CLIC Project Meeting #35 - April 29, 2020

Prospects on Muon Colliders

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INFN TORINO

On behalf of the CERN Muon Colliders WG

Thanks to fruitful contribution by many colleagues from

MAP, MICE, LEMMA Collaborations and

Donatella Lucchesi, Nikolai V. Mokhov, Mark Palmer, Paola Sala, Vladimir Shiltsev, et al.

Muon Collider Working Group

Jean Pierre Delahaye, CERN, Marcella Diemoz, INFN, Italy,
Ken Long, Imperial College, UK, Bruno Mansoulie, IRFU, France,
Nadia Pastrone, INFN, Italy (chair), Lenny Rivkin, EPFL and PSI, Switzerland,
Daniel Schulte, CERN, Alexander Skrinsky, BINP, Russia, Andrea Wulzer, EPFL and CERN

appointed by CERN Directorate in September 2017

to prepare an Input Document to the European Strategy Update

de facto the seed of a renewed on-going international effort

Input Document to EU Strategy Update - Dec 2018:
"Muon Colliders," **arXiv:1901.06150** [physics.acc-ph]
by *CERN-WG on Muon Colliders*

FINDINGS and RECOMMENDATIONS:

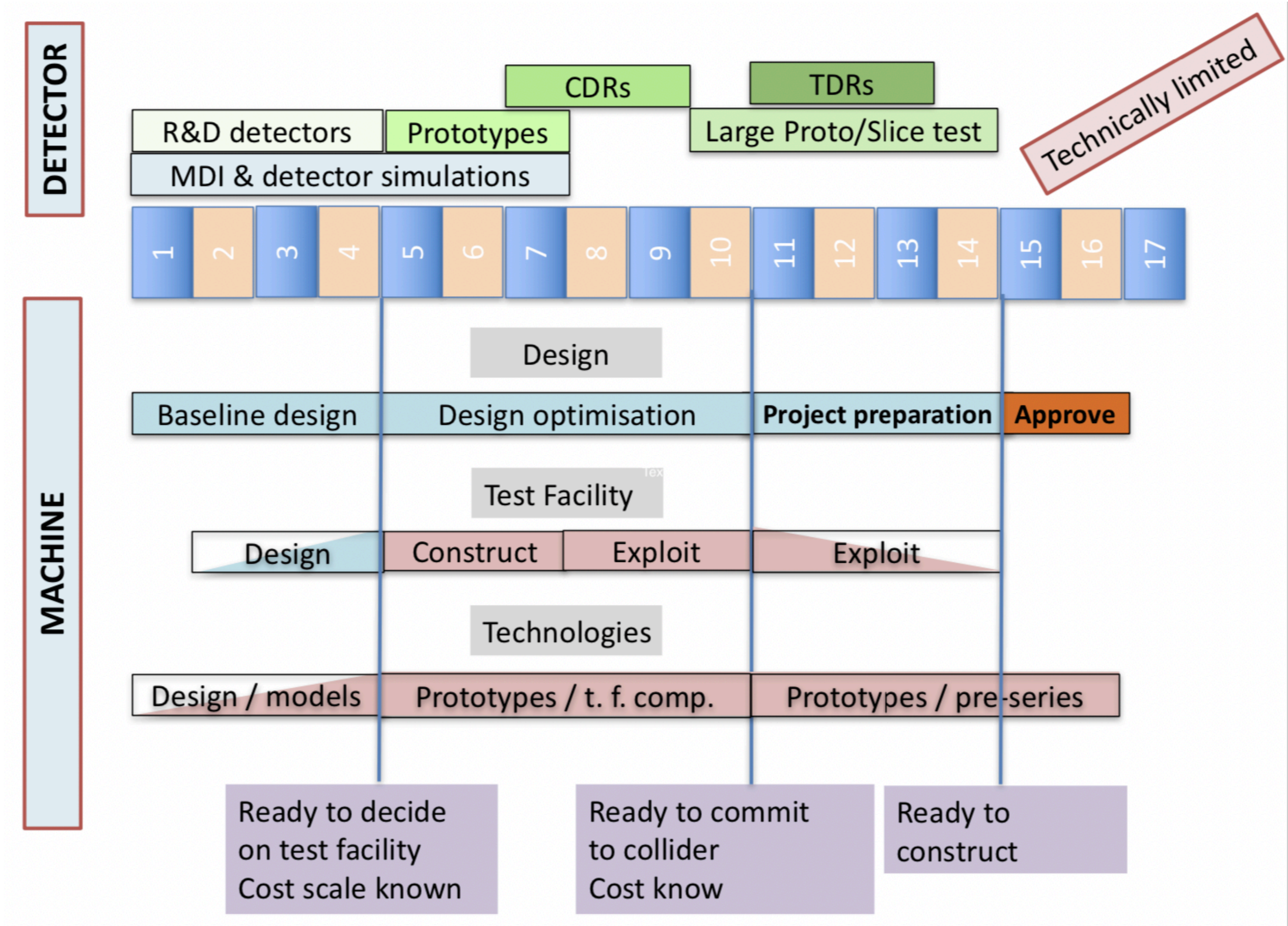
Set-up an international collaboration to promote muon colliders
and **to organize the effort on the development of both accelerators and detectors**
and to define the road-map towards a CDR by the next Strategy update

……

Carry out the R&D program toward the muon collider:
RF, magnets, materials, cooling, targets… ➔ **SYNERGIES with other Future Colliders**

Technically Limited Potential Timeline

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



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

Design

Baseline design

Design optimisation

Project preparation

Approve

Test Facility

Design

Construct

Exploit

Exploit

Technologies

Design / models

Prototypes / t. f. comp.

Prototypes / pre-series

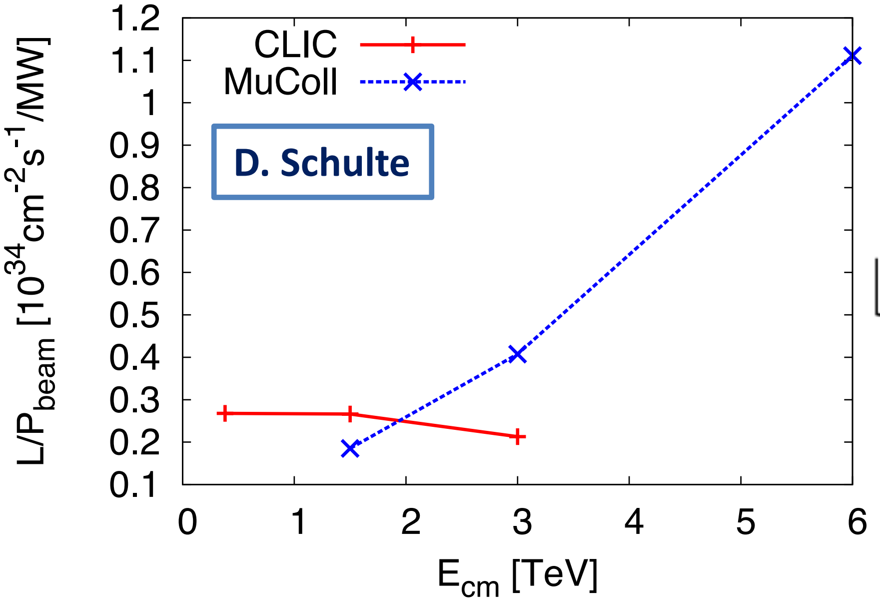
Ready to decide
on test facility
Cost scale known

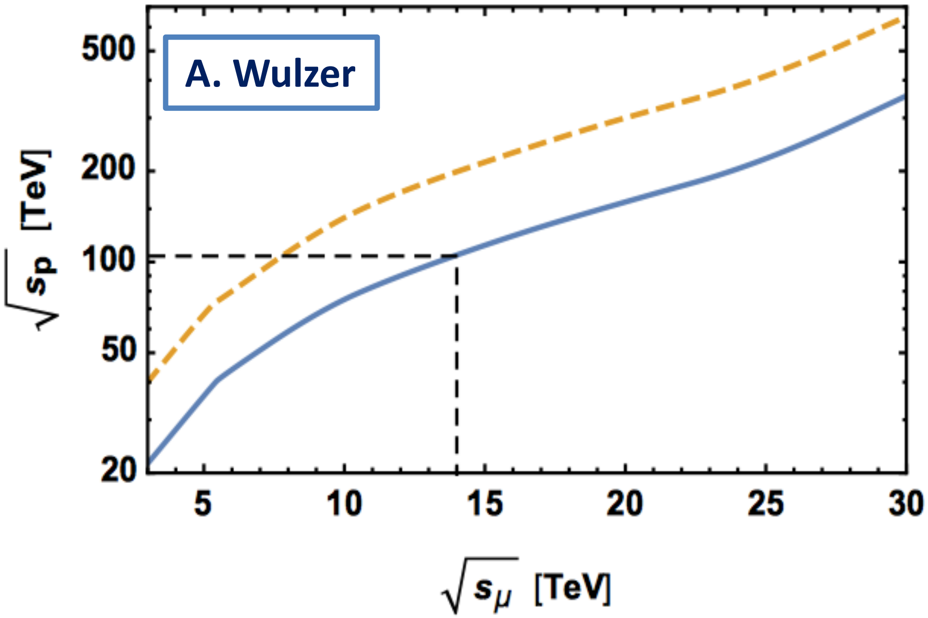
Ready to commit
to collider
Cost know

Ready to
construct

Why a multi-TeV Muon Collider?

cost-effective and unique opportunity for lepton colliders @$\sqrt{s}$ >3 TeV





The luminosity per beam power is independent of collision energy in linear colliders, but increases linearly for muon colliders

Full collision energy available for particle production: 14 TeV lepton collisions are comparable to 100 TeV proton collisions for selected new physics process, **if sufficient luminosity is provided ~ $10^{35}cm^{-2}s^{-1}$**

Strong interest to reuse existing facilities and infrastructure (i.e. LHC tunnel) in Europe

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%

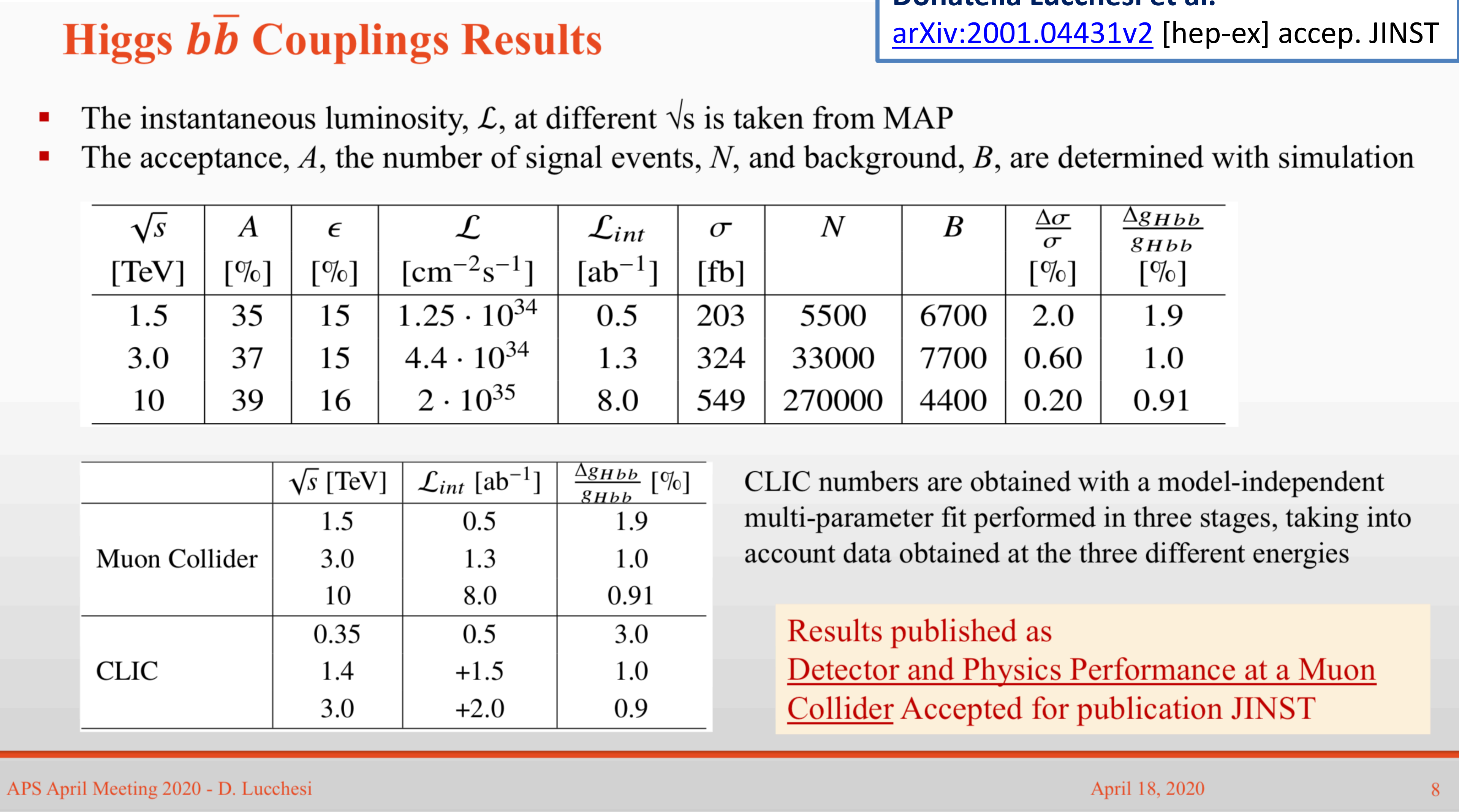
significantly better than what is currently expected to be attainable at the FCC-hh with a similar luminosity
arXiv:1905.03764 [hep-ph]

This just looking at the Higgs sector!

Top and new physics sectors also to be scrutinized

A preliminary comparison

Donatella Lucchesi et al.
arXiv:2001.04431v2 [hep-ex] accep. JINST



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

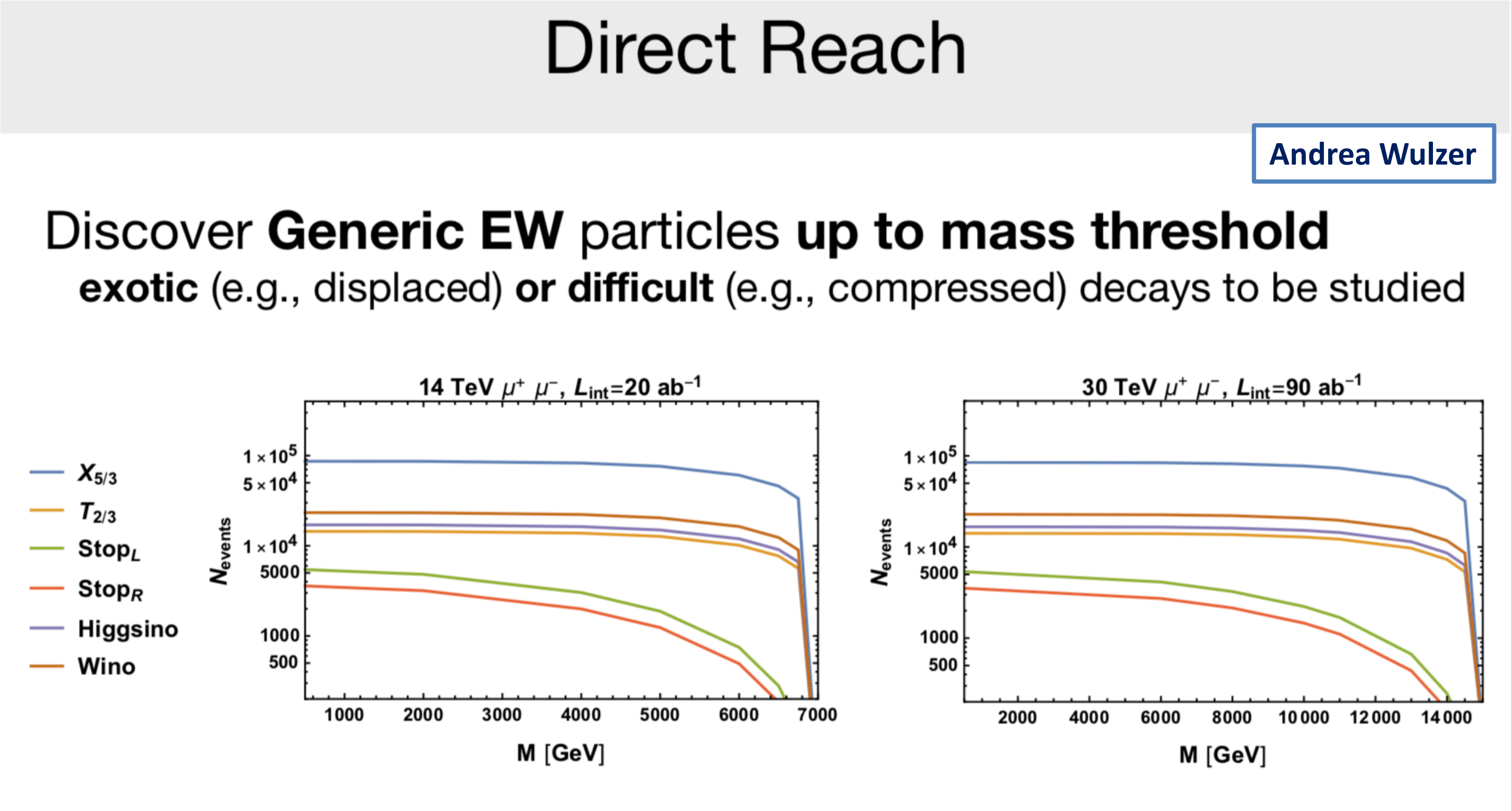
CLIC numbers are obtained with a model-independent multi-parameter fit performed in three stages, taking into account data obtained at the three different energies

Results published as Detector and Physics Performance at a Muon Collider Accepted for publication JINST

APS April Meeting 2020 - D. Lucchesi April 18, 2020 8

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

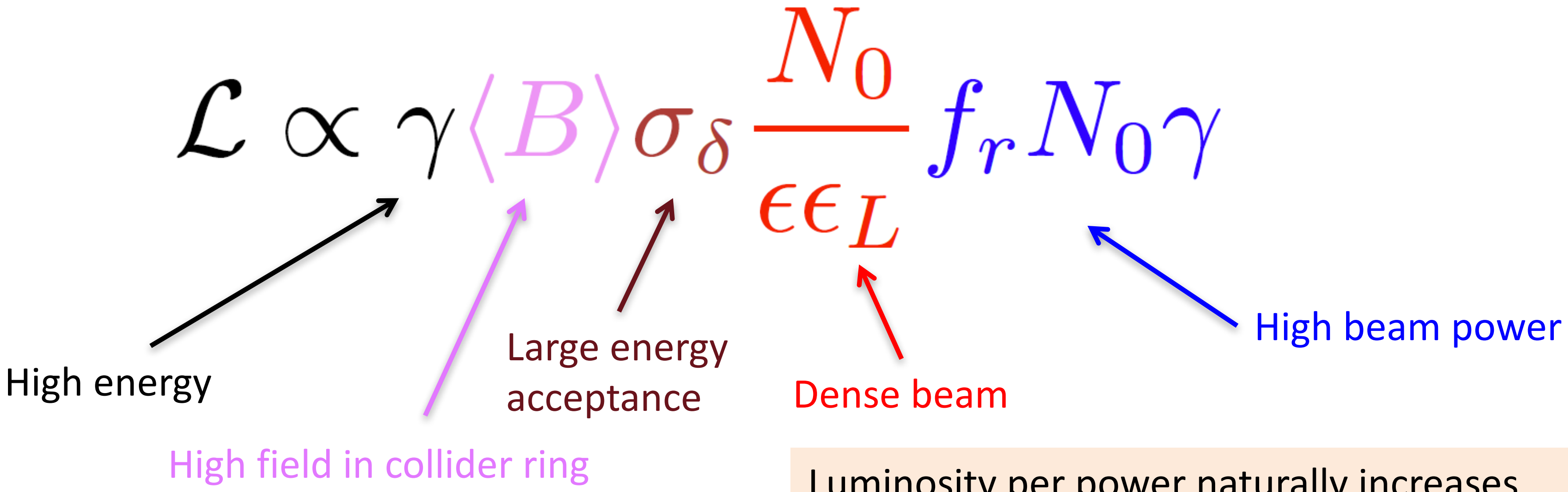
Muon Collider Luminosity Scaling

D. Schulte

Fundamental limitation

Requires emittance preservation and advanced lattice design

Applies to MAP scheme



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

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

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

Luminosity per power naturally increases with energy

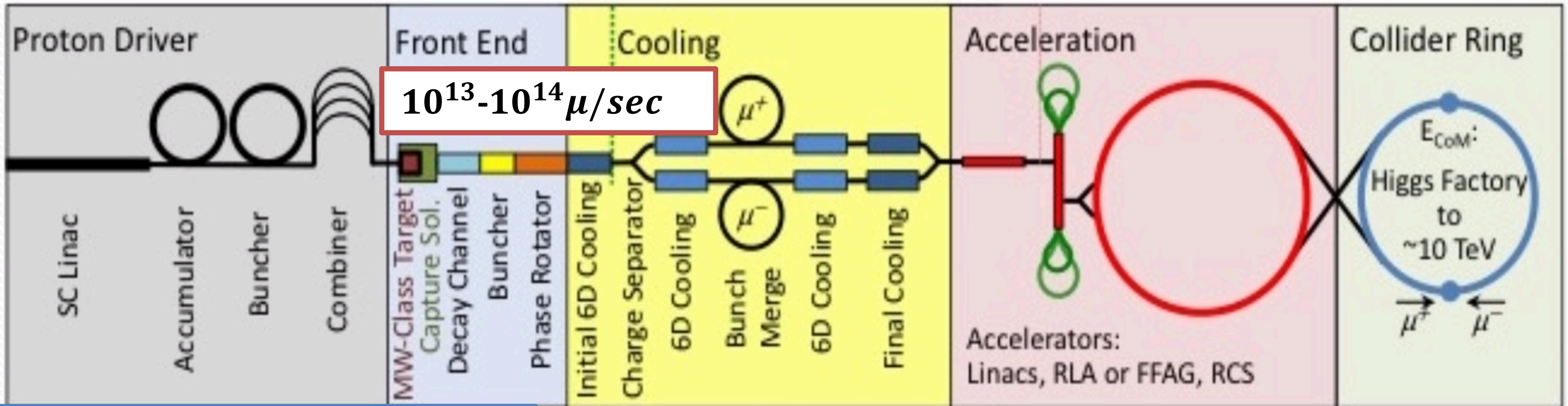
Provided all technical limits can be solved

Constant current for required luminosity increase

Better scaling than linear colliders

proton (MAP) vs positron (LEMMA) driven muon source

MAP

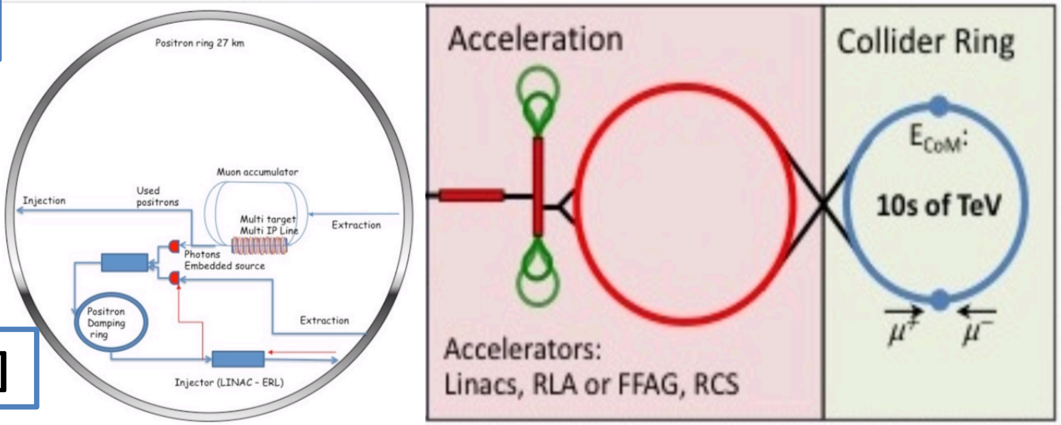


10^{13}-$10^{14}\mu/sec$

MUON JINST, shorturl.at/kxKU7

LEMMA

e+ source



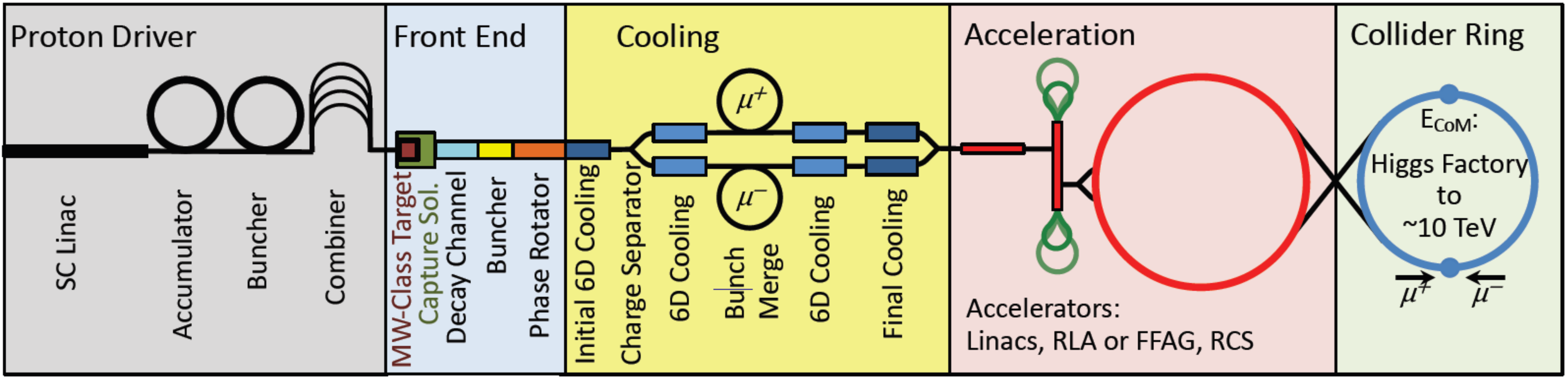
arXiv:1905.05747v2 [physics.acc-ph]

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

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

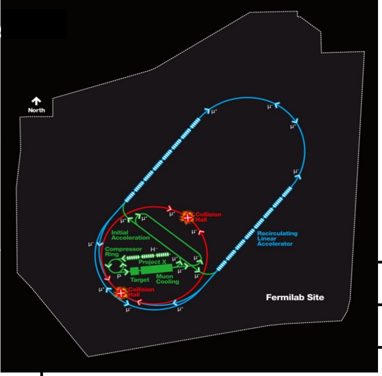
Collision

Pions decay into muons that can be captured

Design is not complete but did not find anything that does not work

No CDR exists No coherent baseline No reliable cost estimate

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



Muon Collider Parameters

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

Muon Collider Parameters

		Higgs Factory		**Top Threshold Options**		**Multi-TeV Baselines**		
Parameter	***Units***	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top^{+} Production/10^{7}sec		3,500*	13,500*	7,000^{+}	60,000^{+}	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4$^{\#}$	4	4	4	4	4	1.6

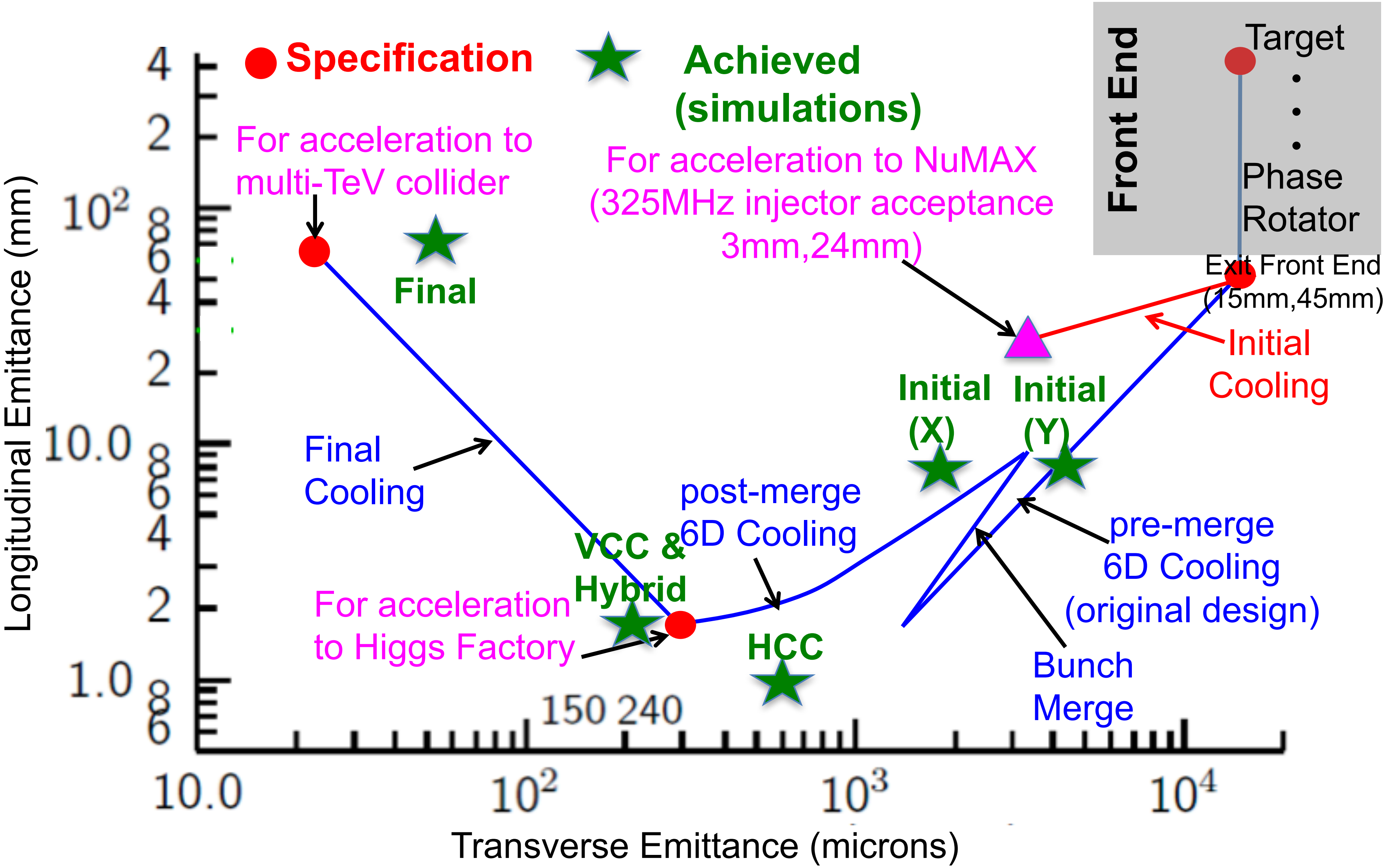
$^{\#}$ Could begin operation with Project X Stage II beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts ⇨ several × 10^{32}

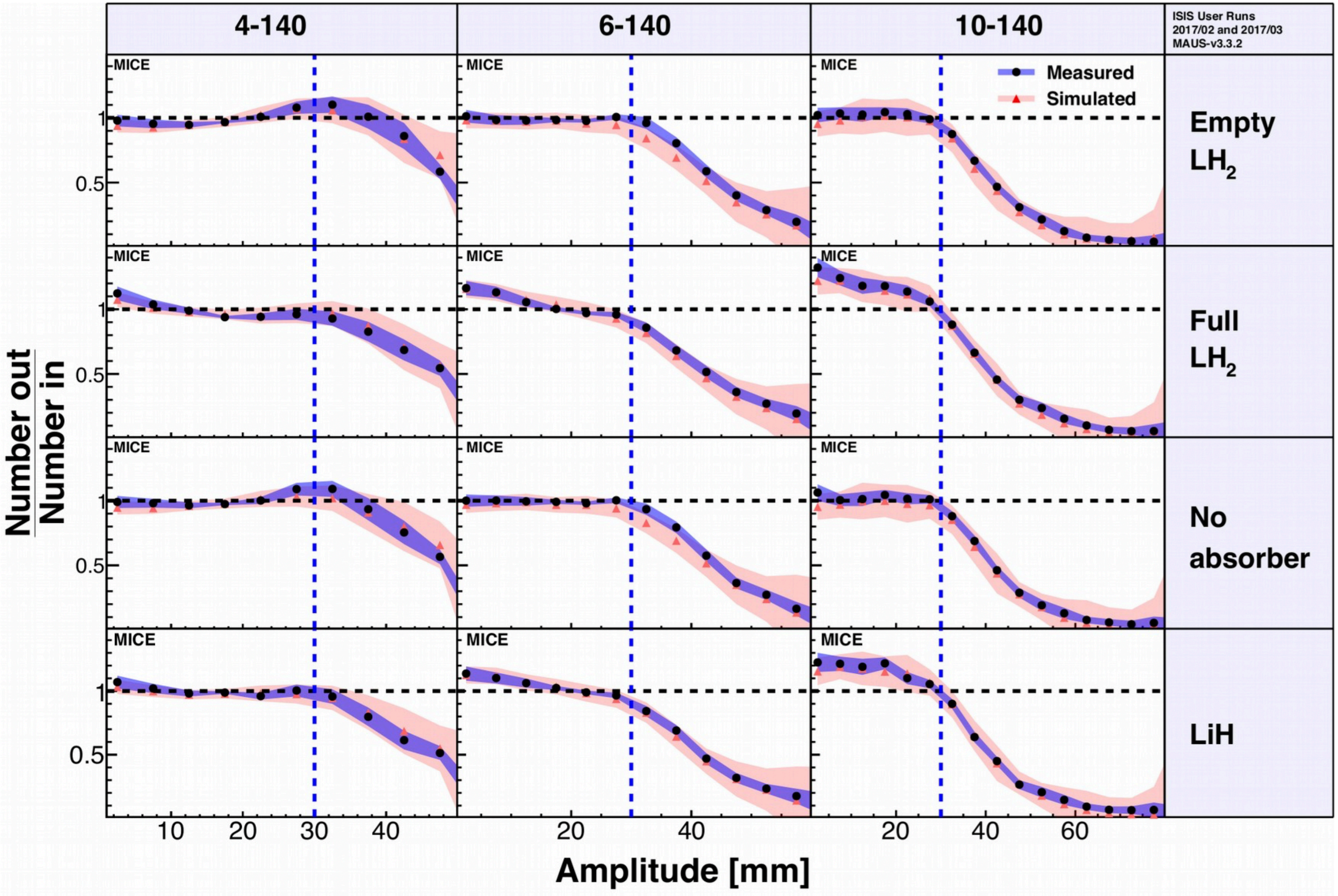
Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

Cooling: The Emittance Path

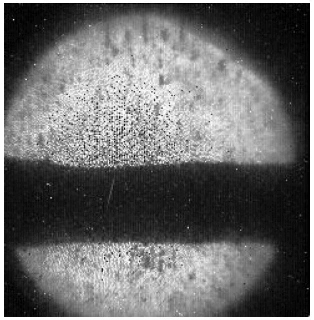


MICE – transverse 4D cooling

MICE collaboration *Nature* 578 (2020) 7793, 53-59

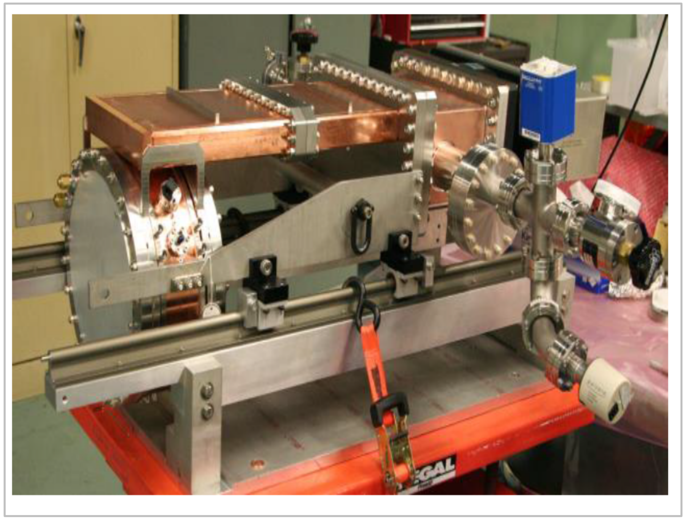


Key components developments

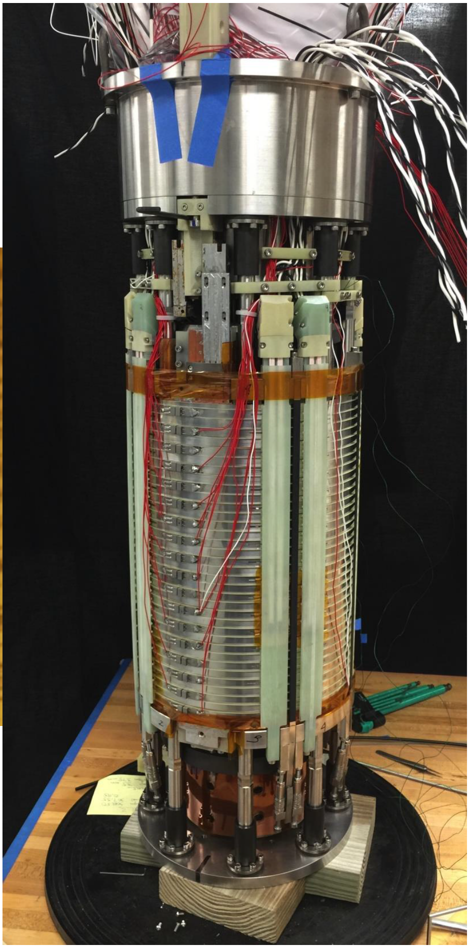


MERIT @ CERN
High power liquid
mercury target

MuCool: >50 MV/m in 5 T field



FNAL
Breakthrough in
HTS cables



NHFML
32 T solenoid
with low-
temperature HTS

FNAL
12 T/s
HTS
0.6 T max

Recent LEMMA effort

M.Antonelli, M.E.Biagini, M.Boscolo, S.Guiducci, P.Raimondi, A.Variola et al.

Asymmetric collisions $\boldsymbol{e^+e^-} \rightarrow \boldsymbol{\mu^+\mu^-}$ at the $\boldsymbol{\mu^+\mu^-}$ threshold ($\sqrt{s} \approx$ **0.212 GeV**)

- maximize $\boldsymbol{\mu^+\mu^-}$pairs production cross section
- minimize the $\boldsymbol{\mu^+\mu^-}$ beam angular divergence and energy spread

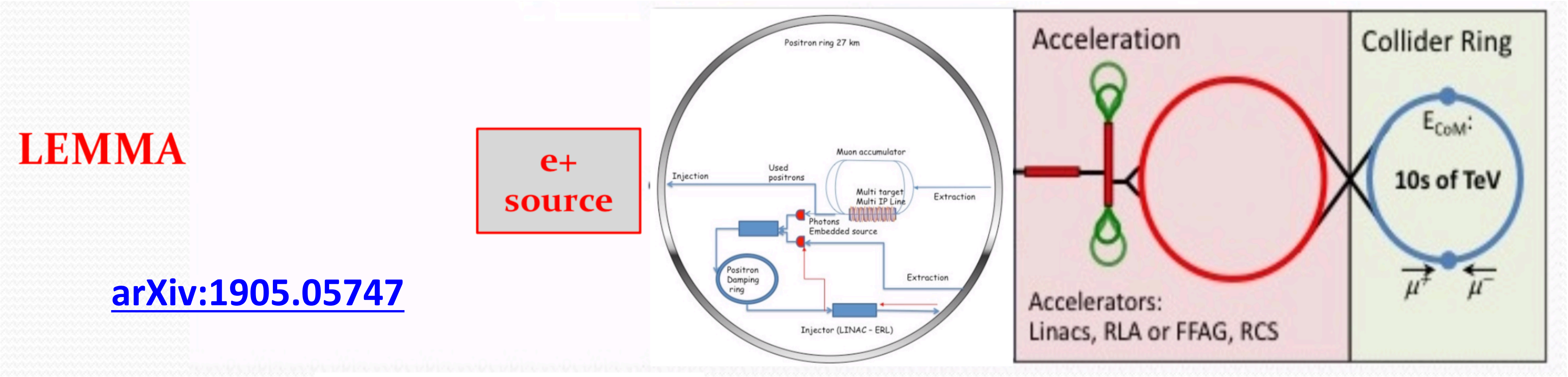
Extremely promising:

- muons produced with low emittance ➔ “no/low cooling” needed

But difficult:

- ✓ **low** production **cross section**: maximum $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1\ \mu\text{b}$
- ✓ **high heat load** and **stress** in μ production target
- ✓ **synchrotron power** O(100 MW) 🡸 available 45 GeV positron sources

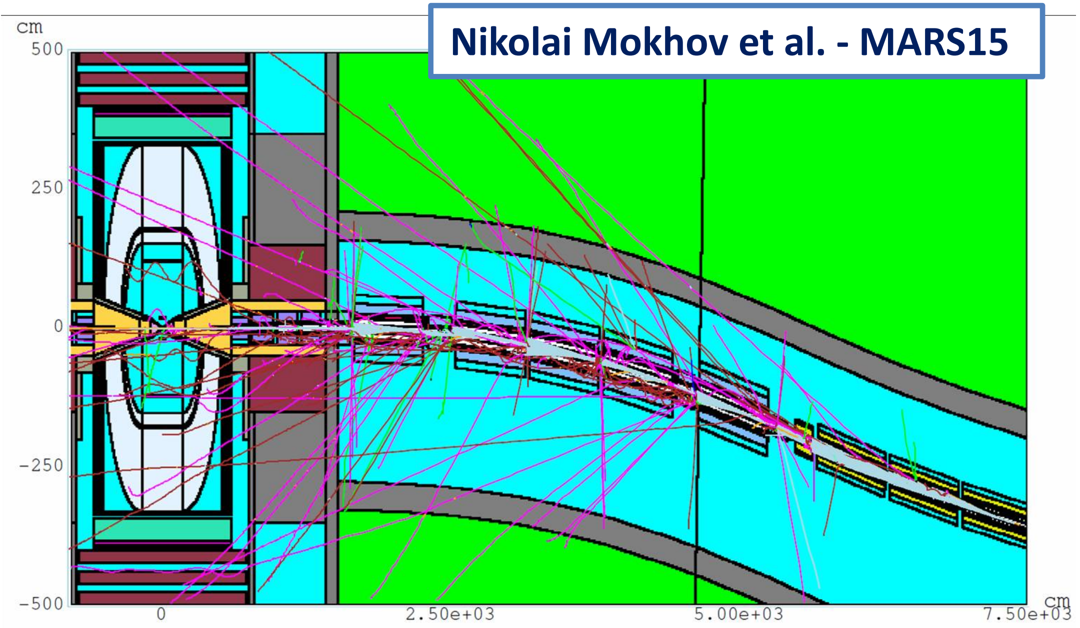
➔ **need consolidation** to overcome technical limitations to reach higher muon intensities

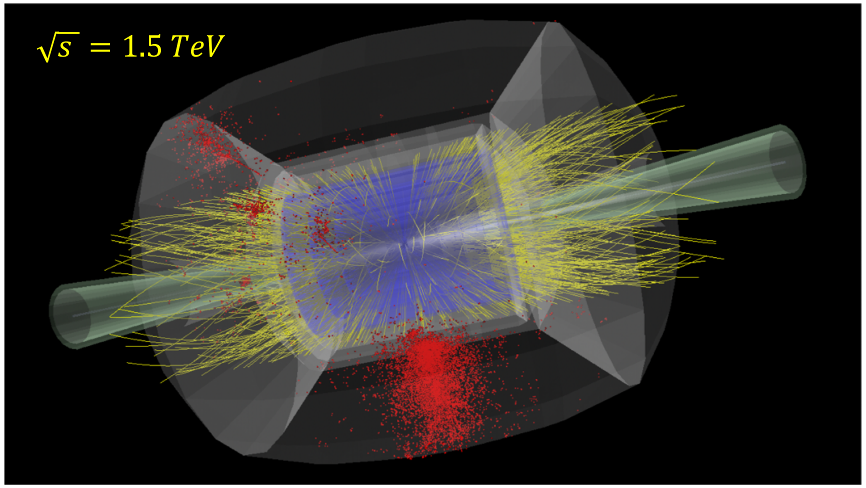


arXiv:1905.05747

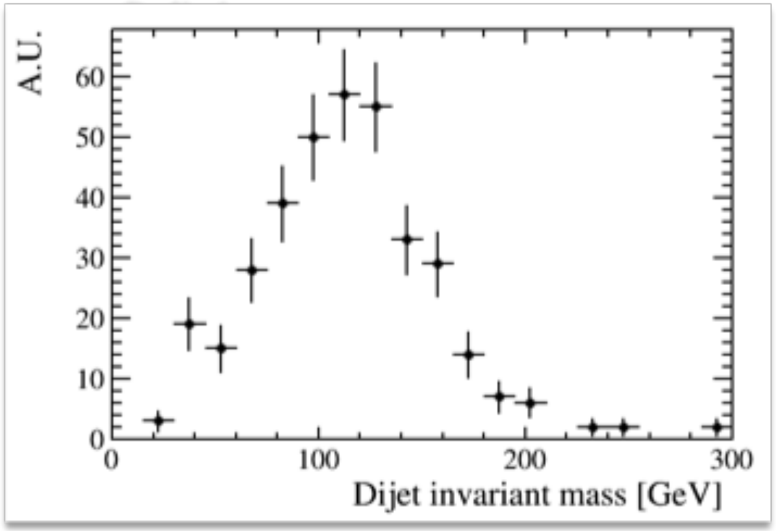
Muon Beams Induced Background

Nikolai Mokhov et al. - MARS15





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

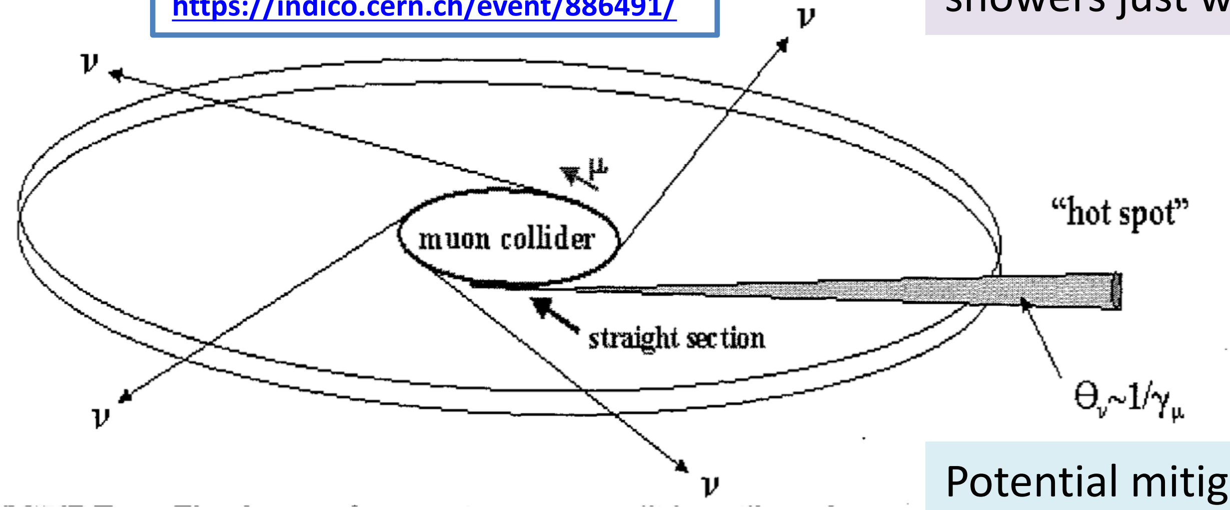


On-going simulations and studies for mitigation even with existing/future tunnels

Neutrino Radiation Hazard

Paola Sala – Youri Robert
CERN Muon Collider Meeting
https://indico.cern.ch/event/886491/

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



Particularly bad in direction of straights
But also an issue in the arcs

Becomes more important at higher energies (scaling E^3)

US study concluded that 6 TeV parameters are OK

Reasonable goal is 0.1 mSv/ year, but to be verified

Potential mitigation by

- Site choice
- Owning the land in direction of experimental insertion

- 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

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

Conclusions

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 and power consumption – 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 @ 3 and 10 TeV

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

- **Opportunity for particle physics with intense stored muon beam**

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

Recent Tentative Target Parameters

D. Schulte – CERN Muon Collider Meeting https://indico.cern.ch/event/886491/

Parameter	Unit	3 TeV	3 TeV*	10 TeV	10 TeV*	14 TeV	14 TeV*
L	$10^{34}\ \mathrm{cm^{-2}s^{-1}}$	1.8	1.8	20	20	40	40
N	10^{12}	~~2~~ 2.2	~~2~~ 2.2	1.8	1.8	1.8	1.8
f_r	Hz	~~6~~ 5	~~35~~ 29	~~4~~ 5	~~10~~ 12	~~4~~ 5	~~7~~ 9
P_{beam}	MW	~~5.8~~ 5.3	~~34~~ 32	~~12.8~~ 14.4	~~32~~ 35	~~18~~ 20	~~32~~ 37
C	km	4.5	26.7	10	26.7	14	26.7
<B>	T	7	1.2	10.5	3.9	10.5	5.5
ε_L	MeV m	7.5	7.5	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1	0.1	0.1	0.1
σ_z	mm	5	5	1.5	1.5	1.07	1.07
β	mm	5	5	1.5	1.5	1.07	1.07
ε	µm	25	25	25	25	25	25
$\sigma_{x,y}$	µm	3.0	3.0	0.9	0.9	0.63	0.63

Adjust for staging, G = 1 MV from 1.5 to 5 TeV, or 1.3 MV from 1.5 TeV to 7 TeV

***Use of LHC tunnel for collider**

Next steps

Muon Colliders is a unique opportunity at the high-energy frontier

- Several teams from different countries already contributed to present knowledge
- **The on-going work is fostering the preparation of an organized study:**
  - **identification of feasibility issues and potential incremental steps**
  - **resurrect studies of Muon Colliders taking advantage of the enormous progress already done**
  - **identify resources required to address most critical issues**
  - **launch international collaboration on Muon Colliders covering Physics, Detector and Accelerator**
- Synergies with other future accelerators can be easily identified for example on:
  - **high field magnets and fast ramping magnets with efficient energy recovery**
  - **efficient RF power production and high field cavities**
  - **robust targets**
  - **techniques for the large acceptance, rapid acceleration (RLA, LEMMA and other applications)**

A strong recommendation for a vigorous R&D on Muon Colliders would be key to enforce the international collaboration needed to promote the development of such a novel and promising project for the future of High Energy Physics

Thanks to all who contributed

Past experiences and new ideas discussed at the joint ARIES Workshop

July 2-3, 2018 – Università di Padova – Orto Botanico

https://indico.cern.ch/event/719240

Preparatory meeting to review progress for the ESPPU Simposium

April 10-11, 2019 – CERN – Council Room

https://indico.cern.ch/event/801616

Future Plans @ CERN October 9-11, 2019

https://indico.cern.ch/event/845054/

ECFA – Novel Accelerator Technologies @ CERN November 14, 2019

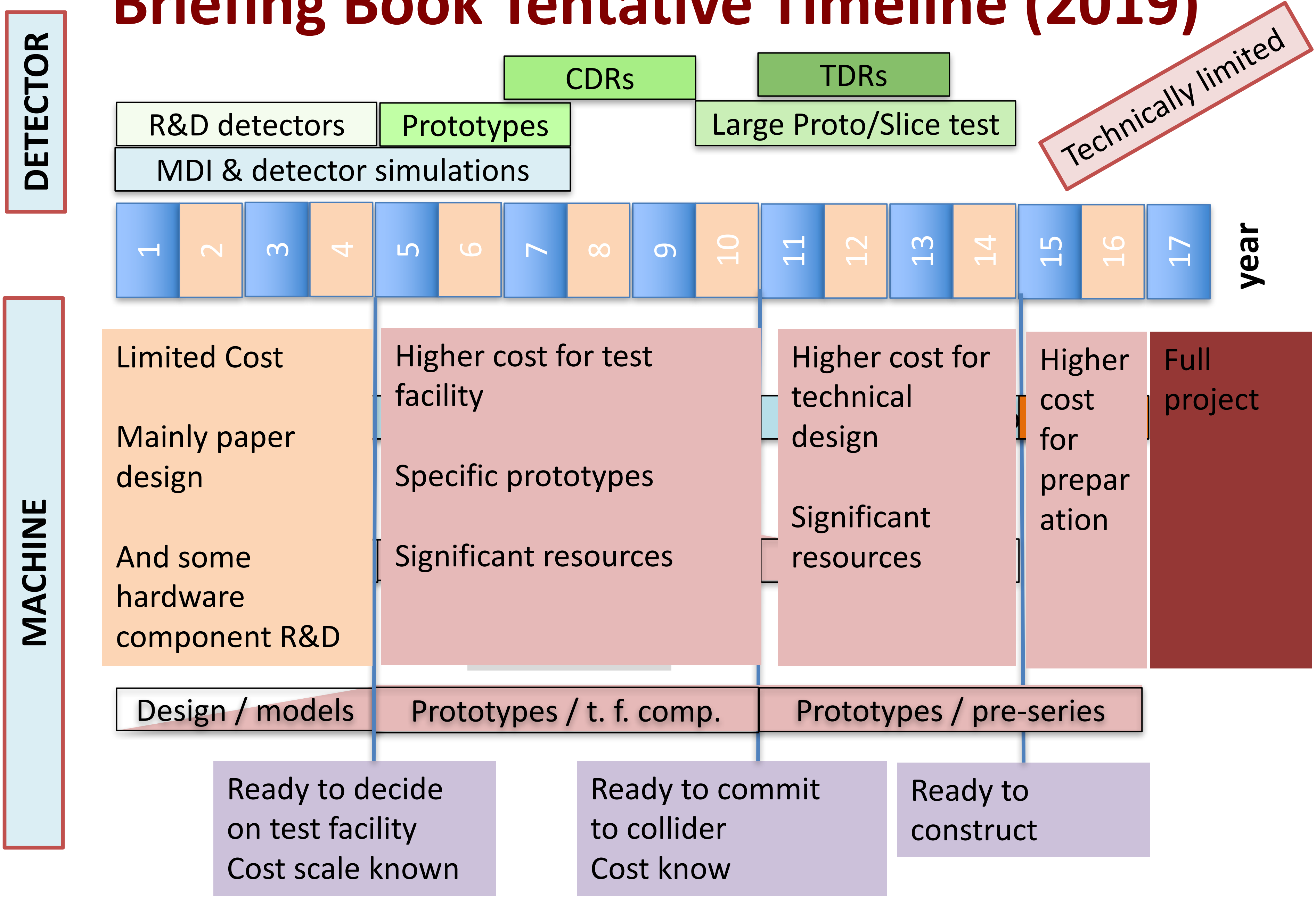
https://indico.cern.ch/event/847002/

Muon Collider General Meeting – remote March 31, April 1-2, 2020

https://indico.cern.ch/event/886491/

extras

Briefing Book Tentative Timeline (2019)



DETECTOR

R&D detectors

Prototypes

CDRs

TDRs

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 **year**

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

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^{7}sec		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

e-groups
towards an international collaboration

E-group: ***MUONCOLLIDER-DETECTOR-PHYSICS***

MUST-phydet@cern.ch

E-group: ***MUONCOLLIDER-FACILITY***

MUST-mac@cern.ch