Neutrino Physics with Muon Colliders

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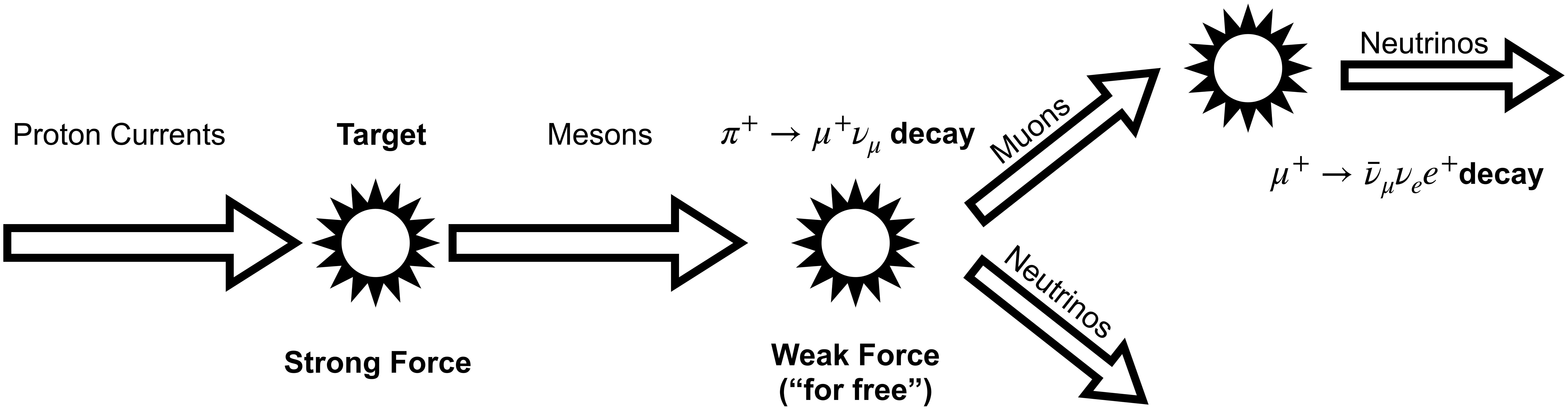
Muons produced by p^+ on target and pion decay $\pi^+ \to \mu^+ \nu_\mu$

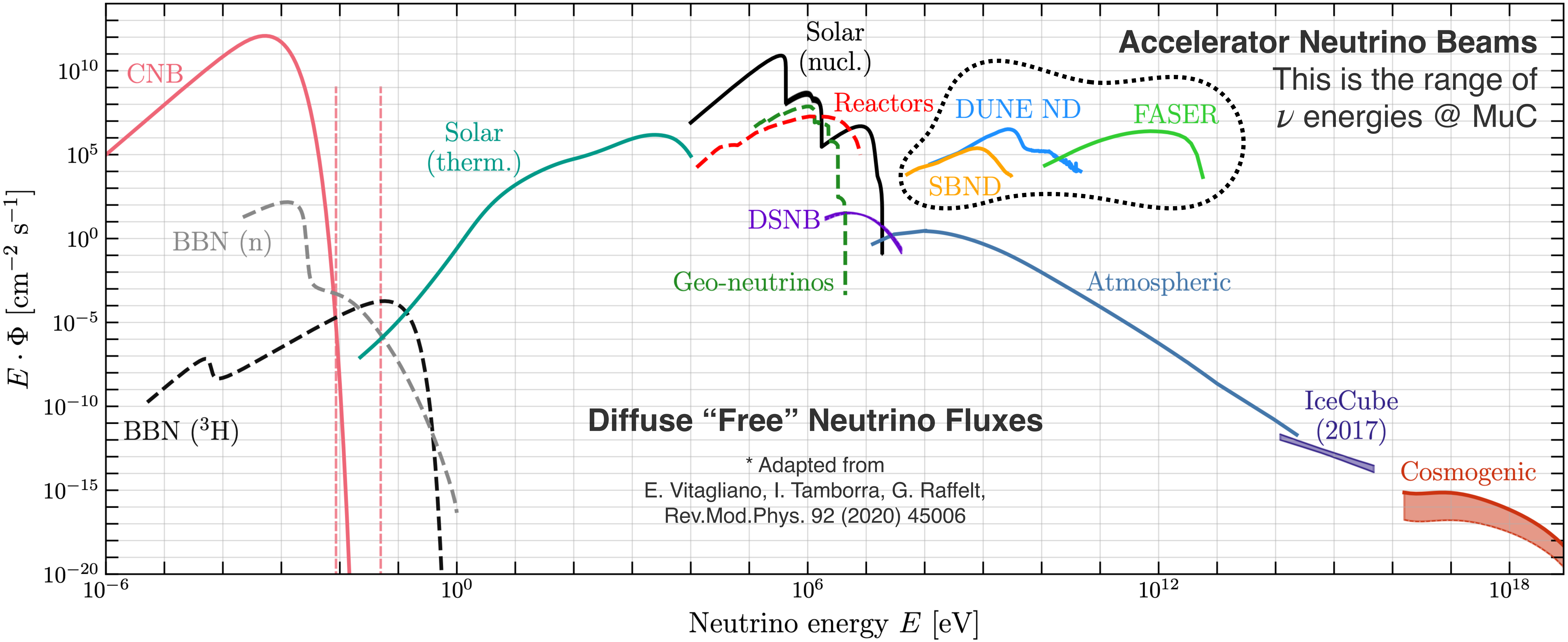


Accelerator neutrino beams are possible because $c\tau_{\pi^+} \sim 6$ meters.

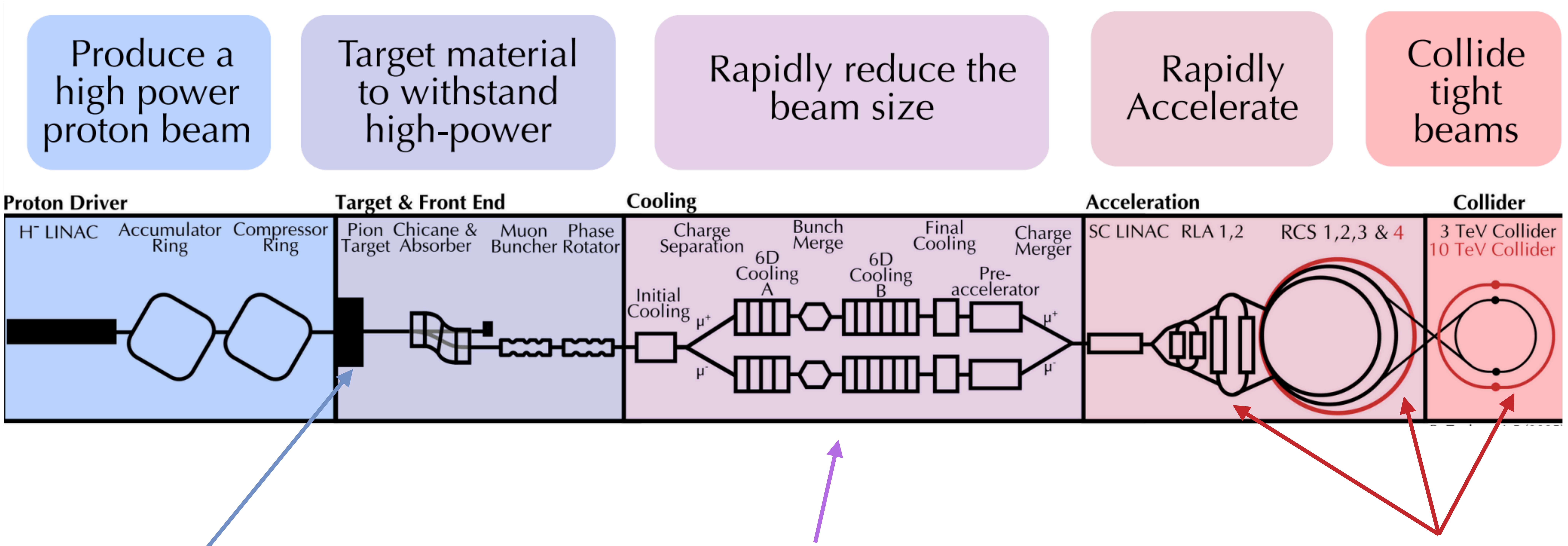
Muon colliders are challenging (though possible) because $c\tau_{\mu^+} \sim 600$ meters.

But more importantly for this talk, these stored/accelerated
muons enable high-precision neutrino beams

Neutrinos Across Energy Scale



R. Taylor, 2nd USMCC meeting 2025



Proton Target

5 (10) GeV, 4 (2) MW proton beam with $\mathcal{O}(1)$ nanosecond pulses.

Extremely bright, unfocused MeV → GeV neutrino source.

Cooling Stage Neutrinos

The neutrino beam size is shrinking over time.

Is it useful? Beam is shrinking as cooling takes place.

Tangential & Forward facilities

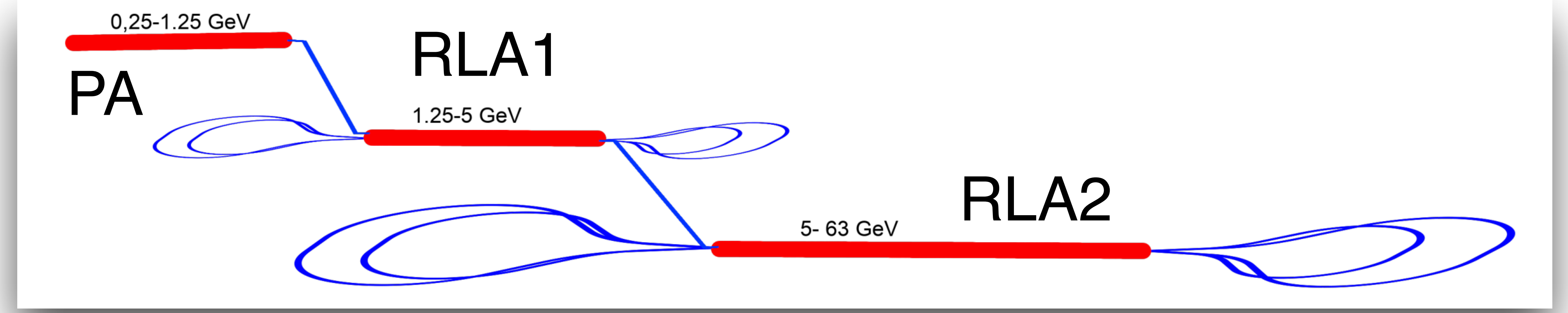
Low-Energy Acceleration (200 MeV — 63 GeV)

Rapid Cycling Synchrotrons

Main Collider Ring
(TeV muons)

Neutrinos from the Accelerator Complex

Muon Acceleration Neutrinos?



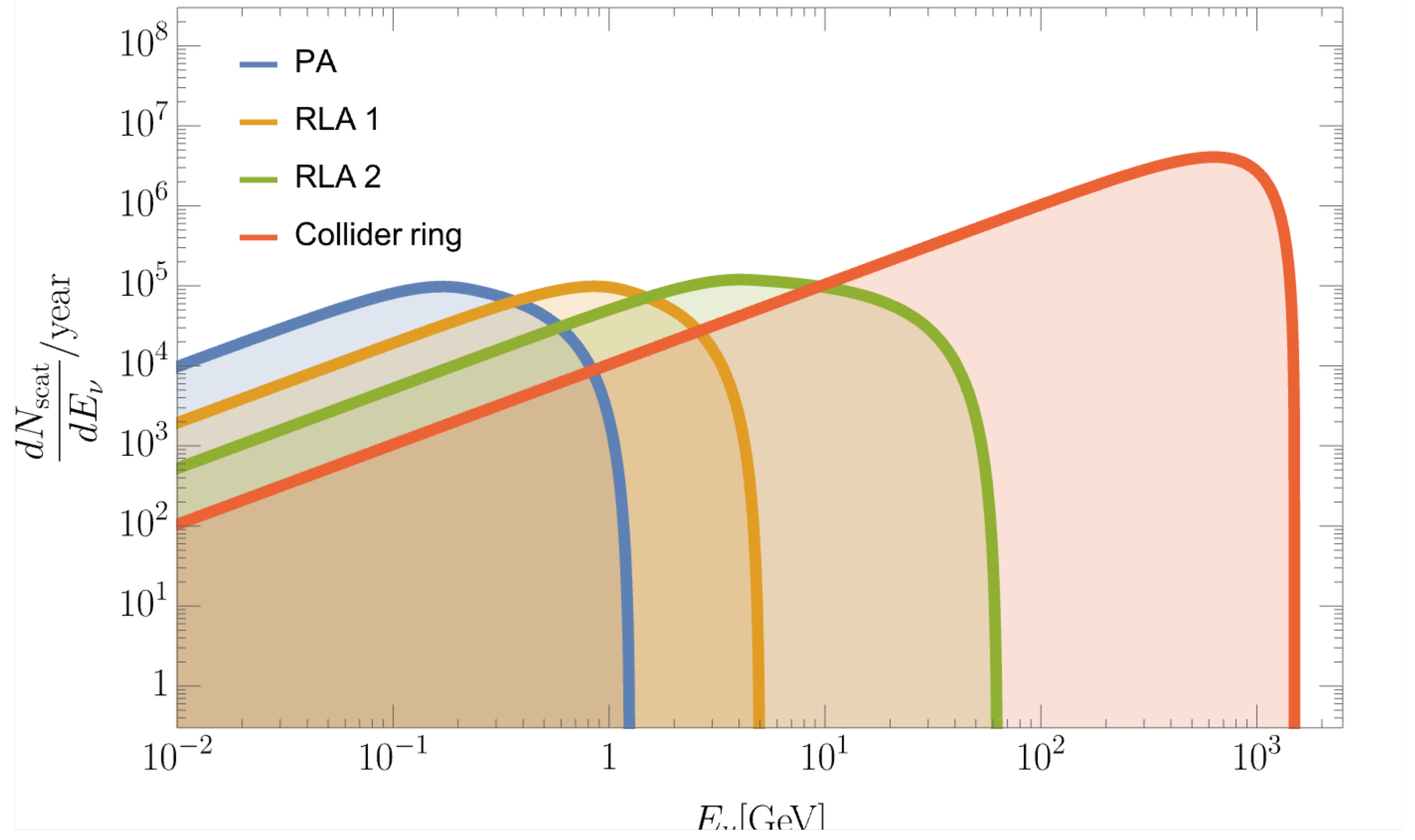
Currently investigating the entire complex and its neutrino flux

Many large detectors at Fermilab and CERN site. Coincidences can happen, but would be better to engineer them…

Pre-Accelerator (PA):
Hyper-K energy range

Recirculating Linear Accelerator (RLA1/RLA2):
DUNE energy range

Courtesy of P. Fox & P. Machado (Fermilab) preliminary
Time-integrated event rate if we catch 100% of all ν emitted w/ 1 meter of LAr (not realistic).



See also Z. Tabrizi's talk at the APS "Muon Physics" session

Neutrinos from the Collider Ring

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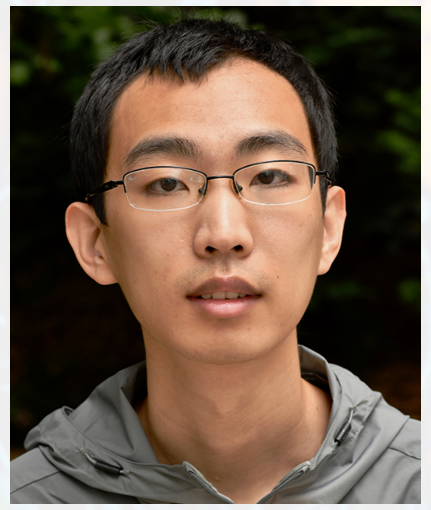


Peiran Li
(U. of Minnesota)

Zhen Liu
(U. of Minnesota)

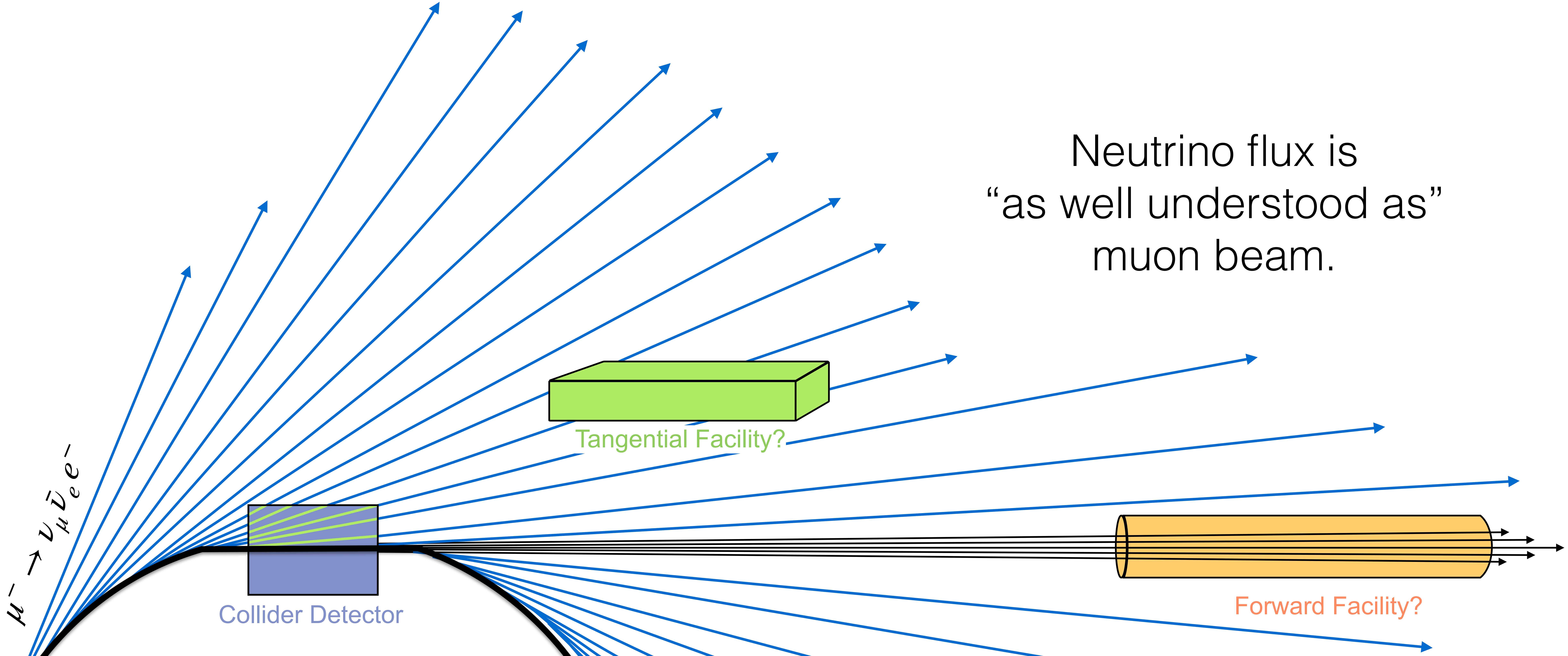
Forward or "Tangential" physics opportunities

L. Bojorquez-Lopez (Undergrad), MH, C. A. Argüelles, Z. Liu
PRL 135 (2025) 9, 091803

A. Thompson, A. De Gouvêa
JHEP 12 (2025) 098

F. Kling, Y. Ma, K. Mękała, J. Reuter, Z. Tabrizi
arXiv:2508.00761

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e \text{ and } \mu^- \to e^- \nu_\mu \bar{\nu}_e$$



Neutrino flux is
"as well understood as"
muon beam.

The Neutrino slice ($\phi \sim \pi$)

L. Bojorquez-Lopez (Undergrad), **MH**, C. A. Argüelles, Z. Liu

The Neutrino Slice at Muon Colliders

Muon Collider
Building toy models of muon collider

More neutrinos than we have ever detected by >3 orders of magnitude.

To give sense of the rate @ MuC 10 TeV:

For every 2 bunch xs, you get 1 BIN$^{\dagger *}$.

(† there are ~infinitely many more BIBs/bunch xs!)
(* this is also a statement on the # of bunch xs)

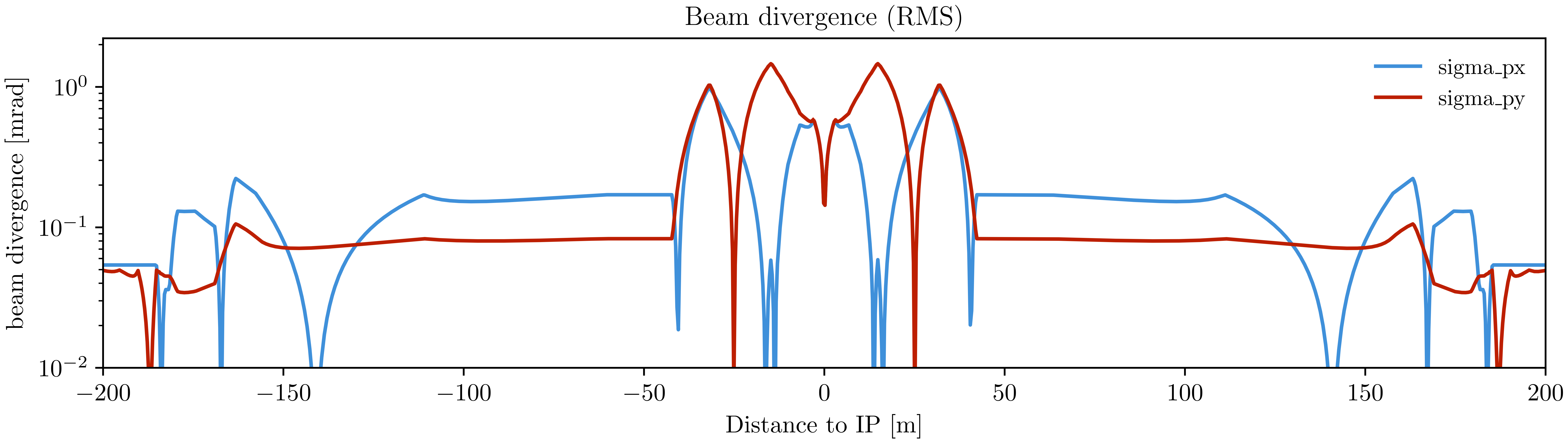
Collider	MuC 10 TeV	MuC 3 TeV	μTRISTAN
Beams	$\mu^+\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^+$
Muons/bunch	1.8×10^{12}	1.8×10^{12}	1.4×10^{10}
bunches/cycle	1	1	40
$f_{\rm inj}$	5 Hz	5 Hz	50 Hz
C	8.7 km	4.3 km	4.3 km
BIN inclusive reactions			
ECal (0.15 kt)	0.9%	3.0%	3.0%
HCal (1.4 kt)	7%	15%	15%
Muon Sys (7.5 kt)	13%	33%	32%
Nozzles (0.14 kt)	79%	48%	48%
Total / bunch xs.	0.44	0.029	0.0053
Total / year	1.5×10^{11}	2.0×10^{10}	1.5×10^{11}

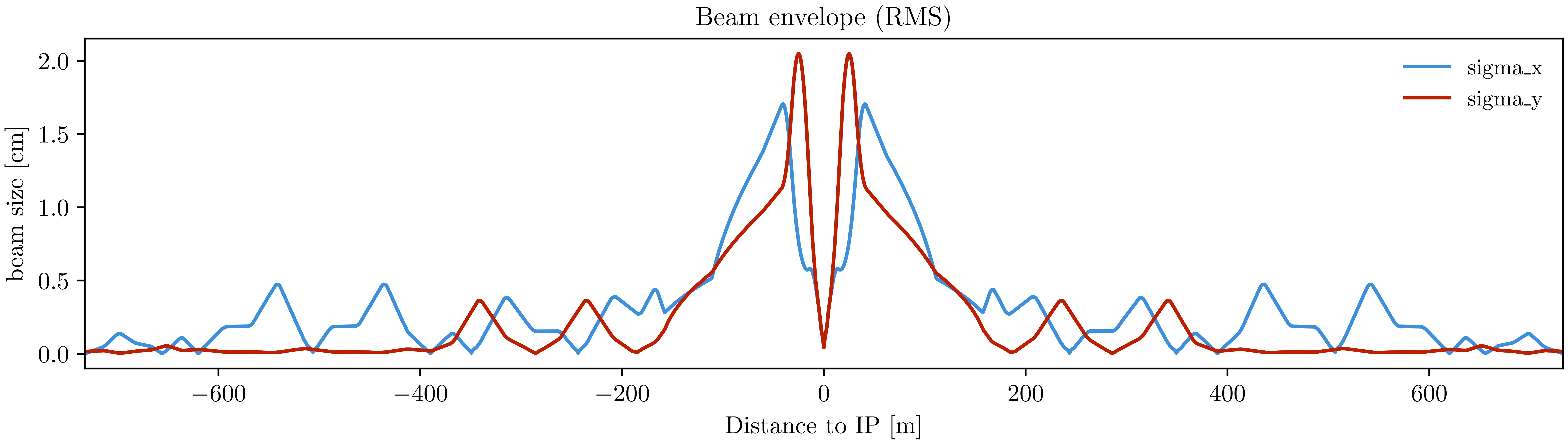
BIN exclusive reactions in HCAL and ECAL/year			
Total NC	1.5×10^{9}	4.6×10^{8}	3.4×10^{9}
Total ν_e CC	4.7×10^{9}	1.4×10^{9}	1.1×10^{10}
Total ν_μ CC	5.4×10^{9}	1.7×10^{9}	1.1×10^{10}

The Straight Section at the Main Collider Ring

Propagating muons according to collider lattice.

Lattice v09 + curved sections from v06. Courtesy of Marion Vanwelde (CERN).

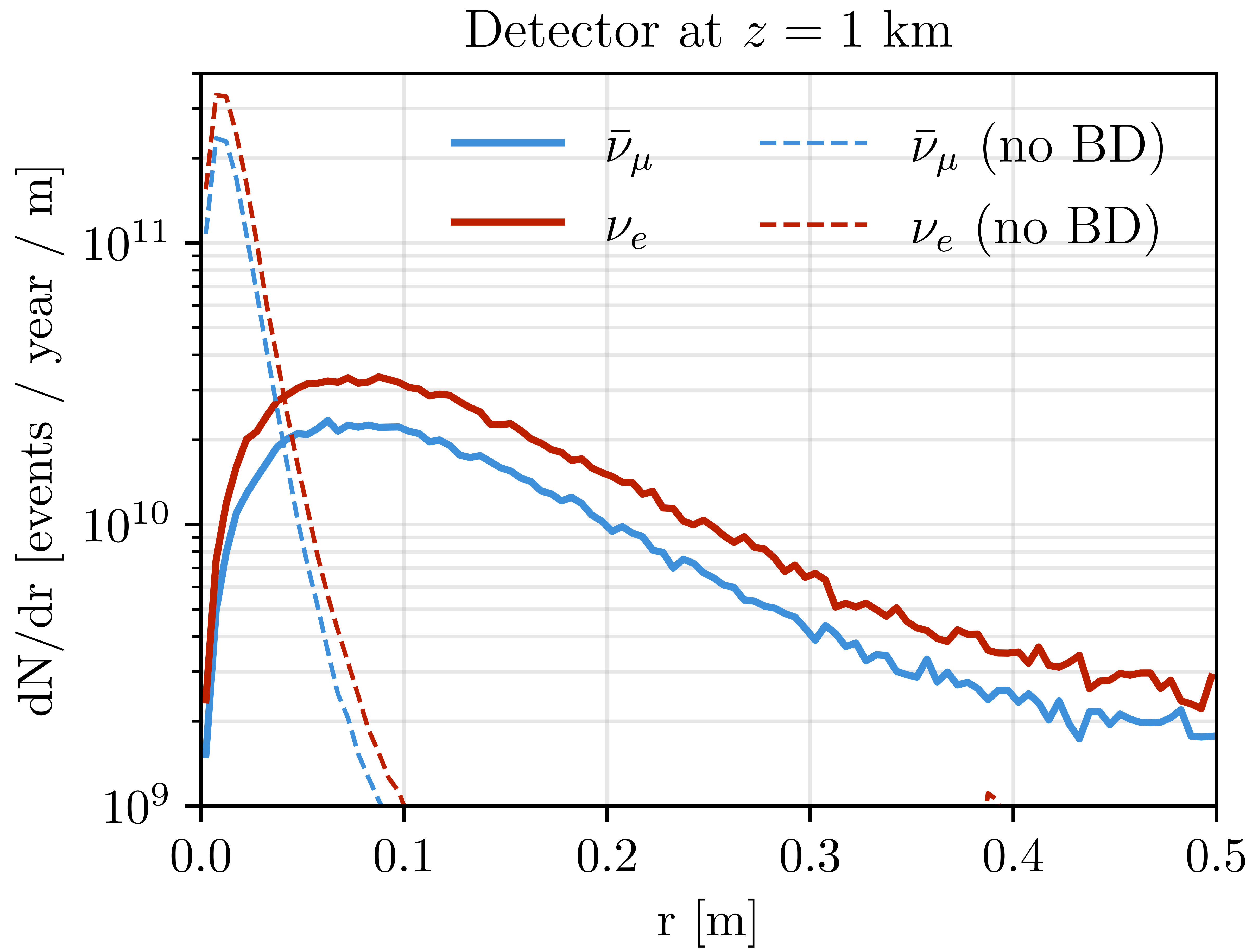


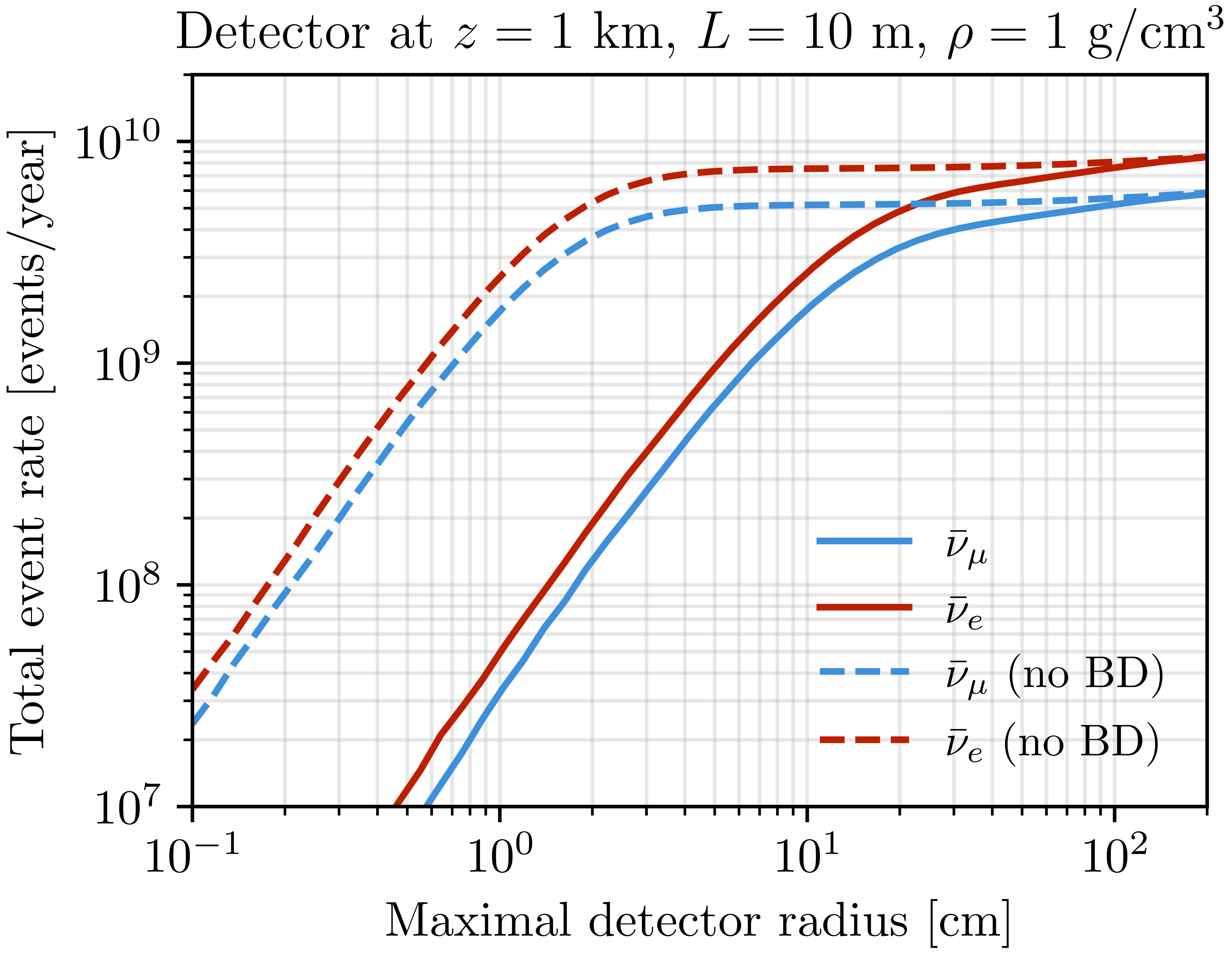


Lattice v09 + curved sections from v06. Courtesy of Marion Vanwelde (CERN).

Neutrino event rate beam dynamics matters

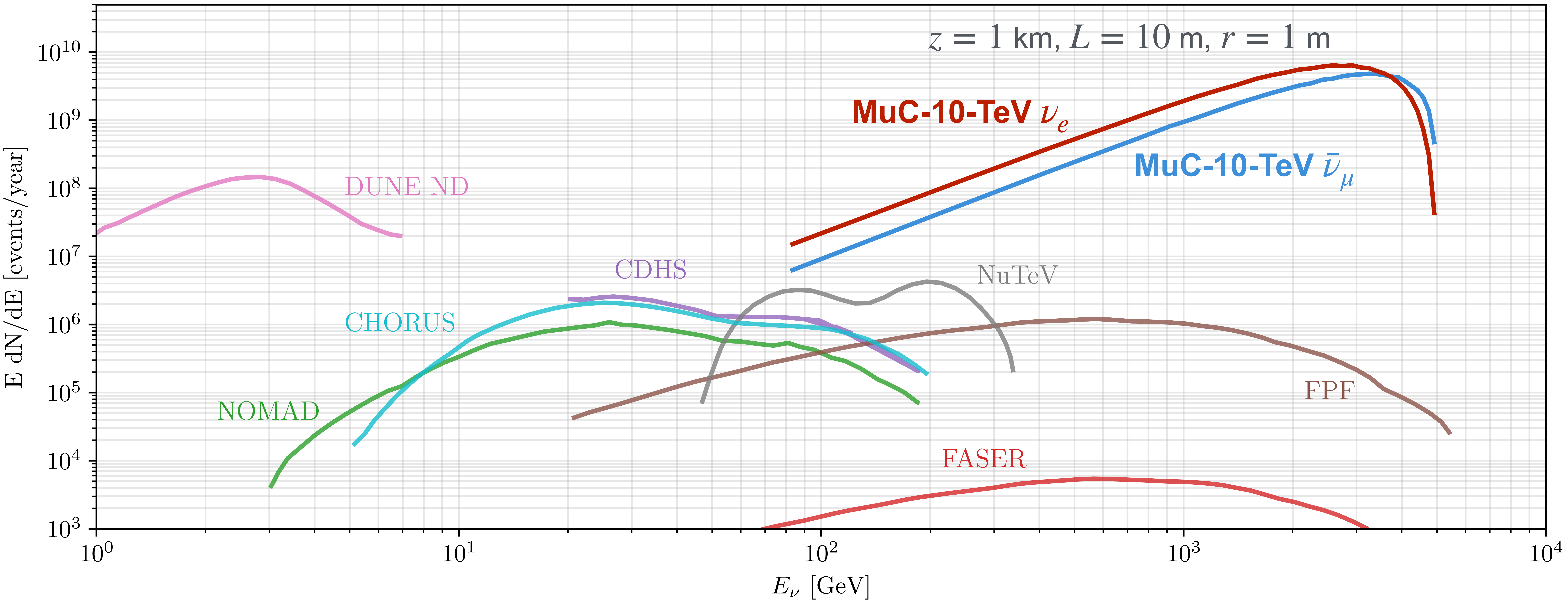
Neutrino flux follows transverse muon dynamics.





Acceptance: beam dynamics matter

Our prediction compared to other curves from arXiv:2409.02163.



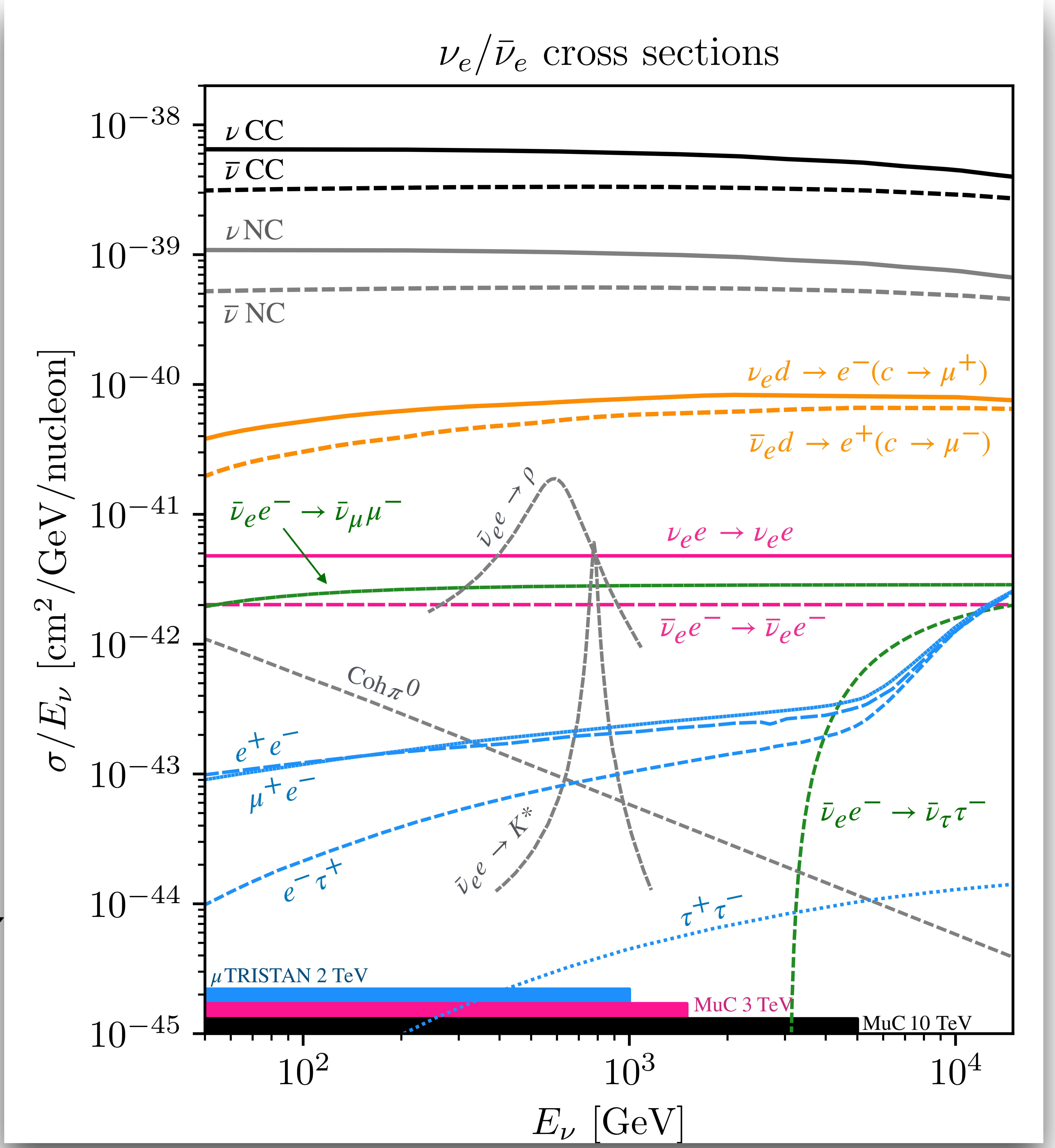
High Energy ν Interactions

MuC BINs would offer a high-Q^2 probe of fundamental matter with Weak interactions.

Access to many other rare exclusive processes.

Example of classes of exclusive processes

- Deep Inelastic Scattering **CC** and NC
- Charm production
- Inverse muon(tau) decay
- Elastic scattering on electrons
- Resonant meson production
- Neutrino trident production



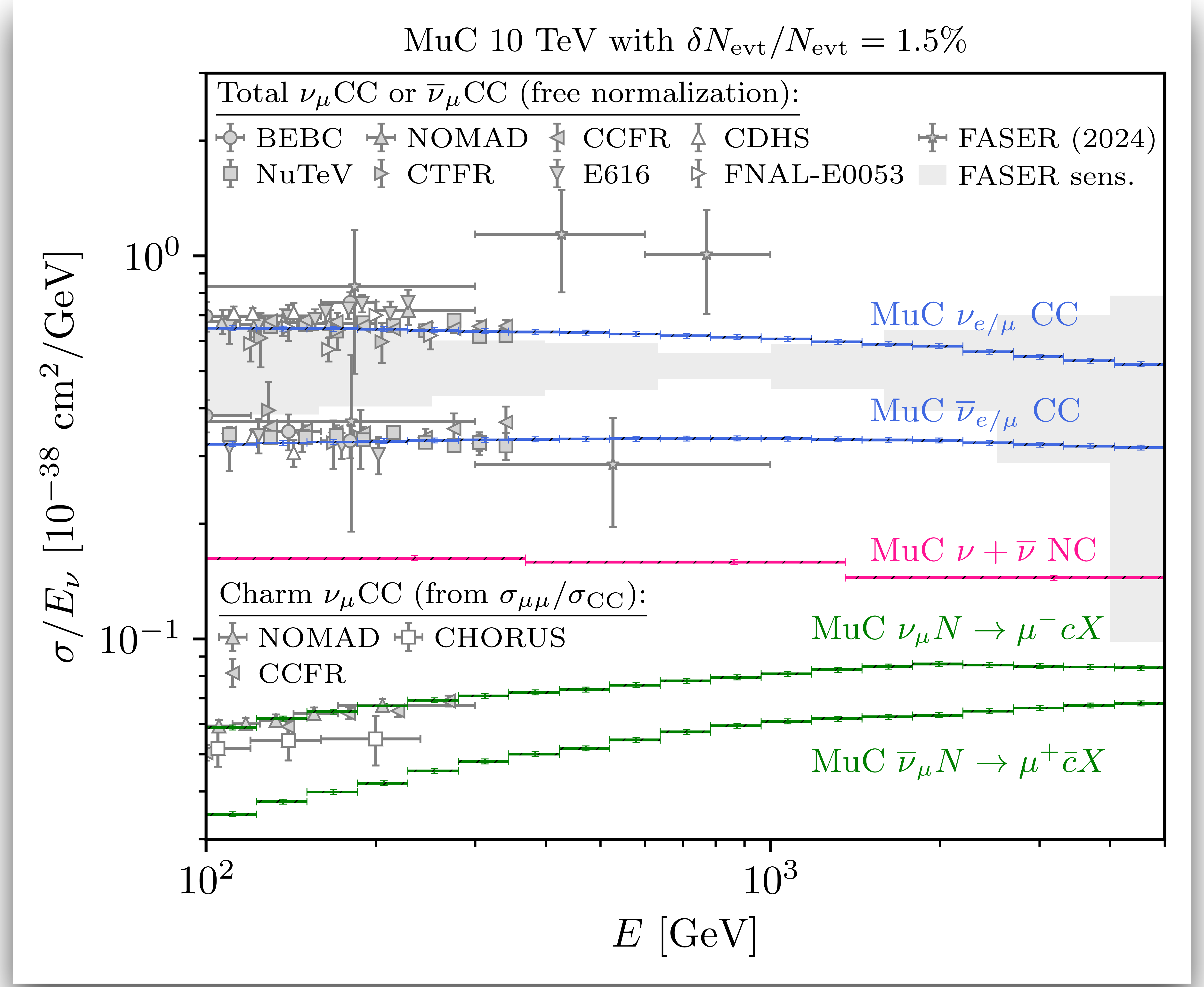
Neutrino-nucleus cross sections

This is what a $1.5\,\%$ uncertainty on TeV neutrino cross sections would look like[†].

Clearly more works required to understand if feasible at the **neutrino slice**, but such precision can undoubtedly be achieved with a **forward/tangential detector.**

[†]1.5% comes from current measurements at LHC. Likely better?

L. Bojorquez-Lopez, MH, C. A. Argüelles, Z. Liu



Muon colliders are high-intensity machines.
Muon decay means we get to do neutrino physics.
We are starting to explore advantages, limitations, and opportunities.

Low-energy acceleration neutrinos:

Likely a “short-baseline”-type of experiment.
Not enough neutrinos for a 3-flavor standard oscillation experiment
(would likely need a dedicated “neutrino factory”)

“2 for 1 sale: MuC+ν (oscillation measurements sold separately)”

Main collider ring neutrinos:
Muon beam dynamics extremely important to understand the shape of the beam.

Energy-angle correlation for neutrinos (prism effect) washed out by beam dynamics.

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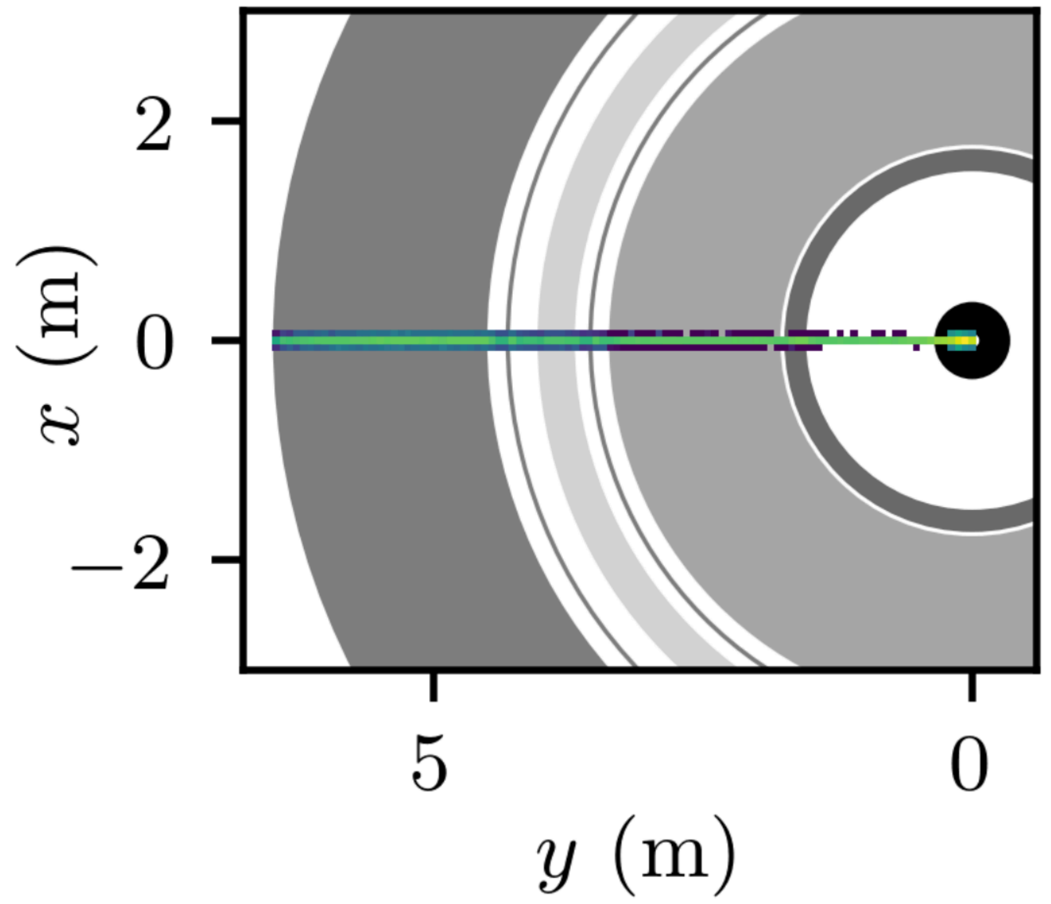
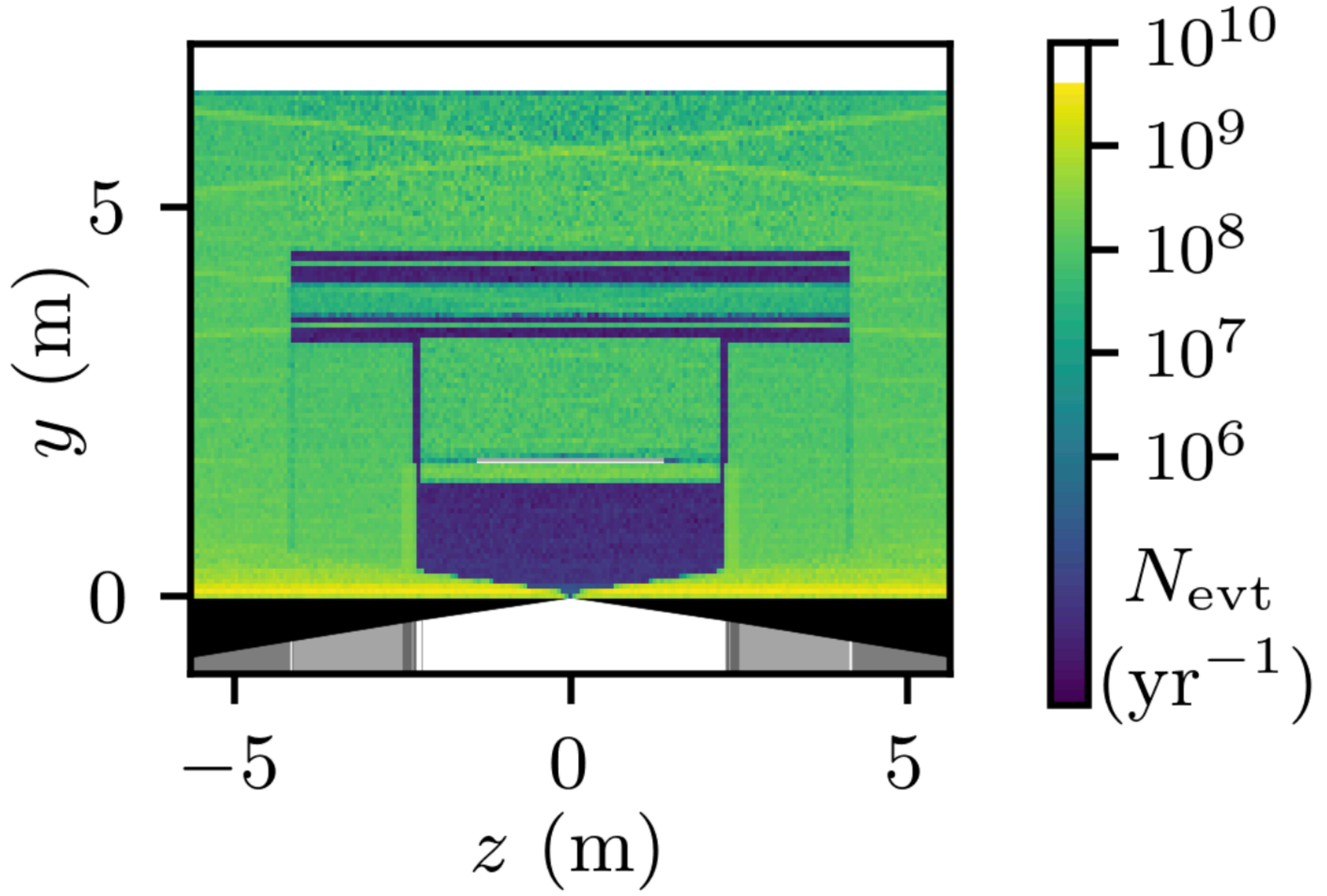
The Neutrino Slice at Muon Colliders



Very simplified detector modeling based on (IMCC studies)

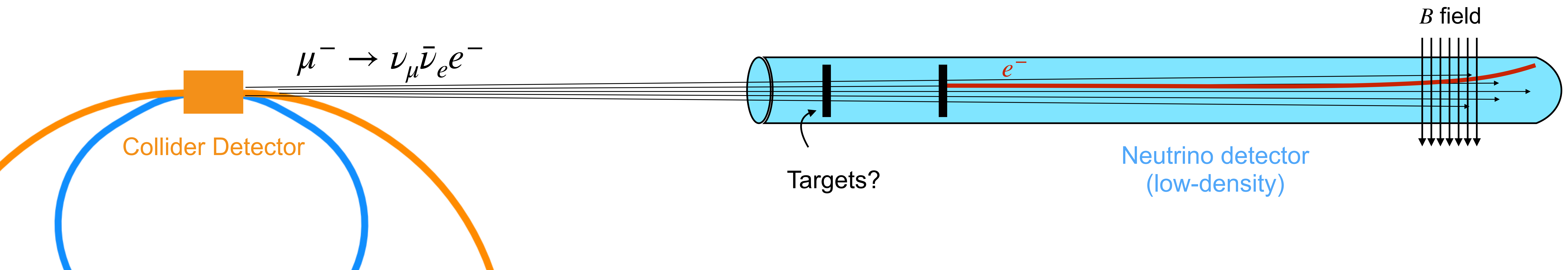


Low-background detectors for $\nu - e$ scattering?

$\nu - e$ scattering measurement @ a **long**, **magnetized**, and **low-density** detector.

Want to **reject hadronic vertex**, **maximize charge-identification**, and **reduce photon conversion**.

Advantage of the $\mu^- \to \nu_\mu \bar{\nu}_e e^-$ beam: $\bar{\nu}_e$CC is no longer a background to $\nu - e$ scattering because of charge ID of positron.



MuC Neutrino Energies

High energy and extremely collimated neutrino beam: $\langle E_\nu^{\mathrm{FASER}} \rangle \lesssim \langle E_\nu^{\text{MuC-10-TeV}} \rangle \lesssim \langle E_\nu^{\mathrm{FCC}} \rangle$

Beam energies are not necessarily new, but flavor composition, sample size, and precision are.

From arXiv:2409.02163