Neutrino Colliders

Reinhard Schwienhorst

MICHIGAN STATE
UNIVERSITY

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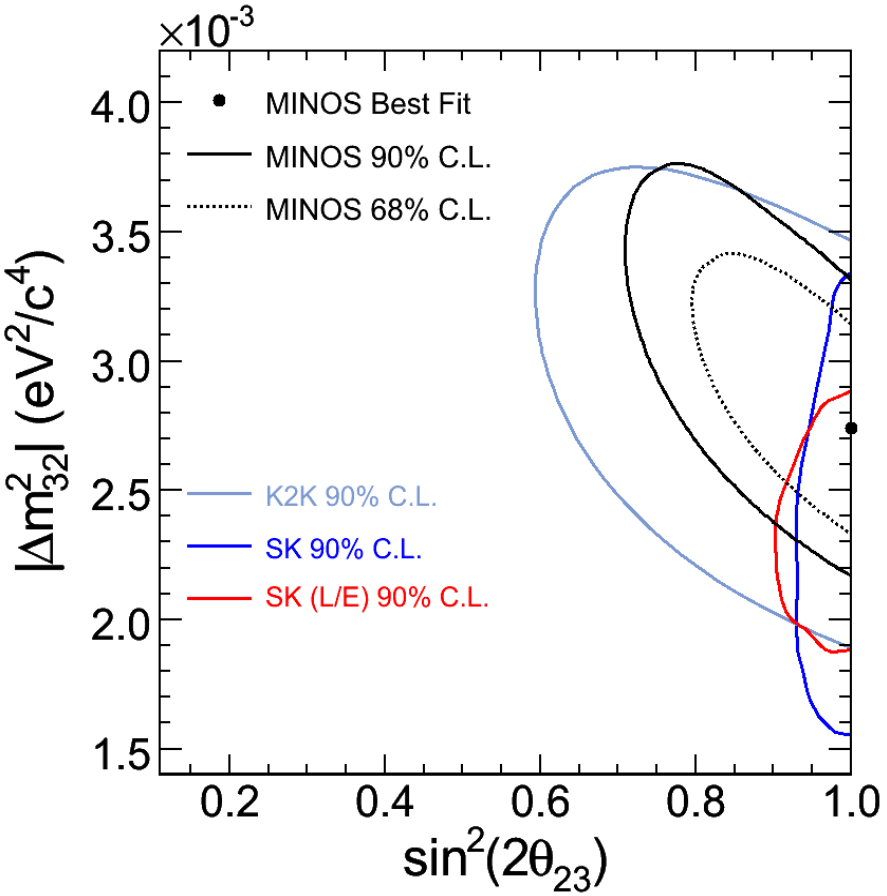
Outline

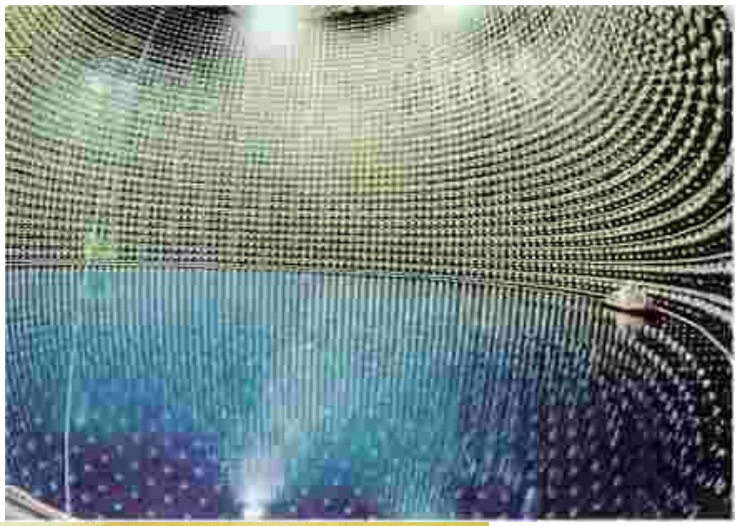
- Introduction
- Colliding neutrinos with other particles
- Neutrino collider configurations
- Cross sections
- Conclusions

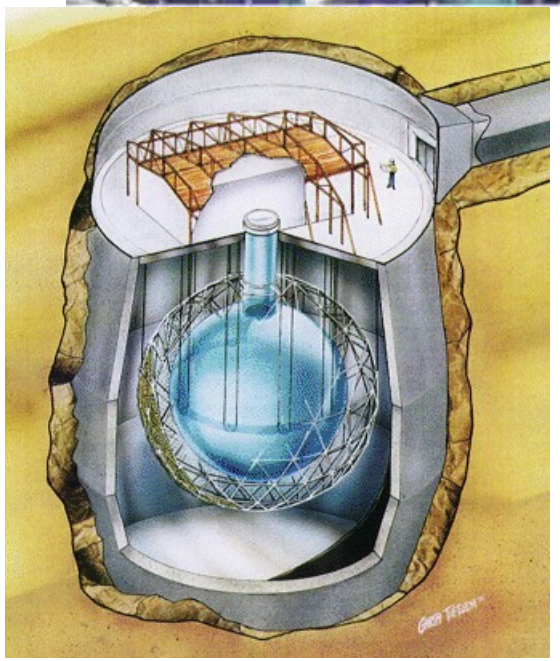
Neutrino beam calculation with BMPT
Cross section calculation with Madgraph

Current neutrino experiments

- Recently established non-zero neutrino mass and neutrino flavor oscillations
- Current experimental goals:
  - Measure parameters (angles, Δm)
  - Identify favored models indirectly







Neutrino physics

- Experiments currently probe mass mixing matrix
  - Questions:
    Parameters of mixing matrix
    CP-violation in neutrino-sector?
  - Maybe in the future also Majorana vs Dirac nature
- But: for other particles, we are currently exploring the mass generation mechanism. Why not for neutrinos?
- 2 main questions:
  - Origin of mass?
  - Nature of right-handed neutrinos?

- Current or planned neutrino experiments do not directly address the origin of neutrino mass

Neutrino mass and new physics

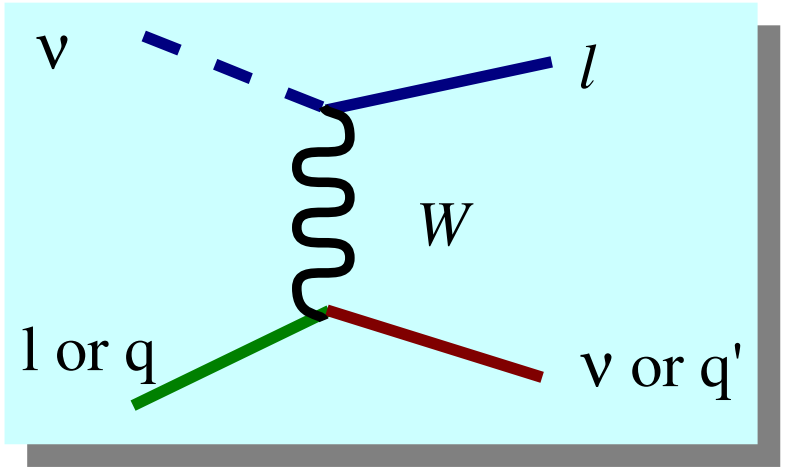
- Neutrino mass
  → right-handed neutrinos exist
  → there must be neutrino interactions beyond SM
  → with other beyond-SM particles
  - Can we produce and observe the right-handed neutrino or other possible non-SM particles coupling to neutrinos?
- Popular theory: see-saw mechanism
  - Right-handed neutrino m_{RH} is heavy

$$m_\nu = \frac{m_D^2}{m_{RH}}$$

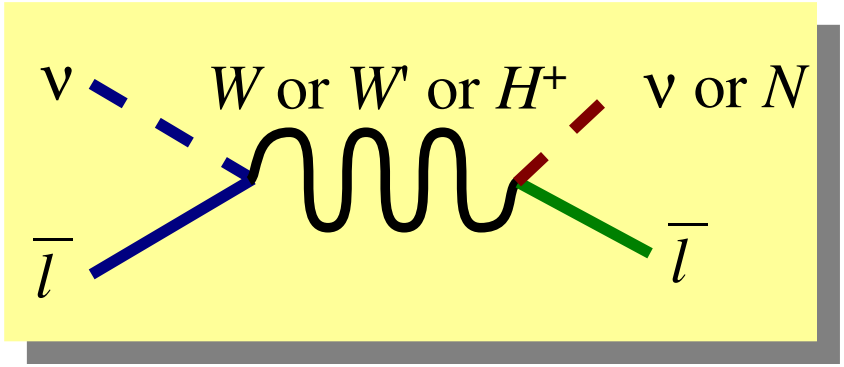
    - At the GUT scale in most theories, but not necessarily
    - Current experimental limits $m_{RH} > 100$ GeV
- Higher order symmetries lead to *W'* and *Z'* bosons
  - Might couple only to right-handed neutrinos
- Many other possibilities: sterile neutrinos, 4th generation, singlets, more Higgses, and many additional particles

Neutrino interactions at high energy

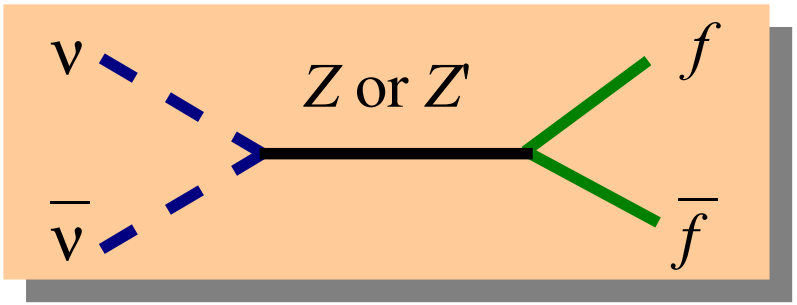
- t-channel *W* boson exchange
  - also *Z* boson exchange



- s-channel *W* boson production
  - Sensitive to new heavy boson *W'* or charged Higgs
  - Or other new new particle coupling to neutrino and lepton
    - Possible new particle might decay to other new particles

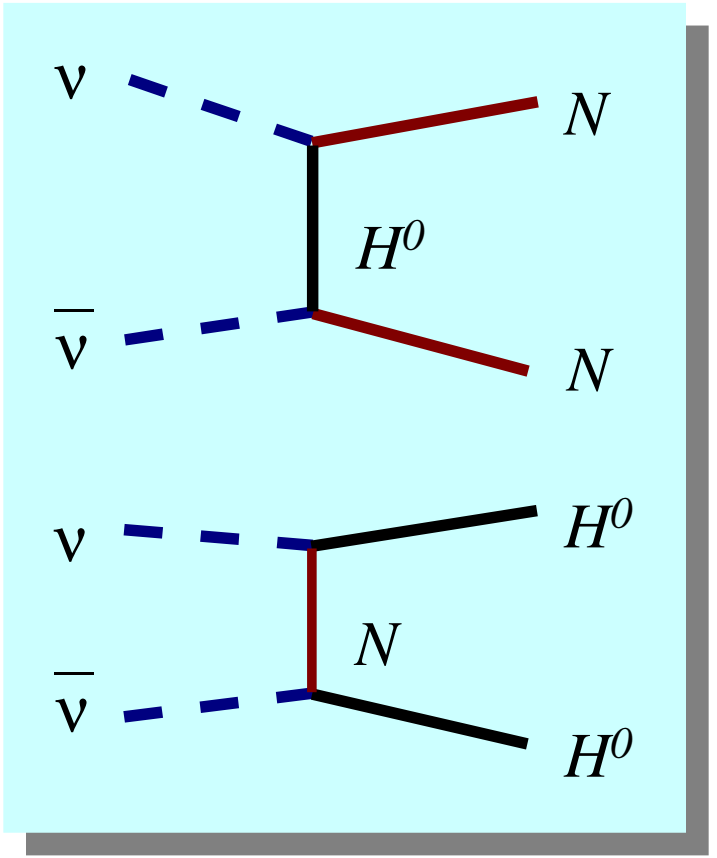


Neutrino-neutrino collisions

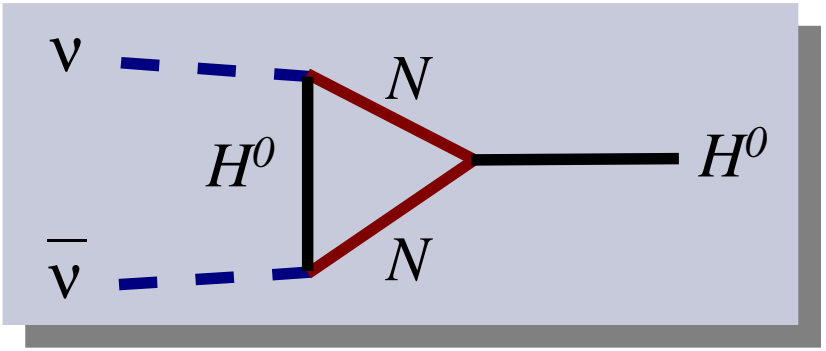


- SM: *Z*-boson production
- New heavy boson *Z'*

- Pair-production of right-handed heavy neutrinos *N*
  - or neutrino-Higgs H^0

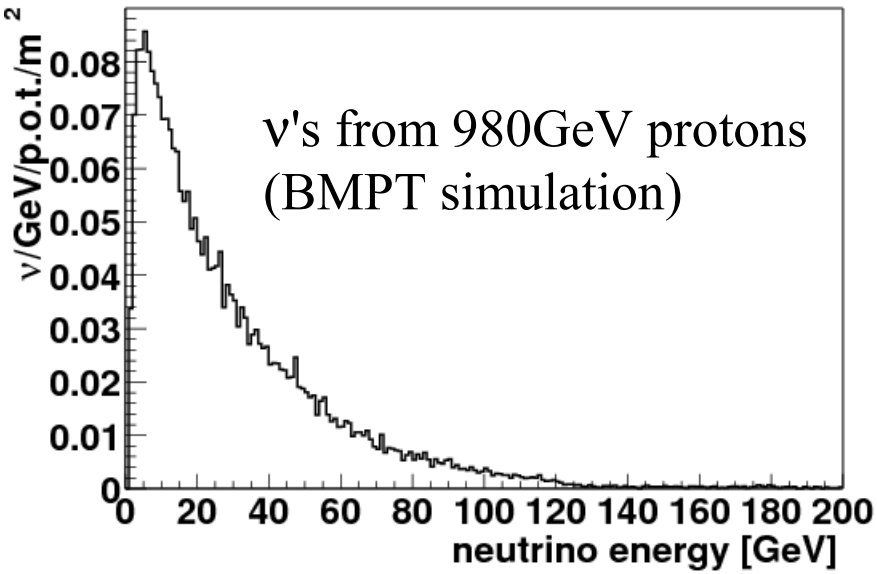


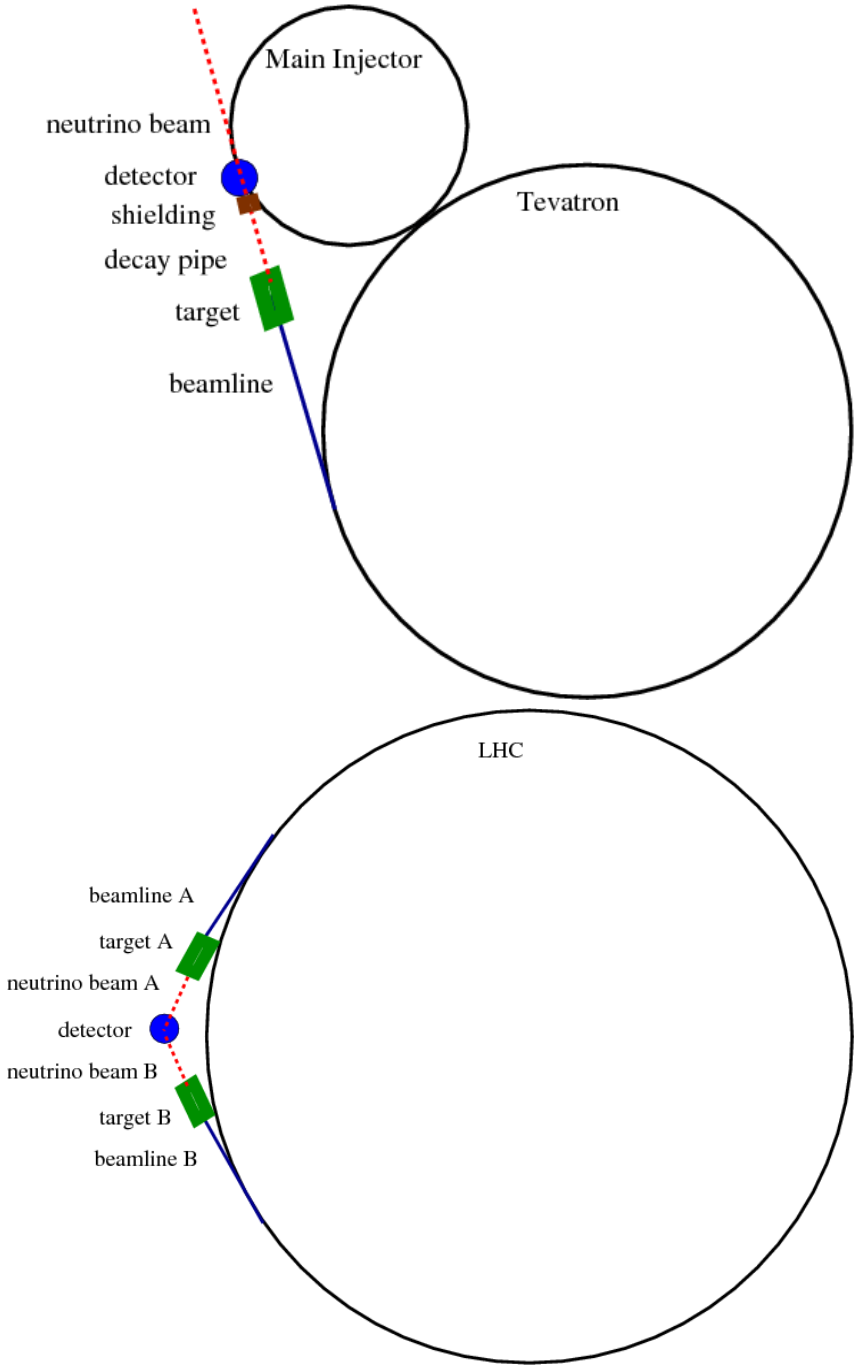
- Neutrino-Higgs production via Majorana neutrinos



Neutrino colliders based on proton machines

- Assume Project X proton intensity
- Protons from Tevatron or LHC incident on production target
  - Tevatron: Neutrino-proton luminosity of 0.02 nb^{-1} per year
    - Need factor ~100 more to get few SM events per year
  - LHC: Neutrino-neutrino luminosity of 20 μb-1 per year
    - Need factor ~100 more to get few SM *Z*'s per year





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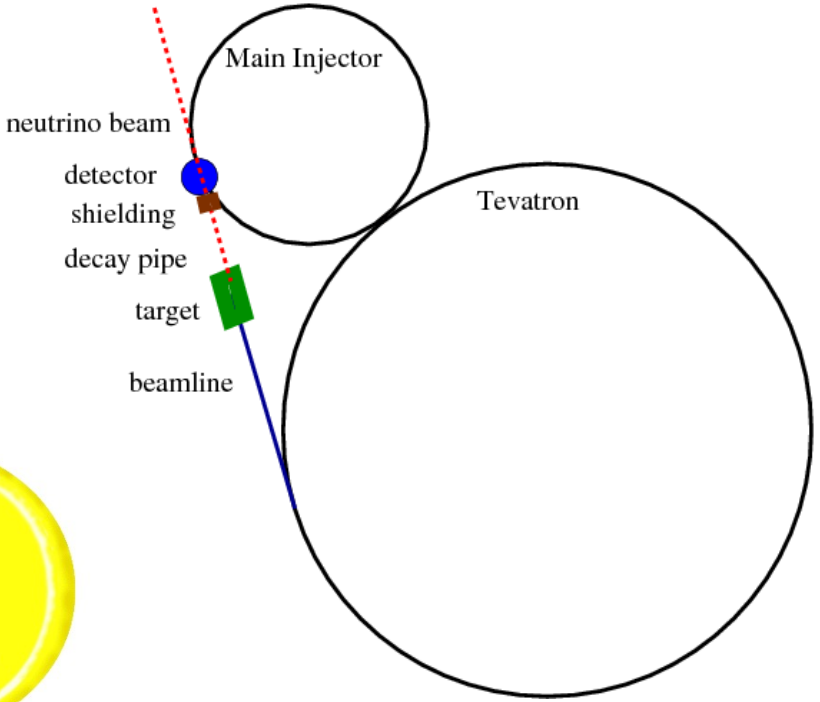
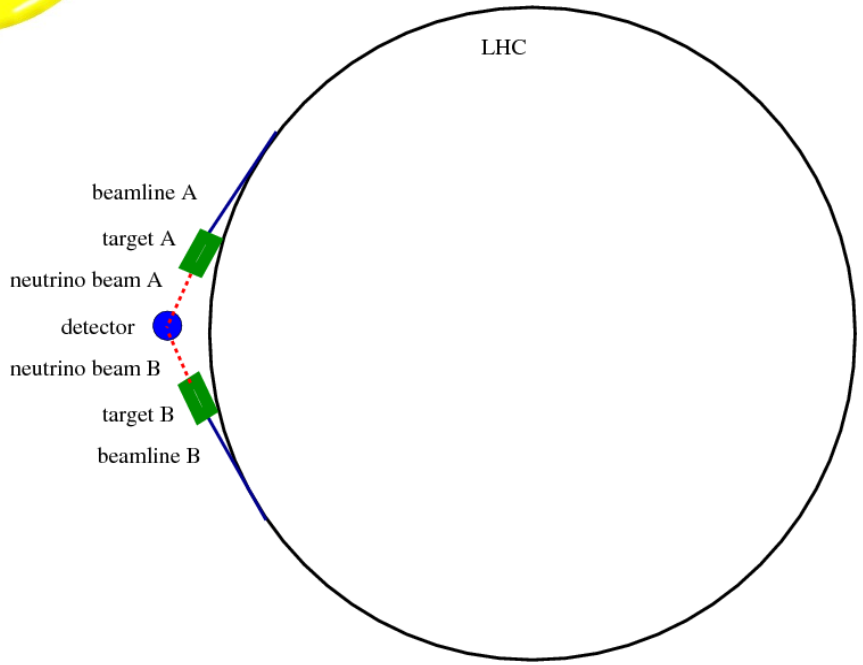
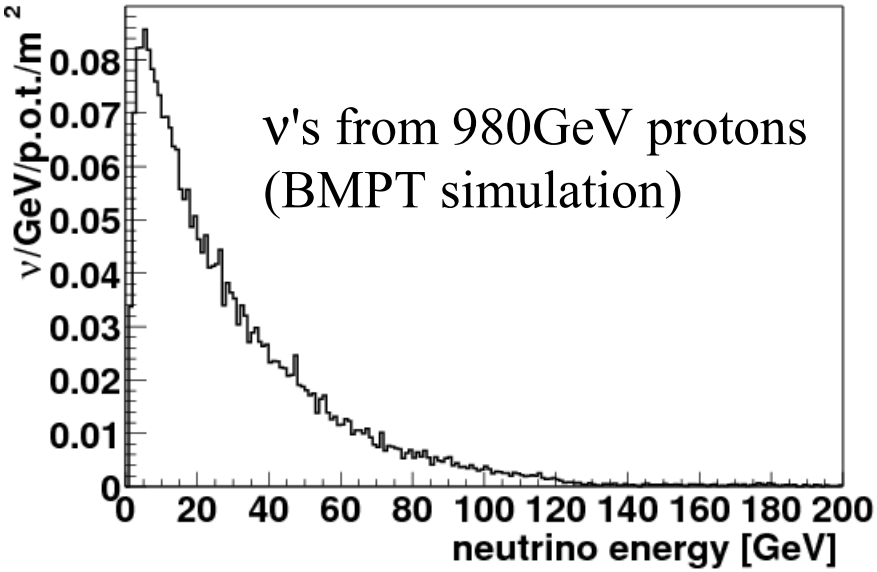
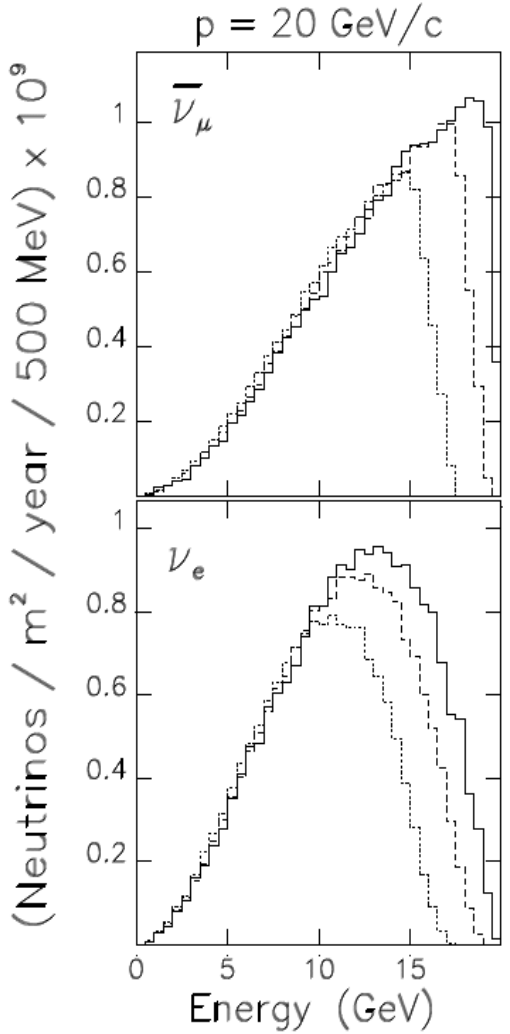






Neutrino production at a muon storage ring

- Results in high energy ν's and many ν's per proton on target
- Assume Project X proton intensity
- 10^{14} protons per bunch and
  5×10^{7} bunches per year
- Assume 0.1 muons/proton, 0.1 neutrinos/muon



from Phys.Rev.D57:6989-6997,1998

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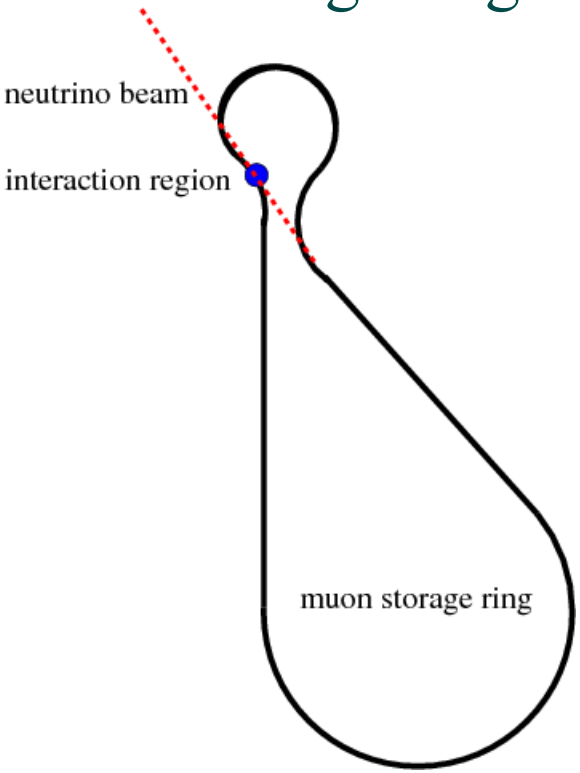
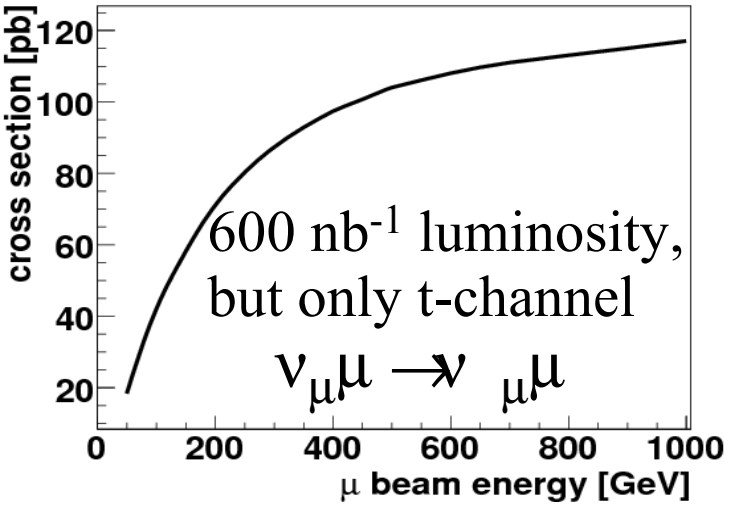
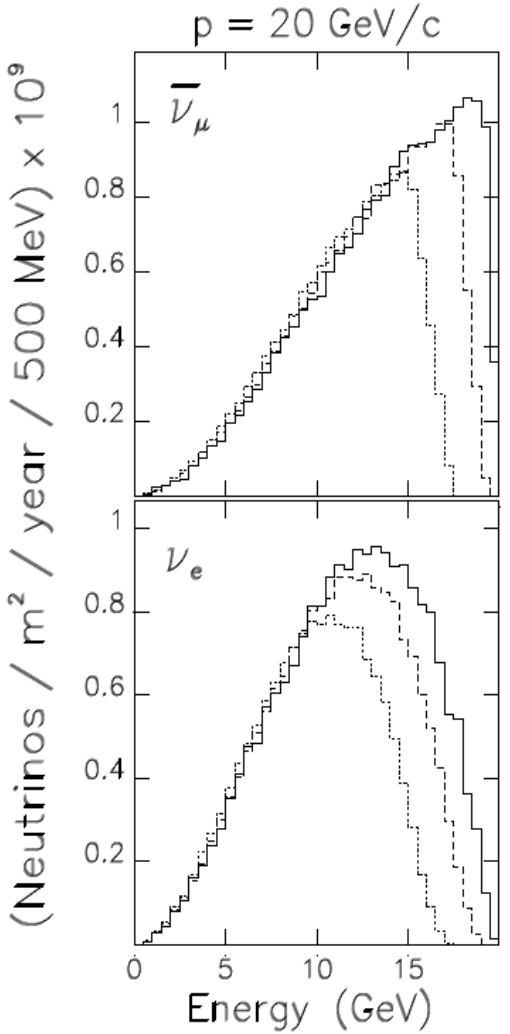
Muon storage ring







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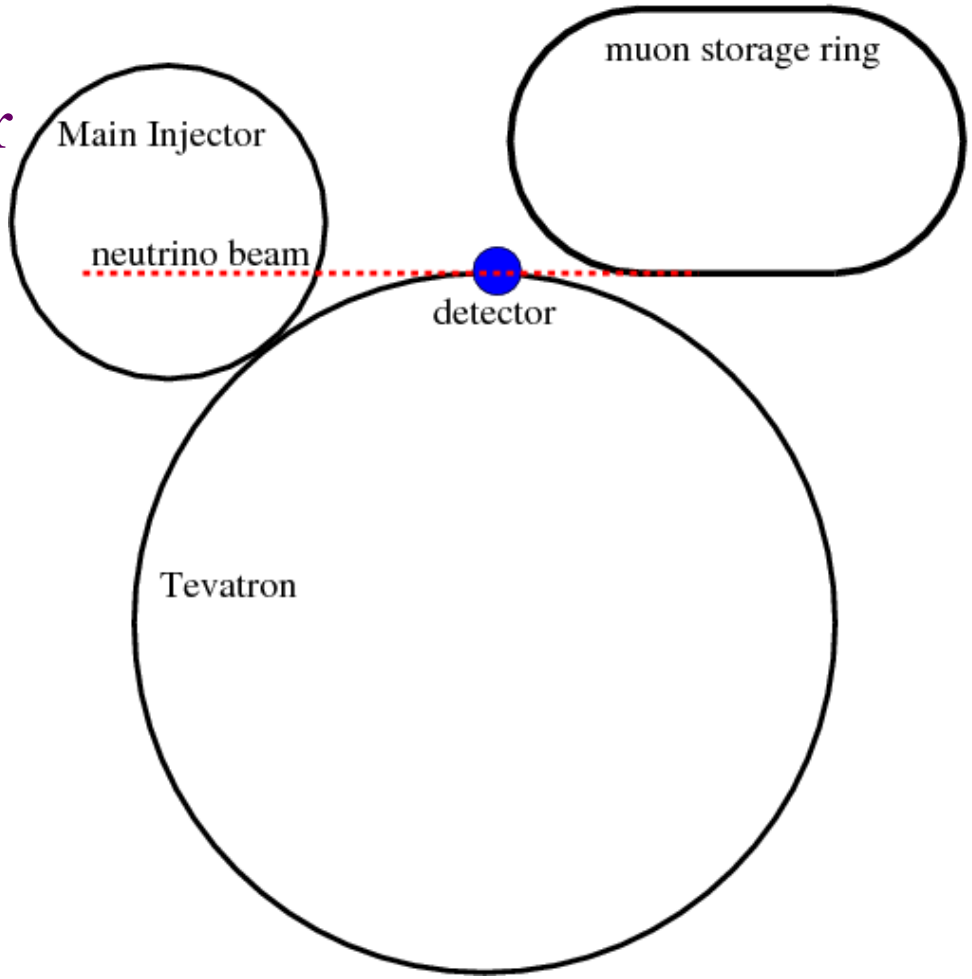
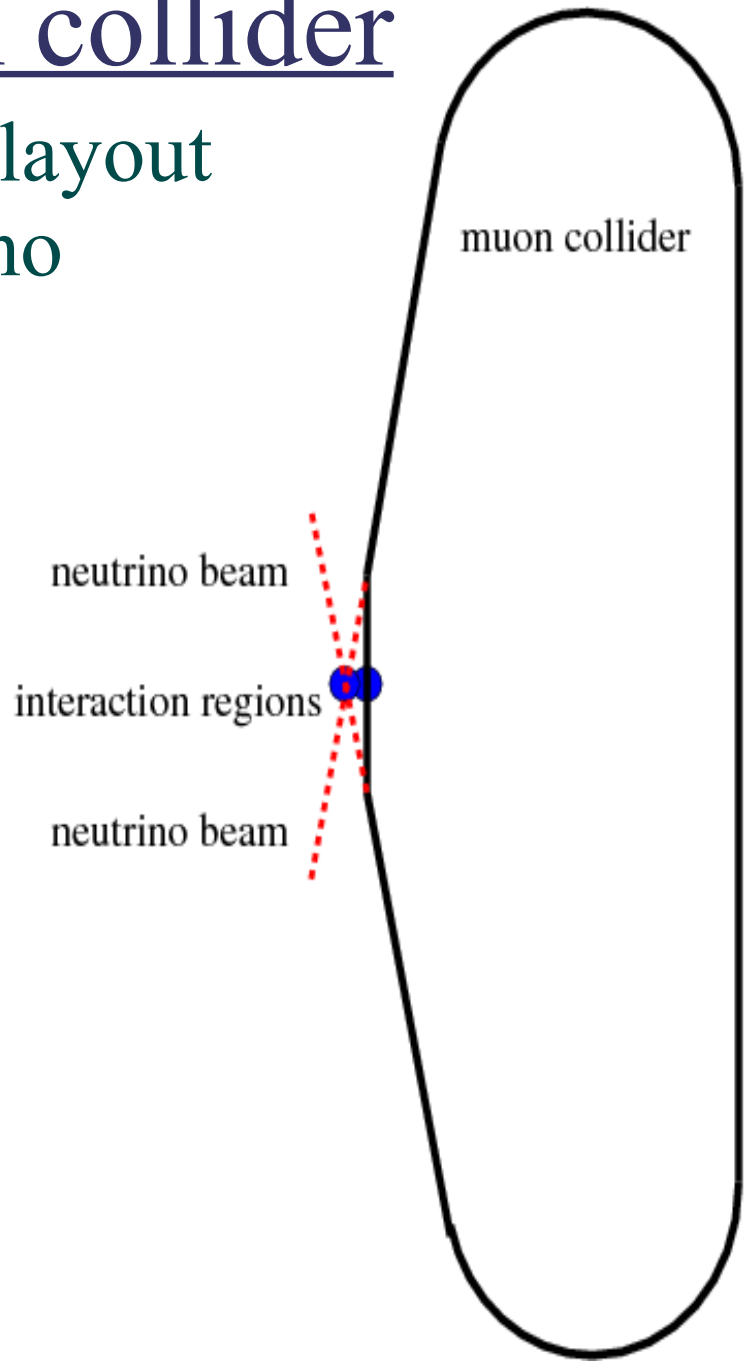
Neutrino factory based neutrino-proton collider

- Neutrino beam from muon storage ring
- Directed at proton beam in Tevatron (10^{14} protons/bunch)
  $\rightarrow$ 40 nb^{-1} luminosity
  - 60 SM interactions per year
  - Increase in protons/bunch ×10 yields luminosity comparable to Hera startup



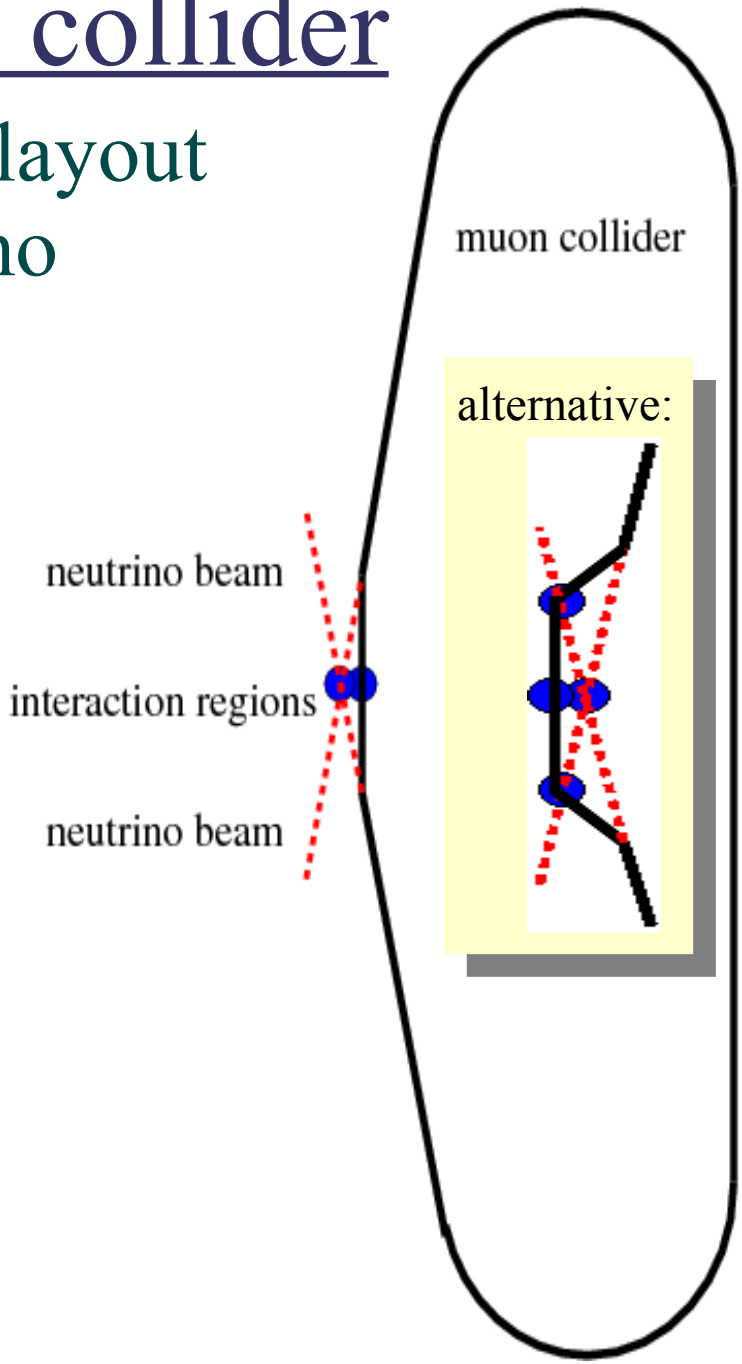
Neutrino and muon collider

- Adjusting the muon collider beam layout slightly produces a separate neutrino collision region
  - Collide muon beams and collide neutrino beams
    - in two separate interaction regions



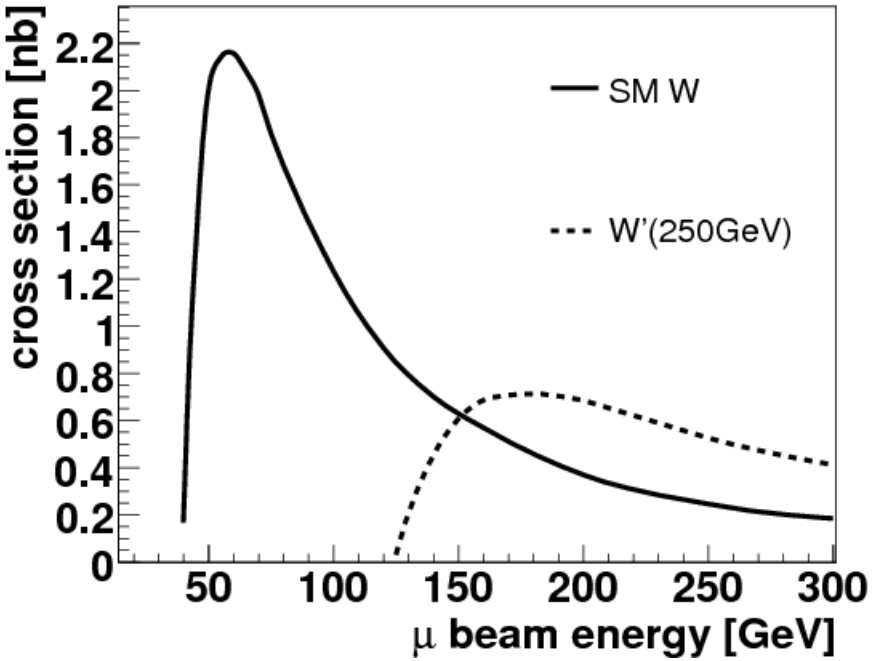
Neutrino and muon collider

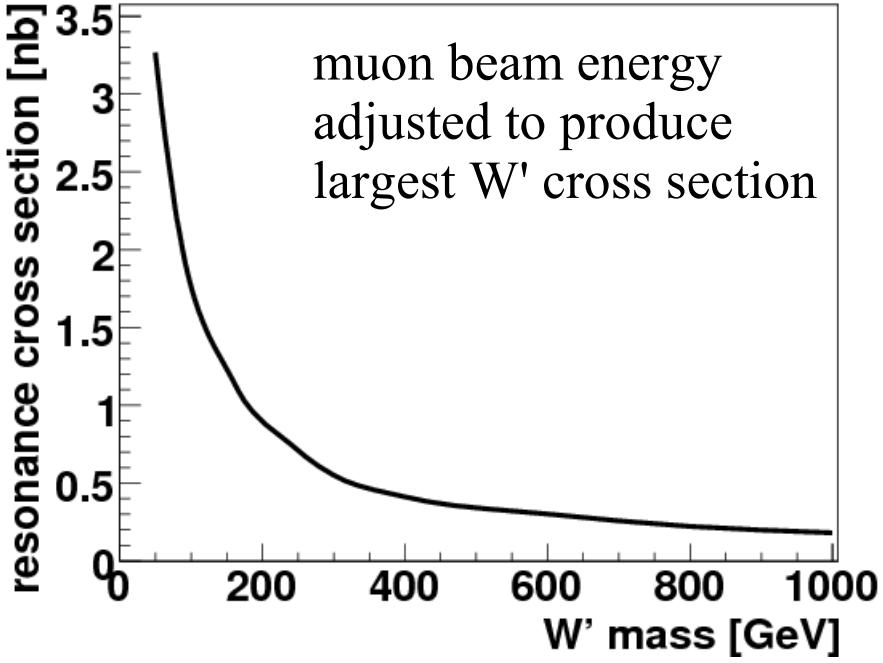
- Adjusting the muon collider beam layout slightly produces a separate neutrino collision region
  - Collide muon beams and collide neutrino beams
    - in two separate interaction regions
- Alternative interaction region also collides lepton and neutrinos
- Luminosity:
  - Neutrino-lepton: 600 nb^{-1} per year
  - Neutrino-neutrino: 60 nb^{-1} per year



W boson production in a neutrino-lepton collider

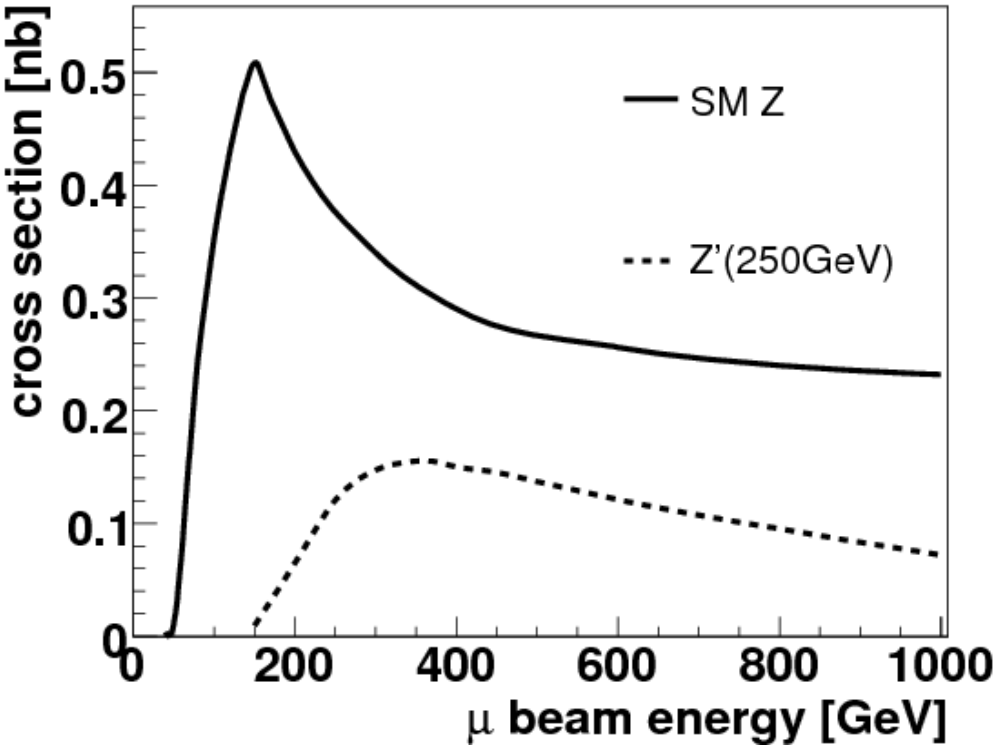
- In a neutrino-lepton collider, the *W* boson is produced in neutrino-lepton annihilation
- With sufficient energy, other heavy objects can also be produced. Example: heavy boson *W'*
- Large cross sections due to resonance production





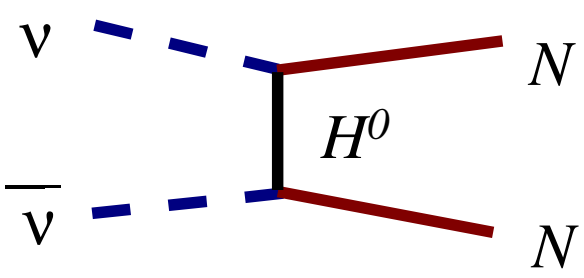
Z or Z' production at a neutrino collider

- SM Z cross section large
  - Neutrino-neutrino collisions will occur in a muon collider, whether we want it or not
  - 30 events per year with current muon collider design
- Sensitive to Z' that couples only to neutrinos

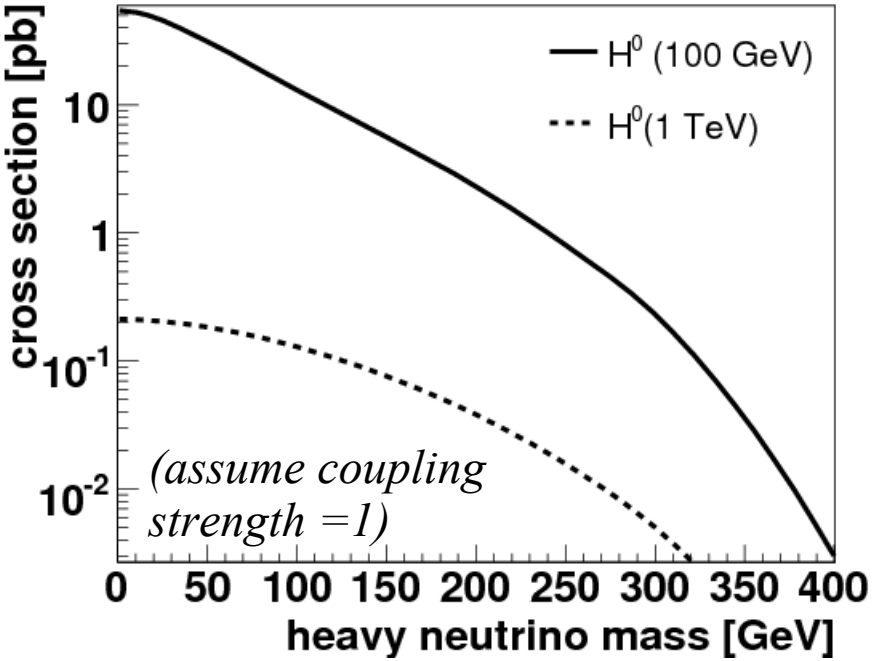


Heavy neutrino production

- Heavy right-handed neutrino production through coupling to neutrino-Higgs (H^0)



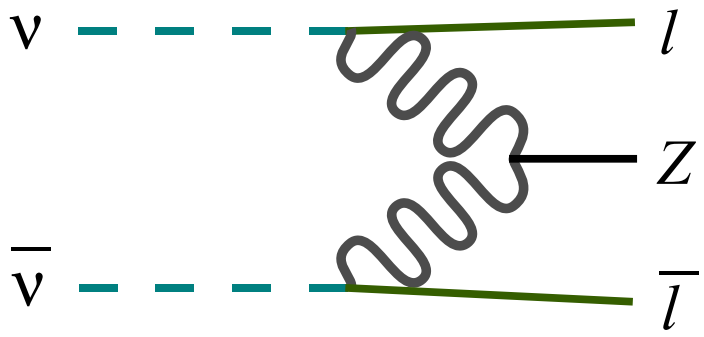
N pair production at a neutrino collider based on 1 TeV muon collider



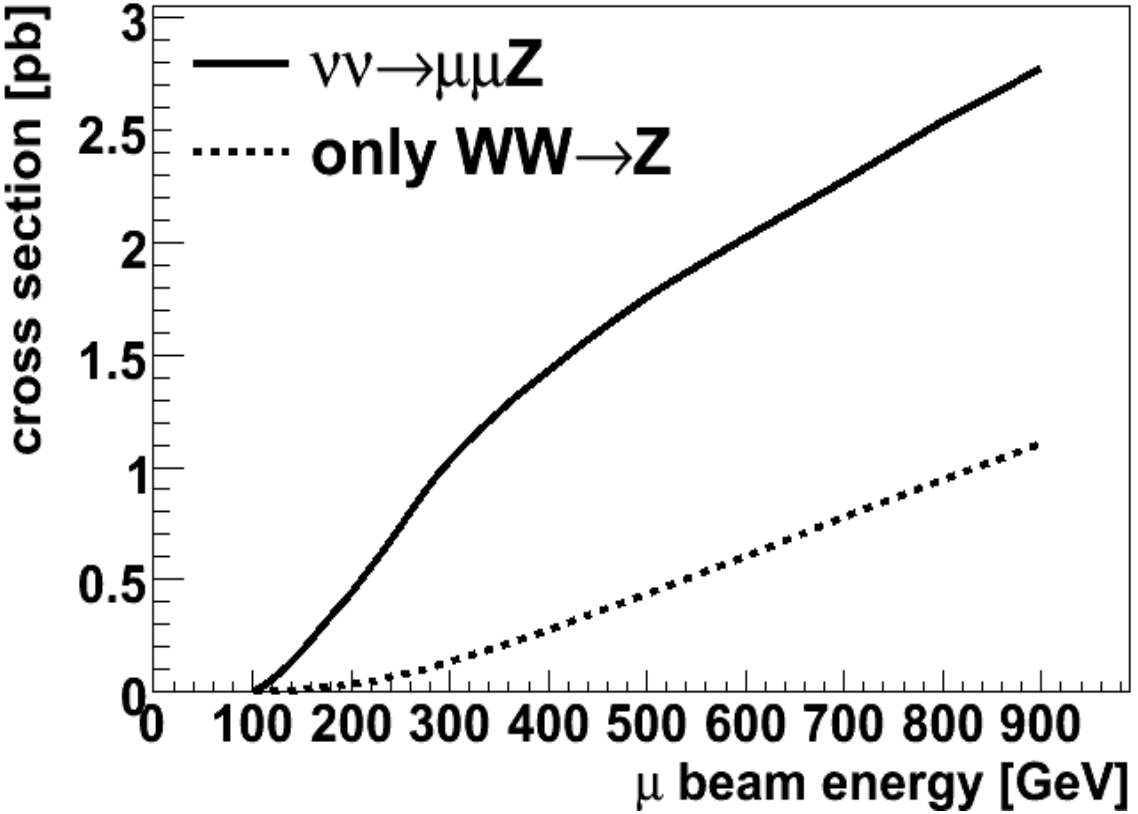
Plus any other new physics in the neutrino sector at the TeV scale

Triple gauge boson coupling: WW collider

- Muon collider → neutrino collider → WW collider



- Physics background:
  - ZZ production
  - Z from initial state or final state radiation



Unique experimental conditions

- Beam crossing at several Hz, but only few interactions per day or even per year
- Beam alignment is a challenge
  - Collision rate to small for immediate feedback
- Large background rate
  - Neutrino interactions in detector and with residual gas
- Large interaction regions
  - Muon storage-ring based neutrino beam diameter ~1mm
  - Proton-beam based neutrino beam diameter ~1cm
  - And plenty of low-energy neutrinos at larger distances

Summary

- Neutrino mass implies the existence of additional particles and interactions (right-handed neutrino, ...)
- If these additional particles are light enough, we can produce them directly at neutrino colliders
- Neutrino colliders based on muon storage rings
  - Provide reasonable luminosity already with existing designs
  - Access the highest CM energies in neutrino collisions
- Any muon collider design should take the neutrino collider into consideration