Beam Cooling with ionisation losses.

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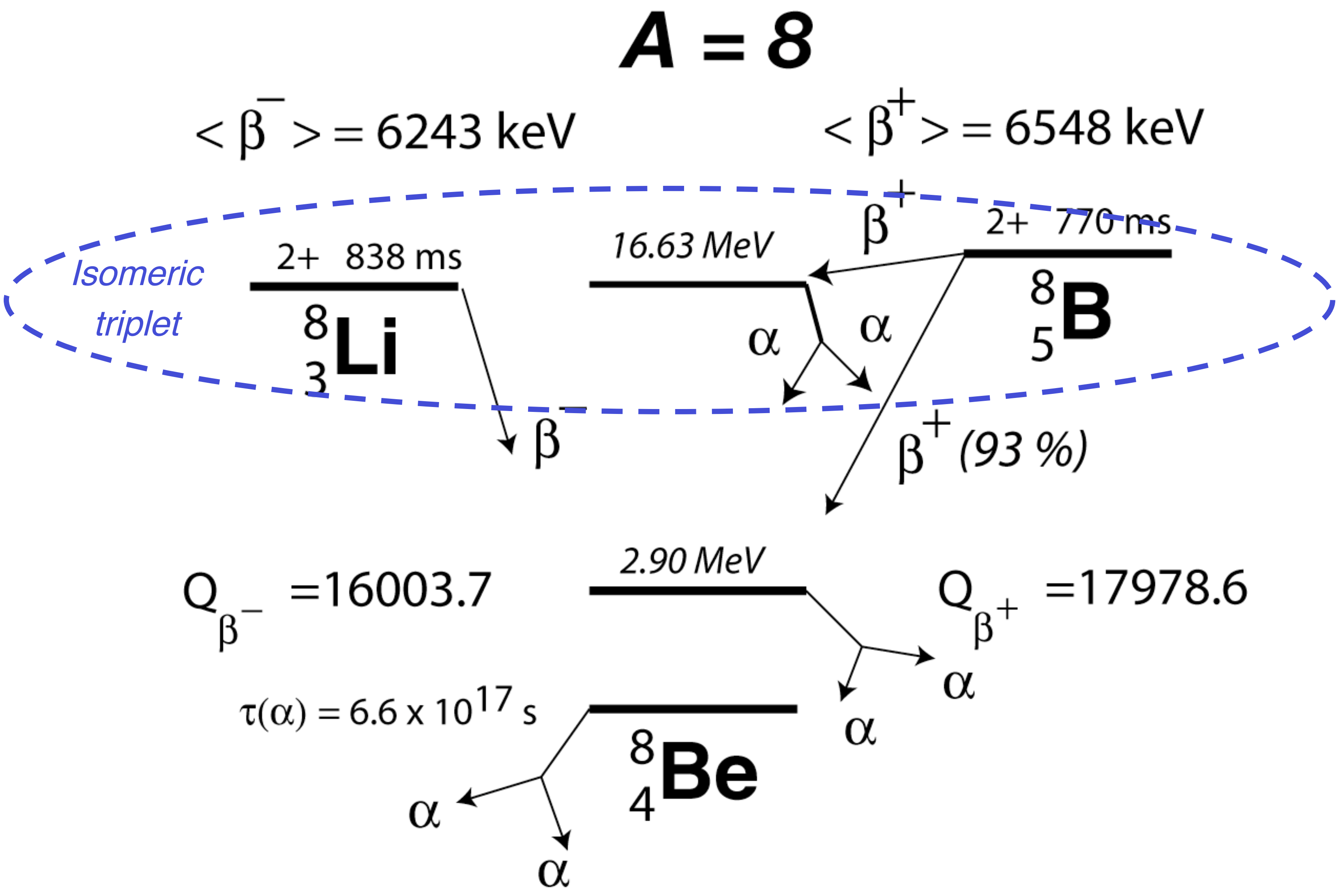
Summary

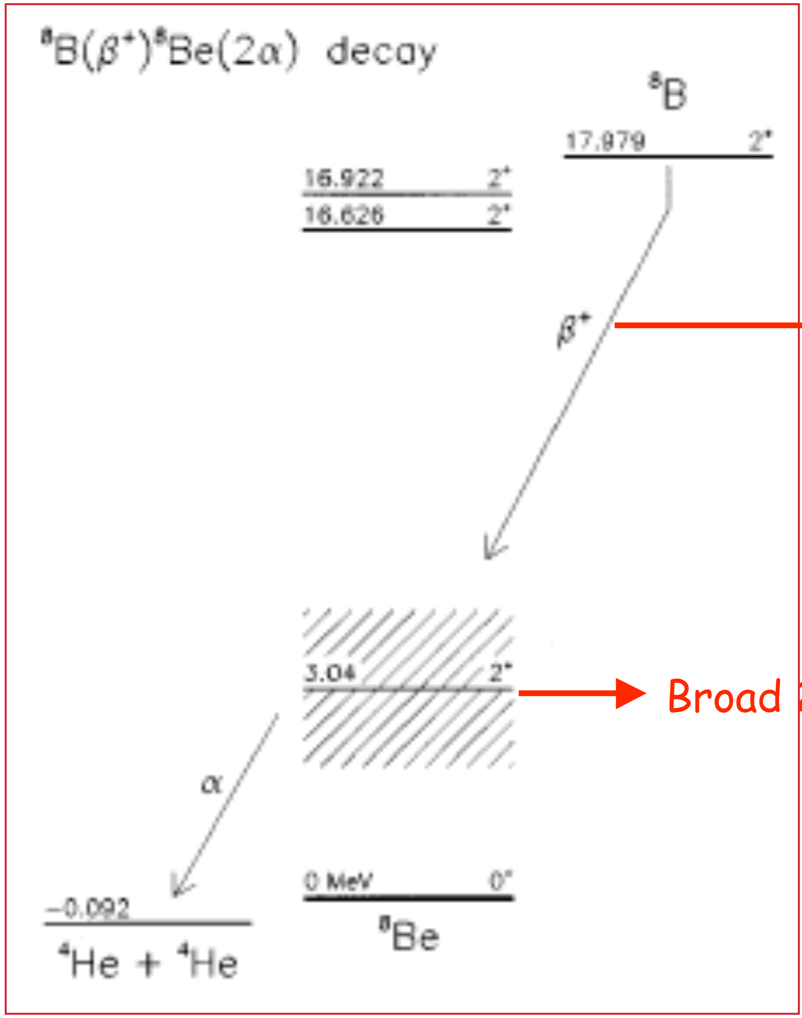
- The method is based a pair of $\beta^{\pm}$ short lived radio-nuclides in a Lorentz boosted frame in order to generate the appropriate ν energy spectrum in the laboratory. We subdivide the presentation in three parts:
  1. *Production of B-8 neutrinos*, with the help of ionization cooling and a gas target. Our choices are the isomeric doublet Li-8 + B-8, because of
     - low mass (A,Z)
     - high decay energies
     - short half-life (≈0.8 s)

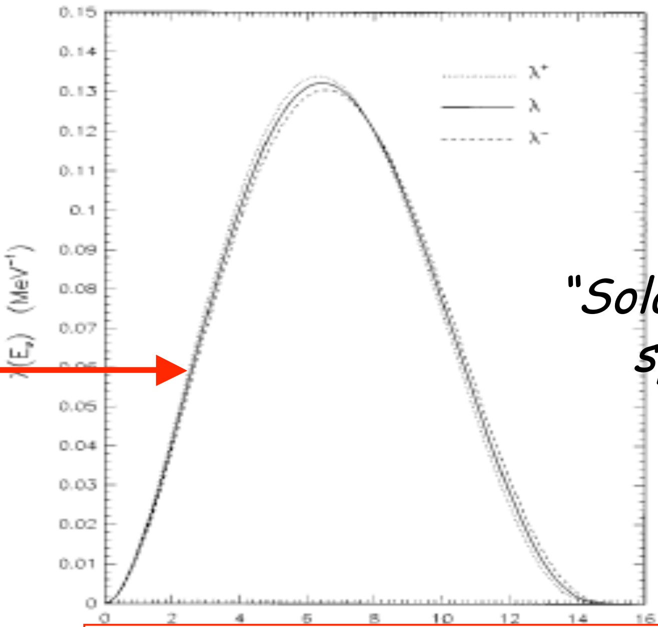
     B-8 is the main high energy component ofSolar Neutrinos
  2. *An accelerator complex,* designed in order to accelerate and to accumulate ≈ 2 x 10^{13}/s nuclei in an racetrack configuration, such as to orient the decay neutrino beam in the direction of the detector, 700÷1200 km away. The magnetic rigidity is equivalent to the one of about 120 GeV protons. Neutrino energies are between 0.5 and 2.5 GeV.
  3. *A massive LAr detector* capable of identifying positively $\sin^2(2\theta_{13})$ down to the lowest possible value ≈ 3 x 10^{-4} without appreciable backgrounds. It is shown a 50 ÷ 100 kt mass has an adequate rejection power and event rate for B-8 decays at 730 km (Soudan, GranSasso).

The Li-Be-B isomeric triplet with A = 8



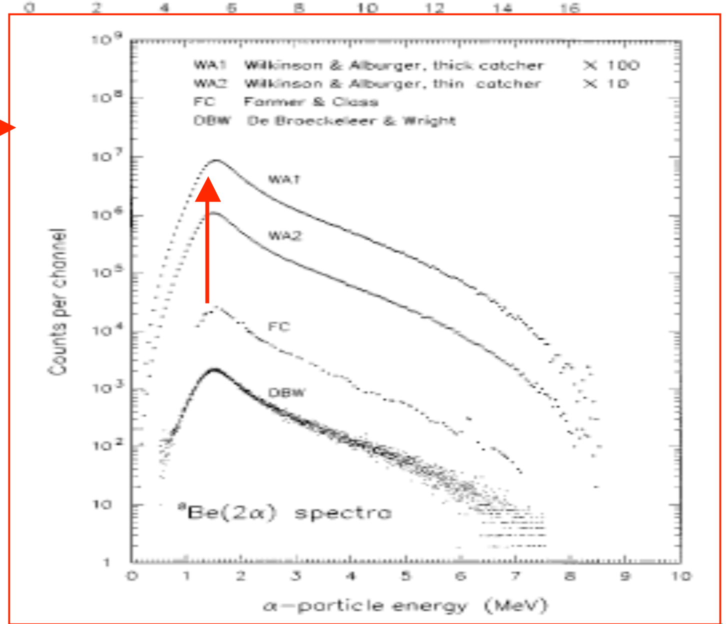
Neutrino spectrum from B-8 decay





"Solar neutrino" spectrum

Broad 2-a peak



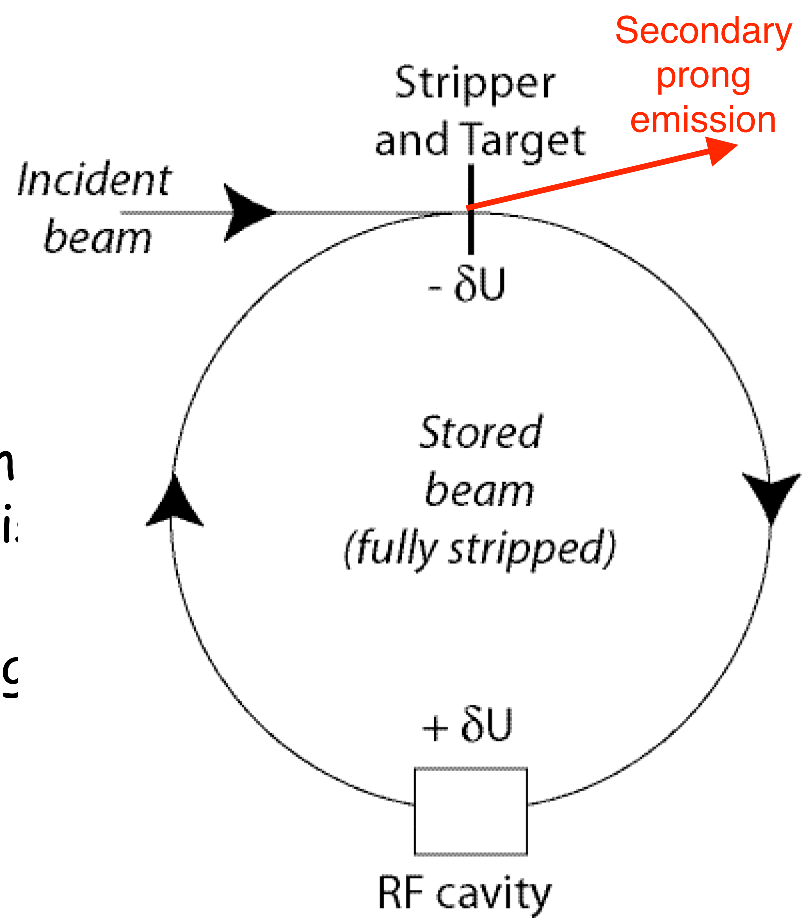
J.N. Bahcall *et al.*
Phys Rev. C
54, 411 (1996)

A new type of ionization cooling

- In contrast with traditional ionization cooling (Budker, Skrinsky) only valid for non-interacting particles (muons) the present method requires the active presence of nuclear collisions, of which it is intended to increment considerably the efficiency because of the large number of traversals and the stability of the cooling process.
- At typical energies of nuclear reactions (few MeV/nucleon) the associated ionisation losses are up to several GeV/gcm^{-2} . The shortness of the particle range makes single pass nuclear interaction probability very small.
- We have considered a new method of "dE/dx cooling" that closely resembles the synchrotron damping of electrons — but with the inization loss in a thin gas target substituting the function of the synchrotron loss.
- The main feature of this method is that it produces an extremely fast cooling, compared to other traditional methods.
- Particles therefore stably circulate in the beam until they undergo nuclear processes in the thin target foil.

Incrementing nuclear interactions with ionization cooling

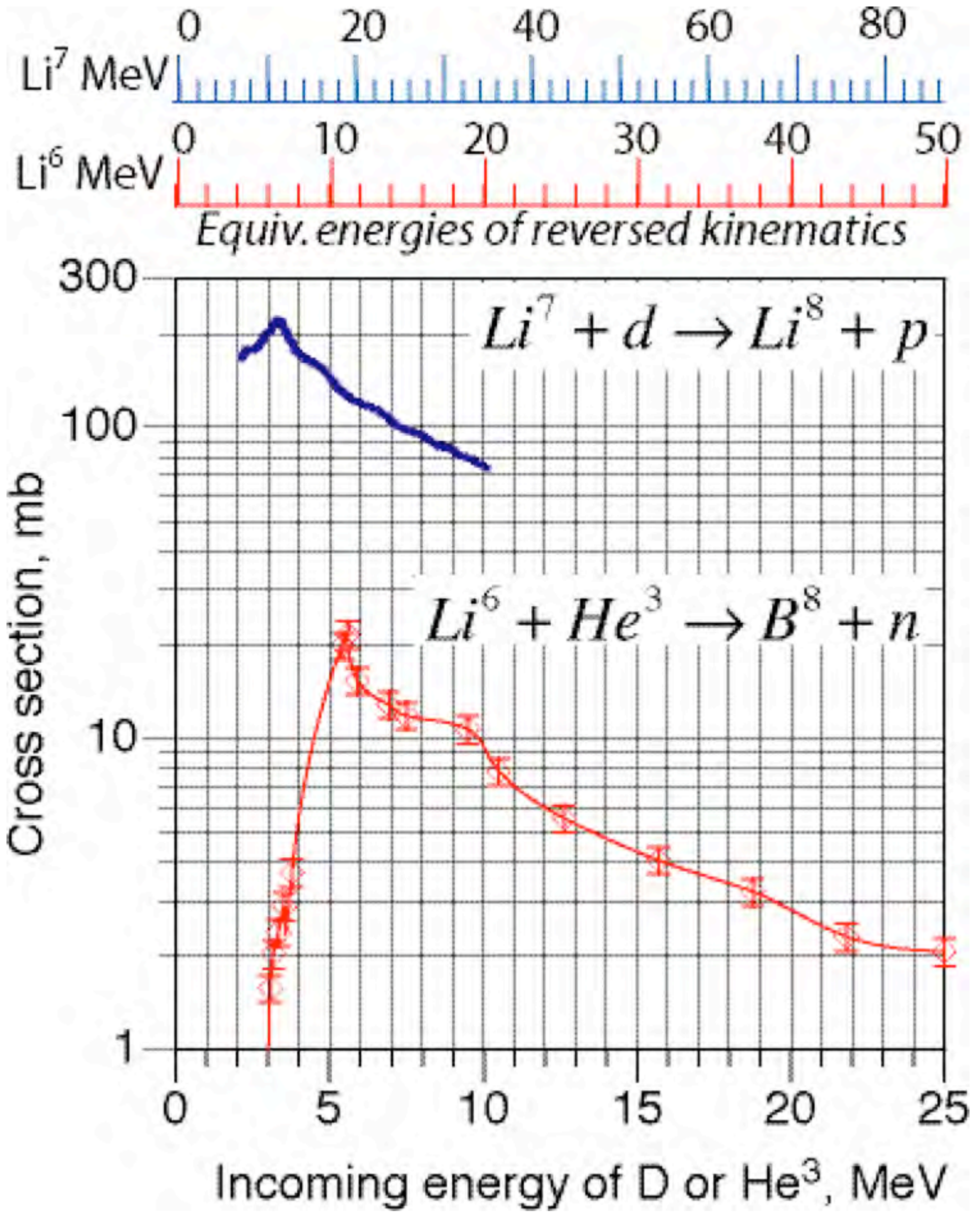
- The basic configuration consists of
  - an appropriate (small) storage ring,
  - a thin target "foil" which induces energy losses and ensures the nuclear interactions
  - an accelerating RF cavity.
- An initially injected ion beam — after being captured by non Liouvillian ionisation stripping in the thin target into its highest charge state — i permanently stored in the ring.
- An accelerating cavity with an appropriate voltag replaces continuously the energy losses of the stored beam maintaining an over all equilibrium (orbit) configuration.
- Non Liouvillian cooling occurs since the scattering is replaced by orderly momentum from the cavity
- The process stops when a nuclear interaction in the jet removes the secondary



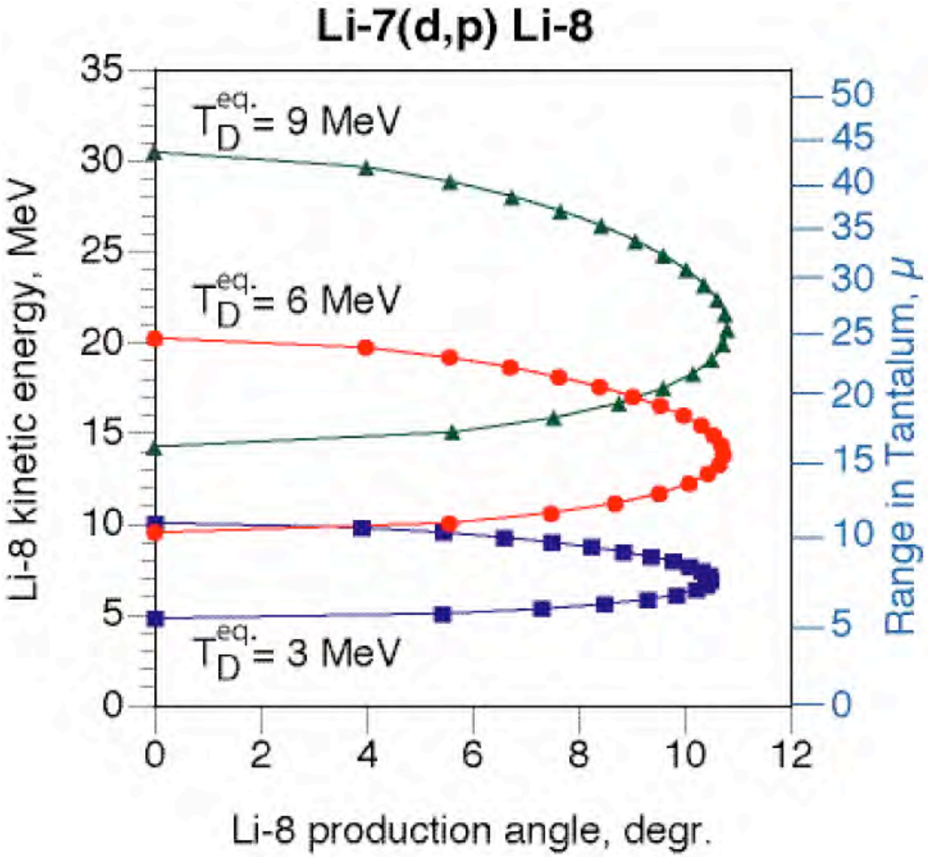
In contrast with the Skrinsky muon cooling, the cooled beam is never extracted

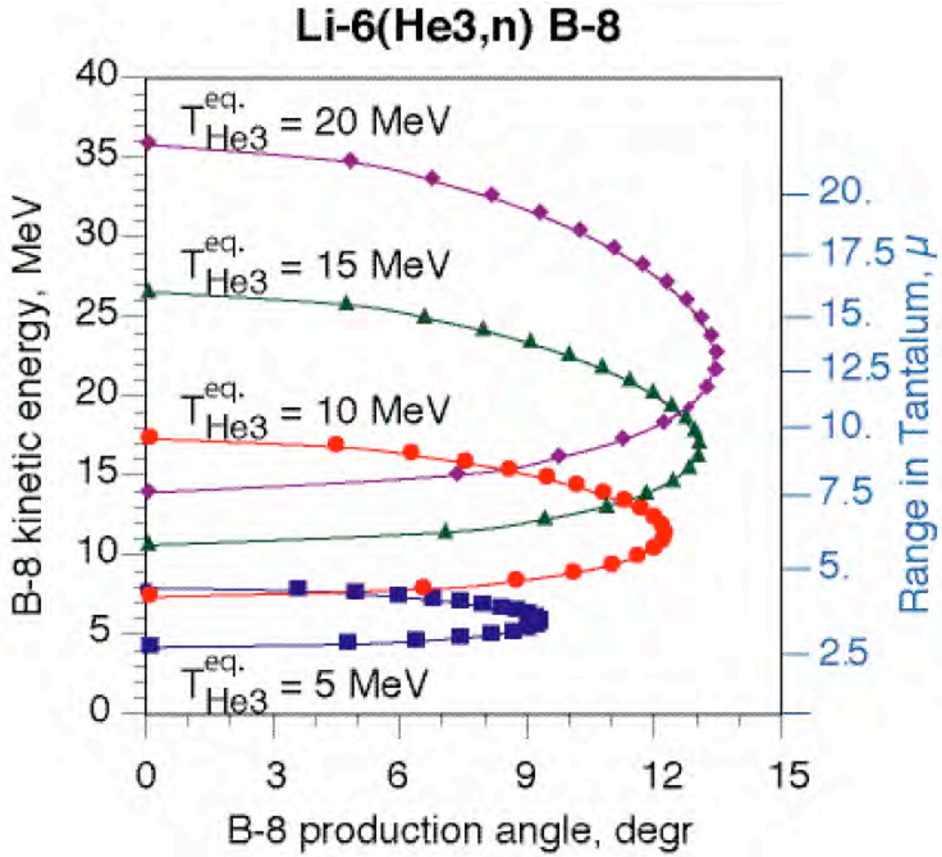
Kinematics

- The recoiling final ions of an accelerated beam of D and He-3 impinging respectively on a Li-7 or a Li-8 target will be distributed in the laboratory over a large angular distribution and with very small kinetic energies, typically a few MeV
- Most of them will necessarily come to rest inside the Li target; for instance the B-8 recoil range at 2 MeV is about 0.5 mg/cm^2.
- Therefore another alternative has been chosen, based on the kinematics of the "mirror" system, namely with a beam of Li-7 or Li-6 hitting a gaseous target either of D or of He-3.



Reversed kinematics

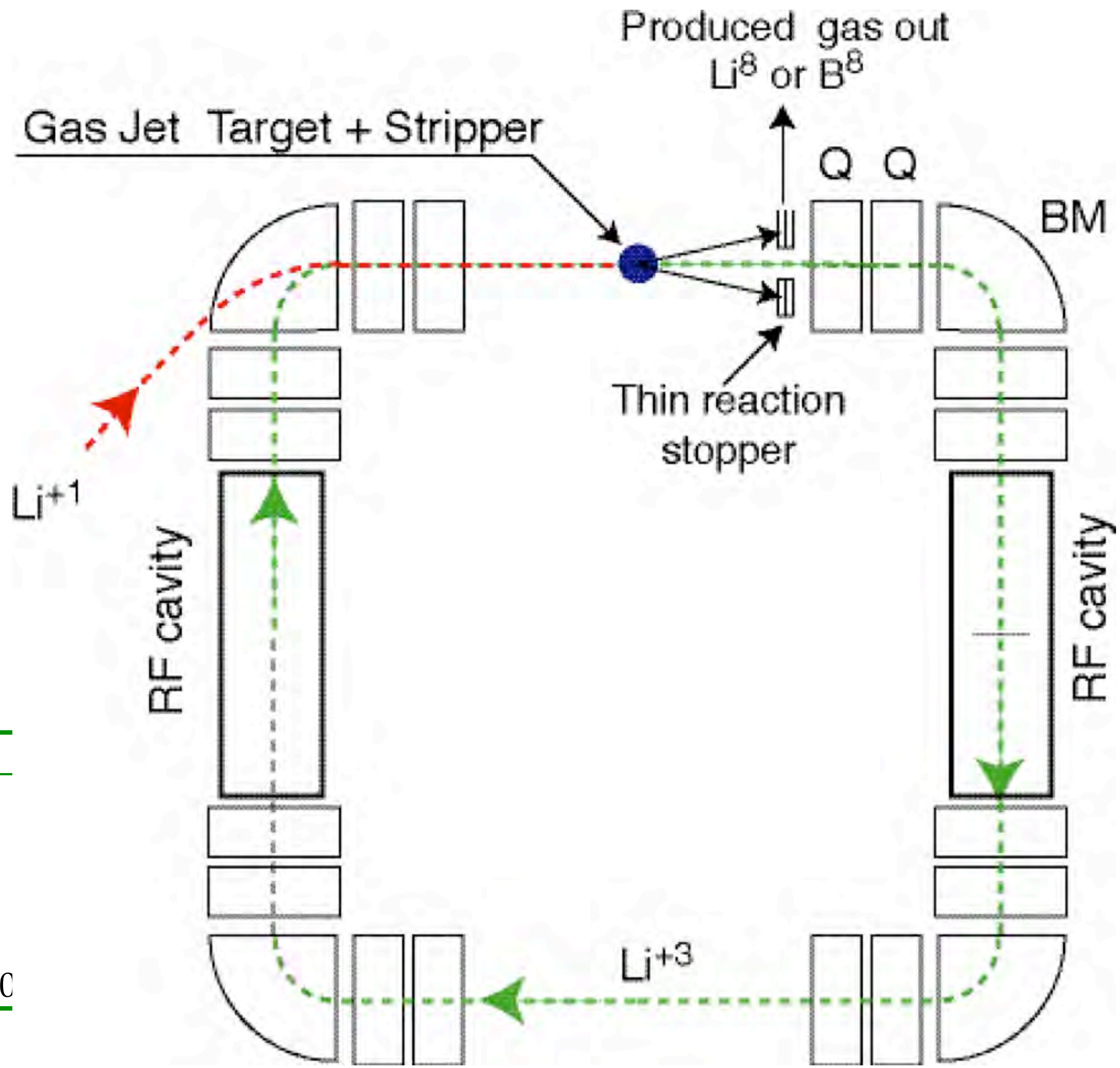




- The kinematics is very favorable, with emission angles of the final Li-8 and B-8 products in a narrow angular cone typically (about 10 and 12 degrees respectively, with a relatively concentrated energy spectrum.
- The penetration power in a thin tantalum stopper is indicated.
- Power to be dissipated is very much larger, since a gas target is used.

Ring configuration

<β>≈ 35 cm



Lattice parameters		
Q-horizontal	Q_x	1.58
Q-vertical	Q_y	1.87
Gamma transition	γ_t	2.50
Orbit circumference	c	4.00
RF peak voltage	V_o	300.0

Simple transverse cooling

- As well known, the energy loss in the foil is compensated by the RF cavity, which adds however momentum only in the longitudinal direction, resulting in a small, proportional reduction of the particle transverse angle (both vertical and horizontal).
- Under the action of the continuous acceleration, the transverse emittances are therefore decreasing exponentially (T is ion k.e. , δU is the energy loss in foil and P_s is rotation period):

$$\alpha_x = \alpha_y = \frac{1}{P_s}\frac{\delta U}{2T}$$

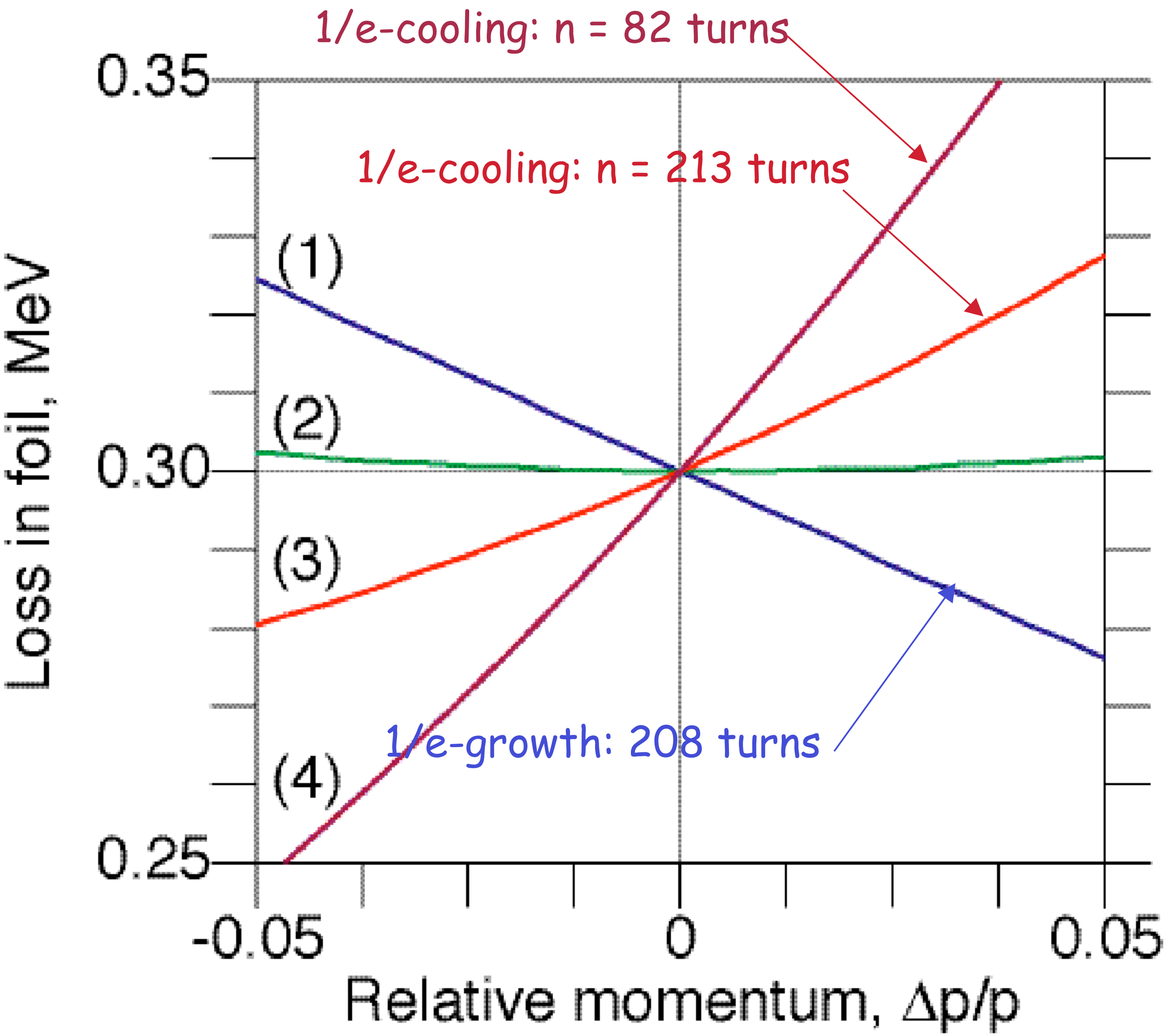
- For T = 25 MeV and δU = 0.3 MeV, the cooling constant is n ≈ 166 turns, an extremely fast cooling, if one considers that the typical revolution frequency of the small storage ring is in the range 5÷10 Mc/s.
- In these conditions, like in the electron case of the synchrotron radiation, the transverse emittance will converge to zero. A finite equilibrium emittance is due to the presence of multiple Coulomb scattering and Landau straggling.
- *Li-7 on D_2 we find as equilibrium 6×10^{-6} rad m (area/π) and <x> ≈ 1.4 mm.*

Longitudinal cooling

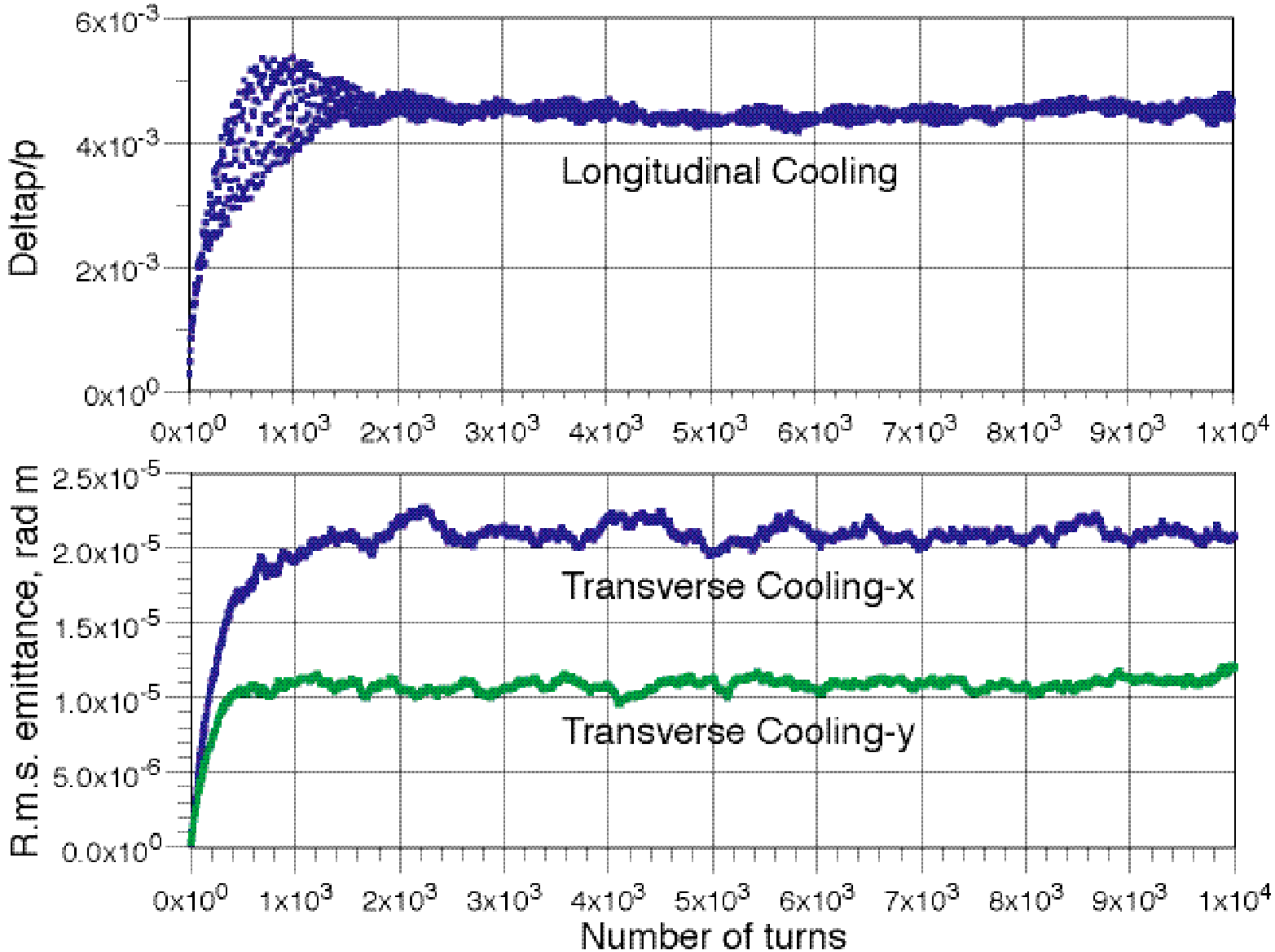
- As well known, synchrotron radiation produces damping also in the longitudinal component, since the energy losses exhibit a significant momentum dependence ($\propto p^4$). A faster particle is loosing more energy and a slower particle less energy.
- In the case of the ionization cooling, the opposite effect occurs, namely ionization losses decrease with energy.
- For instance for Li-6, T = 25 MeV and δU = 0.3 MeV, the e-fold increase of the longitudinal emittance is ≈ 210 turns, i.e. the longitudinal momentum spread grows very fast, in contrast with the transverse cooling which has a e-fold constant of about n = 166 turns.
- In order to achieve longitudinal cooling:
  - ⇨ the gas target may be located in a point with a chromatic dispersion.
  - ⇨ The thickness of the foil must be wedge-shaped.
- Faster particles, (with a larger radius), will find a thicker wedge and consequently an increased ionization loss, such as to reverse the “natural” behaviour of a decreasing energy loss as a function of the energy.

Effects of wedge action

- Energy loss/turn as a function of the momentum
- for cases 1-3 respectively of foil without wedge, and for 2 progressive increments of the wedge action.
- Case (4): synchrotron electrons.



Montecarlo simulation



Beam current limits

- These emittances are intended to show the ability of introducing a very substantial ionisation cooling. These correspond to extremely small beam sizes, since for instance 10^{-5} rad m and β = 15 cm corresponds to an r.m.s. vertical size of 1.2 mm. The transverse heating is due to the Coulomb scattering. Higher local β values generate larger equilibrium emittances.
- The maximum circulating beam current, as equilibrium between incoming beam stripping and nuclear absorption, is primarily determined by the Laslett transverse tune shift due to space charges:

$$N_{Laslett} = \Delta Q \frac{1}{r_p}\left(\frac{A}{Z^2}\right) 2(\pi\varepsilon)\beta_o^2\gamma^3 B_F$$

- Assuming for instance β = 20 m, the resulting equilibrium emittances are respectively 2.4 x 10^{-3} π rad m and 1.4 x 10^{-3} π rad m, corresponding to a r.m.s. vertical size of 1.6 cm at the high beta point, which is reasonable.
- The calculated number of circulating particles is then 10^{12} for the conservative estimate, ΔQ = 0.25 and a bunching factor B_F =5.

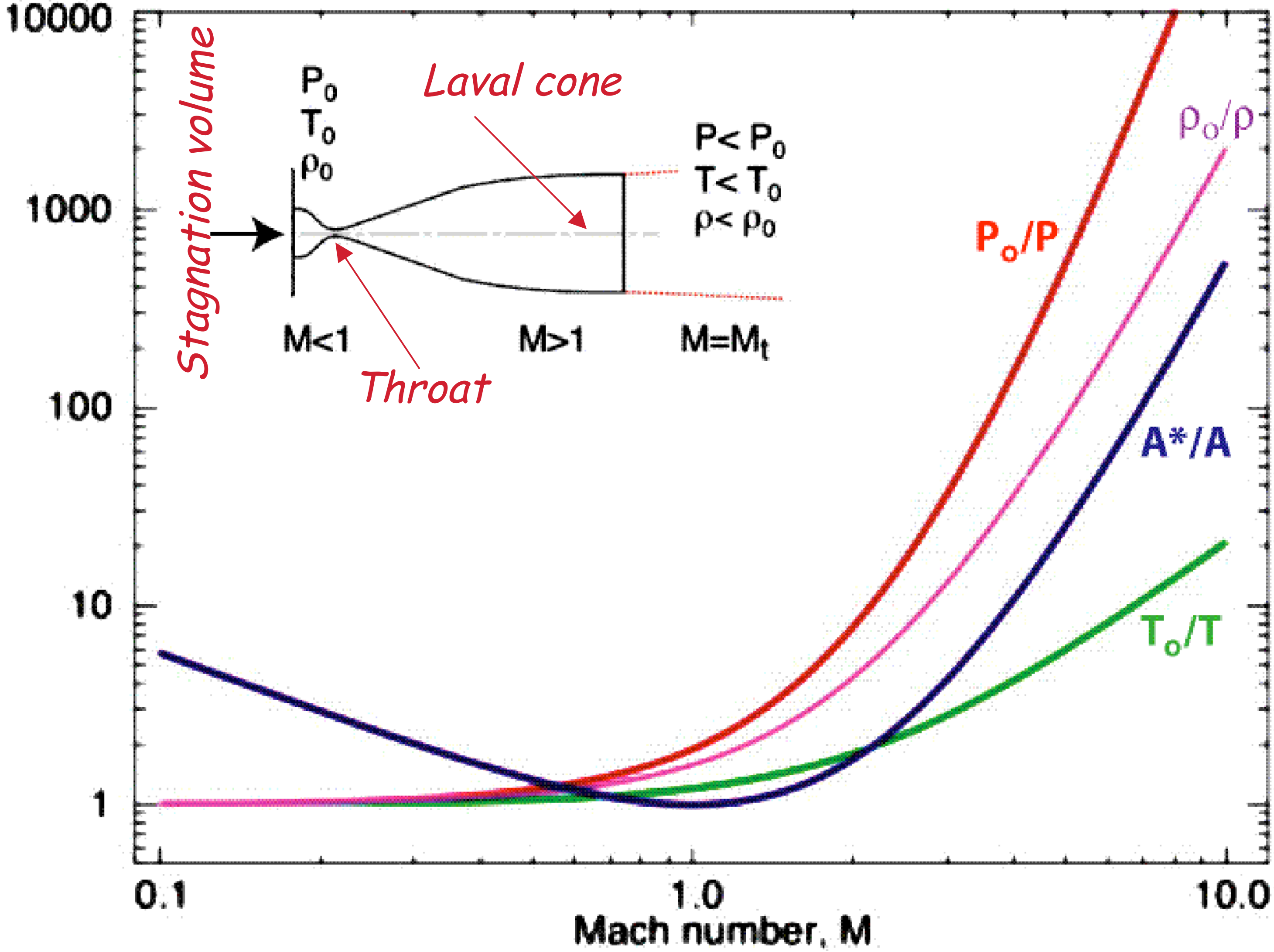
Achievable performance

- The sum of the nuclear elastic and inelastic reaction cross sections for Li-6 and Li-7, producing the ejection of the particle from the beam, are typically $\sigma_{loss} \approx 10^{-24}$ cm^2, i.e. 1/e absorption in D_2 and He-3 are ≈ 3.3 and ≈ 5 g/cm^2.
- With a typical D_2 target thickness of 0.33 mg/cm^2 the nuclear 1/e lifetime is of about $n \approx 10^4$ turns, namely the average beam particle duration in the ring is of the order of 1 ms.
- This is between three and four orders of magnitude greater than the one of a conventional thick target configuration with a single beam passage.
- We assume 10^{14} reactions/s of Li-7(d,p) Li-8, corresponding to the beam injection of about 10^{15} ion/s, namely a circulating current $N_{circ} \approx 10^{12}$ ions, renewed at each every ms.
- The injected current of singly ionised particles before the stripping is then 160 μA. The corresponding injected beam power is only 4 kW for T = 25 MeV. If $\sigma_{loss} > 10^{-24}$ cm^2, current is correspondingly higher, but $i_{circ} \approx 10^{12}$ ions

The gas jet target

- The gas jet target may follow the principle of a Supersonic Gas Injector (SGI) implemented for fuelling and diagnostics of high temperature fusion plasma in several Tokamak, NSTX (USA), Tore Supra (France), HT-& and HL-1M (China), normally operated with H_2, D_2 and He gases.
- The technology is based on the isentropic compressible gas flow and it is well developed in aero-space, molecular beam research and industry. It is designed on a supersonic Laval nozzle with convergent and divergent contours which produces a highly uniform flow with Mach number $M > 1$, responsible for the formation of a low divergence high intensity jet.
- The stagnation volume with $[P_o, T_o, \rho_o]$ is followed by a narrow nozzle throat and a de Laval nozzle — at the end of which the exiting gas has $P < P_o, T < T_o, \rho < \rho_o$ and a Mach number $M_o > 1$.
- The design is usually done using computational fluid dynamics based on the numerical solution of the Navier-Stokes equations.

Isentropic behavior of Laval nozzle



Tentative parameters

- Our result is an extrapolation to larger sizes of the SGI of NSTX fusion machine, and to scaling down of an existing large wind tunnel nozzle operated in air (γ = 1.401) at P = 1 atm and M = 8.
- Deuterium at pnt has a density of 1.8 x 10^{-4} g/cm^3, corresponding to 5.4 x 10^{19} a/cm^3. The gas jet target has an approximate thickness of 1.6 cm of D_2 at pnt. The diameter of the jet may be of the order of 5 cm, providing gas at a pressure P = (1.6/5) x 760 Torr = 250 Torr.
- Following the SGI at NSTX and D_2, the jet velocity is about 2200 m/s, with a narrow divergence half-angle of ≈ 5 ÷ 12 degrees and M_o ≈ 4. The volume of gas (at 250 Torr) is then 4.3 m^3/s, corresponding to 248 g/s .

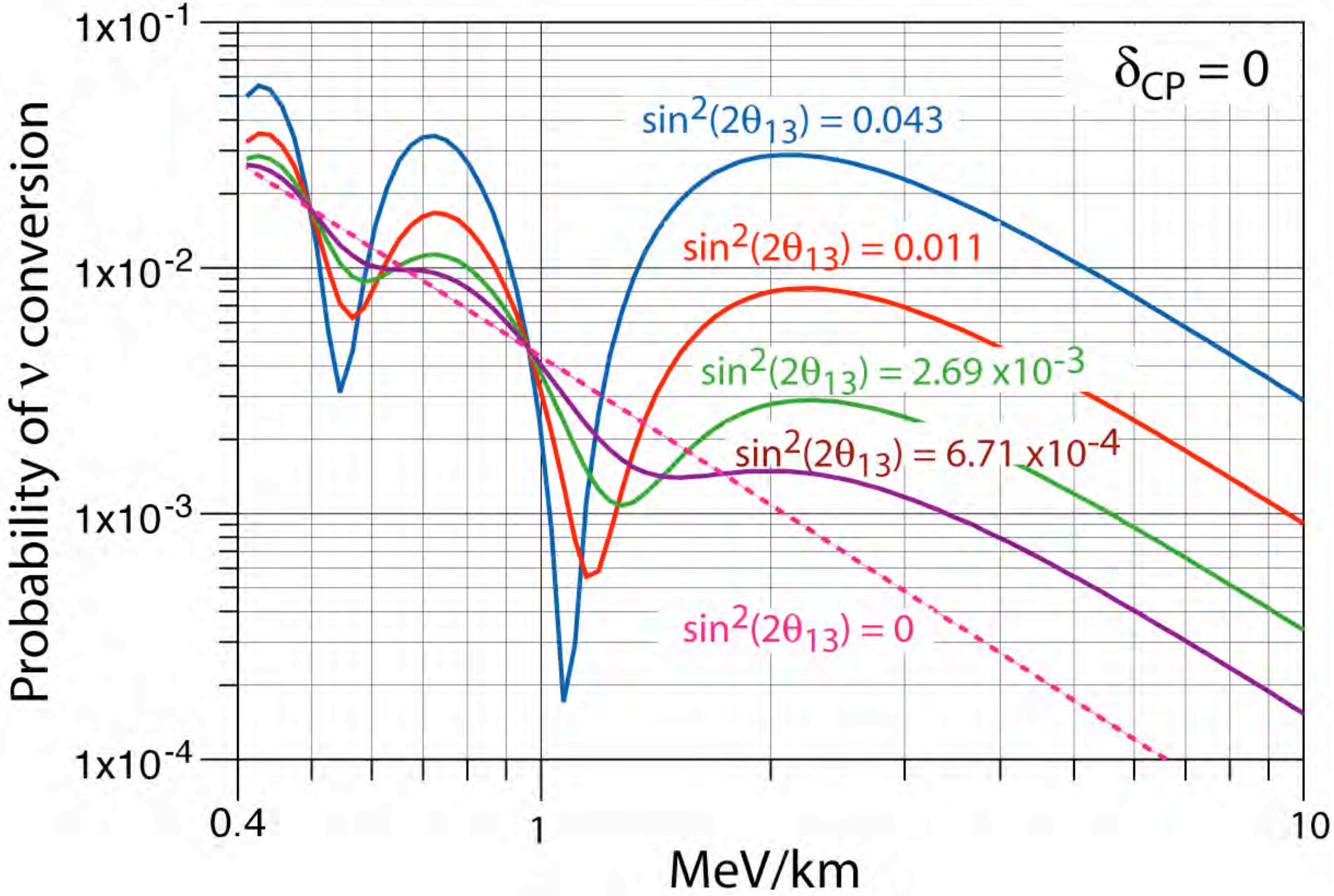
Nozzle diameter	3.36	mm
Inlet diameter	29	mm
Exit diameter	50	mm
Nozzle length	309	mm
Pressure at stagnation	2500	Torr
Pressure at exit	250	Torr
Temperature stagnation	300	K
Temperature, exit	70	K
Mach no, M	4	

- 1 MWatt corresponds to a temperature increase of 775 K through the passage of the jet. The outlet temperature is then about 570 °C.

Collection of produced ions

- The nuclear reaction in the gas jet (f.i. Li-7(d,p) Li-8) produces a secondary ion within a narrow angular spread (≈ 10°) and with kinetic energy comparable with the one of the incoming heavy beam particle.
- The range penetration of the secondary ion is very short, typically some tens of micron of solid material. The technique of using very thin targets in order to produce secondary neutral beams has been in use for many years. Probably the best known and most successful source of radioactive beams is ISOLDE.
- A critical point is the determination of the delay of the collected ions to the catcher-ion-source system (CISS). Two subsequent steps:
  - ⇨ *diffusion* from the place of implantation to the surface of the solid state catcher and
  - ⇨ *effusion* in the enclosure until the emission as a neutral particle.
- It is believed that at sufficiently high temperatures (≈ 2000 °C) an acceptable value $10^{-12} < D(m2/s) < 10^{-10}$ is possible.

Neutrino oscillations as a function of $\sin^2(2\theta_{13})$



Same probability for $\nu_\mu \leftrightarrow \nu_e$

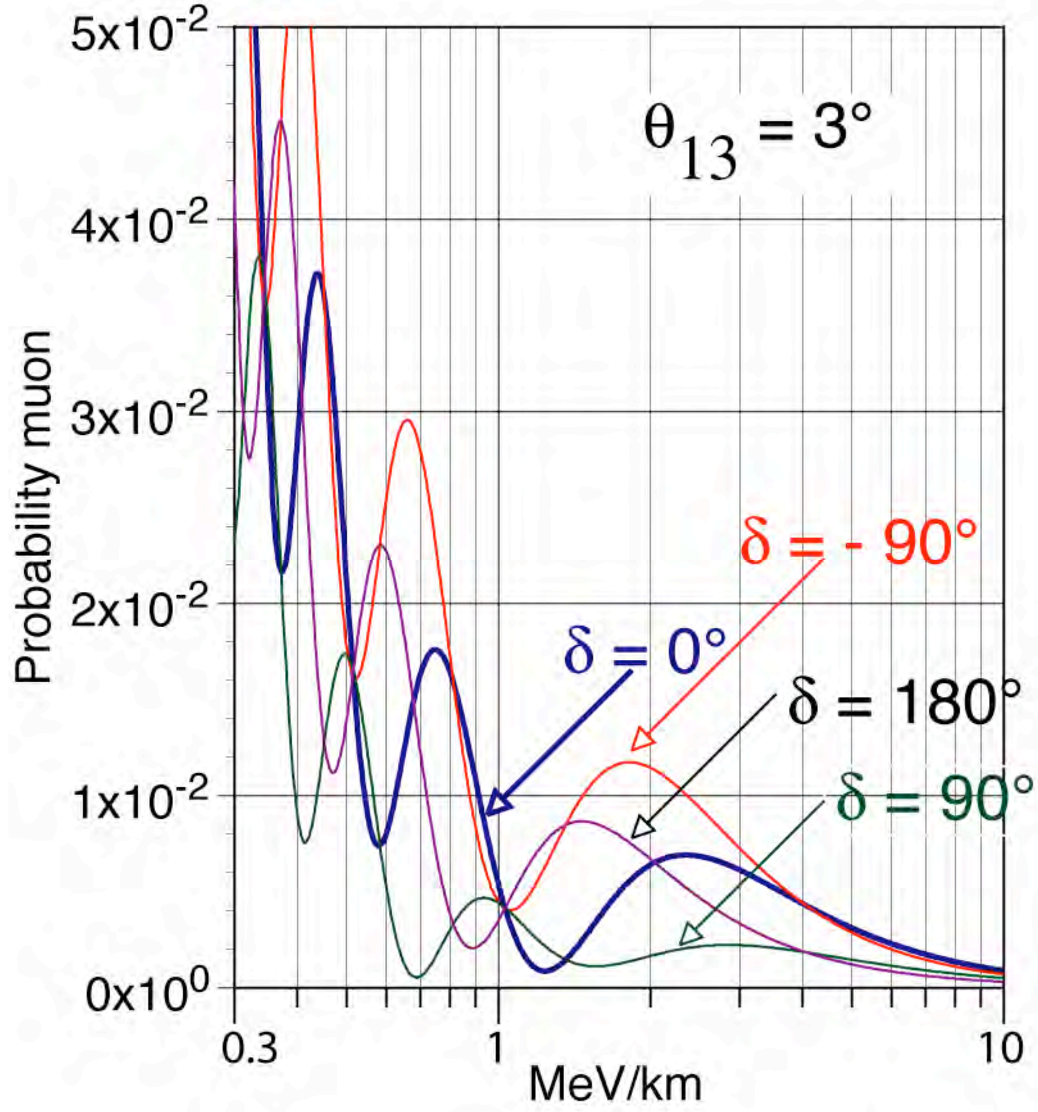
Both for neutrino or antineutrino,

In absence of matter effects

- The present experimental upper limit to $\sin^2(2\theta_{13})$ is 0.14 (CHOOZ)
- Values up to $\sin^2(2\theta_{13}) > 3 \times 10^{-4}$ will give detectable differences in the neutrino conversions with respect to contributions only from other known amplitudes.

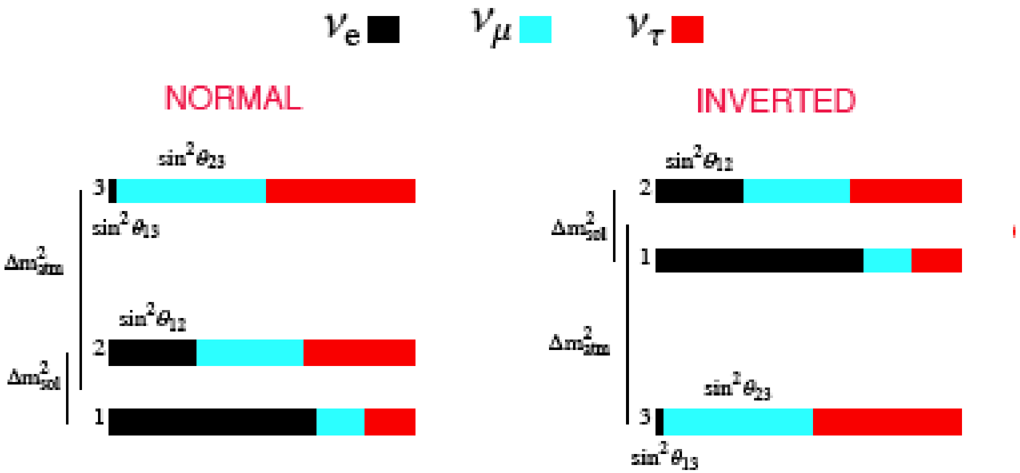
CP violation in neutrino oscillations ?

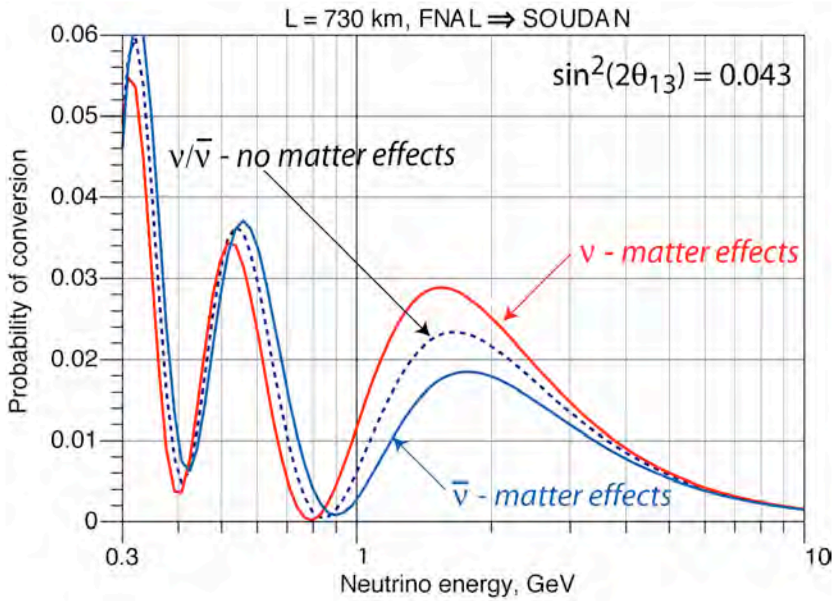
- Cosmological arguments have suggested that strong CP violation in the quark sector should be extended also to the leptonic sector.
- To this effect, all the three neutrino mixing angles must have non zero values, including the presently unknown θ_{13}.
- With sufficient statistics one might evidence the presence of the CP violating phase δ in the mixing matrix and its correlation to the unknown phase θ_{13}.

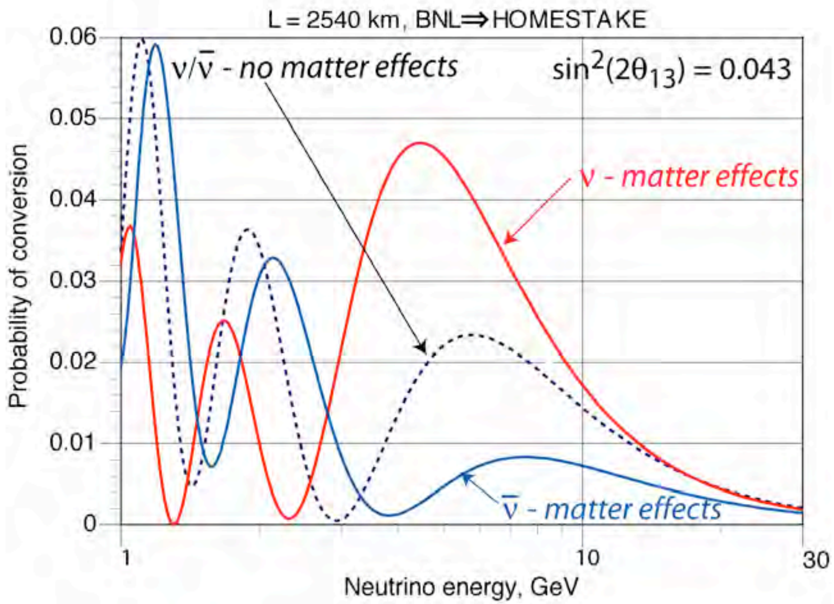


Matter effects

- Like in the case of KL-KS system, the presence of matter (electrons) develops a difference in the probabilities of conversion between neutrino and antineutrino, rapidly growing with the distance L. Therefore distances ≲ 1000 km are optimal.
- The choices for normal/inverted mass differences can be sorted out with the help of matter effects





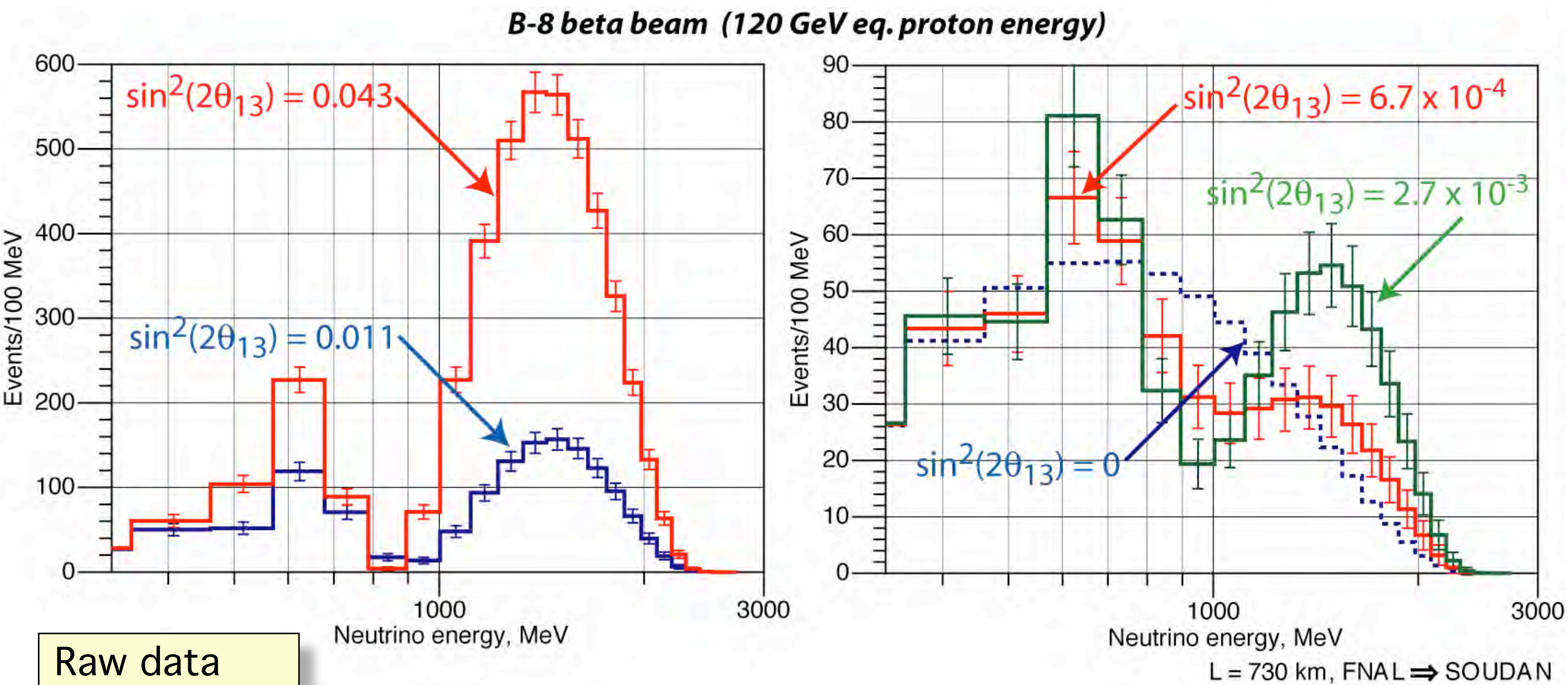


Modifying an existing accelerator ?

- The existing Main Energy Injector at FNAL with the magnetic rigidity for 120 GeV p may be modified to produce fully stripped B-8 beta neutrinos with an end point of 2.5 GeV, perfectly suited for L = 730 km and the Sudan mine. At this magnetic configuration, γ_{B-8} = 80 .
- We assume that the improved accelerator complex, now being currently improved to accelerate up to a 1-2 MWatt proton beam, may be also able to accelerate the same circulating current also for B-8, corresponding to 2 x 10^{13} ions/s.
- Similar modifications may be at hand at CERN in order to produce a sufficiently large B-8 circulating current and a proton equivalent energy in the interval 100 ÷ 200 GeV in order to send neutrinos to LNGS laboratory.

Neutrino production			
End point β-decay energy :	≈ 15	MeV	see
Ion charge:	5		
Ion atomic number:	8		
Half-life at rest:	777.00	ms	
Produced B-8 rate:	2.0	x10^{13} dec/s	
Accumulator properties			
Proton equivalent energy:	120.9	GeV	
Gamma ion:	80.000		
Ion energy:	600.45	GeV	
Guide field:	3.0000	Tesla	
Bending radius:	133.43	m	
Circumference	3.12	km	
Arc radius:	166.79	m	
Bending arcs circumf:	1.048	km	
Decay straight length:	1.048	km	
Fraction neutrino in axis:	0.33333		
Revolution time:	10.48	µs	
Beam/s current to ring:	2290.1	mA	
In flight half-life:	62.16	sec	
Stack current:	142.35	A	
Neutrino max. energy:	2713.2	MeV	
Detector properties			
Detector distance:	730.00	km	
$\pi/2$ oscillated energy:	1781.7	MeV	
Angle of 1 cm at det.:	0.13699E-01	µrad	
Equiv. Angle CM:	2.1918	µrad	
Fraction neutrino within 1 cm^2	0.12743E-12		
Neutrino flux:	3.8228	n/sec/cm^2	
Nu-e average cross section:	1.4965	10^{-38} cm^2	
Detector mass(Ar):	50.0	kton	
CC Event rate without oscill.:	149.77	ev/day	

Data rates from B-8



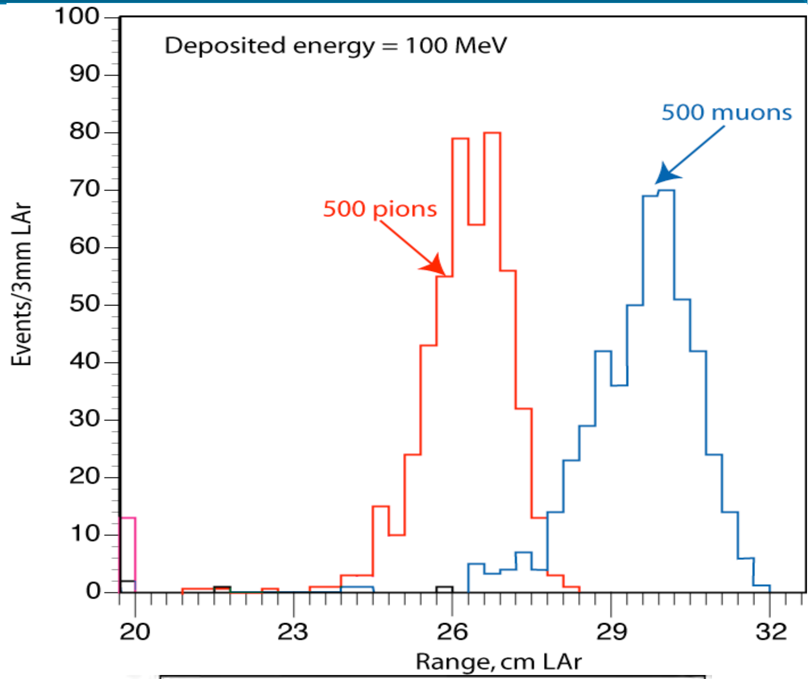
Raw data before cuts

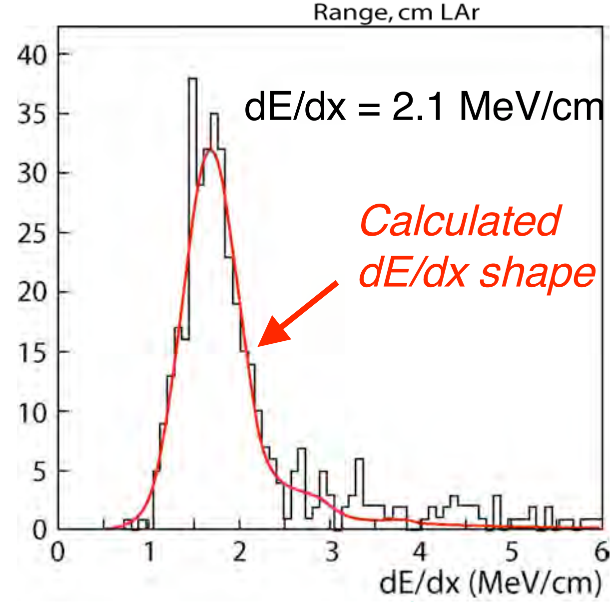
$\sin^2(2\theta_{13})$	4.30E-2	1.10E-2	2.69E-3	6.71E-4	0.00E+0
ktons of LAr, fiducial	50	50	100	100	100
All events, no mixing	110’000	110’000	221’000	221’000	221’000
Oscill. events, no cuts	2276.9	715.05	704.14	557.41	556.02
Ratio oscill/all, no mix	2.06E-2	6.47E-3	3.19E-3	2.52E-3	2.52E-3

Background π's in LAr

- In a water Cherenkov detector π and μ particles have nearly identical signatures.
- NC π production with π misidentified into a μ. In LAr the NC generated π^- background has
  - ⇨ a rate of the order of **1/60** of the CC signal without oscillations.
  - ⇨ The range/energy of a μ^- track is longer than the corresponding case of a π^- . Rejection in LAr is >**1/200**.
  - ⇨ 70% of the μ^- and all π^- will undergo nuclear capture. Stars are large for pions, while an invisible neutrino is produced for μ^-. Pion rejection: at least **1/50**
  - ⇨ Decays in flight are identifiable from kinks.
- The number of surviving background events should be conservatively of the order of about 0.3 events starting from 220.000 un-oscillated events.

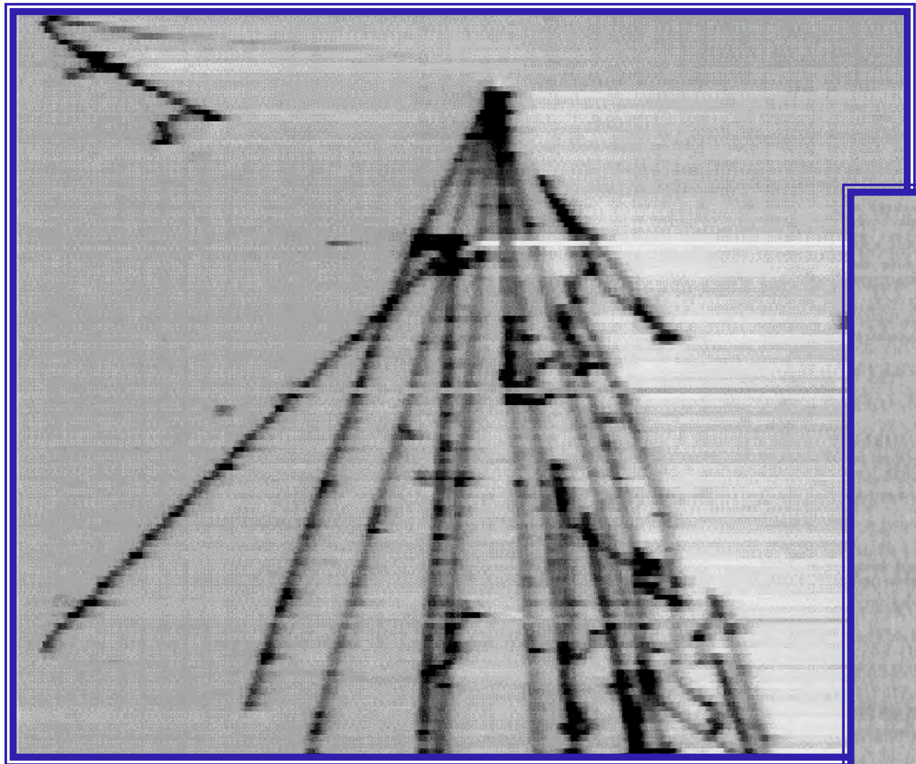
$1/(60 \times 200 \times 50) = 1/600'000 = 1.66 \times 10^{-6}$



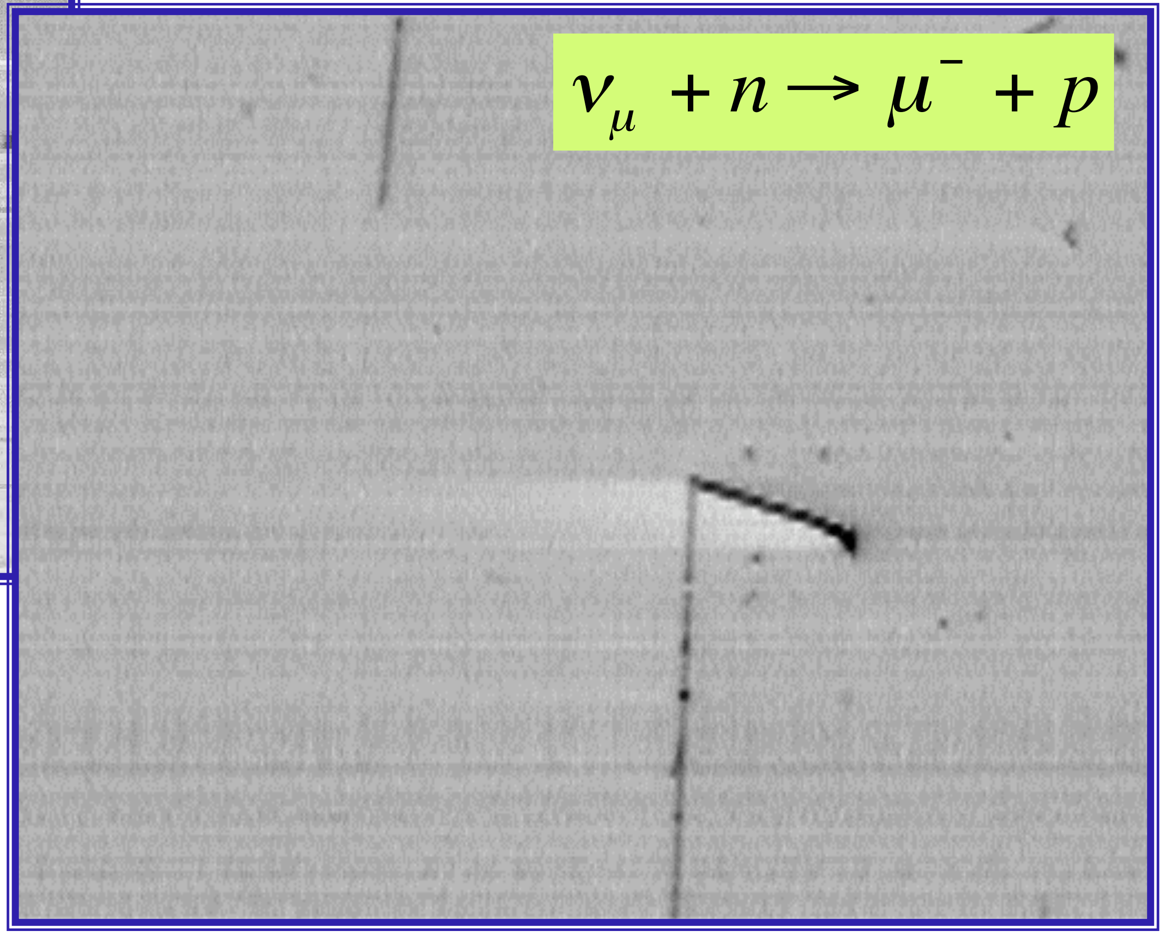


Ionization distribution from a single, long track

50 liter prototype in CERN West Area neutrino beam

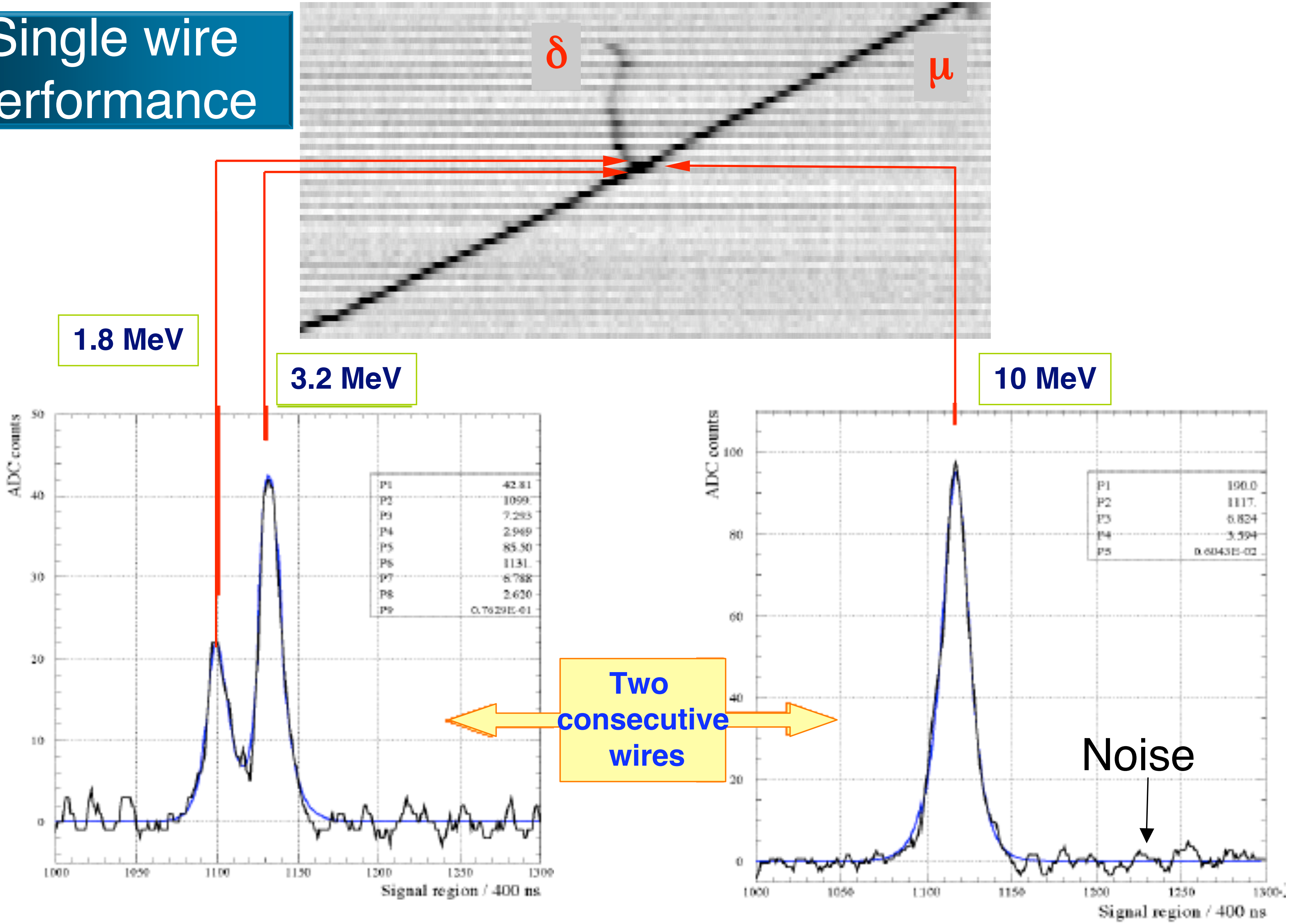


$$\nu_\mu + X \rightarrow \mu^- + many\ \ prongs$$



$$\nu_\mu + n \rightarrow \mu^- + p$$

Single wire performance



Threshold above noise ≈ 200 keV

Comparing B-8 with Zucchelli/CERN solution on He-6

- For a given relativistic ion factor, neutrino energies with B-8 are 4.8 times larger than the ones of He-6. However the relevant factor is the magnetic rigidity of the ring, namely the equivalent proton energy, which depends on the Z and A of the respective ions, which is here $\gamma_{B-8}=1.875\gamma_{He\text{-}6}$. In conclusion:
  - for a given proton energy, the average energy spectrum of B-8 is as much as 9 times larger than the one of He-6.
  - The higher relativistic factor, again for a given proton energy, introduces a increase of the beam intensity which is $\propto\gamma^2$, namely a neutrino flux in favour of B-8 of a factor 3.51, which is by no mean negligible
  - At a given neutrino energy, the CC cross sections for neutrinos are about 3 x larger than the ones of antineutrinos
  - The NC/CC inelastic pion background faking signal muons is ≈ 3 x smaller.
  - The π/μ selectivity is orders of magnitude more effective with negative tracks from B-8 than with positive tracks from He-6 (in water ?)

Anti-neutrino from Li-8

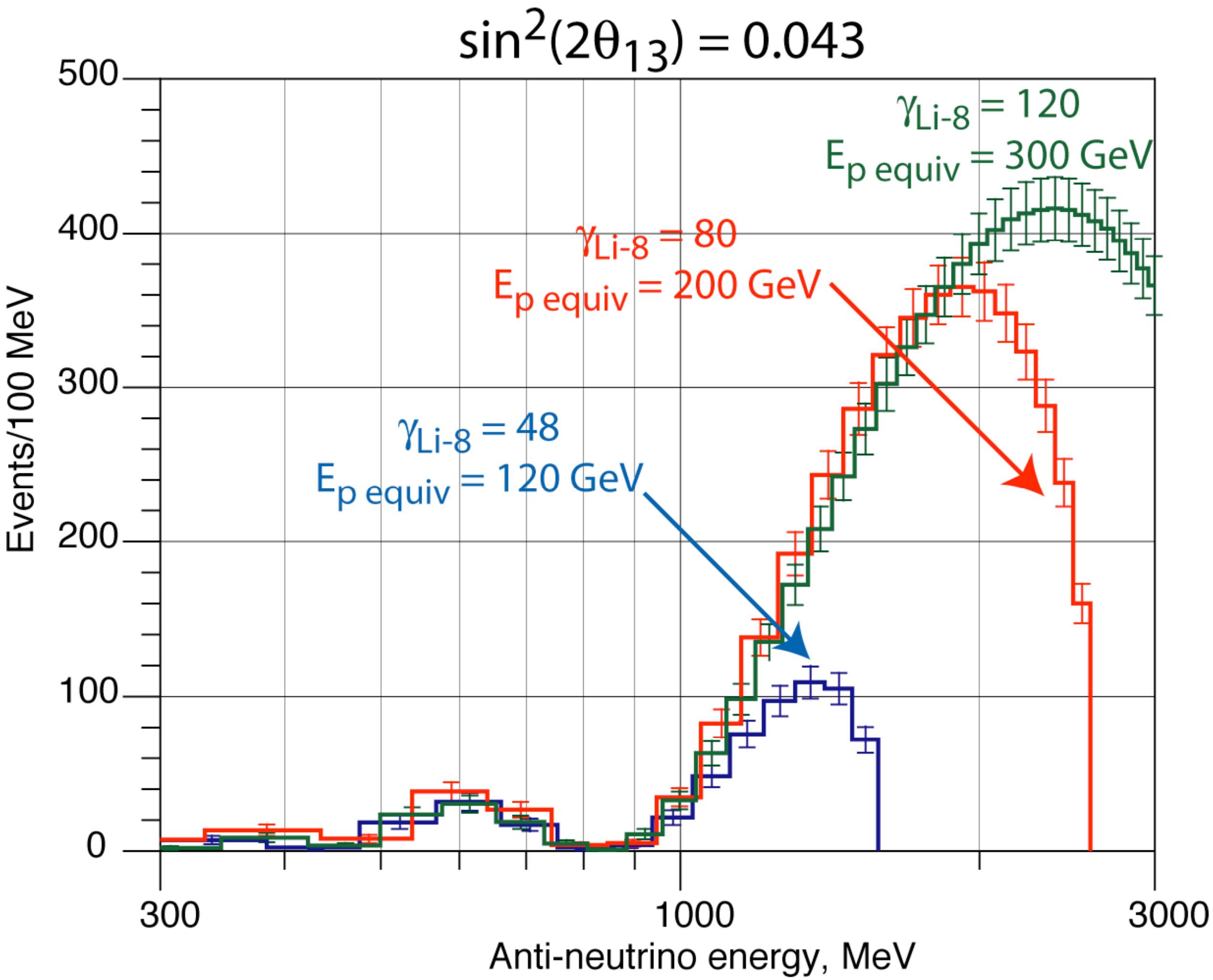
- Like for He-6 chosen by Zucchelli/CERN, the situation is less favourable than of B-8.

  1. Because of the smaller charge of Li-8 when compared to B-8, the main Energy Injector at FNAL (120 GeV protons) has a much smaller γ = 48, corresponding to an end point of 1536 MeV. Therefore the antineutrino flux at the detector, proportional to $1/\gamma^2$, is only 36 % of the one for B-8.
  2. The Li-8 CC x-sect without oscillations, averaged over the spectrum is only 18 % of the one of B-8 because of the lower value of γ and x-sect.
  3. However, for a specified accelerated current, the number of injected ions may be larger because of the fully stripped charge is 3 instead of 5.

- Rates are therefore about a factor 10 smaller. For instance for 100 kton LAr, 5 years of exposure at 200 days/y, the non oscillated antineutrino reference signal is only 33k events, to be compared with the ≈ 300 k events of B-8 neutrinos.

- The event rate may be substantially increased if an additional post-acceleration is provided for instance in the storage ring before decay. The number of oscillated for $\sin^2(2\theta_{13})$ = 0.043 is rising from 608 events at γ = 48 (120 GeV) to 4190 events at γ = 80 (200 GeV) and to 11390 events at γ = 120 (300 GeV).

Antineutrinos from Li-8



Conclusions on ionization cooling

- A novel type of particle "cooling" is discussed, based on slow ions stored in a small ring.
  - Singly ionised ions are fully stripped by a thin foil and remain permanently stored in the small ring.
  - The ionisation losses due to many traversals through a thin foil compensated at each turn by an adequate RF-cavity.
  - We observe that both multiple Coulomb scattering and straggling are "cooled" in all three dimensions, with a method similar to the one of synchrotron cooling, but valid for low energy ions.
  - Particles circulate in the beam indefinitely, until they undergo nuclear processes in the thin target foil.
- The nuclear reaction probability is greatly enhanced with respect to the case of an ordinary target.
- This method is particularly suited for nuclear production of a few MeV/A beams. Simple reactions are more favourably produced in the "mirror" kinematical frame, with a heavier ion colliding against a gas-jet D_2 target.
- This allows an efficient collection as a neutral gas in a tiny volume at high temperatures with the help of a technology perfected at ISOLDE.

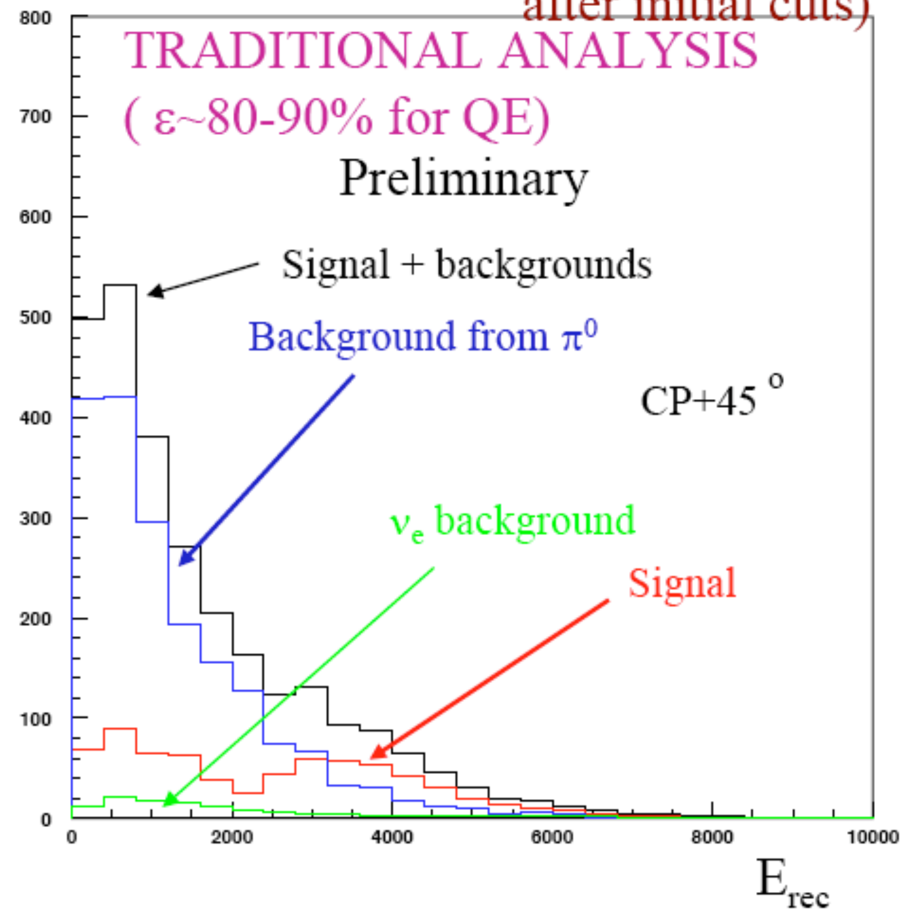
Conclusions on neutrino physics

- It is possible to explore $\sin^2(2\theta_{13})$ down to few times 10^{-4}, namely $\sin^2(2\theta_{13})$ => 0 up to the ne=>nmu values, due only to the other remaining amplitudes - with the help of the following conditions :
  1. we can accumulate with ionization cooling of heavy ions as many as 2×10^{13} B-8/s after acceleration with one or many desk-top storage rings. This corresponds to about 3400 Curie of B-8 activity.
  2. These ions, corresponding to a proton current of 10^{14}p/s, are accelerated (γ =80) to about 120 GeV equivalent protons, for instance with an upgraded Full Energy Injector at FNAL or with a corresponding scenario at CERN.
  3. A storage ring is added to accumulate about 2×10^{15} B-8 ions until they decay with the half-life of about 1 minute. Some of main magnetic hardware surplus components of the Tevatron may be redeployed to that effect.
  4. The optimal oscillation path to a dedicated detector of high resolution is of the order of 750 km (Soudan or GranSasso) and energies in the interval 0.6÷2.5 GeV
  5. A 50-100 kton LAr TPC is run for 5 years at 200 days/y, collecting ≈ 150 raw neutrino events/day. The minimal oscillated fraction is 2.5×10^{-3}.
  6. The background coming from NC events is reduced to a negligible level ($< 10^{-5}$) using the rejection power against negative pions and recording only about 70% of muons, which are captured and have a correct energy-range value.

Thank you !

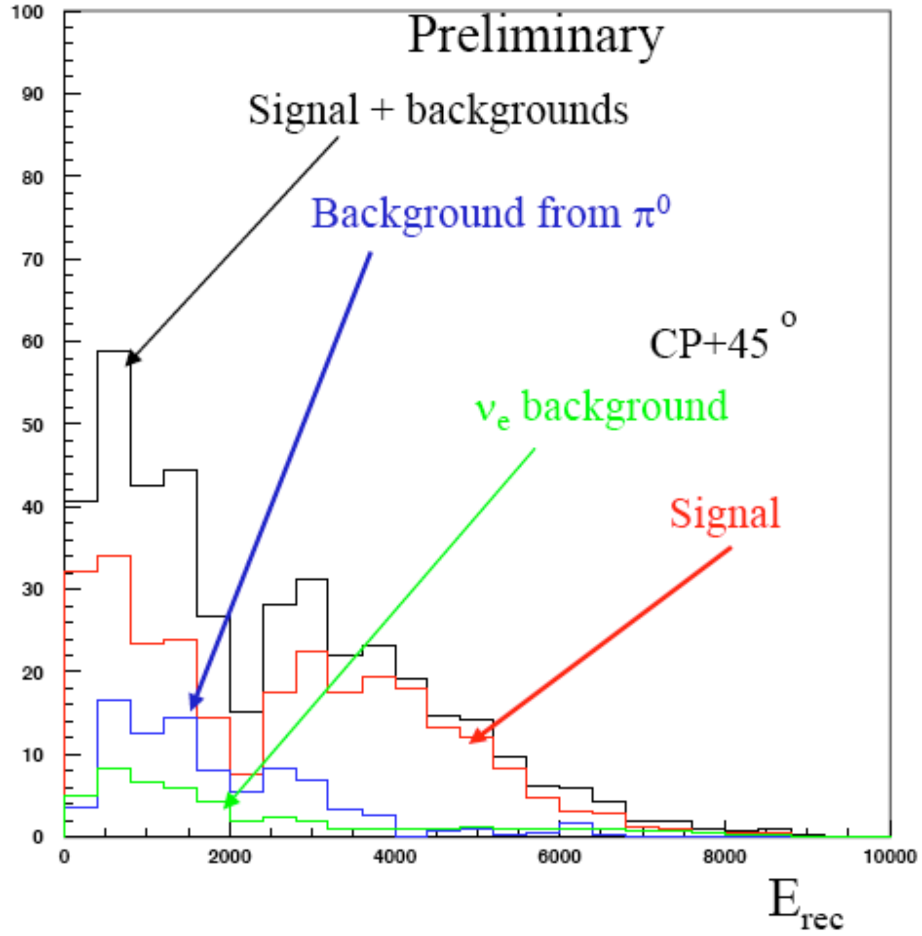
Water Cherenkov counters at $\sin^2(2\theta_{13}) = 0.043$?

No Δ log likelihood cut (100% signal retained after initial cuts)



2500 kton x Mwatt x 10^7 sec

Δ log likelihood cut (40% signal retained)



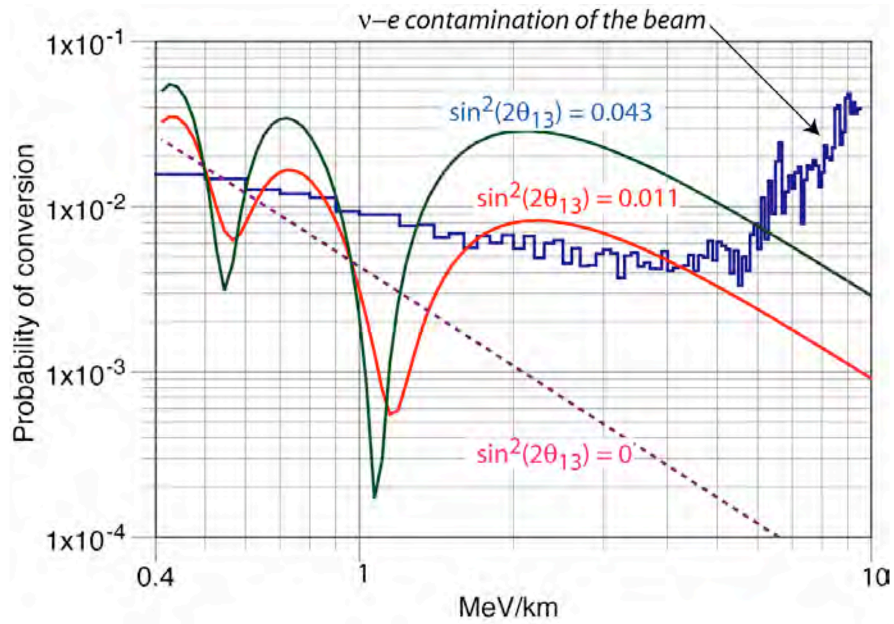
Signal 700 ev Bkgs 2004
(1877 from π^0+others)
(127 from ν_e)

Signal 280 ev Bkgs 136
(87 from π^0+others
(49 from ν_e)

Chiaki Yanagisawa
Workshop at Fermilab, March 6-7, 2006

Very high purity neutrino beams ?

- Ordinary proton and horn driven neutrino beams have a limited range of validity in $\sin^2(2\theta_{13})$, since the natural contamination of $\nu e/\nu\mu \approx 0.007$-$0.009$.
- If $\sin^2(2\theta_{13}) \leq 0.02$, new ultra high purity neutrino beams are necessary. Amongst possible solutions:
  - ⇨Neutrinos from β-decays from a storage ring of relativistic short lived ions (beta-beams), following Zucchelli's idea. These beams are extremely clean $O(10^{-5})$.=>This talk
  - ⇨Neutrinos produced by the decay in flight of cooled and accelerated muons from a high current proton target. The interesting signal, due to e- and μ+. *must be identified by the sign of the charge of the emitted lepton.* =>See Steve Geer's talk



$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

$$\nu_\mu \to \mu^-[O(1)] \quad \nu_\mu \to e^-\left[O\left(10^{-3}\right)\right]$$

$$\bar{\nu}_e \to e^+[O(1)] \quad \bar{\nu}_e \to \mu^+\left[O\left(10^{-3}\right)\right]$$