14 TeV Muon Collider
LHC, MAP, and LEMC

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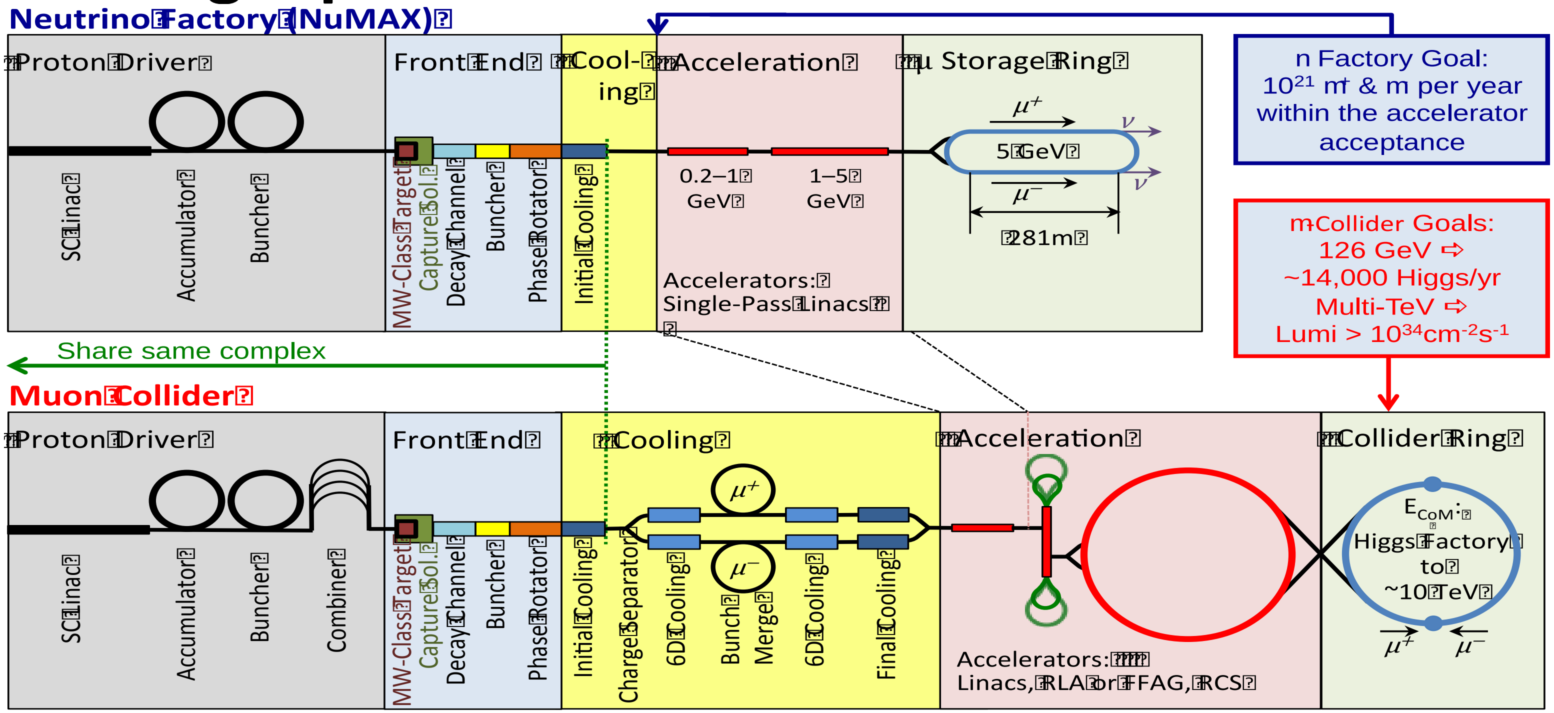
July 2018

Outline

- **Next Heavy Lepton Collider**
  - up to ~14 TeV in LHC tunnel
  - Needs muon source
    - PS or new MW proton Linac/storage ring
      - cooling …
    - or LEMC??
  - Affordable !!
- **neutrino radiation**
  - for 14 TeV in LHC collider
- **Comments on (45 GeV $e^+ + e^-$) source**
  - interesting problems
    - Liouville …

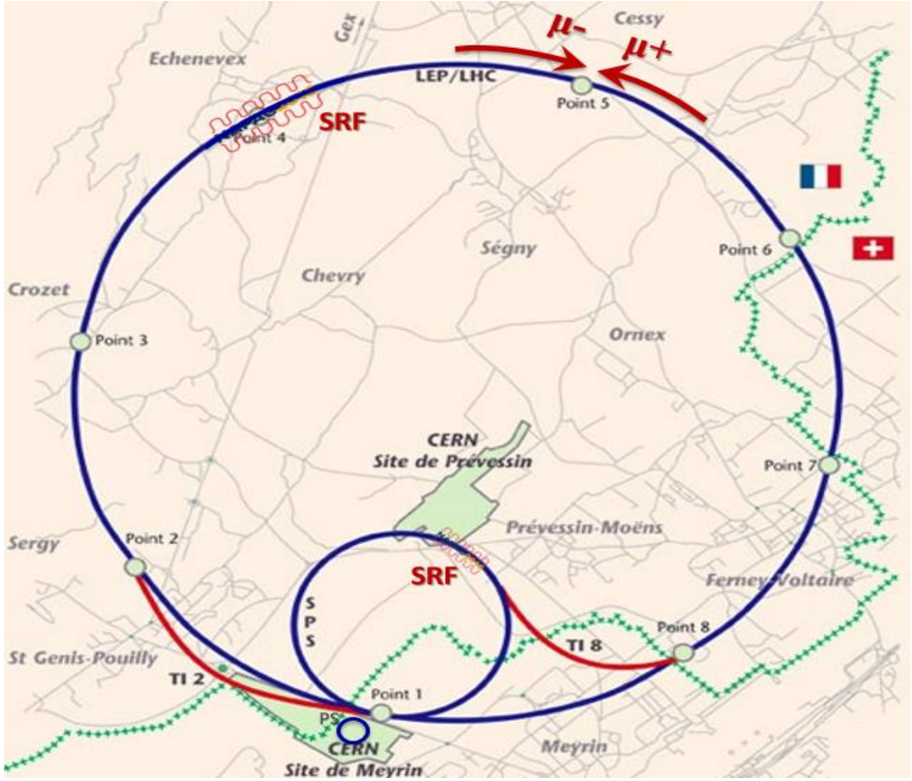
MAP → HEPAP status

- **MAP produced initial designs for muon storage ring neutrino sources and heavy lepton colliders**
  - -including initial beam delivery designs for mu2e and nuSTORM
- **P5 happened –MAP did not fit 2013 physics priorities**
  - too ambitious for US resources >>
- **US Flagship is DUNE**



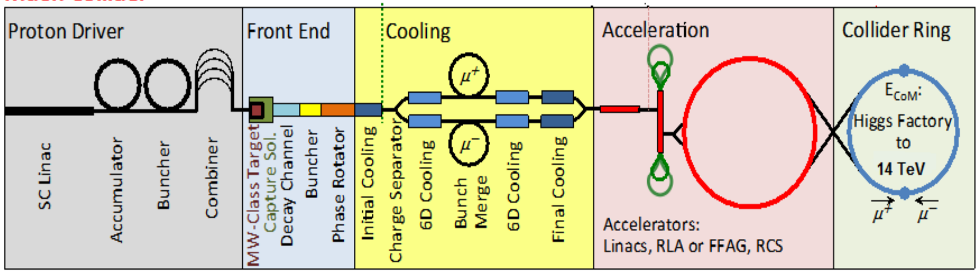
14 TeV "Next Muon Collider" 7×7 TeV

- **CERN needs world-class collider**
- **Use LHC tunnel**
  - Fill with accelerator and collider ring(s)
- **Result:**
  - 7 x 7 TeV collider
- **Reuses existing infrastructure**
  - ~100 m deep tunnel
  - cost possible ?
- **Must add a muon source**
  - high intensity



Shiltsev & Neuffer, IPAC 18

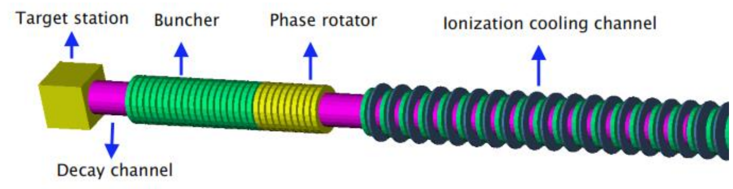
Muon Collider

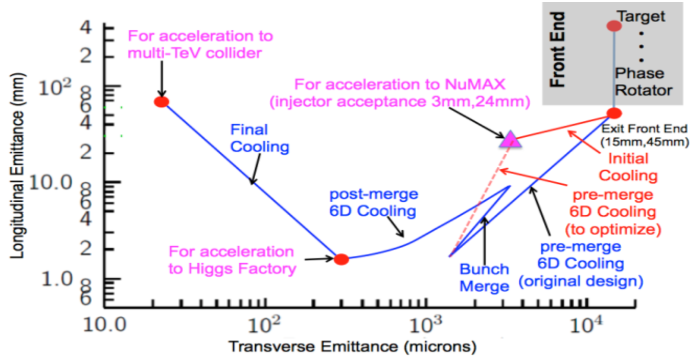


14 TeV machine muon sources

- Possible beam sources
  - **proton** based
  - CERN PS - ~0.13 MW
    - 24 GeV
    - 6 bunches/1.2s
      - 5Hz
  - new MW scale proton source (~MAP)
    - 5—8 GeV linac + storage ring
      - 5Hz
  - **Electron based** Boscolo et al.
  - e^+-e^- → μ^+ - μ^-
    - 45 GeV e^+ → 22GeV $\mu^+ \mu^-$
      - 2.2 kHz
    - no cooling …

- Proton-based source uses MAP-like cooling system
  - ~1 km long single pass
    - ~1—2 G$
    - verified by simulation
  - $\varepsilon_{t,N}$ → 25 μ; ε_L → 60 mm





HEPAP μμ 2020

14 TeV Collider scenarios ..

- Collect parameters from various scenarios
  - limit μ to ~10^{13}/s
  - τ_μ= 0.15s
- Accelerate in LHC tunnel
- Collider in tunnel
  - small β_t lattice
  - 800 luminosity turns (n_t)

$$L = \frac{f_o n_B n_t N_{\mu^+} N_{\mu^-} \gamma}{4\pi \varepsilon_{t,N} \beta_t^*}$$

Collider scenarios:

Parameter	"PS"	"MAP"	"LEMC"
Luminosity $cm^{-2}s^{-1}$	$1.2 \cdot 10^{33}$	$3.5 \cdot 10^{35}$	$2.4 \cdot 10^{32}$
Beam δE/E	0.1%	0.1%	0.2%
Rep rate, Hz	5	5	2200
N_μ/bunch	$1.2 \cdot 10^{11}$	$2 \cdot 10^{12}$	4.5×10^{7}
n_b	1	1	1*
$\varepsilon_{t,N}$ mm-mrad	25	25	0.04
β^* , mm	1	1	0.2
σ^*(IR), μm	0.6	0.6	0.011
Bunch length, m	0.001	0.001	0.0002
μ production source	24 GeV p	8 GeV p	45 GeV e^+
p or e/pulse	$8 \cdot 10^{12}$	$2 \cdot 10^{14}$	$3 \cdot 10^{13}$
Driver beam power	0.15MW	1.3MW	40 MW
Acceleration,	1-3.5, 3.5-7 RCS	1-3.5, 3.5-7 RCS	75 GV, RLA 100 turn
ν rad. (unmitigated)	0.02	0.30	0.003 mSv/yr

Acceleration ...

- 7 TeV μ lifetime = 0.15 s
  - RCS frequencies are manageable: 5 /20 Hz
    - high-field fixed magnets + ±2T rapid-cycling
    - ~18GV rf
  - could also use RLA
    - fixed field magnets
    - nonscaling FFAG arcs ??
  - LEMC with 2 kHz μ source needs fixed-field accelerator
    - 20 turns → 350GV rf
      - 100 turns → 70GV
    - LHC = 11 kHz

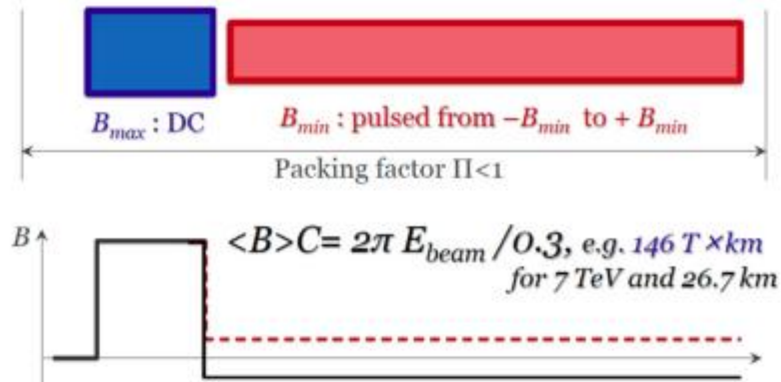


Table 1: Muon RCS Accelerator Parameters

	"LHC-S"	"LHC-D"		"SPS"
C, km	26.7	26.7	26.7	6.9
E_{max}, TeV	7	7	4	0.45
E_{inj}, TeV	0.45	4	0.45	0.03
f_{rep}, Hz	5	4	4	20
ΔE/turn, GeV	14.0	3.5	9.2	3.7
B_{SC}, T	16	16	16	8
L_{SC}, km	4.8	7.1	2.9	0.63
B_{pls}, T	3.8	2.0	1.9	0.8
τ_{ramp}, ms	42	76	34	2.6
dB_{pls}/dt, T/s	180	52	112	615

Costs ??

HEPAP 2020

- **Affordable?**
  - **according to Shiltsev cost model** (JINST 9 T07002 (2014)):

$$TPC \cong \alpha\left(\frac{L}{10\,km}\right)^{\frac{1}{2}} + \beta\left(\frac{E_{cm}}{1TeV}\right)^{\frac{1}{2}} + \gamma\left(\frac{P}{100\,MW}\right)^{\frac{1}{2}}$$

- $\alpha \cong$ 2B$ for civil construction,

$\beta \cong$ 1, 2 or 10 B$ for NC, SC magnets or SRF

- $\gamma \approx$ 2B$ wall plug power

  - **~9 G$**
    - **after ~3 G$ savings from using exiting tunnel(s)**

- **LEMC case ?**
  - **Larger power, rf ?**
  - **needs further design**

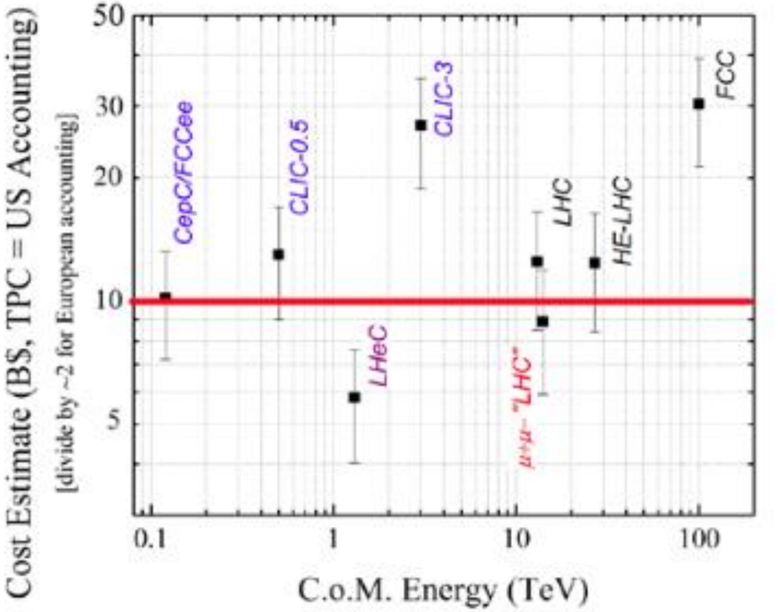


Figure 4: Cost estimates of various future colliders.

Neutrino radiation (CERN 99-12)

B. King PAC 99
Johnson et al. CERN98-34

- **Decay neutrinos are emitted with a 1/γ angle**

$$h \cong 2R\theta_{rms} = 2R/\gamma_\mu$$

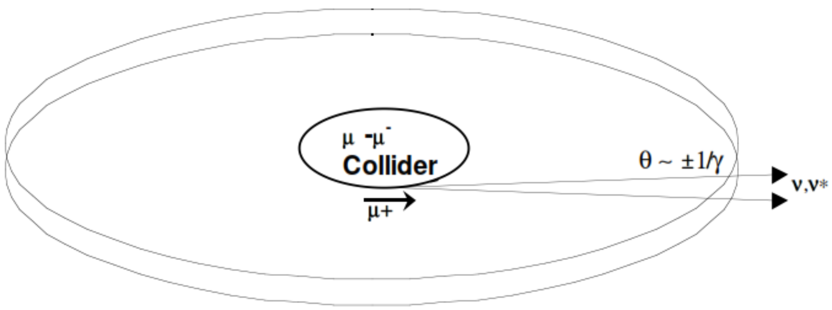
- **10^{20} μ/yr (10^{13}μ/beam/s)**

$N_\nu = 2n_B N_\mu f_0 N_s P_{decay}$

$$Dose \cong \frac{N_\nu}{2\pi hR}\sigma_{\nu-N}10^3 N_A E_\nu$$

- **Dose is ~0.15 mSv/yr/beam**
  - 7TeV μ, D=100m, 36km
    - CERN LHC limit is ~1mSv/yr

ν−Radiation from a μ^+-μ^- Collider



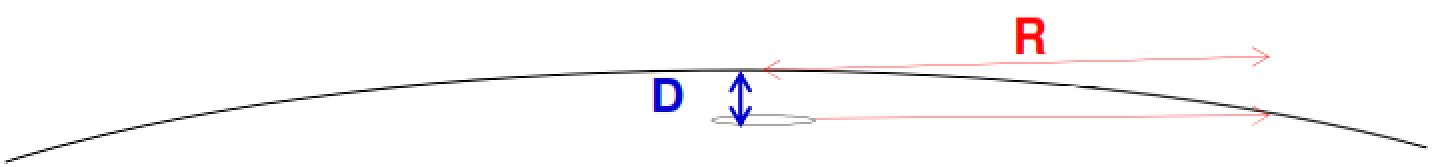
ν−Radiation appears in a disk of thickness ~R/ γ
at a radius R around the collider
(±1.5m thick at ~30km from a 4 TeV Collider)

$$\sigma_\nu \cong 7 \cdot 10^{-40} E_\nu\,(TeV)\; m^2$$

$E_\nu \cong E_\mu/3$

$$Dose \cong 0.57\frac{N_\mu' E_\mu^3}{R_x^2} mSv/year$$

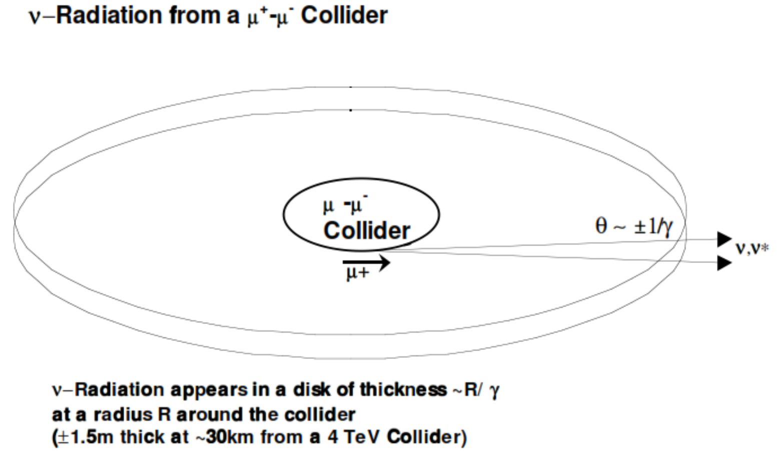
1 rem/yr = 6.25·10⁴ TeV/kg/yr
1mSv/yr= 6.25·10³ TeV/kg/yr

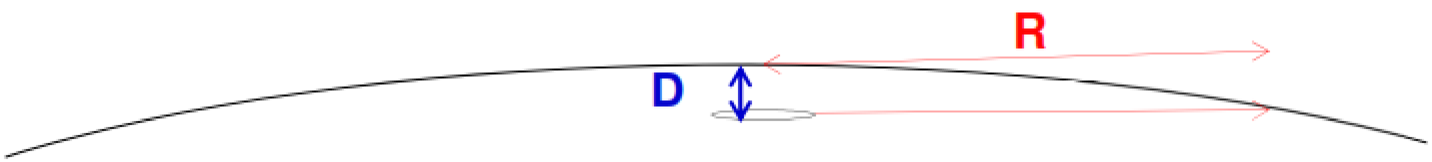


$$R = \sqrt{2R_{earth}D}$$

Oddities of the neutrino radiation

- 100 m deep ring→
  - R=36km band, 0.5m thick
    - μ^+ and μ^- bands differ
- LHC-100 m tilted ring
  - tilt into Lake Geneva and Jura
    - effectively a bit deeper …
- Model assumes target stays within band within material
  - lying in bed in a basement room
  - inside a basement swimming pool
- Could spread out by adding vertical oscillation





$$R = \sqrt{2R_{earth}D}$$

Decay along straight sections?

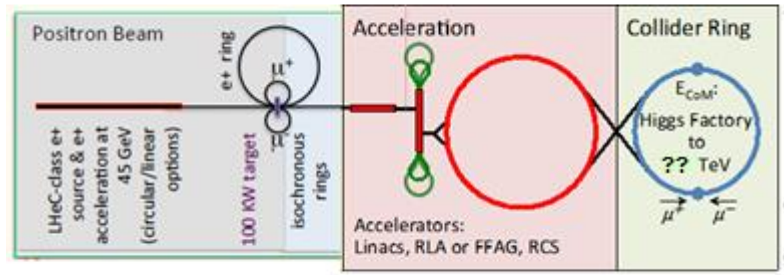
- Downstream intensity enhanced by $\frac{L\gamma}{c}$
- small number of straights
  - most point very far away, or outside habitation zones
  - IR straight beams have large divergence
- a few close emergences
  - 0.5m radius beam at 30k
  - Buy locations; insert neutrino detectors
    - multi-TeV neutrino beams
    - great beam monitors – need 2
- For LHC muon Collider, a feature !!
  - not a bug

Application to 14 TeV Muon Collider

- CERN standard is ~1 mSv/year
  - (approved for LHC)
- Fermilab standard is 0.1mSv/yr
  - 1/10 DOE limit
- High-Luminosity LHC muon collider is ~0.3 mSv/year
  - 10^{20} μ/year/beam
- Can be reduced by orbit modulation
  - ~1/10
- Is a significant consideration
  - limits luminosity, and energy

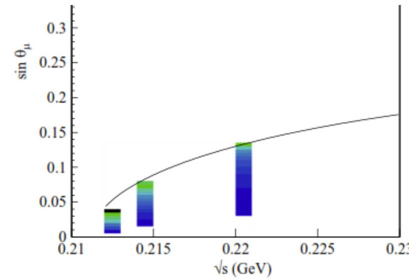
LEMC scenario (Boscolo et al.)

- **Scenario has very interesting features**
  - and problems
    - and solutions ?
- **Requires**
  - positron source
  - 45 GeV positron ring
  - 22 GeV muon accumulator rings
  - ~cw acceleration
  - collider ring
- **no cooling**
  - Liouville's theorem

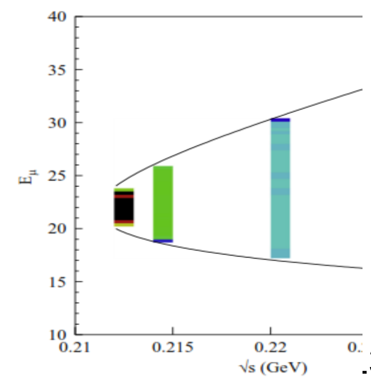


e^+ (45 GeV) $+ e^-$ (rest) $\rightarrow \mu^+ + \mu^-$

- small ε_t : 1mrad $*0.2*10^{-6}$ m
  - at $\varepsilon_e = 0$



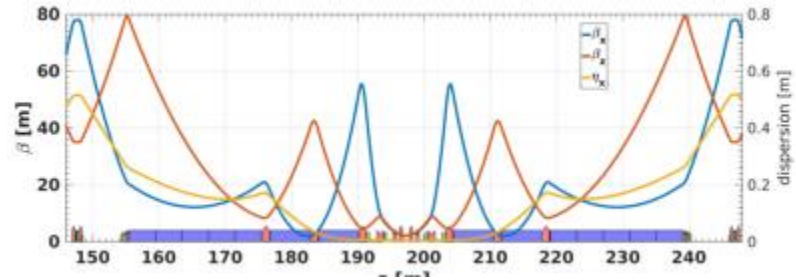
- large ε_L: 2 GeV*0.003m



45 GeV positron ring on Be target

- **A Problem is Be Target (3mm)**
  - e^- + nuclei
  - Lifetime is < 50 turns
    - $3\ 10^{16}$ 45 GeV e^+/s (200MW)

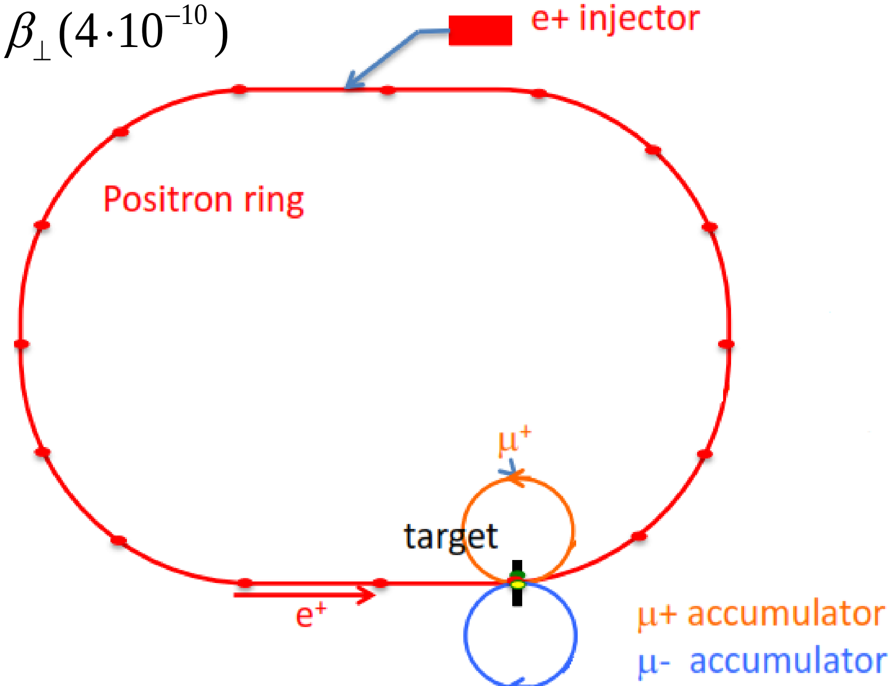
$$\frac{d\varepsilon_N}{ds} = -\frac{g_t}{\beta^2 E}\frac{dE}{ds}\varepsilon_N + \frac{\beta\gamma\ \beta_\perp}{2}\frac{d\langle\theta_{rms}{}^2\rangle}{ds}$$



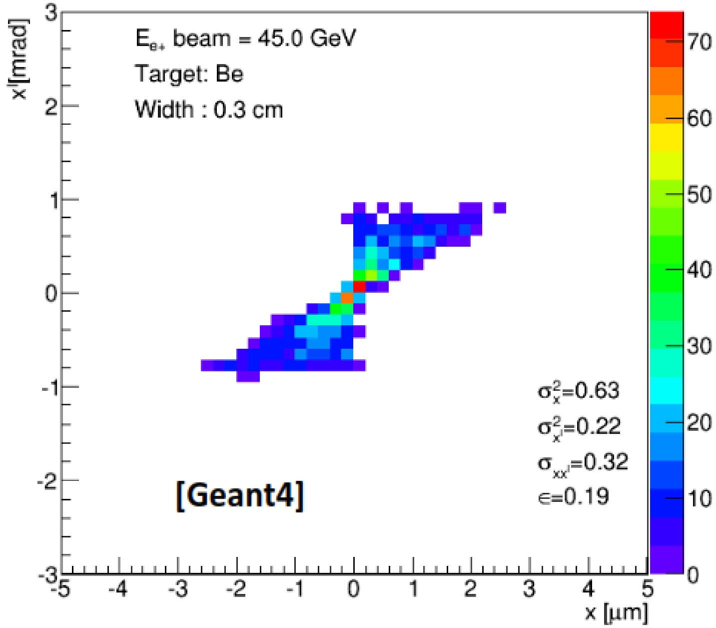
  - multiple scattering & Bremstrahlung

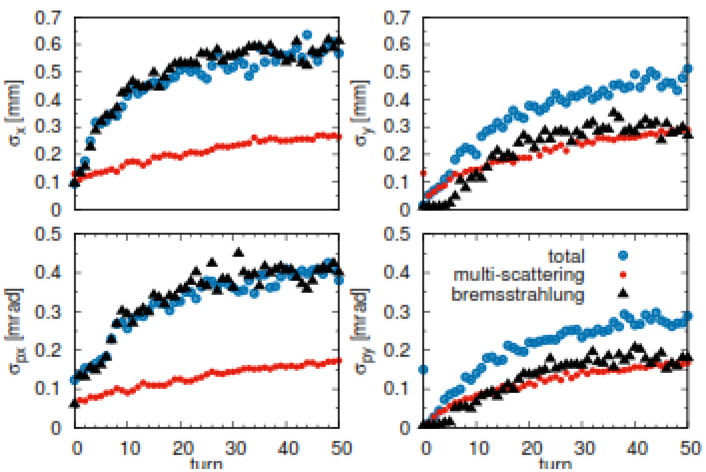
$$\frac{d\varepsilon_{geo}}{dn_{turn}} = \beta_\perp (4\cdot 10^{-10})$$

  - 3mm Be = ~1% X_0
    - ~1% energy loss /turn
  - emittance increase
    - if $\beta_\perp > 0.2$m
    - at $\varepsilon_{x,geo,e}$ = ~6 10^{-9} m



positron and muon beams must match





- $\varepsilon_{\perp,geo,\mu} \rightarrow 0.2 \cdot 10^{-9}$ m
  - IF $\varepsilon_{\perp,geo,e} = 0$ (and $\sigma_{e+}=0$)
  - but $\varepsilon_{x,geo,e} = \sim 6\ 10^{-9}$ m +
- In IPAC 17 (Boscolo et al.)
  - $\sigma_e+ = \sim 0.1 - 0.3$ mm at target
    - should be < 1μm
- To avoid large ε_μ, need:
  - $\varepsilon_{x,geo,e+} < 10^{-9}$ m
  - $\beta_\perp < \sim 0.003$m

Another Problem – high energy stacking

- **Produce bunches every 500 μs**
  - accelerate into 7 TeV ring with RLA/FFAG; collide

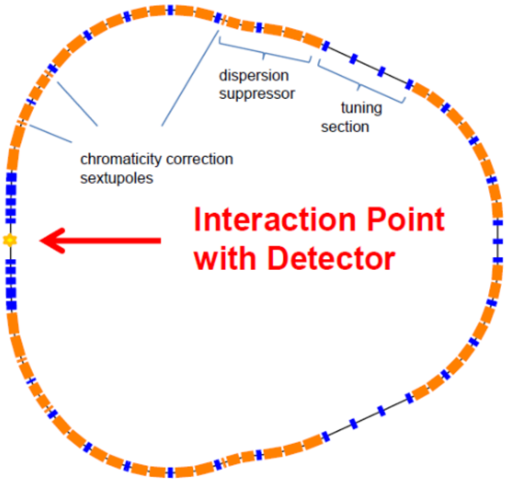
- **Bunch combination at high energy?**
  - The actual number of μ/bunch in the muon collider can be larger by a factor ~ τ_μ^{lab}(HE)/500 μs (~100 @6 TeV) by topping up.

Antonelli, ICHEP2016

  - "topping up" works in electron rings because of radiation damping
  - **Does not work** in muon rings because of **Liouville's theorem**
  - can have multiple bunches in collider ring (but not combined)
- **stacking in longitudinal phase space is limited**
  - 1 bunch = ~ MAP goal longitudinal emittance
- **stacking in transverse phase space reduces luminosity**

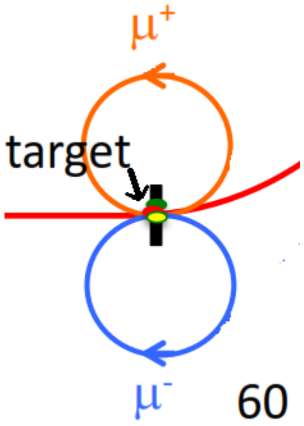
22 GeV muon rings

- For multi turn accumulation (at ~ 2 kHz)
  - $\varepsilon_{t,N} = 4\cdot10^{-8}$ m, ε_L =~3 mm · 2GeV/0.1→ ~0.06m
- C =60m →2290 turns
- If accumulating muons are recirculated through target, can multiturn inject without increasing ε
  - But ....
    - needs matched lattice at target (β^*= 3mm ?),
    - momentum acceptance – 10% - isochronous /matched rf
  - Closest example is 62.5 GeV Higgs collider lattice
    - Y. Alekhin et al.
    - 300m, β^*= 3cm, $\varepsilon_{t,N} = 2\cdot10^{-4}$ m, $\delta < 0.1\%$



But … Liouville …

- 2000 turn multiple scattering is not small
  - even with $\beta_\perp$ = 3mm, ε_N =4· 10^{-8} m



$$\frac{d\varepsilon_N}{dN_{turn}} = +\frac{\beta_\perp}{2}\frac{E_s^2\,\delta z}{\beta^3\gamma L_R\left(m_\mu c^2\right)^2} =\sim 10^{-9}$$

  - $\varepsilon_N \rightarrow 2\cdot 10^{-6}$??

  - dE/turn ~ 1.5 MeV → 2 GeV total
    - need rf for reacceleration

- Solution
  - Use Third Law of Beam physics
    - does not fit in the margins of this talk

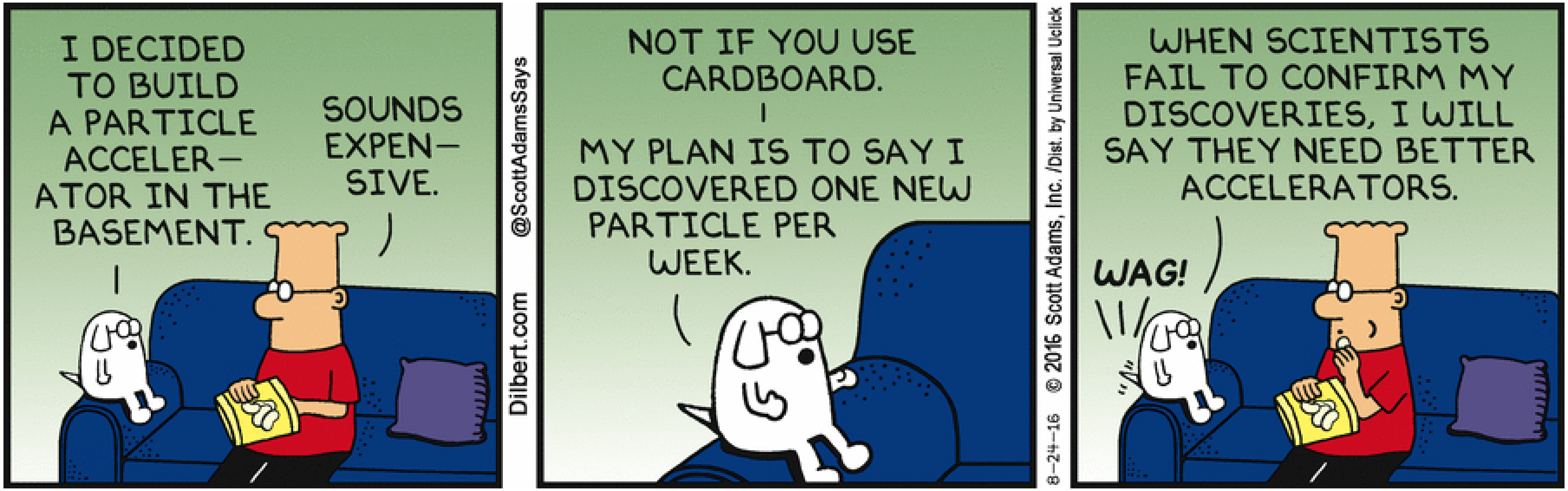
Summary

- **~14 TeV μ^+ μ^- Collider in LHC tunnel is possible**

- **Can use proton driver from PS or new Linac**
  - high luminosity requires muon cooling
    - more cooling is better…
  - or novel low-emittance source

- **neutrino radiation is a constraint**
  - manageable …

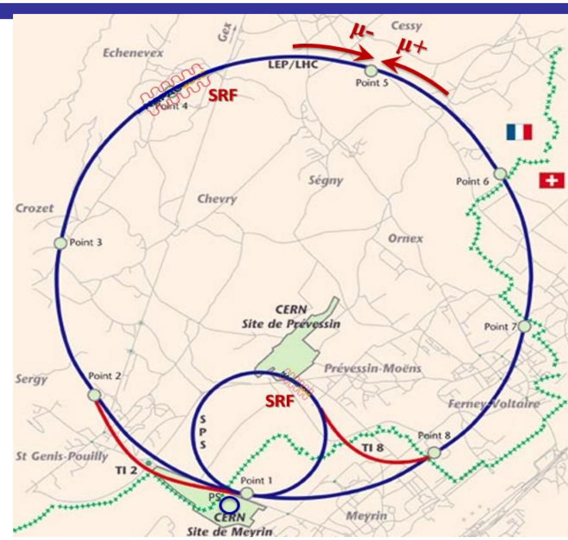
- **new muon source (45 GeV $e^+ + e^- \rightarrow \mu^+ \mu^-$) poses interesting challenges**
  - more beam physics study …
    - use 3rd Law



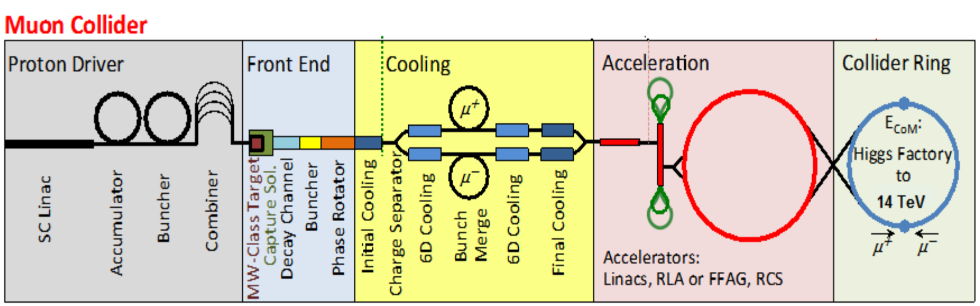
Thank you for your attention

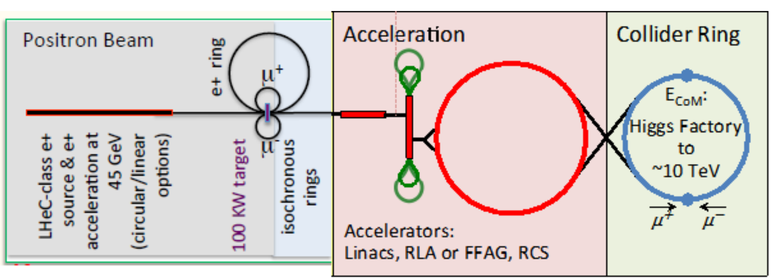
High Energy to 14 TeV at LHC

- **CERN is interested in $\mu^+\mu^-$ site-filler**
  - fits in LHC tunnel
  - 7 x 7 TeV – 14 TeV Collider
- **Could consider for muon source:**
  - PS-based proton source + cooling
  - MAP 8GeV 2MW p + cooling
  - threshold 45 GeV e^+ ring + e^- production
    - LEMC- Boscolo et al. –no cooling



Shiltsev & Neuffer, IPAC 18





Parameter	Units	pos_Ring e+
Energy	GeV	45
Circumference	m	6300
Bending radius	m	709.6
Magnetic rigidity	T m	150
Lorentz factor		88062.62
Coupling (full current)	%	1
Emittance x (from model)	m	5.73E-09
Emittance y	m	5.73E-11
Bunch length (zero current)	mm	3.6
Beam current	mA	240
RF frequency	Hz	5.00E+08
RF voltage	GV	0.768
Revolution frequency	Hz	4.76E+04
Harmonic number	#	10508
Revolution period	s	2.10E-05
Number of bunches	#	100
N. Particle/bunch	#	3.15E+11
Syncronous phase	#	0.73
Syncrotron frequency	Hz	2415.31
Synchrotron tune	#	5.08E-02
synchrotron period	turns	19.70
Overvoltage		1.50
Transverse damping time	turns	175.00
Transverse damping time	s	0.0037
Longitudinal damping time	turns	87.50
Longitudinal damping time	s	1.84E-03
Energy Loss/turn	GeV	0.511
Momentum compaction		1.21E-04
B field	T	0.211
Rf energy acceptance	%	3.98
Energy spread (SR)	dE/E	1.00E-03
SR power loss	GW	0.12
SR power/Circumference	kW/m	19.48

3 Laws of Beam Physics

1. **Beam Phase Space cannot decrease**
   - Liouville's theorem cannot be violated

2. **Beam Phase Space increases**
   - bunch combination is inefficient

3. **Break the 1st Law wherever possible**
   1. radiation damping
   2. stochastic cooling
   3. electron cooling
   4. ionization cooling
   5. charge-exchange injection
   6. "stochastic injection" ($\pi \rightarrow \mu$ decay)
   7. ??