VULCANO Workshop 2018

Frontier Objects in Astrophysics and Particle Physics

20th- 26th, May 2018
Vulcano Island, Sicily, Italy

Organized by Istituto Nazionale di Fisica Nucleare (INFN) and Istituto Nazionale di Astrofisica (INAF)

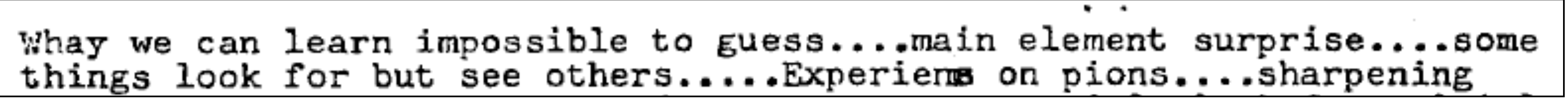
Muon Collider

a personal view

Nadia Pastrone

INFN
TORINO

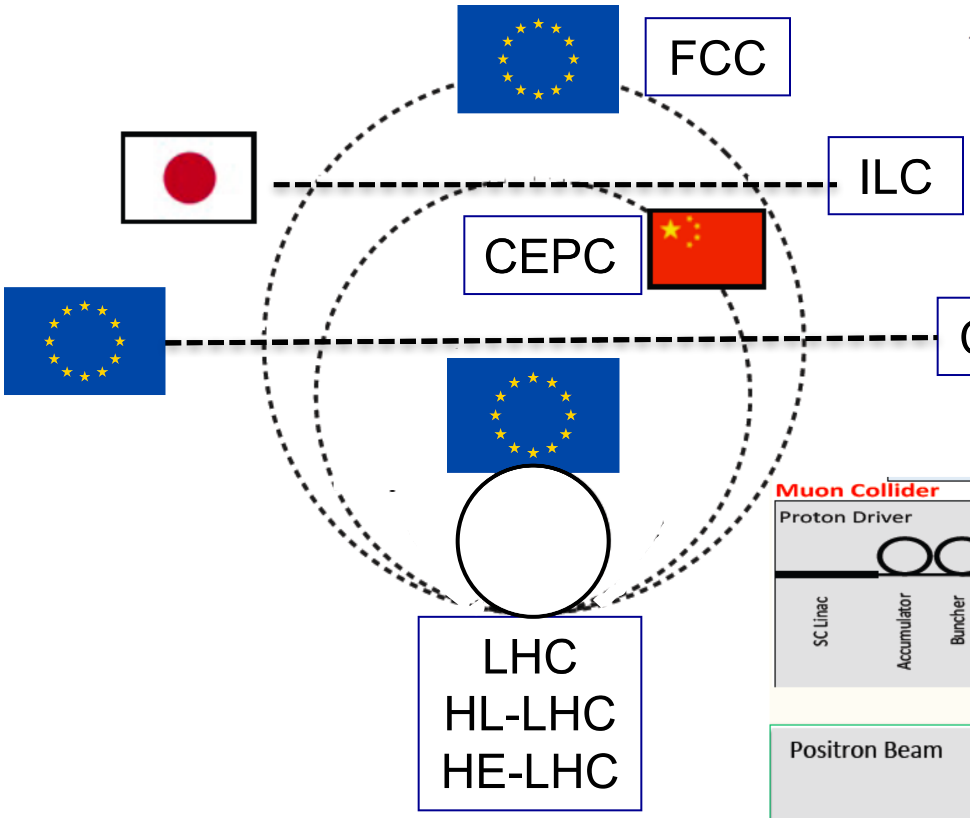
Vulcano – May 25, 2018

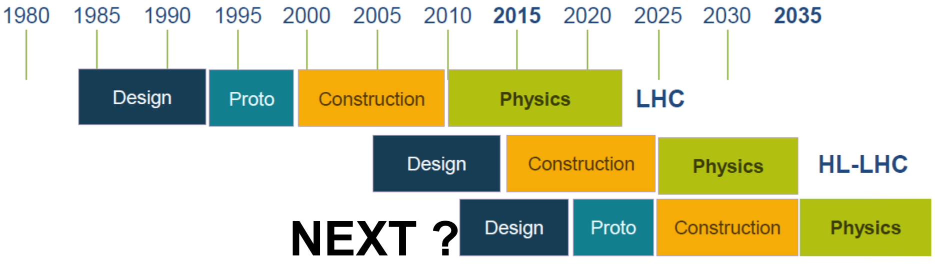


Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiems on pions....sharpening

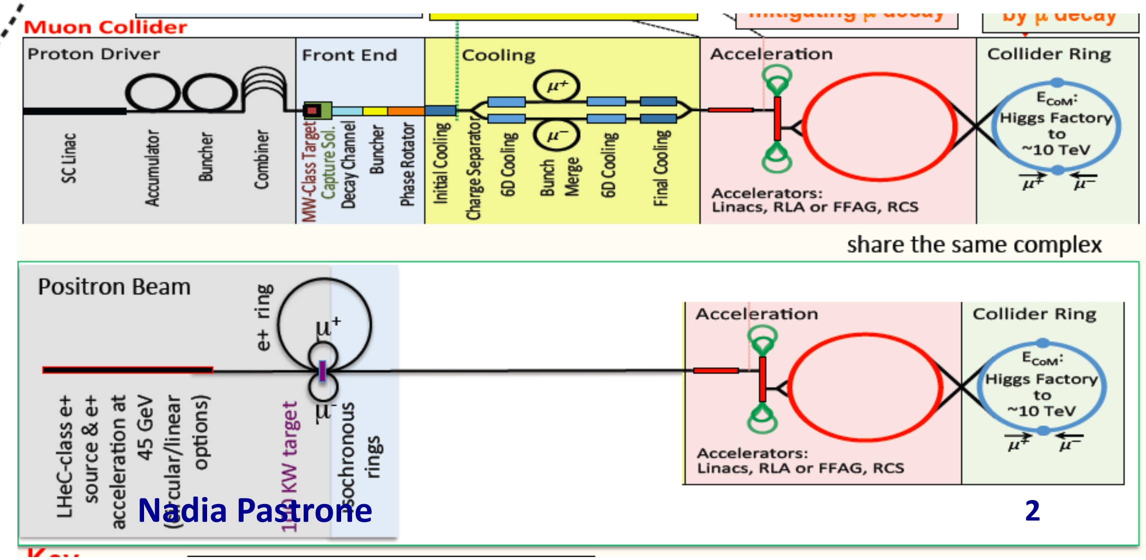
Enrico Fermi - American Physical Society, NY, **Jan. 29th 1954**
"What can we learn with High Energy Accelerators ? "

What's Next after LHC?





MUON COLLIDER



Physics scenario for a Future Collider

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

Andrea Wulzer

Why Muons?

Mark Palmer

Physics Frontiers

- **Intense and cold muon beams a unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

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

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

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs → $\sim \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4 \times 10^4$
  - Reduced synchrotron radiation a multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

Collider Synergies

- High intensity beams required for a **long-baseline Neutrino Factory** are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

A Muon Collider?

Andrea Wulzer

Great advantage in colliding leptons rather than protons

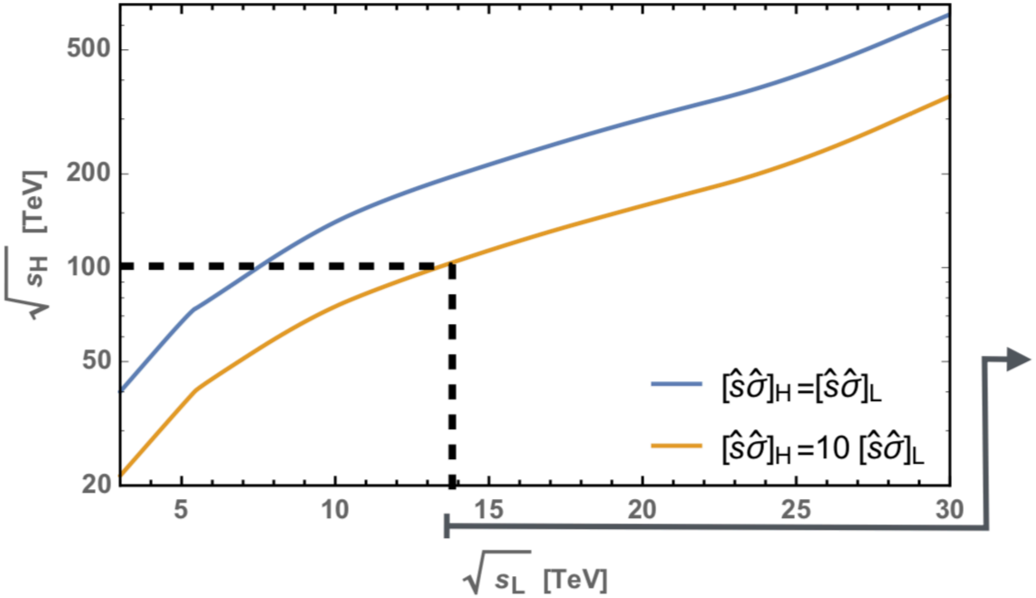
Lepton coll. operating at energy $\sqrt{s_L}$. Cross section for reaction at $E \sim \sqrt{s_L}$ (e.g., production of BSM at M=E)

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

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

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

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



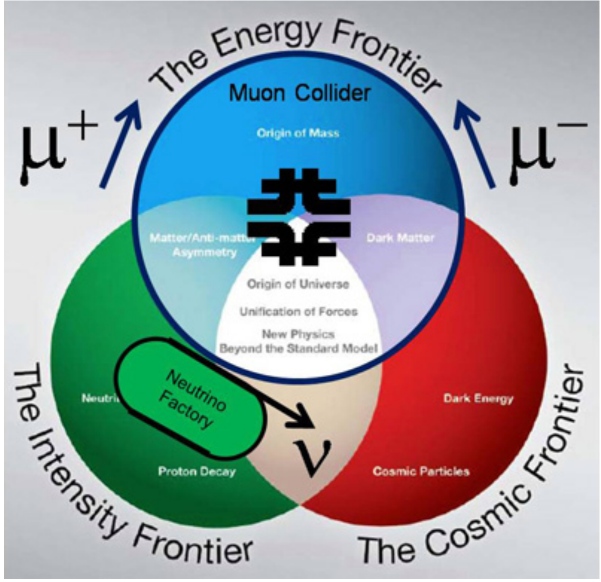
QCD-coloured BSM can easily have much larger partonic XS.

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

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

Physics reach

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier



U.S. Muon Accelerator Program (MAP)

- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011
- Ramp down recommended by P5 in 2014

http://map.fnal.gov/

AIM: to assess feasibility of technologies to develop muon accelerators for the Intensity and Energy Frontiers:

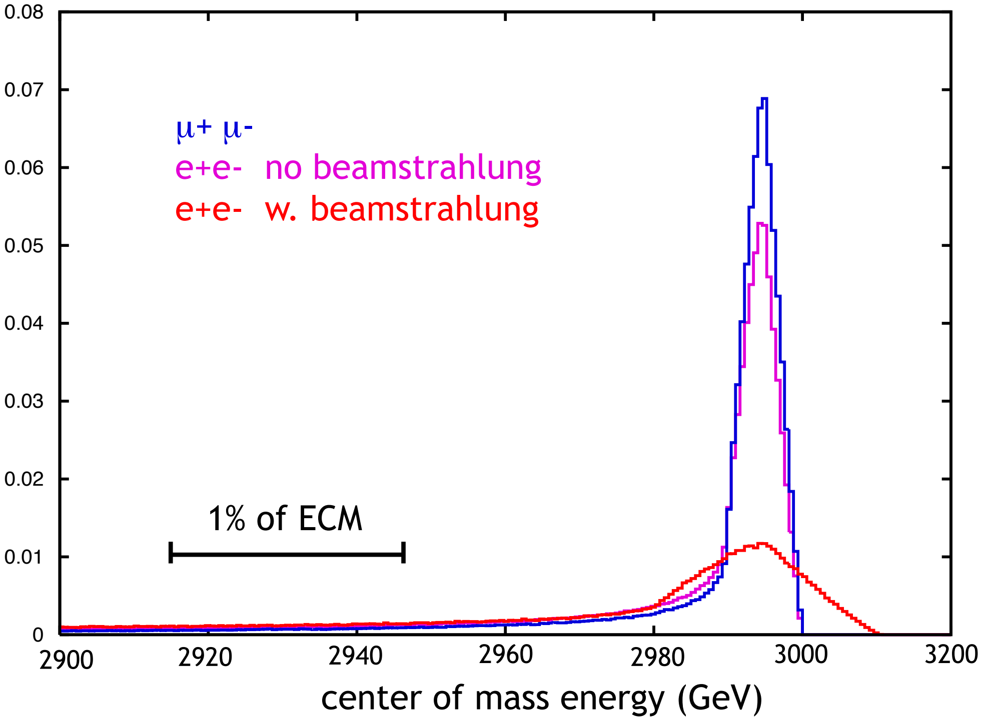
- Short-baseline neutrino facilities (nuSTORM)
- Long-baseline neutrino factory (nuMAX) with energy flexibility
- Higgs factory with good energy resolution to probe resonance structure
- TeV-scale muon collider

Challenging optimization

- 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

CRUCIAL PARAMETERS:

- luminosity
- energy
- energy spread
- wall power
- cost
- background
- radiological hazard
- technical risks



Vulcano 2018

Lepton Colliders: μ vs e @ √s=125 GeV

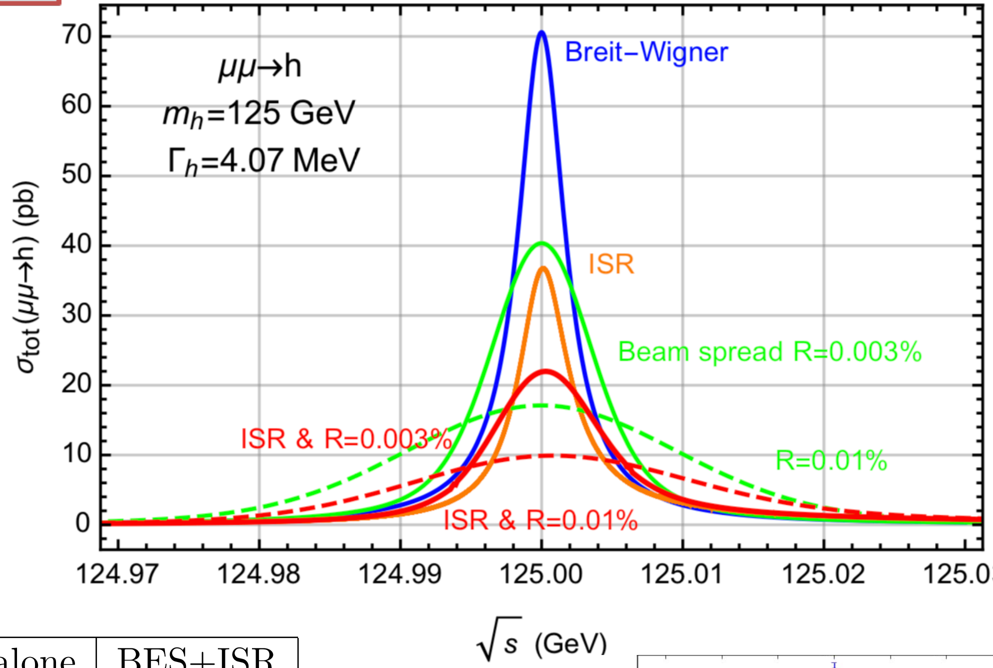
Back on the envelope calculation:

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

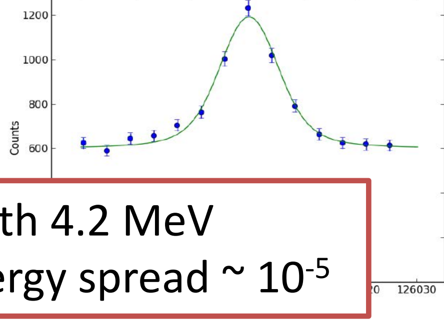
$$\boxed{\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)}$$

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

R: percentage beam energy resolution, key parameter



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



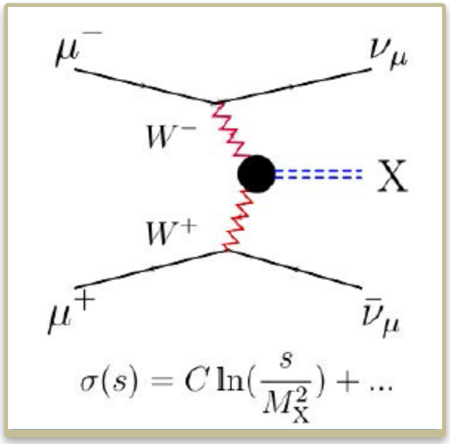
Higgs width 4.2 MeV
Beam energy spread ~ 10^{-5}

High energy Muon Collider

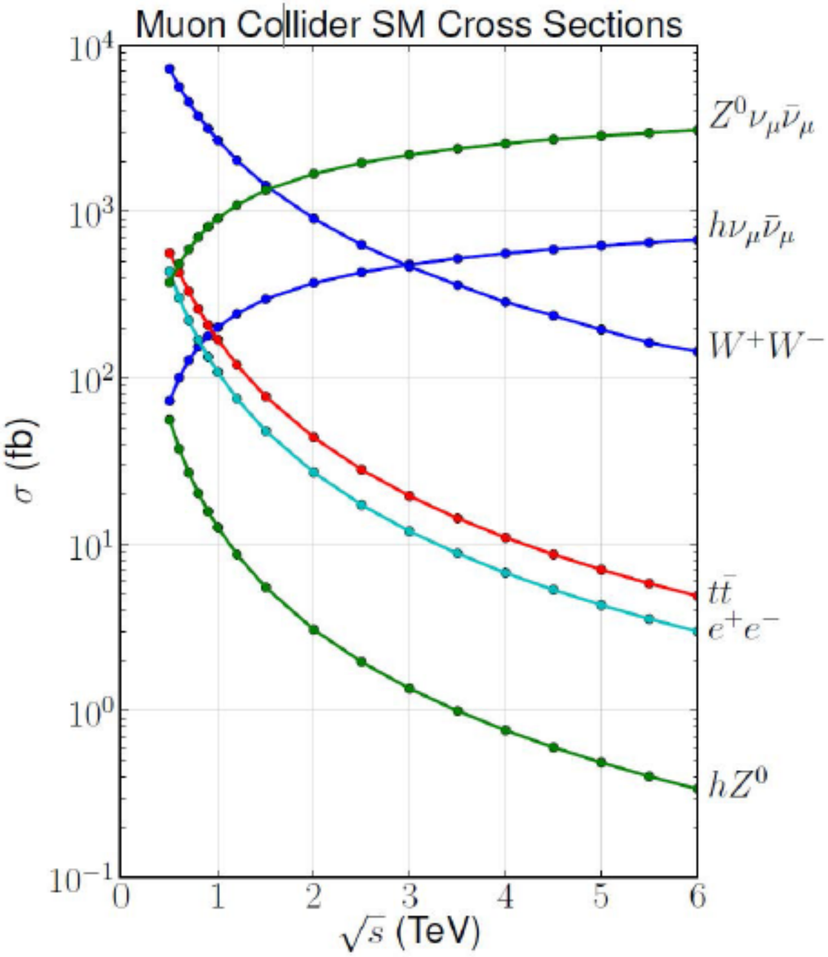
High Energy Collisions

- At √s > 1 TeV:

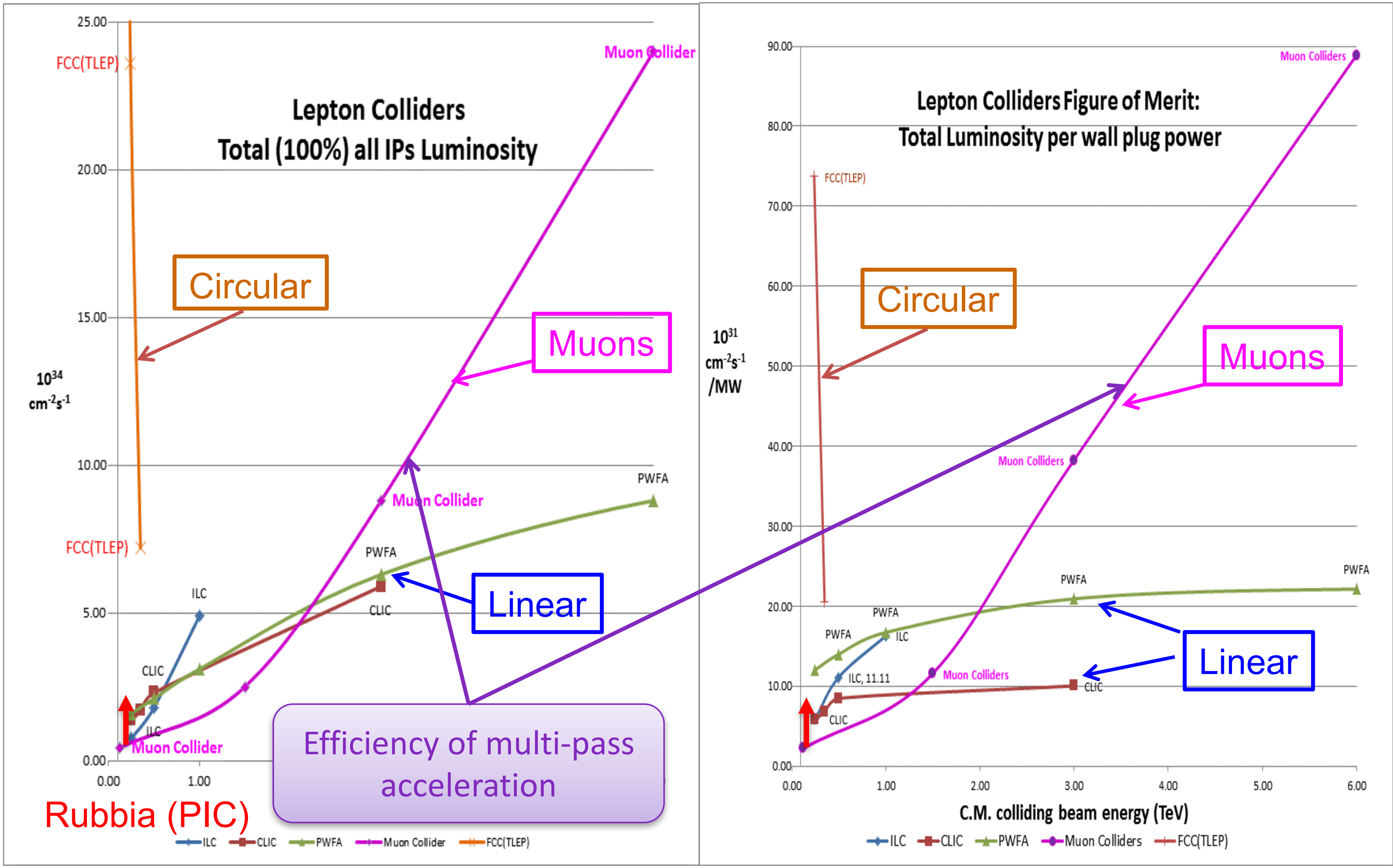
  Fusion processes dominate
  - An Electroweak Boson Collider
  - A discovery machine complementary to very high energy pp collider
- At >5TeV: Higgs self-coupling resolution <10%



$$\sigma(s) = C\ln\left(\frac{s}{M_X^2}\right) + \ldots$$



Multi TeV scale - efficiency



Circular

Muons

Linear

Efficiency of multi-pass acceleration

Rubbia (PIC)

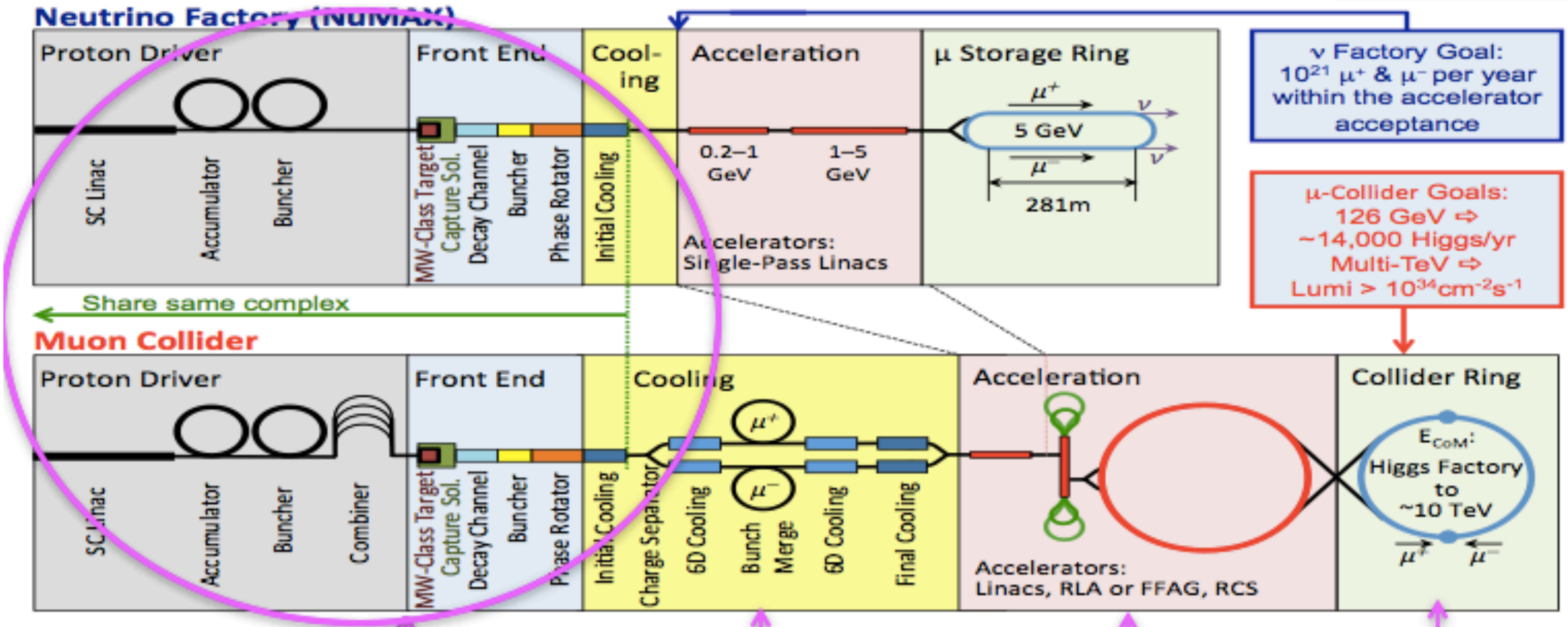
Circular

Muons

Linear

Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



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}cm^{-2}s^{-1}

Key Challenges

$\sim 10^{13}$-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

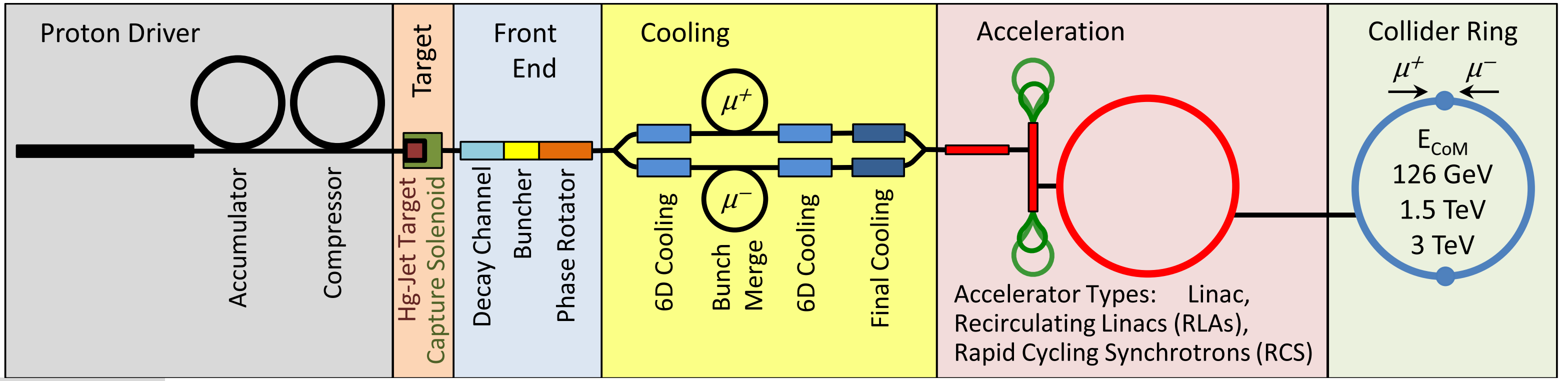
MW proton driver
MW class target
NCRF in magnetic field

Ionization cooling
High field solenoids (30T)
High Temp Superconductor

Cost eff. low RF SC
Fast pulsed magnet
(1kHz)

Detector/
machine
interface

MAP Proposal R&Ds



- Based on 6-8 GeV Linac Source
- H- stripping requirements same as those established for neutrino

- MERIT@CERN studied high power target
- π production in high-field solenoid

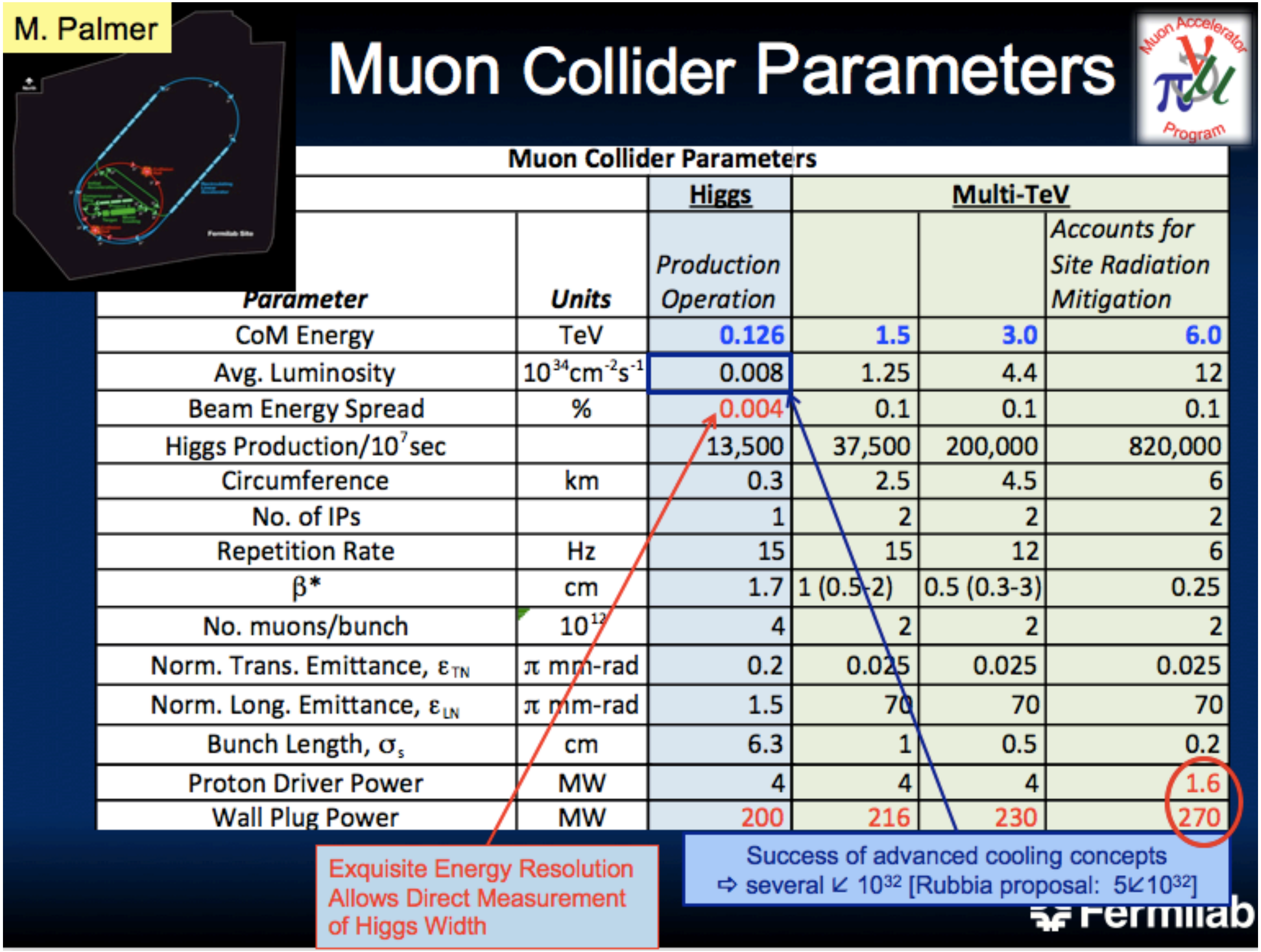
solenoid π→μ decay channel RF cavities bunch & phase rotate $\mu^{\pm}$ into bunch train

- Fast ionization 6D cooling ($\tau = 2\mu s$)
- MICE
- Rubbia demonstrator proposal

- Fast acceleration
- Use RF and SC

$\mu^{\pm}$ decay background Tungsten shielding or bending magnets to avoid issues from e

- Critical Detector Machine Interface



M. Palmer

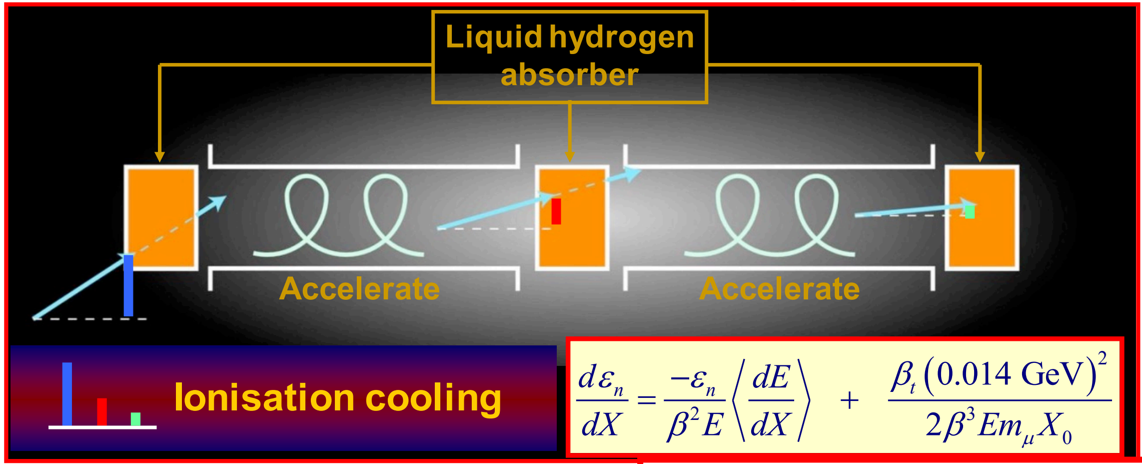
Muon Collider Parameters

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^{7}sec		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}]

Ionization cooling – MICE experiment

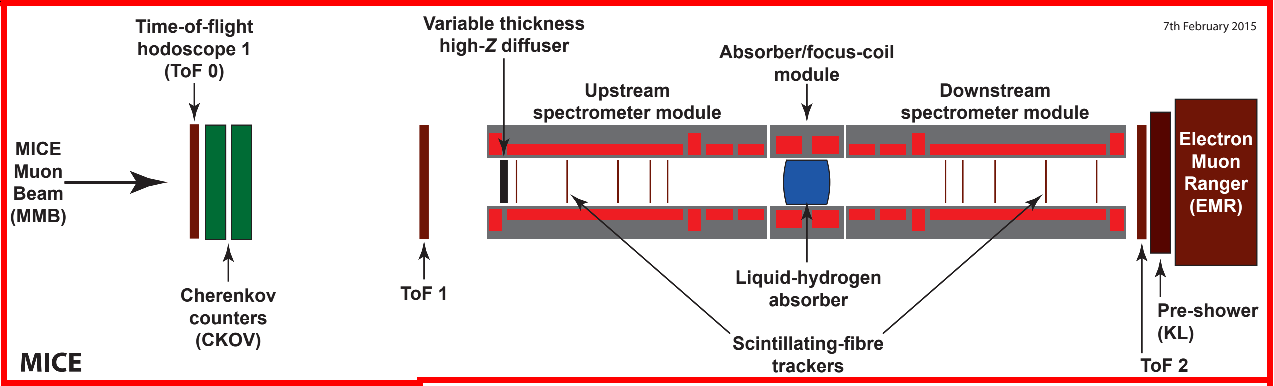


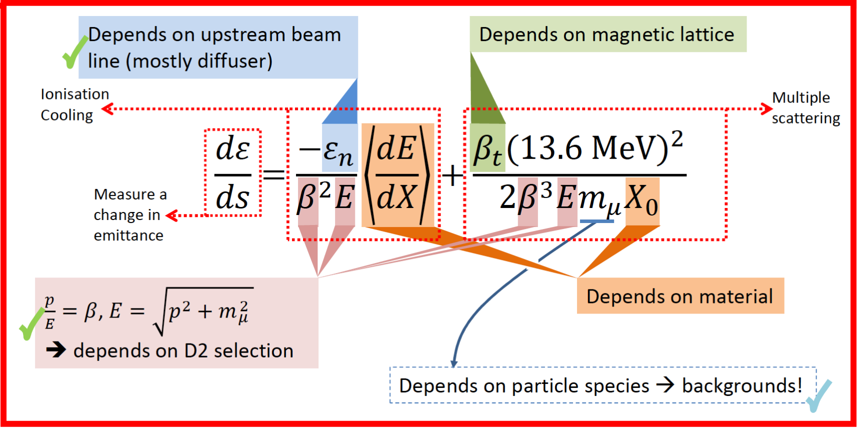
$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (0.014\ \text{GeV})^2}{2\beta^3 E m_\mu X_0}$$

	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

Realistic cooling cell

- Competition between:
  - dE/dx [cooling]
  - MCS [heating]
- Optimum:
  - Low Z, large X_0
  - Tight focus
  - H_2 gives best performance





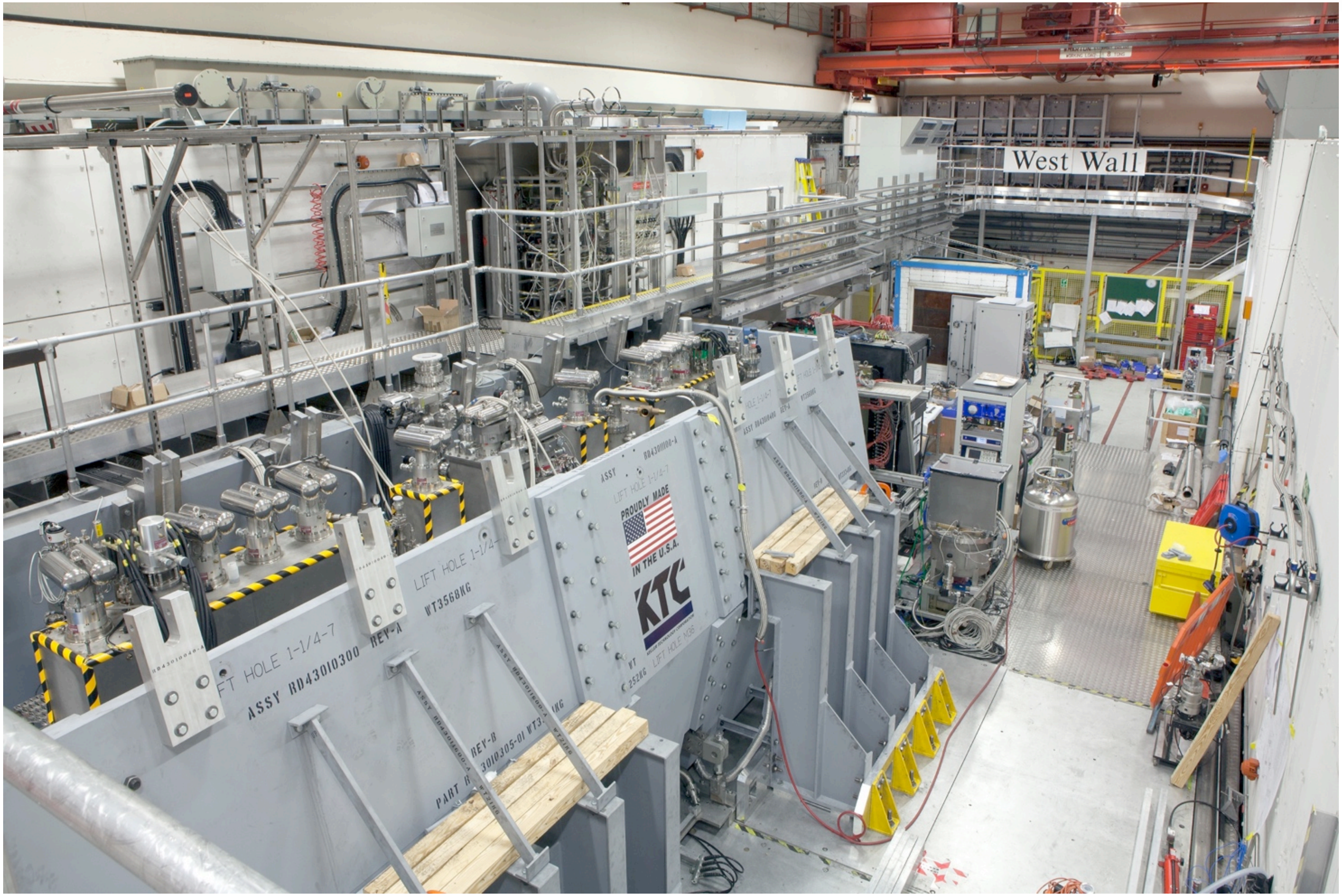
$$\frac{d\varepsilon}{ds} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (13.6\ \text{MeV})^2}{2\beta^3 E m_\mu X_0}$$

$\frac{p}{E} = \beta,\ E = \sqrt{p^2 + m_\mu^2}$

→ depends on D2 selection

http://mice.iit.edu/publications/

MICE experiment @ RAL



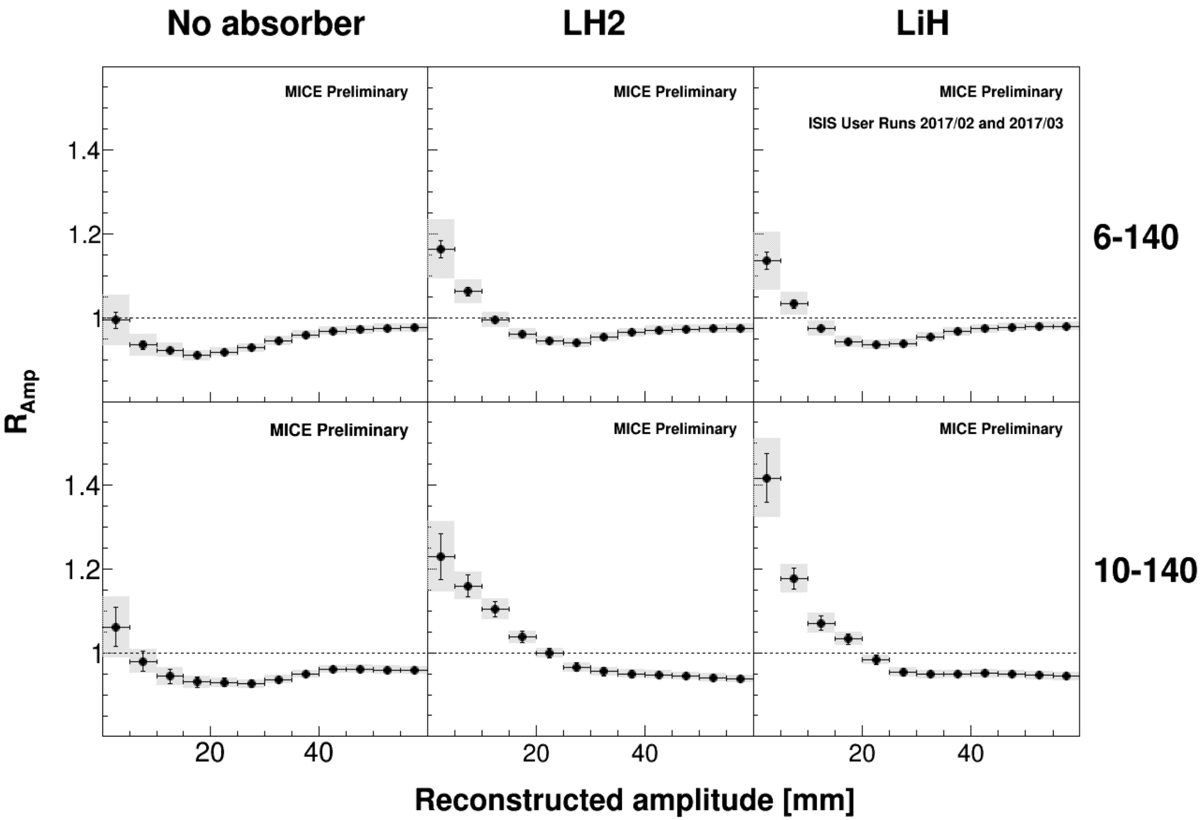
MICE: first results

IPAC2018 – FRXGBE3

Ionization cooling observed: using LiH and LH_2 absorbers

Single Particle Amplitude Result

MICE Data



- **6-140** – $P_{reference}$ of 140 MeV/*c* and ε_{input} of 6 mm
- **10-140** – $P_{reference}$ of 140 MeV/*c* and ε_{input} of 6 mm
- R_{Amp}: ratio of downstream muon count to upstream
- **$R_{Amp} > 1 \rightarrow$ cooling:**
  - ★ Migration of high amplitude muons to low amplitude
- “No absorber” does not show cooling, agrees with Liouville’s theorem

Low EMittance Muon Accelerator

Snowmass 2013 - M. Antonelli e P. Raimondi

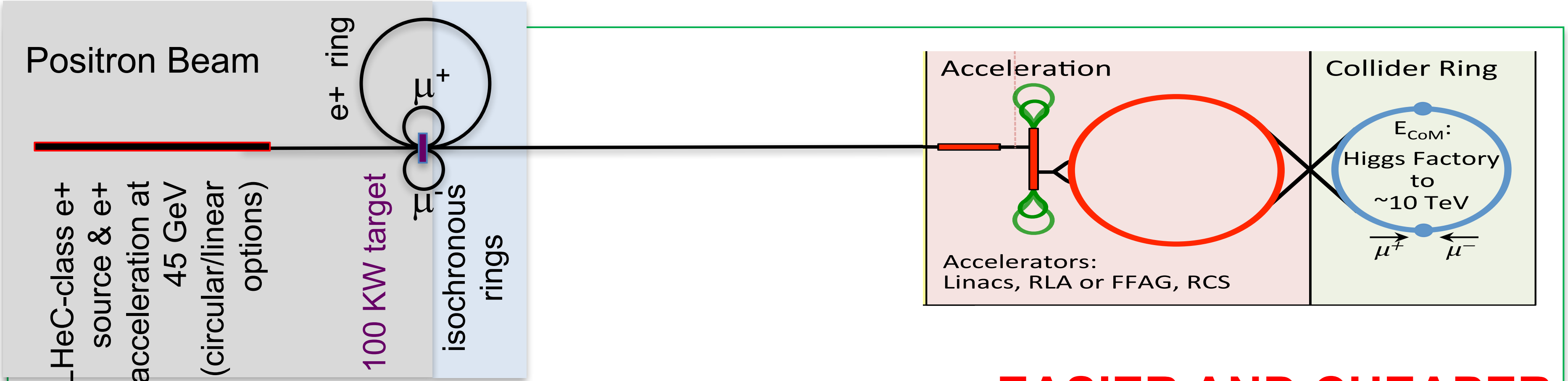
Direct μ pair production: muons produced from $e^+e^-\to\mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold **($\sqrt{s}$~0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

Potential of this idea, but key challenges need to be demonstrated to prove its feasibility ➔ a new proposal for machine studies and measurements

Advantages: Low emittance possible **Low background**

Reduced losses from decay **Energy spread**

Disadvantages: **Rate:** $\sigma(e^+e^-\to\mu^+\mu^-) \approx 1\ \mu b$ at most



Key Challenges

~10^{11} μ / sec from $e^+e^-\to\mu^+\mu^-$

EASIER AND CHEAPER DESIGN, IF FEASIBLE

Key R&D

10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring

LEMMA production scheme

arXiv:1803.06696v1

Goal:

$@T \approx 10^{11}\ \mu/s$

Efficiency $\approx 10^{-7}$ (with Be 3mm)→

$10^{18}\ e^+/s$ needed @T →

e^+ stored beam with T

to minimize positron source rate

Goal: mom. aperture +/-12%

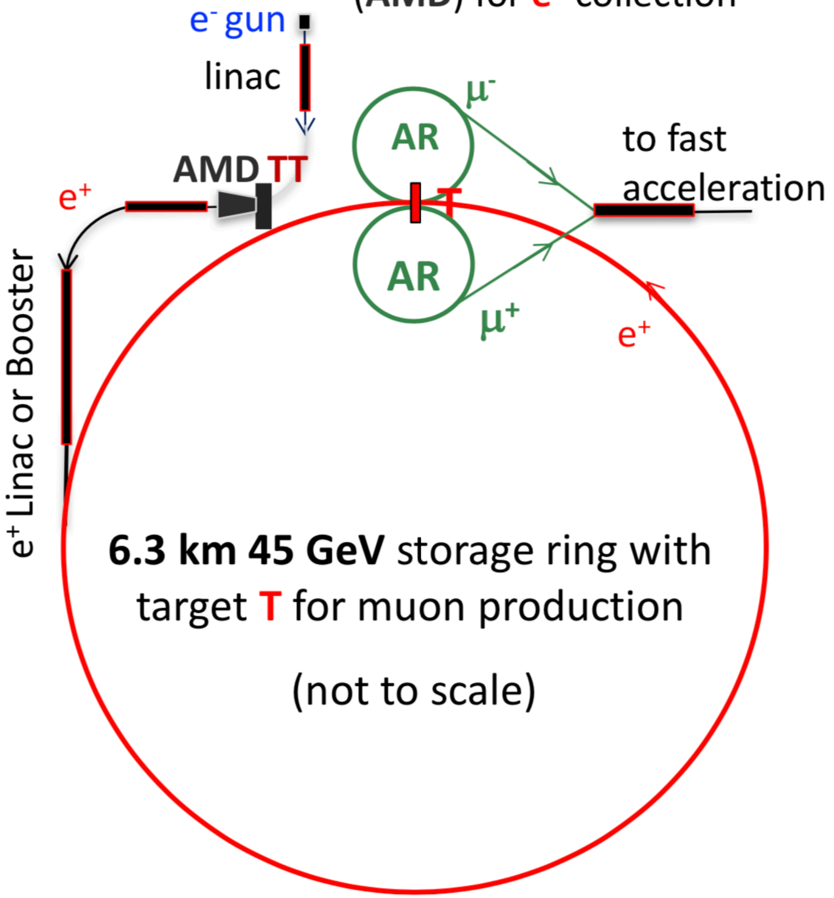
lifetime(e+) ≈ 250 turns

from $\mu^+ \mu^-$ production to collider

- produced by the e^+ beam on target **T** with **$E(\mu) \approx 22$ GeV**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx$ **500μs**
- **AR**: **60 m** isochronous and high mom. acceptance rings will recombine μ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns
- fast acceleration
- muon collider

e^- on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.

Adiabatic Matching Device (**AMD**) for e^+ collection

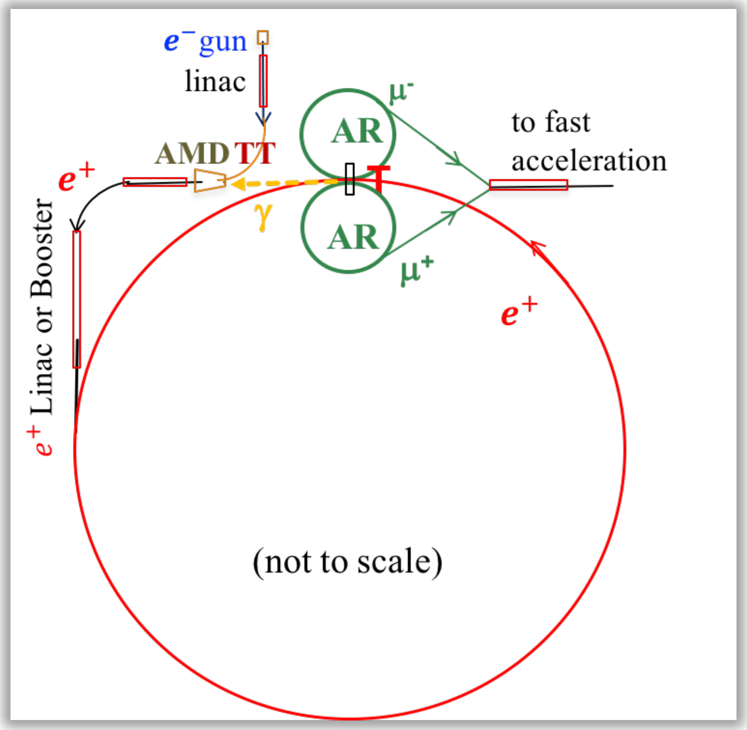


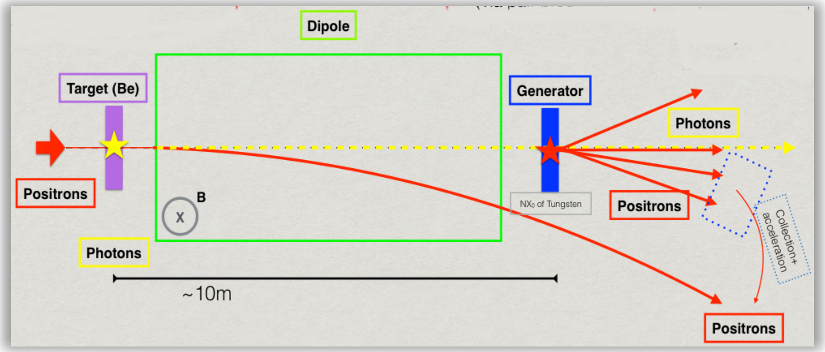
6.3 km 45 GeV storage ring with target **T** for muon production

(not to scale)

Positron source

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





Geant4 Simulation:

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

Key topics for LEMMA scheme

1. **Positron ring**
   - low emittance and high momentum acceptance

Optics design & beam dynamics

2. **Muon Accumulator Rings**
   - High momentum acceptance

IPAC2018 - MOPMF087

Optics design & beam dynamics

3. **Positron source**
   - High rate

Synergy with FCC-ee/ILC/CLIC future colliders

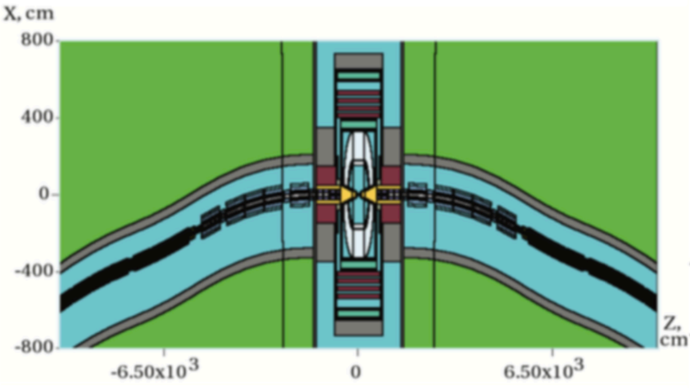
4. **$\mu^{+/-}$ production target**
   - High Peak Energy Density Deposition PEDD
   - Power O(100 kW)

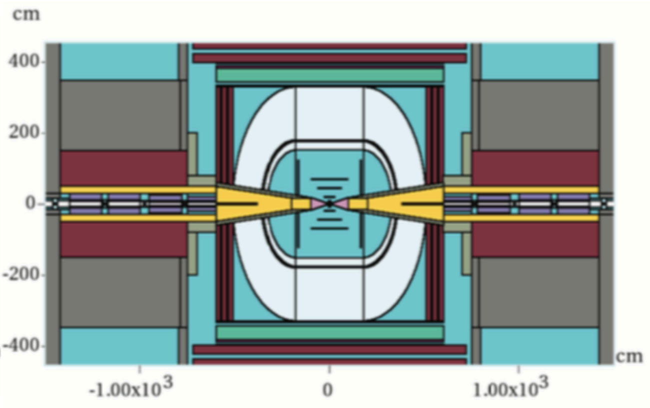
Synergy with High Power Targetry R&D,
HL-LHC beam interceptors

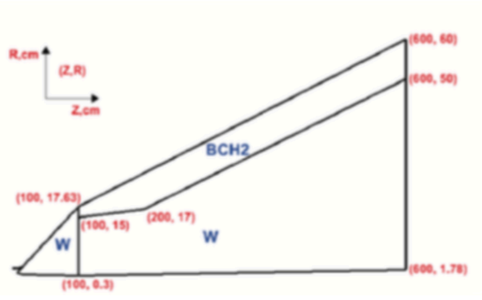
Detector and interaction region simulation

All the material comes from MAP people

- *ILCRoot tracker and vertex detector hits response to MARS15 simulated backgrounds in the muon collider*, TIPP 2011, Physics Procedia 37 (2012) 104 – 11
- *Detector Backgrounds at Muon Colliders*, TIPP 2011, Physics Procedia 37 (2012) 2015 – 2022
- *Neutrino Radiation at Muon Colliders and Storage Rings*, Published Proceedings of ICRS-9 International Conference on Radiation Shielding, Tsukuba, Ibaraki, Japan, October 17-22, 1999







Radiological Hazard simulations

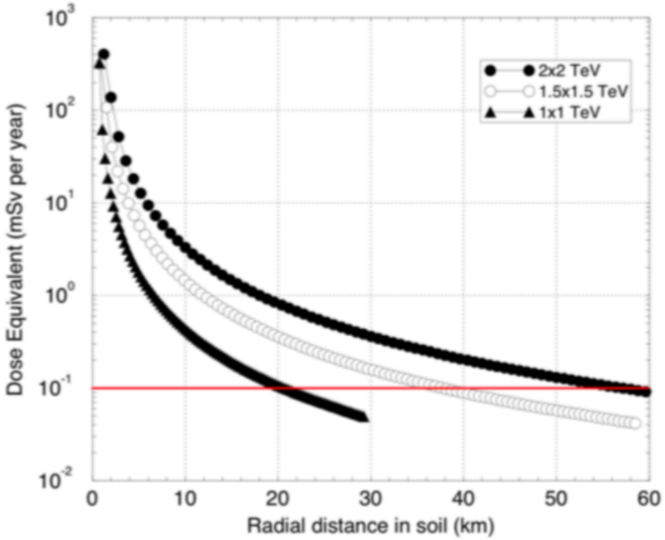


Figure 8: Maximum dose equivalent in TEP embedded in soil in high-energy muon collider orbit plane with 1.2×10^{21} decays per year *vs* distance from ring center.

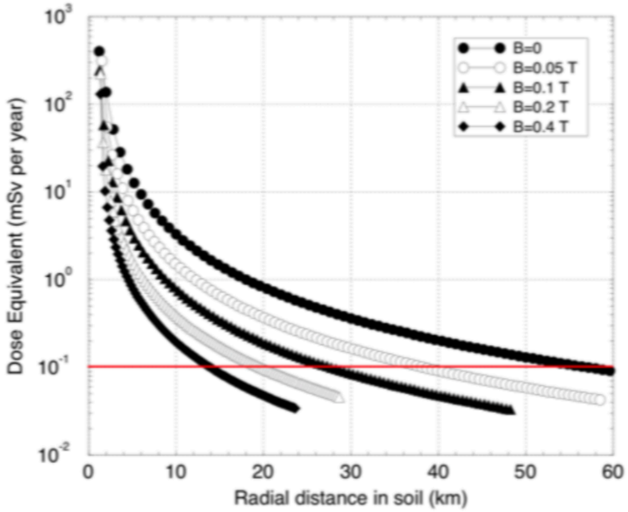


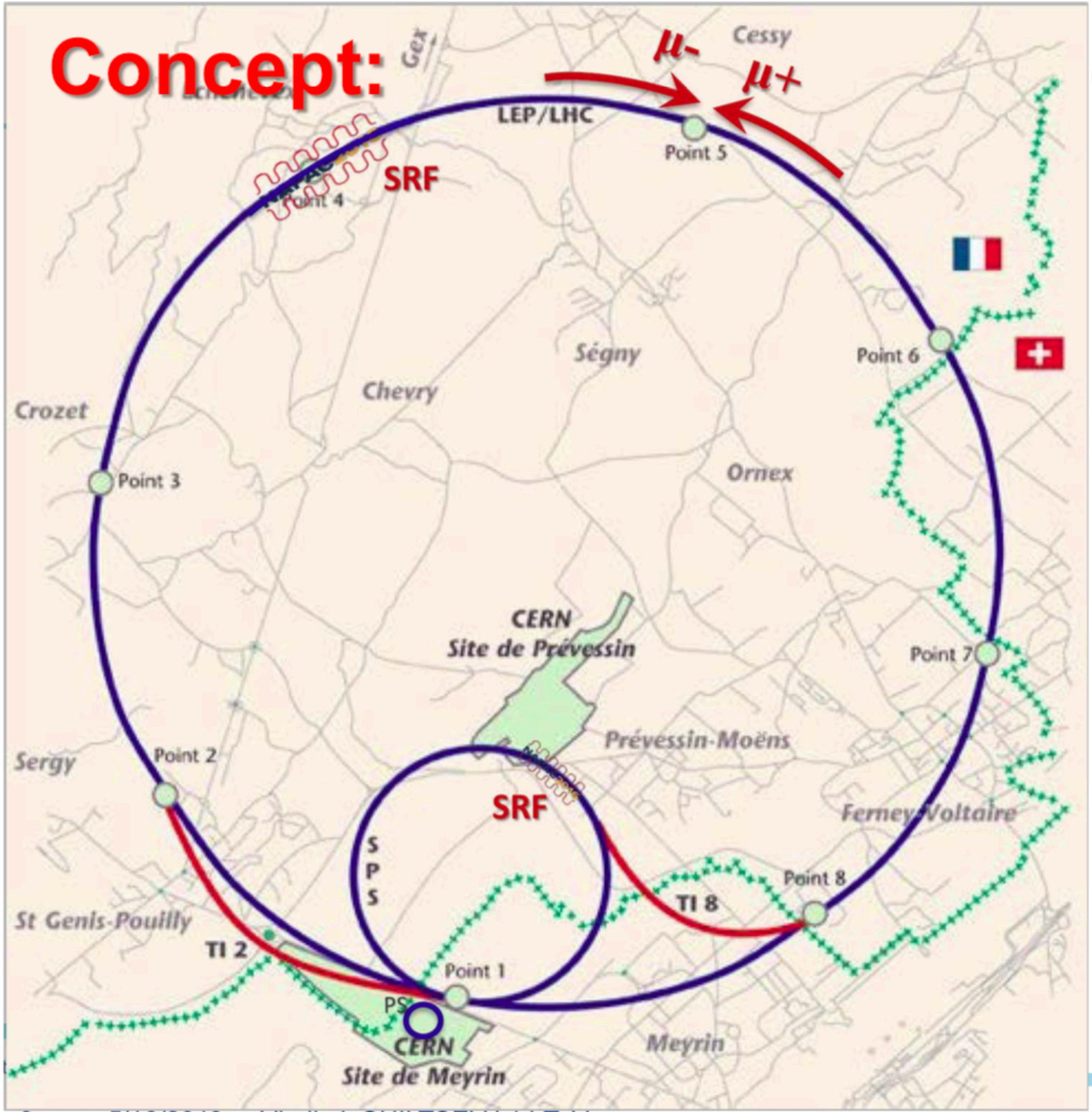
Figure 10: Maximum dose equivalent in TEP located in orbit plane *vs* distance from ring center in soil around a 2+2 TeV muon collider with 1.2×10^{21} decays per year for five values of vertical wave field.

TEP= tissue-equivalent phantom

Plan: re-do the study with LEMMA configuration and FLUKA
Submitted a project for a grant at the University of Padova

Study of multi-TeV muon collider limitations due to collider background induced radiation

Concept:



Options:

- **Muon source:**
  1. CERN PS
  2. MAP Proton Source
  3. LEMMA
- **Cooling :**
  1. MAP-like
  2. LEMMA
- **Acceleratio**
  1. Pulsed magnets
  2. FFAG
  3. RLA

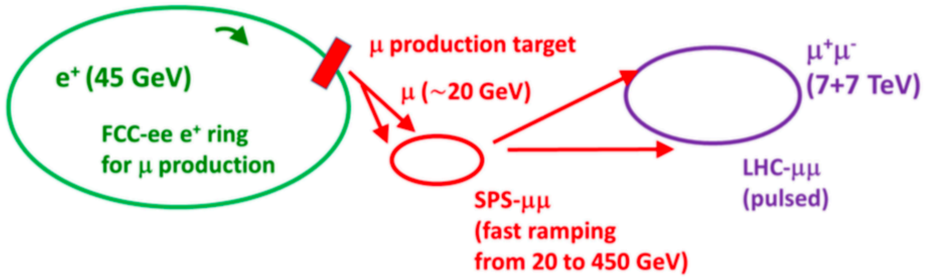
COST:

- **Acceleratio**
- Source/Cooling

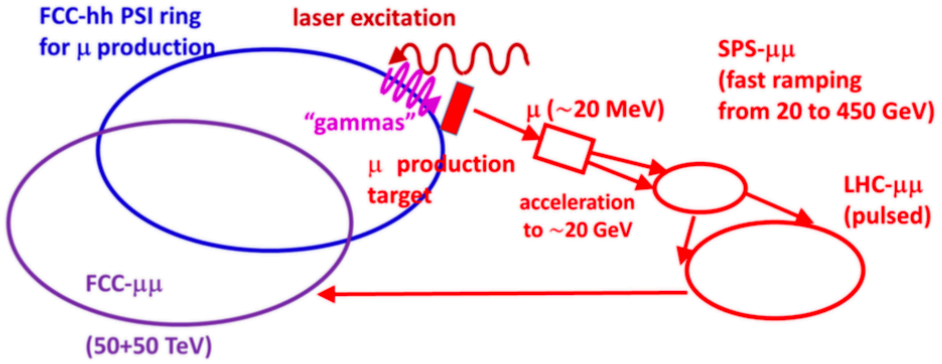
LHCC/FCC Muon Collider

Frank Zimmermann (CERN)

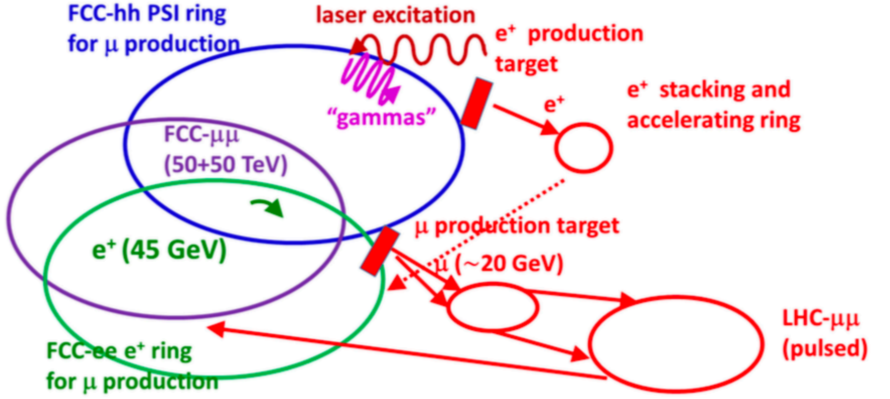
14 TeV μ collider LHC-μμ with FCC-ee μ± production



100 TeV μ collider FCC-μμ with FCC-hh PSI μ± production



100 TeV μ collider FCC-μμ with FCC-hh PSI e⁺ & FCC-ee μ± production



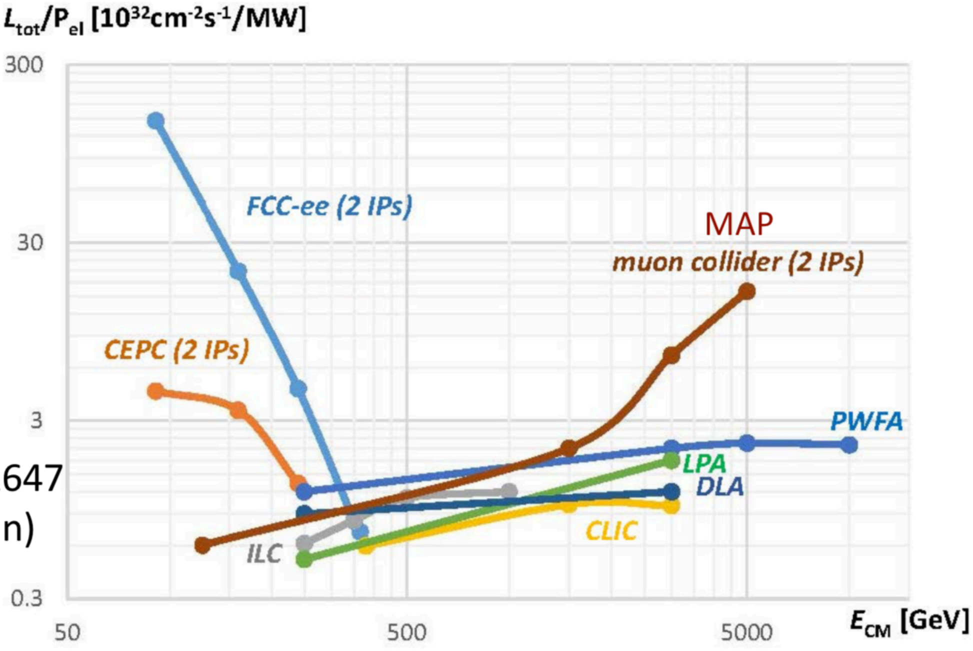
scheme	p-γ	G.-F. μ	e^+	G.-F. e^+
base	LHC/FCC-hh		FCC-ee	FCC
rate $\dot{N}_\mu$ [GHz]	1	400	0.003	100
μ/pulse [10^4]	0.01	4	0.2	6,000
p. spacing [ns]	100	100	15	15
energy [GeV]	2.5	0.1	22	22
rms en. spread	3%	10%	10%	10%
n. emit. [μm]	7	2000	0.04	0.04
$\dot{N}_\mu/\varepsilon_N$ [10^{15} m^{-1}s^{-1}]	0.1	0.2	0.1	3,000

IPAC2018 - MOPMF065

Muon source comparison

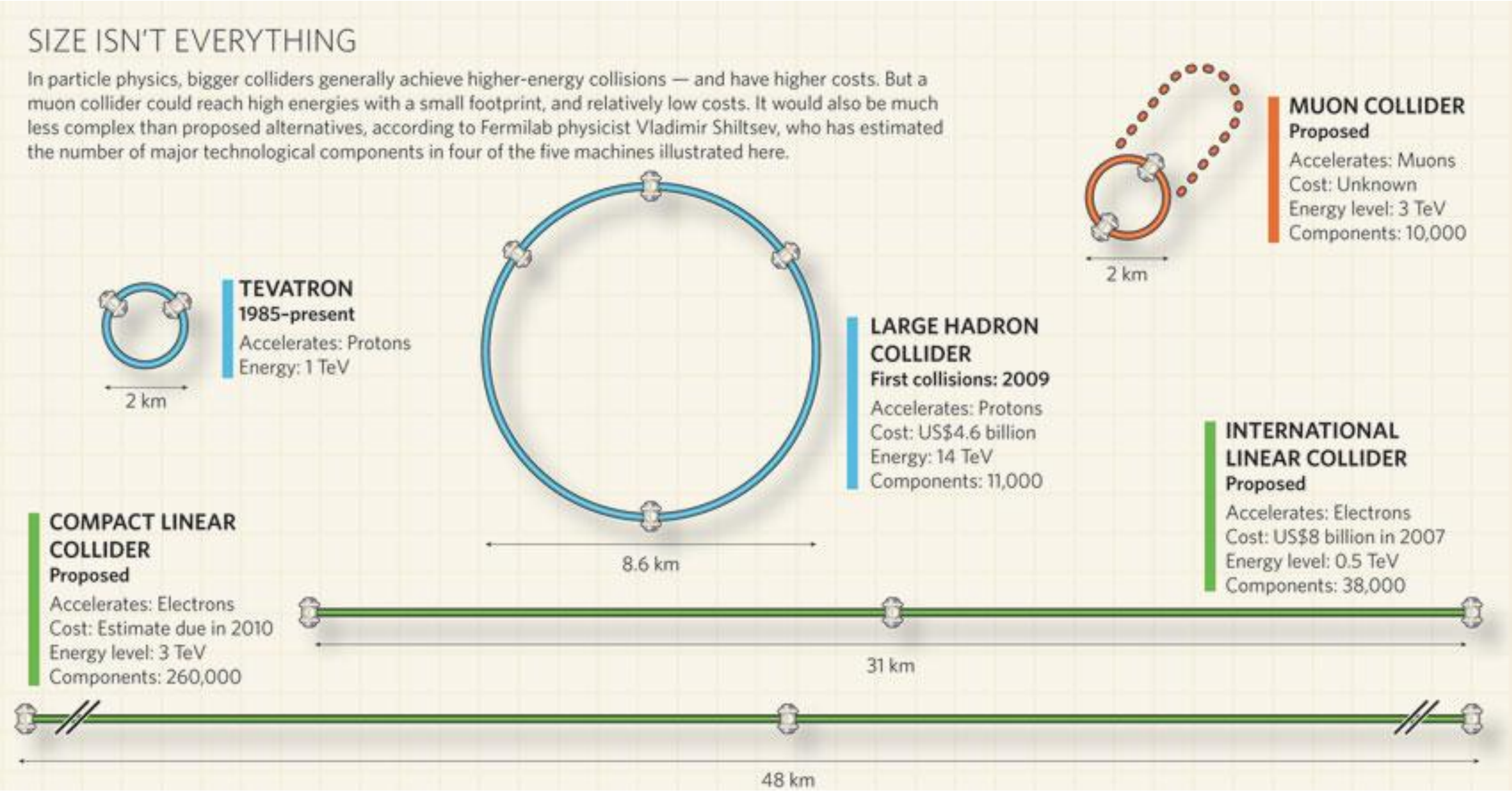
	Physical process	Rate μ/s	normalized emittance ϵ_N [μm-rad]
e+ on target	**e+e-→ μ+μ-**	**0.9×10^{11}**	**0.04**
Protons on target	p N→ πX, kX→ μ X'	10^{13}	25
Compton γ on target	γ N→ μ+μ- N	5×10^{10}	2

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



J.P. Delahaye, M. Palmer, et al., arXiv:1502.01647
(updated by A. Blondel, P. Janot, F. Zimmerman)

The comparison – a challenge



SIZE ISN'T EVERYTHING

In particle physics, bigger colliders generally achieve higher-energy collisions — and have higher costs. But a muon collider could reach high energies with a small footprint, and relatively low costs. It would also be much less complex than proposed alternatives, according to Fermilab physicist Vladimir Shiltsev, who has estimated the number of major technological components in four of the five machines illustrated here.

MUON COLLIDER
Proposed
Accelerates: Muons
Cost: Unknown
Energy level: 3 TeV
Components: 10,000

TEVATRON
1985–present
Accelerates: Protons
Energy: 1 TeV

LARGE HADRON COLLIDER
First collisions: 2009
Accelerates: Protons
Cost: US$4.6 billion
Energy: 14 TeV
Components: 11,000

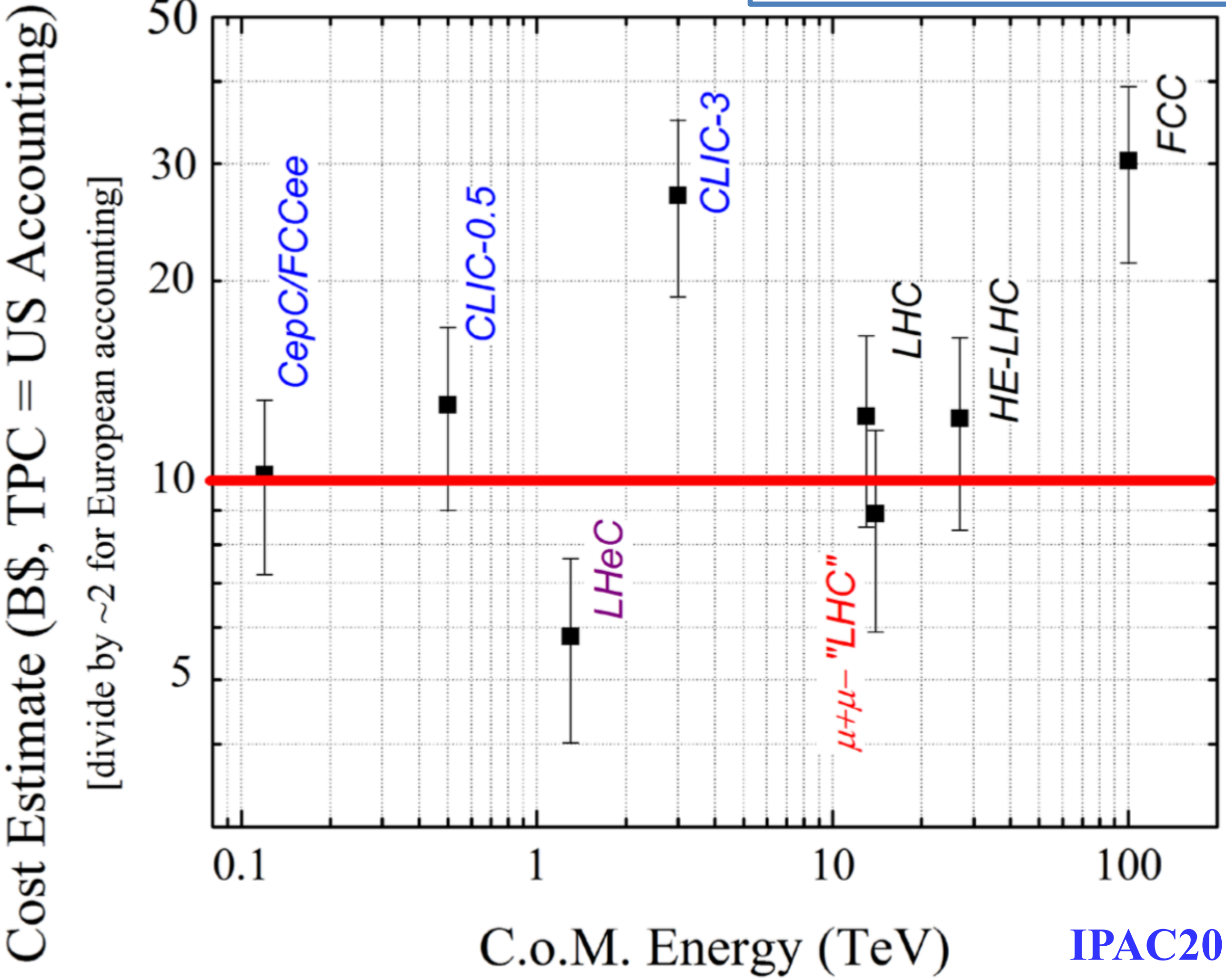
INTERNATIONAL LINEAR COLLIDER
Proposed
Accelerates: Electrons
Cost: US$8 billion in 2007
Energy level: 0.5 TeV
Components: 38,000

COMPACT LINEAR COLLIDER
Proposed
Accelerates: Electrons
Cost: Estimate due in 2010
Energy level: 3 TeV
Components: 260,000

Cost estimate

NB: all $$ - “US Accounting” (divide by 2-2.4 at CERN)

Vladimir SHILTSEV,David NEUFFER (Fermilab)



IPAC2018 - MOPMF072

Conclusions

- The Muon Collider is an appealing solution as the HEP future accelerator and a possibility as neutrino factory to be fully explored
- U.S. Muon Accelerator Program (MAP) provides a well documented set of studies and measurements on the proton-driven option
- First results on ionizing cooling from MICE experiment now available
- A novel scheme to produce very low emittance muon pairs using a positron beam needs to be further investigated to became reality
- Detailed studies and R&Ds, required to design a feasible solution for a Muon Collider, must be planned and pursued
- The Update to the European Strategy for Particle Physics by May 2020 is the perfect opportunity to strengthen the effort!

You are all invited to contribute!

July 2-3, 2018 - Università di Padova - Orto Botanico

https://indico.cern.ch/event/719240/overview

Aknowledgements

From MAP Collaboration among others:
Mark Palmer, Vladimir Shiltsev

From LEMMA collaboration among others:
Mario Antonelli, Manuela Boscolo, Susanna Guiducci, Donatella Lucchesi, Pantaleo Raimondi, Alessandro Variola, Andrea Wulzer

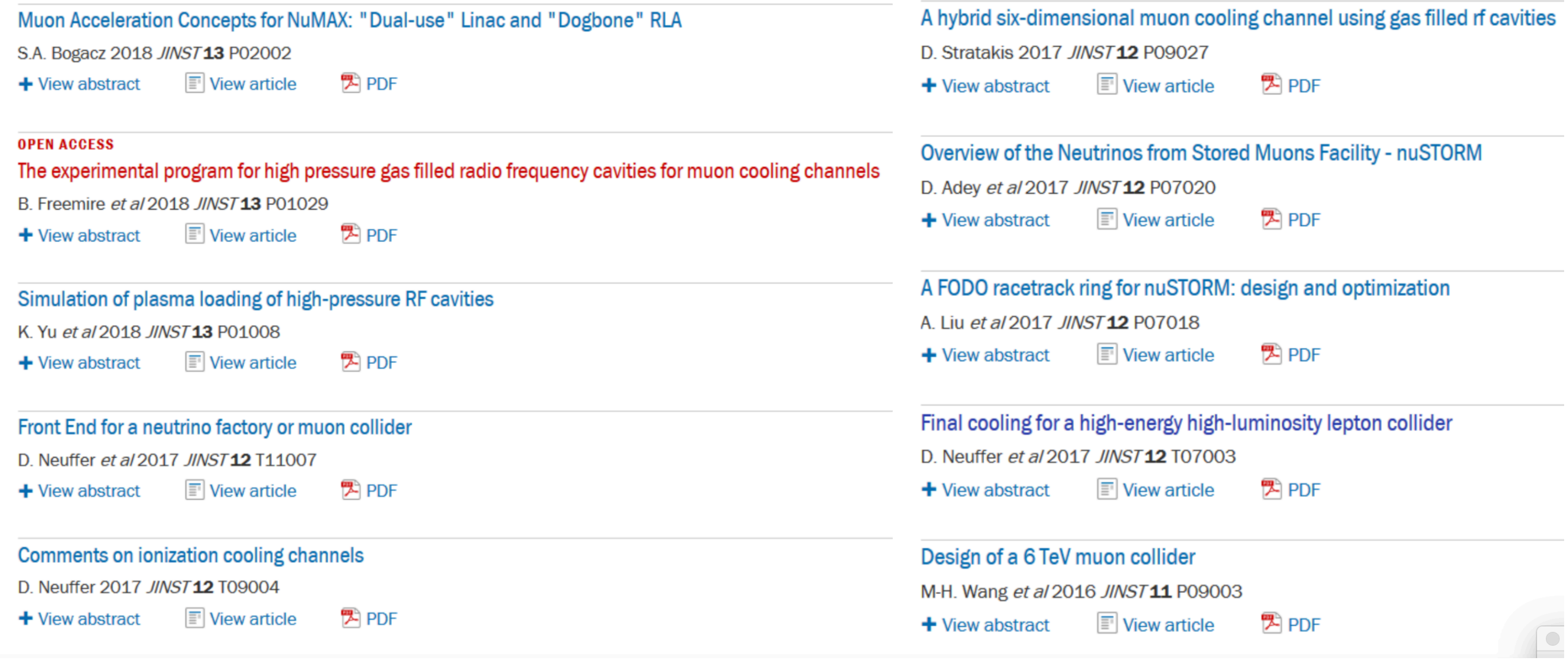
From MICE collaboration:
Ken Long

CERN WG to prepare input document to update EU Particle Physics Strategy:
Jean Pierre Delahaye, Marcella Diemoz, Ken Long, Bruno Mansoulie, N.P., Lenny Rivkin, Daniel Schulte, Andrea Wulzer

References

A lot of material from – *JINST Special Issue MUON*

http://iopscience.iop.org/journal/1748-0221/page/extraproc46



Muon Acceleration Concepts for NuMAX: "Dual-use" Linac and "Dogbone" RLA

S.A. Bogacz 2018 *JINST* **13** P02002

OPEN ACCESS

The experimental program for high pressure gas filled radio frequency cavities for muon cooling channels

B. Freemire *et al* 2018 *JINST* **13** P01029

Simulation of plasma loading of high-pressure RF cavities

K. Yu *et al* 2018 *JINST* **13** P01008

Front End for a neutrino factory or muon collider

D. Neuffer *et al* 2017 *JINST* **12** T11007

Comments on ionization cooling channels

D. Neuffer 2017 *JINST* **12** T09004

A hybrid six-dimensional muon cooling channel using gas filled rf cavities

D. Stratakis 2017 *JINST* **12** P09027

Overview of the Neutrinos from Stored Muons Facility - nuSTORM

D. Adey *et al* 2017 *JINST* **12** P07020

A FODO racetrack ring for nuSTORM: design and optimization

A. Liu *et al* 2017 *JINST* **12** P07018

Final cooling for a high-energy high-luminosity lepton collider

D. Neuffer *et al* 2017 *JINST* **12** T07003

Design of a 6 TeV muon collider

M-H. Wang *et al* 2016 *JINST* **11** P09003

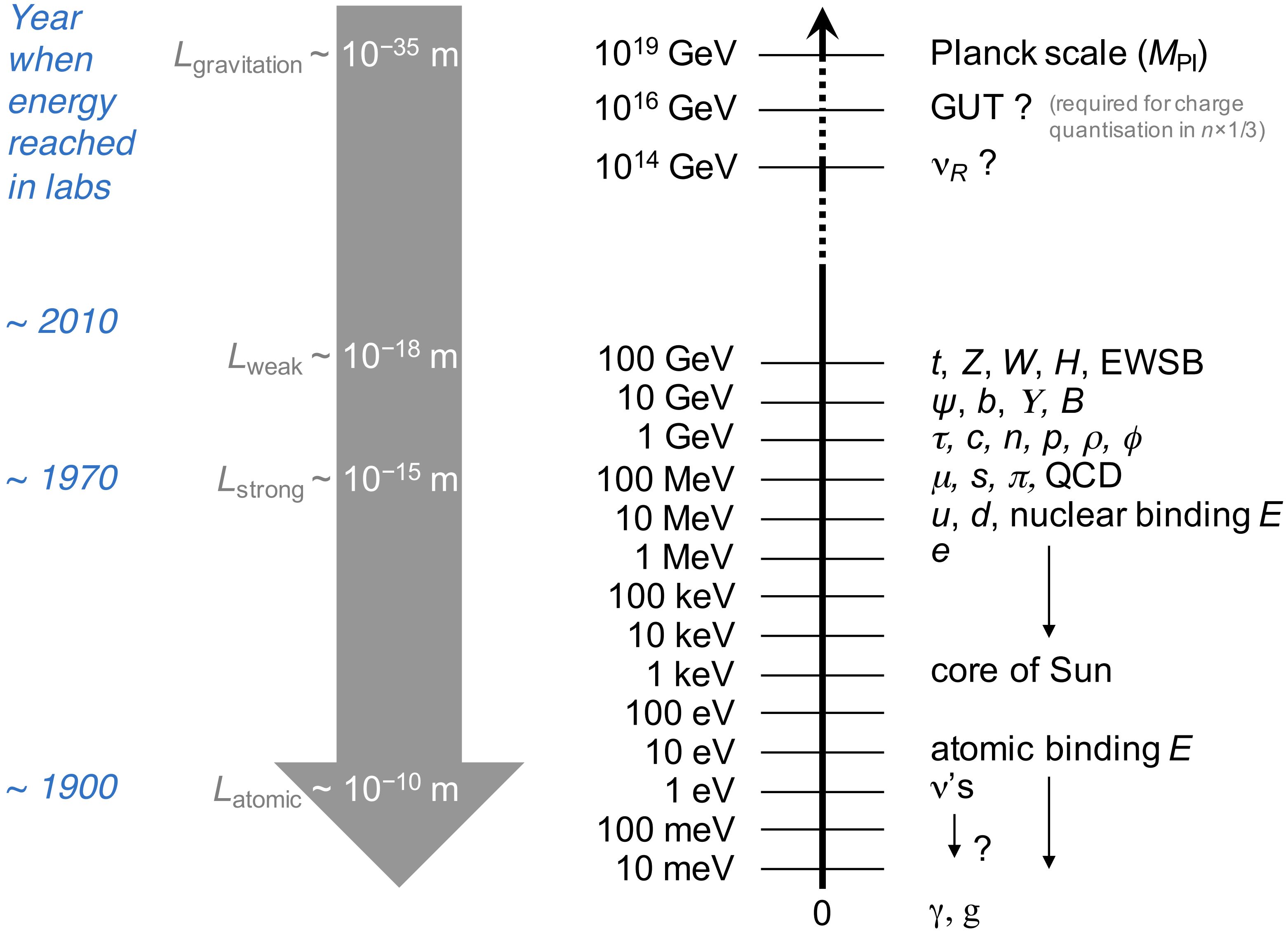
- IPAC2018
- M. Boscolo, M. Palmer and JP Delahaye,
  ‘*The future prospects of muon collider and neutrino factory*’, **Rev Acc Sci Tech J. to be pub**

extras

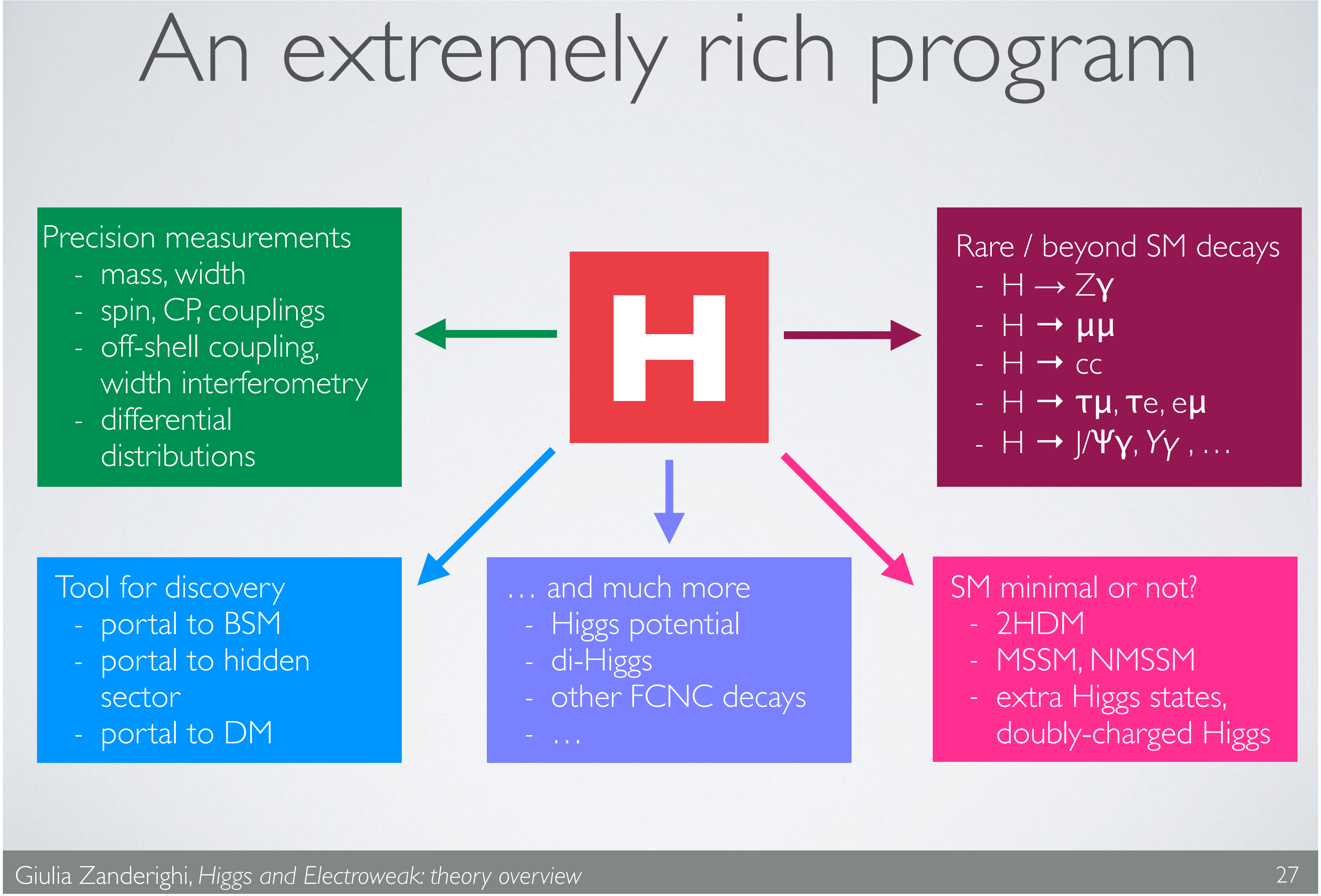
Scales in particle physics

Direct Exploration of the Energy Frontier

Andrea Wulzer



Year when energy reached in labs			
	$L_{gravitation}$ ~ 10^{-35} m	10^{19} GeV	Planck scale (M_{Pl})
		10^{16} GeV	GUT ? (required for charge quantisation in n×1/3)
		10^{14} GeV	ν_R ?
~ 2010	L_{weak} ~ 10^{-18} m	100 GeV	t, Z, W, H, EWSB
		10 GeV	ψ, b, Υ, B
		1 GeV	τ, c, n, p, ρ, ϕ
~ 1970	L_{strong} ~ 10^{-15} m	100 MeV	μ, s, π, QCD
		10 MeV	u, d, nuclear binding E
		1 MeV	e ↓
		100 keV	
		10 keV	
		1 keV	core of Sun
		100 eV	
		10 eV	atomic binding E
~ 1900	L_{atomic} ~ 10^{-10} m	1 eV	ν's ↓
		100 meV	↓ ?
		10 meV	
		0	γ, g



An extremely rich program

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

Rare / beyond SM decays
- $H \to Z\gamma$
- $H \to \mu\mu$
- $H \to cc$
- $H \to \tau\mu, \tau e, e\mu$
- $H \to J/\Psi\gamma, \Upsilon\gamma$, …

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

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

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

Giulia Zanderighi, *Higgs and Electroweak: theory overview* 27

Higgs scenario after HL-LHC

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

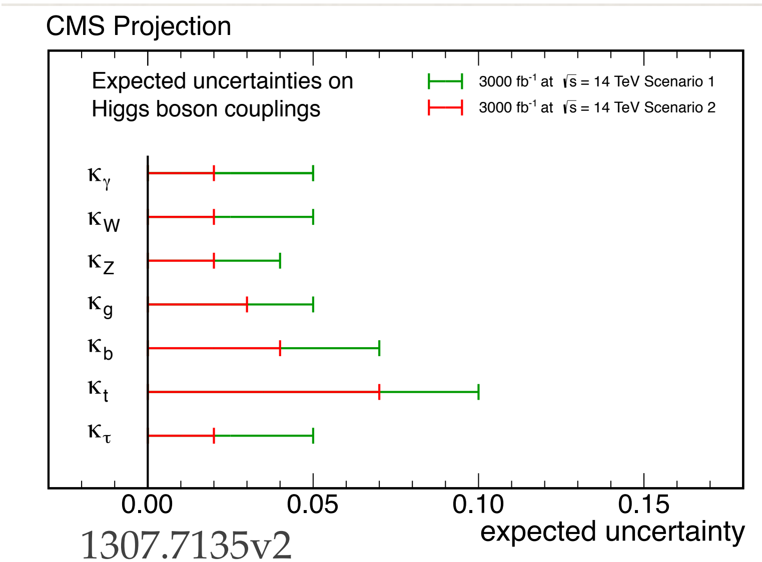
k_x is scale factor respect to the SM, i.e. $g_{HVV} = k_V\, g_{HVV}^{SM}$ (it assumes only one narrow Higgs resonance)

ATLAS has similar, more conservative values

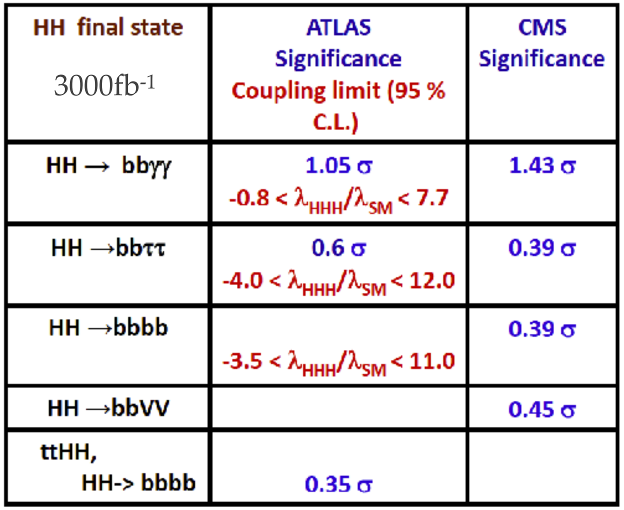
In SM, expanded about the minimum

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

Single H Double H Triple H



1307.7135v2



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

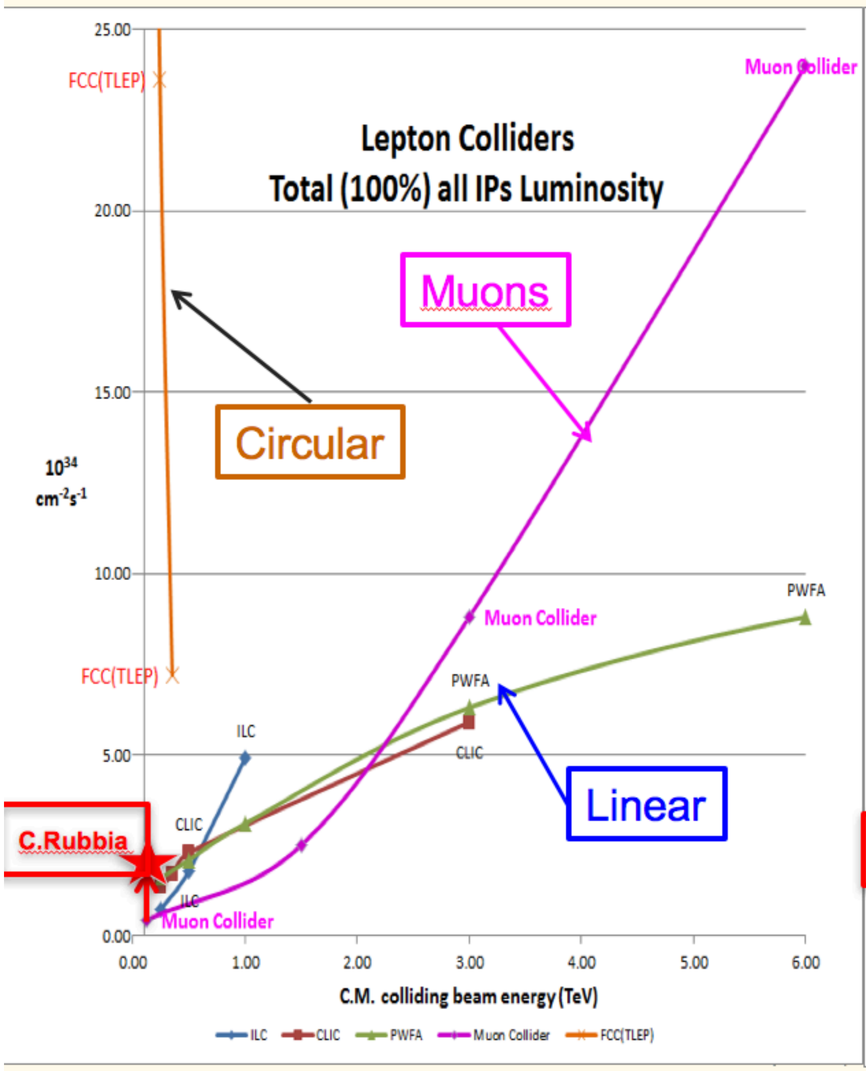
S. Jézéquel, HL-LHC/HE-LHC Workshop 2017

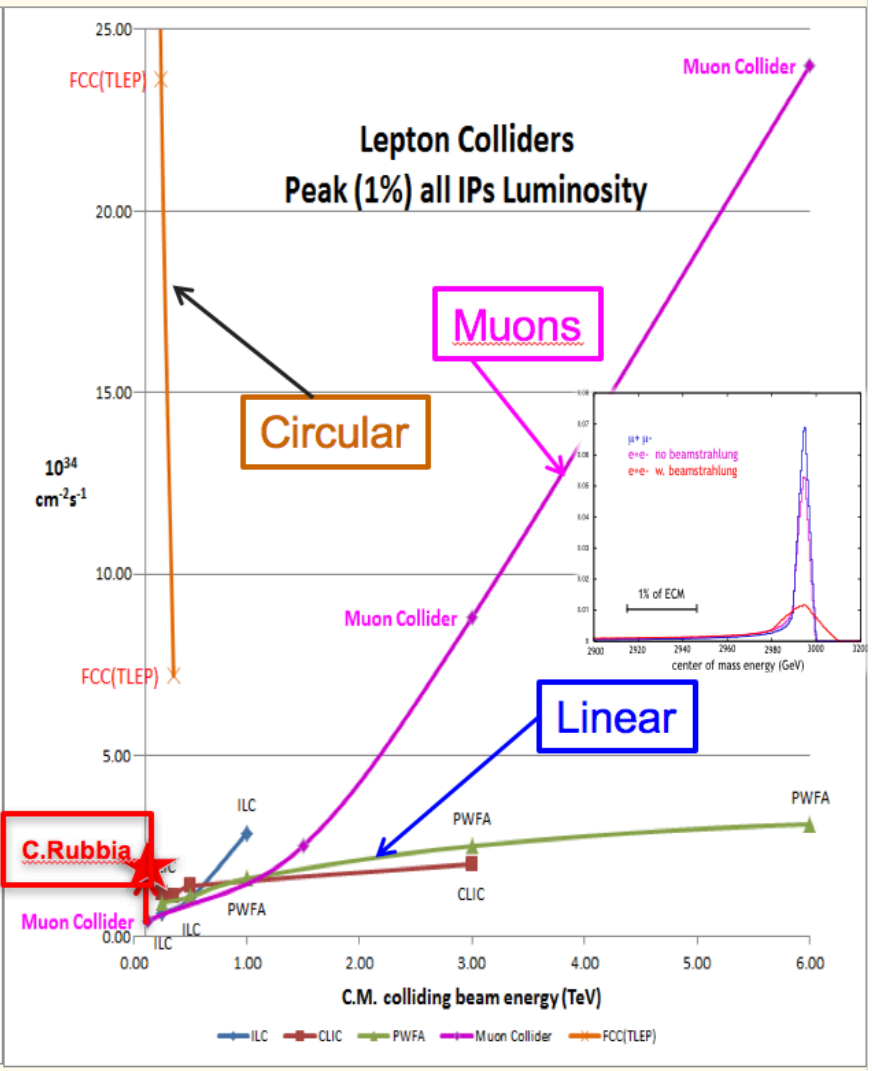
A comparison

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

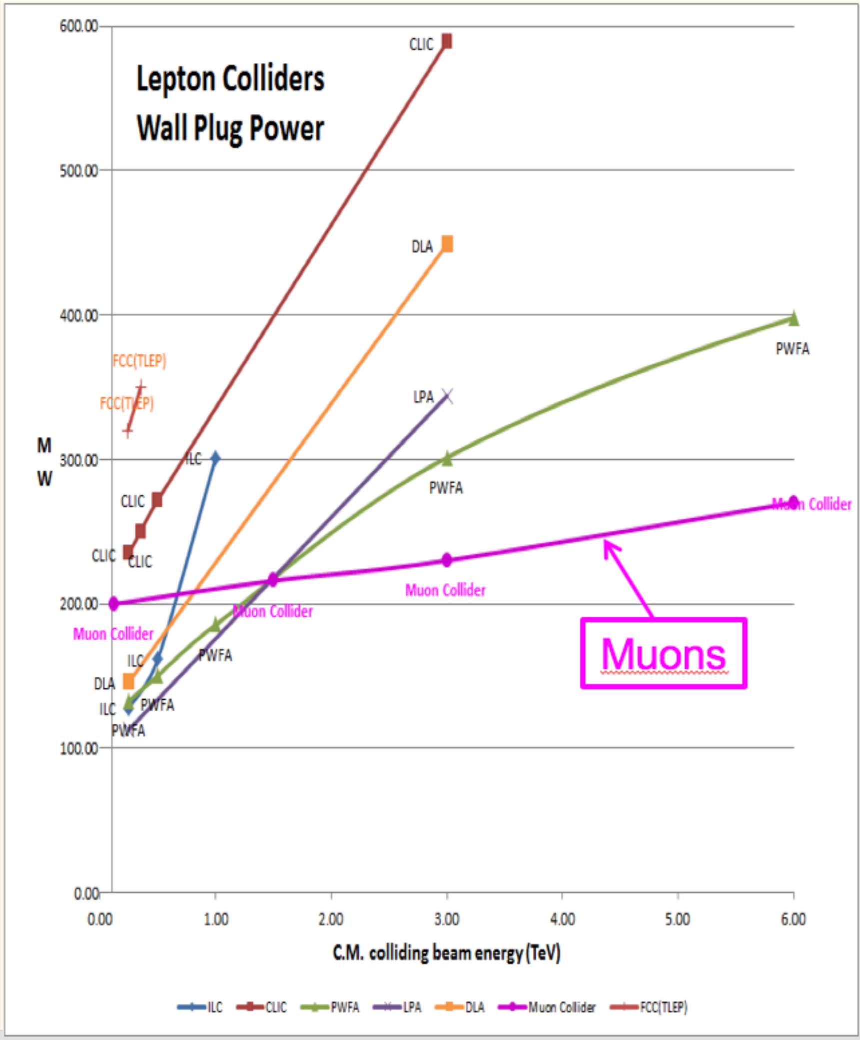
Different parameter definition

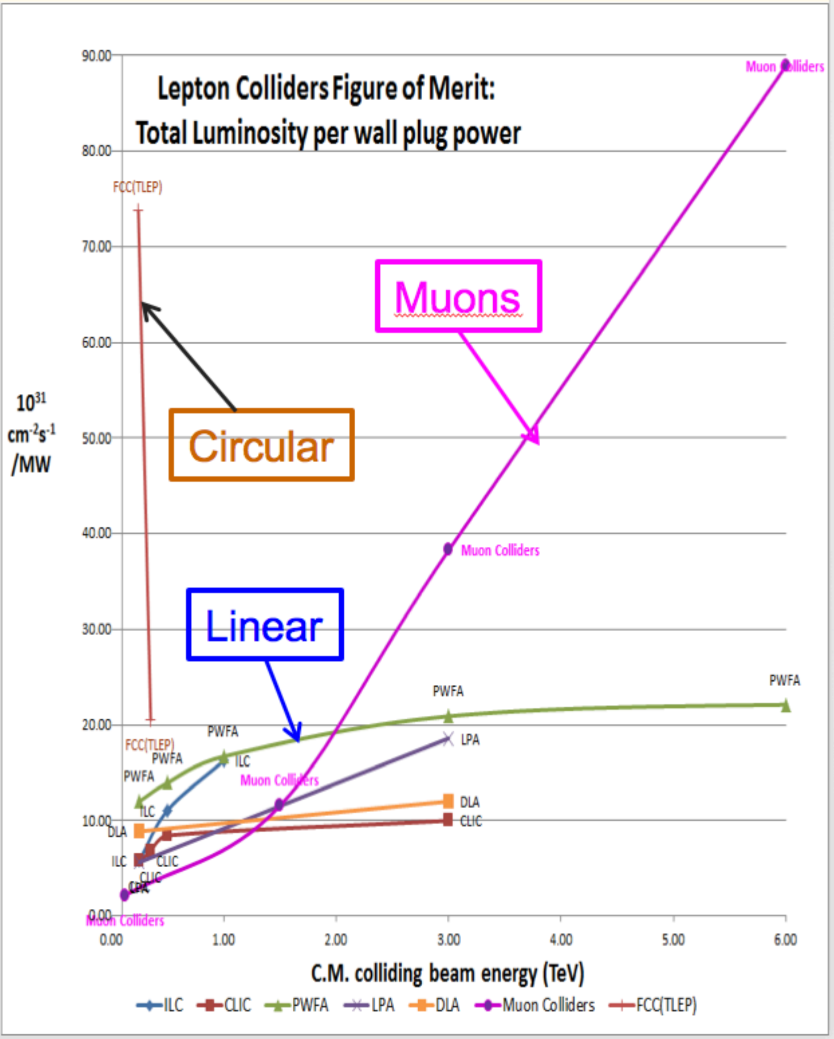
Muon Colliders potential of extending lepton high energy frontier with high performance





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





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 MC
(500 m depth)

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

muon rate:

p on target option
3×10^{13} μ/s

e^+ on target option
9×10^{10} μ/s

neutrino dose equivalent/fluence

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