upgrading FCC into a muon collider

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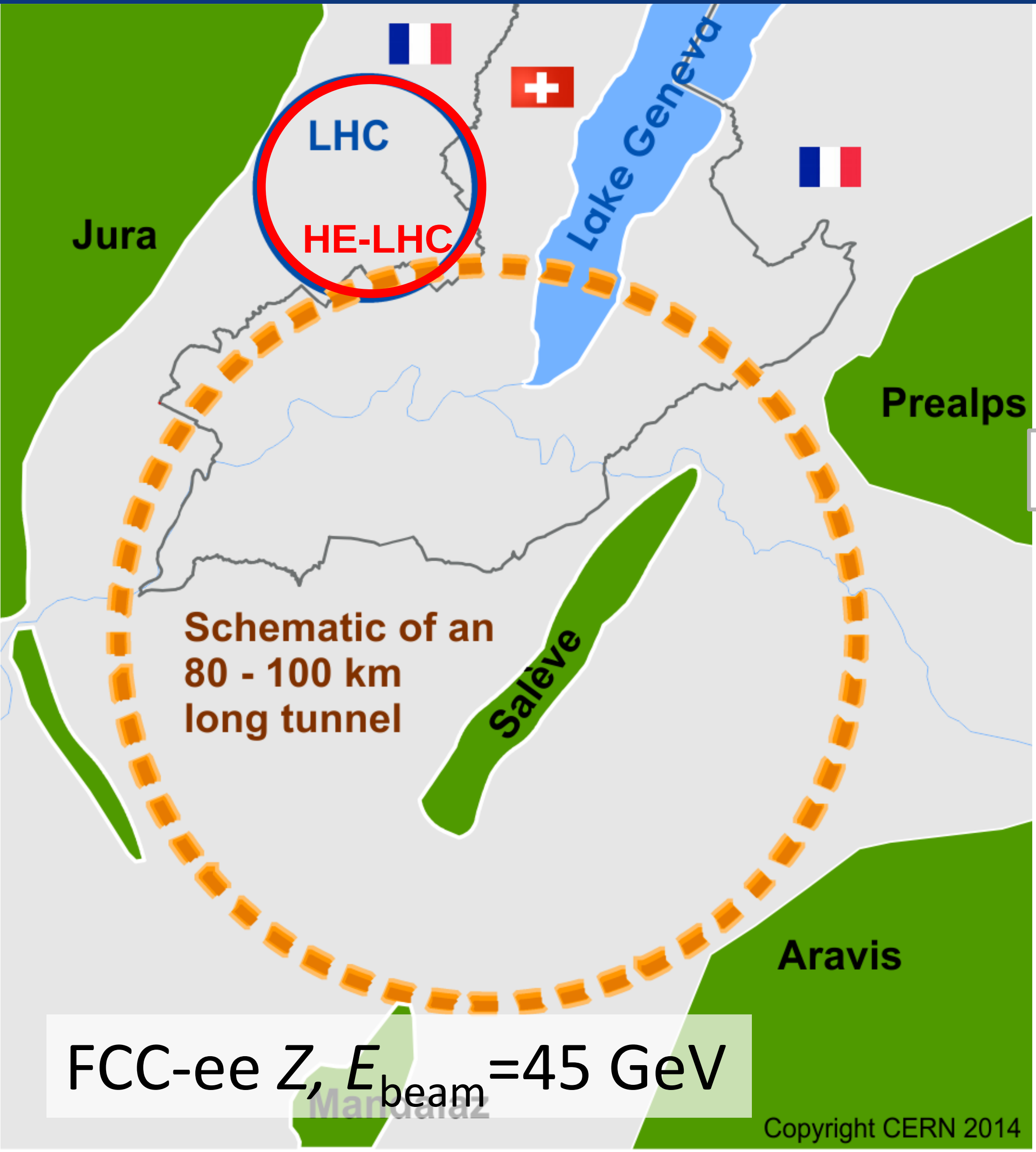
Future Circular Collider (FCC) Study

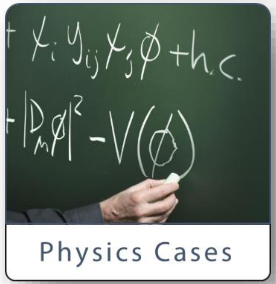


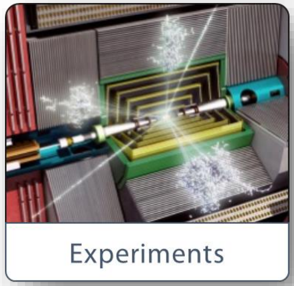
International FCC collaboration (CERN as host lab) to study:

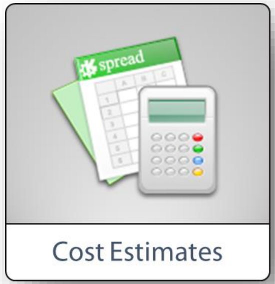
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

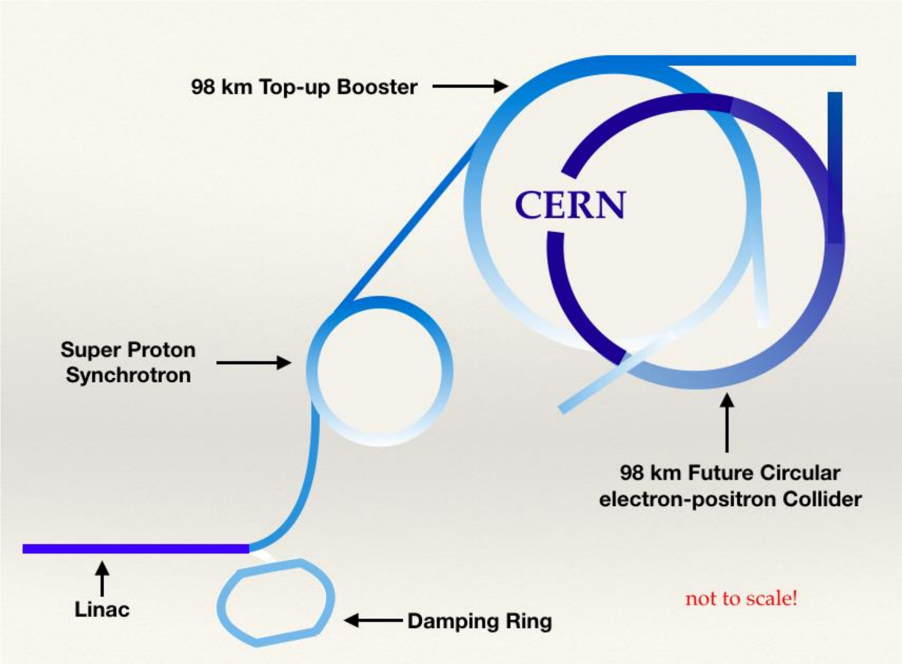
- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e⁻ from ERL

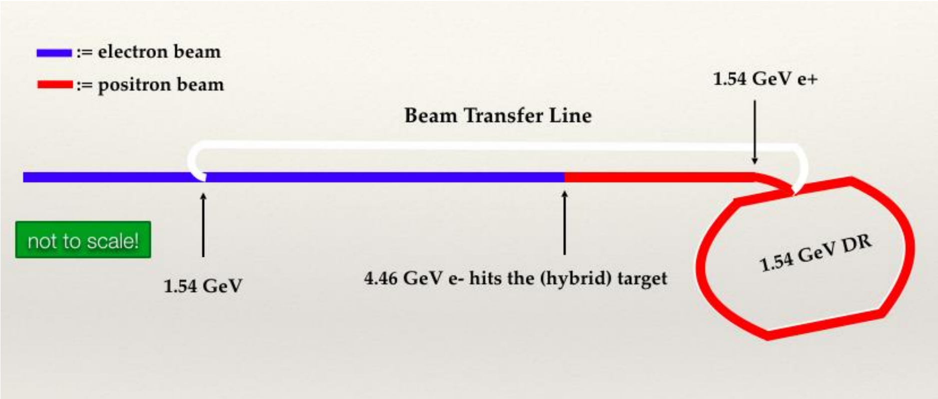






FCC-ee injector layout





- SLC/SuperKEKB-like 6 GeV linac accelerating **1** or **2** bunches with repetition rate of **100-200 Hz**
- **same linac** used for positron production @ **4.46 GeV** Positron beam emittances reduced in DR @ **1.54 GeV**
- injection @ **6 GeV** into of Pre-Booster Ring (SPS or new ring) and acceleration to 20 GeV
- injection to main Booster @ **20 GeV and interleaved** filling of e+/e- (below **20 min** for full filling) and continuous top-up

FCC-ee injector provides ~3×10^{12} e+/s

Motivations/approaches for FCC-based muon-collider study:

Novel three schemes for producing low-emittance muon beams:

1) *e^+e^- annihilation* above threshold using a *positron storage ring with a thin target (LEMMA)*,
2) *laser/FEL-photon back-scattering off high-energy proton beams* circulating in the LHC or FCC-hh,
3) the *Gamma factory* concept where partially stripped heavy ions collide with a laser pulse to directly generate muons.

The Gamma factory would also deliver copious amounts of positrons, which could in turn be used as source for option (1).

On the other hand the top-up booster of the FCC-ee design would be an outstanding e^+ storage ring, at the right beam energy, around 45 GeV.

After rapid acceleration the muons, produced in one of the three or four ways, could be collided in machines like the SPS, LHC or FCC-hh.

Possible collider layouts are suggested.

Ref. IPAC'18 MOPMF065

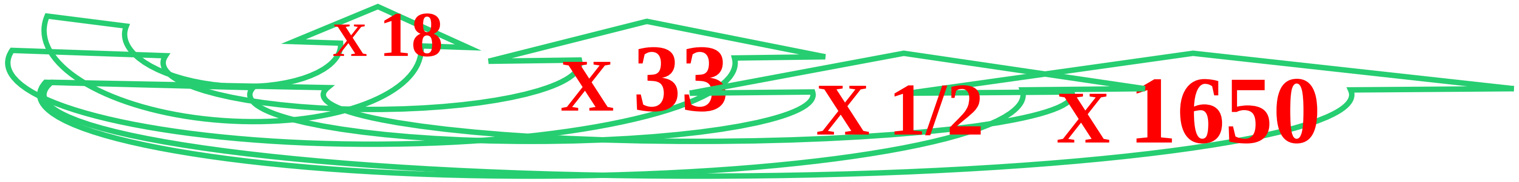
μ production by e$^+$ annihilation

threshold e$^+$ energy for μ production in e$^+$ annihilation on static e$^-$: $E_{e^+,thr} = \frac{4m_\mu^2c^4 - 2m_e^2c^4}{2m_ec^2}$ =43.7 GeV

→ we could use the FCC-ee e$^+$ ring or the FCC-ee top-up booster as μ accumulation & internal target ring!

e$^+$ production rates achieved (SLC) or needed

	S-KEKB	SLC	CLIC (3 TeV)	ILC (*H*)	FCC-ee (*Z*)	Italian μ collider
10^{12} e$^+$ / s	**2.5**	**6**	**110**	**200**	**3**	**10000**



LHC based Gamma Factory could provide 100x more e$^+$/s than needed!

staged approach: FCC-ee → FCC-hh → FCC-μμ?

scheme	*p-γ*	*G-F μ*	*e+* annih.	G-F e+ & e+ annhil.
base	LHC/FCC-hh	LHC/FCC-hh	FCC-ee	FCC-ee & FCC-ee
rate $\dot{N}_{\mu}$ [GHz]	1	400	0.003	100
μ per pulse	100	4×10^{4}	2×10^{3}	6×10^{7}
pulse spacing [ns]	100	100	15	15
energy [GeV]	2.5	0.1	22	22
rms energy spread	3%	10%	10%	10%
norm. emittance [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**

→ The Gamma Factory offers the best performance for muon production, especially if not used for generating muons directly, but for producing positrons in combination with the positron annihilation scheme (profiting from the small emittance available in this scenario).

recirculation for stacking or acceleration

muon lifetime in #turns with recirculation
for stacking or acceleration:

1. constant magnetic field B

$$\frac{\tau}{T_{rev}} = \frac{eB\tau_0 F_{dip}}{2\pi m_\mu}$$

2. constant bending radius ρ

$$\frac{\tau}{T_{rev}} = \frac{E}{\rho}\frac{\tau_0 F_{dip}}{2\pi m_\mu c}$$

stacking

bunch spacing Δt_μ together with magnetic field *B* determine stacking-ring beam energy as

$$E = \frac{\Delta t_\mu c^2 B e F_{dip}}{2\pi}$$

At *B*=16 T:

Δt_μ = 15 ns → 2.4 GeV ,

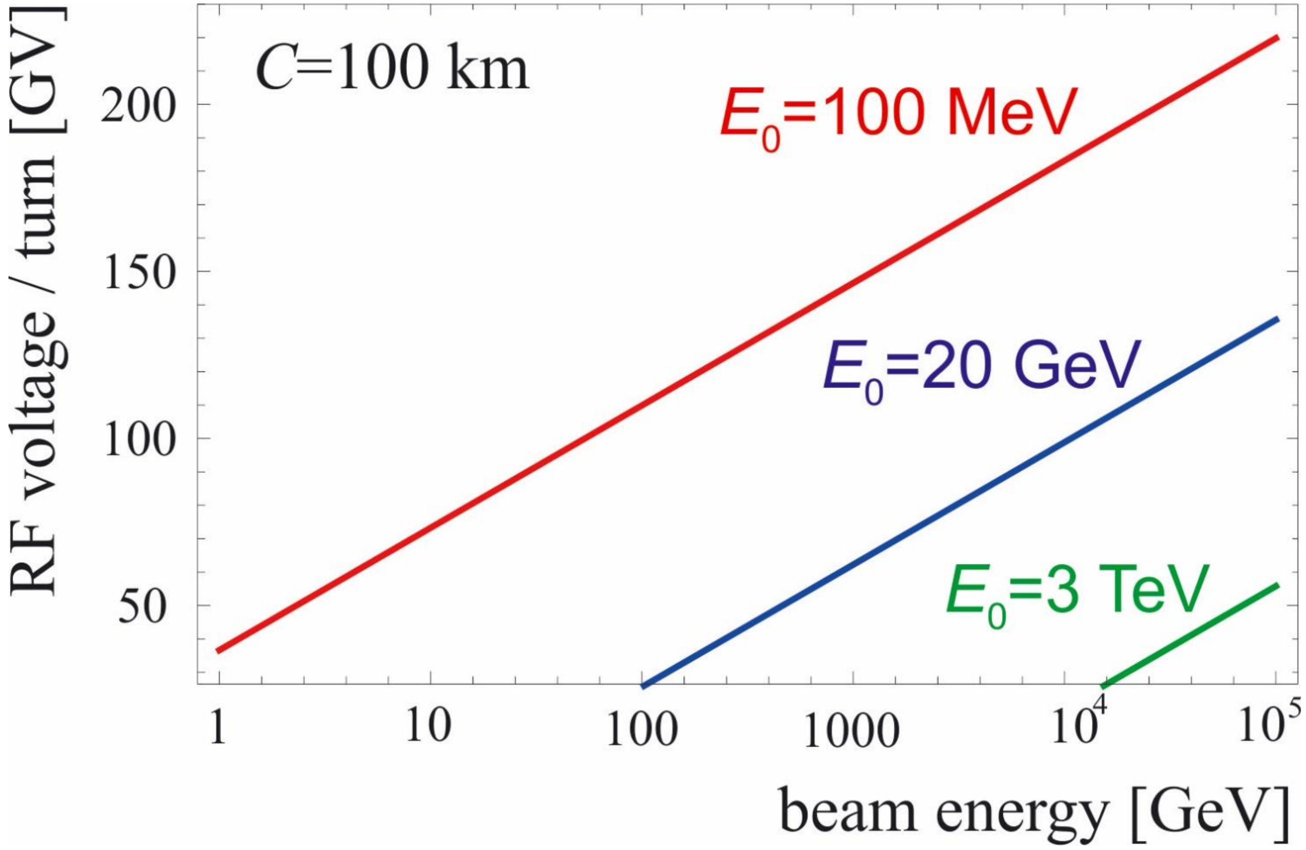
Δt_μ = 100 ns →16 GeV ;

ring circumference = 4.5 m or 30 m, respectively.

acceleration by pulsed synchrotron

minimum ring rf voltage

$$V_{rf} > \frac{m_\mu c^2 C}{ec\tau_0 \ln(E/E_0)}$$



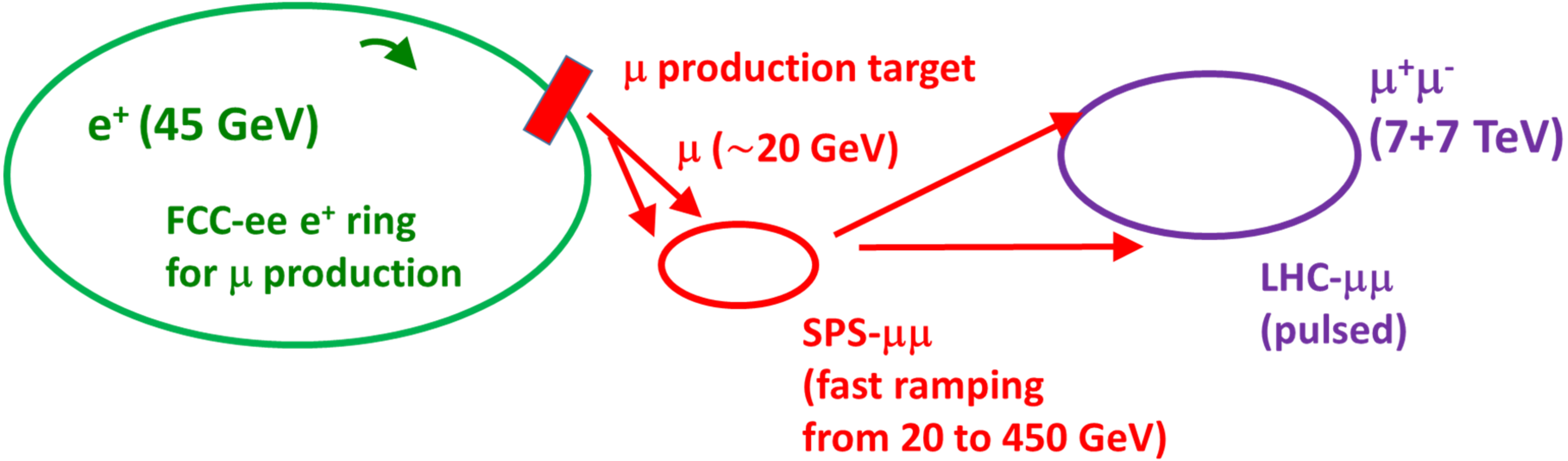
minimum rf voltage as a function of final beam energy, for three different injection energies, at C = 100 km

luminosity

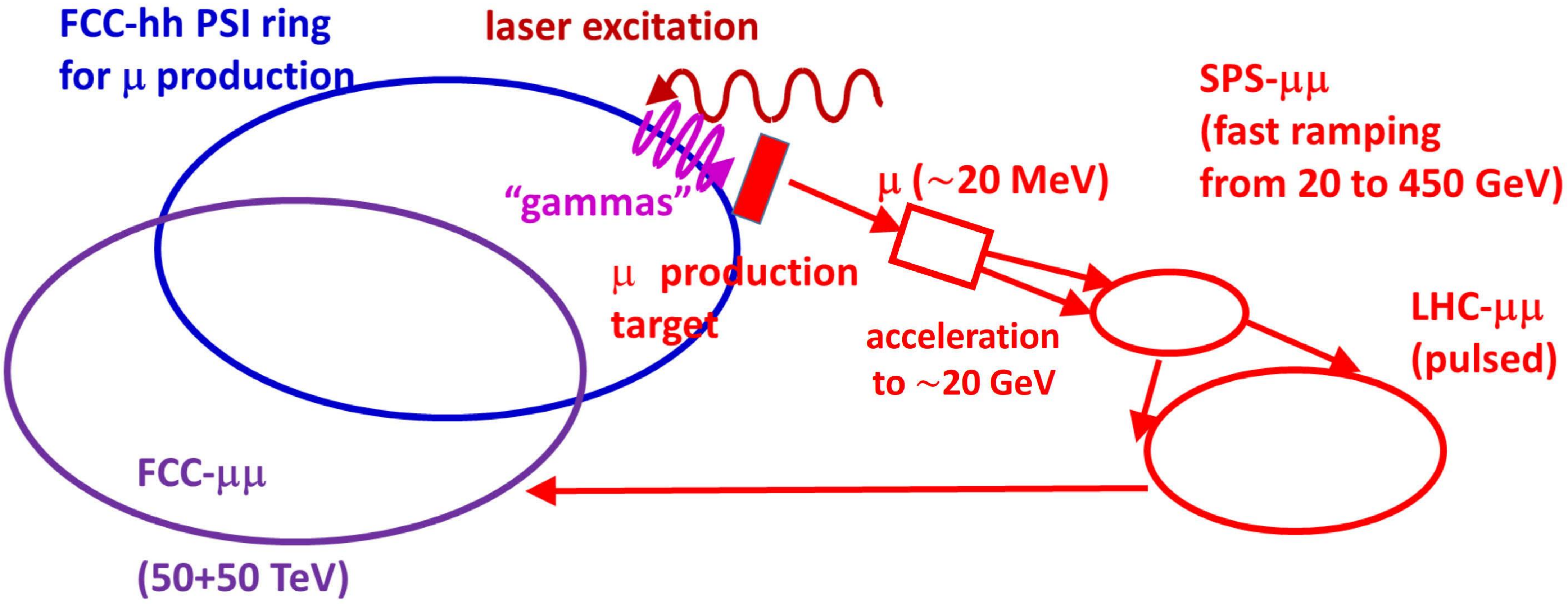
$$L \approx f_{rev} \dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \frac{1}{3^6} \gamma \tau^2 \frac{1}{4\pi\beta^*} = \frac{1}{3^6} \left\{ \left(\frac{eF_{dip}}{2\pi m_\mu} \right)^3 \frac{\tau_0^2}{4\pi c^2} \right\} [B^3 C^2] \left[\dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \right] \frac{1}{\beta^*}$$

100 TeV μ collider in *C*=100 km FCC tunnel with *B*=16 T

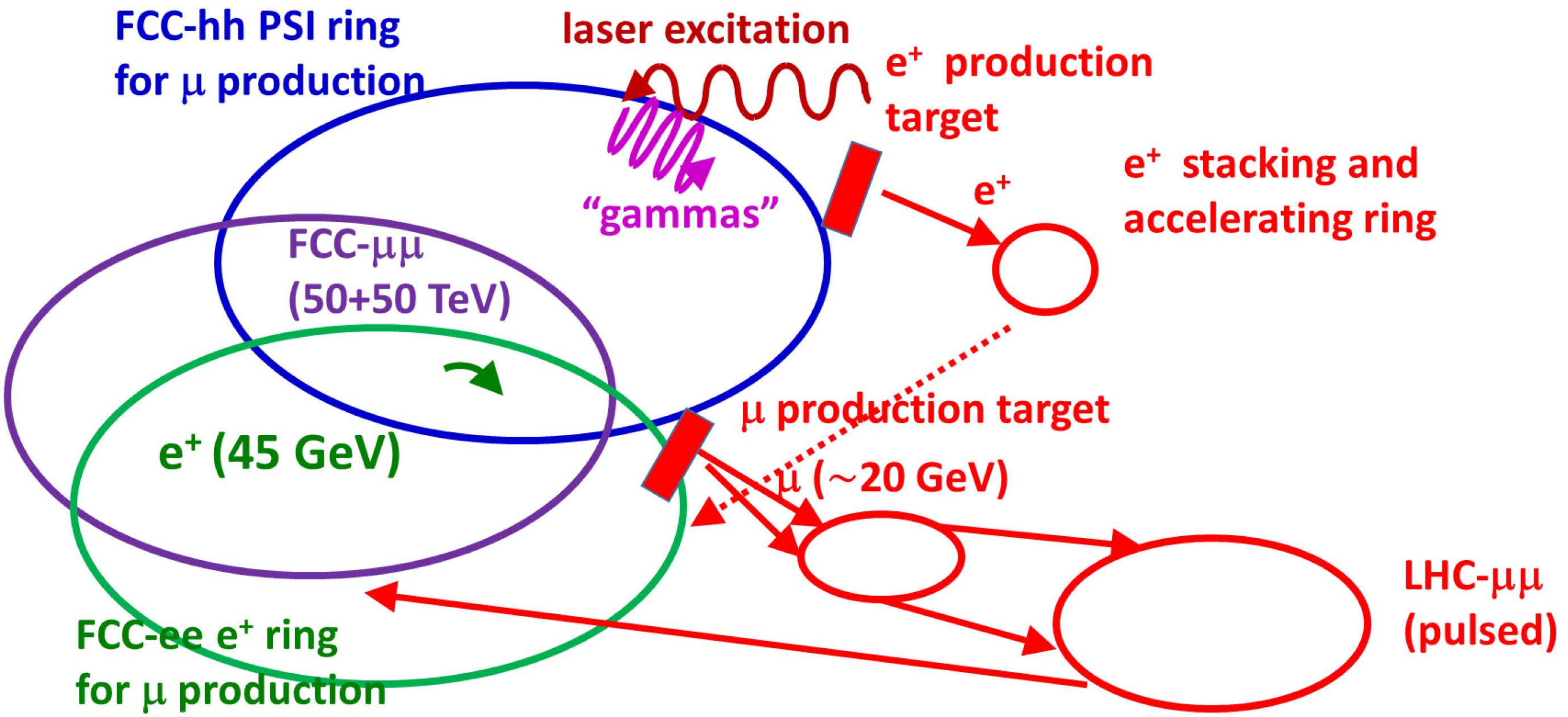
14 TeV μ collider LHC-μμ with FCC-ee $\mu^{\pm}$ production



100 TeV μ collider FCC-μμ with FCC-hh PSI $\mu^{\pm}$ production



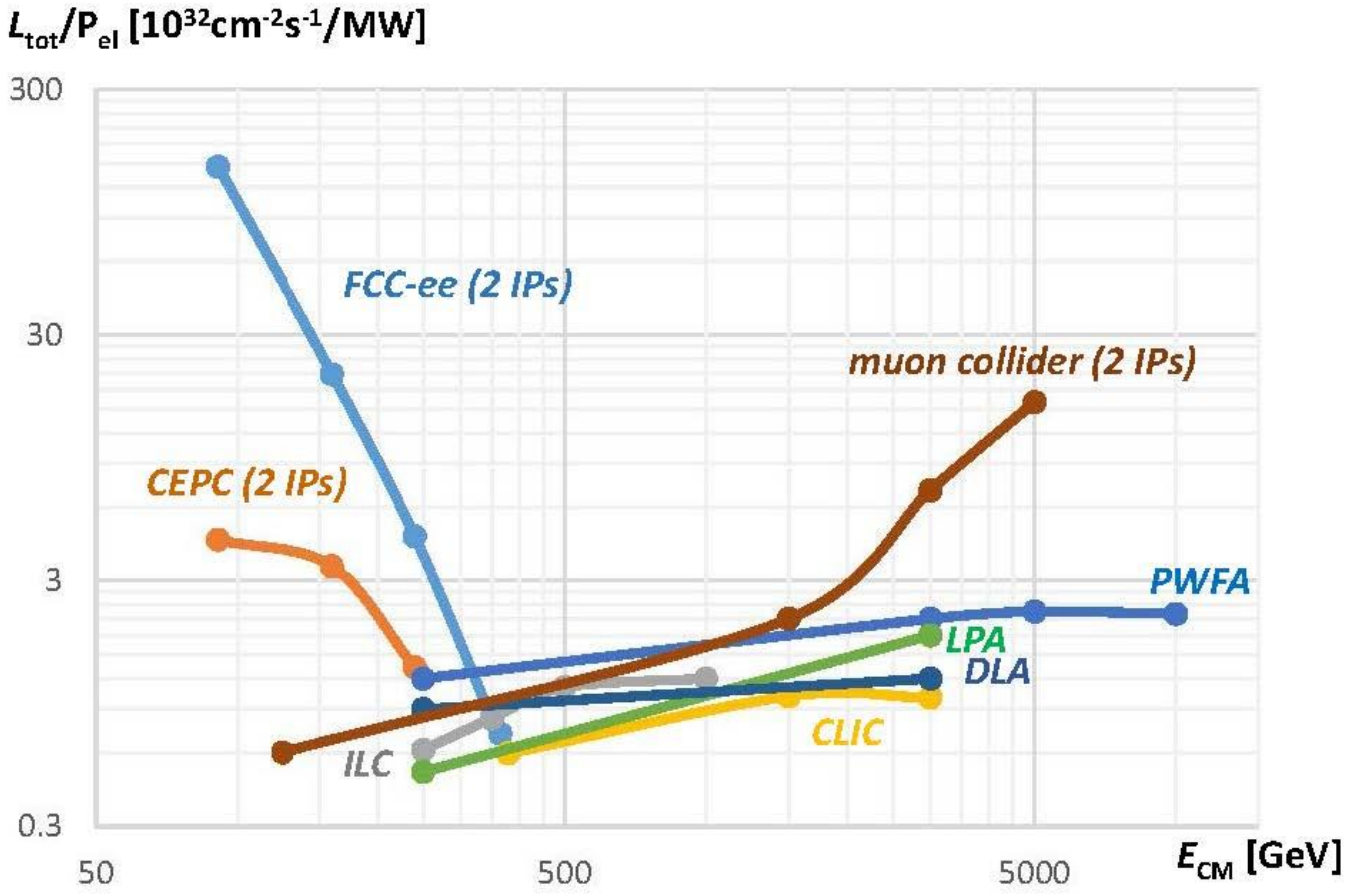
100 TeV μ collider FCC-μμ with FCC-hh PSI e⁺ & FCC-ee μ± production



Parameters of LHC/FCC based muon colliders
- using γ factory concept and optionally also LEMMA scheme

	LHC based, using γ factory e^+ & LEMMA	FCC based, using γ factory muons	FCC based. using γ factory e^+ & LEMMA
$\mu^+\mu^-$ c.m. energy [TeV]	27	100	100
#bunches / beam	1	1	1
average #μ / bunch [10^9]	4	16	4
β^* [mm]	1	1	1
norm. emittance $\gamma\varepsilon$ [μm]	0.04 (0.2?)	2000	0.04 (0.2?)
av. luminosity [10^{34} cm^{-2}s^{-1}]	0.05 (0.01)	0.003	10 (2)
comment	LEMMA emittance ?		LEMMA emittance ?

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



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

Conclusions

upgrade of existing and proposed facilities LEP(3)/LHC, FCC-hh/ee or CECP/SppC into a muon collider !

several key features of these facilities (e+ beam energy, positron flux, magnetic field, availability of intense beams of high-energy protons and partially-stripped heavy ions, etc.) exactly match requirements of future highest-energy muon collider complex

μ collider: ***long-term strategy*** for particle physics

FCC-based μ collider: ***optimum luminosity, best/multiple use of infrastructure***

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