Muon colliders

Outline

- Muons case
- Muon accelerators challenges:
    - **muon production**
    - emittance reduction via **cooling**
    - high-gradient acceleration
- Conclusions

Muons: a long history of development

Rob Ryne

1980: A muon storage ring for neutrino oscillation experiments (Cline & Neuffer)

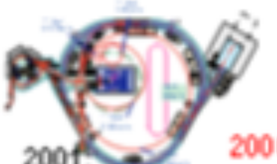
1986 (Madison WI): AAC Symposium: Multi-TeV Muon Colliders (Neuffer)

1991 (Napa,CA): First workshop on muon colliders

Snowmass'96

1997: Muon Collider Collab formed. Later becomes NFMCC

CERN studies 1999

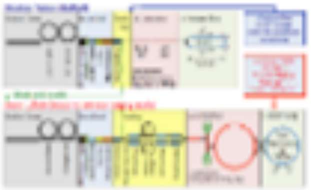


2001: Japanese NuFac Design Study 1

2006: MCTF @ FNAL

2011 IDS-NF Interim Design Report

MASS, IBS, R&D demonstrations



1980

1990

2000

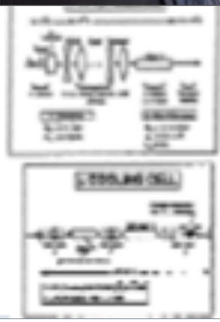
2010

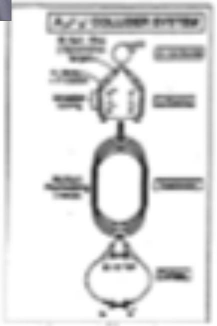
2015

1979: Colliding muon beams at 90 GeV (Neuffer)

1982: Skrinsky & Parkhomchuk: Ionization cooling

ito,CA):
o on muon colliders:
E-HL mu-mu collider
fer/Gallardo)





1997: Workshop on physics at 1st muon collider and FE of a muon collider

2001: US NuFac Design Study 1

Snowmass 2001: The Program in Muon and Neutrino Physics: Super Beams, Cold Muon Beams, Neutrino Factory and the Muon Collider

2002: US NuFac Design Study 2

2005-2006: ISS

2007: IDS-NF initiated

2011: US muon R&D consolidated into a single entity, MAP

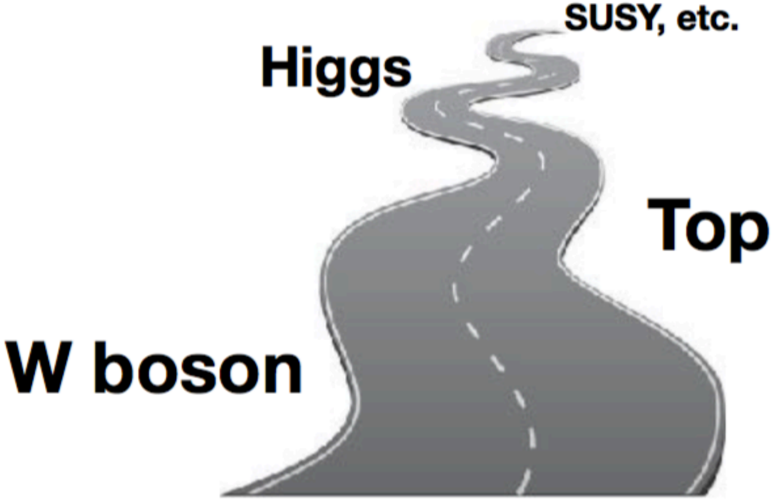
P5 recommends MAP reassessment

Snowmass 2013: Enabling Intensity & Energy Frontier Science w/a Muon Acc. Facility in the U.S.

Ideology

A. Wulzer at last
LEMMA meeting, 20/4/18

HEP before the LHC

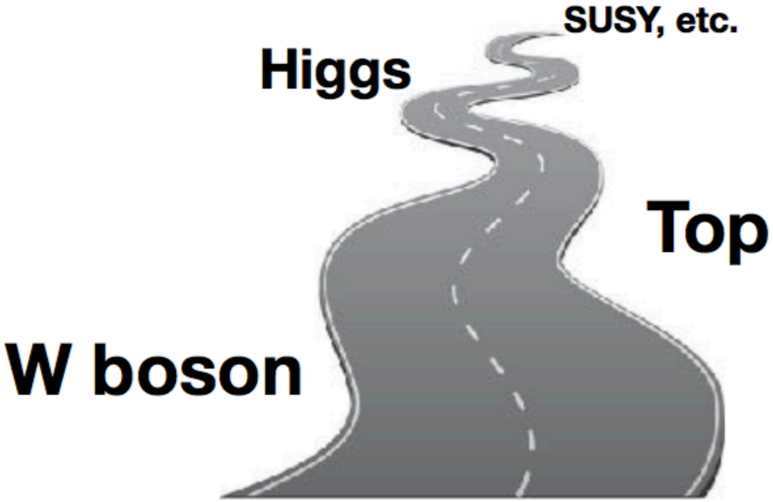


HEP before the F.C.

Ideology

A. Wulzer at last
LEMMA meeting, 20/4/18

HEP before the LHC



HEP before the F.C.

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories** *

* Not necessarily a bad thing. Columbus left for his trip just because he had no idea of where he was going !!

Ideology

A. Wulzer at last
LEMMA meeting, 20/4/18

No single experiment can explore all directions at once.

None can guarantee discoveries.

The next big FC **will exist only if** capable to **explore many directions**, and be **conclusive** on some of those

Dark Matter

A. Wulzer at last
LEMMA meeting, 20/4/18

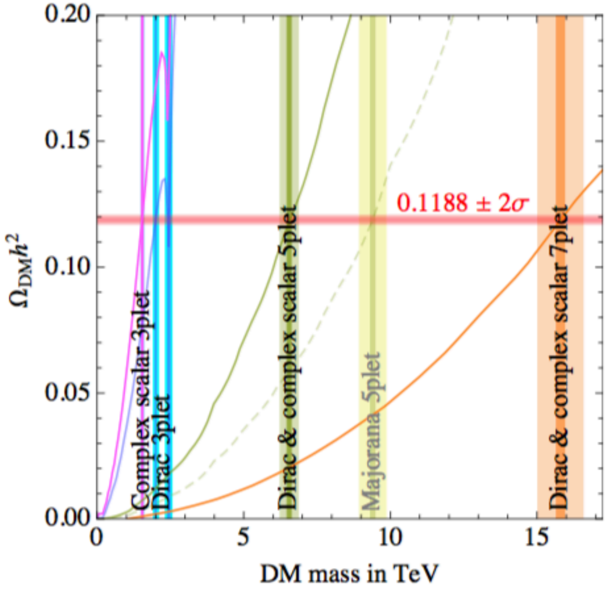
The FC should be capable to tell if DM is **WIMP**

WIMP can have up to **15 TeV** mass

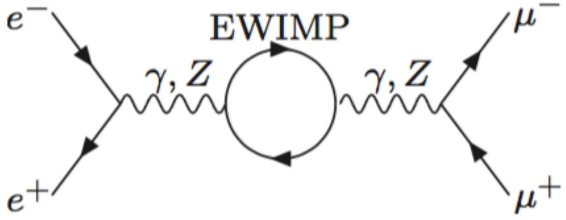
WIMP can be invisible to DD if **inelastic** or **leptofilic**

Accidental DM: stability from **accidental symmetries**

χ	$M_\chi^{(\rm DM)}$ [TeV]
$(1,3,\epsilon)_{\rm CS}$	1.5
$(1,3,\epsilon)_{\rm DF}$	2.0
$(1,3,0)_{\rm MF}$*	3.0
$(1,5,\epsilon)_{\rm CS,DF}$	6.6
$(1,5,0)_{\rm MF}$**	9.6
$(1,7,\epsilon)_{\rm CS,DF}$	16



Searched for directly, but also indirectly



Naturalness

A. Wulzer at last
LEMMA meeting, 20/4/18

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\mathrm{SM}}}{500\,\mathrm{GeV}}\right)^2$$

LHC may push conventional Natural models to

$$\Lambda_{\mathrm{SM}} \gtrsim 2\ \mathrm{TeV} \longrightarrow \Delta \gtrsim 10$$

Still Naturalness might be there in the form of:

Partial Unnaturalness

$$\Delta \sim 100$$

$$\Big\downarrow$$

$$\Lambda_{\mathrm{SM}} \sim 5\ \mathrm{TeV}$$

Neutral Naturalness

$$\Delta \sim \text{few} \longrightarrow \Lambda_{\mathrm{SM}}^{\mathrm{col.}} \sim 5\ \mathrm{TeV}$$

$$\Big\downarrow$$

$$\Lambda_{\mathrm{SM}}^{\mathrm{neut.}} \lesssim 1\ \mathrm{TeV}$$

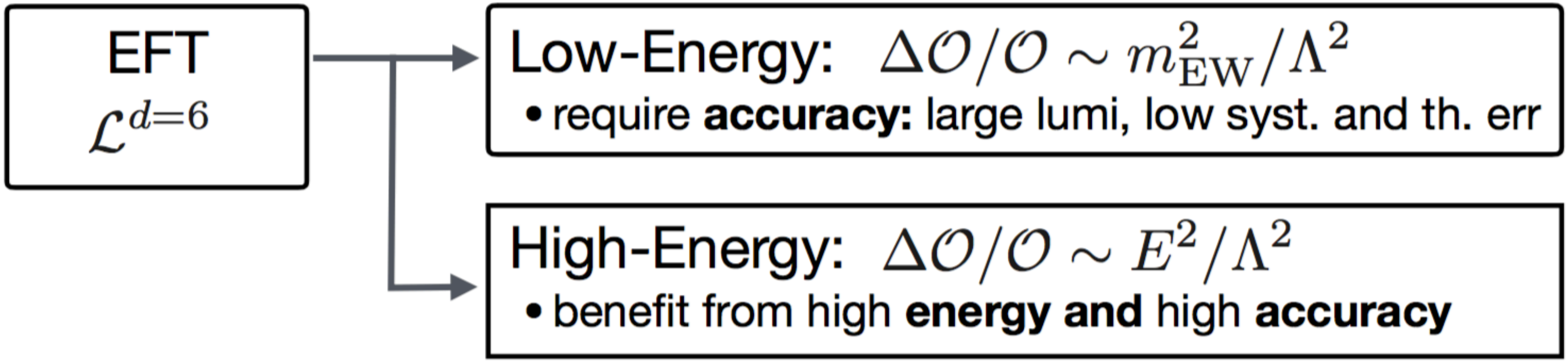
Need **5 TeV** reach on ordinary Top Partners

Still, the higher the reach, the better

If Everything Fails

A. Wulzer at last
LEMMA meeting, 20/4/18

The FC must have indirect reach superior to direct one, on BSM scale, by at least a few



EFT
$\mathcal{L}^{d=6}$

Low-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\mathrm{EW}}^2/\Lambda^2$

- require **accuracy:** large lumi, low syst. and th. err

High-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

- benefit from high **energy and** high **accuracy**

Must be able to **measure** SM proc.'s, at **few% at least**

Muon Colliders

A. Wulzer at last
LEMMA meeting, 20/4/18

We should remind everybody about pdf's!

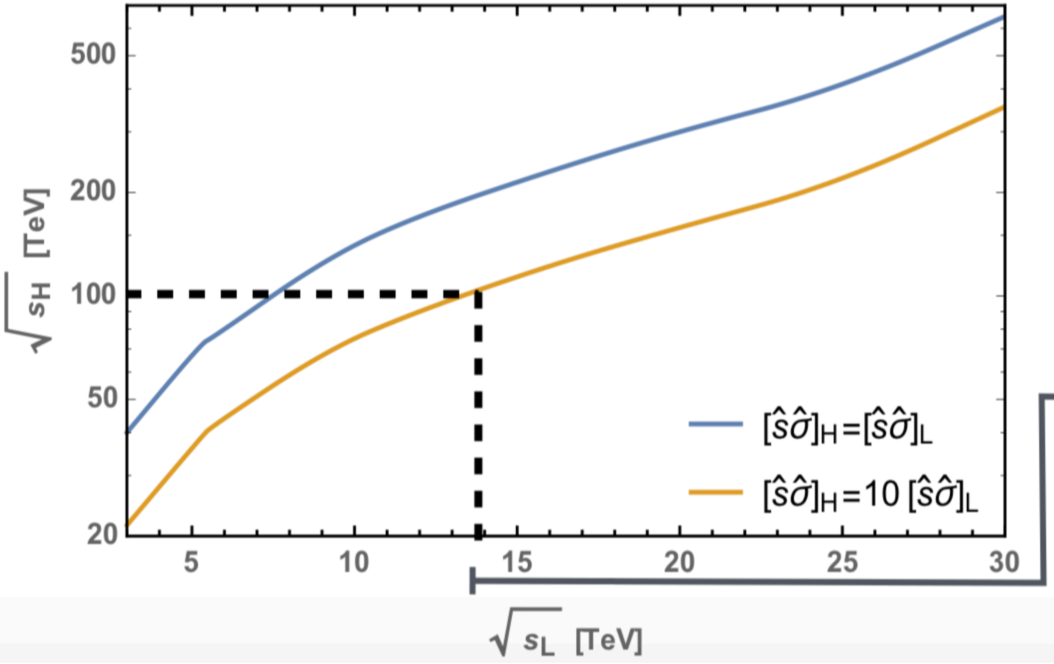
Lepton coll. operating at energy $\sqrt{s_L}$.
Cross section for reaction at E~$\sqrt{s_L}$
(e.g., production of BSM at M=E)

$$\sigma_L(s_L) = \frac{1}{s_L}[\hat{s}\hat{\sigma}]_L$$

Hadron coll. operating at energy $\sqrt{s_H}$.
Cross section for reaction at E.
Parton Luminosity suppression

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

Find **equivalent $\sqrt{s_H}$** for Had. Coll. have **same cross-section** as Lep. Coll. for reactions at E~$\sqrt{s_L}$. Use that $[\hat{s}\hat{\sigma}]$ is nearly constant in τ.



QCD-coloured BSM can easily have much larger partonic XS.

Comparison even more favourable for **QCD-neutral BSM**

14 TeV μ-collider nearly as good as the FCC at 100 TeV?

Muon Colliders Requirements Specification

A. Wulzer at last
LEMMA meeting, 20/4/18

The muon collider must:

0) Run for a reasonable time: $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ → $900\mathrm{fb}^{-1}$

“reasonable” here means 3*LHC

1) Pair produce more than 100 EW particles:

sufficient to probe “**easy**” decay modes (e.g., for top partners/stops)

$$N = 1300 \left(\frac{10\ \mathrm{TeV}}{\sqrt{s}}\right)^2 \left(\frac{L}{10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}}\right)$$

➡

$$L > \frac{1}{13}\left(\frac{\sqrt{s}}{10\ \mathrm{TeV}}\right)^2 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

2) Measure SM cross-sections:

simple estimate for 2 → 2, but what about WW scattering, HH prod…?

$$\boxed{L > \left(\frac{\sqrt{s}}{10\ \mathrm{TeV}}\right)^2 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

3) Probe DM in mono-γ/W/Z, EW singlets, …

L>? This should be assessed!

Muon based colliders great potential

As with an e^+e^- collider, a $\mu^+\mu^-$ collider offers a precision probe of fundamental interactions without energy limitations

- **By synchrotron radiation (limit of e^+e^- circular colliders)**
- **By beam-strahlung (limit of e^+e^- linear colliders)**

Muon Collider is the ideal technology to extend lepton high energy frontier in the multi-TeV range with reasonable dimension, cost and power consumption

Muon based Higgs factory takes advantage of a strong coupling to Higgs mechanism by s resonance

IF THE MUON BEAM NOVEL TECHNOLOGY CAN BE DEMONSTRATED TO BE FEASIBLE

Muons: Issues & Challenges

- **Limited lifetime: 2.2 μs (at rest)**
  - Race against death: generation, acceleration & collision before decay
  - Muons decay in accelerator and detector
    - Shielding of detector and facility irradiation
    - Collider and Physics feasibility with large background environment?

      Not by beamshtrahlung as with e+/e- but by muon decay (e, ν)

      Reduced background at high energy due to increased muon lifetime
  - Decays in neutrinos:
    - Ideal source of well defined electron & muon neutrinos in equal quantities whereas Superbeams by pion decay only provide muon ν:

☹

☺

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

The neutrino factory concept

- **Generated as tertiary particles in large emittances**
  - powerful MW(s) proton driver and pion decay
  - novel (fast) cooling and acceleration methods

☹

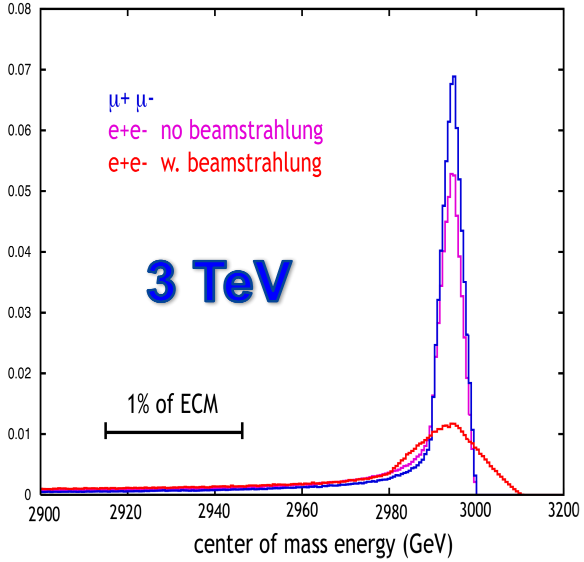
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \nu_\mu$$

Development of novel technologies with key accelerator and detector challenges

Muon beams specific properties

Muons are leptons like electrons & positrons but with a mass (105.7 MeV/c^2) 207 times larger

- **Negligible synchrotron radiation emission (α m^{-2})**
  - **Multi-pass collisions (1000 turns) in collider ring**
    - **High luminosity with reasonable beam power and wall plug power consumption**
      - ☺ **relaxed beam emittances & sizes, alignment & stability**
    - **Multi-detectors supporting broad physics communities**
    - **Large time (15 μs) between bunch crossings**
  - ☺ **No beam-strahlung at collision:**
    - **narrow luminosity spectrum**
  - ☺ **Multi-pass acceleration in rings or RLA:**
    - **Compact acceleration system and collider**
    - **Cost effective construction & operation**
  - **No cooling by synchrotron radiation in standard damping rings**
    - ☹ **Requires development of novel cooling method**



Synchrotron radiation

$$P = \frac{2}{3}\frac{e^2 c}{4\pi\varepsilon_0}\frac{\beta^4\gamma^4}{\rho^2}$$

$$U_0 = \frac{e^2}{3\varepsilon_0}\frac{\beta^3\gamma^4}{\rho}$$

$Uo = 5.5 \times 10^{-18}\ \gamma^4/\rho$

electrons Uo (GeV) = $9\ 10^{-5}$ E^4(GeV)/ρ(m)
muons Uo (GeV) = $5\ 10^{-14}$ E^4(GeV)/ρ(m)
protons Uo (GeV) = $7\ 10^{-18}$ E^4(GeV)/ρ(m)

r =3000 m (LEP/LHC tunnel)

@ Uo/Eb ~ 10% electrons are limited to ~ 150 GeV (Uo = 15 GeV)
@ Uo/Eb ~ 10% muons can go up 200 TeV (Uo = 20 TeV)

Multipass

$E \approx P(\mathrm{GeV}) = 0.3\ B(\mathrm{T})\ \rho\ (\mathrm{m})$

$L_{acc} = 2\pi\ \rho\ 3/2$(dipole filling factor)

$L_{acc}\ (\mathrm{m}) = 3\ \pi\ E/[0.3\ B(\mathrm{T})] \approx 30/B(\mathrm{T})$

decay length $= \gamma\beta c\ \tau_\mu = 6000\ E$ $\tau_\mu = 2.2\ \mu s$

➡

Lifetime (machine turns) = decay length / Lacc = 200 B(T)

B= 16 T 3000 turns

Luminosity and RF acceleration can benefit of this factor !

Luminosity

$$\boxed{N(p)= \sigma(p)\, \mathbf{N(e^{+})}\, \rho(e^{-})\, \mathbf{L}}$$

$N(e^{+})$ number of e^{+}

$\rho(e^{-})$ target electron density

L target length

$$\boxed{N(p)= \sigma(p)\, \mathbf{N(e^{+})N(e^{-})}/A}$$

$N(e^{+})$ number of e^{+}

$N(e^{-})$ number of e-

A area of intersection

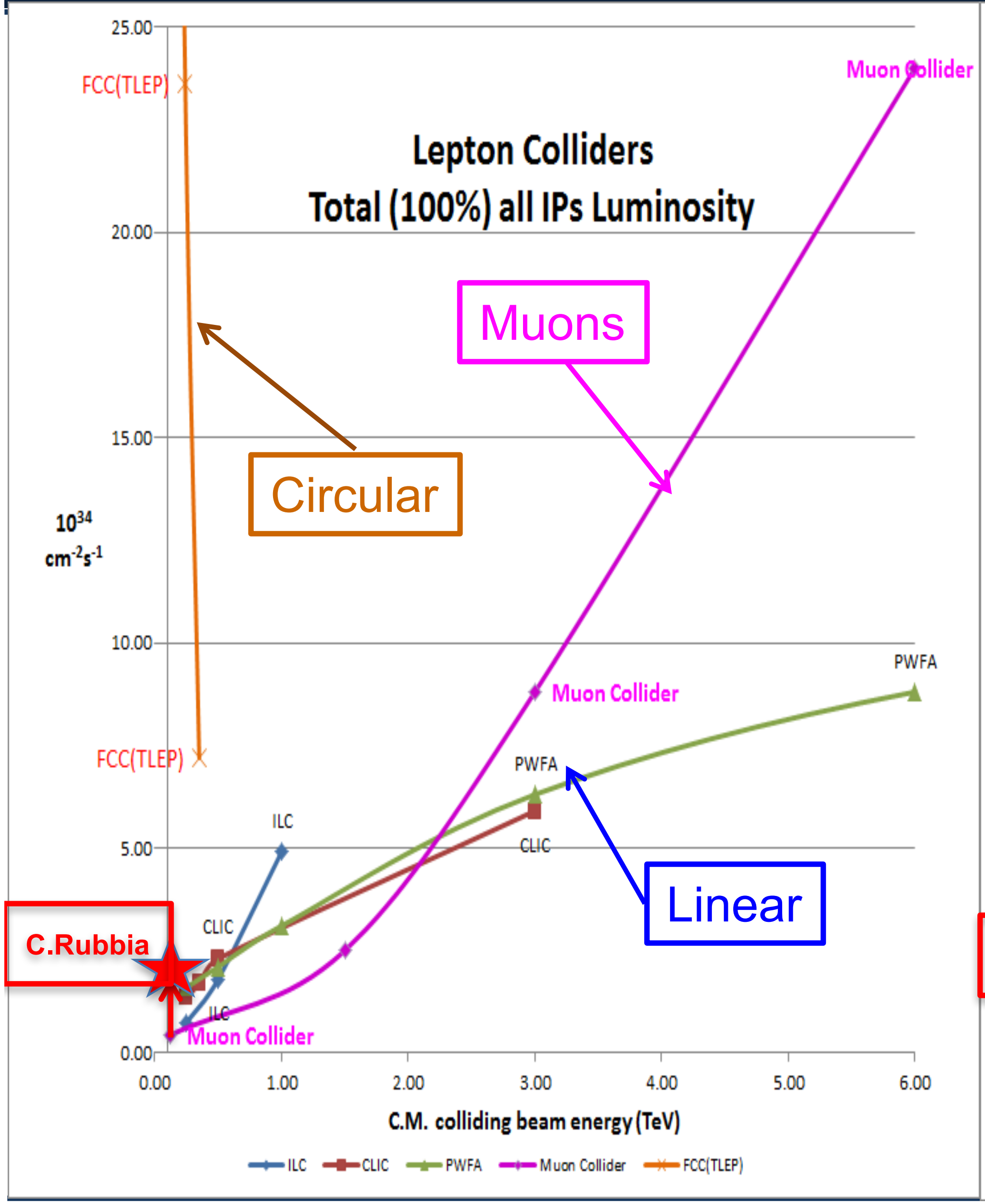
$$\boxed{dN(p)/dt= \sigma(p)\, \mathbf{N(e^{+})}\, \mathbf{N(e^{-})}\, /A\, f}$$

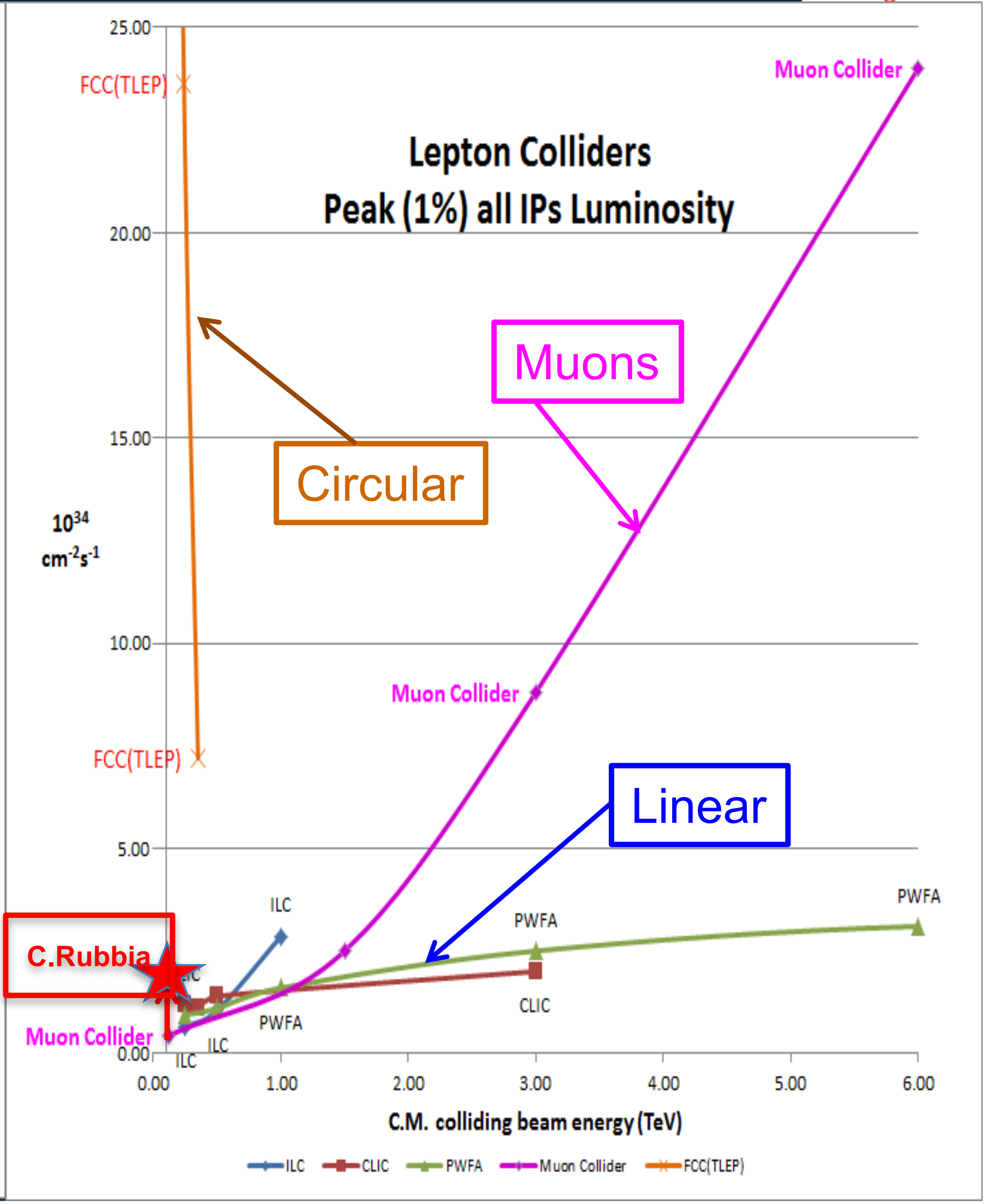
$$\boxed{L=\mathbf{N(e^{+})}\, \mathbf{N(e^{-})}\, /A\, f}$$

f intersection frequency

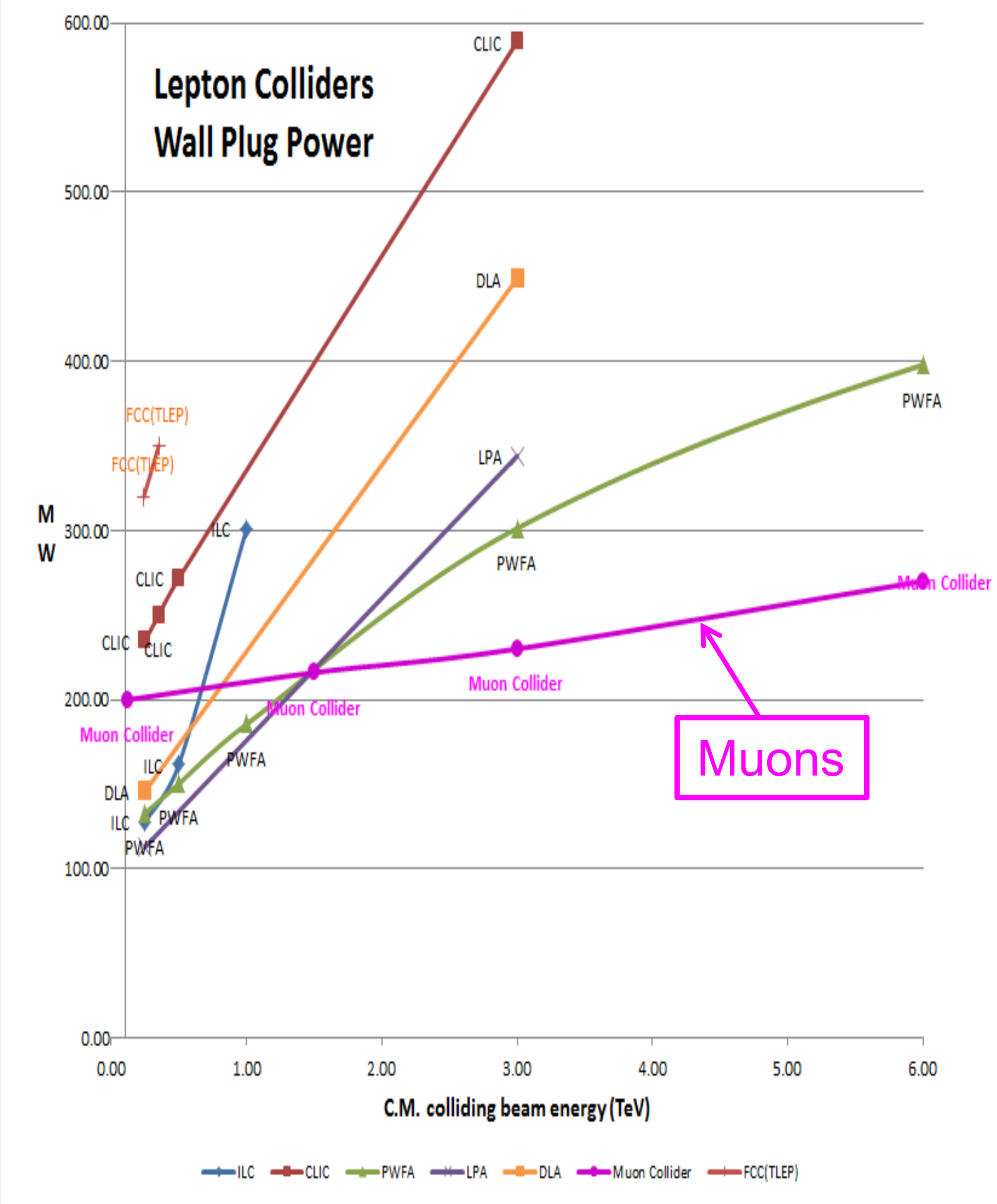
- injection frequency for linear colliders
- revolution frequency for circular with stable particles

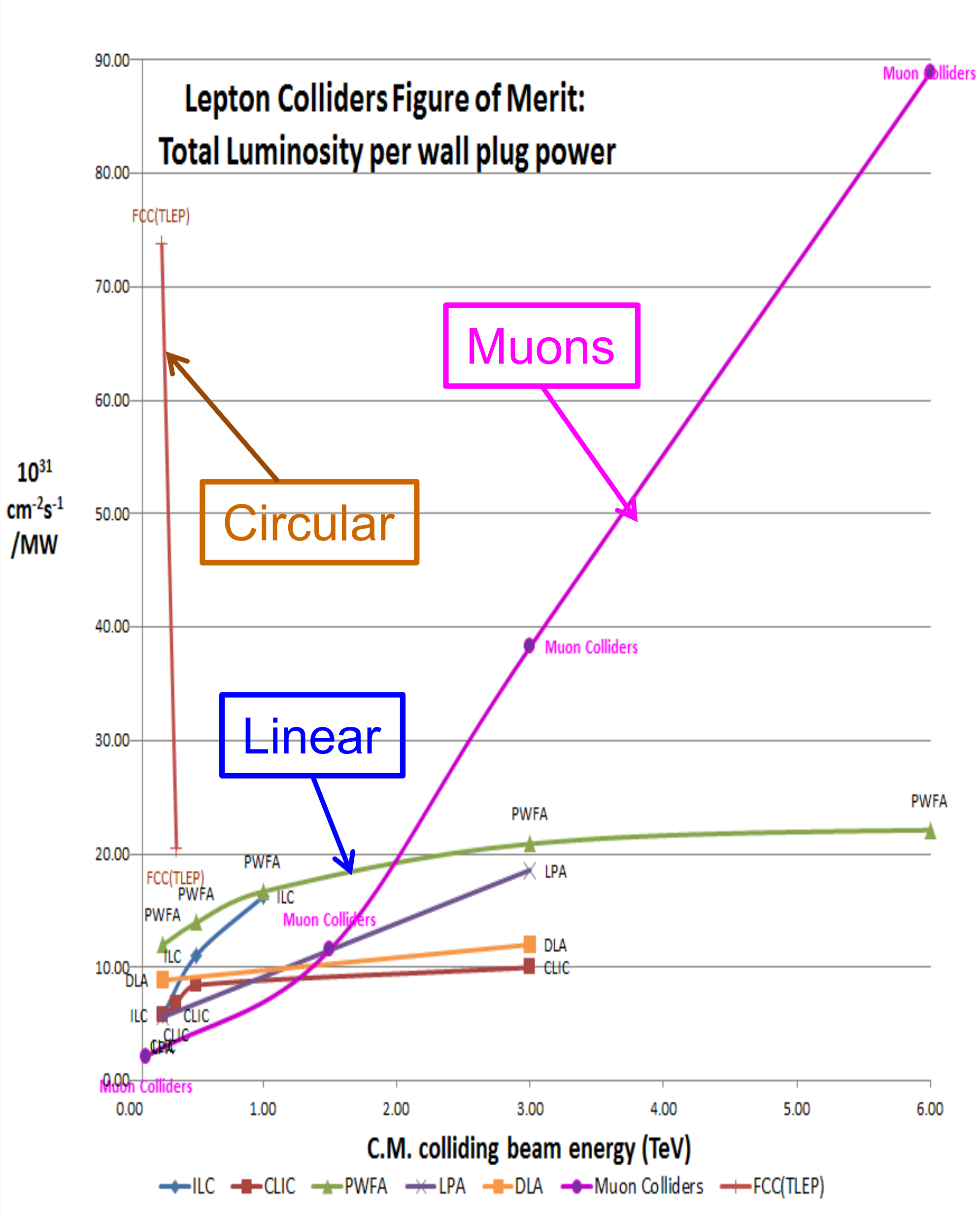
Muon Colliders potential of extending leptons high energy frontier with high performance





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





Muon Source

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

Rate > 10^{13}μ/sec $N_\mu = 2\cdot10^{12}$ /bunch

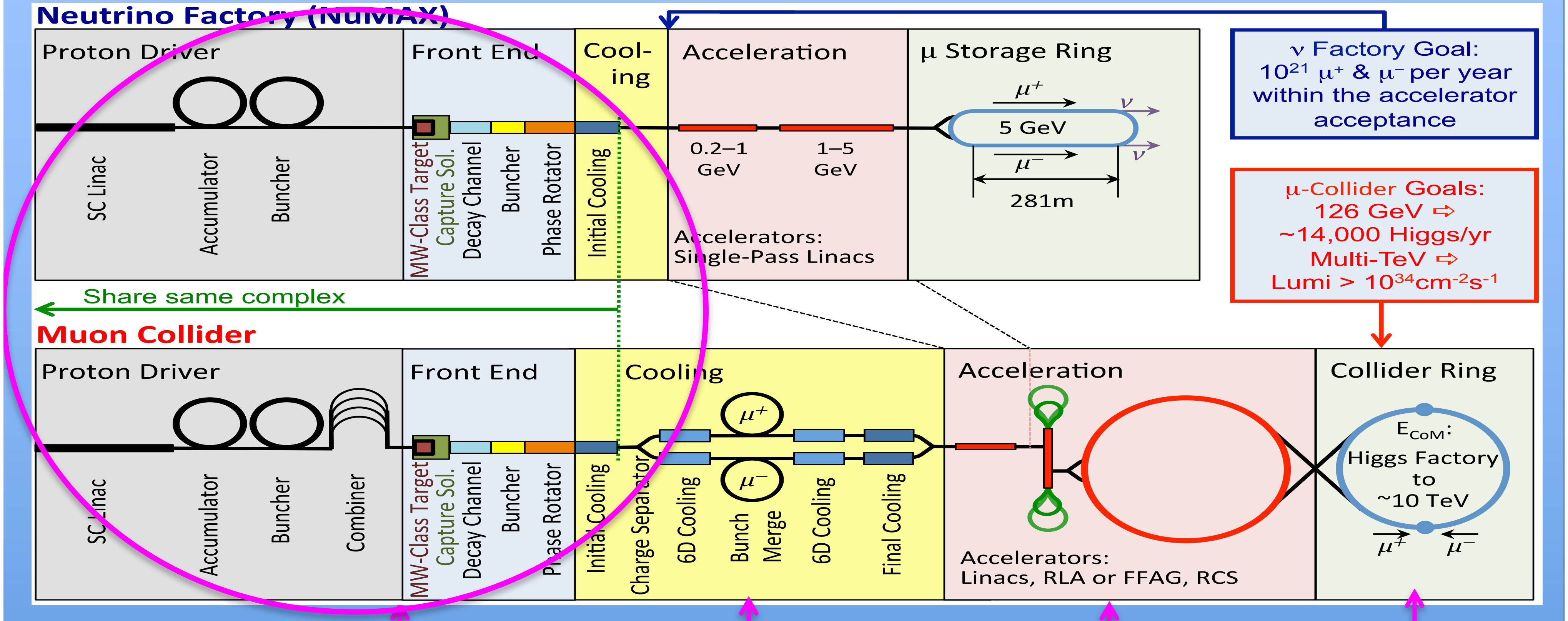
Unconventional:

- **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~ 5×10^7 /bunch

- **by Gammas: GeV-scale Compton γs** not discussed here
  Rate ~ $5\cdot10^{10}$ μ/sec N_μ ~ 10^6 (Pulsed Linac) [V. Yakimenko (SLAC)]
  Rate > 10^{13} μ/sec N_μ ~ few·10^4 (High Current ERL)
  see also: W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44

Proton-Based Source

Muon Accelerator Program (MAP)
Muon based facilities and synergies



ν Factory Goal:
10^{21} μ^+ & μ^- per year within the accelerator acceptance

μ-Collider Goals:
126 GeV ⇨ ~14,000 Higgs/yr
Multi-TeV ⇨ Lumi > $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Key Challenges

- **~10^{13}-10^{14} μ / sec Tertiary particle $p \rightarrow \pi \rightarrow \mu$:**
- **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**

JP.Delahaye

Muon beam facilities - Overview

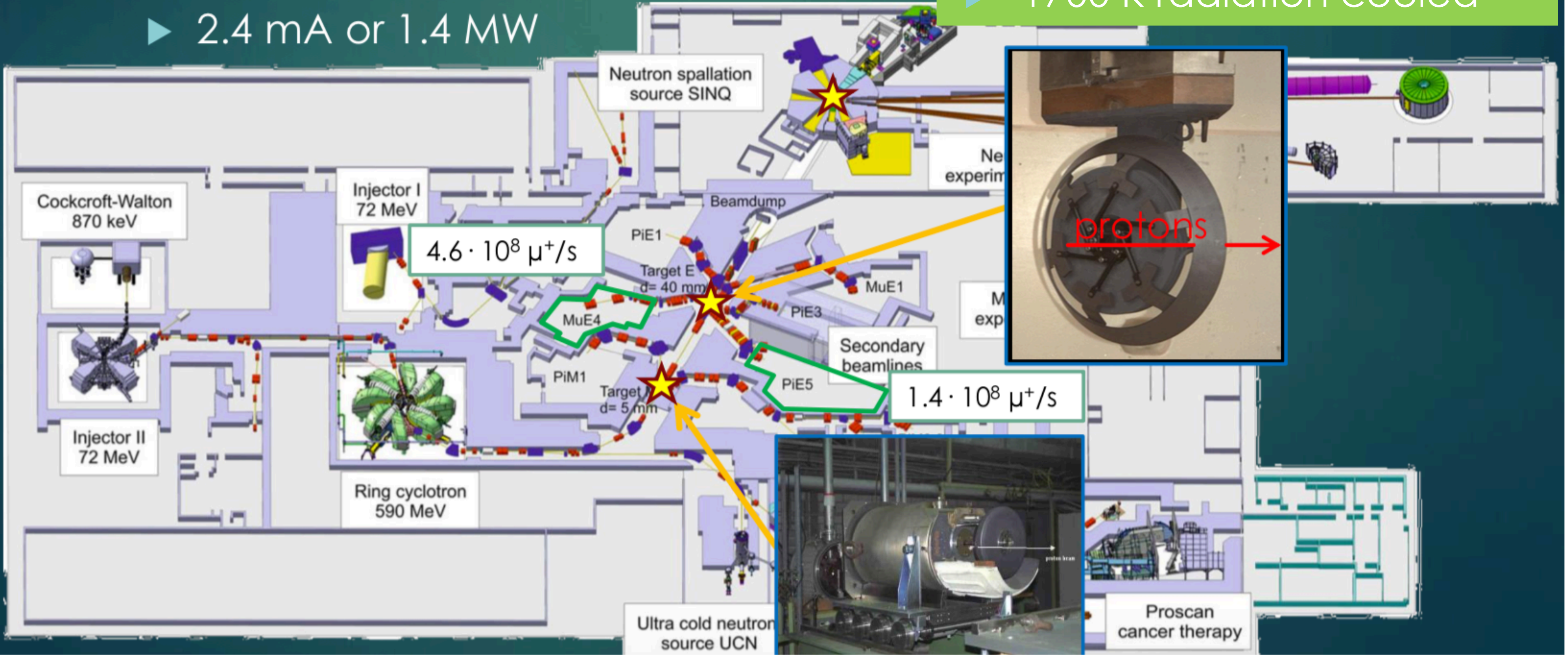
Laboratory/Beamline	Energy/ Power	Present Muon μ^+/μ^- Rates [Hz]	Future estimated μ^+/μ^- Rate [Hz]
PSI (CH)	590 MeV, 1.3 MW DC		
LEM		$4.2\cdot10^8\,\mu^+$	
πE5		$1.3\cdot10^8\,\mu^+$	
HiMB			$O(10^{10})\,\mu^+$ / $O(10^8)\,\mu^-$
JPARC (JP)	3 GeV, 1MW Pulsed Reached 400kW		$2\cdot10^8\,\mu^+$ @ 1MW)
MUSE		$8\cdot10^7$ / $4\cdot10^6$	$10^7\,\mu^-$ @ 1MW
COMET	8 GeV, 56kW Pulsed		$10^{11}\,\mu^-$ 2019/2020
FNAL (USA)			
Mu2e	8GeV, 25kW Pulsed		$5\cdot10^{10}\,\mu^-$ 2019/2020
RAON/RISP (KO)	600 MeV, 400kW DC)		$7\cdot10^8\,\mu^+$
CSNS (CN)	1.6 GeV, 100kW Pulsed		$10^{10}\,\mu^+$
TRIMUF (CA)	500 MeV, 75kW, DC		
M20/M9B		$2\cdot10^6$ / $1.4\cdot10^6$	
RAL ISIS (UK)	800 MeV, 160kW, Pulsed	$1.5\cdot10^6$/ $7\cdot10^4$	
RIKEN RAL			
RCNP Osaka Univ. (JP)	400 MeV, 400W DC		
MUSIC		10^6/$1\cdot10^5$	$4.2\cdot10^8$/$4.2\cdot10^7$

PSI - the world's highest intensity surface μ^+ beams

- Proton beam :
  - 590 MeV
  - 50 MHz / 20 ns → CW surface muons
  - 2.4 mA or 1.4 MW

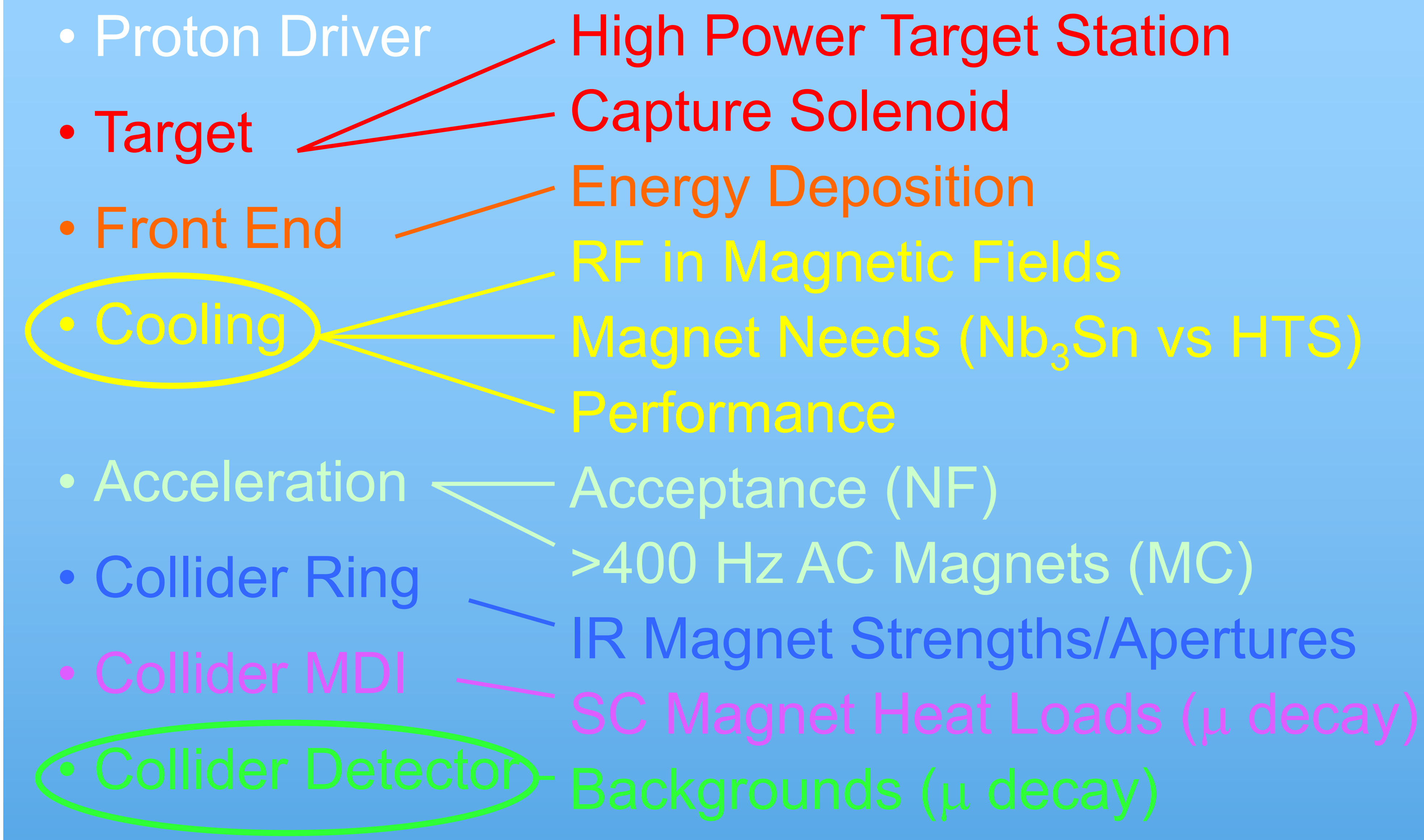
	Capture efficiency	Transmission	Overall efficiency
MuE4	~ 6 %	~ 7%	~ 0.4 %

- 50 kW proton beam energy deposit
  - 1700 K radiation cooled



M. Palmer

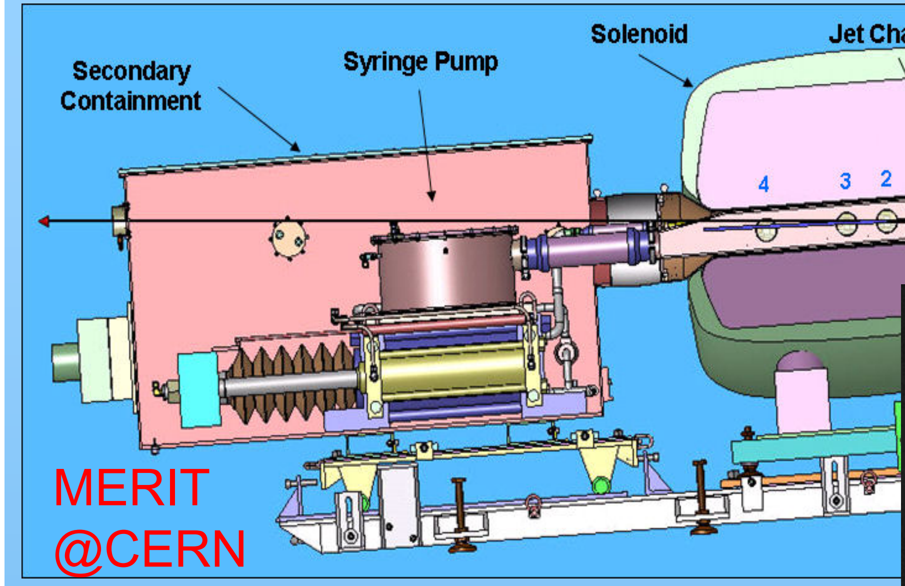
Key Feasibility Issues



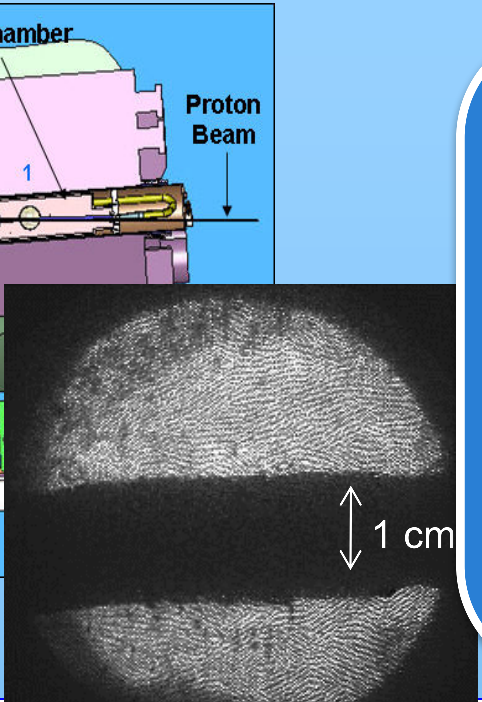
- Proton Driver
- Target
- Front End
- Cooling
- Acceleration
- Collider Ring
- Collider MDI
- Collider Detector

High Power Target Station
Capture Solenoid
Energy Deposition
RF in Magnetic Fields
Magnet Needs (Nb$_3$Sn vs HTS)
Performance
Acceptance (NF)
>400 Hz AC Magnets (MC)
IR Magnet Strengths/Apertures
SC Magnet Heat Loads (μ decay)
Backgrounds (μ decay)

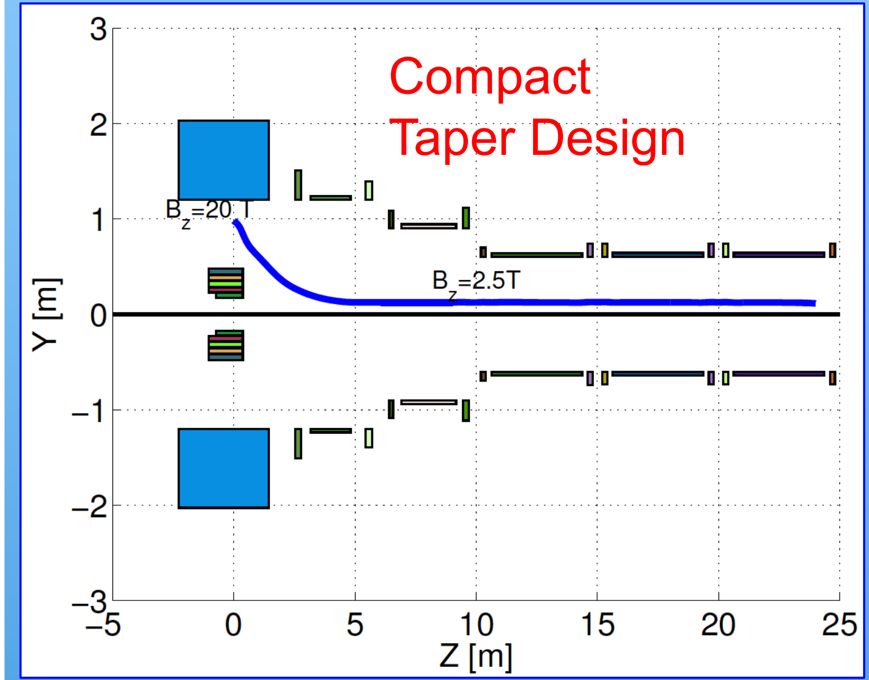
High Power Target



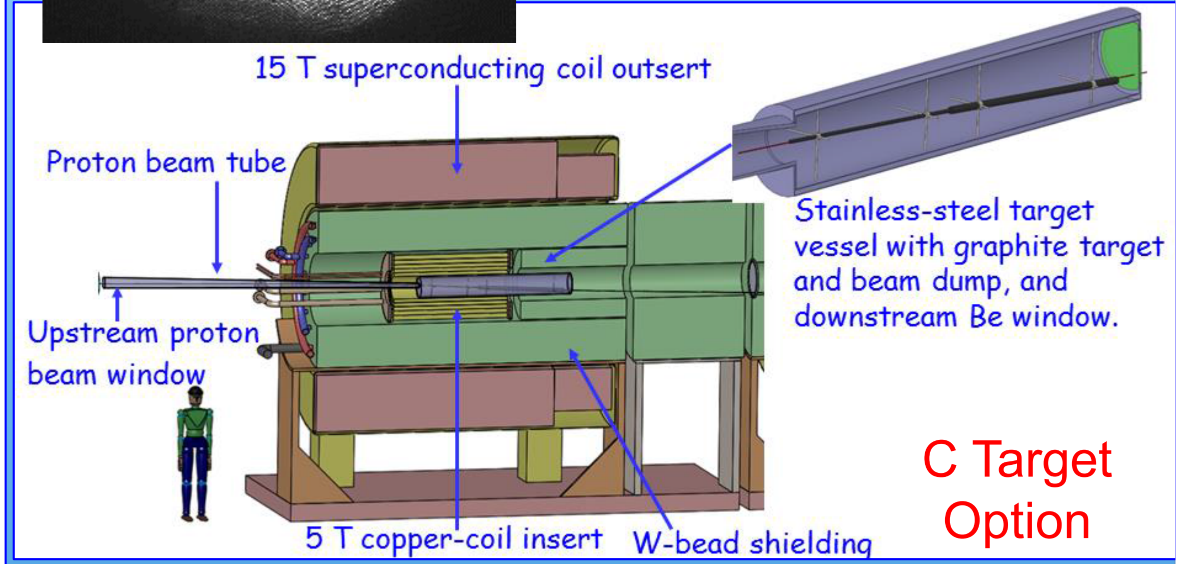
MERIT @CERN



- ✓ MERIT Expt:
  - LHg Jet in 15T
  - Capability: 8MW @70Hz
- ✓ MAP Staging aims at 1-2 MW ⇨ C Target
- ✓ Improved Compact Taper Design
  - Performance & Cost



Compact Taper Design

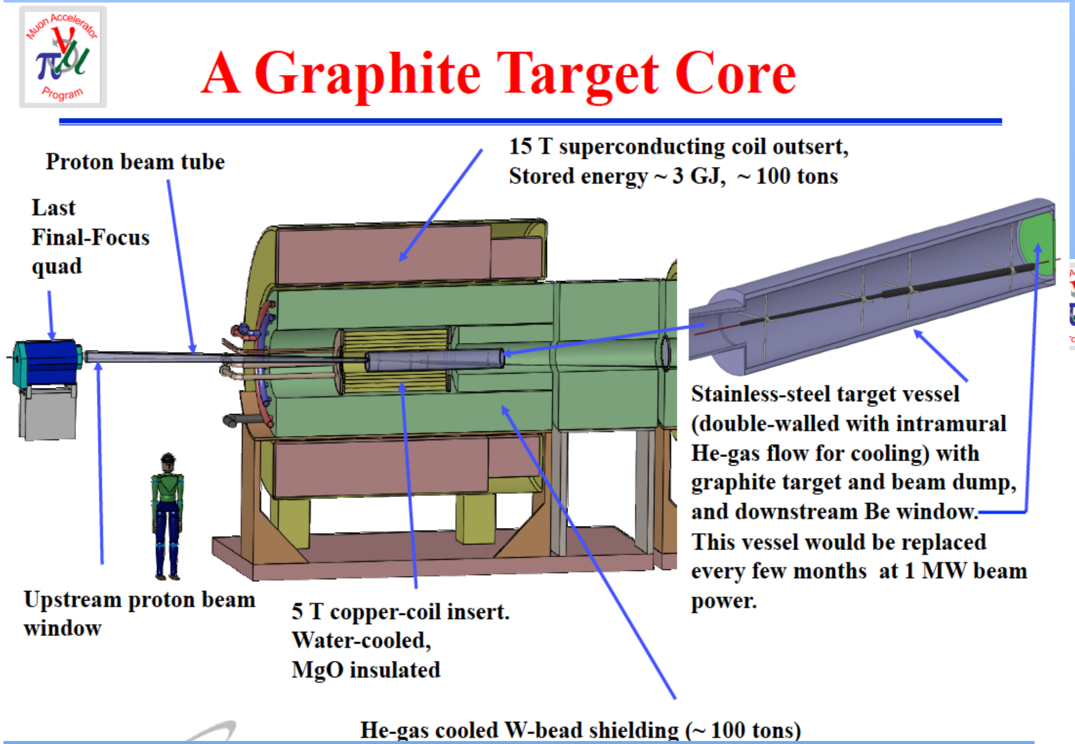


Stainless-steel target vessel with graphite target and beam dump, and downstream Be window.

C Target Option

MAP muon generation by Proton driver

H.Kirk (BNL)



A Graphite Target Core

Proton beam tube

Last Final-Focus quad

15 T superconducting coil outsert, Stored energy ~ 3 GJ, ~ 100 tons

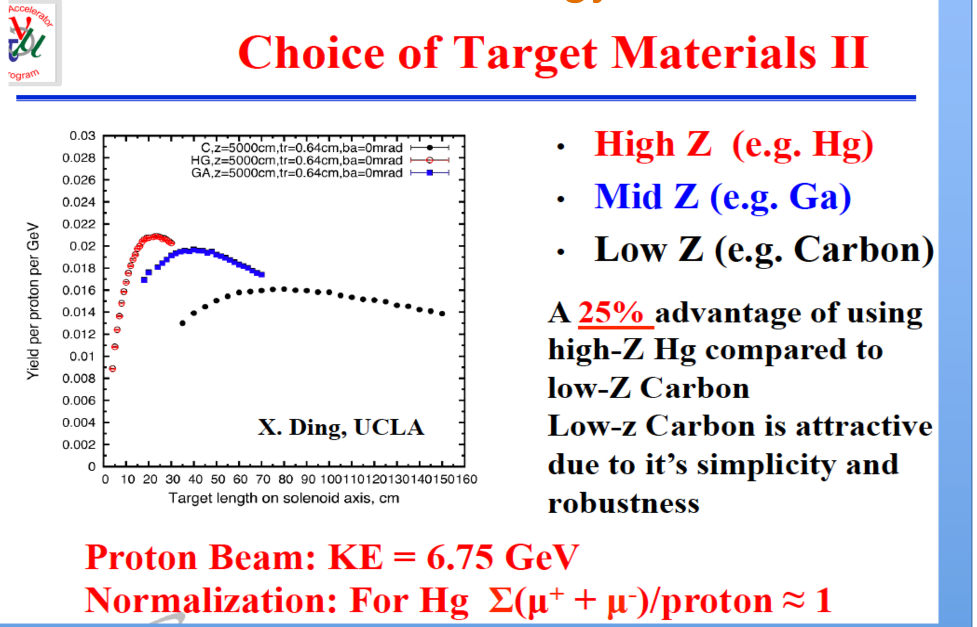
Stainless-steel target vessel (double-walled with intramural He-gas flow for cooling) with graphite target and beam dump, and downstream Be window. This vessel would be replaced every few months at 1 MW beam power.

Upstream proton beam window

5 T copper-coil insert. Water-cooled, MgO insulated

He-gas cooled W-bead shielding (~ 100 tons)

- MW-Class proton driver at ~5-10 GeV
- Capture solenoid system (μ^+ & μ^-)
    - 15 T outsert, 5 T insert
    - ~3GJ stored energy



Choice of Target Materials II

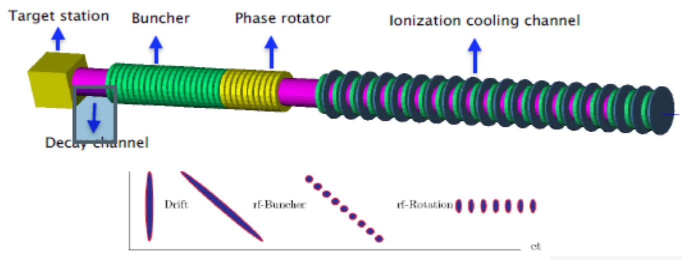
- High Z (e.g. Hg)
- Mid Z (e.g. Ga)
- Low Z (e.g. Carbon)

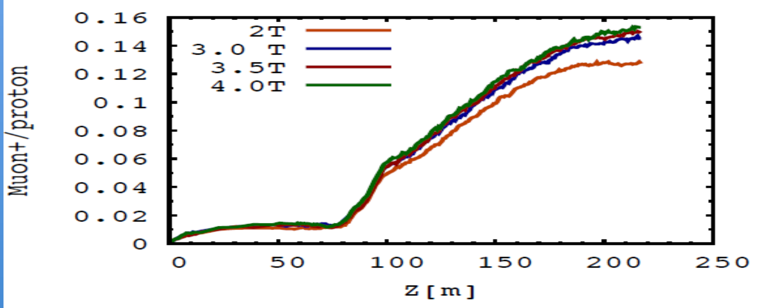
A 25% advantage of using high-Z Hg compared to low-Z Carbon
Low-z Carbon is attractive due to it's simplicity and robustness

Proton Beam: KE = 6.75 GeV
Normalization: For Hg $\Sigma(\mu^+ + \mu^-)$/proton ≈ 1

- Initial operation with 1MW carbon target
- Upgrade to multi-MW with Liquid Metal Jet Technology (demonstrated in MERIT Experim.)

H.K.Sayed (BNL)

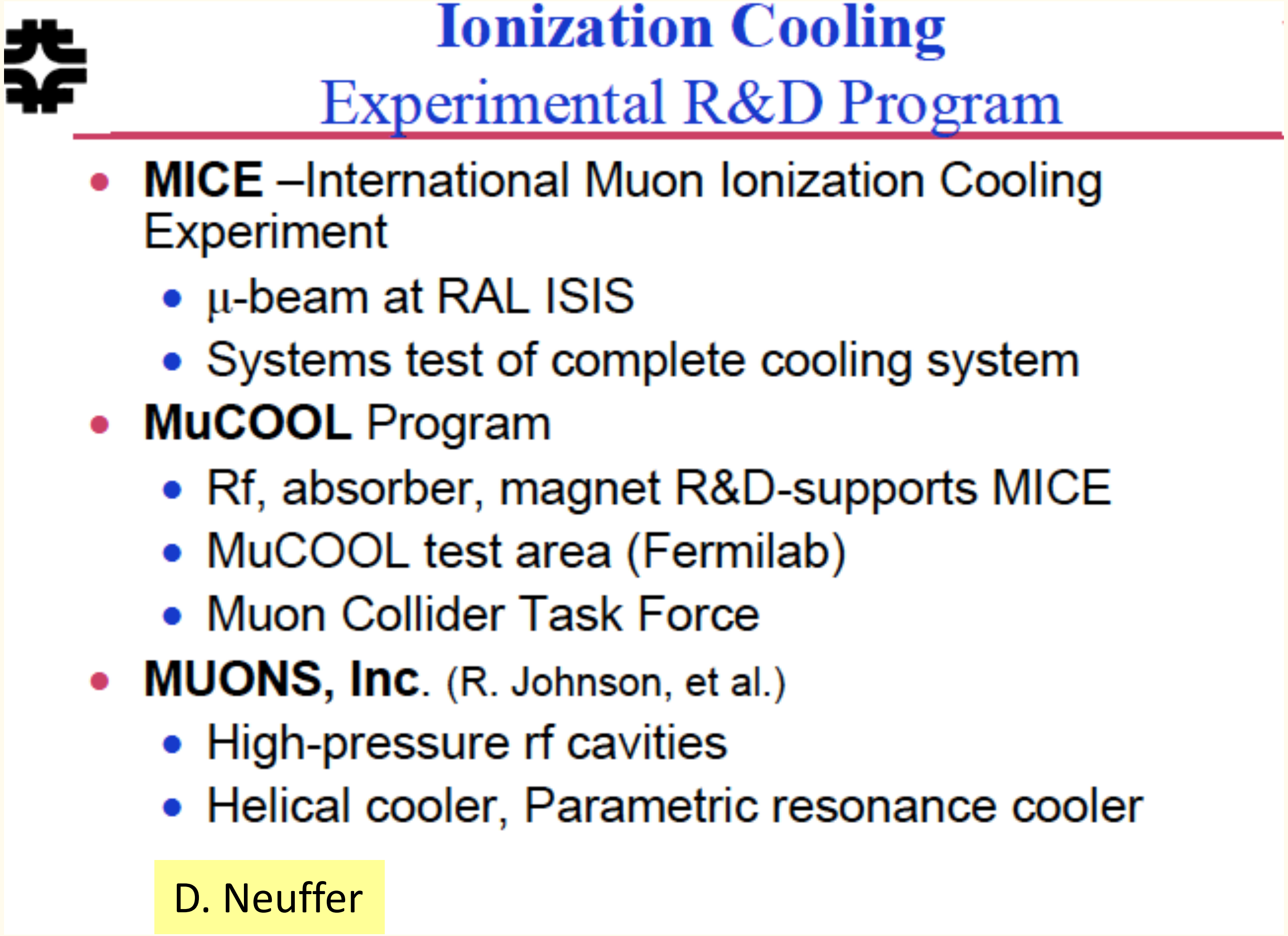




Muon per proton production at Front End exit

Ionization Cooling

- No damping from SR ->Ionization ‘dE/dx’ cooling:
  - Helical 6D Cooling
  - PIC
  - …

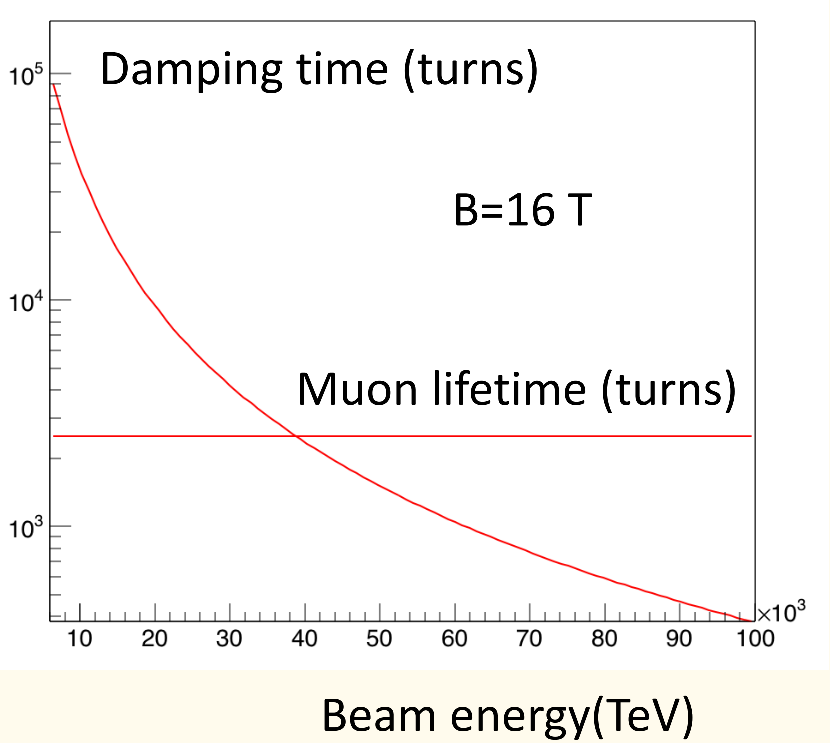


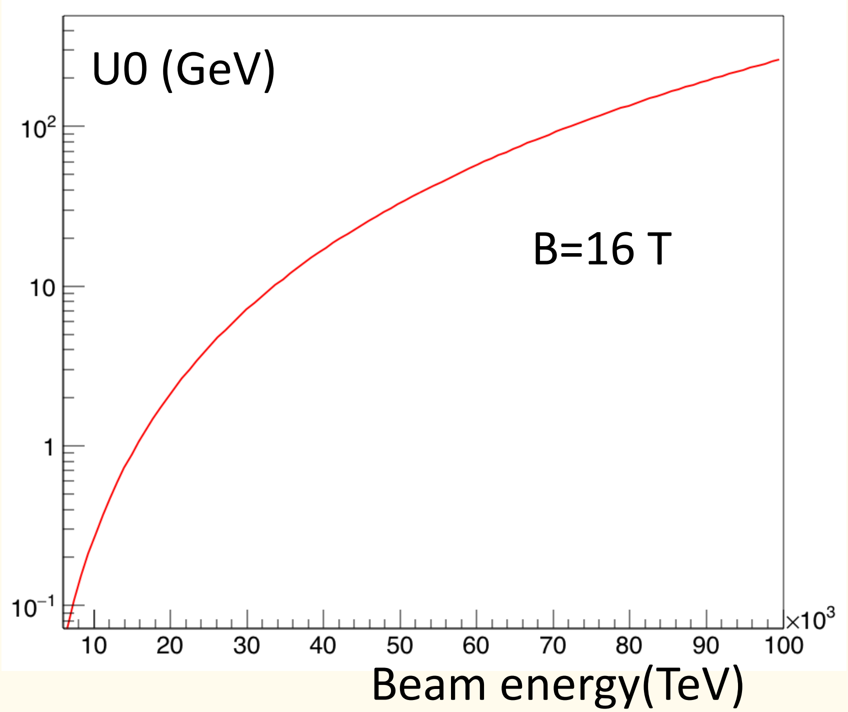
Ionization Cooling Experimental R&D Program

- **MICE** –International Muon Ionization Cooling Experiment
  - μ-beam at RAL ISIS
  - Systems test of complete cooling system
- **MuCOOL** Program
  - Rf, absorber, magnet R&D-supports MICE
  - MuCOOL test area (Fermilab)
  - Muon Collider Task Force
- **MUONS, Inc.** (R. Johnson, et al.)
  - High-pressure rf cavities
  - Helical cooler, Parametric resonance cooler

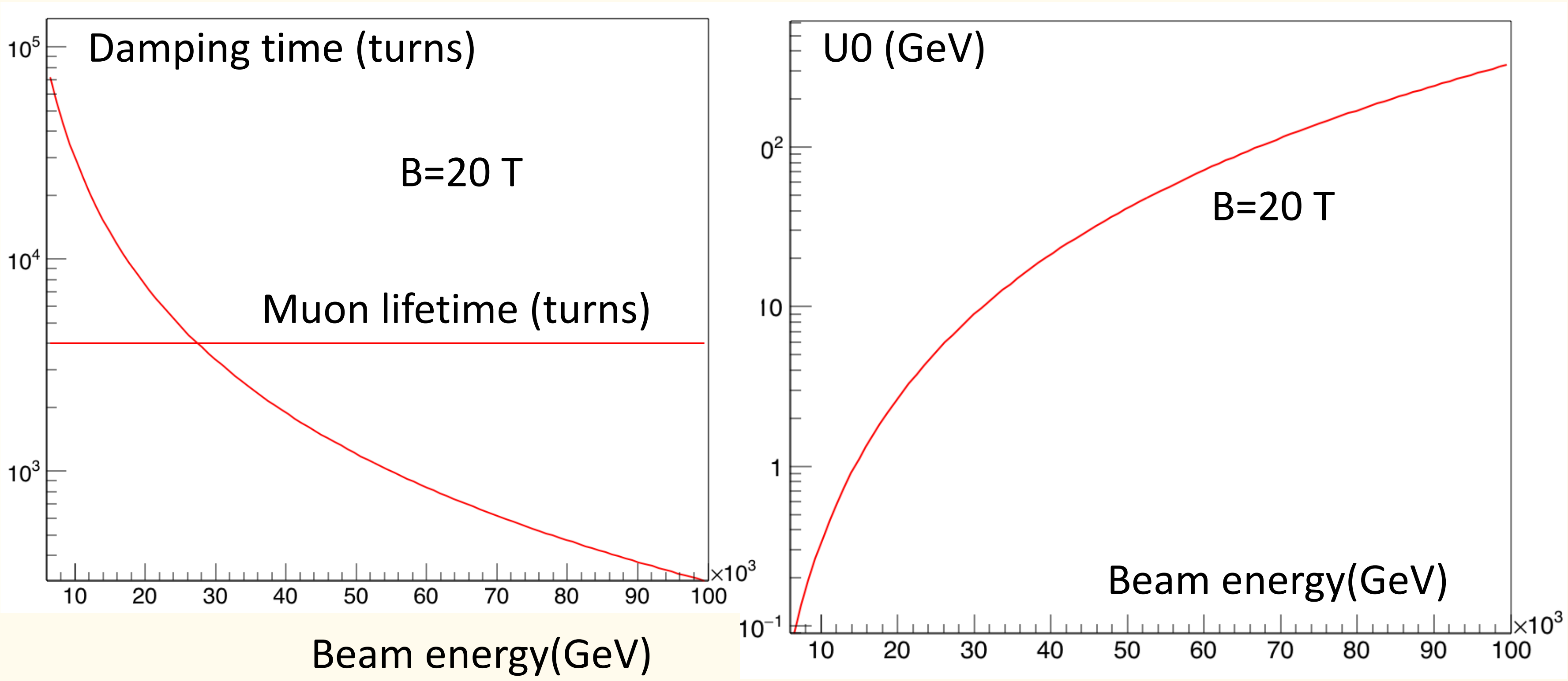
D. Neuffer

SR and damping in μ collider



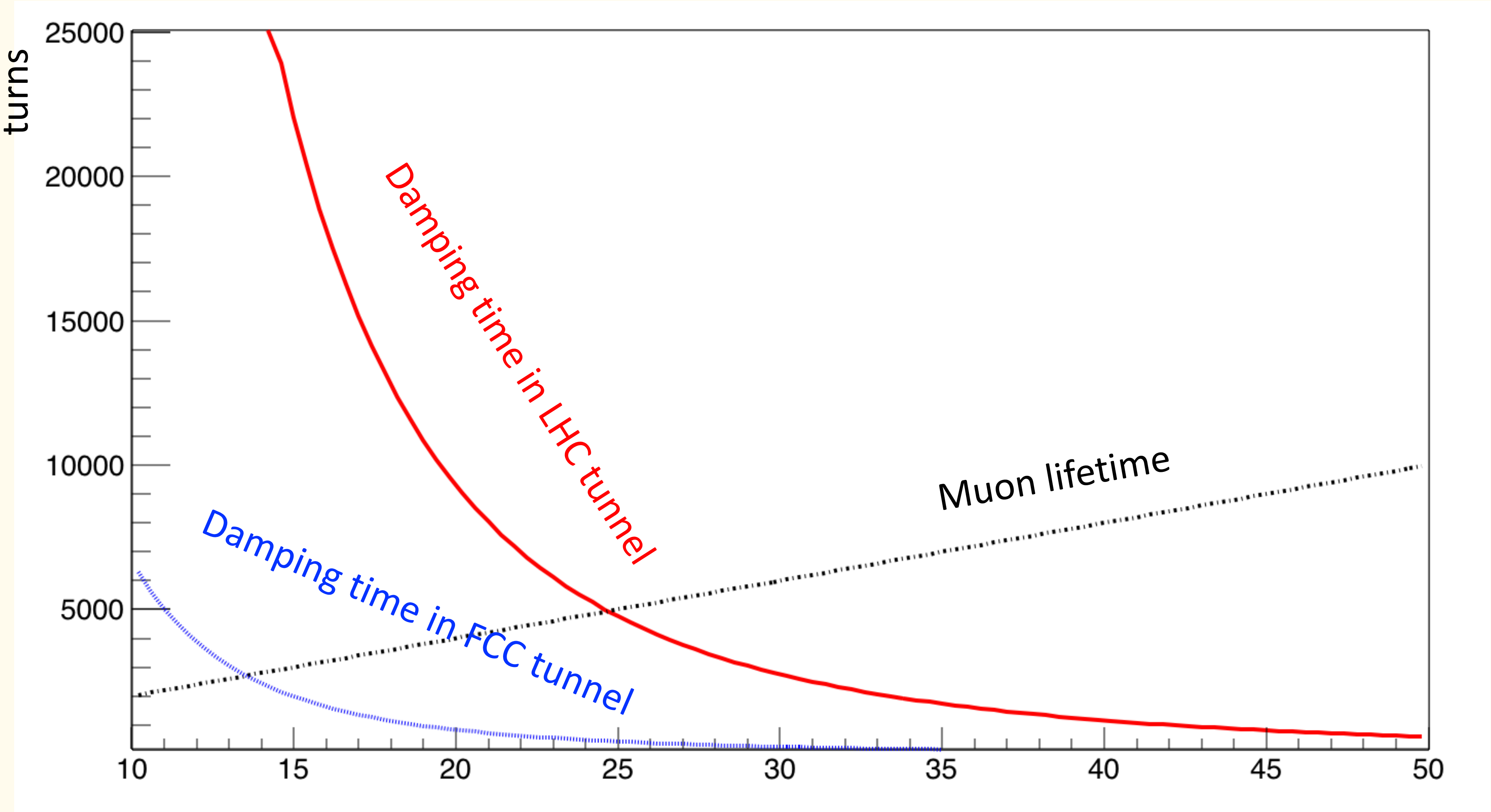


SR and damping in μ collider



$U_o = 5.5 \times 10^{-18}\ \gamma^4/\rho$

Damping time & muon lifetime



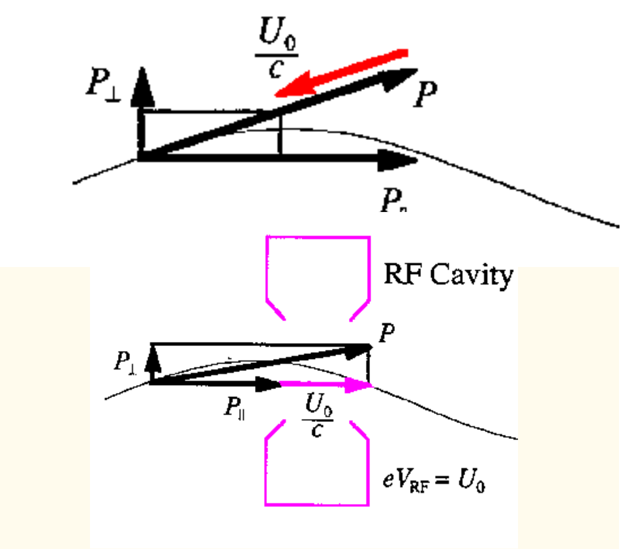
Dipole field (Tesla)

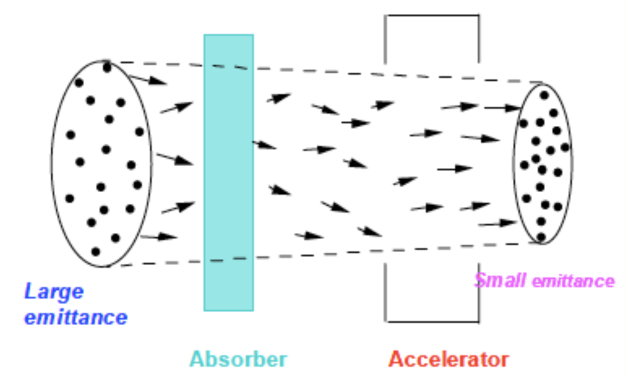
Ionization Cooling-general principle

This method, called “**dE/dx cooling**" closely resembles to the synchrotron compression of relativistic electrons - with the multiple energy losses in a thin, low Z absorber substituting the synchrotron radiated light.

Transverse Cooling:

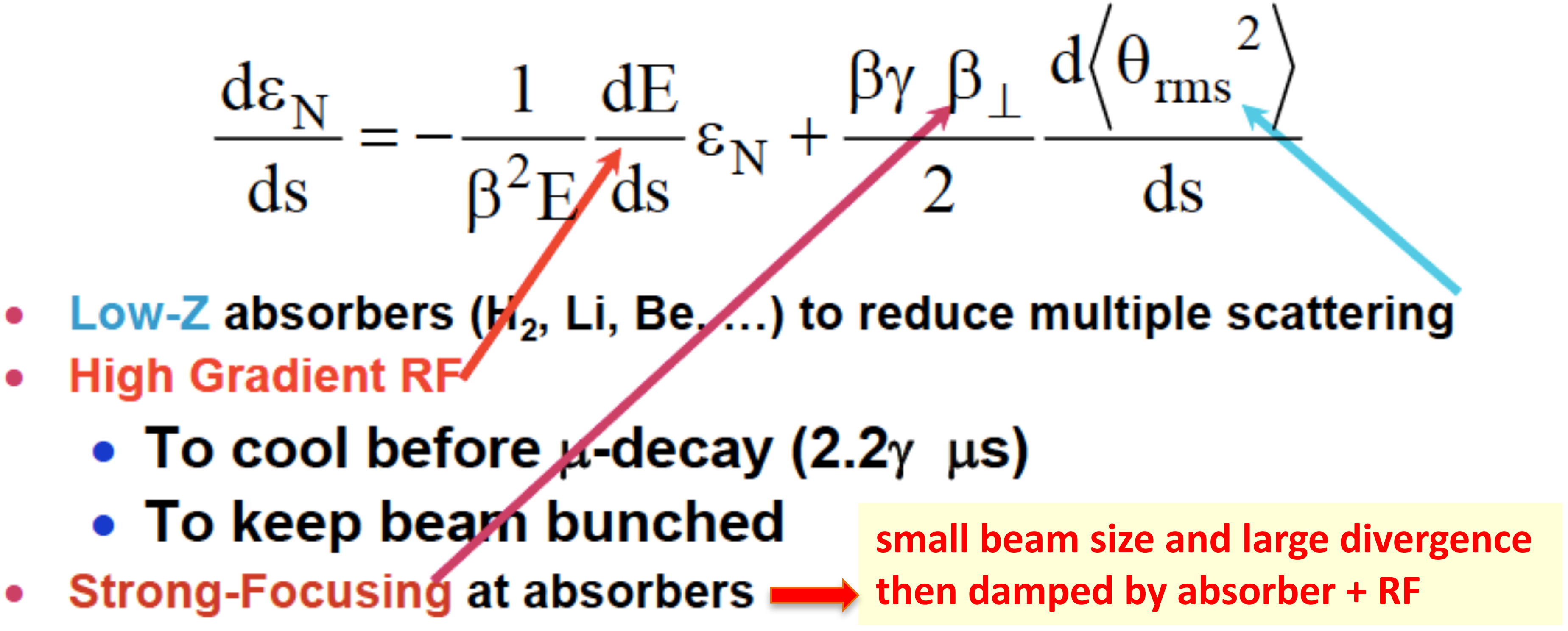
- Particle loses momentum in material
- Particle gains only $p_{||}$ in RF





On the other hand,
Multiple scattering in material increases rms emittance

Combining Cooling and Heating:



$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_N + \frac{\beta\gamma\ \beta_\perp}{2}\frac{d\langle\theta_{rms}{}^2\rangle}{ds}$$

- Low-Z absorbers (H_2, Li, Be, …) to reduce multiple scattering
- High Gradient RF
  - To cool before μ-decay (2.2γ μs)
  - To keep beam bunched
- Strong-Focusing at absorbers

small beam size and large divergence then damped by absorber + RF

  - To keep multiple scattering
  - less than beam divergence …

⇒ Quad focusing ?

⇒ Li lens focusing ?

⇒ Solenoid focusing?

$$\frac{d\langle\theta_{rms}^2\rangle}{ds} = \frac{z^2 E_s^2}{\beta^2 c^2 p_\mu^2 L_R}$$

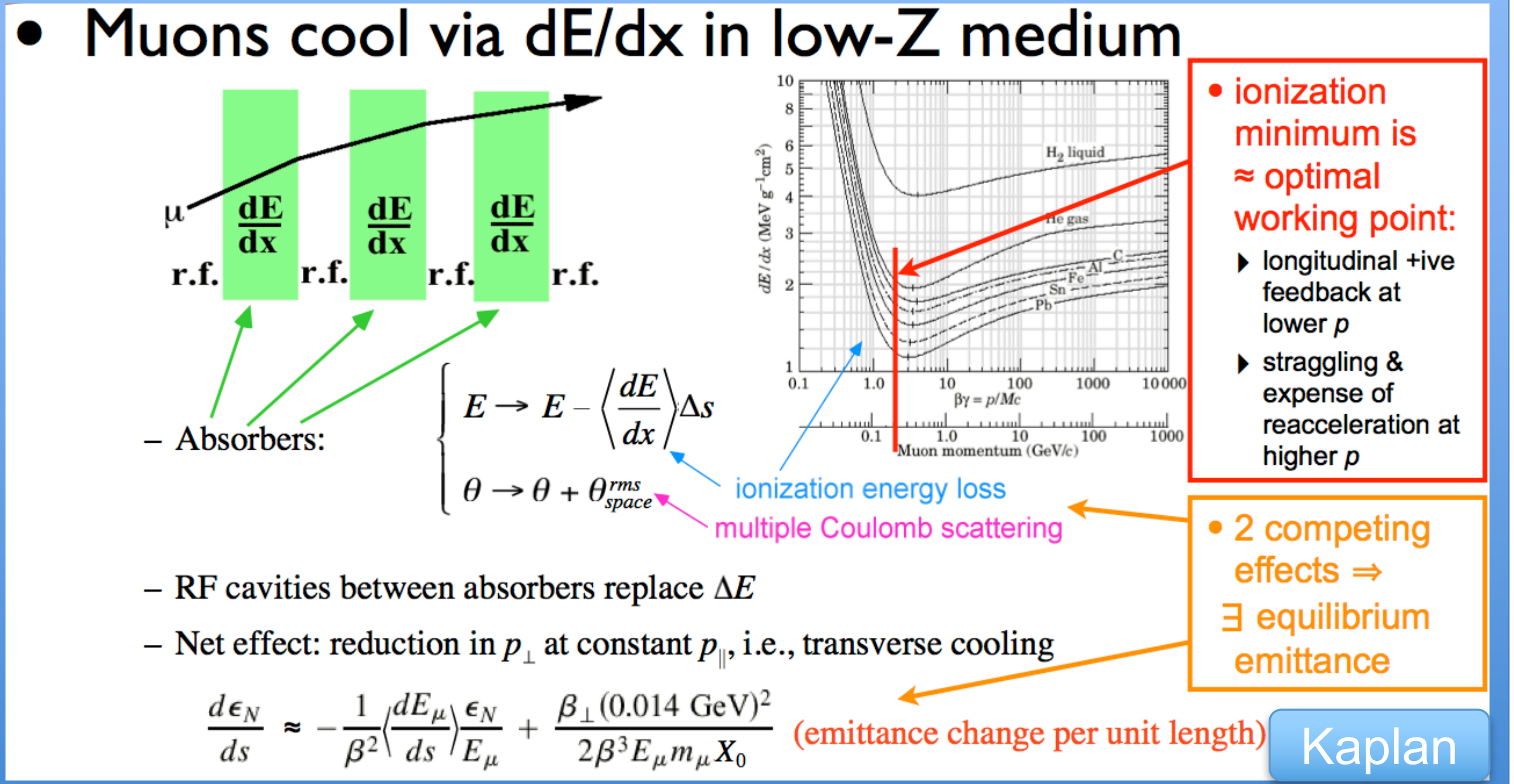
D. Neuffer

M. Palmer

Cooling Methods

- The particular challenge of muon cooling is its short lifetime
  - Cooling must take place very quickly
  - More quickly than any of the cooling methods presently in use
  - ⇨ Utilize energy loss in materials with RF re-acceleration

Muon Ionization Cooling



- Muons cool via dE/dx in low-Z medium

- Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

- RF cavities between absorbers replace ΔE
- Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

(emittance change per unit length)

- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower *p*
  - straggling & expense of reacceleration at higher *p*

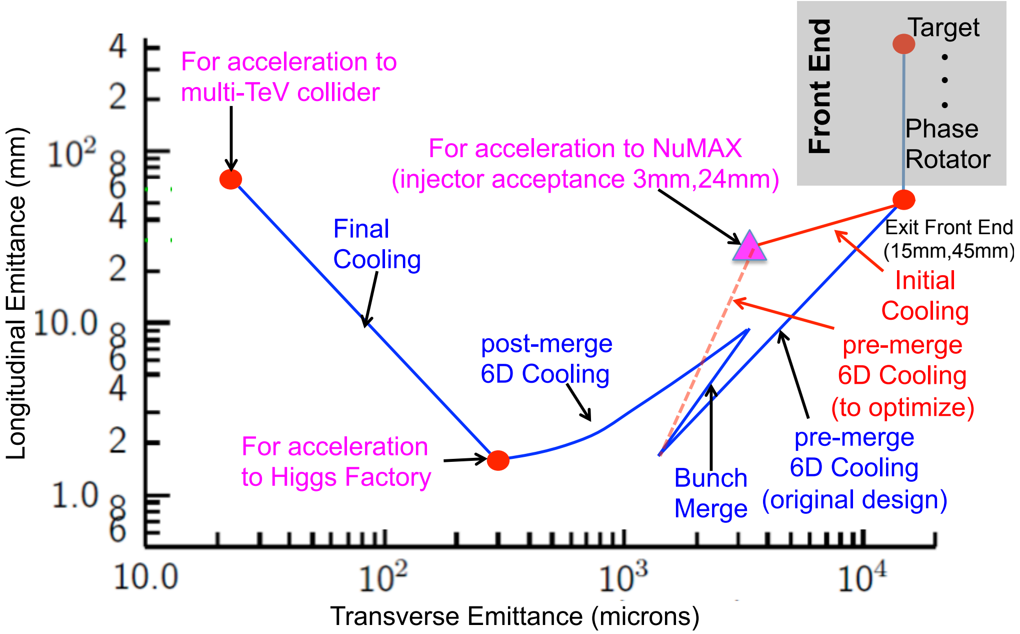
- 2 competing effects ⇒ ∃ equilibrium emittance

Kaplan

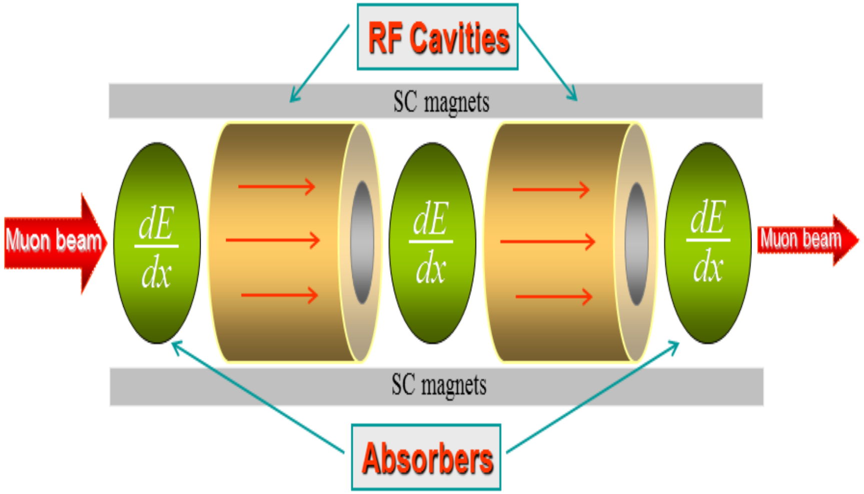
ADVANCED
Accelerator Concepts
WORKSHOP

MAP Cooling scheme overview

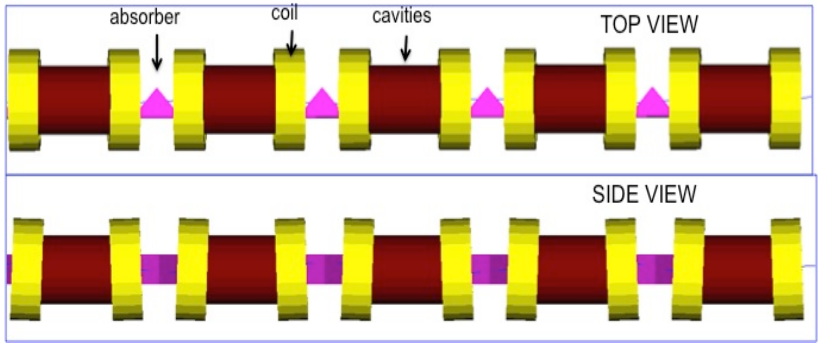
P.Snopok (IIT)



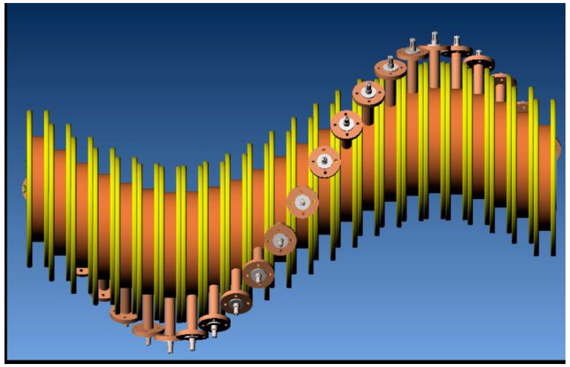
Ionization cooling



Vacuum Cooling Channel (VCC)



Helical Cooling Channel (HCC)



Two methods

Major challenges

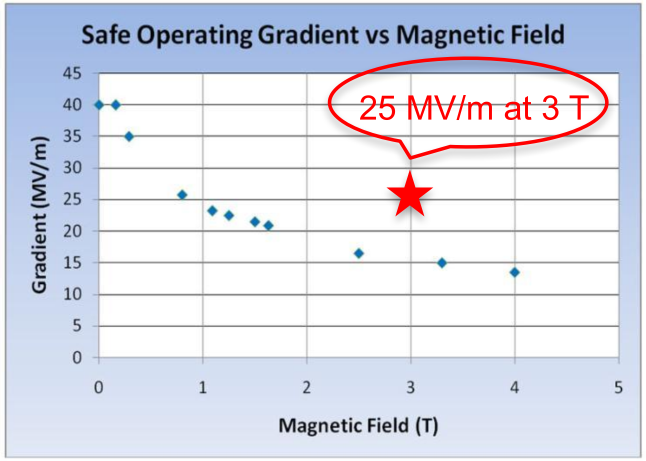
Accelerating field limitation by magnetic field (10 T)

High pressure (160atm) Gas (GH2) filled RF cavities

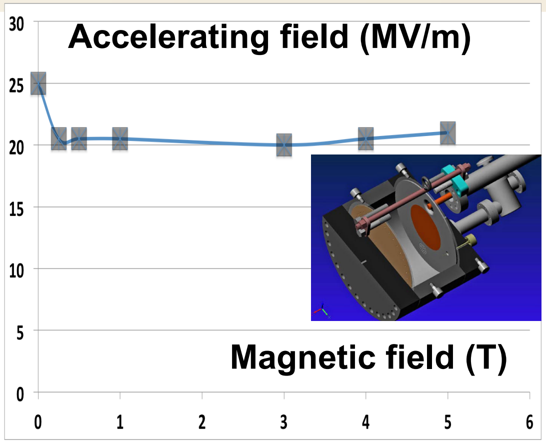
RF cavities in strong magnetic field

D.Li (LBNL)

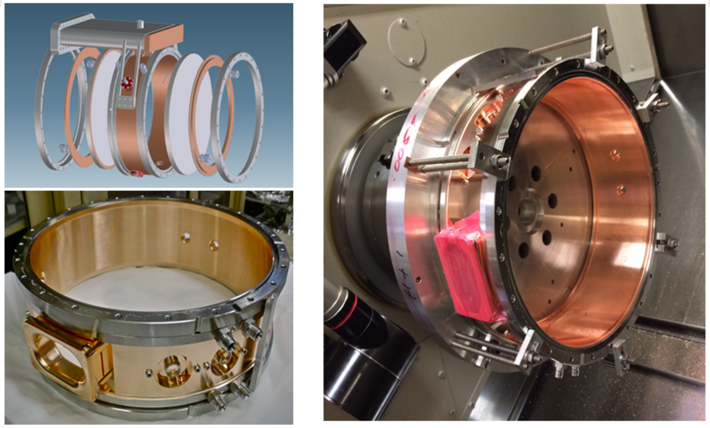
RF cavity in vacuum:



Breakdown by field emission

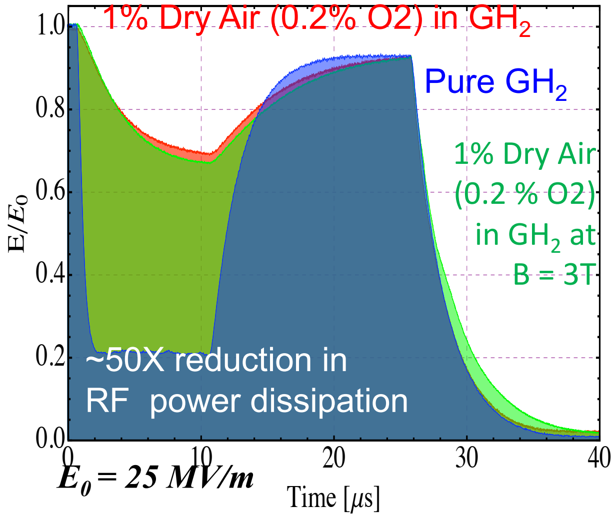


New cavity design very encouraging !



New cavity by LBNL/SLAC for tests in FNAL/MTA

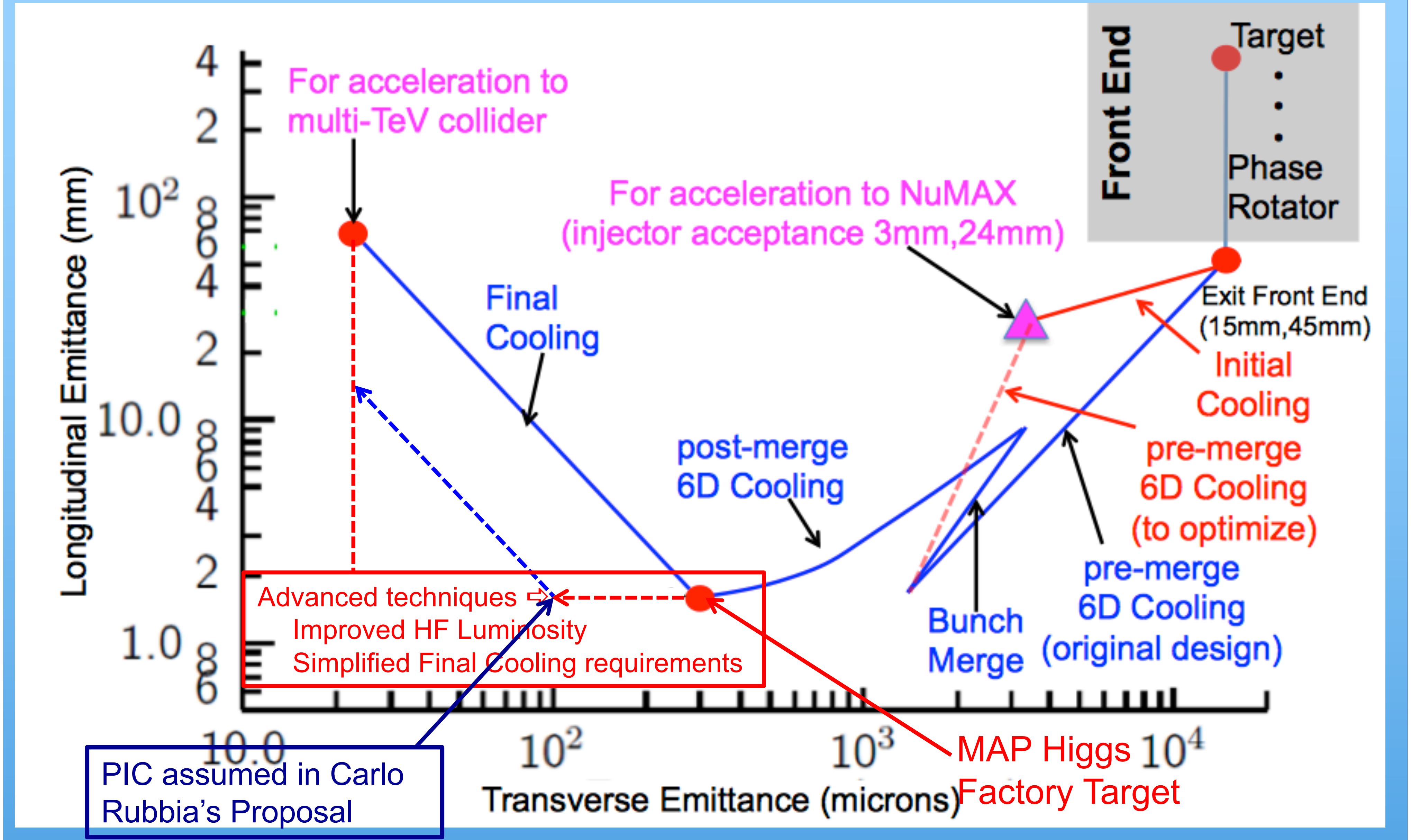
RF cavity filled with gas



No accelerating field degradation up to 3 T
Operation with beam under heavy beam loading

M. Palmer

Muon Ionization Cooling



For acceleration to multi-TeV collider

For acceleration to NuMAX (injector acceptance 3mm,24mm)

Advanced techniques ⇨
Improved HF Luminosity
Simplified Final Cooling requirements

PIC assumed in Carlo Rubbia's Proposal

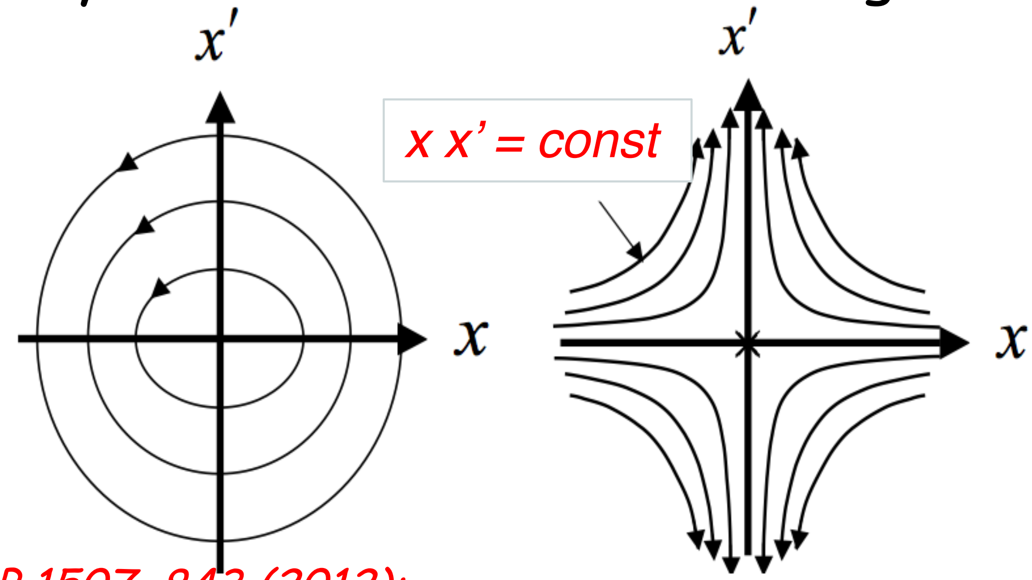
MAP Higgs Factory Target

3.-PIC, the Parametric Resonance Cooling of muons

C. Rubbia

- Combining ionization cooling with parametric resonances is expected to lead to muon with much smaller transv. sizes.
- A linear magnetic transport channel has been designed by Ya.S. Derbenev et al where a half integer resonance is induced such that the normal elliptical motion of particles in x-x' phase space becomes hyperbolic, with particles moving to smaller x and larger x' at the channel focal points.
- Thin absorbers placed at the focal points of the channel then cool the angular divergence by the usual ionization cooling.

LEFT ordinary oscillations
RIGHT hyperbolic motion
induced by perturbations
near an (one half integer)
resonance of the betatron
frequency.

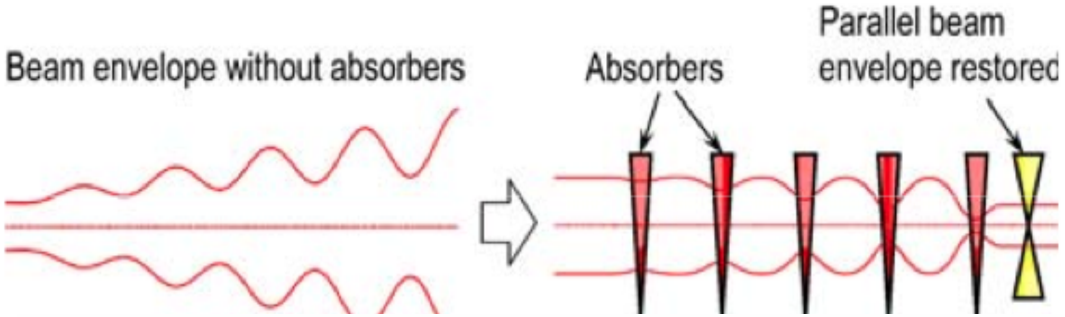


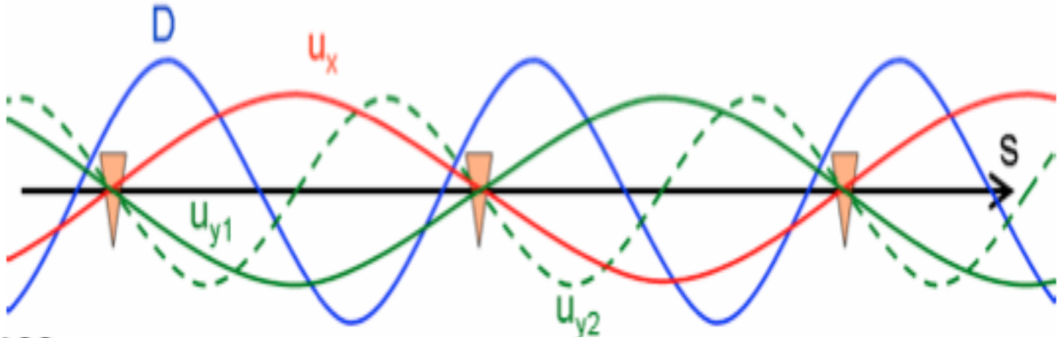
V. S. Morozov et al, AIP 1507, 843 (2012);

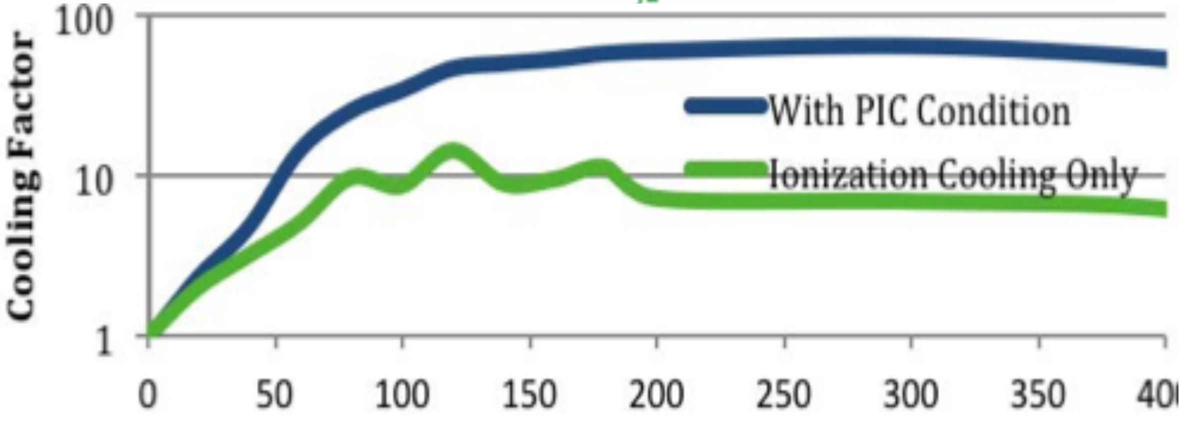
C. Rubbia

Details of PIC

- Without damping, the beam dynamics is not stable because the beam envelope grows with every period. Energy absorbers at the focal points stabilizes the beam through the ionization cooling.
- The longitudinal emittance is maintained constant tapering the absorbers and placing them at points of appropriate dispersion, vertical β and two horizontal β.
- Comparison of cooling factors (ratio of initial to final 6D emittance) with and without the PIC condition vs number of cells: more than 10x gain

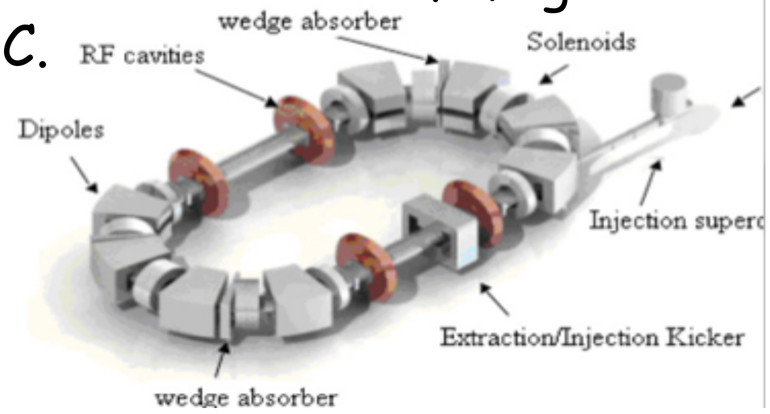






Parametric Resonance Cooling

- The first muon cooling ring should present no unexpected behaviour and good agreement between calculations and experiment is expected both transversely and longitudinally
- The novel Parametric Resonance Cooling (PIC) involves instead the balance between a strong resonance growth and ionization cooling and it may involve significant and unexpected conditions which are hard to predict.
- Therefore the experimental demonstration of the cooling must be concentrated on such a resonant behaviour.
- On the other hand the success of the novel Parametric Resonance Cooling is a necessary premise for a viable luminosity of the initial proton parameters of the future CERN accelerators since the expected Higgs luminosity is proportional to the inverse of the transverse emittance, hence about one order of magnitude of increment is expected from PIC.



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Acceleration Requirements

- Key Issues:
  - Muon lifetime ⇨ ultrafast acceleration chain
  - NF with modest cooling ⇨ accelerator acceptance
  - Total charge ⇨ cavity beam-loading (stored energy)
  - TeV-scale acceleration focuses on hybrid Rapid Cycling Synchrotron ⇨ requires rapid cycling magnets

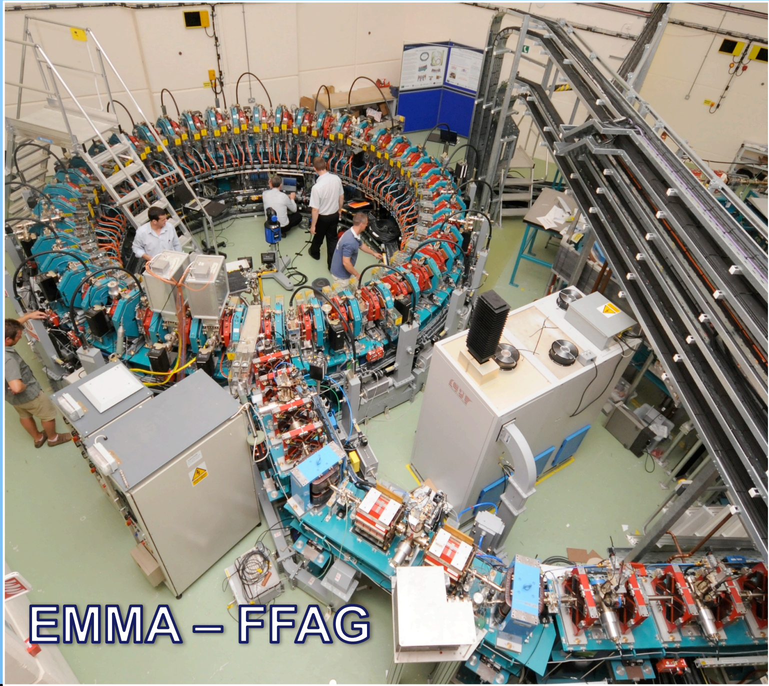
    $B_{peak} \sim 2T$ $f > 400Hz$

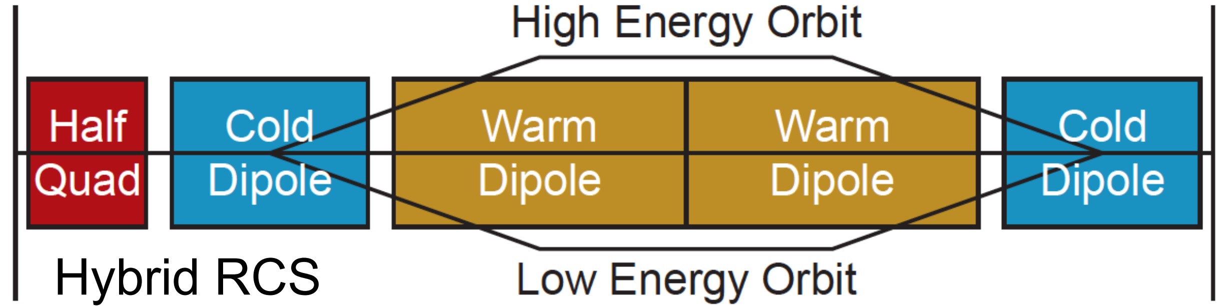
M. Palmer

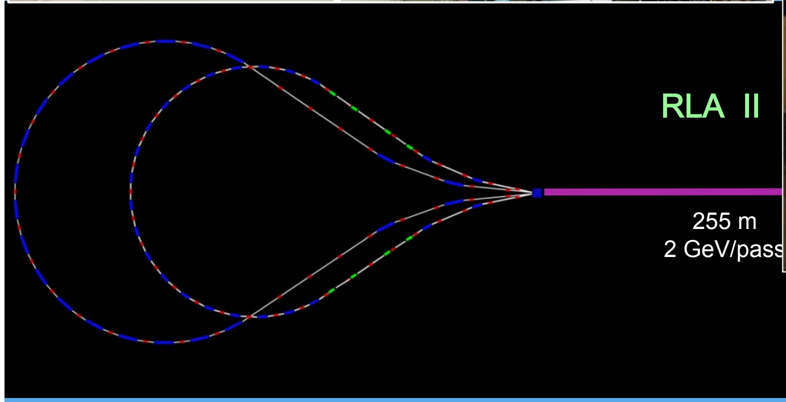
Acceleration

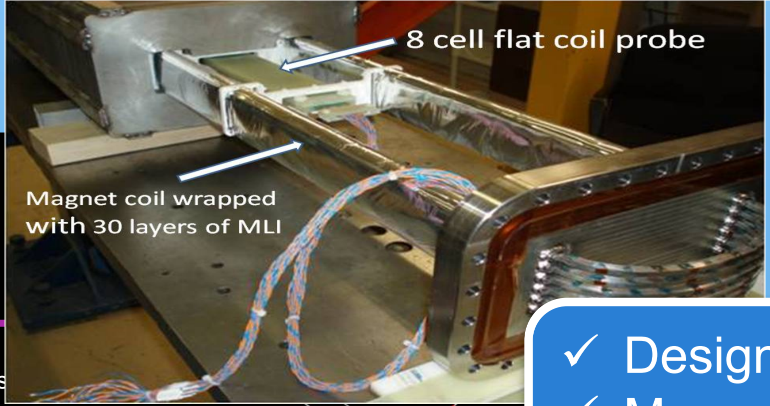
Technologies include:

- Superconducting Linacs (NuMAX choice)
- Recirculating Linear Accelerators (RLAs)
- Fixed-Field Alternating-Gradient (FFAG) Rings
- (Hybrid) Rapid Cycling Synchrotrons (RCS) for TeV energies









RCS requires 2 T p-p magnets at f > 400 Hz (U Miss & FNAL)

- ✓ Design concepts in hand
- ✓ Magnet R&D indicates parameters achievable

CMC

CERN Muon Collider

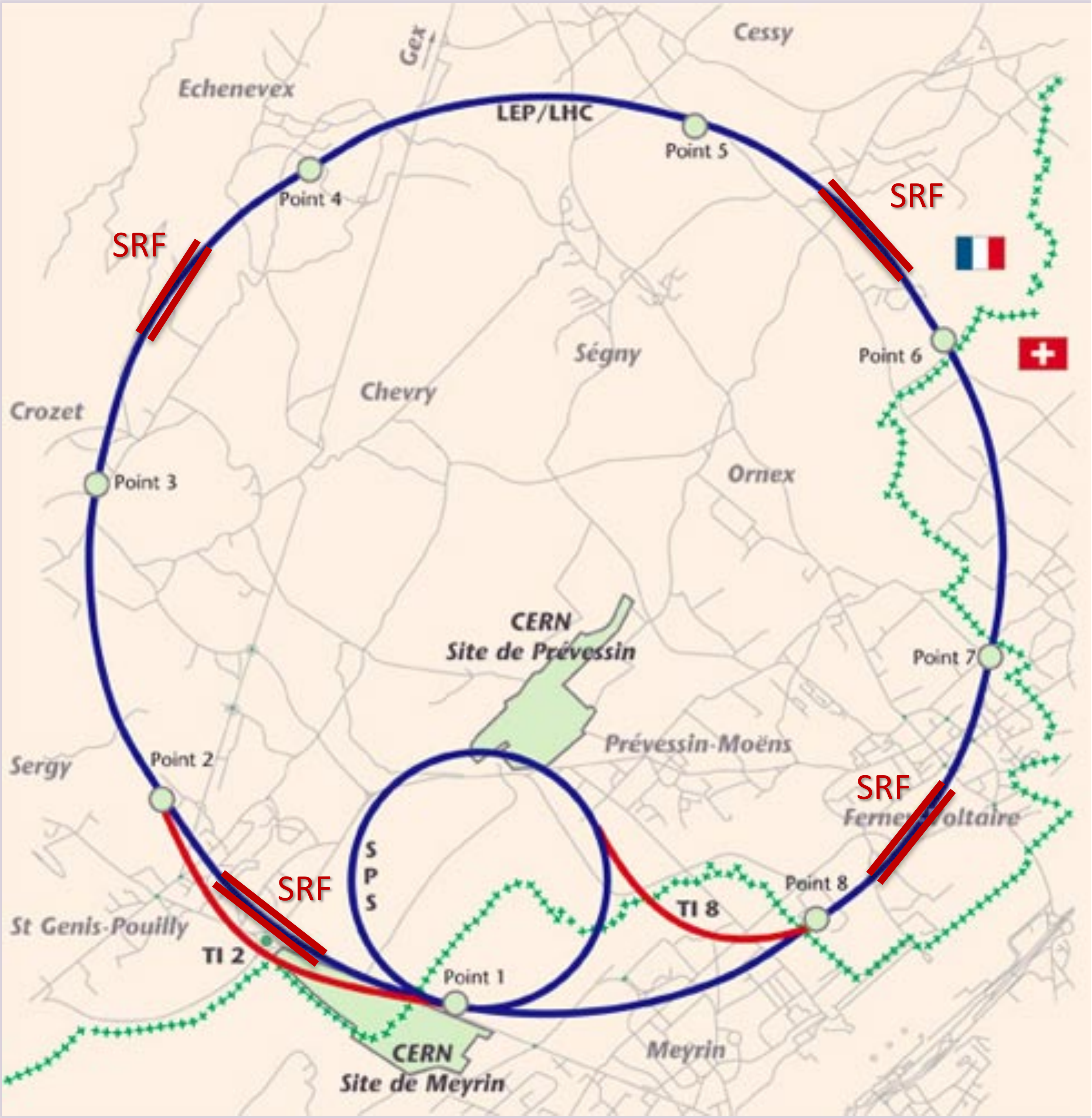
14 TeV cme

LHC tunnel
SPS tunnel and
mb PS

~7GeV SRF

Cost ~LHC

V.Shiltsev

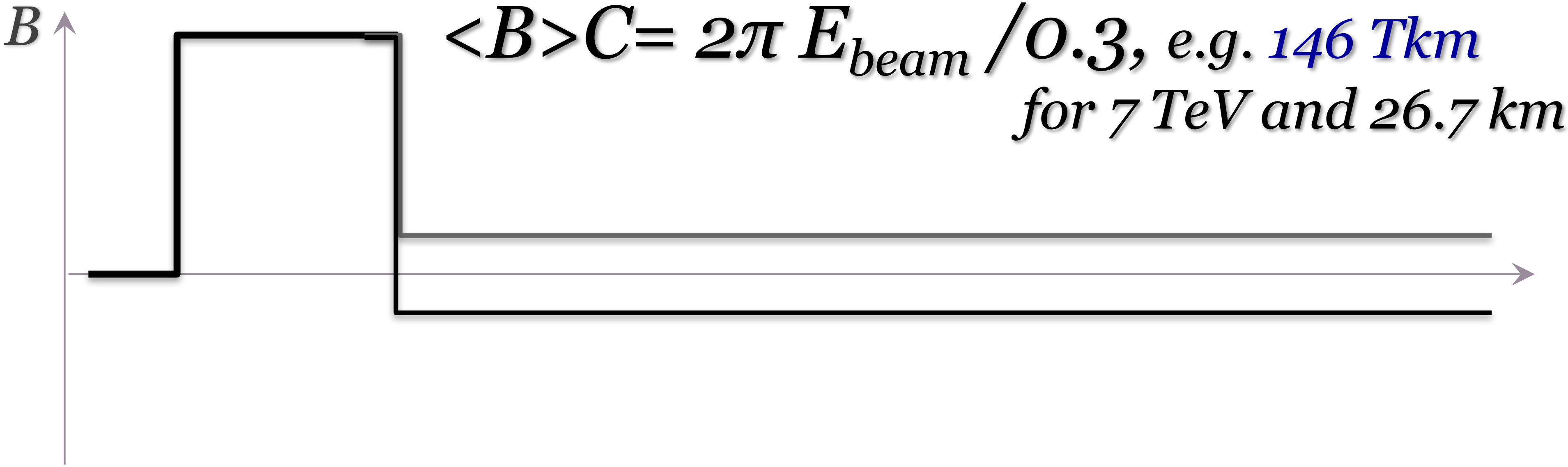


Assume RCS Acceleration

B_{max} : DC

B_{min} : pulsed from $-B_{min}$ to $+B_{min}$

Packing factor $\Pi<1$



$\langle B\rangle C = 2\pi E_{beam}/0.3$, e.g. 146 Tkm for 7 TeV and 26.7 km

(Simple math)

$$R = \frac{E_{max}}{E_{min}} = \frac{B_{max}L_{SC} + B_{min}L_{pulsed}}{B_{max}L_{SC} - B_{min}L_{pulsed}}$$

- If the ratio of fields : $f = \frac{B_{max}}{B_{min}}$ then : $\frac{L_{pulsed}}{L_{SC}} = f\,\frac{R-1}{R+1}$

- and equation for the required fields reads :

$$\frac{2\pi}{0.3}E_{max} = < B > C = B_{max}\Pi C\,\frac{2R}{R(1+f)+1-f}$$

Example: 7 TeV, 26.7 km tunnel, 16T max

$$\frac{2\pi}{0.3}E_{max} =< B > C = B_{max}\Pi C\,\frac{2R}{R(1+f)+1-f}$$

146 T × km   26.7km   16T   0.85   0.4=1/2.5

then :

$f=\frac{B_{max}}{B_{min}}$	$R=\frac{f-1}{f-4}$	B_{min}	E_{inj}
4.2	16	3.8T	0.45TeV
4.5	7	3.5T	1TeV
5	4	3.2T	4TeV
8	1.75	2.0T	9.1TeV

Example 2: 1 TeV, 6.9km tunnel, 16T max

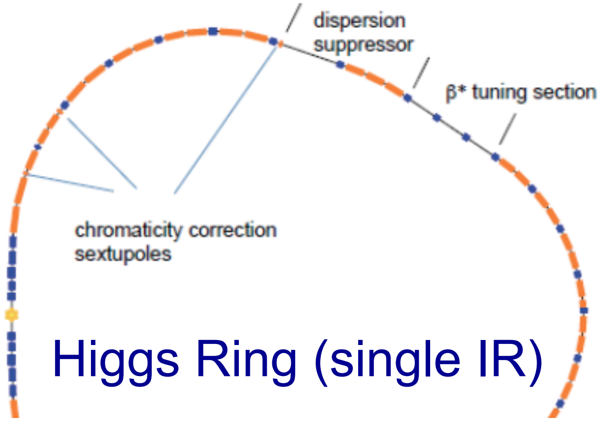
$$\frac{2\pi}{0.3}\underset{\underset{20.9\ \text{T}\times\text{km}}{\uparrow}}{E_{max}} =< B > \underset{\underset{6.9\text{km}}{\uparrow}}{C} = \underset{\underset{16\text{T}}{\uparrow}}{B_{max}}\underset{\underset{0.9}{\uparrow}}{\Pi} C\frac{2R}{R\underset{\underset{0.21=1/5}{\uparrow}}{(1+f)}+1-f}$$

then :

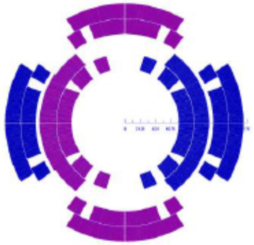
$f = \frac{B_{max}}{B_{min}}$	$R = \frac{f-1}{f-9}$	B_{min}	E_{inj}
10	9	1.6T	110 GeV
9.5	17	1.7T	60 GeV

Collider Rings

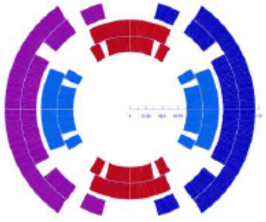
- Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM
  - With supporting magnet designs and background studies



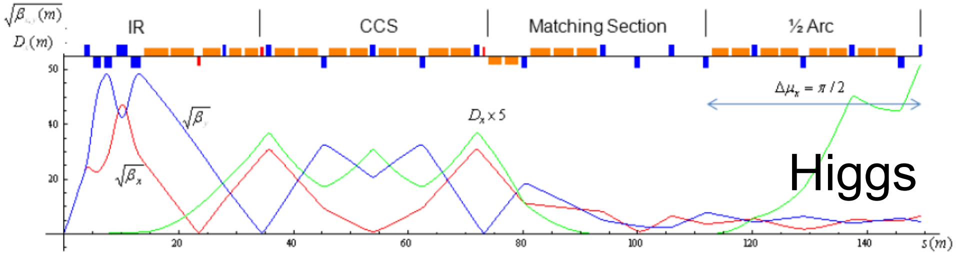
- ✓ Higgs, 1.5 TeV CoM and 3 TeV CoM Designs
  - With magnet concepts
  - Achieve target parameters
- ✓ Preliminary 6 TeV CoM design
  - Key issue is IR design and impact on luminosity
  - Utilizes lower power on target



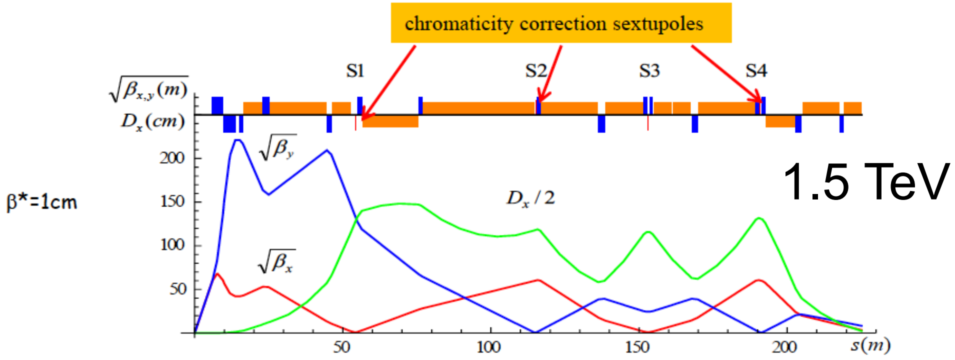
Dipole/Quad

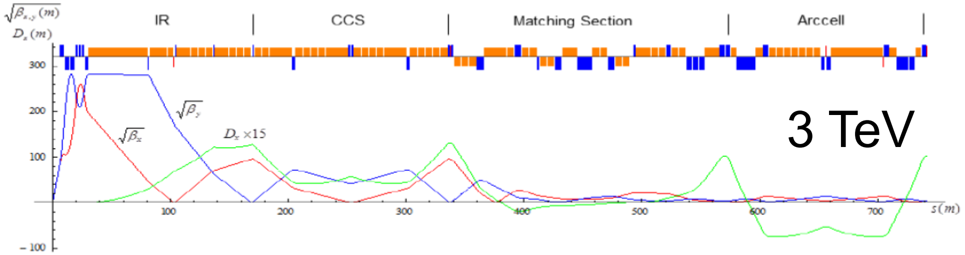


Quad/Dipole



Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP

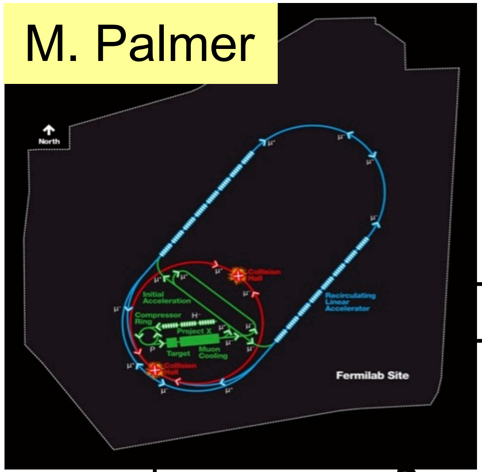




Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

M. Palmer

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}]

Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

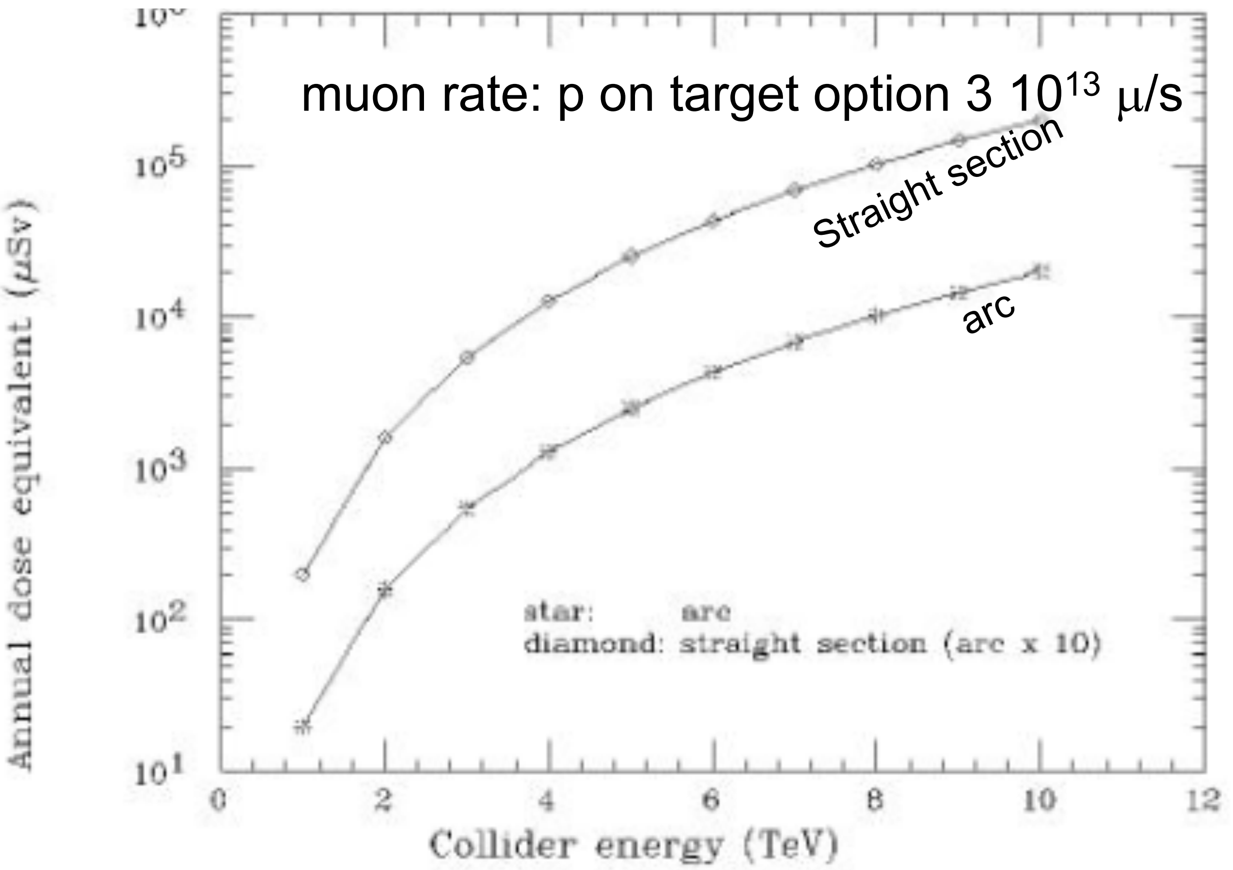

muon rate: p on target option 3 10^{13} μ/s

Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

Limit in centre of mass energy @ 6 TeV

Still competitive with bigger sizes pp colliders?

Is then any way to operate @ lower fluxes?

Is then any way to operate @ lower fluxes?

$L \sim 1/\sigma^2 \sim 1/\varepsilon\beta$
Need low emittances
Same as e+e- colliders

Backup Slides

M. Palmer

Conclusion

- NF ⇨ precision ν microscopes
- Multi-TeV MC ⇨ potentially only cost-effective route to lepton collider capabilities with E_{CM} > 5 TeV
- Key technical hurdles have been addressed:
  - High power target demo (MERIT)
  - Realizable cooling channel designs with acceptable performance
  - Breakthroughs in cooling channel technology
  - Significant progress in collider & detector design concepts

Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*5%*
Muon Storage Ring	**3-4 GeV**	**Useable μ decays/yr***
νSTORM	*3.8 GeV*	*$3\text{x}10^{17}$*
Intensity Frontier ν Factory	**4-10 GeV**	**Useable μ decays/yr***
NuMAX (Initial)	*4-6 GeV*	*$8\text{x}10^{19}$*
NuMAX+	*4-6 GeV*	*$5\text{x}10^{20}$*
IDS-NF Design	*10 GeV*	*$5\text{x}10^{20}$*
Higgs Factory	**~126 GeV CoM**	**Higgs/10^{7}s**
s-Channel μ Collider	~126 GeV CoM	3,500-13,500
Energy Frontier μ Collider	**> 1 TeV CoM**	**Avg. Luminosity**
Opt. 1	*1.5 TeV CoM*	*$1.2\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$*
Opt. 2	*3 TeV CoM*	*$4.4\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$*
Opt. 3	*6 TeV CoM*	*$12\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$*

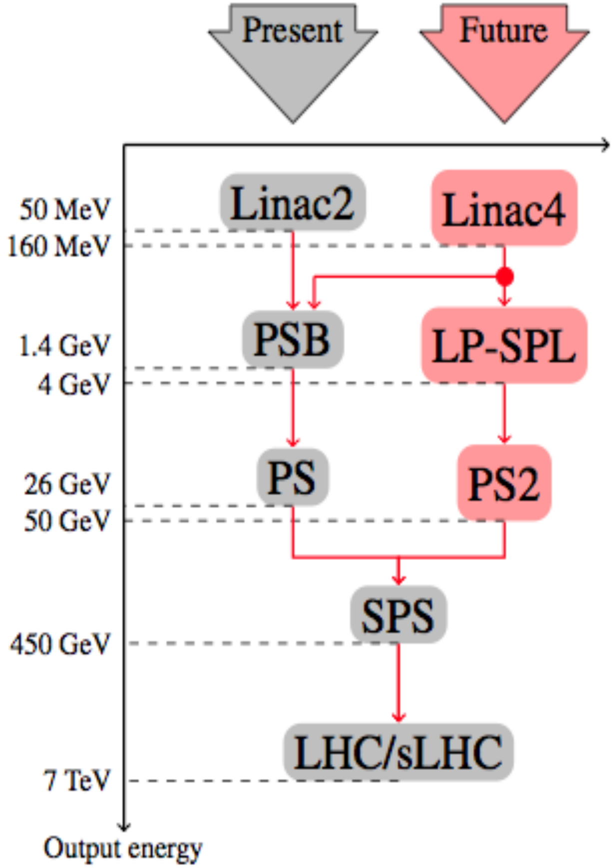
* Decays of an individual species (ie, μ^{+} or μ^{-})

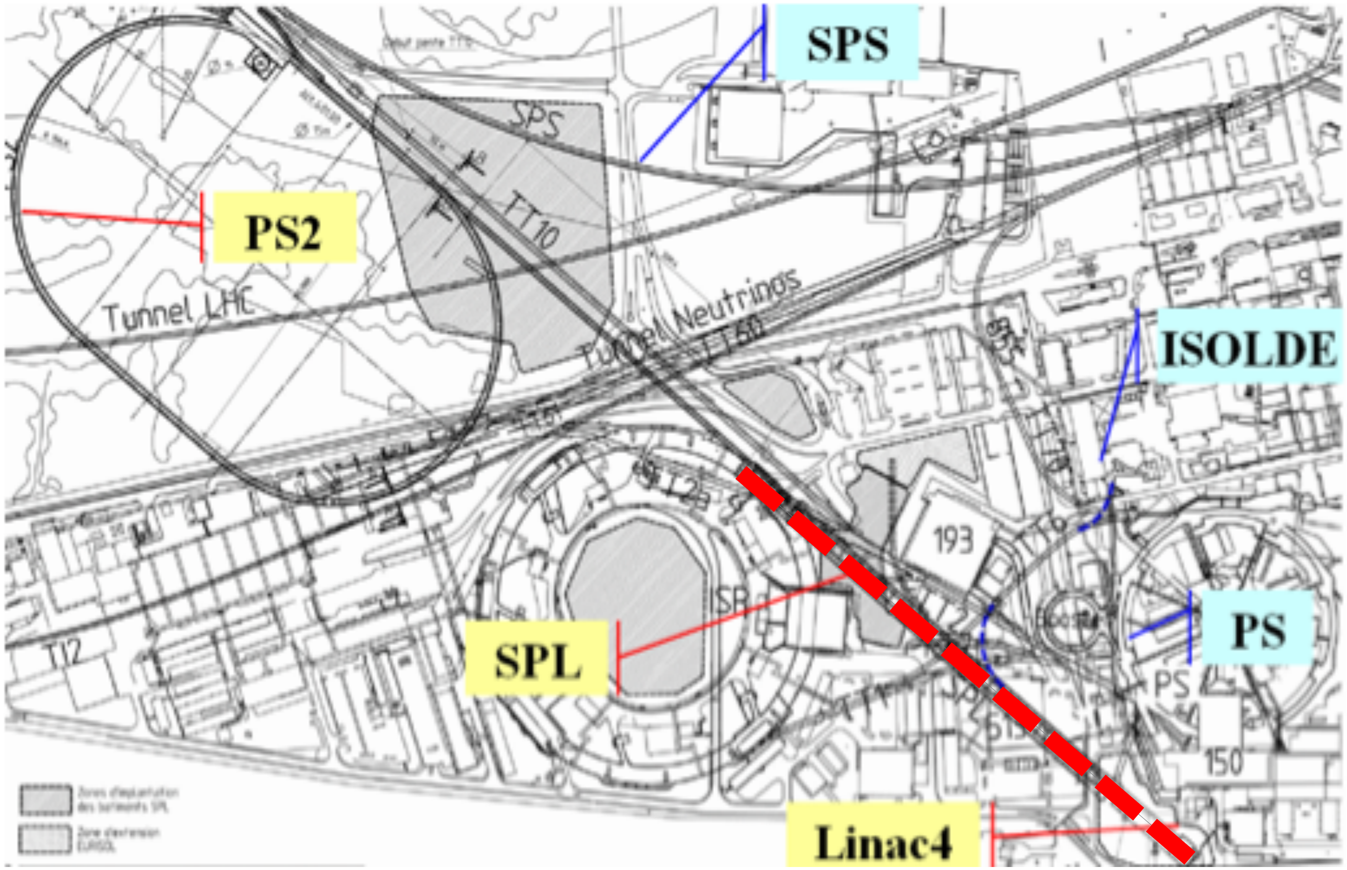
Muon accelerator capabilities offer unique potential for the future of high energy physics research

C. Rubbia

Future accelerators programs at CERN

- A new LHC injector complex to increase the collider luminosity 10x with the High Luminosity LHC (HL-LHC)).
- Two accelerators (the LP-SPL and a new 50 GeV synchrotron, PS2) would replace the three existing ones (Linac2, the PSB, and the PS), with the injection of the SPS at 50 GeV,

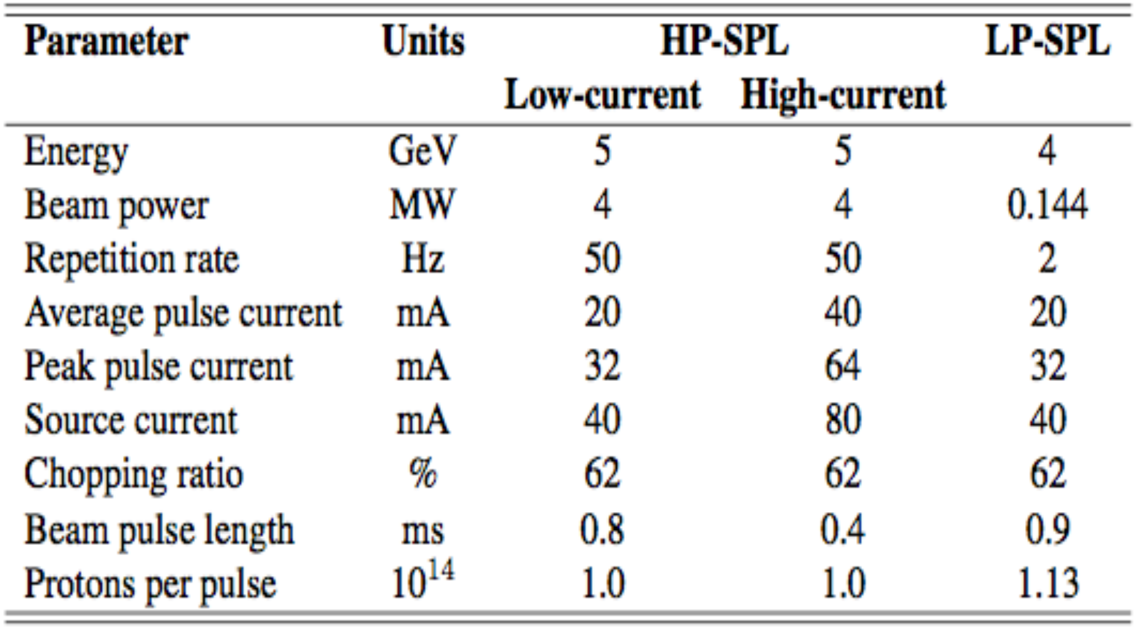




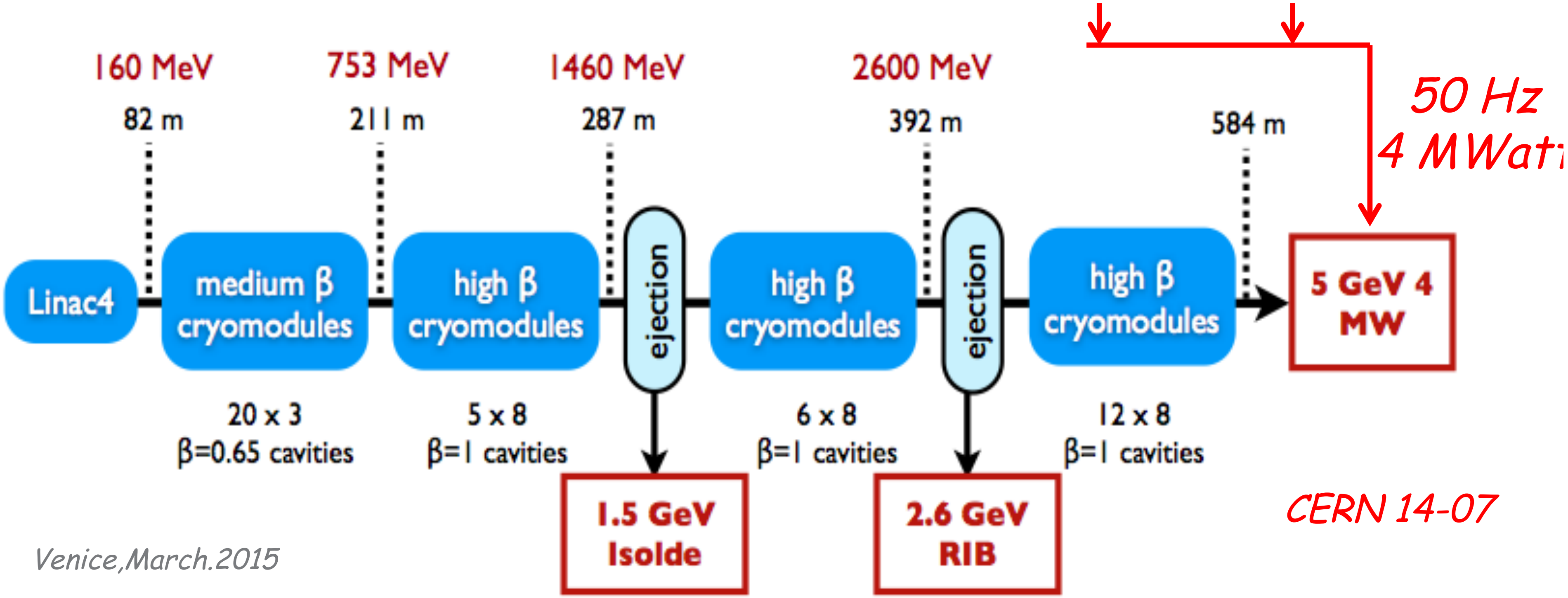
C. Rubbia

CERN-SPL parameters

- Layout of superconducting SPL with intermediate extractions.
- SPL design is very flexible and it can be adapted to the needs of many high-power proton beam applications.



Parameter	Units	HP-SPL		LP-SPL
		Low-current	High-current	
Energy	GeV	5	5	4
Beam power	MW	4	4	0.144
Repetition rate	Hz	50	50	2
Average pulse current	mA	20	40	20
Peak pulse current	mA	32	64	32
Source current	mA	40	80	40
Chopping ratio	%	62	62	62
Beam pulse length	ms	0.8	0.4	0.9
Protons per pulse	10^{14}	1.0	1.0	1.13



CERN 14-07

C. Rubbia

A muon based Higgs factory at CERN

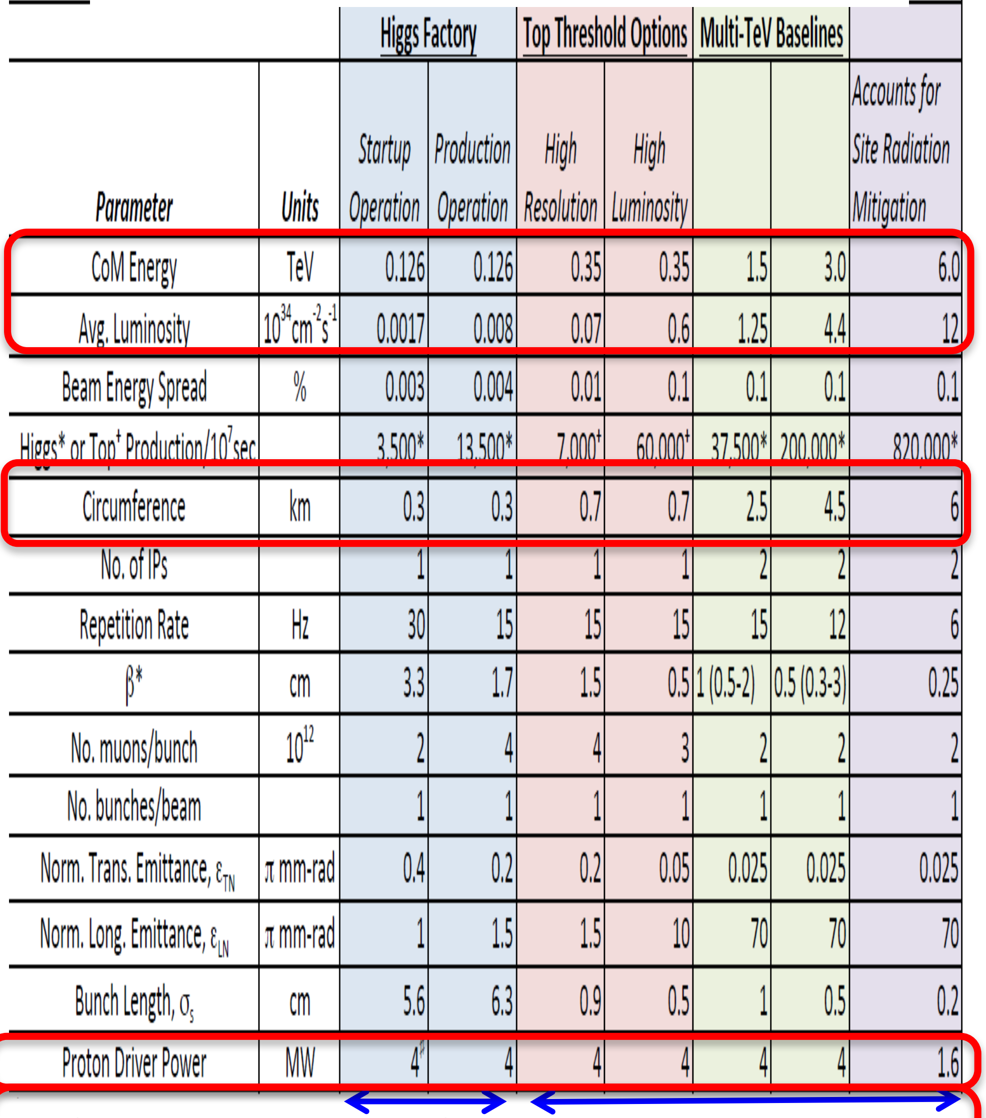
- A muon cooled Higgs factory can be easily housed within CERN
- The new 5 GeV Linac will provide at 50 c/s a multi MWatt H- beam with enough pions/muons to supply the muon factory.
- The basic additional accelerator structure will be the following:
    - Two additional small storage rings with R ≈ 50 m will strip H- to a tight p bunch and compress the LP-SPL beam to a few ns.
    - Muons of both signs are focused in a axially symmetric B = 20 T field, reducing progressively pt with a horn and B = 2 T
    - A buncher and a rotator compresses muons to ≈ 250 MeV/c
    - Muon Cooling in 3D compresses emittances by a factor 106.
    - Bunches of about 2x1012 m± are accelerated to 62.5 GeV
    - Muons are colliding in a SC storage ring of R ≈ 60 m (about one half of the CERN-PS ,1/100 of LHC) where about 104 Higgs events/y are recorded for each of the experiments.

Staged Neutrino Factory and Muon Colliders main parameters

Neutrino Factory at intensity frontier

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Perfor-mance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Detector	***Far Detector:***	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
	Distance from Ring	km	1.9	1300	1300	1300
	Mass	kT	1.3	100 / 30	100 / 30	100 / 30
	Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	1	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight section	m	184	281	281	281
	Number of bunches	-		60	60	60
	Charge per bunch	1×10^{9}		6.9	26	35
Accelerati on	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
		MHz	-	325, 650	325, 650	325, 650
	Repetition	Hz	-	30	30	60
Cooling			No	No	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition	Hz	0.75	15	15	15

Muon Collider at the energy frontier



		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	*Units*	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top^{+} Production/10^{7}sec		3,500*	13,500*	7,000^{+}	60,000^{+}	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	$4^{\#}$	4	4	4	4	4	1.6

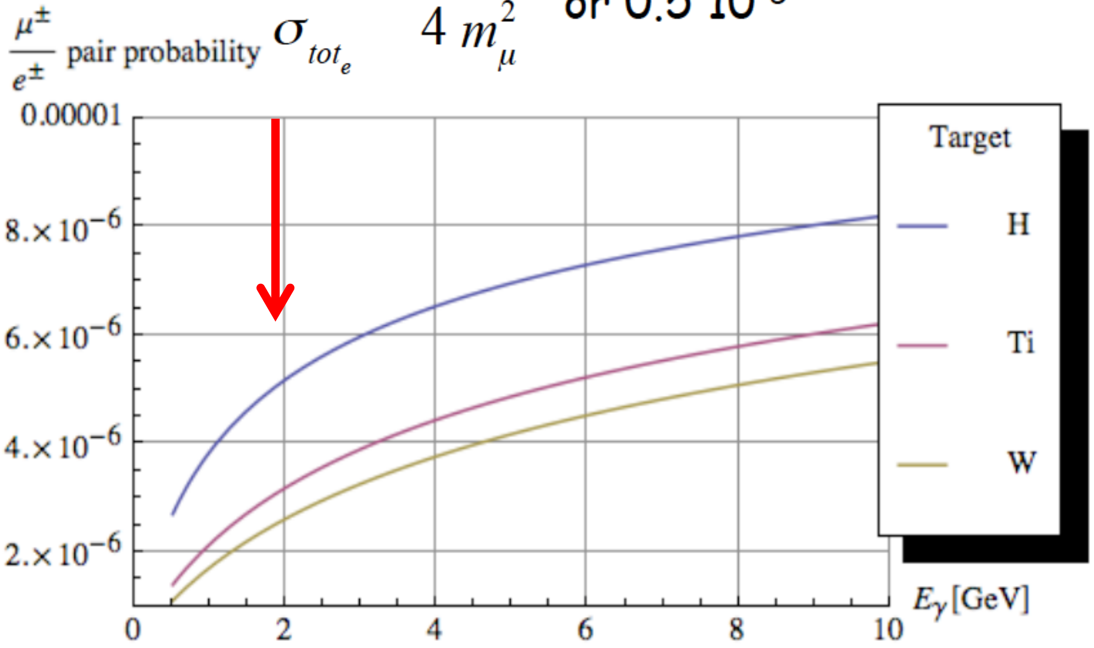
Cooling ⟷ **6D no final** ⟷ **Full 6D**

Muon generation by GeV-scale Compton γs

V.Yakimenko (SLAC)

Probability of creating μ+μ− pairs as a function of the incident photon energy

$$\frac{\sigma_{tot_\mu}}{\sigma_{tot_e}} \approx \frac{1}{4}\frac{m_e^2}{m_\mu^2}$$ or 0.5 10^{-5}



2GeV γ beam	Pulsed Linac	ERL
e-beam energy [GeV]	36	11
Laser wavelength [μm]	10	1
Bunch charge [nC]	10	1.5
Rep. rate [kHz]	0.2	20 / 200
Bunches per beam	250	
Average current [mA]	2	30 / 300
e-beam power [MW]	18	330 / 3300
e-to-γ convers. efficiency	3	0.33
γ-beam power [MW]	3	20 / 200
Total AC-to-γ efficiency	10%	20% / 75%
Peak $\mu^+\mu^-$ [per bunch]	10^6	3 10^4
Average $\mu^+\mu^-$ [per second]	5 10^{10}	3 10^{11} / 3 10^{12}

- Brightness 10^3 larger than with proton driver
- 10^3 too low with pulsed linac
- 10^2 flux increase with high current ERL
- Approaching intensities desired for NF (but train structure not favorable for collider luminosity, N^2 issue)