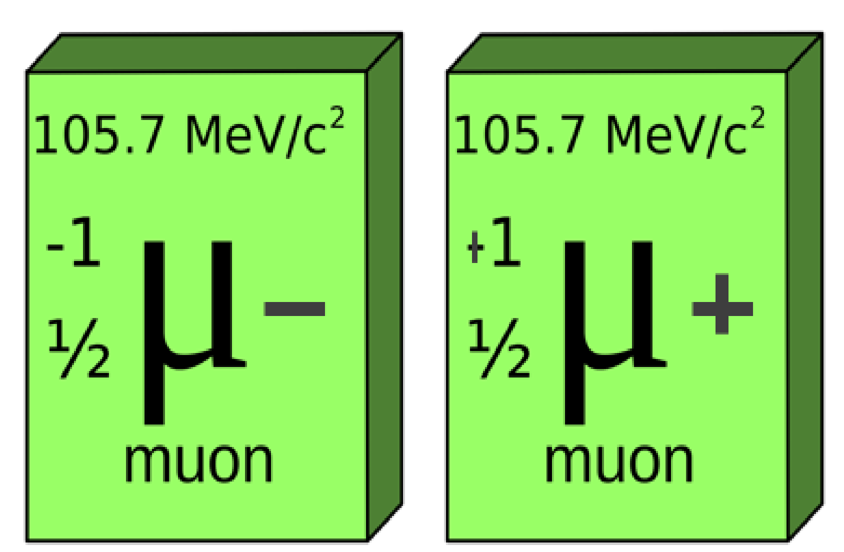


Northern Illinois University

MUON COLLIDER:

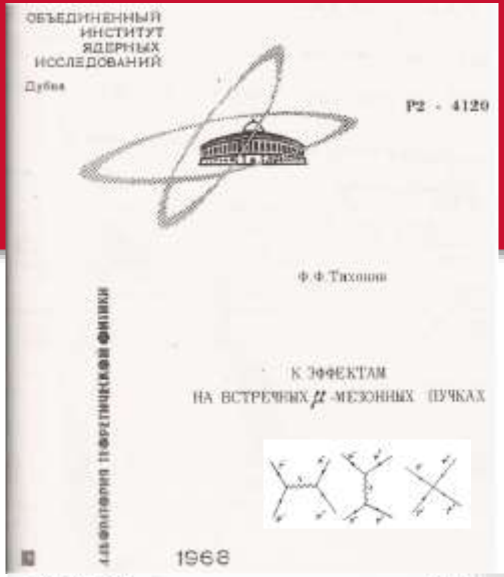
Accelerator Overview

Vladimir SHILTSEV

US MCC Workshop · August 7, 2024 · Fermilab

History (I)

- Fedor Tikhonin (JINR, Dubna, **1968**)
  - QED cross-sections at $\mu^+\mu^-$ c.m.e. upto 100 GeV
  - [Ф.Ф.Тихонин. К эффектам на встречных μ мезонных пучках.] Препринт ОИЯИ Р2–4120. Дубна, 1968) On the effects at colliding μ meson beams, JINR Preprint P2-4120, 1968, translation & scan **arXiv:0805.3961**
- Gersh Budker (INP, Novosibirsk, **1969**)
  - $\mu^+\mu^-$ c.m.e. few 100's GeV; 25 GeV $p \rightarrow \mu$ conversion, 400 turns in 2 T or 4000 turns in 20 T storage ring
  - [Г.И.Будкер. "Ускорители и встречные пучки". – Труды VII Межд. Конф. по высокоэнергетическим ускор. заряженных част. (Ереван, 1969). Ереван 1970, т.1, с. 33; Труды Межд. Конф. Физ. высоких энергий (Киев, 1970). Дубна 1970, с.1017] G. I. Budker, "Accelerators and colliding beams," 7th International Conference on High-Energy Accelerators, Yerevan, USSR, 27 Aug - 2 Sep 1969, pp. 33 , AIP Conf. Proc 352 (1996) 4.)


ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

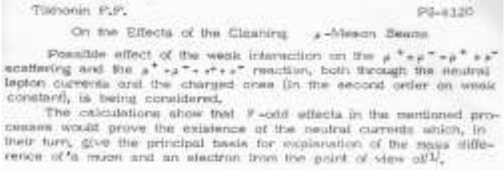
Дубна

P2 - 4120

Ф.Ф.Тихонин

К ЭФФЕКТАМ НА ВСТРЕЧНЫХ μ-МЕЗОННЫХ ПУЧКАХ

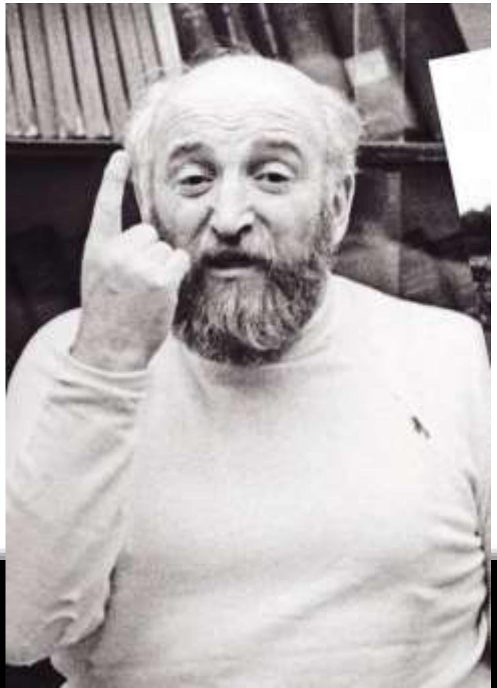
1968


Tikhonin F.F. P2-4120

On the Effects of the Clashing μ-Meson Beams

Possible effect of the weak interaction on the $\mu^+ + \mu^- \to \mu^+ + \mu^-$ scattering and the $\mu^+ + \mu^- \to e^+ + e^-$ reaction, both through the neutral lepton currents and the charged ones (in the second order on weak constant), is being considered.

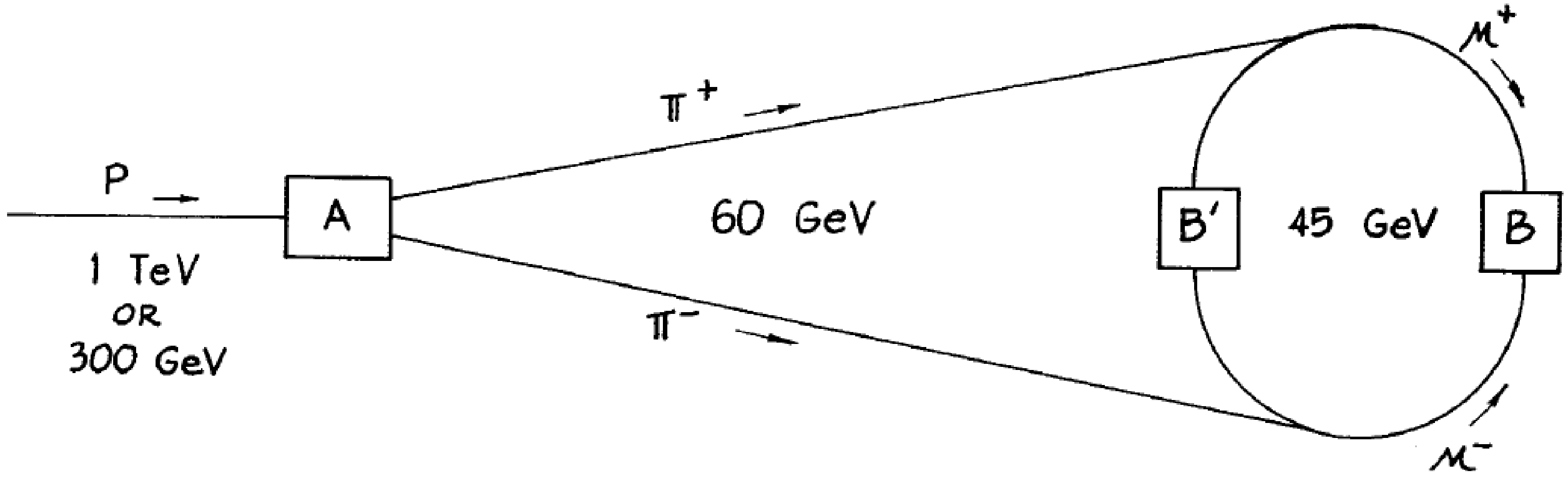
The calculations show that P-odd effects in the mentioned processes would prove the existence of the neutral currents which, in their turn, give the principal basis for explanation of the mass difference of a muon and an electron from the point of view of[1].



“Very Early” Concept – Extremely Low Luminosity

D. Neuffer “COLLIDING MUON BEAMS AT 90 GeV” July 1979 Fermilab FN-319 …

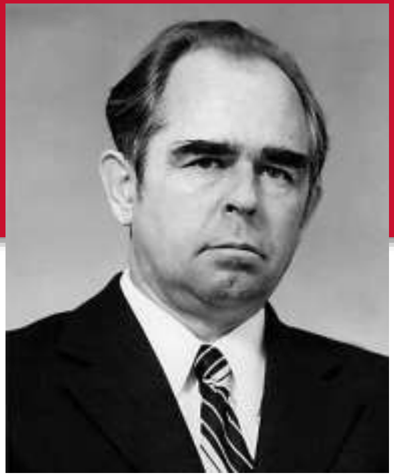
L~1e24



- General appreciation that *dissipation* (foils) in principle can help to damp transverse oscillation of particles

  - overcome the curse of “Liouville theorem”
  - as early as G.K.O’Neill (1956) and D.B.Lichtenberg (1956)

History (II) – 1970’s-1980’s




- Yuri Ado and Valery Balbekov (IHEP, Protvino)
  - Ionization cooling of protons (1971)


- Alexander Skrinsky and Vasily Parkhomchuk (INP, Novosibirsk)
  - MC general design considerations and ionization cooling of muons (1981)

- David Neuffer (Fermilab)
  - Comprehensive theory of ionization cooling of muons (1983)

Early concept (1983)

Particle Accelerators
1983 Vol. 14 pp. 75–90
0031-2460/83/1401/0075$18.50/0

PRINCIPLES AND APPLICATIONS OF MUON COOLING

DAVID NEUFFER†

Fermi National Accelerator Laboratory, Batavia, Ill. 60510 U.S.A.

(*Received February 17; in final form May 24, 1983*)

The basic principles of the application of "ionization cooling" to obtain high phase-space density muon beams are described, and its limitations are outlined. Sample cooling scenarios are presented. Applications of cold muon beams for high-energy physics are described. High-luminosity $\mu^+\mu^-$ and μ-*p* colliders at more than 1-TeV energy are possible.

MUON COOLING RING

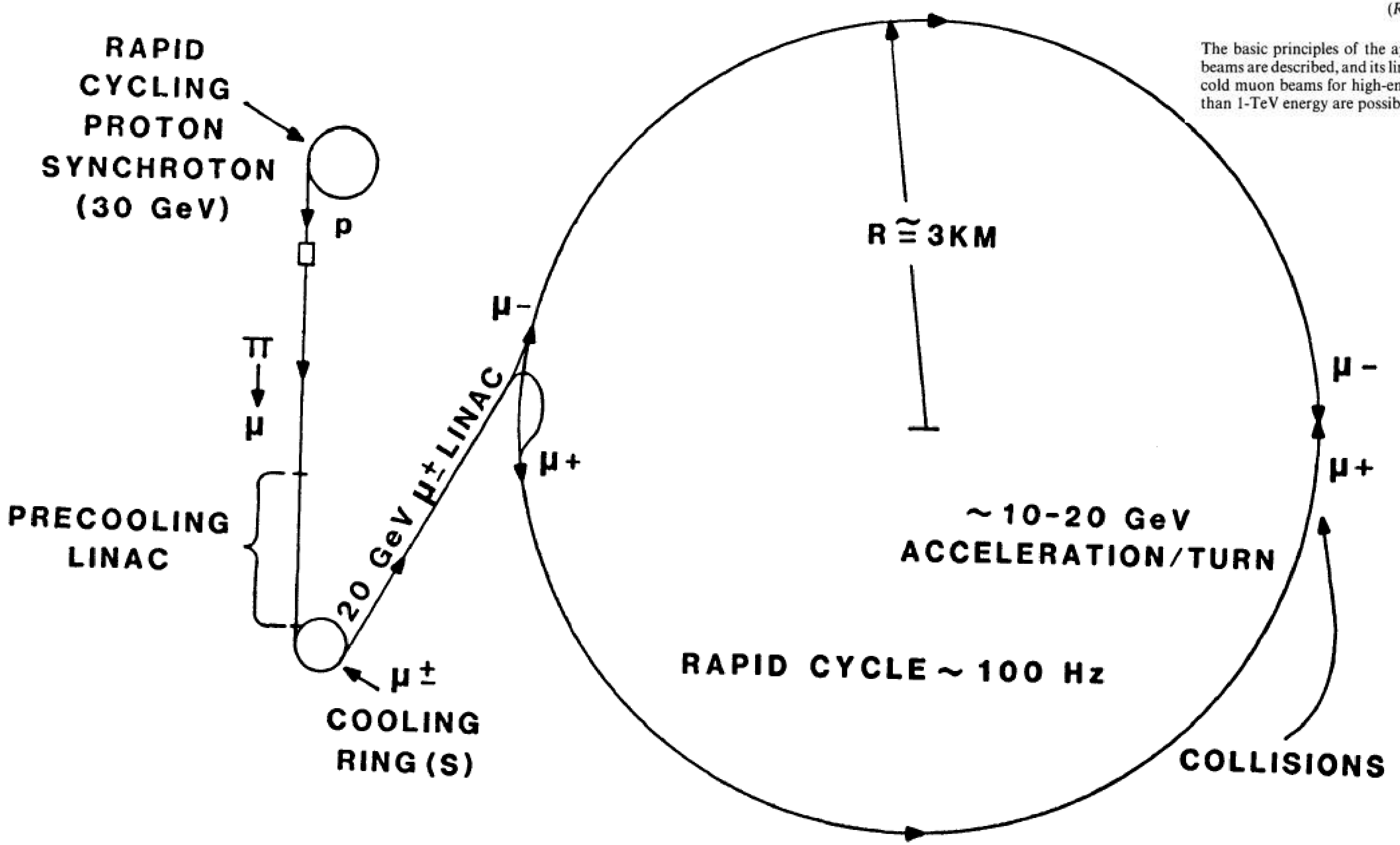


FIGURE 9 1 TeV μ rapid cycling synchroton)

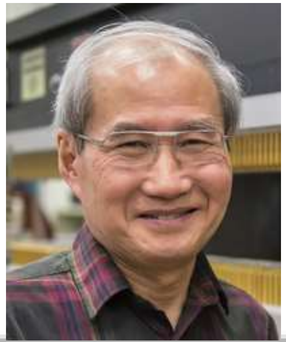
1990's – US Studies

- Andrew Sessler (Berkeley)
- Robert Palmer (BNL)
- Alvin Tollestrup (Fermilab)
- William Barletta (LBNL)
- Norbert Holtkamp (Fermilab)
- Kwang-Je Kim (U.Chicago)
- Mike Zisman (LBNL)



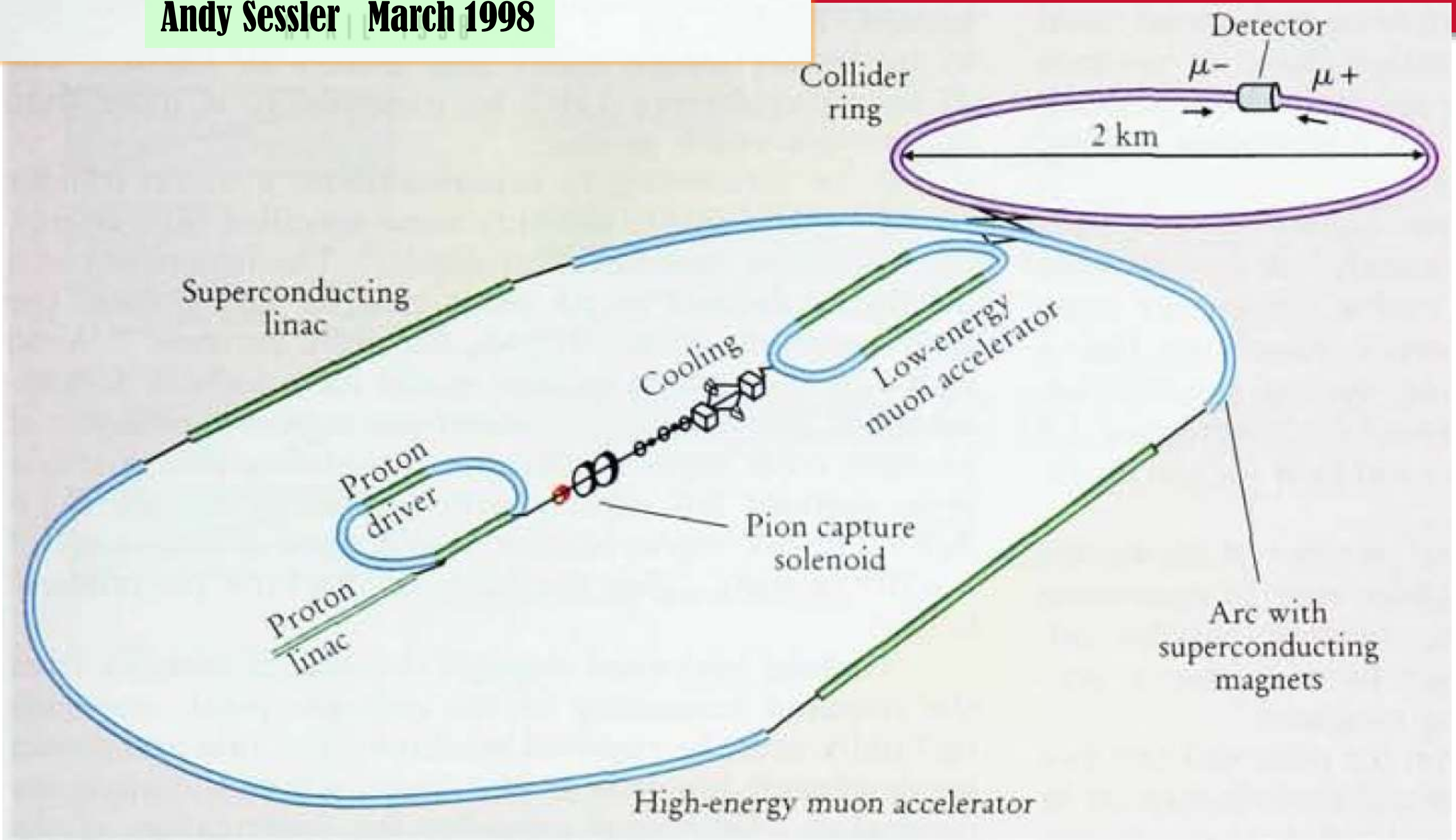






PHYSICS TODAY

Andy Sessler March 1998



MuCollider 1st Design: **Phys.Rev.ST-Accel.Beams 2, 081001 (1999)**

2000's-2010's: NFMCC → US MAP

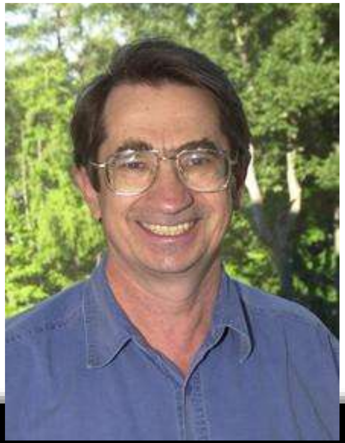
US Muon Accelerator Program (2010-2017)

- Mark Palmer (Fermilab)
  - *Program leader*
- Bruce King (BNL)
  - *Neutrino radiation issue*
- Yuri Alexahin(Fermilab)
  - *FOFO Snake cooling channel, IR optics*
- Nikolai Mokhov(Fermilab)
  - *Beam induced backgrounds*
- Yaroslav Derbenev (JLab)
  - *Parametric Ionization Cooling*
- Alan Bross (Fermilab)
  - *MICE experiment @ RAL, NuSTORM*

… ***and many others…***








"Muon Wave" in Europe

- Alain Blondel (CERN)
  - Physics, detector, accelerator
  - Neutrino Factory, MuColl
- Jean-Pierre Delahaye (CE
  - "Beyond CLIC"
- Ken L

ERN)

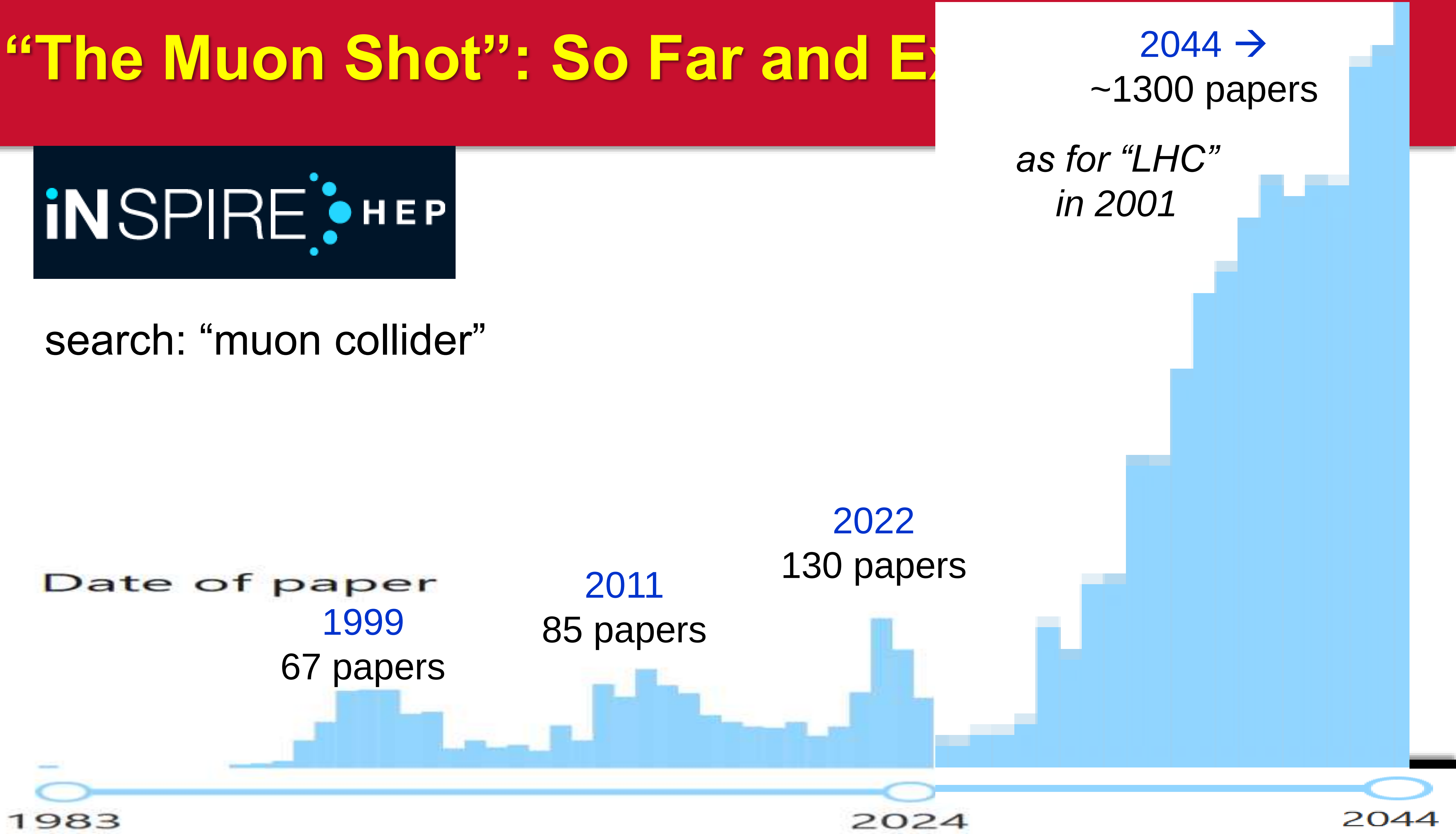
CLIC" muColl design

ICC

…and MANY OTHERS…

“The Muon Shot”: So Far and Ex

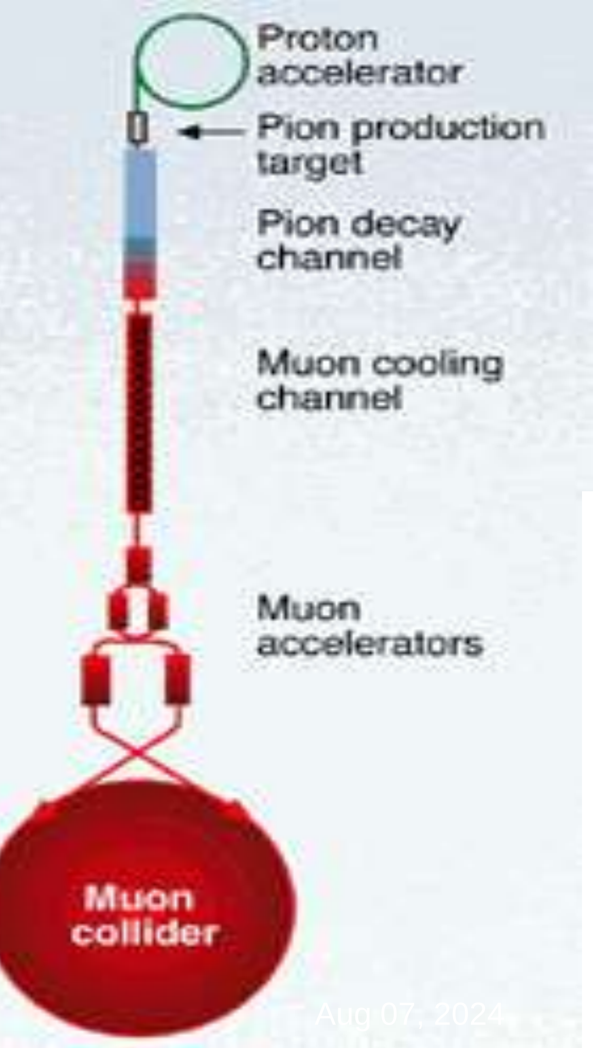
search: “muon collider”

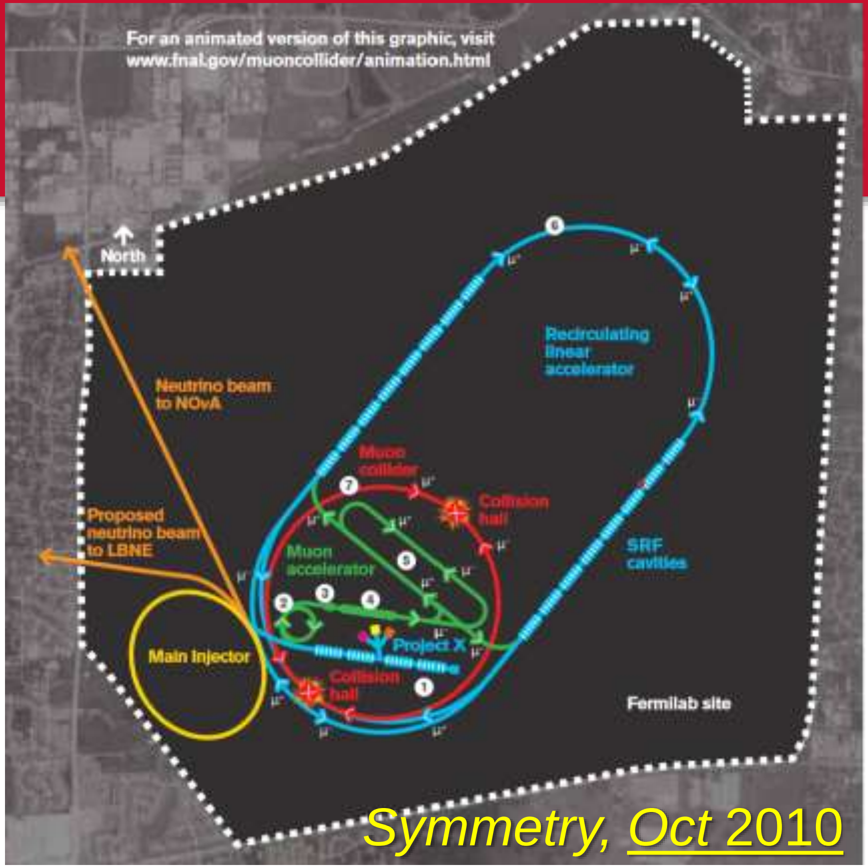


The Machine

SCIENCE, Jan 8 1998

Physicists Dream of a Muon Shot

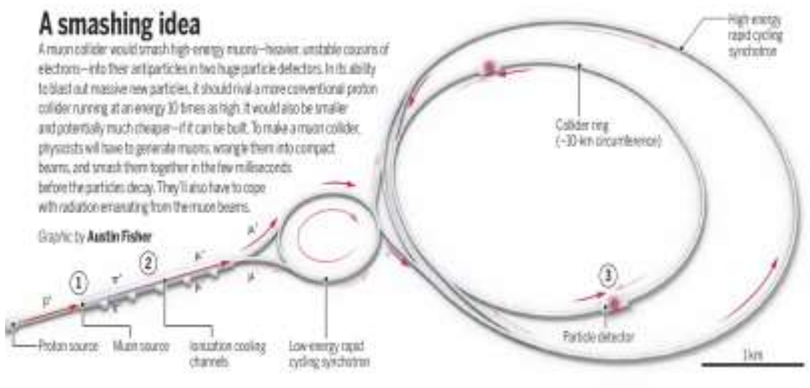




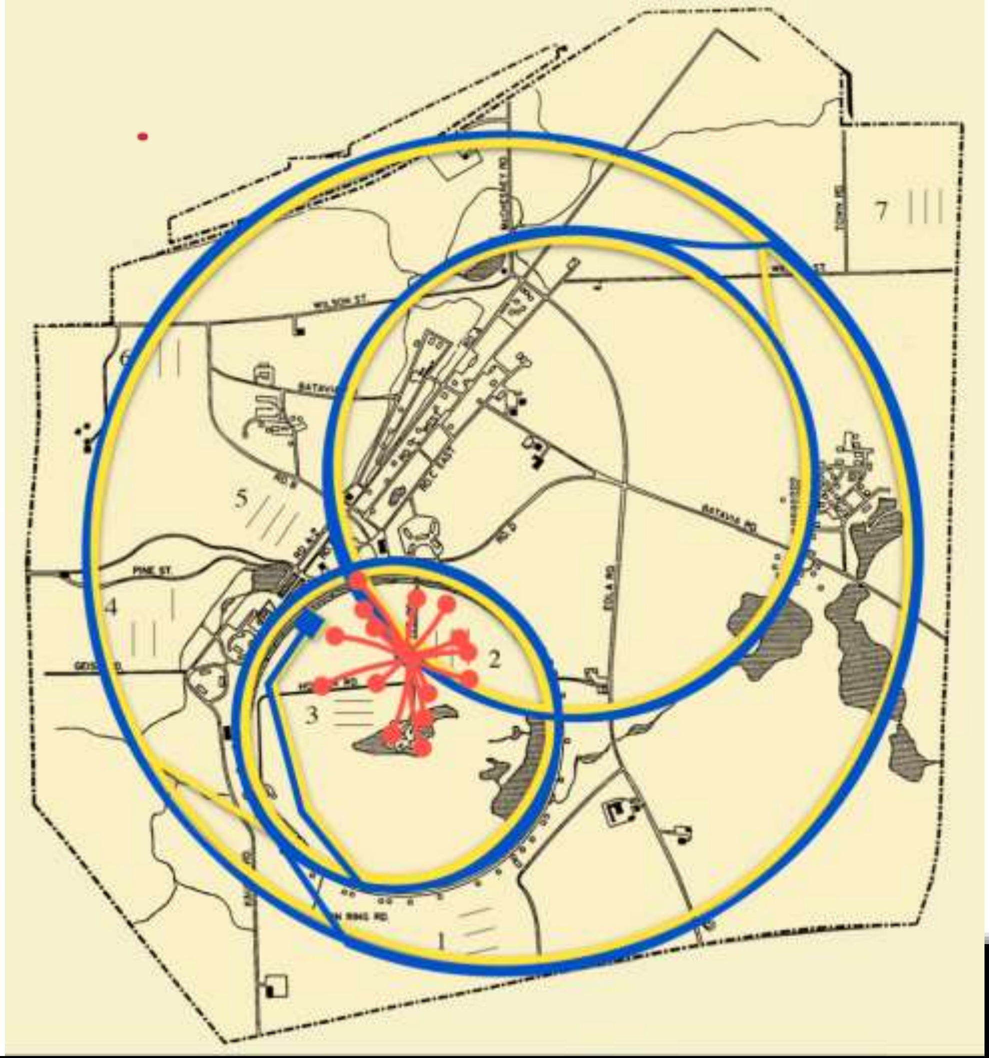
Symmetry, Oct 2010

SCIENCE, Mar 20 2024

The Dream Machine



here we are today, Aug 7 2024



The MACHINE: Key Parameters

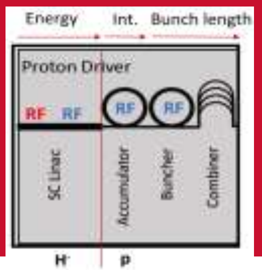
	NFMCC CA *et al* PRSTAB 1999		US MAP Palmer *et al*, RAST 2019			IMCC (US ?) Schulte *et al*, Eur.Phys J 2023		
C.M. Energy (TeV)	0.4	3	1.5	3	6	3	10	14
Luminosity/IP, ab-1/yr no. IPs								
p-Driver power (MW) rate (Hz)								
Cooling, final emm (μm) length (km)								
Fast accelerator type length (km)								
Collider circumf. (km) max B-field (T)								
Wall plug power (MW)								

The MACHINE: Key Parameters

	NFMCC CA *et al* PRSTAB 1999		US MAP Palmer *et al*, RAST 2019			IMCC (US ?) Schulte *et al*, Eur.Phys J 2023		
C.M. Energy (TeV)	0.4	3	1.5	3	6	3	10	14
Luminosity/IP, ab-1/yr	0.01	0.7	0.12	0.44	1.2	0.18	2	4
no. IPs	2?			2			2	
p-Driver power (MW)	4		4	4	1.6		2 - 4	
rate (Hz)	15		15	12	6		5 - 10	
Cooling, final emm (μm)	50	50		25			25	
length (km)	~1			~1 (snake, gugg, rectl, hcc)			~1 (rectilinear)	
Fast accelerator type	Linac → RLA → FFA?			NC RF → RLA → RCS			Linacs → RLA → RCS	
length (km)	2	12		?		?	?	35
Collider circumf. (km)	1	6	2.5	4.5	6	4.5	10	14
max B-field (T)	4.7	5.2		12?		10	16	16
Wall plug power (MW)	120	204	216	230	270		*O*(300) ?	

Fermilab's (Take On The) Proton Driver

J. Eldred, *et al*, IPAC24, TUPC41



Energy	8 GeV
Pulse Intensity	320 e12
Number of Bunches	4
Pulse Rate	10 Hz
Beam Power	4 MW
Bunch Length (AR)	20-40 ns
Bunch Length (CR)	1-3 ns
Ring Circumferences	300-500 m
95% Norm. Emittance	120-216 π mm mrad
Laslett Space-Charge limit	0.2-0.6

Table 2: Example parameters for Fermilab proton driver.

* ACE-MIRT: 2.1MW at 120 GeV, at 1.6 Hz.. but ~500 bunches

8-GeV H- Linac For a 2ms pulses every 10 Hz, 4 MW beam power corresponds to 25mA average current ***(vs 2mA in PIP-II).***

Concept for ILC-type cavities, LCLS-II cryomodule, E-XFEL klystrons.

If accumulated in four 20ns bunches in 300m ring, then 92% of the beam must be chopped and the remaining 8% must average 312mA. Therefore likely will use a longer linac pulse, longer accumulated bunches, and/or multiple linac frontends.

Accumulator Ring (AR) A 500m conventional ring or 300m superconducting ring at 8 GeV. **H^- laser stripping injection** may be necessary for controlling injection losses in the the high power beam.

Option of injecting at lower energy (4-6 GeV) and accelerating to 8 GeV.

Compressor Ring (CR) uses snap bunch rotation to compress four 20-40 ns bunches into four 1-3 ns bunches (space-charge! - next slide)

Likely a separate ring from AR, differs by phase-slip factor, different requirements for injection and RF. But similar aperture and circumf.

At 3 ns, 4 MW, and a stable Laslett space-charge tune-shift parameter of 0.2, the 95% normalized emittance must rise to 216 π mm mrad (~ 20 times the FNAL Booster beam emittance and ~20 x intensity). Further performance gains may be achievable with extreme space-charge R&D (**IOTA**).

Combiner directs the four bunches to converge on the target as simultaneous and narrow pulse. Longitudinally the bunches overlap but transversely the bunches are side-by-side, increasing the effective emittance of the beam on target by at least a factor of four.

Sensitivities: Proton Bunch Length

Optimal rms length 1-3 ns:

Challenges – SC effects, impedances/instabilities

What's the effect?

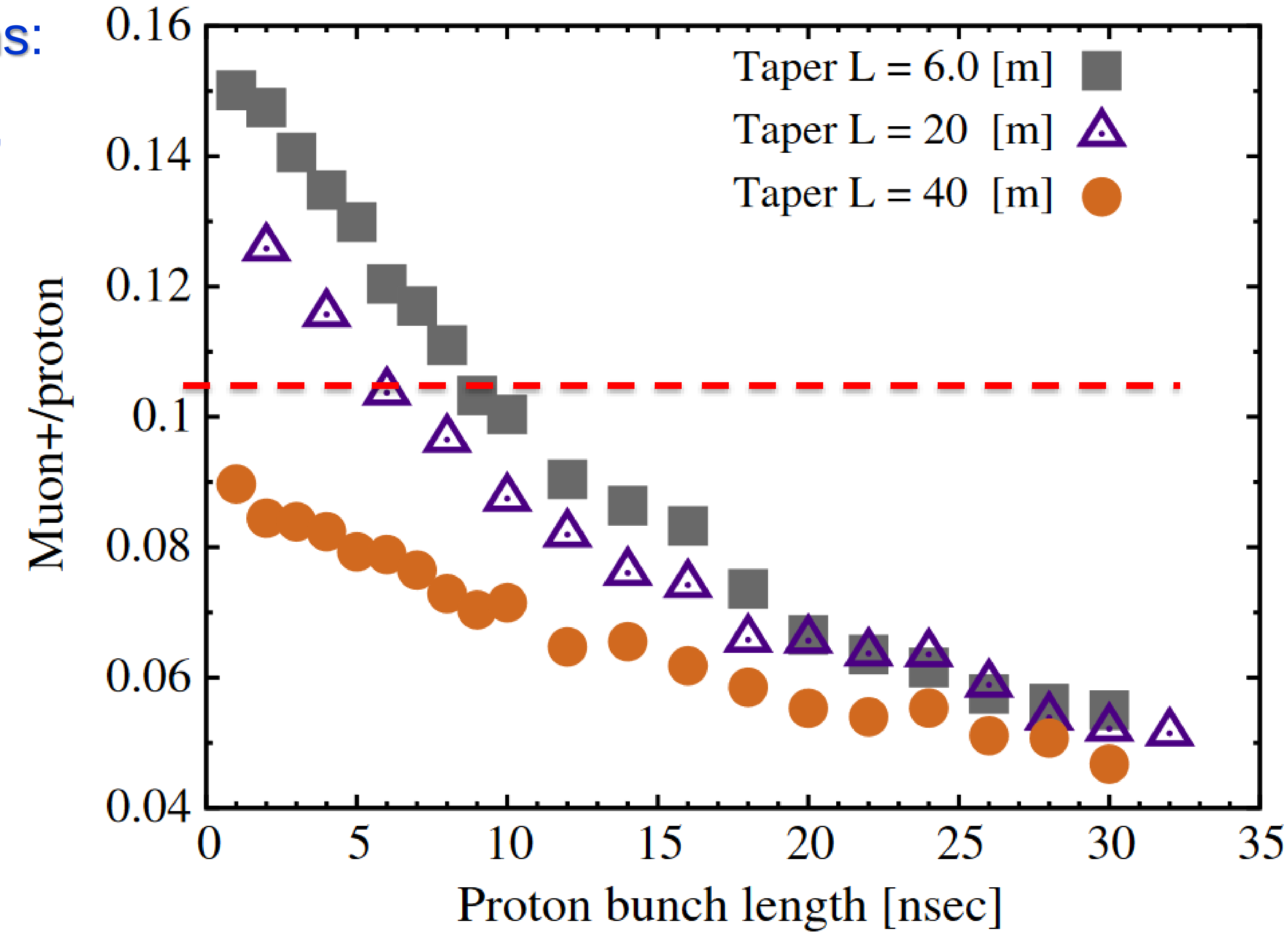
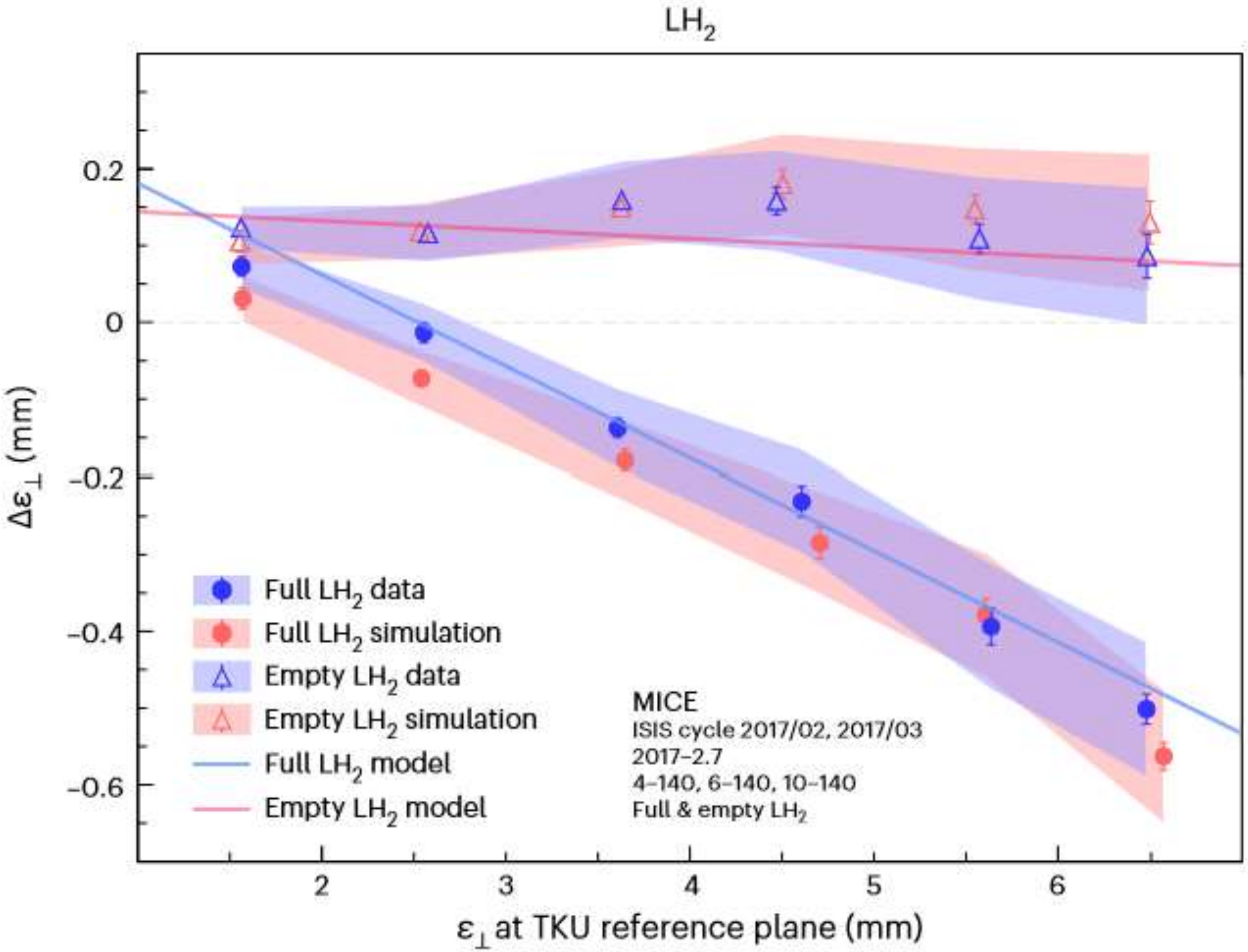


Fig: Accepted positive muons as a function of the proton bunch length for three different taper lengths. The target field is 20T, and the final field is 3.5T.

HISHAM KAMAL SAYED AND J. SCOTT BERG
Phys. Rev. ST Accel. Beams 17, 070102 (2014)

Muon Cooling: Latest MICE (2024)

Fig. 3 | Transverse emittance change measured by MICE. Emittance change between the TKU and TKD reference planes, Δε⊥, as a function of emittance at TKU for 140 MeV/c beams crossing the LH2 MICE absorbers. Results for the empty cases, namely, No absorber and Empty LH2, are also shown. The measured effect is shown in blue, whereas the simulation is shown in red. The corresponding semitransparent bands represent the estimated total standard error. The error bars indicate the statistical error and for some of the points, they are smaller than the markers. The solid lines represent the approximate theoretical model defined by equation (10) (Methods for the absorber (light blue) and empty (light pink) cases. The dashed grey horizontal lines indicate a scenario where no emittance change occurs.

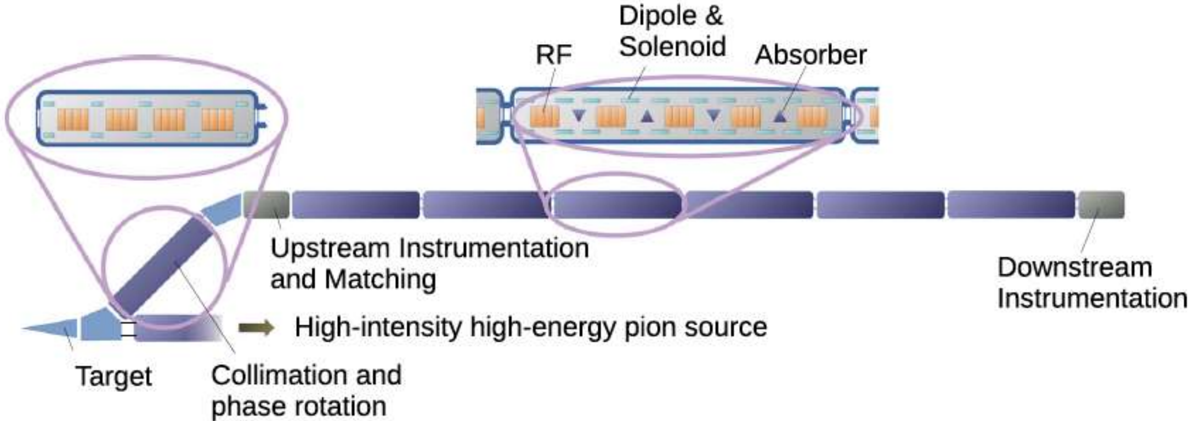


https://doi.org/10.1038/s41567-024-02547-4

Ionization Cooling Demonstrator

https://doi.org/10.1140/epjc/s10052-023-11889-x

- MC ionization cooling channel consists of ~800 muon cooling cells
- The cooling of muons requires very compact assembly of normal conducting RF cavities, superconducting solenoids, and either liquid hydrogen or LiH absorbers
- Large bore solenoids: from 2 T (D=1 m) to 20+ T (D=0.05 m)
- RF cavities (300-800 MHz) must operate in multi-Tesla fields
- Wedge-shaped absorbers must and large muon beam intensities



Schematic of the muon cooling demonstrator

	Muon mom. MeV/c	Total length, m	Total # of cells	Total RF voltage, MV	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	~15,000	2-14	x $1/10^5$	~70%
Demonstrator	200	48	24	~260	0.5-7	x 1/2	4-6%

■ Timeline: 2029-2034 ■ Location: Fermilab or CERN ■ Cost: 300 ? M$

How Much RF Voltage is Needed

Consider future *collider of 5TeV + 5 TeV muon beams*

The final stage of acceleration calls for the muon energy boost

from ~50 GeV to 5000 GeV

IF **it's in a linear accelerator (*G*~100 MeV/m)**

What would be the length?

How many muons would survive?

L = 50 km

$\Delta N/N$=0.7%

IF **it's in a circular accelerator (*C*~30 km)**

What energy gain per turn is

needed for 50% of muons to survive?

ΔE = 43 GeV

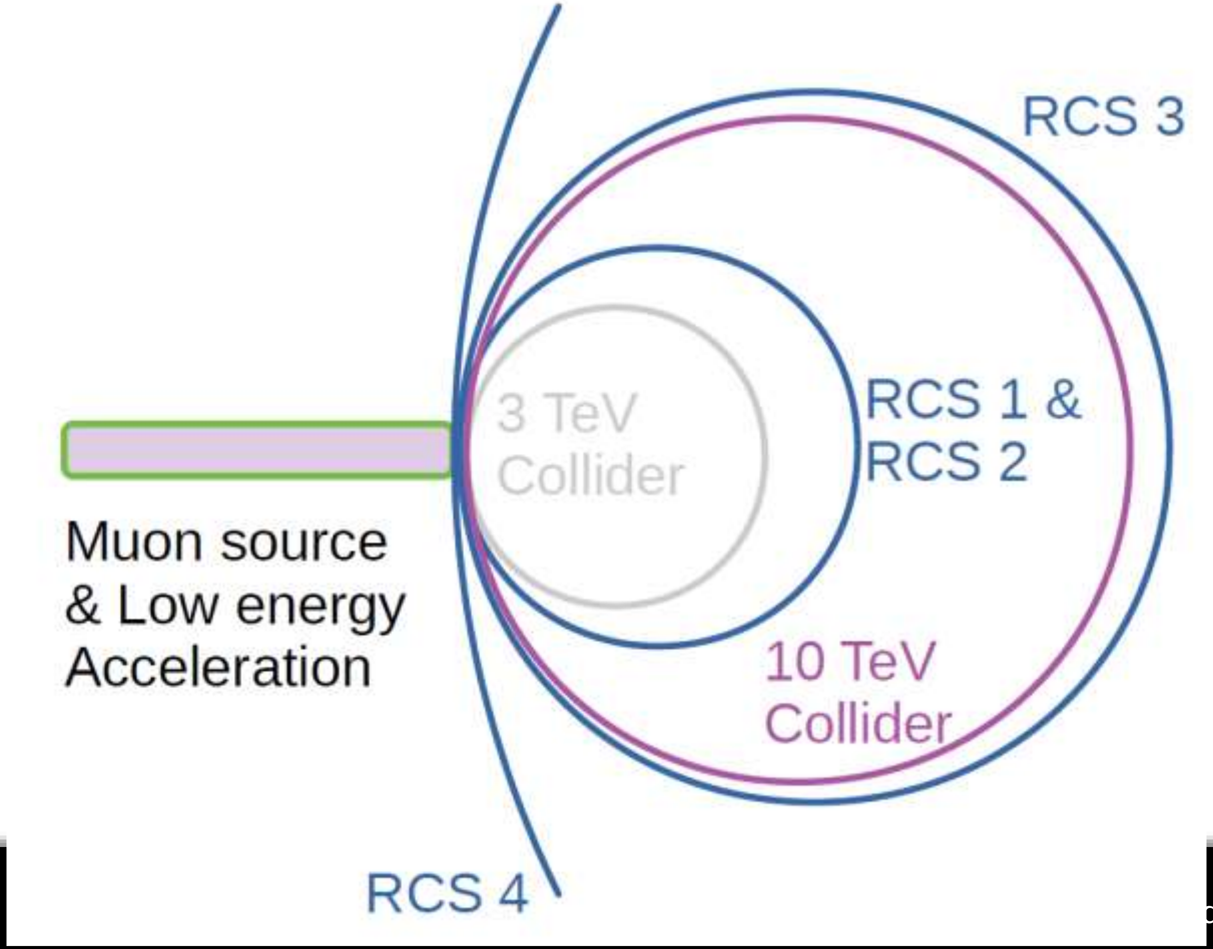
(116 turns)

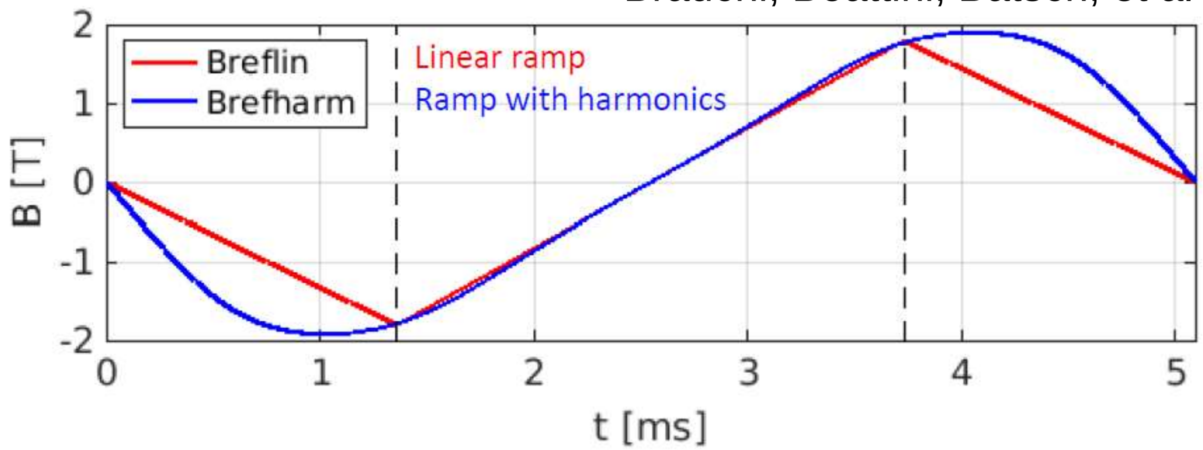
… or ΔE = 22 GeV for C~15 km

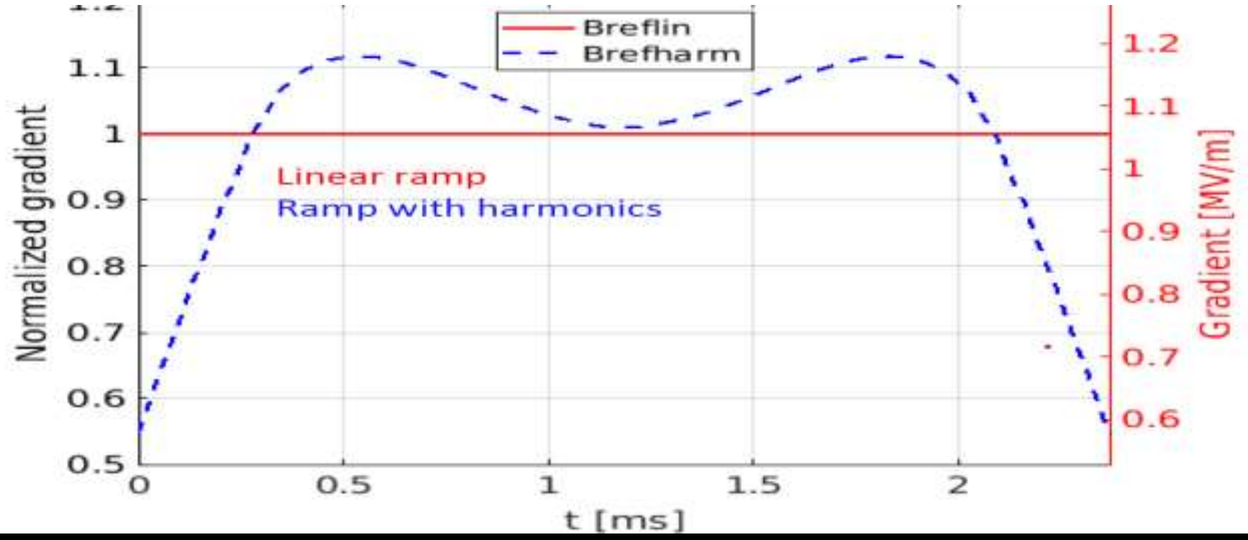
Critical System: Acceleration

$$p(t)c = 0.3\,B(t)\rho$$

Brauchi, Boattini, Batsch, et al

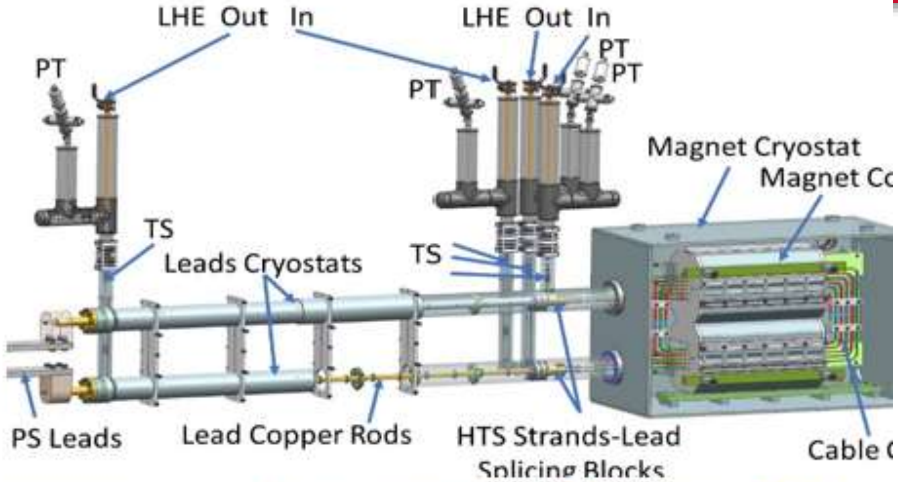




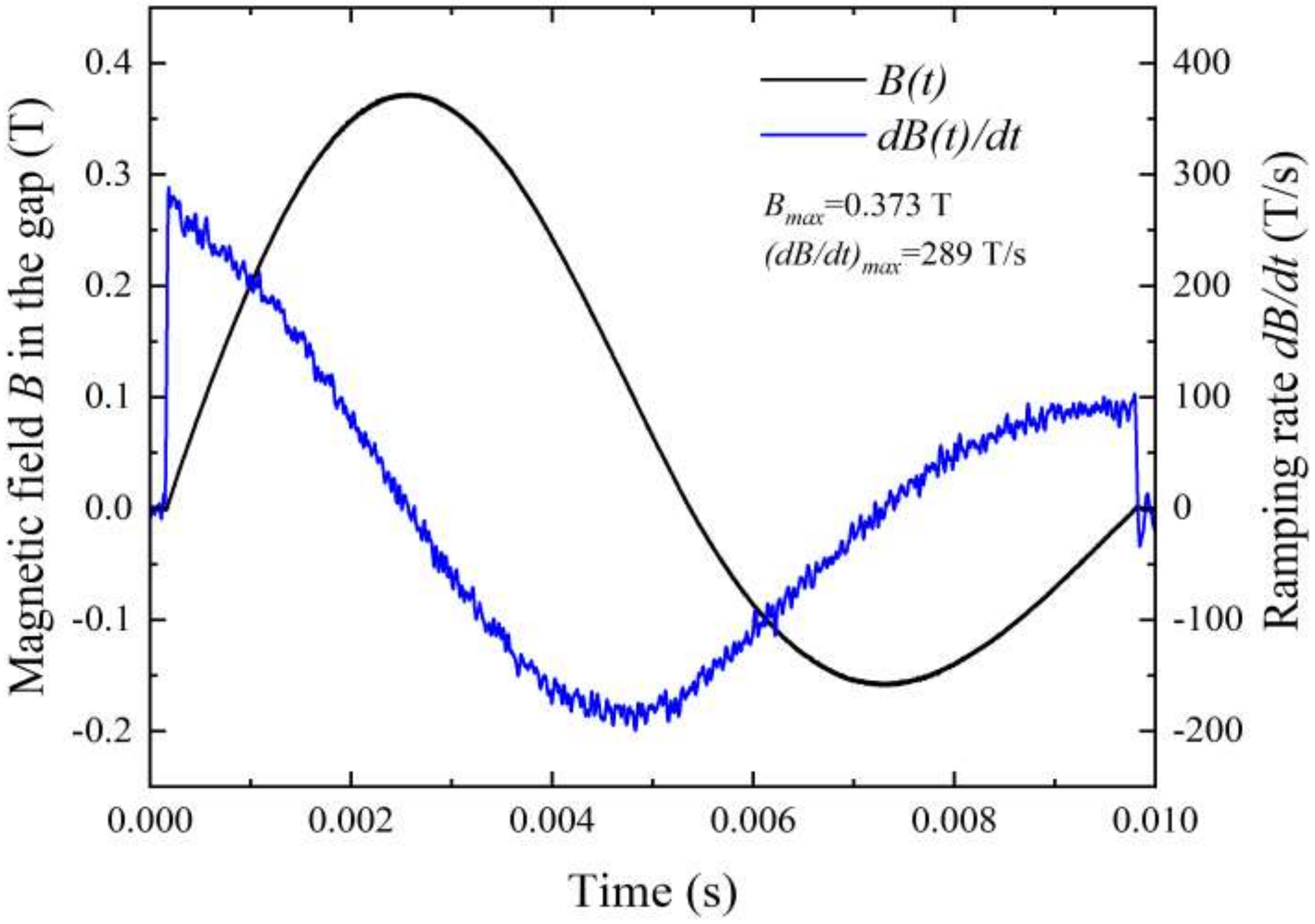


dimin

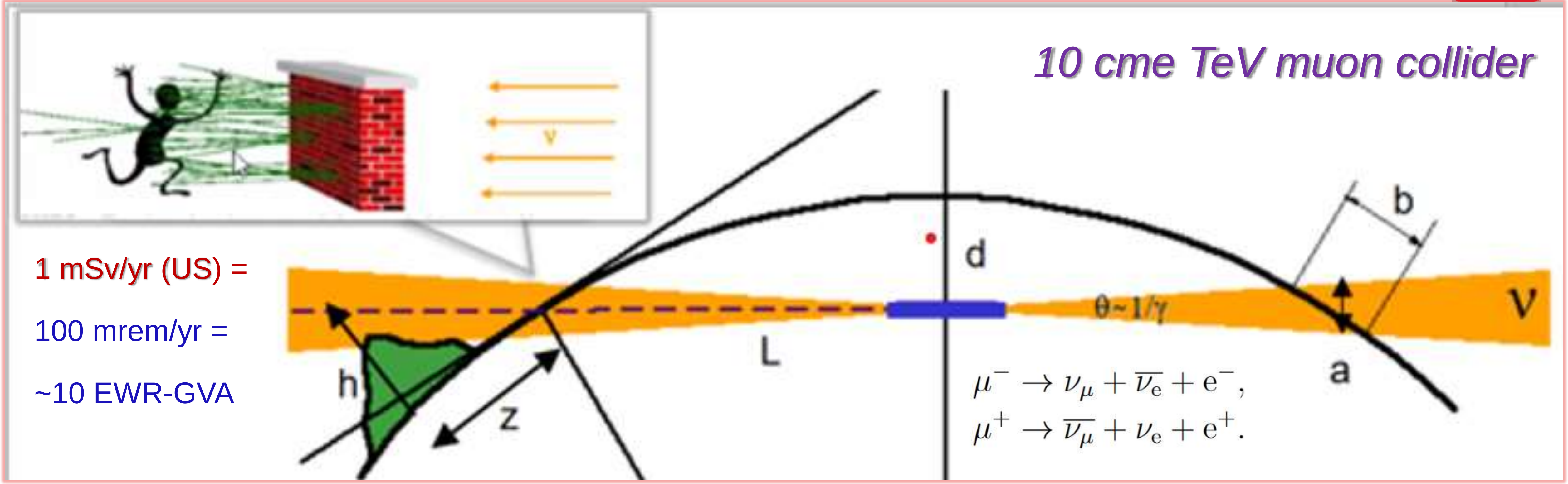
Fermilab's HTS Magnet Test (H.Piekarz *et al*)



1 – Magnet, 2- Current leads, 3- Power supply,
4 – Control electronics, 5- Liquid Helium lines



Dilute Neutrino Flux out of a Muon Collider



5 TeV muon beams … collider circumference *C*~10 km… depth ~100 m

- Neutrinos come out of the Earth ~30 km away
- The neutrino cone (~ 6 μrad rms angular, ~0.2 m geometrical)
- Methods to dilute the flux: a) increase the depth ; b) wiggle the cone by 0.1-1 mrad

Subsystems: Costs and Risks

	Approx. % of the Total Cost	Approx. Luminosity Risk Factor
Proton Driver and Targetry		
Muon Cooling		
Acceleration		
Collider		
TOTAL		

Subsystems: Costs and Risks

	Approx. % of the Total Cost	Approx. Luminosity Risk Factor
Proton Driver and Targetry	15 - 20 %	10^{1-2}
Muon Cooling	10 - 15 %	10^{3-4}
Acceleration	30 - 60 %	10^{1-2}
Collider	25 - 40 %	10^{0-1}
TOTAL	**12 - 18 B$ *ITF?**	**10^{5-9}**

Summary

- The idea of colliding muons ~50 y.o. – *a lot of progre ... years!*
- Many challenges – *worth of >50% of the cos ... n Luminosity*
- New wave of interest – *thanks to IM ... and P5 (!)*
- A lot to do:
  – Form the US MC ... program started in OHEP)
  – Help IM ... European Strategy input/discussions
  – ... onstrator (→ review → approval → construction)
  – ... cl. design work on 10+ TeV cme $\mu\mu$ collider(s)

We'll make the path by walking it!

Thanks for your attention!

Questions?

Acknowledgements

Jeff Eldred
Diktys Stratakys
Ben Simmons
Henryk Piekarz
Alan Bross
Sasha Valishev
Giorgio Apollinari
Steve Gourlay
Derun Li
David Neuffer
Mark Palmer
Sergo Jindariani
Sam Posen
Sergey Belomestnykh
Tor Raubenheimer
Pushpa Bhat
Daniel Schulte
Scott Berg
Robert Palmer
Chris Rogers
Dan Kaplan

[back up slides]

MC Physics (1990's)

- David Cline (UCLA)
  - Since 1992: series of International Conference on "Physics Potential and Development of μ+μ− Colliders"

- V.Barger (UW), M.Berger (IU), J.Gunion, T.Han (UCD)

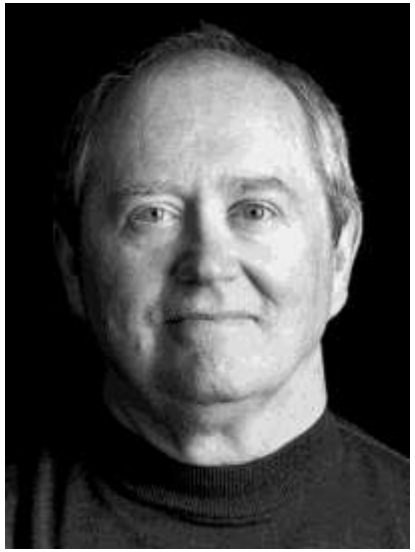
VOLUME 75, NUMBER 8 PHYSICAL REVIEW LETTERS 21 AUGUST 1995

s-Channel Higgs Boson Production at a Muon-Muon Collider

V. Barger,[1] M. S. Berger,[2] J. F. Gunion,[3] and T. Han[3]
[1]*Physics Department, University of Wisconsin, Madison, Wisconsin 53706*
[2]*Physics Department, Indiana University, Bloomington, Indiana 47405*
[3]*Physics Department, University of California, Davis, California 95616*
(Received 24 April 1995; revised manuscript received 3 July 1995)

High luminosity muon-muon colliders would provide a powerful new probe of Higgs boson physics through s-channel resonance production. We discuss the prospects for detection of Higgs bosons and precision measurements of their masses and widths at such a machine.

Physics Case (1990's – 2000's)



- Estia Eichten (Fermilab)
  Chris Hill, Chris Quigg , et al
  - Higgs Sector
  - BSM, SUSY
  - Narrow States
  - R-parity violation
  - Topcolor

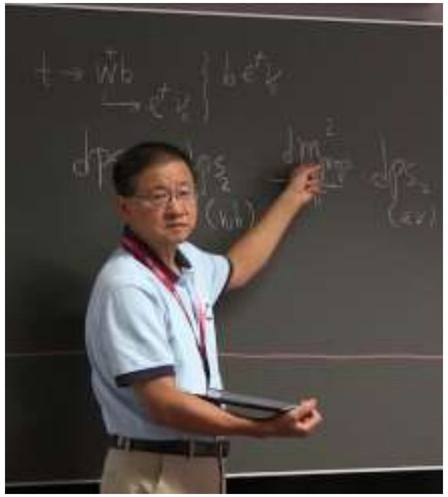
- Steve Geer (Fermilab)
  - Neutrino factory concept (1998)

s

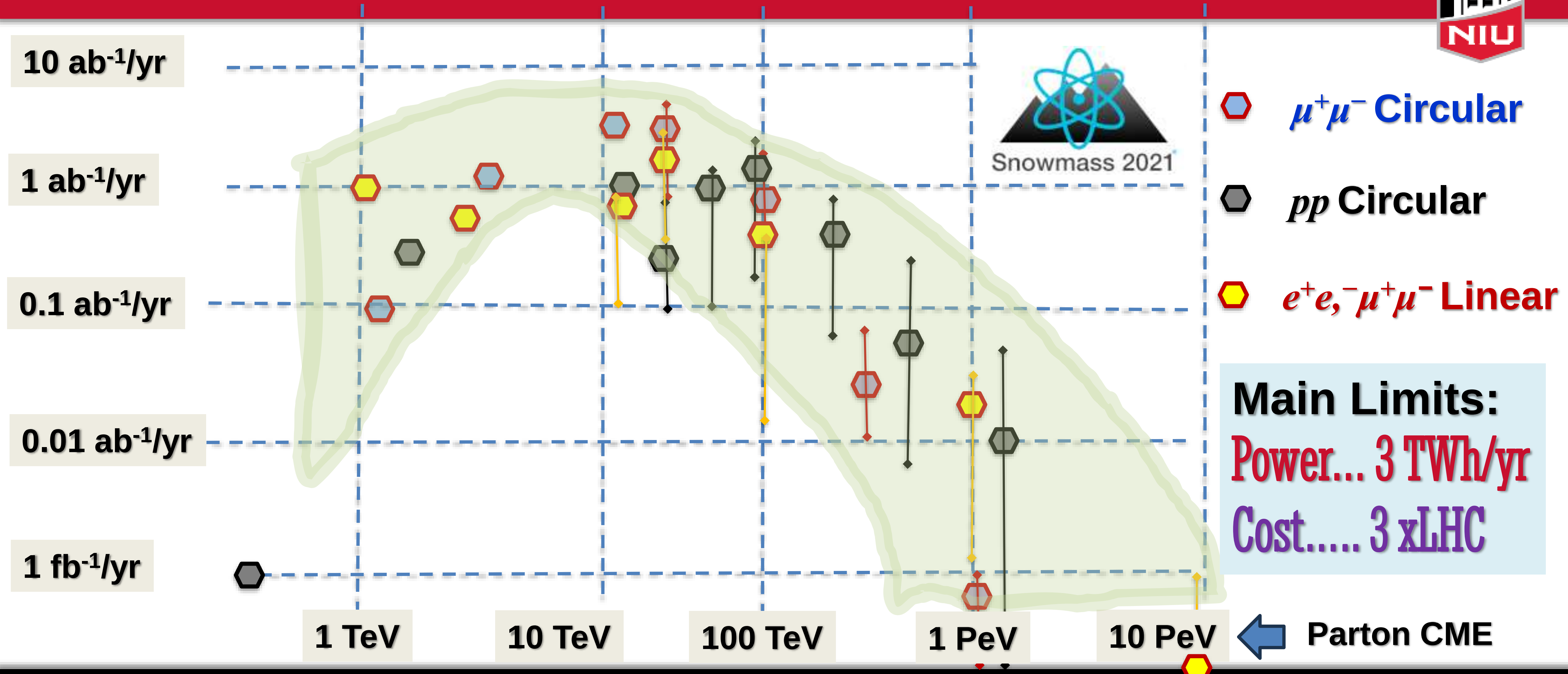
Physic Case (2010 – now)

- Andrea Wulzer (CERN/Padua)
- Tao Han (Pittsburg)
- LianTao Wang (Chicago)

  - *Compositeness* of Higgs
  - Higgs coupling, trilinear and even quartic
  - *DM* searches
  - BSM searches
  - *Direct New Physics* reach
    - Colored particles 10 TeV $\mu\mu$ equiv. 70 TeV *pp*
    - Colorless : 10 TeV $\mu\mu$ equiv. 150 TeV *pp*



Ultimate Colliders *Luminosity* vs *Energy*



Main Limits:

Power… 3 TWh/yr

Cost….. 3 xLHC

V.Shiltsev, "Ultimate Colliders" (Oxford Encyclopedia, 2023); **DOI:** 10.1093/acrefore/9780190871994.013.118

Muon Collider Challenges and R&D Topi

R&D re: Energy Reach/Cost

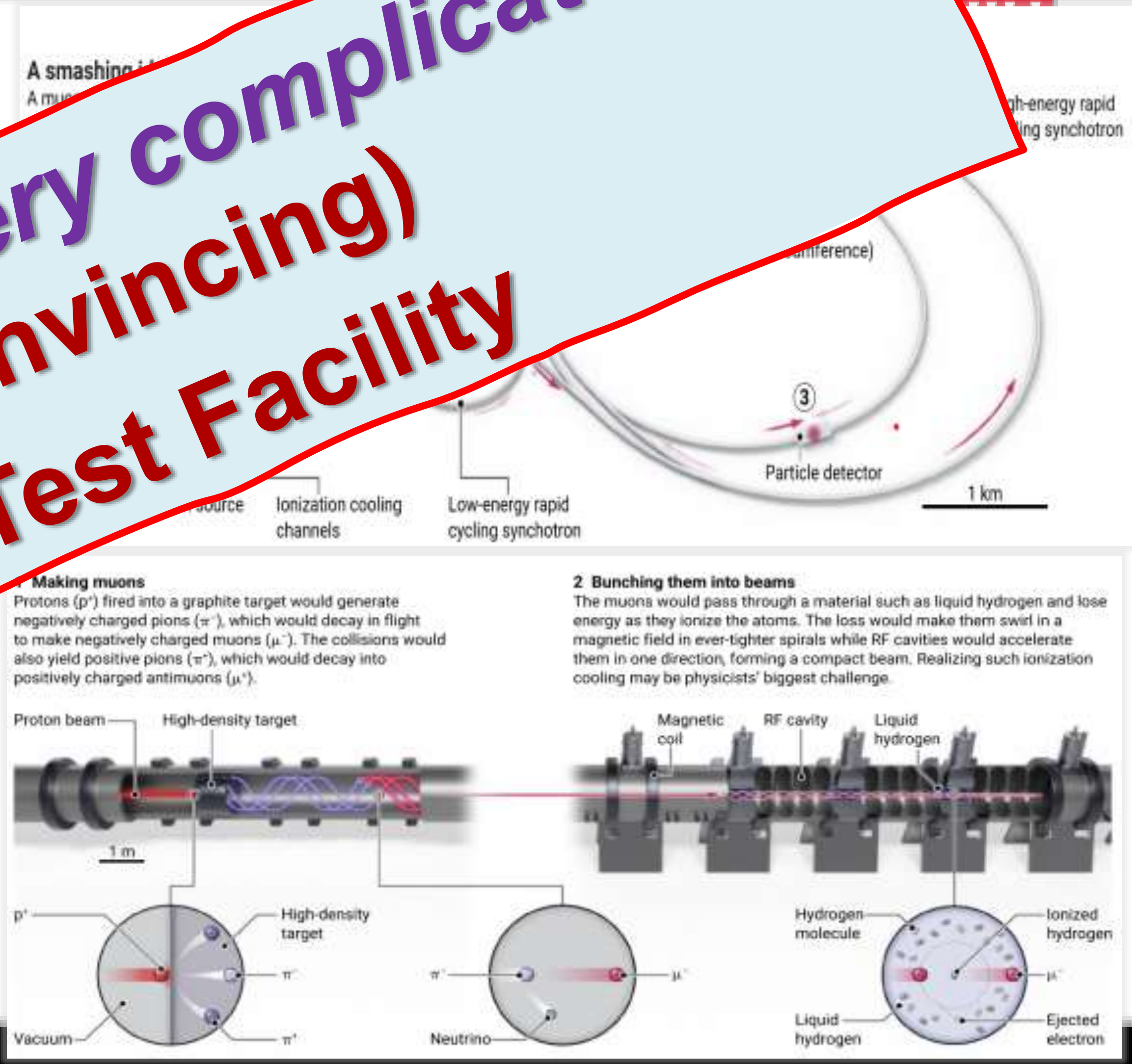
- Fast magnets for the accelerator rings (~few ms, ~20 km)
- Economical high-gradient pulsed SRF (~few ms, ~2 GeV)
- Collider ring 12-16 T superconducting
- Civil construction (~40 km)
- Power infrastructure (~2

R&D re:

- ...nches ...deliver at 5-10
- Ta... SC solenoid with ~2 m ape... RF in 2-14 T SC solenoids of the ioniz... ...nel
- Challe... ...due to muon decays; neutrino flux dilution

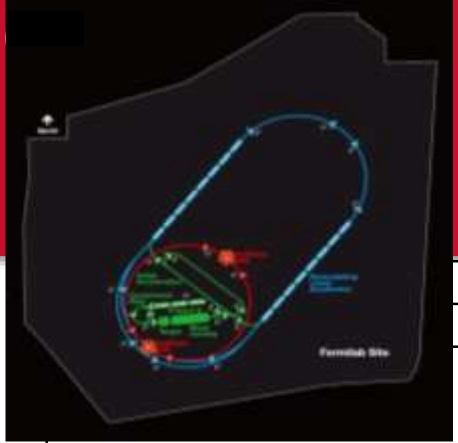
“ …no showstopper, but very complicated…”

Requires a (Convincing) Demonstrator Test Facility



Vladimir SHILTSEV

Muon Collider Parameters – US MAP



Muon Collider Parameters								
		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/10^7sec		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
b*	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, e_{TN}	p mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, s_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

$^\#$ Could begin operation with Project X Stage II beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts ⇨ several ↙ 10^{32}

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV