First Remarks About Neutrino Tridents in FLArE

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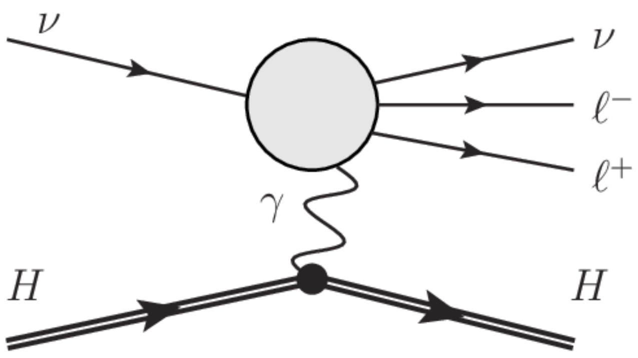
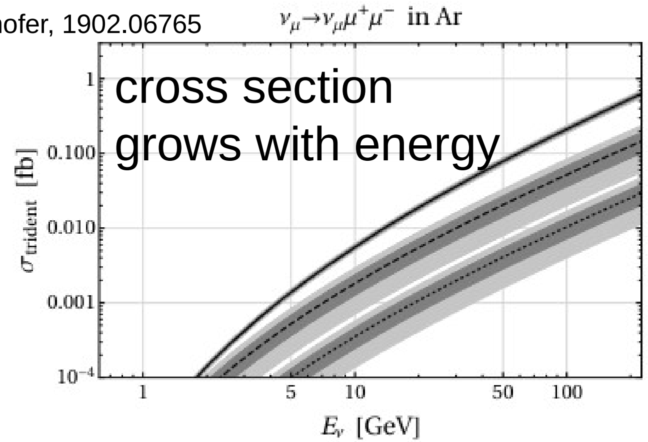
Neutrino tridents

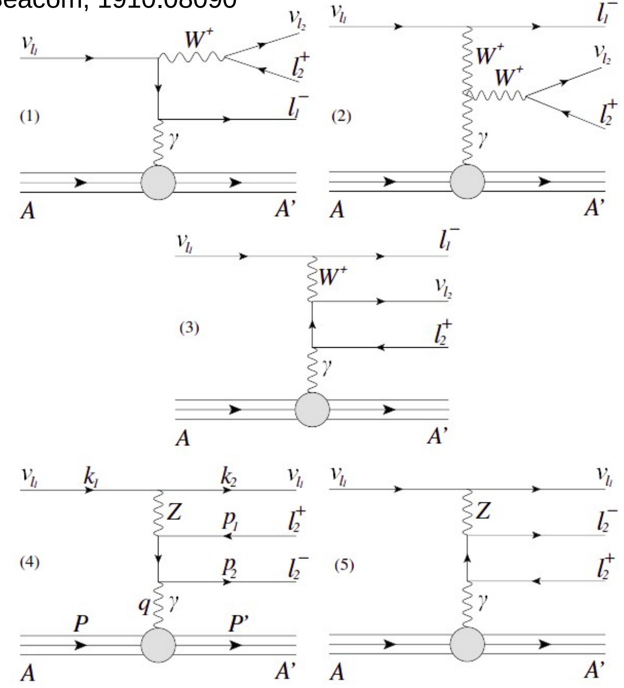
Wolfgang & Alex slides (October meeting)
Bei Zhou – upcoming meeting (December)



W. Altmannshofer, 1902.06765



B. Zhou, J. F. Beacom, 1910.08090



Various interaction modes:

– Coherent scattering – "purely" leptonic final-state (nucleus intact)

– Elastic scattering off individual nucleons

– (deep-)Inelastic scattering

Di-muons can also be produced in other processes
– CCDIS associated with charm production
– W-boson production (on-shell): relevant for larger energies

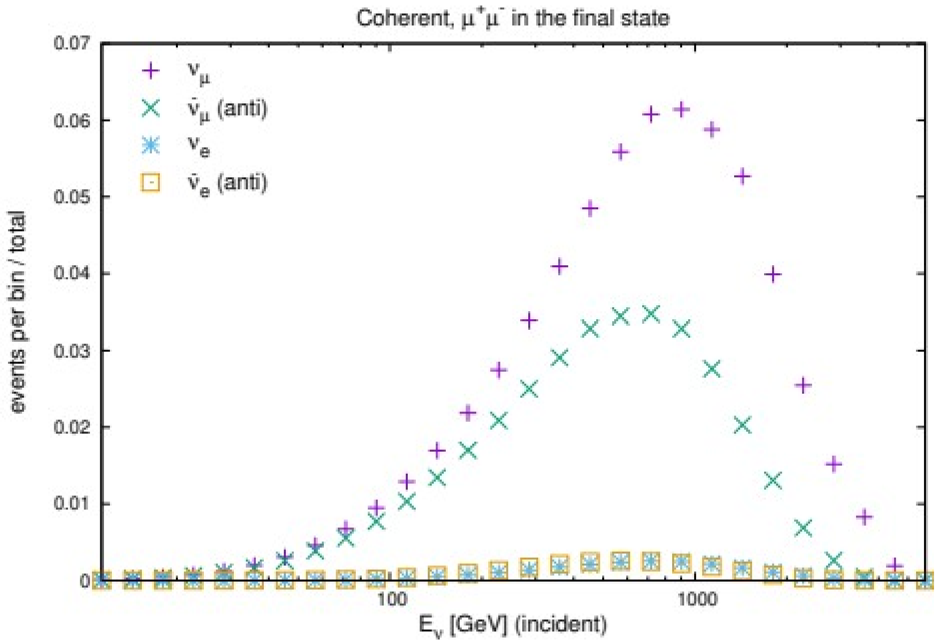
Event rates (HL-LHC, 1m x 1m x 7m detector volume):

Coherent & elastic off nucleons (coherent dominate

MC code: credit W. Altmannshofer

- $\mu^+\mu^-$ final state   4.3 events (~91 for FASERν2)
- $e^+\mu^-$ final state   12.5 events
- μ^+e^- final state   5.0 events
- e^+e^- final state   3.2 events

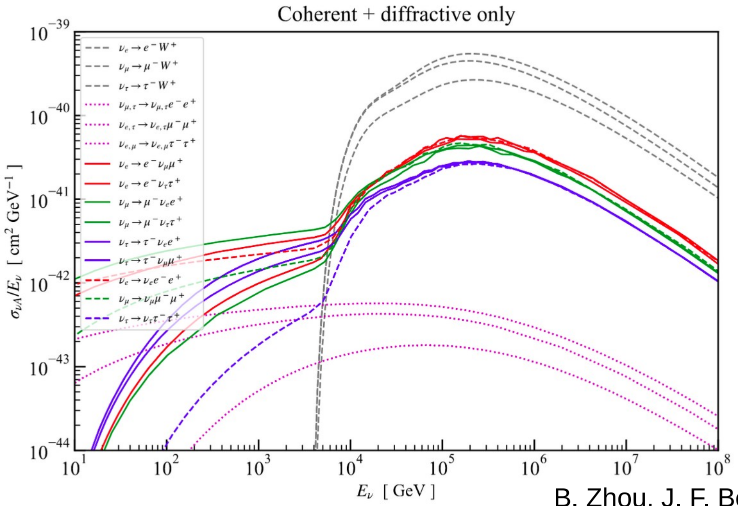
difference driven by:
- Z^2 enhancement
- neutrino flux&spectrum



- dominated by interactions for incident

  E_ν ~ few hundred GeV to ~TeV

- μμ final state dominated by incident ν_μ and anti-ν_μ



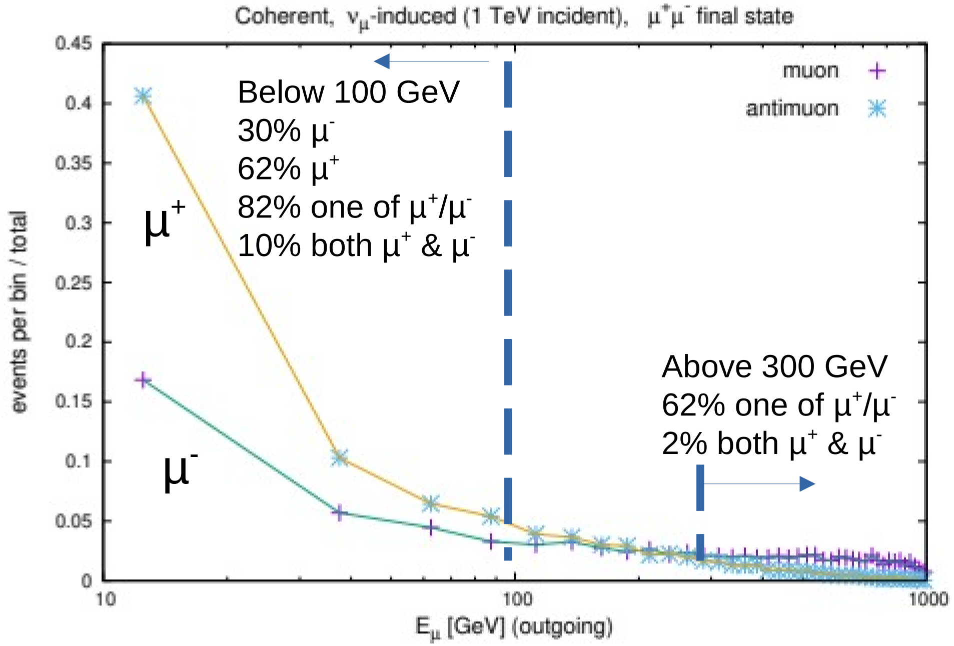
B. Zhou, J. F. Beacom, 1910.08090

Di-muon final state – energy distribution of outgoing muons and anti-muons

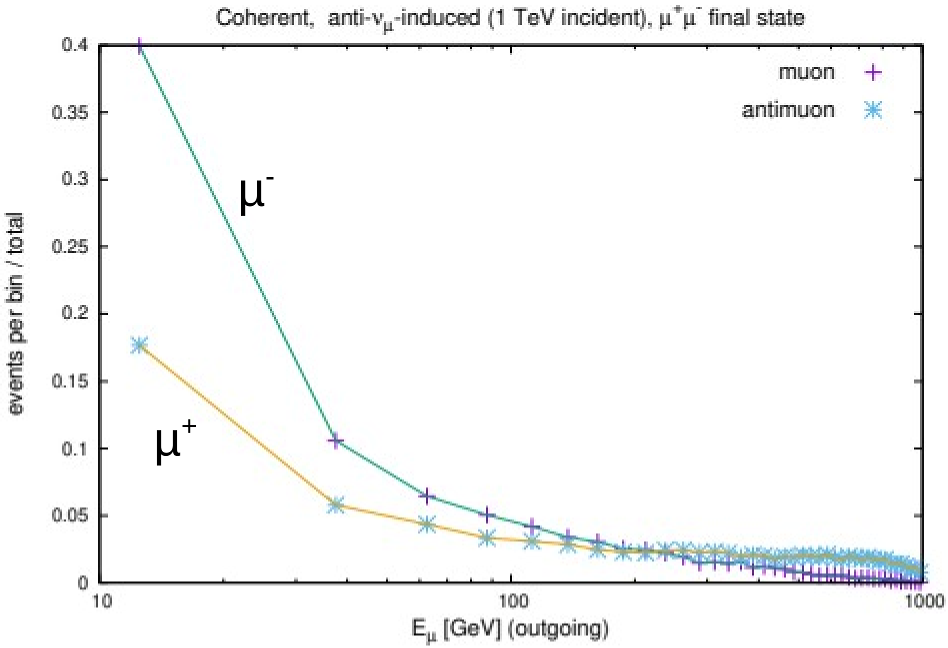
● Incident E_ν ~ TeV but often at least one final-state muon/antimuon has E_μ < few tens of GeV

● Some asymmetry between muons and anti-muons, changes for incident neutrinos / antineutrinos

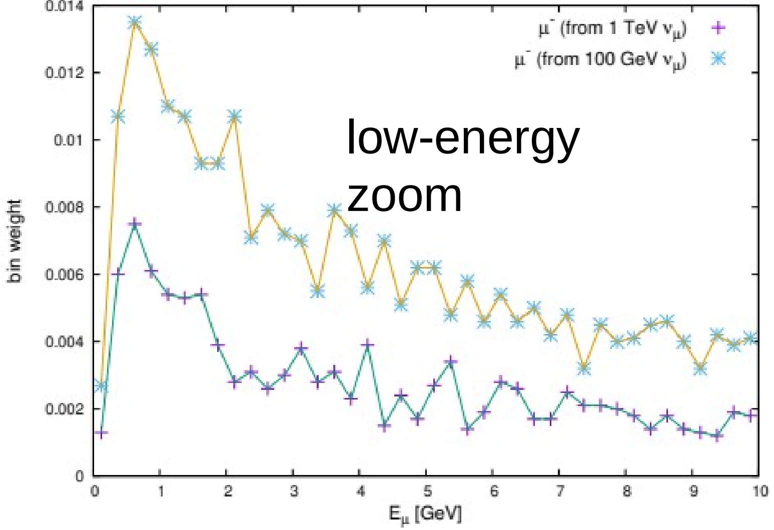
Neutrino ν_μ-induced (1TeV)



Antineutrino anti-ν_μ-induced (1TeV)



Di-muon final state – energy distribution of μ (2)



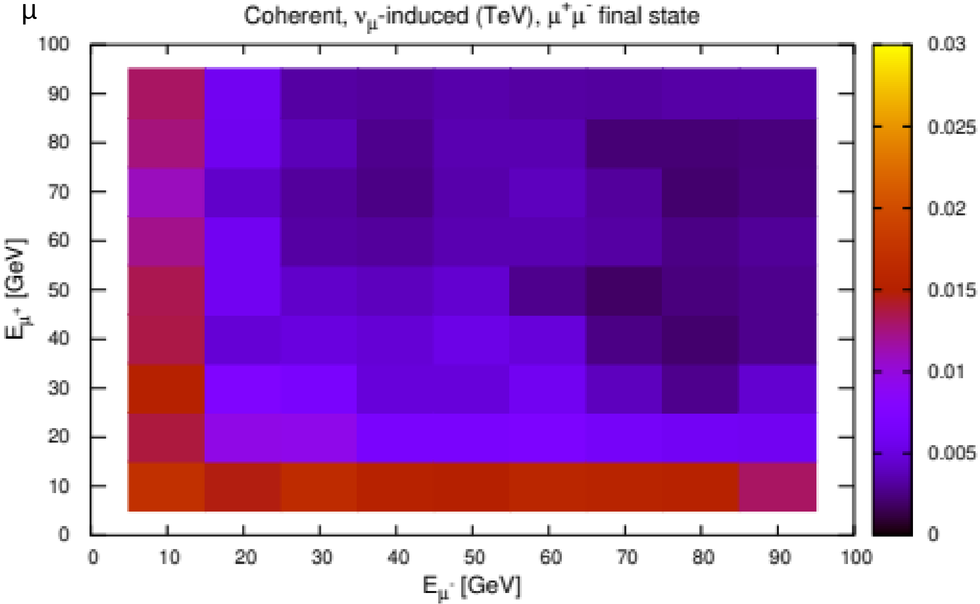
- muon energies can be as low as few hundred MeV but…

- >92% of events have both muons > 1 GeV

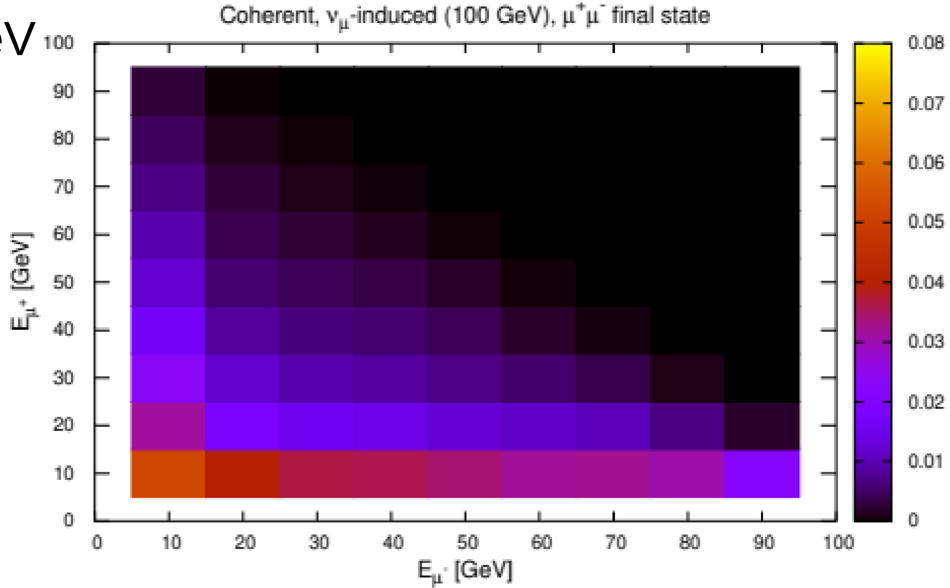
Typical event: one muon with E_μ ~ (1-few tens) GeV

one muon with E_μ ~ few hundred GeV

ν_μ-induced 1TeV



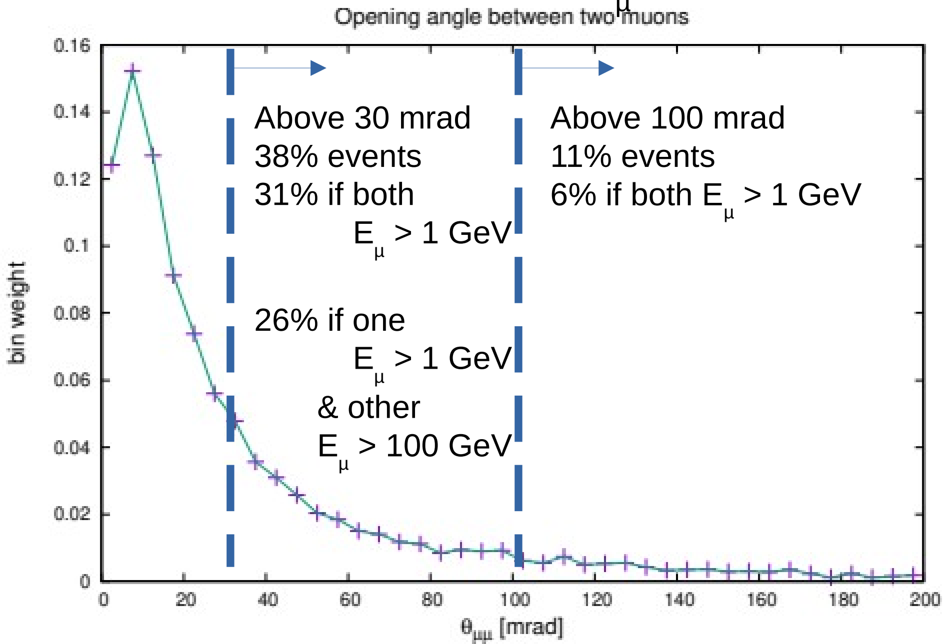
100 GeV

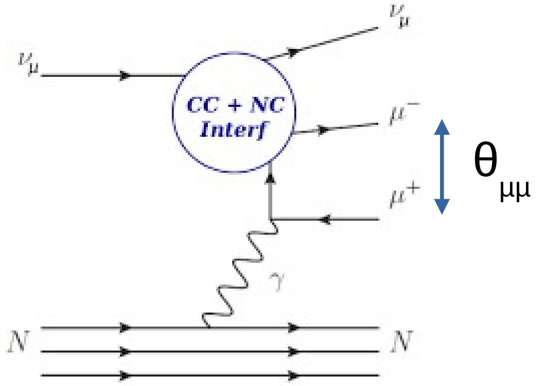


Opening angle distribution (between muons)

- both muons are typically very forward with a small opening angle

Coherent, 1 TeV incident ν_μ





Remarks about muon tridents

– Similar weak “trident” processes could take place with the muon in the initial state
However, the muon flux in the FPF will be suppressed with respect to the neutrino one, so this is not an issue

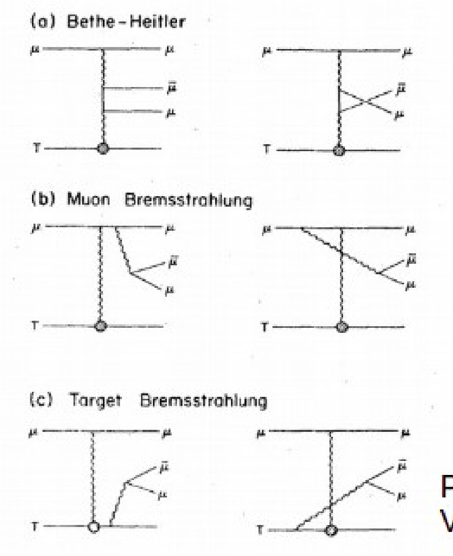
– Muons can also produce further two muons via photon exchange (QED), μN → μμμN

Main SM processes:

- **μN → μγN** (photon bremsstrahlung),
followed by a di-muon pair production, **γN → μμN**

Bremsstrahlung photon typically displaced (separate vertex)

Prompt – muon → tri-muon single vertex
followed by a decay, **X → μμ**



Phys.Rev.D 20 (1979) 630,
V.D. Barger, W.-Y. Keung, R.J.N. Phillips

Prompt di-muons & brem

– Main muon-energy loss mechanism for small fractional energy transfers

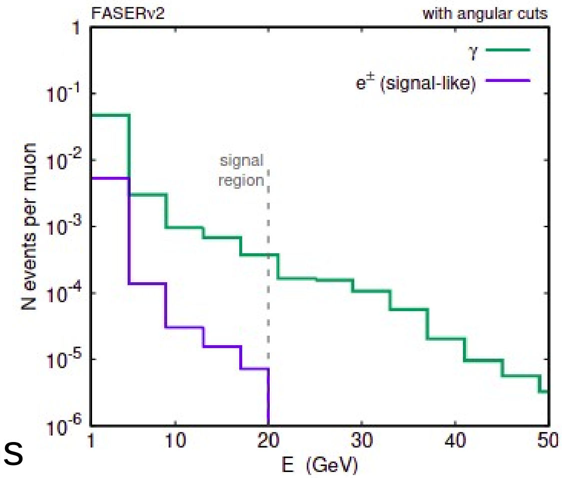
– Mostly produce e^+e^- pairs but $\mu^+\mu^-$ pairs can also be produced

– For e+e-, we estimated photon and resulting e+e- spectrum with one missing e+ or e- in the DM paper (B. Batell, J.L. Feng, ST, 2101.10338)

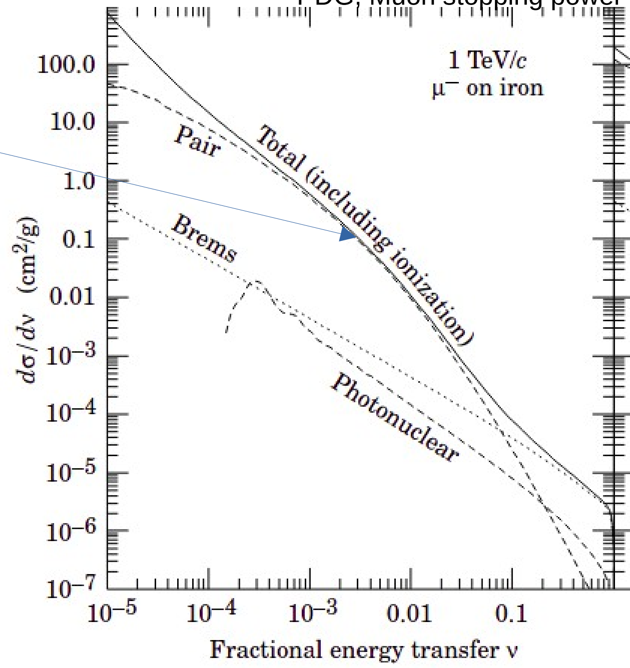
– For di-muon final states, rates $\sim(m_e/m_\mu)^2$

– FASERnu (Run 3)
~ O(1000) di-muons from brem photons expected

– FLArE: should be rescaled up
- for larger muon flux
- prompt di-muon rate is larger for soft muons could be troublesome if one of such photons is missing detection



PDG, Muon stopping power



Energy fraction which goes into a new pair

– **It remains essential to reject incoming muons**

– Better estimates can be obtained either semi-analytically or with GENIE, FLUKA etc.

Conclusions

– Neutrino tridents are interesting physics target,
not measured in this energy regime, largely not measured at all

– Various interaction modes possible: the cleanest could be **coherent** scattering to $\mu^+\mu^-$ final state
(incoherent modes and other final states also possible, including with **τ**)

– **Challenge**: small opening angle between the muons
→ likely crucial to go below 100mrad resolution

– Interplay with FASER 2 spectrometer could help (also with charge identification) but…
one of the muons might be too soft and deflected away

– Neutrino-induced backgrounds:
  – CCRES single-pion production (could be rejected based on too soft pions/muons)
  – CCDIS associated with charm (could be rejected based on non-purely leptonic nature)

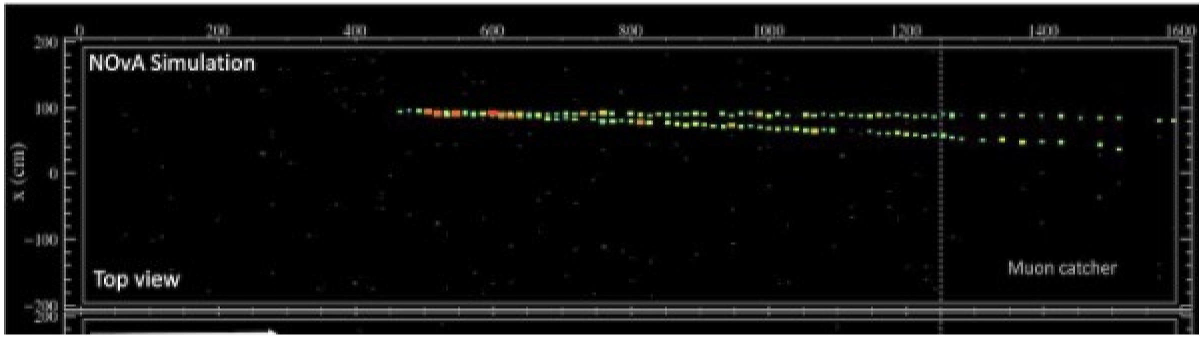
– Muon-tridents: a priori overwhelming rates, important to reject, e.g., detect incoming muon

– BSM opportunities (U(1)_Lμ-Lτ) but first need to understand SM contribution

Further thoughts/questions

– **Experimental:** How good could the angular resolution be for the muon pair?

from Alex’s slides



How well the muon energy can be measured?
Further questions will arise if we consider other final states, e.g., with τ

– **Modeling:** discuss tools, approximations etc.

Di-muon final states interesting also for other reasons
(e.g., charm-associated CCDIS & strange PDFs)
This study is also BG for tridents – could be activity across FPF WGs

$e^+\mu^-$ final state from ν_μ and anti-ν_e (1 TeV)

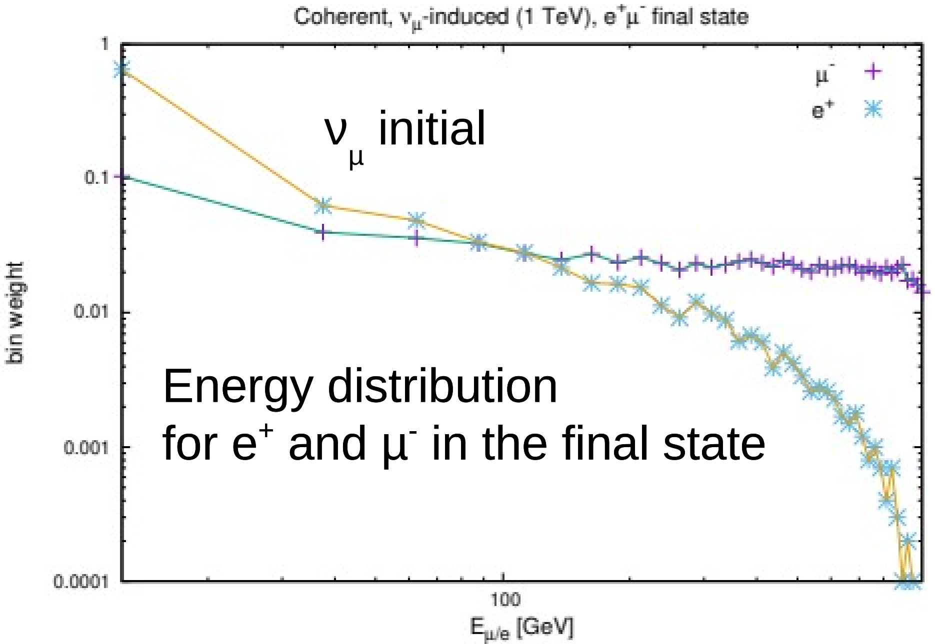
Energy distribution depends on the incident neutrino:

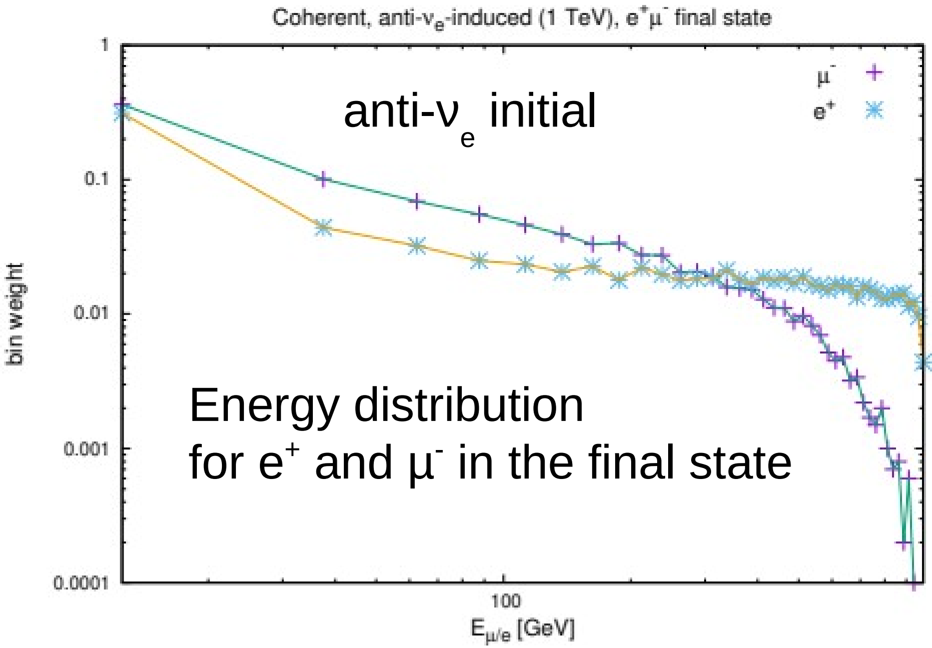
Typical event for incident ν_μ (~60% of events):

- high-energy muon (tens to hundreds GeV)
- softer positron (1 - tens of GeV)

Typical event for incident anti-ν_e (~40%):

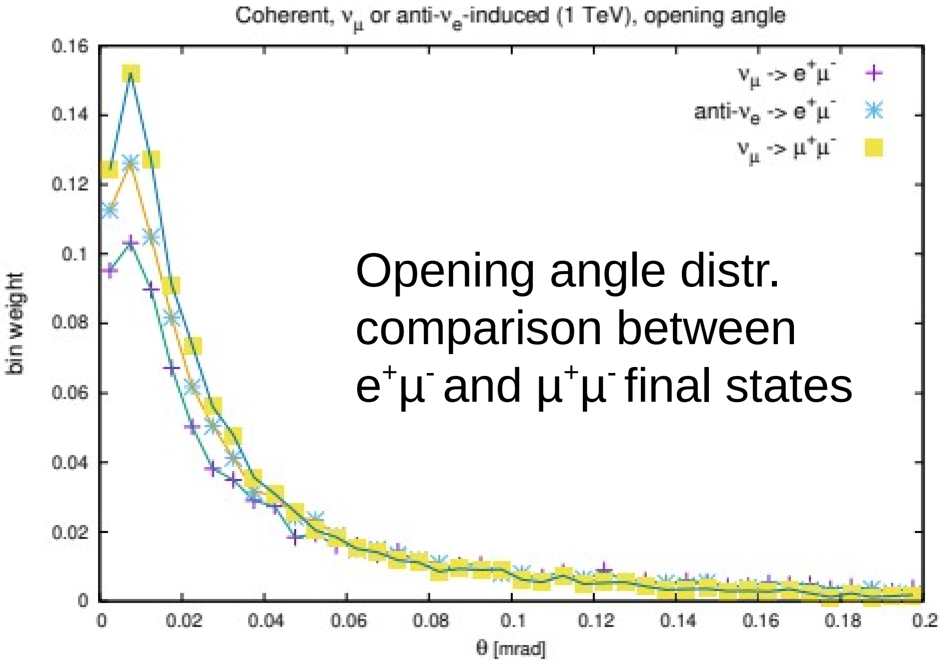
- a bit softer muon
- positron (few hundred GeV)





Opening angle distribution for the $e^+\mu^-$ final state

forward-peaked (generally similar the $\mu^+\mu^-$ final state)



Opening angle distr. comparison between $e^+\mu^-$ and $\mu^+\mu^-$ final states