Muon Collider: studies of a low emittance muon source using positrons on target

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Outline

- Physics motivations
- Muon collider from a proton-based muon source
- The LEMMA proposal for a low emittance muon source
  - Discussion of the critical aspects
  - Presentation of the preliminary studies
- Summary

Why muons?

$m_\mu = 105.7$ MeV/c^2

$\tau_\mu = 2.2\ \mu s$

$$\frac{m_\mu^2}{m_e^2} \cong 4 \times 10^4$$

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

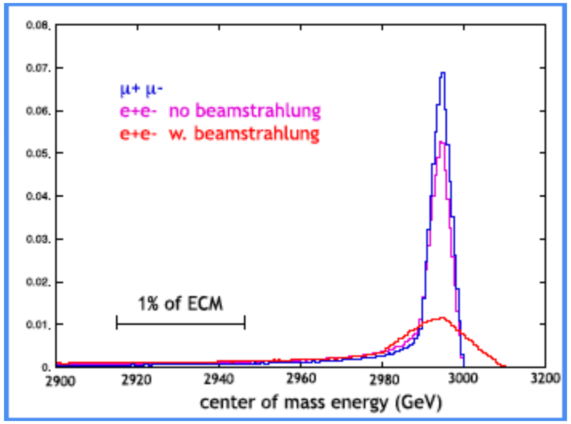
- Intense and cold muon beams can provide a unique physics reach:
  - Search for very rare and forbidden muon decays (LFV tests)
  - Direct measurement of muon g-2
  - Source for neutrino factories
  - Muon colliders (from Higgs mass to multi-TeV energies)

- Great potential both for:
  - **High precision test of the Standard Model**
  - **New Physics discovery**

- The same muon facility can supply one or more of such experimental apparatus, with proper staging strategies

Muon based colliders

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



- Best performances in terms of luminosity and power consumption

- Great potentiality if the technology proves its feasibility:
  - cooled and intense muon source
  - fast acceleration of muons
  - muon collider design
  - radiation safety and background (muon decay in accelerator and detector)

Physics programs at Muon Colliders

Ideally, a Muon Collider could be suitable for:

1. a Higgs-pole machine
   1. via $\mu^+\mu^- \rightarrow H$

2. a more compact version of e^+e^- colliders below 500 GeV
   1. main target is Higgs and top-quark physics

3. a high energy machine well above the TeV
   1. for $\sqrt{s} > 1$ TeV fusion processes becomes dominant: the collider is essentially an Electroweak boson collider

4. a *very* high energy machine with $\sqrt{s} > 10$ TeV
   1. Discovery machine at energy frontier

Muon collider at Higgs pole

Higgs production in annihilation much larger for $\mu^+\mu^-$ than e^+e^-

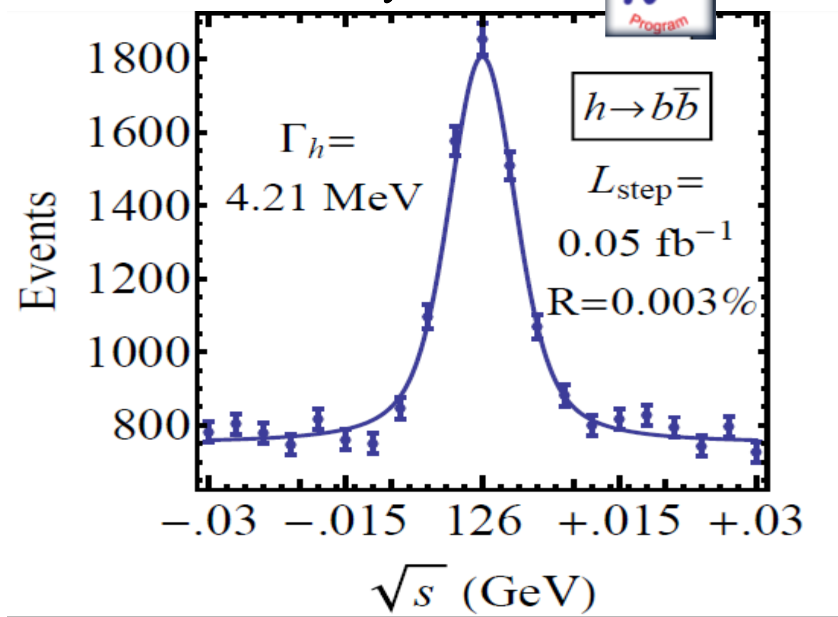
$$\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)$$

Main goals:

1. Study the Higgs line shape => direct determination of Γ_H at few % level
2. Most precise measurement of m_H (at 10^{-6} level)
3. Precise measurement of μ-H Yukawa coupling g_μ

Main issue of this program:
need to provide muon beams with an energy spread comparable to the Higgs width => $\Delta E/E \sim 10^{-5}$

Study for MAP



Energy scan: H→ $b\bar{b}$ event counts *vs* √s

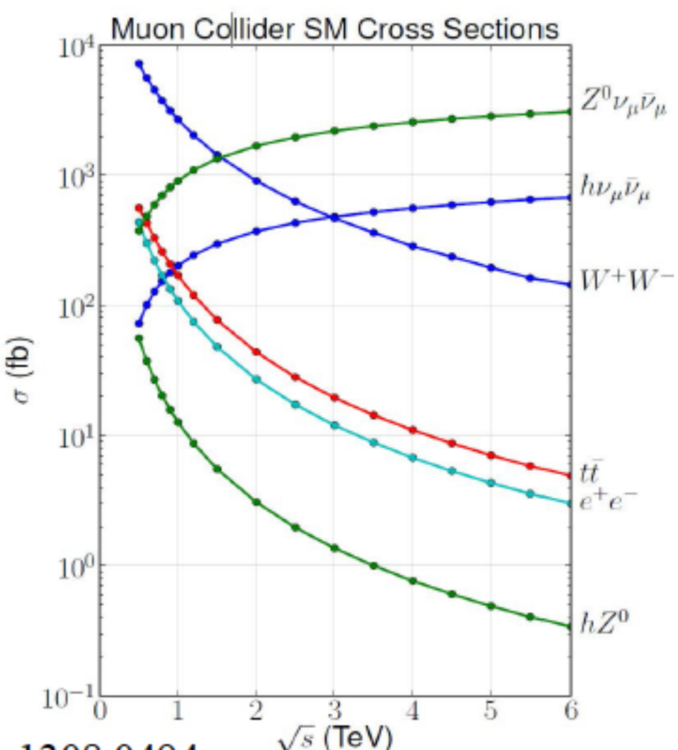
Muon collider at high energies

<u>Multi-TeV MC</u>

- Similar physics reach as CLIC for $\sqrt{s} \sim 6$ TeV (provided the same luminosity L ≳ 10^{34} cm^{-2} s^{-1})
- WW, ZZ → H couplings
- Higgs self coupling at <30% level for $\sqrt{s} > 5$ TeV

<u>MC with √s >10 TeV</u>

- Discovery machine
- Competitive or superior to FCC-hh (depending on NP scenario, and physics channels) both for direct and indirect searches



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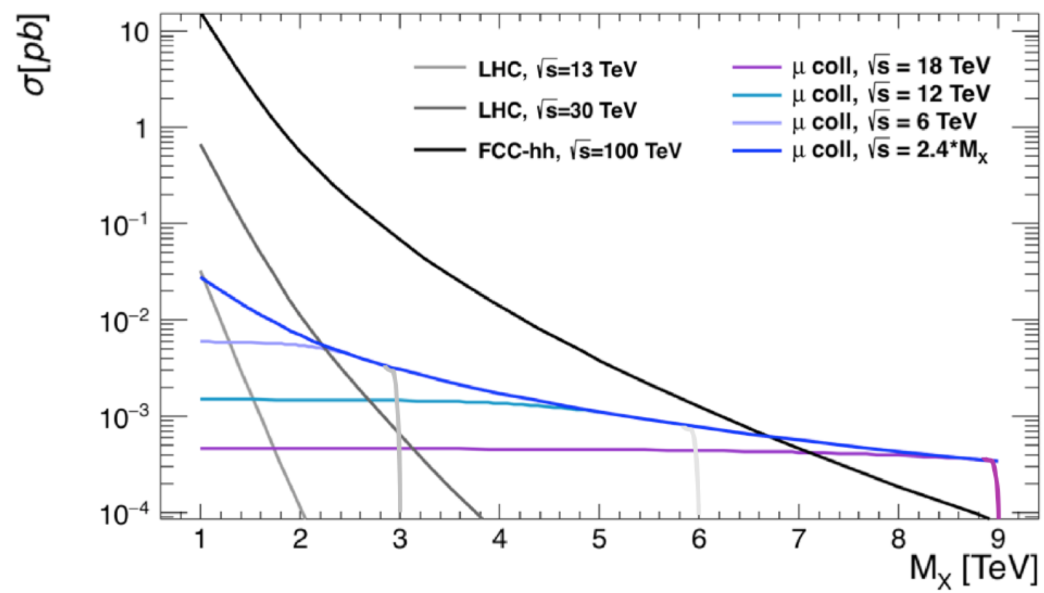
Pair production of heavy-colored vector-like top partners of mass M_X



Muon Sources

Goals

- **Neutrino Factories**: O(10^{21}) μ/yr within the acceptance of a μ ring
- **Muon Collider**: luminosities >10^{34} $cm^{-2}s^{-1}$ at TeV-scale (~N_μ^2)

Options

Conventional: Tertiary production through **proton on target** (and then cool), baseline for Fermilab design study (MAP project)

Rate > 10^{13}μ/sec $N_\mu = 2\times10^{12}$ /bunch

e^+e^- annihilation: positron beam on target (very low emittance and no cooling needed), baseline for our proposal here

Rate ~ 10^{11} μ/sec N_μ~ 5x10^7 /bunch

by Gammas: GeV-scale Compton γs

Rate ~ 5×10^{10} μ/sec $N_\mu \sim 10^6$ (Pulsed Linac)

Rate > 10^{13} μ/sec $N_\mu \sim$ few$\times10^4$ (High Current ERL)

see also: W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44

Muon Sources

Goals

- **Neutrino Factories**: $O(10^{21})$ μ/yr within the acceptance of a μ ring
- **Muon Collider**: luminosities $>10^{34}$ cm^{-2}s^{-1} at TeV-scale ($\sim N_\mu^2$)

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e^+e^- annihilation: positron beam on target (very low emittance and no cooling needed), baseline for our proposal here

Rate $\sim 10^{11}$ μ/sec $N_\mu \sim 5\text{x}10^7$ /bunch

by Gammas: GeV-scale Compton

Rate $\sim 5\times10^{10}$ μ/sec $N_\mu \sim 1$ … (Pulsed Linac)

Rate $>$ 10^{13} μ/sec   … w$\times10^4$ (High Current ERL)

see also: W. Barletta … M. Sessler NIM A 350 (1994) 36-44

Not discussed here

The LEMMA proposal

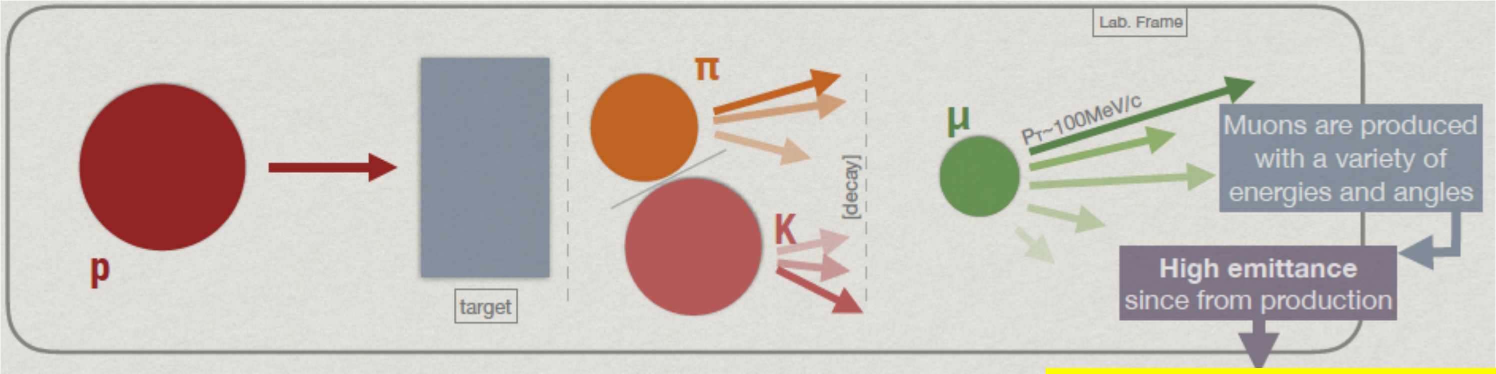
'Novel' muon production concept: e^+ on target

Direct μ-pair production via $e^+e^- \rightarrow \mu^+\mu^-$ just above production threshold ($\sqrt{s}$=212 MeV), by using a beam of ~45 GeV e^+ on a thin target

(NIM A807, 101 (2016) [*arXiv:1509.04454*])

The concept

Proton-based production: muons as tertiary particles with tipically $P_T^{\mu} \sim 100$ MeV

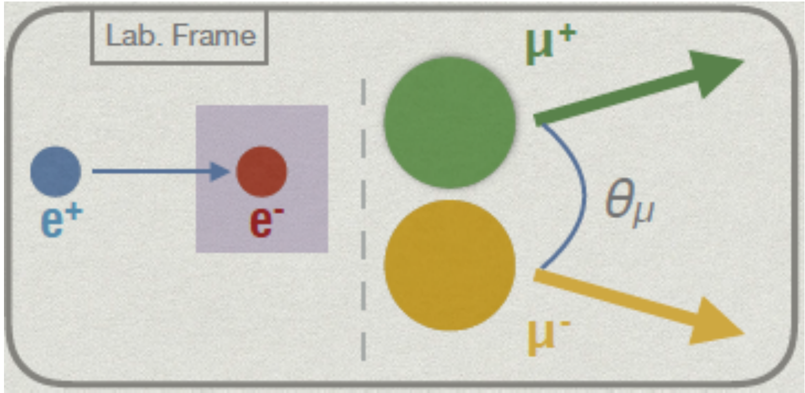


see backup slides for the MAP proposal layout

COOLING mandatory

Direct production of LEMMA proposal : $e^+e^- \rightarrow \mu^+\mu^-$ close to production threshold

$E(e^+) \sim 45$ GeV => $E(\mu^+) \sim 22$ GeV, $\gamma(\mu) \sim 200$ => $\tau_{LAB} \sim 500\mu s$

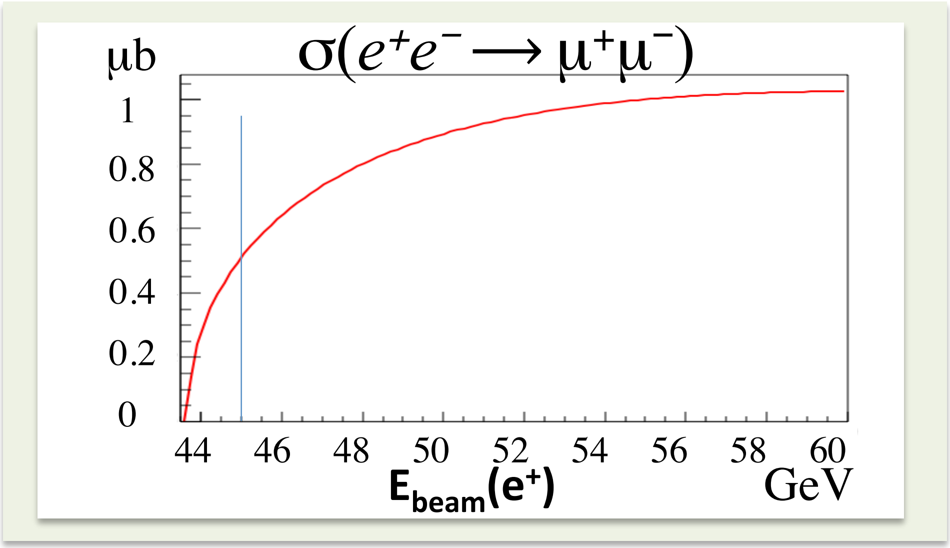


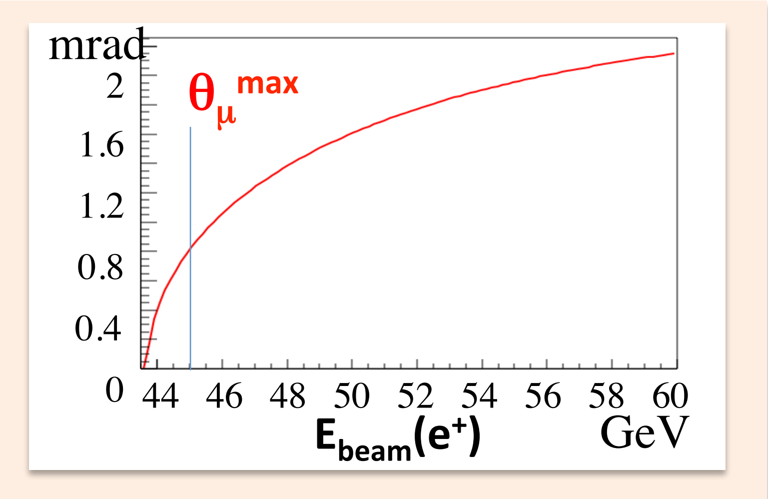
- Very small emittance is obtainable
  => **no cooling needed!**
- Low background
- Large boost at production
  - Reduced losses from muon decays
- Much smaller muon production cross section
  - ~1μb for e^+ source *vs* ~1mb for proton source

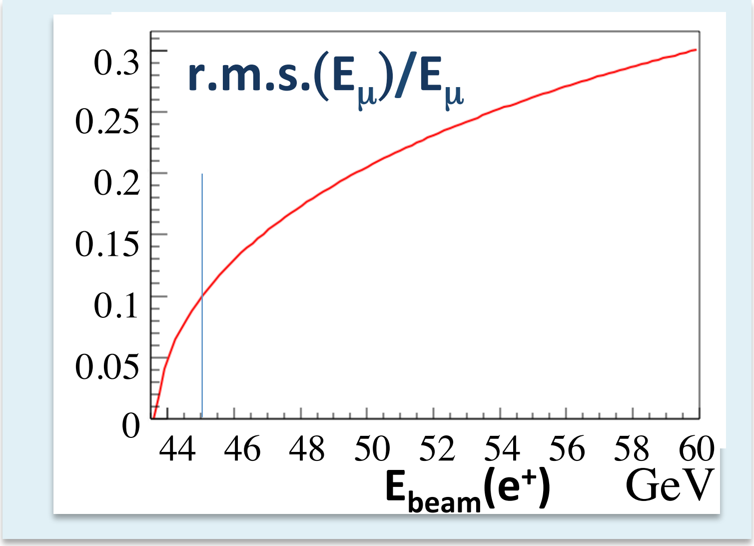
Cross-section, muons beam divergence and energy spread as a function of the e^+ beam energy

Main contributing process

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







$\sqrt{s} \simeq \sqrt{2m_e E(e^+)}$ optimized to:

- maximize the muons production
- minimize muon beam emittance and energy spread

Working hypothesis:

$E(e^+) = 45$ GeV => $\sqrt{s} \approx 214$ MeV

Criteria for target design

- The Luminosity of the muon collider is proportional to $N_\mu{}^2/\varepsilon_\mu$

Number of $\mu^+\mu^-$ pairs produced by an e^+ bunch on target:

$$N_{\mu\mu} = \sigma(e^+e^- \longrightarrow \mu^+\mu^-)\, N^+\, \rho^-\, L$$

N^+: # of e^+ in the bunch
ρ^- target electron density
L target length

- N^+: high intensity source + possible recirculation of e^+ beam
- $\rho^- L$: target to be optimized for high $\mu\mu$ production, low e^+ beam loss μ-beam emittance

Criteria:

- ⬇ **emittance ε_μ** ⇒ thin target ($\varepsilon_\mu \propto L$, if no intrinsic focusing effects)
- ⬆ **rate $N_{\mu\mu}$** ⇒ High Z&ρ
- ⬇ **positron loss** (brem+bhabha) ⇒ Low Z (if recirculation of e^+ beam)

Conventional target options:

- **Heavy materials , thin target (*e.g.* Cu)**
  - **small ε_μ**; high e^+ loss, Bremsstrahlung is dominant. $N_{\mu\mu}/N^+ \approx 10^{-7}$. Limited μ rate
- **Very light materials, thick target (H)**
  - **max. conversion efficiency:** $N_{\mu\mu}/N^+ \approx 10^{-5}$
  - even for liquid need O(1m) target → **large** ε_μ
- **Not too heavy materials (Be, C, Li)**
  - Possible **low ε_μ with limited e^+ loss** $N_{\mu\mu}/N^+ \approx 10^{-5}$-$10^{-6}$

Best compromise: not too heavy and thin target in combination with stored positron beam to reduce requests on positron source.

The actual realization depend on the application case (Higgs *vs* multi-TeV)

Application to a Multi-TeV Muon Collider

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

Goal: 10^{11} μ/s produced @Target (T)

- if $N(\mu^+\mu^-)/N(e^+) \approx 10^{-7}$ (*e.g.* with 3 mm Be Target) ⇒ 10^{18} e^+/s needed @T
- ➢ Store *e*+ beam with the largest possible lifetime to minimize positron source rate
  - ➢ $\tau(e+) \approx 250$ turns [i.e. 25% momentum aperture (±12%)]
  - ➢ LHeC-like *e*+ source rate required

Preliminary scheme for low emittance μ beam production

Positron Source

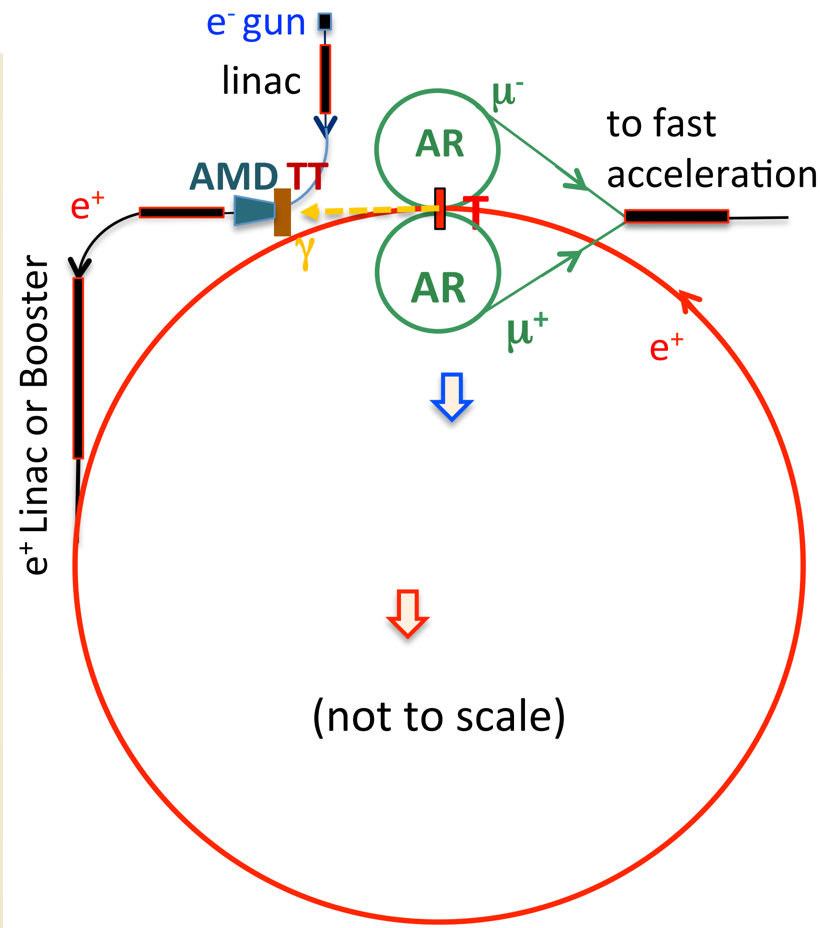
- e^- on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- Adiabatic Matching Device (AMD) for e^+ collection

Positron Ring

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

Muon Beams

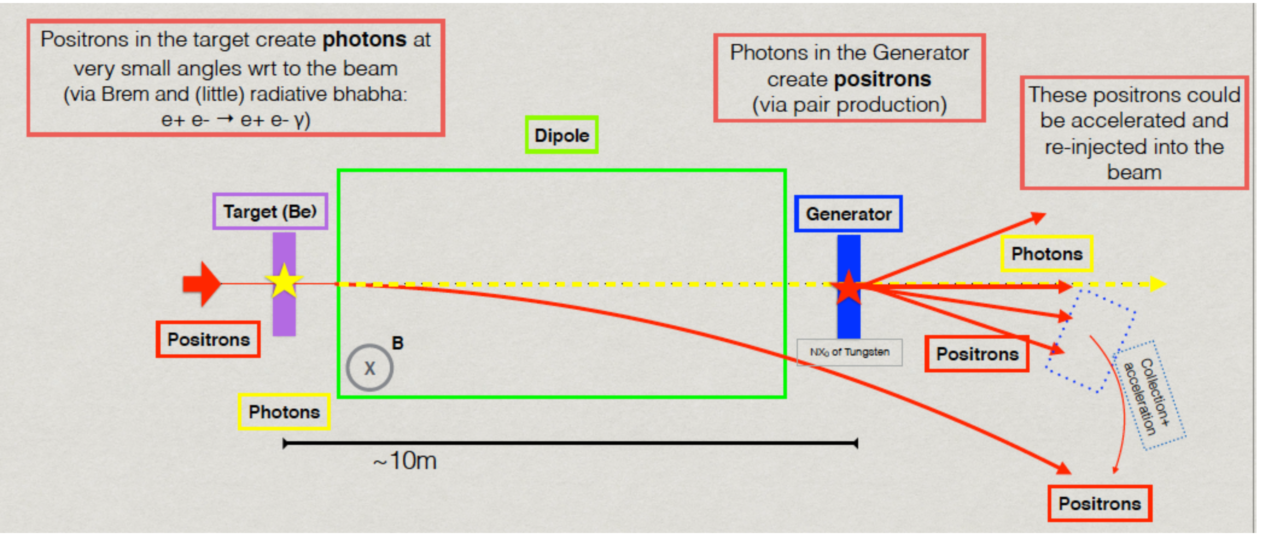
- $\mu^\pm$ produced by e^+ beam on target **T** with E≈ 22 GeV, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx 500\mu s$
- **AR**: 60 m isochronous and high momentum acceptance rings to recombine $\mu^\pm$ bunches in~1 τ_μ^{lab} ≈2500 turns
- $\mu^\pm$ fast acceleration



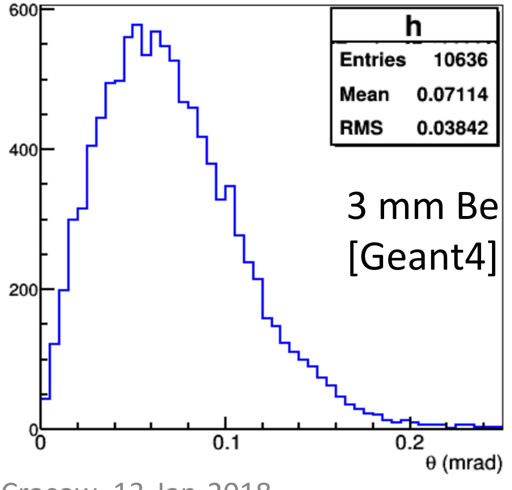
N(e+)/bunch= $3x10^{11}$

Embedded positron source?

Explore the possibility to use the γ's from the μ-production target to produce e^+



γ's angular distribution at the target exit



- High rate of energetic and collimated γ's thanks to the thin target
- Large number of e^+ produced in the W generator
- It would be enough to collect a few percent of these positrons to entirely recover the losses in the primary beams
- Promising preliminary results on collection efficiency

Low emittance 45 GeV positron ring

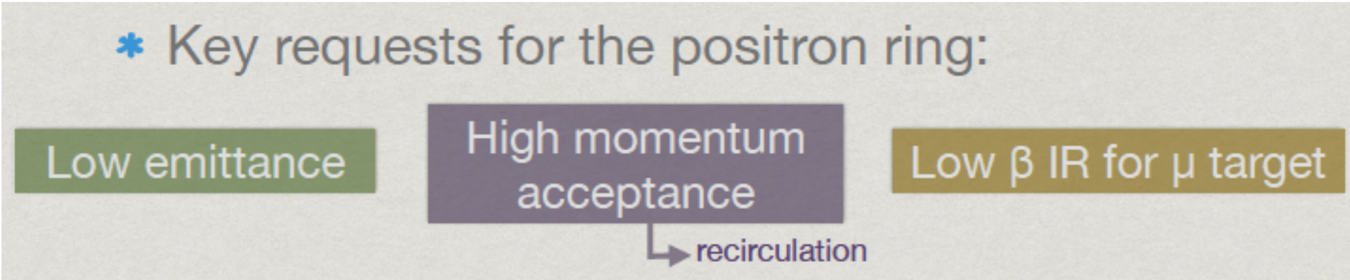
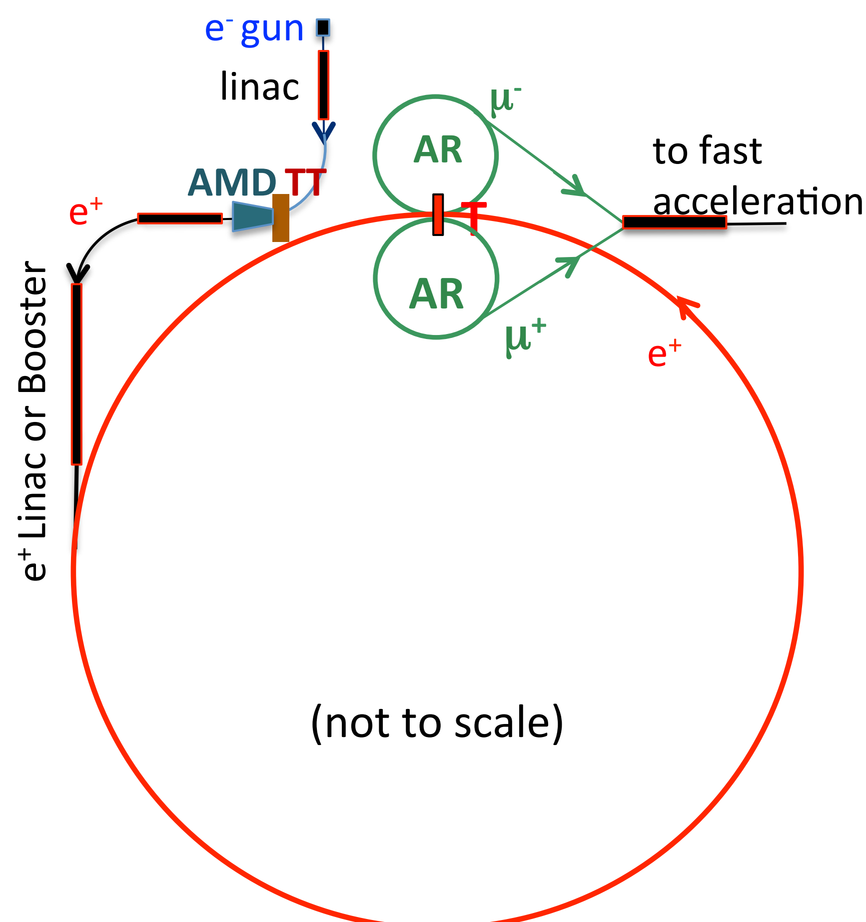


Table e+ ring parameters

e+ ring parameter	unit	
Circumference	km	6.3
Energy	GeV	45
bunches	#	100
e^+ bunch spacing = T_{rev} (AR)	ns	200
Beam current	mA	240
N(e^+)/bunch	#	$3 \cdot 10^{11}$
U_0	GeV	0.51
SR power	MW	120

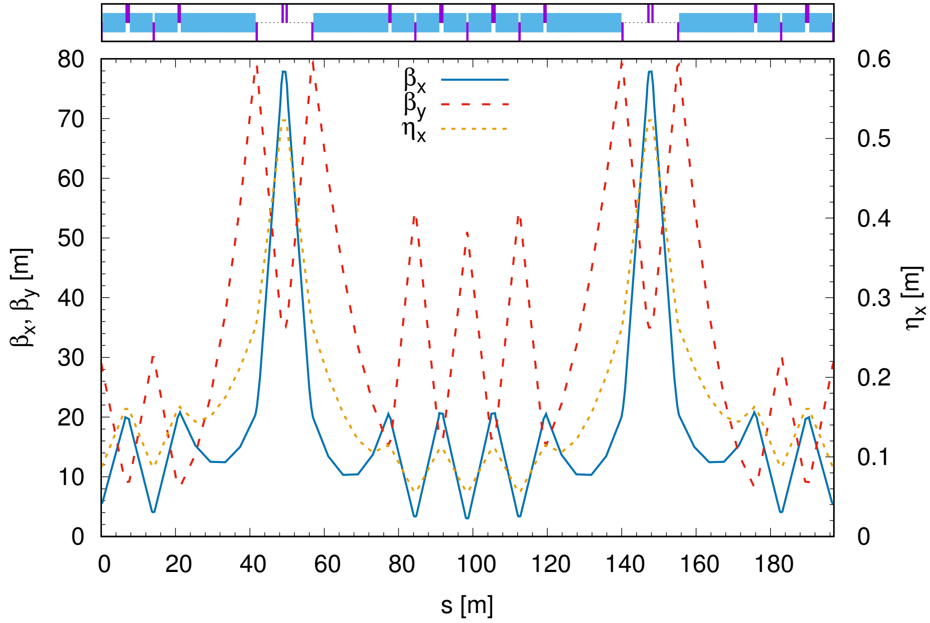
(also 28 km foreseen to be studied as an option)



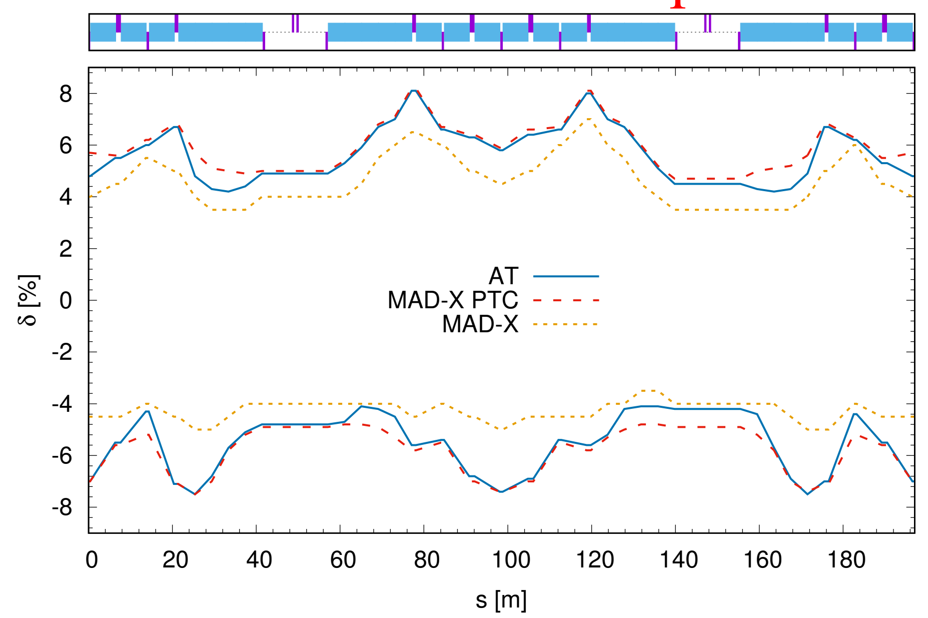
Low emittance 45 GeV positron ring

- Preliminary design of the ring optics available
- Circumference 6.3 km: 197 m x 32 cells

Beam parameters within a cell

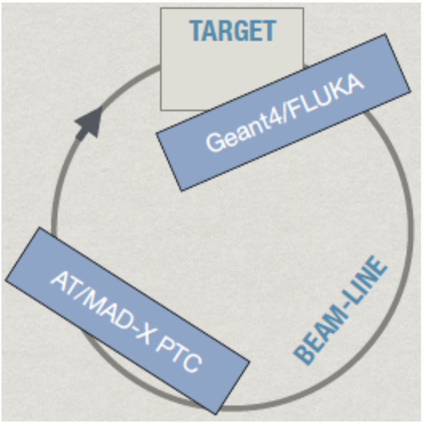


±5% momentum acceptance



Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

Multi-turn simulations



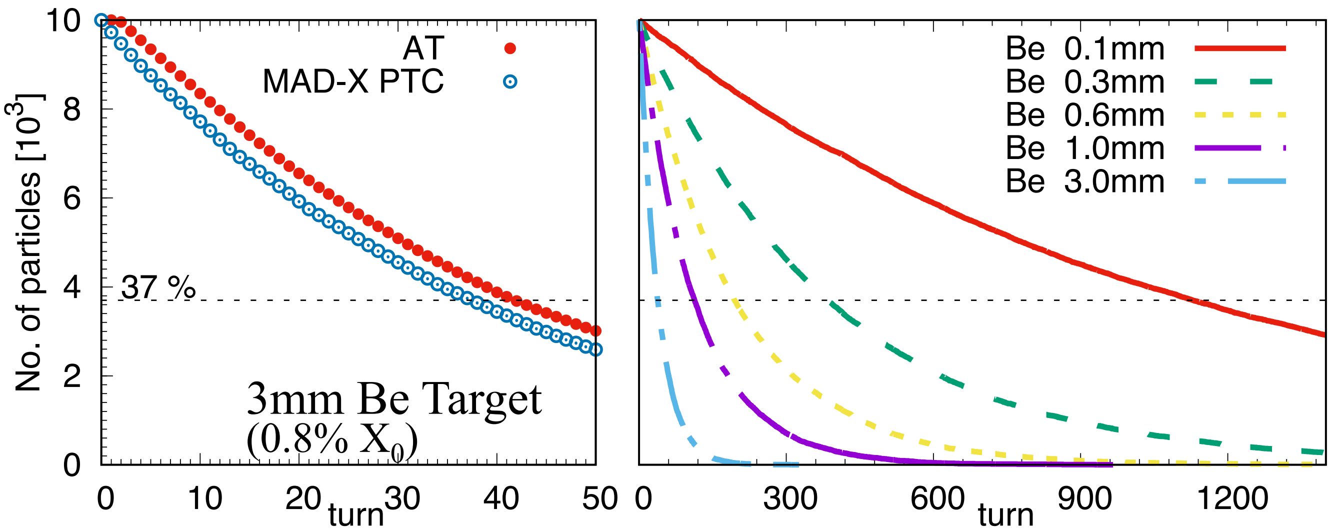
Dedicated multi-turn simulation algorithm developed

1. 6D e^+ distribution tracking in the ring (AT and MAD-X PTC)
2. Positron interaction in the target (with Geant4 and FLUKA)

At each pass through the target the $e+$ beam

- gets an angular kick due to the **multiple Coulomb scattering**
  - e^+ beam divergence and size increase => increase of e^+ emittance
- undergoes **bremsstrahlung energy loss**
  - to minimize the beam degradation due to this effect needs η_x=0 at target
- in addition there is natural radiation **damping** (it prevents an indefinite beam growth)

$e+$ lifetime with Be target of different sizes



Lifetime determined by bremsstrahlung and momentum acceptance

Lifetime ∝ 1/thickness

~2-3% $e+$ losses happen in the first turn

The μ target for multi-TeV case

Muon emittance ε_μ strongly affected by the target choice

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

- $\varepsilon(e^+)$ = emittance of the e^+ beam
- $\varepsilon(MS)$ = multiple scattering contribution
- $\varepsilon(rad)$ = energy loss (brem.) contribution
- $\varepsilon(prod)$ = muon production contribution
- $\varepsilon(AR)$ = accumulator ring contribution

would like all contributions of same size knobs:

- $\beta_x\ \beta_y$ @target & target material
- $\beta_x\ \beta_y\ D_x$ @target & target material
- $E(e^+)$ & target thickness ($\varepsilon(prod) \propto L$)
- AR optics & target

- The target will work in a very harsh environment, with very intense and focused e^+ beam
- Constraints for power removal ($\gtrsim$100 kW) and temperature rise

- Present solution under study: conventional solid thin Be or C targets
  - ε_μ dominated by $\varepsilon(MS) \oplus \varepsilon(rad)$ => need low dispersion & low β-functions at target with beam spot at the limit of the target survival

- Alternative materials/design:
  - crystals in channeling => better: $\varepsilon(MS)$, $\varepsilon(rad)$, $\varepsilon(prod)$ (also gain in lifetime)
  - light liquid jet target => better: $\varepsilon(MS)$, $\varepsilon(rad)$, lifetime & target power removal

Conventional options for μ target

- Aim at bunch (3×10^{11} e^+) transverse size on the 10 μm scale
- Bunch spacing 200 ns
- Envisaged solutions:
  - Fast rotating wheel to avoid temperature rise due to bunch pile up
  - Power removal by radiation cooling
    - see for instance PSI muon beam upgrade project HiMB)

[A. Knecht, NuFact17]]

- Need detailed simulation of thermo-mechanical stresses dynamics
  - Started using FLUKA + Ansys Autodyn
    - collaboration with CERN EN-STI

- Foreseen experimental beam tests of target prototypes:
  - **FACET-II** at SLAC available from 2019
    - 10^{11} e^-/bunch, 10 μm spot size, 100 Hz
    - test of mechanical stresses
  - **DAΦNE** in Frascati available from 2020
    - test also of the LEMMA scheme (e^+ ring with target)
    - plan to measure: transverse beam size, current, lifetime, target heat load

Recap of the key topics for this scheme

- Very high rate positron source
- Low emittance and high momentum acceptance 45 GeV e^+ ring
- O(100 kW) class target in the e^+ ring for $\mu^+ \mu^-$ production
- High momentum acceptance muon accumulator rings

→ At the frontier of present technology. Needs deep investigation.

- Acceleration
- Collider Ring
- Collider Machine Detector Interface
- Detector

→ (Mostly) independent on the muon source. Large sinergy with MAP studies.

LEMMA *vs* MAP (at $\sqrt{s} = 6$ TeV)

Basic features of the muon collider parameters in the two approaches

	LEMMA	**Protons on target (MAP)**
Physical process	$e^+e^- \to \mu^+\mu^-$	**p N→ πX, KX→ μ X'**
Luminosity [$cm^{-2}s^{-1}$]	**~5x10^{34}**	**≳10^{35}**
ε_N [μm-rad]	**0.04**	**25**
Rate N_μ/s	**0.9x10^{11}**	**10^{13}**
N_μ/bunch	**6x10^9**	**2x10^{12}**
ΔE/E [%]	**0,07**	**0.1**

Lower rate of muons in LEMMA for similar luminosity

- lower background from $e^\pm$ in the detector
- lower radiation hazard from neutrino in the site

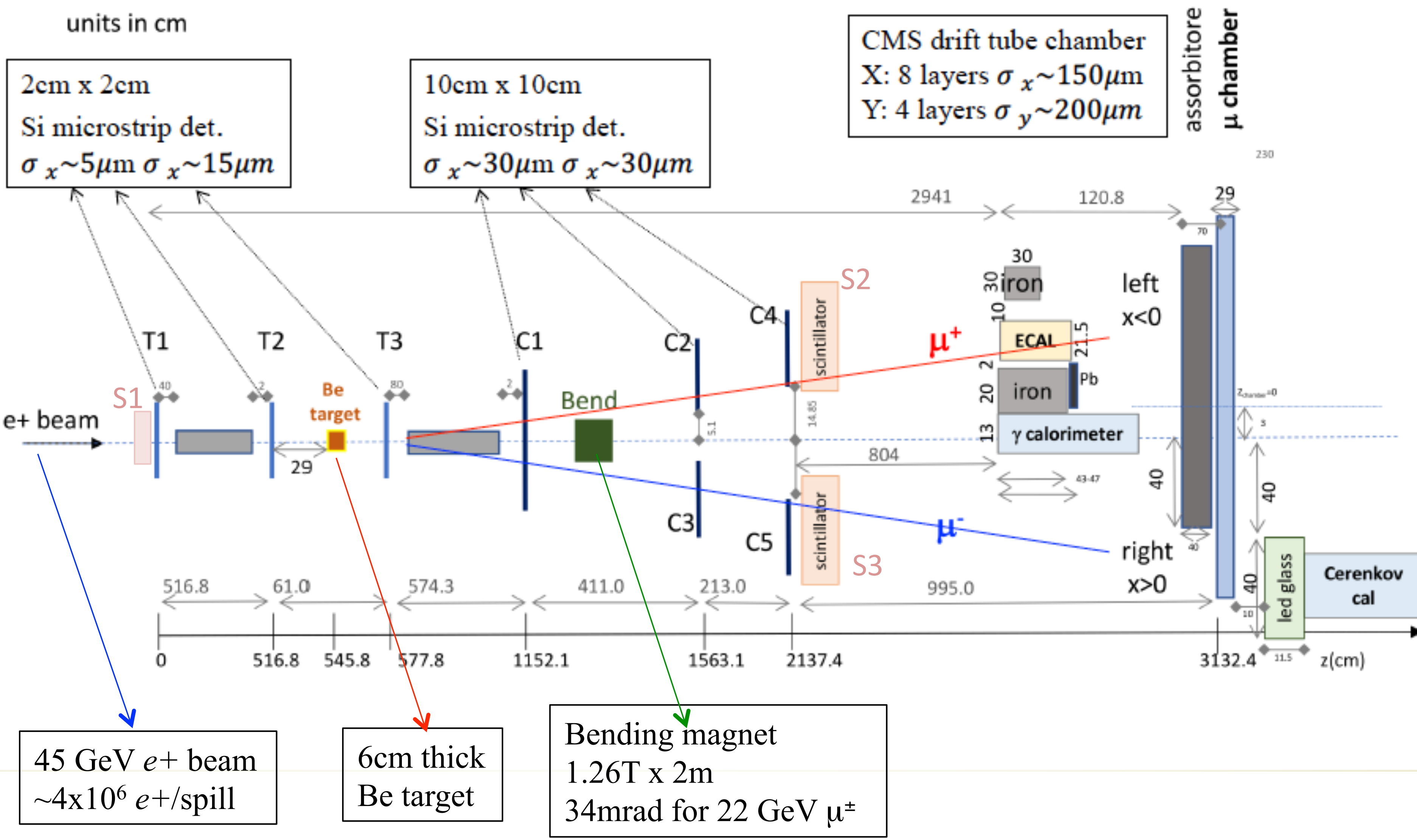
=> LEMMA can go above 10 TeV

Experimental Tests at CERN North Area

- Test muon pair production at threshold with a 45 GeV $e+$ beam on target ($\sqrt{s}\sim 0.214$ GeV)
- Goals:
  I. Measurement of $\mu^+\mu^-$ production cross section and muons kinematic properties
    - use Bhabha events to normalize cross section
    - Interesting by itself and useful to tune simulation

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

  II. Determination of e+ beam degradation crossing the target
    - Useful for simulation tuning
- One week beam test at the end of July 2017, at H4 line extracted from the SPS
- Need:
  - Full tracking of charged particles
  - Detailed simulation for acceptances and efficiency determination
  - Electron/muon identification


units in cm
2cm x 2cm
Si microstrip det.
σ x~5μm σ x~15μm
10cm x 10cm
Si microstrip det.
σ x~30μm σ x~30μm
CMS drift tube chamber
X: 8 layers σ x~150μm
Y: 4 layers σ y~200μm
assorbitore
μ chamber
2941
120.8
29
S1
e+ beam
T1
T2
Be
target
T3
C1
Bend
C2
C4
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scintillator
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2137.4
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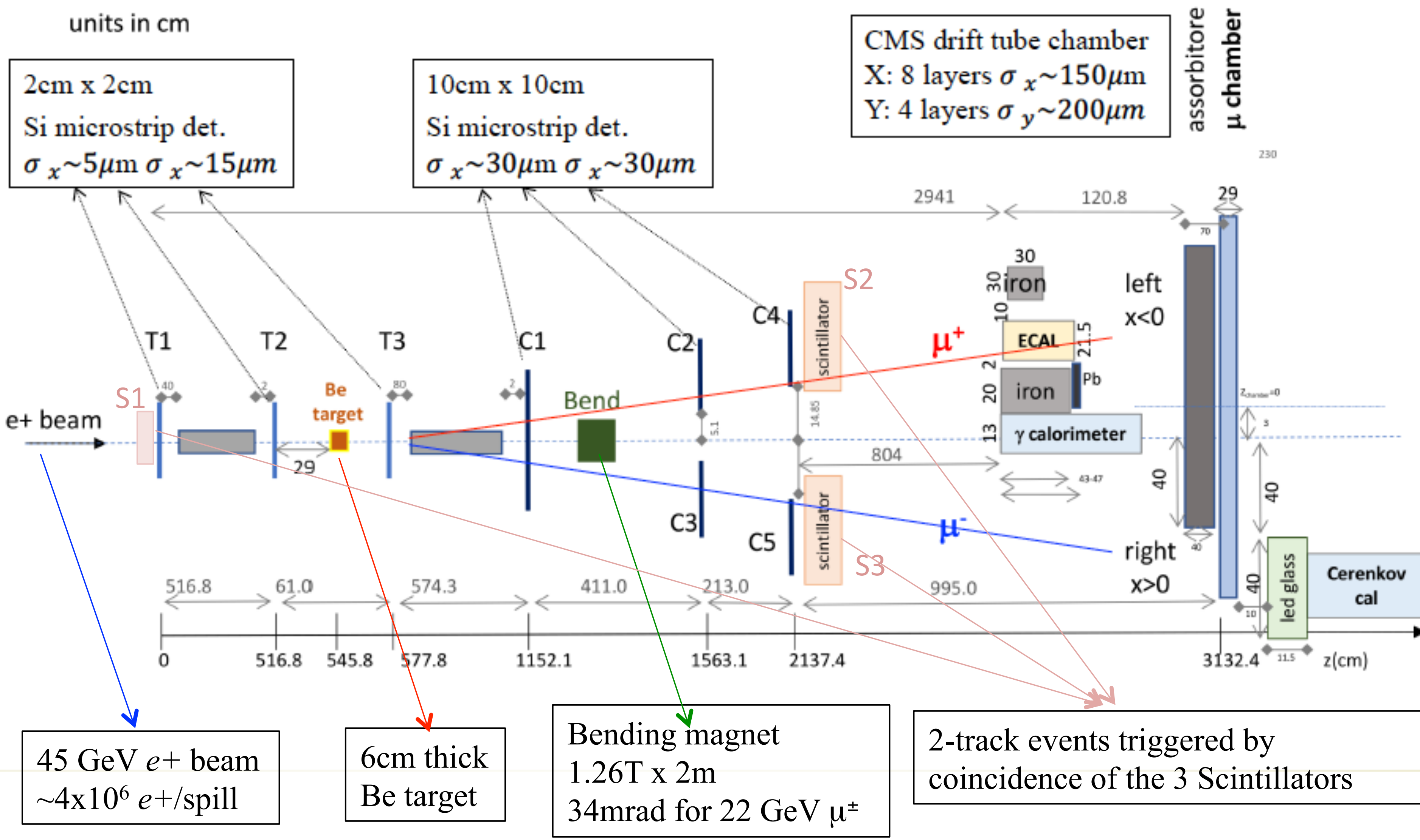
z(cm)
45 GeV e+ beam
~4x10⁶ e+/spill
6cm thick
Be target
Bending magnet
1.26T x 2m
34mrad for 22 GeV μ±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6cm thick
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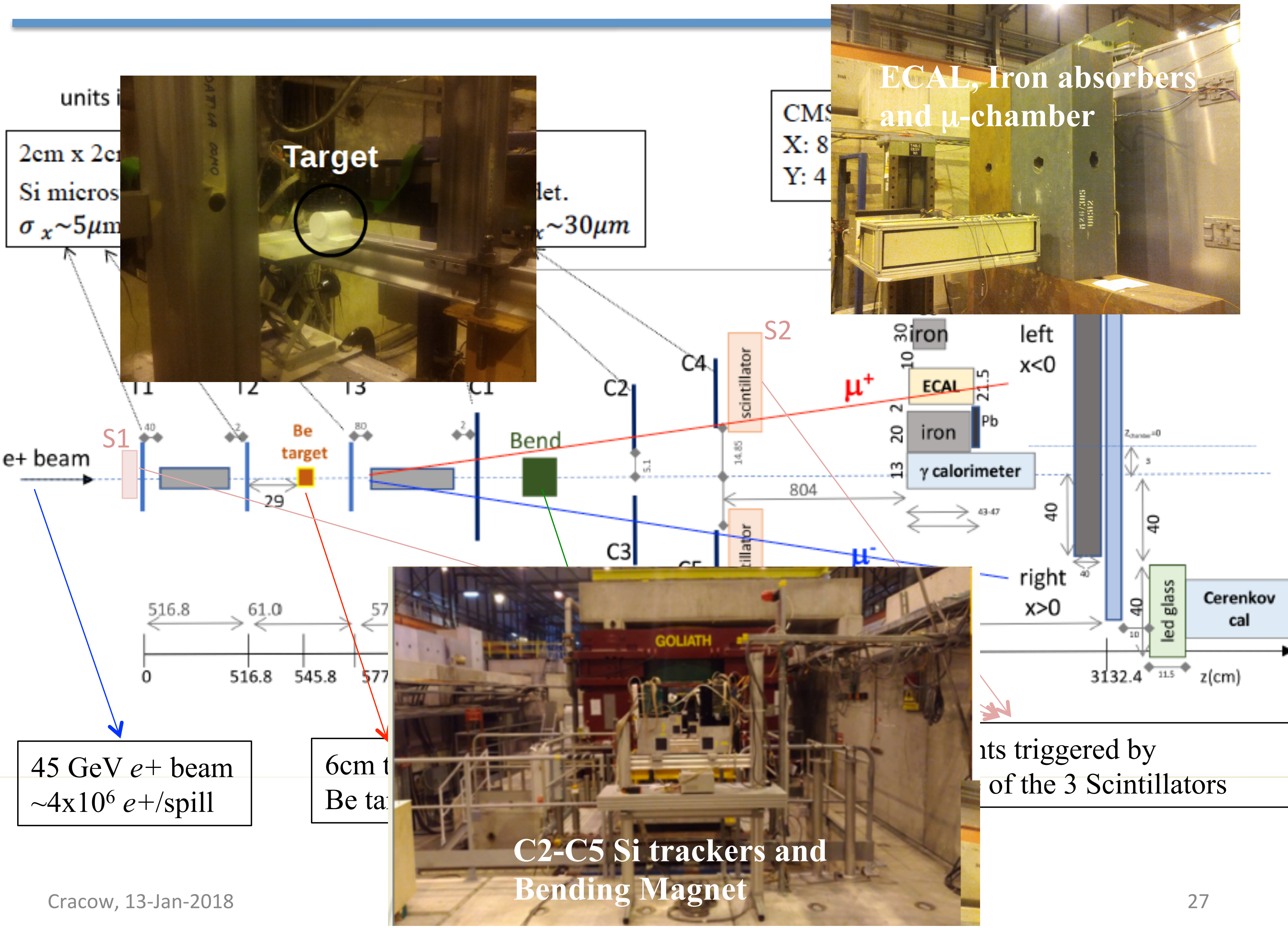
Bending magnet
1.26T x 2m
34mrad for 22 GeV $\mu^\pm$
2-track events triggered by
coincidence of the 3 Scintillators



units i
2cm x 2c
Si micros
σ x~5μm
let.
x~30μm
Target
CMS
X: 8
Y: 4
ECAL, Iron absorbers
and μ-chamber
e+ beam
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z(cm)
45 GeV e+ beam
~4x10^6 e+/spill
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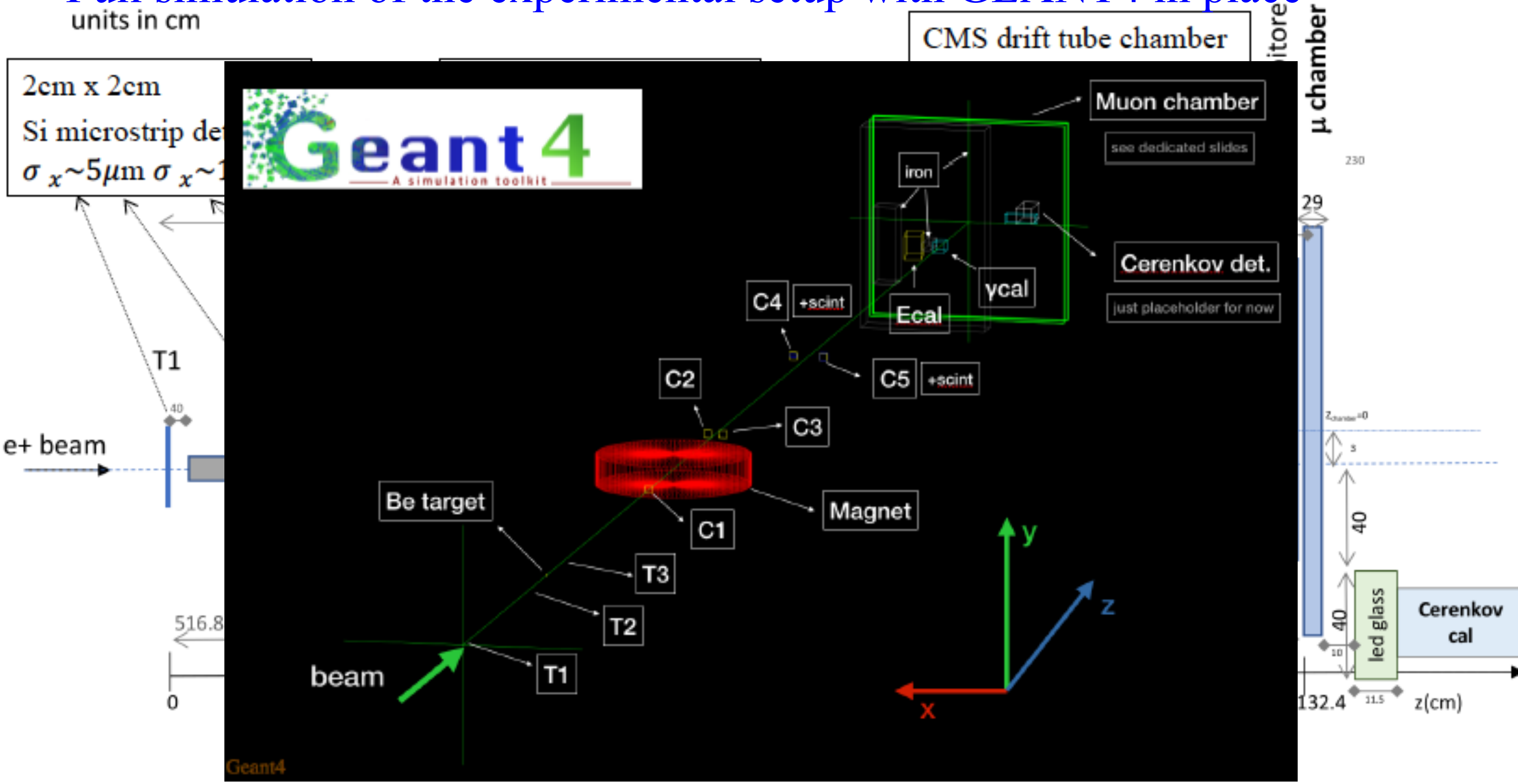
its triggered by
of the 3 Scintillators
C2-C5 Si trackers and
Bending Magnet
GOLIATH

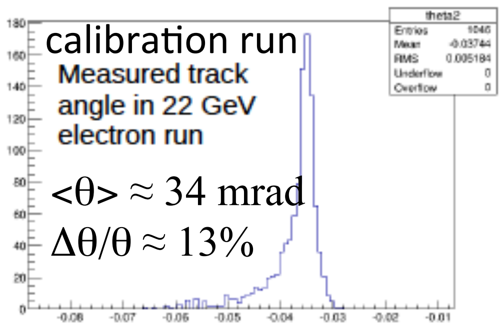
Test beam at CERN North Area

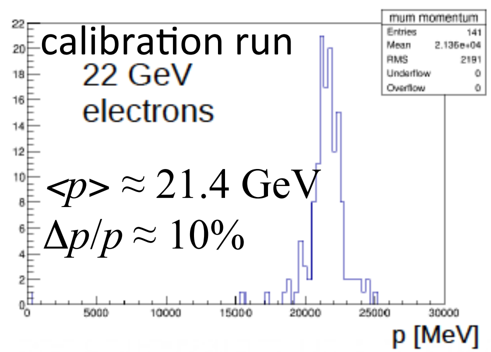
- Full simulation of the experimental setup with GEANT4 in place



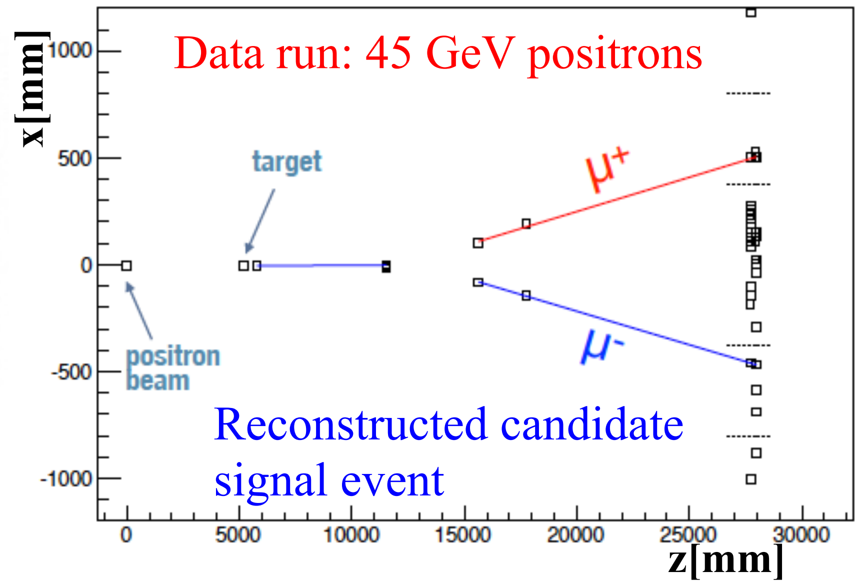
Test beam at CERN North Area

- Tracking reconstruction and analysis software in place
- Muon/electron identification with calorimeters in progress





Tracking of calibration runs with $e^{\pm}$ of 22 GeV show expected values for angles and momenta



- Results expected soon
- A few hundred of μμ events have been collected
  - Not enough for a precise measurement of the physics quantities under investigation
  - Enough to prove the the validity of the experiment
- Requested 1week of beam time in Summer 2018 to complete the original program
- Future tests will include the study of the positron beam degradation through thin solid targets, as well as through crystals in channeling regime

Summary and Plans

- New generation of collider facilities at energy and/or intensity frontiers are considered essential independently of HL-LHC physics output
  - Several proposal on the table: HE-LHC, FCC-hh, FCC-ee, CLIC, LHeC,…
- In this contest a muon collider offers perspectives alternative/complementary to the other options for precision Higgs studies and for NP discovery
- The proposed low-emittance $\mu^+\mu^-$ production via positron-on-target offers several advantages, and it is particularly suited for a high-energy collider
  - Competitive also with FCC-hh!
  - Studies to assess the physics reach with the various configurations must proceed in parallel with the rest of the project
  - Several aspects at the technology frontier (positron source, target, …)
  - Simulation studies and a full set of experimental tests planned for the next 2-3 years, to asses some of these questions
  - The assessment of the ultimate performances of this scheme can be performed on a five to ten years time scale (depending on manpower and funds)
- Great challenge at intrnational level and fantastic opportunity for young people!

BACKUP slides

Exploring the potential for a Low Emittance MC

some References:

- M. Boscolo *et al.*, **“***Studies of a scheme for low emittance muon beam production from positrons on target”,* **IPAC17 (2017)**
- M.Antonelli, *“Very Low Emittance Muon Beam using Positron Beam on Target”*, **ICHEP (2016)**
- M.Antonelli *et al.* , *“Very Low Emittance Muon Beam using Positron Beam on Target”*, **IPAC (2016)**
- M. Antonelli, *“Performance estimate of a FCC-ee-based muon collider”*, **FCC-WEEK 2016**
- M. Antonelli, *“Low-emittance muon collider from positrons on target”*, **FCC-WEEK 2016**
- M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, *“Novel proposal for a low emittance muon beam using positron beam on target”*, **NIM A 807 101-107 (2016)**
- P. Raimondi, *“Exploring the potential for a Low Emittance Muon Collider”*, in **Discussion of the scientific potential of muon beams workshop**, CERN, Nov. 18th 2015
- M. Antonelli, **Presentation Snowmass 2013**, Minneapolis (USA) July 2013, [M. Antonelli and P. Raimondi, Snowmass Report (2013) also INFN-13-22/LNF Note

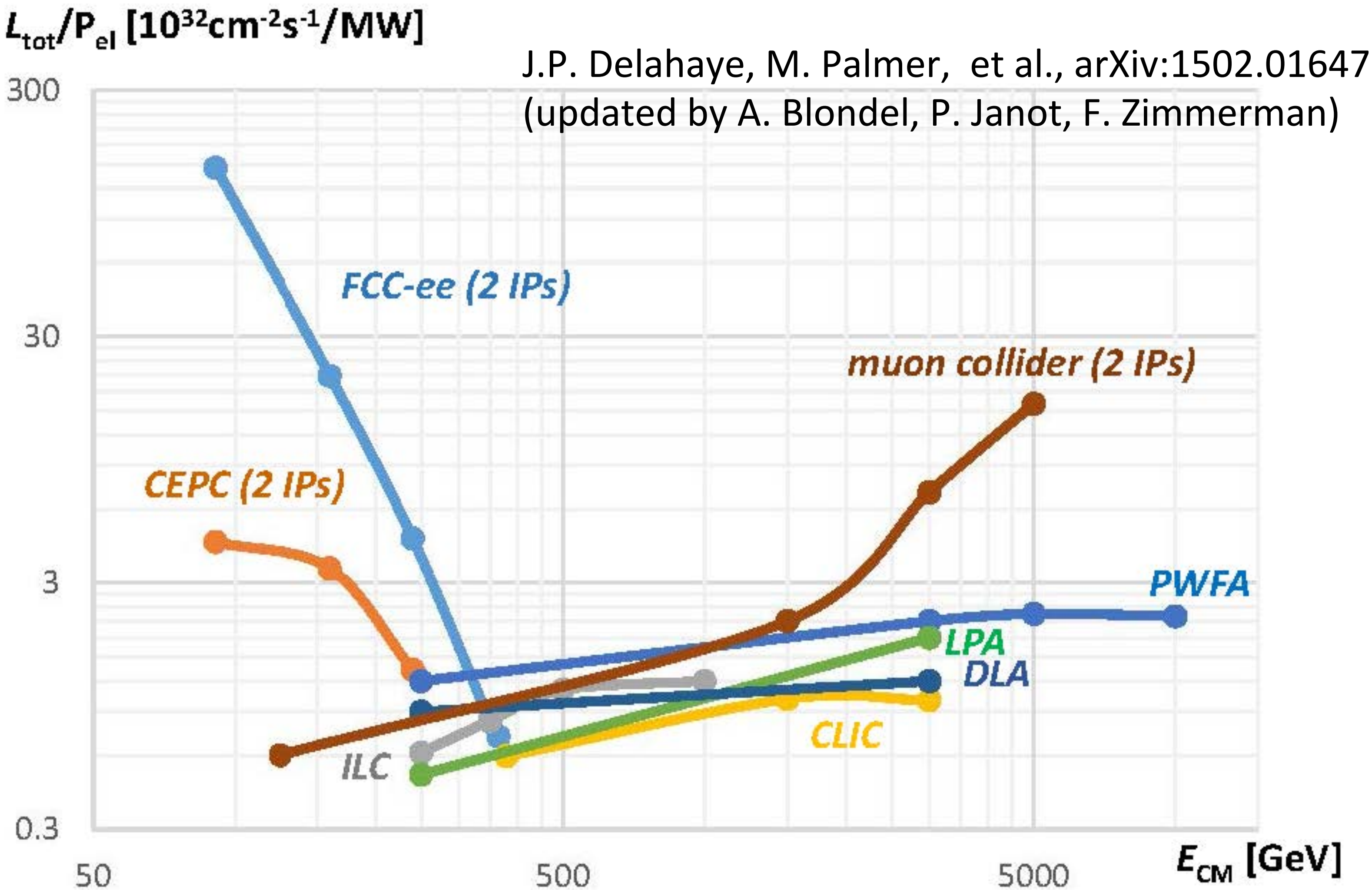
Also investigated by SLAC team:

L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:

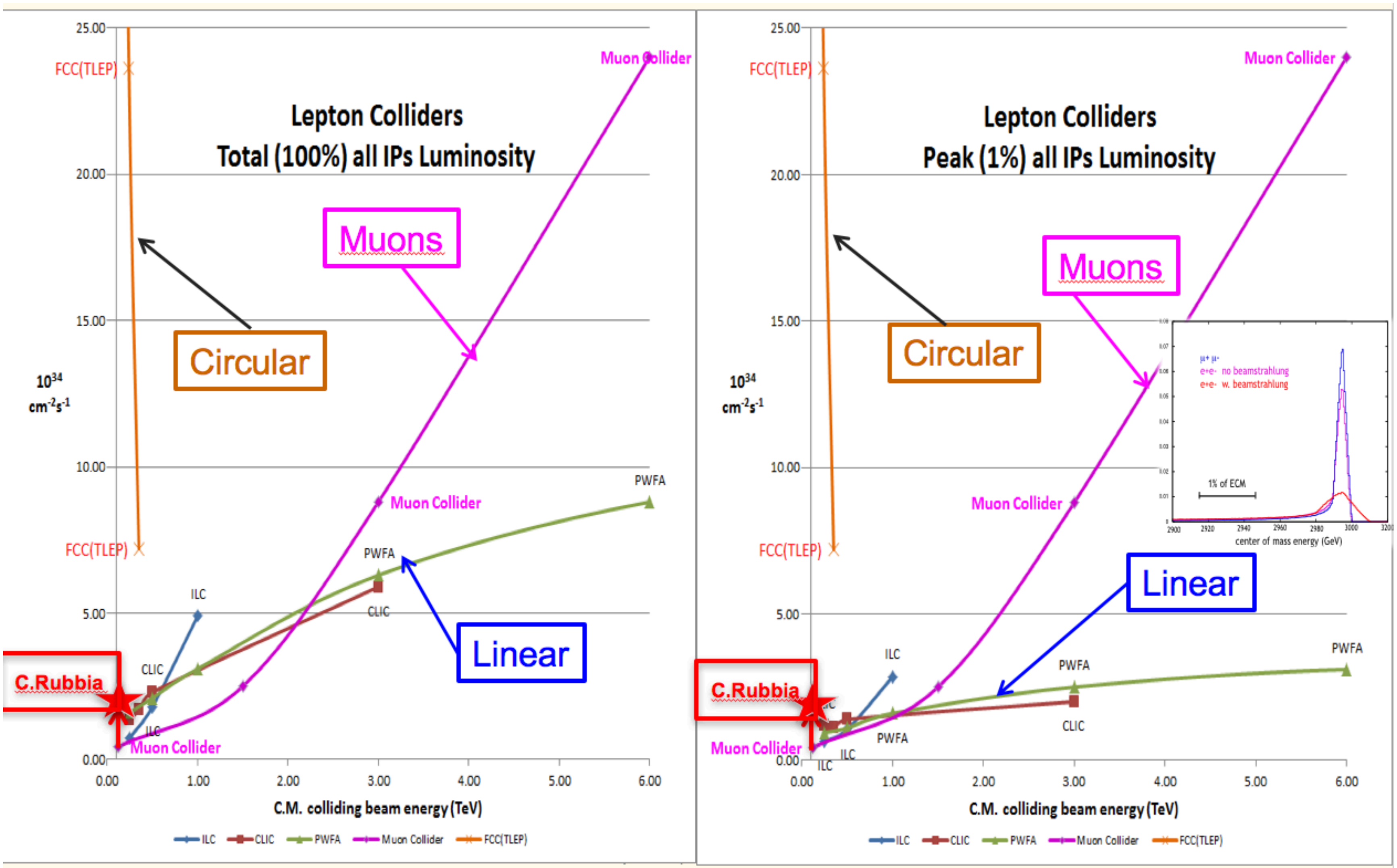
- *“Luminosity Estimate in a Multi-TeV Muon Collider using $e^+e^- \rightarrow \mu^+\mu^-$ as the Muon Source”*, MAP 2014 Spring workshop, Fermilab (USA) May ’14
- Advanced Accelerator Concepts Workshop, San Jose (USA), July ‘14

Lepton Colliders: wall power *vs* ECM

luminosity per wall-plug power vs c.m. energy

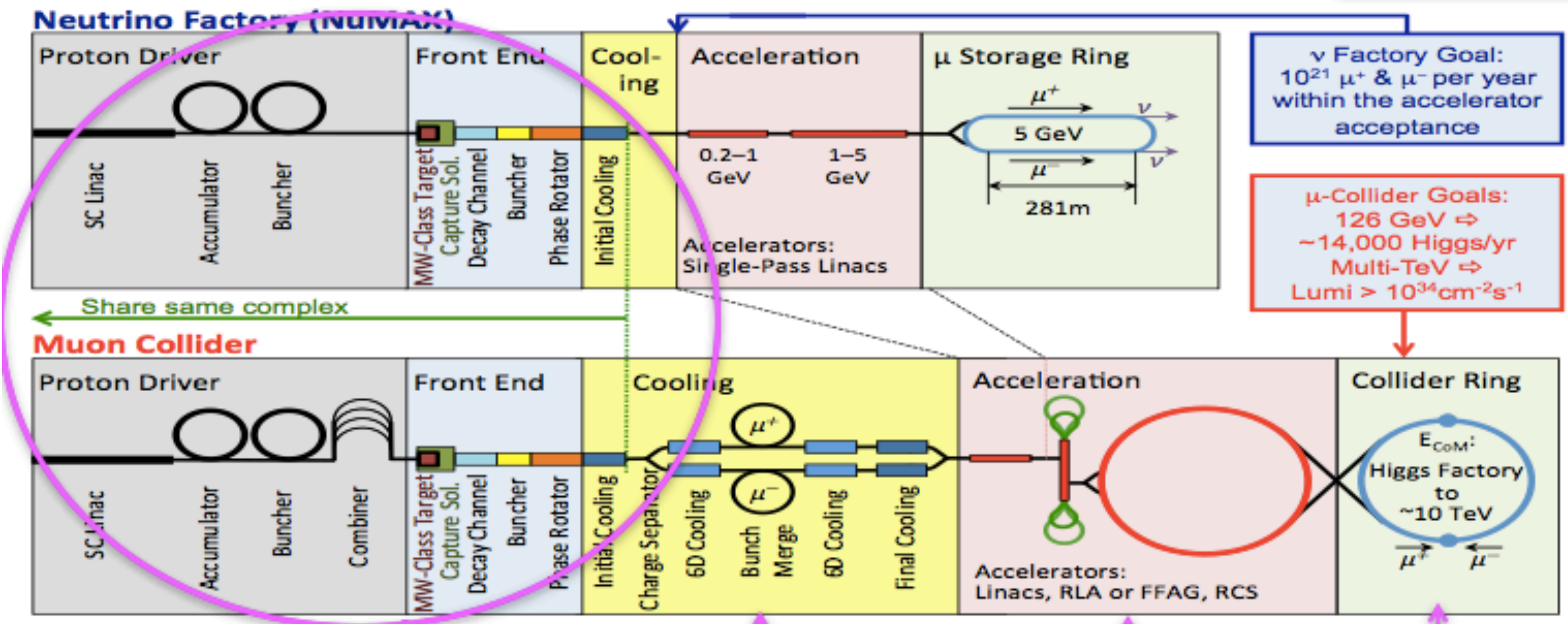


Lepton Colliders: luminosity performances *vs* ECM



Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



Key Challenges	$\sim 10^{13}$-10^{14} μ / sec Tertiary particle $p \to \pi \to \mu$:	Fast cooling (τ=2μs) by 10^6 (6D)	Fast acceleration mitigating μ decay	Background by μ decay
Key R&D	MW proton driver MW class target NCRF in magnetic field	Ionization cooling High field solenoids (30T) High Temp Superconductor	Cost eff. low RF SC Fast pulsed magnet (1kHz)	Detector/ machine interface

M. Palmer

Muon Collider Parameters

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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

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

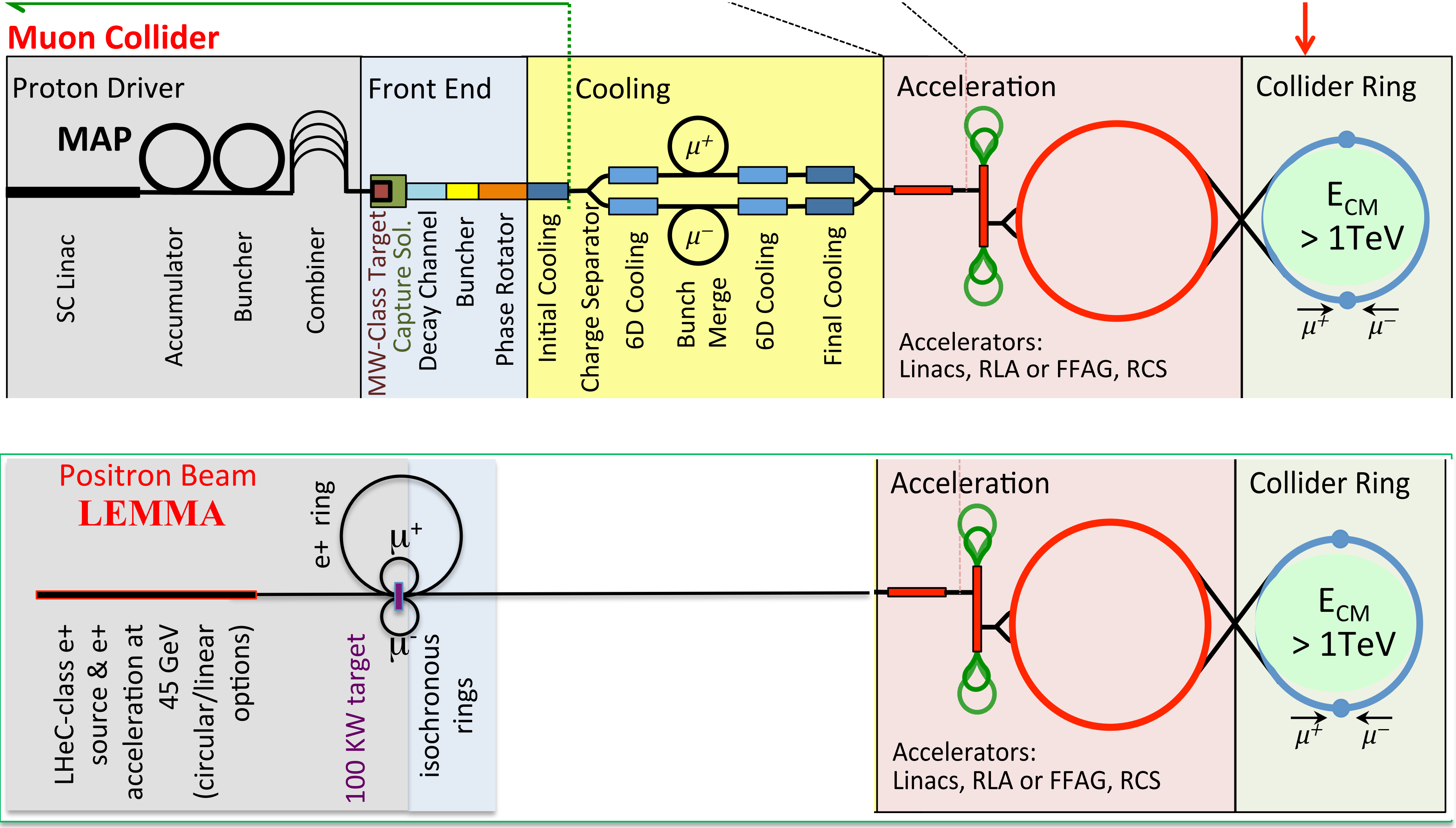
Fermilab

Low-emittance MC draft parameters *vs* √s

NEED deep investigation to be validated

		e+ ERL/LINAC	e+ STORAGE RING						
		MUFACT	MUFACT	MUFACT	MUFACT	MUFACT	MUFACT	MUFACT	MUFACT
Parameter	Units	Higgs	Higgs	ZH	Top	ILC-like	ILC-like-1000	MultiTeV	MultiTeV
LUMINOSITY/IP	$cm^{-2}\ s^{-1}$	4,15E+31	1,69E+31	7,06E+31	1,54E+32	2,94E+32	1,18E+33	5,08E+34	2,03E+35
Beam Energy spread	%	0,46	3,17	1,65	1,13	0,79	0,40	0,07	0,03
Beam Energy	GeV	62,50	62,50	120	175	250	500	3000	6000
Hourglass reduction factor		1,00	1,00	1,000	1,000	1,000	1,000	1,000	1,000
Muon mass	GeV	0,10566	0,10566	0,10566	0,10566	0,10566	0,10566	0,10566	0,10566
Lifetime @ prod	sec	2,20E-06	2,20E-06	2,20E-06	2,20E-06	2,20E-06	2,20E-06	2,20E-06	2,20E-06
Lifetime	sec	0,0013	0,0013	0,0025	0,0036	0,0052	0,0104	0,0625	0,1249
c*tau @ prod	m	658,00	658,00	658,00	658,00	658,00	658,00	658,00	658,00
c*tau	m	3,89E+05	3,89E+05	7,47E+05	1,09E+06	1,56E+06	3,11E+06	1,87E+07	3,74E+07
1/tau	Hz	7,68E+02	7,68E+02	4,00E+02	2,74E+02	1,92E+02	9,61E+01	1,60E+01	8,00E+00
Circumference	m	150,00	150,00	300	450	600	1200	6000	12000
Bending Field	T	15,00	15,00	15	15	15	15	15	15
Bending radius	m	13,89	13,89	27	39	56	111	667	1333
Magnetic rigidity	T m	208,33	208,33	400	583	833	1667	10000	20000
Gamma (Lorentz factor)		591,52	591,52	1135,72	1656,26	2366,08	4732,16	28392,96	56785,92
N turns before decay		2594,80	2594,80	2491,01	2421,81	2594,80	2594,80	3113,76	3113,76
β_x @ IP	m	0,00020	0,00020	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002
β_y @ IP	m	0,00020	0,00020	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002
Beta ratio		1,00	1,00	1,0	1,0	1,0	1,0	1,0	1,0
Coupling (full current)	%	100	100	100	100	100	100	100	100
Normalised Emittance x	m	5,90E-09	4,00E-08	4,00E-08	4,00E-08	4,00E-08	4,00E-08	4,00E-08	4,00E-08
Emittance x	m	9,97E-12	6,76E-11	3,52E-11	2,42E-11	1,69E-11	8,45E-12	1,41E-12	7,04E-13
Emittance y	m	9,97E-12	6,76E-11	3,52E-11	2,42E-11	1,69E-11	8,45E-12	1,41E-12	7,04E-13
Emittance ratio		1,00	1,00	1,0	1,0	1,0	1,0	1,0	1,0
Bunch length (full current)	mm	0,10	0,10	0,1	0,1	0,1	0,1	0,1	0,1
Beam current	mA	0,64	0,04	0,040	0,040	0,040	0,040	0,048	0,048
Revolution frequency	Hz	2,00E+06	2,00E+06	9,99E+05	6,66E+05	5,00E+05	2,50E+05	5,00E+04	2,50E+04
Revolution period	s	0,00	0,00	1,00E-06	1,50E-06	2,00E-06	4,00E-06	2,00E-05	4,00E-05
Number of bunches	#	1,00	1,00	1	1	1	1	1	1
N. Particle/bunch	#	2,00E+09	1,20E+08	2,50E+08	3,75E+08	5,00E+08	1,00E+09	6,00E+09	1,20E+10
Number of IP	#	1,00	1,00	1	1	1	1	1	1
σ_x @ IP	micron	0,04	0,12	8,39E-02	6,95E-02	5,81E-02	4,11E-02	1,68E-02	1,19E-02
σ_y @ IP	micron	0,04	0,12	8,39E-02	6,95E-02	5,81E-02	4,11E-02	1,68E-02	1,19E-02
$\sigma_{x'}$ @ IP	rad	0,00	0,00	4,20E-04	3,47E-04	2,91E-04	2,06E-04	8,39E-05	5,93E-05

MAP and LEMMA schematic layout for Multi-TeV option



EASIER AND CHEAPER DESIGN, IF FEASIBLE

Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

TIS-RP/IR/98-34 (1998) (updated by M.Antonelli)

MAP design for a 6 TeV muon collider

Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

muon rate:

p on target option

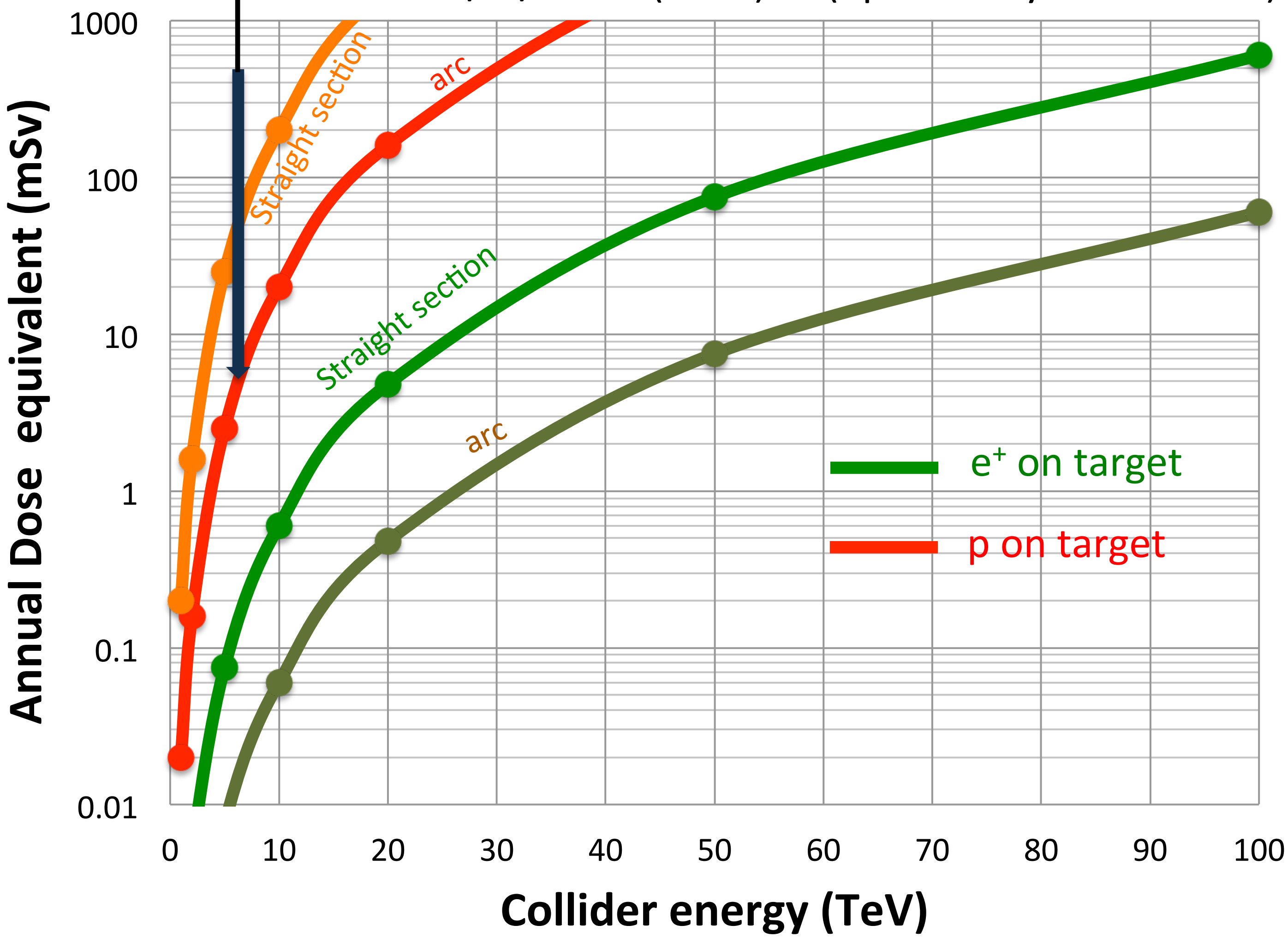
$3 \times 10^{13}\ \mu/s$

e^+ on target option

$9 \times 10^{10}\ \mu/s$

neutrino dose equivalent/fluence

[J.D. Cossairt, N.L. Grossman and E.T . Marshall, Health Phys. 73 (1997), 894-898.]



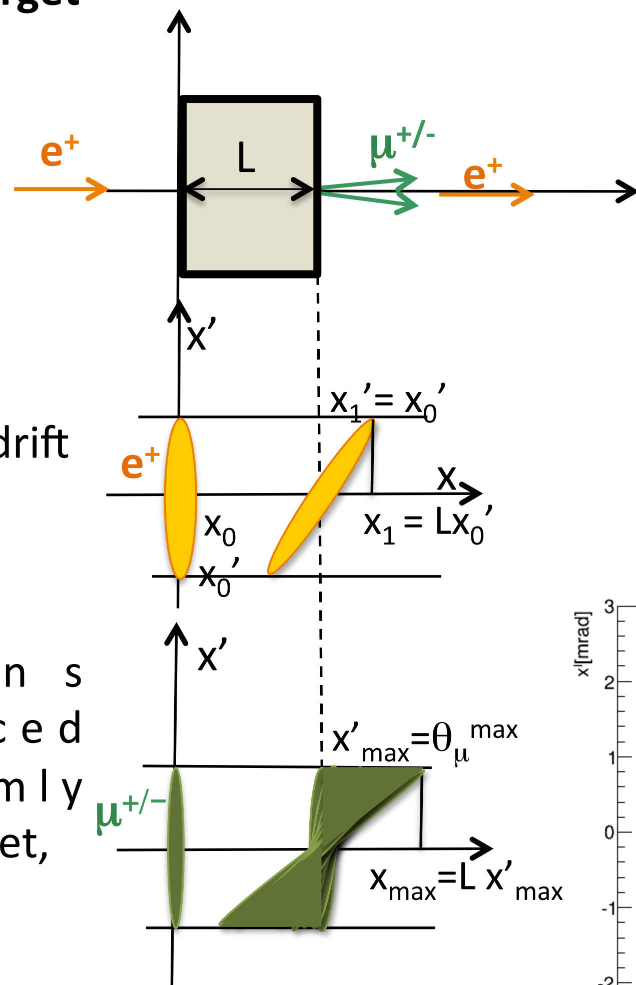
Production contribution to μ beam emittance

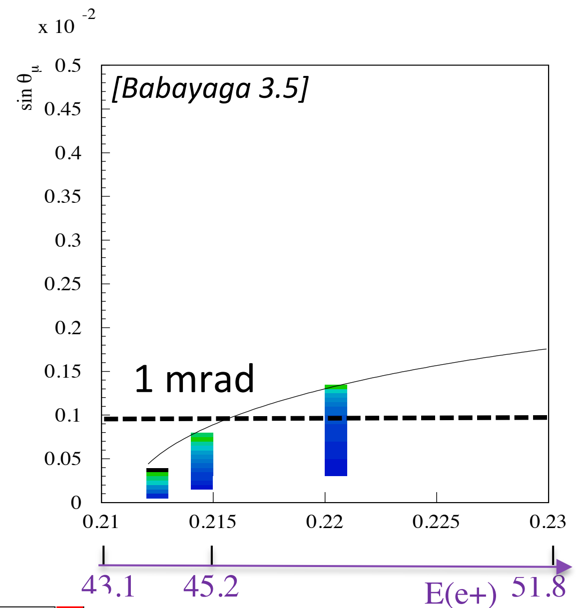
ideal e^- target

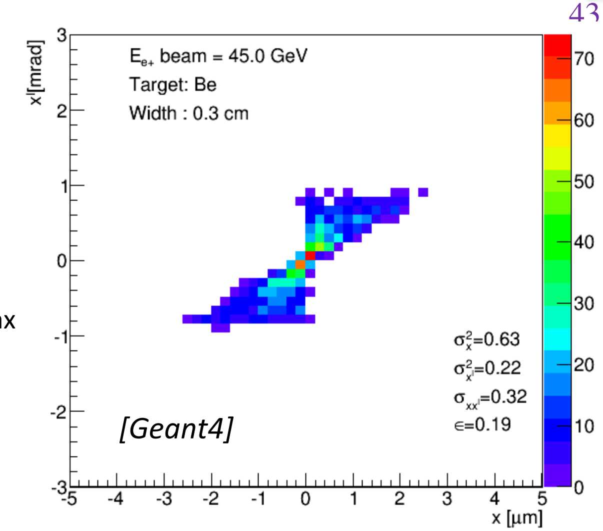
e^+ beam on target

If L was a drift

Muons produced uniformly along target, rifts [0,L]







Muon beam at the exit of a 3 mm Be target ε_μ=0.19 nm (45 GeV e+ beam)

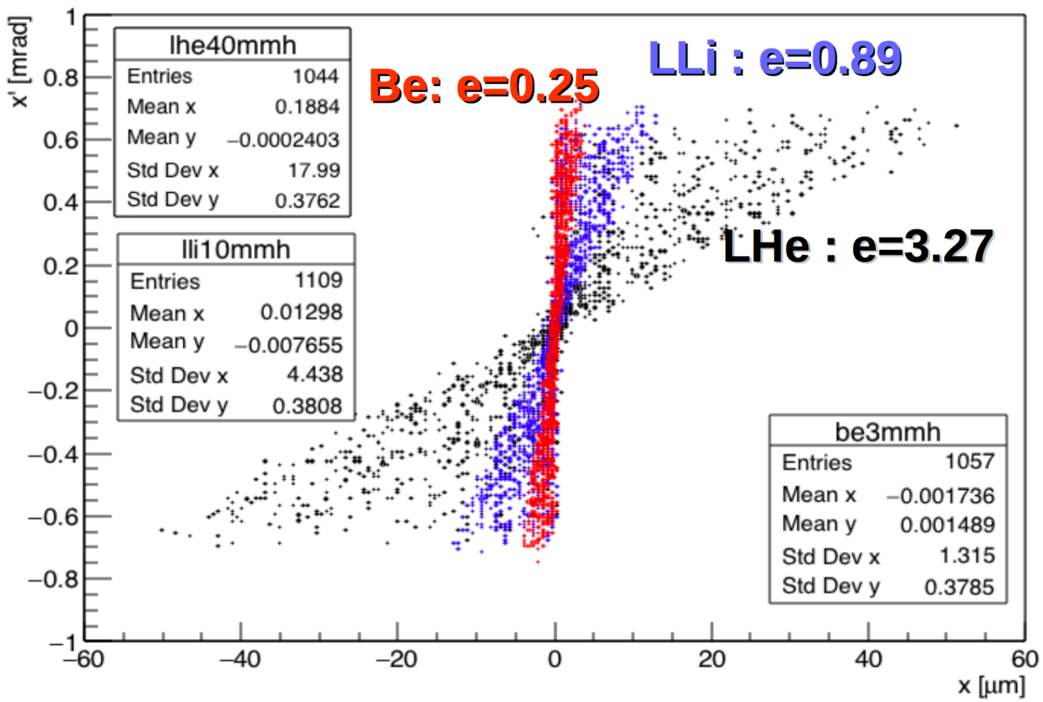
thin light materials targets have negligible multiple scattering contribution

The emittance contributions due to muon production angle: $\varepsilon_\mu = x\, x'_{max}/12 = L\, (\theta_\mu^{max})^2/12$

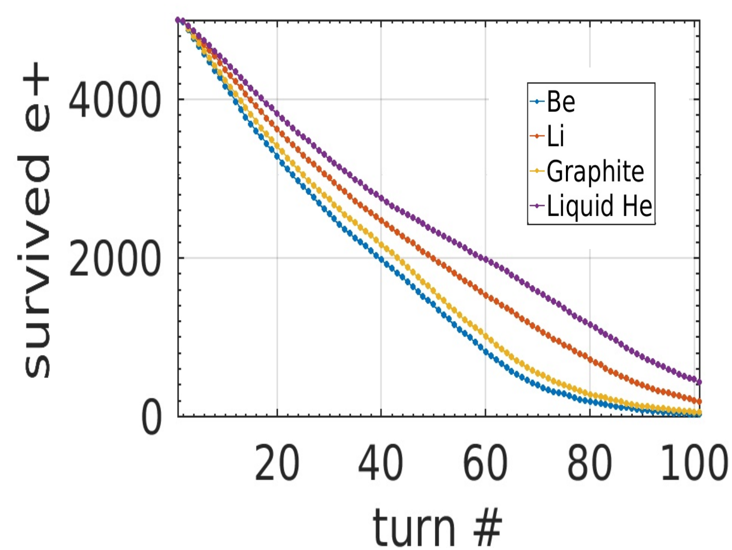
→ ε_μ completely determined by L and s -by target thickness and c.o.m. energy

Going to lighter targets for μ production

Be Beryllium
LLi Liquid Lithium, might be a good option (Proposed/tested for targets for nutron production)
LHe Liquid Helium



thickness according constant muons production

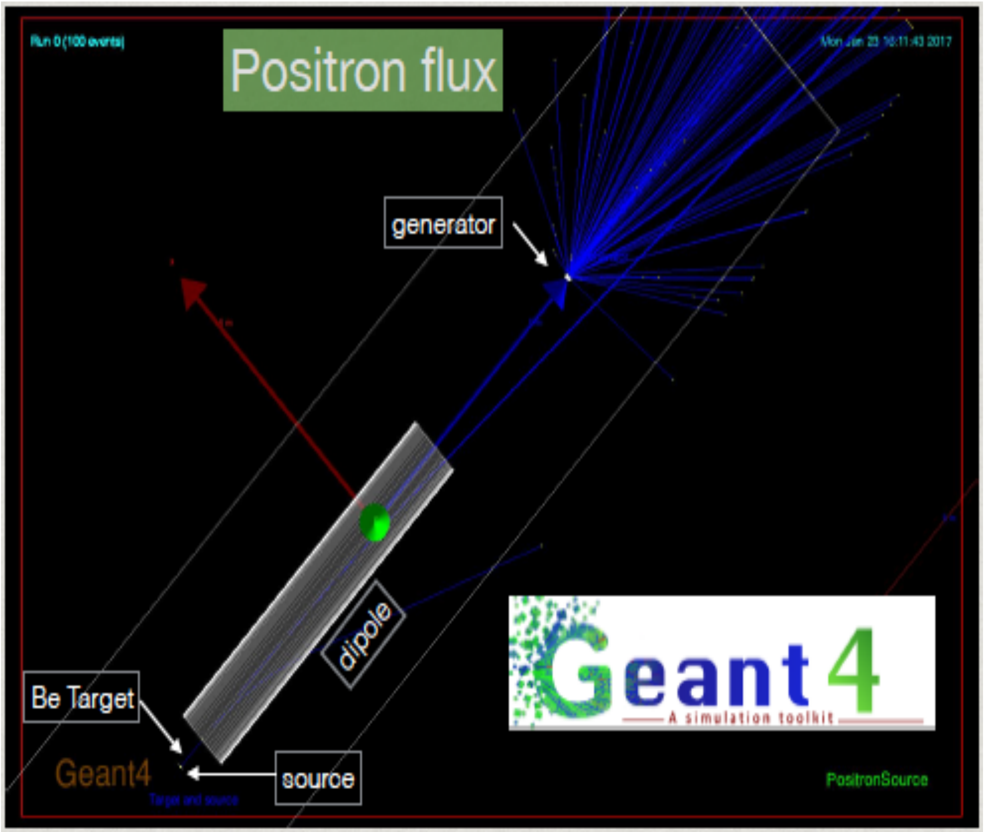


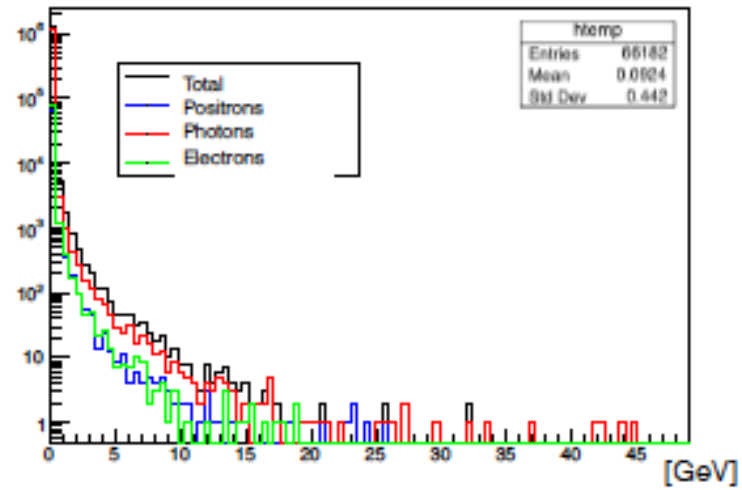
e = muon emittance at production [10^{-9}m-rad]
E(e^+)=45 GeV

Look to light liquid targets to reduce problems of thermo-mechanical stresses

Embedded positron source?

GEANT4 simulation for a generator of $5X_0$ (=1.8cm) of Tungstene





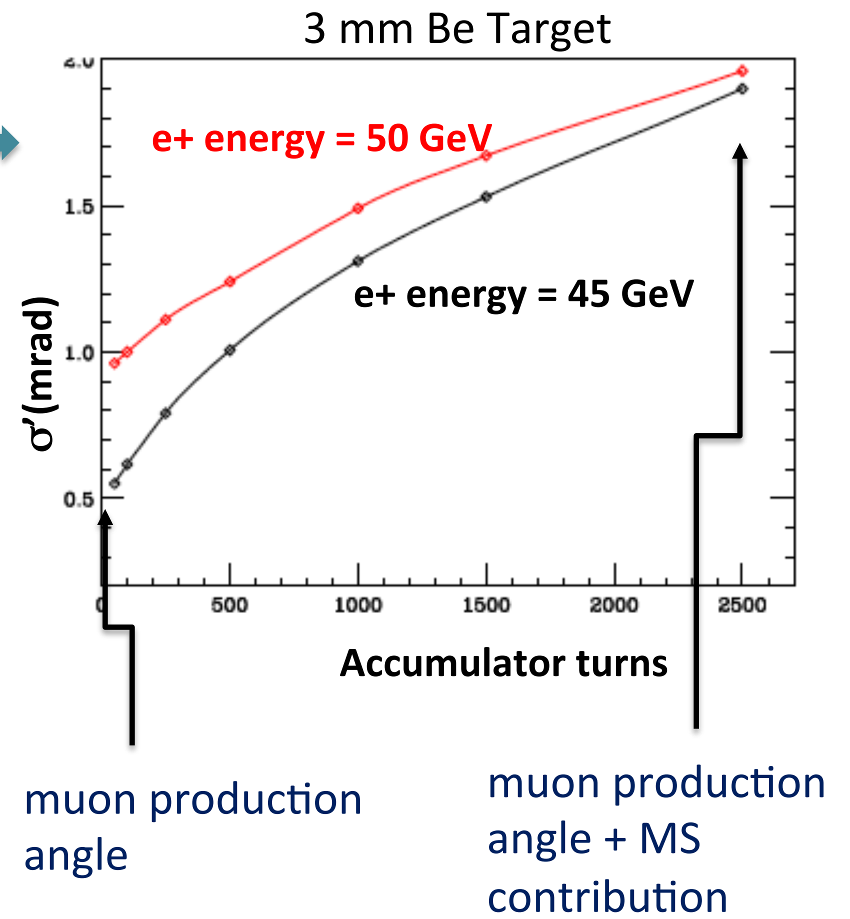
yield / 100 primaries		
ENTERING GENERATOR	γ	10.6
EXITING GENERATOR	all	1322
	e+	**65**
	e-	77
	γ	1180

It would be sufficient to collect ~5% (3/65) of these positrons to entirely recover the losses in the primary beam!

μ Accumulator Rings considerations

isochronous optics with high momentum acceptance ($\delta \gtrsim 10\%$)
optics to be designed

Multiple Scattering effect using one-turn matrix



beam divergence:
a factor 3-2 increase at 45-50 GeV w.r.t. muon production angle contribution
beam size:
depends on optics need low-β to suppress size increase

this contribution can be strongly reduced with crystals in channeling

better performances at 50 GeV provided >15% momentum acceptance

Test at DAΦNE

- **Beam dynamics studies of the ring-plus-target scheme:**
  - transverse beam size
  - current
  - lifetime
- **Measurements on target:**
  - temperature (heat load)
  - thermo-mechanical stress

Table 8: DAFNE parameters for the test with thin target at IP.

Parameter	Units	
Energy	GeV	0.51
Circumference	m	97.422
Coupling(full current)	%	1
Emittance x	m	0.28×10^{-6}
Emittance y	m	0.21×10^{-8}
Bunch length	mm	15
Beam current	mA	5
Number of bunches	#	1
RF frequency	MHz	368.366
RF voltage	kV	150
N. particles/bunch	#	1×10^{10}
Horizontal Transverse damping time	ms/turns	42 / 120000
Vertical Transverse damping time	ms/turns	37 / 110000
Longitudinal damping time	ms/turns	17.5 / 57000
Energy loss/turn	keV	9
Momentum compaction		1.9×10^{-2}
RF acceptance	%	$\pm$ 1

- The SIDDHARTA-2 experiment run will end on 2019 => our tests in 2020
- The target will be inserted at the IP:
  - To minimize modifications of the existing configuration
  - low-β and D_x=0 is needed
- First studies with the SIDDHARTA optics and target placed at the IP ongoing
- Limited energy acceptance of the ring (~1%) => we plan to insert light targets (Be, C) with thickness in the range 10-100μm.
- Crystal targets can be foreseen too, modified Geant4 tool needed for simulation