Cogne 2019

Towards a future Muon Collider

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INFN TORINO

Cogne – February 15, 2019

Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiems on pions....sharpening

Enrico Fermi - American Physical Society, NY, **Jan. 29th 1954**
"What can we learn with High Energy Accelerators ? "

What's Next after LHC?

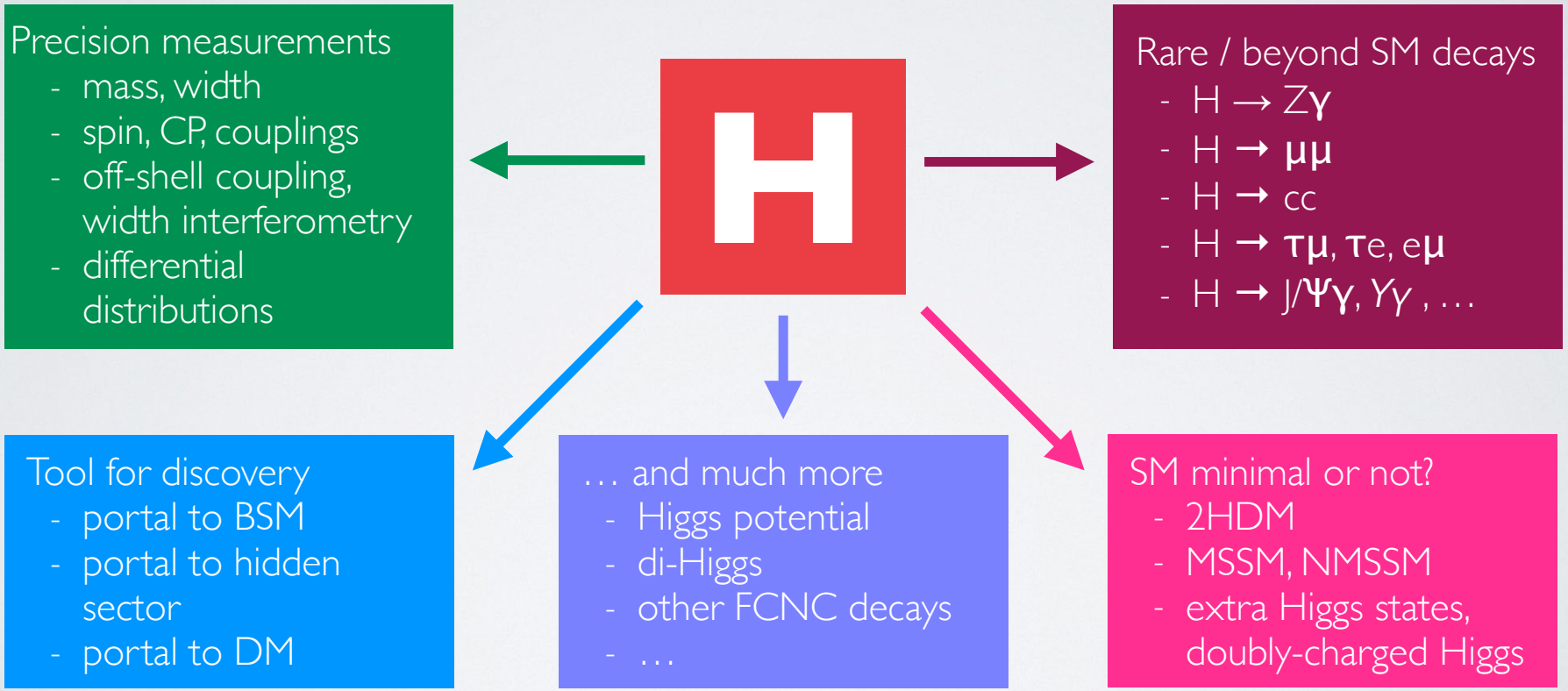
Physics scenario for a Future Collider

No single experiment can explore all directions at once.

None can guarantee discoveries.

The next big FC **will exist only if** capable to **explore many directions**, and be **conclusive** on some of those

An extremely rich program

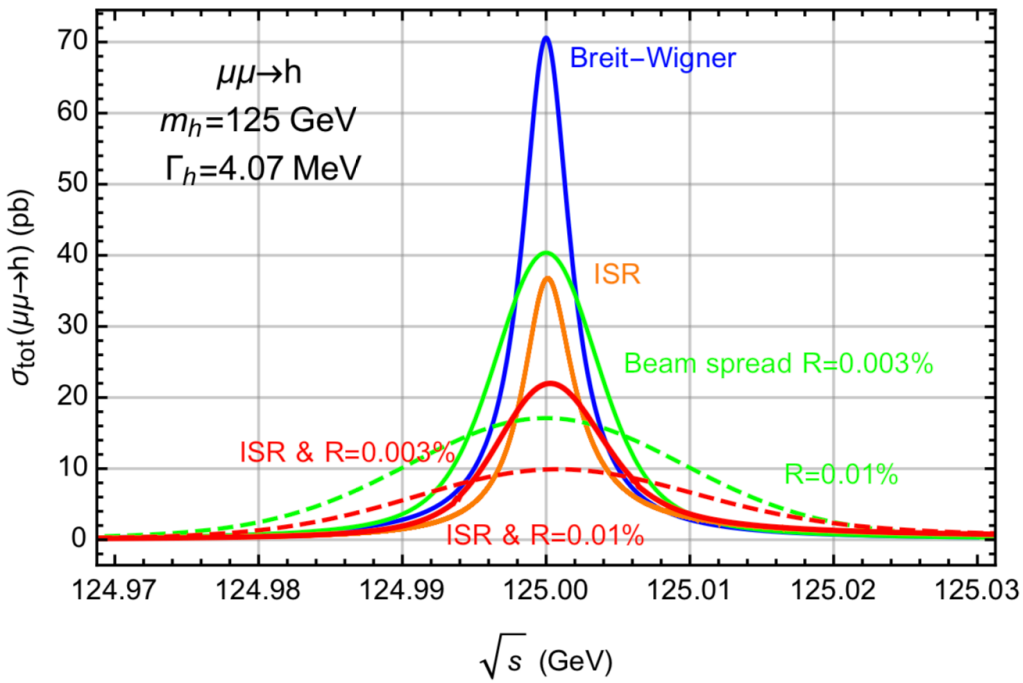


Lepton Colliders: μ vs e @ √s=125 GeV

Back on the envelope calculation:

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

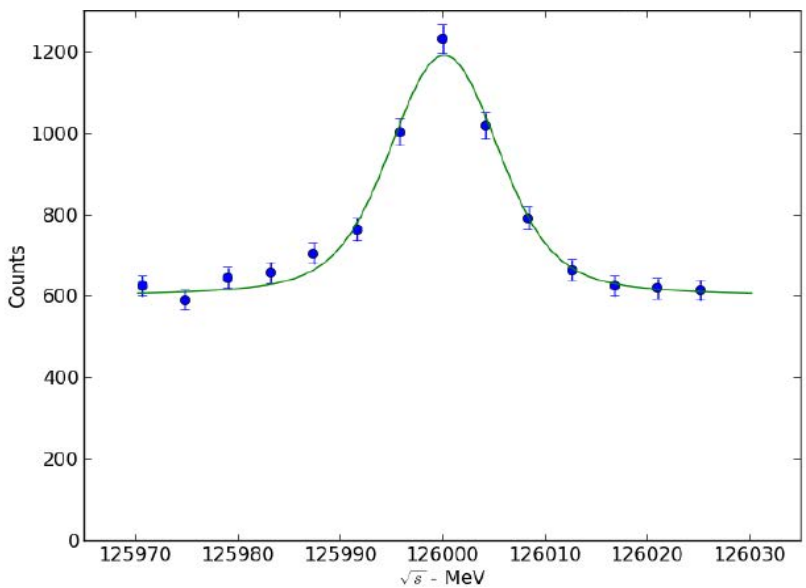
$$\boxed{\sigma(\mu^+\mu^- \to H) = 4.3\times10^4 \times \sigma(e^+e^- \to H)}$$



R: percentage beam energy resolution, key parameter

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

Higgs total width scan: μ @ $\sqrt{s}$=125 GeV



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

Why Muons?

Physics Frontiers

- **Intense and cold muon beams a unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\,MeV/c^2$$
$$\tau_\mu = 2.2\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs
  - Reduced synchrotron radiation a multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

$$\sim \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times 10^4$$

Collider Synergies

- High intensity beams required for a **long-baseline Neutrino Factory** are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

"rate for new particle production"

point x-section

$$\sigma_{EW} \sim \sigma(\mu^+\mu^- \to \gamma^* \to e^+e^-) \sim \frac{4\pi\alpha^2}{3\,S}$$

no m_e dependence
up to $m_e \sim \sqrt{S}/2$!

$$\to 1\,fb\,(\frac{10\,TeV}{\sqrt{S}})^2$$

$$L \sim 10^{35} cm^{-2} s^{-1} \sim 1\,ab^{-1}/y$$

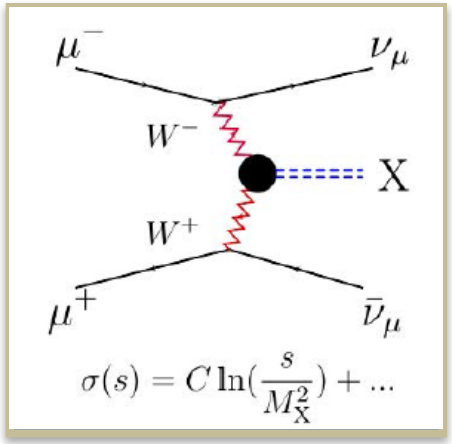
point x-section: $\to 1000\ evs/y\,(\frac{10\,TeV}{\sqrt{S}})^2$

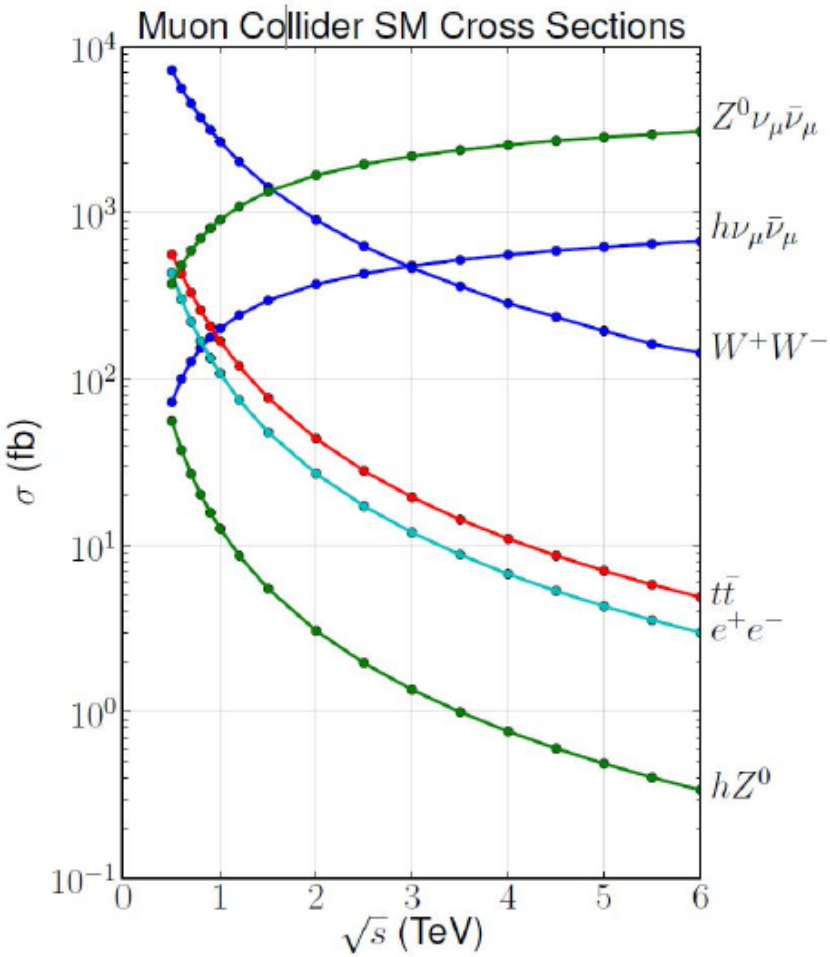
High energy Muon Collider

High Energy Collisions

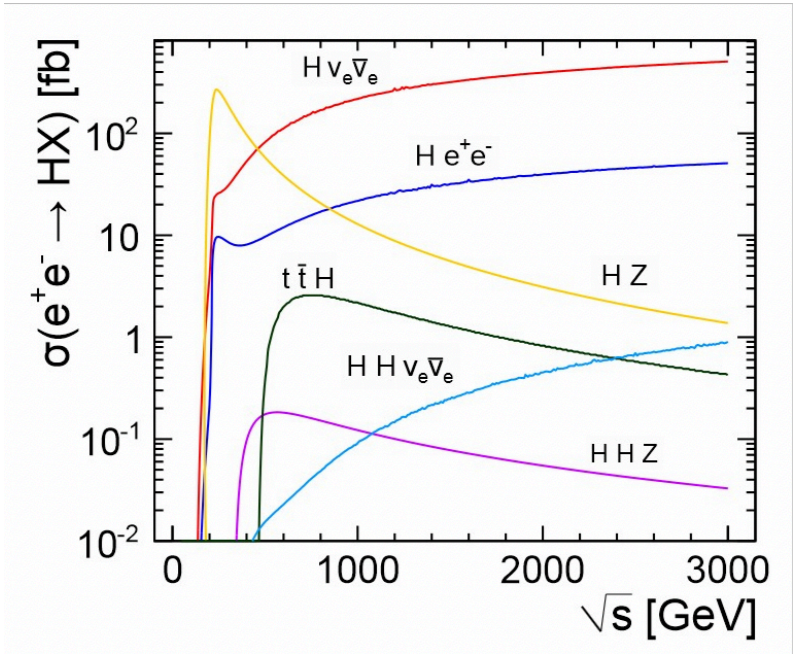
- At √s > 1 TeV:

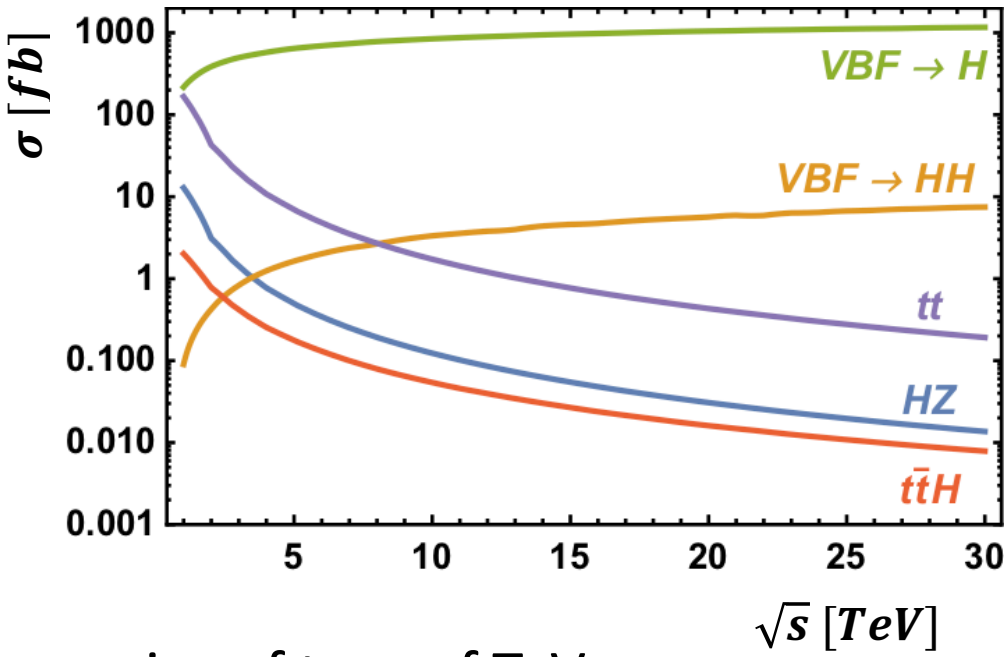
  Fusion processes dominate
  - An Electroweak Boson Collider
  - A discovery machine complementary to very high energy pp collider
- At >5TeV: Higgs self-coupling resolution <10%





Higgs production at Lepton Collider



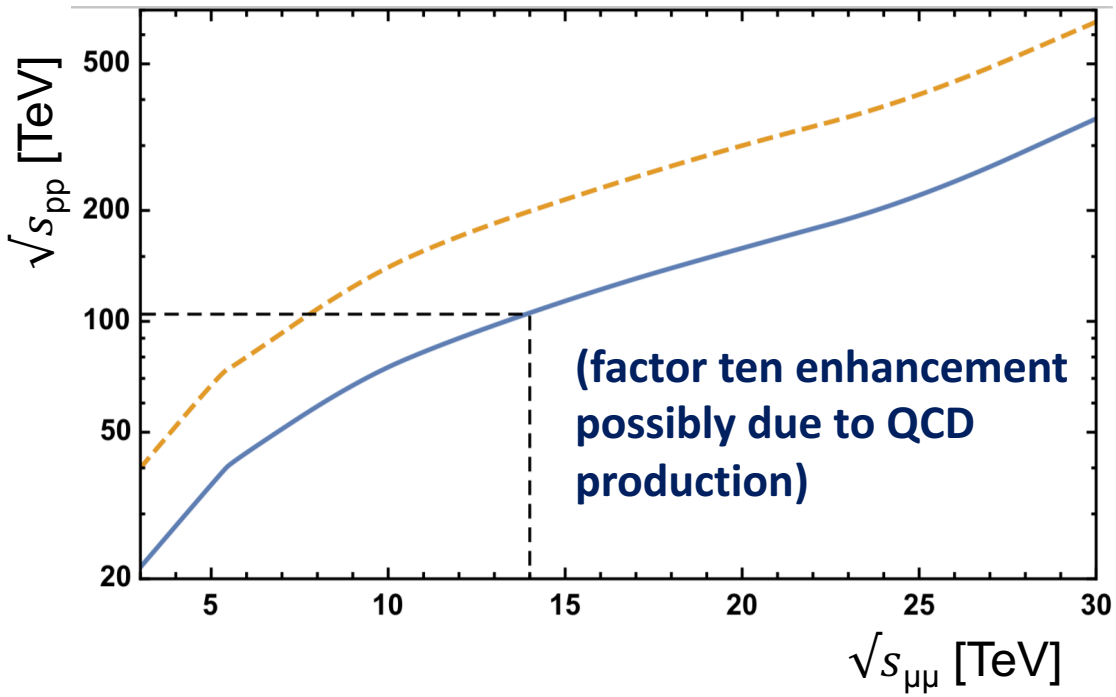


Circular muon colliders
might reach center-of-mass energies of tens of TeV thanks to the limited amount of synchrotron radiation compared to ee colliders

Proton vs Muon Colliders

Cross section comparison for pair production of heavy particles with M ~ ½ $\sqrt{s_{\mu\mu}}$

Muon collider energy $\sqrt{s_{\mu\mu}}$ is entirely available, while proton constituents collide carrying only a fraction of $\sqrt{s_{pp}}$



Equal muon and proton collider cross-sections obtained for $\sqrt{s_{\mu\mu}} \ll \sqrt{s_{pp}}$

➔ **discovery machine for complete exploration of multi-TeV energy scale**

Machine challenges

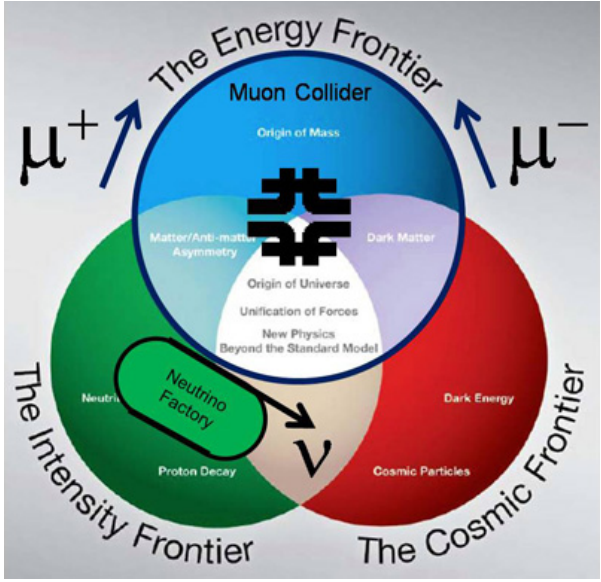
- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in terms of luminosity and power consumption

CRUCIAL PARAMETERS:

- luminosity
- energy
- energy spread
- wall power
- cost
- background
- radiological hazard
- technical risks

Physics reach

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier



U.S. Muon Accelerator Program (MAP)

- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011
- Ramp down recommended by P5 in 2014

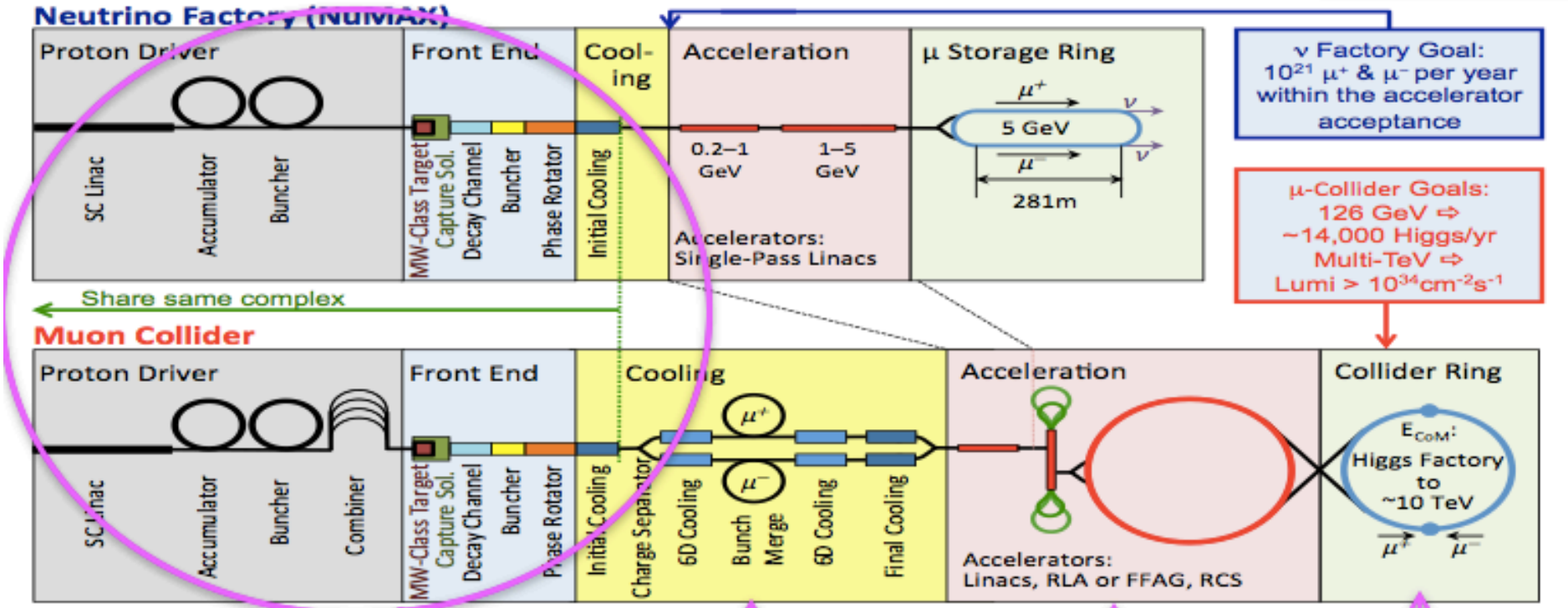
http://map.fnal.gov/

AIM: to assess feasibility of technologies to develop muon accelerators for the Intensity and Energy Frontiers:

- Short-baseline neutrino facilities (nuSTORM)
- Long-baseline neutrino factory (nuMAX) with energy flexibility
- Higgs factory with good energy resolution to probe resonance structure
- TeV-scale muon collider

Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



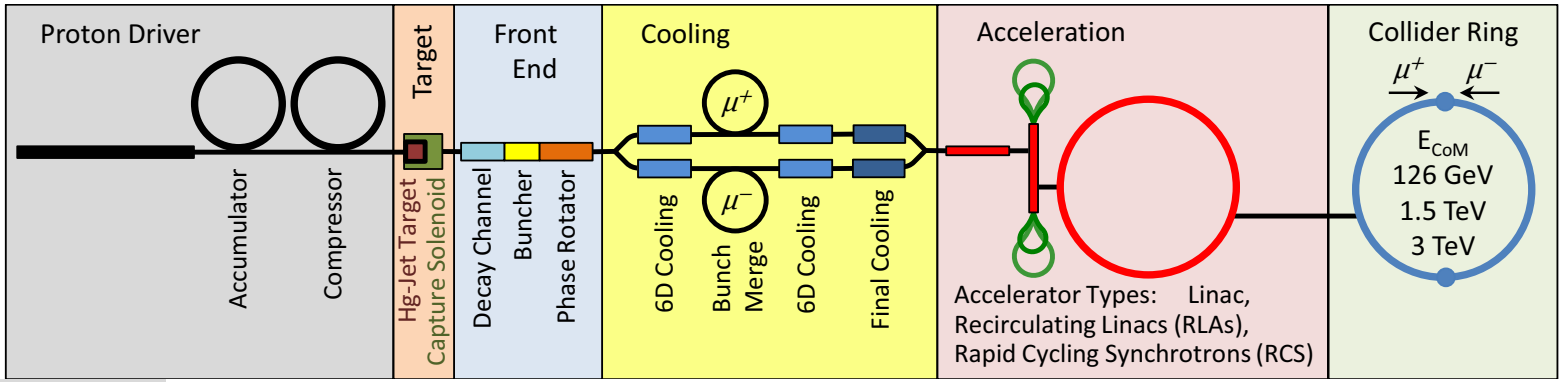
Key Challenges

- ~10^{13}-10^{14} μ / sec Tertiary particle $p \rightarrow \pi \rightarrow \mu$
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key R&D

- MW proton driver; MW class target; NCRF in magnetic field
- Ionization cooling; High field solenoids (30T); High Temp Superconductor
- Cost eff. low RF SC; Fast pulsed magnet (1kHz)
- Detector/ machine interface

MAP Proposal R&Ds



- Based on 6-8 GeV Linac Source
- H- stripping requirements same as those established for neutrino

- MERIT@CERN studied high power target
- π production in high-field solenoid

solenoid $\pi \rightarrow \mu$ decay channel RF cavities bunch & phase rotate $\mu^{\pm}$ into bunch train

- Fast ionization 6D cooling ($\tau = 2\mu s$)
- MICE
- Rubbia demonstrator proposal

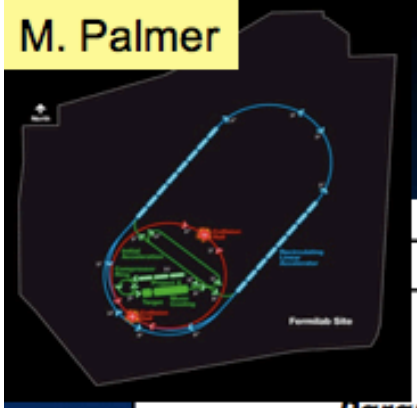
- Fast acceleration
- Use RF and SC

$\mu^{\pm}$ decay background Tungsten shielding or bending magnets to avoid issues from e
- Critical Detector Machine Interface

A lot of material from – *JINST Special Issue MUON*

http://iopscience.iop.org/journal/1748-0221/page/extraproc46

M. Palmer



Muon Collider Parameters

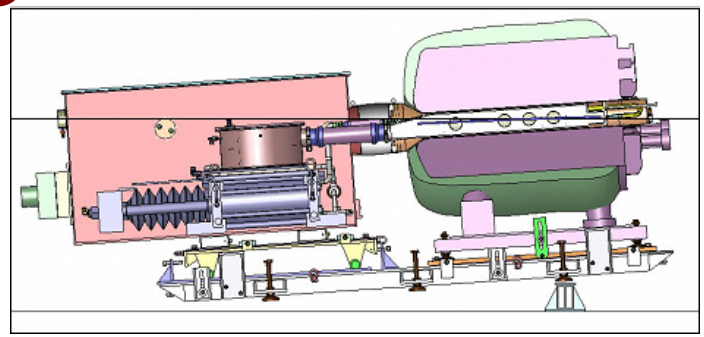
Muon Collider Parameters					
		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts
⇨ several ↙ 10^{32} [Rubbia proposal: 5↙10^{32}]

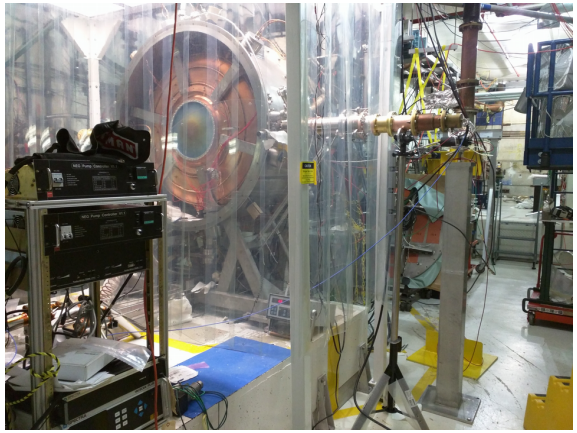
Fermilab

International R&D program



MERIT - CERN

Demonstrated principle of liquid Mercury jet target

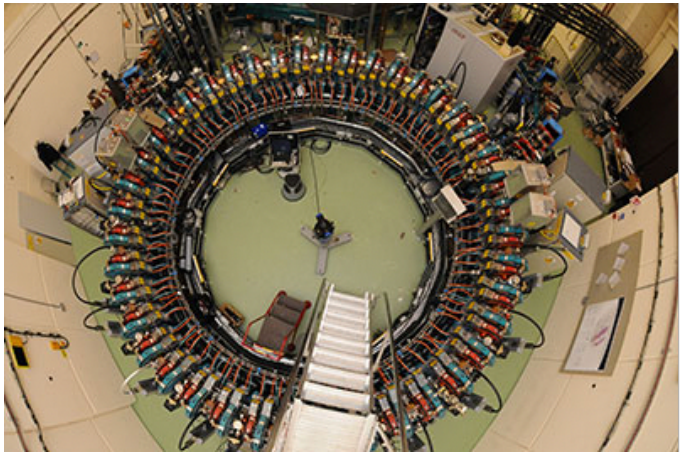


MuCool Test Area - FNAL

Demonstrated operation of RF cavities in strong B fields

EMMA - STFC Daresbury Laboratory

Showed rapid acceleration in non-scaling FFA



MICE - RAL

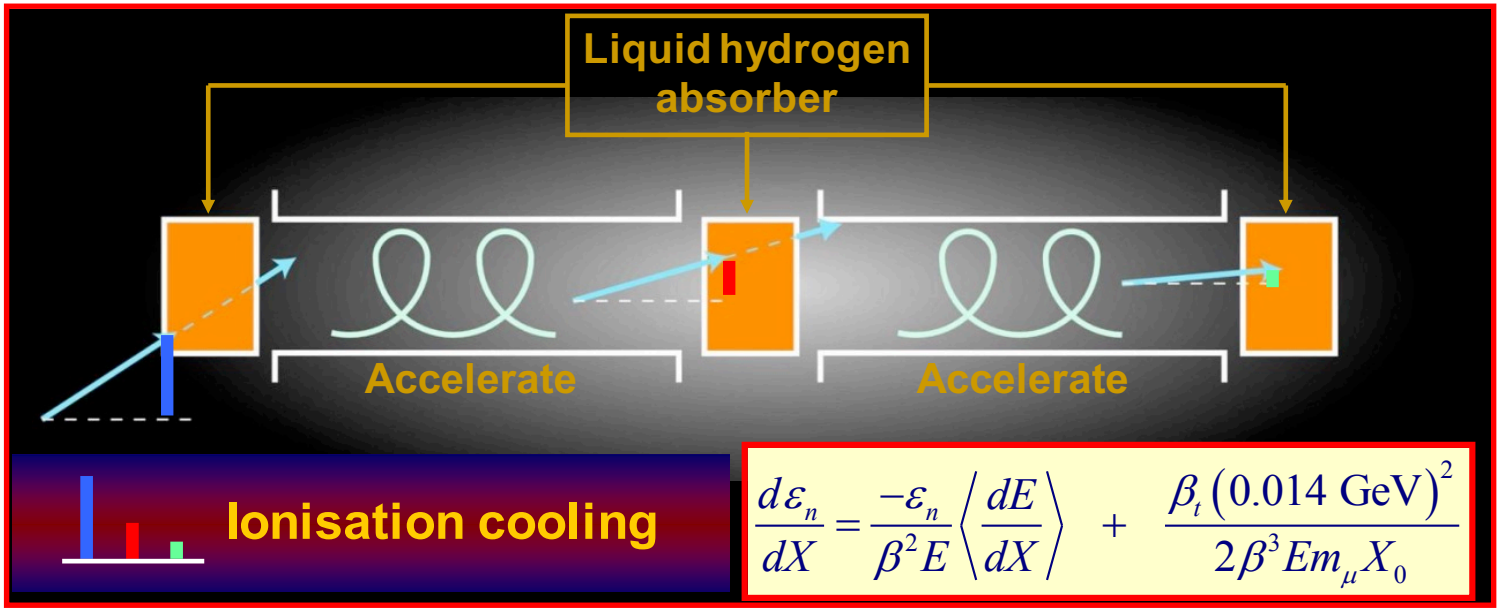
Demonstrate ionization cooling principle

Increase inherent beam brightness

→ number of particles in the beam core

"Amplitude"

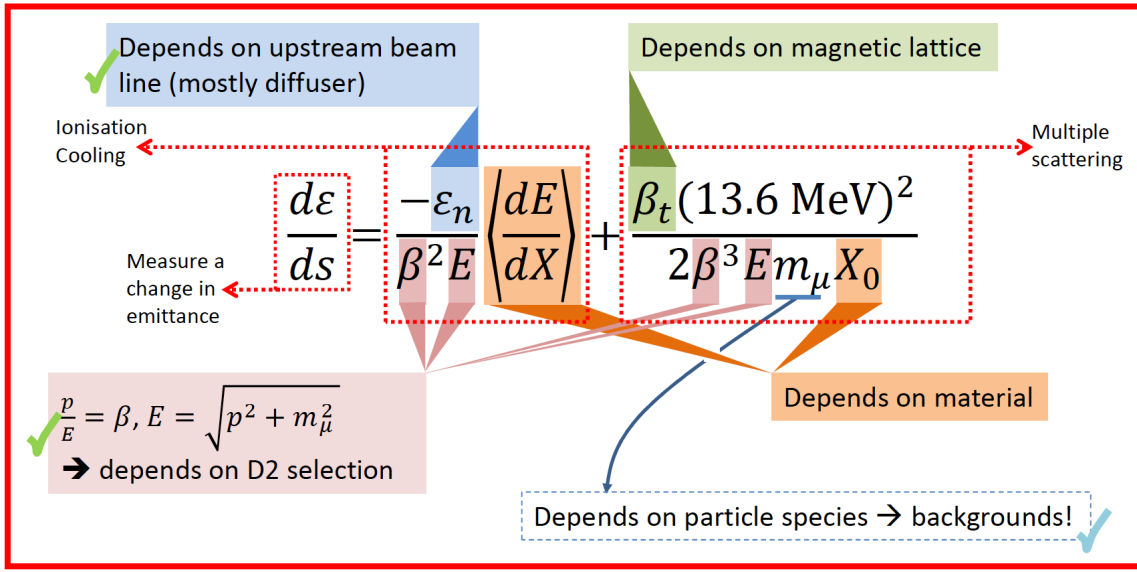
Ionization cooling – MICE experiment



$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

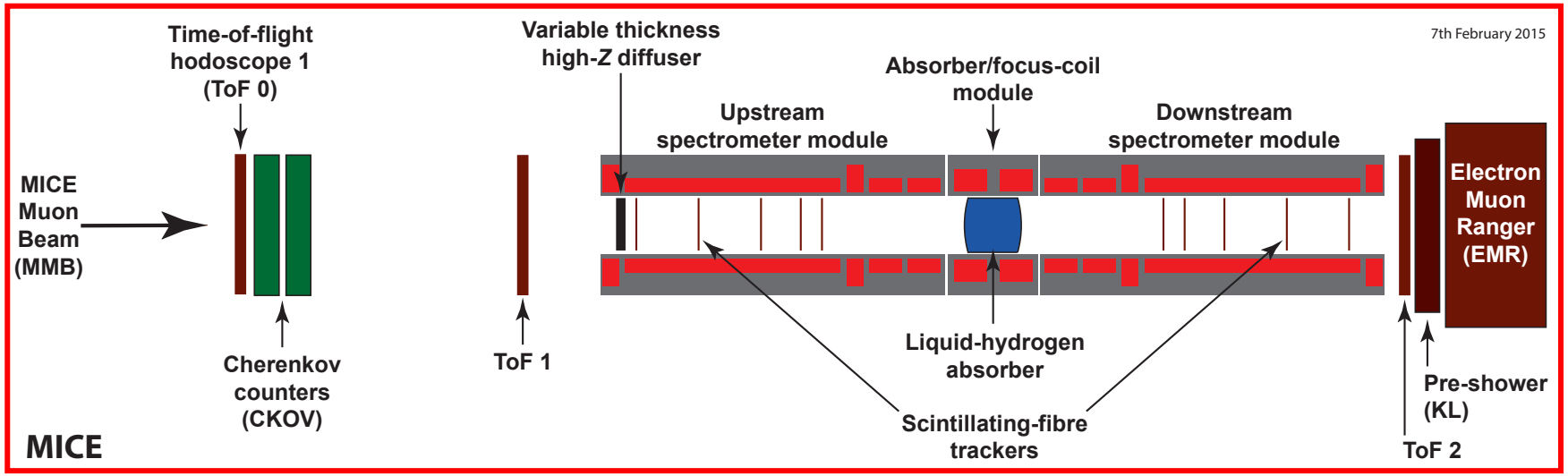
Realistic cooling cell

- Competition between:
  - dE/dx [cooling]
  - Multiple scattering [heating]



http://mice.iit.edu/publications/

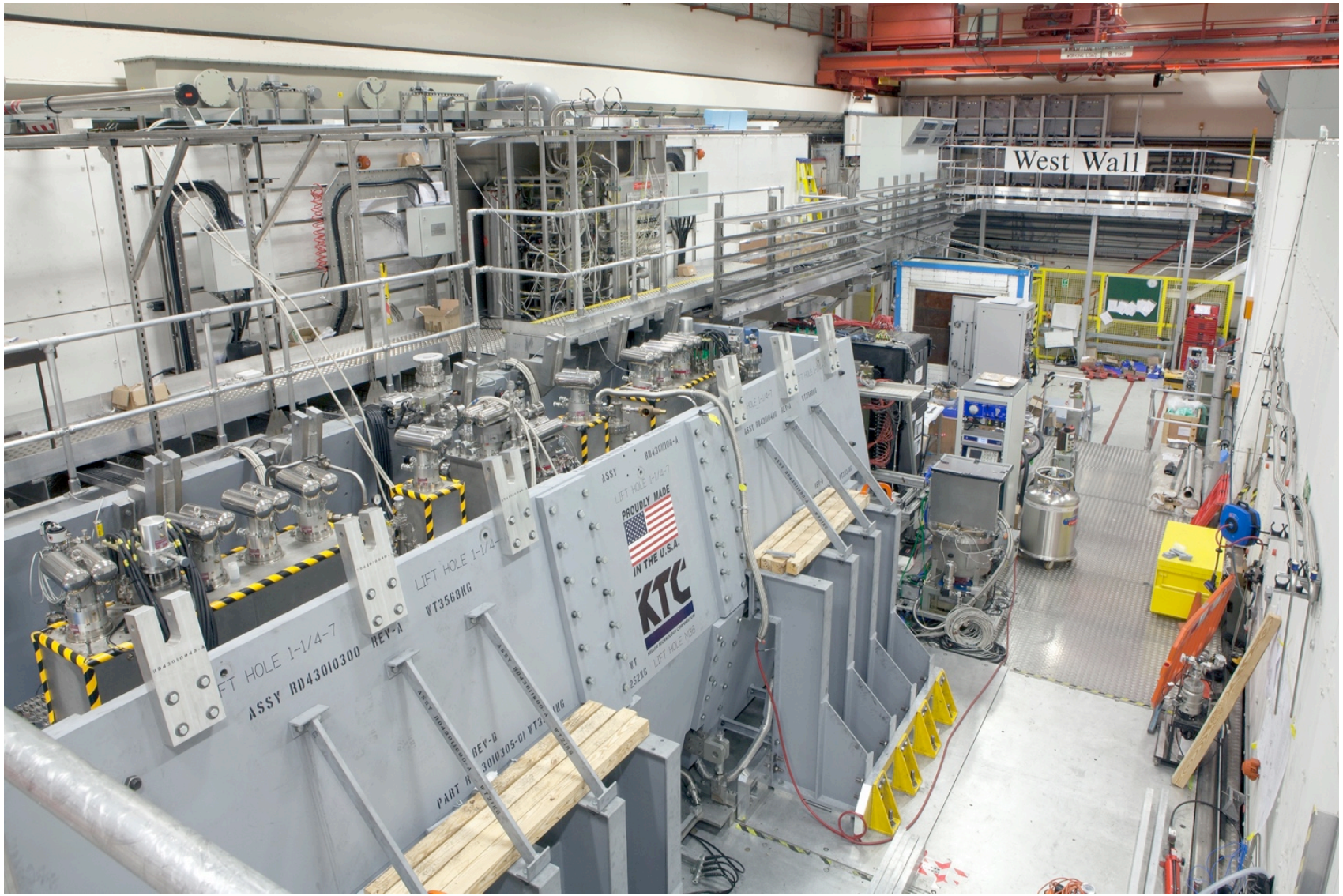
Ionization cooling – MICE experiment



- Optimum absorber:
  - Low Z, large X_0
  - Tight focus
  - H_2 gives best performance

	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

MICE experiment @ RAL

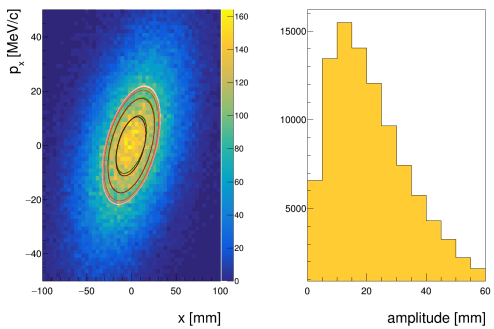


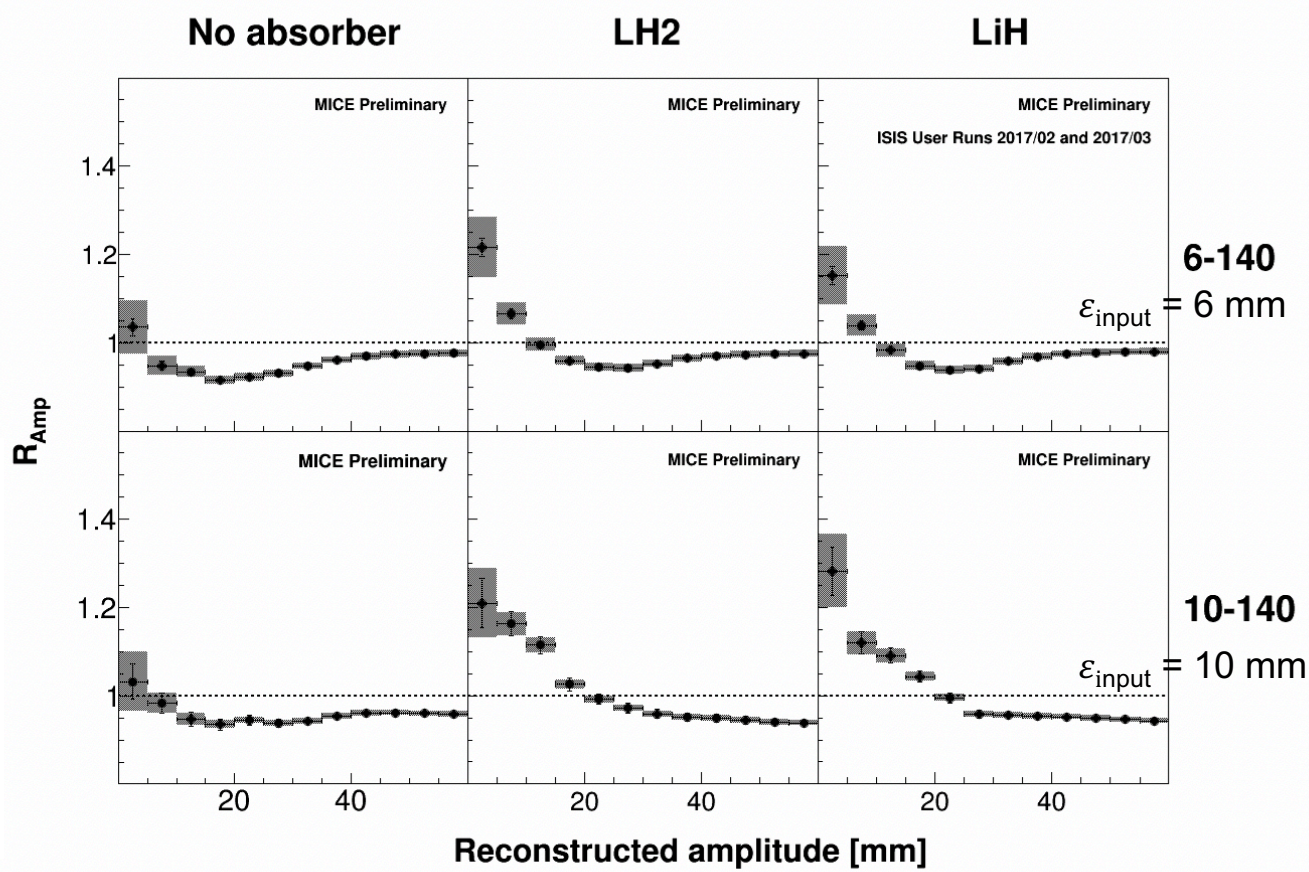
MICE: first results

μ @ 140 MeV/c

IPAC2018 – FRXGBE3

Ionization cooling observed: using LiH and LH_2 absorbers





- R_{Amp}: ratio of downstream muon count to upstream
- **$R_{Amp} > 1 \rightarrow$ cooling:**
  - ★ Migration of high amplitude muons to low amplitude
- "No absorber" does not show cooling, agrees with Liouville's theorem

MICE has measured the underlying physics processes that govern cooling

Low EMittance Muon Accelerator

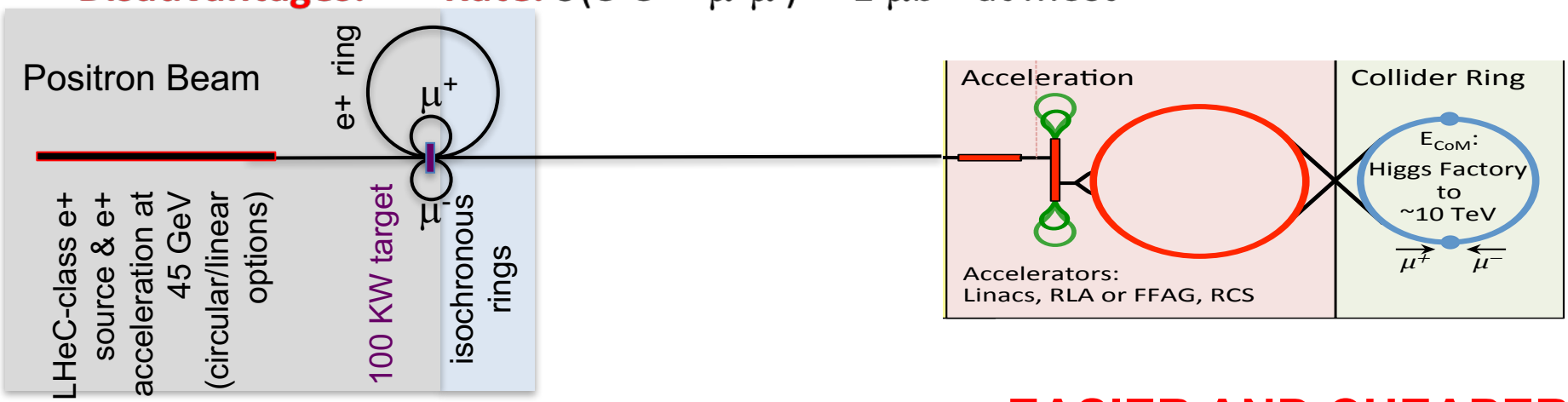
Snowmass 2013 - M. Antonelli e P. Raimondi

Direct μ pair production: muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at √s around the $\mu^+\mu^-$ threshold **(√s~0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

Potential of this idea, but key challenges need to be demonstrated to prove its feasibility ➔ a new proposal for machine studies and measurements

Advantages: **Low emittance possible** **Low background**
Reduced losses from decay **Energy spread**

Disadvantages: **Rate:** $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1\ \mu b$ at most



Key Challenges

~10^{11} μ / sec from e+e-→μ+μ−

Key R&D

10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring

EASIER AND CHEAPER DESIGN, IF FEASIBLE

Key topics for LEMMA scheme

1. **Positron ring**
   - low emittance and high momentum acceptance

Optics design & beam dynamics

2. **Muon Accumulator Rings**
   - High momentum acceptance

IPAC2018 - MOPMF087

Optics design & beam dynamics

3. **Positron source**
   - High rate

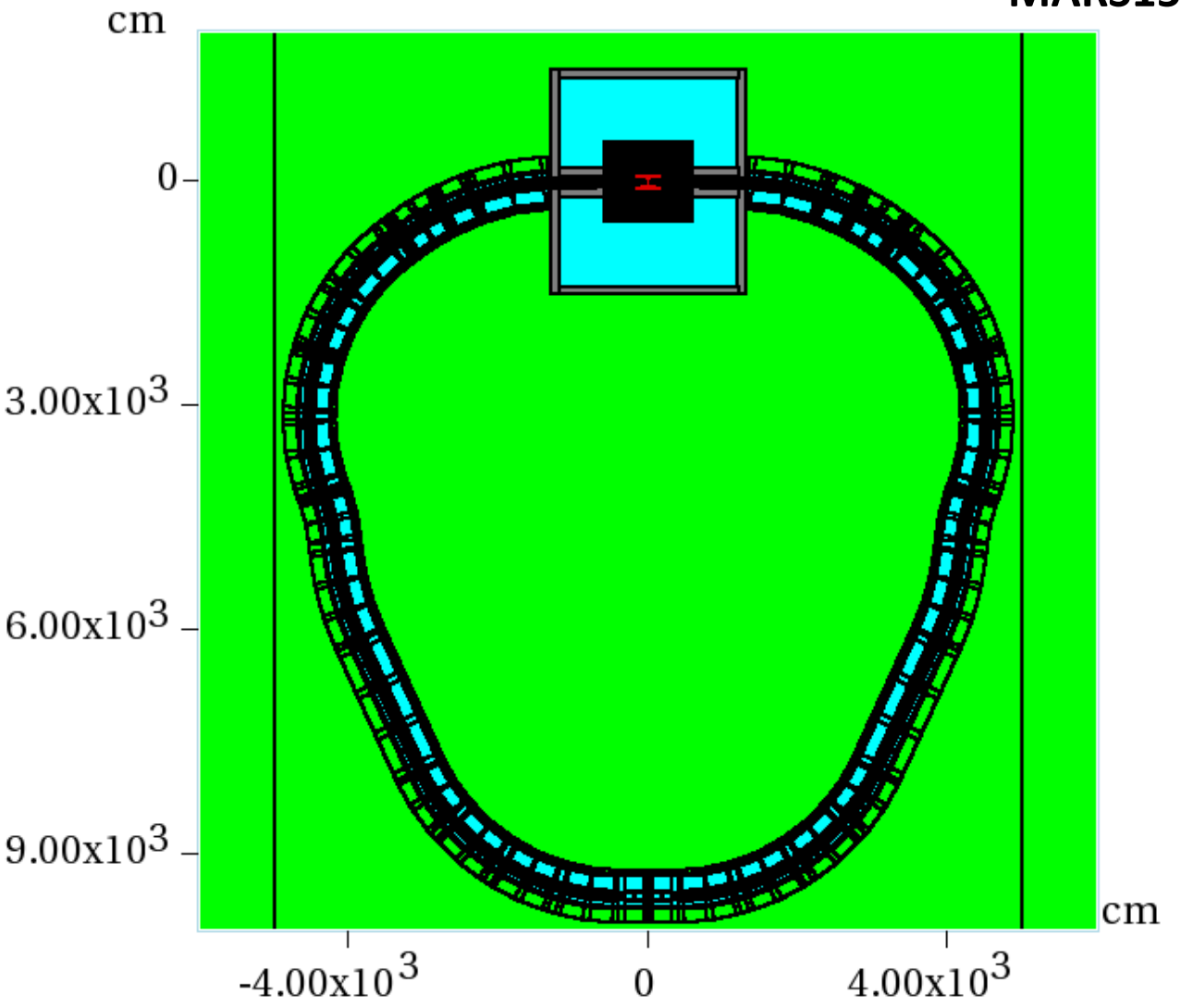
Synergy with FCC-ee/ILC/CLIC future colliders

4. **$\mu^{+/-}$ production target**
   - High Peak Energy Density Deposition PEDD
   - Power O(100 kW)

Synergy with High Power Targetry R&D, HL-LHC beam interceptors

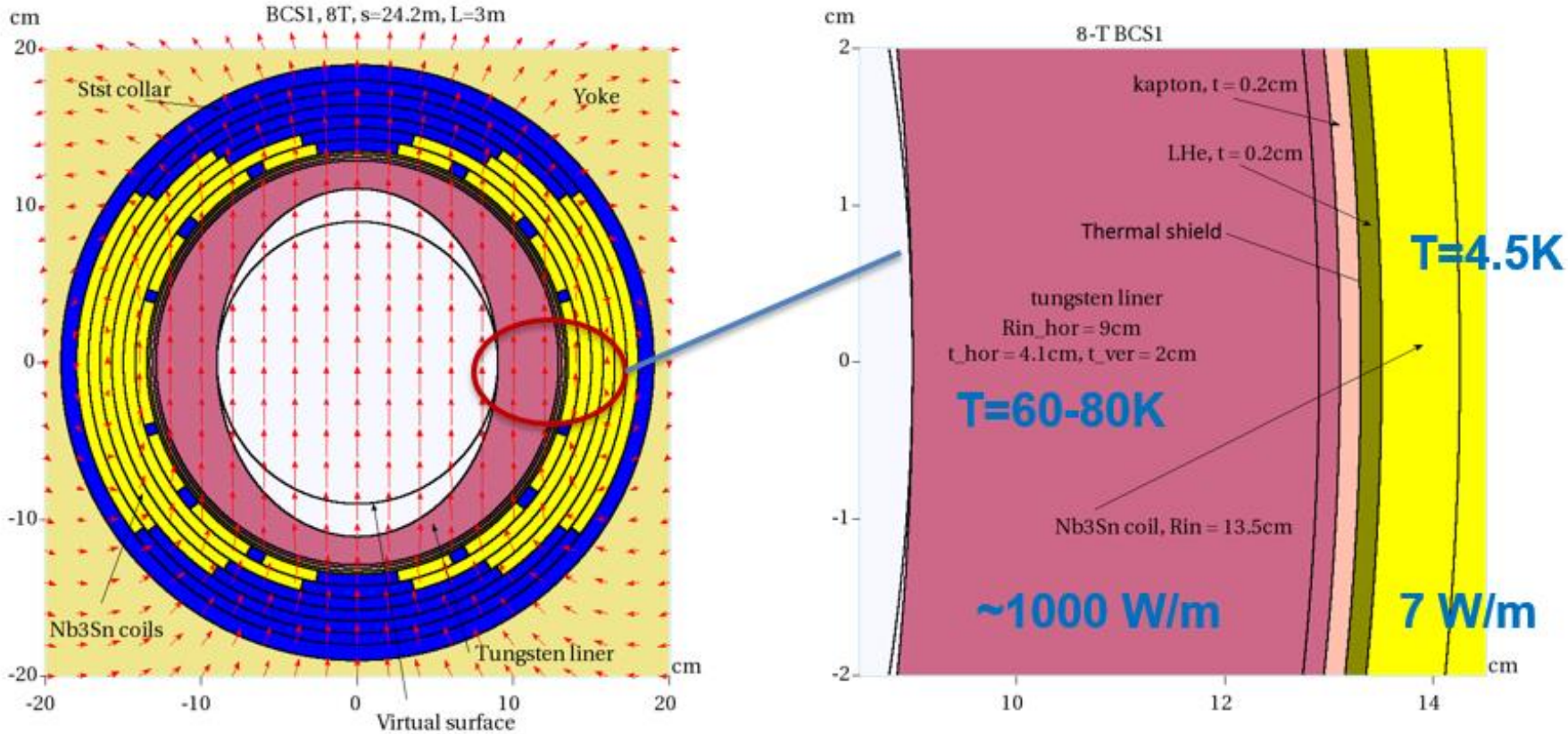
MAP Higgs Factory design

MARS15 Monte Carlo code

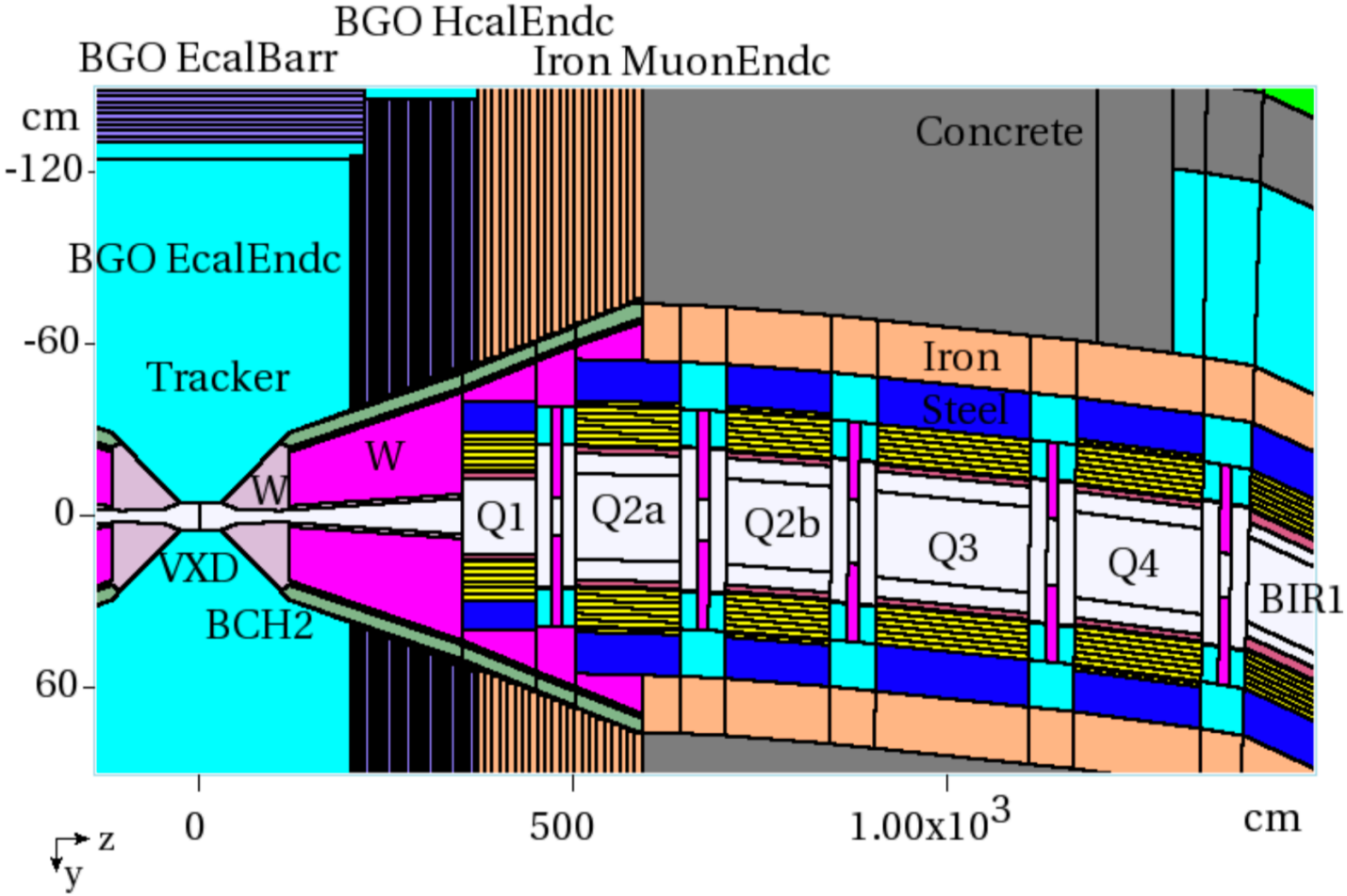


MAP magnets design

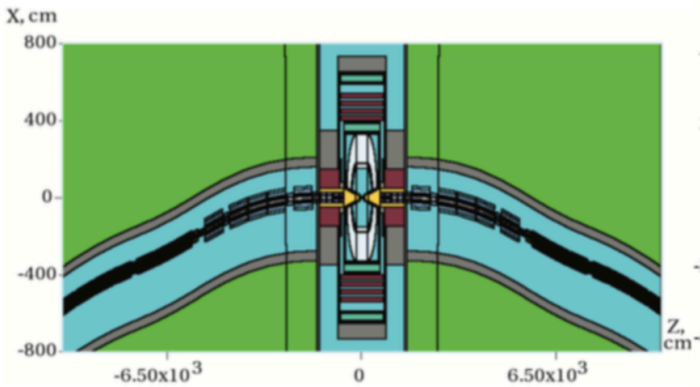
MARS15 Monte Carlo code

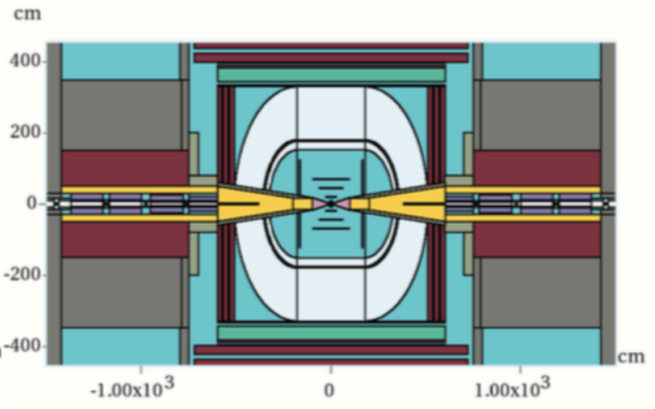


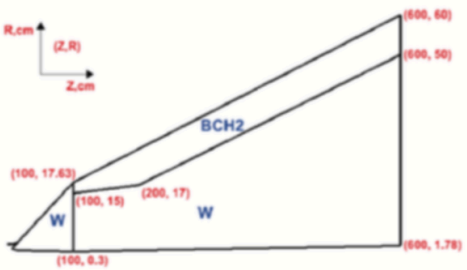
MARS –MDI design



Detector and interaction region





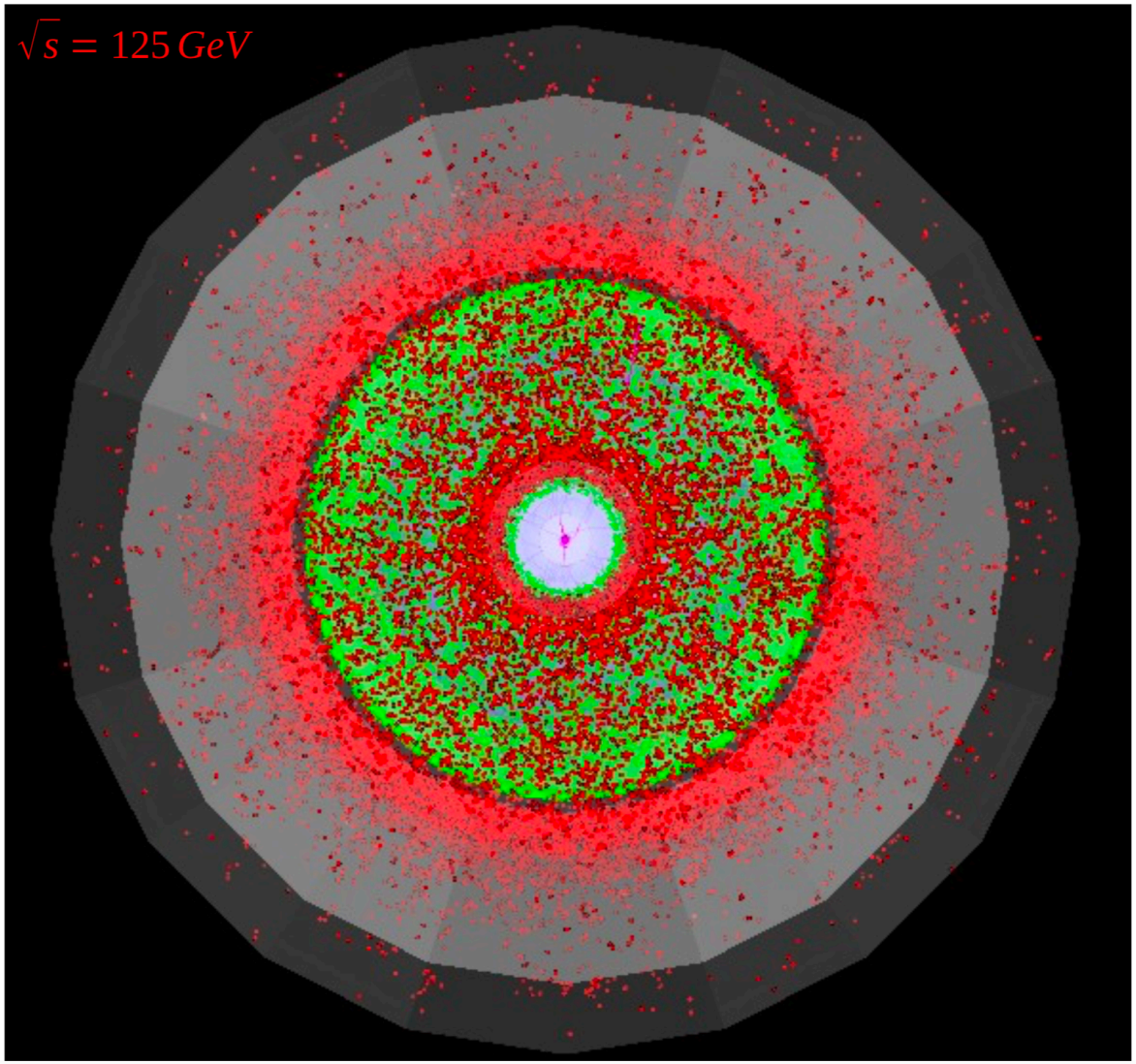


Detailed studies performed by MAP Collaboration for √s=1.5 TeV collider using MAR15 simulation of particle transport and interactions in accelerator, detector and shieldings

N.V. Mokhov, S.I. Striganov *Detector Backgrounds at Muon Colliders*, TIPP 2011, Physics Procedia 37 (2012) 2015 – 2022

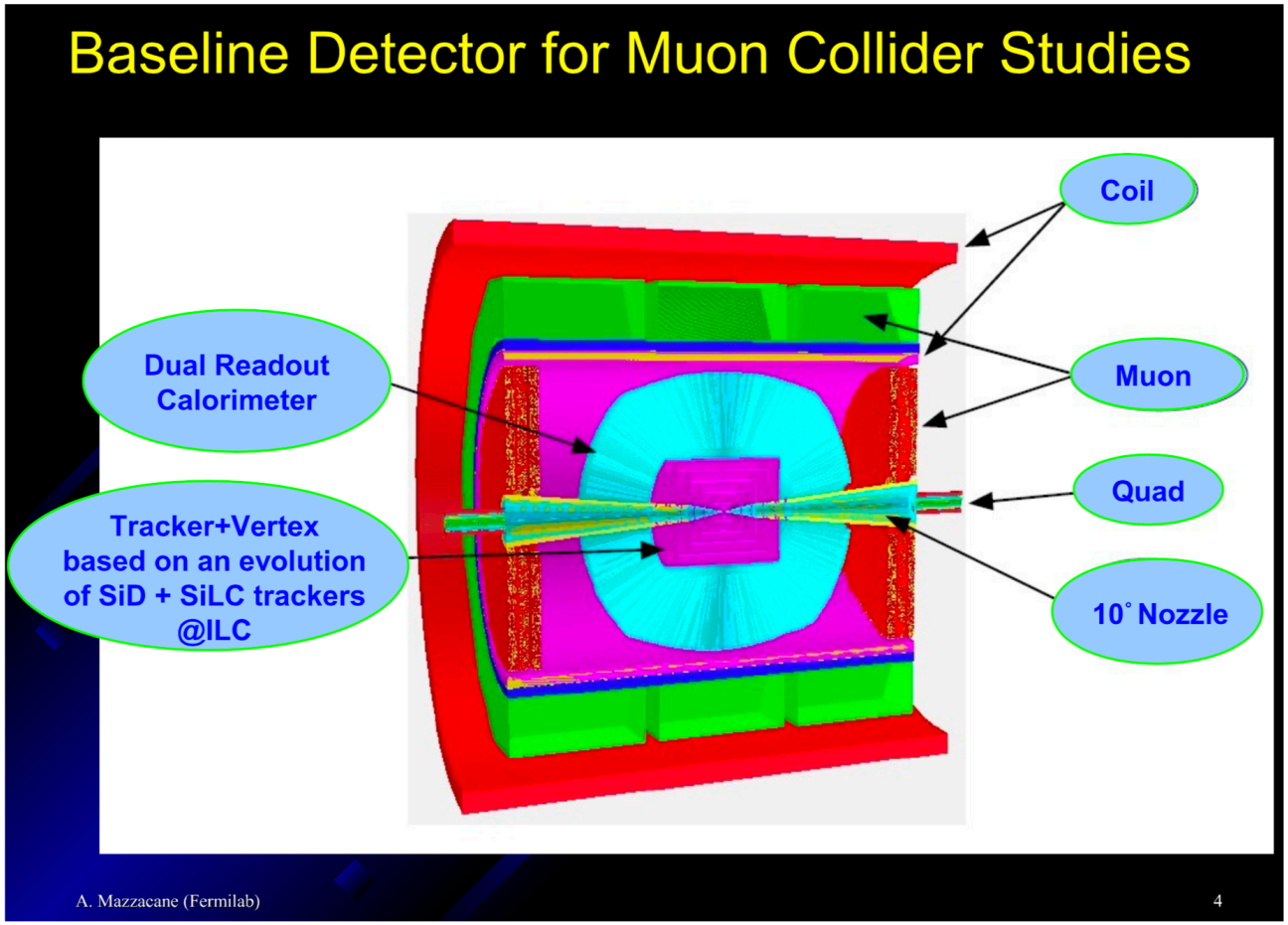
N.K. Terentiev, V. Di Benedetto, C. Gatto, A. Mazzacane, N.V Mokhov, S.I. Striganov *ILCRoot tracker and vertex detector hits response to MARS15 simulated backgrounds in the muon collider*, TIPP 2011, Physics Procedia 37 (2012) 104 – 11

The detector challenge



MAP detector design

A. Mazzacane



Modelled in the ILCroot framework, response simulated with GEANT

- Vertex detector:
  - 20x20 μm^2 Si pixels;
  - 5 barrel layers at 5.4 cm < r < 15.4 cm;
  - 4 + 4 endcap disks, |z| < 42 cm.
- Si tracker:
  - 50x50 μm^2 Si pixels;
  - 5 barrel layers at 19.5 cm < r < 121.5 cm;
  - (4+2) + (4+2) endcap disks at |z| < 165 cm.
- Dual readout calorimeter:
  - lead glass + scintillating fibers;
  - fully projective geometry with ~1.4° tower aperture angle;
  - depth: >100 X_0 and ~7.5 λ_{int}.
- Muon spectrometer:
  - precision drift tubes.
- Shielding nozzle:
  - tungsten core with a borated polyethylene coat.

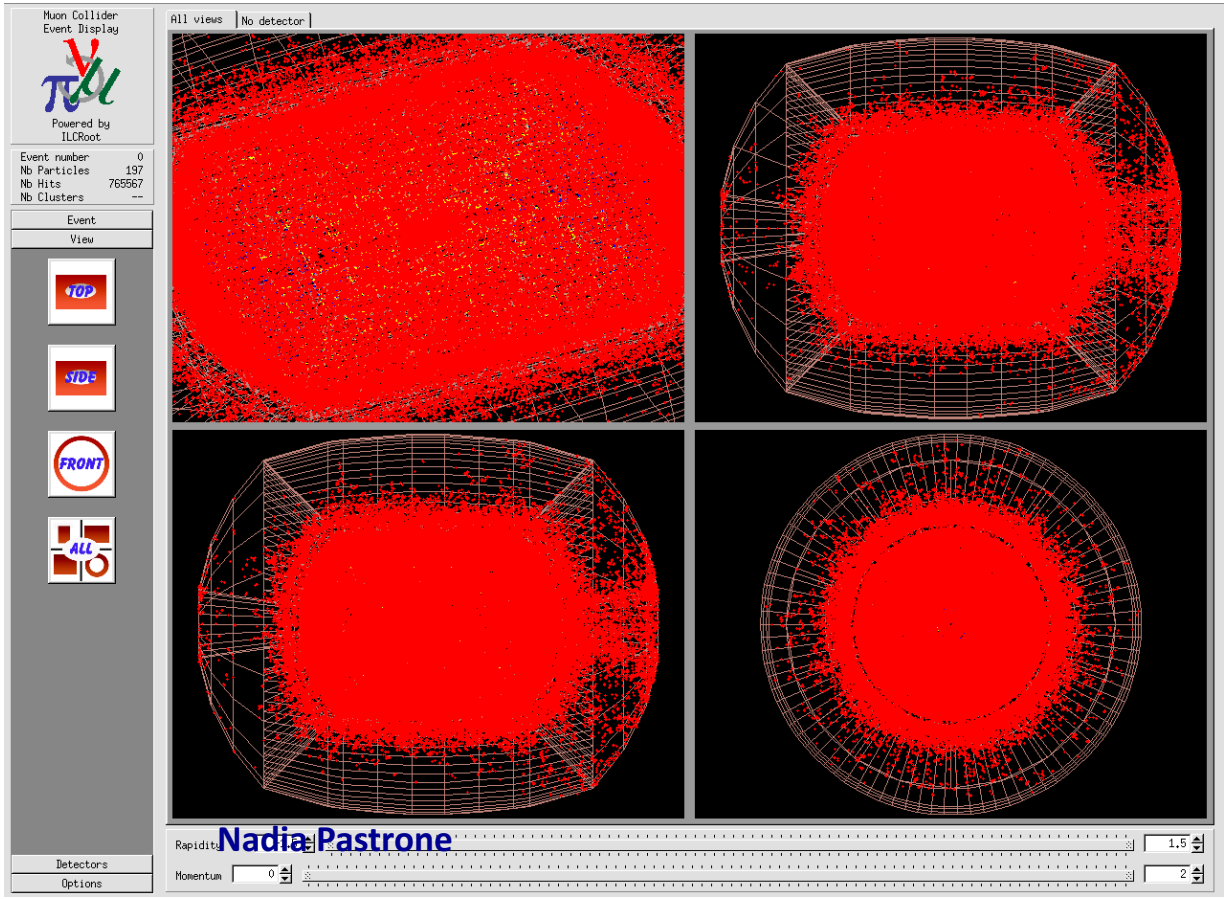
Detector challenges

Muon Collider simulation: MAP package
$\mu^+\mu^- \longrightarrow H \longrightarrow b\bar{b}$ Pythia @ √s=125 GeV

Background (MARS simulation)
from muon decays and interaction with machine elements included

Background @ √s=125 GeV is the worst possible case

No cuts: all hits



Muon decays background:
beam @ 0.75 TeV

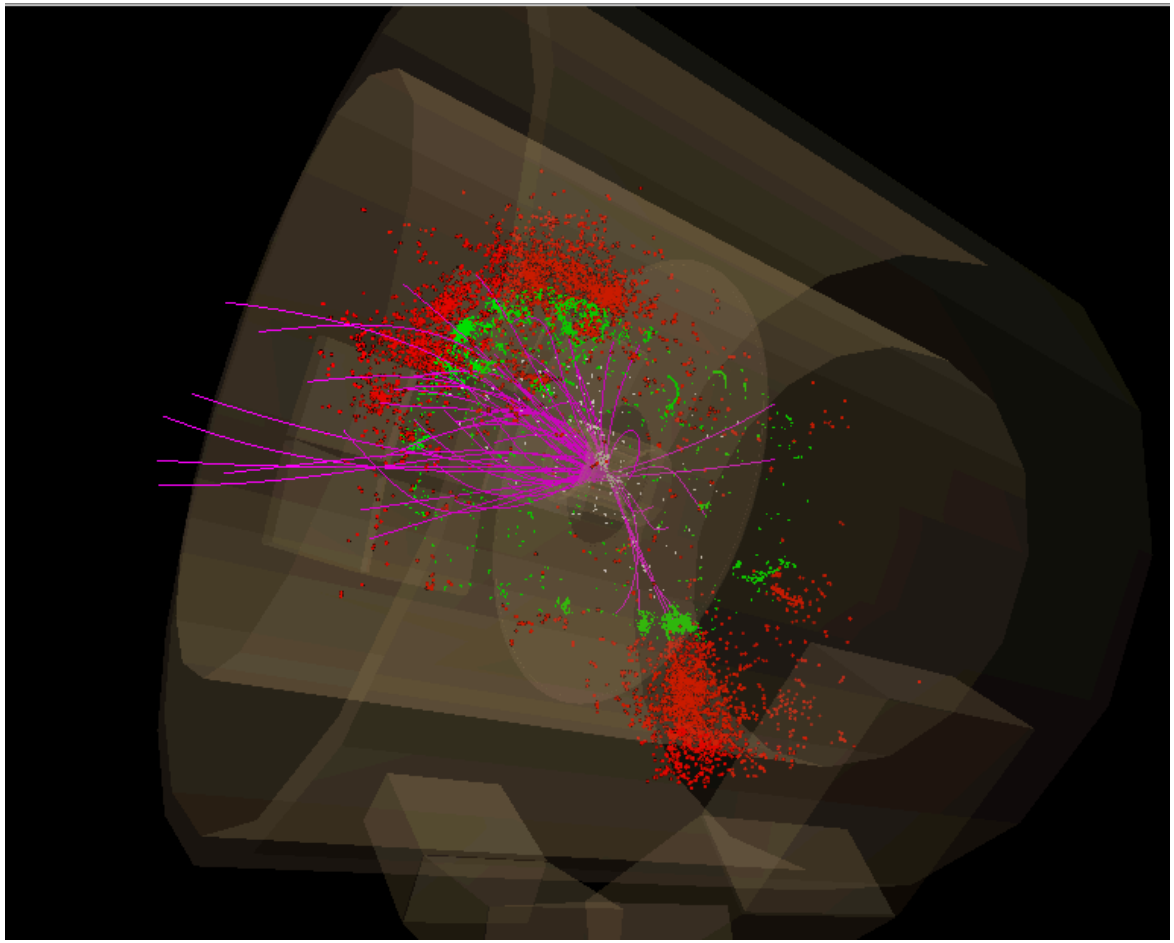
$\lambda = 4.8\times10^6$m
with $2\times10^{12}\mu$/bunch

➔ 4.1×10^5decay
per meter of lattice

Cogne 2019

Nadia Pastrone

Timing powerful to remove background



Tools are in place!
work just started....

- ✓ higher energies need to be studied
- ✓ a new detector must be designed based on more recent R&D effort

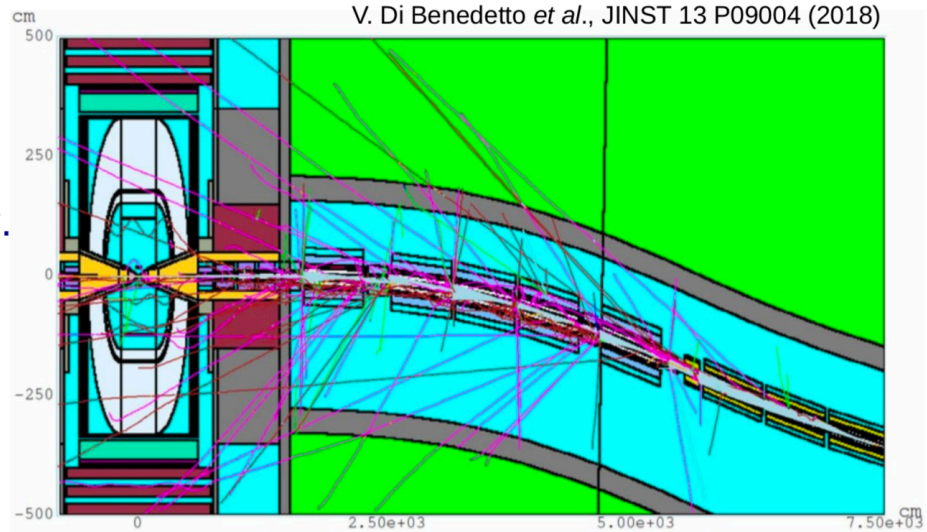
Detector studies plan

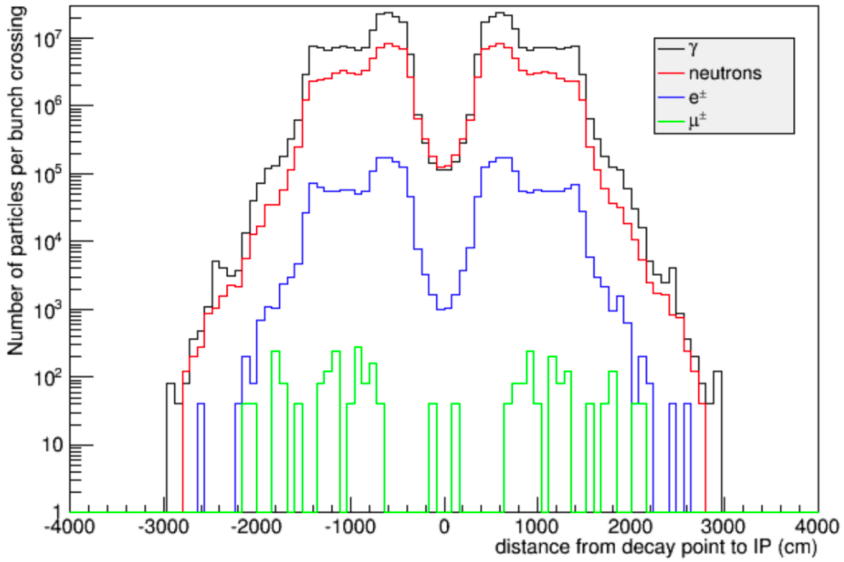
- **short term:**
  - ✓ study the **125-GeV case** with the full machine and detector simulation, estimate detector resolutions and efficiencies for physics objects of interest, in order to implement a parameterized fast detector simulation;
- **long term:**
  - ✓ study a **multi-TeV case** (6-10 TeV) and evaluate the physics reach on benchmark channels (i.e. double Higgs production).

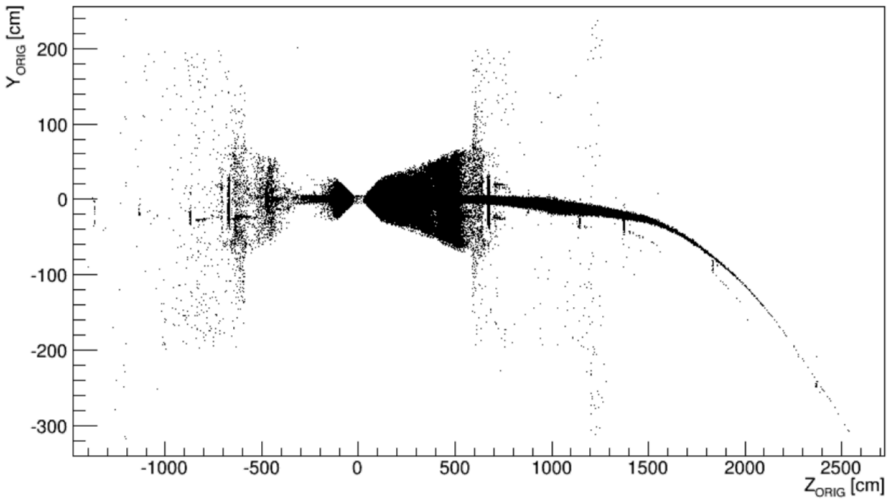
Beam-induced backgound

- Beam-induced background in the detector:
  - $e^{\pm}$ from $\mu^{\pm}$ decays radiate synchrotron photons;
  - $e^{\pm}$ and γ interact with machine components producing hadrons, secondary muons, $e^{\pm}$ and γ.
- Currently we have a bkg sample for a 62.5-GeV beam, produced by N.V. Mokhov with MARS15 (https://mars.fnal.gov/) in the range -10 m < $Z_{\mu\ decay}$ < 30 m.

V. Di Benedetto *et al.*, JINST 13 P09004 (2018)







Backgound levels/bunch crossing

- The background levels in the detector are strongly dependent on the beam energy and the configuration of the machine-detector interface.

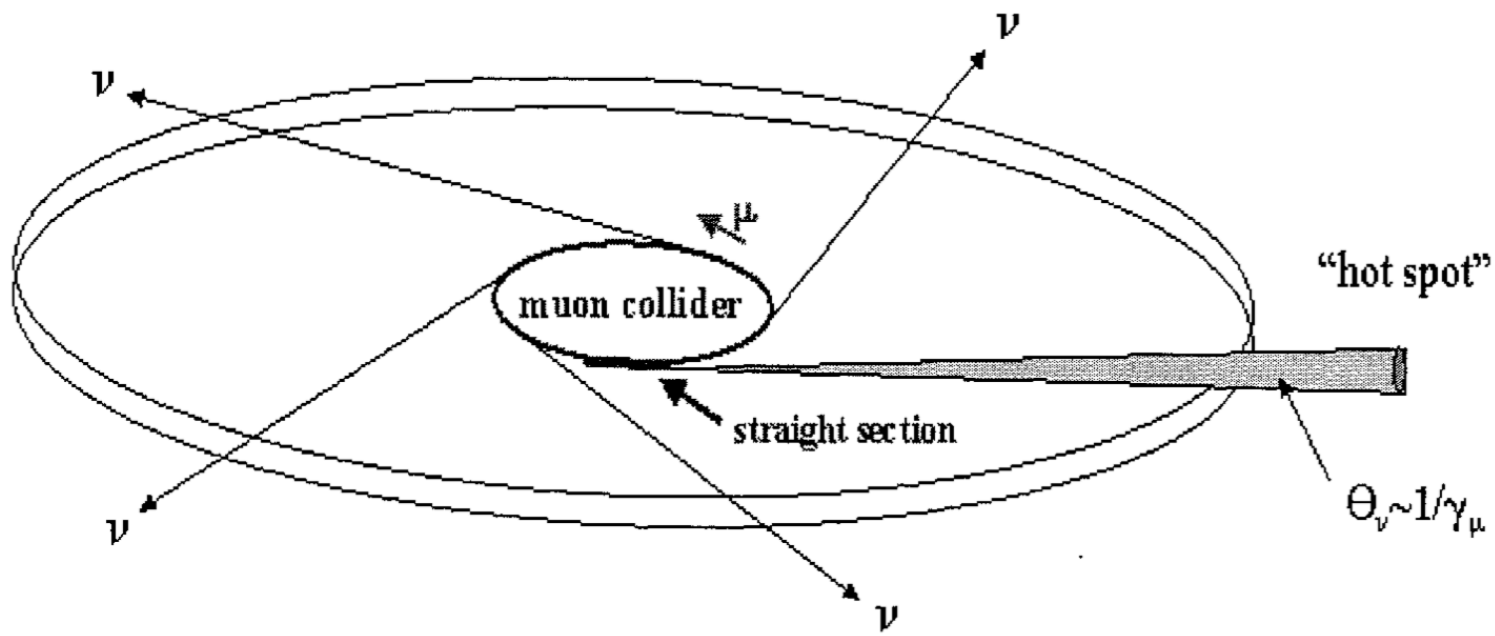
beam energy [GeV]	62.5	750
μ decay length [m]	3.9×10^5	46.7×10^5
μ decays/m per beam (for 2×10^{12} μ/bunch)	51.3×10^5	4.3×10^5
photons/BX (*) ($E_\gamma > 0.2$ MeV)	280×10^6	177×10^6
neutrons/BX (*) ($E_n > 0.1$ MeV)	52×10^6	41×10^6
$e^\pm$/BX (*) ($E_e > 0.2$ MeV)	2×10^6	1×10^6
charged hadrons/BX (*) ($E_h > 1$ MeV)	0.01×10^6	0.048×10^6
muons/BX ($E_h > 1$ MeV)	not available	0.008×10^6

bkg particles entering the detector per bunch-crossing

(*) N.V. Mokhov *et al.*, Fermilab-Conf-14-184-APC (2014)

Neutrino induced hazard

Neutrino radiation imposes major design and siting constraints on multi-TeV muon colliders or inventing smart solutions!



Neutrino induced hazard - simulation

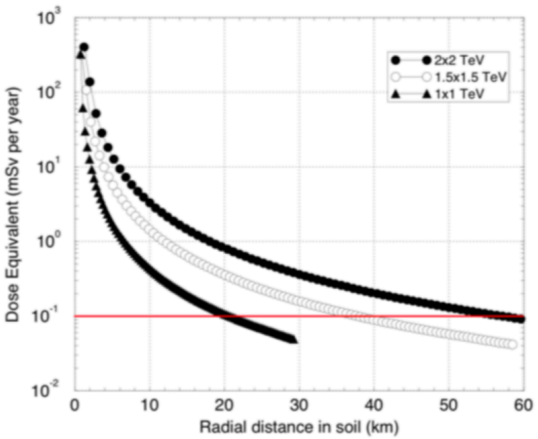


Figure 8: Maximum dose equivalent in TEP embedded in soil in high-energy muon collider orbit plane with 1.2×10^{21} decays per year *vs* distance from ring center.

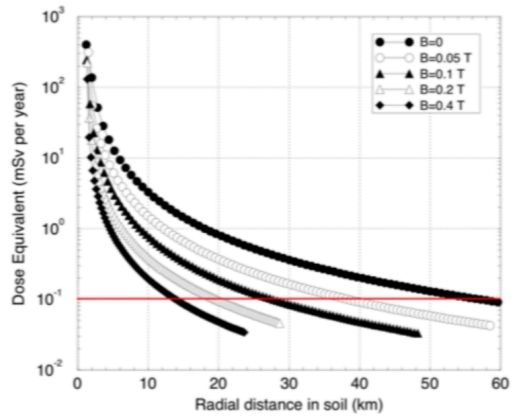


Figure 10: Maximum dose equivalent in TEP located in orbit plane *vs* distance from ring center in soil around a 2+2 TeV muon collider with 1.2×10^{21} decays per year for five values of vertical wave field.

TEP= tissue-equivalent phantom

New background generation with new neutrino cross sections planned with FLUKA

Table 4. Constraints on lattice designs to limit neutrino radiation.

E	B(min)	L(max)	$\mathscr{L}$
TeV	T	m	10^{34} cm^{-2} s^{-1}
1.5	0.25	2.4	0.008
3.0	1.5	0.28	0.6
6.0	1.5	0.28	12*

One concept

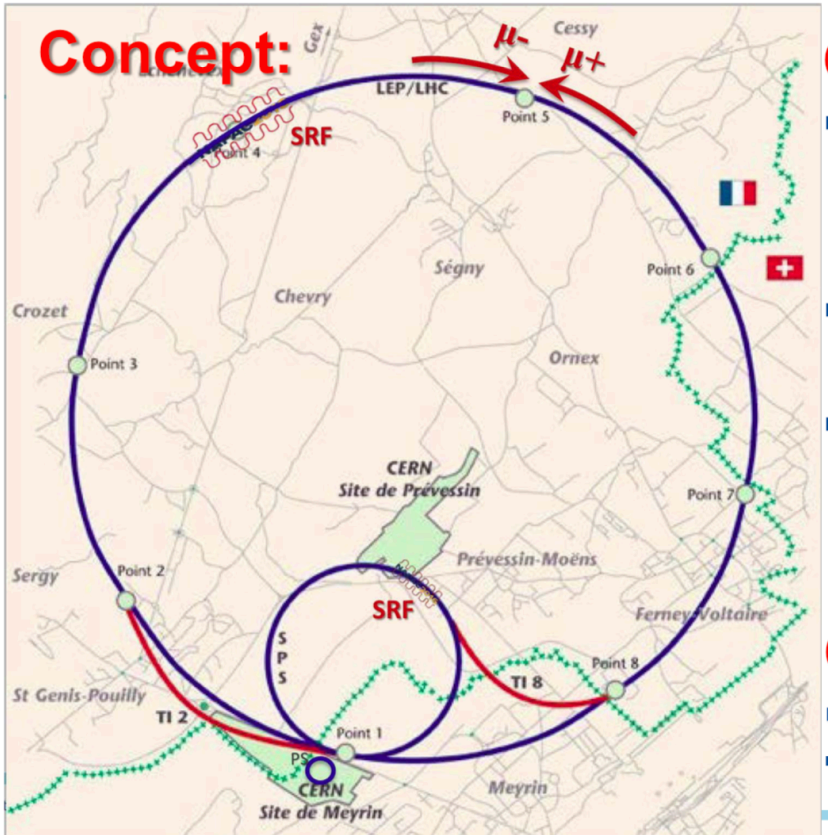
- Solution beyond 10 TeV unclear at present†

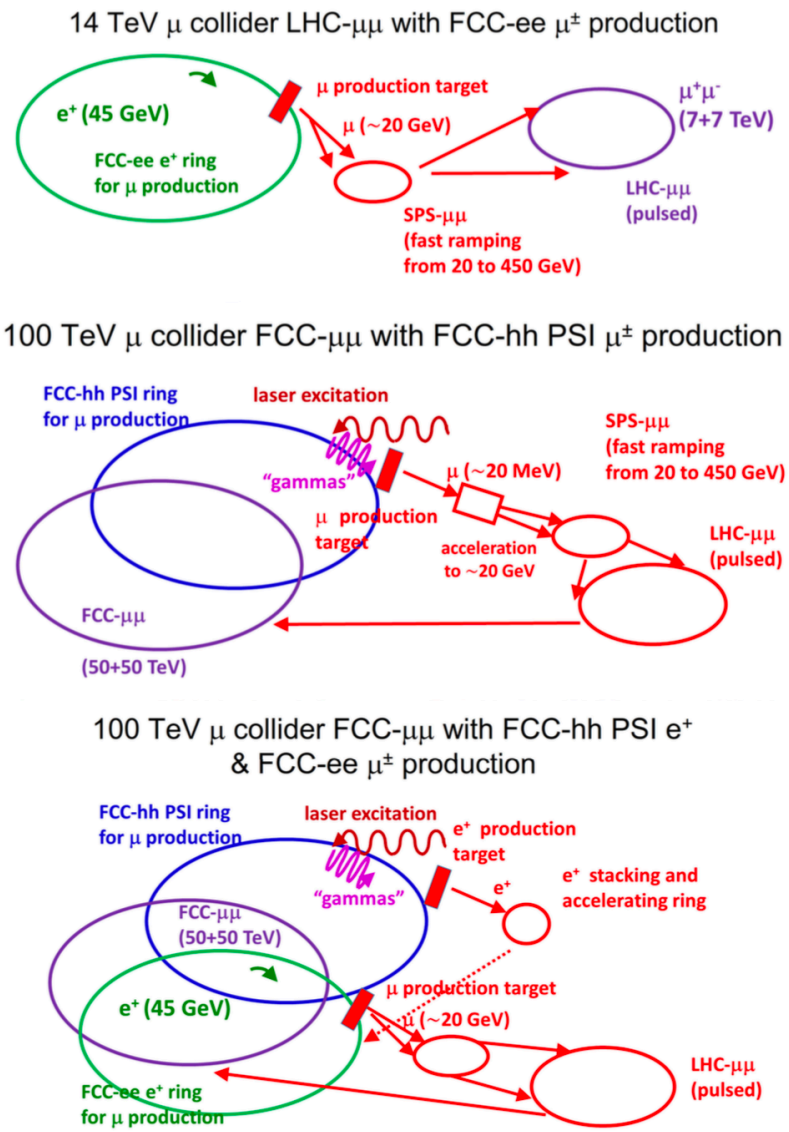
* constrained by ν radiation

† although cf. AIP Conf. Proc. 1507 (2012) 860

D. M. Kaplan — Muon Collider '18, U Padova 7/1–3, 2018 — 12/17

Dream or possibility?





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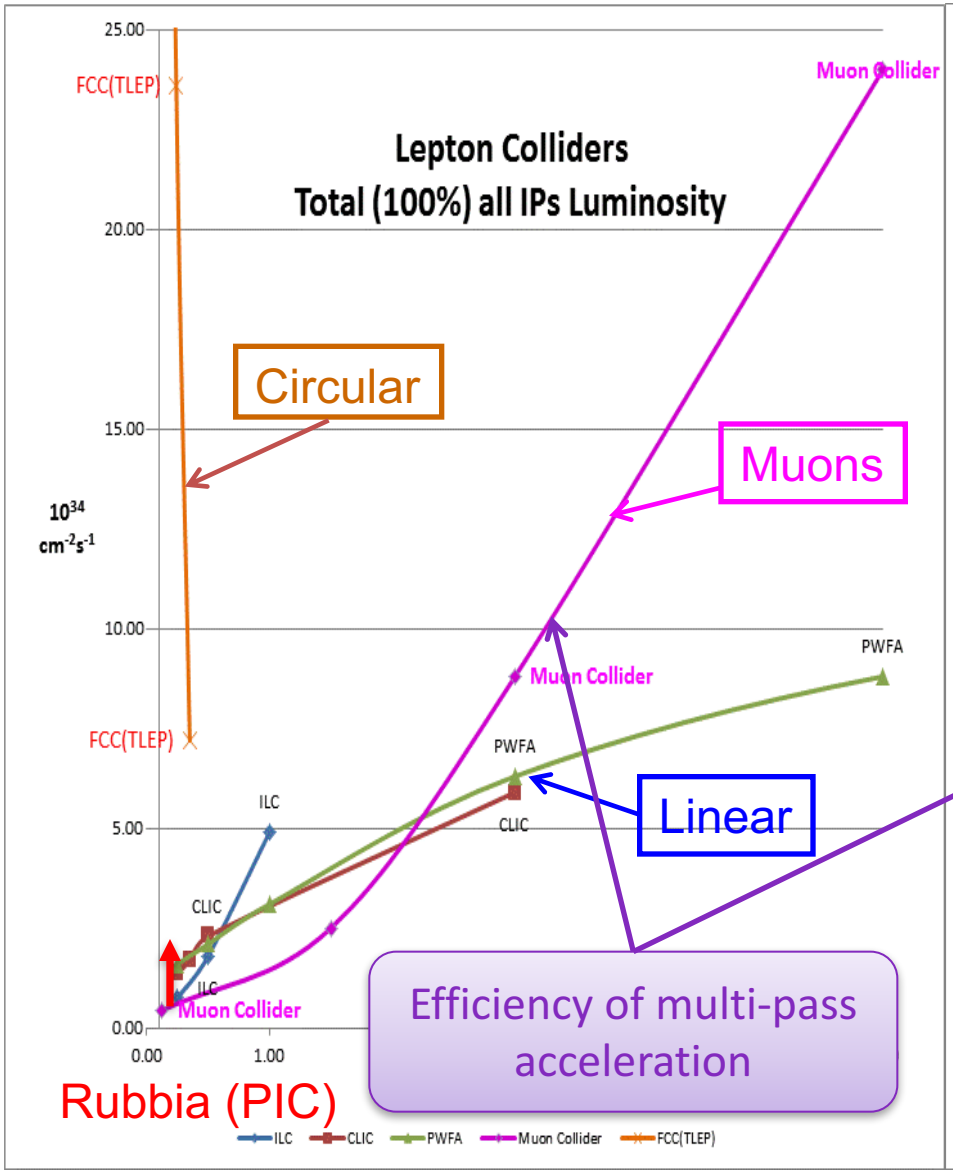
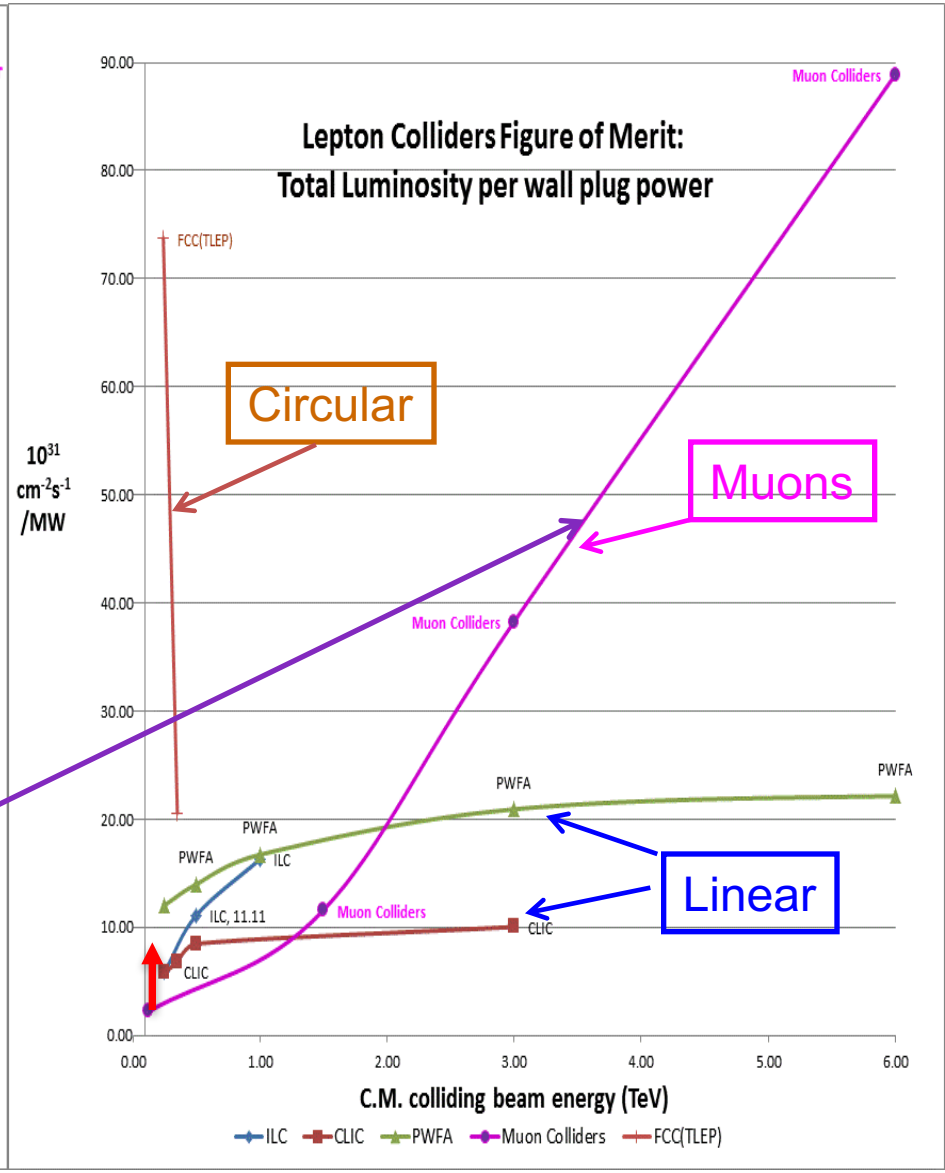
Multi TeV scale - efficiency



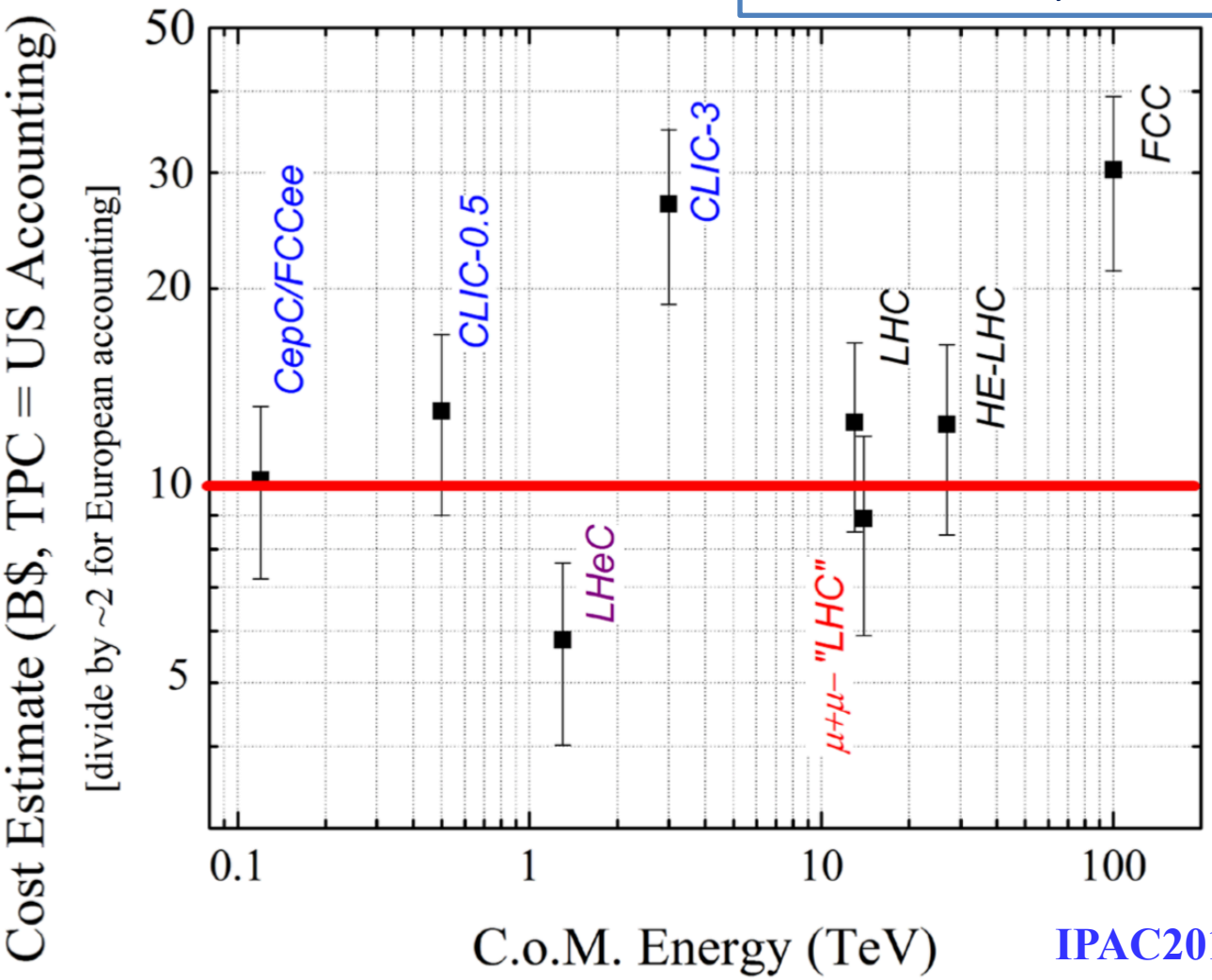
Rubbia (PIC)



Cost estimate

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

Vladimir SHILTSEV,David NEUFFER (Fermilab)



IPAC2018 - MOPMF072

Conclusions

- Muon Collider is an appealing solution as the HEP future accelerator
- U.S. Muon Accelerator Program (MAP) provides a well documented set of studies and measurements on the proton-driven option
- First results on ionizing cooling from MICE experiment now available
- A novel scheme to produce very low emittance muon pairs using a positron beam needs to be further investigated to became vialable
- Detailed studies and R&Ds, required to design a feasible solution for a Muon Collider, must be planned and pursued at international level
- The Update to the European Strategy for Particle Physics is the fly-wheel and the perfect opportunity to revise previous work and launch new studies

Seed of a renewed international effort

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 Laboratory Directors Group
to prepare the Input Document to the European Strategy Update
https://arxiv.org/abs/1901.06150
see related material @ muoncollider.web.cern.ch

A lot of 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/overview