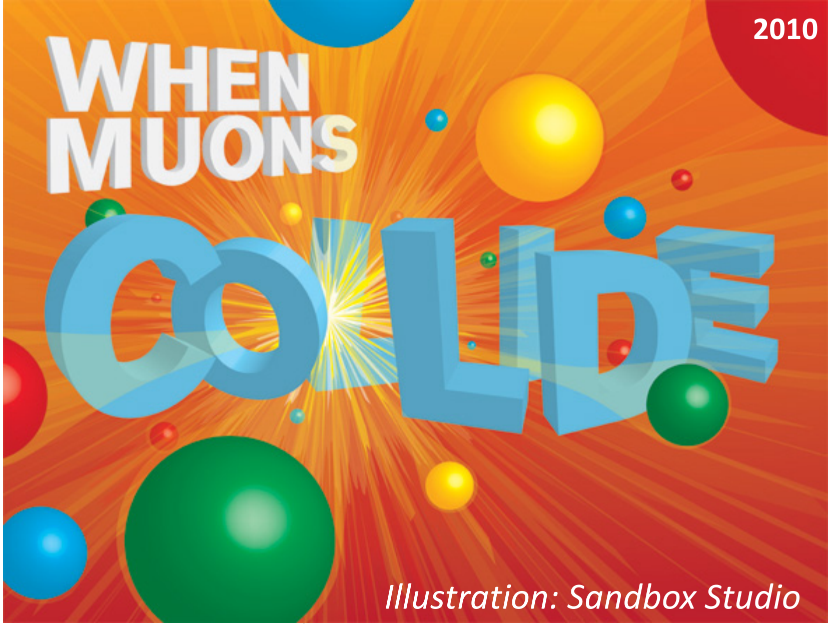


Illustration: Sandbox Studio

www.symmetrymagazine.org

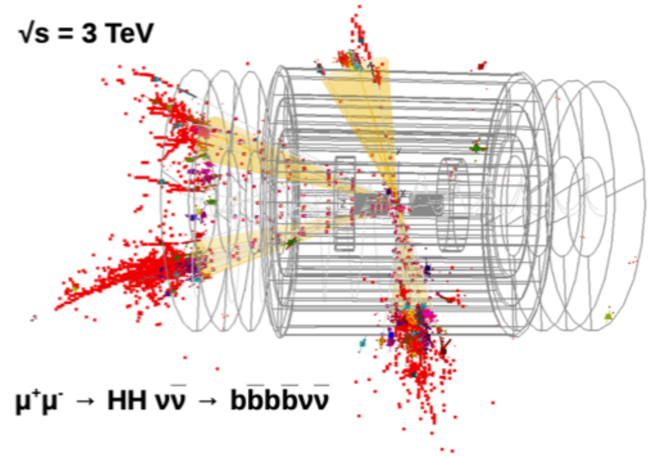
Torino Colloquium
January 29, 2021

Muon Colliders: a challenging opportunity

Present status & Future plans

Nadia Pastrone

INFN TORINO
Istituto Nazionale di Fisica Nucleare
Sezione di Torino



Thanks to many colleagues in Torino, Italy, EU, USA

Open questions

Michelangelo L. Mangano

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

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

  ...

- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation

  ...

One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction....

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

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 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/

….up to now and here!

- Muon Collider for the first time in CERN MTP 2021-2025 (2 MCHF/year)
- MoU is ready to be signed with CERN
- Strong interest and collaboration in USA during the ongoing SnowMass process

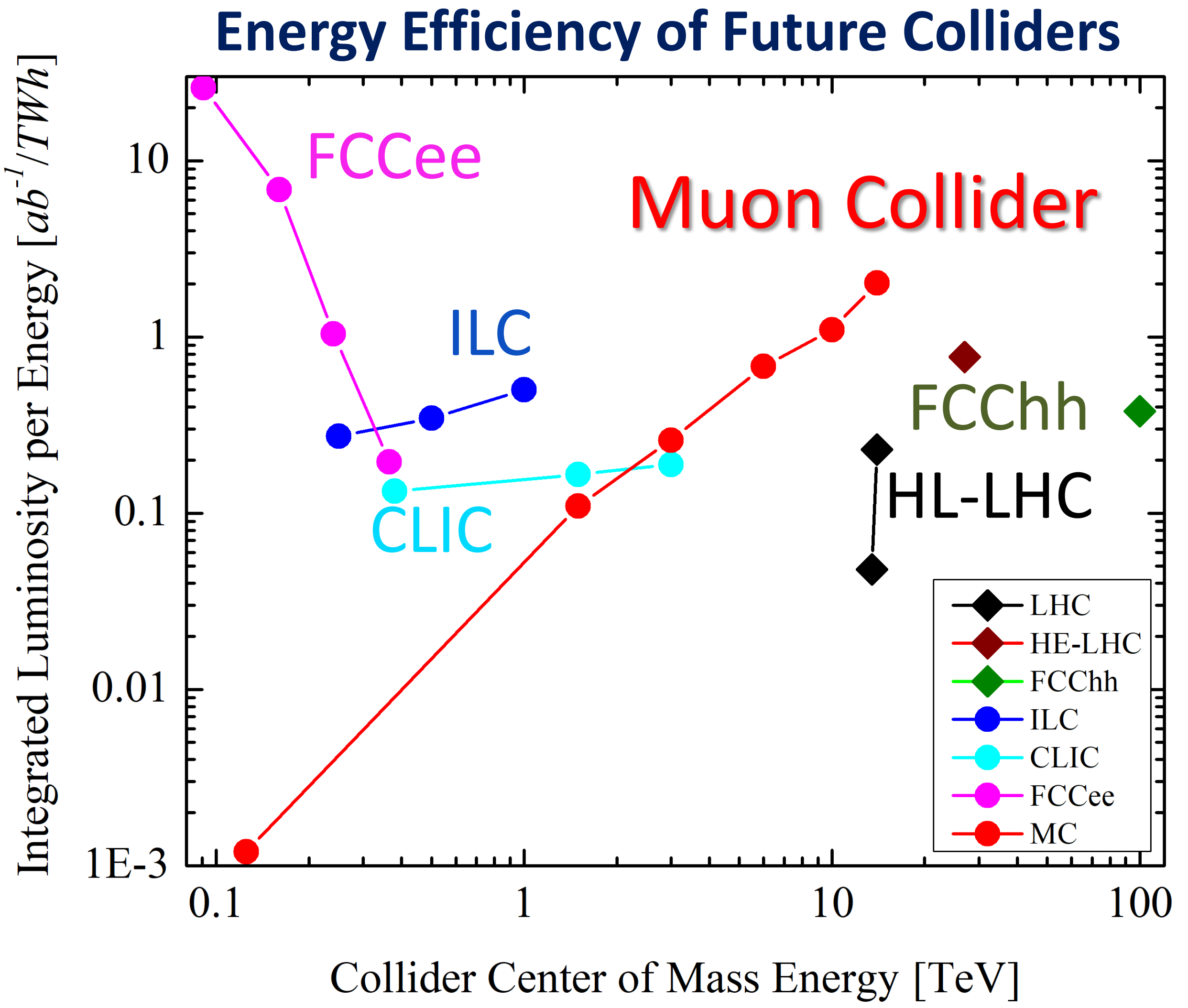
➔ Muon Collider Forum kick-off meeting

https://indico.fnal.gov/event/47038/

- INFN effort in CSN1: RD_MUCOL   ~ 100 people in 13 sections
- Open to collaboration, advice

Figure of merit

doi-org.ezproxy.cern.ch/10.1038/s41567-020-01130-x



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

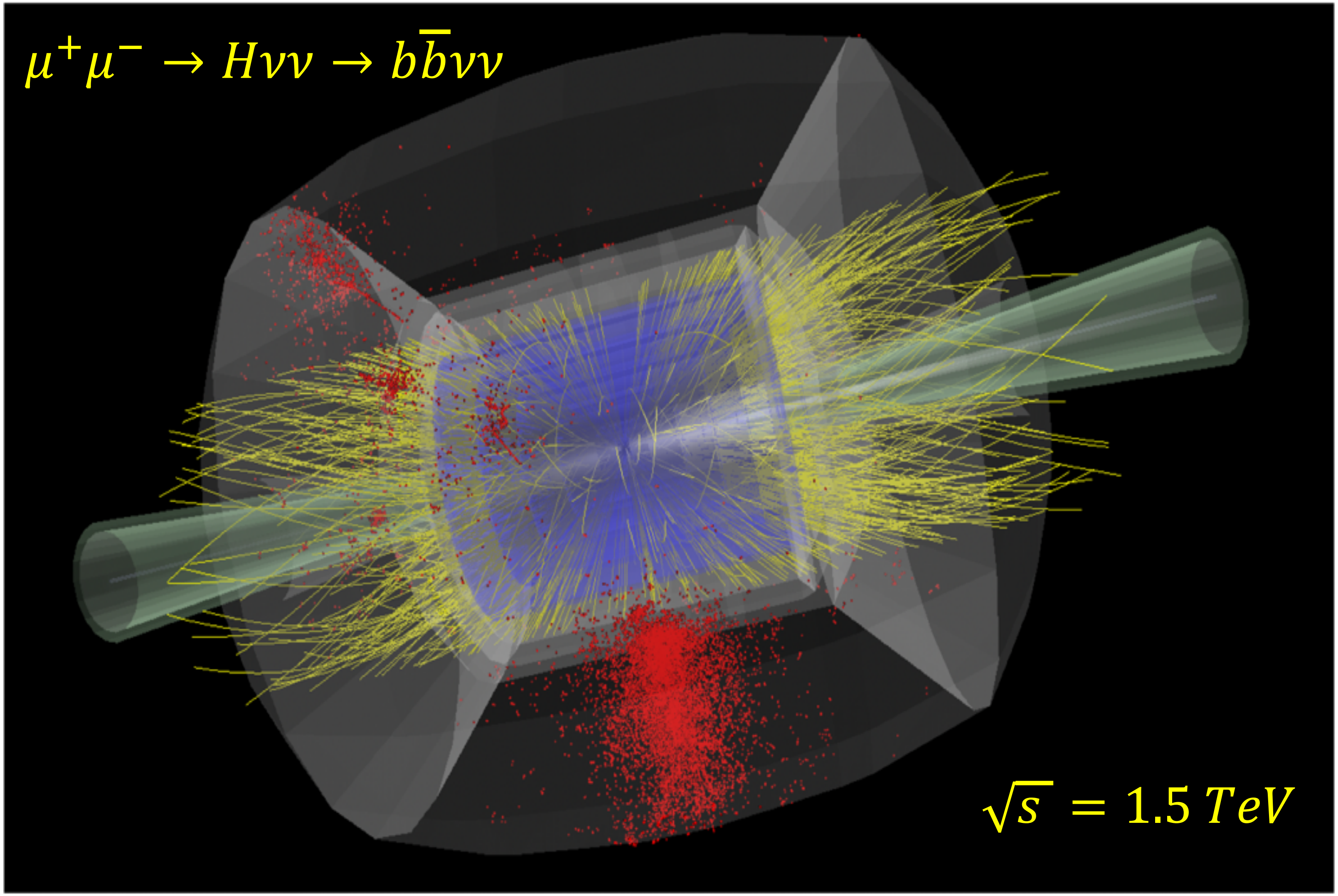
- Intense neutrino beams may cause radiation hazard ➔ could limit ultimate energy

- 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

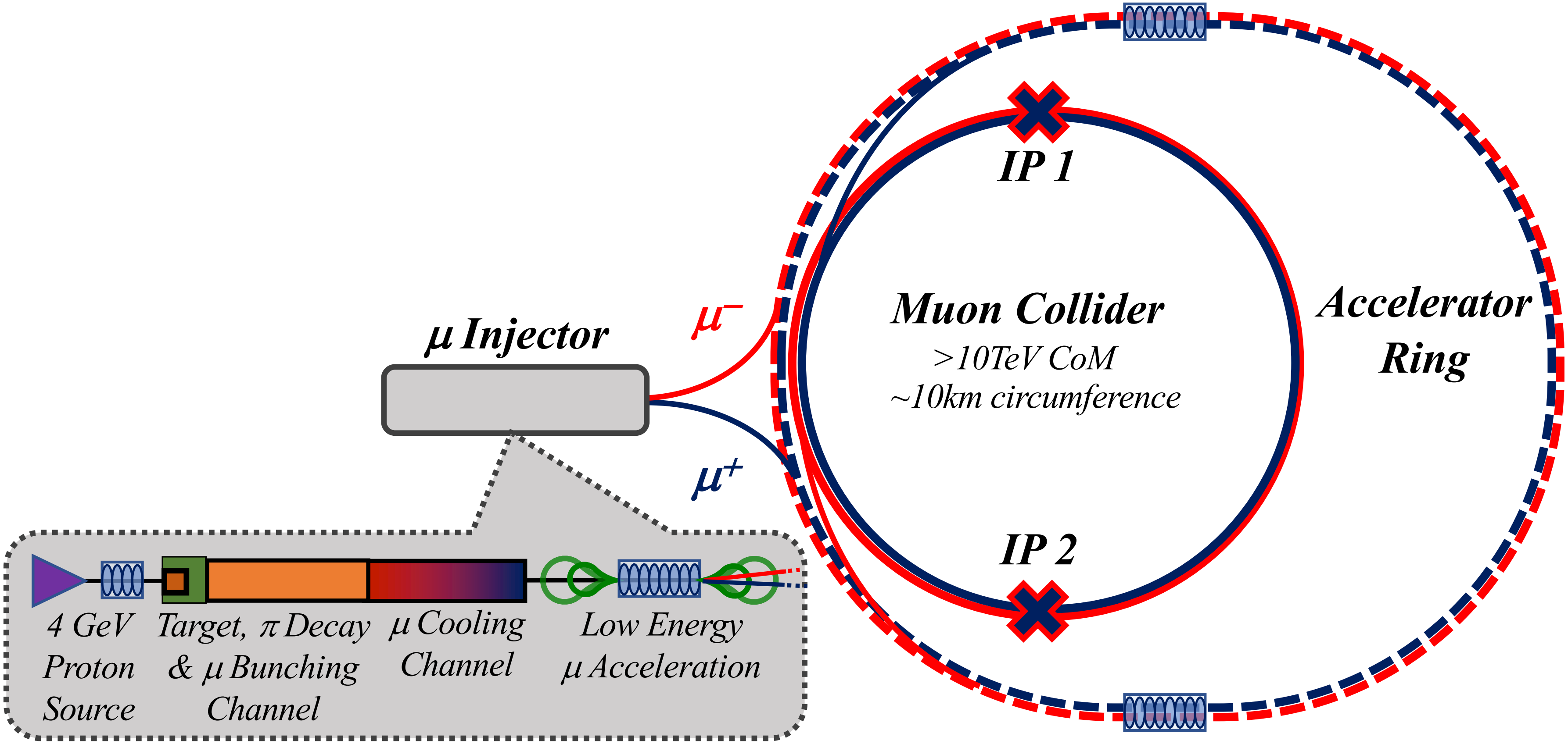
Great opportunities to develop novel ideas and technologies

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

Donatella Lucchesi et al.

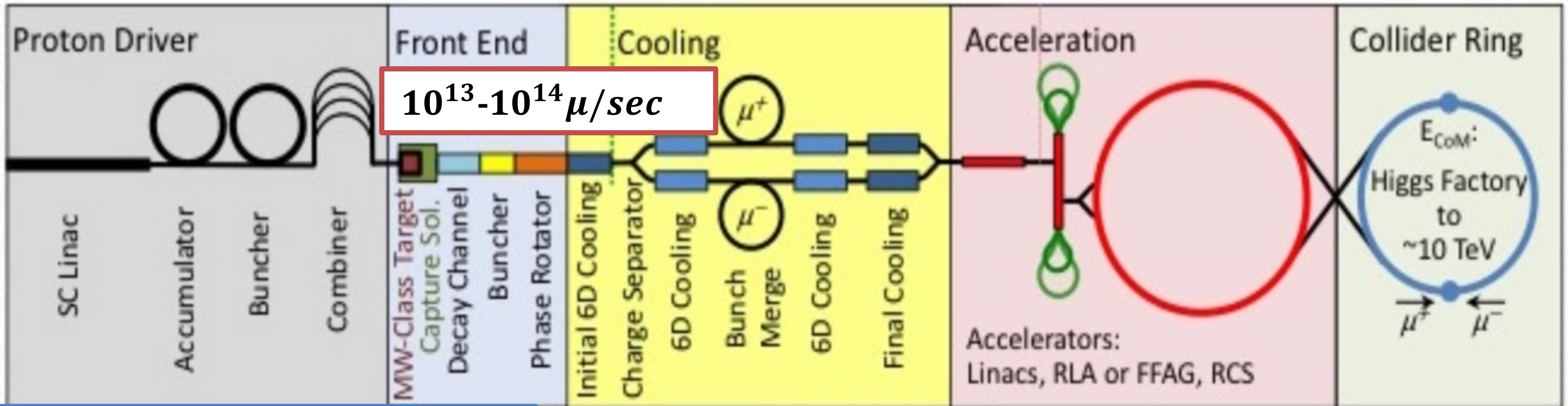


Sketch of the facility



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

MAP

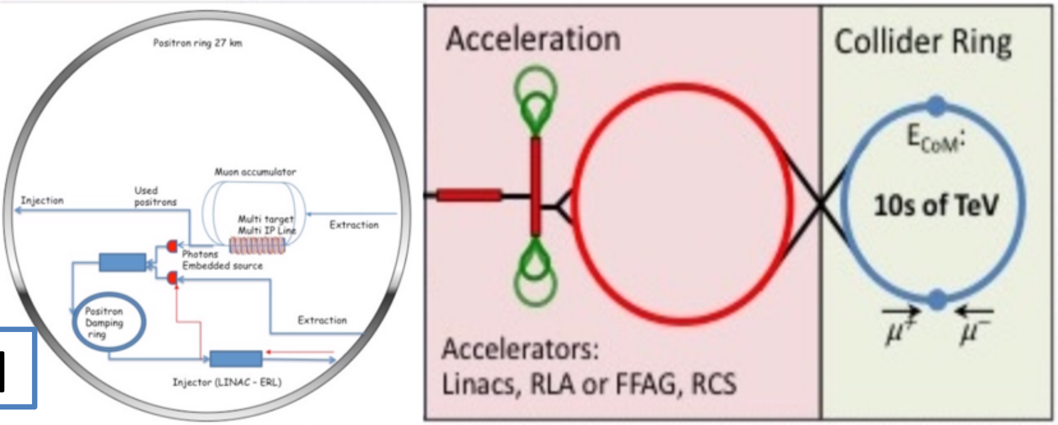


10^{13}-$10^{14}\,\mu/sec$

MUON JINST, shorturl.at/kxKU7

LEMMA

e+ source



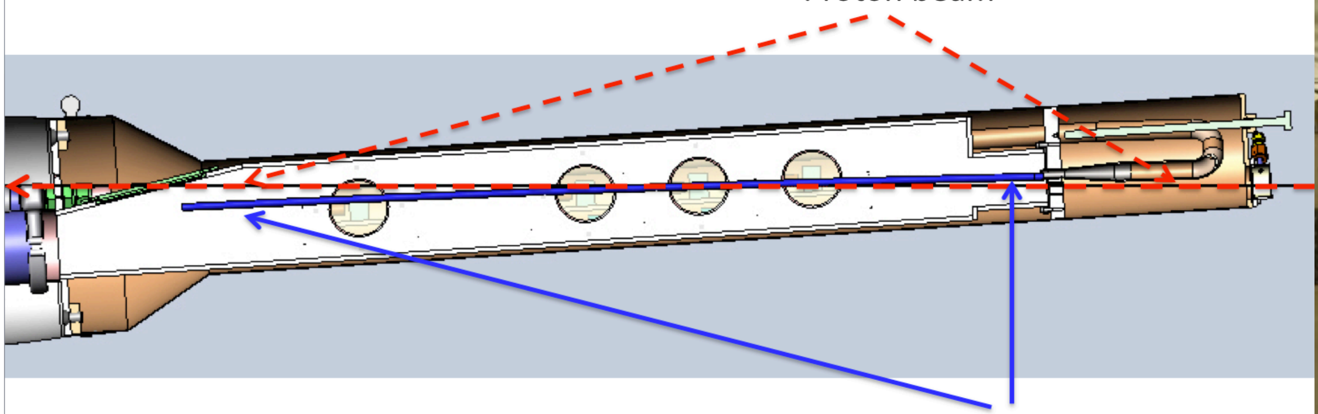
arXiv:1905.05747v2 **[physics.acc-ph]**

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

Source

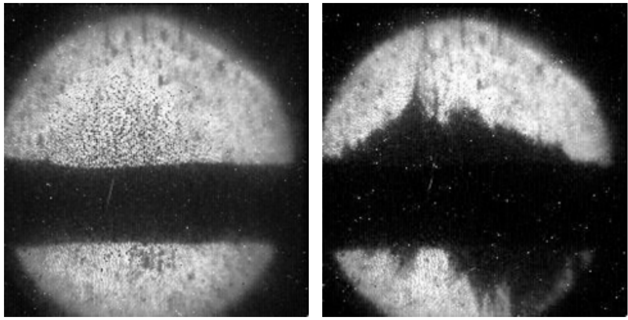
Protons → Target → Pions → Muons

Proton beam



Liquid mercury target to avoid destruction

MERIT experiment at CERN



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

Maximum pulse tested 30x10^{12} protons with 24 GeV

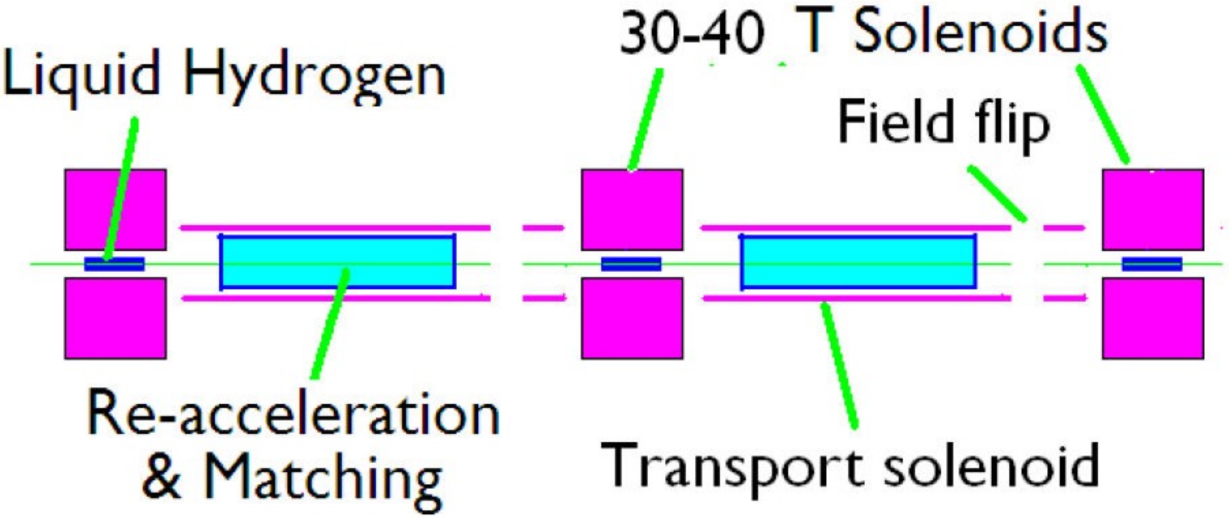
- 9x10^{12} muons (loose 90%)

But radiation issues?

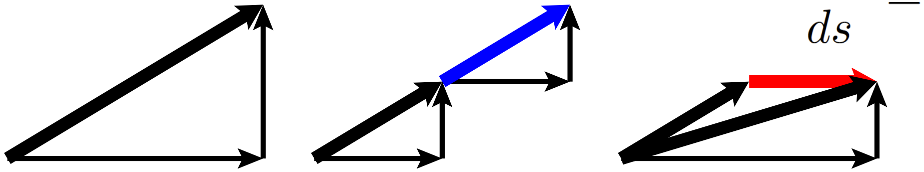
Maybe can use solid target

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

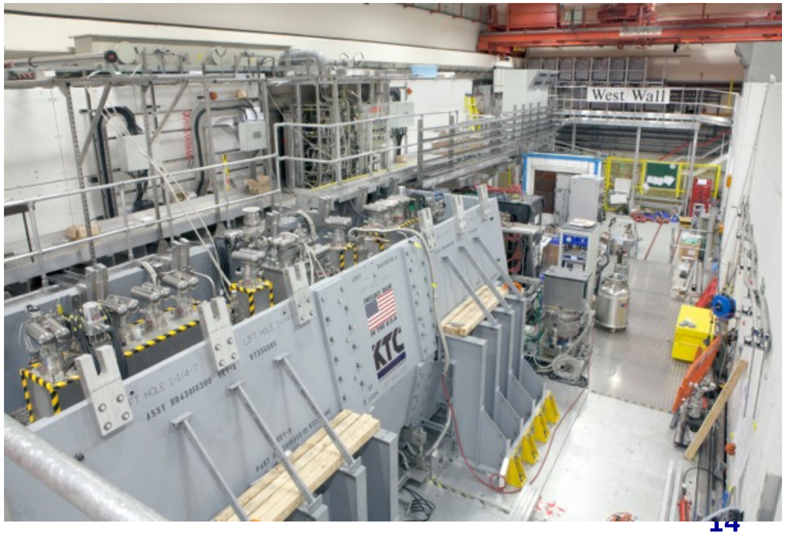
Transverse Cooling Concept



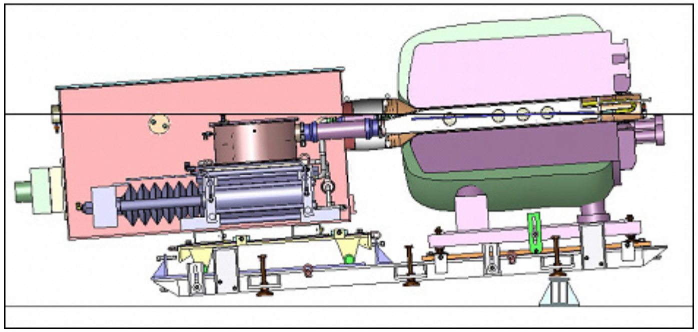
$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$



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

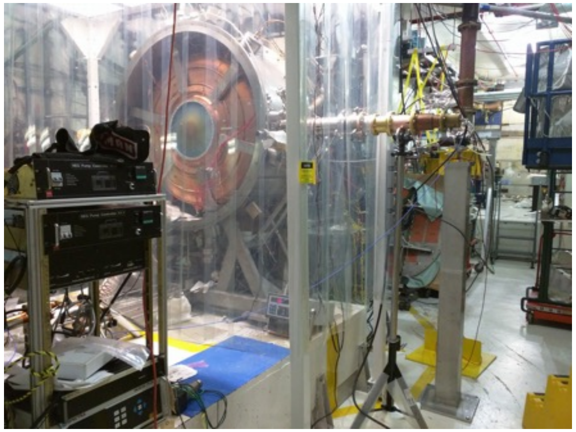


International R&D program



MERIT - CERN

Demonstrated principle of liquid Mercury jet target

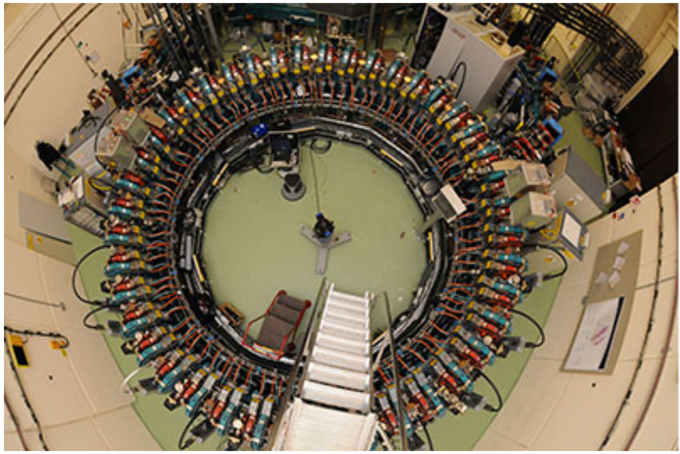


MuCool Test Area - FNAL

Demonstrated operation of RF cavities in strong B fields

EMMA - STFC Daresbury Laboratory

Showed rapid acceleration in non-scaling FFA



MICE - RAL

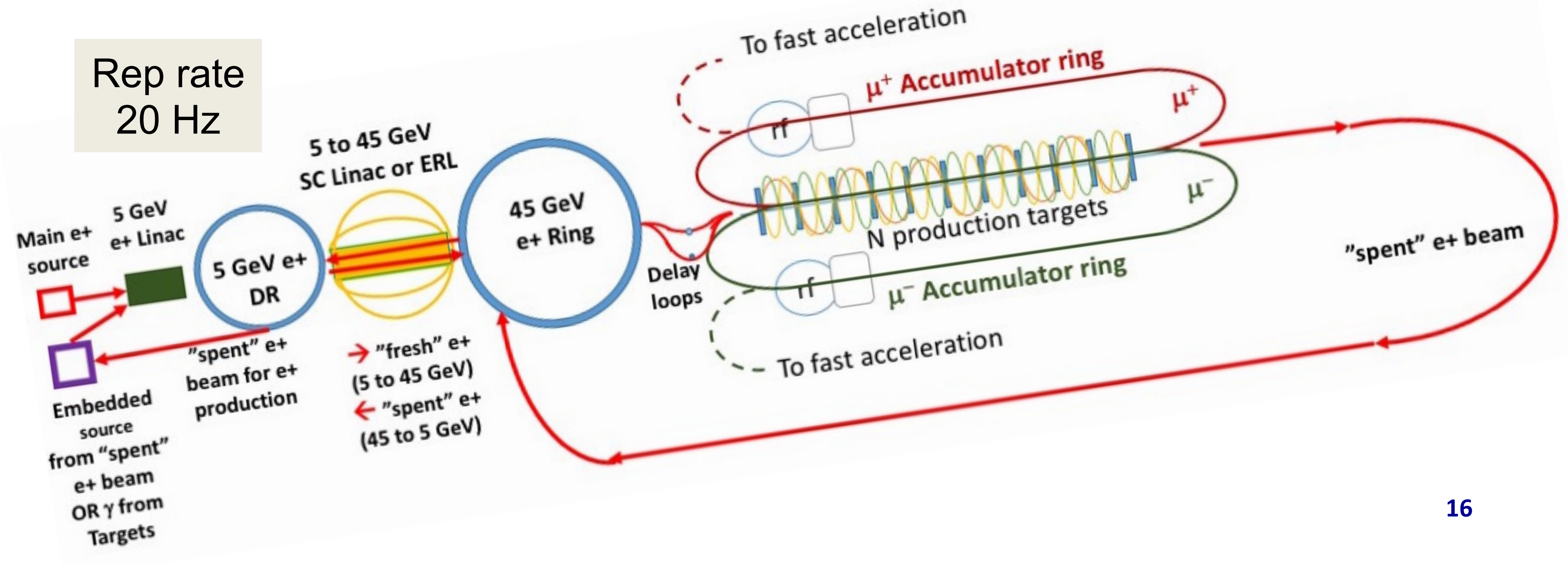
Demonstrate ionization cooling principle
Increase inherent beam brightness
→ number of particles in the beam core
“Amplitude”

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**:

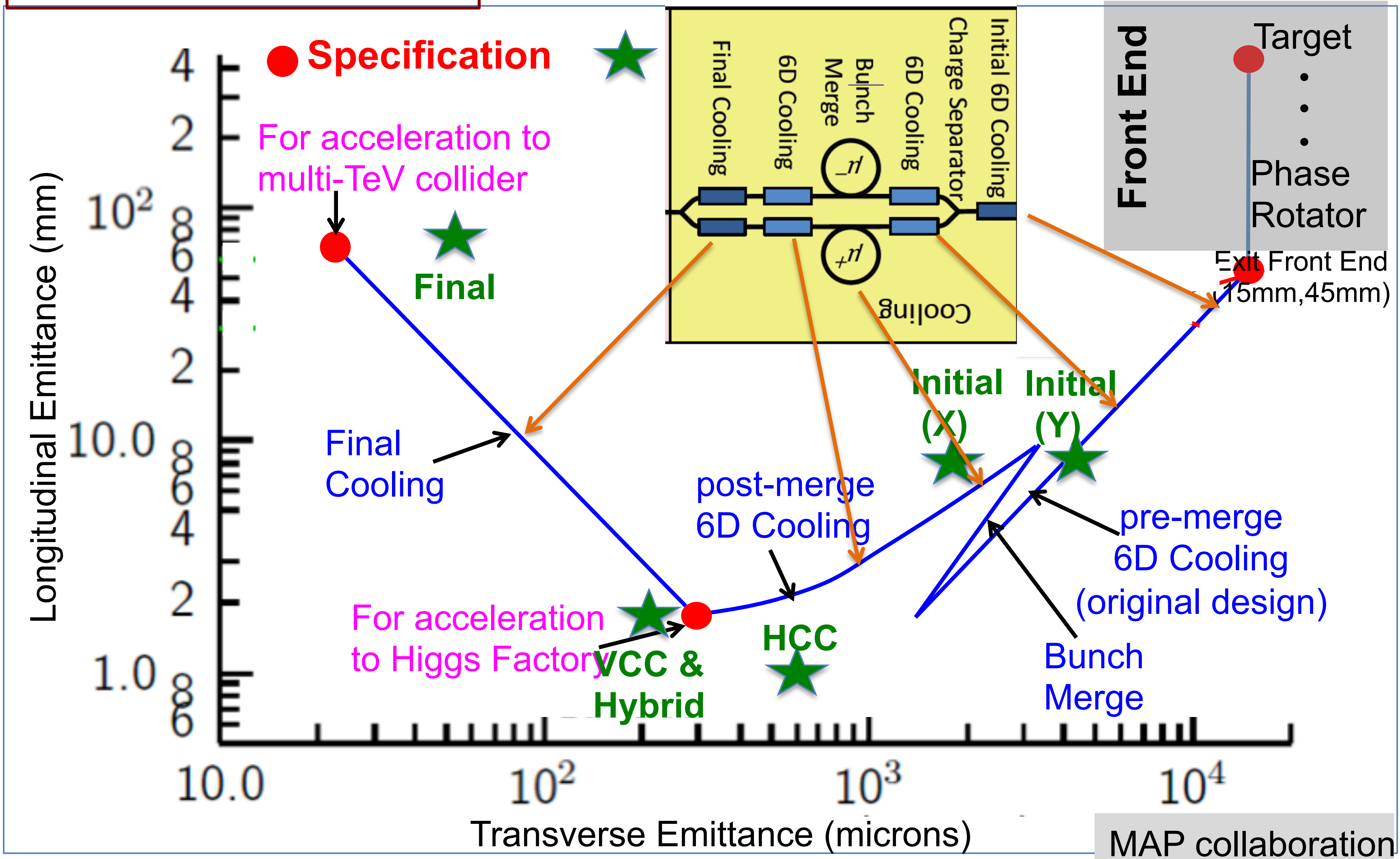
  from 5 ➔ 45 GeV and 45 ➔ 5 GeV to cool spent e^+ beam after $\mu^\pm$ production
- **45 GeV e^+ Ring** to accumulate **1000 bunches**: **5×10^{11} e^+/bunch** for $\mu^\pm$ production and e+ spent beam after $\mu^\pm$ production, for slow extraction towards decelerating Linac and the DR
- Delay loops 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



Cooling: Emittance Path

Highest field HTS
Phase space beam manipulations



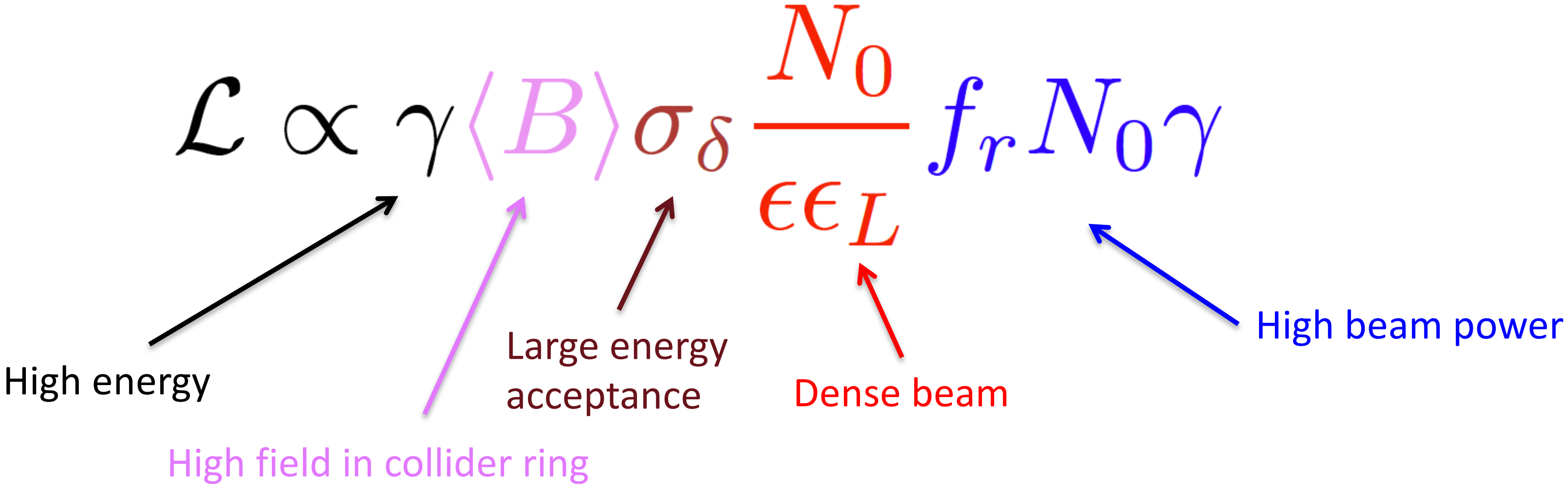
MAP collaboration

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

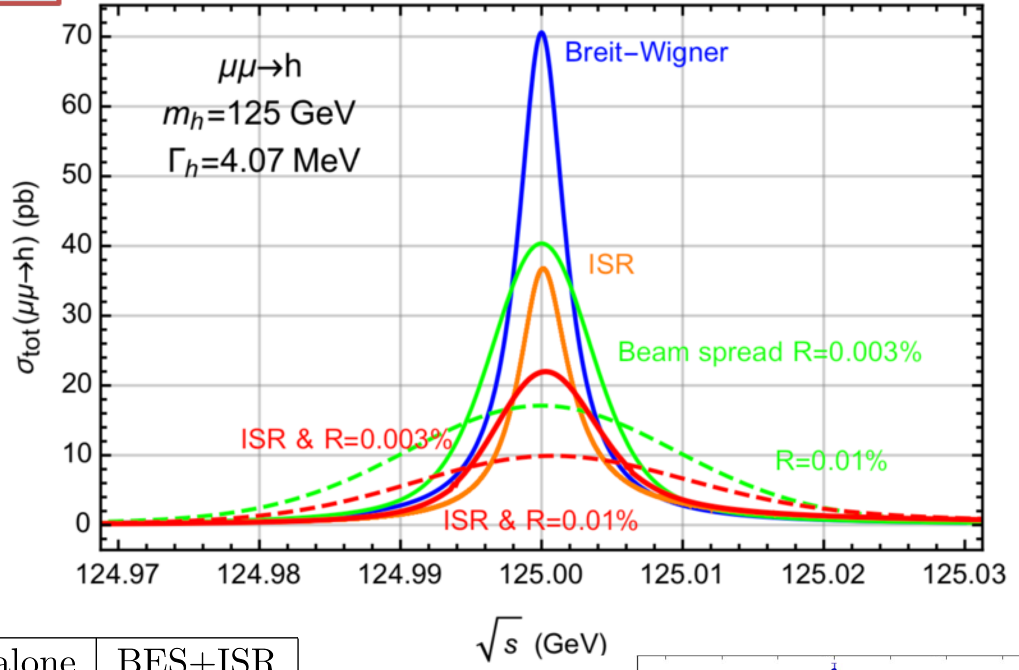
Lepton Colliders: μ vs e @ $\sqrt{s}$=125 GeV

Back on the envelope calculation:

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

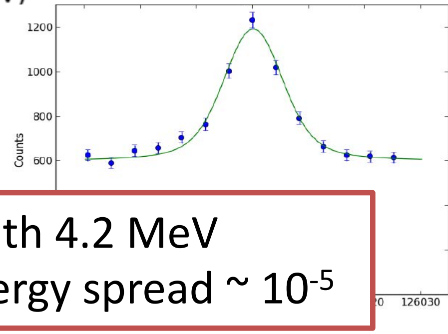
$$\boxed{\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)}$$

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}

Towards the highest possible energy

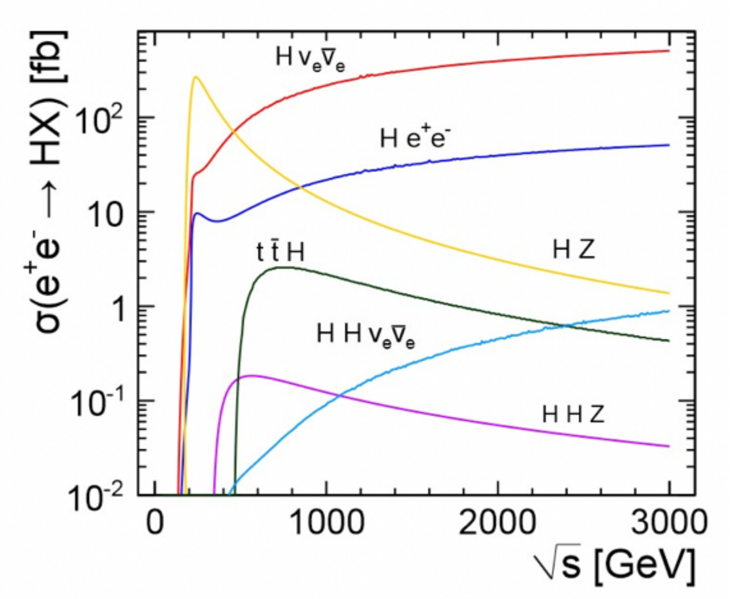
- **Overwhelming physics potential:**
  - Discovery searches ➔ high energy at pointlike level ➔ new perspectives! (pair production of heavy particles up to M ~ ½ $\sqrt{s_{\mu\mu}}$)
  - Precision measures ➔ Higgs physics
  - Many new directions for BSM

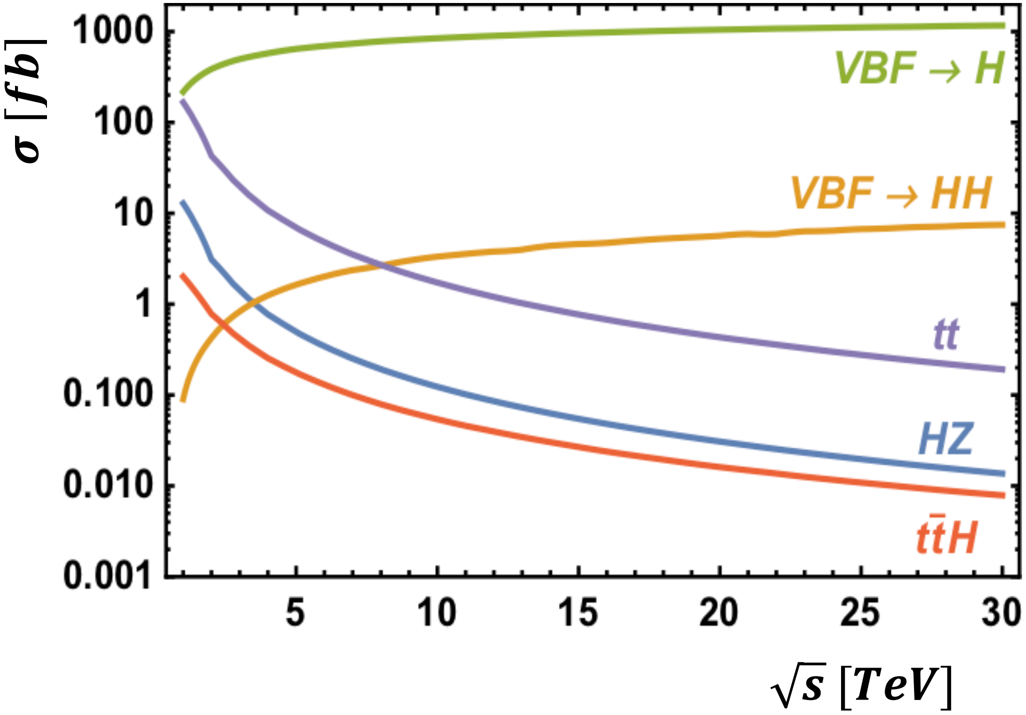
- Focus on two energy ranges:
  - **1-3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, requires more advanced technology: enters uncharted territory

➔ **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]

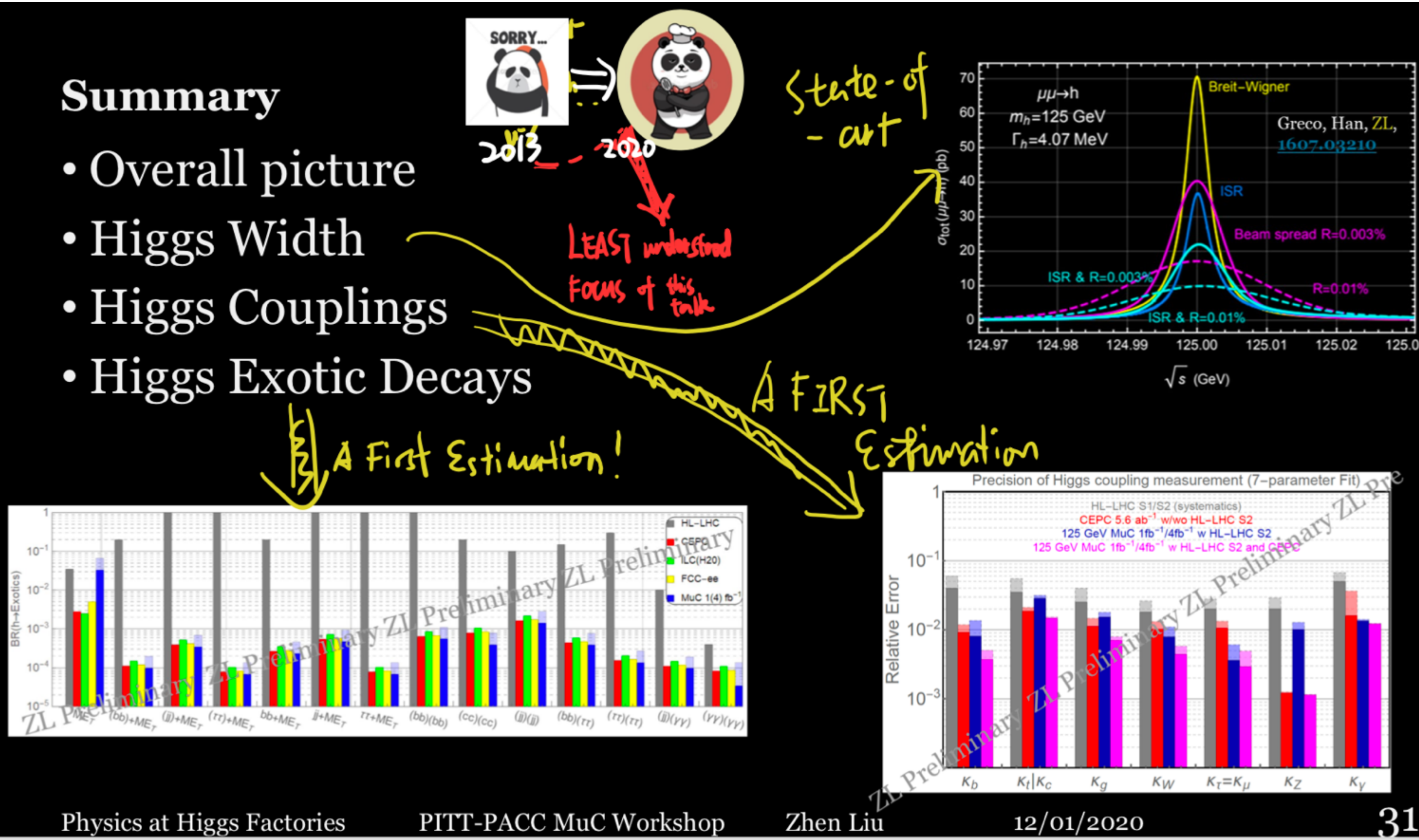
Quadrilinear coupling k_4

$\sqrt{s}$=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



Summary

- Overall picture
- Higgs Width
- Higgs Couplings
- Higgs Exotic Decays

2013 → 2020

LEAST understood

Focus of this talk

State-of-art

A FIRST Estimation

A First Estimation!

Greco, Han, ZL, 1607.03210

Precision of Higgs coupling measurement (7-parameter Fit)

Physics at Higgs Factories PITT-PACC MuC Workshop Zhen Liu 12/01/2020 31

Physics at high energy

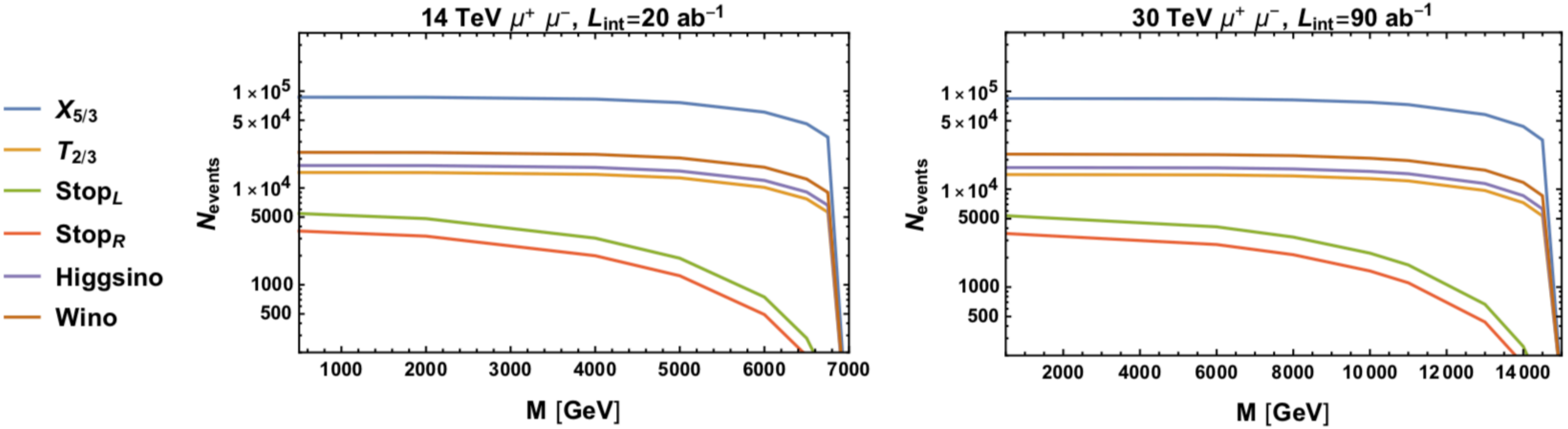
Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly

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



Few Preliminary Results

A. Wulzer et al.

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

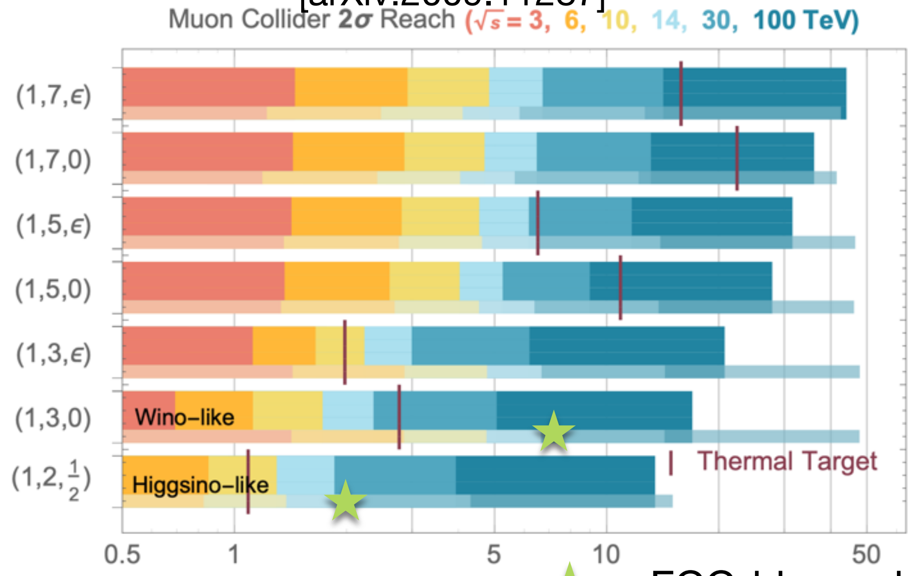
[2008.12204; 2005.10289; Buttazzo, Franceschini, Wulzer, to appear]
[FCC reach is from 3.5 to 8.1% depending on systematics assumptions]

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]

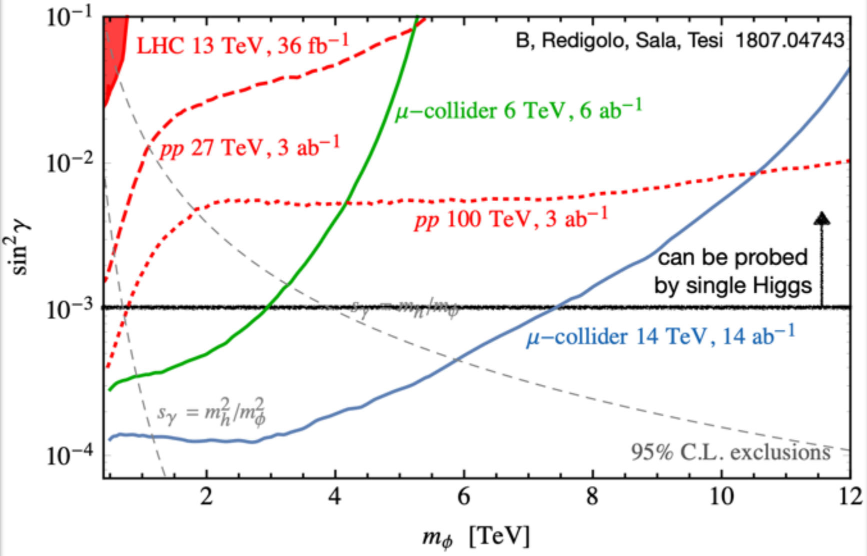
WIMP DM

[arXiv:2009.11287]



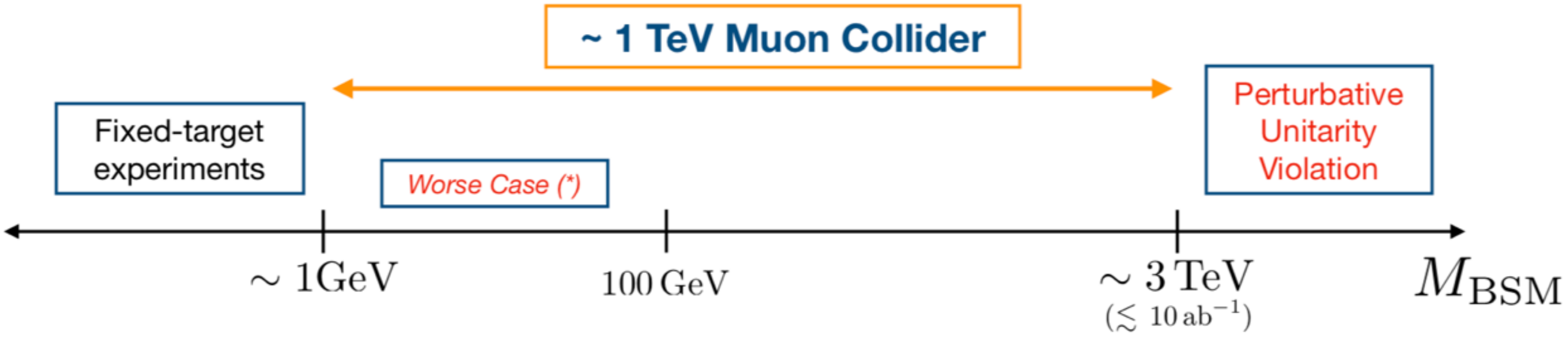
★ = FCC-hh reach

Scalar Singlet



g-2 @ Muon Collider

- Singlet Models



~ 1 TeV Muon Collider

Fixed-target experiments

Worse Case (*)

Perturbative Unitarity Violation

$\sim 1\,\mathrm{GeV}$

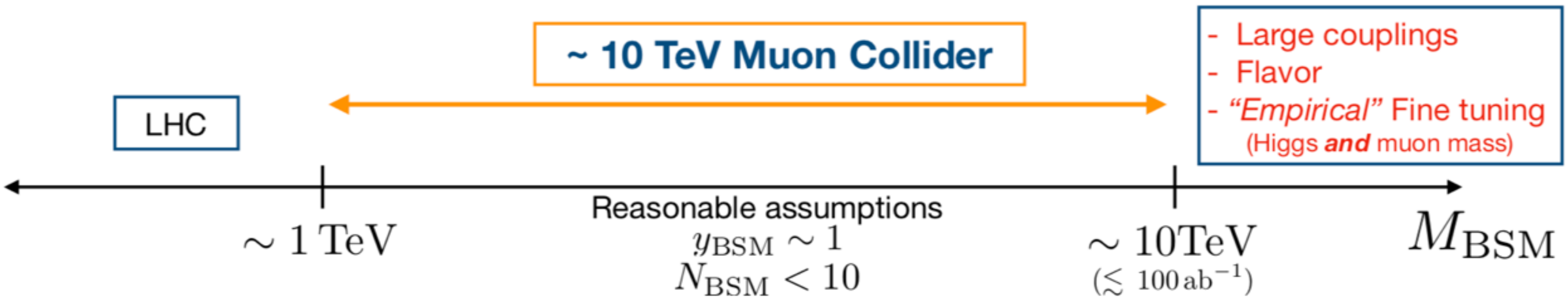
$100\,\mathrm{GeV}$

$\sim 3\,\mathrm{TeV}$

$(\lesssim 10\,\mathrm{ab}^{-1})$

M_{BSM}

- High-Scale EW Models



~ 10 TeV Muon Collider

LHC

- Large couplings
- Flavor
- *"Empirical"* Fine tuning
  (Higgs ***and*** muon mass)

$\sim 1\,\mathrm{TeV}$

Reasonable assumptions

$y_{\mathrm{BSM}} \sim 1$

$N_{\mathrm{BSM}} < 10$

$\sim 10\,\mathrm{TeV}$

$(\lesssim 100\,\mathrm{ab}^{-1})$

M_{BSM}

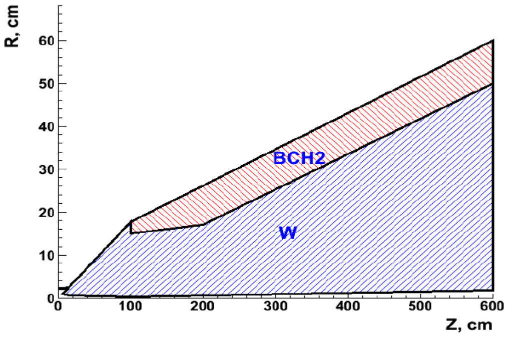
Full simulation: beam induced background

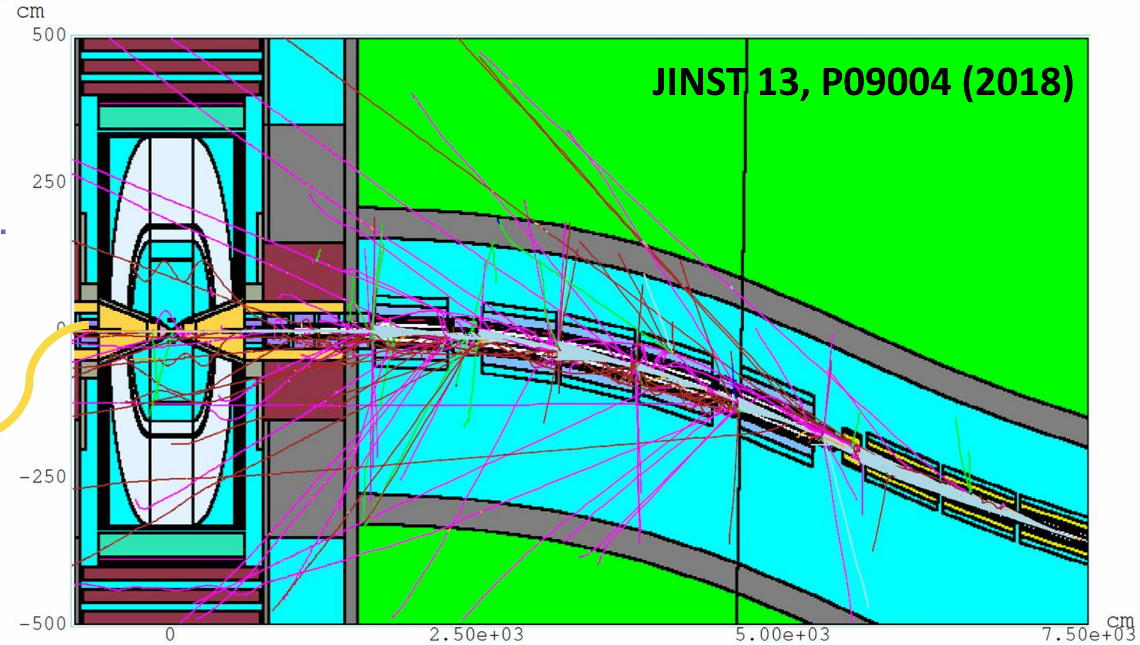
Nikolai Mokhov et al. - MARS15

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.





JINST 13, P09004 (2018)

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

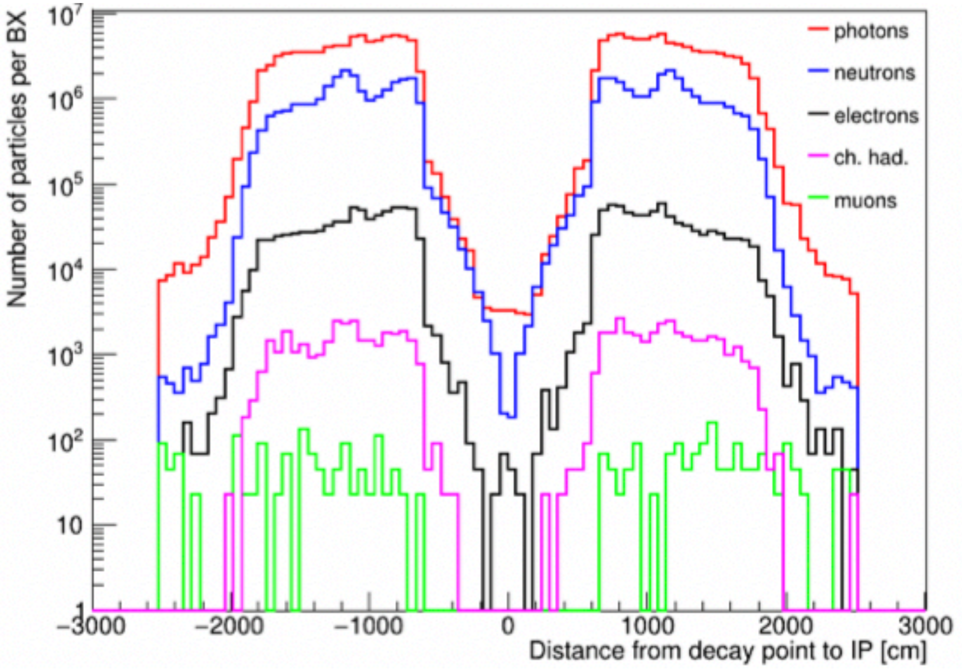
Beam Induced background @ 1.5 TeV

Nikolai Mokhov et al. - MARS15

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

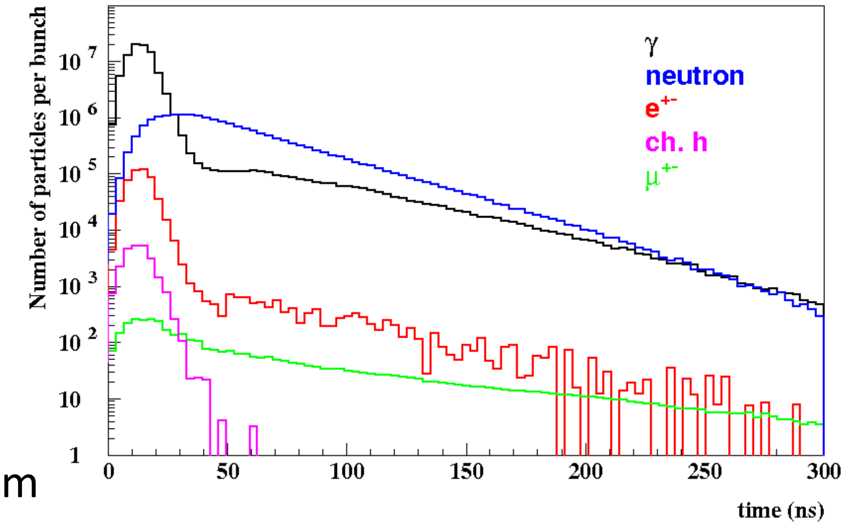
Beam muons decay products interact with machine elements and cause a continuous flux of secondary and tertiary particles (mainly γ, n, e±, h±) that eventually reach the detector

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



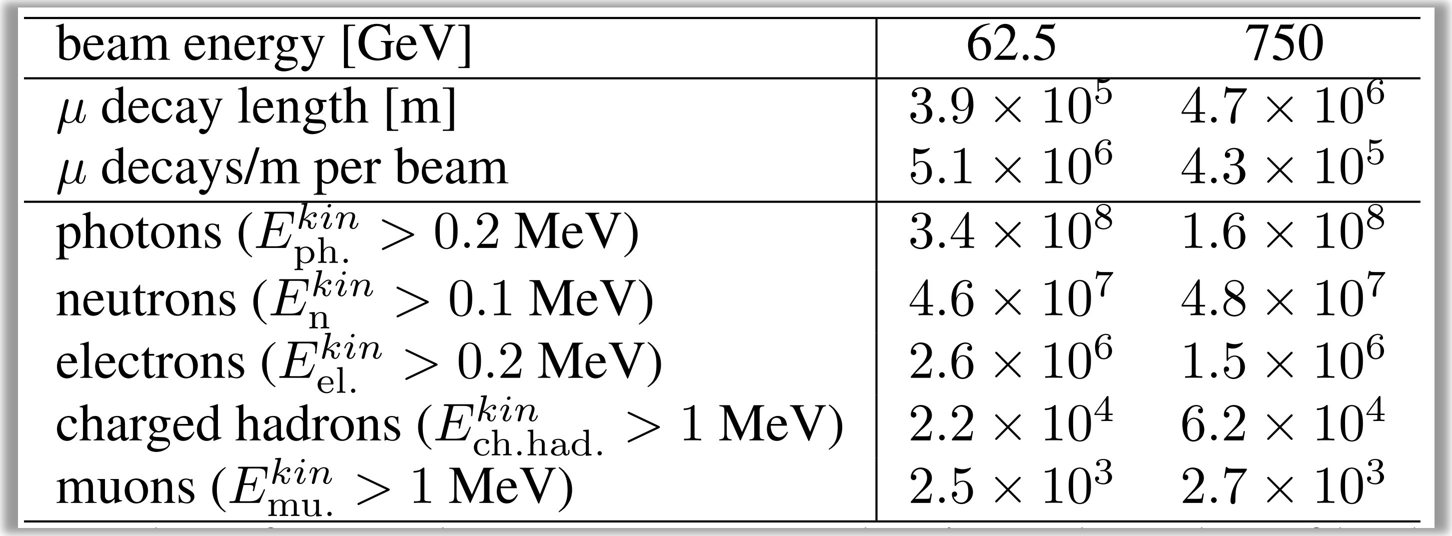
muon beams of **0.75 TeV** with **2×10^{12}muons/bunch**

➔ **4×10^5 muon decays/m** in single bunch crossing



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

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



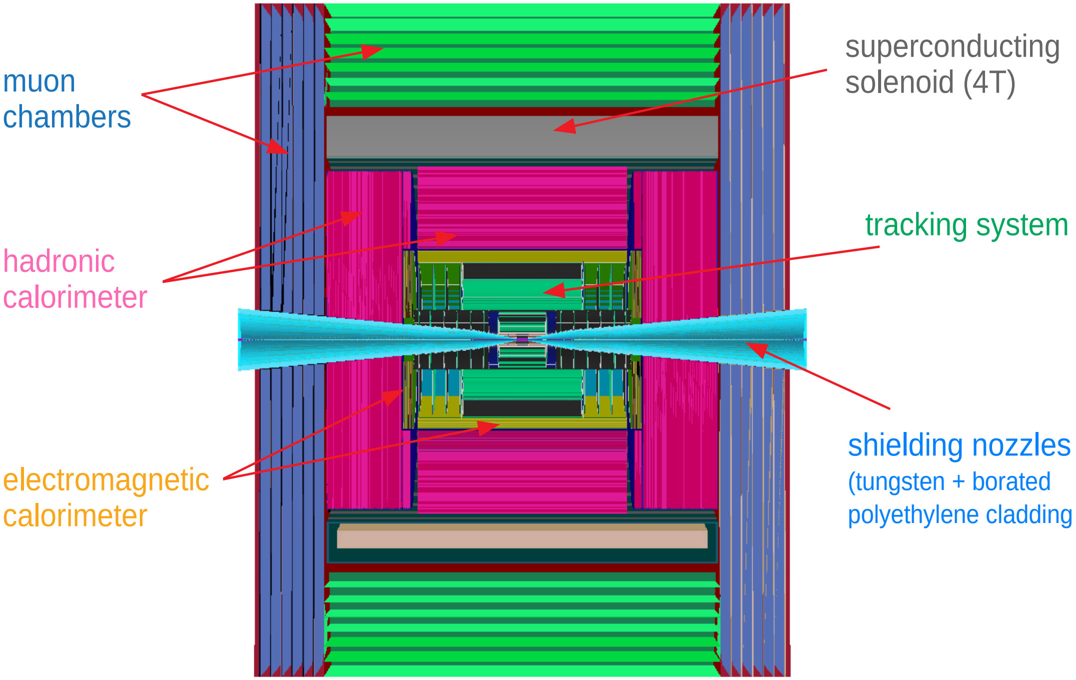
beam energy [GeV]	62.5	750
μ decay length [m]	3.9×10^5	4.7×10^6
μ decays/m per beam	5.1×10^6	4.3×10^5
photons ($E^{kin}_{\mathrm{ph.}} > 0.2$ MeV)	3.4×10^8	1.6×10^8
neutrons ($E^{kin}_{\mathrm{n}} > 0.1$ MeV)	4.6×10^7	4.8×10^7
electrons ($E^{kin}_{\mathrm{el.}} > 0.2$ MeV)	2.6×10^6	1.5×10^6
charged hadrons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

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 25x25μm^2
- 4+4 double-sensor disks 25x25μm^2

Inner Tracker (IT)

- 3 barrel layers 50x50μm^2
- 7+7 disks ”

Outer Tracker(OT)

- 3 barrel layers 50x50μm^2
- 4+4 disks ”

Electromagnetic Calorimeter (ECAL)

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

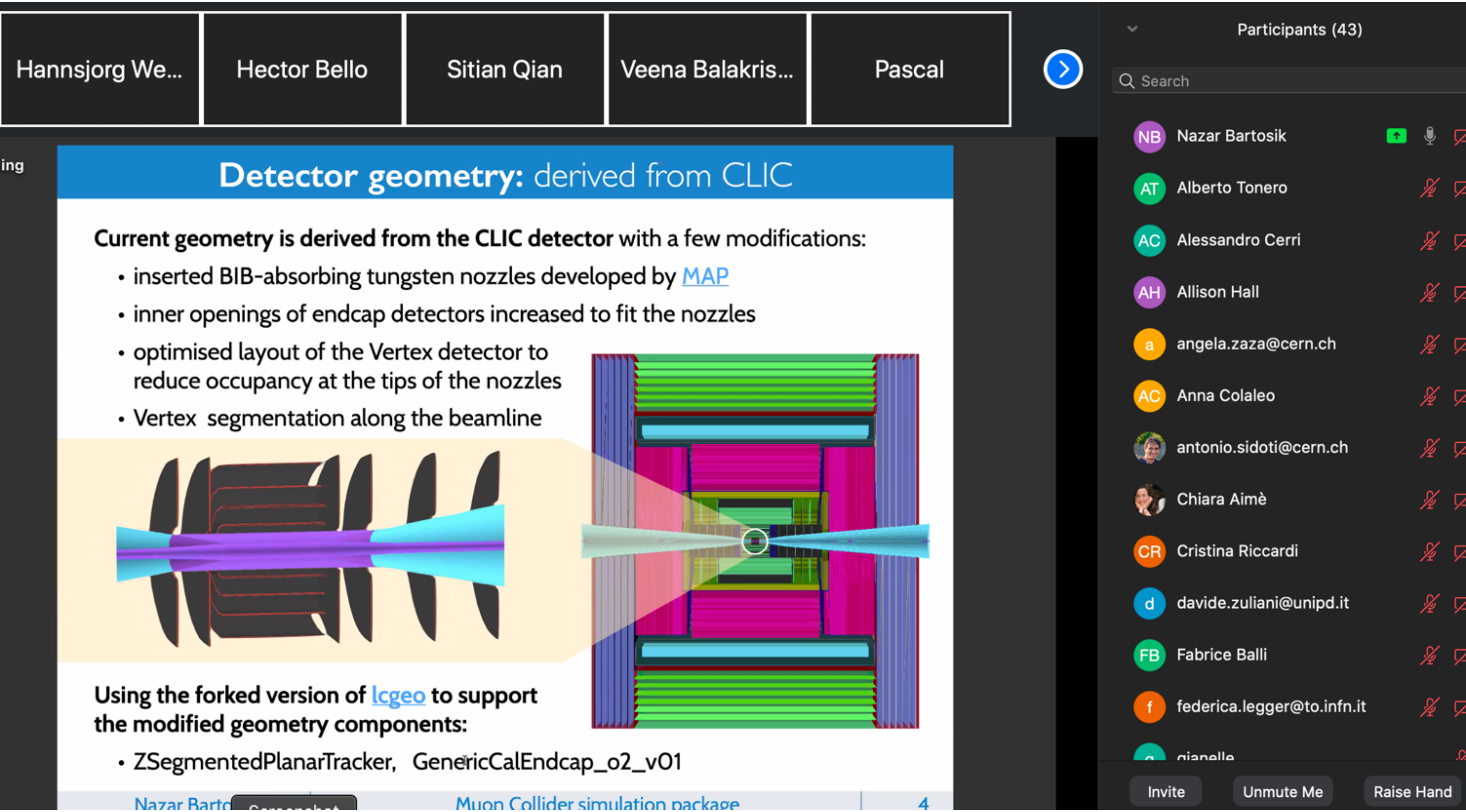
Hadron Calorimeter (HCAL)

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

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



Detector geometry: derived from CLIC

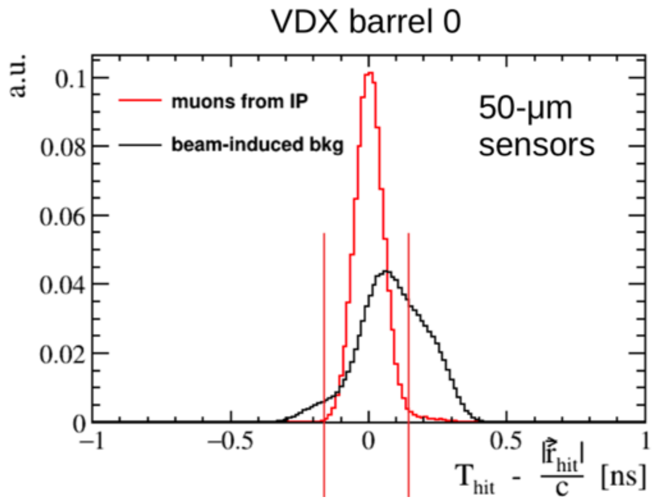
Current geometry is derived from the CLIC detector with a few modifications:

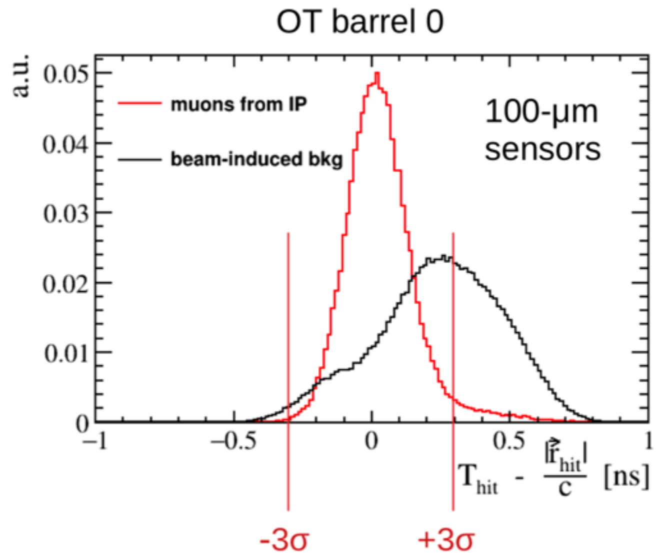
- inserted BIB-absorbing tungsten nozzles developed by MAP
- inner openings of endcap detectors increased to fit the nozzles
- optimised layout of the Vertex detector to reduce occupancy at the tips of the nozzles
- Vertex segmentation along the beamline

Using the forked version of lcgeo to support the modified geometry components:

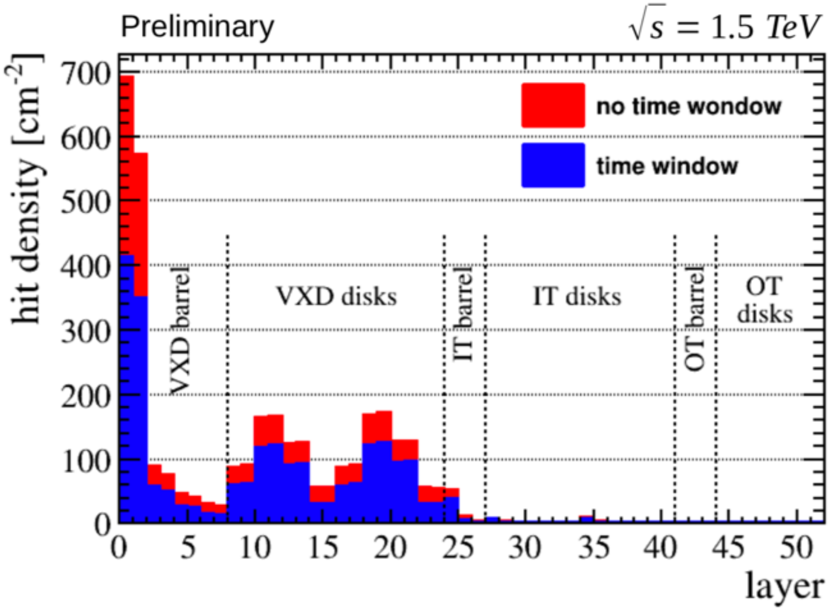
- ZSegmentedPlanarTracker, GenericCalEndcap_o2_v01

Tracking requirements ➔ R&D needs





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

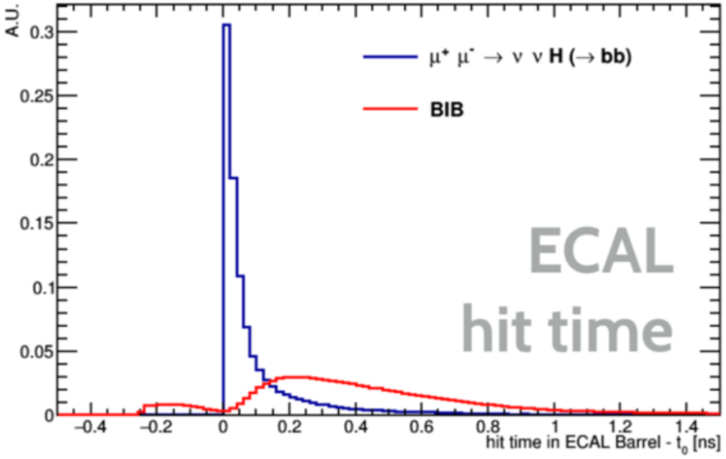


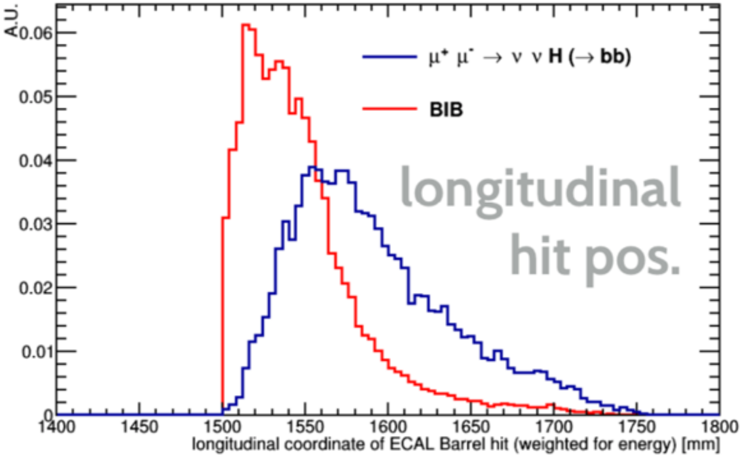
- Handles to reject spurious hits from BIB:
  - applying a time window to readout only hits compatible with particles originating from interaction region;
  - exploiting energy deposited in the tracker sensors (under development);
  - correlating hits on double-layer sensors (under development).

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

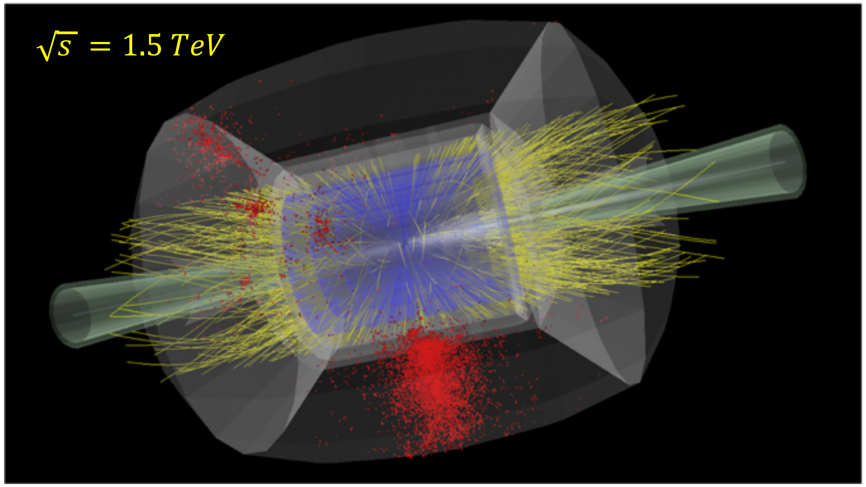
Physics and Detector

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

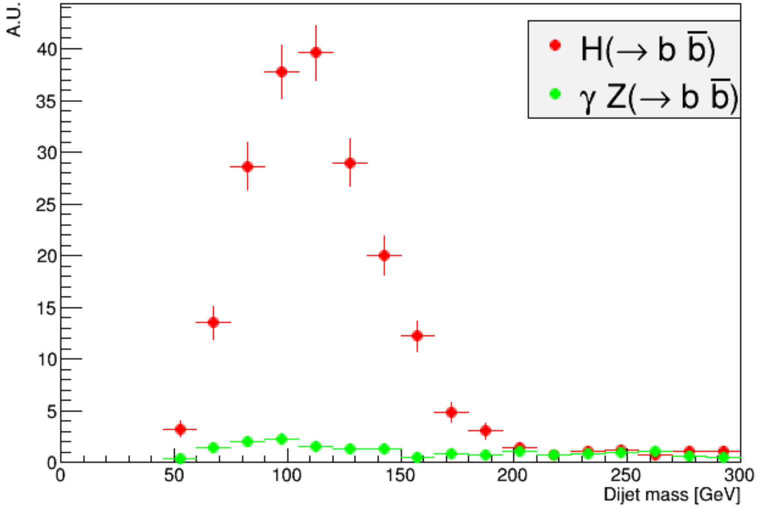
Detailed design of machine is required

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

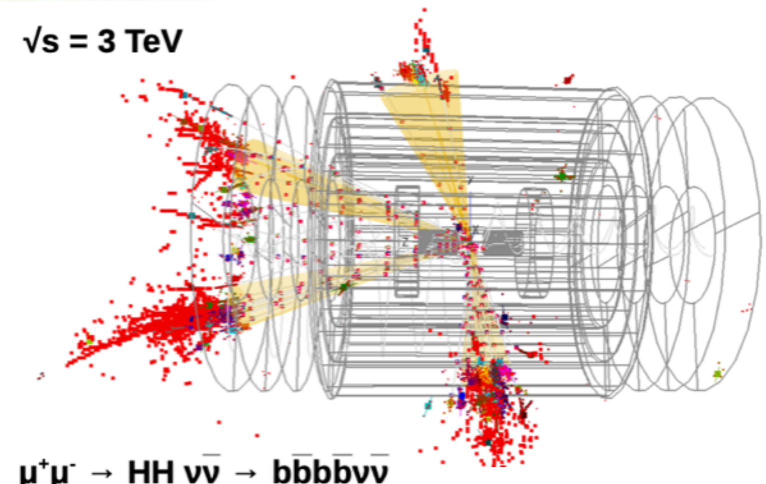
	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

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

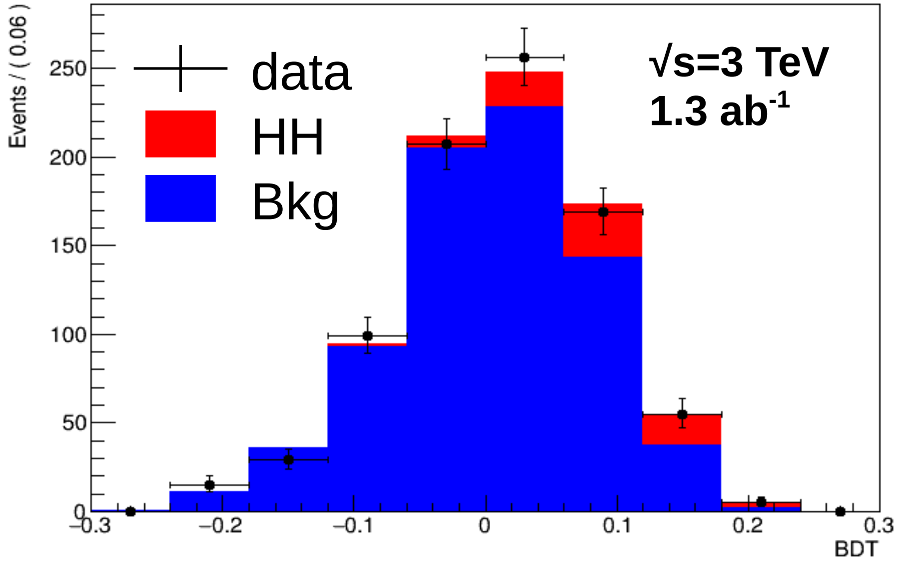
Double Higgs in full simulated detector

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

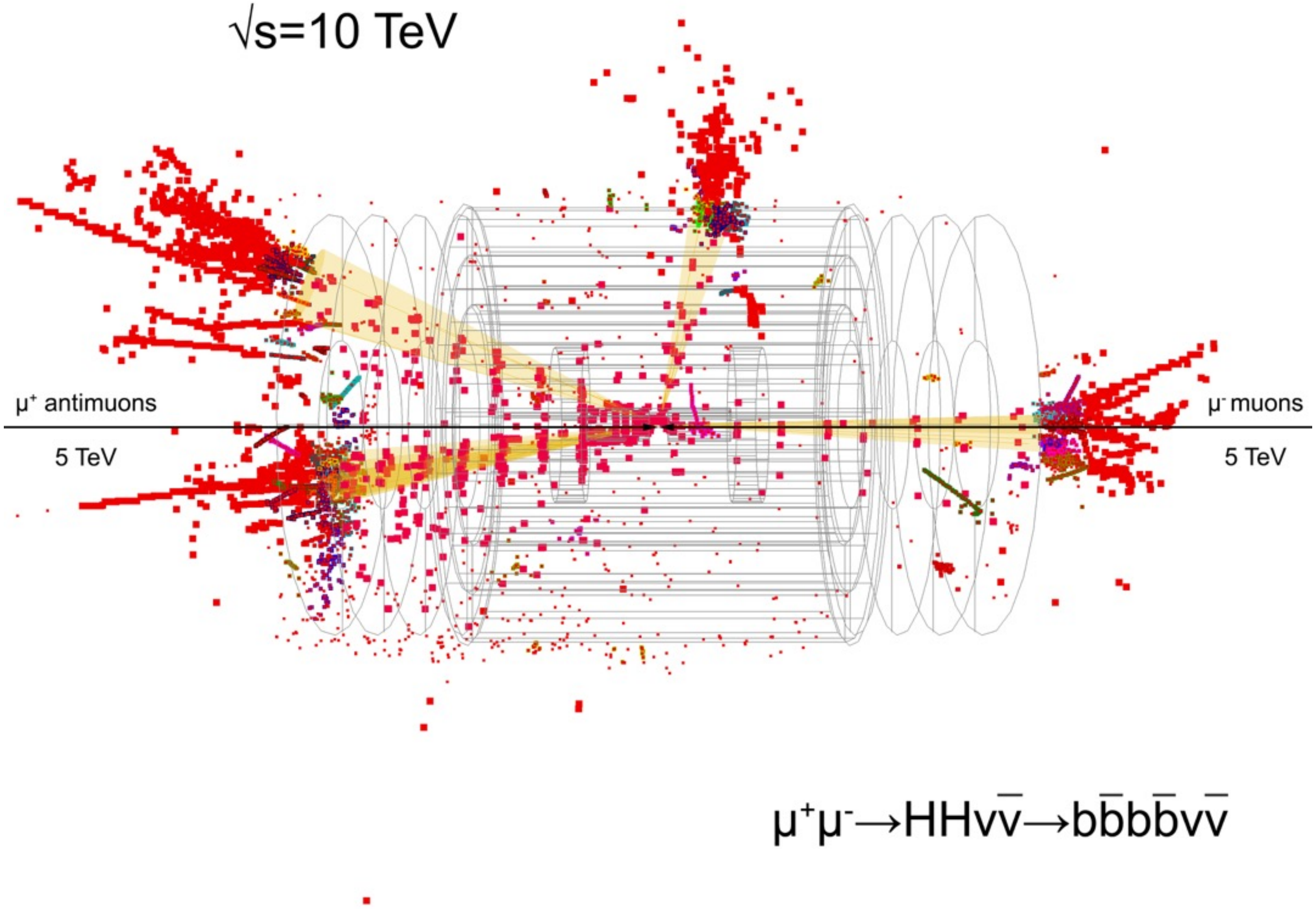


With a simple fit to the BDT output

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

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

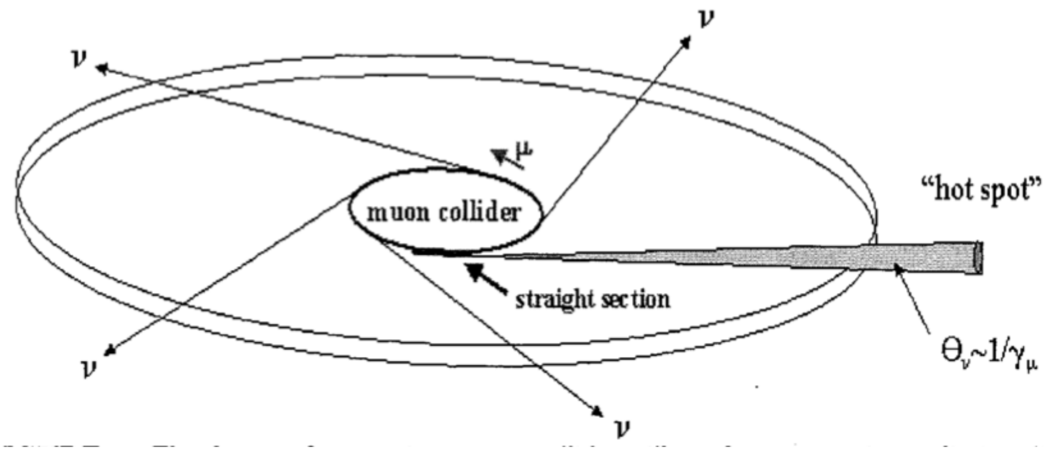
10 TeV $HH\nu\bar{\nu}$ event – no Beam Induced Background



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

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

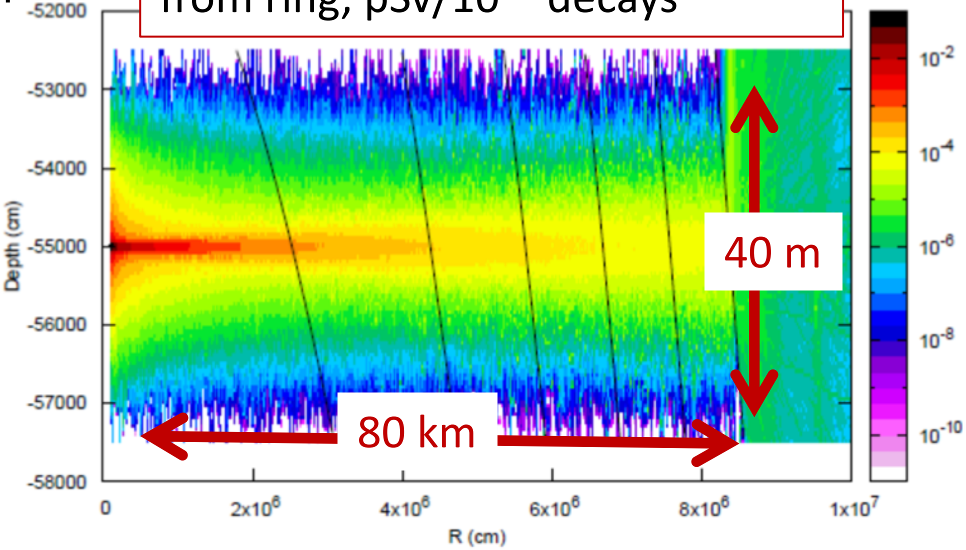
More important at higher energies (scaling E^3)

US study concluded: 6 TeV parameters are OK

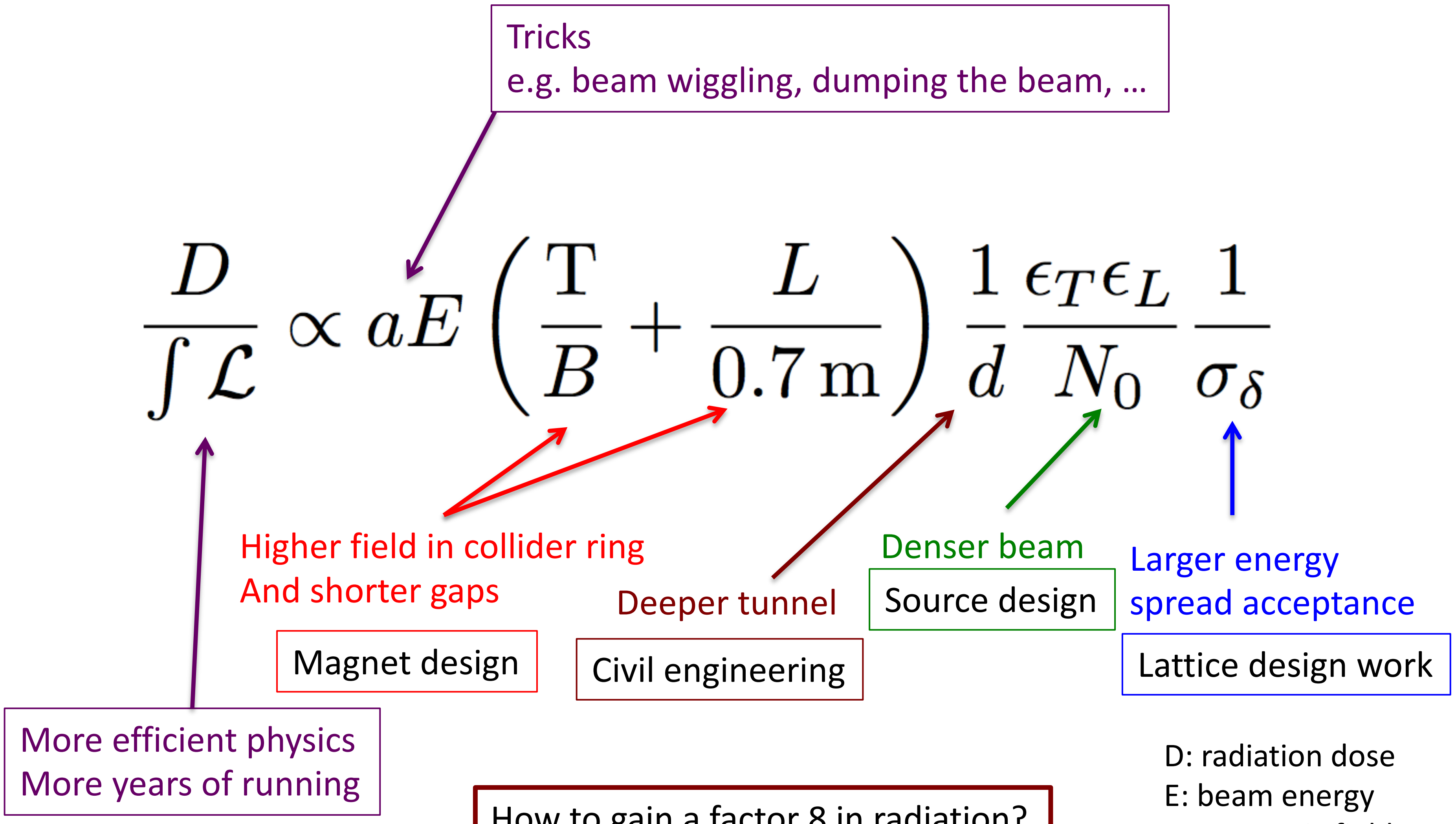
Reasonable goal 0.1 mSv/ year, to be verified

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



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:

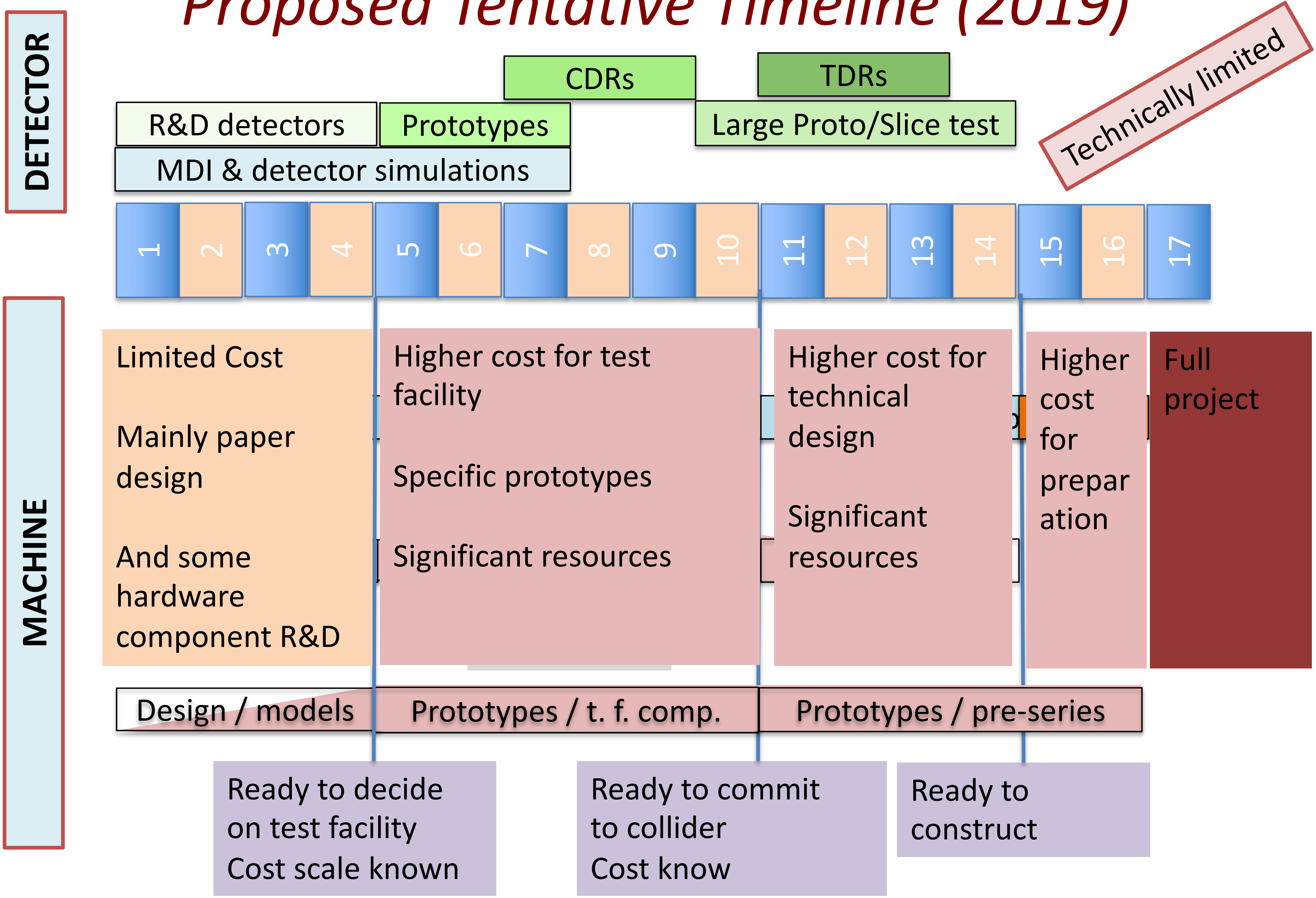
→ **proton driver option can be used NOW as baseline for a CDR of a 3-6 TeV machine**

→ **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

CDRs

TDRs

R&D detectors

Prototypes

Large Proto/Slice test

MDI & detector simulations

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.

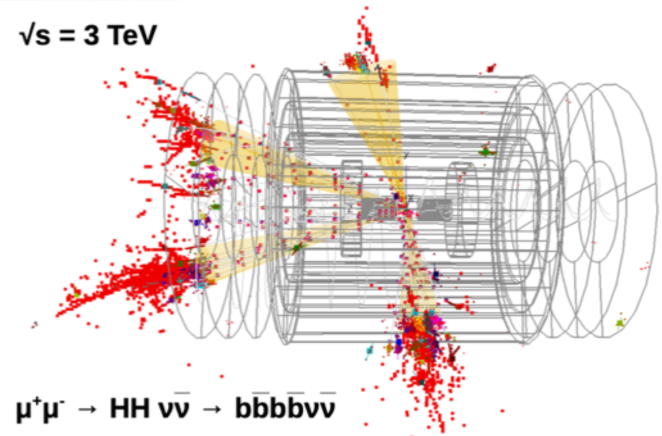
Prototypes / pre-series

Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

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



Please register at the following CERN:

e-group: *MUONCOLLIDER-DETECTOR-PHYSICS*

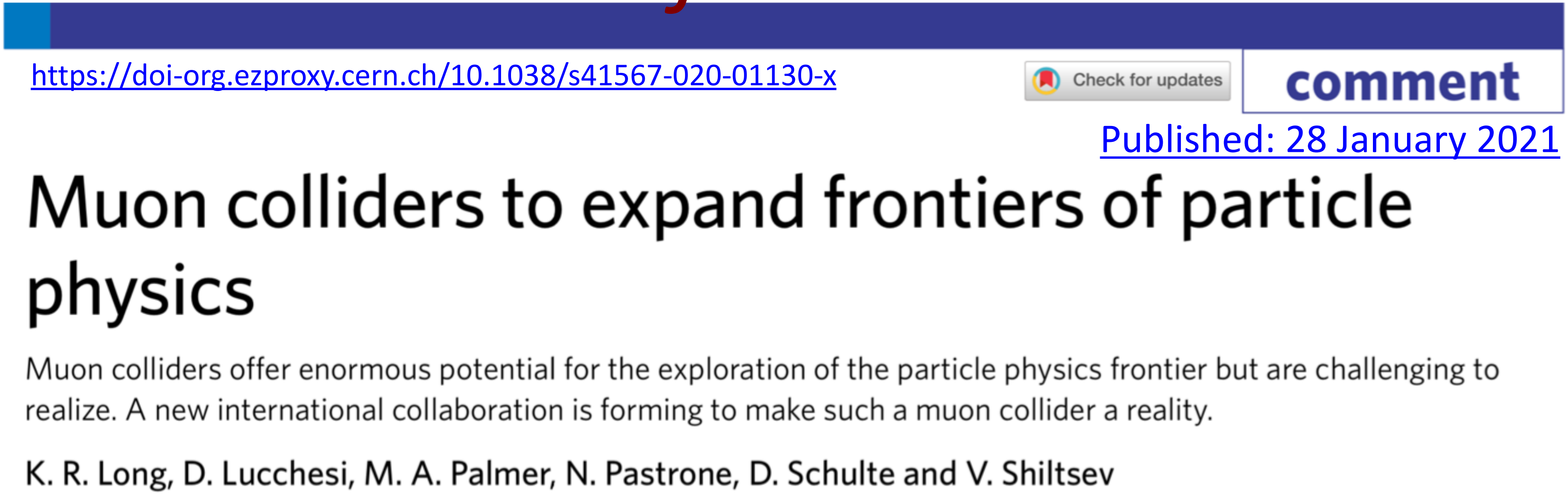
MUST-phydet@cern.ch

e-group: *MUONCOLLIDER-FACILITY*

MUST-mac@cern.ch

Thanks for the attention!

https://doi-org.ezproxy.cern.ch/10.1038/s41567-020-01130-x



comment

Published: 28 January 2021

Muon colliders to expand frontiers of particle physics

Muon colliders offer enormous potential for the exploration of the particle physics frontier but are challenging to realize. A new international collaboration is forming to make such a muon collider a reality.

K. R. Long, D. Lucchesi, M. A. Palmer, N. Pastrone, D. Schulte and V. Shiltsev

Recent workshops, indico

- **INFN Confluence website: full simulation** https://confluence.infn.it/display/muoncollider
- **International Design Study Indico @ CERN** https://indico.cern.ch/category/11818/
- **PITT PACC Workshop: Muon collider physics** https://indico.cern.ch/event/969815/
- **Muon Collider SnowMass Forum USA** https://indico.fnal.gov/event/47038/