M1+M3 SESSION ON mu-LCs

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e^+e^-

+

$\mu^+\mu^-$

GOAL OF SESSION

To determine whether the linacs of a TeV-scale e+e- linear collider can be used to accelerate muons for energy frontier muon colliders *assuming that muon collider technology works*.

CAVEAT: we don't yet have a complete lattice design for a muon collider cooling channel.

Potential Benefits:

- it would provide one potential upgrade path for an existing TeV-scale e+e- linac to reach multi-TeV energy scales
- the acceleration would otherwise be the most expensive part for energy frontier muon colliders

INTRODUCTION

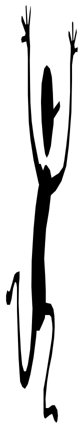
- THE IDEA: DAVE NEUFFER'S SLIDES FROM 1996 SNOWMASS
- MOTIVATION & STRAW-MAN PARAMETER SETS
- MUON COLLIDER TECHNOLOGY ISSUES
- NEUTRINO RADIATION CONSTRAINTS
- DESY & FERMILAB SITE SUITABILITY
- LEAD-IN TO DISCUSSION ON MU-TESLA ISSUES

Dave Neuffer's Slides

(showed slides supplied by David Neuffer)

WHY MAKE THE UPGRADE: e+e- -> INCLUDE MUON COLLIDER?

Extend the energy frontier!



Electrons are too light

Discovery reach of ~10 TeV ?

Protons are composite & strongly interacting

Discovery reach of some 10's of TeV ?

⇨

Add Muons, though unstable

Discovery reach of ~100 TeV (circular)? ~1 PeV (linear)???

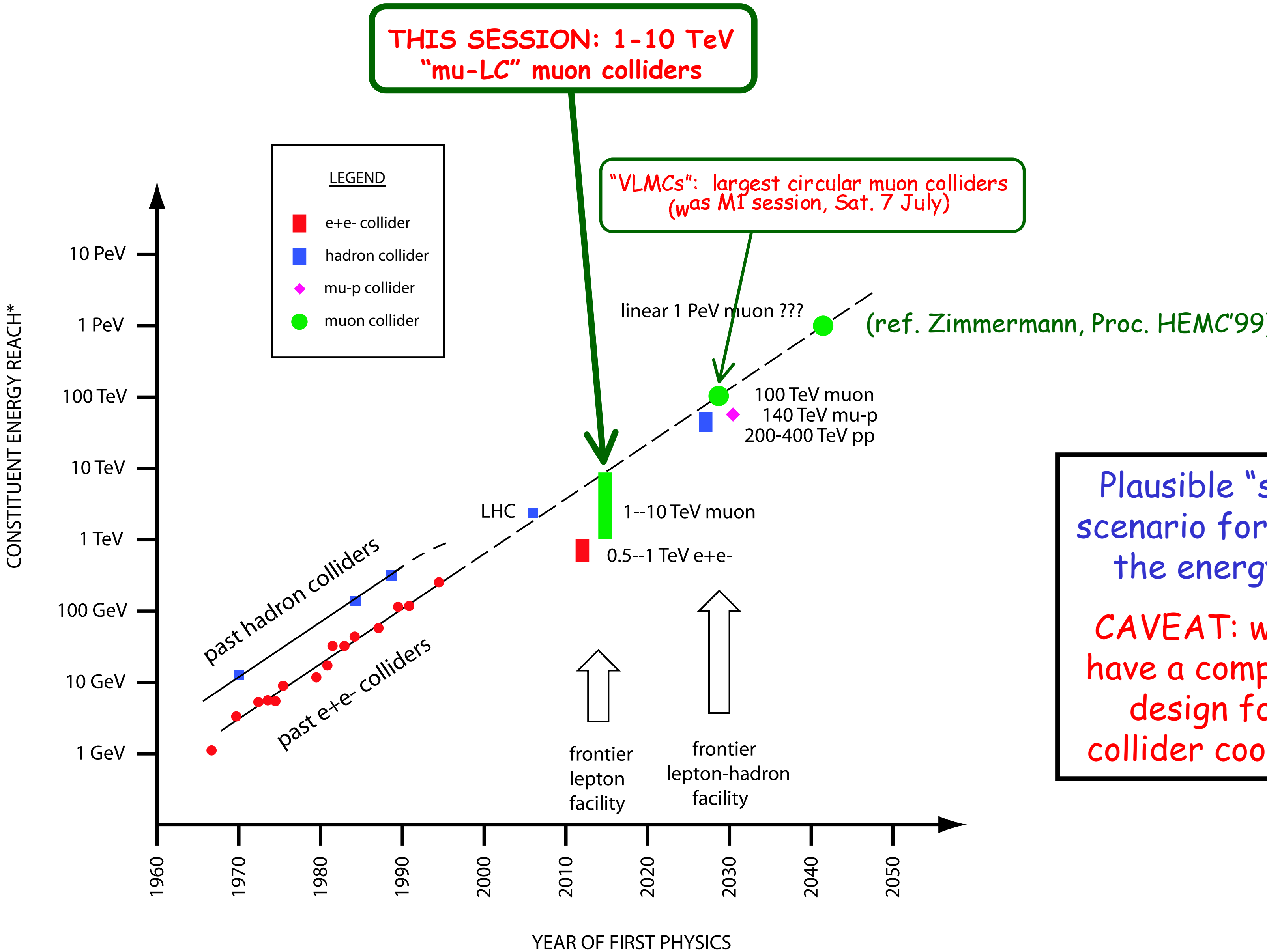
$m_\mu \sim 206 \times m_e$

$\mu \to e\nu\nu$

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

Muons give the potential for an even higher potential discovery reach than with proton colliders, using clean lepton-lepton collisions.

INTRODUCING MUON COLLIDERS CAN HELP TO MAINTAIN STEADY PROGRESS IN HEP DISCOVERY REACH



Plausible "straw-man" scenario for progress at the energy frontier

CAVEAT: we don't yet have a complete lattice design for a muon collider cooling channel

(SEE STRAW-MAN PARAMETER SETS)

Luminosity = 1×10^{34} $cm^{-2} \cdot s^{-1}$

SOME LUMINOSITY SCALINGS

With plausible assumptions & for a given muon collider energy, it can be easily shown that:

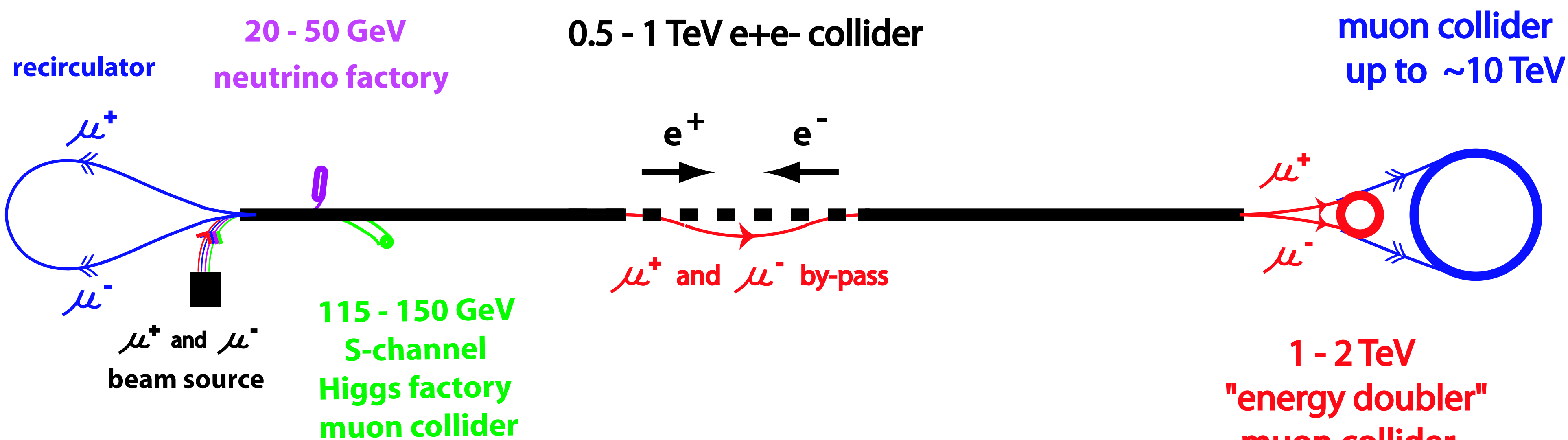
$$\text{Luminosity} \propto \frac{I}{C}\sqrt{\frac{\mathrm{B}_6.\delta.N}{\beta^*}}$$

where

- I = beam current, which is constrained by neutrino radiation
- C = collider ring circumference, depending on dipole magnet strength
- B6 = the 6-dimensional beam phase space density or "brightness", determined by the final stages of the muon cooling channel
- δ = the fractional momentum spread at collision
- β^* = the beam's beta function at collision, determined by the beam delivery lattice design and magnet performance

The parameter sets are just examples - the scheme is very flexible ...

"Swiss army knife" accelerator: choice of gadgets is dictated by cost and HEP results from LHC etc.



e.g. a neutrino factory could be a $100-million-class add-on & the cold muon beam would produce a better characterized neutrino beam than at a stand-alone neutrino factory.

MUON COLLIDER TECHNOLOGIES FOR muLCs

… includes comparing technologies & straw-man parameters to stand-alone muon collider parameters in Muon Collider Collaboration's "Status Report" **(MC SR)** (108 authors), *Phys. Rev. Special Topics, Accel. Beams 2, 081001 (1999)* - available at Snowmass on Muon Collaboration's "Recent Reports" CD

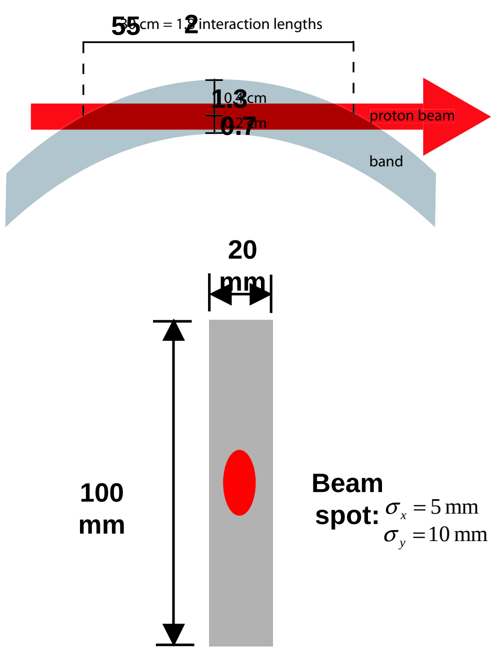
Proton Driver & Pion Production Target Should be OK

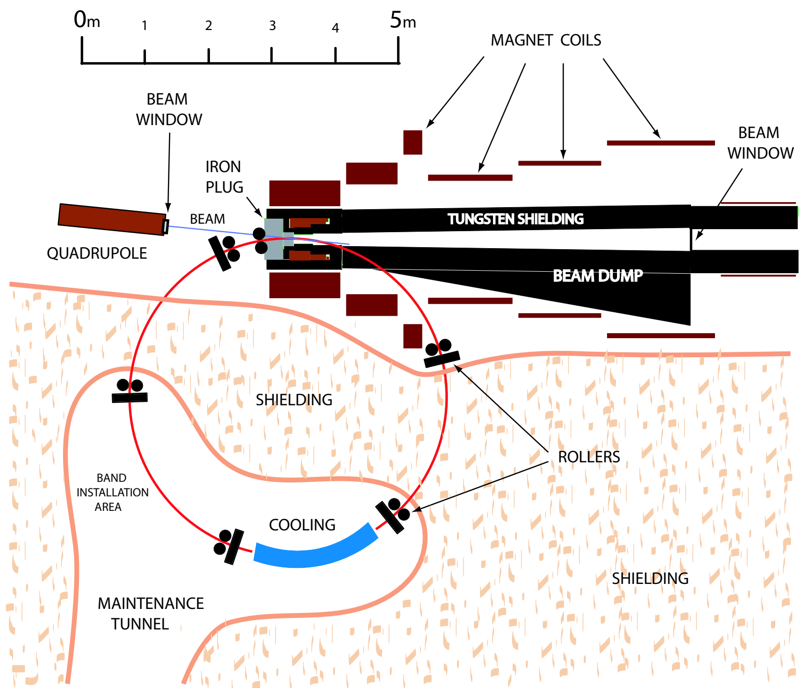
Much fewer muons needed: low currents for conservative neutrino radiation => parameter sets only use 0.007 - 0.44 of muons/year used in specs. of MC SR, which assumed a 4 MW proton driver

=> the proton driver for muLCs might be tens of kW to a couple of MW.

Existing target design concepts can comfortably handle this, e.g.:

Ti-alloy band target



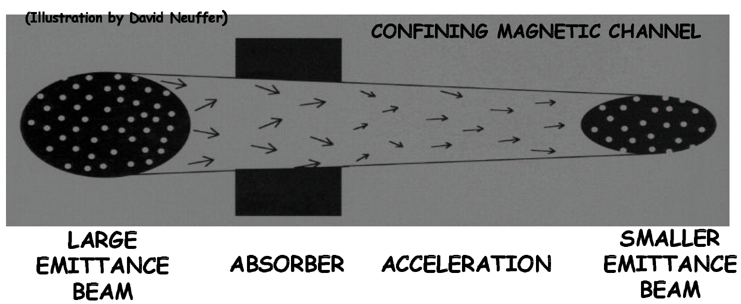


Ref. BJK, Mokhov, Simos & Weggel, "A Rotating Metal Band Target for Pion Production at Muon Colliders", *Proc. 6-Month Study on HEMC's* (available on CD here at Snowmass)

"IT'S THE COOLING"

The high-performance ionization cooling channel is the signature technology and dominant technical challenge for muon colliders.

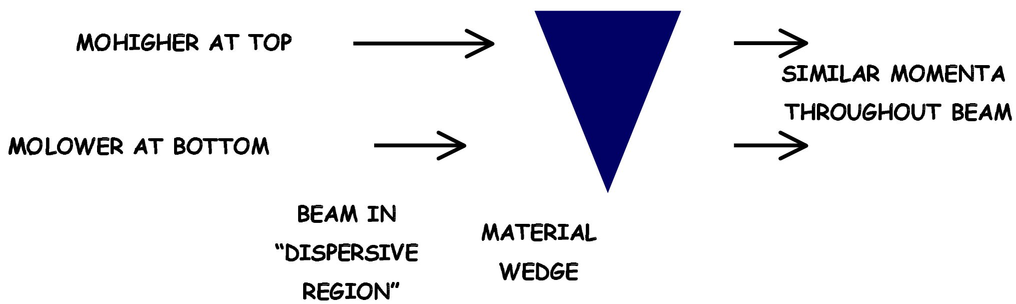
Simple concept:



However, Coulomb scattering and energy straggling compete with cooling,

A) confines cooling to a difficult region of parameter space (low energy, large angles)

B) need to control beam energy spread to obtain required ~10^6 reduction in 6-D phase space:



"emittance exchange"

COOLING: WHAT WE HAVE & WHAT WE NEED NEXT

We have:

a) general theoretical scenarios & specs. to reach the desired 6-D emittances

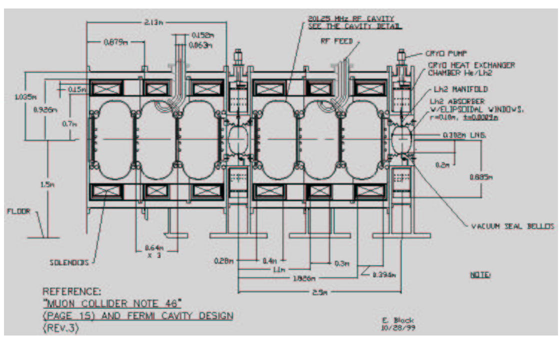
b) detailed particle-by-particle tracking codes (modified GEANT,ICOOL) & (new) higher order matrix tracking code (modified COSY-infinity) + (new) wake field code interface

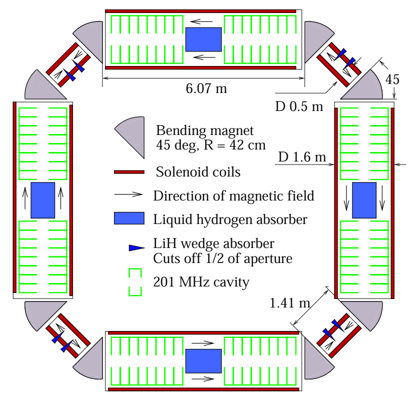
c) engineering designs of pieces

d) neutrino factory designs for first factor of ~10 *transverse* cooling

e) "ring cooler" design progressing for MUCOOL expt. with predicted full 6-D cooling by factor of ~32 (c.f. muon collider needs ~10^6 ~ 32^4)

2 sub-units of a cooling stage (Black, IIT)





"ring cooler"

(Balbekov, FNAL)

But we have yet to put the pieces together to "build the muon collider cooling channel on a computer" - particularly the final stages, where the parameters are very different to those for neutrino factory designs => This is our #1 item of business

COOLING DIFFERENCES TO MC SR SPECS.

- **bunch charges are much smaller** than in MC SR: (0.2-9)x10^{11} vs. (20-40)x 10^{11}.
- assumed muon **phase space densities are 1-2 times larger** than for MC SR Higgs factory parameter set. The highest densities correspond to the lowest beam currents where it is assumed that cooling performance can be traded off against a low muon survival efficiency.
- the **ratio of transverse/longitudinal emittances is typically smaller** than in MC SR, probably corresponding to a lower-momentum final cooling stage.
- the lower energy specs. additionally assume a **final rebunching** into a train of smaller bunches, without much blow-up in the phase space density.

The above assumptions are plausible but all need to be verified in final-stage cooling channel lattice designs and simulations (and, eventually, hardware).

RECIRCULATING ARCS FOR ACCELERATION

Require average accelerating gradient >> $m_\mu c/\tau_\mu$ = 0.16 MeV/m

The bountious rf acceleration from the e+e- linacs makes the muon recirculation **easier for muLCs** than for stand-alone muon colliders, with fewer recirculating passes required

=> all the parameter sets can use conventional magnet lattices for the recirculating arcs. At the higher energies, where several passes are required, FFAGs or fast-ramping magnets might be considered as potentially cheaper alternatives.

(See Scott Berg's talk later in the session.)

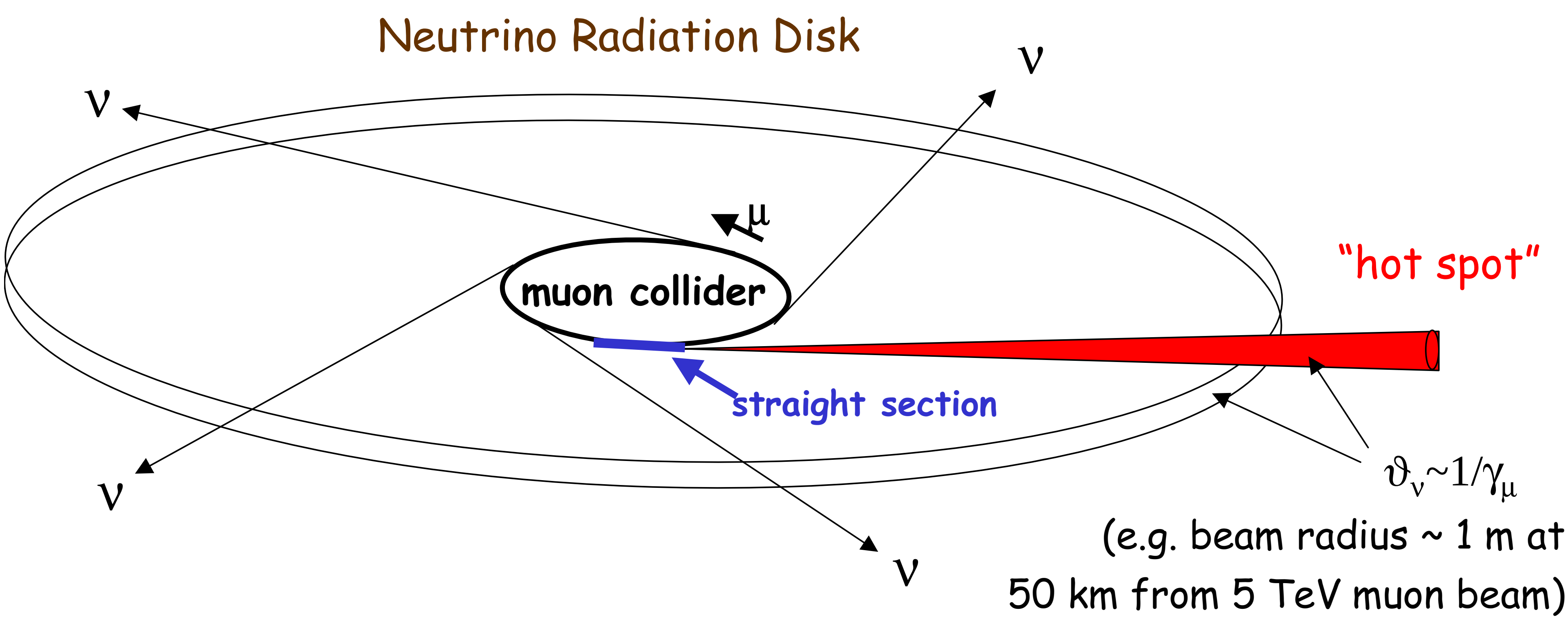
COLLIDER RING & DETECTOR

- smaller currents than MC SR => less energy deposited in beam pipe
  14-820 W/m c.f. 1000-1700 W/m for MC SR
- more aggressive average bending fields
  5.6-10.5 T/m c.f. 5.2 for MC SR @ 1.5 TeV/beam
- smaller bunch sizes & currents => lower backgrounds in detector
- smaller transverse emittances & beta*'s => similar angular spreads at IP:

see Carol Johnstone's talk on final focus design

NEUTRINO RADIATION ISSUES

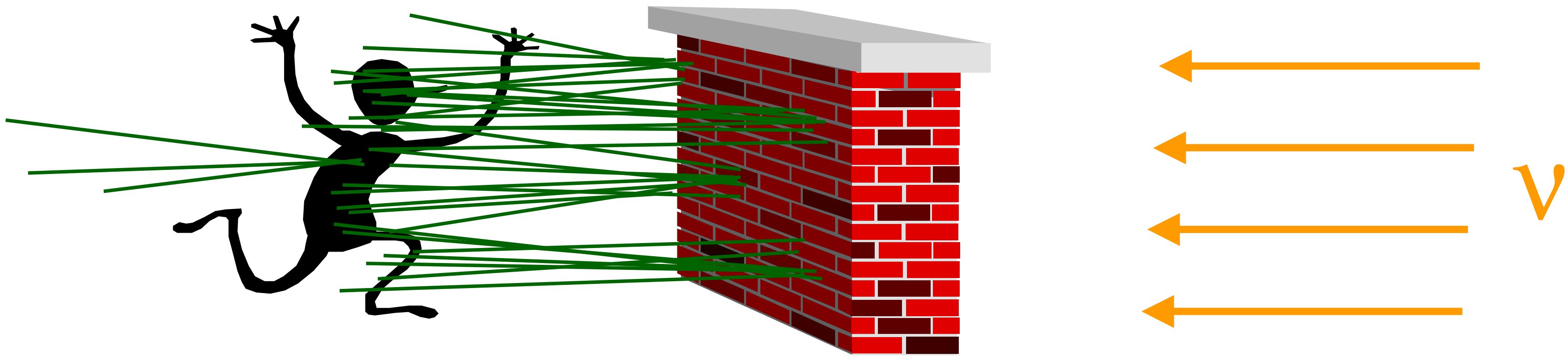
NEUTRINO RADIATION => VLMC SITE CONSTRAINTS (1 of 2)



neutrino production: μ->eνν

THE OFF-SITE RADIATION CONSTRAINT

Neutrino interactions in the surroundings initiate the charged particle showers that lead to the radiation constraint ...



The predicted dose rises sharply with collider energy for a fixed muon current => muLCs at higher energies will need smaller currents

The beam current etc. have been chosen in the straw-man parameter sets to give direction-averaged worst case nu-rad ~ 9×10^{-4} mSv/year for mu-TESLA and $(2\text{-}3)\times10^{-3}$ mSv/year for mu-NLC at all energies (1.6-11.2 TeV), all with $L=1\times10^{34}$ $cm^{-2}.s^{-1}$.

c.f. 1 mSv/yr = U.S. Federal off-site limit ~ natural background

Predicted Radiation Dose up to ~TeV Energies*

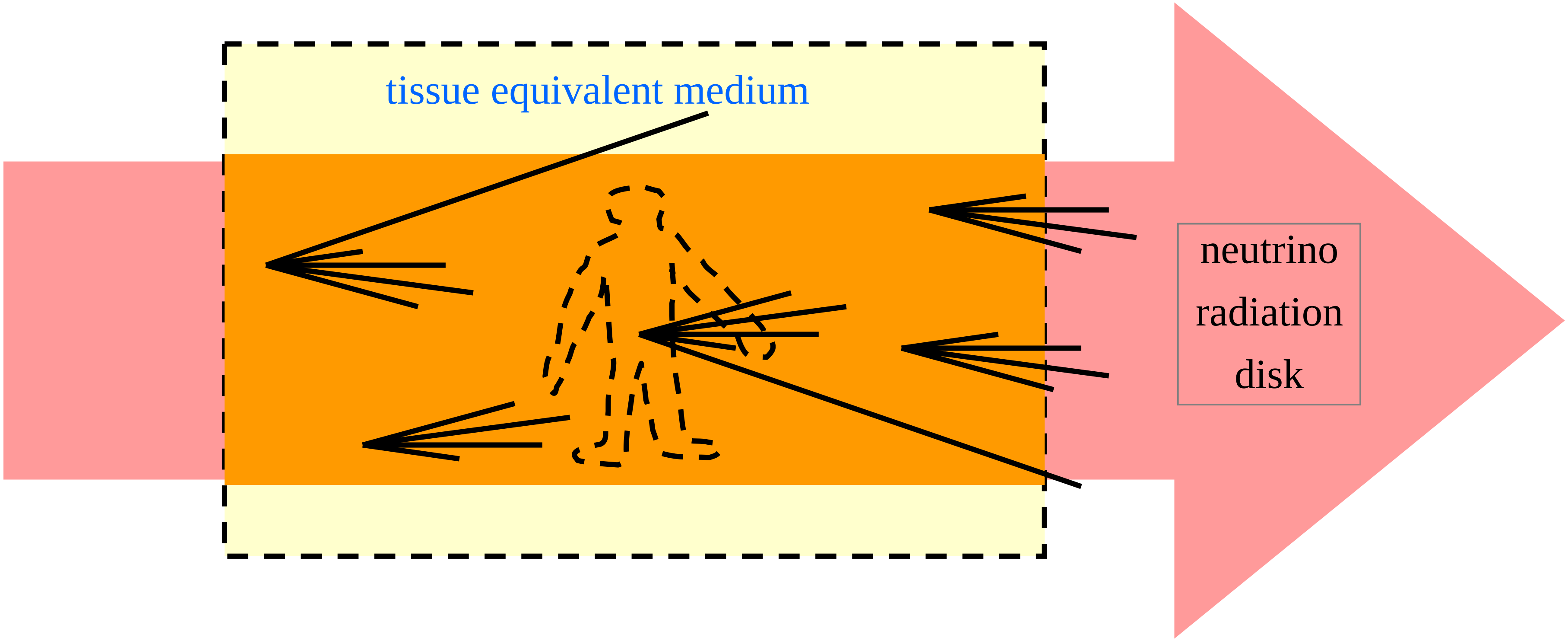
$$\text{Radiation Dose[mSv]} \cong 0.4 \times N_{\mu+}[10^{20}] \times \left(\frac{\text{length of str. section}}{\text{collider depth}} \right) \times \left(E_{\text{CoM}}[\text{TeV}] \right)^3$$

1 mSv/yr = U.S. Federal off-site limit ~ natural background

- a conservative, order-of-magnitude analytic calculation
- collider depth ~ (distance to surface)^2 for a non-tilted ring and locally spherical Earth
- the formula overestimates the dose close-by & at many-TeV energies

*ref. BJK, "Neutrino Radiation Hazards at Muon Colliders", physics/990817

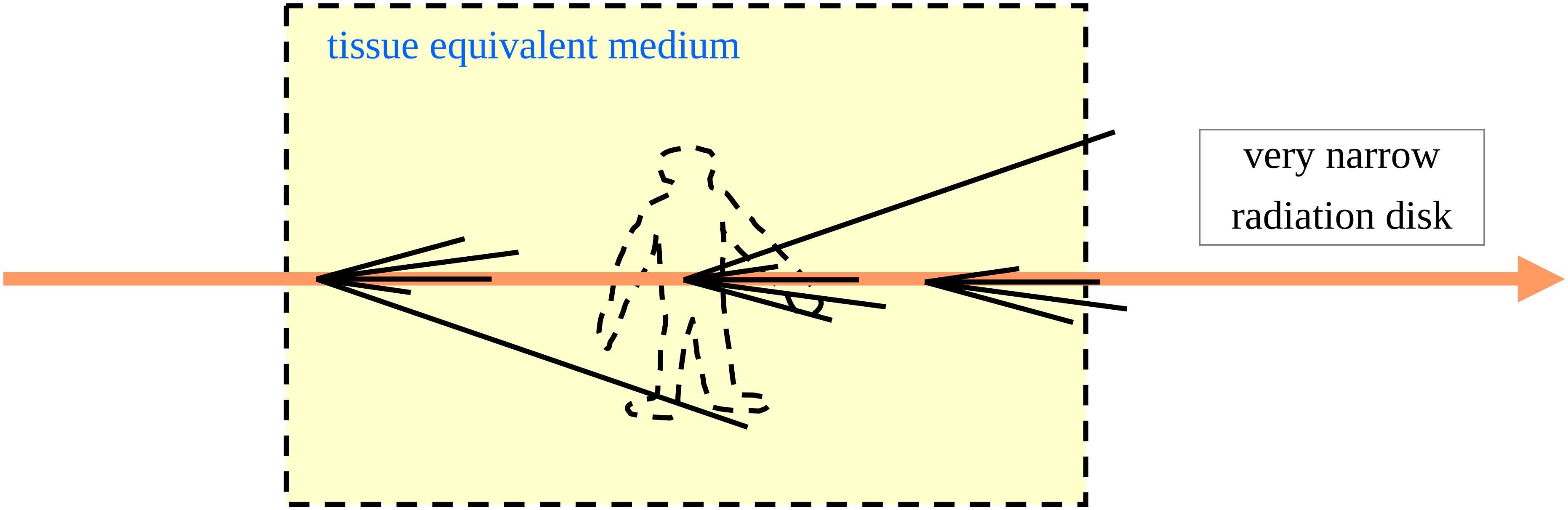
"Equilibrium Approximation" for Dose Calculation



Dose absorbed = energy of neutrino interactions in person

(N.B. breaks down close-by & at many-TeV energies)

1) equilibrium approximation breaks down:

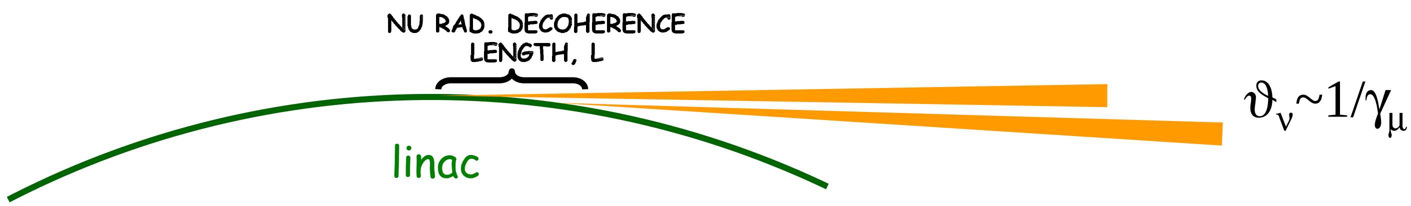


2) neutrino cross-section levels off:

$$\frac{\left(\frac{\sigma_\nu}{E_\nu}\right)_{E=100\,\mathrm{TeV}}}{\left(\frac{\sigma_\nu}{E_\nu}\right)_{E=1\,\mathrm{TeV}}} = 0.33$$

NEUTRINO RADIATION FROM THE LINACS

- radiation reduced relative to collider ring due to only a few passes instead of several hundred passes
- rough analytical calculation for straight line linac predicts dose rising from O(0.1) mSv/year to O(10) mSV/year for E_{CoM} range of straw-man parameter sets => a straight linac could be problematic
- want gentle curve in linacs so nu rad. doesn't all line up - should be sufficient to follow curvature of Earth (no problem for e+e- collider):



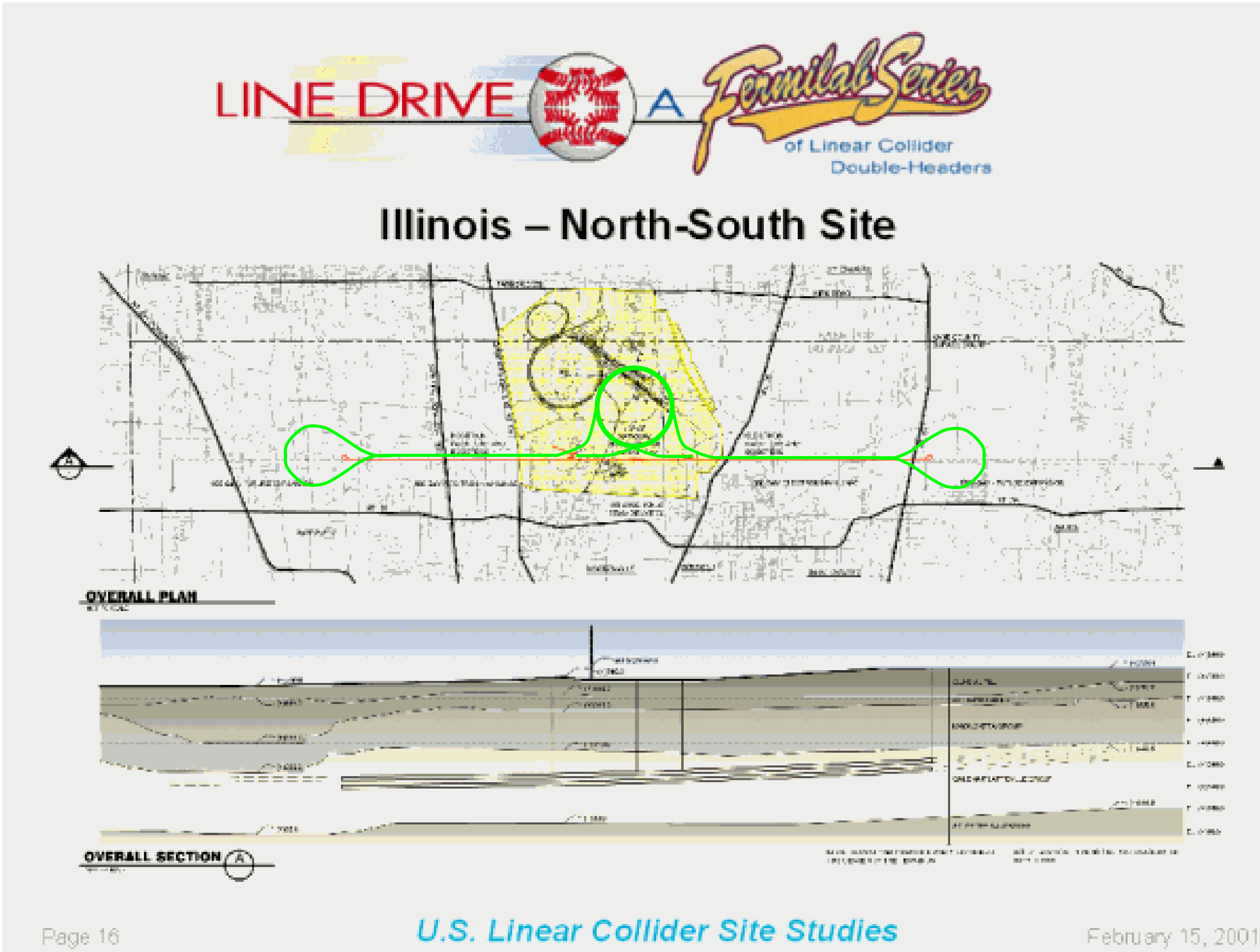
$$\vartheta_\nu \sim 1/\gamma_\mu \sim 10^{-4}/E_\mu[\mathrm{TeV}]$$

$$\Rightarrow L \sim R_{Earth}/\gamma_\mu \sim 660\ \mathrm{m}/E_\mu[\mathrm{TeV}]$$

SITE SUITABILITY ISSUES FOR DESY & FERMILAB

With thanks to Wilhelm Bialowons (DESY)

THE FERMILAB DEEP SITE LOOKS VERY SUITABLE ...



THE LINACS' NEUTRINO RADIATION WOULD EVEN EMERGE IN UNPOPULATED AREAS ...

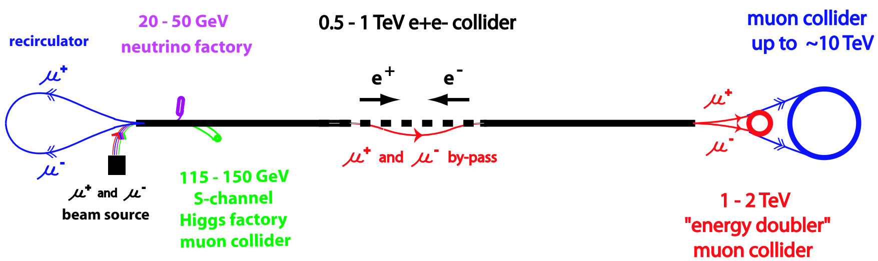
LINE DRIVE A Fermilab Series of Linear Collider Double-Headers

Illinois North-South Site Photos

Page 17 | U.S. Linear Collider Site Studies | February 15, 2001

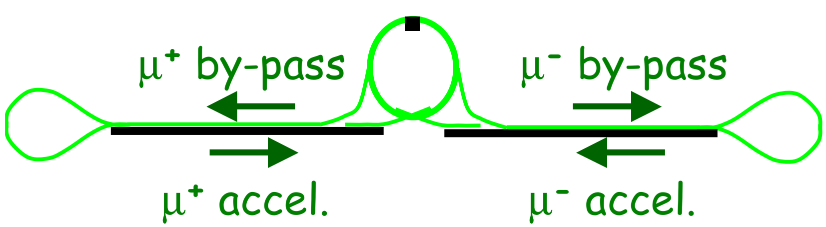
mu-TESLA vs. mu-NLC Differences

Mu-TESLA



- cold cavities => stay on & can match rf to beam
- standing wave => can traverse linacs in both directions
- larger cavities (e.g. 70 mm aperture) => smaller wakefields & can transport larger bunch charges
- 2K cryogenic cavities => issues with heating from decay electrons & HOM losses

Mu-NLC



- warm cavities => rf fields die quickly (~μs) => short bunch trains & need new power pulse for each beam pass
- travelling wave (probably) => direction sense chosen(?) => use by-pass lines beside linac to recirculate beam
- smaller cavities (e.g. 8 mm aperture) => limited to smaller bunch charges

Mu-TESLA

SOME mu-TESLA ISSUES

✓ cryogenic heat load from decay electrons

Power in decay electrons is **0.07 -> 0.7 W/m** for 11.2 TeV -> 1.6 TeV mu-TESLA parameters, c.f. **0.43 W/m** total heat load at 2K for 500 GeV TESLA and considerably more for 800 GeV TESLA.

? cryogenic heat loads from HOM excitation

HOM power/bunch goes as square of bunch charge so will be larger than for TESLA

✓ rf time-structure for bunch trains

Compare to 285 km nominal TESLA bunch train length => time for several passes even without changing rf pulse parameters

? transportation of larger bunch charges

Assumed N_μ = (2-9)x10^{11}

-> Reinhard Brinkmann transparency

SESSION SUMMARY

- mu-TESLA looks very promising
- mu-NLC has a chance NEW!
- we need a muon collider cooling channel design or none of this will matter