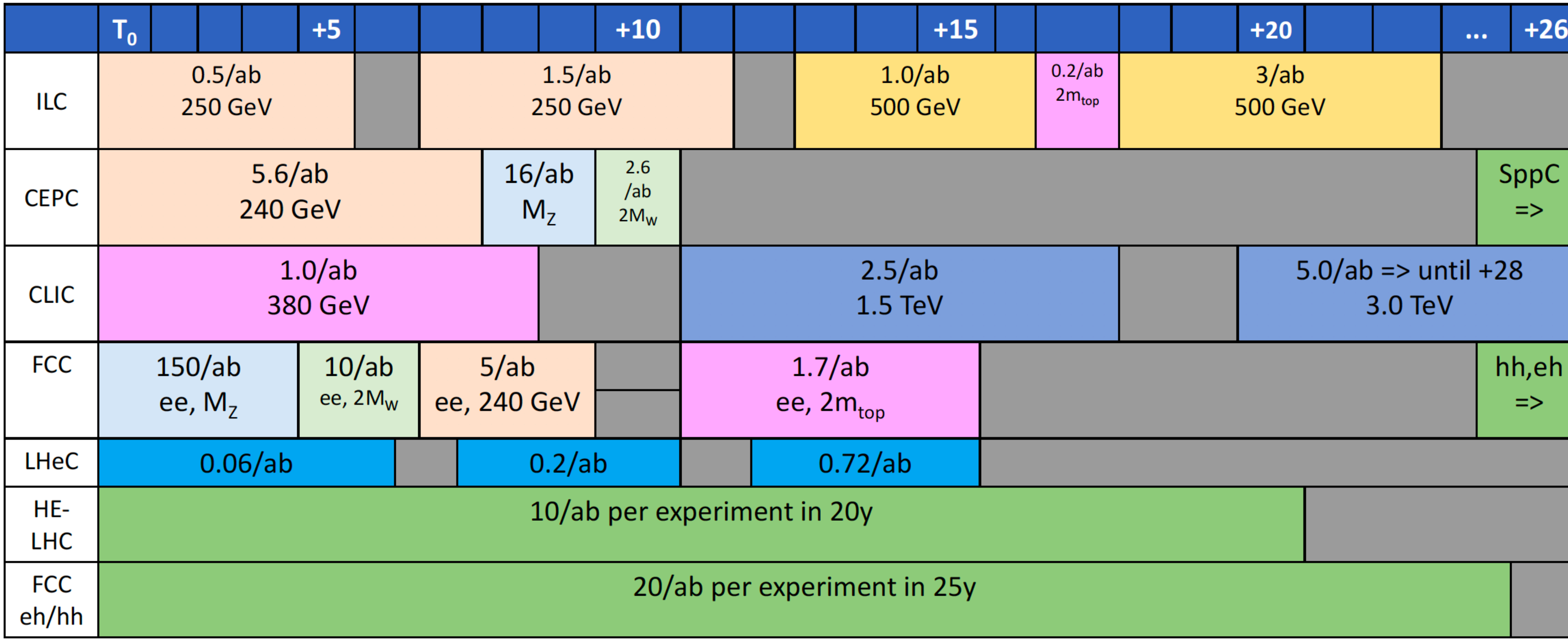
Lepton collider



Extracting the value of the Higgs self-coupling, in red, requires a knowledge of the other Higgs couplings that also contribute to the same process

Proposed schedule

Open Symposium May 13-16 2019

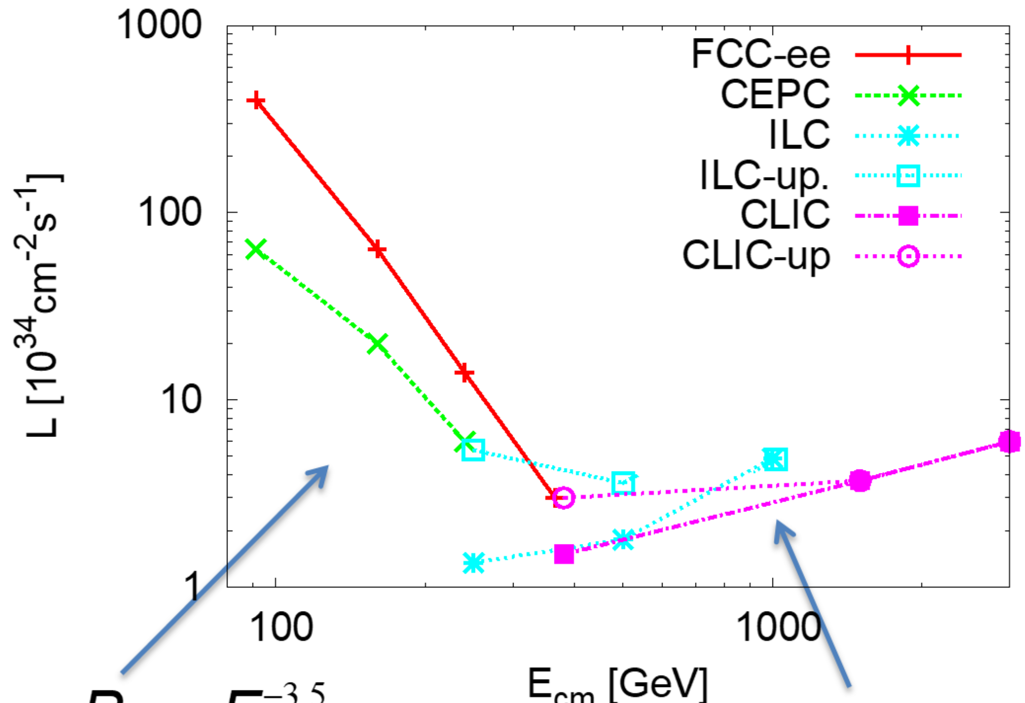


Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

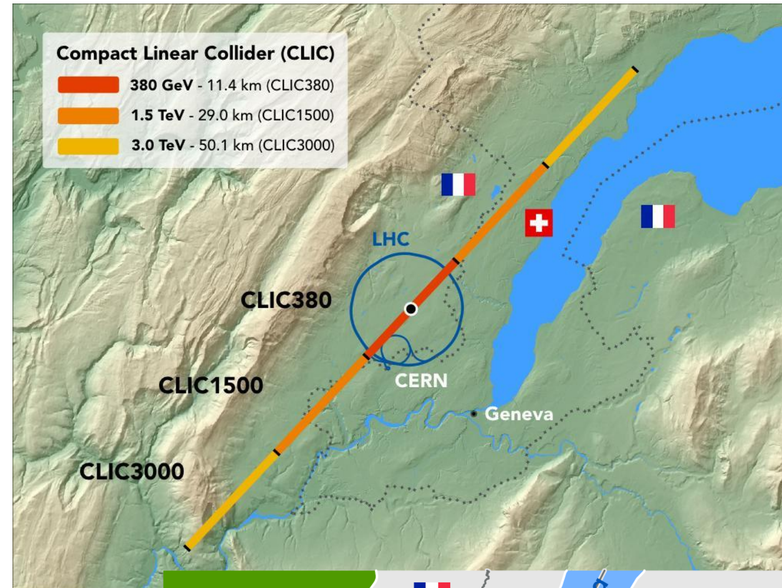
Linear vs Circular lepton collider

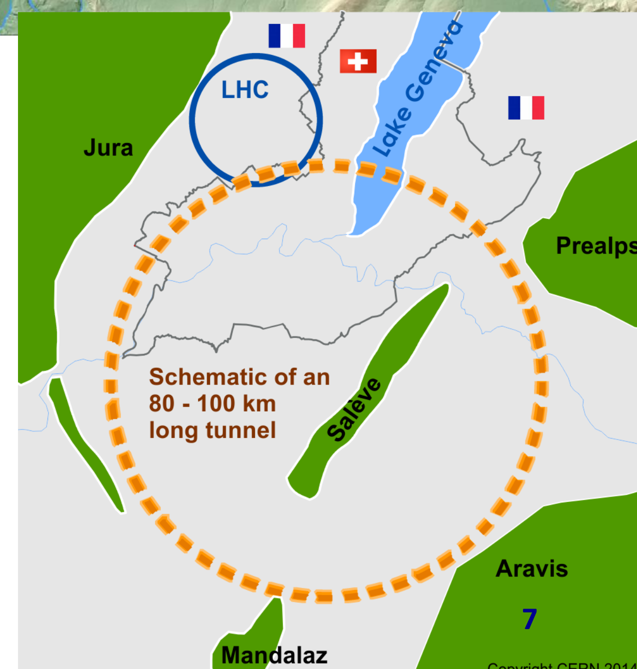
Luminosity per facility



$$L \propto P_{synrad} E_{cm}^{-3.5}$$

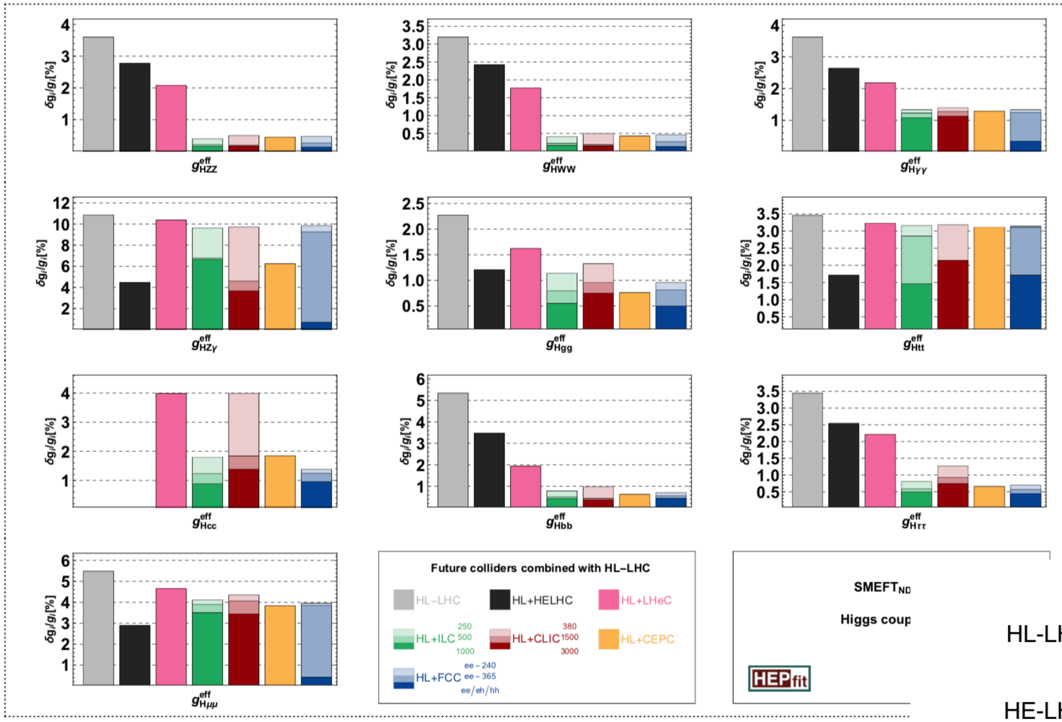
$$L \propto P_{RF} E_{cm}$$





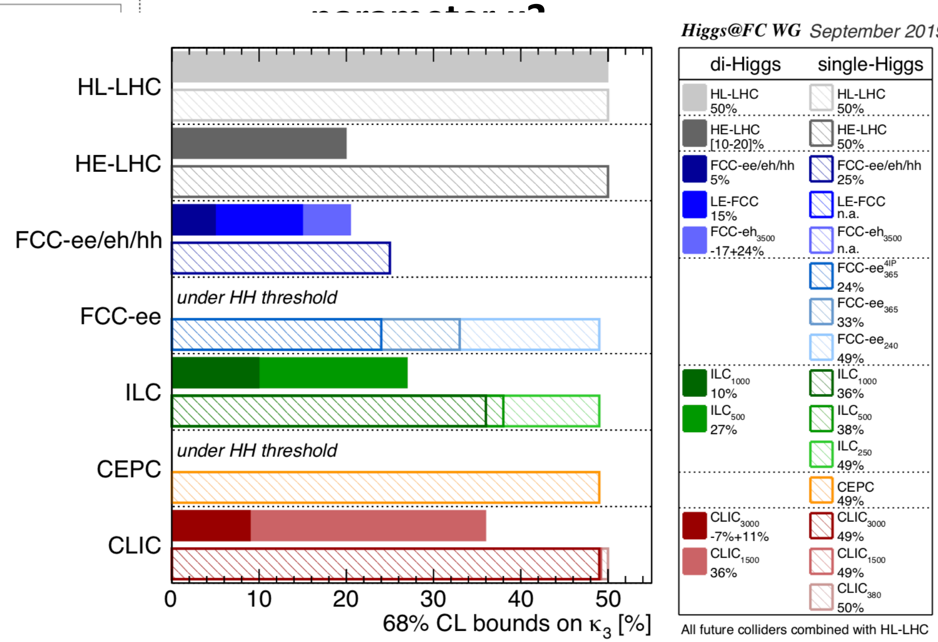
Higgs @ future colliders

[Physics Briefing Book](#)



One of the goal of future colliders is the measurement of Higgs couplings with SM particles with precision below the 1% precision scale.

Sensitivity at 68% probability on the Higgs self-coupling



68% probability reach on Higgs couplings from Global fit SMEFTND

What is the role of a Muon Collider?

A brief history of muon colliders

(A wholly incomplete timeline)

1968
F. Tikhonin
"On the effects at colliding μ meson beams"

1969
G.I. Budker
"Accelerators and colliding beams"

1979
D. Neuffer
"Colliding Muon Beams at 90 GeV"

1981
Skrinsky, Parkhomchuk
"Methods of cooling beams of charged particles"

1995
Barger, Berger, Gunion, Han
"s channel Higgs boson production at a muon muon collider"

2001-
Muon Ionization Cooling Experiment (MICE)

2010-2017
Muon Accelerator Program (MAP)

2015
Antonelli et al.
"Novel proposal for a low emittance muon beam using positron beam on target"
Low Emittance Muon Accelerator (LEMMA) proposal

2019
Input to European Strategy Update

2020-
International Muon Collider Collaboration

2021-
Muon Collider Forum (Snowmass 2021)

Outline

- ✓ A powerful tool for HEP exploration: discoveries and precise measurements
- ✓ Many challenges:
  - to explore an uncharted territory for theory at 10 TeV and over
  - to define a baseline facility design with key issues, risks and costs drivers
  - to design a system (accelerator+detector) able to meet physics requirements
  - to study and develop new technologies for machine and detectors
  - to define key R&Ds in synergies with other projects
- ✓ The international Design Study and the US SnowMass effort
- ✓ Future plans

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

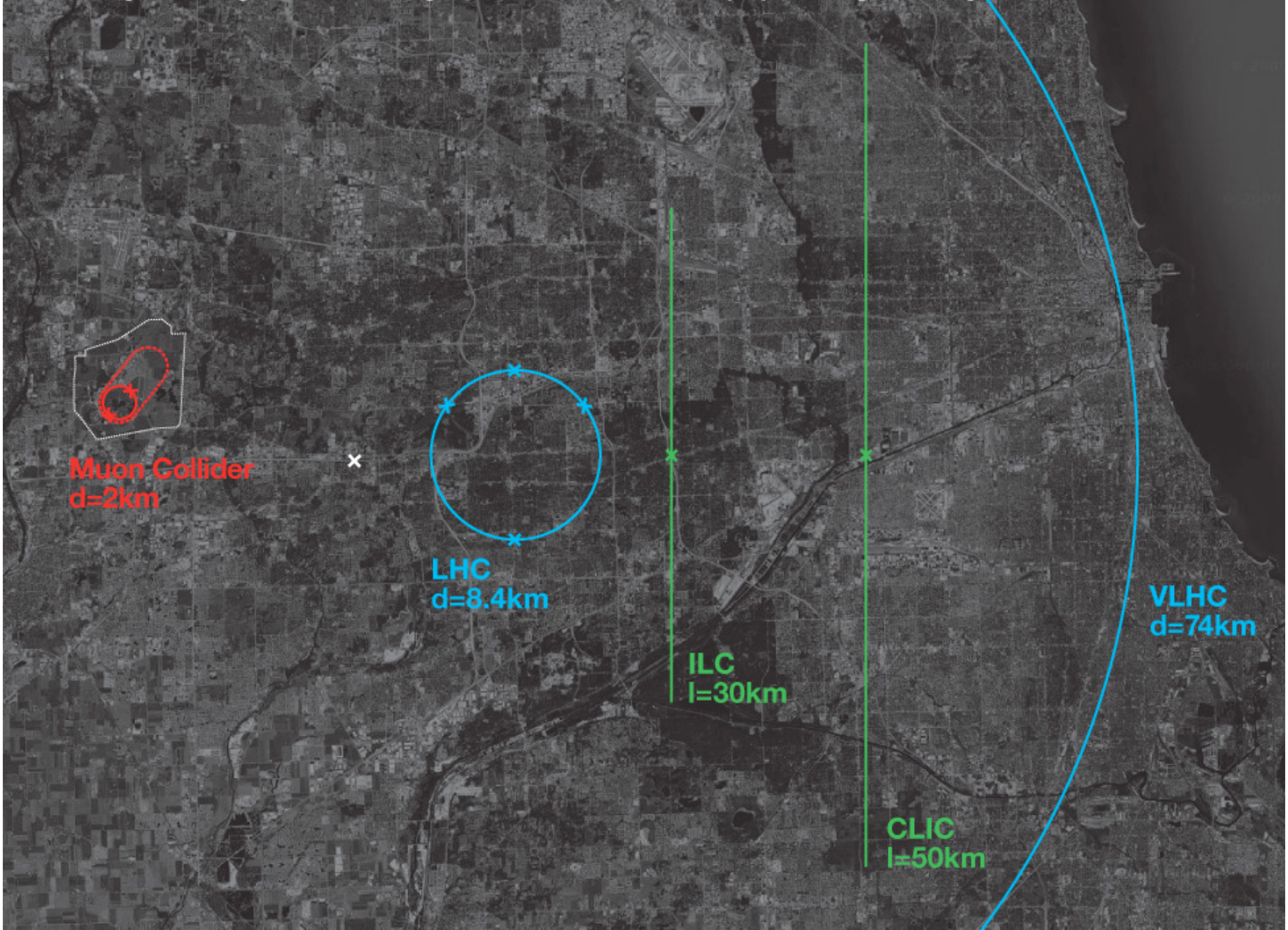
- Unique opportunity for lepton colliders @ $\sqrt{s}$ > 1 TeV
- Possible reuse of existing facilities and infrastructure (i.e. LHC tunnel) in Europe

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

Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.



A long story…

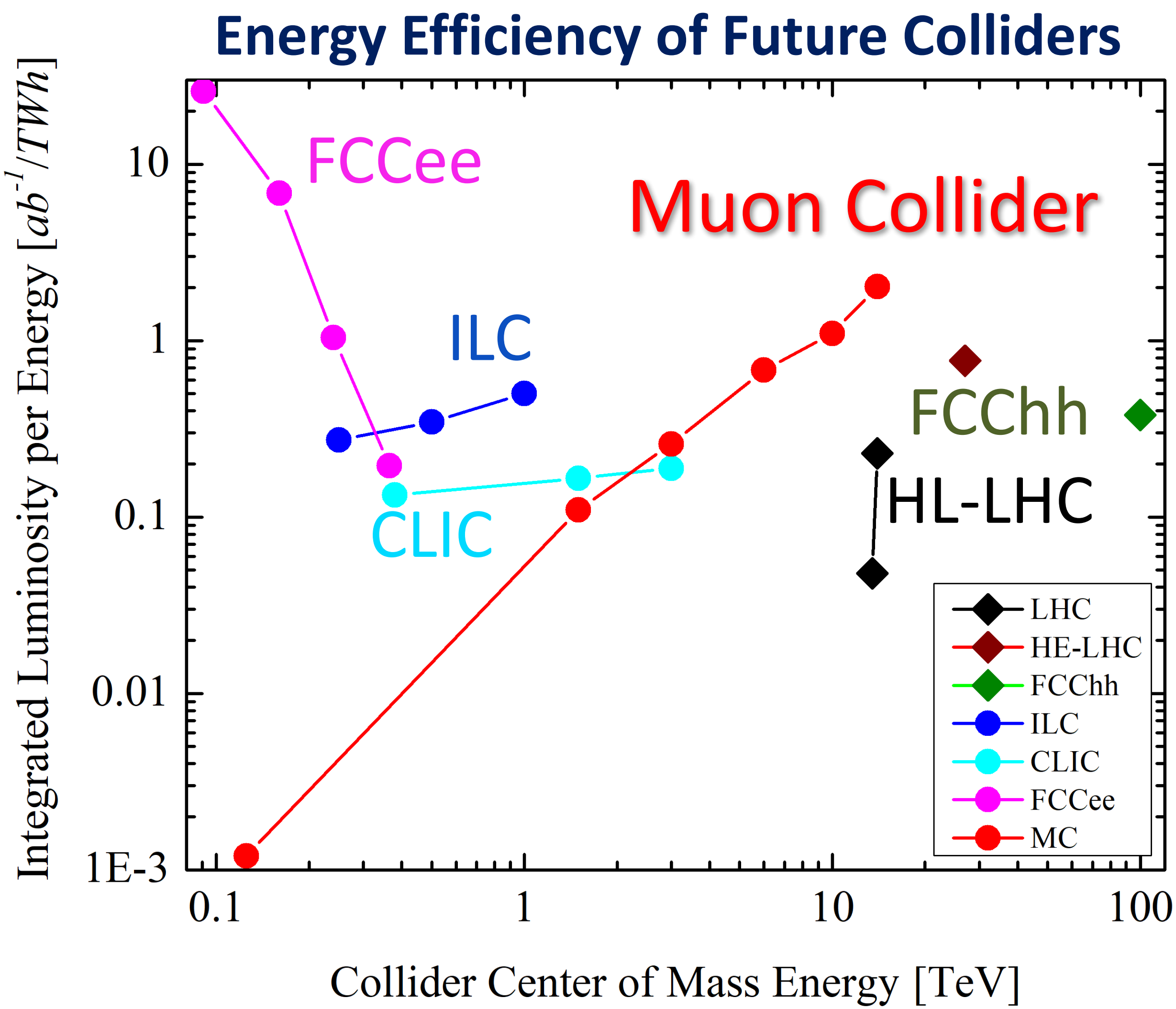
- The **muon collider idea** was first introduced in **early 1980's** *[A. N. Skrinsky, D. Neuffer et al.,]*
- Idea further developed by a **series of world-wide collaborations**
- **US M**uon **A**ccelerator **P**rogram **– MAP,** created in **2011,** was terminated in **2014**
  MAP developed a ***proton 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 (L**ow **EM**ittance **M**uon **A**ccelerator**)** 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

Figure of merit

nature physics

[Muon colliders to expand frontiers of particle physics]



EU Strategy → International Design Study

European Strategy Update – June 19, 2020:

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*

3 High-priority future initiatives

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

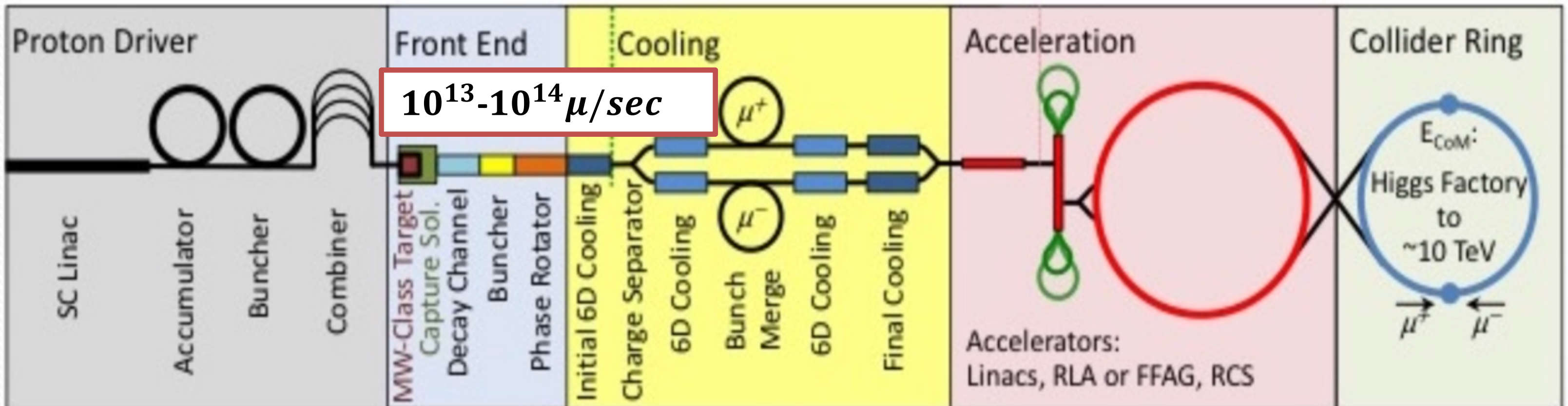
Core team: N. Pastrone, L. Rivkin, D.Schulte

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

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

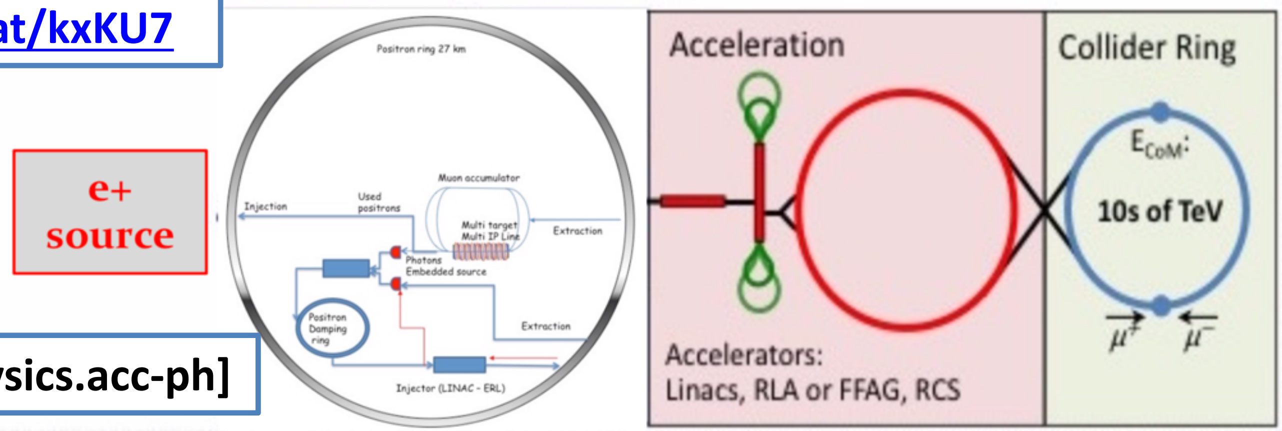
proton (MAP) vs positron (LEMMA) driven Muon Source

MAP



MUON JINST, shorturl.at/kxKU7

LEMMA



arXiv:1905.05747v2 [physics.acc-ph]

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

International Muon Collider Collaboration

Project Leader: *Daniel Schulte*

Objective:

In time for the next European Strategy for Particle Physics Update, the study 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 two energy ranges:

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

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

- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

Web page: http://muoncollider.web.cern.ch

….up to now and here!

CERN Medium Term Plan 2021-2025 - dedicated budget line – 2MCHF/year

International Design Study based at CERN ➔ MoC ready to be signed

European LDG Accelerator R&D Roadmap by fall 2021

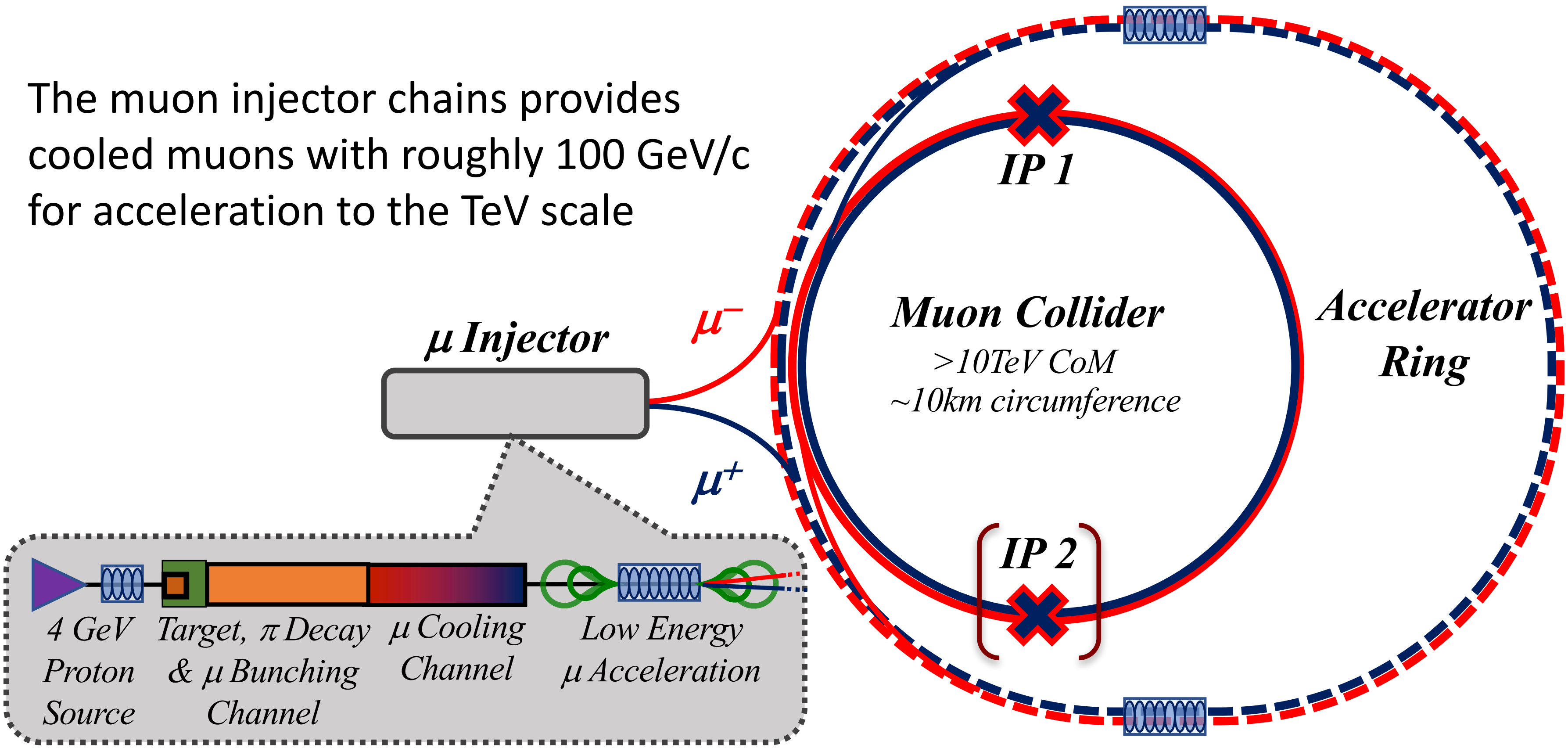
European ECFA Detector R&D Roadmap by fall 2021

US SnowMass Muon Collider Forum since 2021

Snowmass/P5 process in the US by spring 2023

Sketch of the multi-TeV facility

The muon injector chains provides cooled muons with roughly 100 GeV/c for acceleration to the TeV scale



~ $2\times10^{12}\mu/bunch$

1 bunch/beam colliding each 20-30 μs

➔ max 2 Interaction Points - IP

ONLY 1 EXPERIMENT CONSIDERED at present

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

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

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

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

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

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

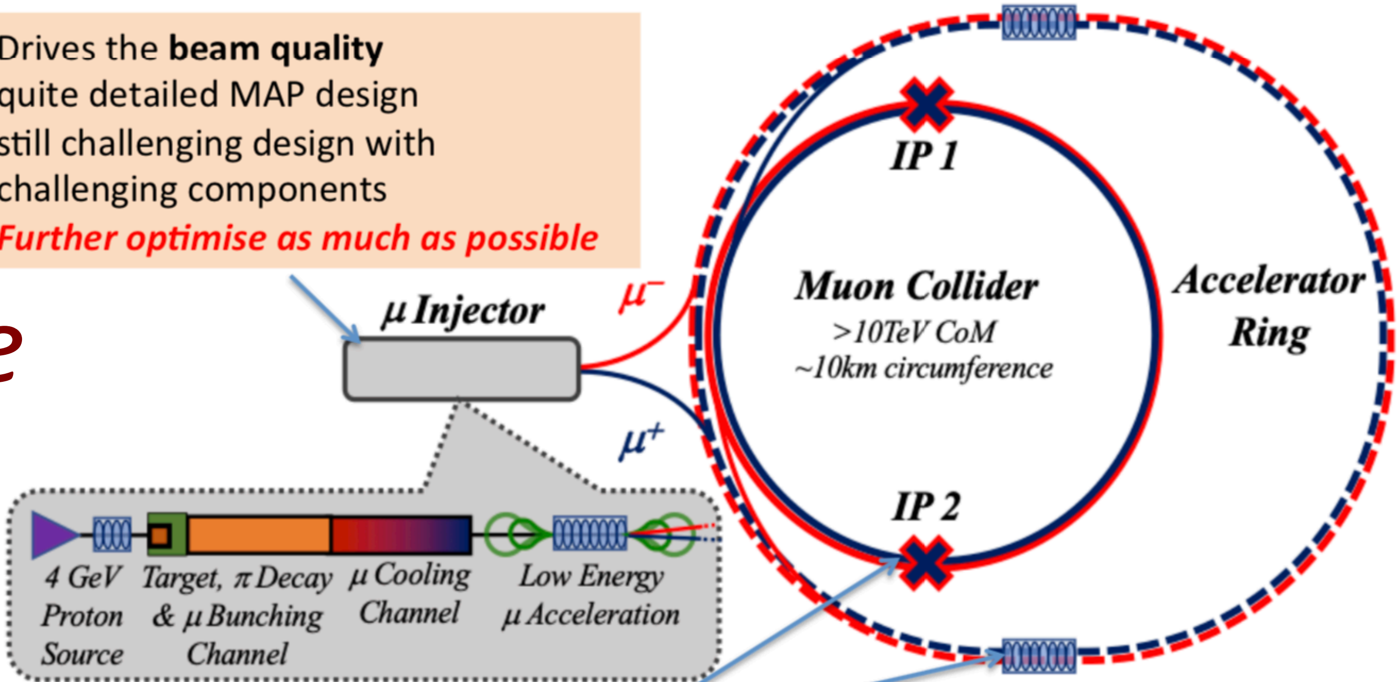
Dense beam

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

Baseline facility sketch

Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
Further optimise as much as possible



Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**
Drives **neutrino radiation** and **beam induced background**
Improve compared to MAP design and design for high-energy

Alternative Muon production Sources, such as LEMMA, could be also considered

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 a full demonstrator of innovative 6D ionization cooling
  - Positron driven – not yet mature ➔ requires new production studies and ideas

Great opportunities to develop novel ideas and technologies

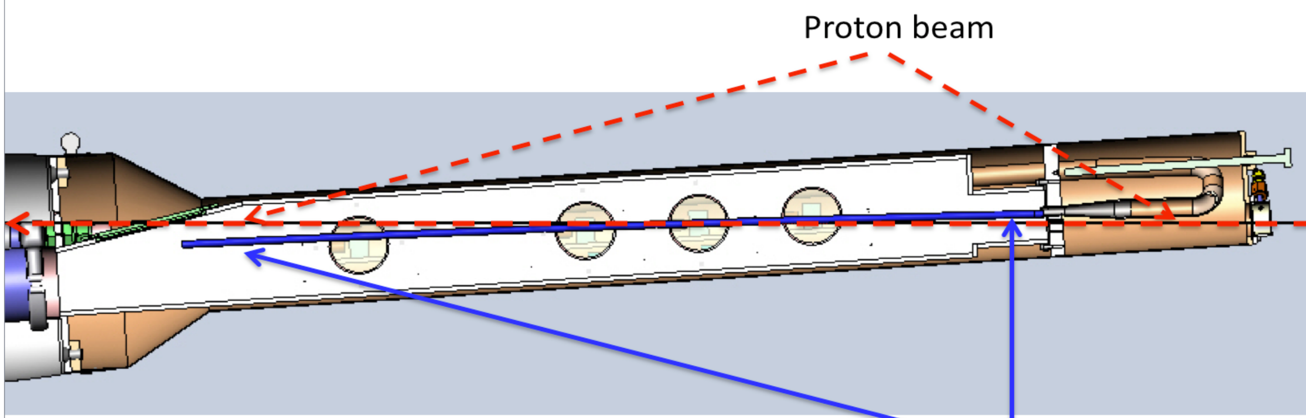
Proton driver key R&D challenges

Key R&D Challenges

	Issues	Status
Target	• Multi-MW Targets • High Field, Large Bore Capture Solenoid	• Ongoing >1 MW target development • Challenging engineering for capture solenoid
Front End	• Energy Deposition in FE Components • RF in Magnetic Fields (see Cooling)	• Current designs handle energy deposition
Cooling	• RF in Magnetic Field • High and Very High Field SC Magnets • Overall Ionization Cooling Performance	• MAP designs use ~20 MV/m→50 MV/m demo • >30 T solenoid demonstrated for Final Cooling • Cooling design that achieves most goals
Acceleration	• Acceptance • Ramping System • Self-Consistent Design	• Designs in place for accel to 125 GeV CoM • Magnet system development needed for TeV-scale • Self-consistent design needed for TeV-scale
Collider Ring	• Magnet Strengths, Apertures, and Shielding • High Energy Neutrino Radiation	• Self-consistent lattices with magnet conceptual design up to 3 TeV • > ~5 TeV – ν radiation solution required
MDI/Detector	• Backgrounds from μ Decays • IR Shielding	• Further design work required for multi-TeV • Initial physics studies at 1.5 TeV promising

Target

Protons → Target → Pions → Muons



MERIT experiment at CERN

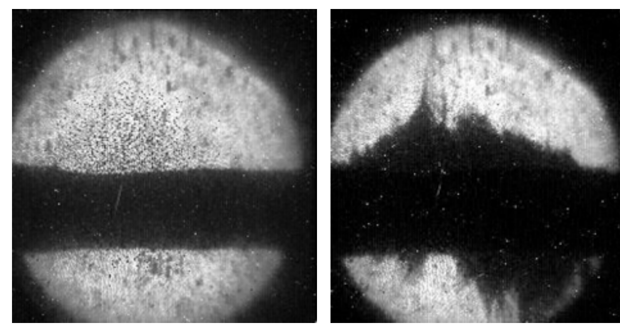
High power target (8 MW vs. 1.6-4 MW or even less required) has been demonstrated

Maximum pulse tested 30×10^{12} protons with 24 GeV

- 9×10^{12} muons (loose 90%)

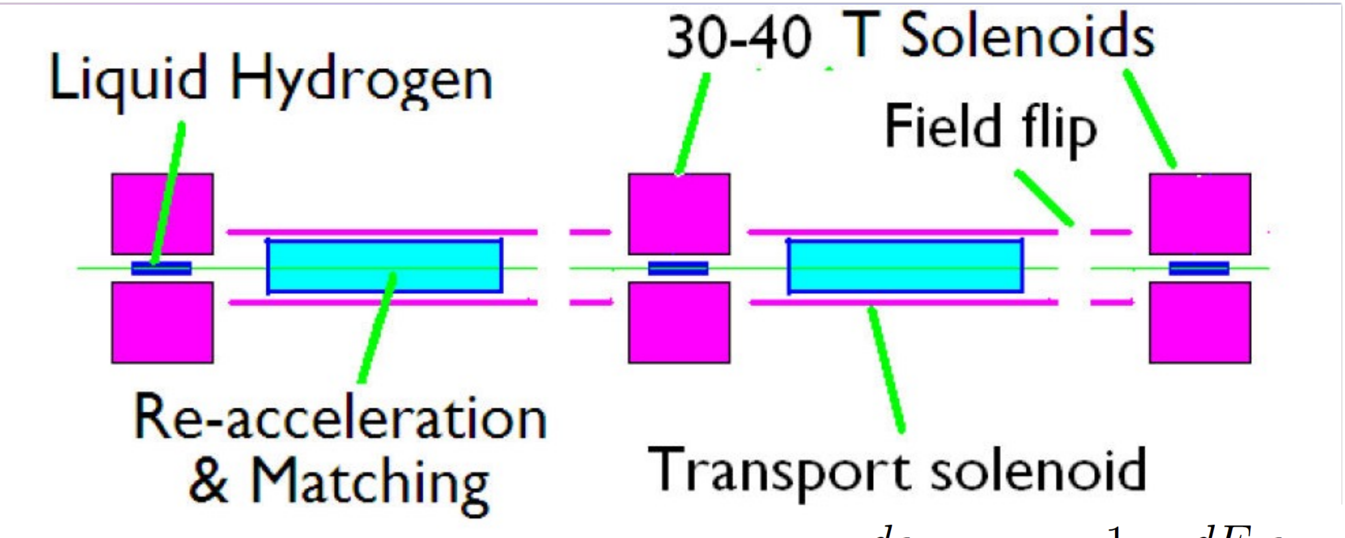
But radiation issues?

Maybe can use solid target

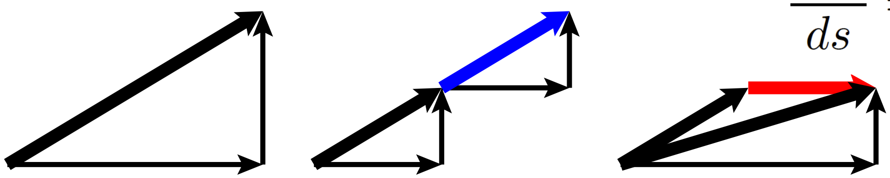


What could be made available at CERN (or elsewhere) as a proton driver for a potential test facility?

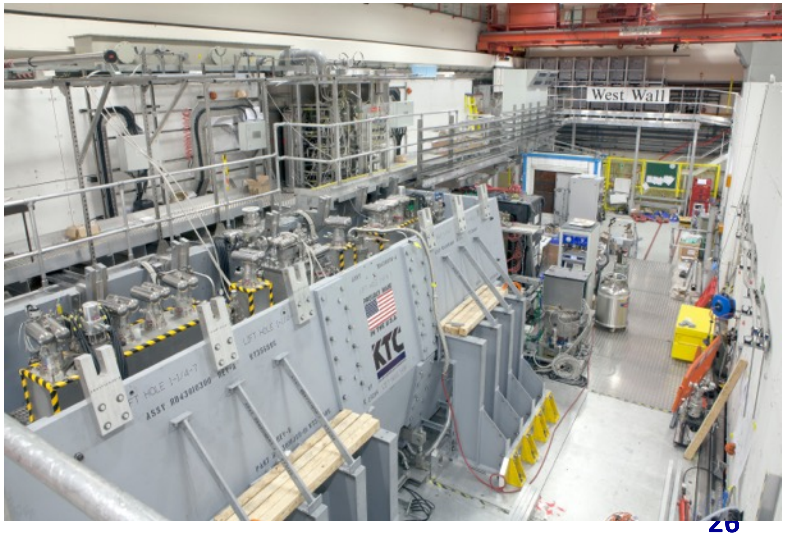
Transverse Cooling Concept



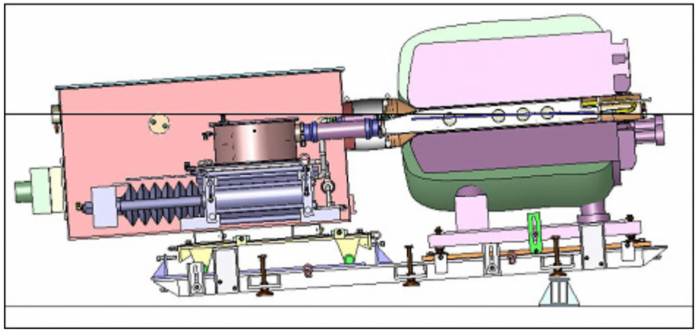
$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$



MICE allows to address 4D cooling
with low muon flux rate

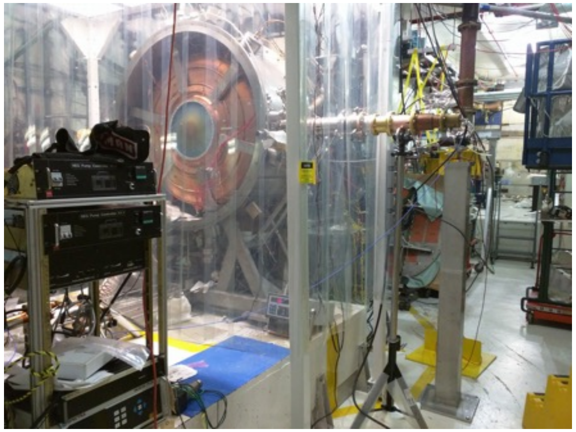


International R&D program



MERIT - CERN

Demonstrated principle of liquid Mercury jet target

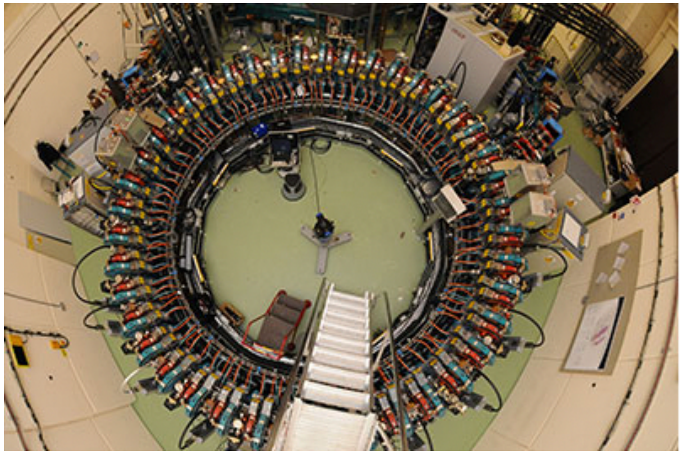


MuCool Test Area - FNAL

Demonstrated operation of RF cavities in strong B fields

EMMA - STFC Daresbury Laboratory

Showed rapid acceleration in non-scaling FFA

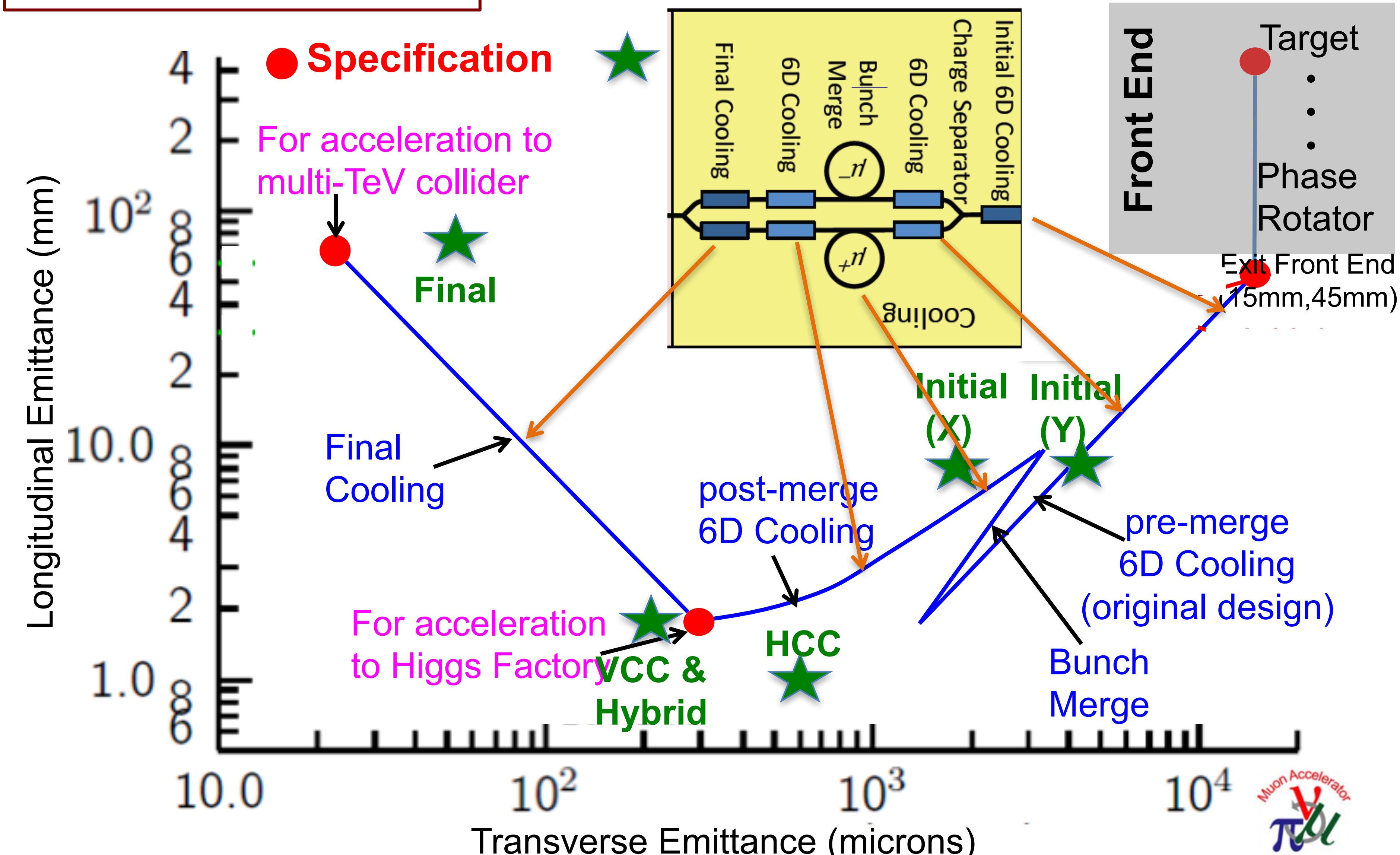


MICE - RAL

Demonstrate ionization cooling principle
Increase inherent beam brightness
→ number of particles in the beam core
"Amplitude"

Cooling: Emittance Path

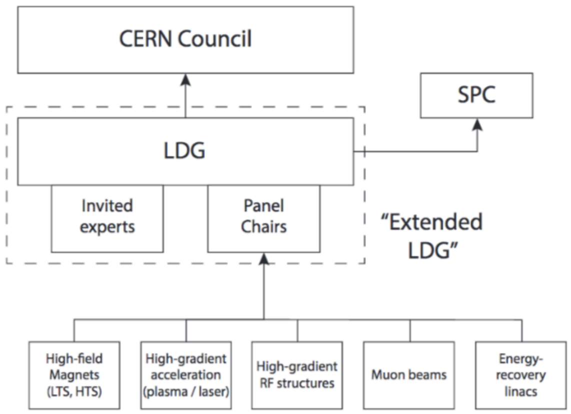
Highest field HTS
Phase space beam manipulations



European Accelerator R&D Roadmap

Council charged Laboratory Directors Group (LDG) to deliver European **Accelerator R&D Roadmap**

Panels
- Magnets: P. Vedrine
- Plasma: R. Assmann
- RF: S. Bousson
- Muons: D. Schulte
- ERL: M. Klein



Muon Beam members: Daniel Schulte (CERN, chair), Mark Palmer (BNL, co-chair), Tabea Arndt (KIT), Antoine Chance (CEA/IRFU) Jean-Pierre Delahaye (retired), Angeles Faus-Golfe (IN2P3/IJClab), Simone Gilardoni (CERN), Philippe Lebrun (European Scientific Institute), Ken Long (Imperial College London), Elias Metral (CERN), Nadia Pastrone (INFN-Torino), Lionel Quettier (CEA/IRFU), Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI), Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN)

Roles of panel members and European (other regions to be added) contact persons at https://muoncollider.web.cern.ch/organisation

Muon Beam Panel
Community Meeting May 20-21:
https://indico.cern.ch/event/1030726/

RF
Magnets
High-energy complex
Muon production and cooling
Proton complex
Beam Dynamics
Radiation protection and other technologies
MDI

***MU*on collider *ST*rategy network**
MUST - activities and goals

*INFN, CERN (+BINP), CEA, IJCLAB, KIT, **PSI**, UKRI /STFC*

- **Support the effort to design a muon collider and to project and plan the required R&D**
- **Consolidate the community devoted to develop an international future facility**
- **Prepare the platform to disseminate the information (website, meetings, simulation tools)**
- A Europe-wide network is essential for the development of the collider design and technology, which will serve as a common forum to coordinate with the growing international muon-collider efforts, including the US-MAP collaboration, sharing data and results
- The muon collider requires an intense muon source, fast muon acceleration to high energies and efficient collisions to provide high luminosity:
  - The fast acceleration stage and the collider ring are critical for the collider cost, power consumption and performance, and technologies that can be developed in synergy with other future projects.
  - The decay of muons produces intense fluxes of neutrinos and electrons, sources of background in the machine and in the detector. Dedicated technology development and close collaboration between the accelerator and the detector will be needed to address this issue.

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

Many new theory papers….
and a big one

The Muon Smasher's Guide

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Dario Buttazzo[3], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[4], Nathaniel Craig[1], Majid Ekhterachian[5], JiJi Fan[6], Matthew Forslund[7], Isabel Garcia Garcia[8], Samuel Homiller[9], Seth Koren[10], Giacomo Koszegi[1], Zhen Liu[5,11], Qianshu Lu[9], Kun-Feng Lyu[12], Alberto Mariotti[13], Amara McCune[1], Patrick Meade[7], Isobel Ojalvo[14], Umut Oktem[1], Diego Redigolo[15,16], Matthew Reece[9], Filippo Sala[17], Raman Sundrum[5], Dave Sutherland[18], Andrea Tesi[16,19], Timothy Trott[1], Chris Tully[14], Lian-Tao Wang[10], and Menghang Wang[1]

[1] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ, 08540, USA*
[3] *INFN, Sezione di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy*
[4] *Institute for Fundamental Science, University of Oregon, Eugene, OR 97403, USA*
[5] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA*
[6] *Department of Physics, Brown University, Providence, RI 02912, USA*
[7] *C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA*
[8] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
[9] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[10] *Department of Physics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[11] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*
[12] *Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong S.A.R., P.R.C*
[13] *Theoretische Natuurkunde and IIHE/ELEM, Vrije Universiteit Brussel, and International Solvay Institutes, Pleinlaan 2, B-1050 Brussels, Belgium*
[14] *Princeton University, Princeton, NJ 08540, USA*
[15] *CERN, Theoretical Physics Department, Geneva, Switzerland*
[16] *INFN Sezione di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy*
[17] *LPTHE, CNRS & Sorbonne Universite, 4 Place Jussieu, F-75252 Paris, France*
[18] *INFN Sezione di Trieste, via Bonomea 265, 34136 Trieste, Italy*
[19] *Department of Physics and Astronomy, University of Florence, Italy*

[arXiv: 2103.14043]

Coarse-grained approach to phenomenology: interested in rates, simple parton-level analyses, setting aside beam-induced background & reconstruction issues.

Broad goal: to figure out what energies & luminosities might provide a comprehensive physics case, bring new targets into focus.

Various luminosity assumptions & energies:

$\sqrt{s}$ [TeV]	1	3	6	10	14	30	50	100
$\mathcal{L}_{\rm int}^{\rm opt}$ [ab^{-1}]	0.2	1	4	10	20	90	250	1000
$\mathcal{L}_{\rm int}^{\rm con}$ [ab^{-1}]	0.2	1	4	10	10	10	10	10

Physics at high energy

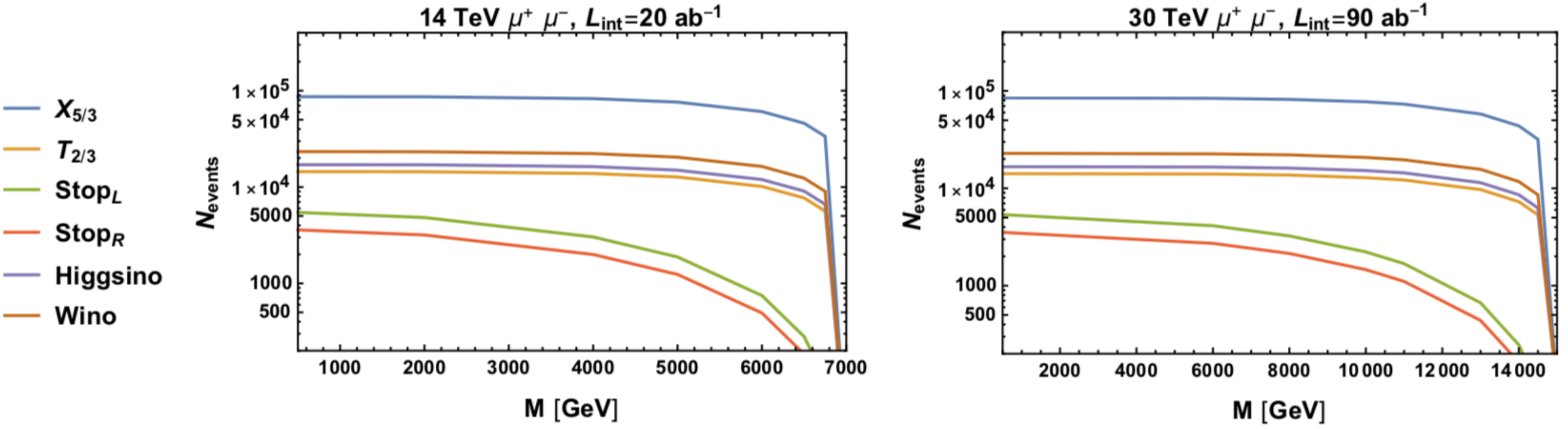
Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly

Direct Reach

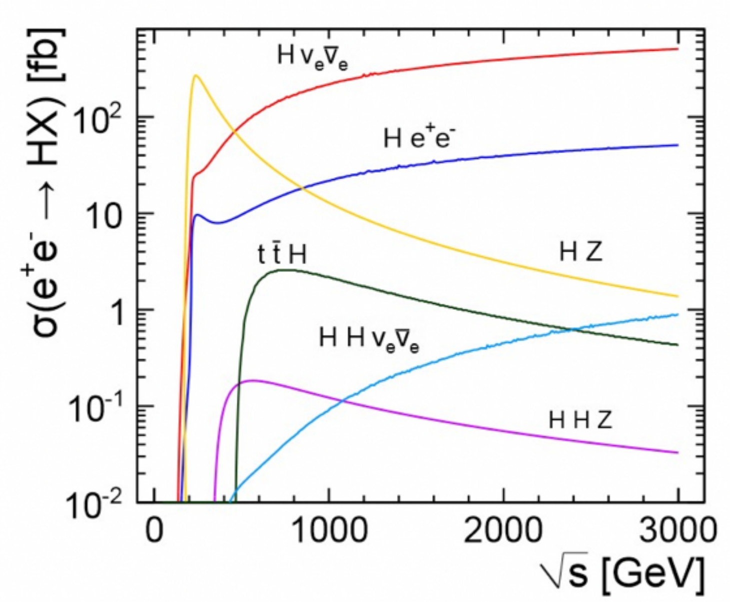
Andrea Wulzer et al.

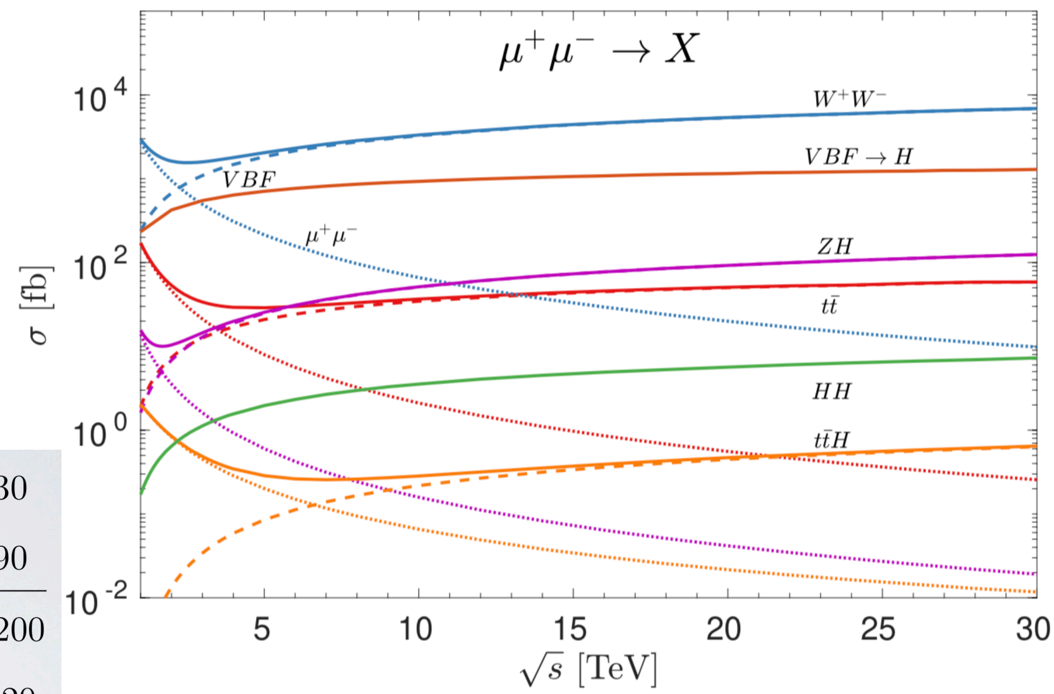
Discover **Generic EW** particles **up to mass threshold**

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



Higgs production at Lepton Collider





$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91

$\mathcal{O}(10^6 - 10^8)$ Higgs $\Rightarrow \mathcal{O}(10^{-3} - 10^{-4})$ precision

$\mathcal{O}(10^3 - 10^5)$ di-Higgs $\Rightarrow \mathcal{O}(10^{-2} - 10^{-3})$ precision

Electroweak Couplings of the Higgs Boson

Tao Han, Da Liu, Ian Low, Xing Wang

$\sqrt{s}$ (TeV)	3	6	10	14	30	Comparison	
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% (68% C.L.)	**CLIC**
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% (95% C.L.)	**CEPC**
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% , 1% (68% C.L.)	**CLIC/ FCC-hh**
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% (68% C.L.)	**FCC-hh SppC**

Recent results @APS-APR21 Meeting

Nathaniel Craig

Is our Higgs the only one?

Many possible extensions of the scalar sector…

For illustration: a Standard Model singlet mixing with the Higgs.

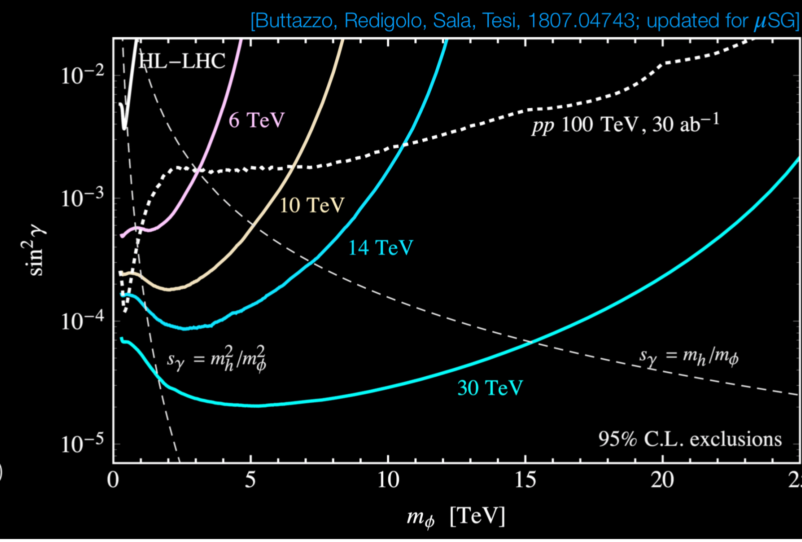
$$h = h^0 \cos\gamma + S \sin\gamma$$
$$\phi = S \cos\gamma - h^0 \sin\gamma$$

Production:

$$\sigma_\phi = \sin^2\gamma \cdot \sigma_h(m_\phi)$$

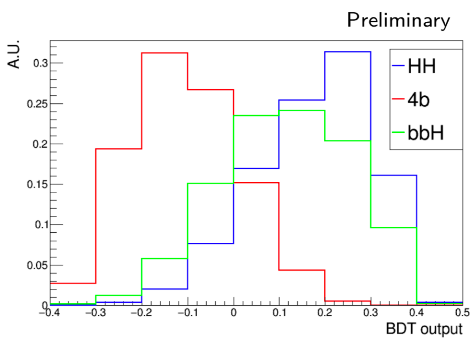
Decay:

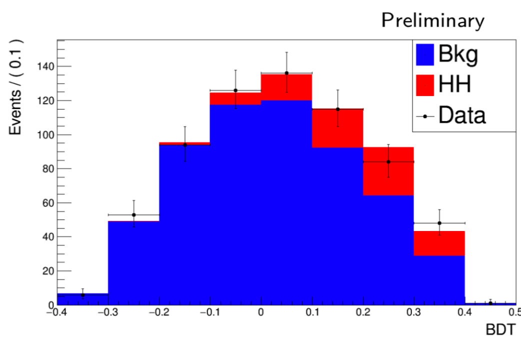
$$\mathrm{BR}_{\phi\to f\bar{f},VV} = \mathrm{BR}_{h\to f\bar{f},VV}(1-\mathrm{BR}_{\phi\to hh})$$
$$\mathrm{BR}_{\phi\to hh} \sim 25\%$$



HH cross section measurement

- Classification of signal and background events by using a Machine Learning technique (Boosted Decision Tree)
- With 1.3 ab^{-1} (4 years of data taking) at 3 TeV we expect to select 65 HH events and 561 background events.
- With a simple fit to the BDT an uncertainty of $\sim 30\%$ on the cross section has been obtained.





Laura Buonincontri et al.

https://indico.fnal.gov/event/48798/

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

Higgs potential

- the bounds on the quartic couplings δ_4 are very loose (68% CL)
  - ILC: $\sim [-10, +10]$ ($\pm 1000\%$!)
  - CLIC: $\sim [-5, +5]$
  - FCC: $\sim [-5, +15]$, from $pp \to HHH$
  - FCC: $\sim [-2, +4]$, from $pp \to HH$

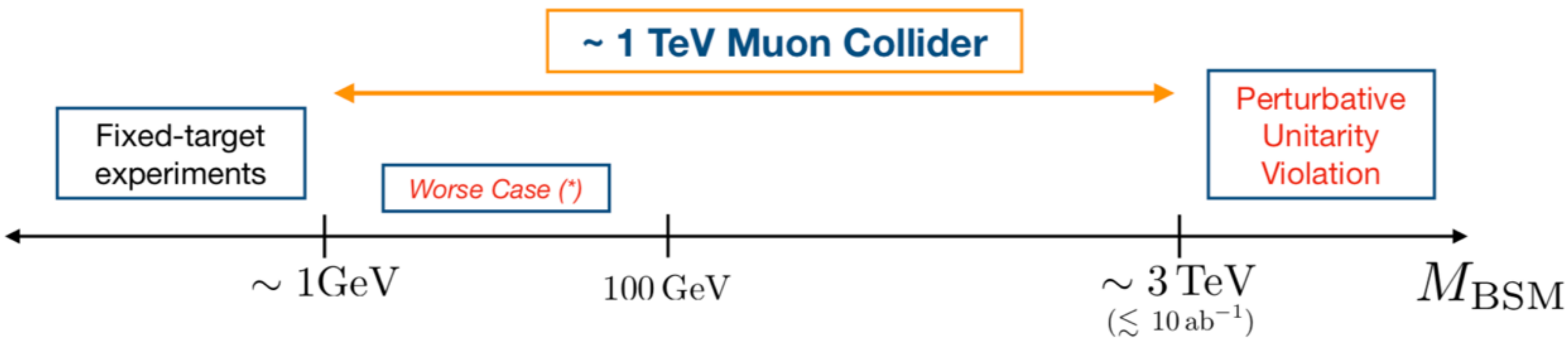
- we studied the sensitivity of the muon collider to the Higgs quartic coupling by considering the process $\mu^+\mu^- \to HHH\nu\bar{\nu}$
- no background was considered
- (almost) no optimization based on kinematics was performed
- the sensitivity increases with $\sqrt{s}$ and/or the luminosity

$\sqrt{s}$ [TeV]	L [ab^{-1}]	δ_4 (arbitrary δ_3)	δ_4 ($\delta_3 = 0$)
6	12	[-1,1.7]	[-0.45,0.8]
10	20	[-0.7,1.55]	[-0.4,0.7]
14	33	[-0.55,1.4]	[-0.35,0.6]
30	100	[-0.35,1.2]	[-0.2,0.5]

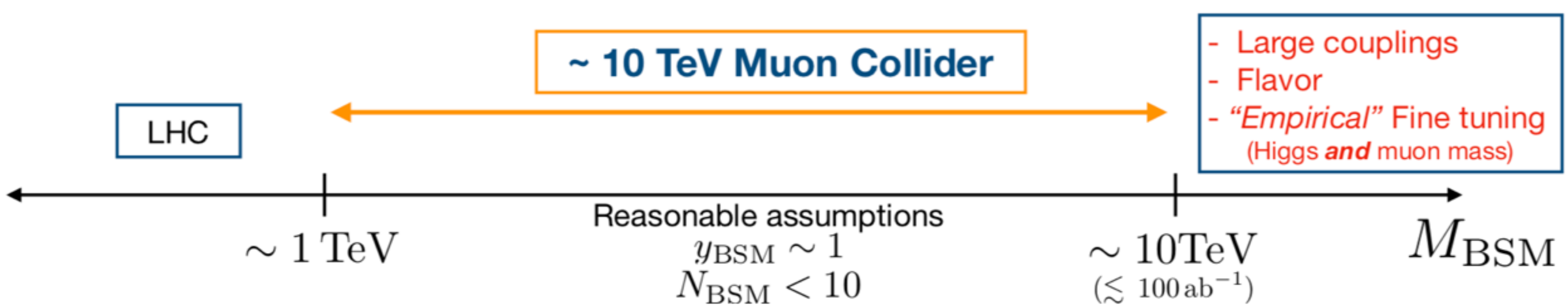
- under (reasonable) assumptions on the energy and the luminosity, the muon collider can do a pretty good job in constraining the quartic Higgs coupling

g-2 @ Muon Collider

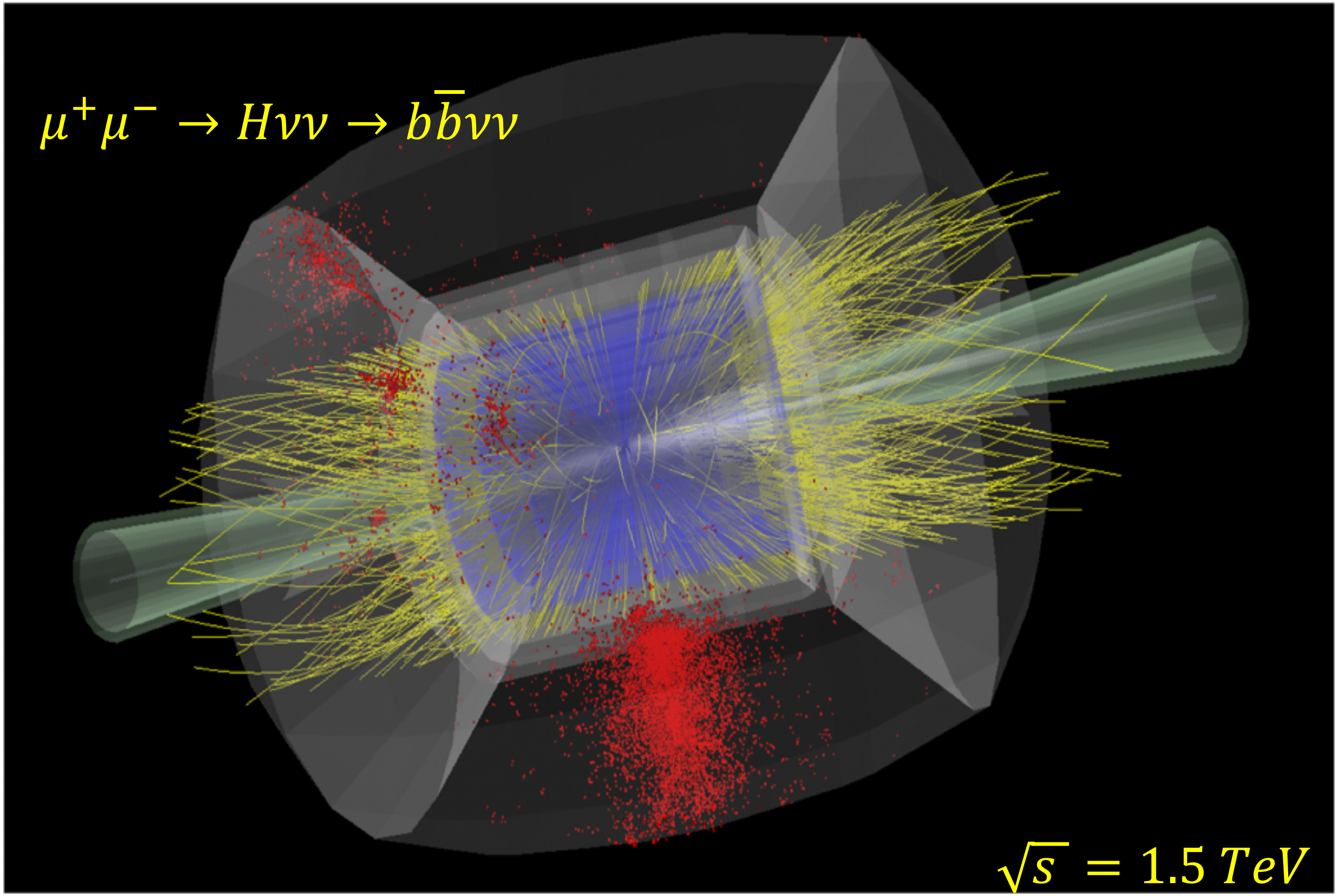
- Singlet Models



- High-Scale EW Models



$H \to b\bar{b}$ + muon beams induced backgound



Status of existing and on-going studies at 1.5 and 3 TeV center-of-mass energy
Future steps towards 10 TeV and higher center-of-mass energy to exploit physics reach

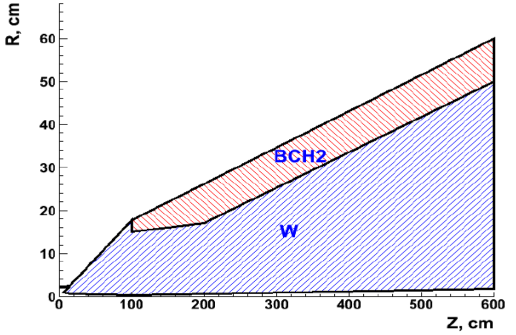
Full simulation: beam induced background

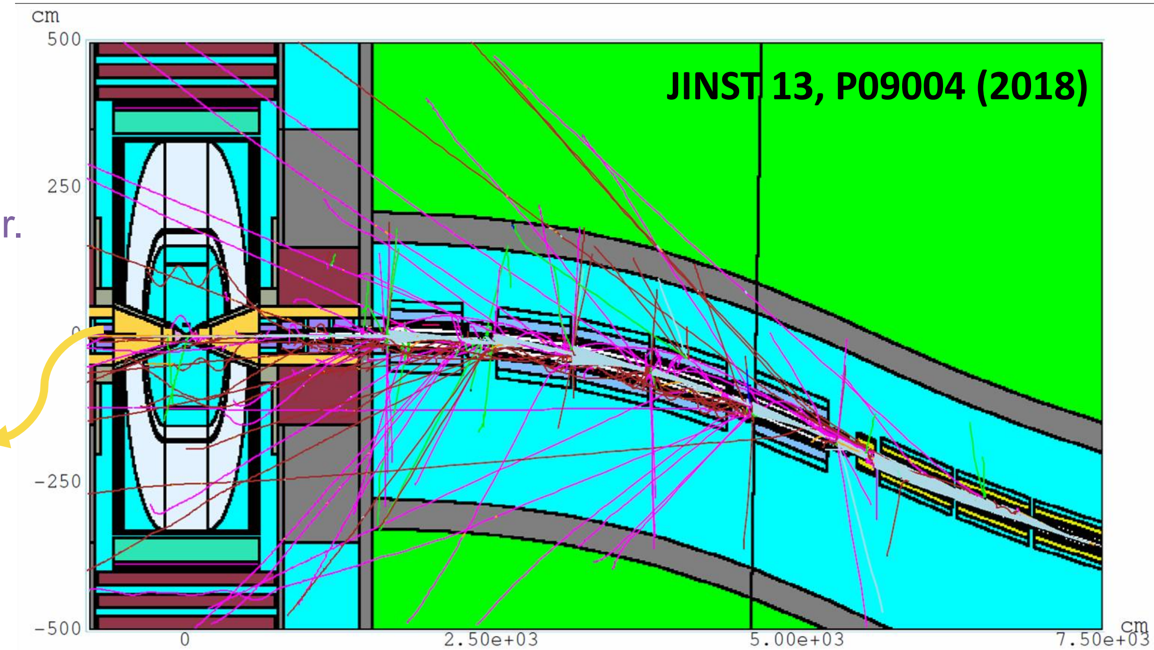
Nikolai Mokhov et al. - MARS15

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.

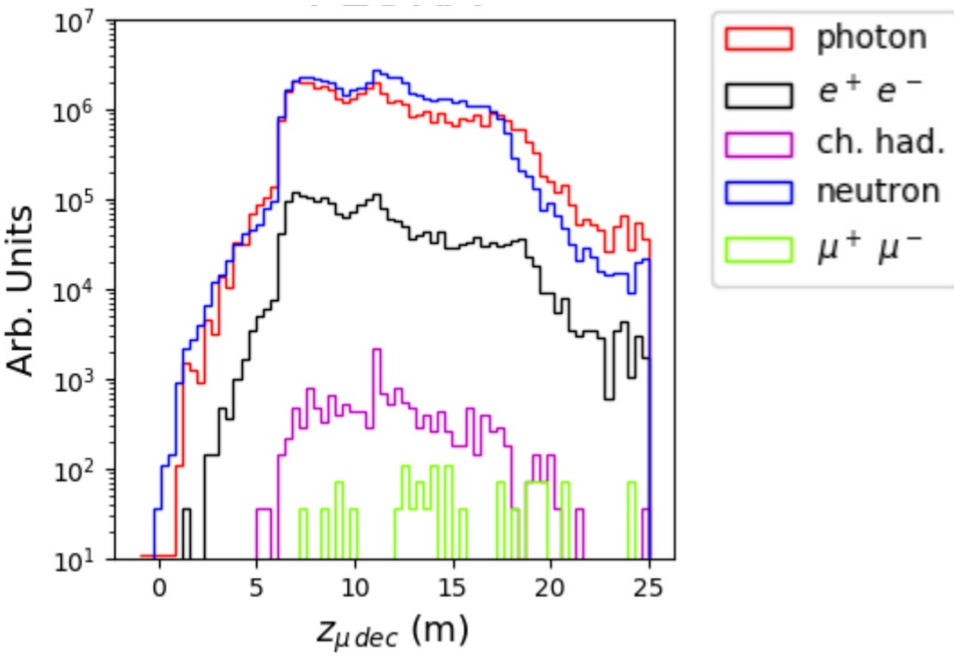


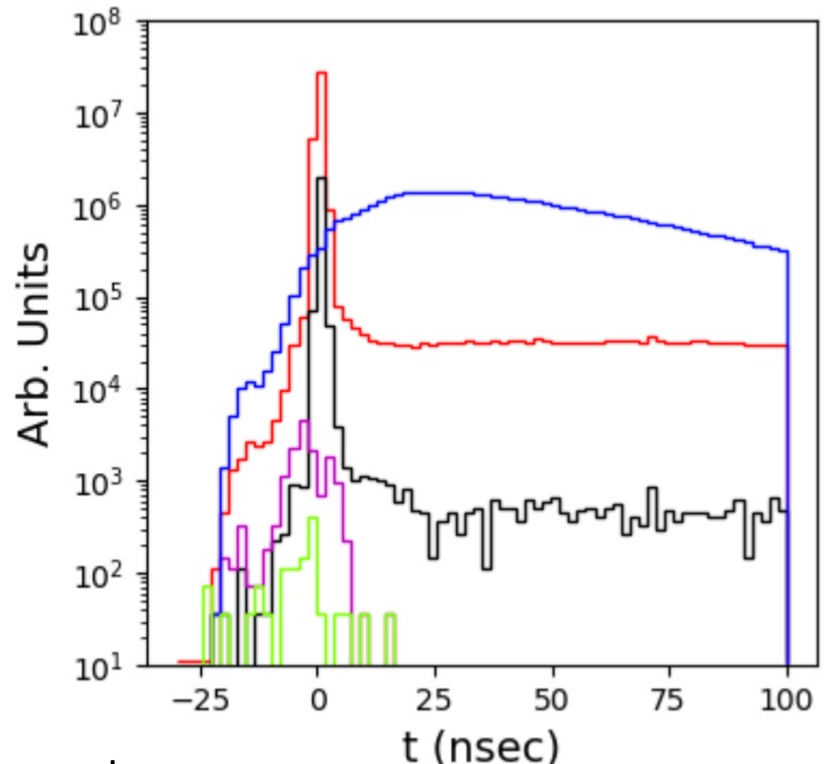


For each collider energy the machine elements, the MDI and interaction region have to be properly designed and optimized

Beam Induced background @ 1.5 TeV

Donatella Lucchesi, Nikolai Mokhov et al.





Particle (E_{th}, MeV)	MARS15	FLUKA
Photon (0.2)	8.3 10^7	4.29 10^7
Neutron (0.1)	2.44 10^7	5.37 10^7
Electron/positron (0.2)	7.23 10^5	2.2 10^6
Ch. Hadron (1)	3.07 10^4	1.52 10^4
Muon (1)	1.47 10^3	1.22 10^3

muon beams
@ **0.75 TeV** with **2×10^{12}muons/bunch** ➔
4×10^5 muon decays/m single bx

JINST 13 (2018), P09004
***JINST* 15 (2020) 05, P05001**

BIB @ 10 TeV only general consideration

- Not expected to dramatically change compared to lower energies
- BIB timing distributions to be verified

BIB characteristics at $\sqrt{s} = 1.5$ *TeV, 125 GeV*

beam energy [GeV]	62.5	750
μ decay length [m]	3.9×10^5	4.7×10^6
μ decays/m per beam	5.1×10^6	4.3×10^5
photons ($E_{\text{ph.}}^{kin} > 0.2$ MeV)	3.4×10^8	1.6×10^8
neutrons ($E_{\text{n}}^{kin} > 0.1$ MeV)	4.6×10^7	4.8×10^7
electrons ($E_{\text{el.}}^{kin} > 0.2$ MeV)	2.6×10^6	1.5×10^6
charged hadrons ($E_{\text{ch.had.}}^{kin} > 1$ MeV)	2.2×10^4	6.2×10^4
muons ($E_{\text{mu.}}^{kin} > 1$ MeV)	2.5×10^3	2.7×10^3

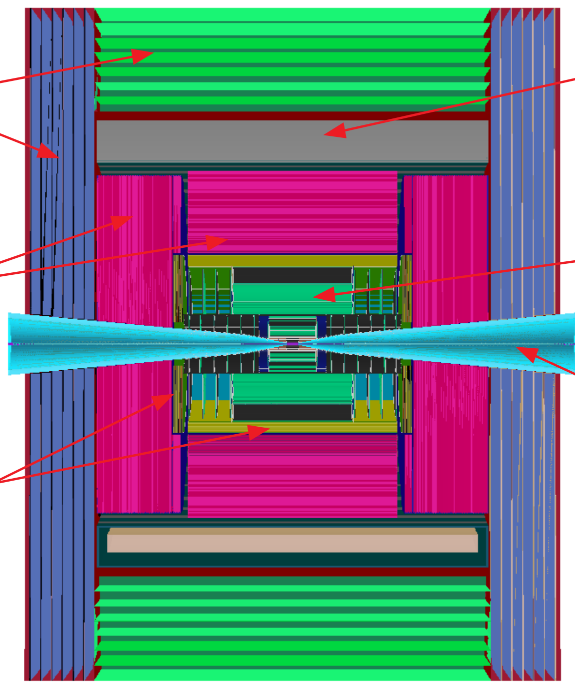
arXiv:1905.03725

- Key findings for discrimination:
  - Precise timing and Directional information (not from IP)
  - Energy deposit (especially for low-energy γ/n interaction in Si)
  - Majority of particles with low transverse momentum

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

Detector for $\sqrt{s}$ =1.5 TeV Collisions

- CLIC Detector technologies adopted with important modifications to cope with BIB
- Detector design optimization at $\sqrt{s}$=1.5 (3) TeV is one of the Snowmass goals.



Vertex Detector (VXD)

- 4 double-sensor barrel layers $25x25\mu m^2$
- 4+4 double-sensor disks $25x25\mu m^2$

Inner Tracker (IT)

- 3 barrel layers $50x50\mu m^2$
- 7+7 disks ”

Outer Tracker(OT)

- 3 barrel layers $50x50\mu m^2$
- 4+4 disks ”

Electromagnetic Calorimeter (ECAL)

- 40 layers W absorber and silicon pad sensors, $5x5$ mm^2

Hadron Calorimeter (HCAL)

- 60 layers steel absorber & plastic scintillating tiles, $30x30$ mm^2

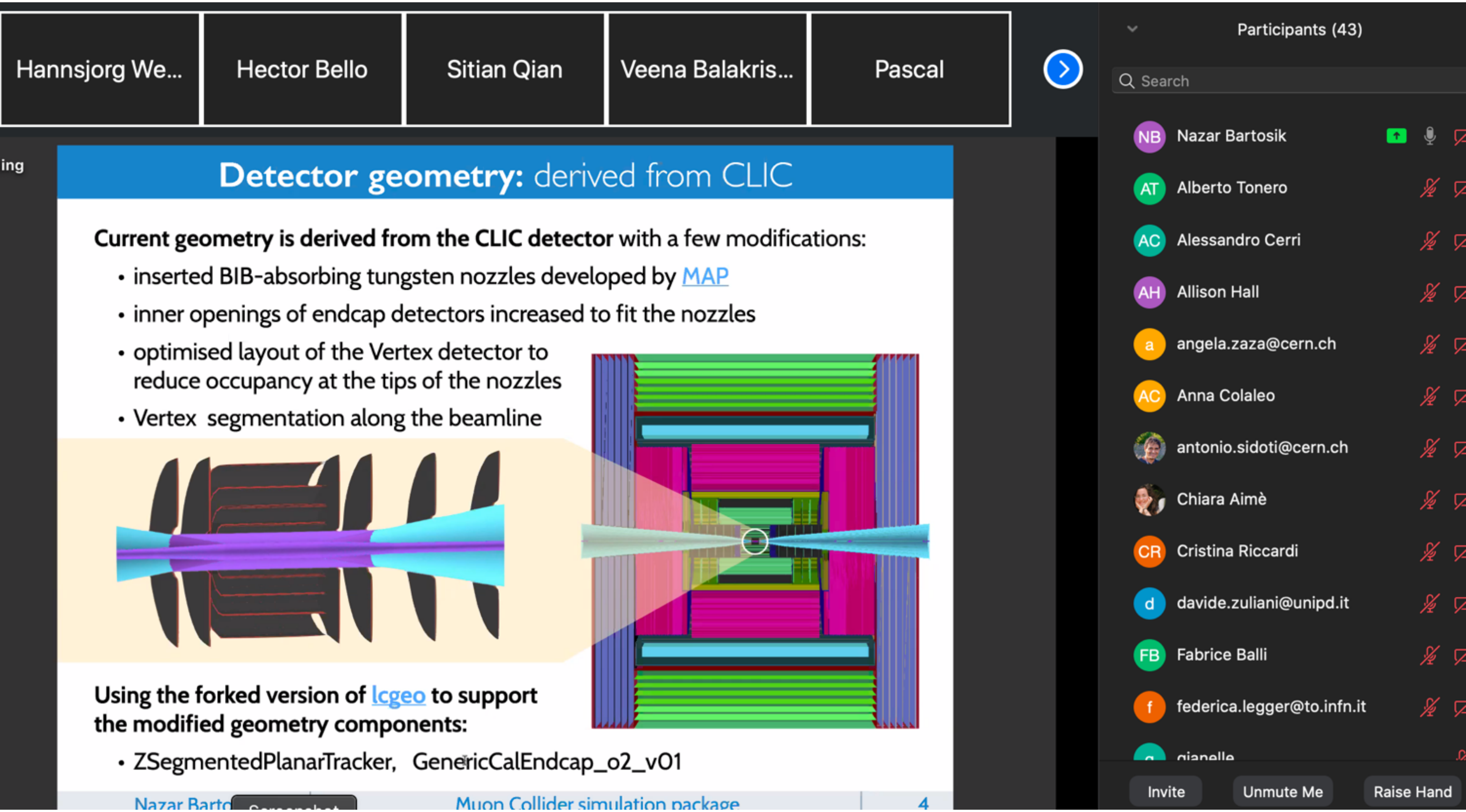
Full simulation available on github

B = 3.57 T to be studied and tuned

Different stages of design depending on CoM energy

Quite advanced conceptual design for Higgs factory, 1.5 TeV and 3 TeV

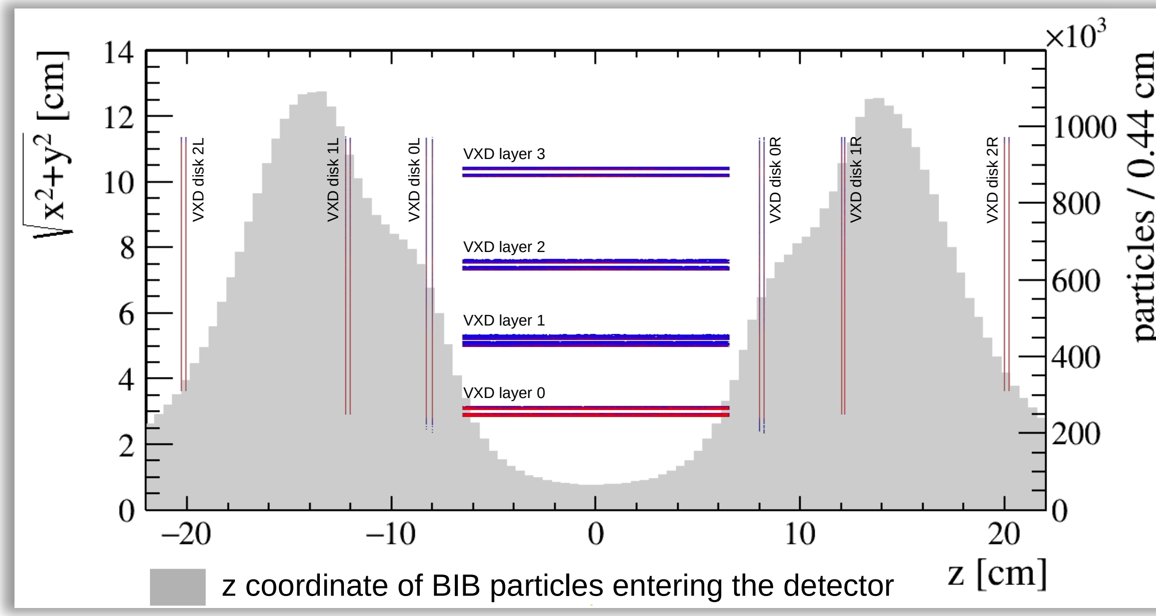
Experiment design to be improved

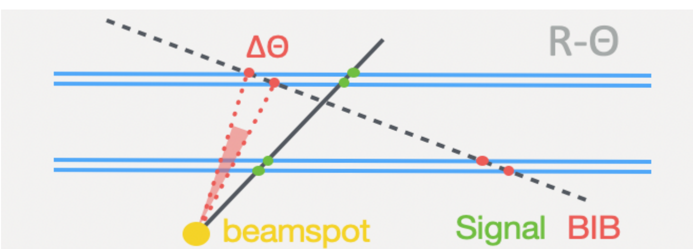


Tracking performances

The impact of BIB on tracking system could be severe if not mitigated:

- vertex detector barrel designed in such a way not to overlap with the BIB hottest spots around the interaction region



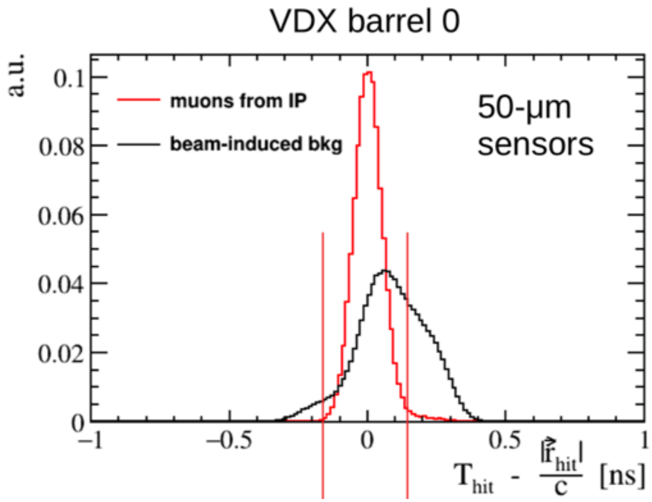


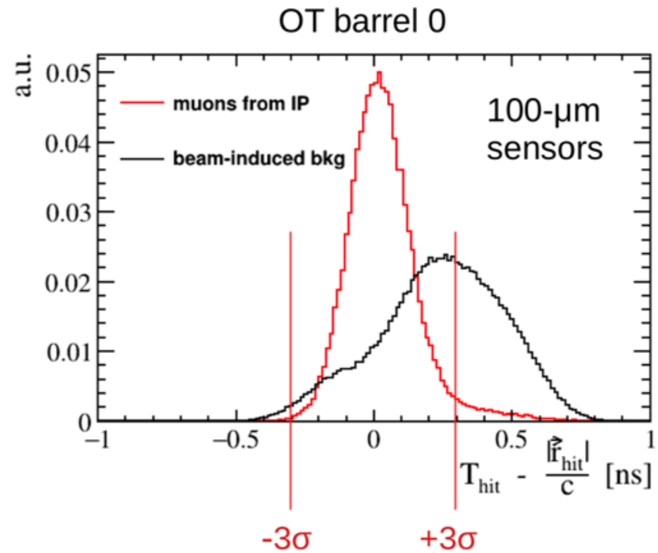
Angles can be measured by correlating hits between adjacent sensors

➔ used by CMS track trigger

- Tracking performance have been studied applying loose timing and energy cuts on clusters reconstruction.

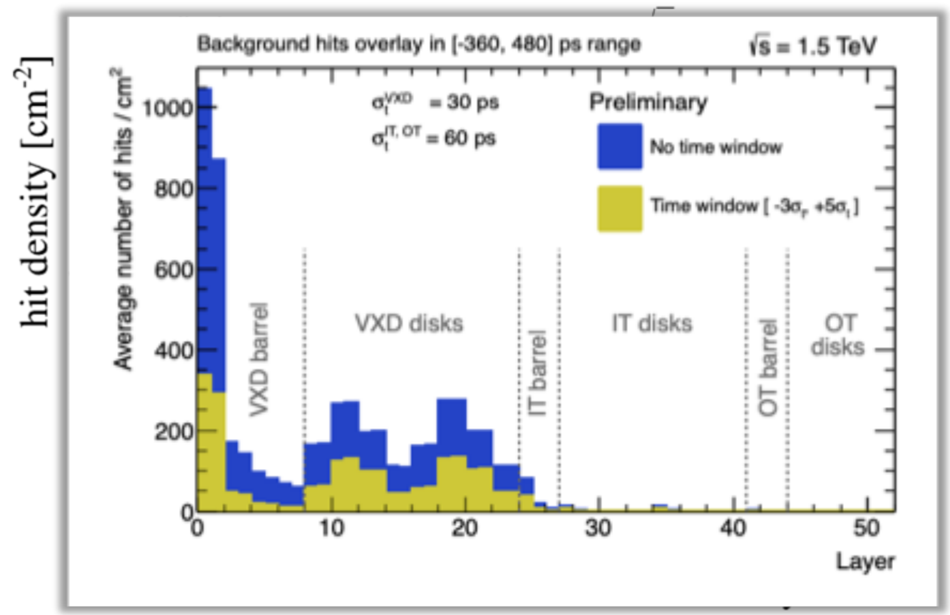
Tracking requirements ➔ R&D needs





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

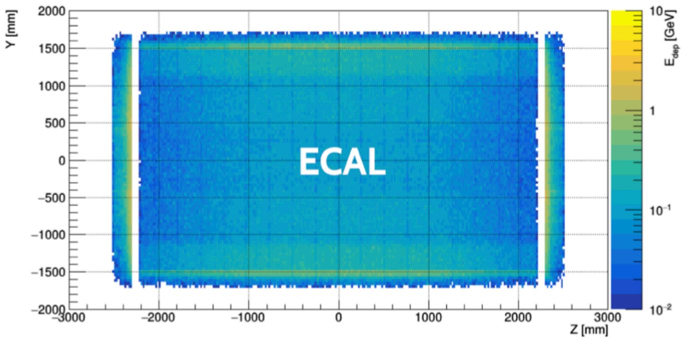
- Handles to reject spurious hits from BIB:
  - applying a time window to readout only hits compatible with particles originating from interaction region;
  - exploiting energy deposited in the tracker sensors (under development);
  - correlating hits on double-layer sensors (under development).

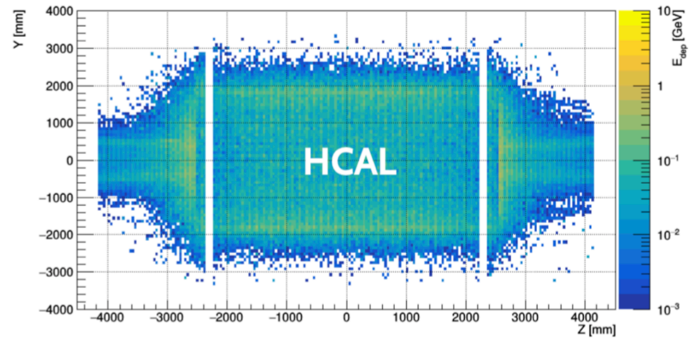


State of the art fast tracking sensors can push this even further: σ_t~10ps

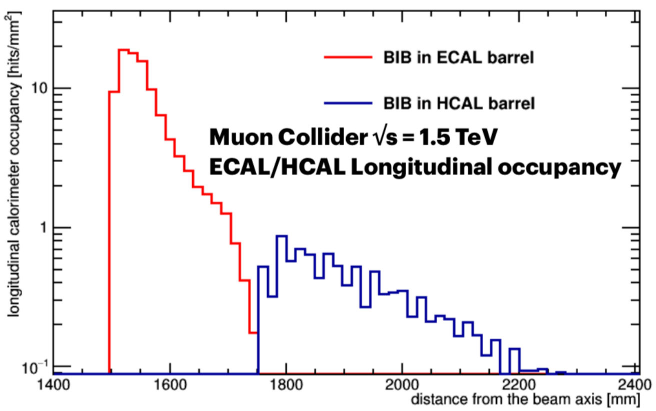
Calorimeters

About 6 TeV (2.5 TeV) of energy deposited in ECAL (HCAL) by BIB



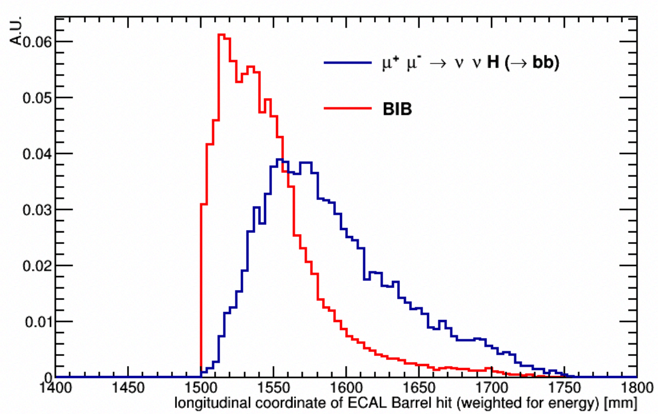


Energy deposition in calorimeters per bunch crossing

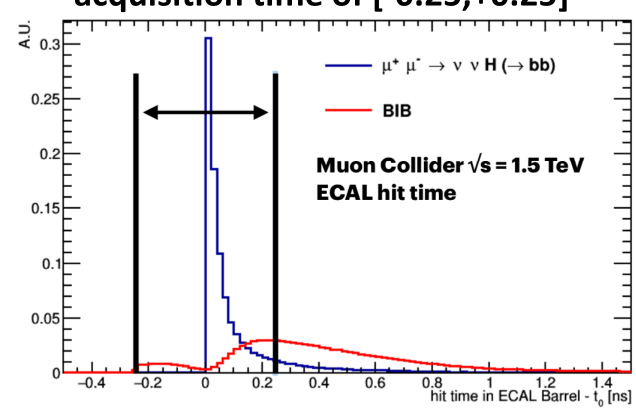


- **BIB is diffused in the calorimeters**: at the ECAL barrel surface the flux is 300 particles/cm^2, most of them are photons with <E>=1.7 MeV.
- BIB occupancy is lower in HCAL with respect to ECAL.

timing and longitudinal measurements play a key role in the BIB suppression



acquisition time of [-0.25,+0.25]

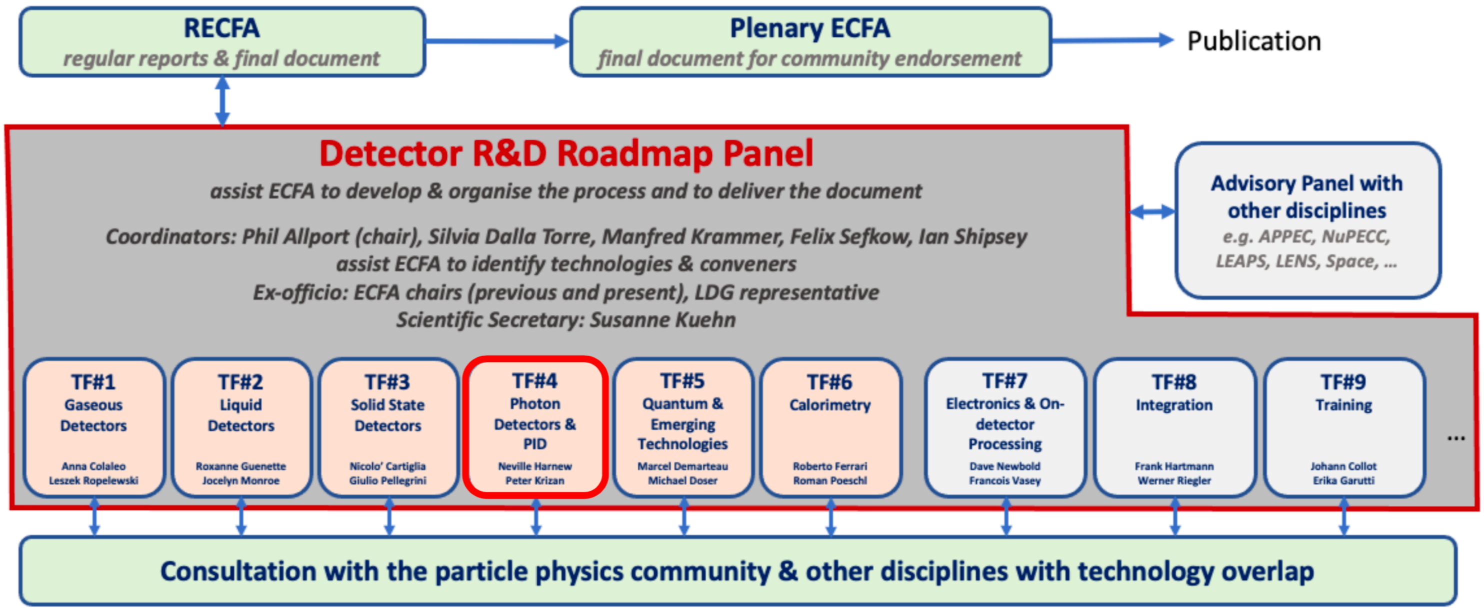


Detector R&D Roadmap

ECFA
European Committee for Future Accelerators

Detector R&D Roadmap

Organization for Consultation of Relevant Communities



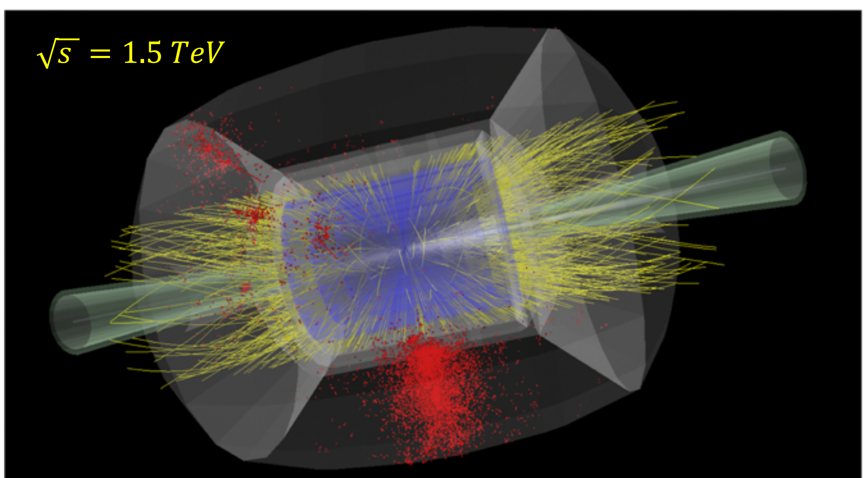
Grouped targeted facilities/areas emerging from the EPPSU

1. Detector requirements for full exploitation of the HL-LHC (R&D still needed for LS3 upgrades and for experiment upgrades beyond then) including studies of flavour physics and quark-gluon plasma (where the latter topic also interfaces with nuclear physics).
2. R&D for long baseline neutrino physics detectors (including aspects targeting astro-particle physics measurements) and supporting experiments such as those at the CERN Neutrino Platform.
3. Technology developments needed for detectors at e^+e^- EW-Higgs-Top factories in all possible accelerator manifestations including instantaneous luminosities at 91.2GeV of up to $5\times10^{36} cm^{-2}s^{-1}$.
4. The long-term R&D programme for detectors at a future 100 TeV hadron collider with integrated luminosities targeted up to $30 ab^{-1}$ and 1000 pile-up for 25ns BCO.
5. Specific long-term detector technology R&D requirements of a muon collider operating at 10 TeV and with a luminosity of the order of $10^{35} cm^{-2} s^{-1}$.

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

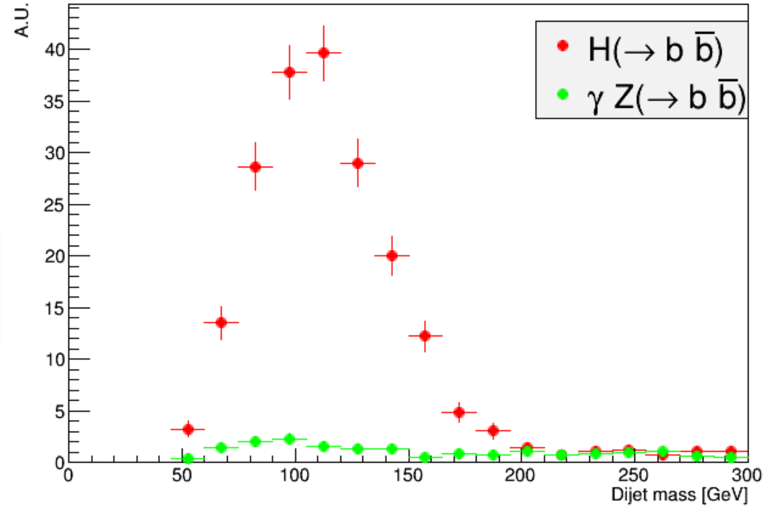
Detailed design of machine is required

H→bb @ 1.5 TeV

D. Lucchesi et al.

JINST 15 (2020) 05, P05001

$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ + 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

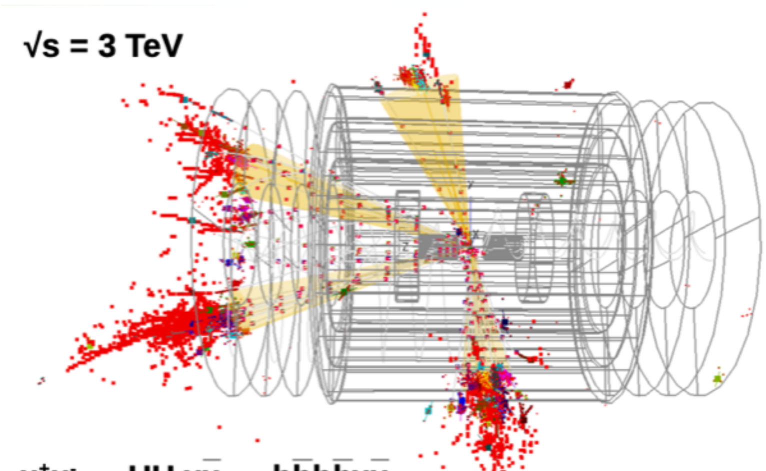
	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

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

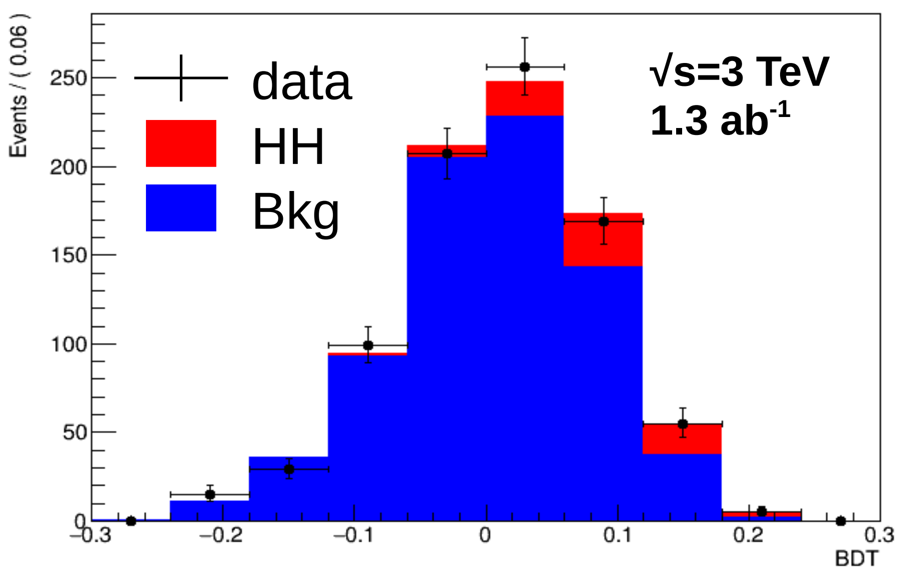
Double Higgs in full simulated detector

The process $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ at $\sqrt{s} = 3\text{TeV}$ is under study by using the full detector simulation



Assumptions

- $\mathcal{L}_{int} = 1.3\ ab^{-1}$
- Running time = $4 \cdot 10^7$ s
- one detector

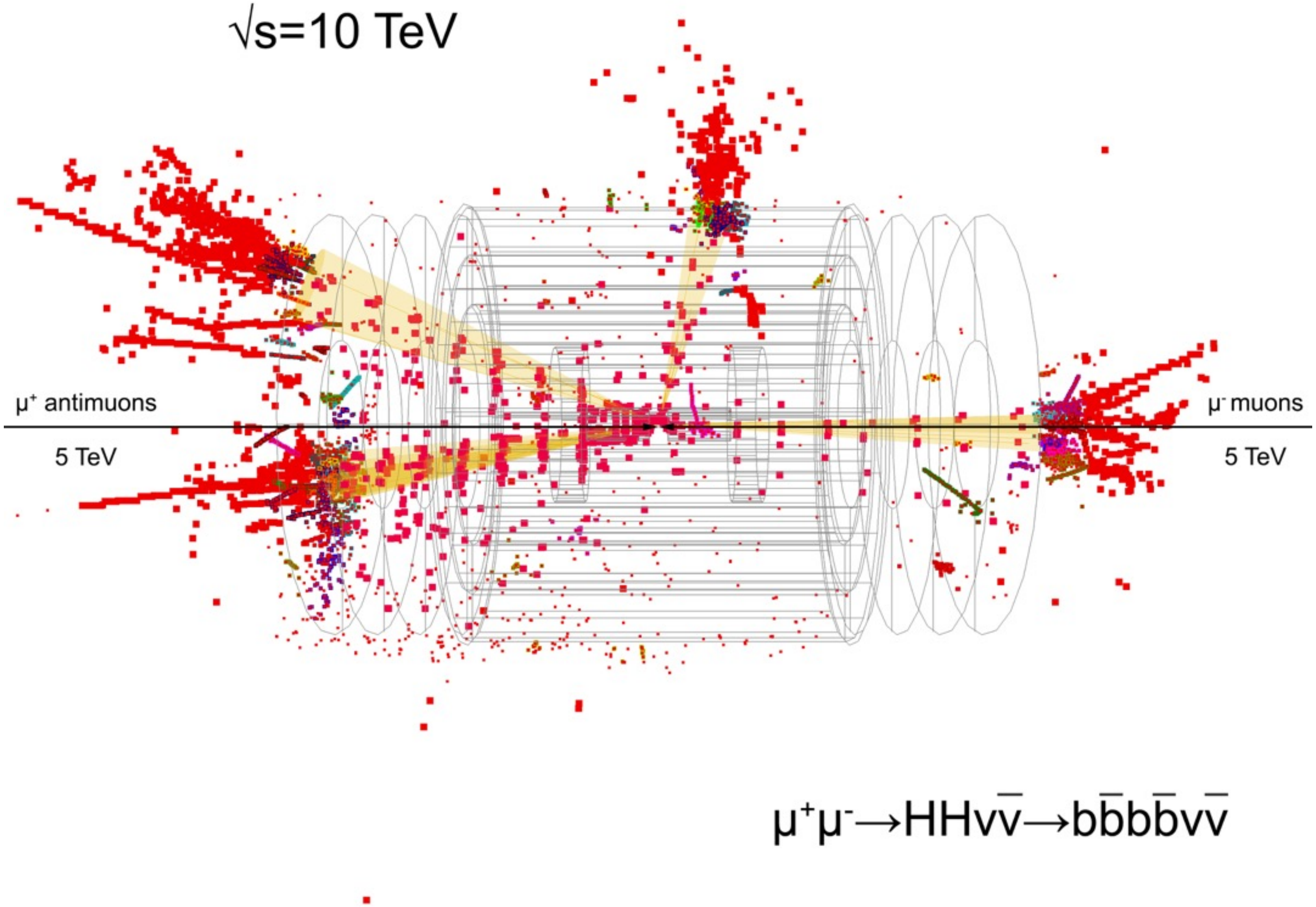


With a simple fit to the BDT output

$$\frac{\Delta\sigma}{\sigma} = 0.33$$

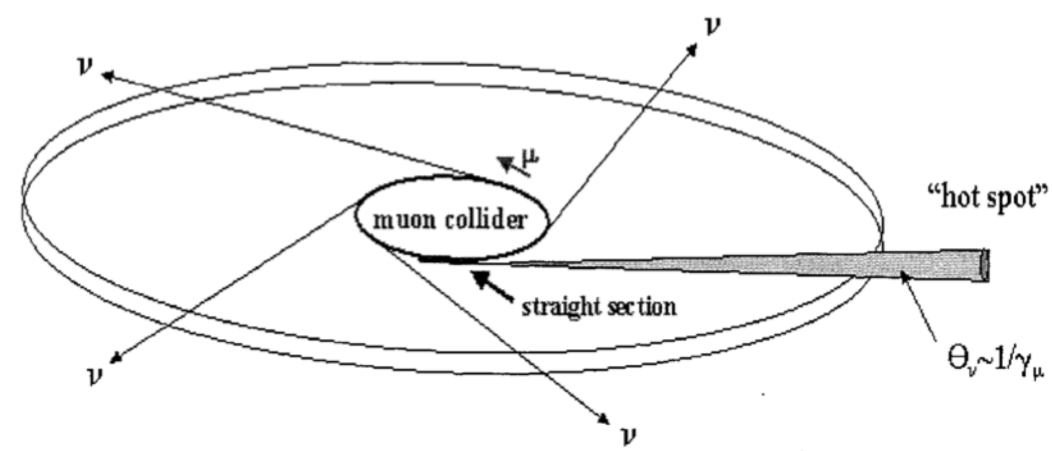
CLIC has 10% with 5 ab^{-1} and very refined analysis

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



Challenge: Neutrino Radiation Hazard

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



Potential mitigation by

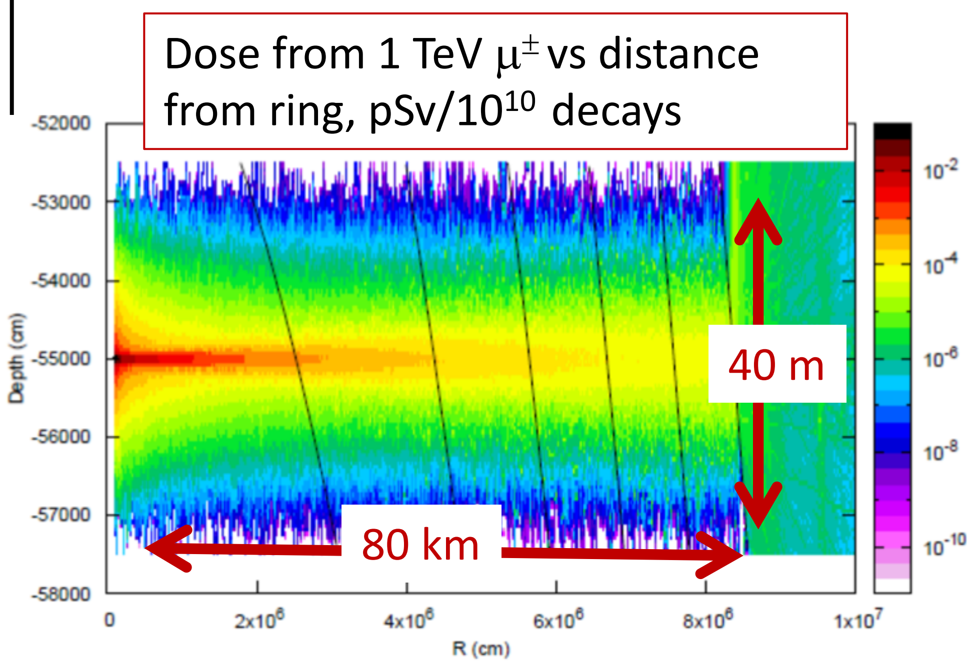
- Site choice
- Having a dynamic beam orbit so it points in different directions at each turn in the arcs
  - Or at least paint the beam in the the straights to dilute radiation

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



Mitigation Approaches

Tricks
e.g. beam wiggling, dumping the beam, …

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

Higher field in collider ring
And shorter gaps

Magnet design

Deeper tunnel

Civil engineering

Denser beam

Source design

Larger energy spread acceptance

Lattice design work

More efficient physics
More years of running

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

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

Synergies on Technologies

- 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
  - …

One year ago…we could state

A Muon Collider has the potential to largely extend the energy frontier:

➔ **an immense physics reach**

➔ **detector studies with beam induced background recently proved physics feasible**

➔ **a possibly affordable cost: [5-10] GCHF - also exploiting existing tunnels**

MAP studies addressed design issues from muon production to final acceleration:

➔ **proton driver option can be used NOW as baseline for a CDR of a 3-6 TeV machine**

➔ **however a 6D cooling TEST FACILITY is MANDATORY to demonstrate feasibility**

A new idea not requiring 6D cooling – **LEMMA** – could represent an appealing scheme:

➔ **further studies and solid R&D program needed for such positron driven option**

Proposed Tentative Timeline (2019)

DETECTOR

- R&D detectors
- Prototypes
- MDI & detector simulations
- CDRs
- TDRs
- Large Proto/Slice test

Technically limited

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

MACHINE

Limited Cost Mainly paper design And some hardware component R&D	Higher cost for test facility Specific prototypes Significant resources	Higher cost for technical design Significant resources	Higher cost for preparation	Full project
Design / models	Prototypes / t. f. comp.	Prototypes / pre-series		

- Ready to decide on test facility
Cost scale known
- Ready to commit to collider
Cost know
- Ready to construct

Looking forward

International Muon Collider Design Study (Accelerator, Detector and Physics)

AMBITION: successful implementation of an **international plan** to address all studies and key issues towards the design of a muon collider capable to reach multi-TeV collision energies with an adequate luminosity for high-precision measurements and new discoveries
CHALLENGES: establish an organized international collaboration to address key issues and plan future steps. Evaluate reuse of existing infrastructures taking into account neutrino radiation hazards. Design of needed **test facilities** to address **final feasibility**.

- **CERN website**
  https://muoncollider.web.cern.ch/
- **INFN Confluence website: full simulation**
  https://confluence.infn.it/display/muoncollider
- **International Design Study Indico @ CERN**
  https://indico.cern.ch/category/11818/
- **Muon Collider SnowMass Forum USA**
  https://indico.fnal.gov/event/47038/

Please subscribe at the

CERN e-group "muoncollider":

MUONCOLLIDER-DETECTOR-PHYSICS

MUST-phydet@cern.ch

MUONCOLLIDER-FACILITY

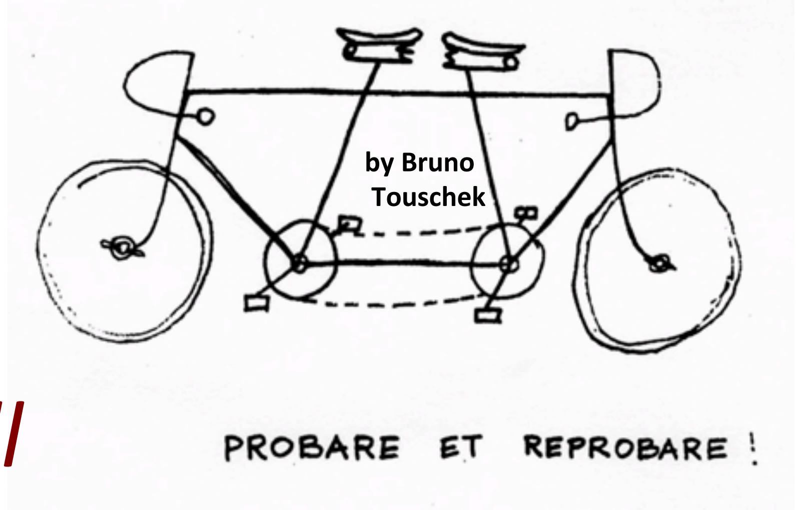
MUST-mac@cern.ch

A special thanks

to many colleagues

in Italy, EU and USA

for sharing this effort and dream



to you all

for the attention, the questions

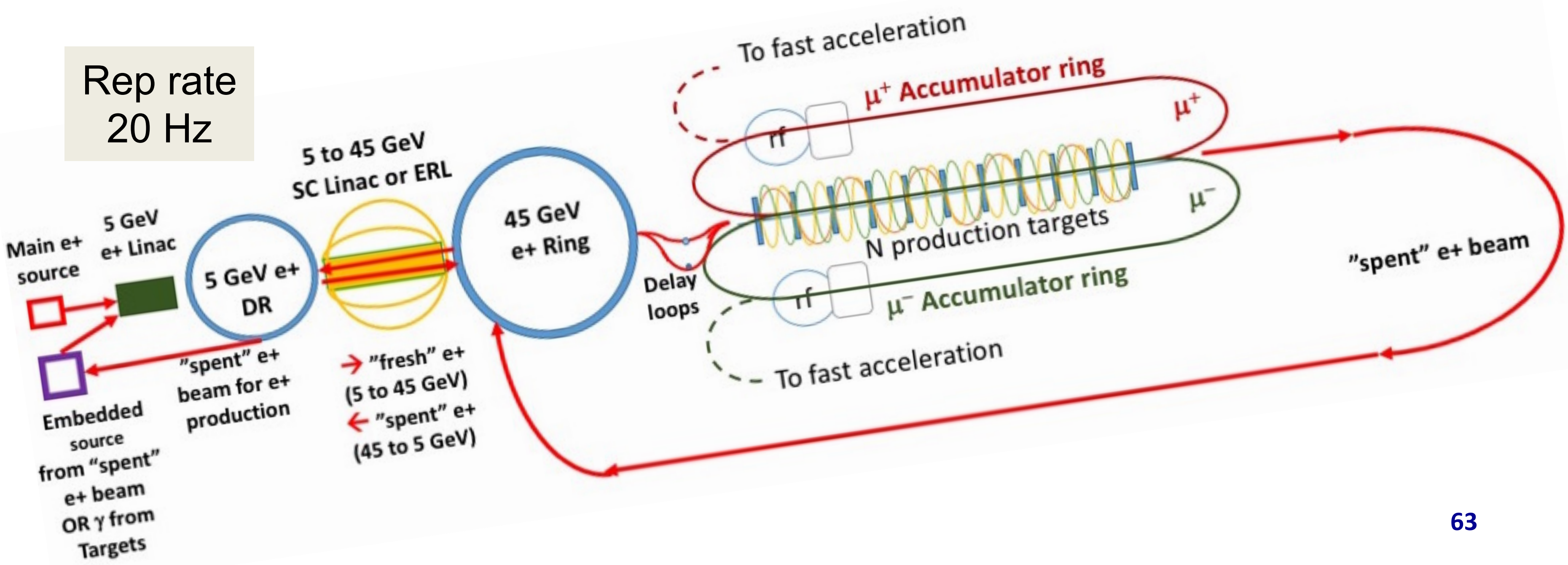
and hopefully a future collaboration!

extras

Low EMittance Muon Accelerator complex layout

- **e^+ source** @300 MeV ➔ 5 GeV Linac
- 5 GeV e^+ **Damping Ring** (damping ~10 ms)
- **SC Linac or ERL**:
  from 5 ➔ 45 GeV and 45 ➔ 5 GeV to cool spent e^+ beam after $\mu^\pm$ production
- **45 GeV e^+ Ring** to accumulate **1000 bunches**: **5×10^{11} e^+/bunch** for $\mu^\pm$ production and e+ spent beam after $\mu^\pm$ production, for slow extraction towards decelerating Linac and the DR
- Delay loops to synchronize e^+ and $\mu^\pm$ bunches
- **One (or more) Target Lines** where e^+ beam collides with targets for direct $\mu^\pm$ production
- 2 Accumulation Rings where $\mu^\pm$ are stored until the bunch has **~10^9 μ/bunch**

Rep rate
20 Hz



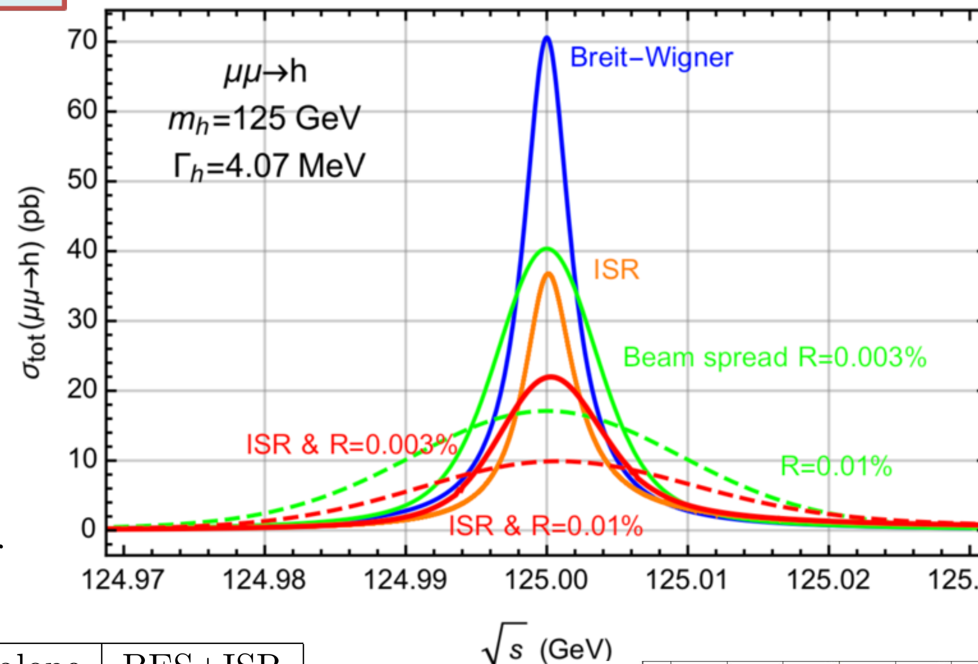
Lepton Colliders: μ vs e @ $\sqrt{s}$=125 GeV

Back on the envelope calculation:

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

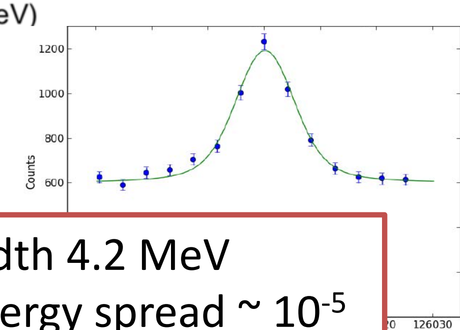
$$\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)$$

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



R: percentage beam energy resolution, key parameter

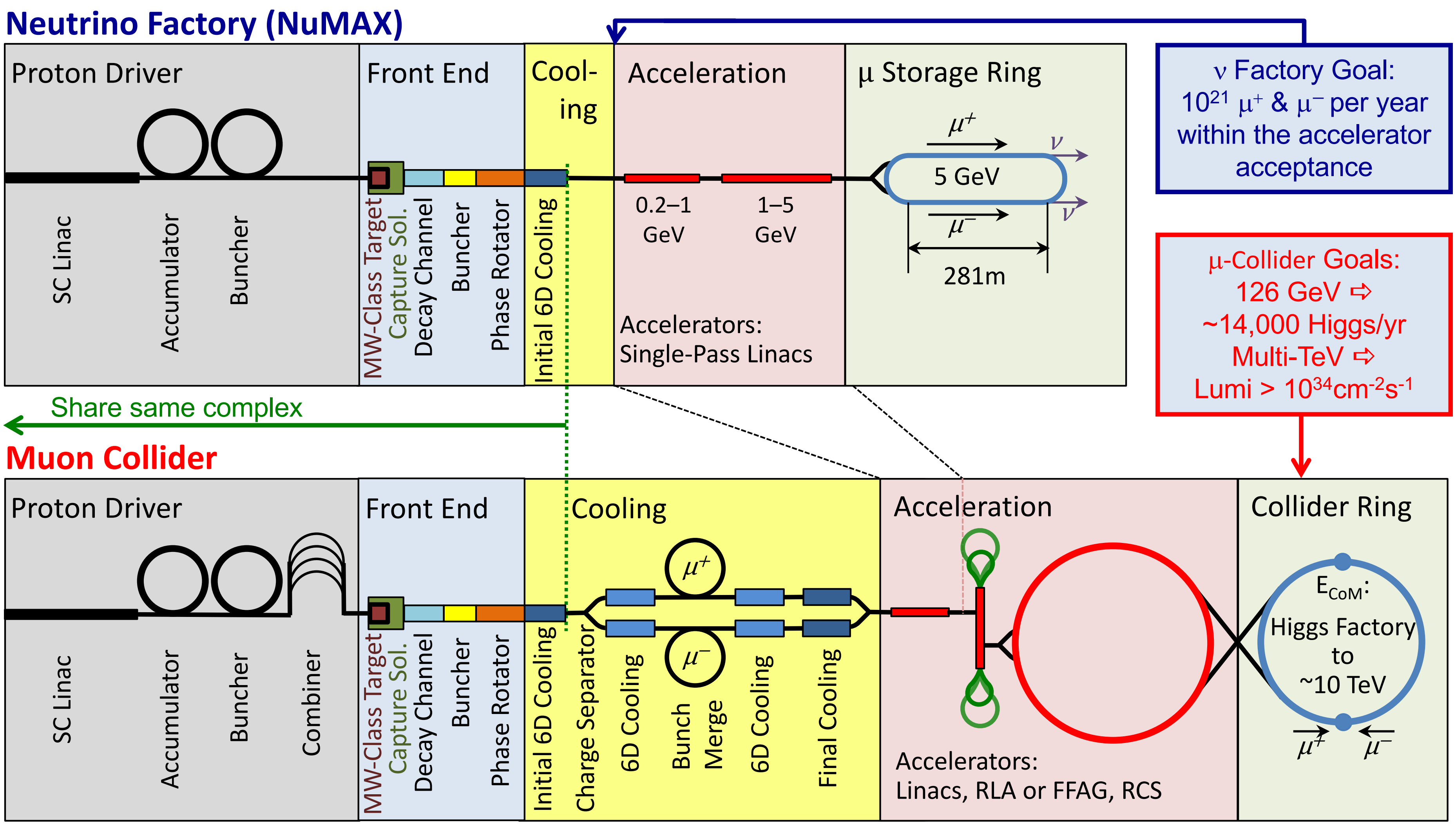
σ(BW)	ISR alone	R (%)	BES alone	BES+ISR
$\mu^+\mu^-$: 71 **pb**	37	0.01	17	10
		0.003	41	22
e^+e^-: 1.7 **fb**	0.50	0.04	0.12	0.048
		0.01	0.41	0.15



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

MAP studies

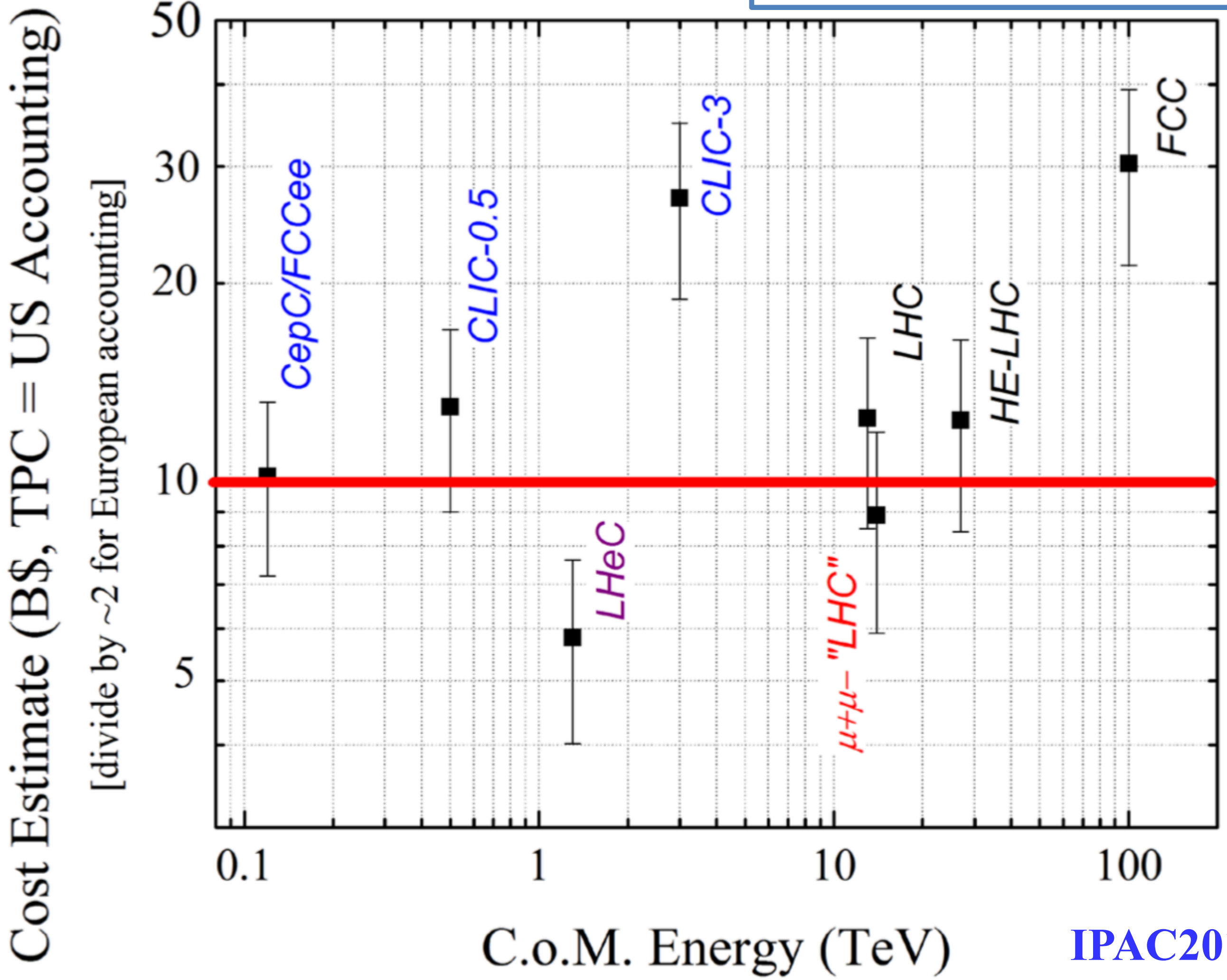
US Muon Accelerator Program (MAP) was established in 2010 to evaluate key ***feasibility issues*** for neutrino factories and muon colliders



Cost estimate

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

Vladimir SHILTSEV, David NEUFFER (Fermilab)



IPAC2018 - MOPMF072