Muon collider feasibility: new studies of a low emittance muon source using positron beam

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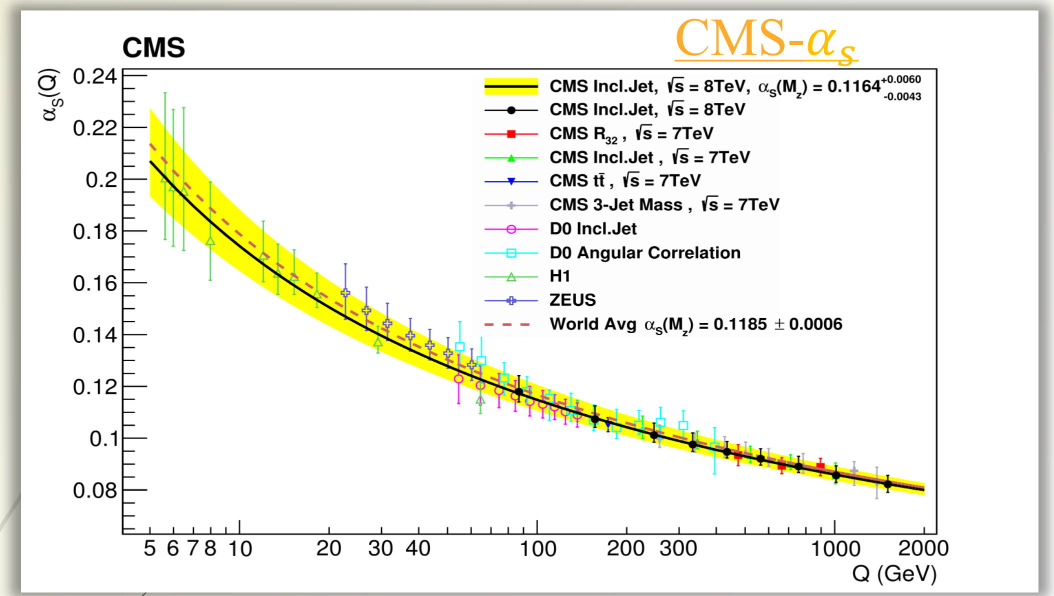
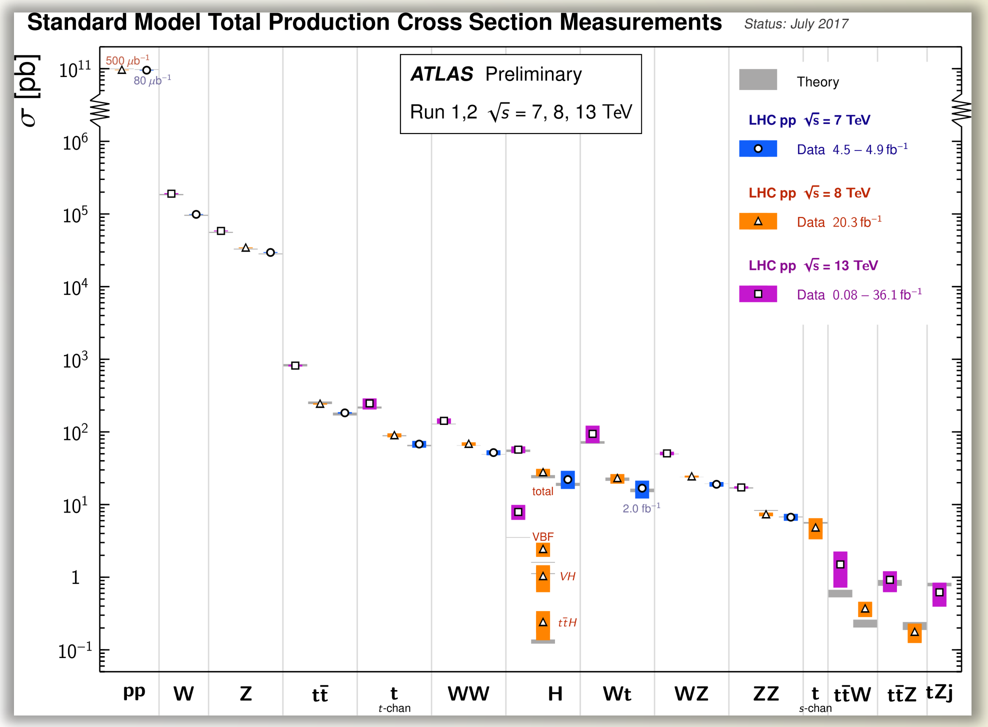
Outline

- Physics Scenario
- Future Lepton Colliders
- Muon Collider Idea
- Proposal for a different muon source

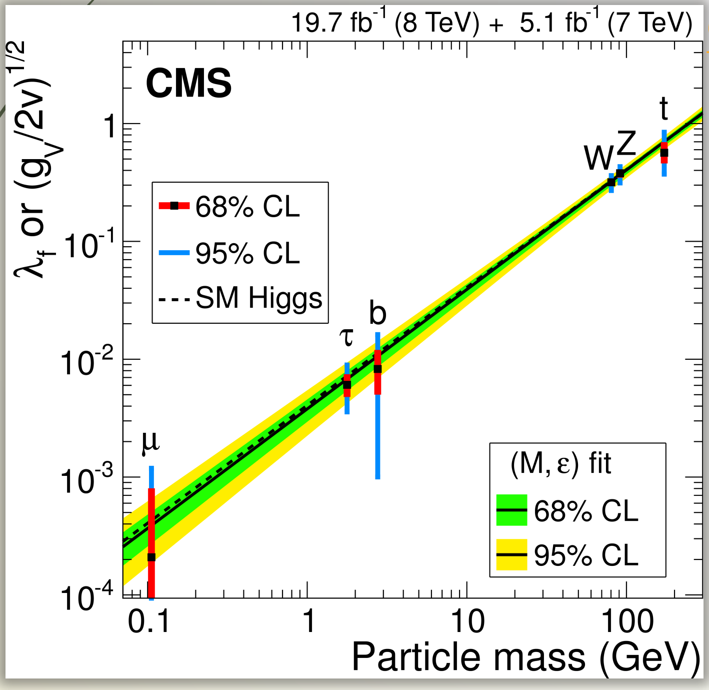
CMS-α_s



ATLAS-Cross Sections

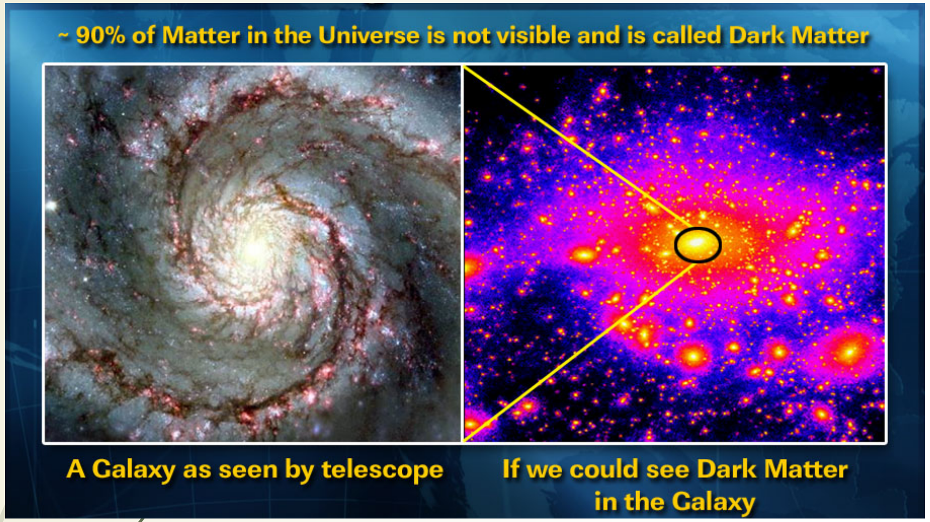


CMS-Higgs



The Standard Model theory is the right language to describe physics up to LHC energies

Standard Model is not the ultimate theory, several questions are not answered



Nasa

The nature of dark matter

Matter – Antimatter asymmetry

Primordial Matter	Primordial Anti-Matter
10,000,000,001	10,000,000,000

Hierarchy Problem

Why is Higgs mass so much less than other energy scales in particular the scale of gravity?

$$m_h \simeq 125.5 \text{ GeV} \lll M_{\text{Planck}} = 1/\sqrt{G_N} \simeq 1.2 \times 10^{19} \text{ GeV??}$$

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How to investigate the Nature?

I. If something new, a new particle, is found at LHC
   - precision machine to study it and the Higgs

II. If nothing is found at LHC after High Luminosity data taking
   a. Hadronic machine, FCC-hh, to investigate up to 100 TeV
   b. precision machine to study the Higgs as the portal for Physics Beyond Standard Model and to investigate at the highest possible energies.

Focus on II b: lepton machine

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An extremely rich program

H

Precision measurements
- mass, width
- spin, CP, couplings
- off-shell coupling, width interferometry
- differential distributions

Rare / beyond SM decays
- H → Zγ
- H → μμ
- H → cc
- H → τμ, τe, eμ
- H → J/Ψγ, Υγ , …

Tool for discovery
- portal to BSM
- portal to hidden sector
- portal to DM

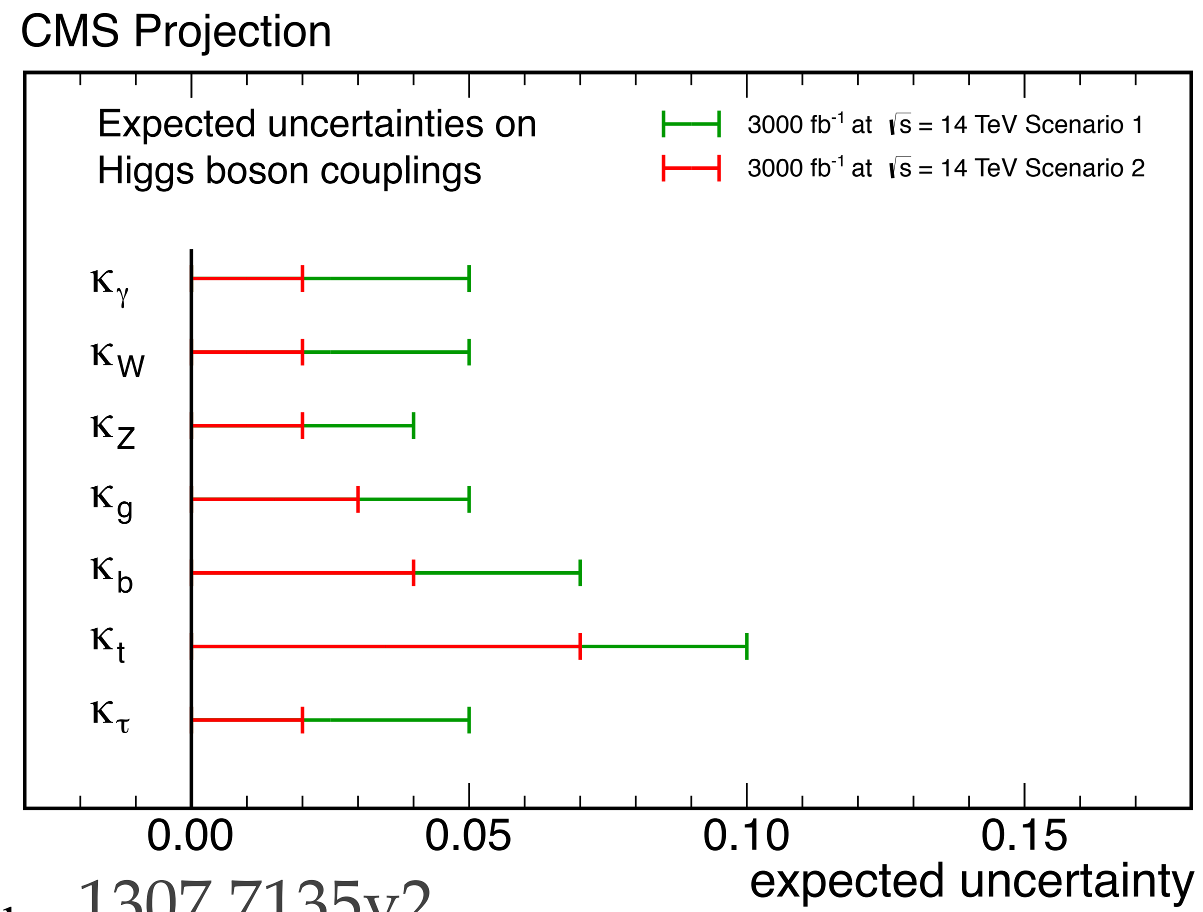
… and much more
- Higgs potential
- di-Higgs
- other FCNC decays
- …

SM minimal or not?
- 2HDM
- MSSM, NMSSM
- extra Higgs states, doubly-charged Higgs

Expected Scenario after HL-LHC

k_x is scale factor respect to the SM, i.e. $g_{HVV} = k_V g_{HVV}^{SM}$ (it assumes only one narrow Higgs resonance)

ATLAS has similar, more conservative values



1307.7135v2

Deviation from SM predictions due to various New Physics models are expected to be ~ few %

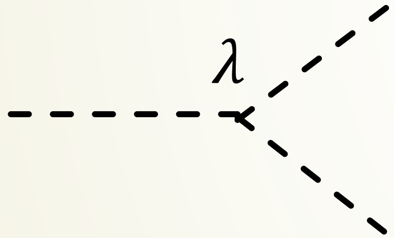
The Higgs Potential has to be determined to understand the EW symmetry breaking

In SM, expanded about the minimum

$$V(H) = \boxed{\frac{1}{2} m_H^2 H^2} + \boxed{\lambda v H^3} + \boxed{\frac{\lambda}{4} H^4}$$

Single H Double H Triple H

λ is sensitive to New Physics



HH final states are needed

HH final state 3000fb^{-1}	ATLAS Significance Coupling limit (95 % C.L.)	CMS Significance
HH → bbγγ	1.05 σ $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$	1.43 σ
HH →bbττ	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$	0.39 σ
HH →bbbb	$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11.0$	0.39 σ
HH →bbVV		0.45 σ
ttHH, HH-> bbbb	0.35 σ	

S. Jézéquel, HL-LHC/HE-LHC Workshop 2017

Indirect sensitivity to λ of single Higgs production but theory and experimental measurements must have enough precision

Why is this difficult at hadron colliders ?

The expected effects of new physics on the 125 GeV Higgs boson are small, at the few-percent level, due to Haber's decoupling theorem.

Higgs events are not characteristic at hadron colliders, except in a few rare modes. Typical Higgs boson samples are 10% Higgs, 90% other.

Not all Higgs decay modes can be observed at hadron colliders. So, it is not possible there to determine Higgs couplings in a model-independent way. LHC experiments typically measure μ, a combination of couplings.

M Peskin ICFA 2017

Lepton Colliders: Muon versus Electrons @ √s=125 GeV

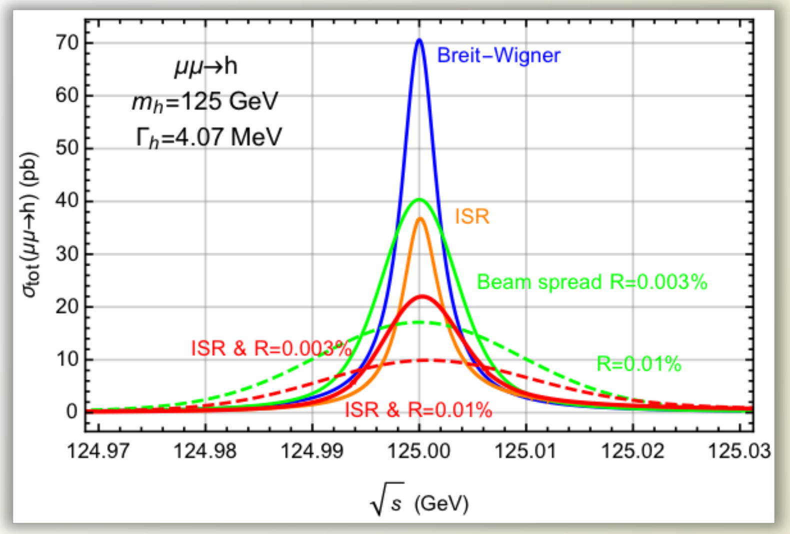
Back on the envelope calculation:

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

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

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

σ(BW)	ISR alone	R (%)	BES alone	BES+ISR
$\mu^+\mu^-$: 71 **pb**	37	0.01	17	10
		0.003	41	22
e^+e^-: 1.7 **fb**	0.50	0.04	0.12	0.048
		0.01	0.41	0.15



R: percentage beam energy resolution, key parameter

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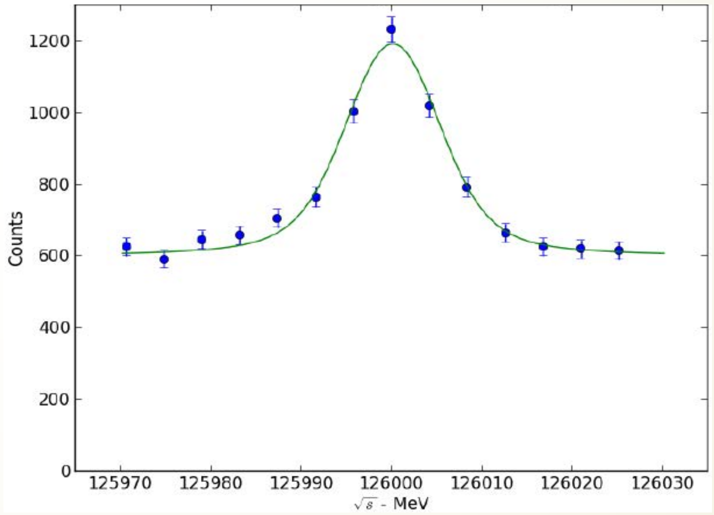
Muon Collider at the Higgs pole

The s-channel Higgs production affords:

- most precise measurement of a second generation fermion Higgs-Yukawa coupling constant, g_{μ}
- best mass measurement, precision of ~ (few)$\times 10^{-6}$
- best direct measurement of the width to a precision of ~ few% model independent ⇒ most powerful test of new physics

- Assumed Higgs width 4.2 MeV
- Energy Scan:
  $H \to b\bar{b}$ event count as function of $\sqrt{s}$
- Critical parameter : Beam Energy Spread $\sim 10^{-5}$



Muon Accelerator Program

Parameter	HL-LHC	FCC-ee	FCC-ee	ILC	CLIC	CLIC	CEPC	μ-Coll.
√s[TeV]	14	350	240	250	350	1400	240	125
Lum/IP[E34]	5	1.3	5.0	1.35	1.5	1.5	2	0.01
Lum.Tot.[ab^{-1}]	3	0.65x4	2.5x4	2	0.5	1.5	2.5x2	0.004
Years[10^7s]	6	5	5	15	3	10	10	4
Δm_H[MeV]	100			14	-	47	5.9	0.06
Γ_H[%]		1.2	2.4	3.9	2.0	1.1	2.8	4
Δk_{HZZ}[%]	4	0.15	0.16	0.38	0.6	0.5	0.25	-
Δk_{HWW}[%]	4.5	0.19	0.85	1.8	1.2	0.5	1.2	0.2
Δk_{Hbb}[%]	11	0.42	0.88	1.8	2.6	1.5	1.3	0.4
$\Delta k_{H\tau\tau}$[%]	9	0.54	0.94	1.9	4.2	2.1	1.4	1.5
$\Delta k_{H\gamma\gamma}$[%]	4.1	1.5	1.7	1.1	-	5.9	4.7	-
Δk_{Hcc}[%]		0.71	1.0	2.4	6.3	3.2	1.7	-
Δk_{Hgg}[%]	6.5	0.8	1.1	2.2	5.1	4.0	1.5	-
Δk_{Htt}[%]	8.5	-	-	-	-	4.2	-	-
$\Delta k_{H\mu\mu}$[%]	7.2	6.2	6.4	5.6	-	14	8.6	-
Δk_{HHH}[%]	limits	-	-	-	-	40	-	-
References	ATL-PHYS-PUB-2014-016	1308.6176	1308.6176	1710.07621	1608.07538	1608.07538	IHEP-CEPC-DR-2015-01	1308.2143

Different parameter definition

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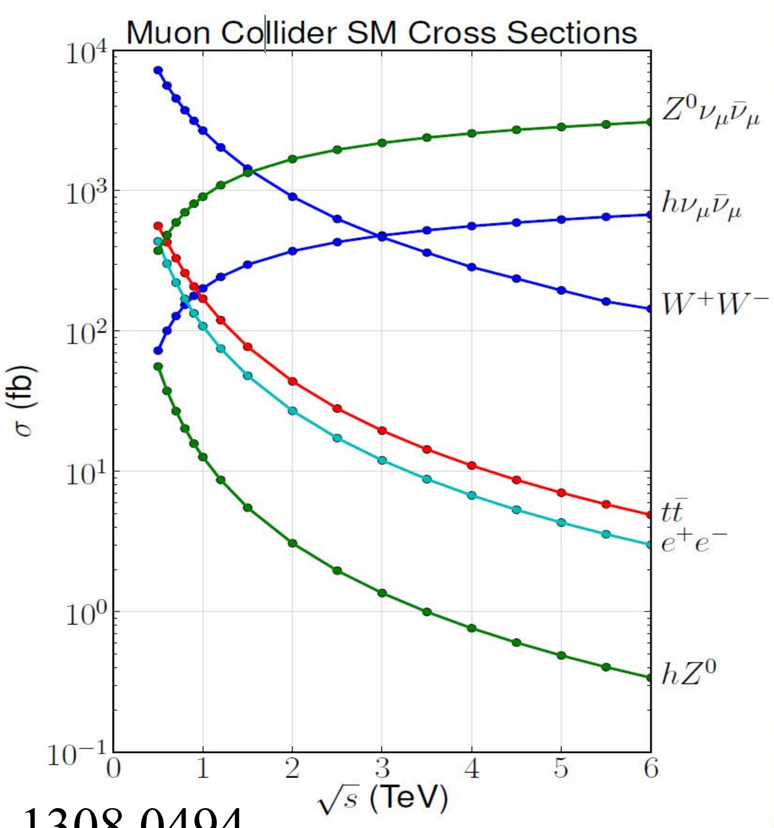
Multi TeV Muon Collider Possibilities

When √s>1 TeV fusion process dominate



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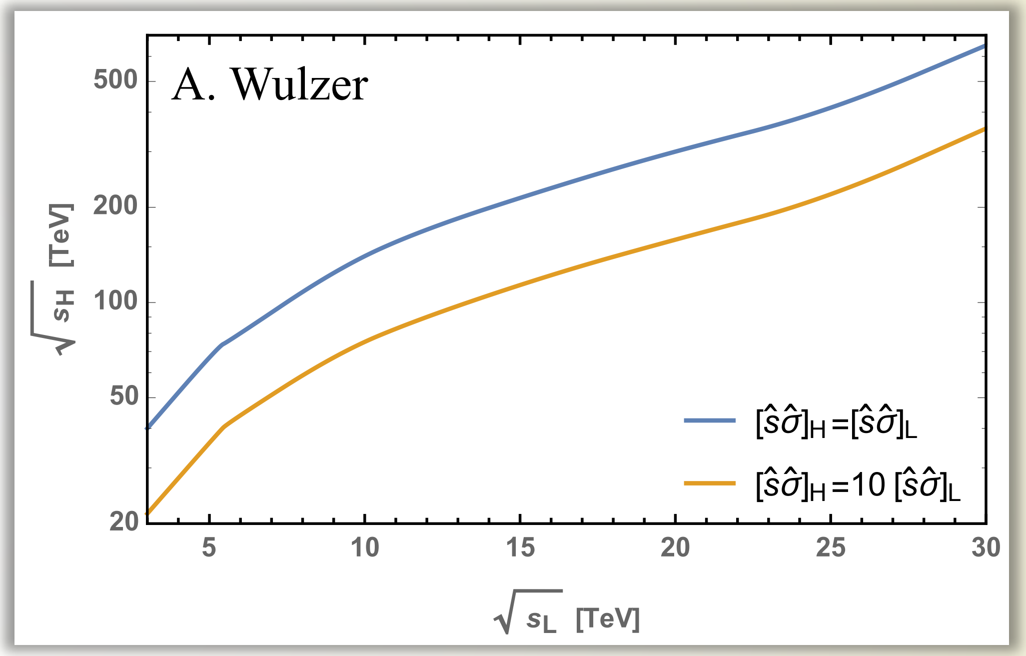
Detailed studies are needed but we can expect a 6 TeV muon collider with the same luminosity as CLIC have comparable performances in boson fusion phenomena

At very high energy it's a discovery machine!



$$\sigma_L(s_L) = \frac{1}{s_L}[\hat{s}\hat{\sigma}]_L \qquad \sigma_H(E, s_H) = \frac{1}{s_H}\int_{E^2/s_H}^{1}\frac{d\tau}{\tau}\frac{dL}{d\tau}[\hat{s}\hat{\sigma}]_H$$

It does not take into account physics process

Detailed simulations are needed to assess the reach

Current Status of Muon Collider Projects

A lot of work done within the MAP , Muon Accelerator Program
μ from hadrons, mainly π decay
Main difficulty is the muon cooling

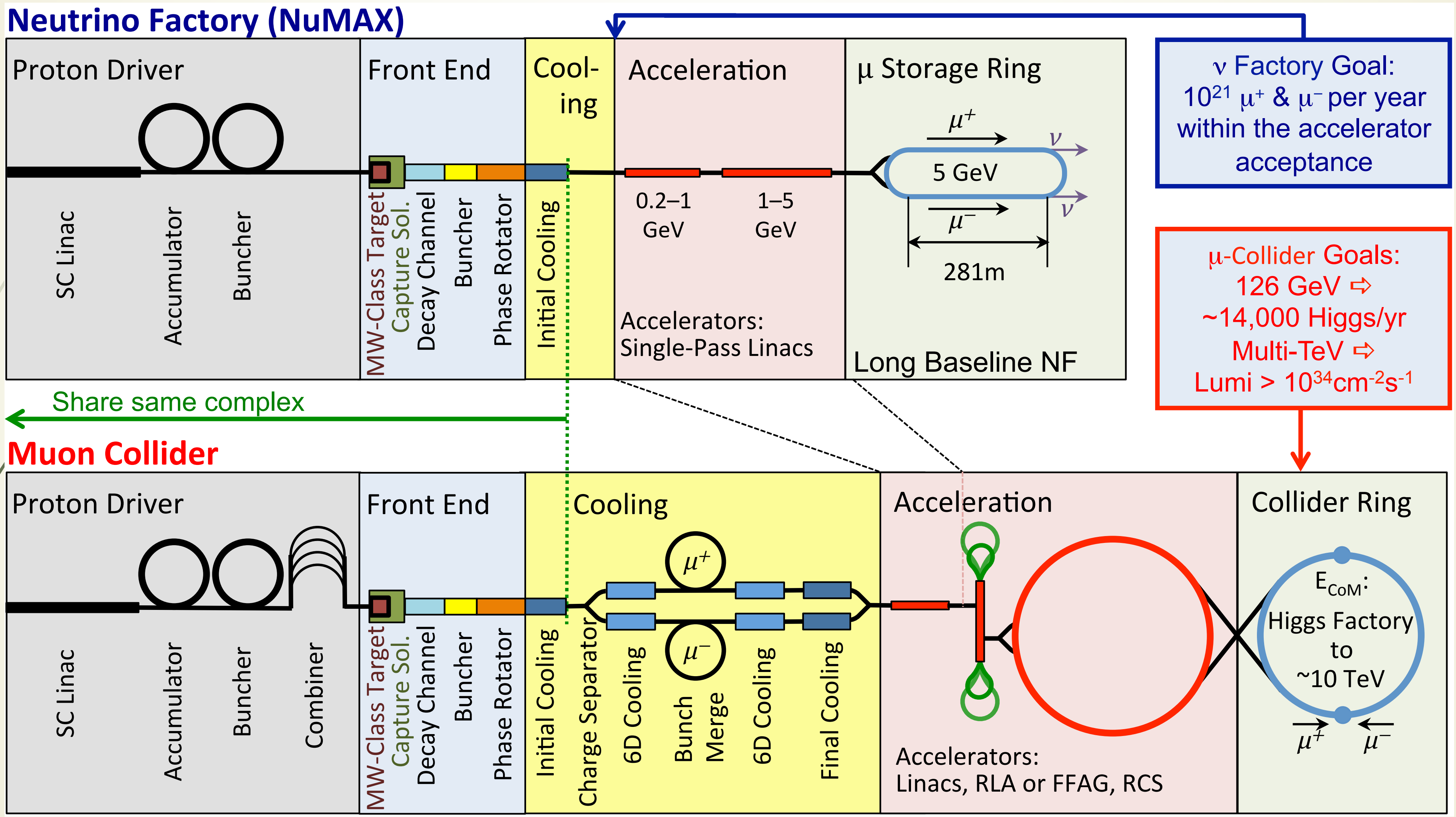
Other new ideas

- e^{+} annihilation on target, Low Emittance Muon Source
- π/μ production from γ-p collision at LHC or FCC L. Serafini et al.
- $e^{\pm}$ and μ production in γ-PSI (Partially Stripped Ions) collisions at LHC or FCC –"Gamma Factory" W. Krasny

Muon Collider Main Features

- Muon Source
  - Hadron production
    - $p \rightarrow Target \rightarrow \pi^{\pm} X \rightarrow \mu^{\pm} \nu X$
    - Phase space of $\pi^{\pm}, \mu^{\pm}$ is very large $\Rightarrow$ emittance has to be cooled by factors $\sim 10^6$
    - High production rate, Rate > 10^{13} μ/sec $N_{\mu} = 2\times10^{12}$/bunch
  - e^+ annihilation on target e^-
    - $e^+ \rightarrow Target \rightarrow \mu^+\mu^-$
    - No cooling needed
    - Modest production rate, Rate ≈ 10^{11} μ/sec $N_{\mu} \approx 6\times10^{9}$/bunch
- Acceleration
- Collider Ring
- Collider Machine Detector Interface
- Collider Detector

MAP Proposal



[Muon Accelerator Program](#)

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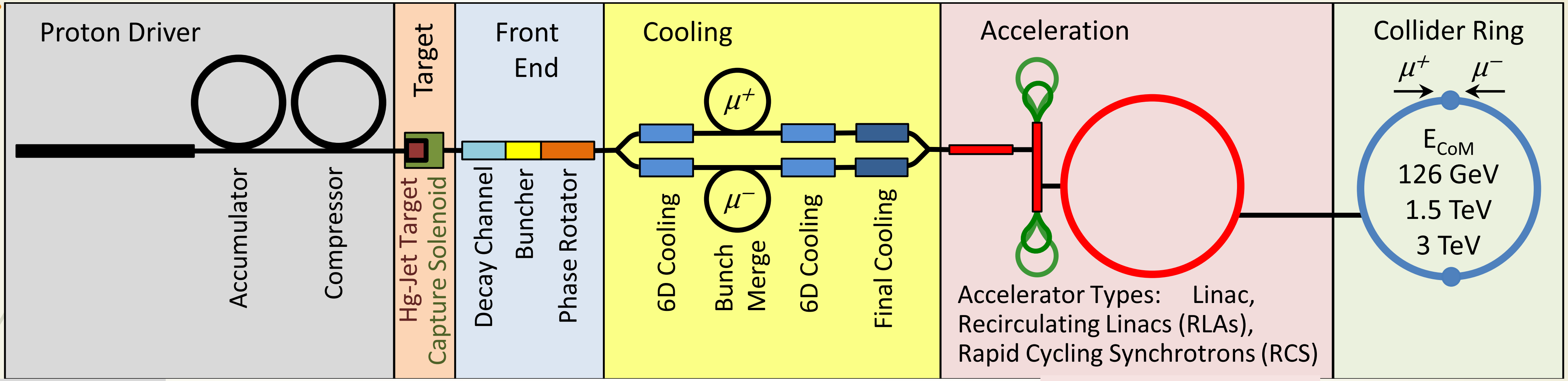
MAP Proposal – Muon Collider

Muon Accelerator Program



- 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

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M. Palmer

Muon Collider Parameters

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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

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

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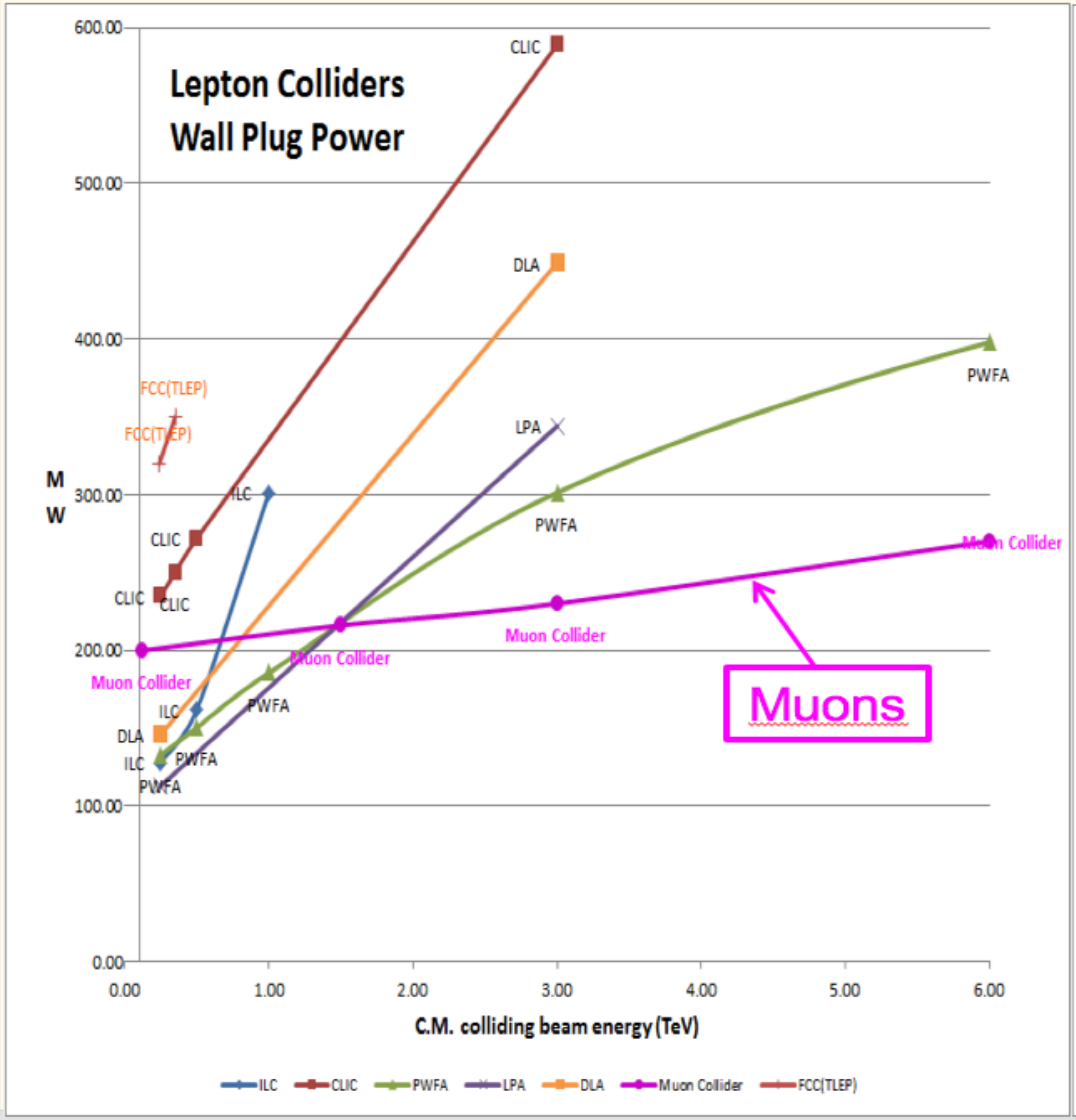
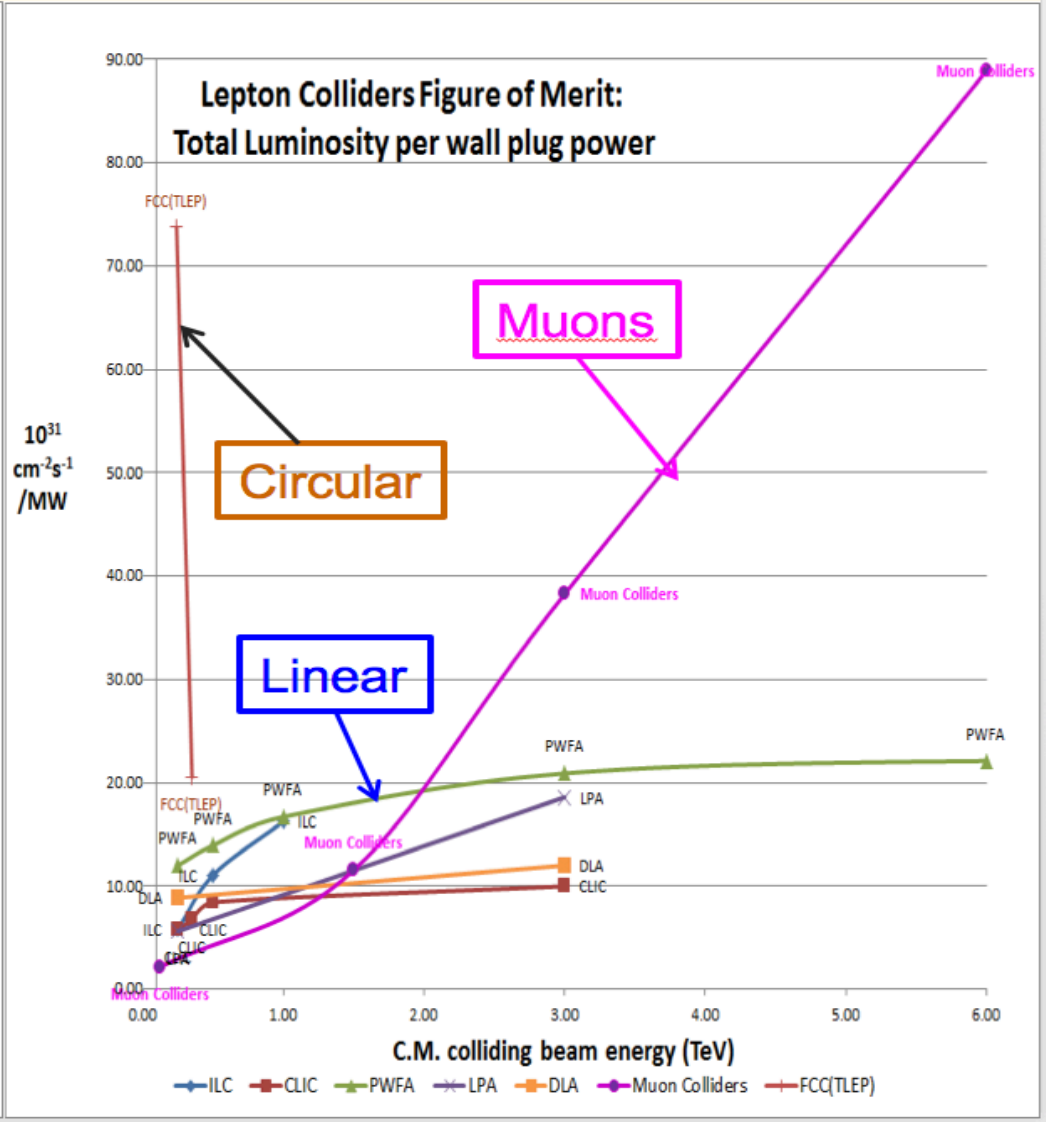
Muon Colliders extend leptons high energy frontier with potential of considerable power savings





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The lesson I learnt

- It will be perfect to have a:
  - Higgs factory, a muon collider machine running at Higgs mass energy
  - multi-TeV muon collider machine to explore the very high energy regime
- These two are different options and it is necessary to:
  - study and tune dedicated machine parameters
  - design and simulate the experimental apparatus to collect data, taking into account the background conditions
- The physics reaches in both cases require detailed studies including detectors simulation and machine background conditions

Low Emittance Muon Source Idea

Exploit $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold, $\sqrt{s} \sim 0.212$ GeV, in asymmetric collisions to generate beams of μ^+ and μ^-

Pro's

1. Low emittance: muon emission angle respect to the beam, θ_μ, is tunable with $\sqrt{s}$, it can be very small around the $\mu^+\mu^-$ production energy threshold
2. Energy spread: muon energy spread small at threshold, it gets larger as $\sqrt{s}$ increases
3. Low background:
   - muon can be produced with a relatively high boost in asymmetric collisions reducing losses from decay
   - low emittance allows high luminosity with modest muon fluxes $\Rightarrow$ low background and low ν radiation therefore we can reach high energy

Con's

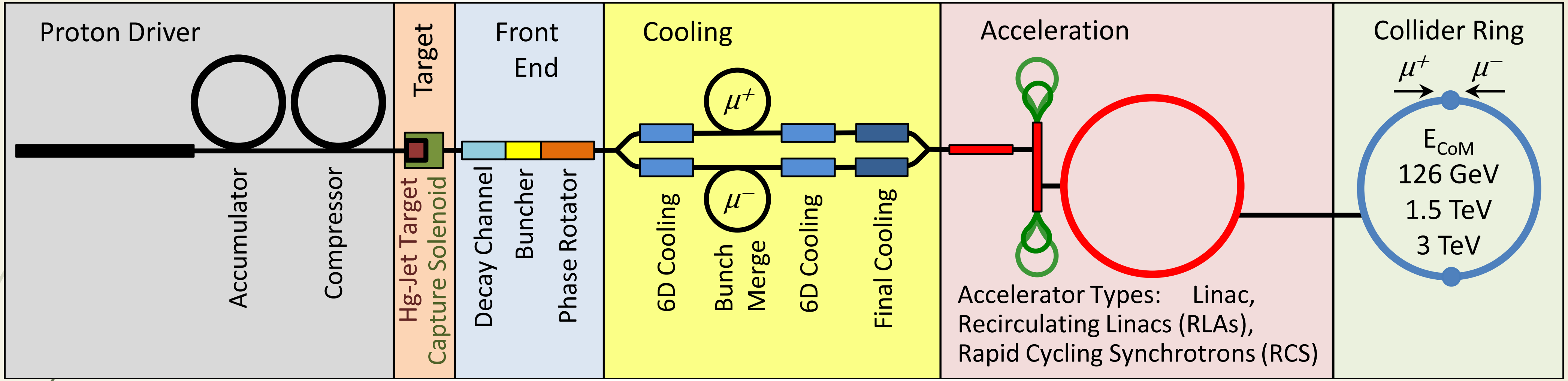
Low Rate: $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1\mu b$ (at most), to be compared to $\sigma(\text{ph} \rightarrow \mu^+\mu^-) \approx$ mb

The possibility to use low energy e^+e^- beams is not viable, it requires luminosity $\approx 10^{40}$ cm^{-2} s^{-1}

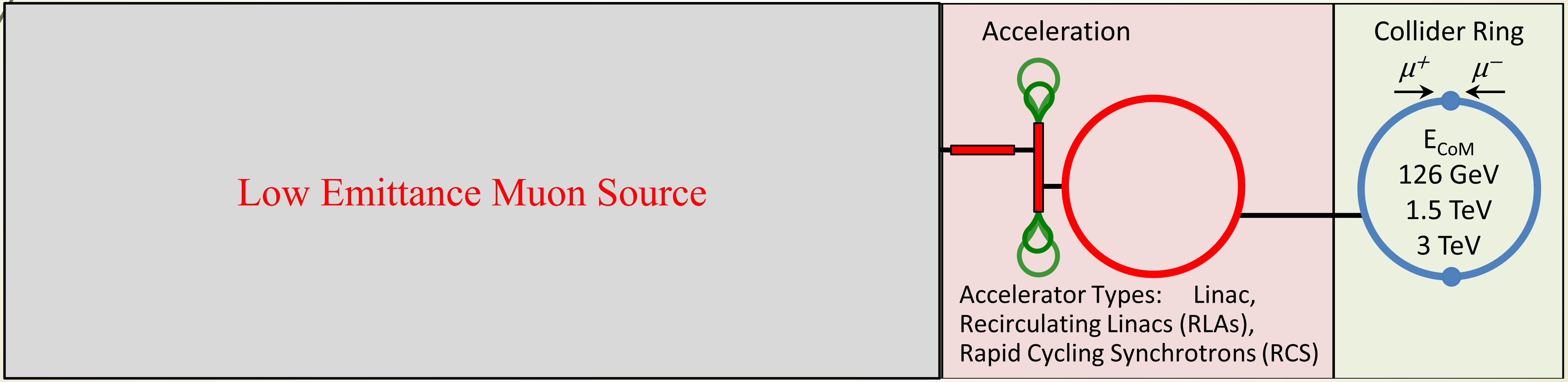
Positron on target are considered

Low Emittance Muon Collider

Original proposal



becomes



Study of $e^+e^- \rightarrow \mu^+\mu^-$ at the threshold

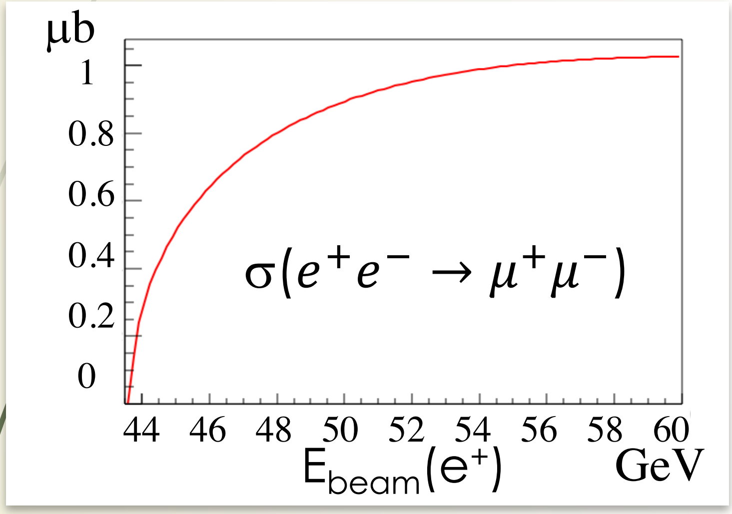
Main contributing process

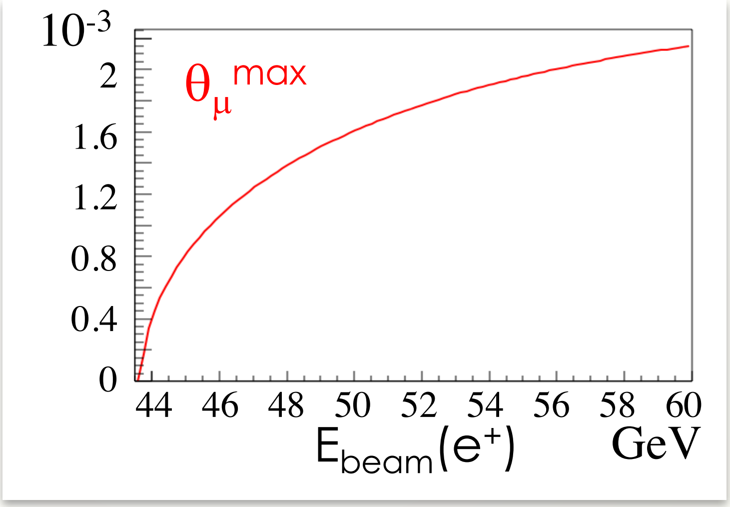
- $e^+e^- \rightarrow \mu^+\mu^-$
- $e^+e^- \rightarrow e^+e^-\gamma$ (dominant)
- $e^+e^- \rightarrow \gamma\gamma$

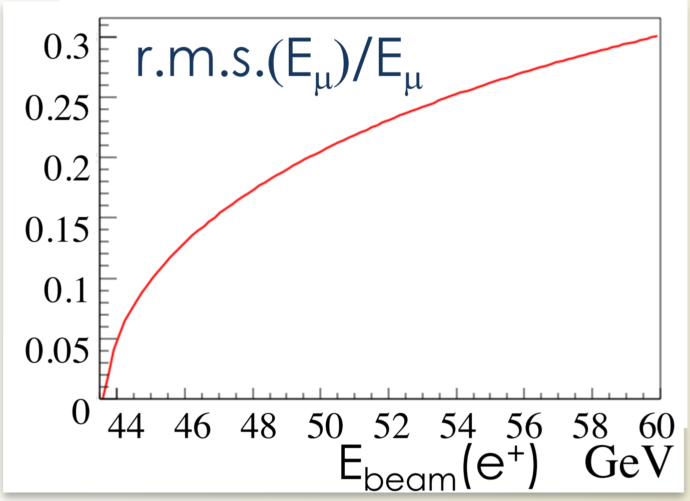
We need

- Maximum muon production
- Minimum muon bunch emittance
- Minimum muon energy spread

From very simple calculation







E_{beam} (e^+) = 45 GeV is assumed

$\gamma(\mu)\approx 200 \Rightarrow$ laboratory lifetime of about 500 μs

"Natural" Beam Energy Spread 0.05

Target Considerations

Choice driven by:

- High number of $\mu^+\mu^-$ pair production $\Rightarrow$ high Z and high density
- Low positron loss for beam re-circulation $\Rightarrow$ low Z
- Low muon bunch emittance $\Rightarrow$ thin target

Plasma target option

- Best approximation of an electron target
- Size of electrons high density region goes as ~ 1/(plasma density)
- If n(e^-)= $O(10^{20})$ $\Rightarrow$ length-scale O(μm) range therefore it is too short to be used

Conventional target study

- Preliminary study with GEANT4:
  - e^+ beam of 44 GeV
  - Cu, C, Diamond, Be
- Tuning thickness to have same

$$eff(\mu^+\mu^-) = \frac{N(\mu^+\mu^-)}{N(e^+)}$$

	Cu	C	Diamond	Be
target thickness (cm)	0.4	0.9	0.5	1.0
target thickness (X_0)	0.29	0.04	0.04	0.03
target thickness (10^{-7} $\lambda(\mu)$)	2.7	1.6	1.6	1.6
muon emittance at production (nm)	0.19	0.16	0.09	0.17
$eff(\mu^+\mu^-)(10^{-7})$	1.6	1.6	1.6	1.6
e^+ fraction for $\delta E/E < 10\%$	0.46	0.90	0.90	0.93

Target Considerations: Crystals

	Cu	C	Diamond	Be
target thickness (cm)	0.4	0.9	0.5	1.0
target thickness (X_0)	0.29	0.04	0.04	0.03
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e^+ fraction for $\delta E/E < 10\%$	0.46	0.90	0.90	0.93

- In presence of channeling phenomena, target does not contribute to the muon emittance
- Dimuon production cross section for e^+ beam of 44 GeV on diamond ~ 0.1 μb
- It could be an option for a muon collider at 125 GeV

Full simulation study is needed to evaluate also thermomechanical characteristics of the target

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The Luminosity

By using a 45 GeV e^+ beam on target, maximum $eff(\mu^+\mu^-) = \frac{N(\mu^+\mu^-)}{N(e^+)} = 10^{-5}$

A very intense e^+ beam is needed

	SLC	CLIC	ILC	LHeC	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}\text{s}^{-1}]$	0.06	1.1	3.9	18	440

Conference Proc.

Assuming e^+ beam with $N(e^+)/s \sim 10^{14}$ (CLIC) $\Rightarrow$ $N(\mu^+\mu^-)/s \sim 10^8$ $\Rightarrow$ Low luminosity

Multipass scheme is considered in order to reach $N(\mu^+\mu^-)/s \sim 10^{11}$

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Multi-Tev Muon Source Study

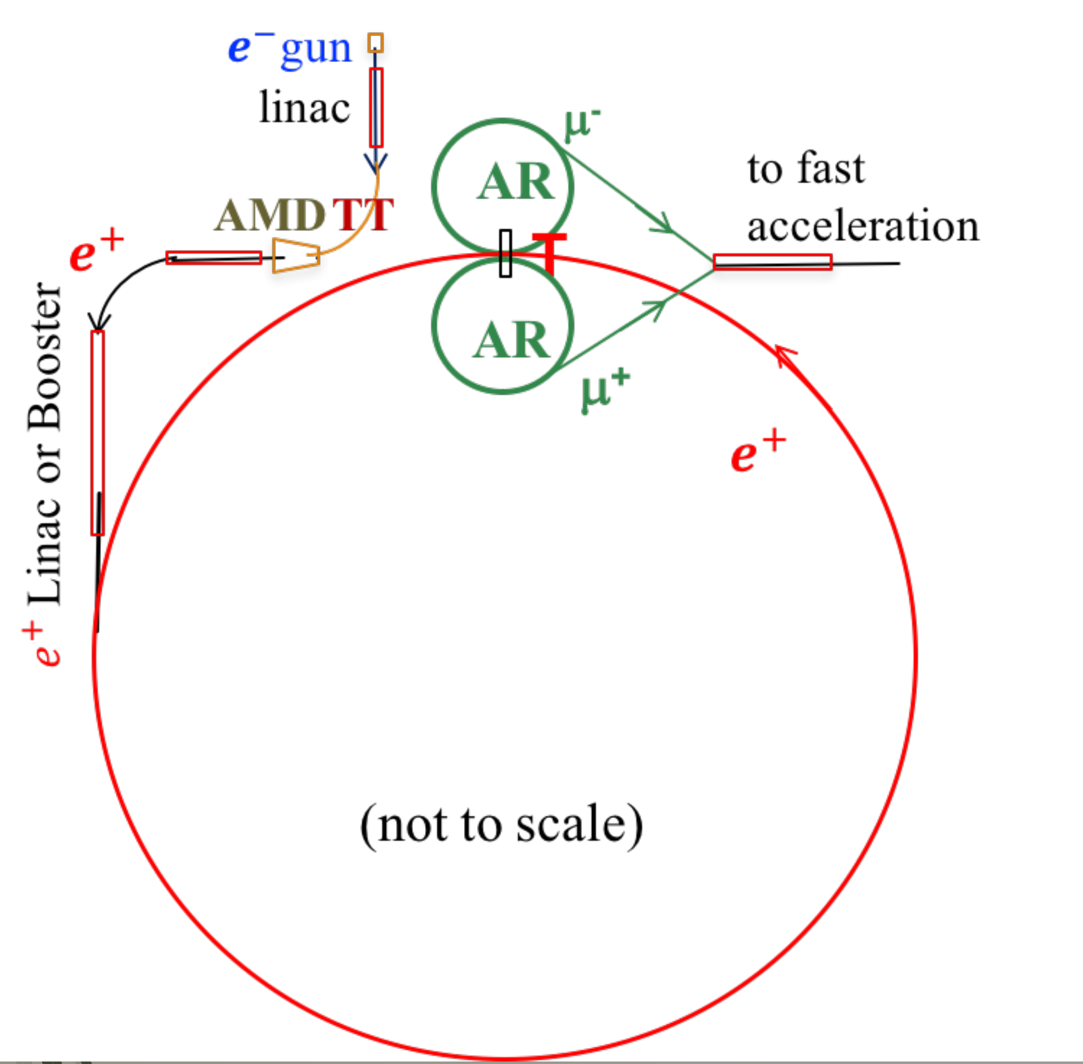
"easy" case:

- No need of extreme beam energy resolution
- Use thin target with high efficiency and small e^+ loss
- Positrons in storage ring with high momentum acceptance

The goal is: $N(\mu^+\mu^-)/s \sim 10^{11}$

- If $eff(\mu^+\mu^-) \approx 10^{-7}$ with a Be target $\Rightarrow N(e^+)/s \sim 10^{18}$ needed on the target
- Positron beam with the largest possible lifetime to minimize positron source rate
- LHeC-like positron source rate

Possible Schema for Low Emittance Muon Source



Positron Source

- e^- on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- Adiabatic Matching Device (AMD) for e^+ collection

Positron Ring

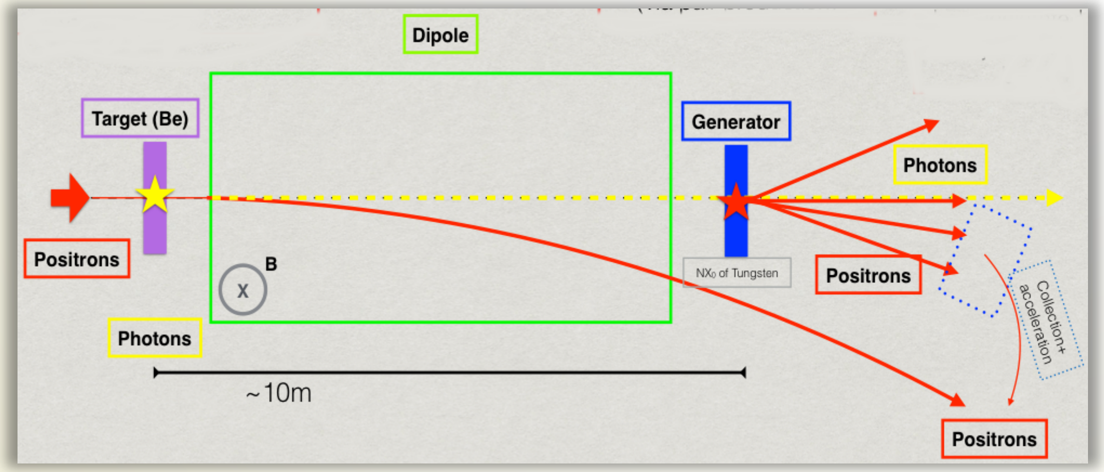
- Acceleration and injection (Linac/Booster)
- 6.3 km 45 GeV storage ring with target **T** for muon production

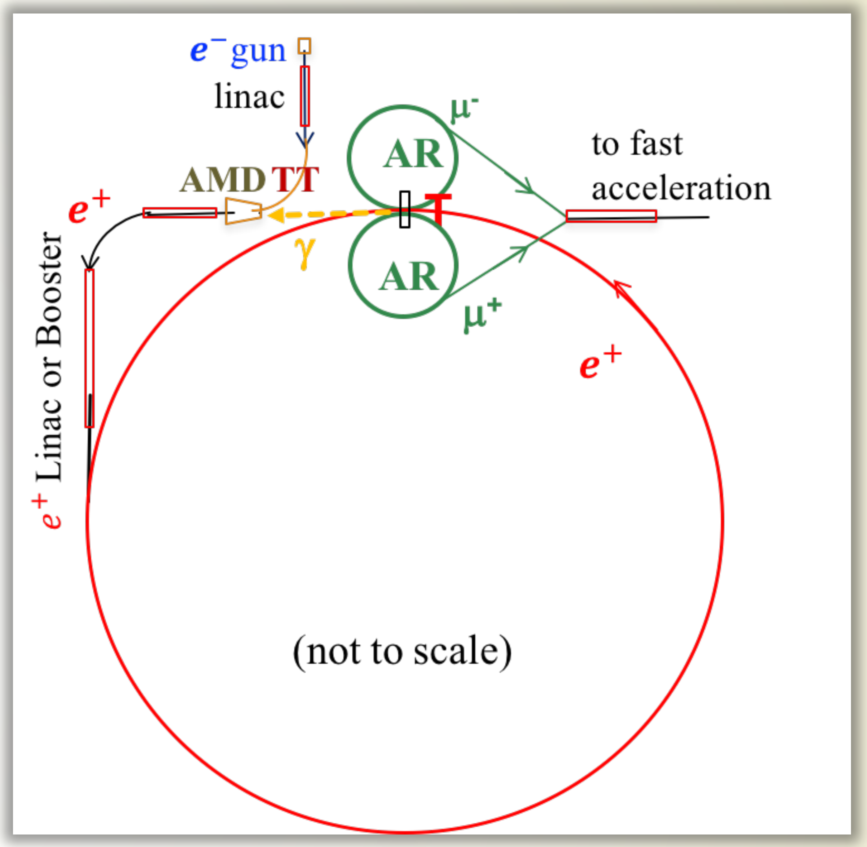
Muon Beams

- $\mu^\pm$ produced by e^+ beam on target **T** with E≈ 22GeV, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx 500\mu s$
- **AR**: 60 m isochronous and high momentum acceptance rings to recombine $\mu^\pm$ bunches in~1 τ_μ^{lab} ≈2500 turns
- $\mu^\pm$ fast acceleration

Considerations on Positron Source

- Positron source of $N(e^+)/s \sim 10^{18}$ or $N(e^+)/bunch \sim 3\times10^{11}$ is about two order of magnitude higher of LHeC ERL and much more the existing positron sources
- Monte Carlo simulation indicates ~3% of primary positrons are lost due to interaction in the target (re-circulation)
- An hybrid (not conventional) scheme:
  - γ produced in the target (T) are sent to a generator to produce e^+e^-





Geant4 Simulation:

- $5X_0$ of Tungsten as generator
- Preliminary results seem promising, more to come

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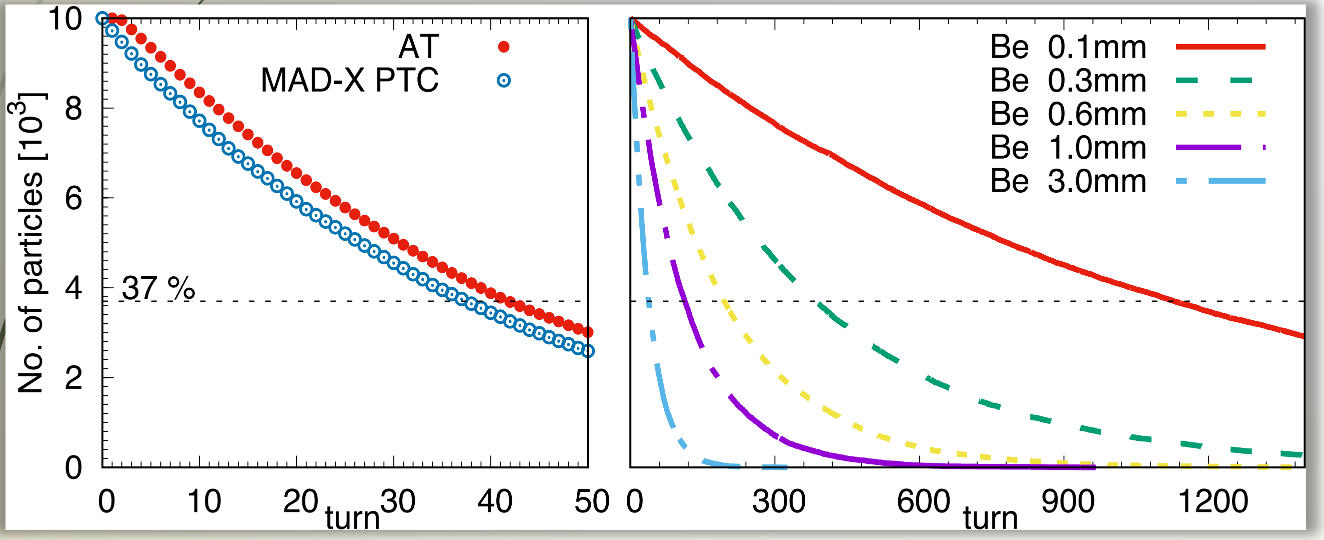
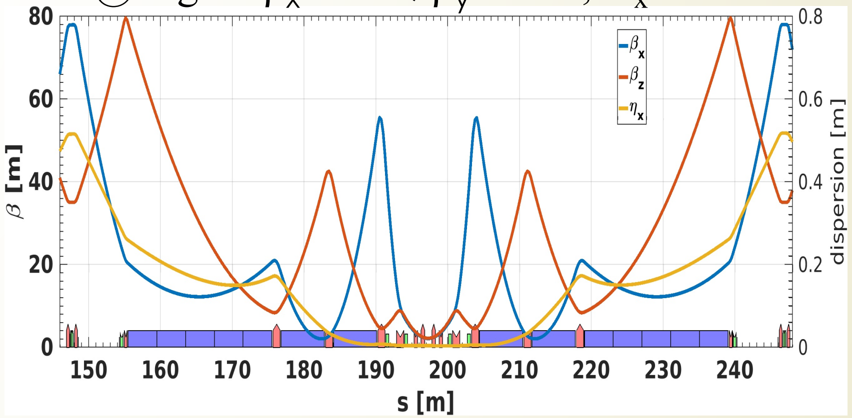
The Positron Ring

- Positron ring has to have: low emittance, high momentum acceptance and low-β Interaction Region (IR)
- First design of the optics is available: circumference 6.3 km: 197 m x 32 cells
- Dedicated multi-turn simulation algorithm developed:
  - Particle tracking in the ring (AT and MAD-X PTC)
  - Positron interaction in the target (Geant4beamline, FLUKA and GEANT4)
- Detailed IR simulated but optimization is needed



@target: β_x=1.6m; β_y=1.7m; D_x=5.4mm



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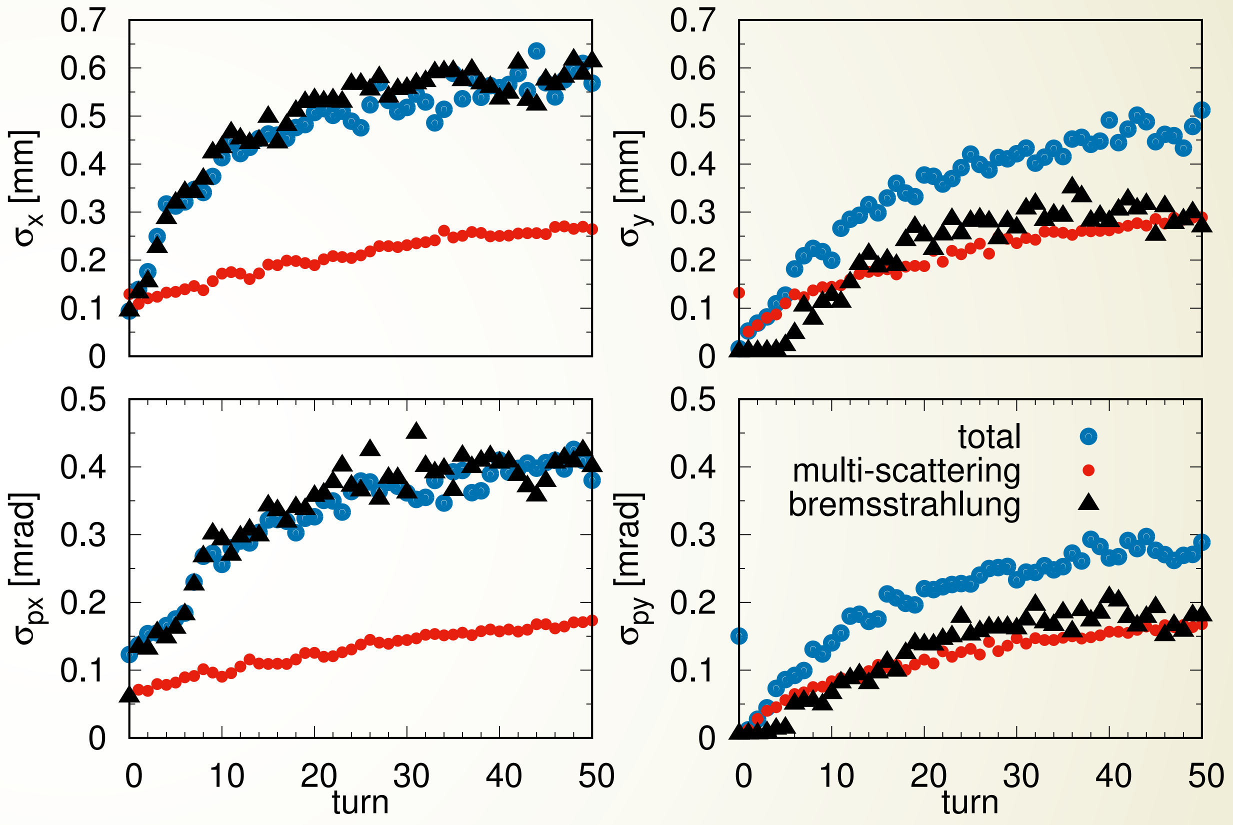
Positron Beam evolution: Size and Divergence

Study performed as function of the beam turns by separating multiple scattering and bremsstrahlung effects:

- Longitudinal (beam direction) phase space growth dominated by radiative energy loss
- Transversal to the beam phase space size dominated by multiple scattering
- Use 3mm Be Target (0.8% X_0) at center of IR



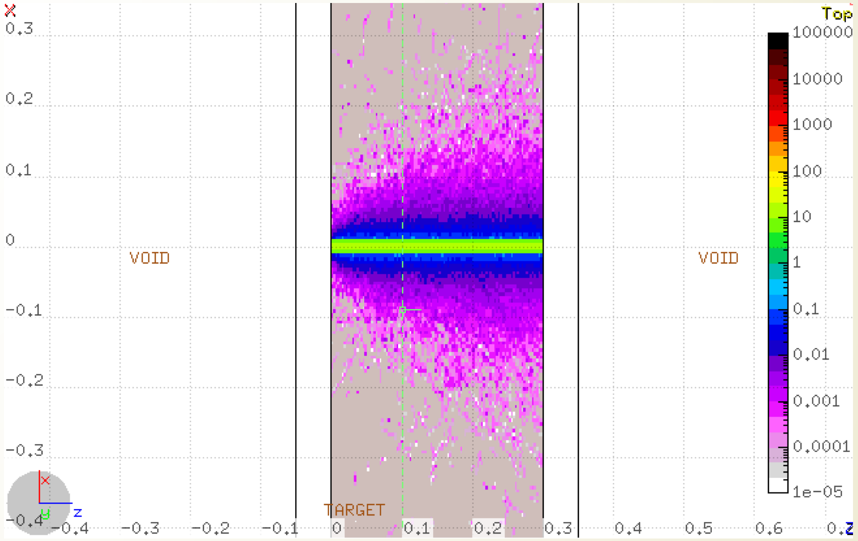
Target related Issues

Assumption:

- bunch of $N(e^+) \sim 10^{11}$with a transverse size of $\sim 10\mu m$
- Bunch spacing 200 ns
- no pile-up bunches in the same position of the target, obtained for example with a rotating target

About ~100 kW of power has to be removed from the target to keep temperature under control and avoid damages.

Just started the simulation using FLUKA + Ansys Autodyn with 3mm Be target $\sim 20\mu m$ beam size and $N(e^+) = 3\times10^{11}$



We would like to perform experimental tests:

- **FACET-II** available from 2019

  10^{11} e^-/bunch, 10 mm spot size, 100 Hz
- **DAFNE** available from 2020

6 TeV Muon Collider Parameters

Muon Emittance
$\varepsilon(\mu) = \varepsilon(e^+) \oplus \varepsilon(MS) \oplus \varepsilon(rad) \oplus \varepsilon(prod) \oplus \varepsilon(AR)$

$\varepsilon(e^+) = e^+$emittance
$\varepsilon(MS)$ = multiple scattering contribution , target & material
$\varepsilon(rad)$ = energy loss contribution, target & material
$\varepsilon(prod)$ = muon production contribution, $\varepsilon(e^+)$ & target thickness
$\varepsilon(AR)$ = accumulator ring contribution, optic & target

No Lattice simulation, only calculation

Parameter	Units	Value
√s	TeV	6
Luminosity/IP	$[10^{34}]$	5
BES	%	0.07
Circumference	km	6
N. of IP		1
Frequency	Hz	5×10^4
Beta	m	2×10^{-4}
N. of muon/bunch		6×10^9
Norm. Emittance	m	4×10^{-8}
Bunch length	mm	0.1

Experimental Tests @H4 CERN Summer 2017

Goals of the tests:

I. measurement of $\mu^{+}\mu^{-}$production cross section and muons kinematic properties
   - Interesting measurement and useful to tune simulation

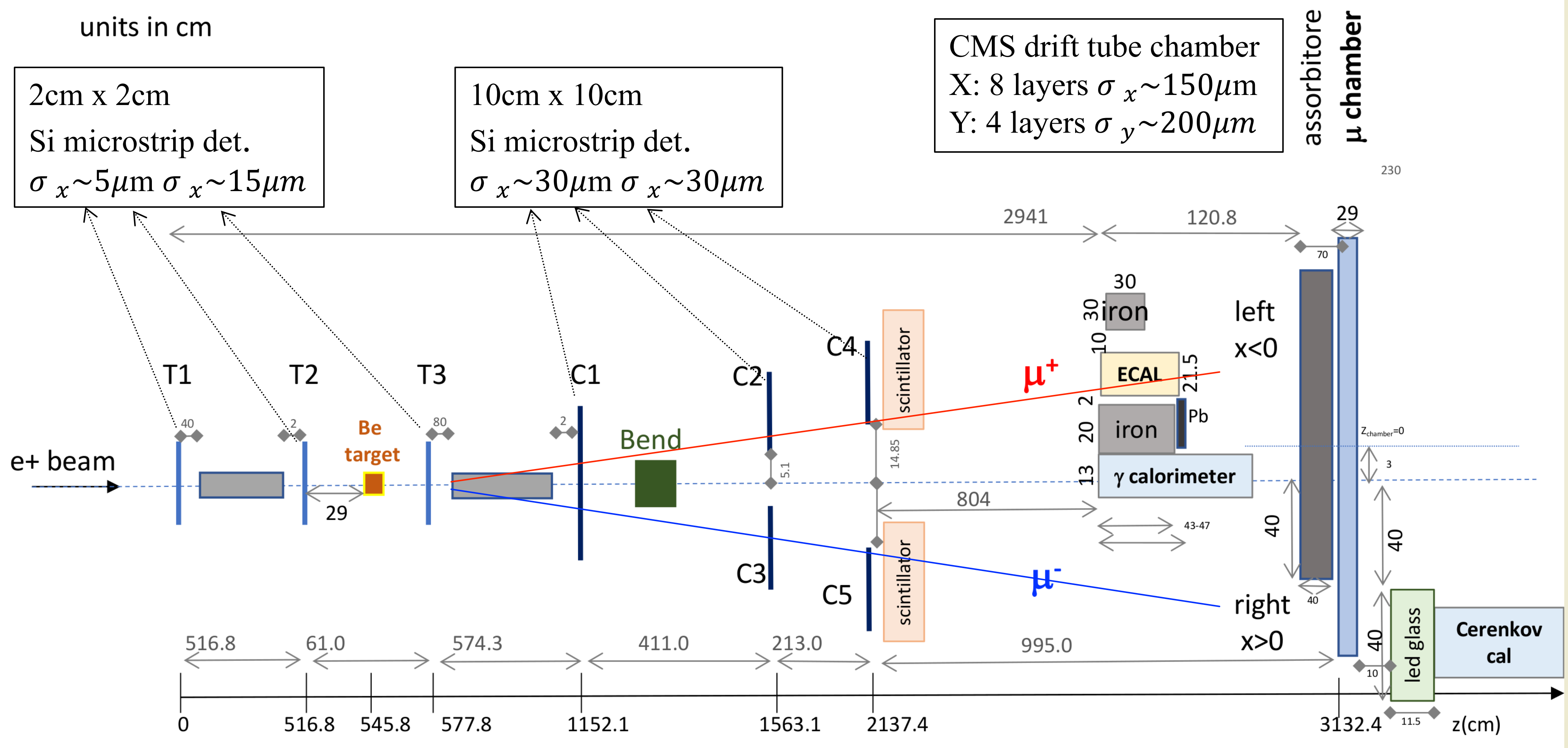
II. determination of beam degradation: emittance and energy spectrum
   - useful for simulation tuning

Procedure:

- ❑ Set up almost from scratch of an experimental facility in H4
- ❑ Use of 6 cm Be target
- ❑ Requested: 45 GeV e^{+} on target, beam spot 2 cm, mrad divergence
- ❑ High intensity beam, up to 5 x 10^{6} e+/spill, (spill ~15s)
  - o Measurement of $\mu^{+}\mu^{-}$ properties
- ❑ Low intensity beam
  - o Measurement of beam properties

- ✓ Assigned 1 week out of 2 requested
- ✓ We gave priority to high intensity beam, we had 2 days at $\approx 10^{6}$ e^{+} /spill
- ✓ Requested one week in 2018 to complete original program

Experimental Tests: facility layout



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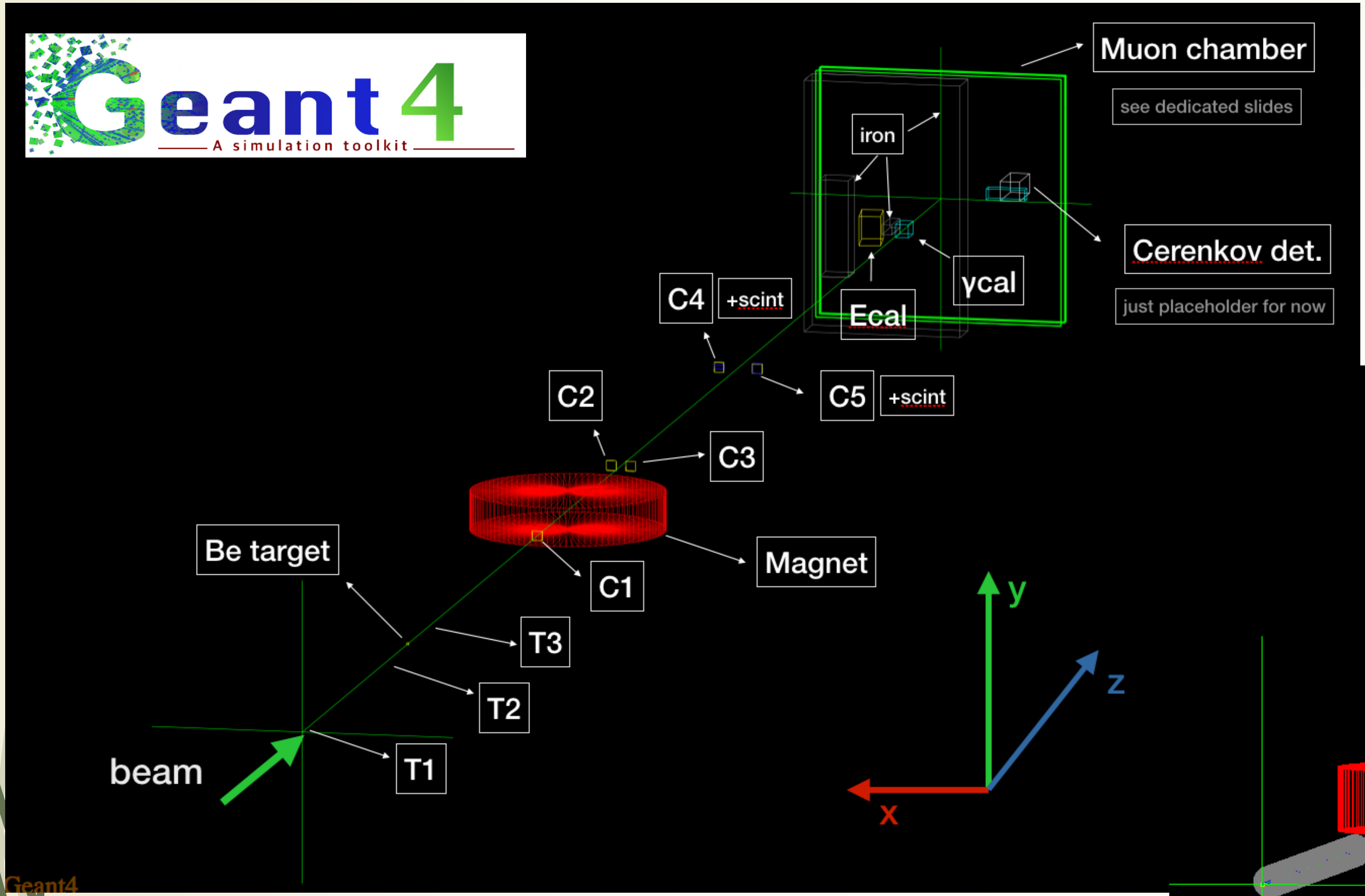
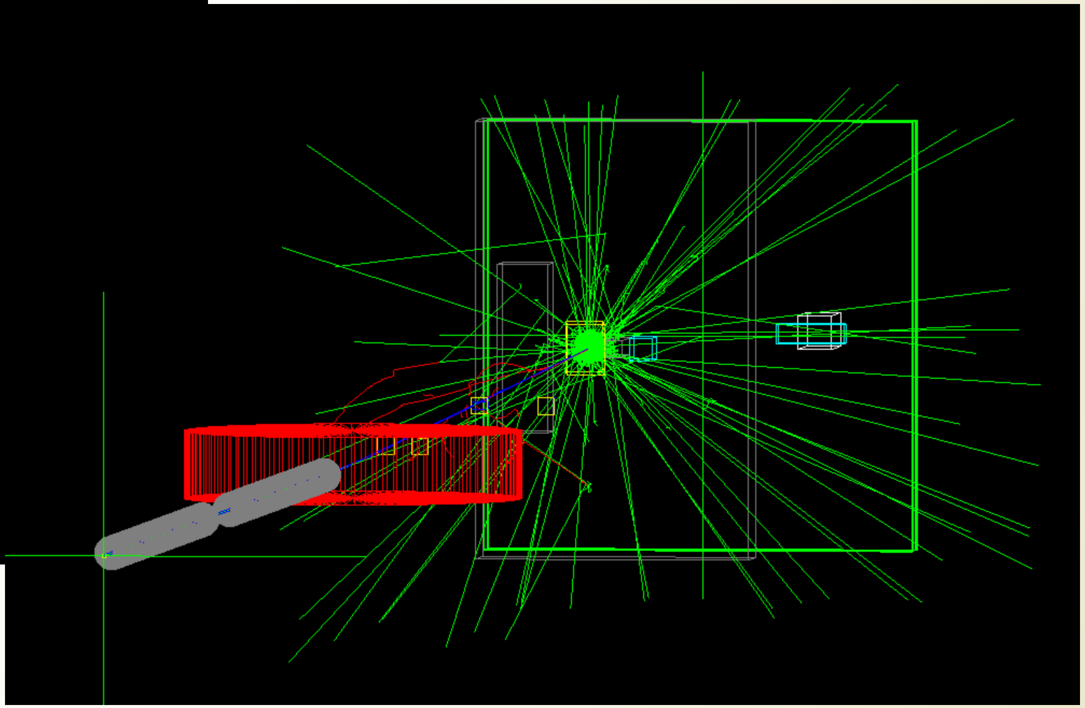
Experimental Tests: facility layout simulation





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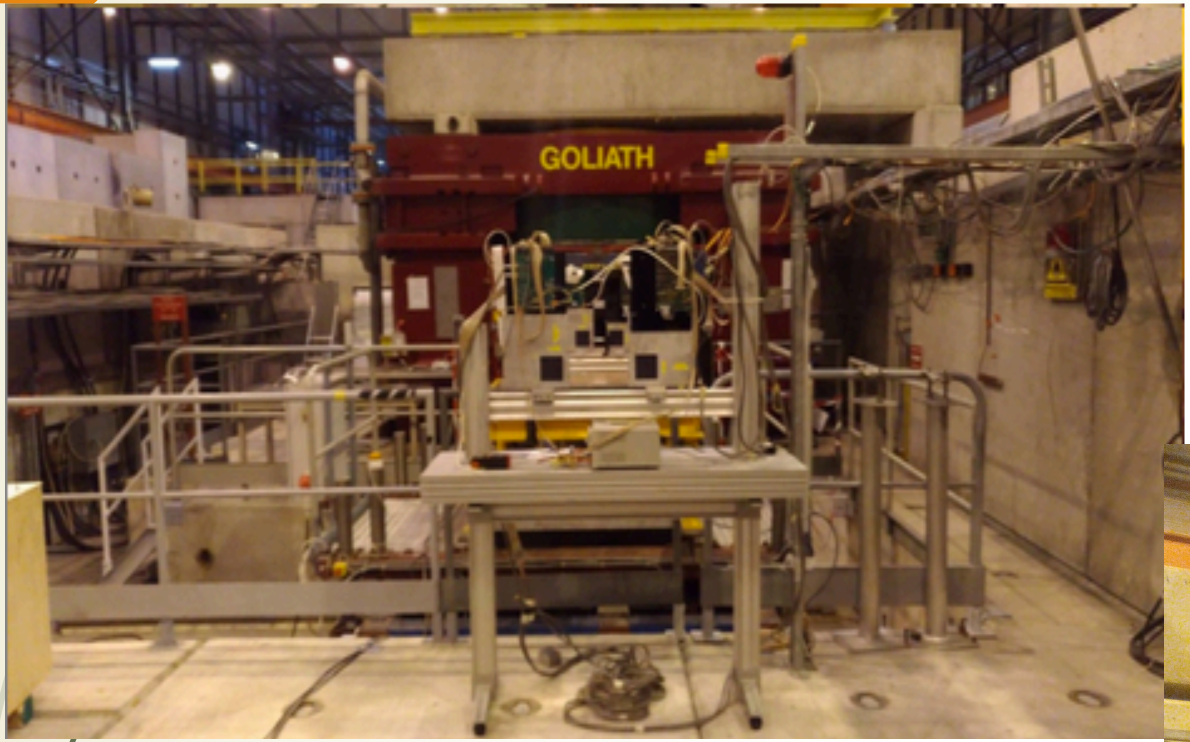
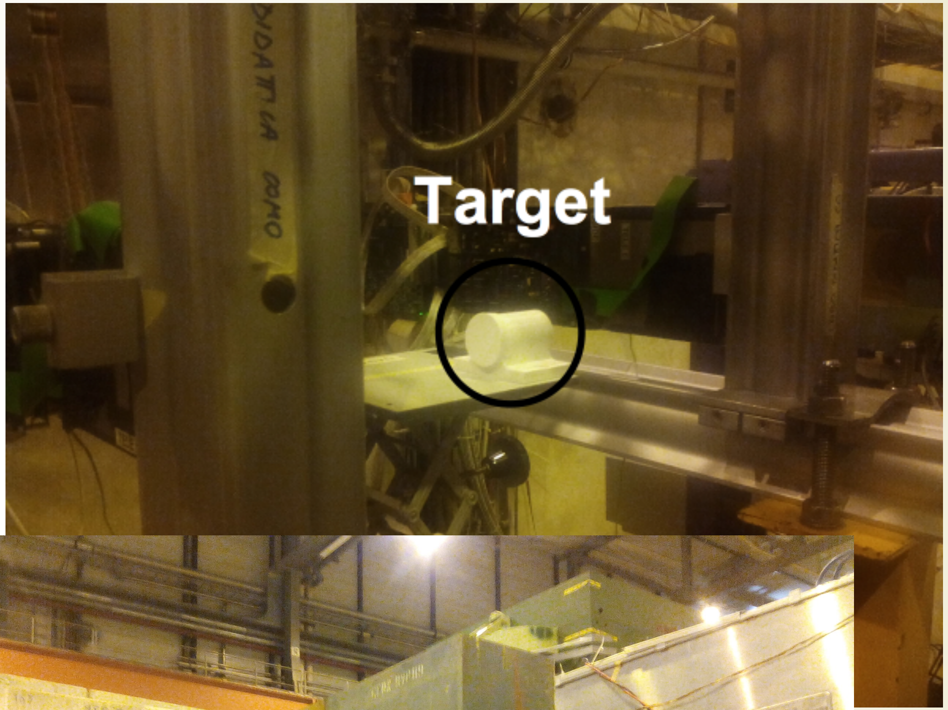
Experimental Tests: the facility@H4 CERN North Area



Front view



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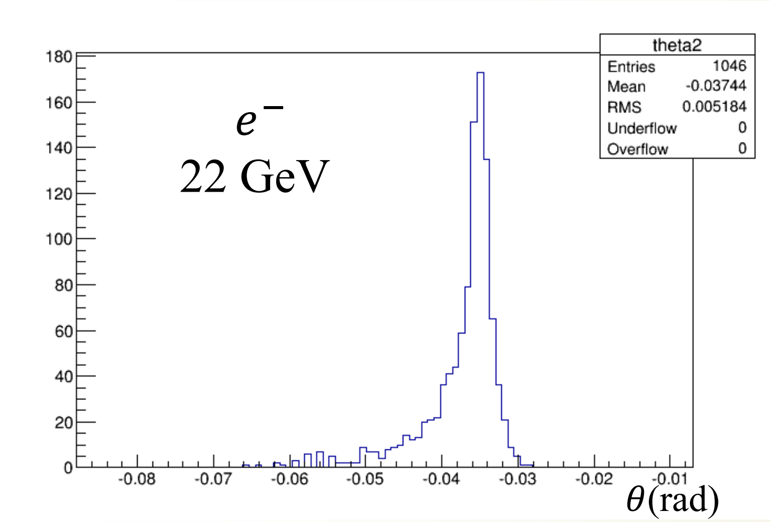
Tracks reconstruction

Developed stand-alone tracking fitting code for μ^- (μ^+ affected by multiple scattering)

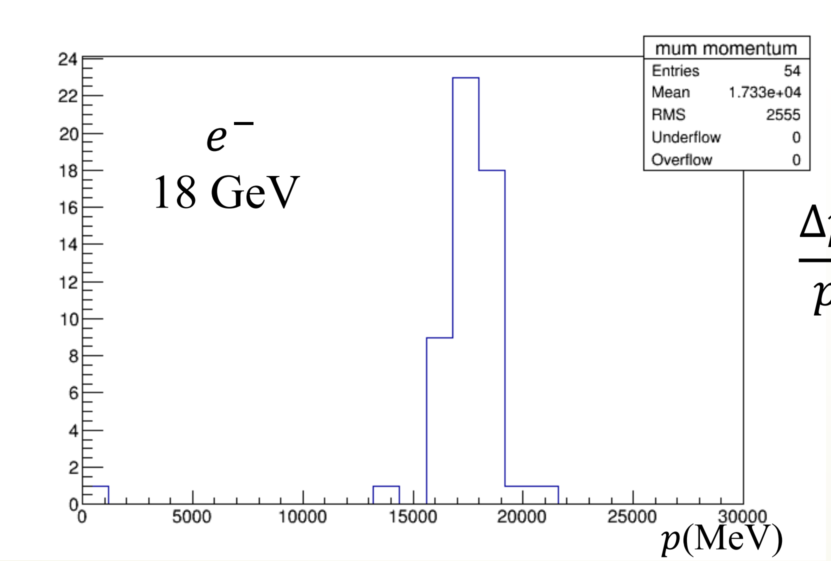
- Start from hits in the muon chamber
- Propagate backward to silicon planes

Calibrations

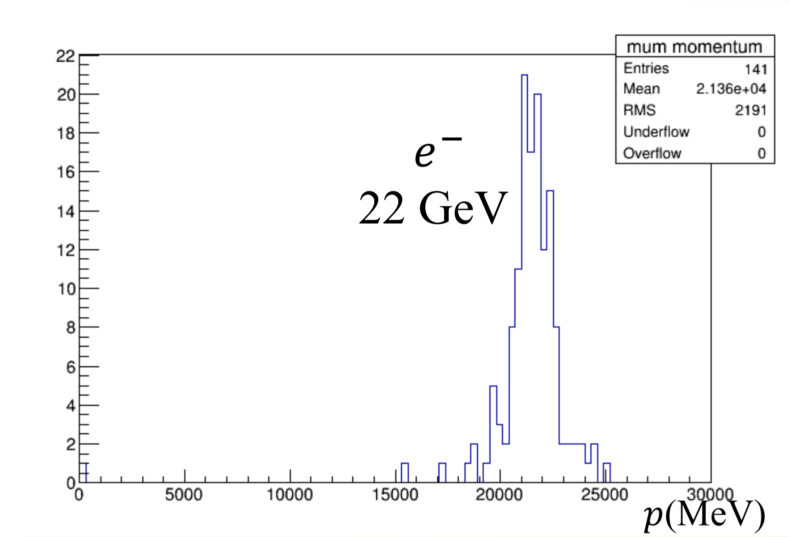
- electrons beam of 18 and 22 GeV
- no target



$\frac{\Delta\theta}{\theta} \sim 13\%$



$\frac{\Delta p}{p} \sim 14\%$



$\frac{\Delta p}{p} \sim 10\%$

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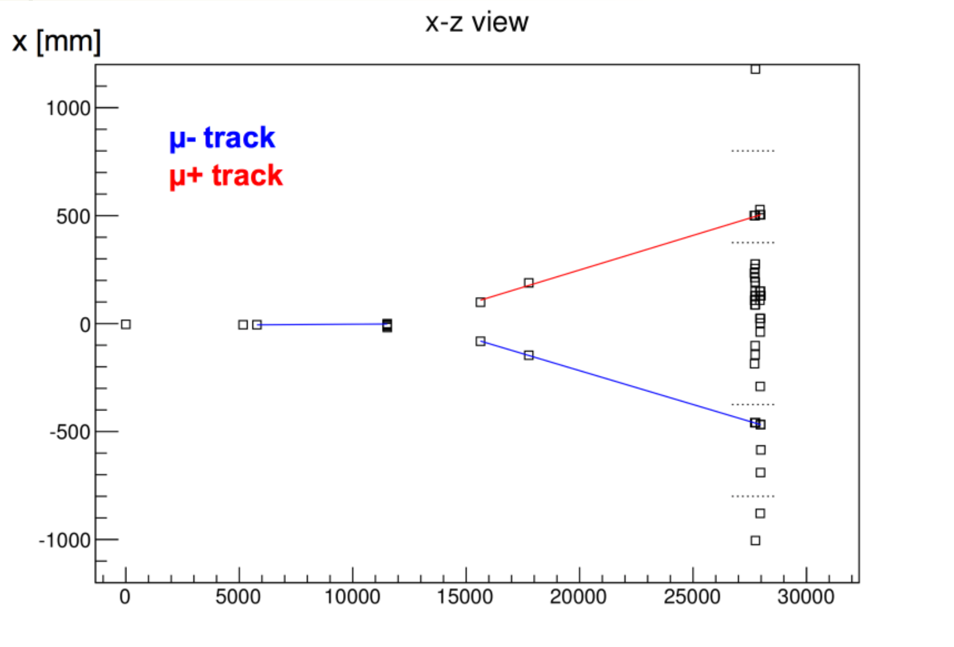
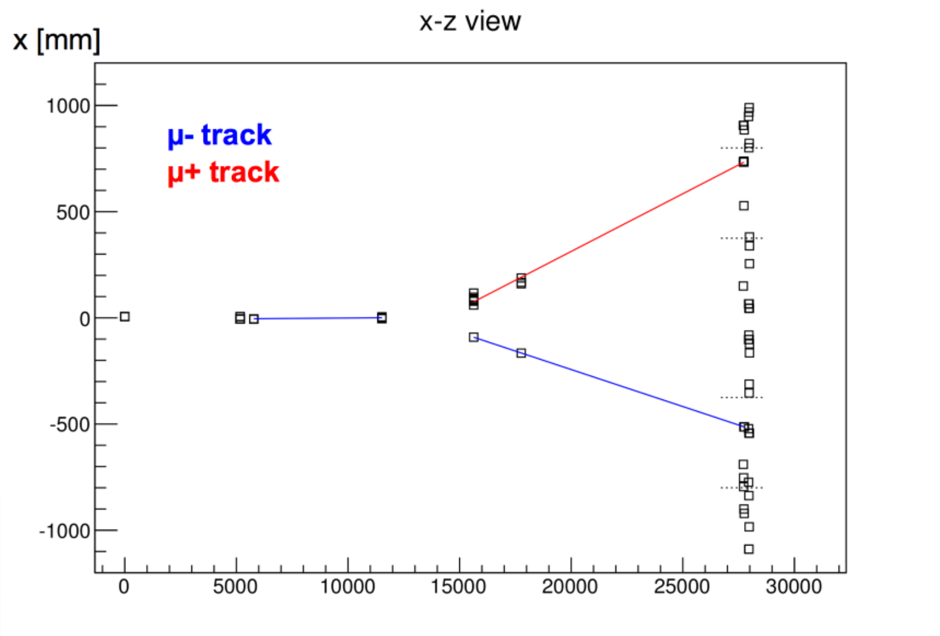
Preliminary results

Search for $\mu^+\mu^-$ candidates:

- Full reconstruction of a negative charge track (can be μ^- or e^-)
- Find a stub in the muon chamber with good χ^2





Not enough statistics to perform the measurements we aimed at.

Low Emittance Muon Source Summary

The preliminary study of the $e^+e^- \rightarrow \mu^+\mu^-$ process as a muon source seems promising but a lot of work has to be done. In particular we identified three main areas:

- High intensity positron source, in progress also for other accelerators but has to be tuned for this case;
- Target optimization, both simulation and experimental test need to address thermomechanical issues
- Experimental tests to verify the low emittance muon production and the effects of the target on the beam

Final Summary

For the first time in several years the high energy physics path is not obvious.
A great occasion to make a big step forward!

The European Strategy update study is starting.
The discussion on the future collider machine will have to take into account everything:

- ✓ Physics reaches
- ✓ Costs
- ✓ Time from construction to physics results

Muon Collider is back on the table:

- a novel accelerator technique, interesting by itself
- unique Higgs and new Physics measurements well within reaches
- technological developments can inspire new spin-offs
- great challenge at international level and fantastic opportunity for young people