RD_MUCOL

INFN activities for Muon Colliders

- CERN Open Council Announcement on June 19 released the update of the EU Strategy
- U.S. Snowmass21 process was lauched at: https://snowmass21.org/start
- Muon Collider community is ready to establish the

  international collaboration

  → **Meeting July 3**

- **CSN1 activities**
- **Bari interests**

EU Strategy update

High-priority future initiatives

In addition to the high field magnets the accelerator R&D roadmap could contain:

- the R&D for an effective breakthrough in plasma acceleration schemes (with laser and/or driving beams), as a fundamental step toward future linear colliders, possibly through intermediate achievements: e.g. building plasma-based free-electron lasers (FEL). Developments for compact facilities with a wide variety of applications, in medicine, photonics, etc., compatible with university capacities and small and medium-sized laboratories are promising;
- an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e^+e^- colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;
- a vigorous R&D on high-intensity, multi-turn energy-recovery linac (ERL) machines, promoting the realisation of a demonstrator with a view also to low-energy applications.

Toward the international collaboration

to develop an integrated muon collider design concept that encompasses the physics, the detectors, and accelerator

- to develop fully the muon collider design study
  ➔ exploring the various options
- to pursue R&D priorities, according to an agreed upon work plan

The first meeting for the muon collider to prepare an actual collaboration on July 3 at 14:00-18:00

https://indico.cern.ch/event/930508/

The goal of this meeting is to start identifying who intents to contribute to a muon collider study and, if already possible, in which field.

Brief history

Muon collider: *Strong coupling to particles like the Higgs; reduced synchrotron radiation a multi-pass acceleration; beams can be produced with small energy spread*

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

- The **muon collider idea** was first introduced in **early 1980's** *[A. N. Skrinsky and V.V. Parkhomchuk, D. Neuffer]*
- **US Muon Accelerator Program – 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

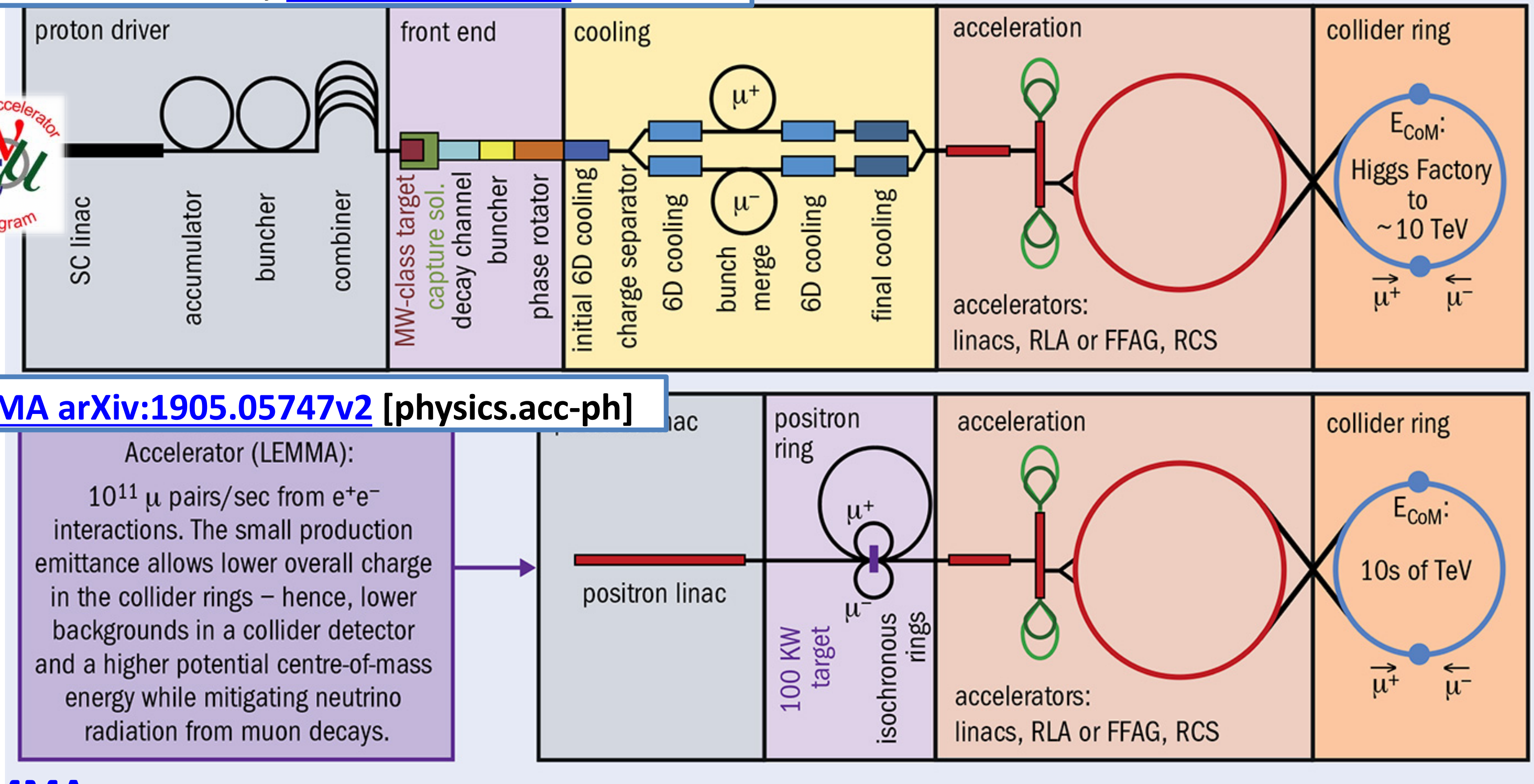
- **LEMMA (Low EMittance Muon Accelerator)** concept was proposed in **2013**
  - *a new end-to-end design of a **positron driven scheme** is presently under study by INFN-LNF et al. to overcome technical issues of initial concept* ➔ **arXiv:1905.05747**

  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

Two options

MAP: MUON JINST, shorturl.at/kxKU7



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

LEMMA

- **Positron Source** (PS) @ 300 MeV, plus **LINAC** to accelerate up to 5 GeV
- 45 GeV e^+ **Ring** (PR) to accumulate 1000 bunches needed for μ production
- 2 **Muon Accumulation Rings** (AR) – 123 m – to store typically 10^9 μ
- Average muon energy 22 GeV ($\gamma(\mu) = 200\ \mu s$, $\tau(\mu)_{lab} = 500\ \mu s$)

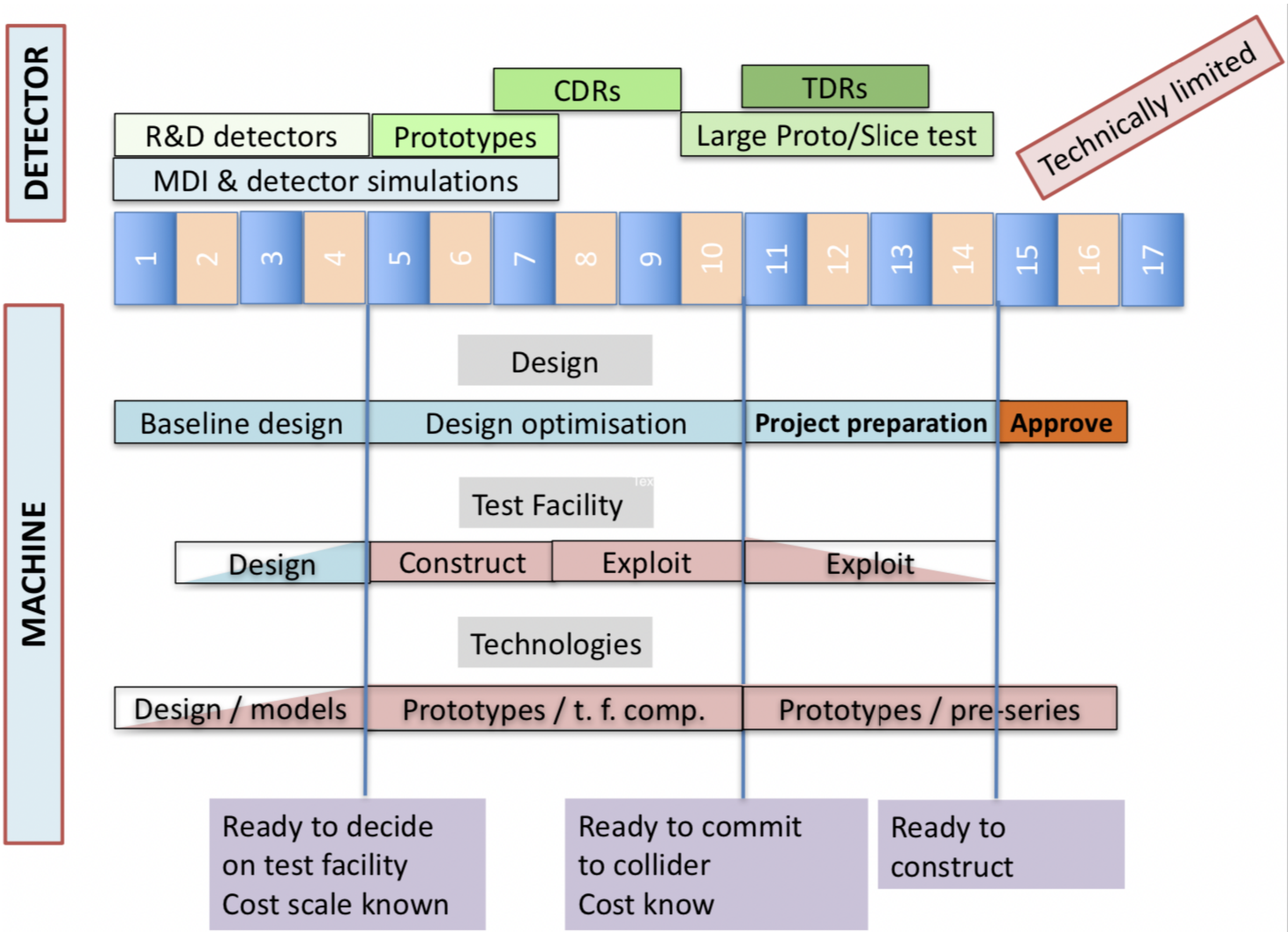
  muons produced with low emittance ➔ "no/low cooling" needed

  low production **cross section**: maximum $\sigma(e^-e^+ \to \mu^-\mu^+) \sim 1\ \mu b$

Reuse of the infrastructure:
Es. FCC-ee/FCC-hh/γ–factories for the prod. LHC o FCC for the collider.

Technically Limited Potential Timeline

Physics Briefing Book [arXiv:1910.11775v2](https://arxiv.org/abs/1910.11775v2) [hep-ex]



INFN activities (1)

1)Parametri di macchina cruciali e strettamente legati al disegno dell'esperimento e al raggiungimento degli obbiettivi di fisica

Marica Biagini - Donatella Lucchesi - Nadia Pastrone

2) Simulazioni di fisica → Bari

Barbara Mele - Antonio Costantini - Roberto Franceschini - Mauro Chiesa

==> reach di fisica vincolato dal disegno dell'esperimento

Donatella Lucchesi - Massimo Casarsa

3)Disegno dell'esperimento: richiede simulazioni e R&D anche in sinergia con altri sviluppi in corso (attivita' in AIDAinnova) → Bari

Nadia Pastrone - Massimo Casarsa - Lorenzo Sestini

INFN activities (2)

4)Machine Detector Interface ==> studi linebuilder e FLUKA - in collaborazione con esperti di acceleratori

Francesco Collamati - Paola Sala

5)Studi di radiazione da neutrino prodotti dal decadimento dei fasci - in collaborazione con esperti di acceleratori → Bari

Paola Sala ==> in futuro - sviluppi per l'utilizzo di fasci intensi di neutrini

6) Sorgente LEMMA: fascio di positroni - materiali per bersagli– accumulatore

Nadia Pastrone ==> da discutere nel contesto internazionale

7)Test Beam @ CERN in ambito LEMMA (primi test 2017-2018) ==> richiesto ora per 2022 → Bari

Fabio Anulli - Marco Zanetti - Nicola Amapane - Mario Antonelli

8) R&D tecnologia per magneti (et al.) dedicati al muon collider

Attivita’ INFN – Fisica

Studi di fisica: prossimi passi da discutere anche con CSN4

@ 1.5-3 TeV benchmark per confronto con studi di CLIC

➔ primo studio della misura $\mu\mu \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ pubblicato (J. Inst. **15** P05001, 2020)

@ 10+ TeV completamente nuovi

➔ studio fisica potenziale di Higgs (arXiv:2003.13628) – manca simulazione esperimento

The idea is to study the following items in the next months at the center of mass energies: 1.5, 3 10 TeV

Higgs fermions couplings

$\mu^+\mu^- \to HX, H \to b\bar{b}$

$\mu^+\mu^- \to HX, H \to \tau^+\tau^-$

Higgs self-couplings

$\mu^+\mu^- \to HHX, H \to b\bar{b}, H \to b\bar{b}$

$\mu^+\mu^- \to HHHX, H \to b\bar{b}, H \to b\bar{b}, H \to b\bar{b}$

Higgs bosons couplings

$\mu^+\mu^- \to HX, H \to W^+ W^-$

$\mu^+\mu^- \to HX, H \to ZZ$

$\mu^+\mu^- \to HX, H \to \gamma\,\gamma$

Direct production of heavy states (Z’, Higgsino, Wino, stop etc)

Con il software esistente (rivelatore non ottimizzato) possible realizzare l’analisi: opportunita’ per tesi di laurea.

Attivita' INFN – Esperimento

Esperimento: da disegnare ex novo

studi conclusi con apparato di MAP pubblicati (J. Inst. 15 P05001, 2020) studi in corso con nuovo software condiviso
https://sites.google.com/site/muoncollider/home

➔ Sinergia con AIDAinnova a Bari:

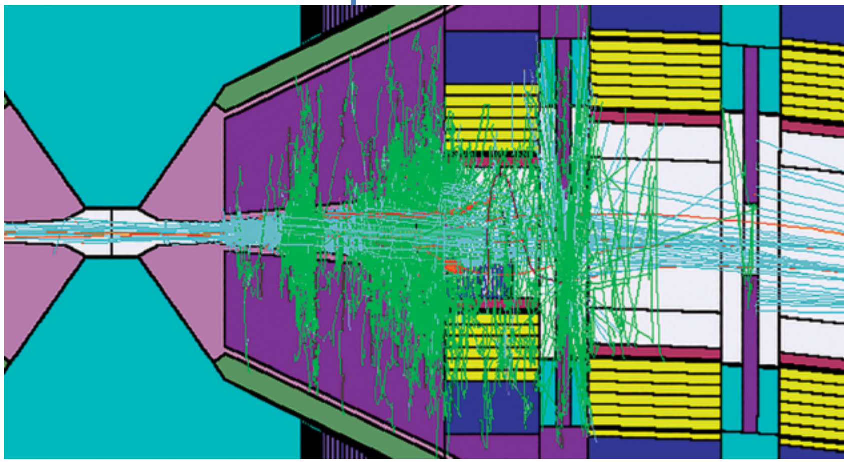
WP7 (gas detector MPGD, RPC,TPC)

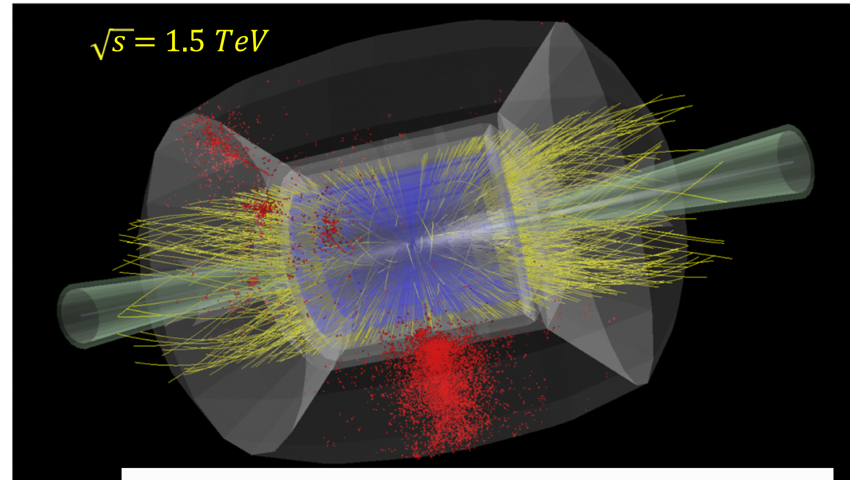
WP11 (microlectronics: ASIC design)

WP12 (software/reco, frameworks for heterogeneous infrastructures (CPU/GPU) at future accelerators)→ Capire sinergie con RD_FCC e altre attivita' in corso)

Muon Beams Induced Background

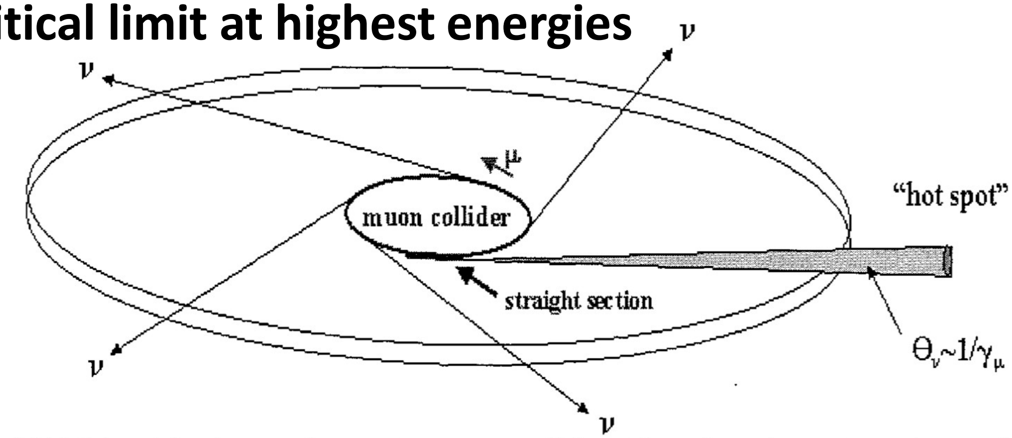
Nikolai Mokhov et al. - MARS15



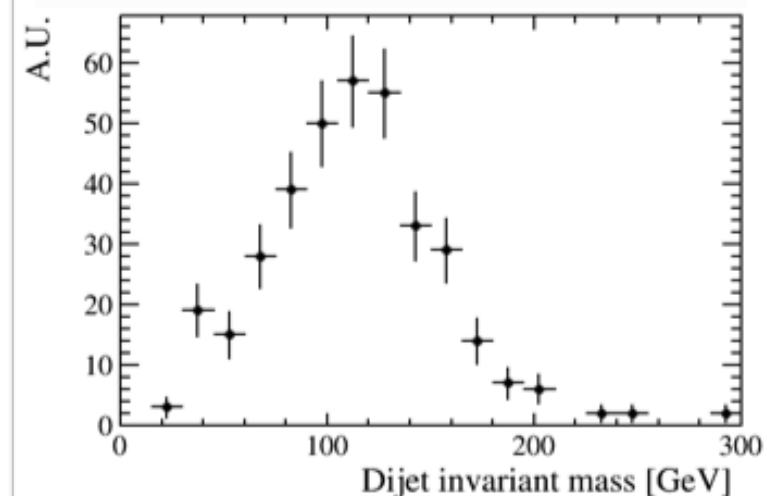


Neutrino radiation

critical limit at highest energies



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

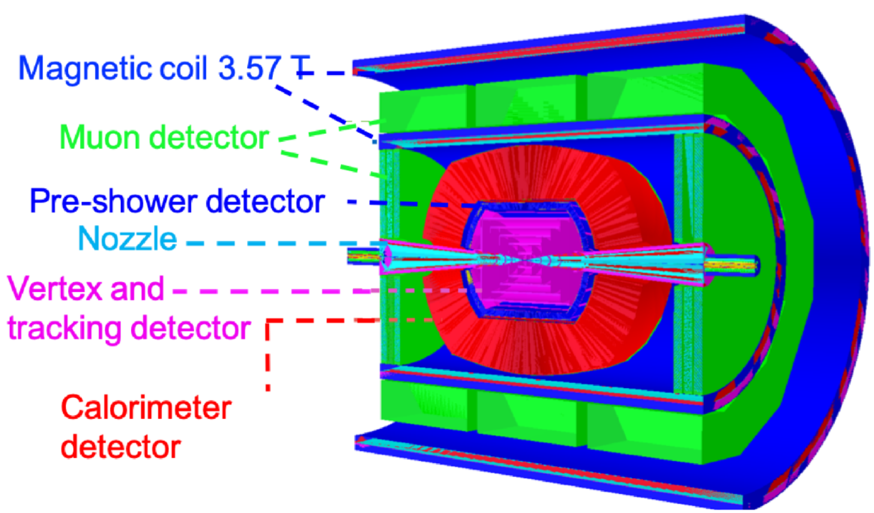


Paola Sala – Youri Robert CERN Muon Collider Meeting
https://indico.cern.ch/event/886491/

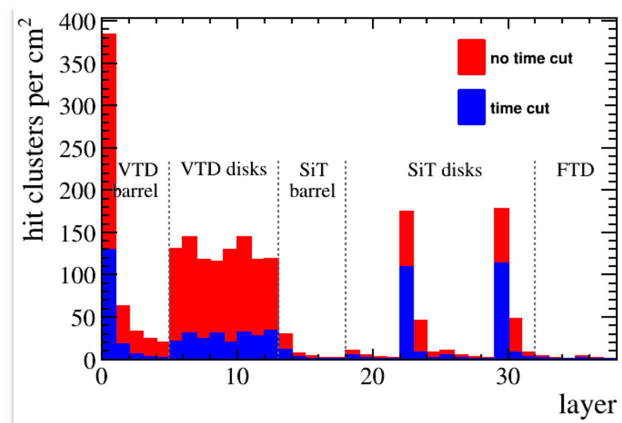
Highly collimated neutrino beam: background but also opportunity for neutrino's studies at Bari
Dose comes from energy released by neutrino interaction products. Collider is underground: problem is when beam reaches surface.

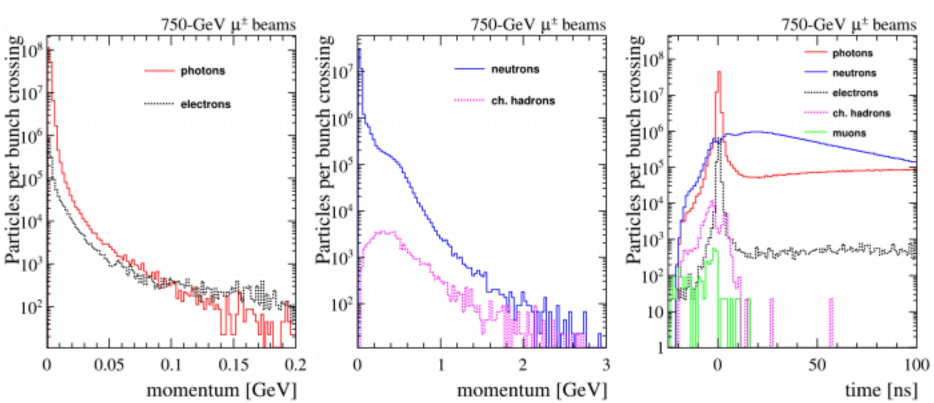
Detector Response Simulation at =1.5 TeV

Use the simulation/reconstruction tools previously developed within the MAP collaboration based on the ILCroot package: it supports signal + MARS15 background merging



Effects of beam-induce background can be mitigated by exploiting "5D" detectors, i.e. including timing





For the moment the studies done with an existing geometry (MAP) but the final detector needs to be assess.

Attivita' in corso sul disegno esperimento

The work done so far used the MAP framework. Now moved to a Future Collider Framework, ILCSoftware. Set up a GRID VO, muoncoll.infn.it everybody can register

Issue to reconstruct background + signal due to high occupancy in the inner tracking. (also CPU consuming)

.

- Ongoing activities:
  - implementation of a more realistic simulation of the tracker readout that includes:
    - a segmentation of the Si sensors into pixels;
    - digitization of the pixel signals;
    - pixel clusterization and hit reconstruction.
  - rejection of tracker spurious hits exploiting double layer correlations;
  - tuning of pattern recognition and track finding to cope with the beam-induced background;
  - inclusion of muon detectors in event reconstruction.

Opportunity for Bari contributions

- Evaluate the impact of the background on the different detectors (hit occupancy, rates) and impact on the reconstructions
  → improve by hardware (better detectors)
  → improve by software: better algorithms, contribution to KEY4HEP, integration of software for heterogeneous resource and usage of Bari farm)

Key4HEP

- Future detector studies critically rely on well-maintained software to model detector concepts and to understand a detector's potential and physics reach
- Aim at a low-maintenance common stack for FCC, ILC/CLIC, CEPC, SCT/STC, Muon Collider, . . . with ready to use plug-ins to develop detector concepts
- Reached consensus among all communities for future colliders to develop a common turnkey software stack at recent **Future Collider Software Workshop**
- Identified as an important project in the **CERN EP R&D initiative**, submitted EoI for AIDA++ → AIDAInnova WP12

Task 12.2. Turnkey Software

- Integrated Turnkey Software Stack, for physics and performance studies
- Simplified data model toolkit for modern hardware platforms
- Digitisation extensions for geometry toolkit
- R&D study on frameworks to manage heterogeneous resources

Rif. Lucia Silvestris a Bari.

Test beam @ CERN

- Positrons (45 GeV) on target (e- at rest), aiming at e+e- → mu+ mu-
- **Study of the emittance at the test beam:**

Intrinsic emittance due to muon kinematics and interaction with the target is tiny
How much does it depend on the properties of the e+ beam, kinematics, target features?

CERN-SPSC-2020-004 / SPSC-P-364
07/03/2020

LEMMA-TB: an experiment to measure the production of a low emittance muon beam

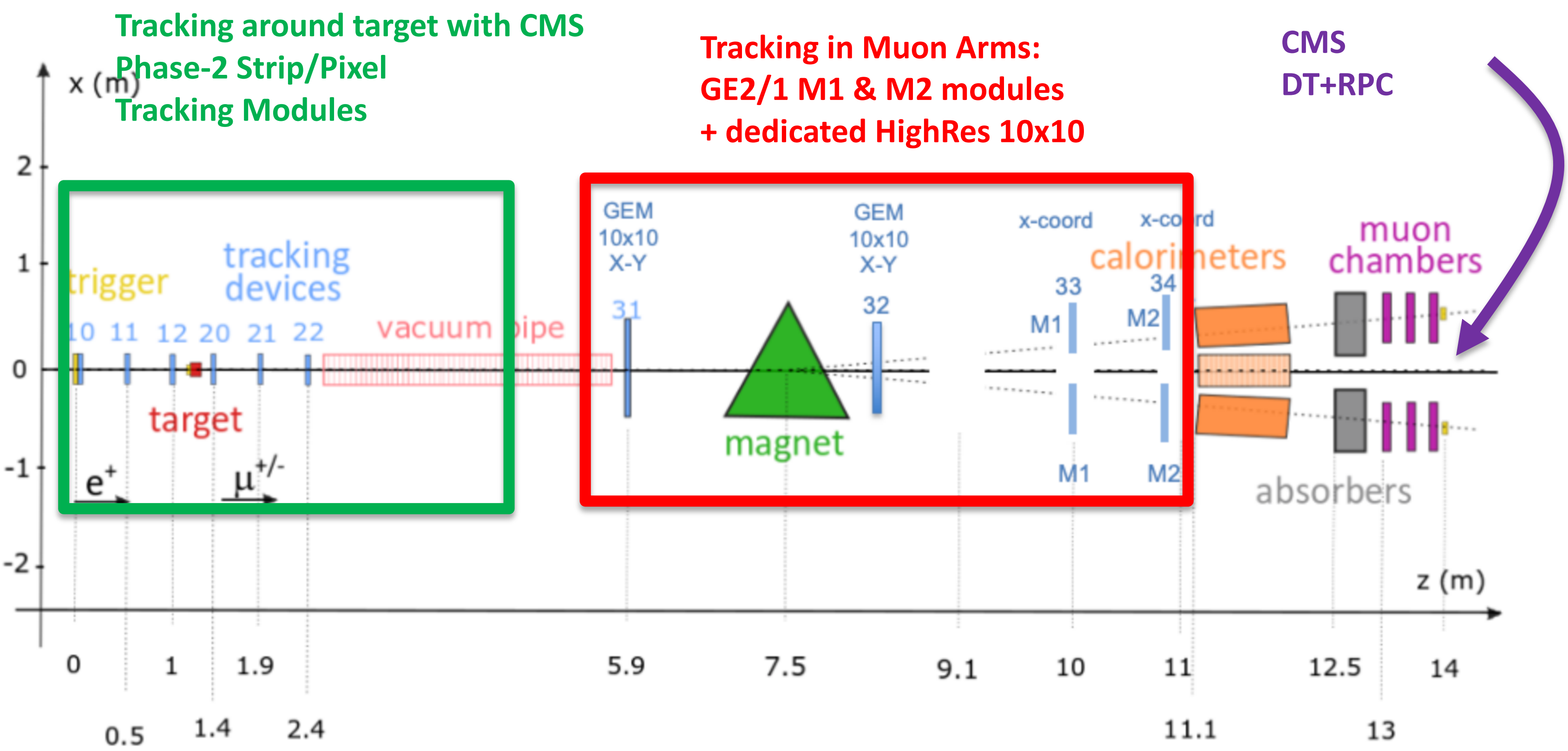
N. Amapane[a,b], M. Antonelli[c], F. Anulli[d], N. Bacchetta[h], N. Bartosik[b], M. Bauce[d], A. Bertolin[h], M. Bianco[m], C. Biino[b], O. R. Blanco-Garcia[c], M. Boscolo[c], A. Braghieri[q], A. Cappati[a,b], F. Casaburo[l,d], M. Casarsa[i], G. Cavoto[l,d], N. Charitonidis[*m], A. Colaleo[p], F. Collamati[d], G. Cotto[a,b], D.Creanza[p], C. Curatolo[h], N. Deelen[t], F. Gonella[h], S. Hoh[n,h], M. Iafrati[c], F. Iacoangeli[d], B. Kiani[b], D. Lucchesi[n,h], V. Mascagna[e,f], S. Mersi[m], A. Paccagnella[n,h], N. Pastrone[b], J. Pazzini[n,h], M. Pelliccioni[b], B. Ponzio[c], M. Prest[e,f], C. Riccardi[q,r], M. Ricci[c], R. Rossin[n,h], M. Rotondo[c], P. Salvini[q], O. Sans Planell[a,b], L. Sestini[h], L. Silvestris[p], A. Triossi[o], I. Vai[q,s], E. Vallazza[f], R.Venditti[p], S. Ventura[h], P. Verwilligen[p], P. Vitulo[q,r], and M. Zanetti.[n,h]

proposal for test beam In 2022 submitted to SPSC

Key to get >2 weeks of continuous operations at NA

2022 layout

- Fast and high-resolution pixel-based telescopes (CMS modules) in the target region
- Fast GEM detectors from CMS beyond the magnet
- Combination of several Calorimeters (included CMS ECAL)
- 4+2 CMS Muon DT chambers (triggerless readout) + CMS iRPC and new electronics
- Improved (integrated, low dead time) CMS DAQ system and trigger system



Summary of possible interest in Bari

Considerando le nostre competenze e sinergie con le attivita' in corso, possibili ambiti di interesse :

- Physics studies:
  - Utilizzando il framework esistente
- Detector optimization
  - Studio del fondo e interazione con detector: ottimizzazione detector
    - ➔ Sinergia con AIDAINNOVA WP7 per rivelatori di muoni
- Software and computing development for future collider
    - ➔ Sinergia con LHC experiment (CMS/ALICE/LHCb new tracking algo/GPU)
    - ➔ Sinergia con AIDAINNOVA WP12.2 (R&D software framework)
    - ➔ Sinergia con IBISCO (GPU/CPU and storage)
- Test beam:
    - ➔ Sinergia CMS Phase2 (pixel, GEM, DT , RPC, ECAL e DAQ/Trigger)
- Neutrino background and physics
  - Expertise a Bari su fisica neutrino

RD_MUCOL anagrafica

Attualmente

C.Aruta	10%
G. Catanesi	10% (tbc)
A. Colaleo	20%
M. Maggi	10%
S. My	10%
F. Simone	10%
L. Silvestris	10%
R. Venditti	10%
P. Verwilligen	10%
Totale	110 %

Sigla su dot1z.

Le percentuali non sono sinergiche con altre sigle al momento. Ma e' prevista sinergia con AIDAINNOVA (approvazione sigla inizio 2021).

Ovviamente siete invitati a contribuire al progetto:

→ ma non e' indispensabile avere delle percentuali.

BACKUP

Physics at high energy

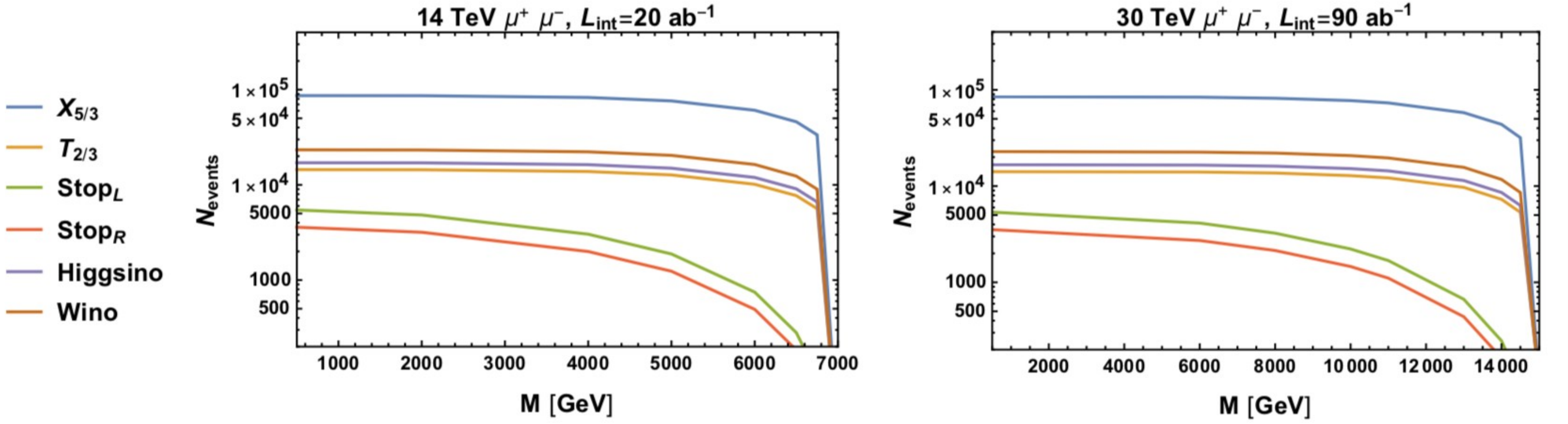
Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly

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

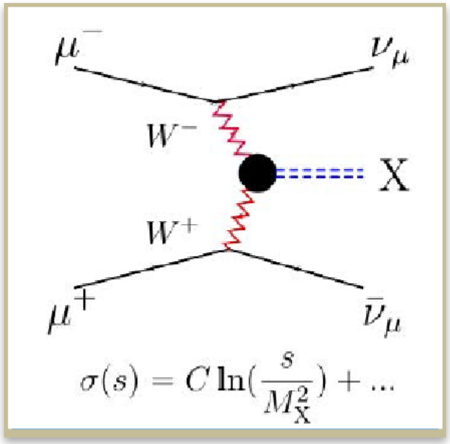


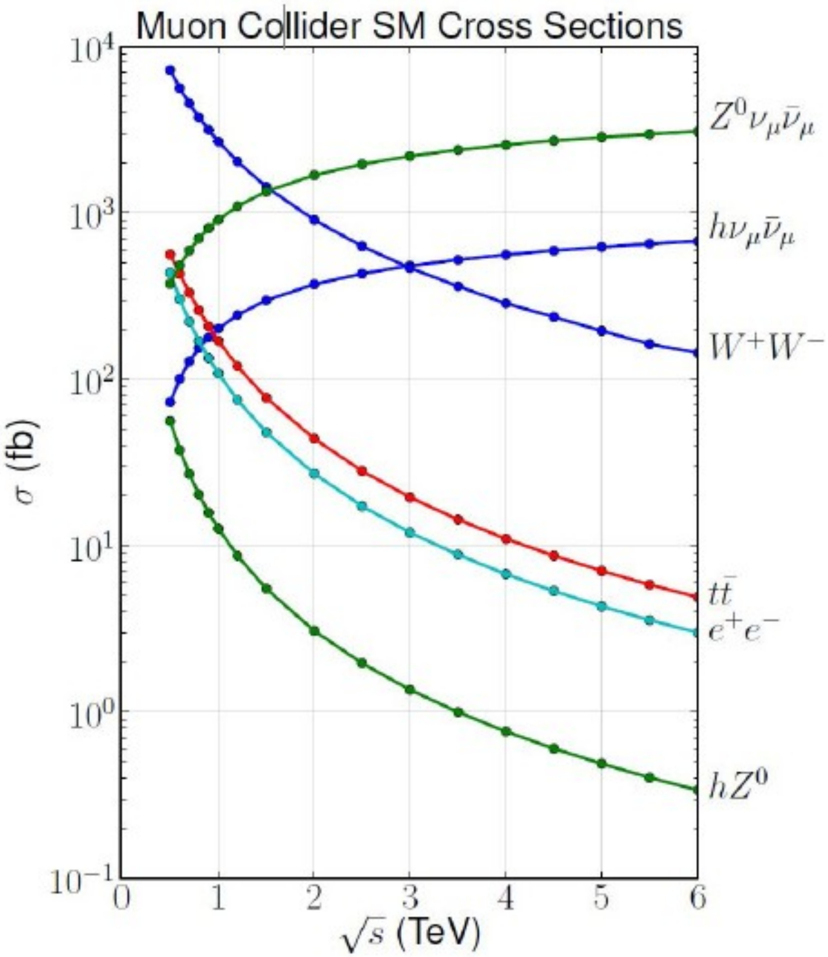
High energy Muon Collider

High Energy Collisions

- At √s > 1 TeV:

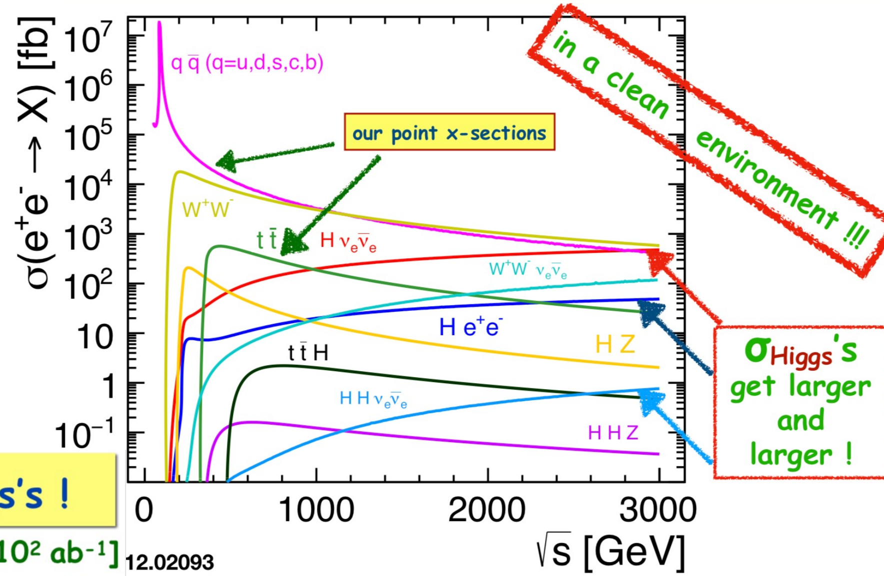
  Fusion processes dominate
  - An Electroweak Boson Collider
  - A discovery machine complementary to very high energy pp collider
- At >5TeV: Higgs self-coupling resolution <10%





Higgs production at Lepton Collider

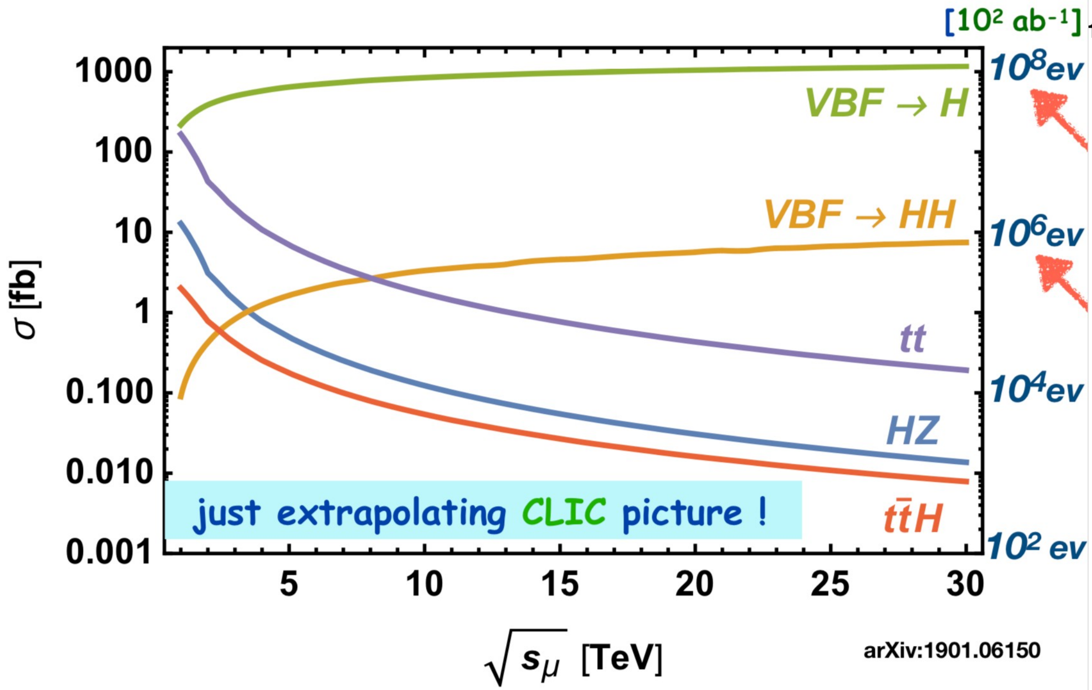
point x-sections dominant at CLIC !



Circular muon colliders

might reach center-of-mass energies of tens of TeV thanks to the limited amount of synchrotron radiation compared to $e^{<}e^{2}$ colliders

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



B. Mele et al.

Computing issues

- Il Muon Collider presenta un **beam-induced background** di notevole entità, generato dal decadimento in volo dei muoni e dalle interazioni dei prodotti di decadimento con la macchina.

- Data la sua unicità le strategie di mitigazione devono essere studiate tramite **full simulation:**
  - → Sviluppo del detector
  - → Disegno della Machine Detector Interface
  - → Benchmark di Fisica

- Le simulazioni sono pesanti sia in termini di storage che di CPU time: necessità di adottare un **sistema di calcolo distribuito sulla GRID**.

- Accesso a file di simulazione comuni, sia per INFN che per collaboratori esterni (es. USA)

- VO è già stata aperta, SE in preparazione al CNAF. Il framework di CLIC dispone già di un suo sistema di sottomissione dei job sulla GRID.

Opportunity for contributions from Bari

Computing in 2021: richieste CPU

- Benchmark: CPU Intel Xeon ES-2670 → 200 HS06 per 10 Multi-Thread
- **Simulazione:** 1 evento di BIB richiede 10 processi in parallelo per 7 giorni
- **Ricostruzione:** 3 giorni per processare 10 eventi di segnale+BIB
- **Goal:**
  10k eventi di BIB simulati (per essere usati a rotazione nella ricostruzione)
  100k eventi di segnale + BIB ricostruiti (2-3 canali di Fisica)
- **10k eventi * 200 HS06 * 7/365 = 38k HS06 per la simulazione**
- **100k eventi * 200 HS06 * 0.3/365 = 16k HS06 per la ricostruzione**
- **Si richiedono in totale 54k HS06**
- **Una frazione consistente delle risorse calcolo puo' essere su GPU o su CPU dei siti IBISCO/RECAS**

Computing in 2021: richieste storage

- **Simulazione:** 1 evento simulato di BIB occupa ~10 GB

- **Ricostruzione:** 1 evento ricostruito di segnale+BIB occupa ~5 GB

- **10k eventi * 10 GB = 100 TB per i campioni simulati di BIB**
- **100k eventi * 5 GB = 500 TB per i campioni di segnale+BIB ricostruiti**

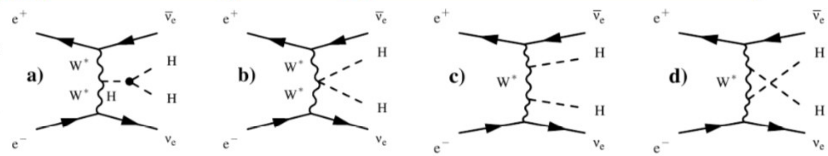
- **Si richiedono in totale 600 TB di storage**

- Contributi aggiuntivi**:**
  - 5k euro per Cloud-Veneto (INFN-Padova)
  - 5k euro per acquisto macchina a INFN-Trieste

Trilinear and Quadrilinear couplings

trilinear Higgs coupling at MC

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



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	10476.8 ϵ_b	$\frac{0.023919}{\sqrt{\epsilon_b}}$
After θ>5°	1.79402	5386.76 ϵ_b	$\frac{0.0333575}{\sqrt{\epsilon_b}}$
PT>30 GeV on top	1.81422	3346.09 ϵ_b	$\frac{0.0313633}{\sqrt{\epsilon_b}}$
PT>50 GeV on top	2.42269	1291.06 ϵ_b	$\frac{0.0674256}{\sqrt{\epsilon_b}}$
PT>80 GeV on top	1.35534	328.448 ϵ_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	216726. ϵ_b	$\frac{0.00833272}{\sqrt{\epsilon_b}}$
After θ>5°	2.03452	64812. ϵ_b	$\frac{0.0152375}{\sqrt{\epsilon_b}}$
PT>30 GeV on top	2.08392	41492.2 ϵ_b	$\frac{0.0102305}{\sqrt{\epsilon_b}}$
PT>50 GeV on top	1.88029	17637.2 ϵ_b	$\frac{0.0141583}{\sqrt{\epsilon_b}}$
PT>80 GeV on top	1.24629	5513.52 ϵ_b	$\frac{0.0167844}{\sqrt{\epsilon_b}}$

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

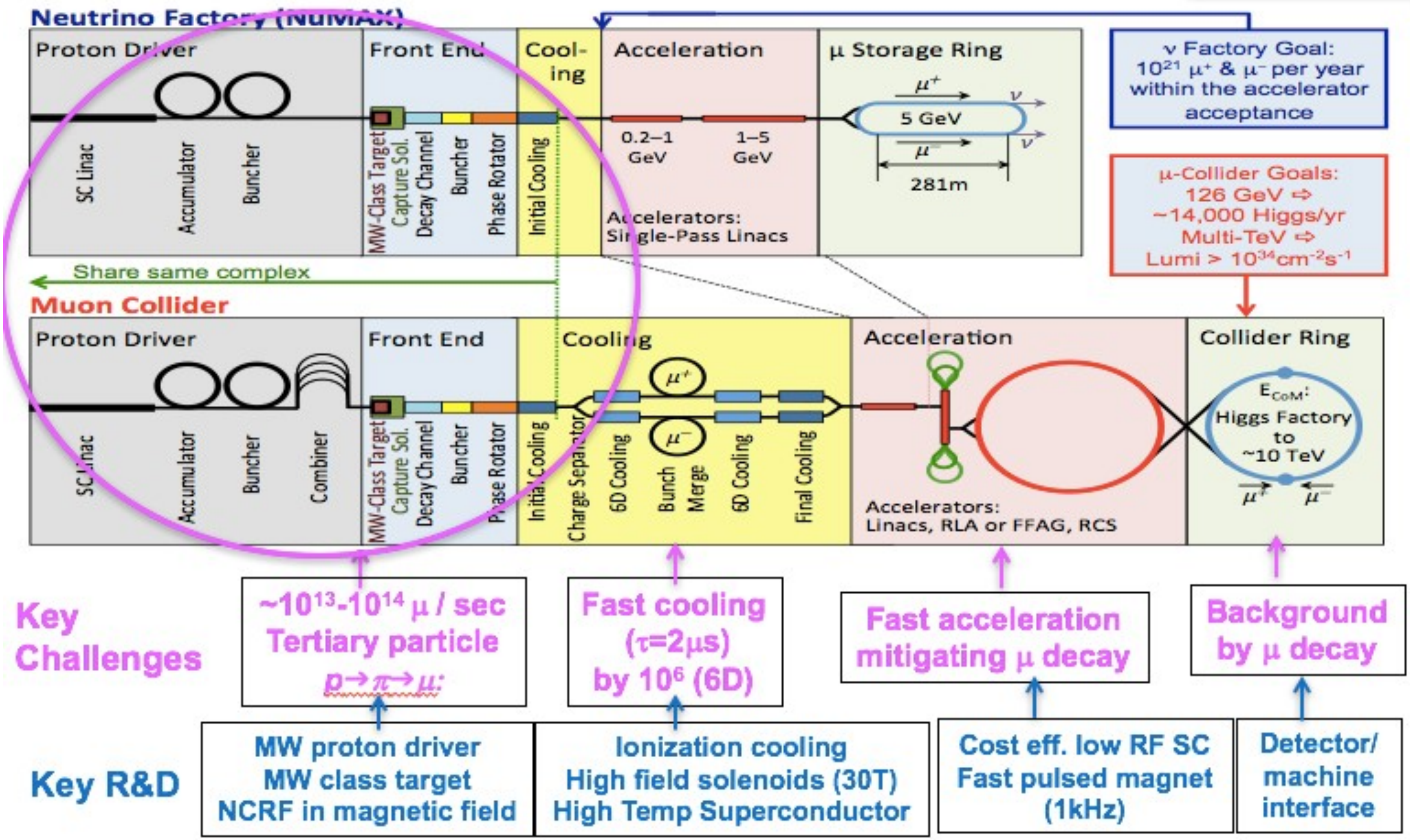
If **reasonable detector performances.** First detector benchmark.

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

Wulzer

Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



Main design requirements

- **Positron Source** like CLIC/ILC ➔ ***1 x 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 x 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

Tentative Considerations on Baseline

- **Focus on first stage with energy of O(1.5 + 1.5 = 3 TeV)**
  - To come after higgs factory and matching highest CLIC energy
  - Using the high-energy strength of muon colliders
  - Realistic design for implementation at CERN, with cost power and risk scale
  - If successful, feasibility demonstration for CDR

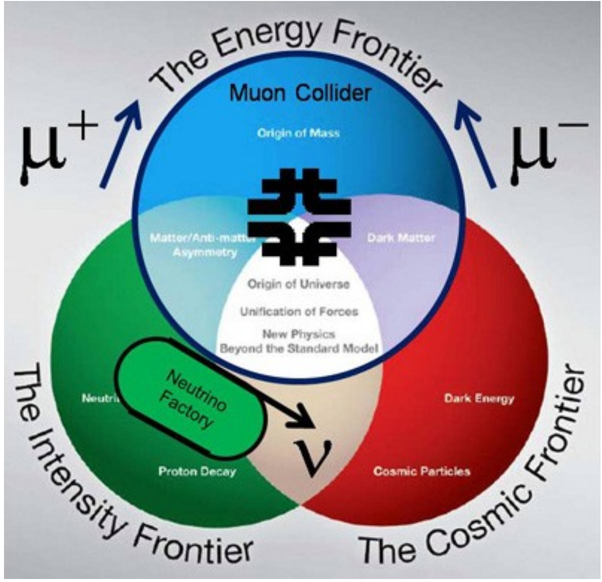
- **Explore 14 TeV as further step**
  - To match FCC-hh discovery potential
  - Mainly exploration of parameters to guide choices
  - Provide evidence for feasibility, maybe cost frame

- **Some exploration of lower energies / Higgs factory**
  - Scaling from higher energies
  - Not a main focus, except if other projects do not cover lower energies

- Open for input

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

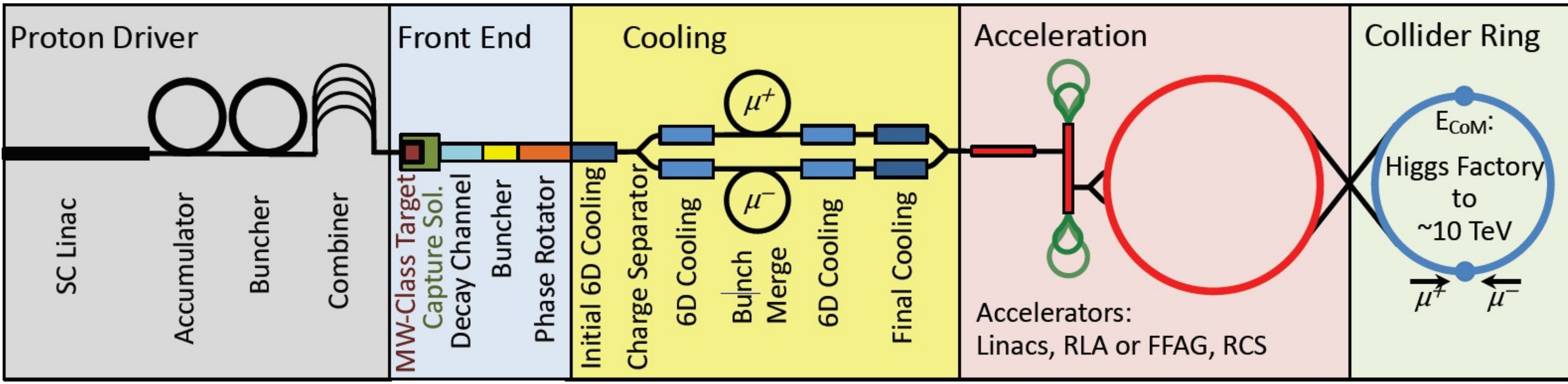
Fields of interest

- **Physics Motivation.** Physics potential of the collider, physics benchmark points, requirements for energy and luminosity.
- **Experiment and Physics Simulation.** Performance of collider and detector, event reconstruction, simulation tools, performance benchmark points, detector performance goals.
- **Detector Design and R&D.** Detector development, prototypes, detector performance goals, . . .
- **Machine Detector Interface.** Background, . . .
- **High-energy Collider Design.** Experimental insertion, collider ring, accelerator ring, linacs, . . .
- **Proton-based Muon Source.** Proton complex, muon production, muon cooling, bunch merging
- **Positron-based Muon Source.** Positron production, positron acceleration, muon target, muon accumulation
- **Magnets.** High-field superconducting magnets, final focus quadrupoles, collider ring dipoles/combined function magnets, cooling solenoids, fast ramping magnet systems in accelerator, . . .
- **Radio Frequency Technology.** Superconducting RF for high energy acceleration and and normal-conducting high-gradient RF for the cooling, proton and positron RF, . . .
- **Radiation, Shielding, Losses, Targets, Collimation, Materials.** Detector/magnet shielding, high-power production target, neutrino radiation, beam losses, background, . . .
- **Other Technologies.** Including efficient cooling, good vacuum, robust instrumentation, . . .
- **Civil engineering and Infrastructure.**
- **Synergies.** Includes application of muon collider technology for other purposes, such as a neutrino factory.

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

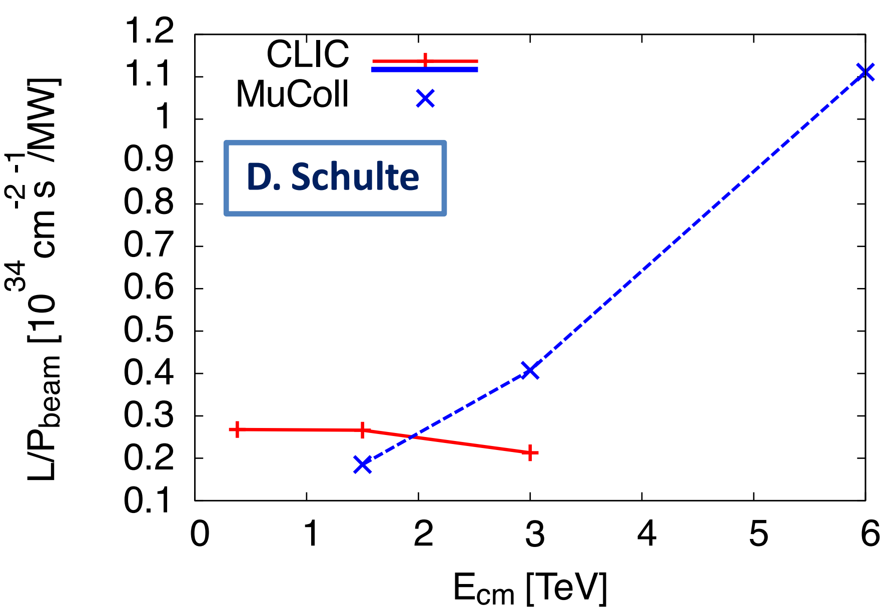
Design is not complete but did not find anything that does not work

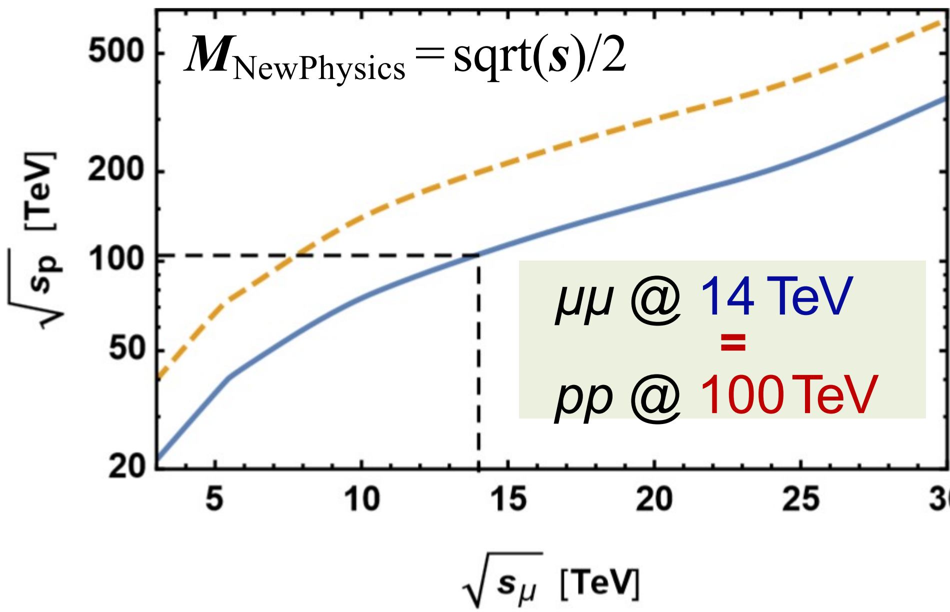
No CDR exists No coherent baseline No reliable cost estimate

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

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

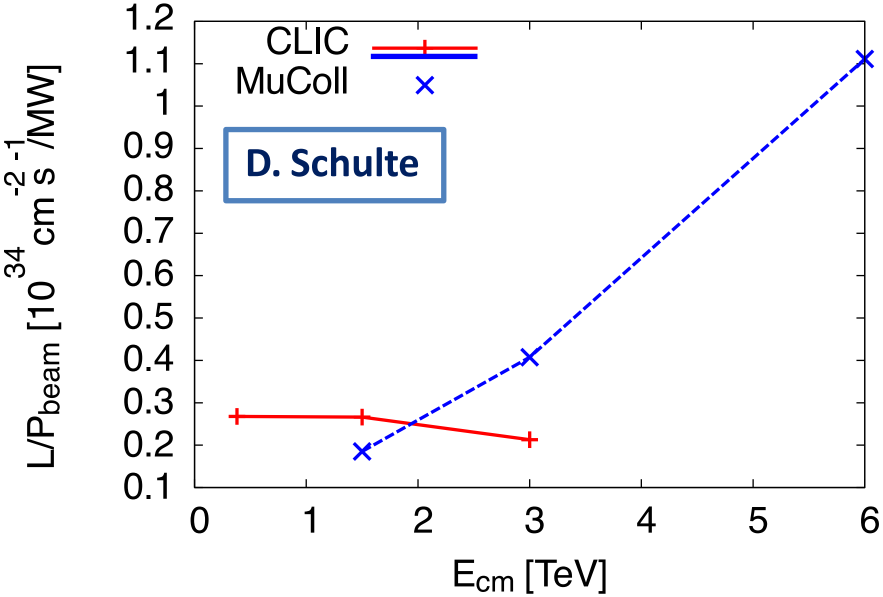
Full collision energy available for particle production: 14 TeV lepton collisions are comparable to 100 TeV proton collisions for selected new physics process, **if sufficient luminosity is provided ~ $10^{35} cm^{-2} s^{-1}$**

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

INFN @ WP

WP			Indus	INFN
7	gas detector MPGD, RPC,TPC	ATLAS – CMS – LHCb – EIC – Higgsfact - neutrino	CAEN ELTOS	BA, BO, LE, LNF, PV, RM3, TS
11	microlectronics: ASIC design	all		BA, BO, PV, TO, MI, CA, FE, LNF
12	software/reco for future accelerators	all		FE, PD, PI, BA, RM3, BO,PV

Factor of merit



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

➔ **proton driver option: advanced studies for a 3-6 TeV machine**

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

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

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

Recent LEMMA effort

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

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

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

Extremely promising:

- muons produced with low emittance ➔ "no/low cooling" needed

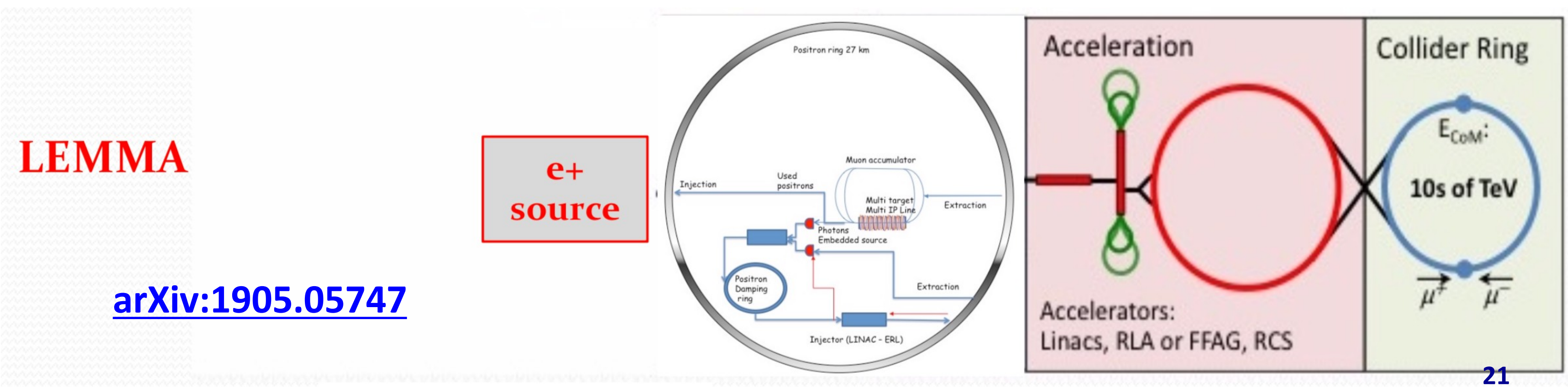
But difficult:

✓ **low** production **cross section**: maximum $\sigma(e^+e^- \to \mu^+\mu^-) \sim 1\,\mu\text{b}$

✓ **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

Use of Existing Infrastructure

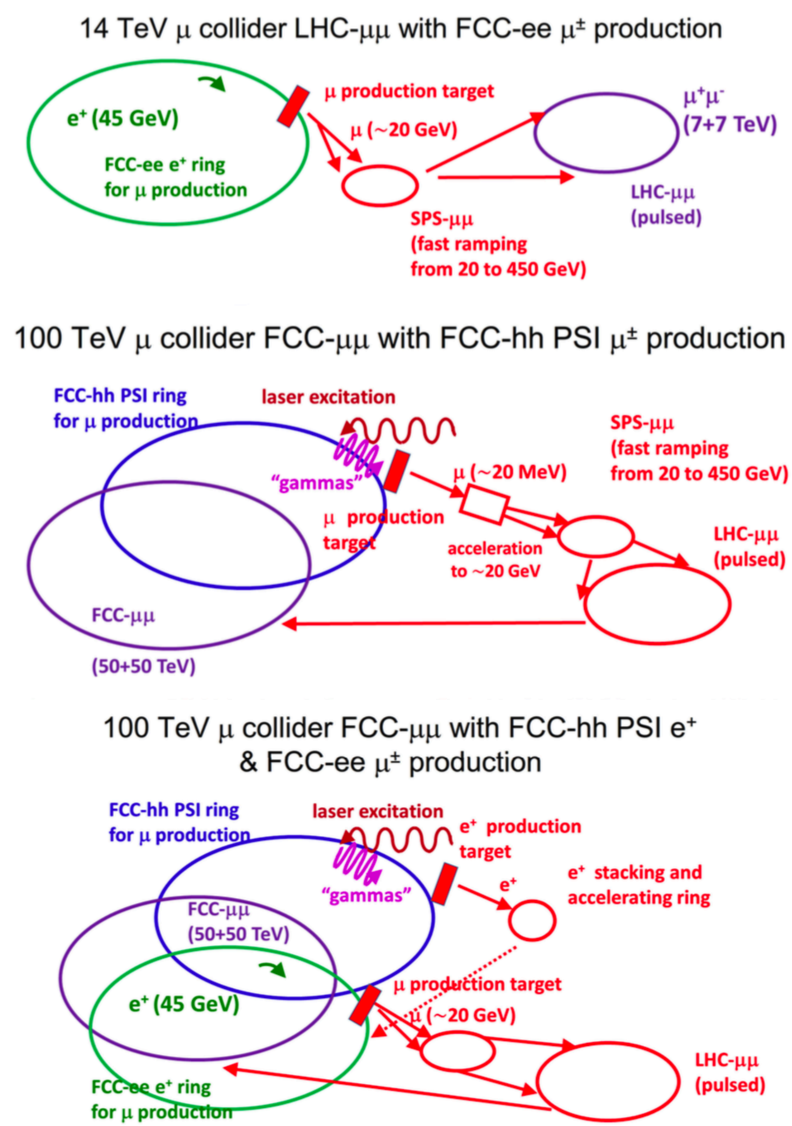
Might be able to reuse much of the proton and general infrastructure

- Needs detailed study
- Much of the expertise is available

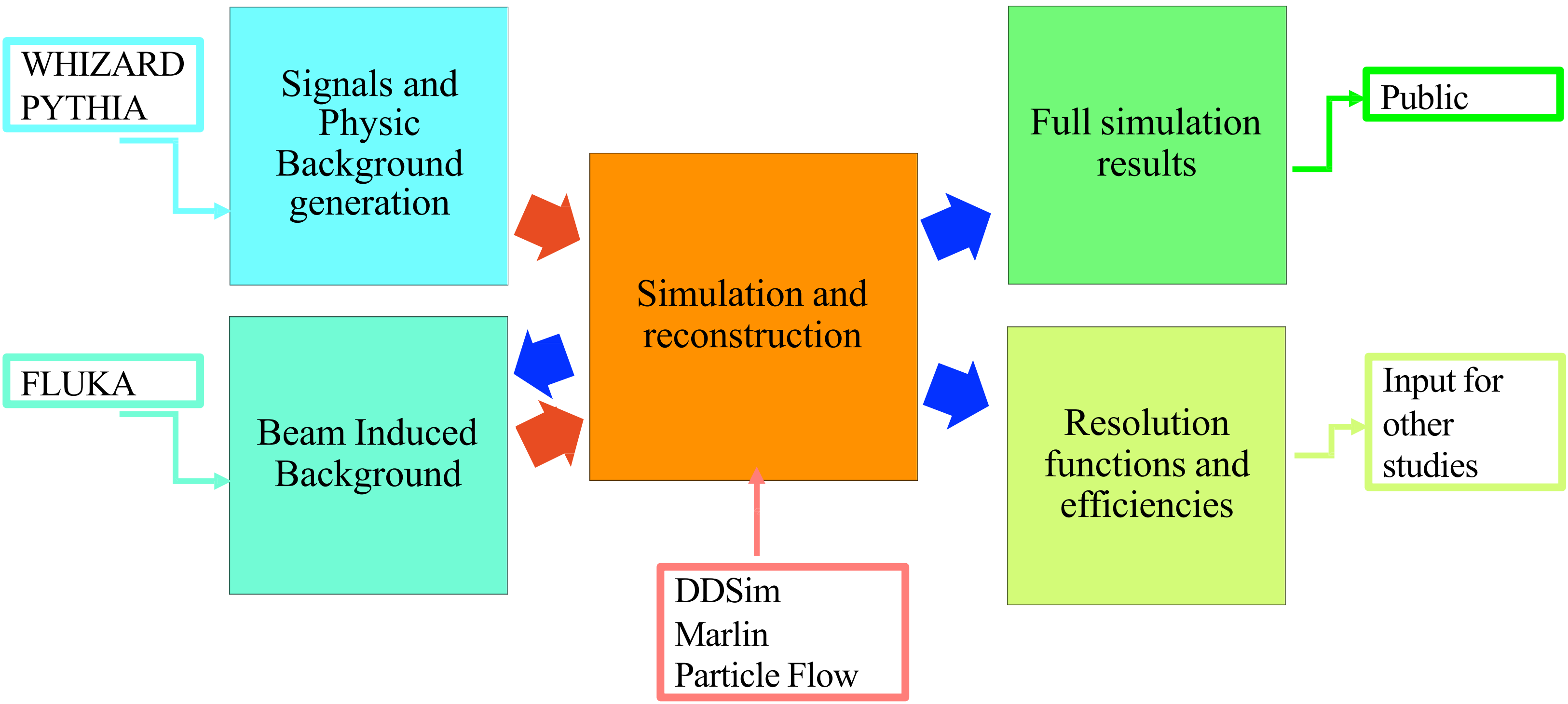
Use of the largest tunnels, i.e. LHC or potentially FCC

- Can house positron ring in the LEMMA case
    - In FCC, even lepton equipment might exist from FCC-ee
    - Large rings means less synchrotron radiatior and power consumption
- Consider to use ring as a collider
    - But means to have larger ring for acceleratic
    - Or to use combined final accelerator / collid
        - This compromises luminosity and generates technical challenges but may save cost

- **Use tunnel for final accelerator**
    - Have a small optimised collider ring
    - Seems natural solution



Simulation Framework



The work done so far used the MAP framework
Now moved to a Future Collider Framework, ILCSoftware.
https://sites.google.com/site/muoncollider/home
Set up a GRID VO, muoncoll.infn.it everybody can register
Preparing the environment to be able to submit to the GRID/cloud
Right now we have a cloud VM that can be installed anywhere
Some resources, machines and disk space is available on CloudVeneto
Code on github

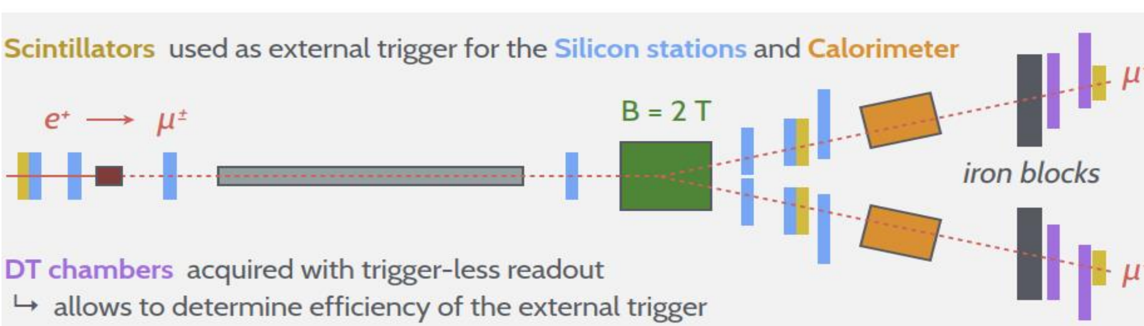
Attivita’ INFN – LEMMA Test Beam

- misure test beam al CERN su fascio di muoni (*J. Inst.* **15** P01036, 2020
- proposta nuova presa dati – fascio al CERN 2022 (2023 ?)

two beam tests in the CERN NA in the past (2017 and 2018) - → Bari not involved

both done with essentially ~0 budget, reusing equipment from other experiments

One week only at the time



JINST
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Revised: November 27, 2019
Accepted: January 8, 2020
Published: January 29, 2020

Study of muon pair production from positron annihilation at threshold energy

N. Amapane,[a,b] M. Antonelli,[c] F. Anulli,[d] G. Ballerini,[e,f] L. Bandiera,[g] N. Bartosik,[b] M. Bauce,[d] A. Bertolin,[h,1] C. Biino,[b] O.R. Blanco-Garcia,[c] M. Boscolo,[c] C. Brizzolari,[e,f] A. Cappati,[a,b] M. Casarsa,[i] G. Cavoto,[j,d] F. Collamati,[d] G. Cotto,[a,b] C. Curatolo,[h] R. Di Nardo,[k] F. Gonella,[h] S. Hoh,[l,h] M. Iafrati,[c] F. Iacoangeli,[d] B. Kiani,[b] D. Lucchesi,[l,h] V. Mascagna,[e,f] A. Paccagnella,[l,h] N. Pastrone,[b] J. Pazzini,[l,h] M. Pelliccioni,[b] B. Ponzio,[c] M. Prest,[e,f] M. Ricci,[c] R. Rossin,[l,h] M. Rotondo,[c] O. Sans Planell,[a,b] L. Sestini,[h] M. Soldani,[e,f] A. Triossi,[m] E. Vallazza,[f] S. Ventura[h] and M. Zanetti[l,h]

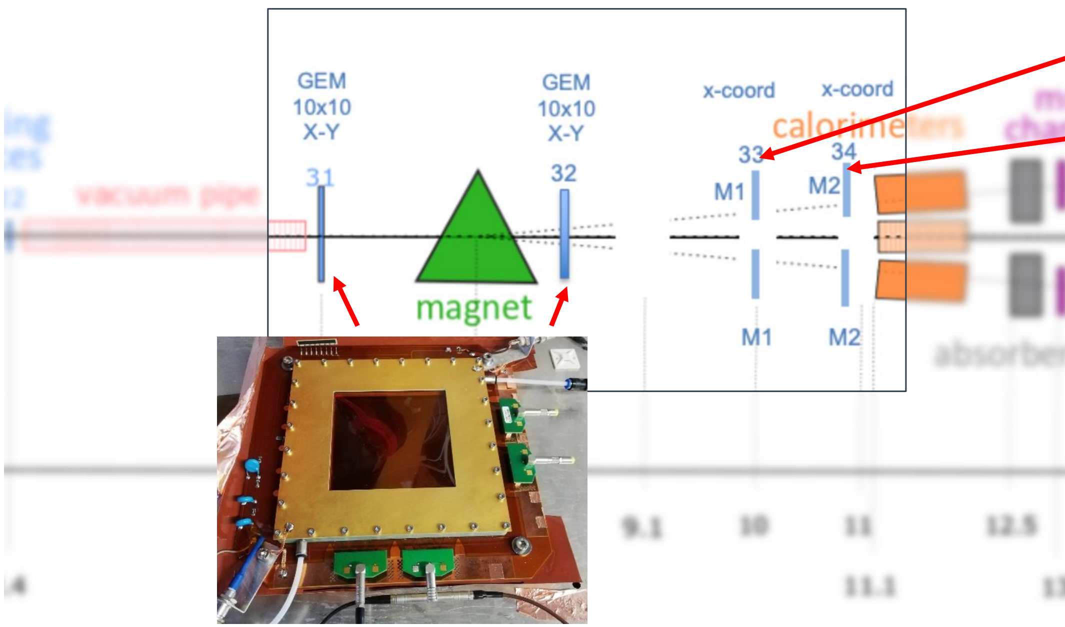
GEM

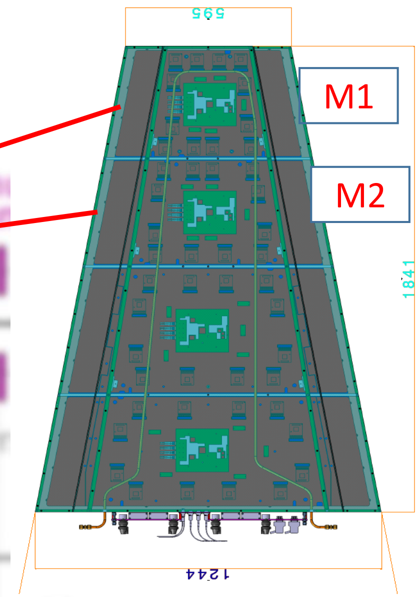
- *2 Dedicated hi-resolution 10x10 triple-GEM X-Y, 260 um pitch (75 um resolution)*
- *Standard CMS GE2/1 M1 and Me2 modules in muon arms*

  Trapezoidal, 360-600 um resolution

All (to be..) read-out by CMS phase2 DAQ

We plan to have a dedicated CMS TB before Lemma TB to assess the performance of the detectors and integrate the electronics.





A. Colaleo et al.

EU Strategy update

http://europeanstrategyupdate.web.cern.ch/

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

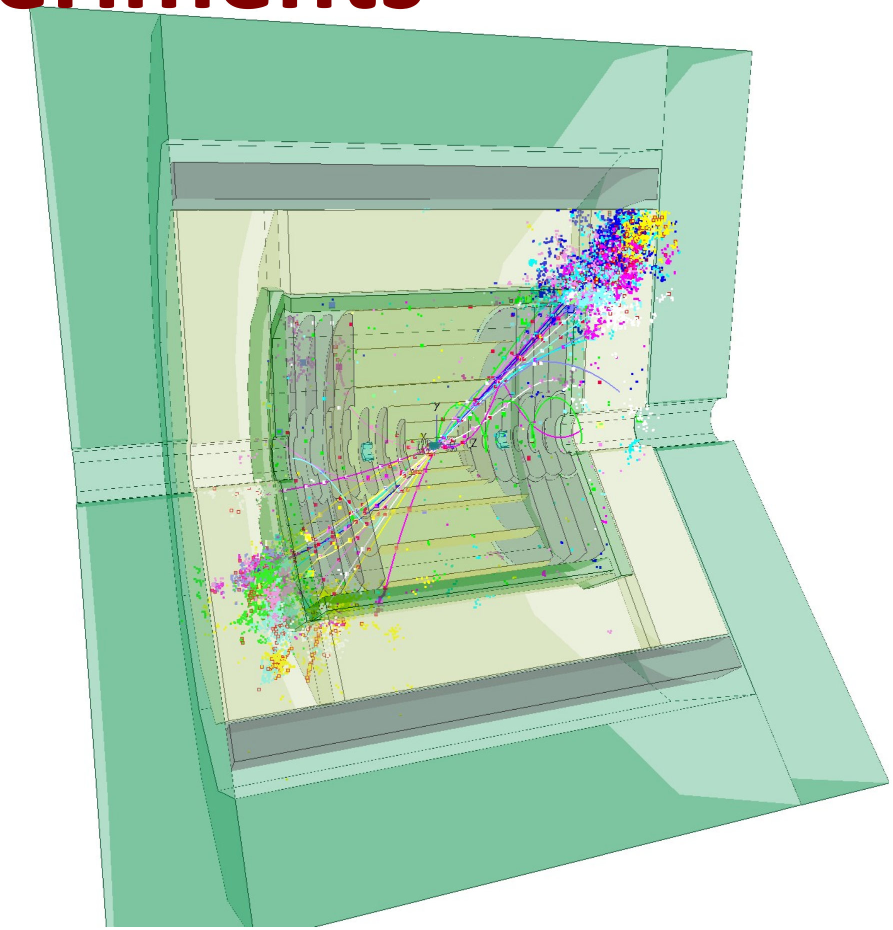
• ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

• ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

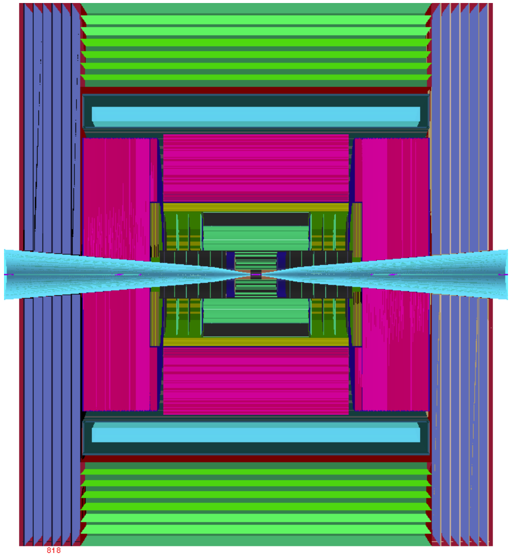
The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs.

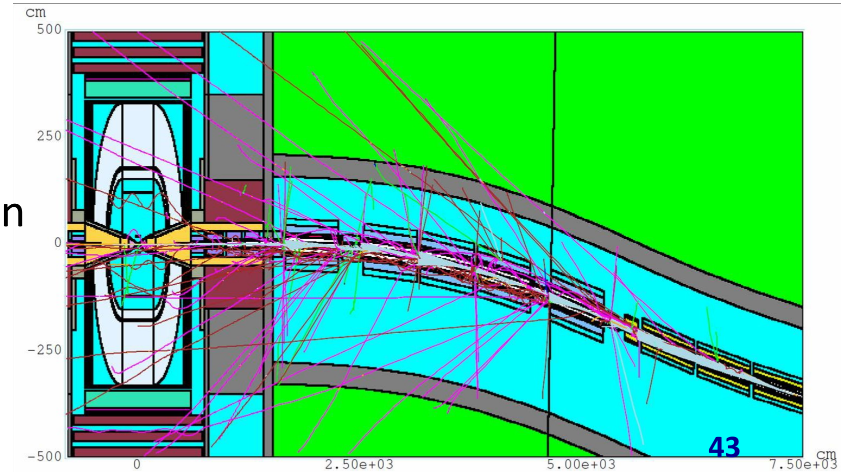
Key4HEP: Turnkey Software for Future Collider Experiments



Next steps



- ❑ **Move to use the Future Collider Framework**
  - Description of the detector already done including the nozzle
  - A new, up to the state of the art detector is needed
- ❑ **Simulate the beam-induced background with FLUKA**
  - MDI and IR descriptions provided by MAP collaboration for 1.5 and 3 TeV $\sqrt{s}$
  - Importing the description in FLUKA and generate new beam-induced background
- ❑ **Re-evaluate Physics performance @** $\sqrt{s}$=1.5 TeV as double check then study Physics performance @ $\sqrt{s}$=3 TeV with full simulation
- ❑ **Collaborate with MAP to have MDI and IR @** $\sqrt{s}$**=10 TeV to evaluate Physics performance**
- ❑ Determine physics objects efficiency and resolution for each configuration and parametrize them to estimate broad physics reaches smearing Monte Carlo generated process



Attivita' INFN – zona di interazione

Zona di interazione (Machine Detector Interface): da capire come/se contribuire

richiede disegno di macchina: parametri dell'ottica – esiste solo per MAP

disegno nozzle da integrare nell'esperimento

fondi di macchina prodotti con FLUKA utilizzando line-builder (postdoc PD)

Studi di radiazione in funzione del sito e del disegno di macchina

studi preliminari simulazione completa FLUKA (parzialmente pubblicati)

supporto definizione parametri macchina con esperti di acceleratori

valutazioni con FLUKA dell'ottica e in base a siti e disegni di macchina

Attivita’ INFN – LEMMA sorgente

LEMMA (sorgente di produzione dei fasci di muoni da positroni):

- **studio start-to-end completo ➔ articolo in fase di pubblicazione**
- studi per la sorgente di positroni in collaborazione con LAL – sinergia FCCee
- studi materiali bersagli di produzione positroni e muoni in collaborazione con SBAI-Roma ➔ articolo da pubblicare
  - simulazioni (postdoc)
  - test su fascio con camera a vuoto e termocamera (LNF e CERN +?)
- studi accumulatore (grant giovani CSN5 e dottorando):
  - FFAG (collaborazione UK)
  - 0ttica multibend-achromat (con ESRF)

PIANO DI LAVORO preCDR MACCHINA sottoposto alla GE da A. Variola (10/2019)

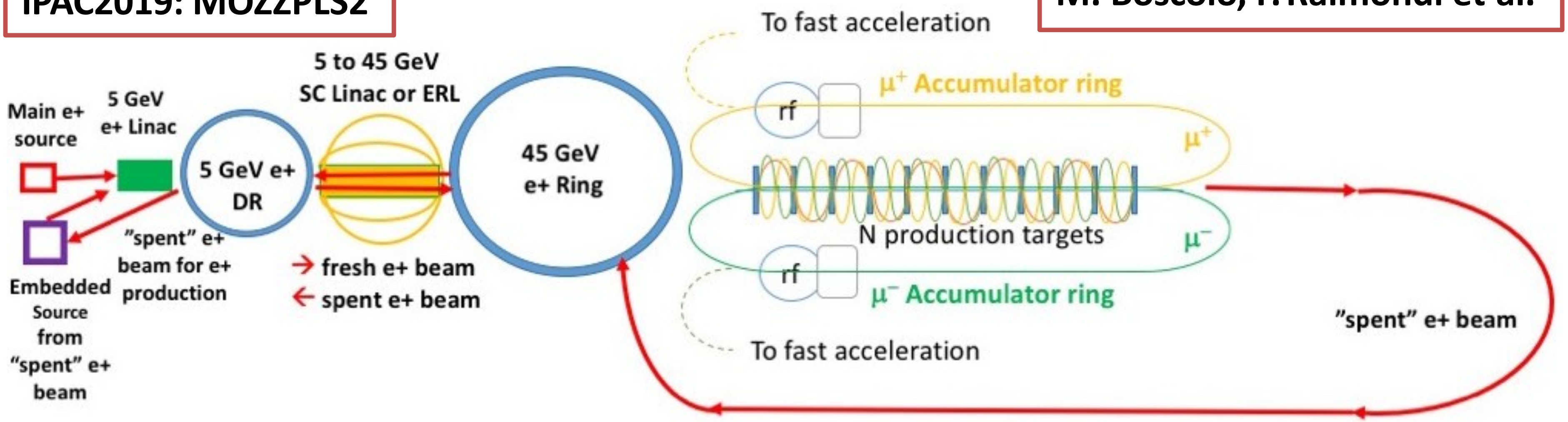
➔ **richiede intensa attività anche in ambito internazionale per valutarne fattibilità**

Positron driven muon source

recent developments (2019)

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

IPAC2019: MOZZPLS2



- **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
- Average muon energy 22 GeV ($\gamma(\mu) = 200\ \mu s$, $\tau(\mu)_{lab} = 500\ \mu s$)
- **Embedded e^+ source** to restore the design e^+ beam current using γ coming from μ production targets, or using the 45 GeV "spent" beam

Effort for Baseline Design

- **Put together coherent design requires (mainly human) resources**
  - This goes beyond US effort
  - Consistent parameters and layouts
  - Integration of collider systems, trade-offs, choices, …
  - May highlight additional important issues
  - Requires (mainly human) resources
  - Currently MAP is main option, LEMMA is alternative

- **Key R&D list with priorities**
  - Identify key / feasibility issues
    - i.e. largest technical risks
    - Key cost driver, if critical
    - Key power consumption, if critical
  - Entry point for collaborators

Proposed MUST
(MUon collider STudy network)
submitted I.FAST EU project

Objectives

Task 12.1. Coordination and Communication

See introductory section on page 29.

Task 12.2. Turnkey Software

- Integrated Turnkey Software Stack, for physics and performance studies
- Simplified data model toolkit for modern hardware platforms
- Digitisation extensions for geometry toolkit
- R&D study on frameworks to manage heterogeneous resources

Task 12.3. Simulation

- Fast simulation techniques integrated into Geant4
- Machine learning based calorimeter simulation toolkit for training and inference

Task 12.4. Track Reconstruction

- Develop complete track reconstruction chain with Acts composable algorithms
- Implement a portable version of Acts algorithms, for heterogeneous computing
- Machine learning reconstruction algorithm for MPGD detectors

Task 12.5. Particle Flow Reconstruction

- Advanced PFA algorithms for DUNE detectors using new readout technologies
- PFA algorithm with particle ID for dual-readout calorimeters
- Optimised APRIL PFA algorithm for hadronic jets

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

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

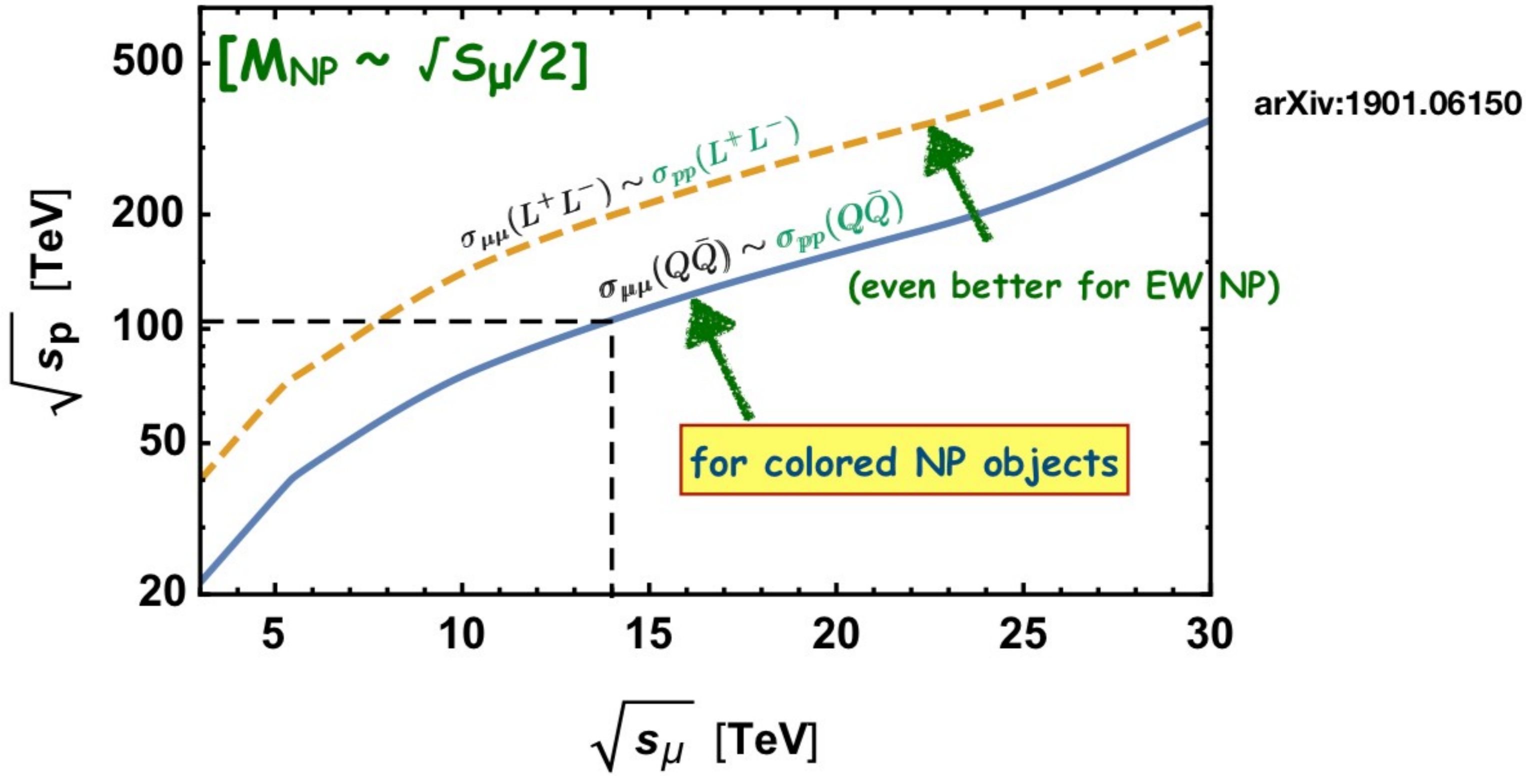
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

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

Proton vs Muon Colliders

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



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

yet unexplored pheno !!!