WG 8: Muon Collider

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,** launched in **2011,** was terminated 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

- **MICE (M**uon **I**onization **C**ooling **E**xperiment**) @ RAL**
- **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 under study by INFN-LNF et al. to overcome technical issues of initial concept* → **arXiv:1905.05747**

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

"Muon Colliders," **arXiv:1901.06150**

de facto it is the seed for a renewed international effort

Past experiences and new ideas discussed at the joint ARIES Workshop

July 2-3, 2018 **Università di Padova - Orto Botanico** https://indico.cern.ch/event/719240

Preparatory meeting to review progress for the ESPPU Simposium

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

NEW WORKSHOP @ CERN October 9-11, 2019

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

Recommendations

Set-up an international collaboration:

organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR

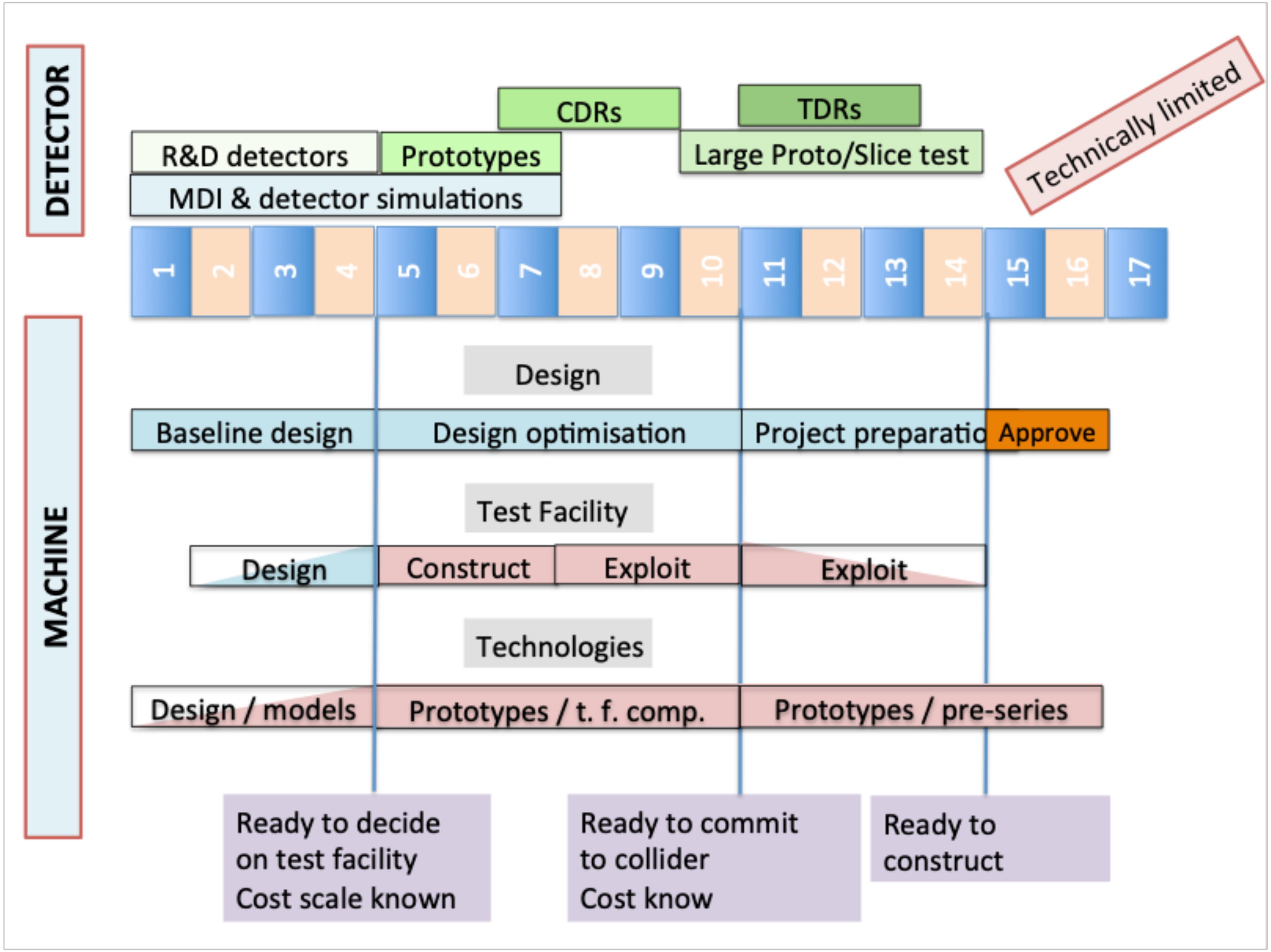
➔ resources needed are not negligible in terms of cost and manpower and this calls for a well-organized international effort.

Develop a muon collider concept based on the proton driver and considering the existing infrastructure

Consolidate the positron driver scheme

Carry out the R&D program toward the muon collider

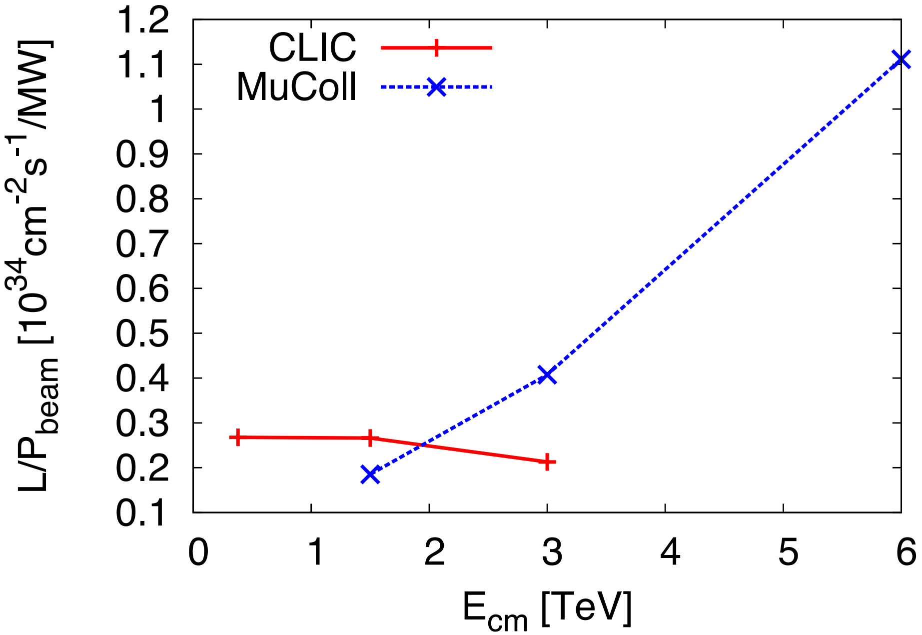
Proposed Tentative Timeline

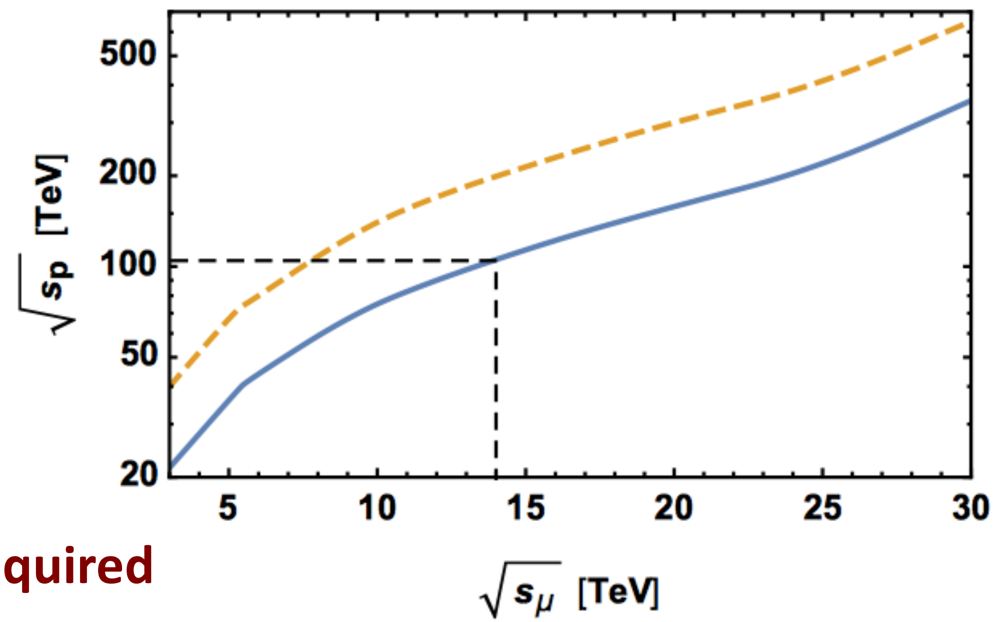


Why a multi-TeV Muon Collider?

cost-effective and unique opportunity

for lepton colliders @ Ecm > 3 TeV





sufficient luminosity required

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

Motivation: Higgs potential

$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Trilinear coupling, k_3

- $\sqrt{s} = 10\ TeV, \mathcal{L} \sim 10^{35} cm^{-2} s^{-1}$
- 10 ab^{-1}

k_3 sensitivity ~ 3%

Best sensitivity ~5% FCC combined (arXiv:1905.03764)

Quadrilinear coupling, k_4

- $\sqrt{s} = 14\ TeV, \mathcal{L} \sim 10^{35} cm^{-2} s^{-1}$
- 20 ab^{-1}

k_4 sensitivity few 10%

FCC-hh in a optimistic scenario 30 ab^{-1}

$\lambda_4 = \in [\sim -4, \sim +16]$@68% $C.L.$ (arXiv:1905.03764)

Estimates to be fully studied and demonstrated!

Physics at high energy

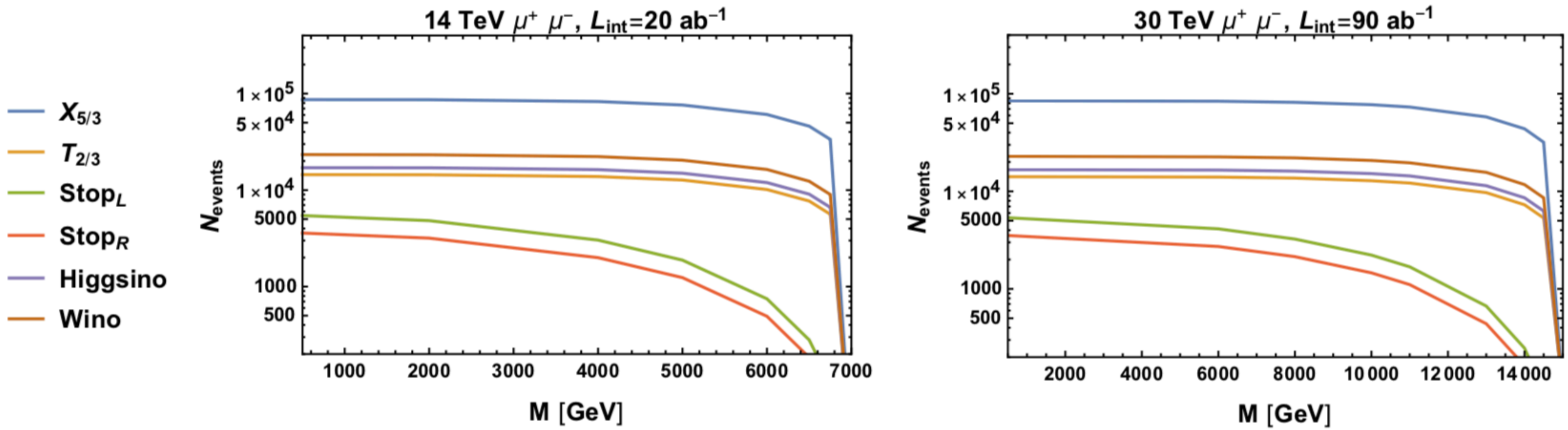
Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly

Direct Reach

Andrea Wulzer

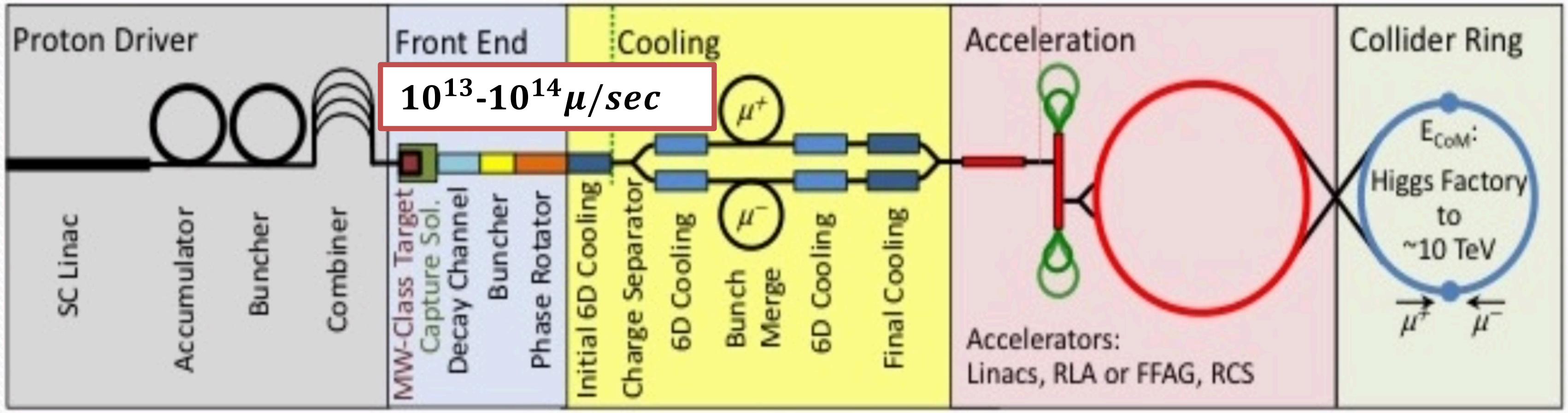
Discover **Generic EW** particles **up to mass threshold**

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

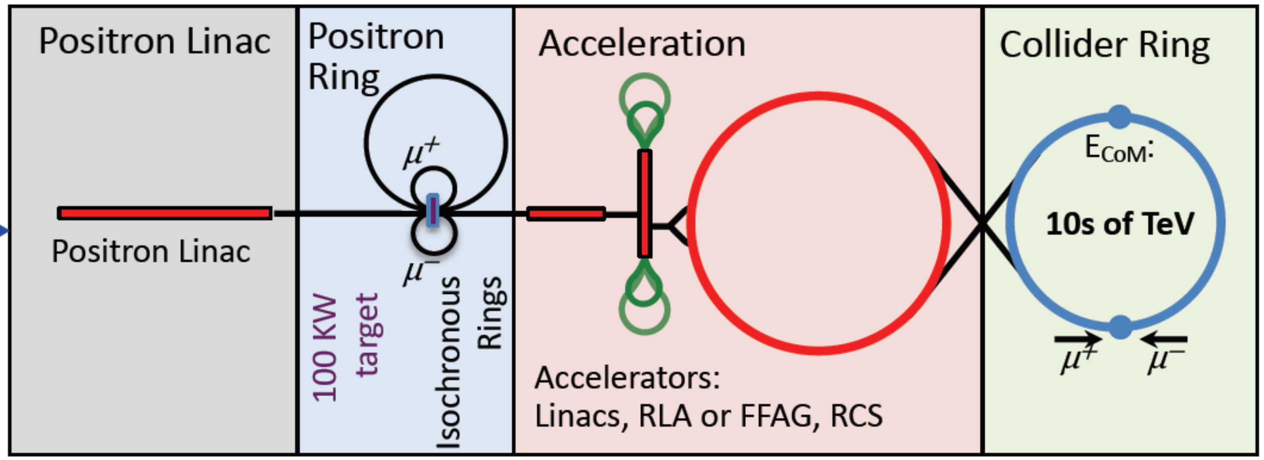


proton (MAP) vs positron (LEMMA) driven

MAP



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



LEMMA: extremely promising

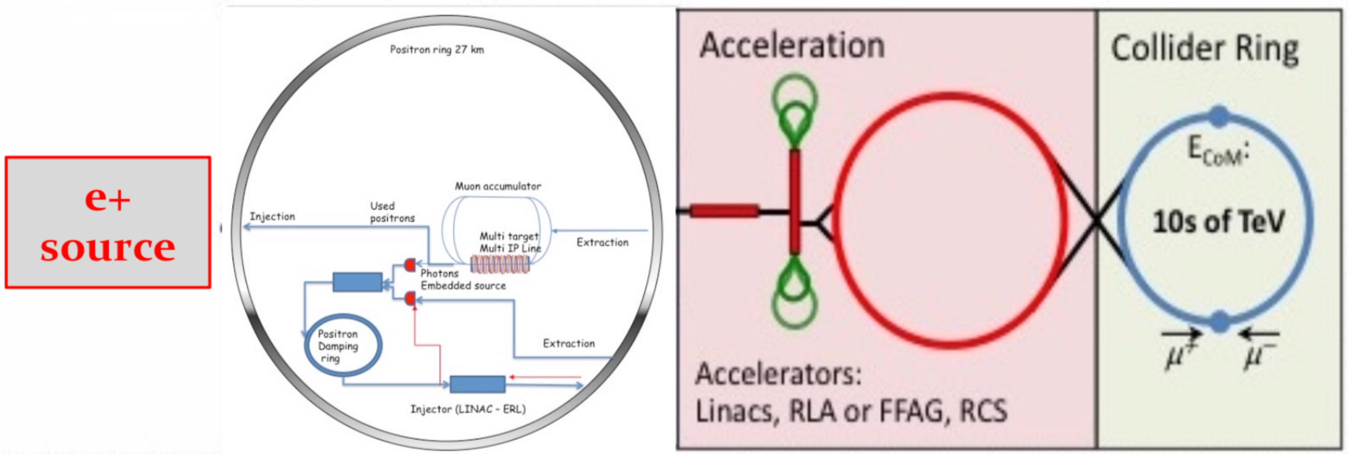
1) muon produced with low emittance ➔ "no/low cooling" needed
2) muon produced already boosted with low energy spread

But difficult

1) **Low** production **cross section**: maximum $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1\ \mu b$
2) **Low** prodution **efficiency** ($\sim 9\times10^{-8}$ μ per e^+ using a 3 mm Be target)
3) **Bremsstrahlung** (high Z → Z^2) & **multiple scattering** ($\sqrt{X_0}$) in production target
4) **High heat load** and **stress** in μ production target
5) **Synchrotron power** O(100 MW) 🡐 available 45 GeV positron sources

➔ **need for consolidation** to overcome some technical limitations

LEMMA
arXiv:1905.05747



LEMMA muon source new scheme

arXiv:1905.05747

A viable accelerator complex layout has to overcome known technical limitations:

- too large required # of e^+ from source with respect to state-of-the-art (ILC, CLIC)
- too large instantaneous and average energy deposited on production target
- muon bunch charge must be increased

A new scheme envisage a reasonable R&D program to verify the feasibility of the proposed layout, assuming the e^+ beam is extracted and imping on external targets

Precise requirements set on the muon source chain:

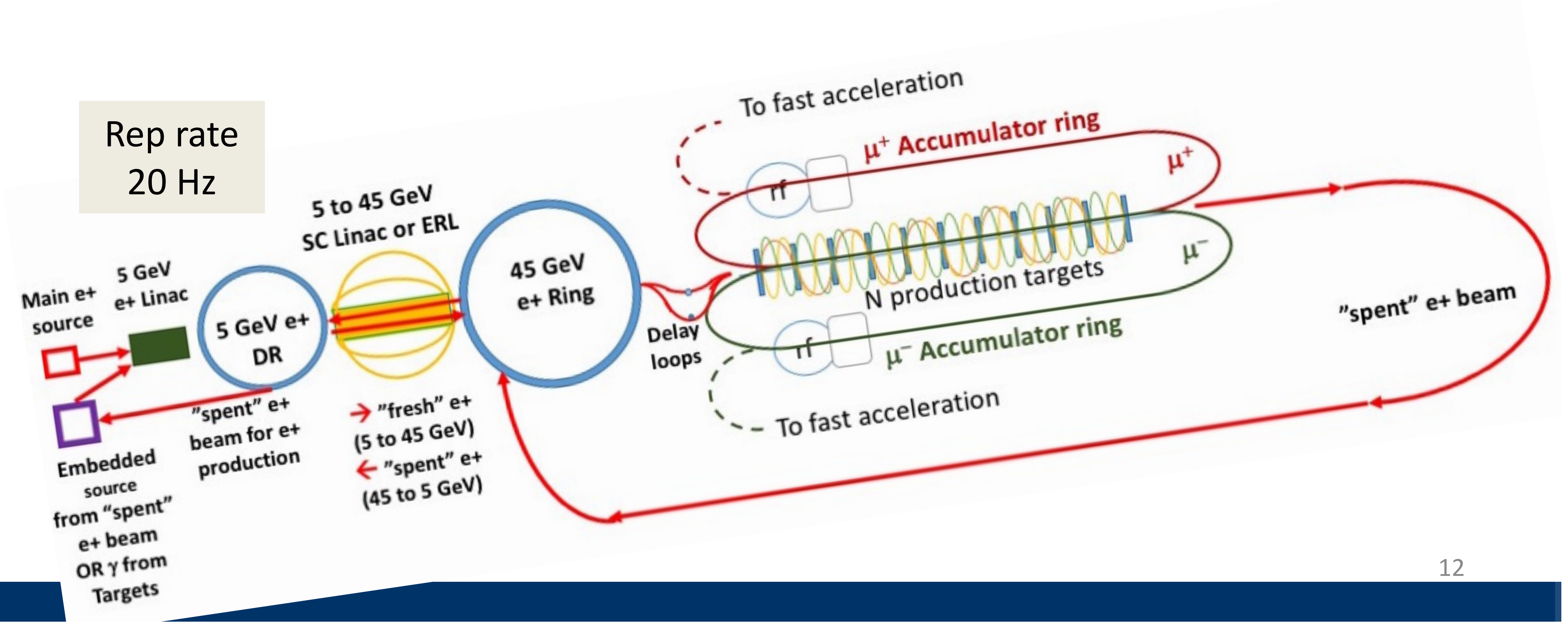
- complete **μ** production cycle **~410 μs** (lifetime = 467 μs @ 22.5 GeV)
- one complete cycle must last enough time for e^+ production and damping
- damping time must be compatible with a reasonable amount of synchrotron power emitted → Damping Ring to cool e^+ at lower energy
- possibility to recuperate e^+ bunches "*spent*" after the **μ** production, to produce e^+ ("*embedded*" e^+ source)
- study of **different types of targets** (material, thickness, resistance to heating,…)

Complex layout

- ***e^+* source** @300 MeV ➔ 5 GeV Linac
- 5 GeV e^+ **Damping Ring** (damping ~10 ms)
- **SC Linac or ERL**:

  from 5 ➔ 45 GeV and 45 ➔ 5 GeV to cool spent e^+ beam after $\mu^\pm$ production
- **45 GeV e^+ Ring** to accumulate **1000 bunches**: **5×10^{11} e^+/bunch** for $\mu^\pm$ production and e+ spent beam after $\mu^\pm$ production, for slow extraction towards decelerating Linac and the DR
- Delay loops to synchronize e^+ and $\mu^\pm$ bunches
- **One (or more) Target Lines** where e^+ beam collides with targets for direct $\mu^\pm$ production
- 2 Accumulation Rings where $\mu^\pm$ are stored until the bunch has **$\sim10^9$ μ/bunch**

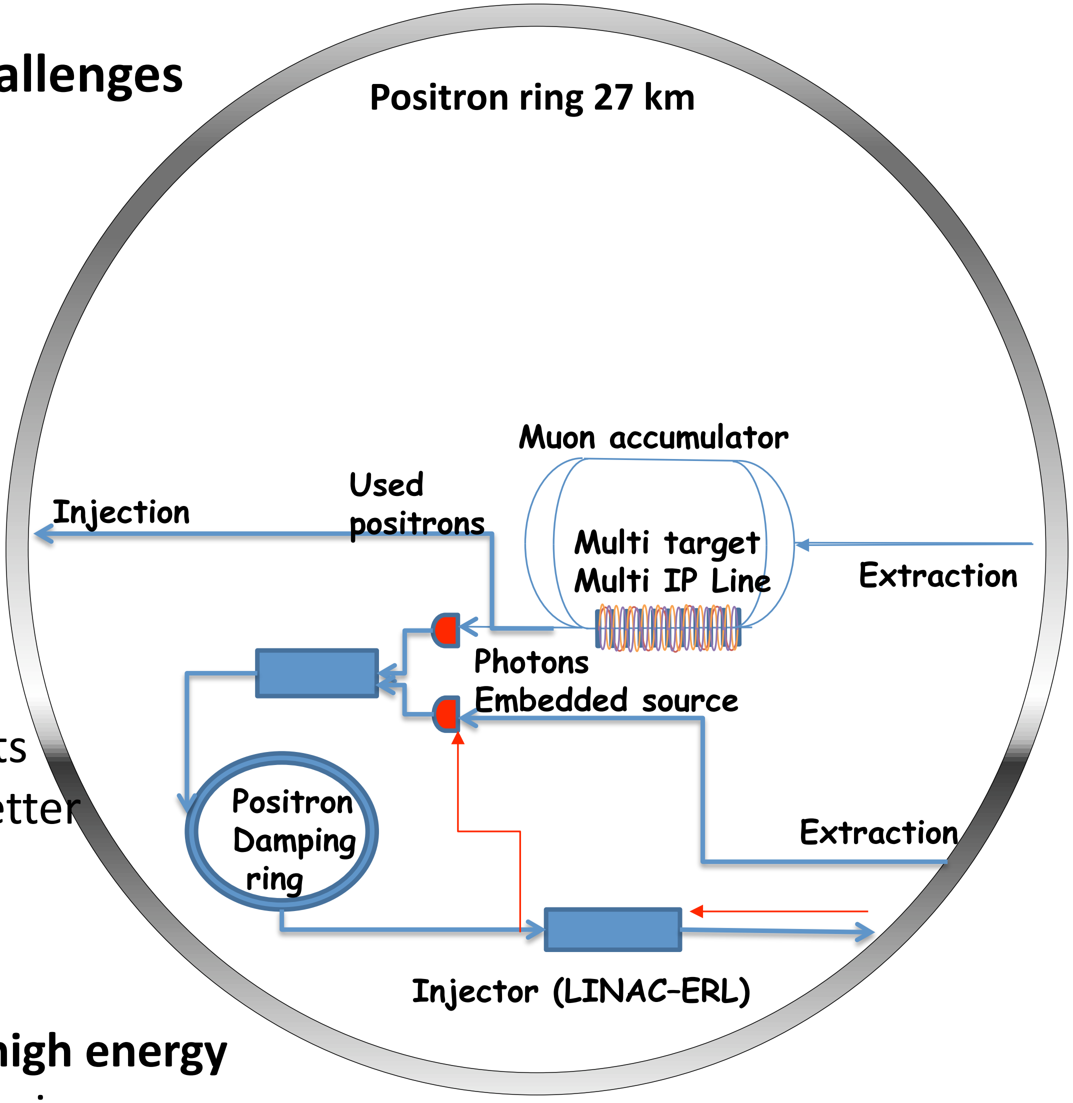
Rep rate
20 Hz



Ongoing LEMMA Effort

Ongoing effort to address identified challenges

- **Positron production**
  - Rotating target (like ILC)
  - Use of positron beam for production
- **Positron ring challenge**
  - larger ring, pulsed ring, lower energy accumulator ring
- **Large emittance from target**
  - use sequence of thin targets, H_2 targets
  - Increased muon bunch charge, e.g. better capturing, …
  - muon cooling (crystals, stochastic, …)
- **Difficulty of combining muon bunches at high energy**
  - Increasing charge at the source (producing bunches in pulsed fashion)
  - increase muons per positron bunch



Contributo INFN

Essenziale per dimostrare la potenzialità del Muon Collider come futura macchina acceleratrice nella regione multi-TeV con:

- studi di fisica, in collaborazione con il gruppo teorico;
- studi per il disegno di una sorgente di muoni positron-driven (LEMMA);
- studi del punto di interazione e degli effetti del fondo di macchina sul rivelatore e danno da radiazione indotta da neutrini - collaborazione con MAP;
- studi di nuovi materiali per i bersagli;
- ionizing cooling in MICE;
- test su fascio al CERN.

➔ **da ora occorre perseguire al meglio:**

1) Studi di fisica ed esperimento

2) Studi di macchina e nuove tecnologie

INFN @ Muon Collider

Grande attività INFN su vari fronti che sono stati cruciali per Granada:

1) Gruppo di **fisica**: **B. Mele**, F. Piccinini, A. Wulzer, A. Nisati et al.
2) Gruppo LNF **LEMMA** et al. coordinati da **A. Variola** ➔ **arXiv:1905.05747**
   - Nuovo disegno sorgente muoni positron driven
   - Nuovi studi su bersagli
3) Gruppo **simulazione rivelatore** coordinati da **D. Lucchesi**
   - Fondi da MAP
4) Gruppo **FLUKA** coordinati da **D. Lucchesi/P. Sala:**
   - analisi rischio **radiazione da neutrini**

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

Introduction

- Core activities:
  - Machine studies
  - Experiment @ CERN with 45 GeV e+ beam
  - Experimental/theoretical activity on targets
  - Machine background and radiation hazard studies

Machine studies

Group that has performed the work described in arXiv:1905.05747

Accelerator Complex	Positron source (Conventional and embedded)	Muon Production	Positron accumulator	Positron recuperation LINACS	Targets	Vuoto	R&D
VARIOLA	Drive LINAC	Muon production ring	e+ Ring	LINACS	Target	Vuoto	
Raimondi	GUIDUCCI	BOSCOLO	BIAGINI	VACCAREZZA	ANTONELLI	ALESINI	
Guiducci	Giribono	Raimondi	Raimondi	Giribono	Collamati	Cimino	
Boscolo		Blanco	Biagini	Studente	Pellegrino		
Biagini	Vaccarezza	Boscolo	Guiducci		Livoti		
Antonelli		Ciarma	Blanco		Carra		
Pastrone	Production and Capture	Liuzzo	Liuzzo		Variola		
		Keller	Zobov? Migliorati?		Pastrone		
	Bacci				Bauce		
	Chehab						
	Chaikovska				Termica		
	Guiducci				Livoti		
	Collamati				Carra		
	Variola				Iafrati		
					Scapin		
					Peroni		
					Cesarini		

Variola incaricato dall giunta fare un piano di lavoro e di risorse richieste per esplorare l'opportunita di aprire una sigla dedicata al muon collider. Basandosi sul lavoro fatto poi si valutera l'opportunite di una collaborazione

Experiment with 45 GeV e^+ beam

General considerations

- From TB (proof of concept) to a proper experiment
  - Collaboration, planning, budget, running-time need to be arranged accordingly
- The 3 TBs we had do NOT sum up to a 3-weeks long experiment
  - 1 continuous week is merely enough to set up such a complex experiment
  - 3 weeks is the minimum amount of time to achieve our physics goals
- we learned a lot from the past TBs; that knowledge must be used to planned the actual experiment

Paper in preparation

Towards a measurement of the emittance of muons produced by positron annihilation at threshold energy

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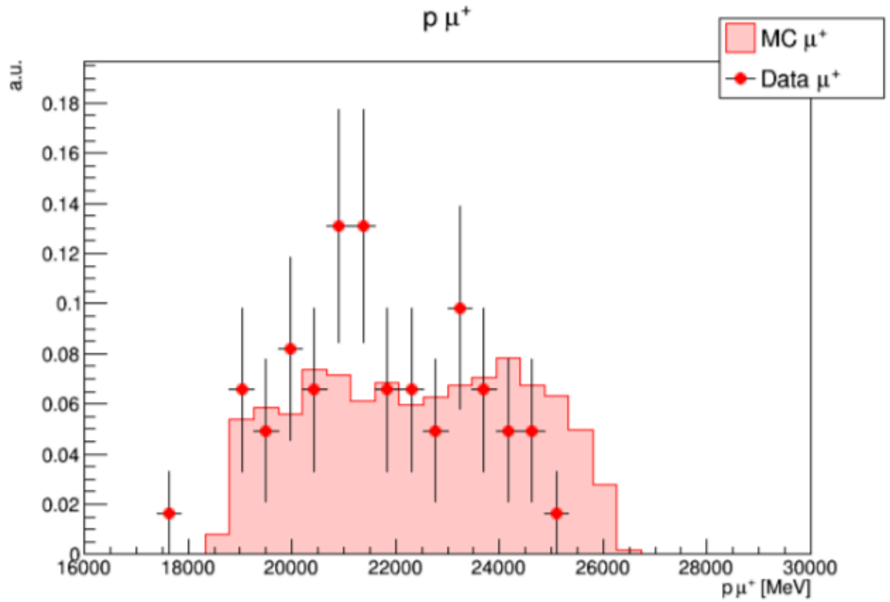
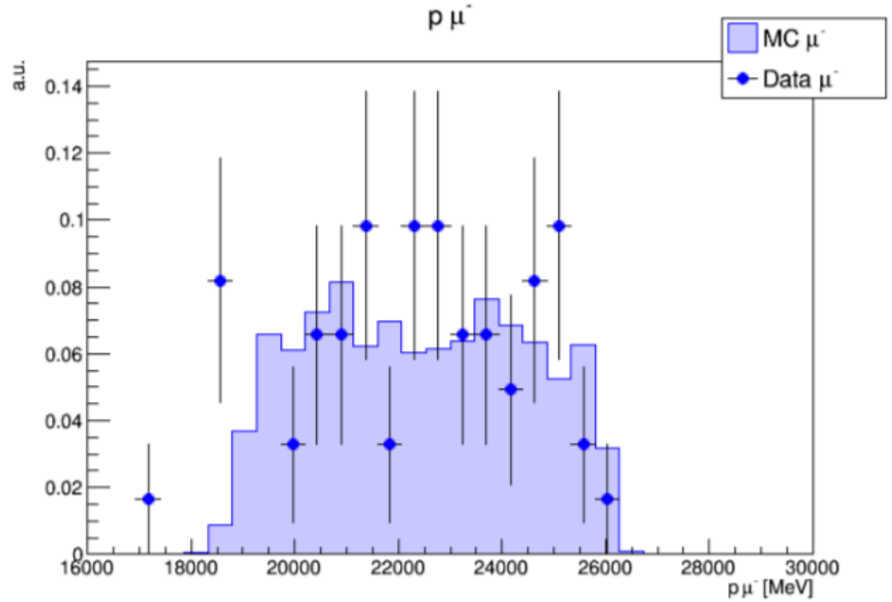
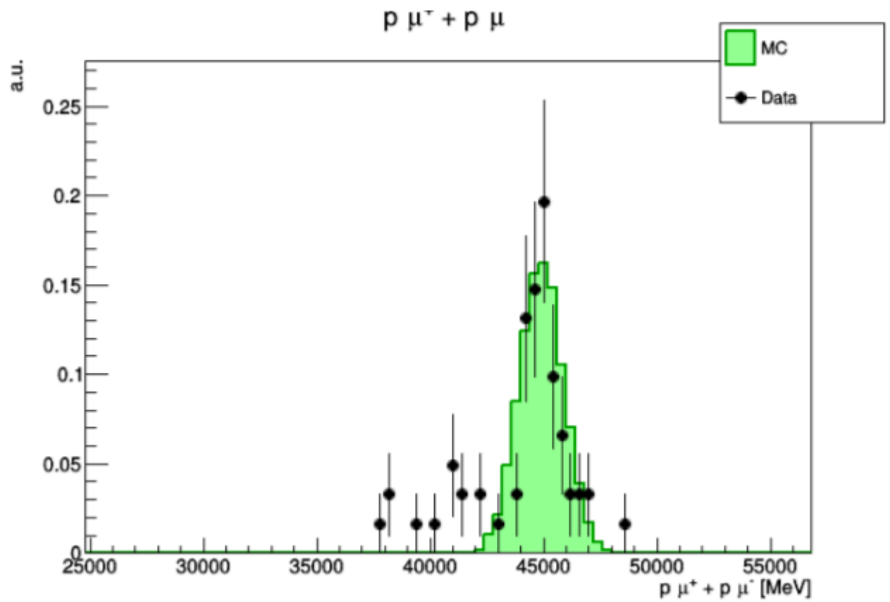
N. Amapane,[a,b] M. Antonelli,[c] F. Anulli,[d] G. Ballerini,[e,f] L. Bandiera,[g] N. Bartosik,[b] A. Bertolin,[h] C. Biino,[b] O. R. Blanco-Garcia,[c] M. Boscolo,[c] C. Brizzolari,[e,f] A. Cappati,[a,b] M. Casarsa,[i] G. Cavoto,[l,d] F. Collamati,[d] G. Cotto,[a,b] C. Curatolo,[h] R. Di Nardo,[m] F.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

TB results



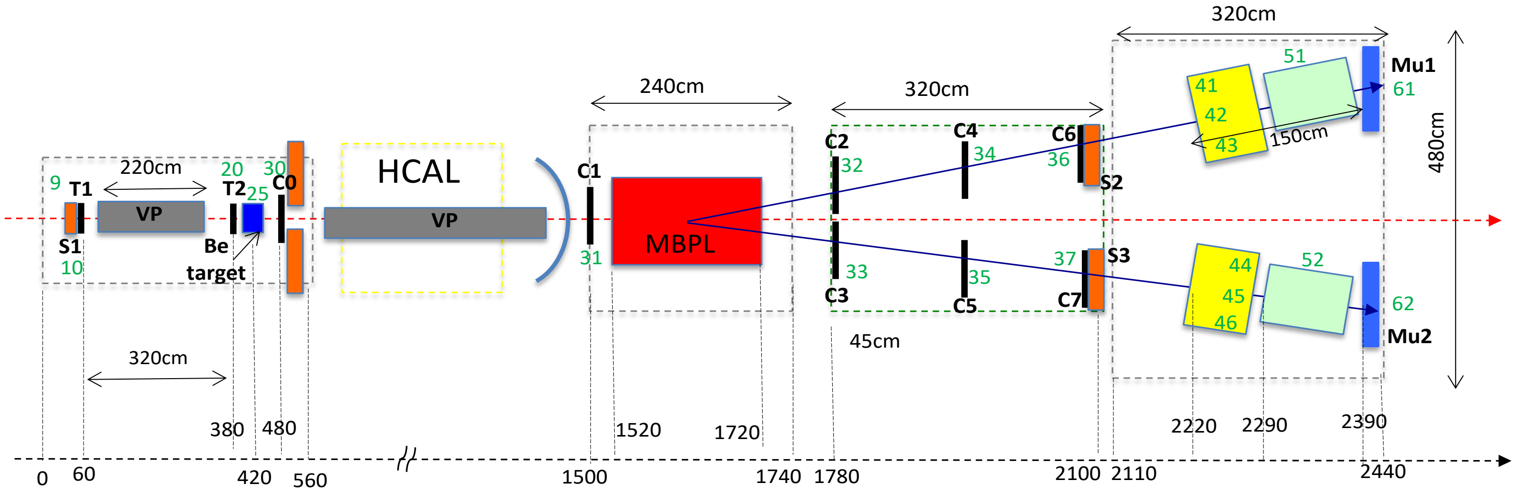


Low stats. Because of a bad DAQ:
2 patched DAQ systems

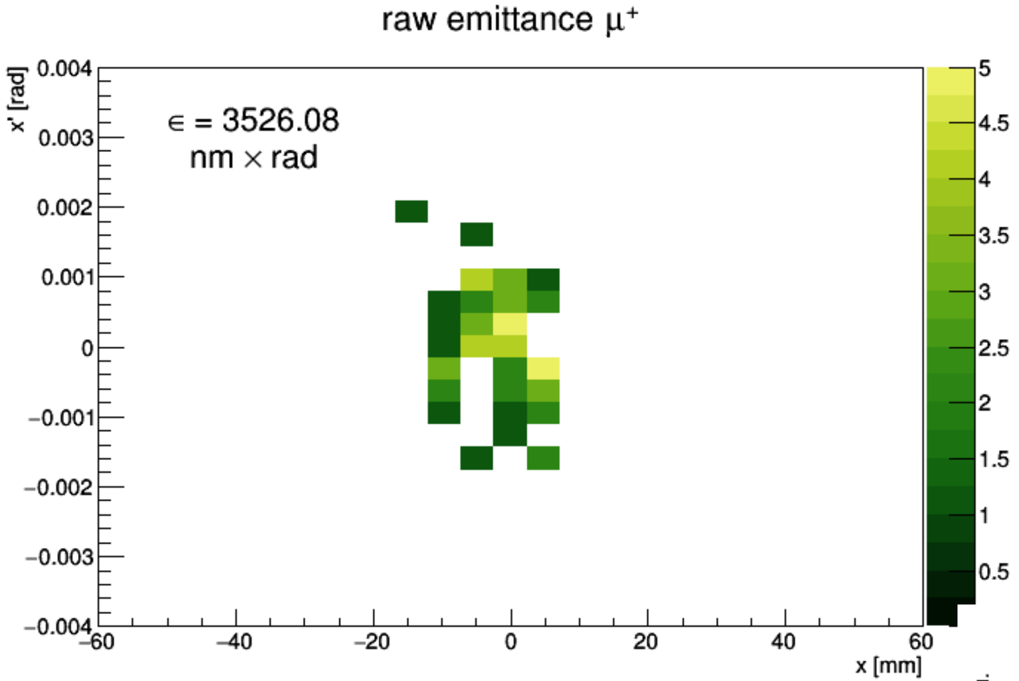


Trigger/DAQ

- Main issue during previous TBs
  - Cumbersome/patched system, enormous dead-time (impossible to determine)
- Whatever detector technology will be employed, we need to develop well in advance a common DAQ infrastructure
- The same is true for the trigger system, the physics performances relies critically on that
  - In terms of efficiency and its determination
- 25kE requested



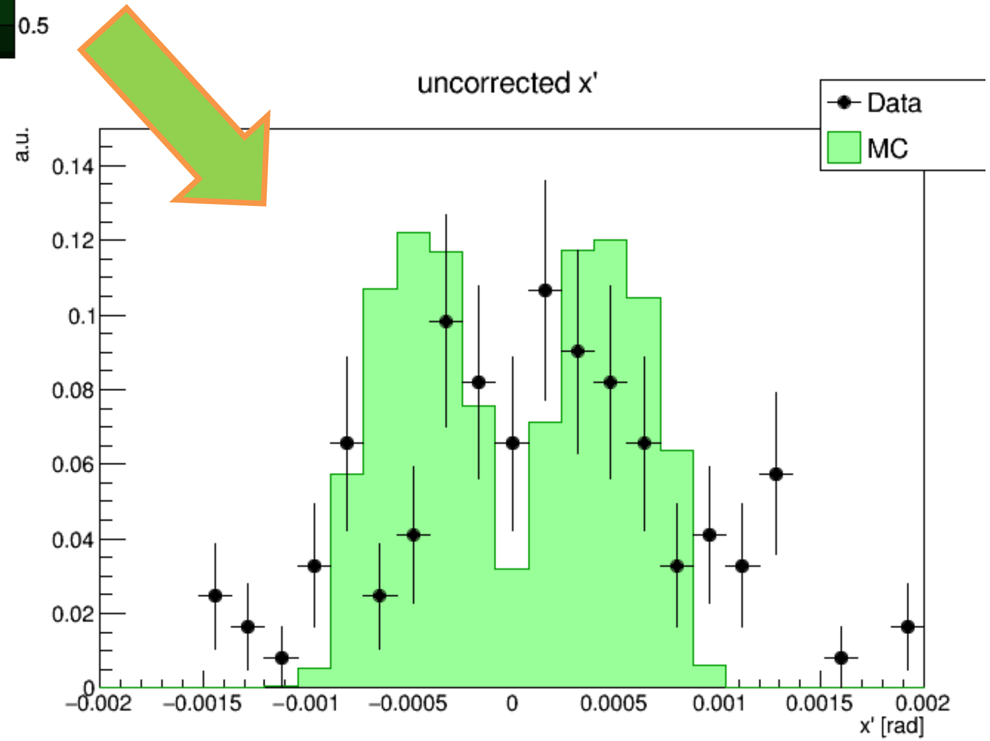
TB results



emittance uncorrected from the incoming positron beam spread (in space and slope coordinates)

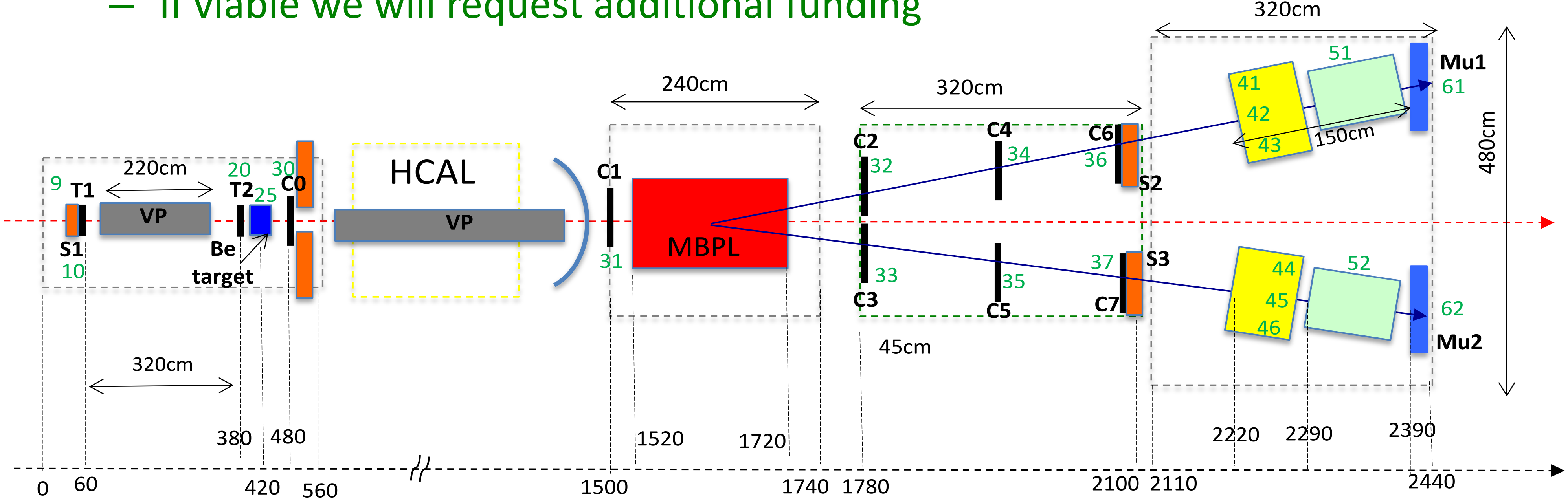
• resolution in x not good enough to perform this correction
• however resolution in x' acceptable

• deep at 0 due to a muon track overlap effect in the x z plane
• reproduced in the MC
• determination of a reliable efficiency correction to account for it is not possible given the very limited data sample available to validate it



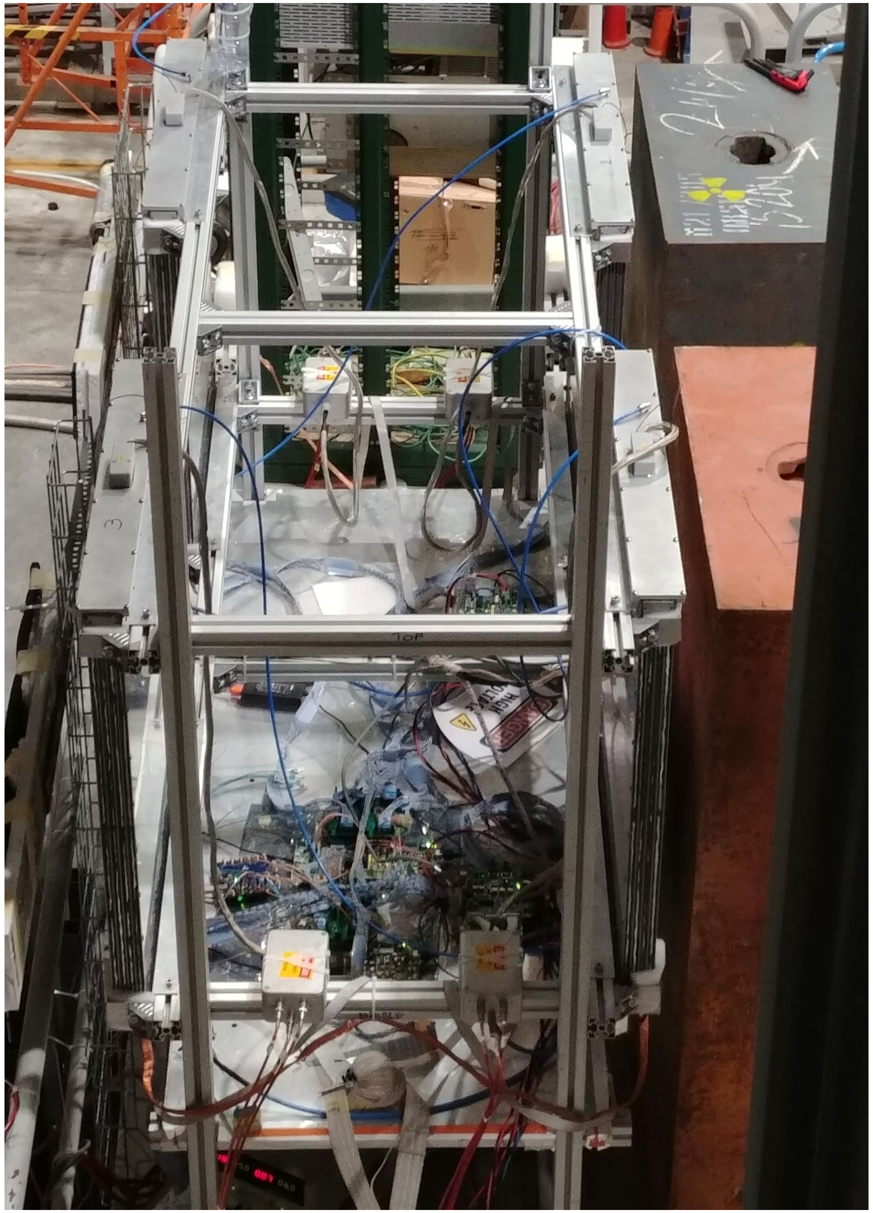
Tracking devices

- Most critical component of the apparatus. Area and resolution of the stations close to the target not sufficient
- At least 1 more strip station
- 5k requested
- Best option: 3 stations of pixels (under investigation)
  - 2 before and 1 after the target
  - If viable we will request additional funding



Muon Chambers

- In 2018 already employed dedicated detectors
  - Exploited to identify and tag di-muon tracks/events
  - So far providing only 1 coordinate
  - Is the spatial/angular resolution enough? (it should be)
  - Trigger-less readout, but need to be integrated in whatever global DAQ
- New detectors are being built, they'll provide the other coordinate
  - No money requested



Calorimeters

- Used for confirming di-muon events, can they be used to tag/measure Bhabha (or $\gamma\gamma$) as well?
- Current Lead-Glass with a too small dynamic range
  - It doesn’t make much sense to build a new calorimeter
  - Exploit something with a better longitudinal segmentation?
  - Separate PID from calorimetric measurement?
- What could be available
  - KLOE’s modules? Quartz calorimenter from Cavoto (still under development)
- Not a priority now

Thermo-mechanical tests for targets

Studio e test dell’opzione multitarget

- La principale opzione per la produzione di muoni in studio consiste nell’estrarre il fascio di positroni dal positron ring e inviarlo su una o piu` “target lines”, ognuna delle quali puo` avere uno o piu` punti di interazione (IP), oppure un singolo IP con piu` targhette sottili.
- A causa dell’effetto di hourglass del fascio nel punto di interazione non si puo avere un Sistema a multitarghette con distanze considerevoli tra le targhette. Bisogna quindi capire quando la frammentazione in piu targhette porta un reale vantaggio sulla dissipazione termica rispetto a una targhetta singola piu spessa.
- Vogliamo studiare la configurazione singolo IP con piu` targhette in termini di salita e distribuzione della temperature e l’efficenza di dissipazione in funzione della distanza tra le targhette.

- Lo studio si compone di simulazioni e misure in laboratorio per valutare gli aspetti termici medi in modo da determinare le migliori configurazioni in termini di numero e forma delle targhette, e della loro distanza relativa.
- Uno studio su fascio sarebbe determinante per consentire anche di considerare l’aspetto della deposizione locale e della propagazione del gradiente termico
- In una seconda fase si puo` implementare lo studio di targhette rotanti.

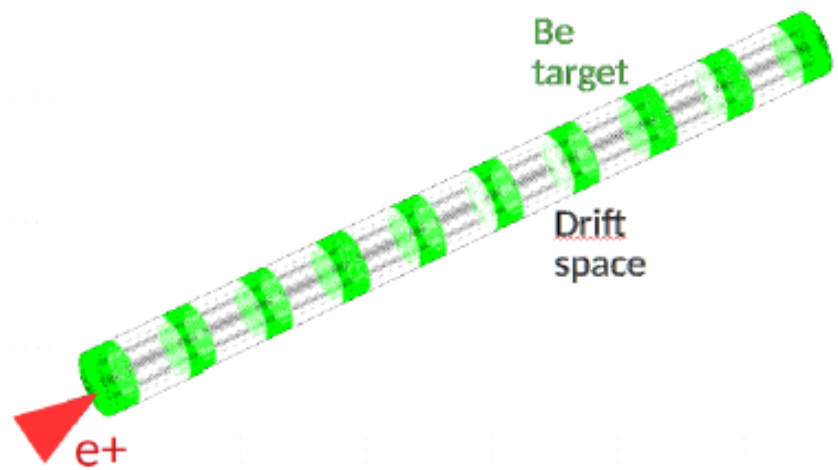
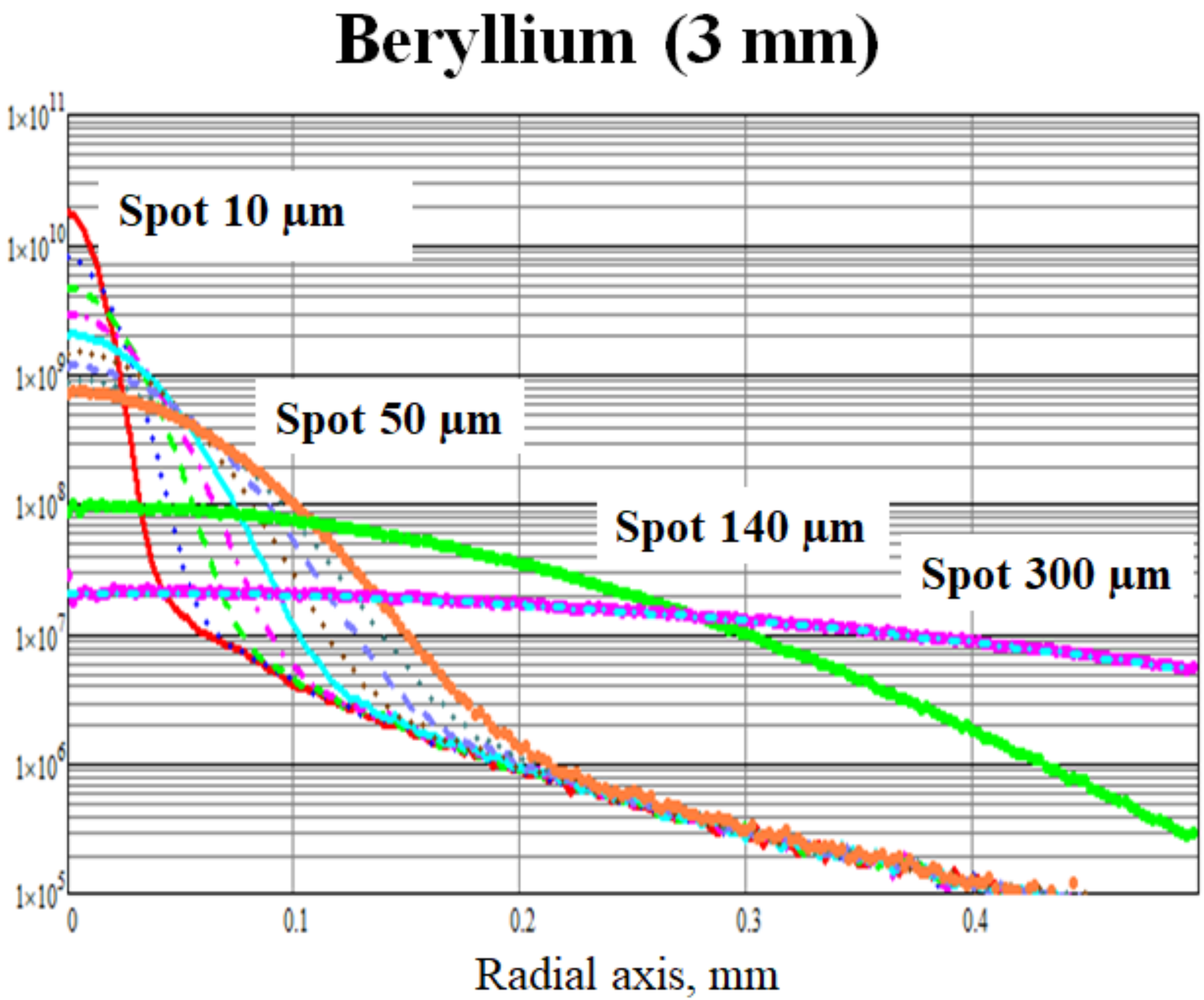
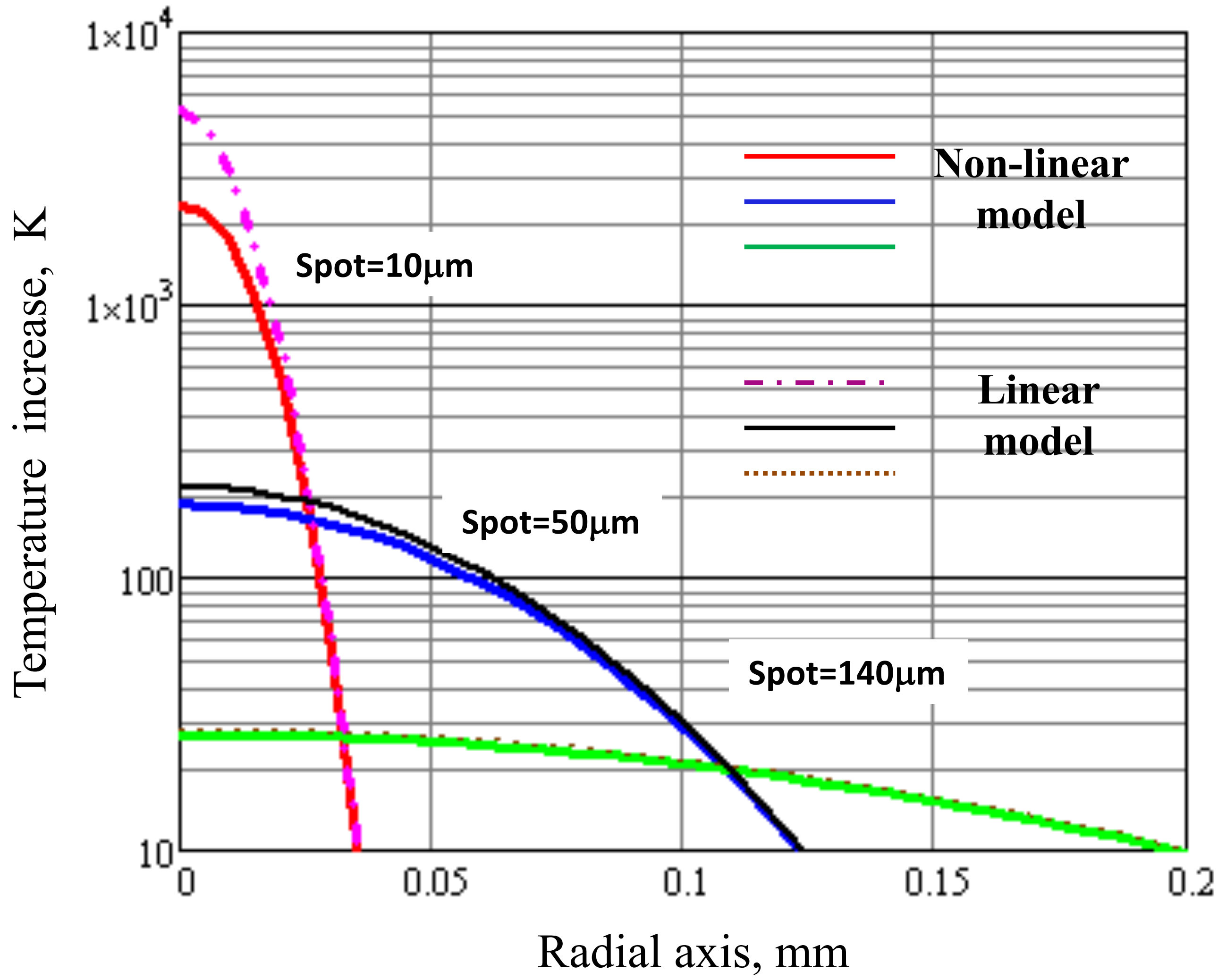


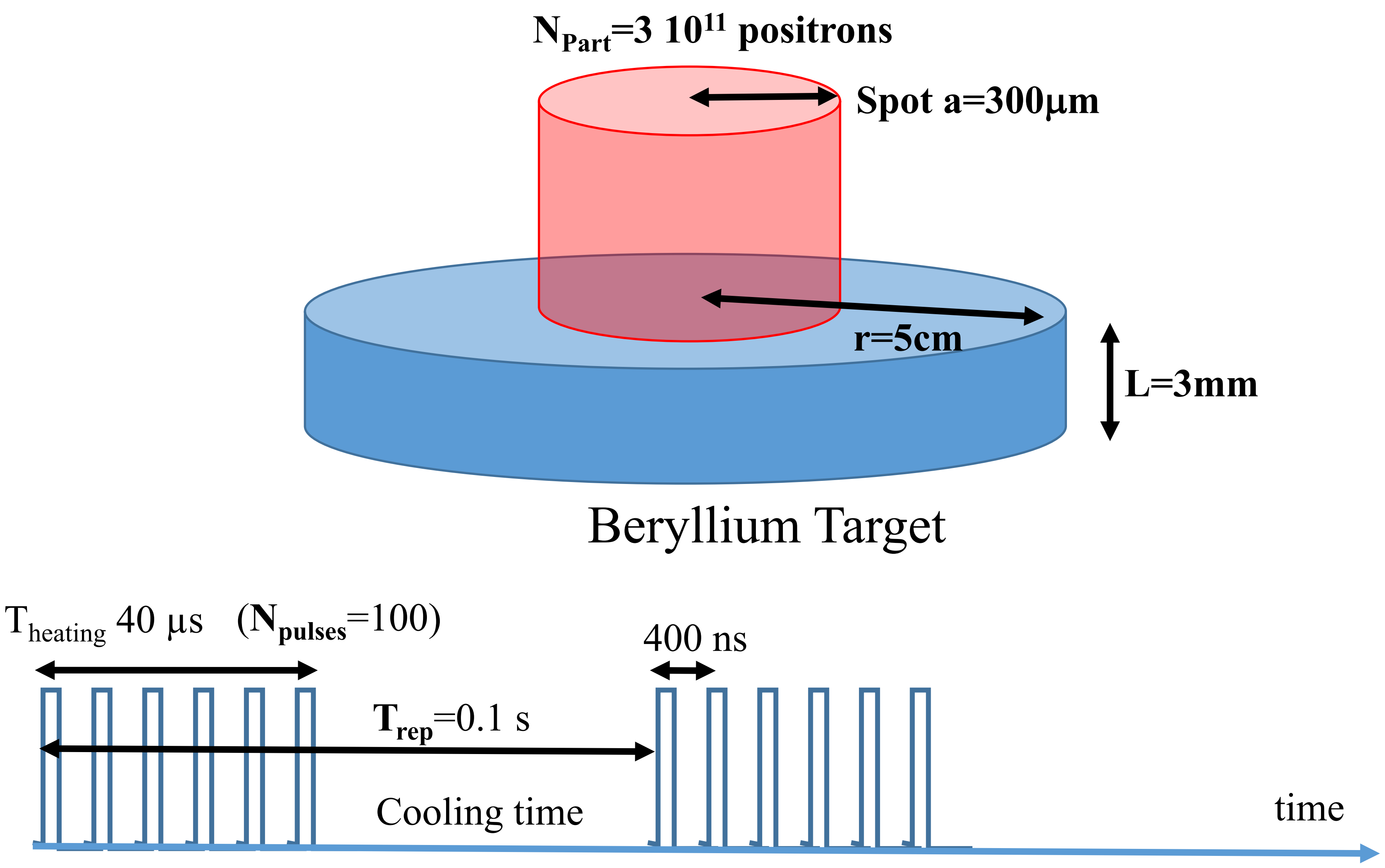
Figure 24: Single IP with multiple targets.

Single Bunch – Energy density deposition

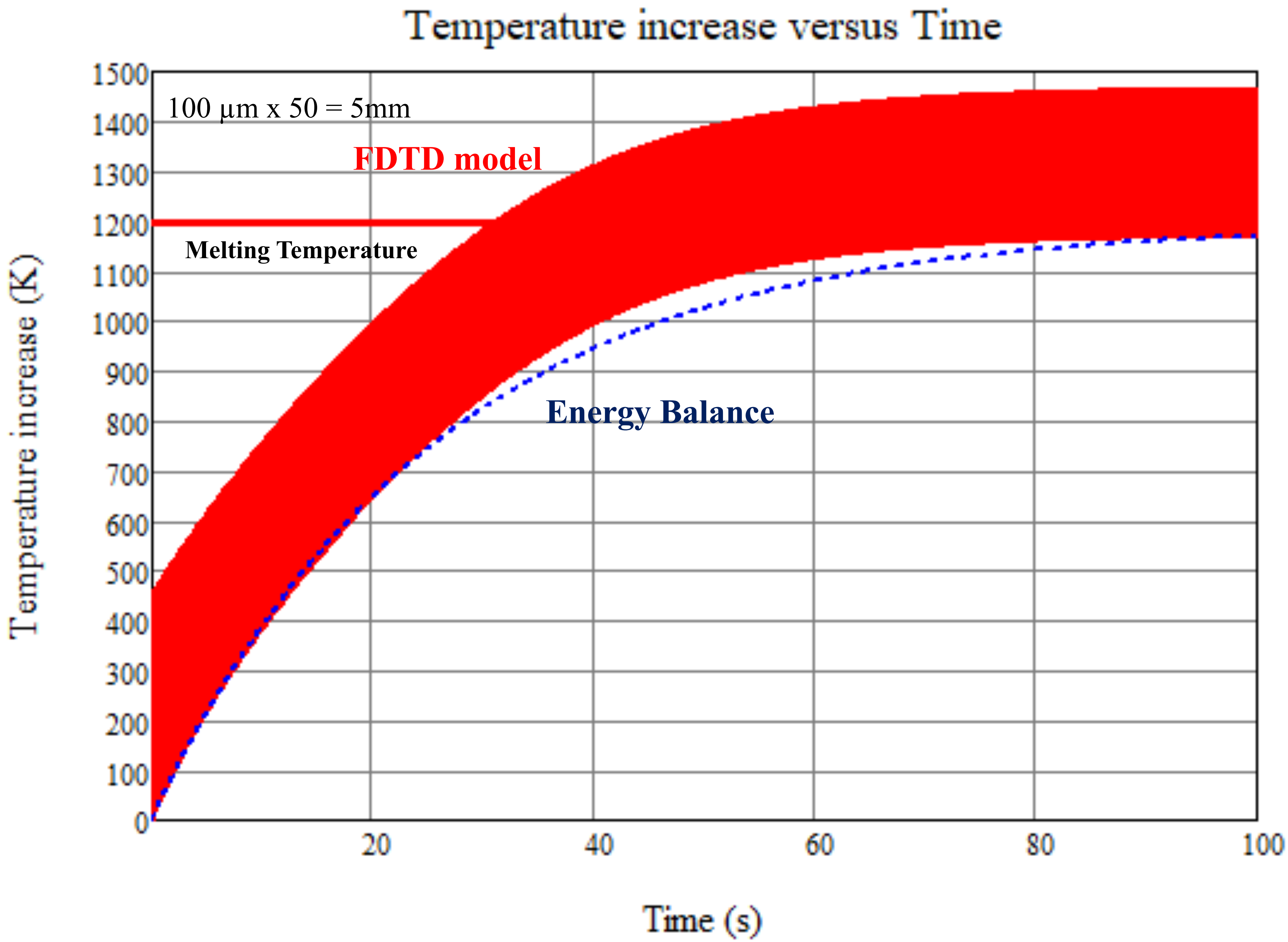


Linear vs Non-linear





N_Part=3 10^11 positrons
Spot a=300µm
r=5cm
L=3mm
Beryllium Target
T_heating 40 µs (N_pulses=100)
400 ns
T_rep=0.1 s
Cooling time
time


Temperature increase versus Time
100 μm x 50 = 5mm
FDTD model
Melting Temperature
Energy Balance
Temperature increase (K)
Time (s)
1500
1400
1300
1200
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1000
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600
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200
100
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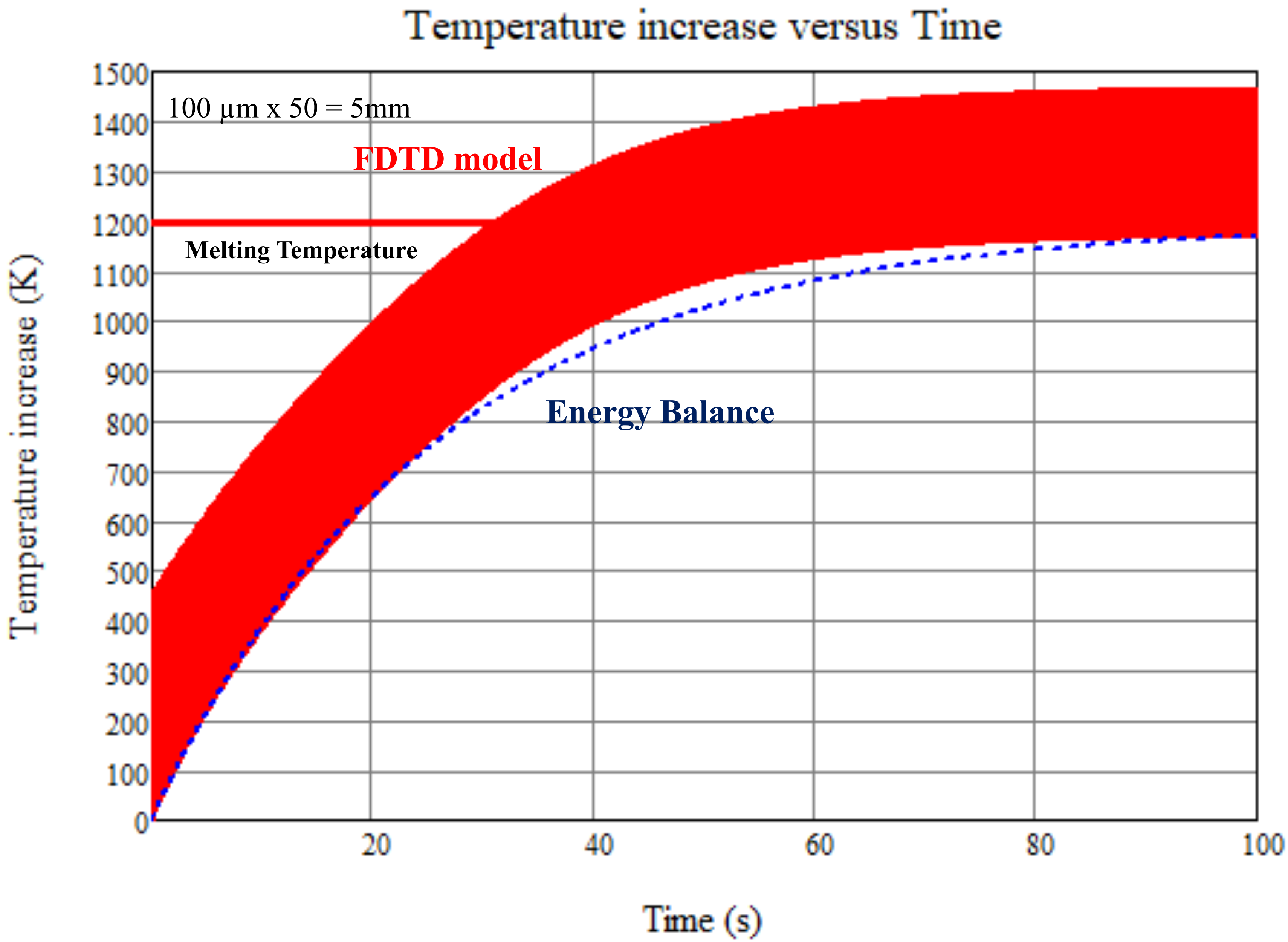
20
40
60
80
100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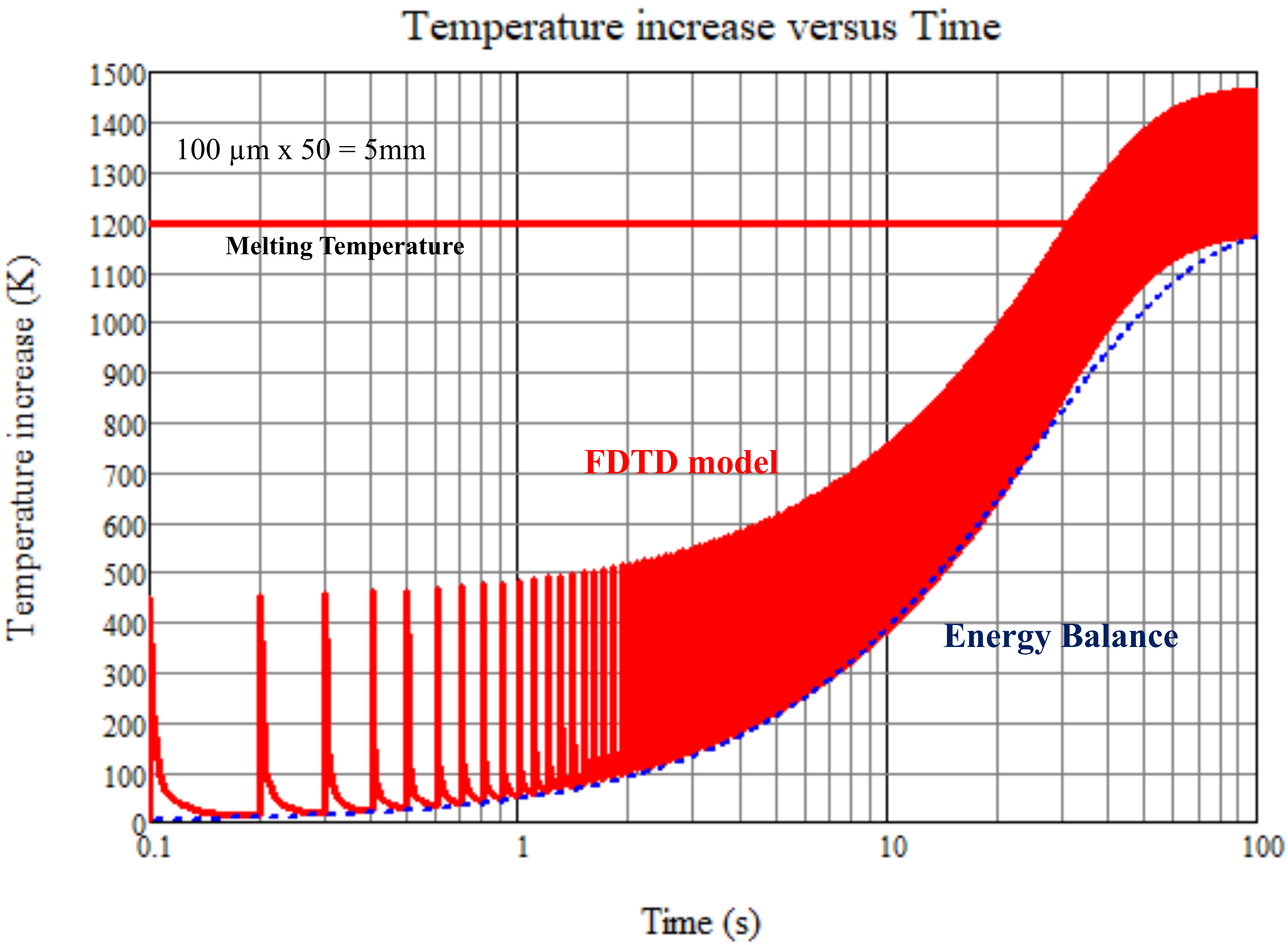

Temperature increase versus Time
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Time (s)
0
100
200
300
400
500
600
700
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900
1000
1100
1200
1300
1400
1500
0.1
1
10
100

Studio e test dell’opzione multitarget

- Si vuole iniziare un programma di studi per testare le varie configurazioni di targhette
- L’apparato sperimentale da realizzare dovra` quindi essere *upgradabile* e facilmente trasportabile
  - test presso il LINAC di DAFNE il primo anno
  - successivamente opzioni da esplorare

- **Richieste per il 2020**
- Acquisto targhette Be o C — **15 kEuro**
- Meccanica motorizzata con controllo remoto per posizionamento bersagli — **15 kEuro**
- Camera a vuoto con passaggi di acquisizione e finestra per infrarossi — **10 kEuro**
- Camera a infrarossi — **30 kEuro(*)**
- Sistema di termocoppie e di acquisizione dei dati — **10 kEuro**

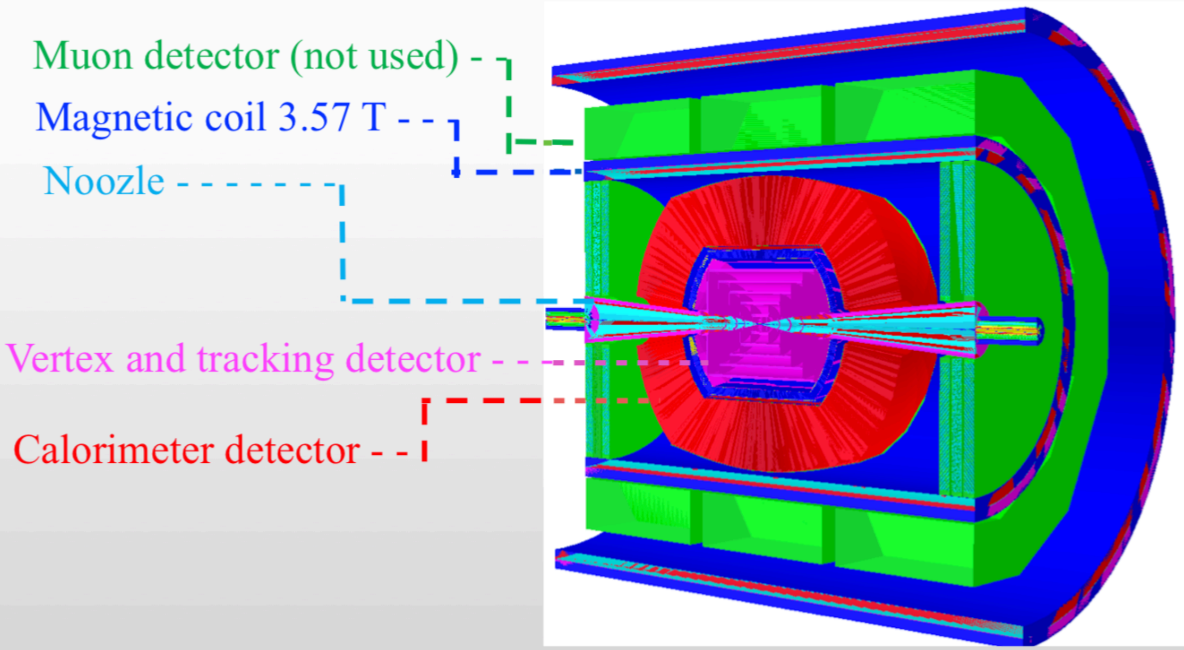
Totale: 80 kEuro(*)

(*) L’acquisto della termocamera puo` andare sub judice, poiche’ vogliamo esplorare possibilita` diverse dall’acquisto, o differire l’acquisto all’anno successivo

Beam induced background

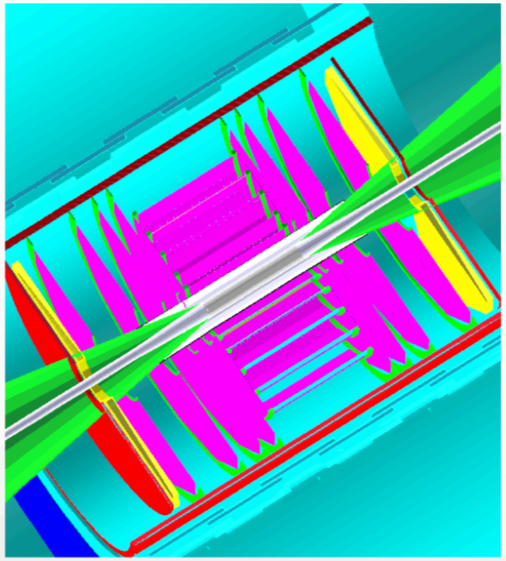
Detector Response Simulation

- A detailed simulation of the potential detector is necessary to assess the achievable precision of future physics measurements
- Making use of the simulation/reconstruction tools previously developed within the MAP program based on the ILCroot package: supports signal + MARS background merging

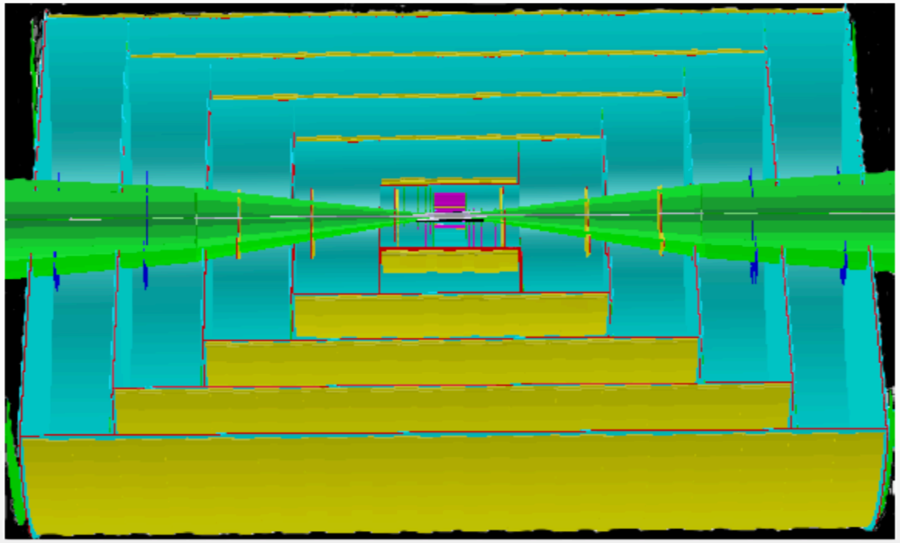


Inherited from MAP

Tracking detectors



Beam pipe:
Beryllium *(Be)*
thickness: 400 μm



Vertexing detector (VXD) precise tracking
***Si* pixel sensors:** 20×20 μm pitch
R: 3-13 cm **L:** 42 cm
Granularity:
- **Barrel:** 5 layers *(75 μm thick)*
- **Endcap:** 2 × 4 disks *(100 μm thick)*

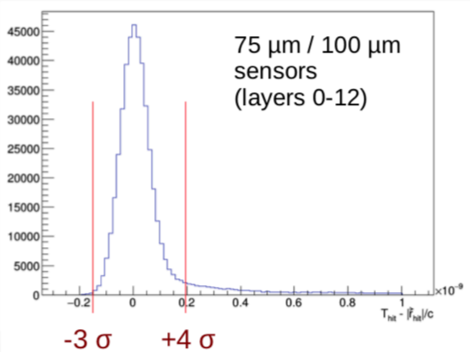
Silicon Tracker (SiT) and
Forward Tracking Detector (FTD):
***Si* pixel sensors:** 50×50 μm pitch, **thickness:** 200 μm
SiT: **Barrel:** 5 layers **Endcap:** 2 × (4 +3) disks
FTD: **Endcap:** 2 × 3 disks

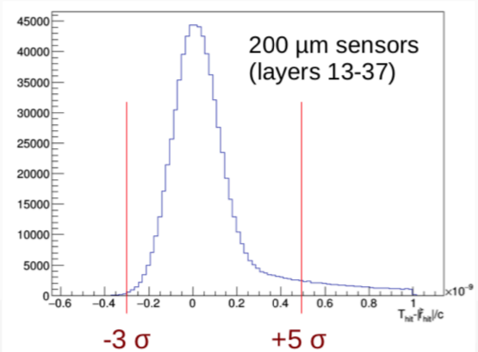
Tracking Performances

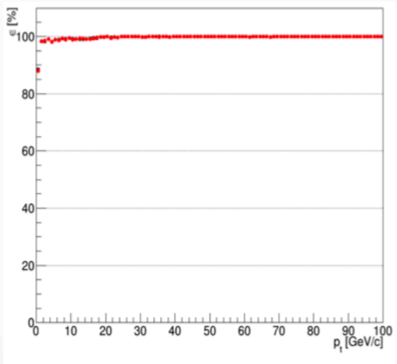
Assuming different time resolution for different Si detectors

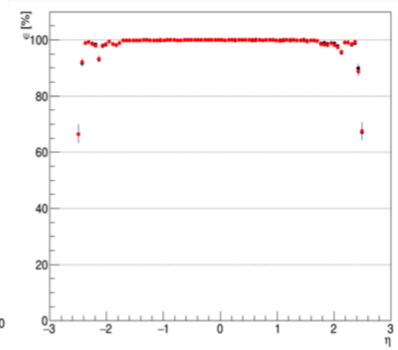
Pitch 75 and 100 μm: 50 ps

Pitch 200 μm:100 ps

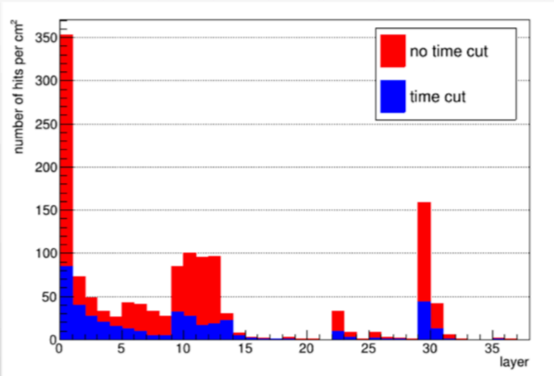




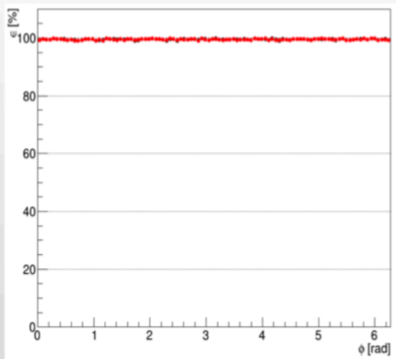




A lot of background is removed

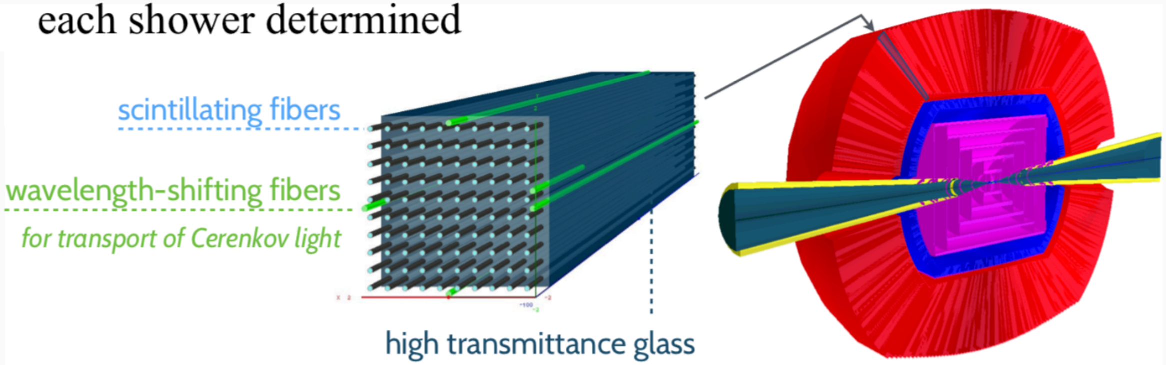


Keeping high efficiency on signal

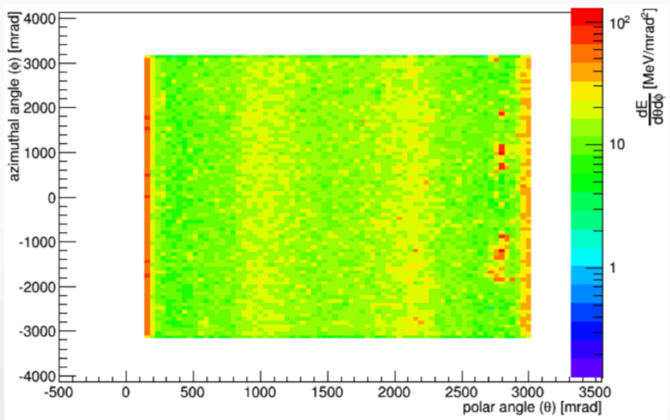


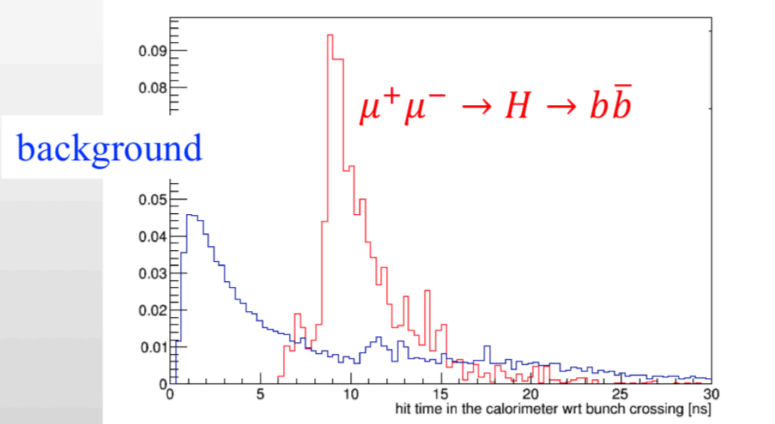
Calorimeter detector: dual readout calorimeter for the moment

Cerenkov + scintillation light simultaneously measured -> electromagnetic and hadronic fraction of each shower determined



Beam-induced background influence also the calorimeter performances





Time can help to reduce Beam-induced background

Next Steps

- Publish a paper with the current simulation software
- Move to a new framework: meeting next week with CLIC people to speed up the adoption of their code. We will move to the FCC framework when usable.
- Design a new detector where position, energy and time resolution are pushed to the limit.
- Collaborate with other R&D activities to study performances of such detector solutions.
- Set up a framework FLUKA-based to produce background for center-of-mass energies $\sqrt{s} = 3\,TeV$, $\sqrt{s} = 6\,TeV$, $\sqrt{s} = 10\,TeV$, $\sqrt{s} = 14\,TeV$
- Study interaction region and detector for the above center-of-mass energies.

- Requests:
  - We need support for computing resources, 15kE

Riassunto richieste

- Consumi tot 80 Keuro + 45(*)
  - TDAQ 25 keuro TDAQ
  - Strip 5. Keuro
    - Acquisto targhette Be o C **15 kEuro**
    - Meccanica motorizzata con controllo remoto per posizionamento bersagli **15 kEuro**
    - Camera a vuoto con passaggi di acquisizione e finestra per infrarossi **10 kEuro**
    - Camera a infrarossi **30 kEuro(*)**
    - Sistema di termocoppie e di acquisizione dei dati **10 kEuro**
  - Calcolo 15KEuro(*)

(*) non inserite nel DB

missioni

- ~ 12 FTE
- Metabolismo
- 2 riunioni nazionali
- 2 workshop internazionali

} ~ 96 keu

- Coinvogimento in AIDA++ e ARIES2 → progetti nel 2020
- Preparazione testbeam 2021 14 keu
- Preparazione setup test multitarghetta 6 keu