Fermilab
Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Muon Colliders – “Light at the End of the Tunnel” for HEP

Vladimir Shiltsev

FNAL LPC Meeting, June 9, 2020

ABSTRACT

Tighter requirements of new green standards for power consumption, the need to stay within reasonable costs of accelerator facility while aspiring for order of magnitude beyond the LHC center of mass energy in particle collisions call for a drastic paradigm shift from the “bigger, more powerful and more costly” tradition of HEP colliders of the past 50 years. I will review comparative advantages and challenges of multi-TeV muon colliders and argue that only since very recently we have proven the machine feasibility and are ready to start working toward complete technical design two decades from now for the concept of muon colliders, which offer unique option to advance the particle physics frontier and open the *Promise land* beyond the Standard Model.

High Energy $\mu+\mu-$ Colliders

Advantages:

- ***μ***'s do not radiate when bent → acceleration in rings →

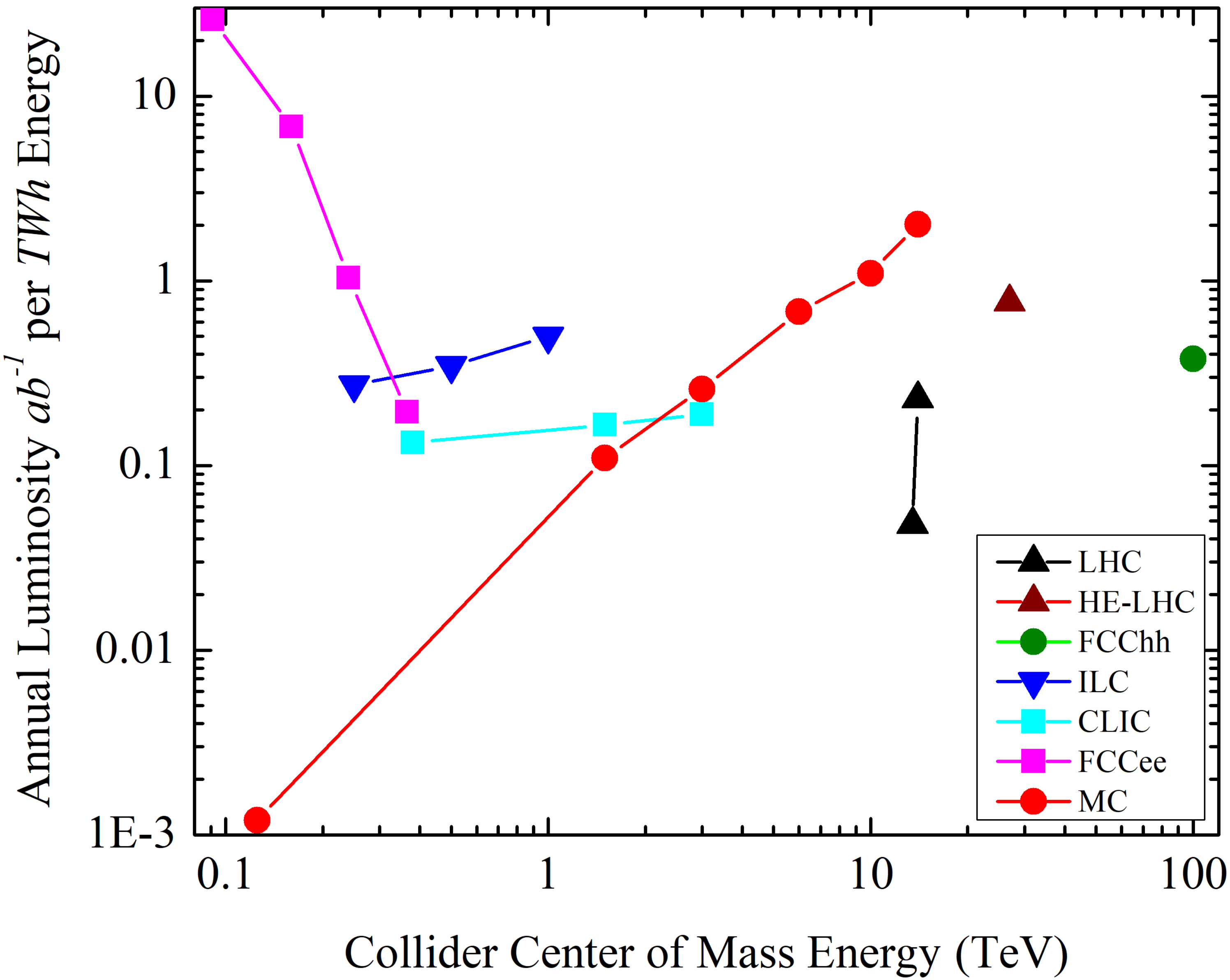
smaller footprint
low cost
great power efficiency

- ~ x7 energy reach vs *pp*

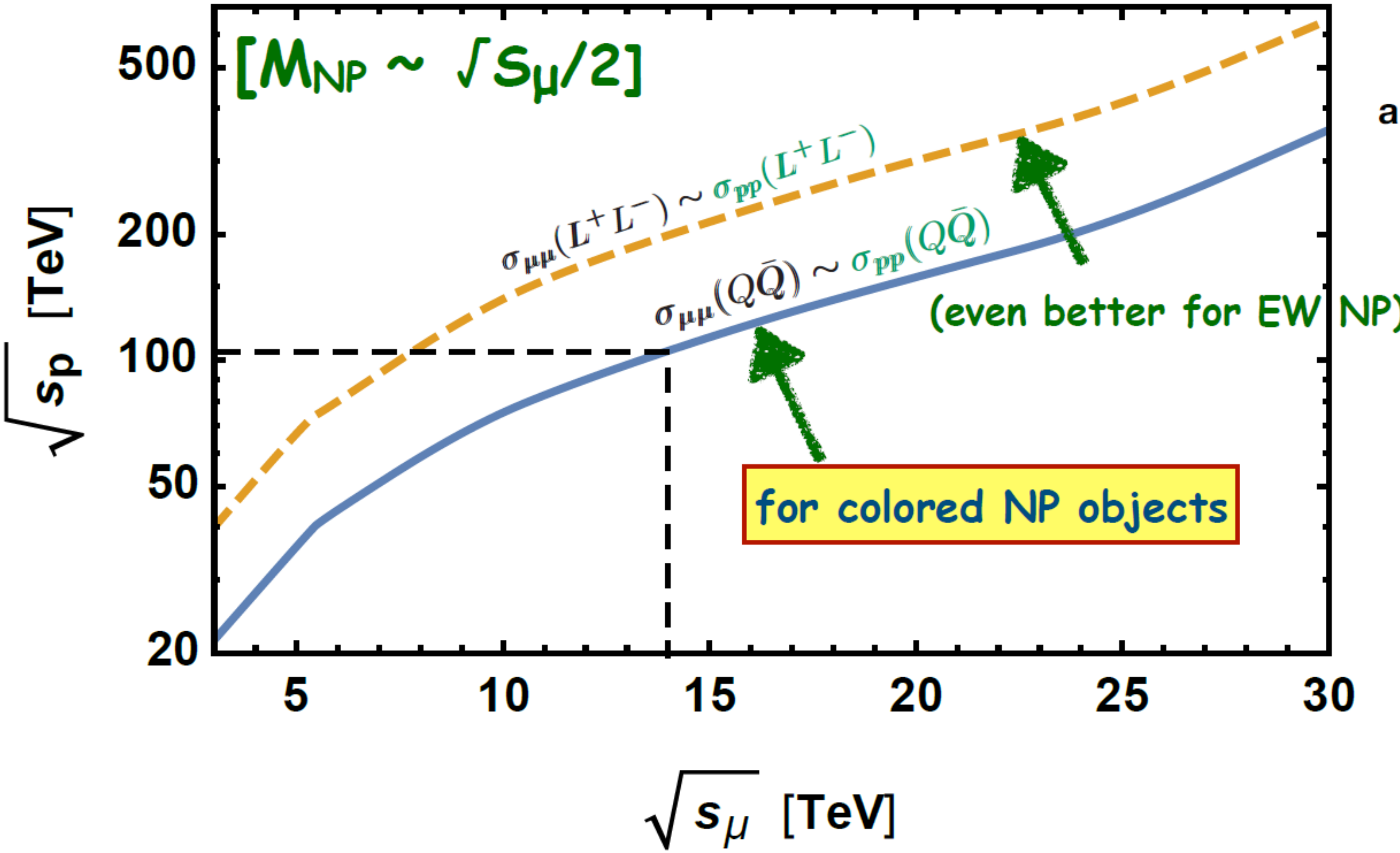
Offer *"moderately conservative - moderately innovative"* path **to cost affordable** energy frontier colliders:

Power efficiency

arXiv:2003.09084



"equivalent" reach in pp after rescaling for pdf's



arXiv:1901.06150

- ✱ μμ @ 14 TeV → pp @ 100 $(200)_{EW}$ TeV !
- ✱ μμ @ 30 TeV → pp @ 350 $(600)_{EW}$ TeV !!

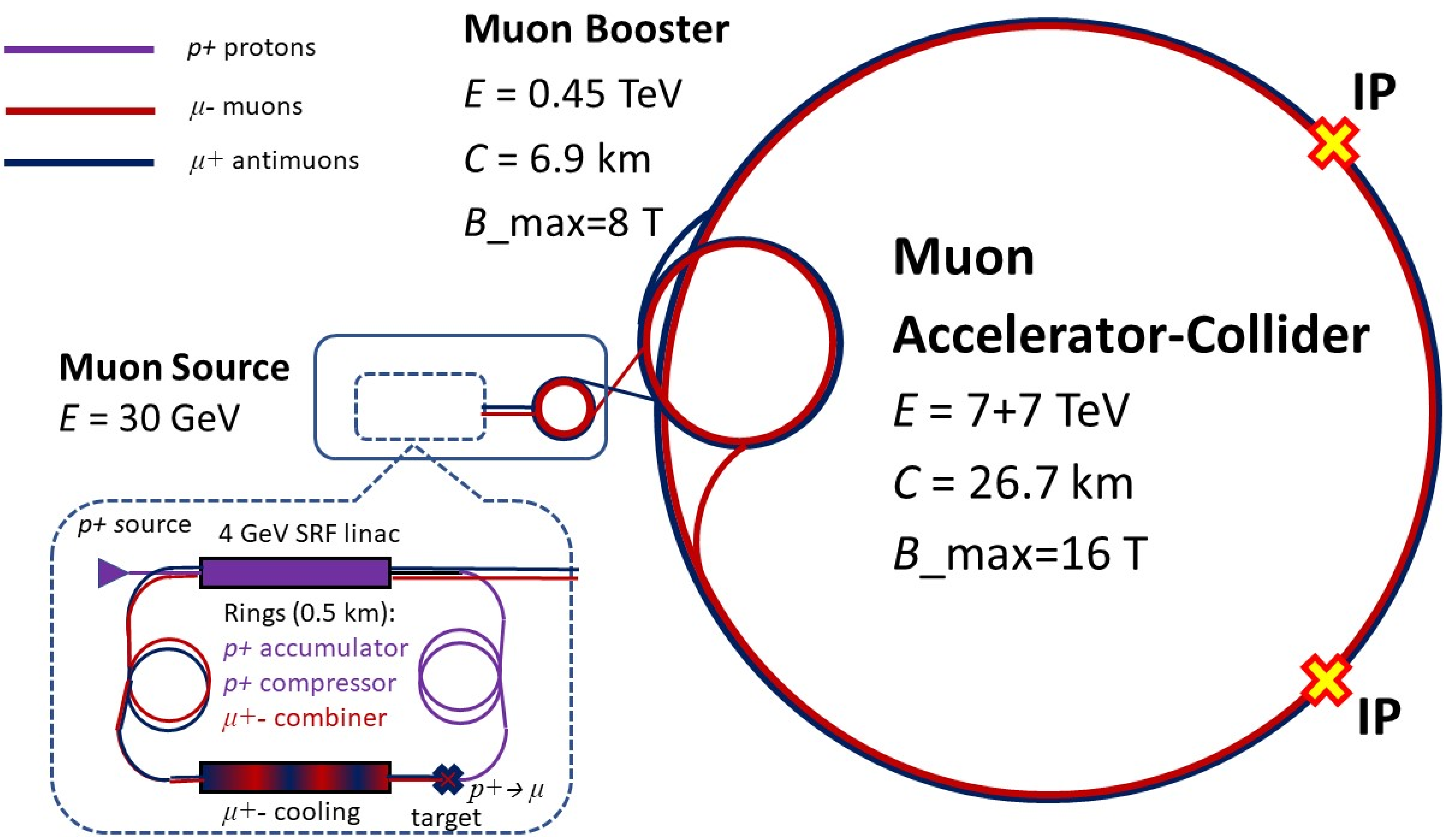
yet unexplored pheno !!!

Cost

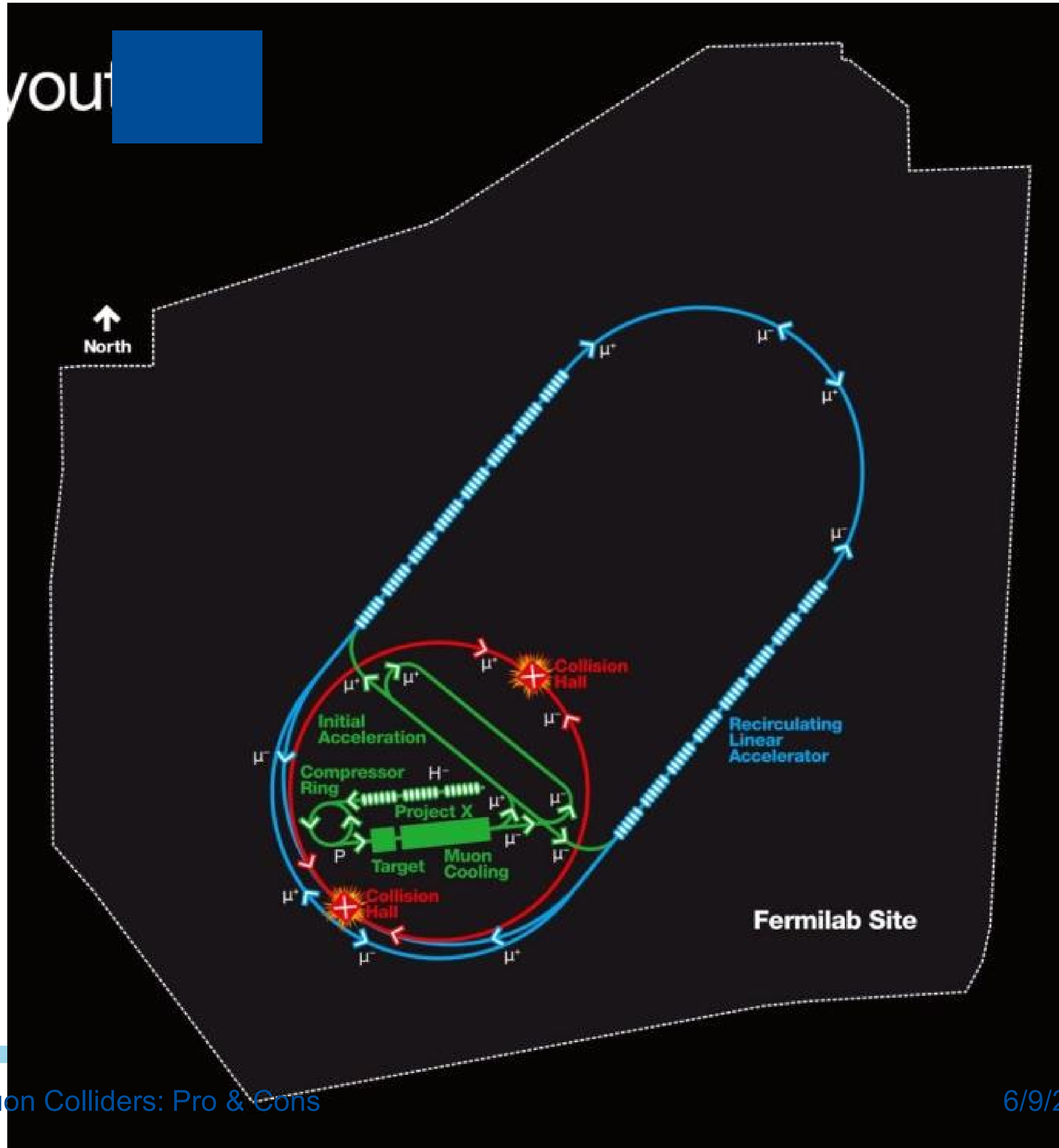
arXiv:2003.09084

Project	Type	Energy (TeV, c.m.e.)	N_{det}	$\mathcal{L}_{int}$ (ab^{-1})	Time (years)	Power (MW)	Cost
ILC	e^+e^-	0.25	1	2	11	129	4.8-5.3BILCU
		0.5	1	4	10	163(204)	8.0 BILCU
		1	1			300	+(n/a)
CLIC	e^+e^-	0.38	1	1	8	168	5.9 BCHF
		1.5	1	2.5	7	370	+ 5.1 BCHF
		3	1	5	8	590	+7.3 BCHF
CEPC	e^+e^-	0.091&0.16	2	16+2.6	2+1	149	5 B USD
		0.24	2	5.6	7	266	+(n/a)
FCC-ee	e^+e^-	0.091&0.16	2	150+10	4+1	259	10.5 BCHF
		0.24	2	5	3	282	
		0.365 & 0.35	2	1.5+0.2	4+1	340	+1.1 BCHF
LHeC	ep	1.3	1	1	12	(+100)	1.75* BCHF
HE-LHC	pp	27	2	20	20	220	7.2 BCHF
FCC-hh	pp	100	2	30	25	580	17(+7) BCHF
FCC-eh	ep	3.5	1	2	25	(+100)	1.75 BCHF
Muon Collider	$\mu\mu$	14	2	50	15	290	10.7* BCHF

Muon Collider (2020) : Sub-Systems (approx. in scale)

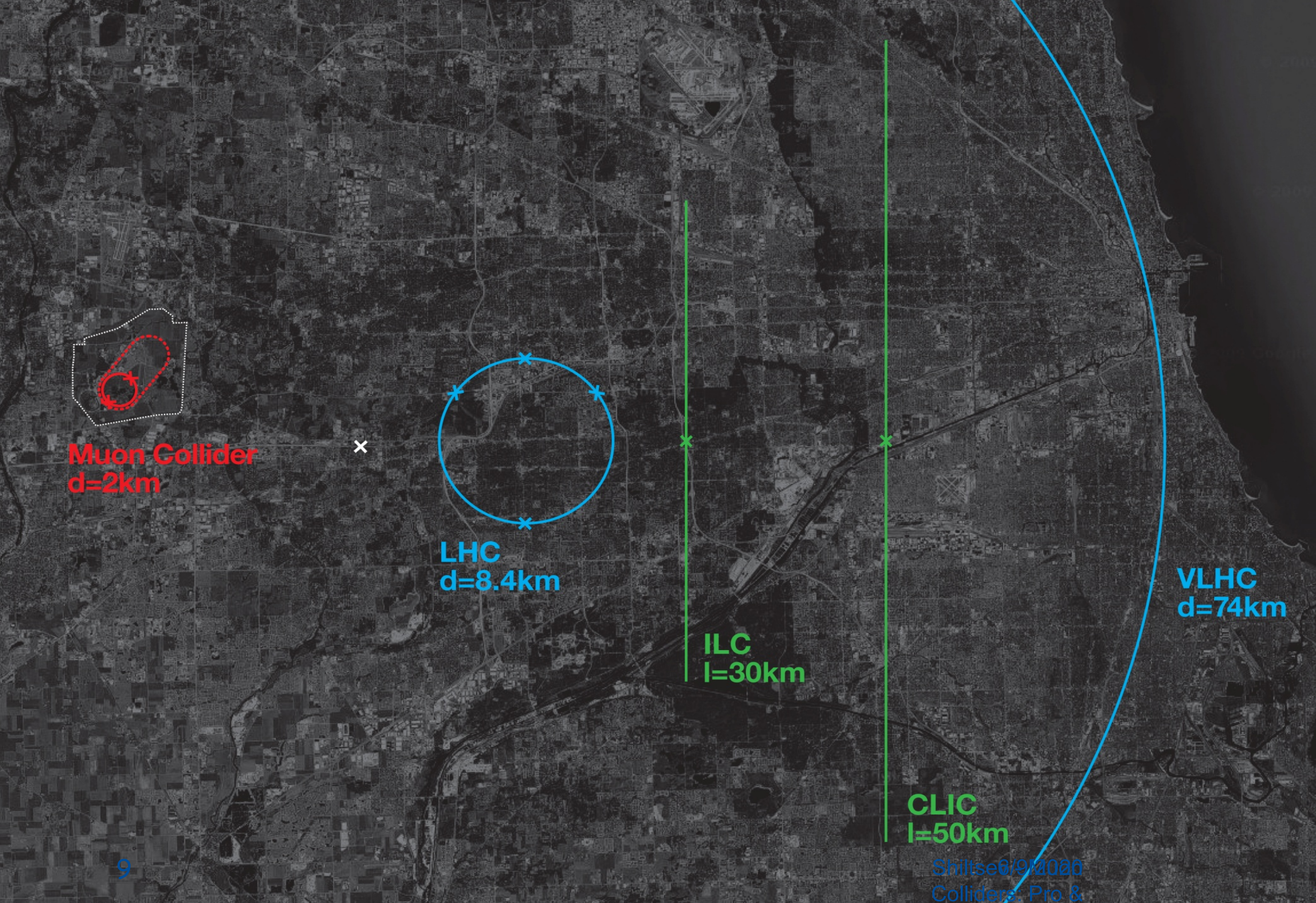


1.5-4 TeV Muon Collider (ca.2007)



Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.



Why the cost is so low ?

A. (Most important) much less RF

B. (Smaller) size matters

C. (Lower) Power consuption

! WARNING !

αβγ - Cost Estimate Model:

$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

a) **±33% estimate, for a "green field" accelerators**

b) **"US-Accounting" = TPC !** (~ 2-2.5 × *European Accounting*)

c) **Coefficients** (units: 10 km for *L*, 1 TeV for *E*, 100 MW for *P*)

- **$\alpha \approx$ 2B$/sqrt(*L*/10 km)**
- **$\beta \approx$ 10B$/sqrt(*E*/TeV)** for SC/NC RF **!!!**
- **$\beta \approx$ 2B$ /sqrt(*E*/TeV)** for SC magnets **!!**
- **$\beta \approx$ 1B$ /sqrt(*E*/TeV)** for NC magnets **!**
- **$\gamma \approx$ 2B$/sqrt(*P*/100 MW)**

USE AT YOUR OWN RISK!

Luminosity goal

arXiv:1901.06150

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$

Collecting 100 events might be sufficient to discover new particles with easily identifiable decay products, such as Stops and Top Partners related with Naturalness. An instantaneous luminosity of $2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$, at 10 TeV, would be sufficient to probe these particles up to the collider reach. Ten thousands events would instead be needed to aim at percent-level measurements of electroweak SM processes at high invariant mass, allowing to probe hundreds of TeV New Physics scales indirectly as previously mentioned. In this case the luminosity requirement becomes:

b

Parameter table

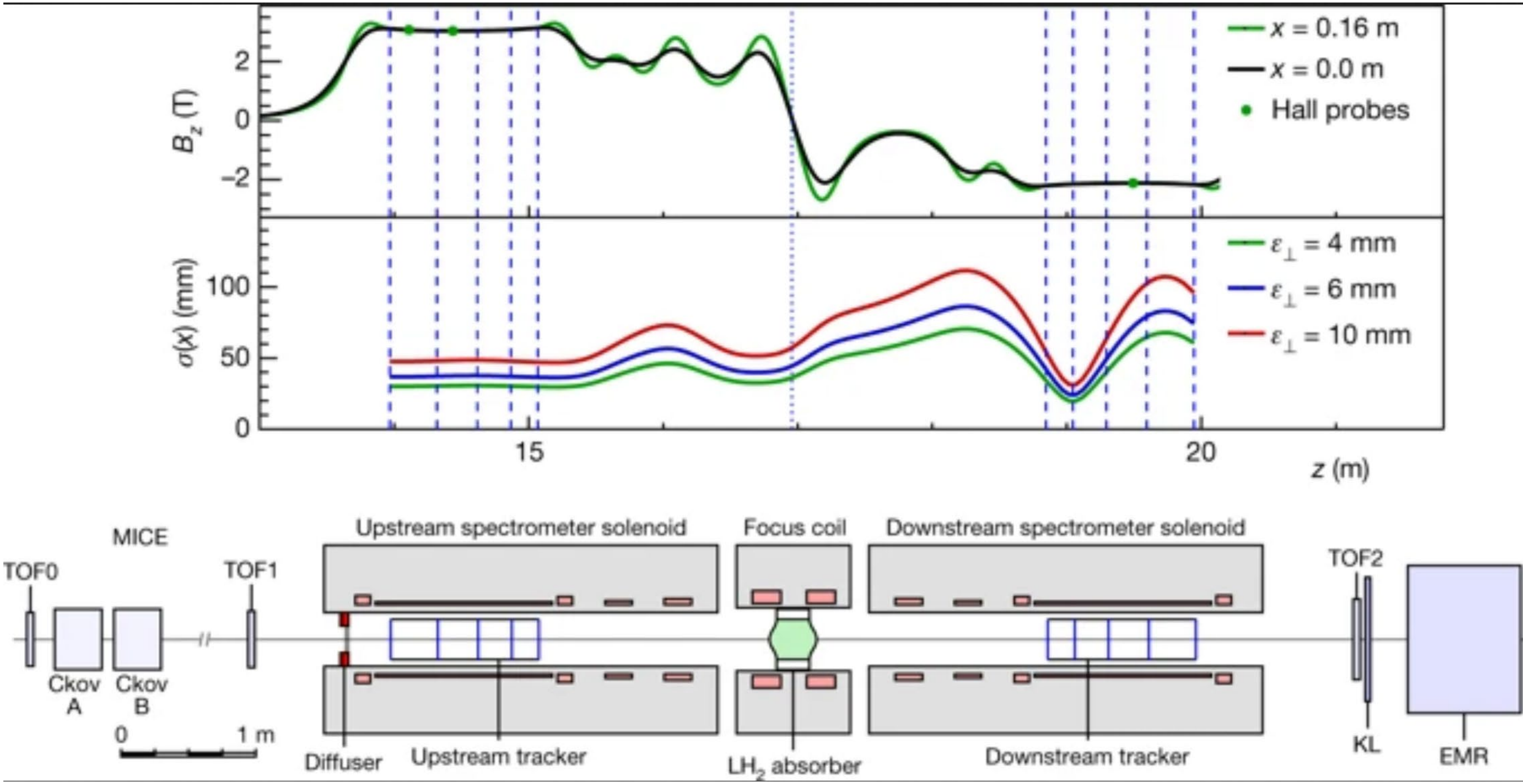
(* indicates collider rings which fit the LHC tunnel)

Center of mass energy $\sqrt{s}$ (TeV)	.126	3	14
Circumference (km)	.3	4.5 (26.7*)	14 (26.7*)
Interaction regions	1	2	2
Peak luminosity (10^{34} cm^{-2} s^{-1})	0.008	4.4	40
Int. lum. per exp. (ab^{-1}/year)	0.001	0.5	3
Time between coll. (μs)	1	0.025	90
Cycle rep. rate (Hz)	1	6(35*)	4(7*)
Energy spread (rms, %)	0.004	0.1	0.1
Bunch length (rms, mm)	63	5	1
IP beam size (μm)	75	3.0	0.6
β^*, amplitude function at IP (mm)	17	5	1
Avg. magnetic field (T)	10(?)	8(5.5*)	10.5(5.5*)
Max. magnetic field (T)	10(?)	12	16
Proton driver beam power (MW)	4	4	1
Total facility AC power (MW)	200	230	290

Subsystems

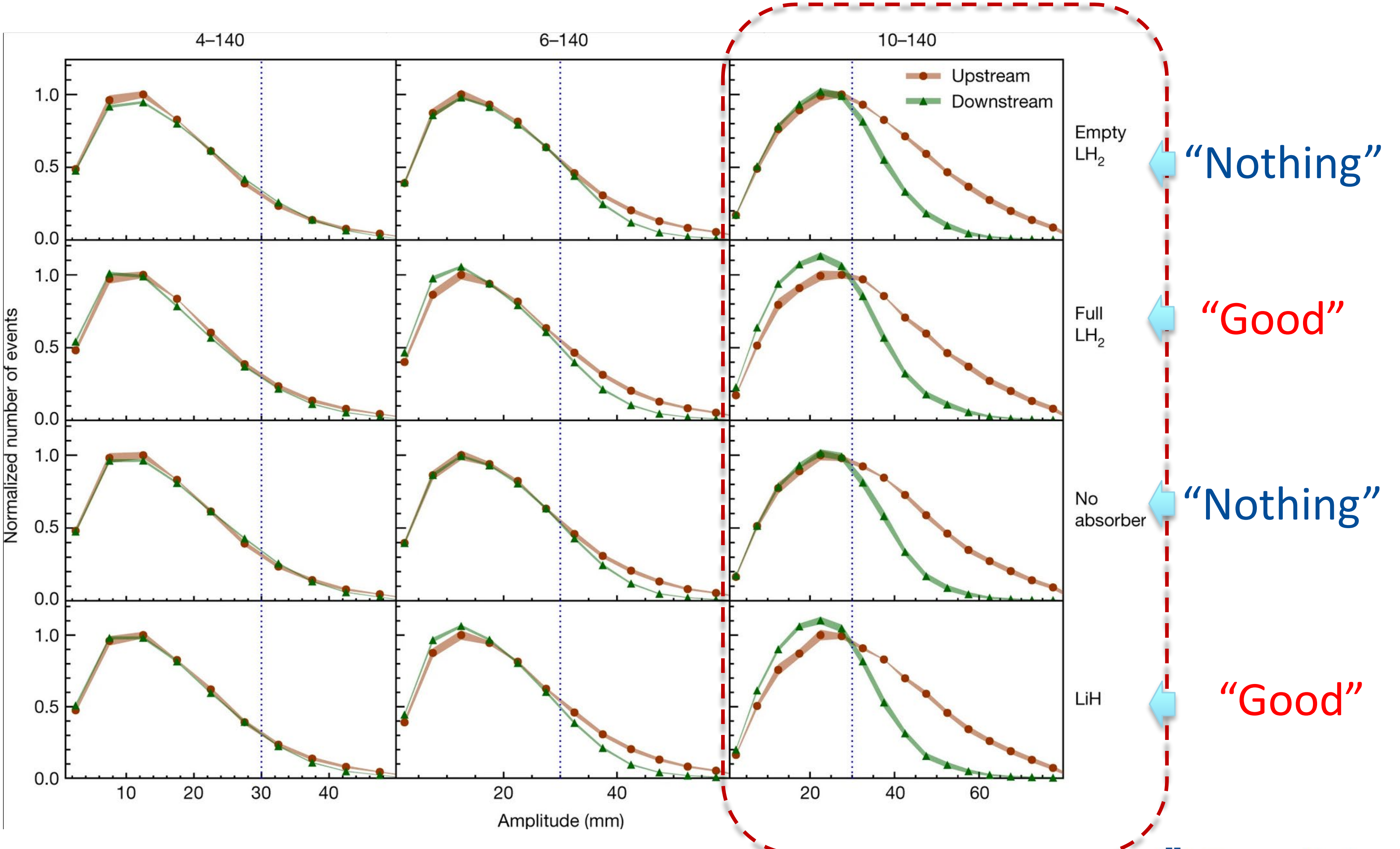
- (i) a high power proton driver (SRF 4 GeV 2-4 MW H- linac);
- (ii) pre-target accumulation and compressor rings, in which high-intensity 1-3 ns long proton bunches are formed;
- (iii) a liquid mercury target for converting the proton beam into a tertiary muon beam with energy of about 200 MeV;
- (iv) a multi-stage ionization cooling section that reduces the transverse and longitudinal emittances and, thereby, creates a low emittance beam;
- (v) a multistage acceleration (initial and main) system --- the latter employing a series recirculating rapid cycling synchrotrons (RCS) to accelerate muons in a modest number of turns up to 3-7 TeV using high gradient superconducting RF cavities;
- (vi) about 8.5 km diameter collider ring located some 100 m underground, where counter-propagating muon beams are stored and collide over the roughly 1000--2000 turns corresponding to the muon lifetime.

MICE(1)



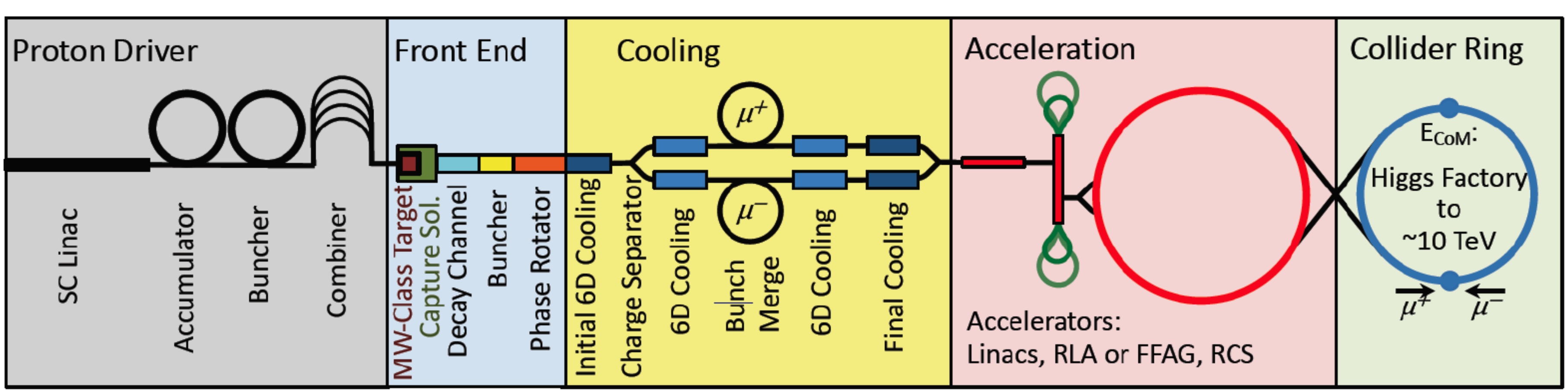
x = 0.16 m
x = 0.0 m
Hall probes
B_z (T)
2
0
−2
$\varepsilon_\perp$ = 4 mm
$\varepsilon_\perp$ = 6 mm
$\varepsilon_\perp$ = 10 mm
σ(x) (mm)
100
50
0
15
20
z (m)
MICE
TOF0
Ckov A
Ckov B
0
1 m
TOF1
Upstream spectrometer solenoid
Focus coil
Downstream spectrometer solenoid
TOF2
Diffuser
Upstream tracker
LH$_2$ absorber
Downstream tracker
KL
EMR

MICE(2)

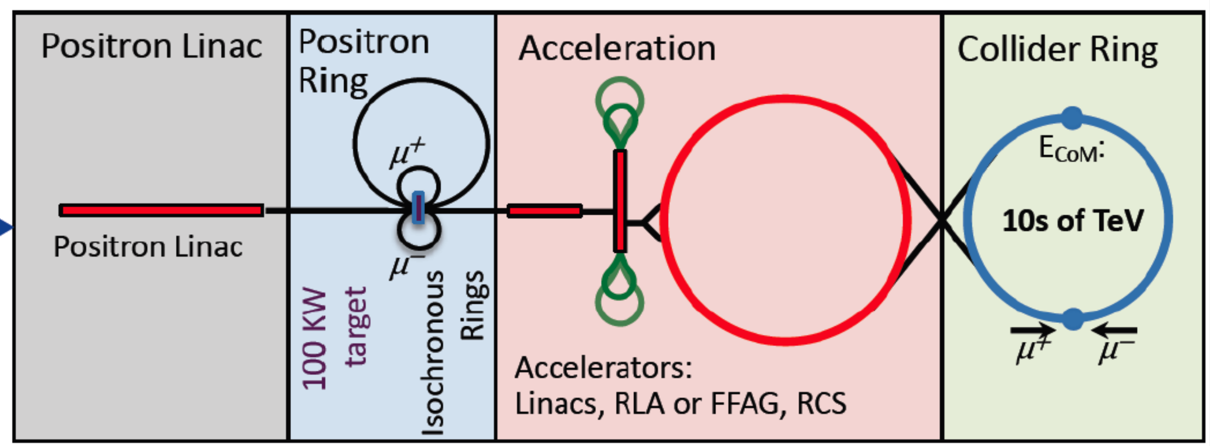


Fermilab

Alternative Concepts: μ's from protons vs μ's from e+

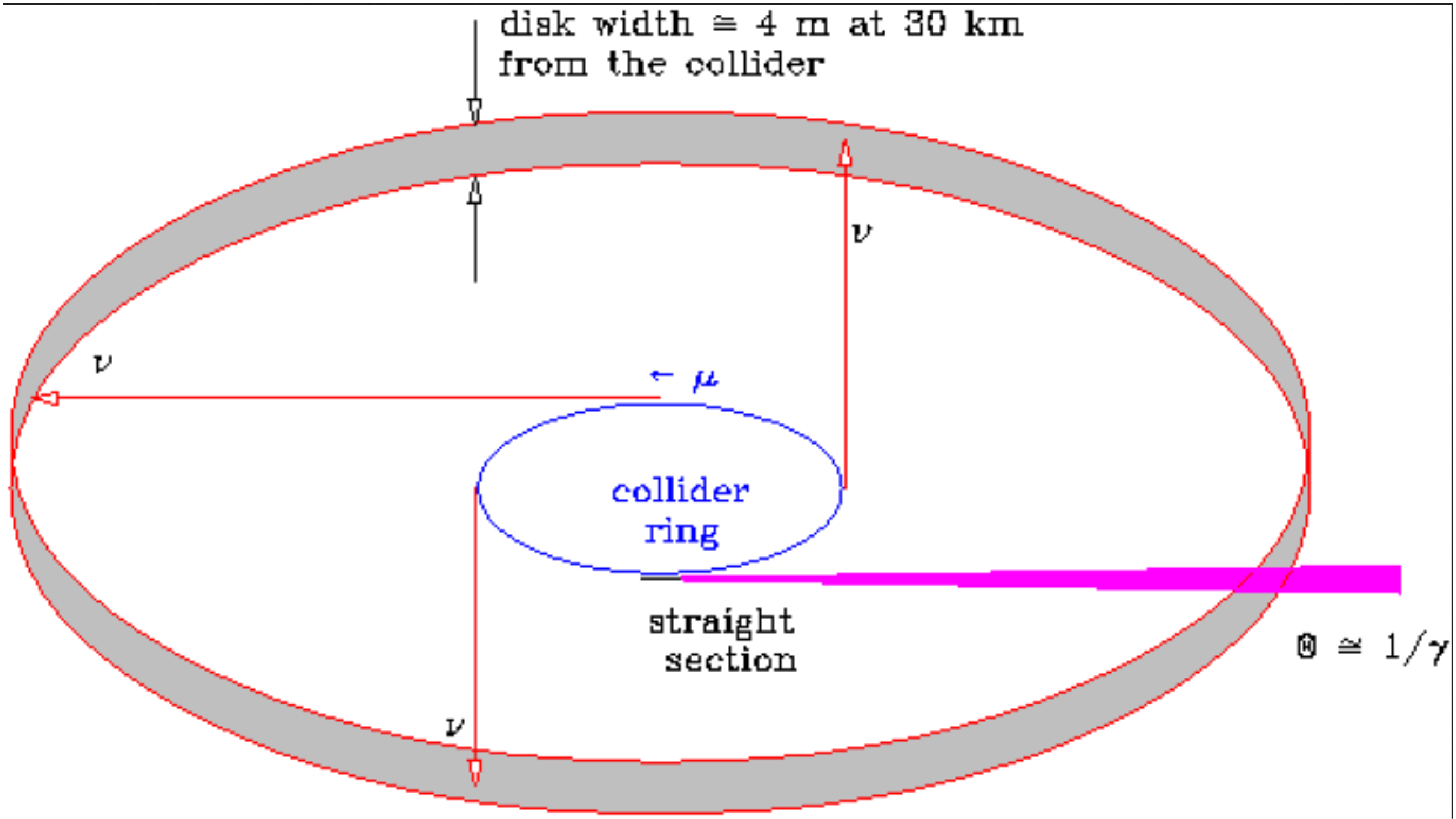


Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Fermilab

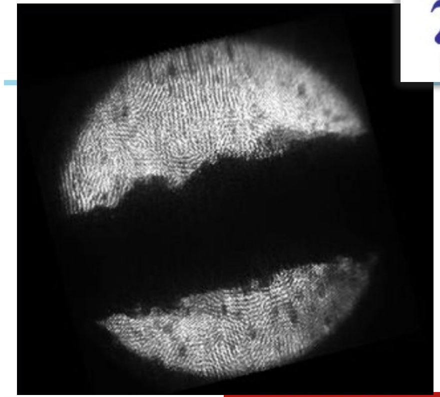
Neutrino Radiation

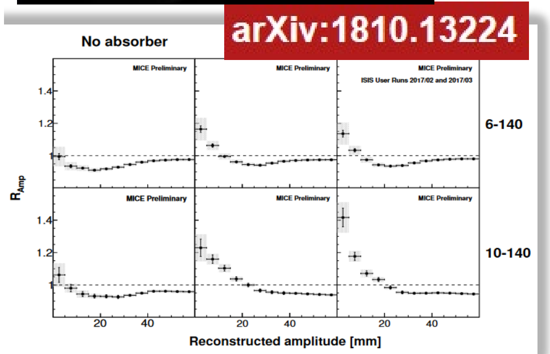


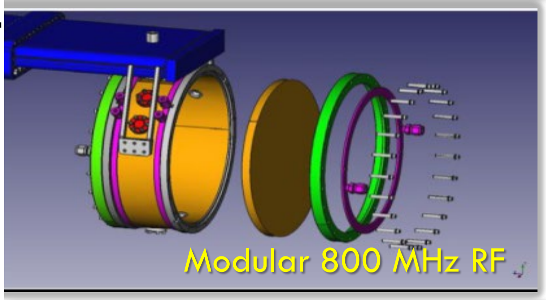
1 mSv/yr mitigation ideas: a) depth; b) few mm vertical collider orbit Variation; c) less muons → muon production via positrons

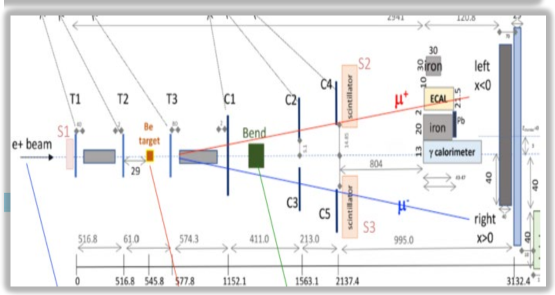
Other notable progress

- Liquid mercury targets:
  - MERIT beam test @ CERN
  - Equivalent to ~ 8 MW avg beam power
- NC RF 50 MV/m in 3 T field
  - Developed and tested at Fermilab
- Rapid cycling HTS magnets
  - Record 12 T/s – built and tested at FNAL
- First RF acceleration of muons
  - J-PARC MUSE RFQ 90 KeV
- US MAP Collaboration → Int'l
- Low emittance (no cool) concept
  - 45 GeV $e^+ + e^- \rightarrow \mu^+\mu^-$: CERN fixed target









Path forward

- Become *post-LHC* (TDR by 2040) = CERN Test Facility by 2025
- Key R&D to secure low cost and power and high Lumi:
    1. high field, robust and cost-effective 12-16 T superconducting magnets for the muon production, cooling, acceleration and collision, with power- efficient cryogenics subsystems;
    2. high-gradient and robust normal-conducting RF to minimize muon losses during cooling and power-efficient superconducting RF for fast muon acceleration;
    3. fast ramping normal-conducting, superferric or superconducting magnets that can be used in a RCS to accelerate the muons;
    4. advanced detector concepts and technologies to deal with the background induced by the muon beams, as well as fast, robust, high-resolution beam diagnostics instrumentation.
- **Develop STRONG physics case and detector concepts !!!**

Fermilab

Back up slides

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Design Studies														
	Pre-Conceptual Design				Conceptual Design Report				Technical Design Report					
		Hardware Prototypes												
				Test Facility Deployment									Proposal	
							Test Facility Measurements							
	3TeV		14 TeV											

Finding *Common Denominators* * – Three Factors

** to be further discussed in the Symposium's accelerator sessions*

- ***F1*** **"Technology Readiness" :**

Green	-	TDR
Yellow	-	CDR
Red	-	R&D

- ***F2*** **"Energy Efficiency"**

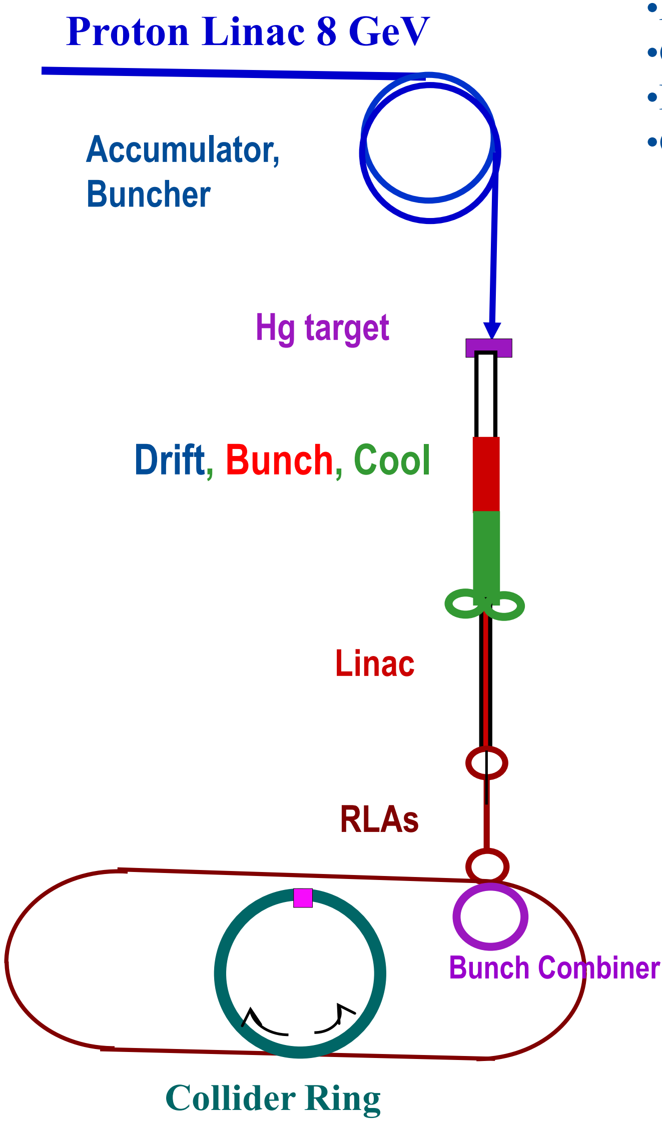
Green	:	100-200 MW
Yellow	:	200-400 MW
Red	:	> 400 MW

- ***F3*** **"Cost" :**

Green	:	< LHC
Yellow	:	1-2 x LHC
Red	:	> 2x LHC

Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear *250 GeV*			
ee Rings *240GeV/tt*			
μμ Collider *125 GeV*			*
Multi-TeV Colliders			
ee Linear *1-3TeV*			
pp Rings *HE-LHC*			
FCC-hh/SppC			
μμ Coll. *3-14 TeV*			*

"~NoCooling" Muon Collider



- Reduce transverse emittance to 0.001m
- Could then use 1300MHz ?
- IR quads less than r =10cm
- Combine 12 bunches to 1

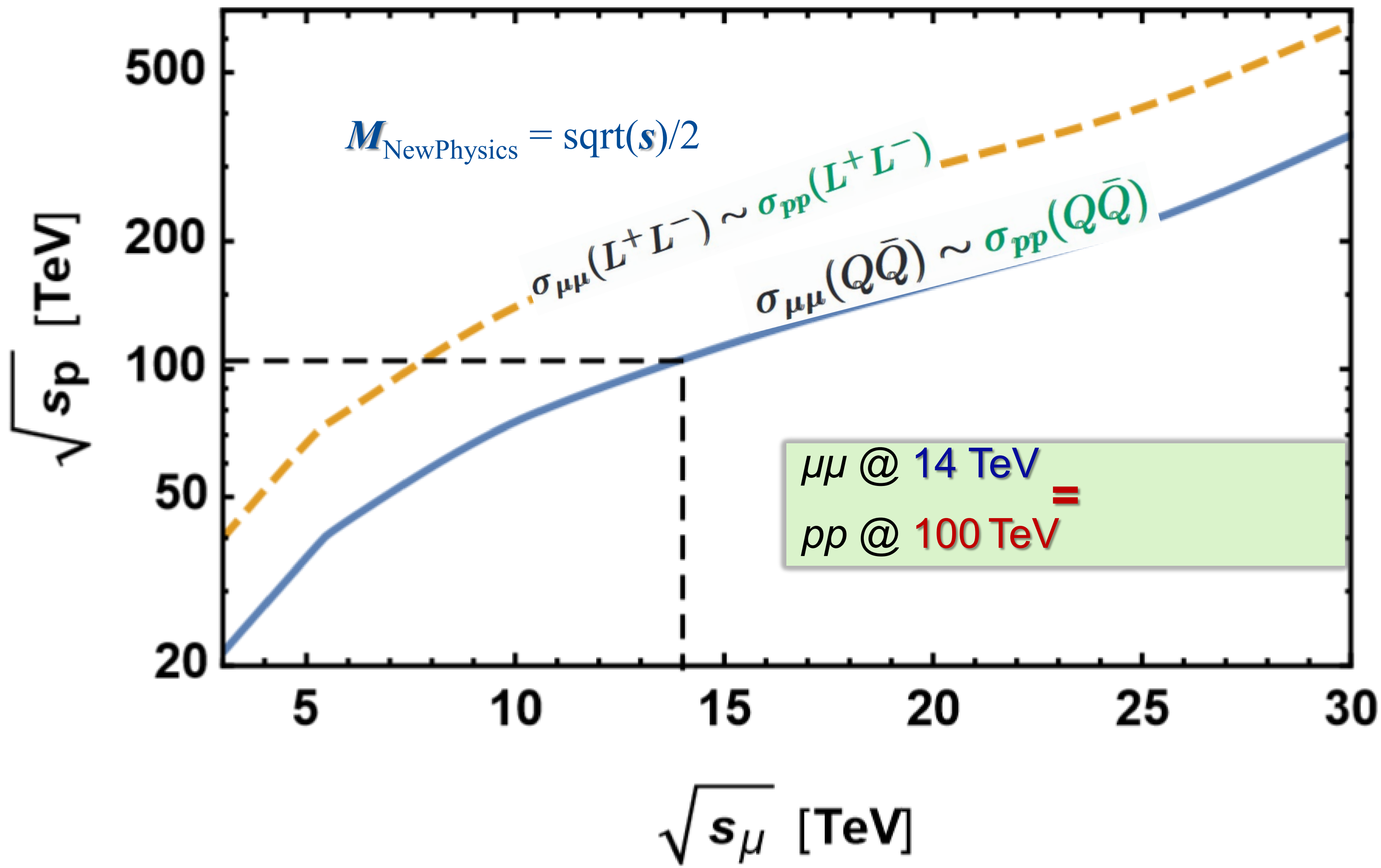
D.Neuffer (2011)

Parameter	Symbol	Value
Proton Beam Power	P_p	2.4 MW
Bunch frequency	F_p	60 Hz
Protons per bunch	N_p	3×10^{13}
Proton beam energy	E_p	8 GeV
Number of muon bunches	n_B	1
$\mu^{+/-}$/ bunch	**N_μ**	**10^{12}**
Transverse emittance	**$\varepsilon_{t,N}$**	**0.001m**
Collision β^*	β^*	0.04m
Beam size at collision	$\sigma_{x,y}$	**0.0063cm**
Beam size (arcs)	$\sigma_{x,y}$	0.3cm
Beam size IR quad	σ_{max}	3cm
Collision Beam Energy	$E_{\mu+},E_{\mu\_}$	1 TeV (2TeV total)
Luminosity	L_0	1.2×10^{32}

$\delta\nu_{BB}$ =0.0014

Energy reach

arXiv:1901.06150



Discussion : "Granada Message"

1. despite ups and downs over the past 20 years, the mumu concept is not going away and the reasons are [...]
   - *Muons are particles of the future – e+e- LCs don't work above 3-6 TeV, pp rings above 100-300TeV*
   - *Generally feasible and VERY cost saving (physic reach 14 Tev mumu = FCChh)*
   - *Great results from MERIT, MAP and MICE*
2. μμ offers a "moderately conservative-moderately innovative" way to cost affordable energy frontier colliders
   - *We do not call for basic technology breakthroughs – MC can be built with magnets and RF (not even record breaking ones)*
3. major advantages/promises are [...]
   - *C.M.Energy reach and resolution (<0.1%)*
   - *Cost ("LHC ±30%" even for 14 TeV)*
4. key challenges are [...]
   - *Muon production and cooling, cost efficient acceleration, detector background and neutrino radiation*
   - *They are not showstoppers – (just) implications on performance , little on energy*
5. to claim feasibility (CDR in 5 yrs, TDR in 10-15 yrs from now) we need [....R&D program goals ....]
   - *Int'l collaboration with CERN as host, move toward a test facility in ~3-5 years to demo PD- and/or LEMMA- concepts, detector studies and tests*

Future pp Colliders at CERN

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

- HE-LHC and FCC-hh will be part of the European strategy 2018-2020 exercise
- Selection of “optimal” pp collisions energy is challenging

Future Energy Frontier Colliders

- All proposals are focused on :
  - *(Affordable) Cost and (High) Luminosity*
- Usually :
  - *Scale of civil construction grows with Energy*
  - *Cost of accelerator components grows with Energy*
  - *Requirement site power grows with Energy*
- So, the total cost grows with ENERGY
  - Thankfully, not linearly , more like $cost \sim \beta E^{\kappa}$, $\kappa \approx ½ \ldots 2/3$
    - *Take ILC as an example: 0.25 → 0.5 → 1 TeV* **0.69 : 1 : 1.67**
  - Still, huge challenge for energies E some x10 of LHC
  - Choice of technology (β) and *prior investments* are critical

Fermilab

Comparisons

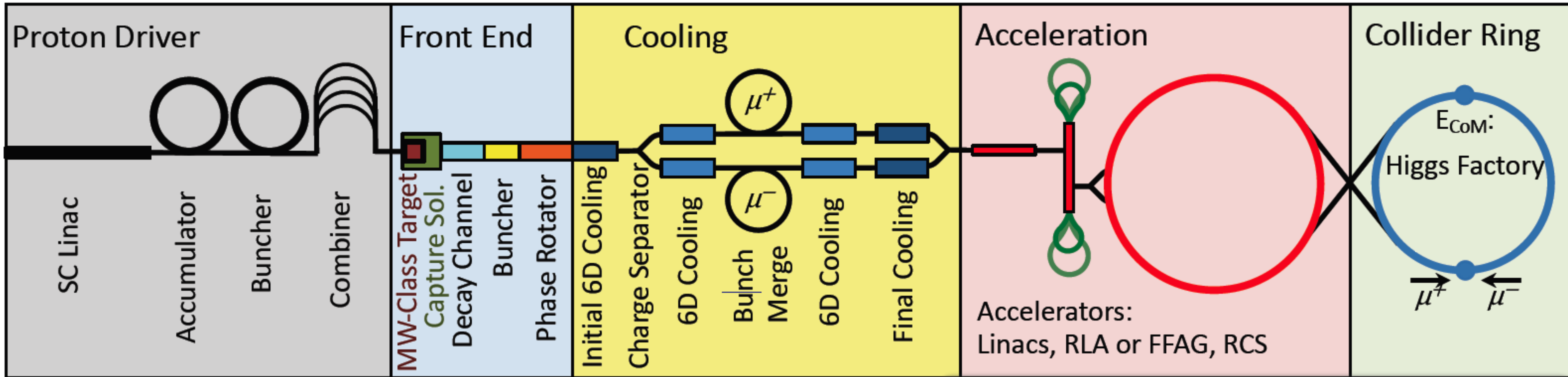
Project	Type	Energy [TeV]	Int. Lumi. [a-1]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Input #41 Input #120 Input #141

$\mu^+\mu^-$ Higgs Factory

V. Barger, et al, *Physics Reports* 286, 1-51 (1997)

JINST Special Issue (*MUON*)



Key facts:

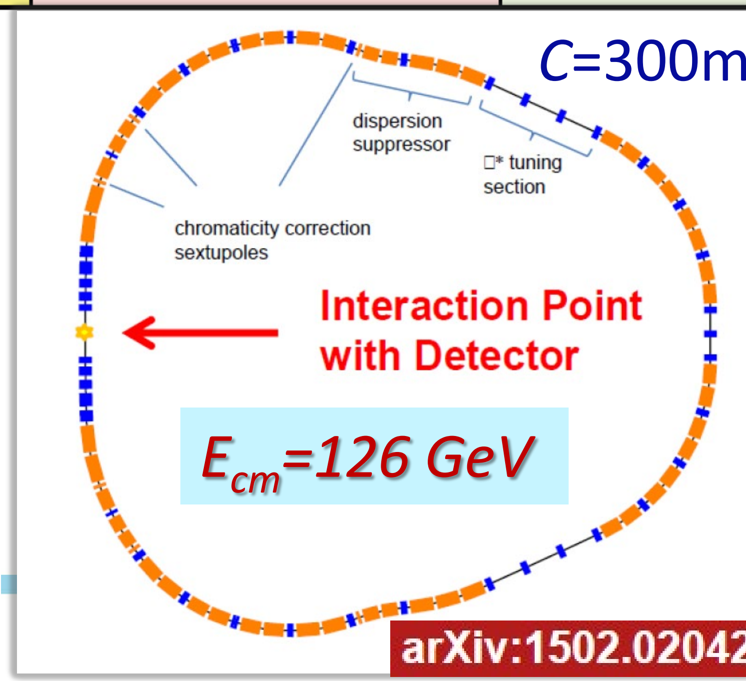
1/100 luminosity requirements (large cross-section in *s*-channel)

Half the energy 2 x 63 GeV $\mu^+\mu^- \rightarrow H_0$

Small footprint (<10 km) and low cost

Small(est) energy spread ~3 MeV

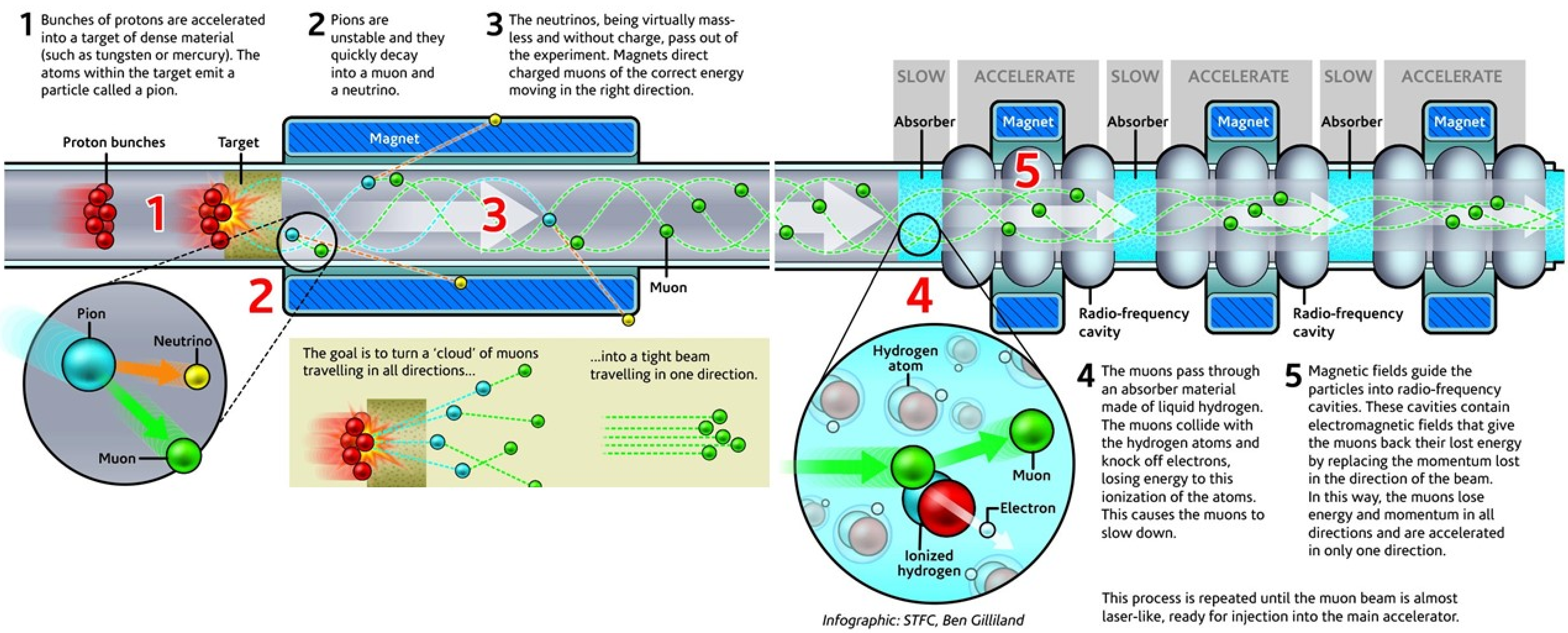
Total site power ~200MW (tbd)



arXiv:1502.02042

Facility "Standard Table"

Muon Collider	μ+μ-	
Beam Energy	GeV	
Peak Luminosity (10^34)	cm-2 s-1	
Int. Luminosity	ab-1/yr	
Beam dE/E at IP		
Transv. beam sizes at IP x/y	um	
Rms bunch length / beta*	cm	
Crossing angle	urad	
Rep./Rev. frequency	Hz	
Bunch spacing	ns	
# of IPs		
# of bunches		
Length/Circumference	km	
Facility site power	MW	
Cost range		
Timescale till operations		


1 Bunches of protons are accelerated into a target of dense material (such as tungsten or mercury). The atoms within the target emit a particle called a pion.
2 Pions are unstable and they quickly decay into a muon and a neutrino.
3 The neutrinos, being virtually mass-less and without charge, pass out of the experiment. Magnets direct charged muons of the correct energy moving in the right direction.
SLOW
ACCELERATE
SLOW
ACCELERATE
SLOW
ACCELERATE
Proton bunches
Target
Magnet
Absorber
Magnet
Absorber
Magnet
Absorber
Magnet
1
3
5
2
4
Muon
Pion
Neutrino
Muon
Radio-frequency cavity
Radio-frequency cavity
The goal is to turn a 'cloud' of muons travelling in all directions...
...into a tight beam travelling in one direction.
Hydrogen atom
Muon
Electron
Ionized hydrogen
4 The muons pass through an absorber material made of liquid hydrogen. The muons collide with the hydrogen atoms and knock off electrons, losing energy to this ionization of the atoms. This causes the muons to slow down.
5 Magnetic fields guide the particles into radio-frequency cavities. These cavities contain electromagnetic fields that give the muons back their lost energy by replacing the momentum lost in the direction of the beam. In this way, the muons lose energy and momentum in all directions and are accelerated in only one direction.
This process is repeated until the muon beam is almost laser-like, ready for injection into the main accelerator.
Infographic: STFC, Ben Gilliland