Joint 9th IDPASC SCHOOL and
XXXI INTERNATIONAL SEMINAR of
NUCLEAR and SUBNUCLEAR PHYSICS
"Francesco Romano"
27 May - 4 June 2019, Otranto (Italy)

IDPASC

Otranto School

European Strategy Update

Future particle colliders

Nadia Pastrone

INFN TORINO

Serra degli Alimini - June 2st, 2019

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

Accelerator Science and Technology

Caterina Biscari and ***Lenny Rivkin***

BIG QUESTIONS for the Accelerator Science and Technology

- **What is the best implementation for a Higgs factory?**
  Choice and challenges for accelerator technology: linear vs. circular?

- **Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?**

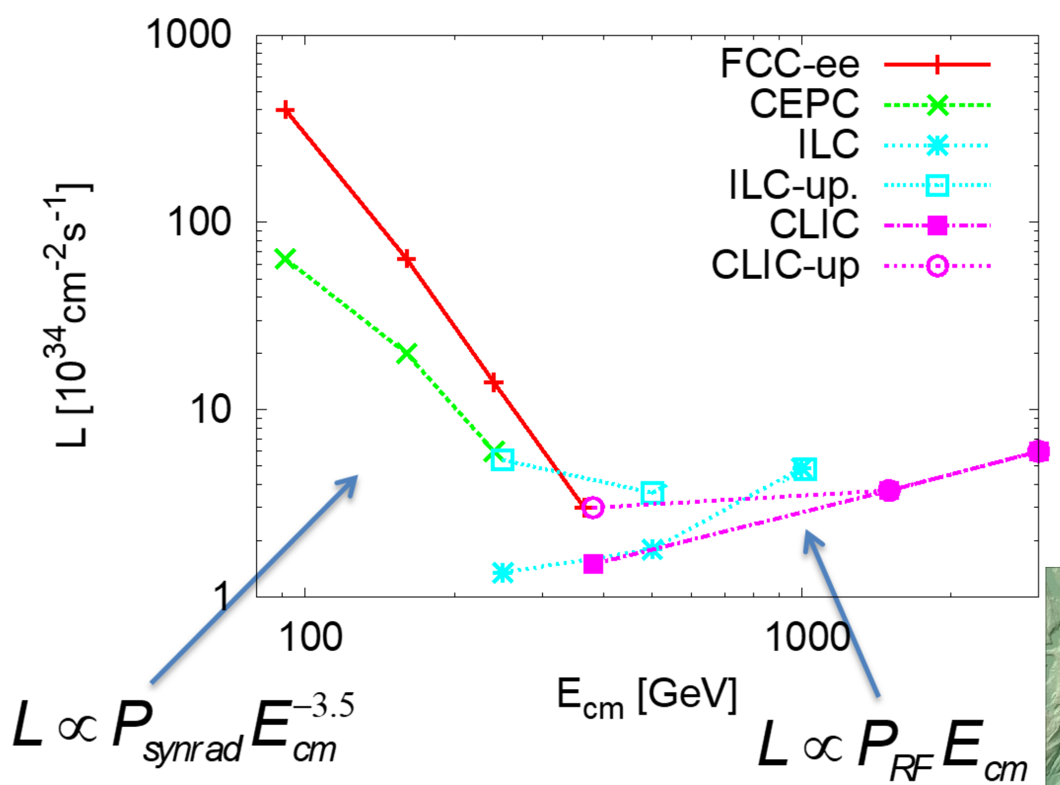
- **How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?**

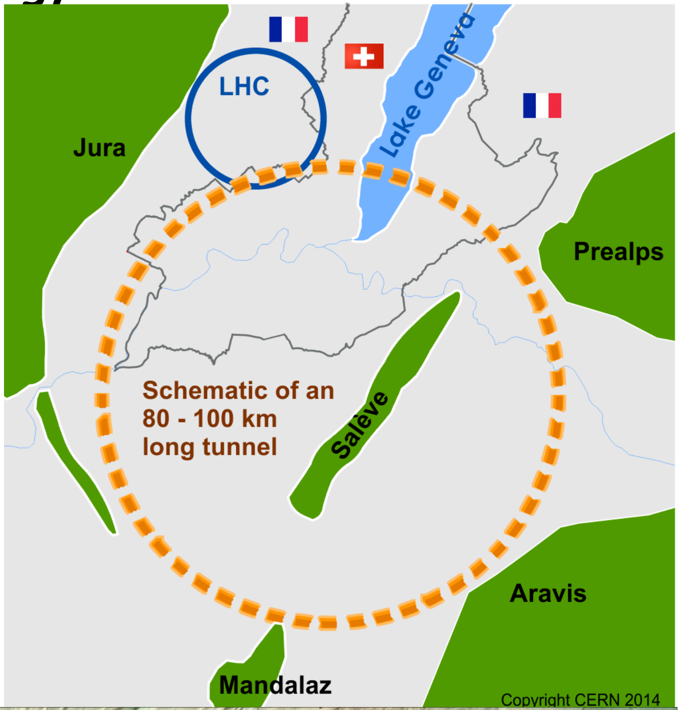
- **Energy management in the age of high-power accelerators?**

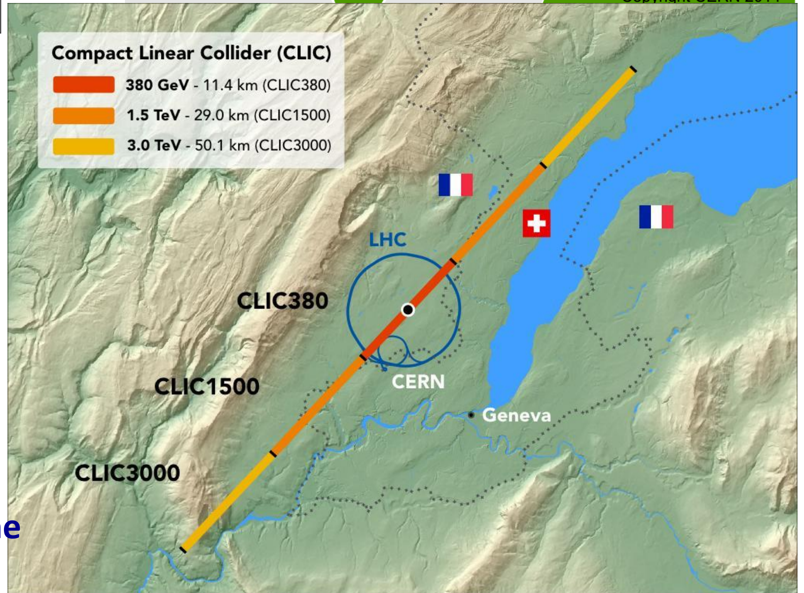
The future is in accelerating muons in plasma!
Vladimir Shiltsev

Q1: What is the best implementation for a Higgs factory?
Choice and challenges for accelerator technology: linear vs. circular?

Luminosity per facility

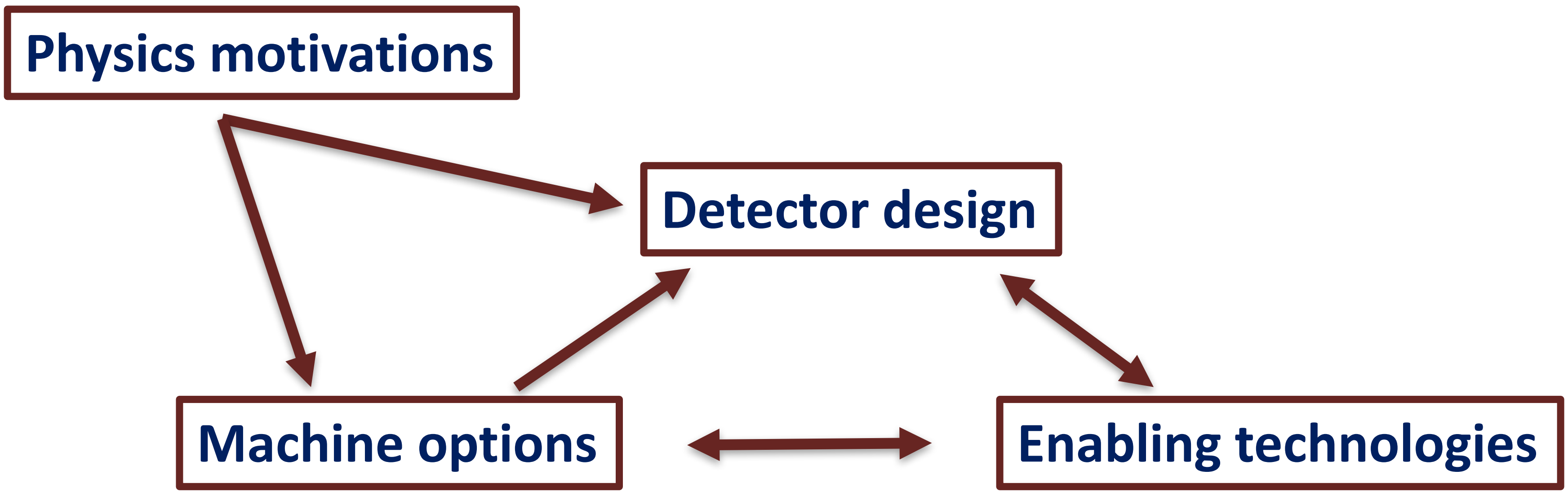






Ours is a very dynamic field!
(Luminosity upgrades for ILC, CLIC)

How do we plan?



See also lectures by Albert De Roeck and Michelangelo Mangano

The Muon Collider challenges

towards the highest possible energy

NEWS

Strategy update: Dream machine

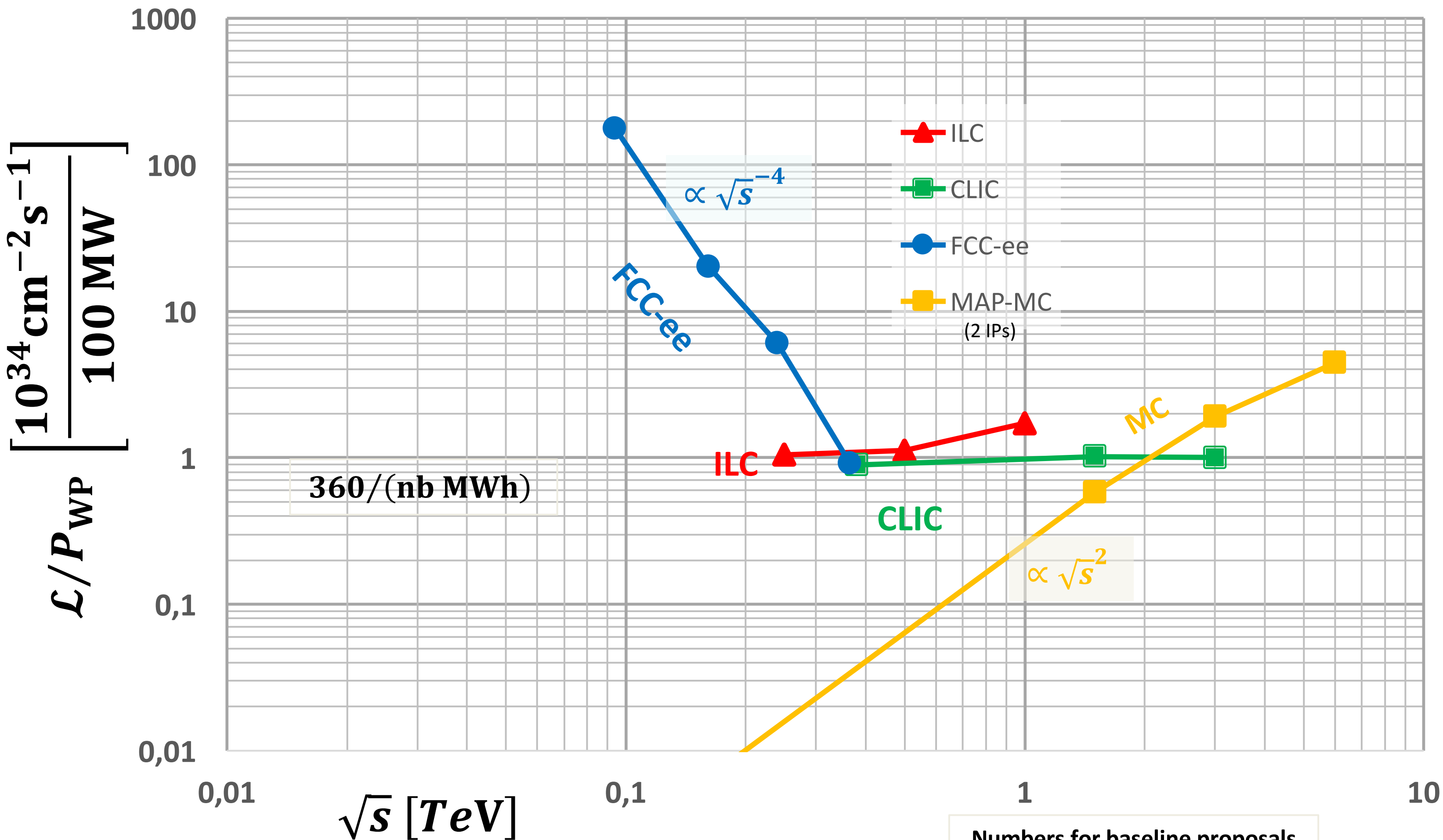
17 May 2019

Muon colliders are both precision and discovery machines, but significant R&D is required before they can be considered candidates for a next collider.

https://cerncourier.com/strategy-update-dream-machine/

Figure of merit for proposed lepton colliders

Disclaimers:
1. This is not the only possible figure of merit
2. The presented numbers have different levels of confidence/optimism; they are still subject to optimisations



Numbers for baseline proposals

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

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

- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

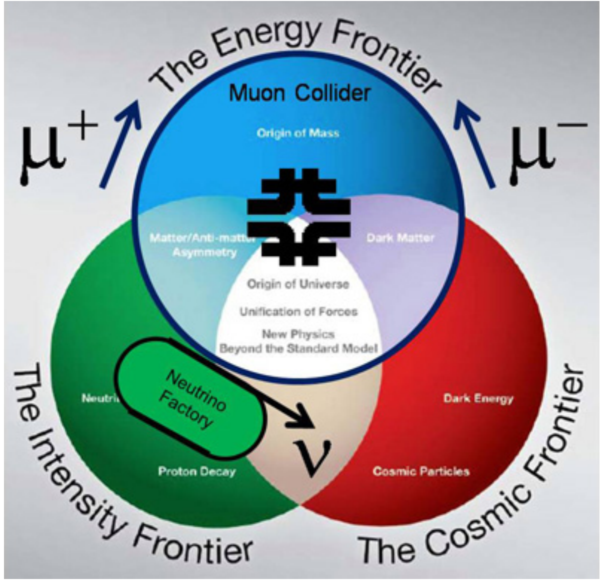
Collider Synergies

- 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

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

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

Physics at high energy

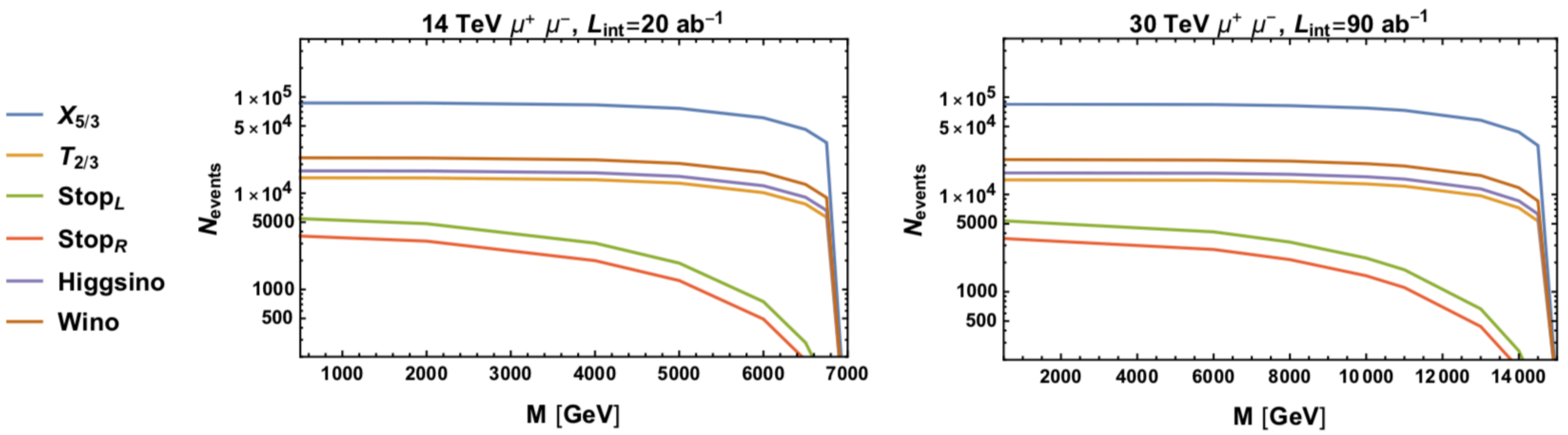
Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly

Direct Reach

A. Wulzer

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

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

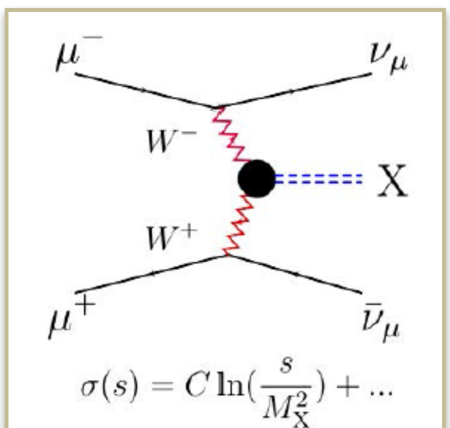


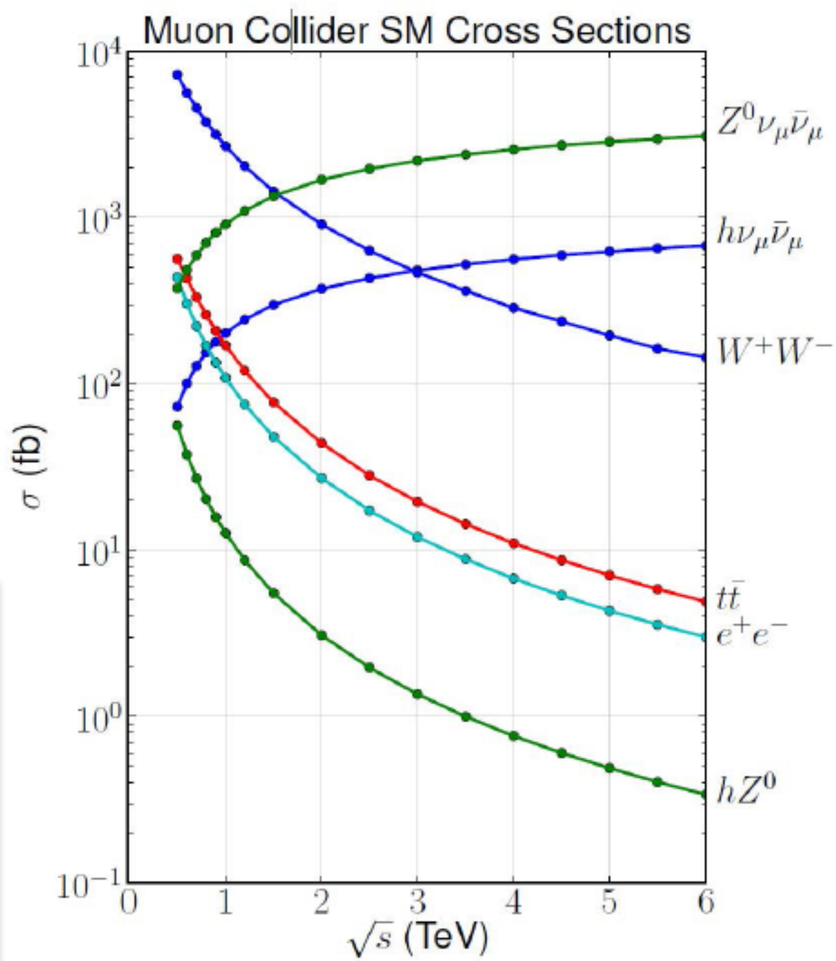
High energy Muon Collider

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%

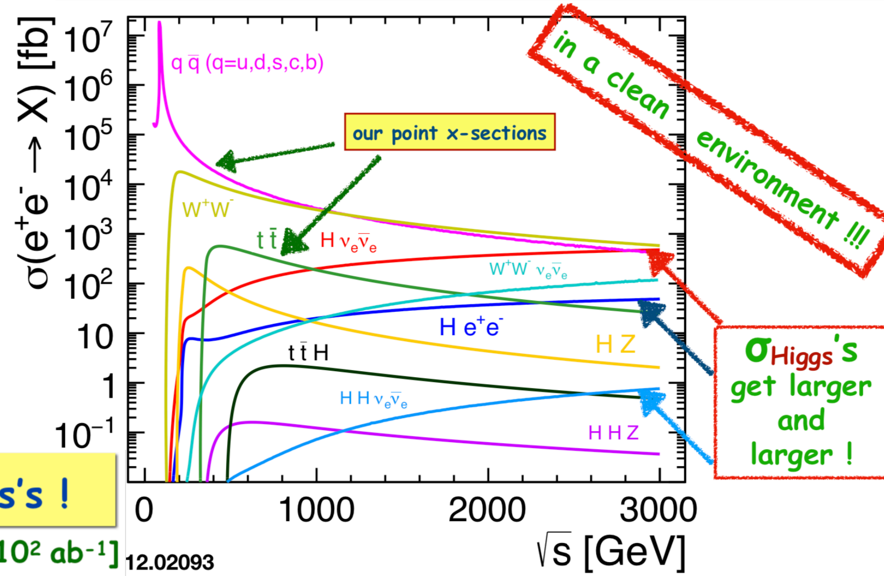




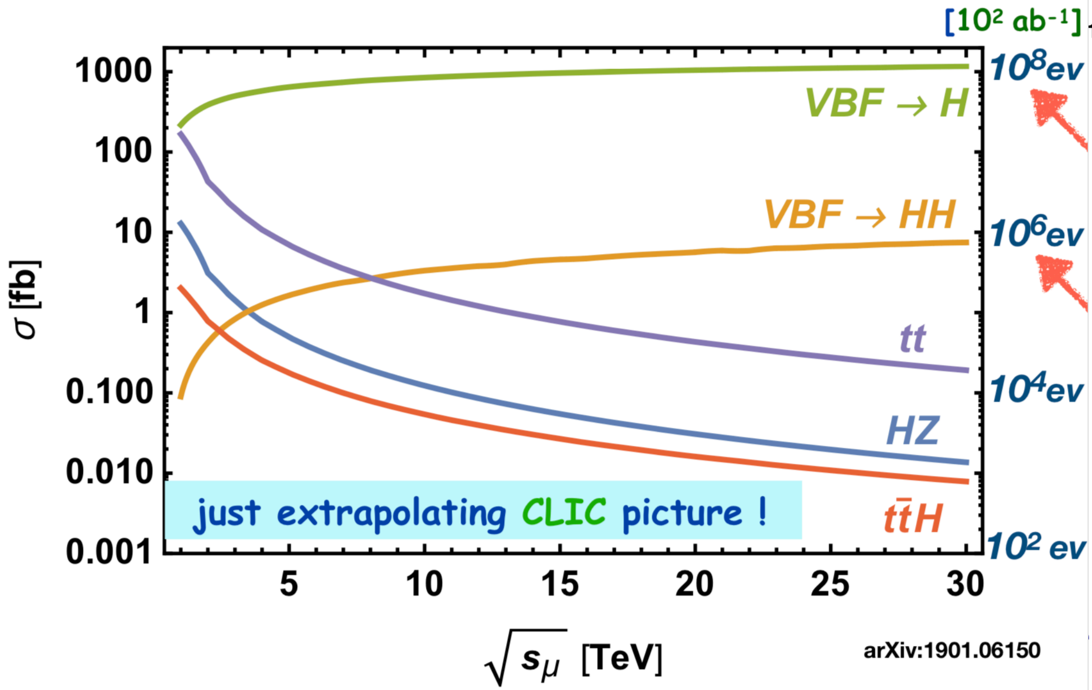
Higgs production at Lepton Collider

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

point x-sections dominant at CLIC !



at $\sqrt{s_{\mu\mu}}$~10-30TeV [L~10$^{1-2}$ ab^{-1}] plenty of Higgs's !

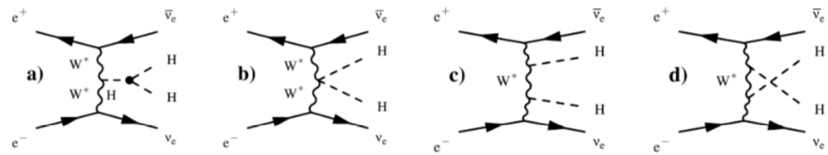


B. Mele et al.

Trilinear and Quadrilinear couplings

trilinear Higgs coupling at MC

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \boxed{\lambda_3} \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$



Huge VBF Higgs: ~ 10^7 Higgses, 30'000 Higgs pairs [at 10 TeV]

$HH \to 4b$

10 TeV	Sens. Degradation	N_{SM} [10 ab^{-1}]	$\frac{\text{Degradation}}{\sqrt{N_{SM}}}$ [10 ab^{-1}]
Total HH	2.44826	$10\,476.8\,\epsilon_b$	$\frac{0.023919}{\sqrt{\epsilon_b}}$
After θ>5°	1.79402	$5386.76\,\epsilon_b$	$\frac{0.0333575}{\sqrt{\epsilon_b}}$
PT>30 GeV on top	1.81422	$3346.09\,\epsilon_b$	$\frac{0.0313633}{\sqrt{\epsilon_b}}$
PT>50 GeV on top	2.42269	$1291.06\,\epsilon_b$	$\frac{0.0674256}{\sqrt{\epsilon_b}}$
PT>80 GeV on top	1.35534	$328.448\,\epsilon_b$	$\frac{0.0747853}{\sqrt{\epsilon_b}}$

$\left|\frac{1}{\sigma}\frac{\partial\sigma}{\partial(\delta\lambda)}\right|^{-1}$ $\Delta(\delta\lambda)$

30 TeV	Sens. Degradation	N_{SM} [90 ab^{-1}]	$\frac{\text{Degradation}}{\sqrt{N_{SM}}}$ [90 ab^{-1}]
Total HH	3.8792	$216\,726.\,\epsilon_b$	$\frac{0.00833272}{\sqrt{\epsilon_b}}$
After θ>5°	2.03452	$64\,812.\,\epsilon_b$	$\frac{0.0152375}{\sqrt{\epsilon_b}}$
PT>30 GeV on top	2.08392	$41\,492.2\,\epsilon_b$	$\frac{0.0102305}{\sqrt{\epsilon_b}}$
PT>50 GeV on top	1.88029	$17\,637.2\,\epsilon_b$	$\frac{0.0141583}{\sqrt{\epsilon_b}}$
PT>80 GeV on top	1.24629	$5513.52\,\epsilon_b$	$\frac{0.0167844}{\sqrt{\epsilon_b}}$

10 TeV:
$\delta\lambda_3$= 3%

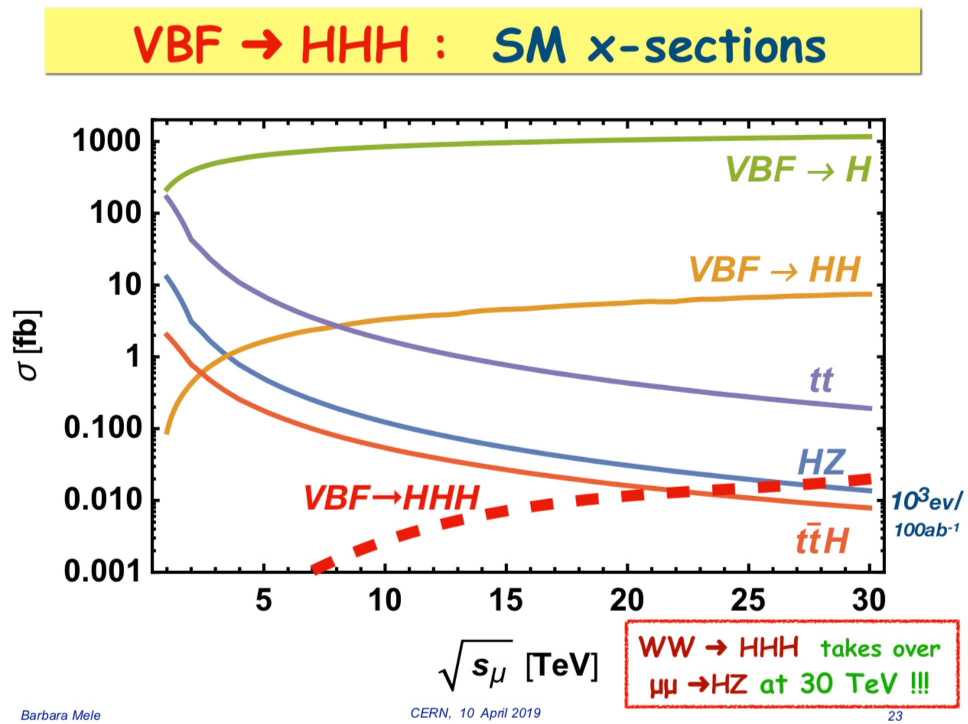
If **reasonable detector performances.** First detector benchmark.

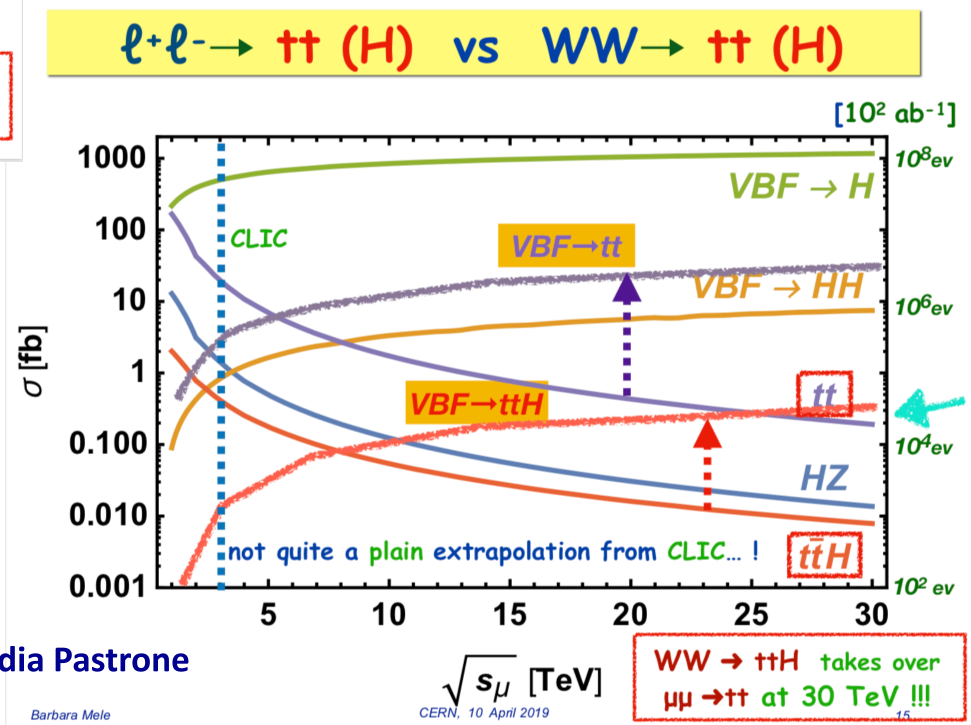
30 TeV:
$\delta\lambda_3$= 1%

Wulzer

Many new physics studies ongoing…

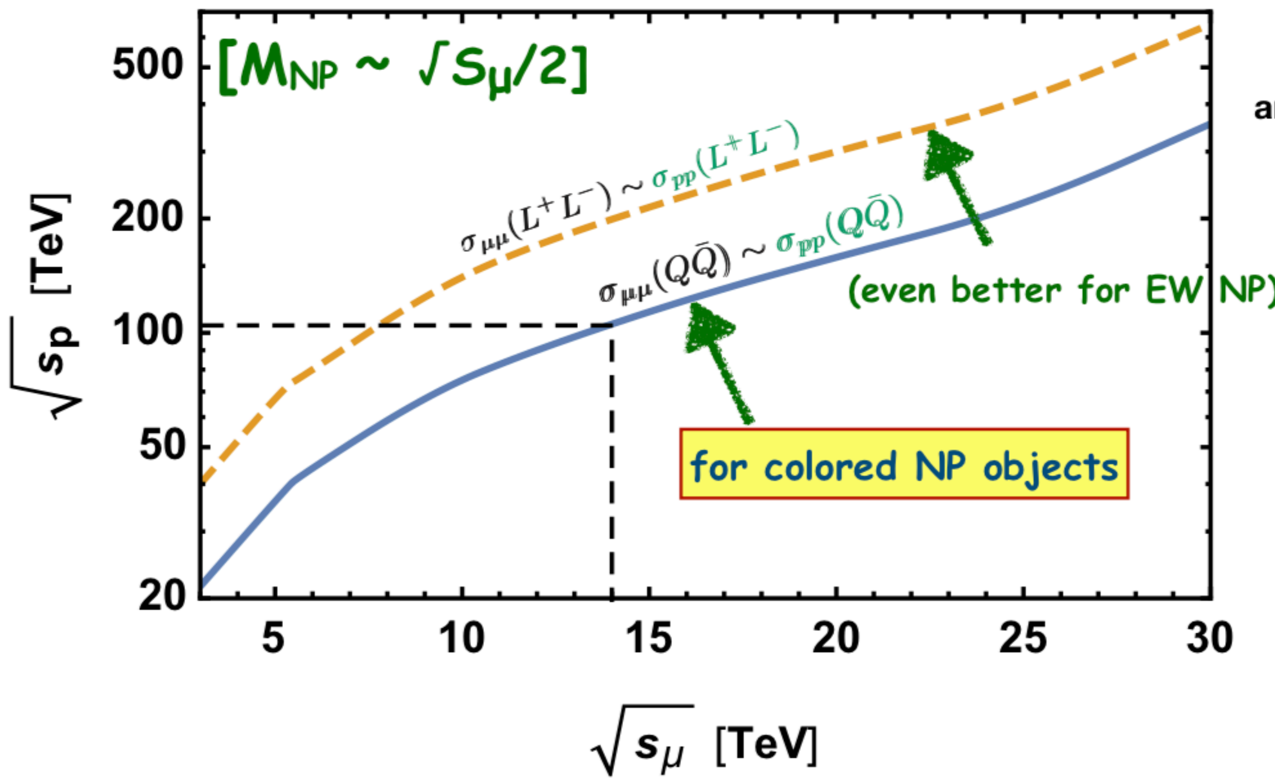
B. Mele et al.





Proton vs Muon Colliders

"equivalent" reach in pp after rescaling for pdf's



arXiv:1901.06150

- μμ @ 14 TeV → pp @ 100 $(200)_{EW}$ TeV !
- μμ @ 30 TeV → pp @ 350 $(600)_{EW}$ TeV !!

yet unexplored pheno !!!

Accelerator physics at high energy

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

our "reference frame"

$\mu^+ \longrightarrow \quad \longleftarrow \mu^-$

$\sqrt{S_{\mu\mu}} \sim 10,\ 14,\ 30$ TeV

→ Luminosity ruled by heavy pair x-section

rate for new p.le pair production :

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

point x-section

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

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

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

$$\to 1000\,evs/y\,(\frac{10\,TeV}{\sqrt{S}})^2$$

10^4 evs /(10 years)

$\delta_{stat} \sim 1\%$

$\sqrt{S_{\mu\mu}}$	$\int L_{10y}$
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}
30 TeV	100 ab^{-1}

$L \sim 10^{36} cm^{-2} s^{-1}$

Barbara Mele CERN, 10 April 2019 5

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

Key to Luminosity

Integrated luminosity of one bunch $$\Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \frac{\left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2}{4\pi\sigma_x\sigma_y}$$

High bunch charge

High energy

$$\mathcal{L} \propto B \frac{N_0}{\epsilon} \gamma P_{beam}$$

High beam power

High field in collider ring

Small emittance

Win luminosity per power as the energy increases

linear colliders: luminosity per power tends to be energy independent
except if one changes technology (very short bunches, smaller vertical emittance)

circular electron-positron colliders: luminosity drops rapidly with energy (power ≈3.5)

High Energy μ+μ- Colliders

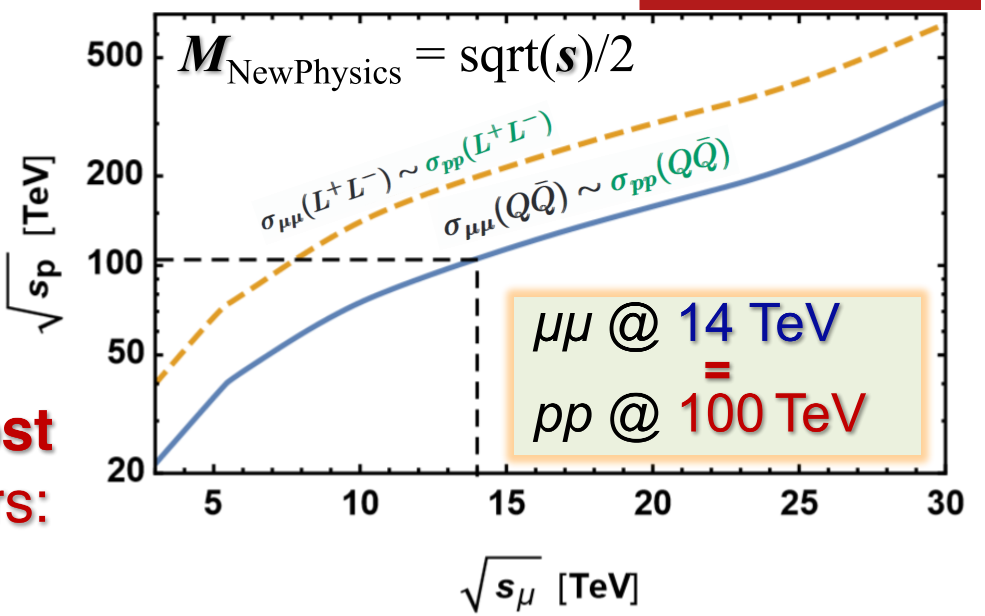
V. Shiltsev

JINST Special Issue (*MUON*)

arXiv:1901.06150

***Advantages*:**

- ***μ***’s do not radiate / no beamstrahlung→ acce-leration in rings → *low cost & great power efficiency*
- ~ *x7* energy reach vs *pp*



Offer *“moderately conservative - moderately innovative”* path **to cost affordable** energy frontier colliders:

- US MAP feasibility studies were very successful → MCs can be built with present day SC magnets and RF; there is a well-defined path forward
- ZDRs exist for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV * in the LHC tunnel

** more like “strawman” parameter table*

Key to success:

- Test facility to demonstrate performance implications - muon production and 6D cooling, study LEMMA e^+-45 GeV + e^- at rest →μ^+-μ^- , design study of acceleration, detector background and neutrino radiation

Brief history

- The **muon collider idea** was first introduced in **early 1980's**
  [A. N. Skrinsky and V. V. Parkhomchuk, D. Neuffer]
- the idea was further developed by a **series of world-wide collaborations**
- **US M**uon **A**ccelerator **P**rogram **– MAP,** created in **2011,** was killed in **2014**
  MAP developed a ***proton driver scheme*** *and addressed the feasibility of the 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**)** concept was proposed in **2013**
  a new end-to-end design of a ***positron driven scheme*** *is presently under study by INFN-LNF et al. to overcome technical issues of initial concept* ➔ **arXiv:1905.05747**

an **input document** was submitted to the European Particle Physics Strategy Update on existing muon collider studies, to support further R&Ds

"Muon Colliders," arXiv:1901.06150

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 in September 2017

to prepare the Input Document to the European Strategy Update

see related material @ muoncollider.web.cern.ch

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

Preparatory meeting to review progress for the ESPPU Simposium

April 10-11, 2019
CERN – Council Room
https://indico.cern.ch/event/801616

Recommendations (dec 2018)

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. As demonstrated in past experiences, the resources needed are not negligible in terms of cost and manpower and this calls for a well-organized international effort.
For example, the MAP program required an yearly average of about 10M$ and 20 FTE staff/faculty in the 3-year period 2012-2014.
Develop a muon collider concept based on the proton driver and considering the existing infrastructure. This includes the definition of the required R&D program, based on previously achieved results, and covering the major issues such as cooling, acceleration, fast ramping magnets, detectors, ...
Consolidate the positron driver scheme addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.
Carry out the R&D program toward the muon collider. Based on the progress of the proton-driver and positron-based approaches, develop hardware and research facilities as well as perform beam tests. Preparing and launching a conclusive R&D program towards a multi-TeV muon collider is mandatory to explore this unique opportunity for high energy physics. A well focused international effort is required in order to exploit existing key competences and to draw the roadmap of this challenging project. The development of new technologies should happen in synergy with other accelerator projects. Moreover, it could also enable novel mid-term experiments.

INFN @ Muon Collider (LEMMA)

1) Physics benchmarks: **B. Mele**, F. Piccinini, A. Wulzer, A. Nisati et al.
2) LEMMA machine studies: **A. Variola et al.** ➔ **arXiv:1905.05747**
   - New design muon source positron driven
   - New target studies
3) Detector simulations: **D. Lucchesi et al**
   - Backgrounds from MAP design
4) FLUKA simulations: **D. Lucchesi/P. Sala:**
   - Risk assesment of radiation hazerd from **neutrinos**

➔ a preliminary report on the study of beam-induced background effects at a muon collider **arXiv:1905.03725**

LEMMA: positron driven option

- A Muon Collider is the only cost-effective opportunity for lepton colliders to go to $E_{cm} > 3$ TeV
- LEMMA concept (P. Raimondi & M. Antonelli, first presented at Snowmass 2013):
  - $\mu^{\pm}$ produced by **e^+** beam interacting with **e^-** in a target in a ring → small $\mu^{\pm}$ beam emittance and long laboratory lifetime due to the $\mu^{\pm}$ boost in the laboratory frame
  - average $\mu^{\pm}$ energy **22 GeV** (average laboratory lifetime of **~500 μs**) eases the acceleration scheme
  - Aimed at obtaining high luminosity with relatively small $\mu^{\pm}$ fluxes thus reducing background rates and activation problems due to high energy $\mu^{\pm}$ decays
- Advantages: final state $\mu^{\pm}$ highly collimated and with small emittance → muon cooling not required

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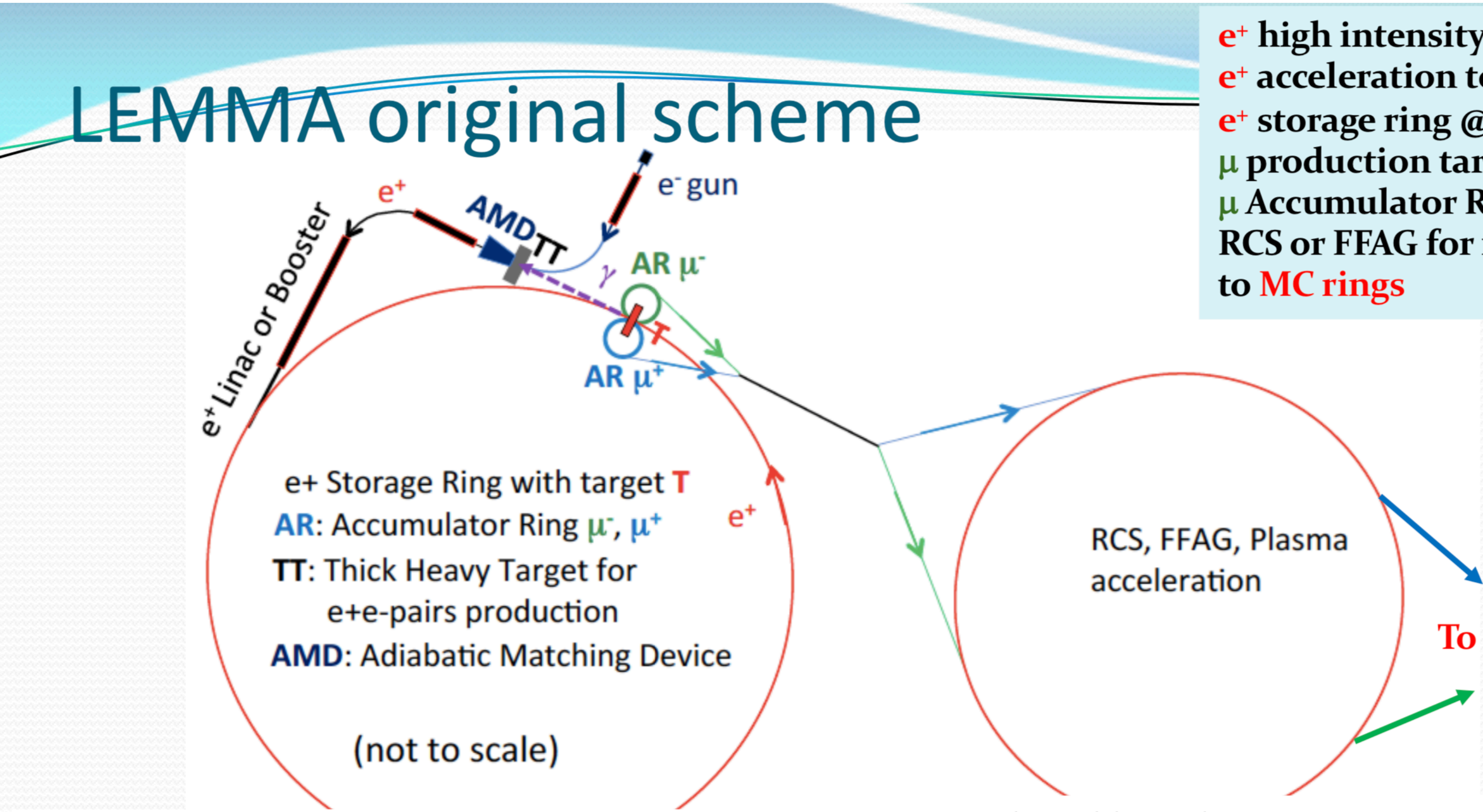
- Original LEMMA scheme showed some technical limitations:
  - Required # of **e^+** from source too large with respect to state-of-the-art (ILC, CLIC)
  - Instantaneous and average energy deposited on target too large
  - Recombination scheme of muon bunches in the $\mu^{\pm}$ collider not clear

LEMMA: original idea



- e^+ high intensity source
- e^+ acceleration to 45 GeV
- e^+ storage ring @ 45 GeV
- μ production target @ 22 GeV
- μ Accumulator Rings
- RCS or FFAG for fast μ acceleration to MC rings

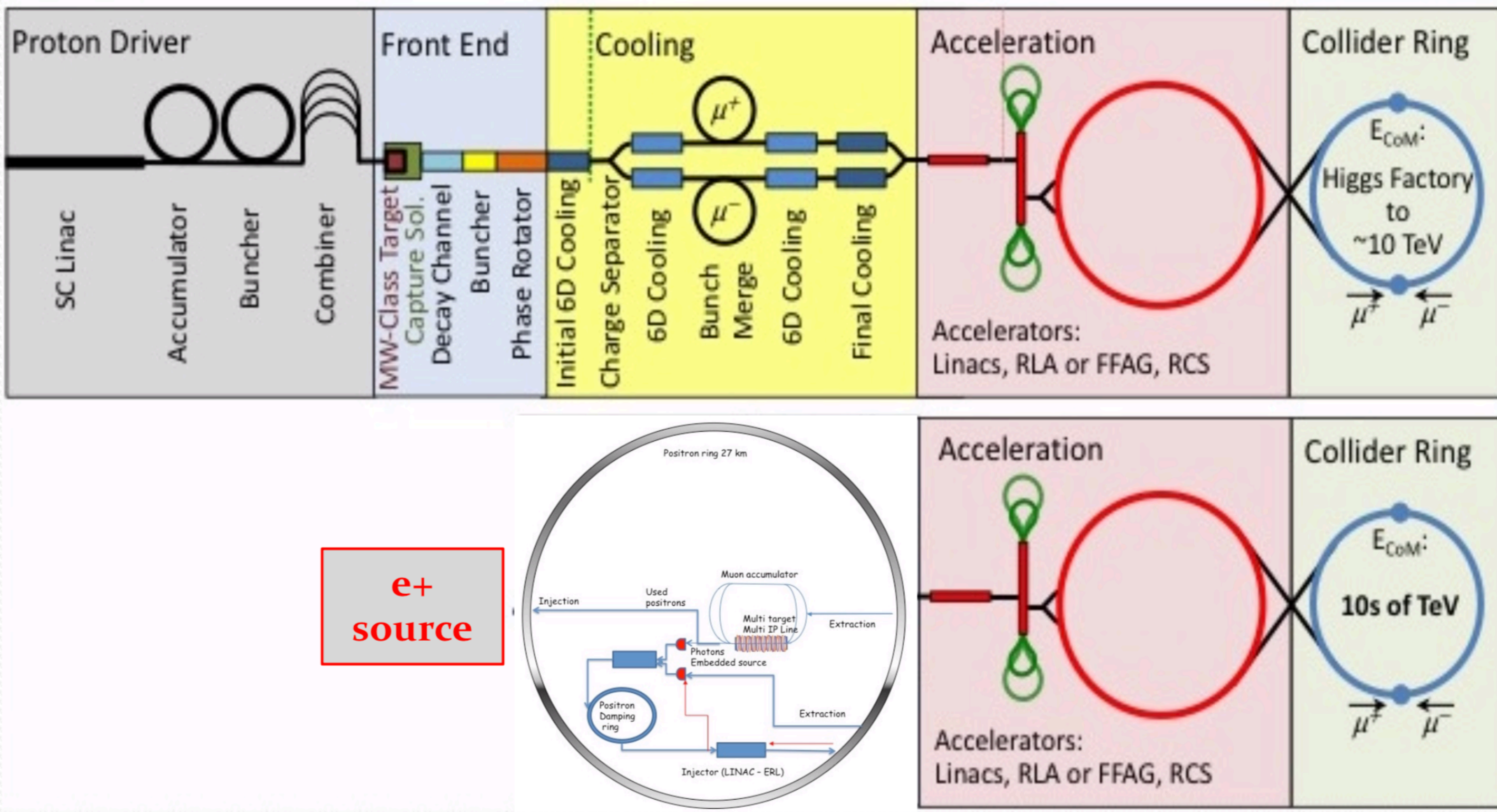
Goal: $\approx 10^{11}$ μ/s produced at target
with target efficiency $\approx 10^{-7}$ (Be, 3mm)
Request: 10^{18} e^+/s impinging on target → 45 GeV e^+ storage ring with target insertion

$\mu^{\pm}$ produced by e^+ beam on target T @ ~ 22 GeV →
$\tau_{lab}(\mu) \approx 500\mu s$ $(\gamma(\mu) \approx 200)$
Muon Accumulator Rings (MA) isochronous with high momentum acceptance, recombine $\mu^{\pm}$ bunches for ~ 1 $\tau_{\mu}^{lab} \approx 2500$ turns

Proton vs positron driven option

MAP

LEMMA

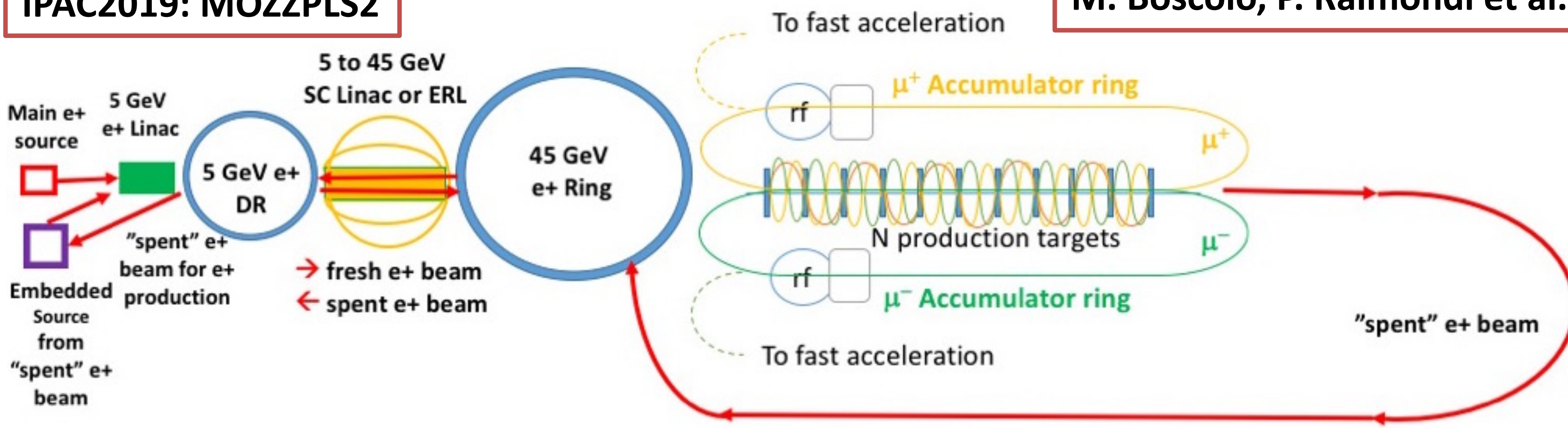


Positron driven muon source

recent developments (2019)

IPAC2019: MOZZPLS2

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



- **Positron Source** (PS) @ 300 MeV, plus **LINAC** to accelerate up to 5 GeV
- 5 GeV e^+ **Damping Ring** (DR) with damping time order of 10 msec
- SC Linac or ERL accelerate e^+ @ 45 GeV, and decelerate @ 5 GeV after μ production
- 45 GeV e^+ **Ring** (PR) to accumulate 1000 bunches needed for μ production
- 1/more **Target Lines** (TL): *e*+ beam collides with targets for the direct μ production
- 2 **Muon Accumulation Rings** (AR) – 123 m – to store μ till μ bunch reach typically 10^9 μ
- **Embedded e^+ source** to restore the design e^+ beam current,
  using γ coming from μ production targets, or using the 45 GeV "spent" beam

Main design requirements

- **Positron Source** like CLIC/ILC ➔ ***1×10^{14} e^+/s*** ➔ injection 5 s
- **Damping Ring** has to provide **fast e^+ cooling**, limiting total collider cycle

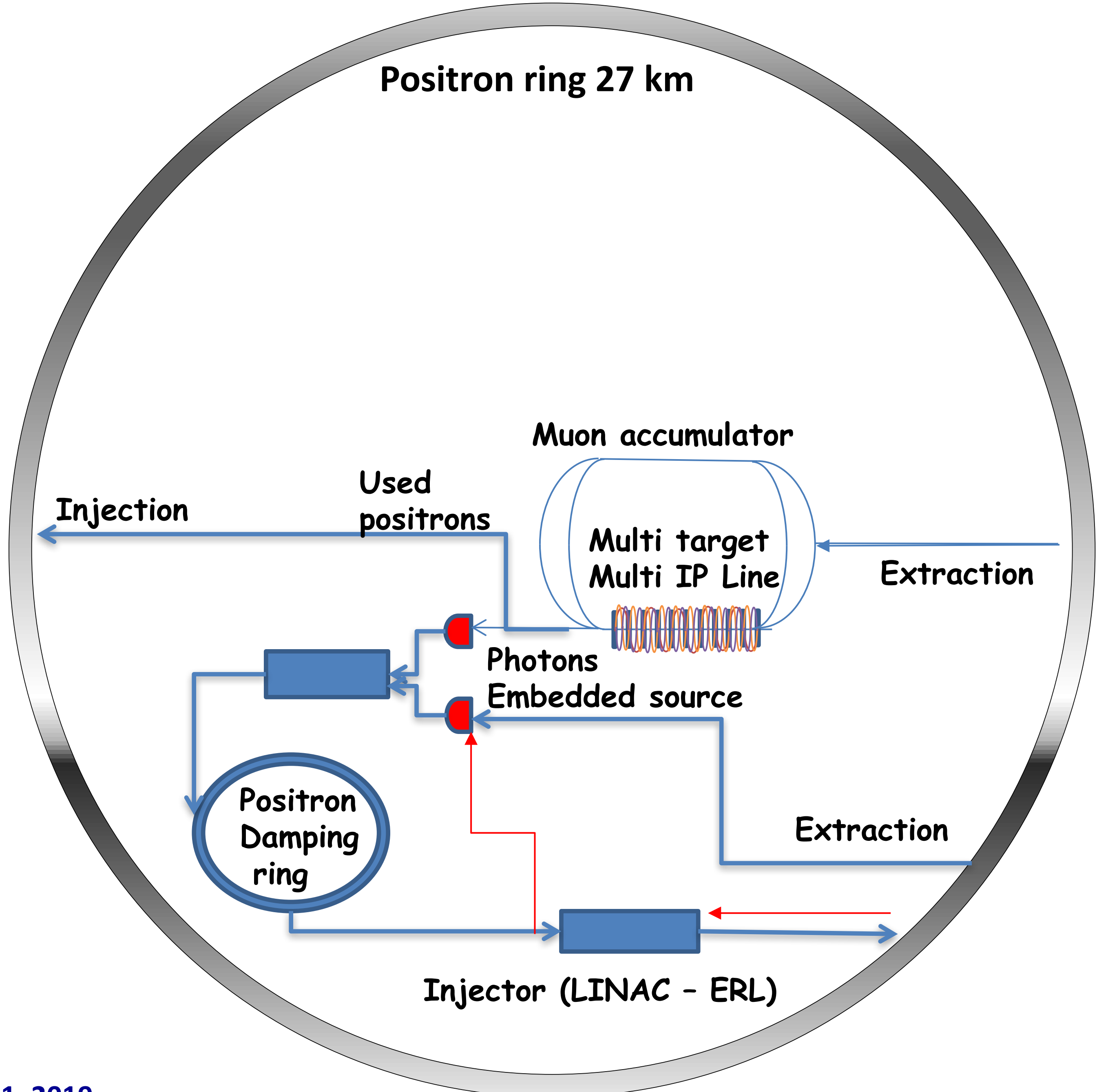
Lattice may be similar to the main Positron Ring
A DR similar to ILC one could provide needed damping time (12 msec) and emittance
➔ *about 100 wigglers (ILC type) to be installed*
➔ *a shorter ring (i.e. 6.3 km) is preferred to minimize number of damping wigglers*
*First injection - no time constraints, then **1000 bunches** with **5×10^{11} e^+** need to be injected*

- 45 GeV **Positron Ring**: high energy acceptance and low emittance with 27 km ring
➔ *choice of final lattice based on the larger energy acceptance: it is mandatory to successfully re-inject all the "spent" beam from the muon production to be later decelerated and re-injected in the DR for cooling*
100 km solution will increase the luminosity of at least a factor 3.5

- **Multi-target system** to alleviate issues due to power deposited and integrated PEDD (*)

Source needed to replace the positrons lost in the muon production process is a real challenge, since the time available is very short

(*) Peak Energy Density Deposition

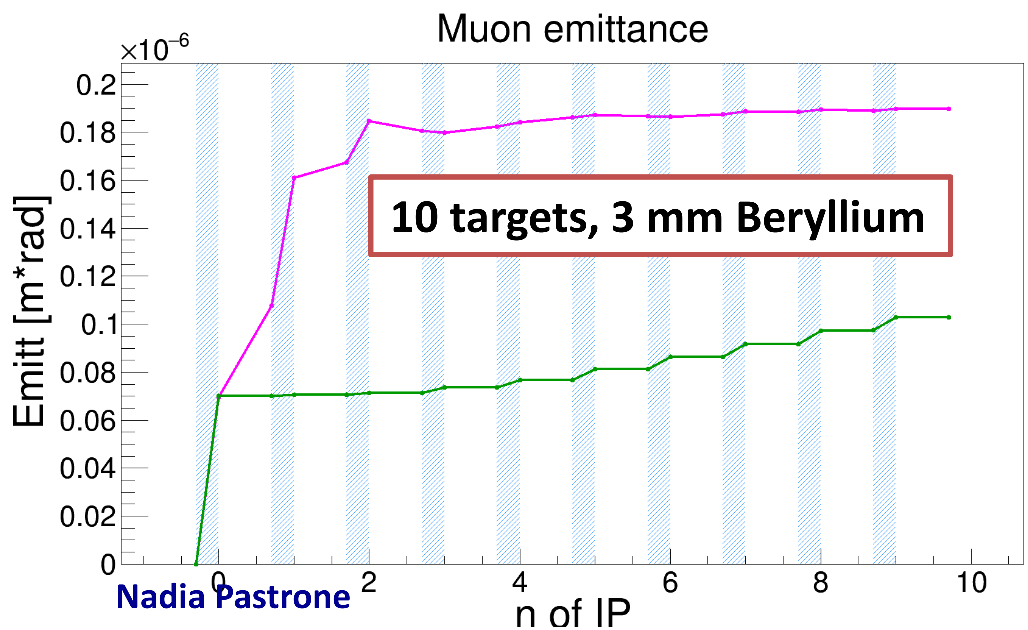

Positron ring 27 km
Muon accumulator
Used positrons
Injection
Multi target
Multi IP Line
Extraction
Photons
Embedded source
Positron Damping ring
Extraction
Injector (LINAC – ERL)

Muon production requirements

- Beamline has to maximize muon production ➔ constraint @ target e^+ spot size/divergence
- Beamline has to preserve e^+ beam (to relax e^+ source requirements)

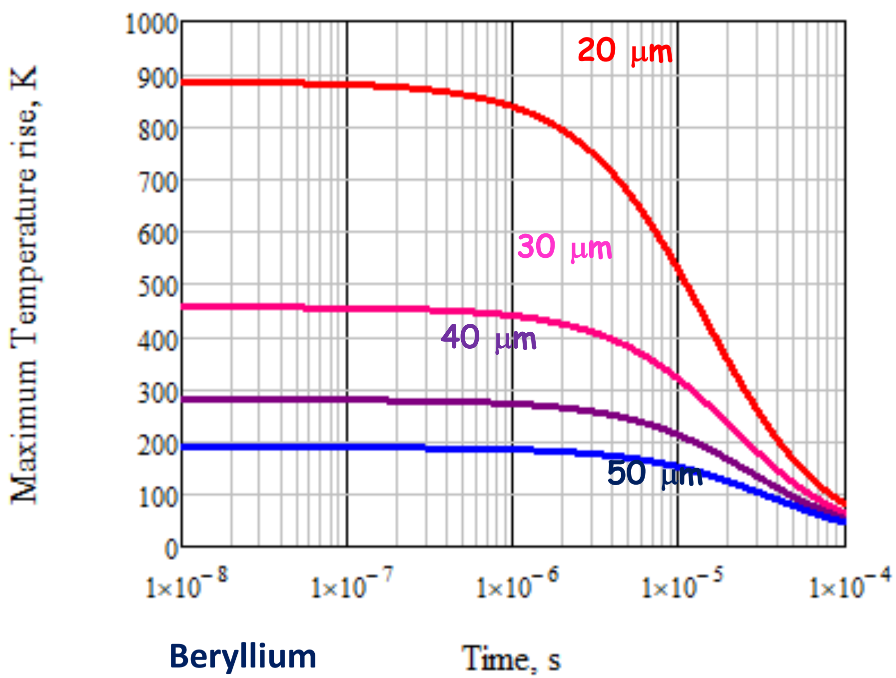
  ➔ constraint to the target but also to the energy acceptance of the beamline
- Beamline as short as possible due to the short lifetime of muons
- Many different **multi-IP beamline optics** (need to split the power on target)
- **Multi-IP beamline optics** made of regular unit cells where targets are placed at the beginning and at the end of each cell.
- Three beams will pass through this beamline: **e^+, $\mu^+\mu^-$**

Comparison of μ emittance growth in the Multiple (magenta) and Single (green) IP schemes.
The e^+ beam size is 150 μm.

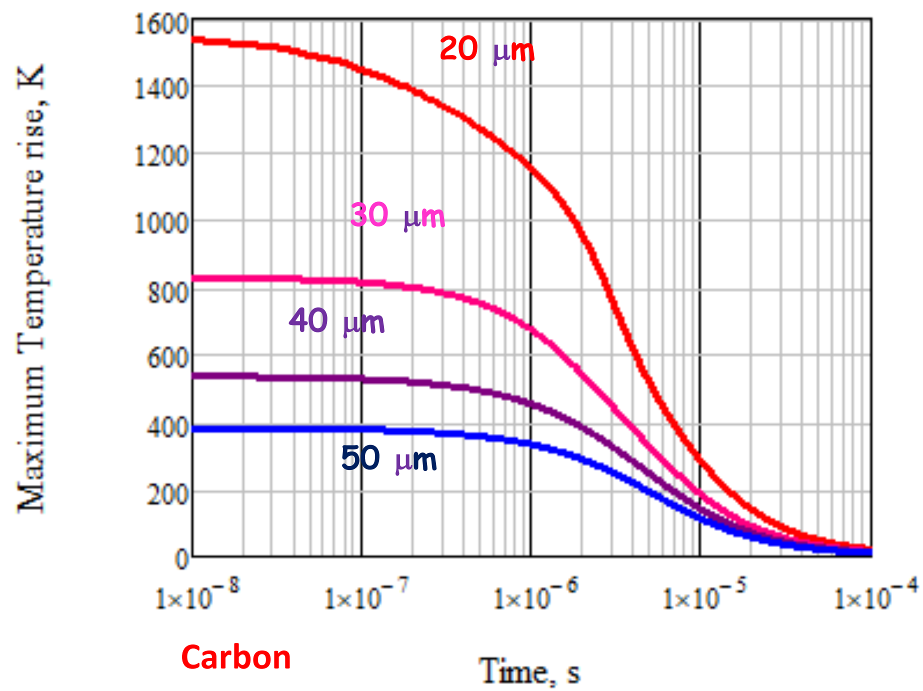


Target studies

Different target material: carbon, hydrogen, liquids, pellet…
Rotation target / multi an single IP test, target rotation and target cooling feasibility
Hydrogen - Spaghetti target instead of pellets
Curved crystals as recombiner, crystal cooling
MW class target for positron source



Beryllium



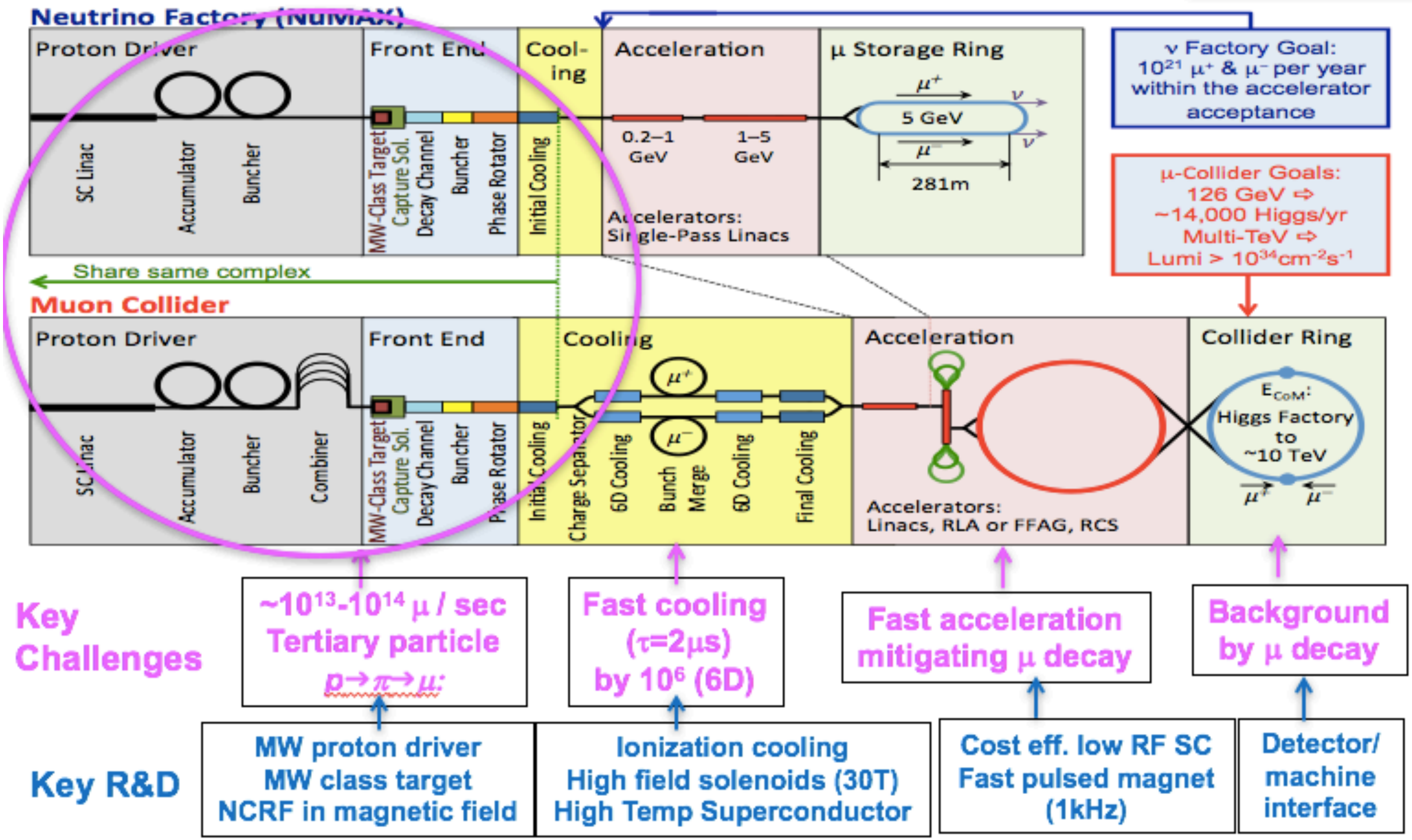
Carbon

Increase in target surface temperature

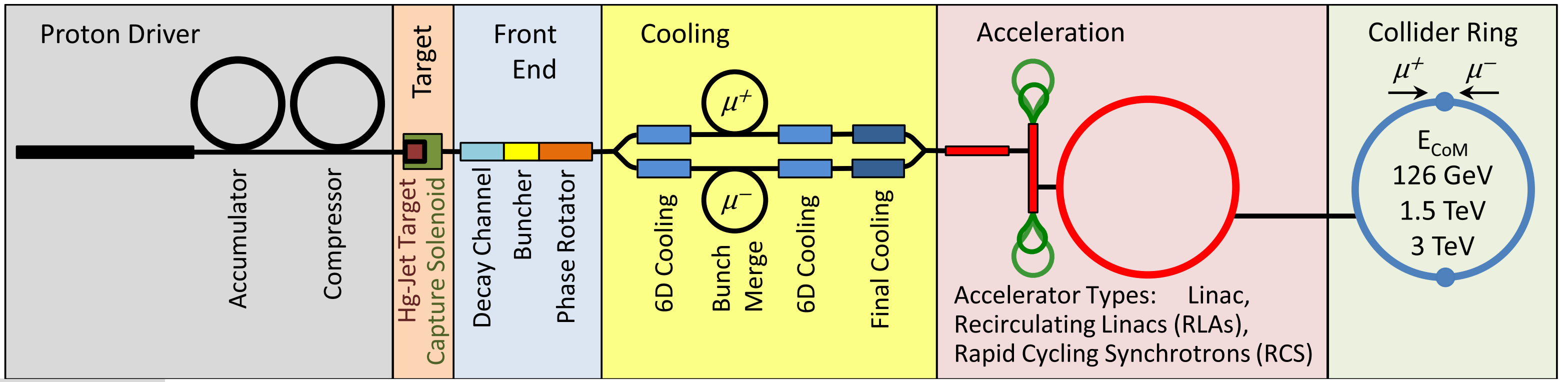
(varying the spot size of the Gaussian beam)

Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



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 π→μ 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

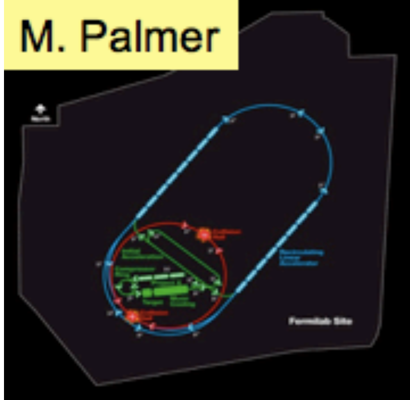
$\mu^{\pm}$ decay background Tungsten shielding or bending magnets to avoid issues from e

- Critical Detector Machine Interface

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

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

M. Palmer



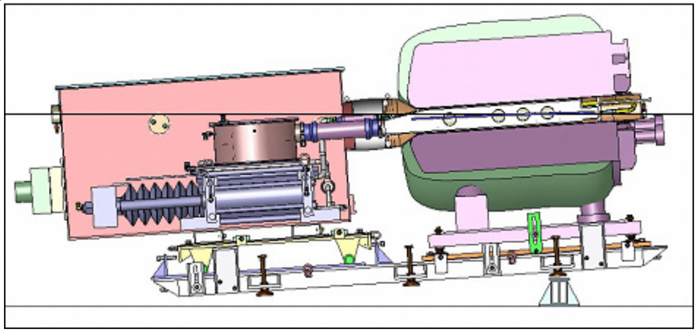
Muon Collider Parameters

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^{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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

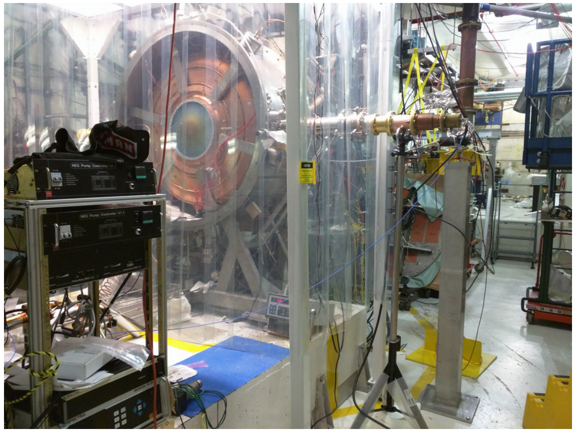
Success of advanced cooling concepts
⇨ several × 10^{32} [Rubbia proposal: 5×10^{32}]

International R&D program



MERIT - CERN

Demonstrated principle of liquid Mercury jet target

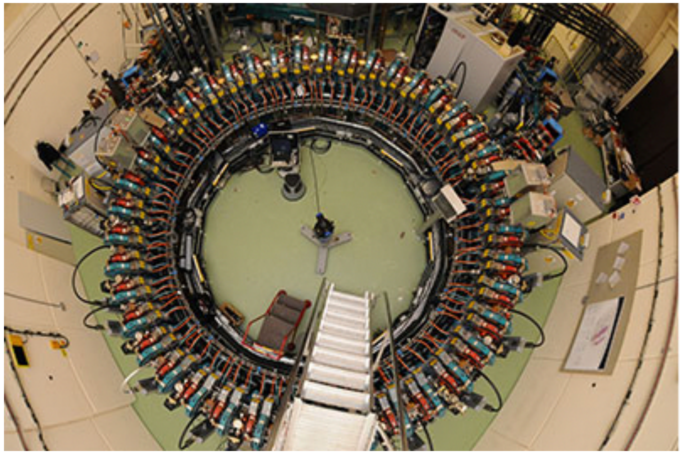


MuCool Test Area - FNAL

Demonstrated operation of RF cavities in strong B fields

EMMA - STFC Daresbury Laboratory

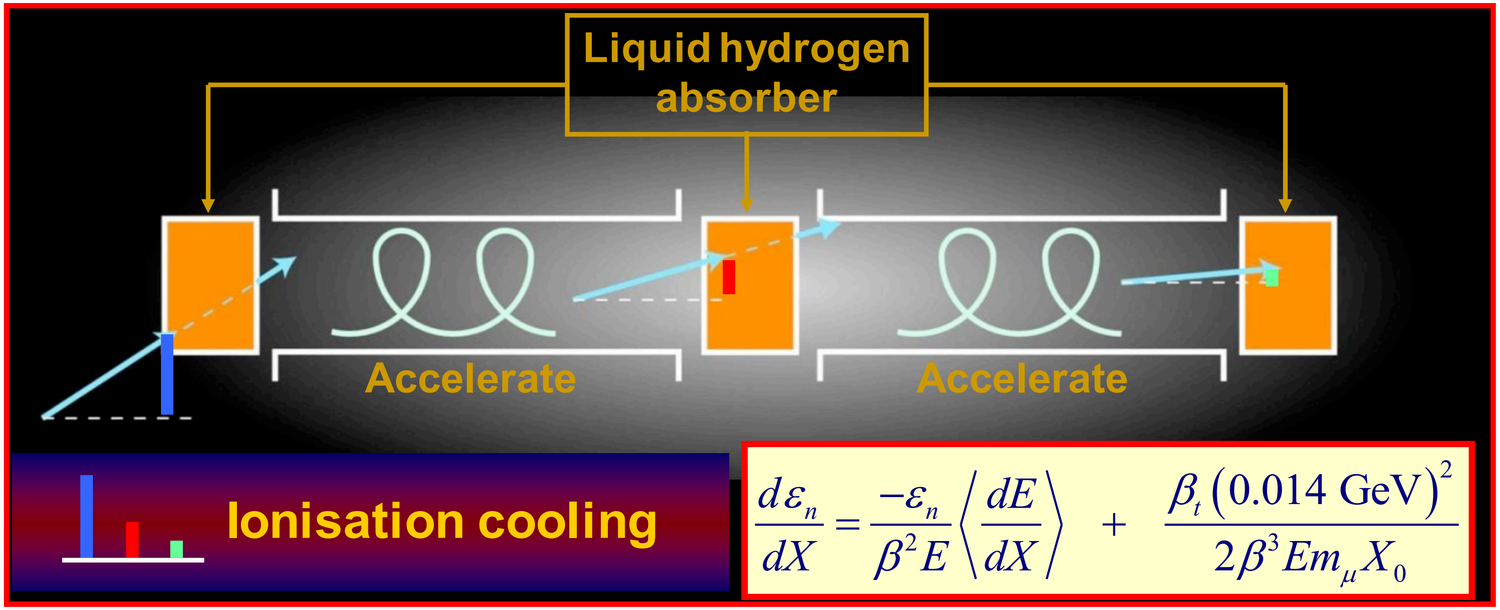
Showed rapid acceleration in non-scaling FFA



MICE - RAL

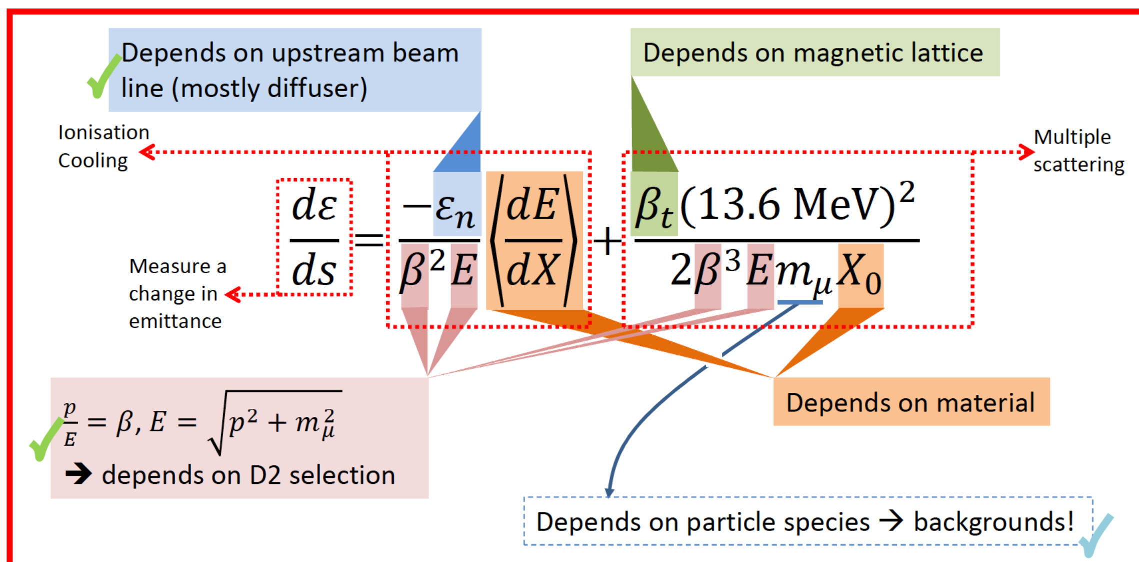
Demonstrate ionization cooling principle
Increase inherent beam brightness
→ number of particles in the beam core
“Amplitude”

Ionization cooling – MICE experiment



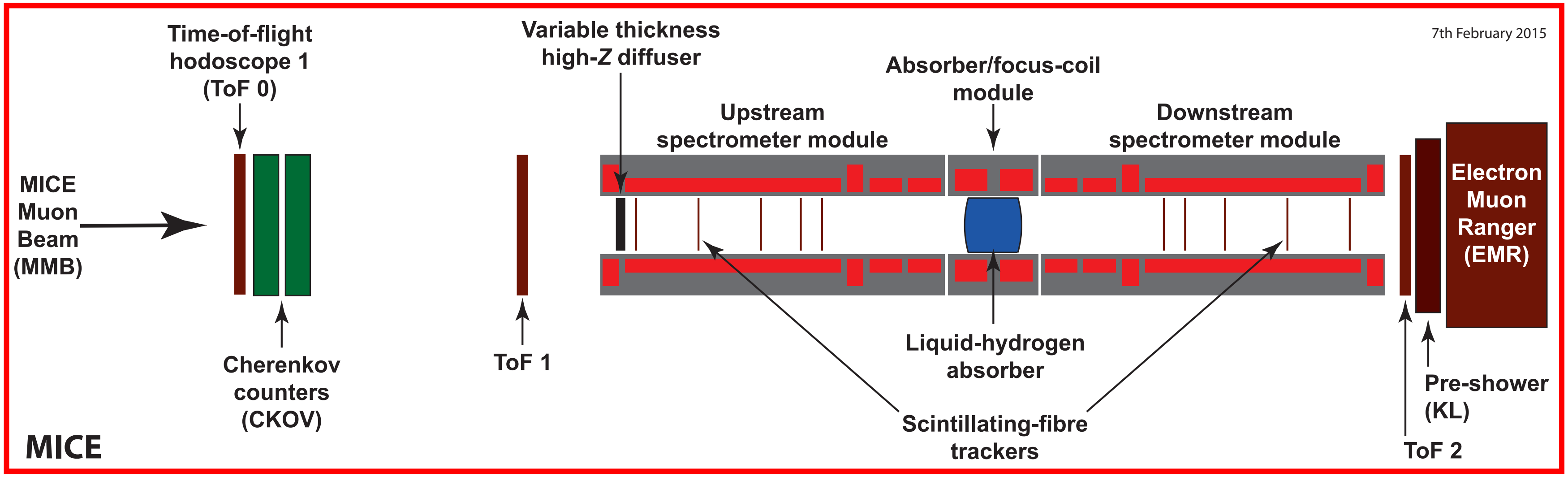
Realistic cooling cell

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



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

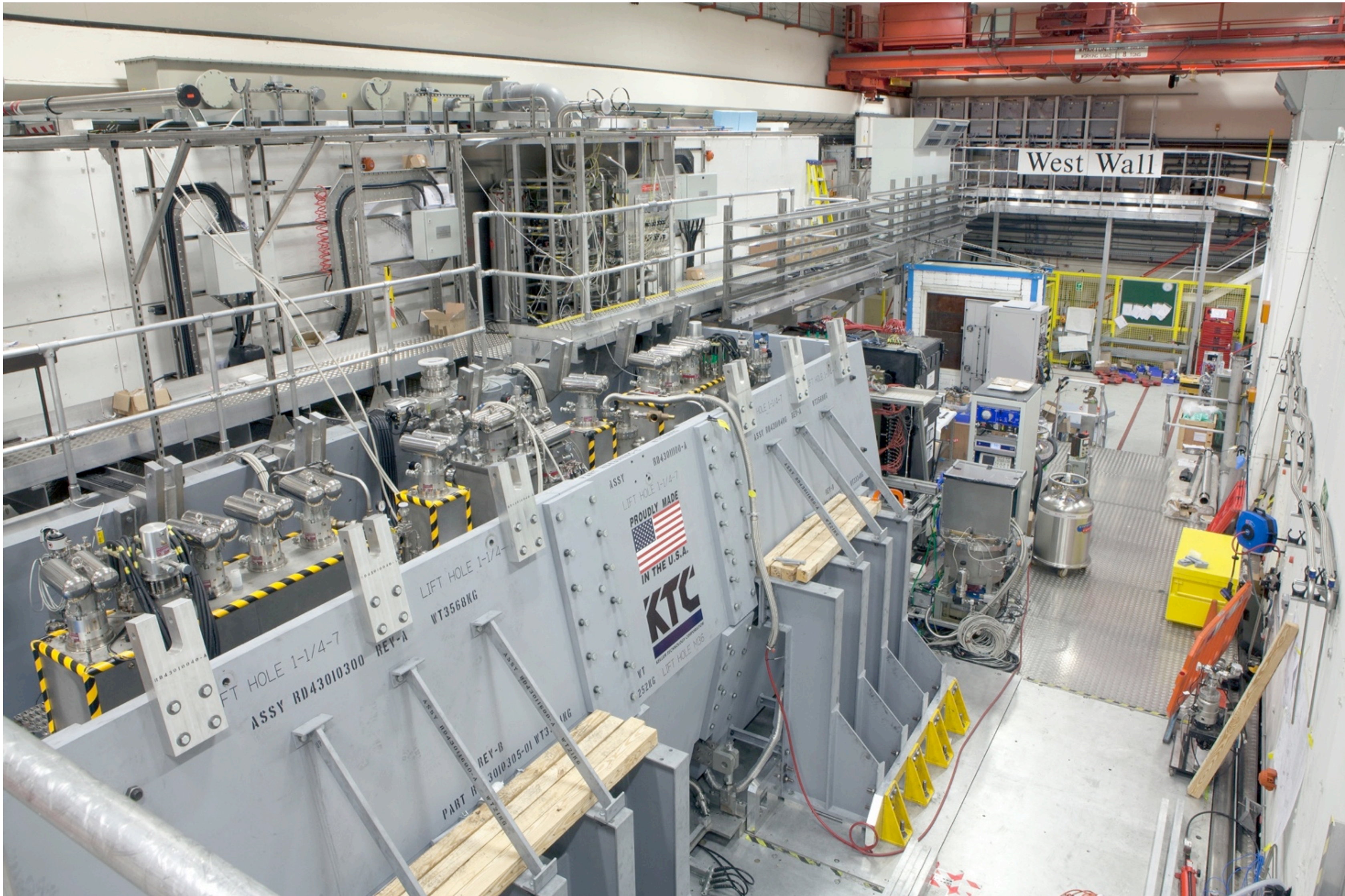
Ionization cooling – MICE experiment



- 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

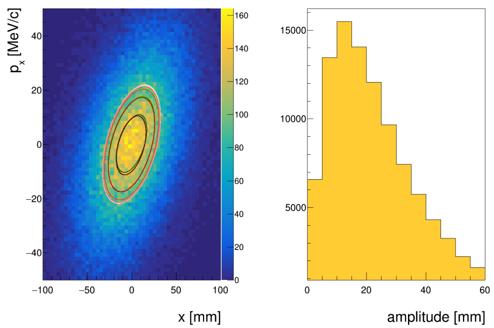


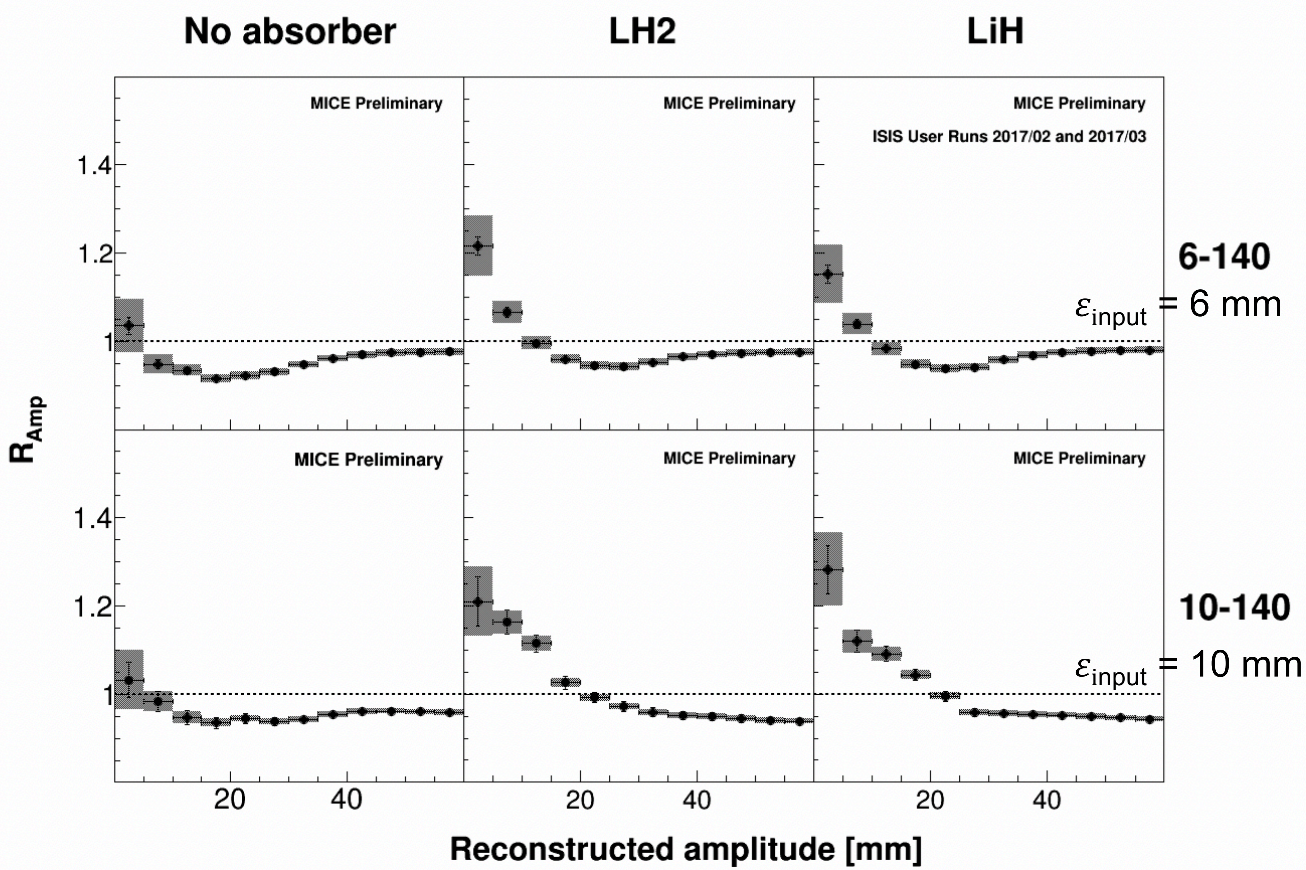
MICE: first results

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

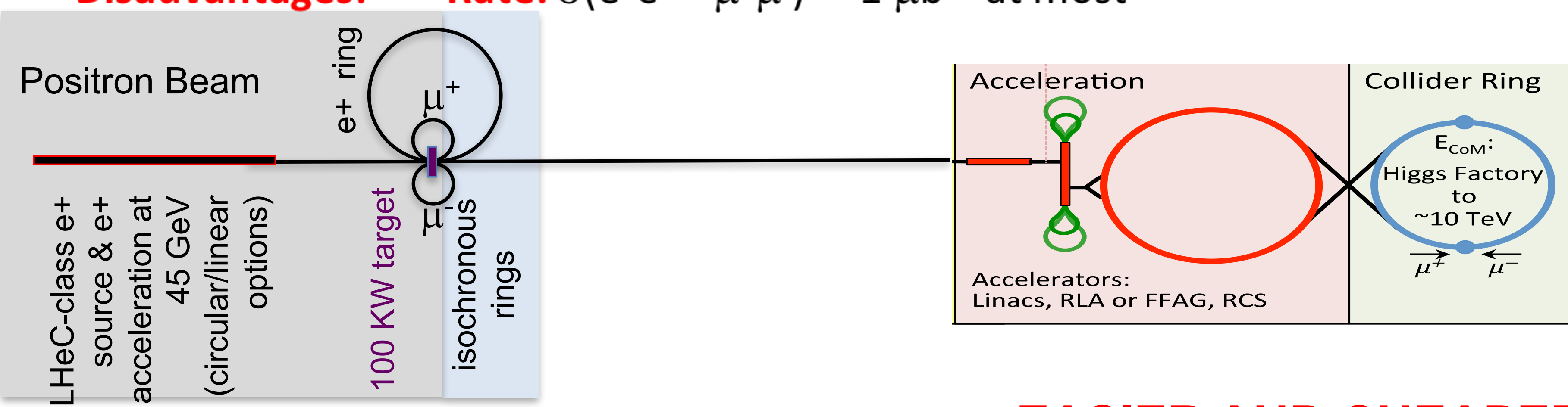
Snowmass 2013 - M. Antonelli e P. Raimondi

Direct μ pair production: muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold **($\sqrt{s}$~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 $e^+e^- \rightarrow \mu^+\mu^-$

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

Optics design & beam dynamics

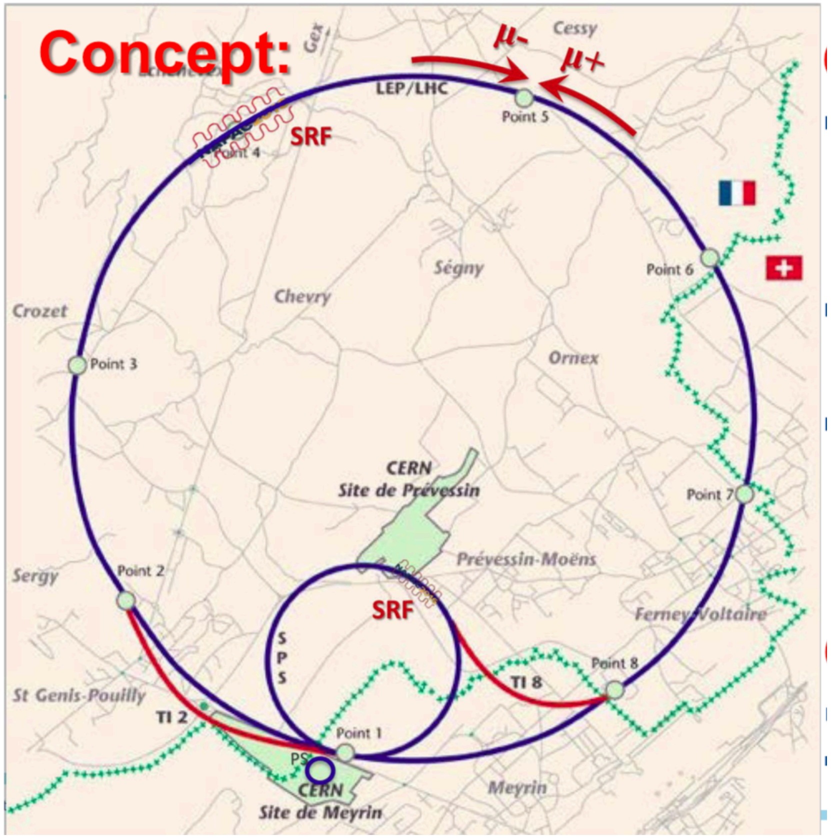
3. **Positron source**
   - High rate

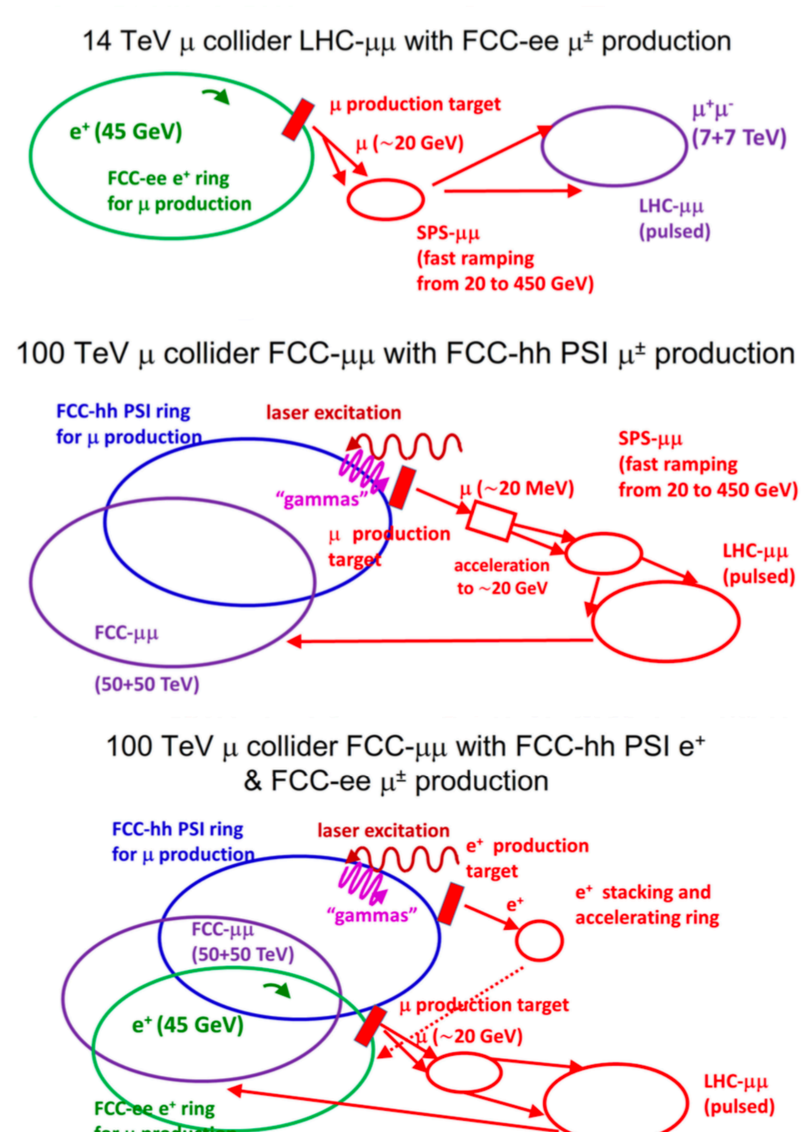
Synergy with FCC-ee/ILC/CLIC future colliders

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

Dream or possibility?





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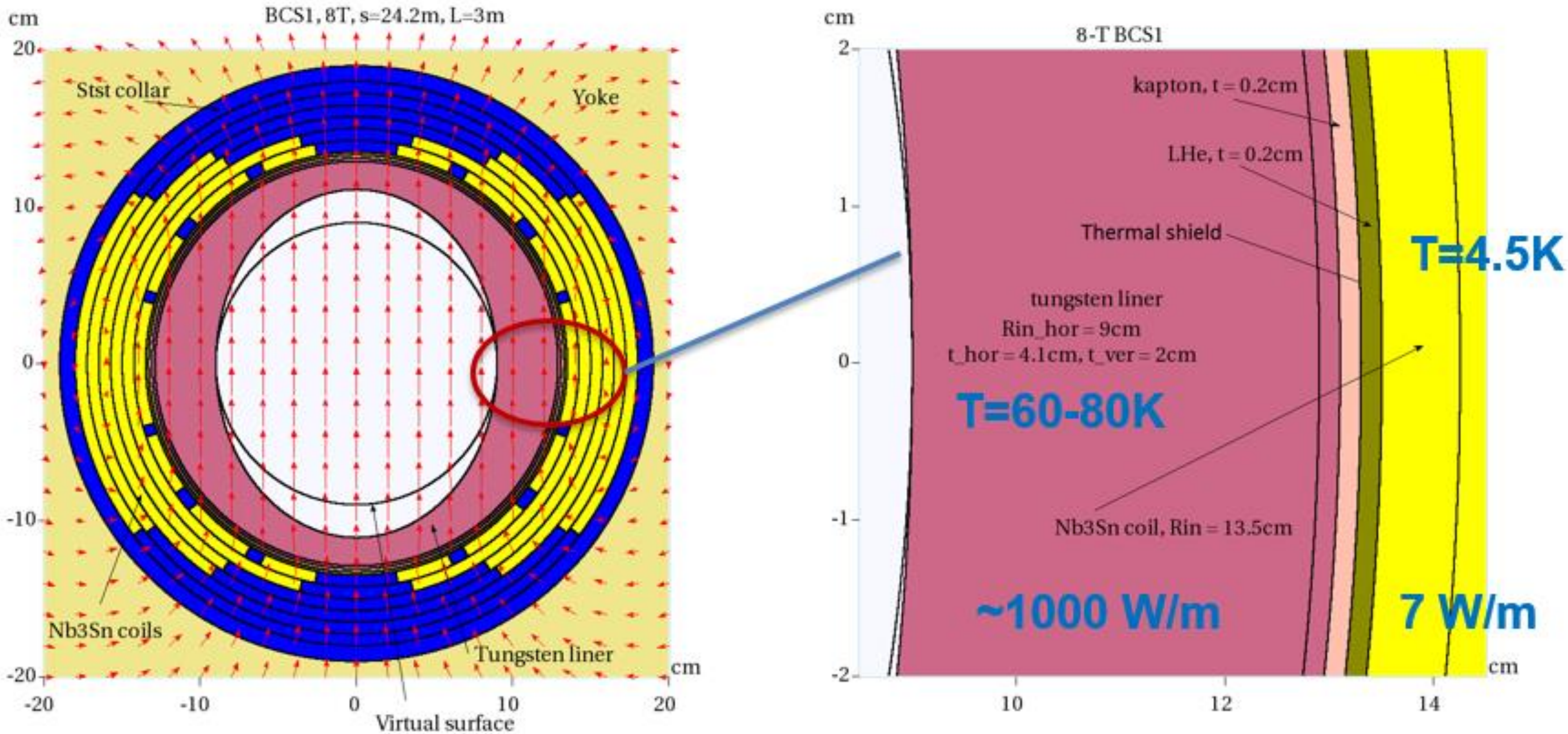
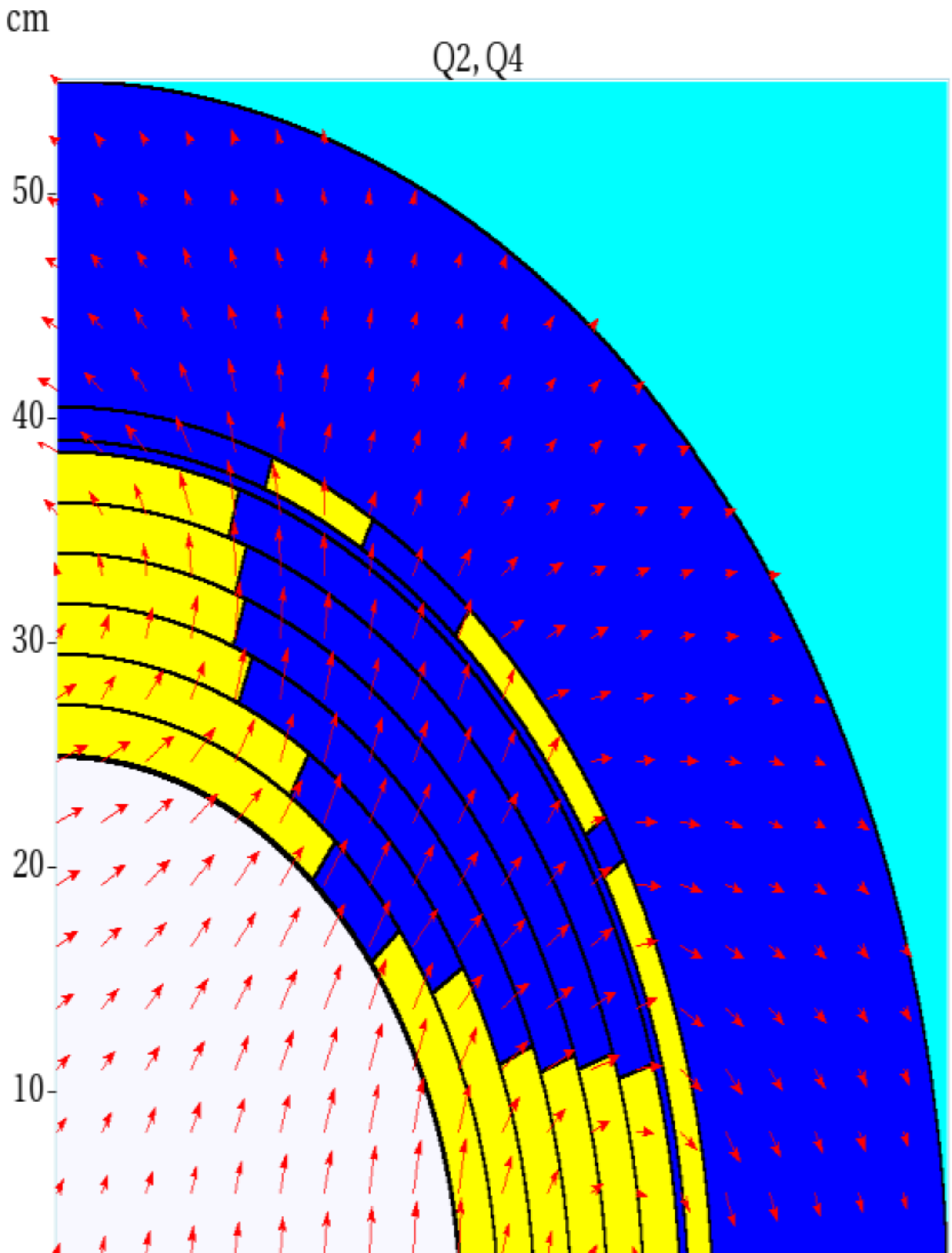
MAP magnets design

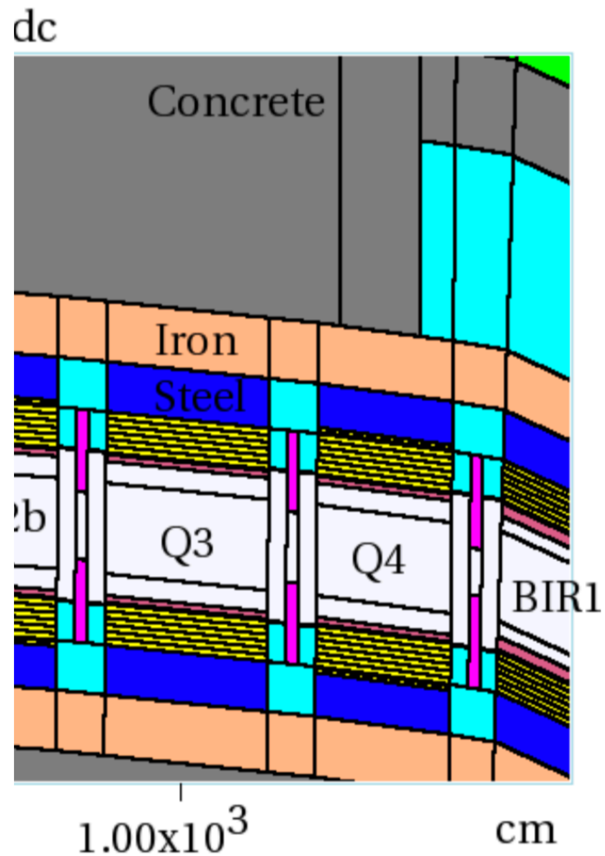
MARS15 Monte Carlo code



design

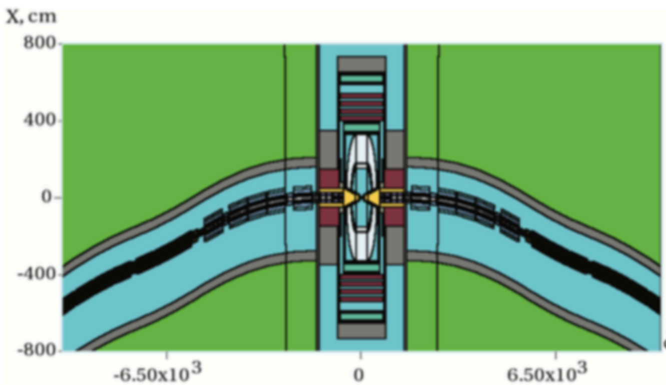


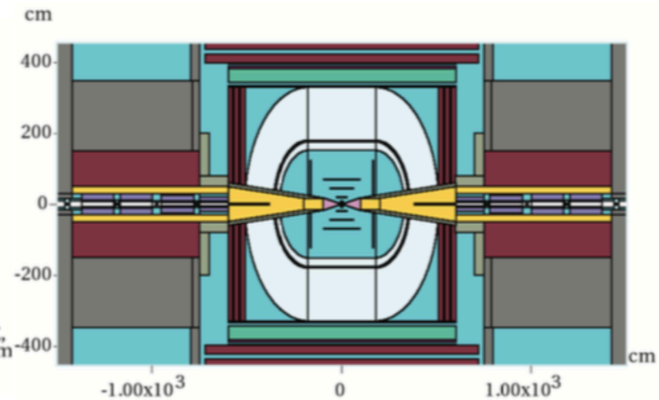
cm
Q2, Q4
50
40
30
20
10

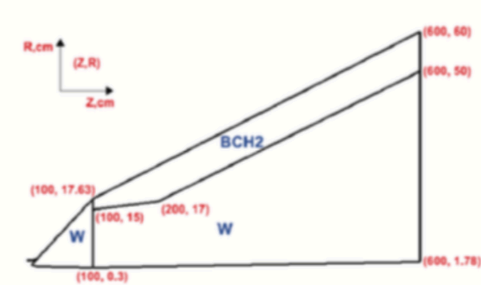


dc
Concrete
Iron
Steel
Q3
Q4
BIR1
1.00×10^3
cm

Detector and interaction region







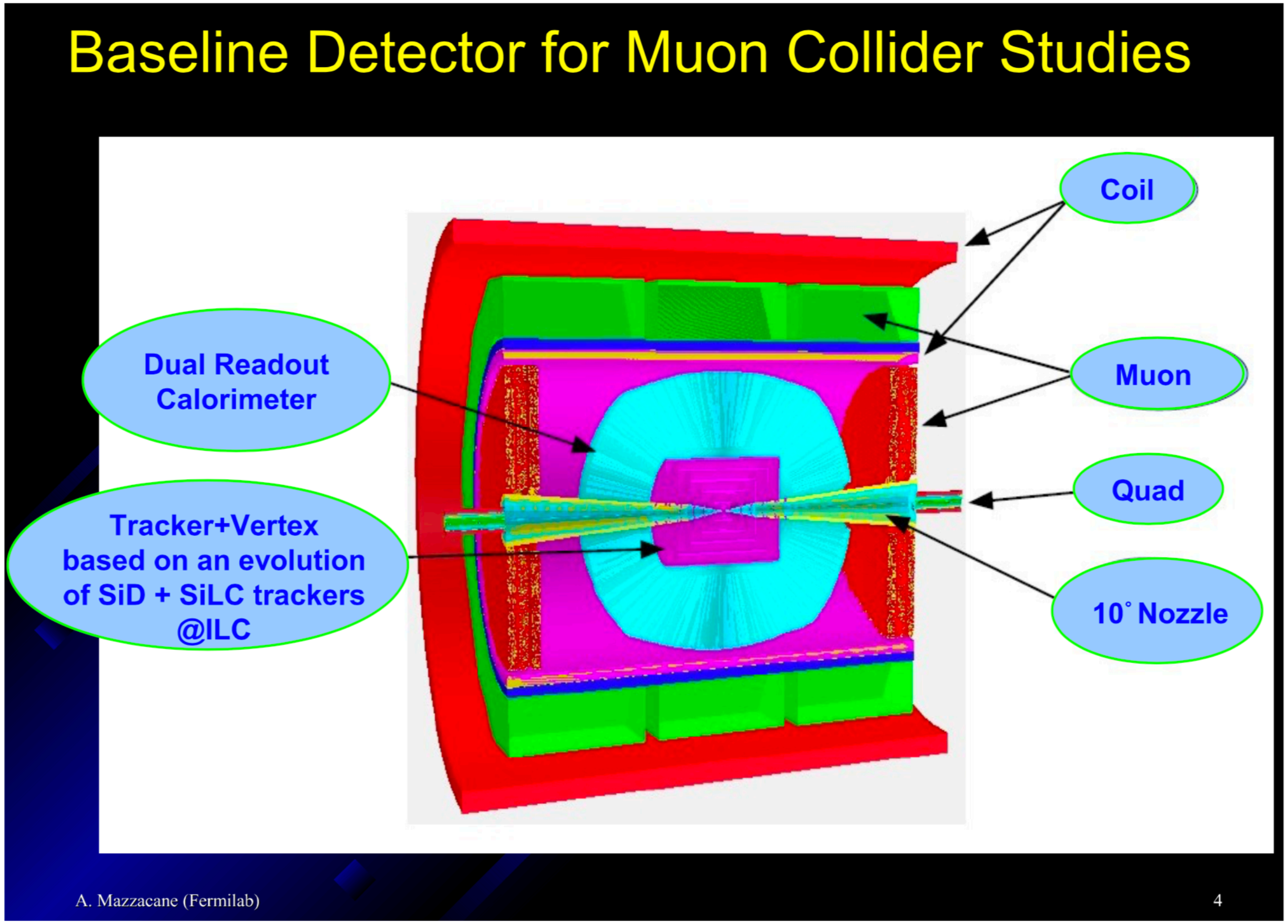
Detailed studies performed by MAP Collaboration for √s=1.5 TeV collider using MAR15 simulation of particle transport and interactions in accelerator, detector and shieldings

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

MAP detector design

A. Mazzacane



- Vertex detector:
  - 20x20 μm² Si pixels;
  - 5 barrel layers at 5.4 cm < r < 15.4 cm;
  - 4 + 4 endcap disks, |z| < 42 cm.
- Si tracker:
  - 50x50 μm² 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.

Modelled in the ILCroot framework, response simulated with GEANT

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

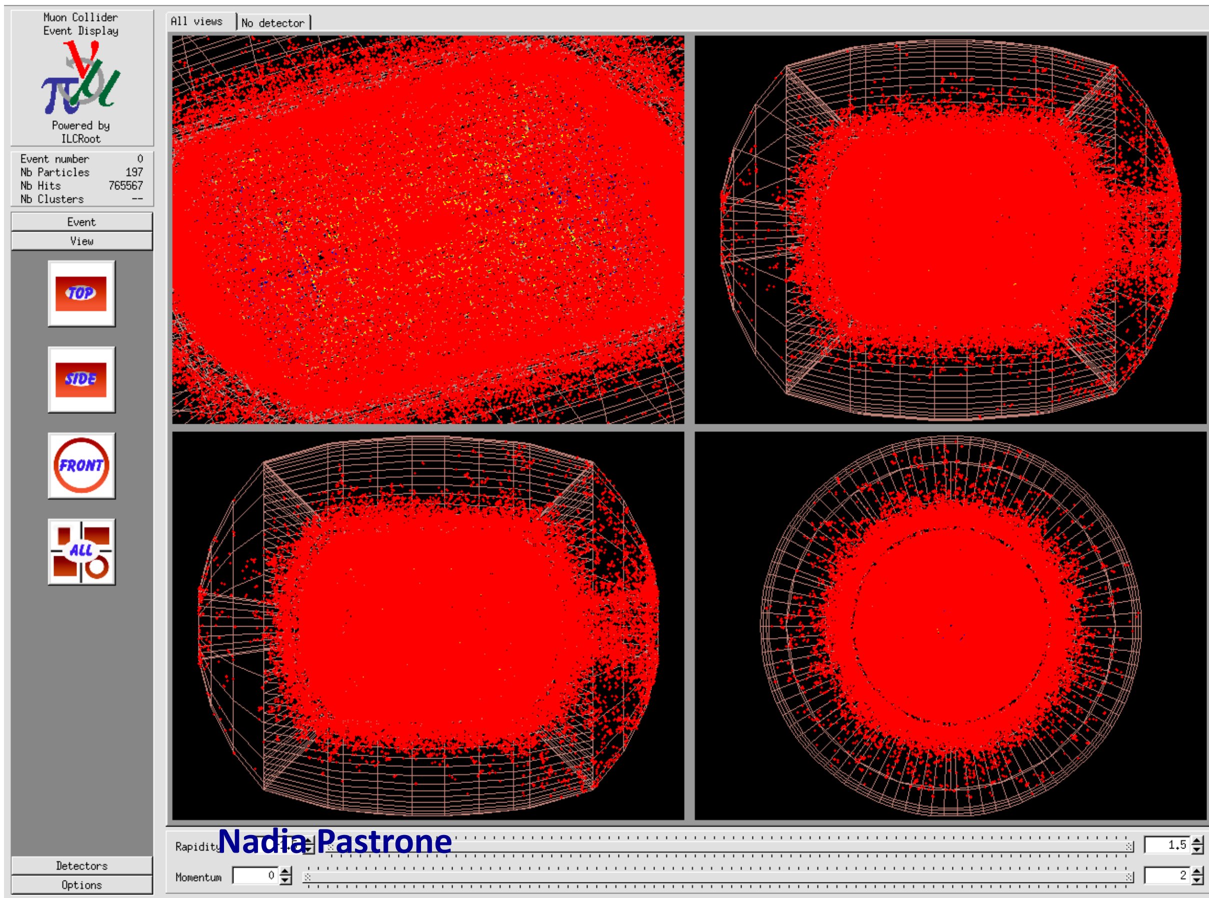
Background @ √s=125 GeV is the worst possible case

Muon decays background:
beam @ 0.75 TeV

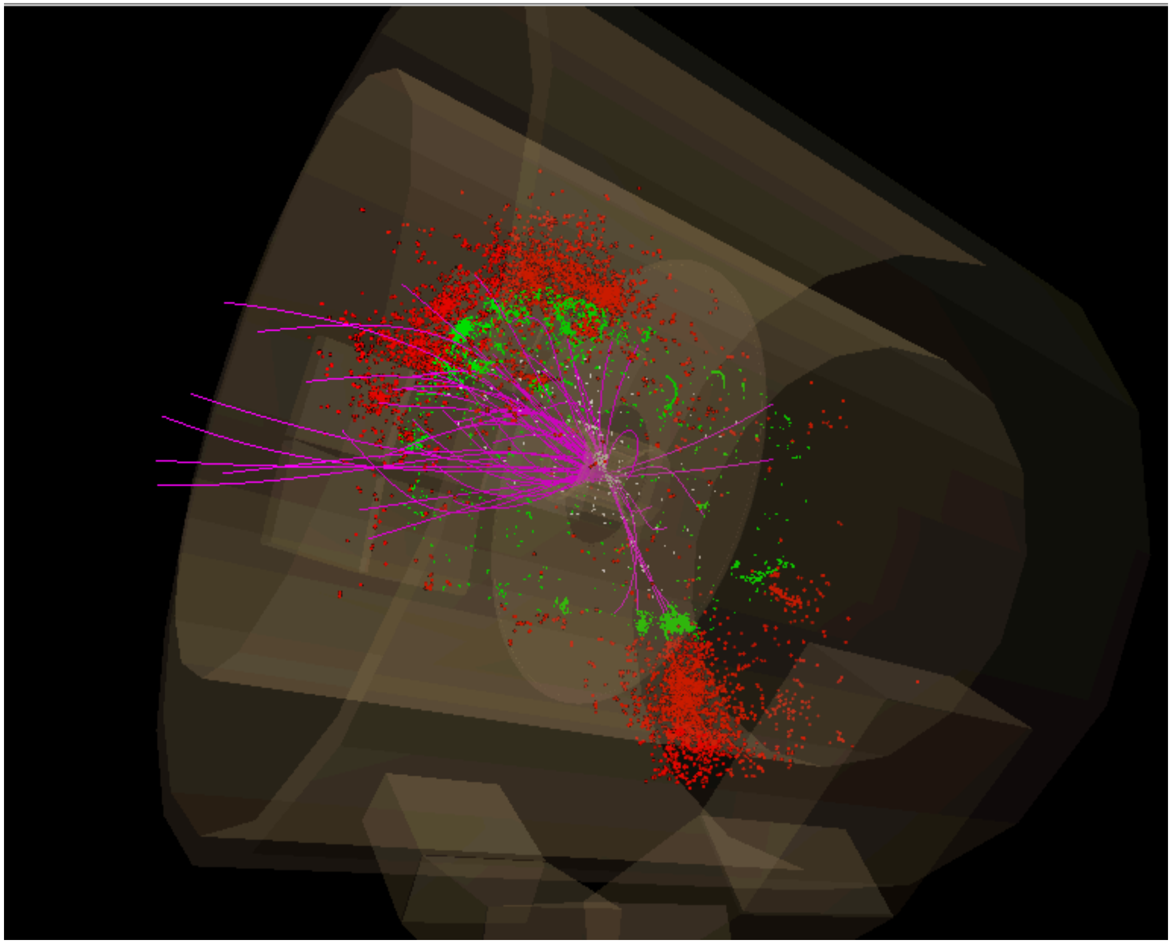
$\lambda = 4.8{\times}10^6$m
with $2{\times}10^{12}\mu$/bunch

→ $4.1{\times}10^5$decay
per meter of lattice

No cuts: all hits



Timing powerful to remove background

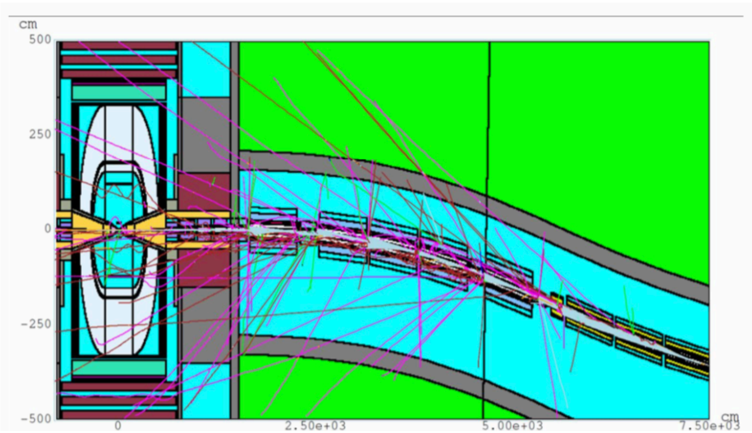


Tools are in place!
work just started....

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

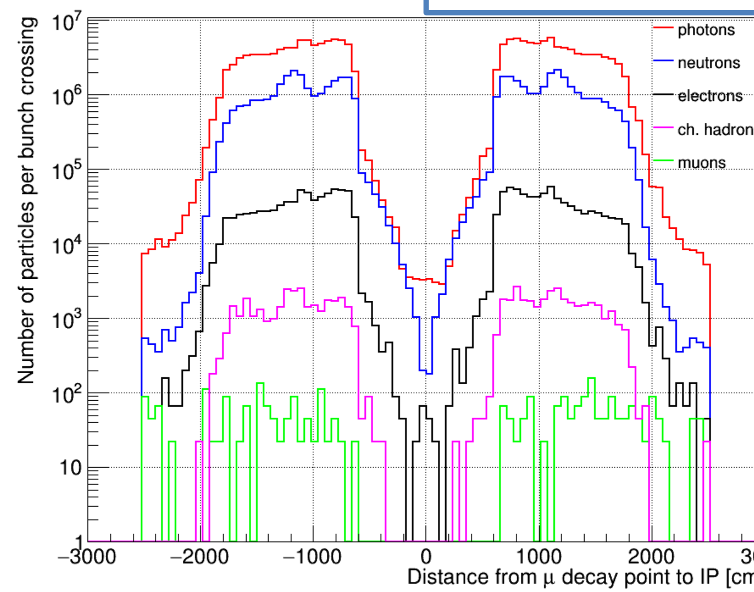
Beam induced background studies
on detector at $\sqrt{s}$ =1.5 TeV

arXiv:1905.03725

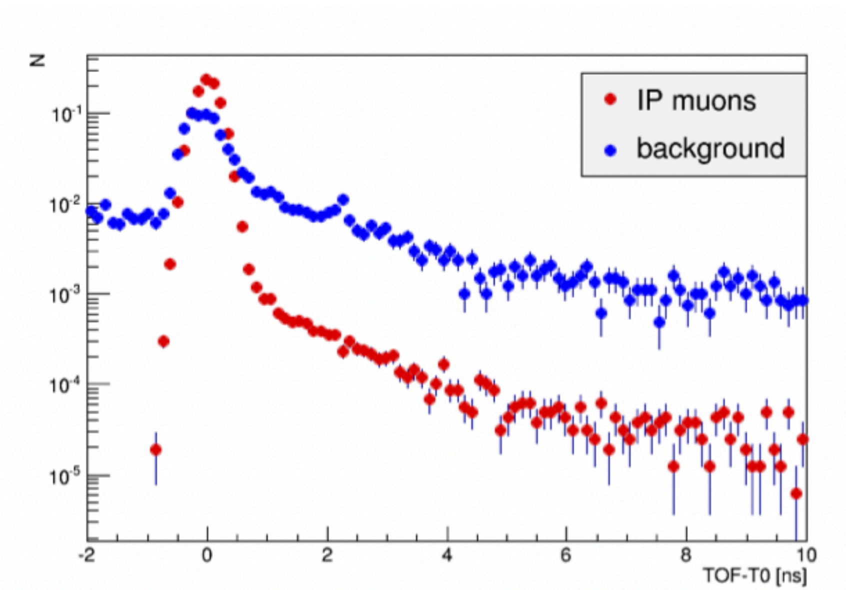


MARS15 simulation in a range of ±100 m around the interaction point

750 GeV beam



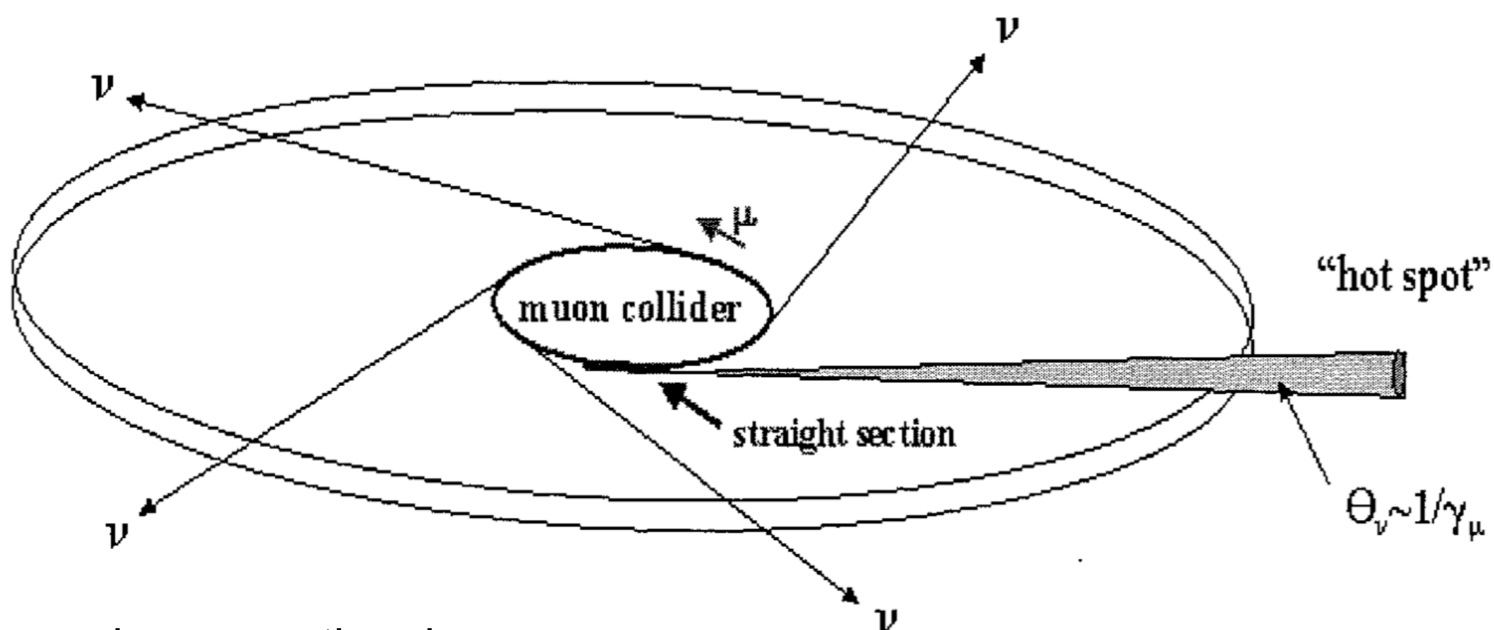
Particle composition of the beam-induced background as a function of the muon decay distance from the interaction point



Simulated time of arrival (TOF) of the beam background particles to the tracker modules with respect to the expected time (T0) of a photon emitted from IP

Neutrino induced hazard

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



The source, ring or section, is placed at the fixed depth of 550 m.

Neutrino induced hazard - simulation

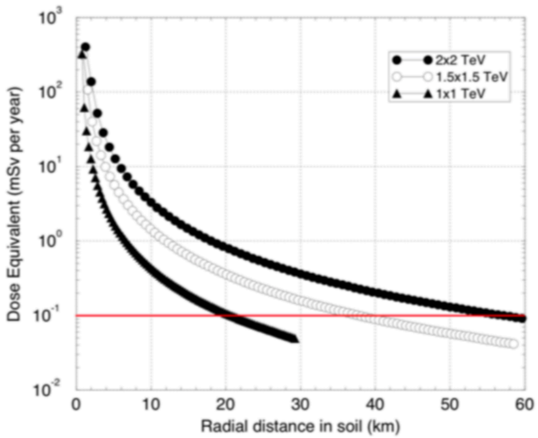


Figure 8: Maximum dose equivalent in TEP embedded in soil in high-energy muon collider orbit plane with 1.2×10^{21} decays per year *vs* distance from ring center.

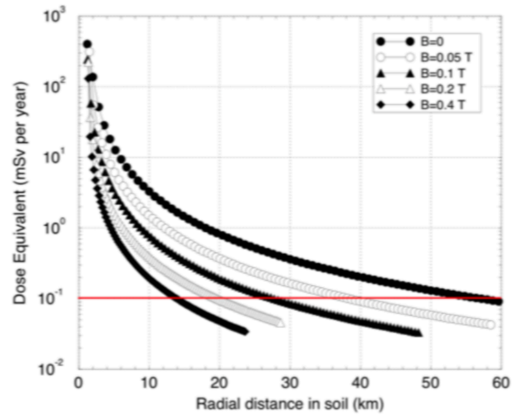


Figure 10: Maximum dose equivalent in TEP located in orbit plane *vs* distance from ring center in soil around a 2+2 TeV muon collider with 1.2×10^{21} decays per year for five values of vertical wave field.

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*

* constrained by ν radiation

One concept

- Solution beyond 10 TeV unclear at present†

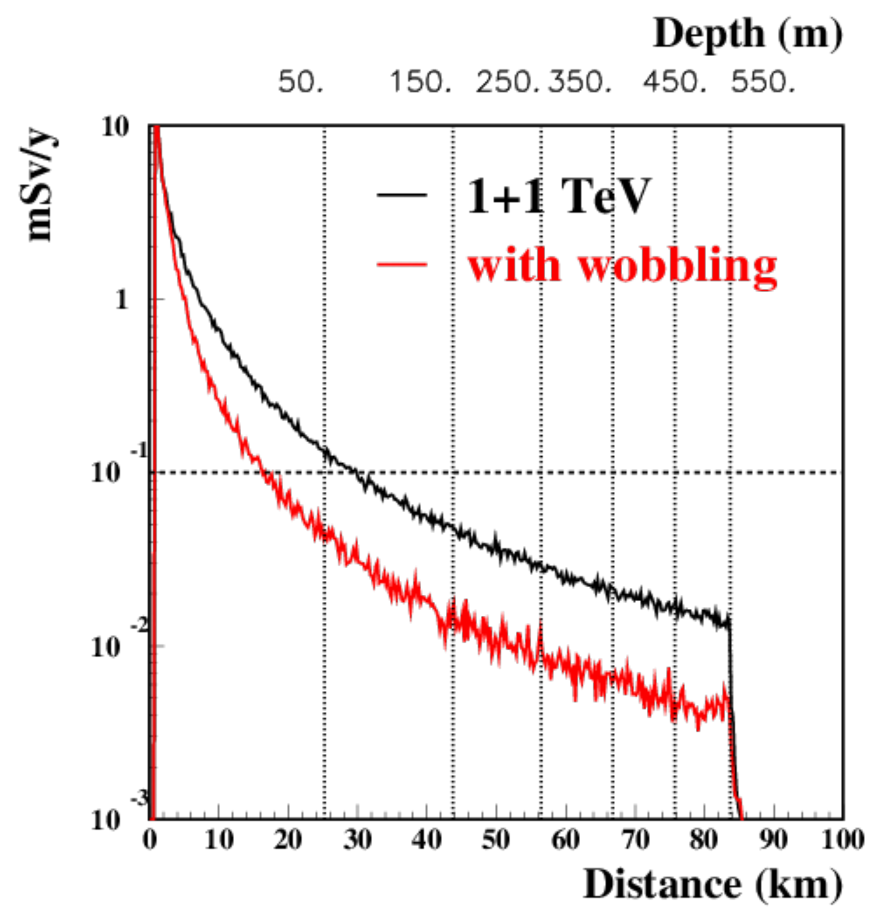
† although cf. AIP Conf. Proc. 1507 (2012) 860

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

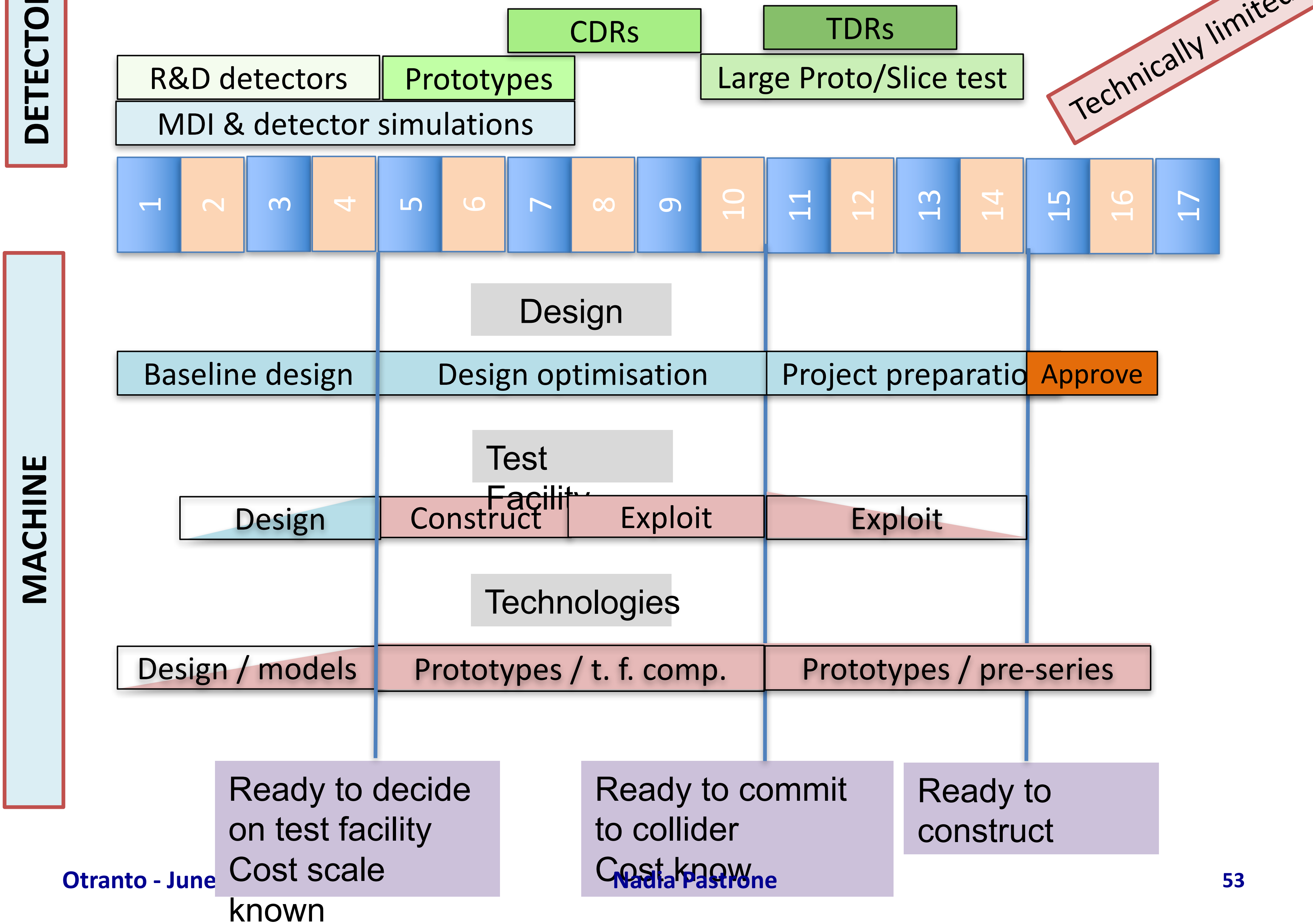
Beam induced background studies
neutrino radiation hazard

Neutrinos forced to interact along the path from the source to Earth boundary, with a probability proportional to cross section and constant material density.

Ambient dose equivalent calculated trough convolution of particle fluence and conversion coefficients,assuming 1.2×10^{21} decays/year



Proposed tentative timeline



Conclusion @ Granada Symposium

We think we can answer the following questions

- **Can muon colliders at this moment be considered for the next project?**

New developments in the recent years:

  - large progress for the proton-source option from the MAP study
  - new possibility opened by the LEMMA scheme
  - but still a long way to go...

- **Is it worthwhile to do muon collider R&D?**

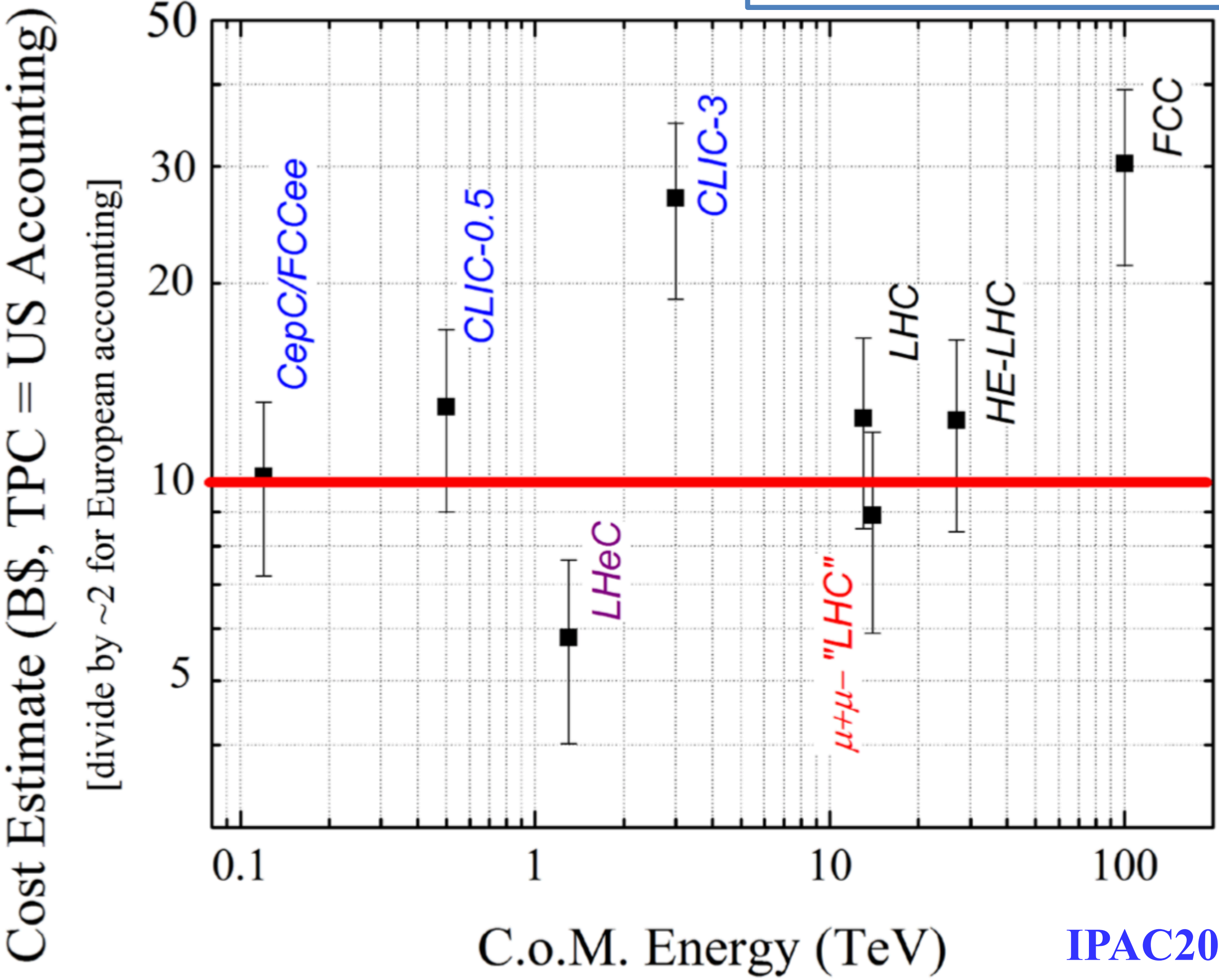
The great physics reach of a high-energy (multi-TeV) calls for a vigorous R&D programme

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

Cost estimate

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

Vladimir SHILTSEV,David NEUFFER (Fermilab)



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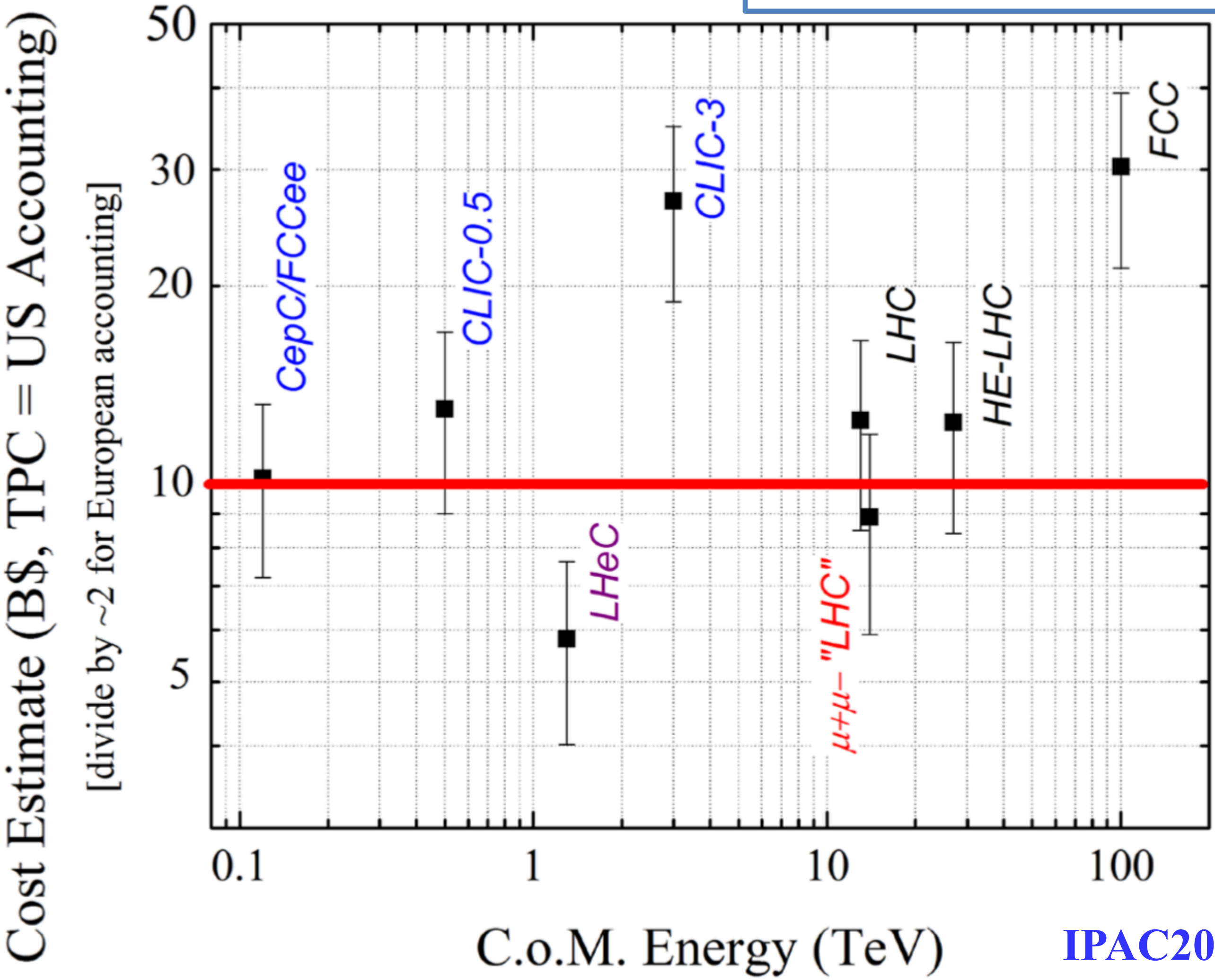
Cost estimate

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

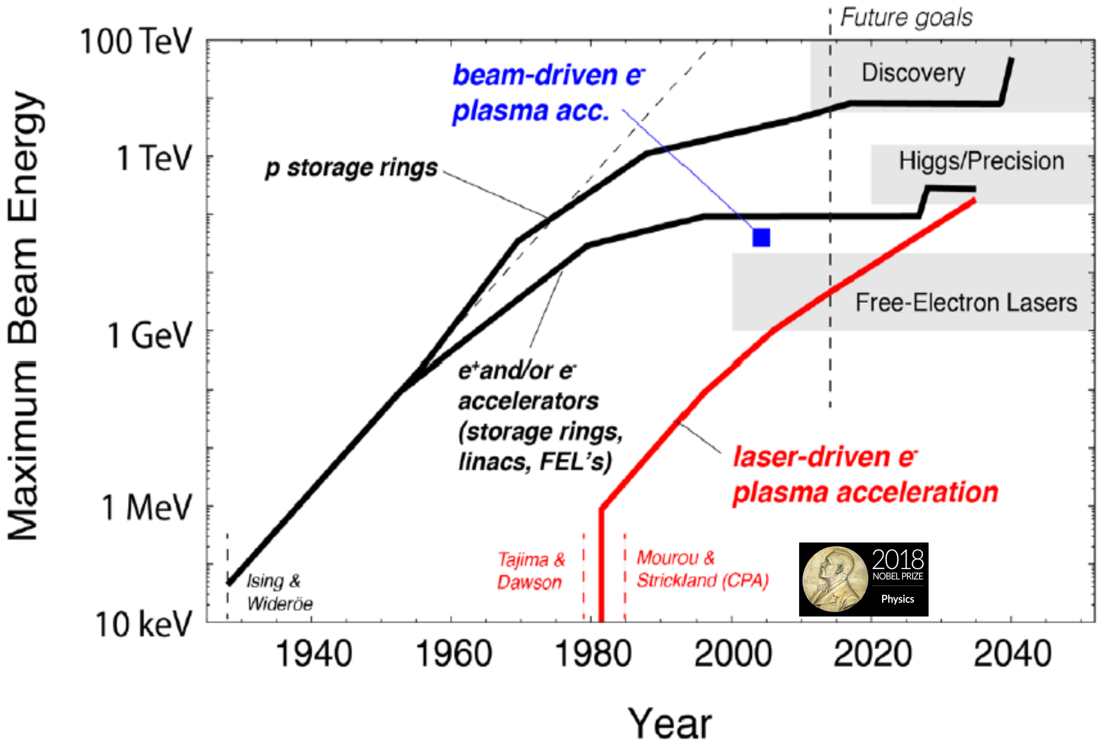
Vladimir SHILTSEV,David NEUFFER (Fermilab)



IPAC2018 - MOPMF072

ALTERNATIVE ACCELERATION TECHNIQUES

promise, status and challenges



Options towards higher energies

Hadron (p) circular collider

$$p = e \cdot R \cdot B_y$$

Increase bending field
SC bend magnet work (FCC-hh)

Increase radius = size (FCC-hh)

Lepton (e-,e+) circular collider

$$p \propto E_0 \cdot \sqrt[4]{\rho \cdot U_0}$$

Increase supplied RF voltage
(FCC-ee)

Increase mass of acc. particle (muon)

Increase radius = size (FCC-ee)

Lepton (e-,e+) linear collider

$$p = L \cdot G_{acc}$$

Increase accelerating gradient
(a) Pushing existing technology (ILC, CLIC)
(b) New regime of ultra-high gradients (plasma, dielectric accelerators)

Increase length (ILC, CLIC)

Beam Quality Requirements

Future accelerators will require also high quality beams :

==> High Luminosity & High Brightness,

==> High Energy & Low Energy Spread

$$L = \frac{N_{e+} N_{e-} f_r}{4\pi\sigma_x\sigma_y}$$

- N of particles per pulse => 10^9
- High rep. rate f_r=> bunch trains
- Small spot size => low emittance

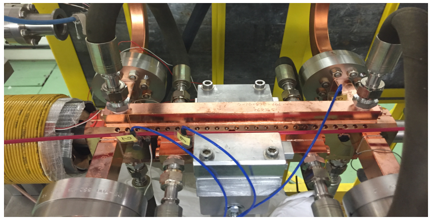
$$B_n \approx \frac{2I}{\varepsilon_n^2}$$

- Short pulse (ps => fs)
- Little spread in transverse momentum and angle => low emittance

High Gradient Options

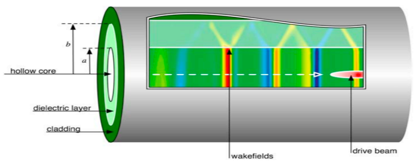
Metallic accelerating structures =>

100 MV/m < E_{acc}< 1 GV/m



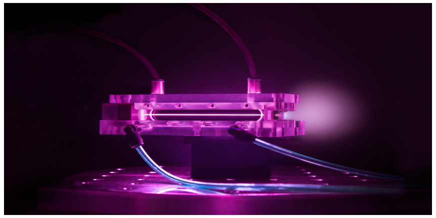
Dielectrict structures, laser or particle driven =>

E_{acc} < 10 GV/m



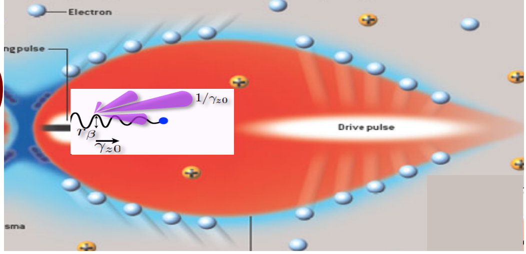
Plasma accelerator, laser or particle driven =>

E_{acc} < 100 GV/m



Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small (μm) spot to match high gradients

Conclusions on plasma R&D



- Accelerator-based High Energy Physics will at some point become practically limited by the size and cost of the proposed e^+e^- colliders for the energy frontier.
- **Novel Acceleration Techniques and Plasma-based, high gradient accelerators open the realistic vision of very compact accelerators for scientific, commercial and medical applications.**

- The R&D now concentrates on **beam quality, stability, staging and continuous operation**. These are necessary steps towards various technological applications.
- The progress in advanced accelerators benefits from strong synergy with general advances in technology, for example in the laser and/or high gradient RF structures industry.

- **A major milestone is an operational, 1 GeV compact accelerator. Challenges in repetition rate and stability must be addressed. This unit could become a stage in a high-energy accelerator..**
- **➔ PILOT USER FACILITIES Needed**

Plasma Wakefield Accelerators

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Key facts:

Three ways to excite plasma (drivers)

laser $dE \sim 4.3$ GeV (10^{18} cm^{-3} 9cm)

e- bunch $dE \sim 9$ GeV ($\sim 10^{17}$ cm^{-3} 1.3m)

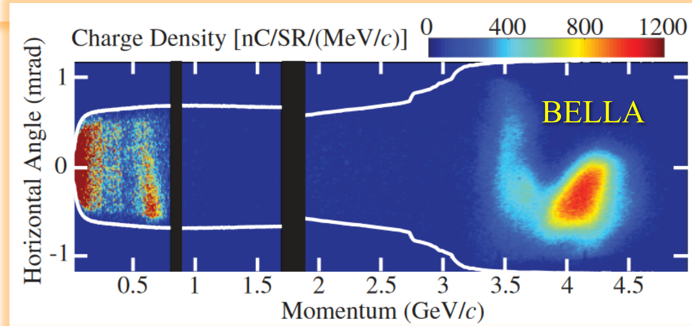
p+ bunch $dE \sim 2$ GeV ($\sim 10^{15}$ cm^{-3} 10m)

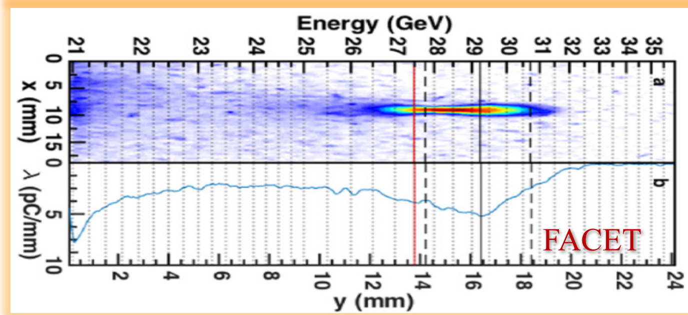
Impressive proof-of-principle demos

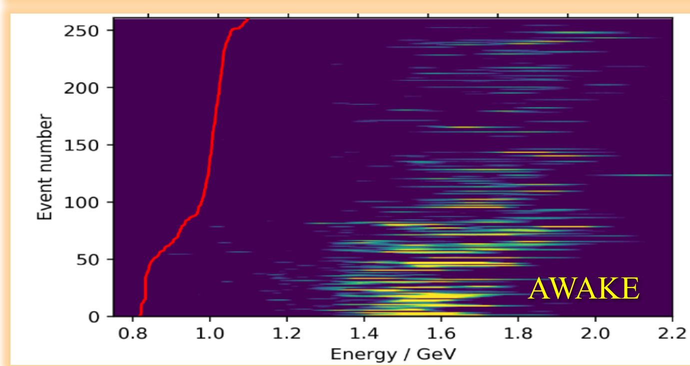
In principle, feasible for *e+e-* collisions

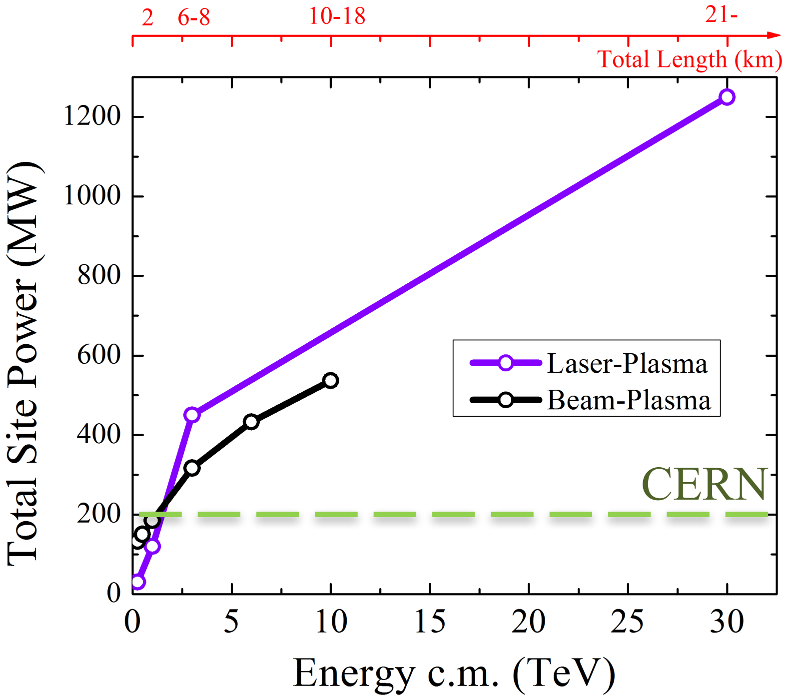
Collider cost and power will greatly depend on the driver technology:

- lasers, super-beams of electrons or protons







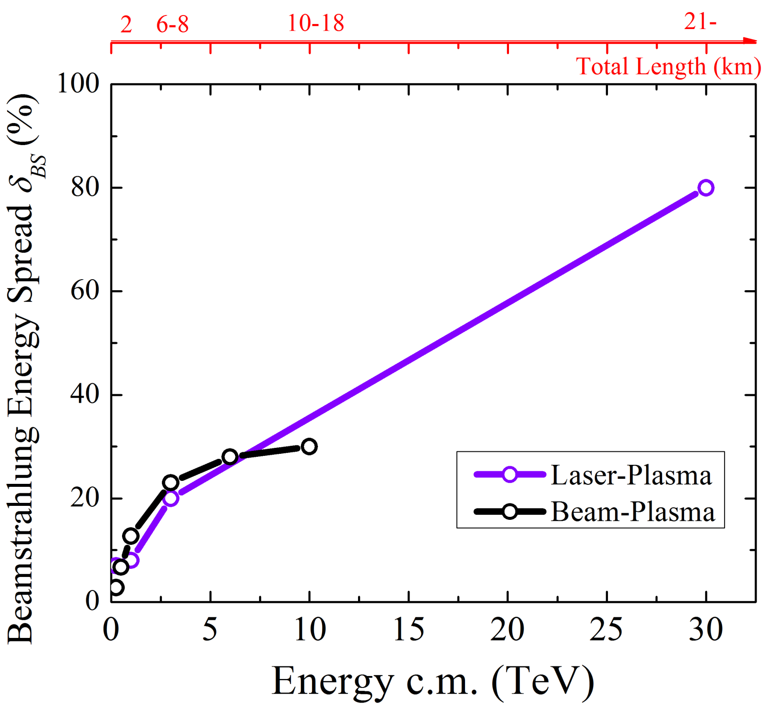


arXiv:1308.1145

Plasma Colliders :

- **Key Issues to Study:**
  - acceleration of positrons
  - Staging efficiency
  - emittance control vs scatter
  - beamstrahlung
  - HP lasers / HP operation
  - power efficiency

    * the first four can be addressed by using μ's in 10^{22} cm^{-3} crystals – up to 1 PeV

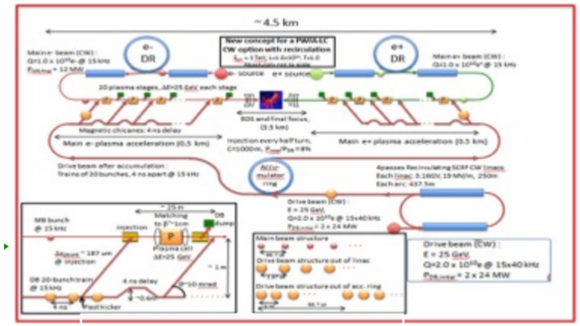


- **Plenty of interest and opportunities:**
  - **Collaborations:** *EuPRAXIA, ALEGRO study, ATHENA*
  - **Facilities:** *PWASC, ELBE/HZDR, AWAKE, CILEX, CLARA and SCAPA, EuPRAXIA @ SPARC_LAB at INFN-LNF, Lund, JuSPARC at FZJ and FLASHFor-ward and SINBAD at DESY; also in Japan (ImPACT), China (SECUF) and in the US (FACET-II, BELLA)*
  - Advanced Acceleration Concepts **US roadmap** : **CDR by 2035**
  - Proposals of plasma *e-* injectors:
    - 100 MeV to IOTA (FNAL)
    - 700 MeV to PETRA-IV booster (DESY)

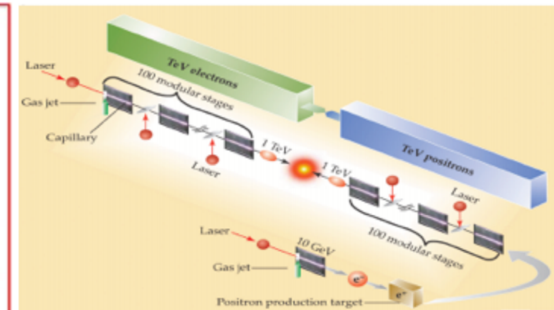
Plasma acceleration based colliders

Drive beams
Lasers: ~40 J/pulse
Electrons: 30 J/bunch
Protons: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams
Electrons: 1010 particles @ 1 TeV ~few kJ



E. Adli et. al.,arXiv:1308.1145



Leemans & Esarey, Phys. Today 63 #3 (2009)

Key achievements in last 15 years in plasma based acceleration using lasers, electron and proton drivers

- Focus is now **on high brightness beams, tunability, reproducibility, reliability, and high average power**

The road to colliders passes through **applications** that need compact accelerators (Early HEP applications, FELs, Thomson scattering sources, medical applications, injection into next generation storage rings …)

Many key challenges remain as detailed in community developed, consensus based roadmaps (ALEGRO, AWAKE, Eupraxia, US roadmap,…)

Strategic investments are needed:

- **Personnel** – advanced accelerators attract large numbers of students and postdocs
- Existing **facilities** (with upgrades) and a few new ones (High average power, high repetition rate operation studies; fully dedicated to addressing the challenges towards a TDR for a plasma based collider)
- **High performance computing** methods and tools

Energy Efficiency

Q4: Energy management in the age of high-power accelerators?

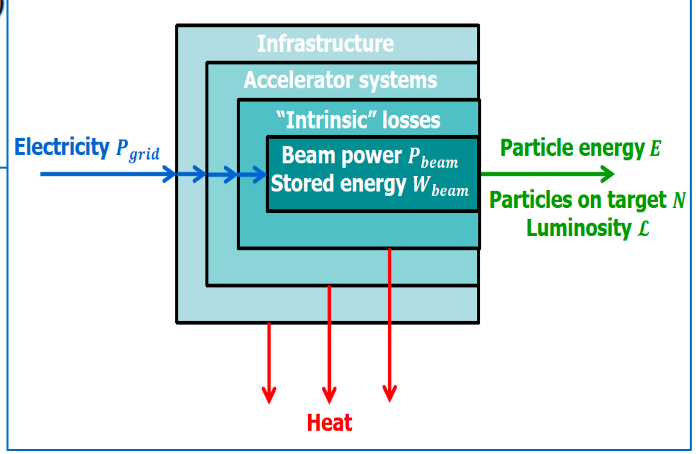
- Energy efficiency is not an option, it is a must!
- Proposed HEP projects are using $\mathcal{O}(\mathrm{TWh/y})$, where energy efficiency and energy management must be addressed.
- Investing in dedicated R&D to improve energy efficiency pays off since savings can be significant.
- This R&D leads to technologies which serve the society at large.
- District heating, energy storage, magnet design, RF power generation, cryogenics, SRF cavity technology, beam energy recovery are areas where energy efficiency can be significantly be improved.

Energy Management

A reference: Outlook – Strategies pointed out by Ph. Lubrun (EUCARD2 study)

- Maximize energy-luminosity performance per unit of beam power
  - Minimize circumference for a given energy (high-field magnets)
  - Operate at beam-beam limit
  - Low-emittance, high-brilliance beams
  - Low-beta insertions, small crossing angle ("crabbing")
  - Short bunches (beamstrahlung)
- Contain "intrinsic" losses
  - Synchrotron radiation
  - Beam image currents
  - Electron-cloud
- Optimize accelerator systems
  - RF power generation and acceleration (deceleration)
  - Low-dissipation magnets (low current density, pulsed, superconducting, permanent)
- Optimize infrastructure systems
  - Efficient cryogenics (heat loads, refrigeration cycles & machinery, distribution)
  - Limit electrical distribution losses (cables, transformers)
  - Absorb heat loads preferably in water rather than air
  - Recover and valorise waste heat

Ph. Lebrun Workshop on Magnet Design Nov 2014



Energy Efficiency and Management in Accelerators

Summary
Reasons for low efficiency

4th Workshop
Energy for Sustainable Science
at Research Infrastructures

- For all types of accelerators, the average beam power is proportional to the product of particle energy and luminosity or delivered particle flux
- The energy-luminosity performance, and possibly the physics reach of a collider can be represented by a single "coefficient of performance"
- The ratio of "coefficient of performance" to beam power quantifies the relation between collider performance and beam parameters: it is lower for single-pass machines than for circular colliders
- "Intrinsic" losses due to basic physics processes add up to the beam power and often exceed it (synchrotron radiation)
- Accelerator systems and infrastructure represent the bulk of electrical power consumption
- Comparing total power consumption and average beam power yields very low values for overall "grid-to-beam" efficiency
- Linear colliders show higher overall "grid-to beam" efficiencies than circular colliders. This partly compensates for their much lower COP/beam power ratio

Consideration on timeline:

LHC possible because SSC developed the superconductor…

L. Rossi

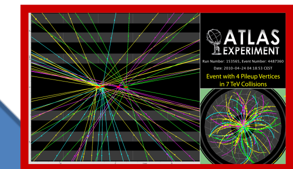
9 T - 1 m single bore

10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole



1985 1987 1990 1994 2000 2006 2010

Only 2 y to make a short magnet «near to final». Conductor available(SSC)

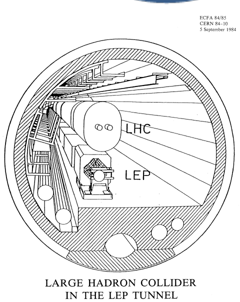
7 years from start R&D to 1st Industry proto

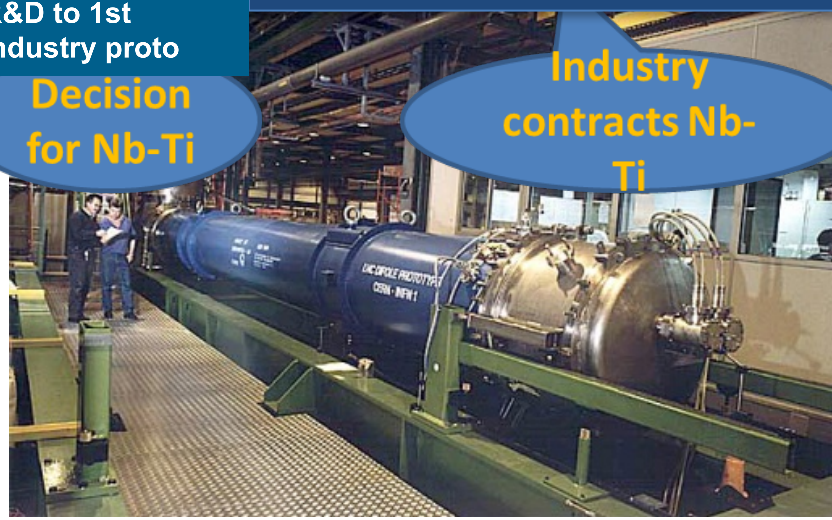
12 y from first working prototype to last magnet

Decision for Nb-Ti

Industry contracts Nb-Ti

LHC start-up

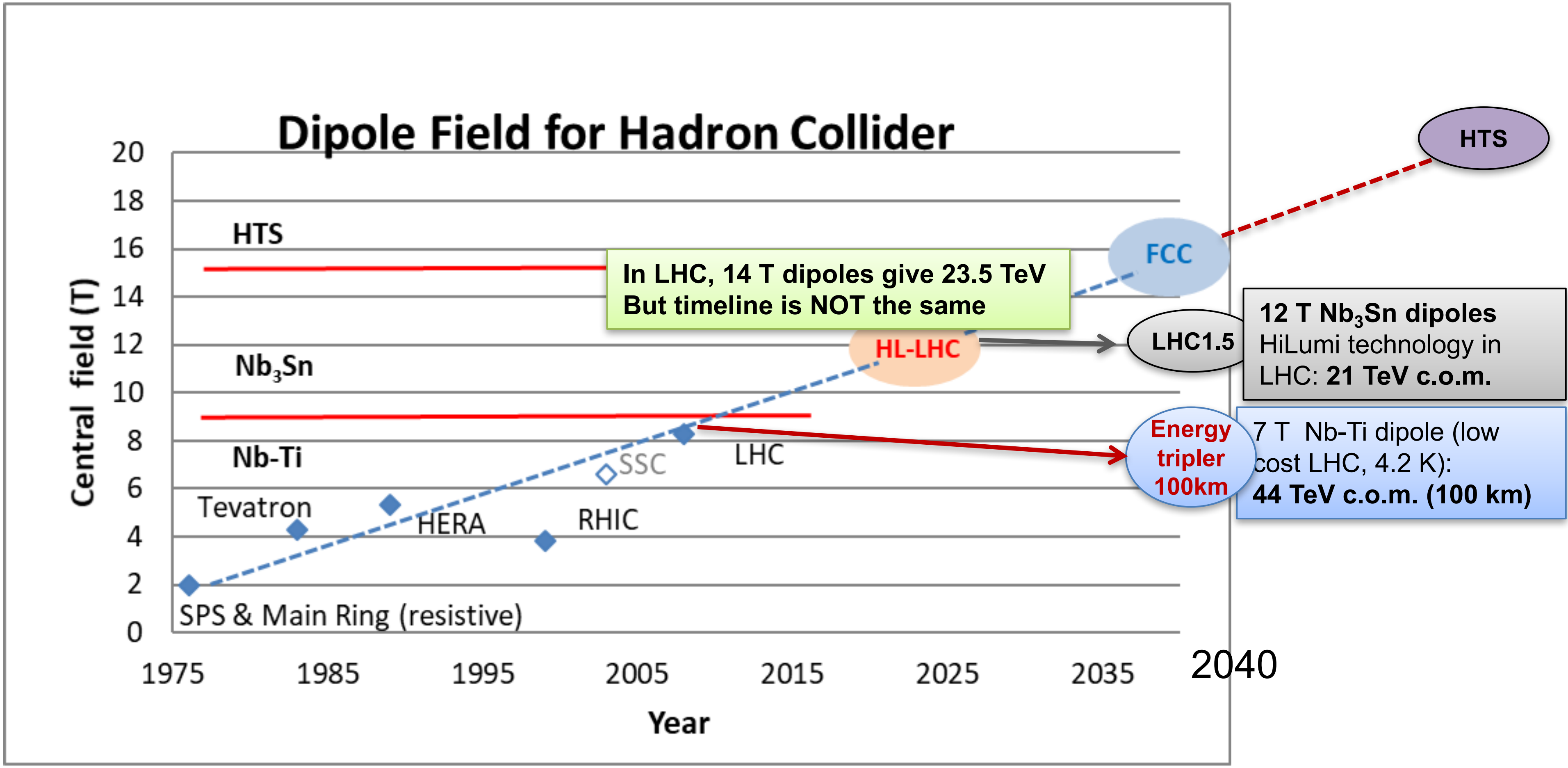




Q2: Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?

High field magnet development

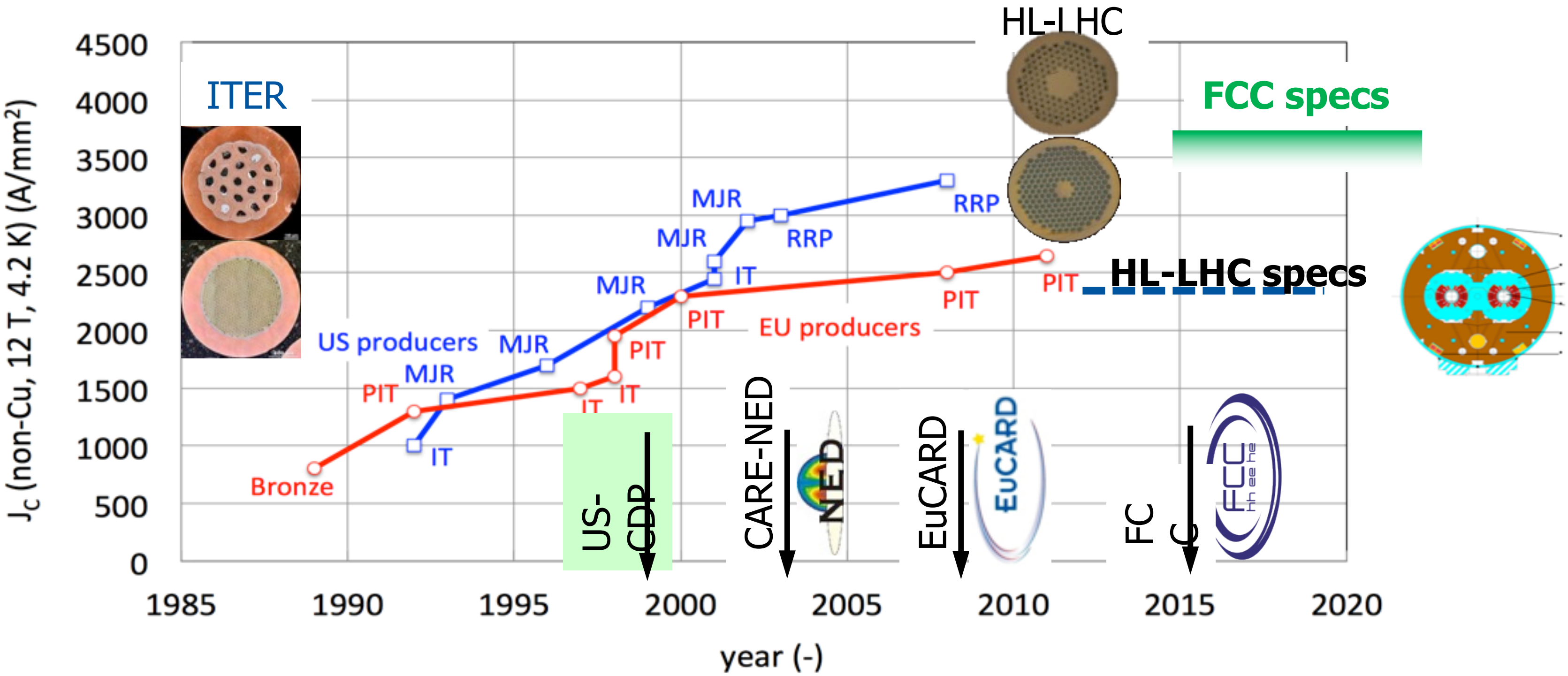
L. Rossi



The set up of a SC Open Lab for fostering development of superconductors (F. Bordry and L. Bottura proposal) is critical for HEP HC progress

Nb_3Sn Conductor development for Accelerators (1998 ~)

Courtesy, G. de Rijk



After 10 years of development, the US and EU development gave us the Nb_3Sn conductor for HILUMI.

s.c. magnet technology

- Nb_3Sn superconducting magnet technology for hadron colliders, still requires **step-by-step** development to reach **14, 15, and 16 T**.
- It would require the following **time-line** (in my personal view):
  - **Nb_3Sn, 12~14 T:** 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in **10 – 20 yrs** for the construction to start,
  - **Nb_3Sn, 14~16 T:** 10-15 years for short-model R&D, and the following 10 ~ 15 years for protype/pre-series with industry. It will result in **20 – 30 yrs** for the construction to start, (consistently to the FCC-integral time line).
  - **NbTi , 8~9 T:** proven by LHC and **Nb_3Sn, 10 ~ 11 T** being demonstrated. It may be feasible for the construction to begin in > ~ 5 years.
- **Continuing R&D effort** for high-field magnet, present to future, should be critically **important**, to realize highest energy frontier hadron accelerators in future.

Intensify HTS accelerator magnet development

Personal (A. Yamamoto) View on Relative Timelines

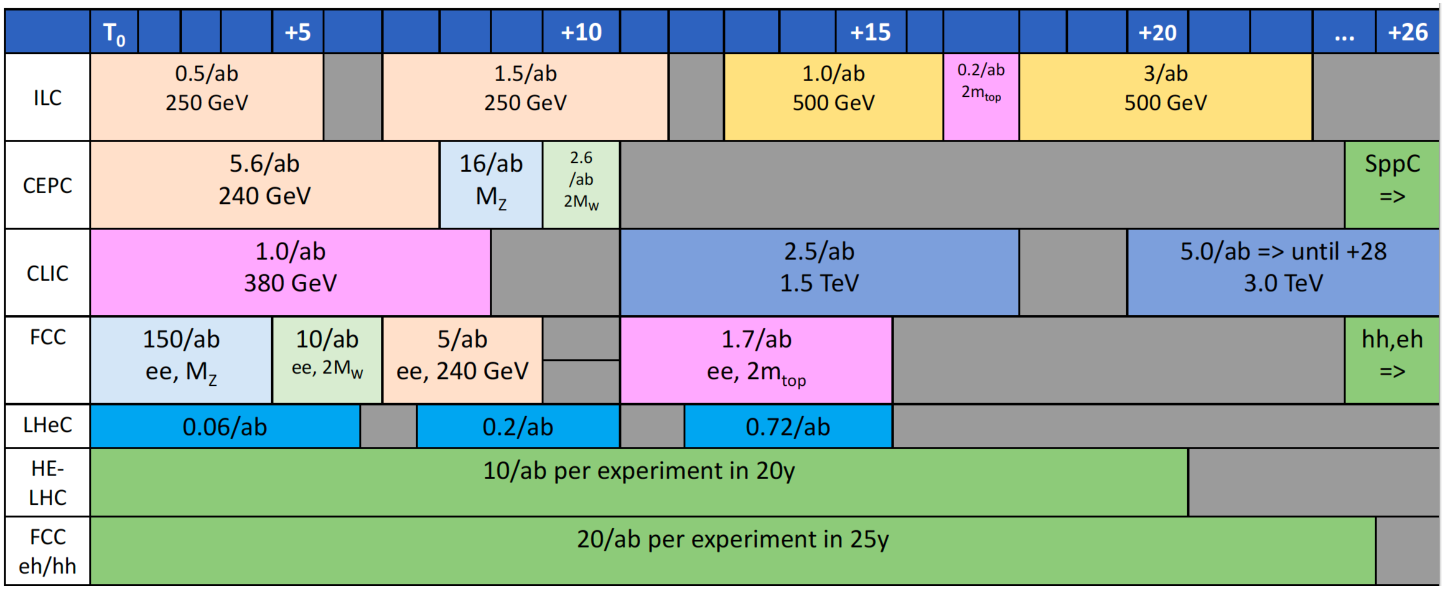
Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF–LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collider (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

Note: **LHC experience**: **NbTi (10 T)** R&D started in 1980's --> (**8.3 T)** Production started in late 1990's, in **~ 15 years**

Higgs Factories Comparisons

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Proposed Schedules and Evolution

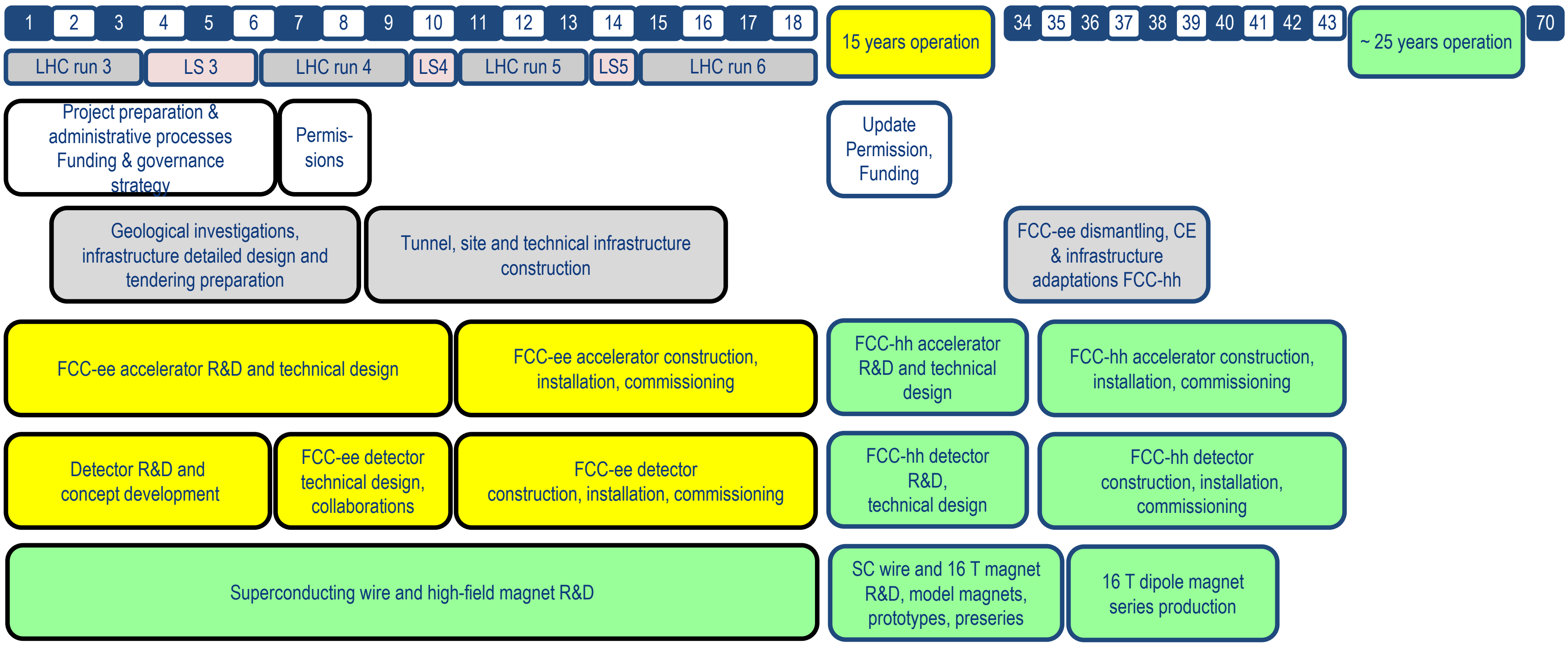


Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Proposed dates from projects

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

FCC integrated project technical schedule



FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.

key parameters of future circular e^+e^- colliders

Collider (all double rings)	Beam energy [GeV]	Peak luminosity (per IP) [10^{34} $cm^{-2}s^{-1}$]	β_y^* [mm]	beam current [mA]	Collision scheme	Beam lifetime [min]	e^+ top-up rate [10^{11}/s]
SuperKEKB	4 (e^+), 7 (e^-)	**80**	**0.3**	**3600 (e^+), 2600 (e^-)**	**Nano-beam**	**<5**	**10**
BINP c-t	1-3	**5-20**	**0.5**	**2200**	**Crab waist**	**<10**	**1**
HIEPA c-t	1.5-3.5	~**10**	**0.6**	**2000**	**Crab waist**	**<10**	**1**
FCC-ee (Z)	45.6	**230**	**0.8**	**1500**	**Crab waist**	**68**	**7**
FCC-ee (H)	120	**8.5**	**1.0**	29	**Crab waist**	**12**	**1**
FCC-ee (t)	182.5	1.6	**1.6**	5	**Crab waist**	**12**	**0.2**
CEPC (Z)	45.5	**32**	**1.0**	**460**	**Crab waist**	150	**1.1**
CEPC (H)	120	3	**1.5**	17	**Crab waist**	**26**	**0.2**

Many similar parameters and strong synergies for design

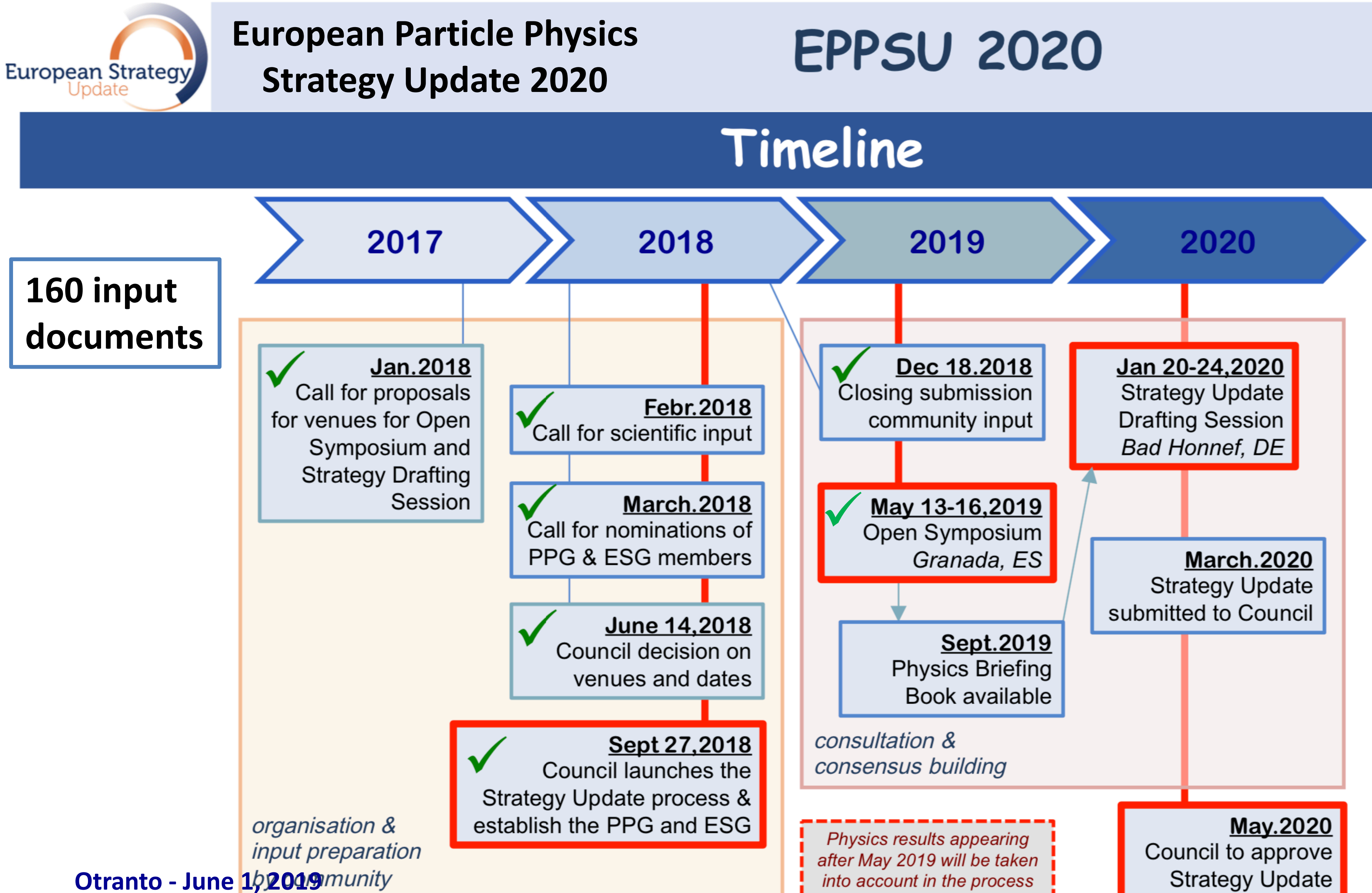
RF systems for circular e^+e^- colliders

	f_{RF} [MHz]	#cavities	#cell/cavity	$V_{RF,tot}$ [MV]	acc. gradient [MV/m]	technology
SuperKEKB	**509**	30 (ARES) 8 (SCC)	1 1	15 12	2 6	warm Cu bulk Nb
charm-tau	**500**	1 / ring	1	2x1	6	bulk Nb
FCC-ee-H	**400**	136 / ring	4	2000	10	Nb/Cu
FCC-ee-t (addt'l)	**800**	372	5	6930	19.8	bulk Nb
CEPC	**650**	240	2	2200	19.7	bulk Nb

- all systems between 400 and 800 MHz, various technologies,
- preference for SC cavities,
- FCC-ee RF system optimized for each working point, CEPC features single system

Now drafting the Briefing Book….

160 input documents



Planning and Executing