ν_e cross-section in a tagged beam

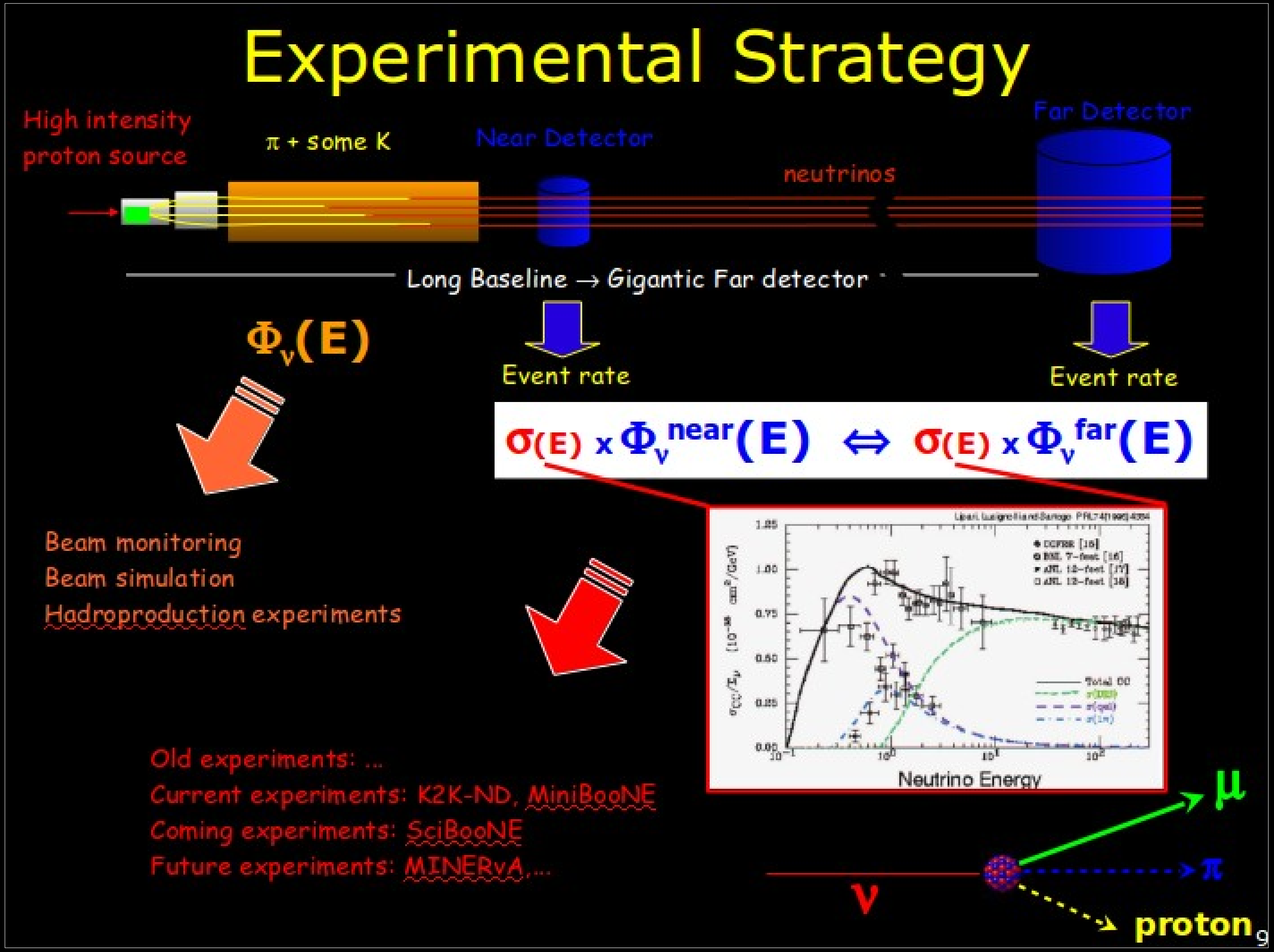
L. Ludovici
What Next: sezioni d'urto di neutrini
Bologna, 9-10 novembre 2015

A.Berra, S.Cecchini, F.Cindolo, C.Jollet, A.Longhin, G.Mandrioli, A.Meregaglia, A.Paoloni, L.Pasqualini, L.Patrizii, M.Pozzato, M.Prest, F.Pupilli, G.Sirri, F.Terranova, E.Vallazza, L.Votano

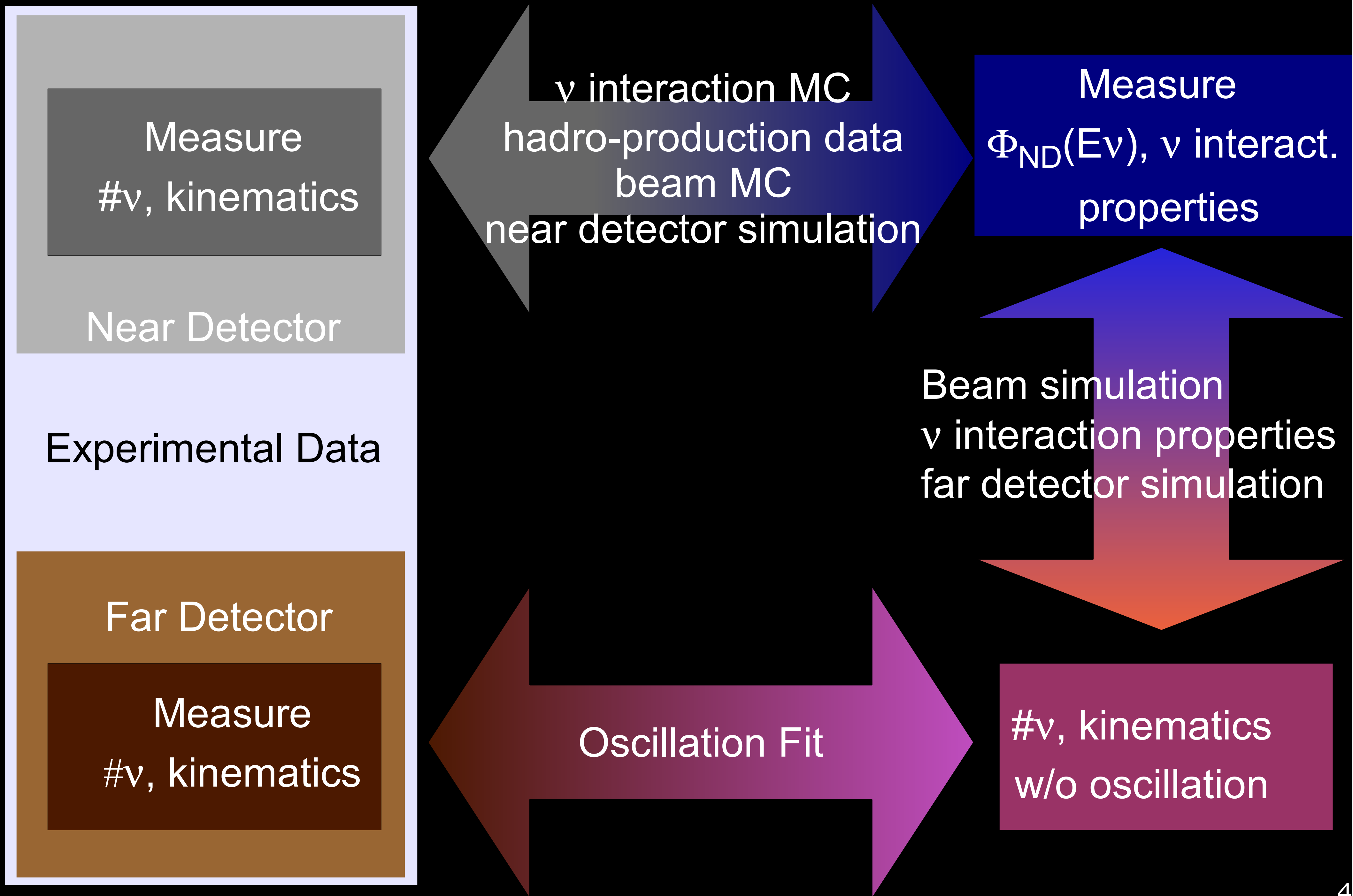
A.Longhin, L.L, F.Terranova   EPJC 75 (2015) 155

Cross-sections are important
in LBL oscillation experiments

Una slide d'annata (2006)

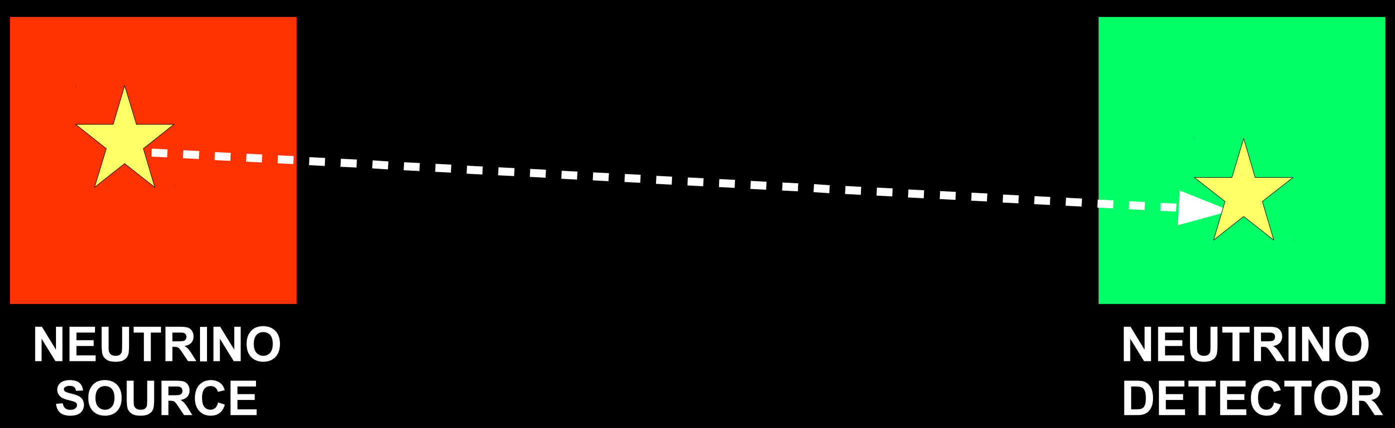


Analysis Strategy



Tagged neutrino beams principle

Detects simultaneously the neutrino interaction at the neutrino detector and the associated lepton at the neutrino source



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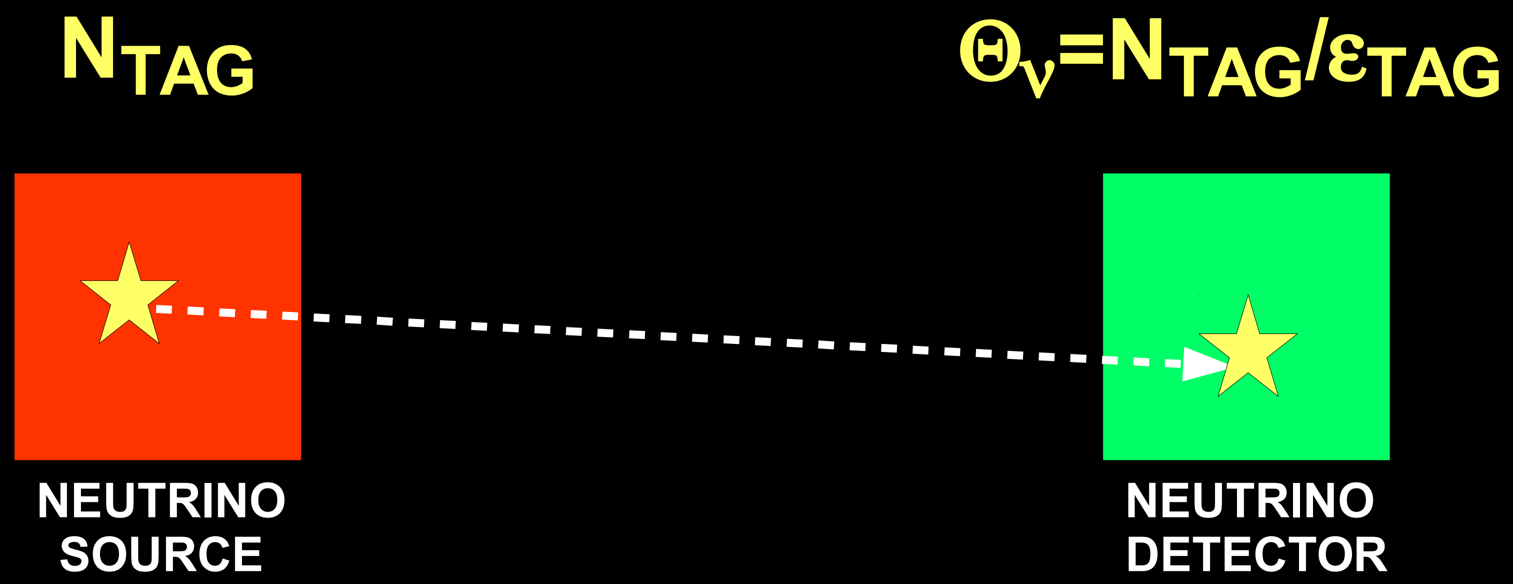

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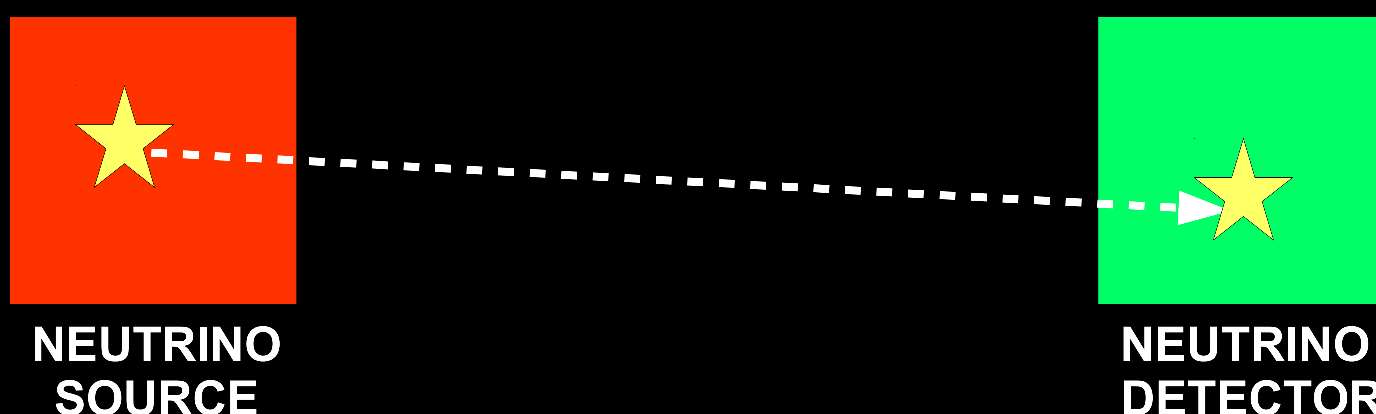
N_{TAG}

$\Theta_{\nu}=N_{TAG}/\varepsilon_{TAG}$



Tagged neutrino beams (partial) literature

L.N. Hand (1969)
B. Pontecorvo (1979)
G.Vesztergombi, D.Kiss (1981)
I.P. Nedyalkov (1981)
L. Nodulman (1982)
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Broad energy range

from ~GeV to ~TeV

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Different reactions

muons from charm
muons from $\pi_{\mu 2}$ / $K_{\mu 2}$
electrons from K_{e3}

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Many layouts

conventional neutrino beams
beam dumps
neutral channels (K°)
anti-tag (veto)

Tagged neutrino beams (partial) literature

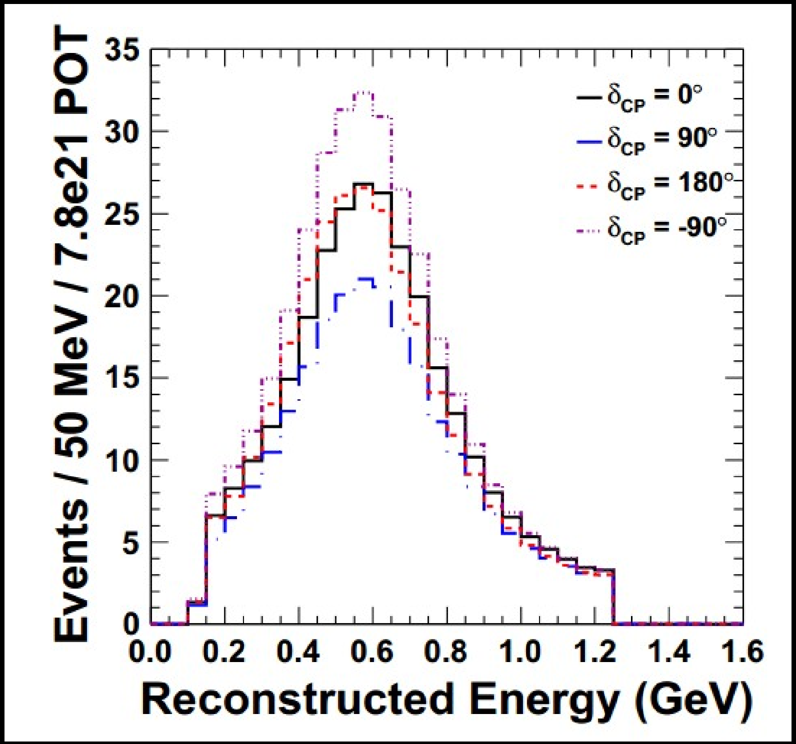
The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino creation ($\pi \to \mu\nu$, $K \to \mu\nu$, $K \to e\nu\pi, \ldots$). Of course, in tagged-neutrino experiments the properties of neutrino beams (type, direction and energy) will be much better known than in the experiments performed so far. The main difficulty in designing such a facility is that the effective neutrino source (which is also the source of the charged particles to be detected in coincidence with the neutrino event) has a length equal to the decay length (of the order of hundreds of metres). In spite of the difficulties it seems that sooner or later such facilities will be available at various high-energy accelerators. Naturally such a « maximum » programme would provide an extremely useful facility.

B. Pontecorvo, Lett. Nuovo Cimento 25 (1979) 257

Why ν_e cross-section ?

cross-sections are the limiting systematic source already for the present generation of LBL

next generation of experiments searching tiny effects bearing CP, hierarchy, unexpected.., in particular in the golden $\nu\mu \rightarrow \nu e$ channel



Despite impressive improvements in the cross-section measurements, difficult to get below O(10%) due to the flux uncertainty

νe cross-section data sparse (sub-dominant component of conventional beams), extrapolation from $\nu\mu$ introduces additional uncertainties due to nuclear effects [Phys. Rev. D86 (2012) 052003]

Tagged electron neutrinos

EPJC 75 (2015) 155

A beam layout optimized for electron neutrinos from $K^+ \rightarrow e^+ p^\circ \nu_e$

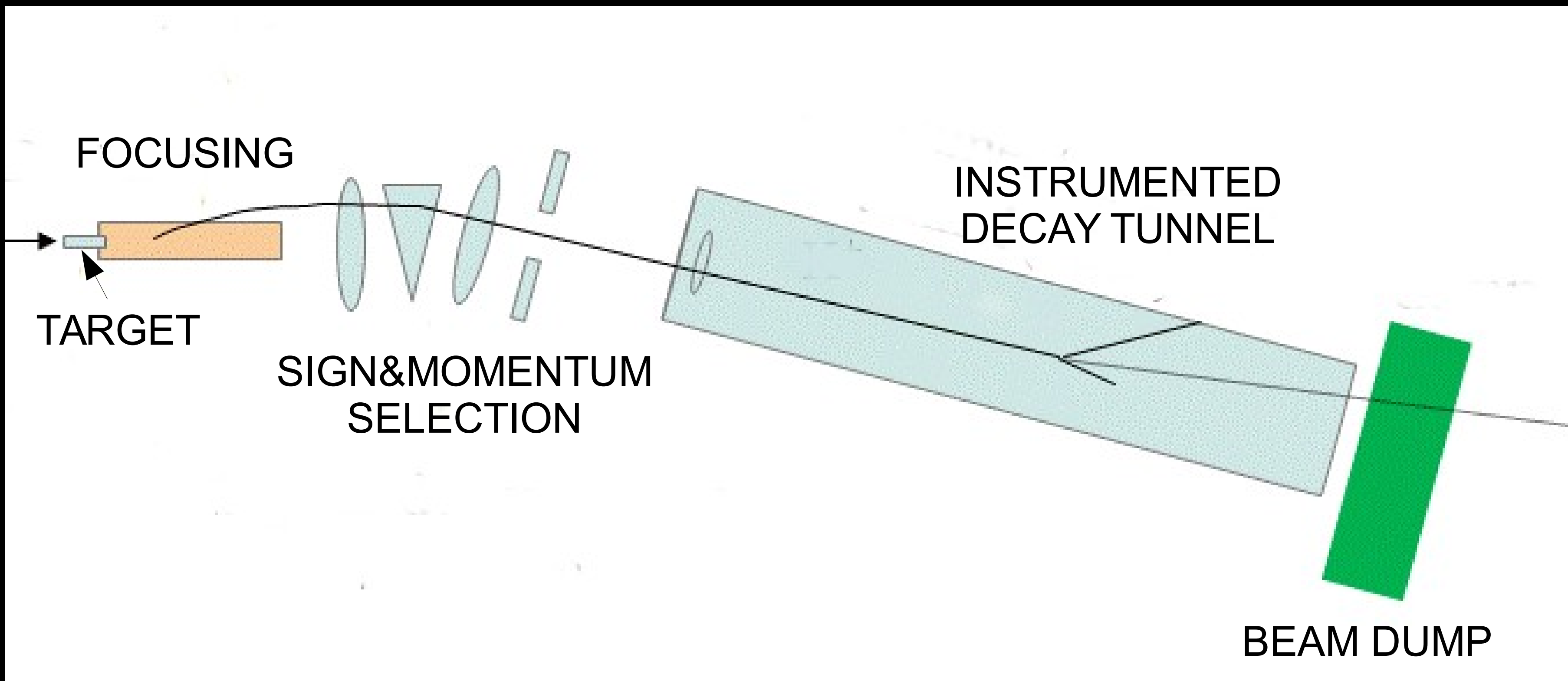
Detect positrons as a direct measurement of the ν_e flux

Take advantage of LHC development of fast, radiation hard detectors

Goal

ν_e cross-section measurement down to O(1%) precision using available today technology for beam and detectors

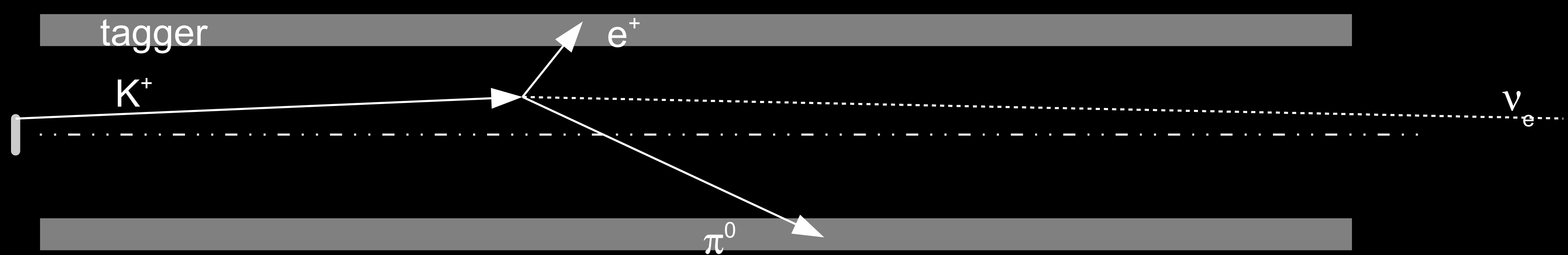
Conceptual Layout



Let's assume the secondary beam is sign and momentum selected with P = 8.5 GeV/c ± 20% and focused with Θ_{max} = 3mrad in a 10x10cm window at the entrance of the instrumented decay tunnel

Tagger Concept

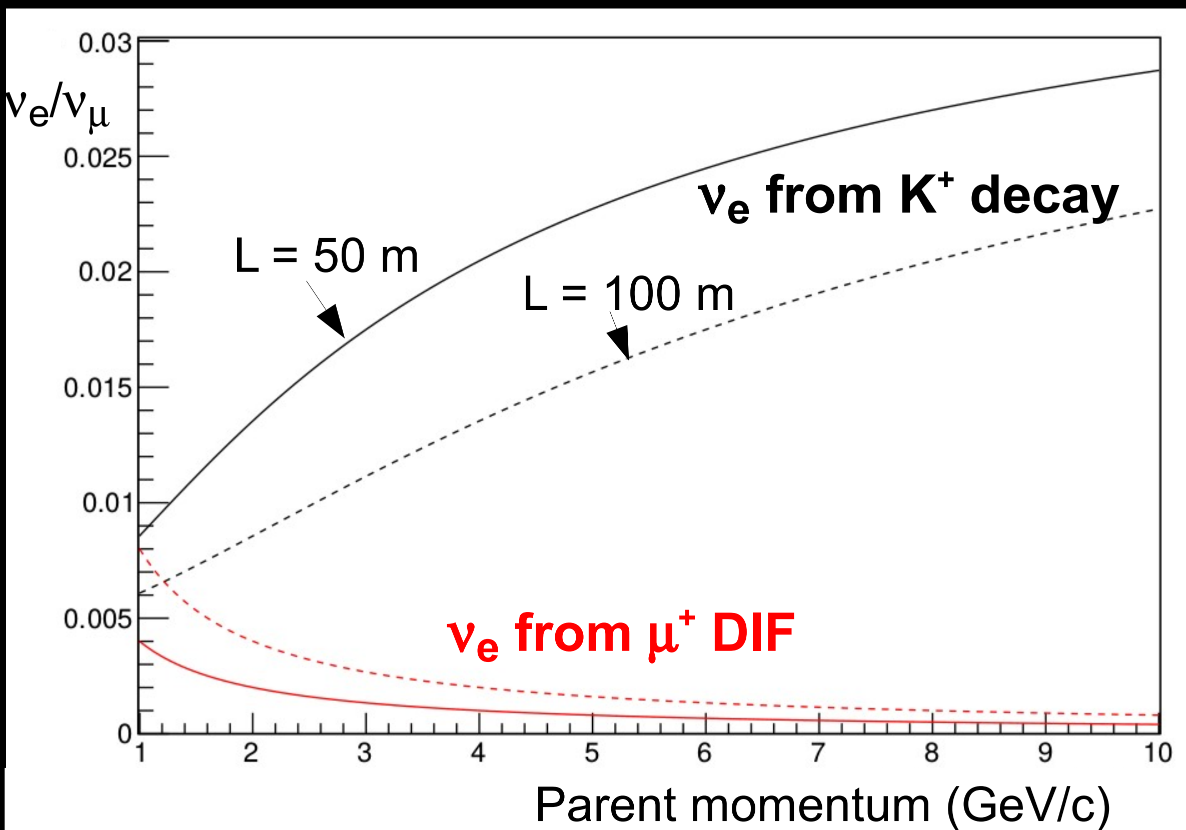
Channel	ν at detector	Angular RMS	Notes
$\pi^+ \rightarrow \mu^+ \nu_\mu$	Bulk of ν_μ	~ 4 mrad for μ^+	2-body decay
$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ (muon DIF)	$\nu_e + \bar{\nu}_\mu$	~28 mrad for e^+	3-body decay (low parent mass)
$K^+ \rightarrow \pi^0 e^+ \nu_e$ (i.e. K_{e3})	ν_e from K_{e3}	**~ 88 mrad** for e^+	3-body decay (high parent mass)
Undecayed K^+,π^+ and protons	none	< 3 mrad	
Other K^+ decays	ν_μ or none		no prompt positrons
Wrong sign and off-momentum π/K, neutrals			negligible if particles are sign selected after the horn



Undecayed beam particles, including muons from $\pi_{\mu 2}$, are almost contained within a hollow cylindrical tagger 50m long and of 40 cm inner radius

Beamline design for K_{e3} ν_e

Shorter decay tunnel + Higher energy secondaries → Increase the fraction of ν_e from K_{e3} + Reduce the fraction of ν_e from μ DIF



With increasing energy

PRO

Higher kaon/pion ratio

Better e/π separation

<loss in focus/transport

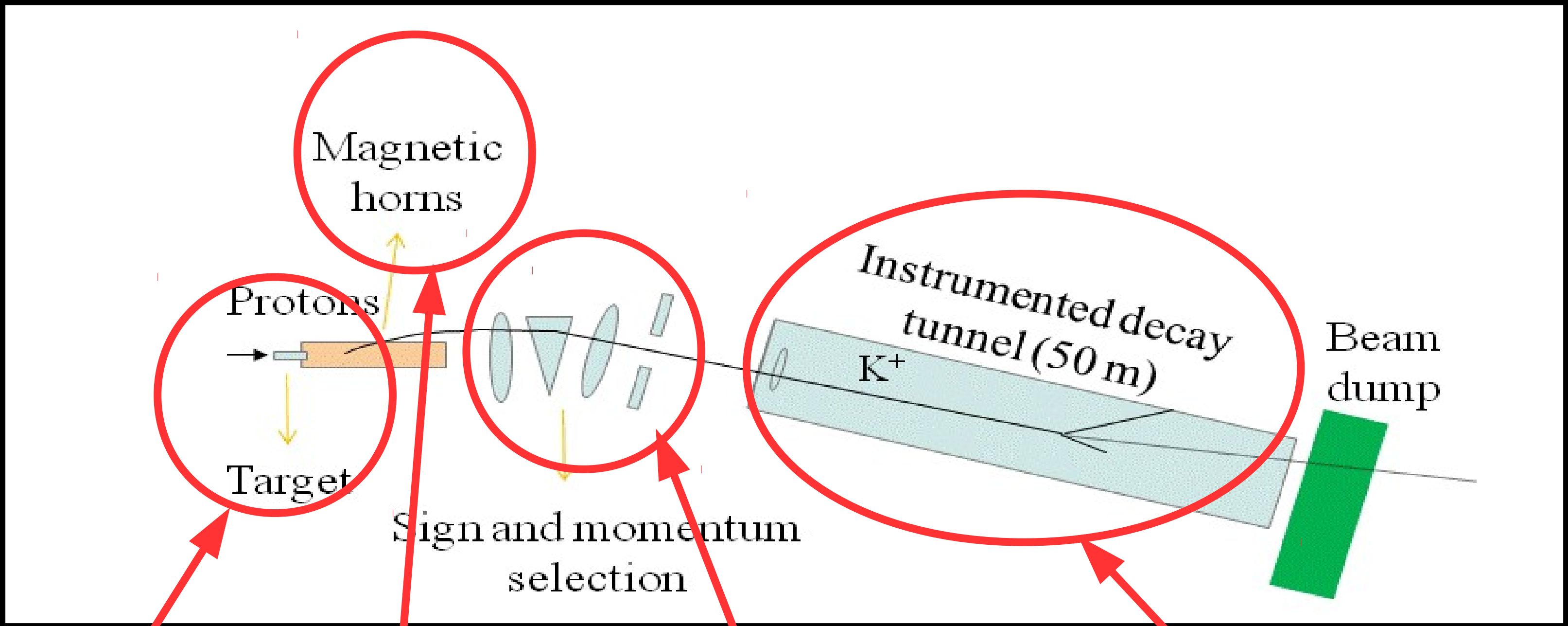
CONS

Longer decay tunnel

ν_e energy higher than ~GeV

Chosen trade-off: **$p(K^+/\pi^+) \sim 8.5$ GeV/c ± 20%** **L = 50 m**

Beamline simulation



FLUKA2011 cross-checked with hadro-production data

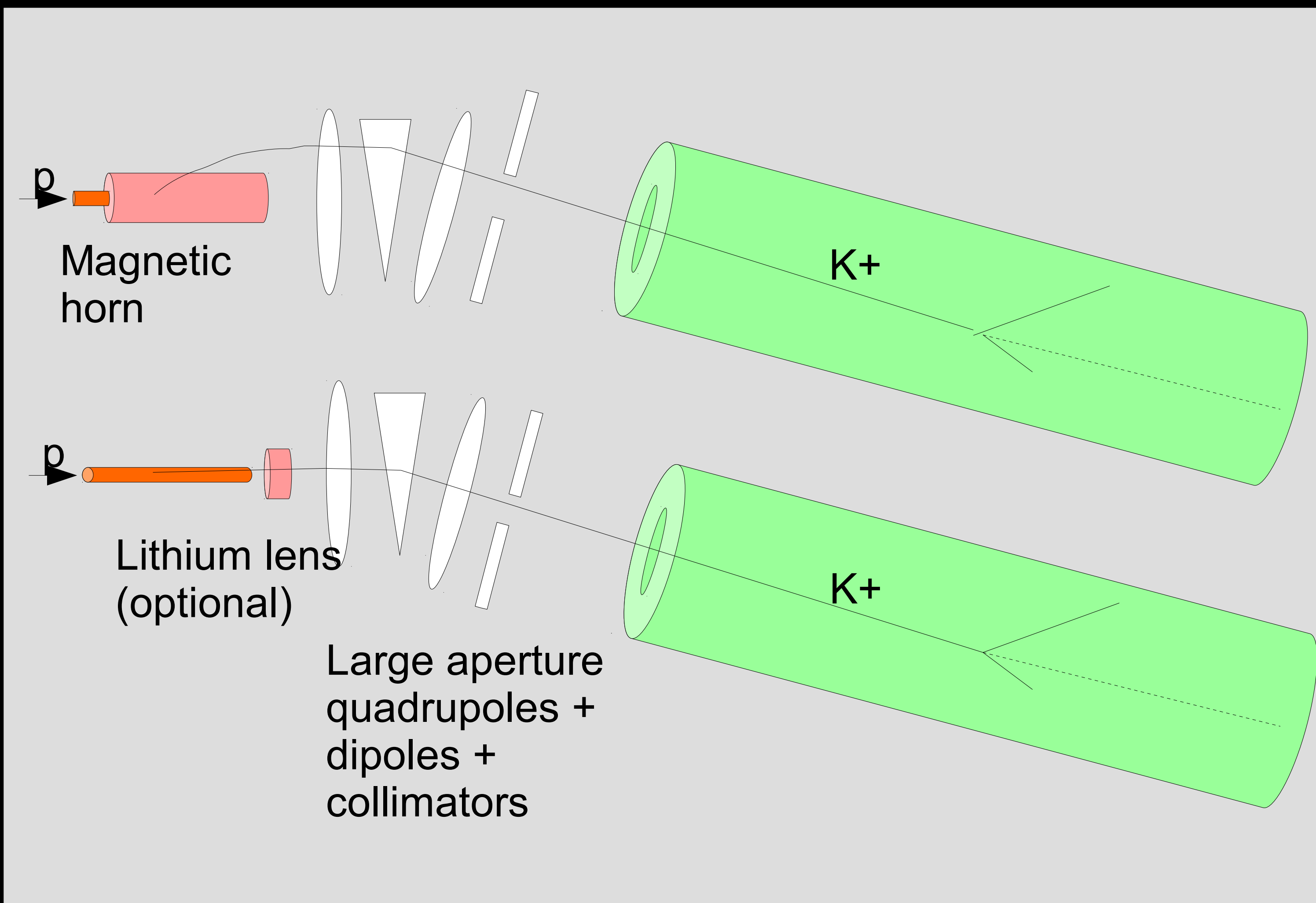
No design and full simulation, yet. Assume 85% efficiency for secondaries inside the ellipse $\varepsilon_{xx'}=\varepsilon_{yy'}=0.15$ mm rad in the transverse phase space

GEANT4 simulation at hit level of a preliminary design. Further simulation in progress.

No design and full simulation, yet. Assume 20% momentum bite at P=8.5GeV/c and a 10m length to evaluate the flux reduction due to early decays

Focusing options

No detailed optimization/simulation. Two focusing schemes considered, based on realistic figures and educated guesses



+ Large acceptance

- Need pulsing (<10ms)

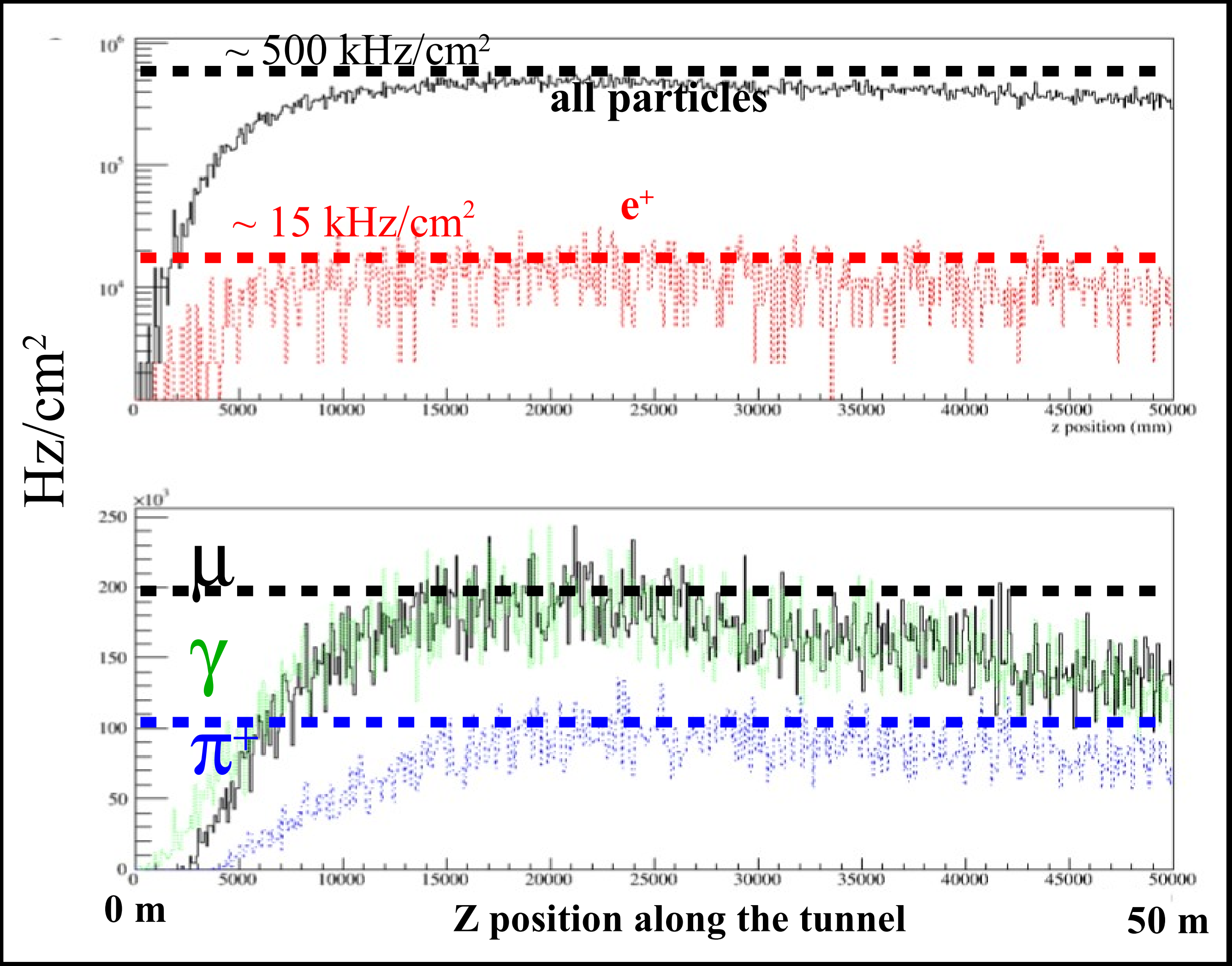
- Only forward acceptance

+ Allow long beam extractions (~seconds)

Rates from beamline simulation

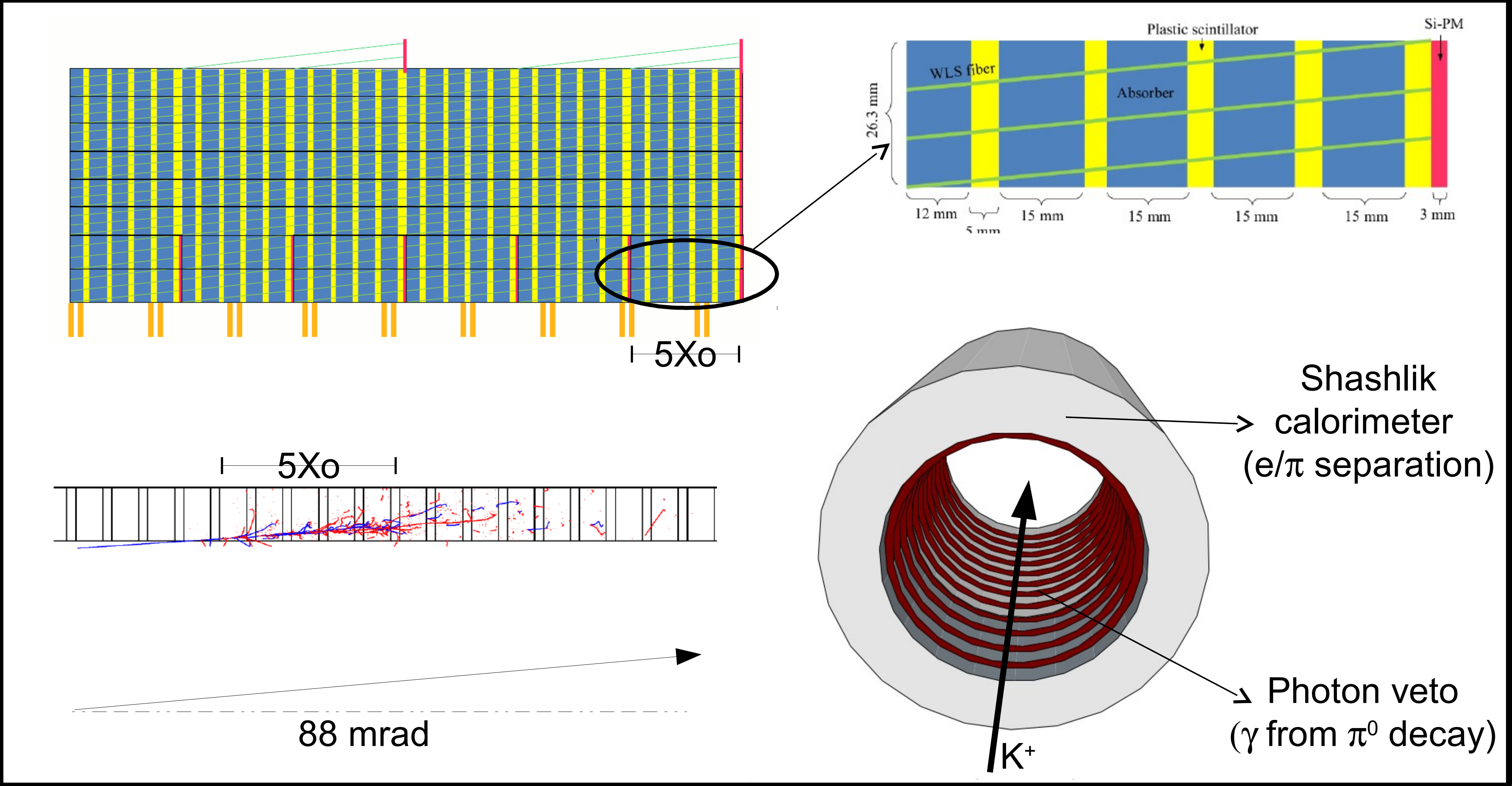
For a spill duration of 2ms and 10^{10} π^+ at the entrance of the decay tunnel, the total rate is 500 kHz/cm^2 → manageable with a proper choice of detector technology

Particle	Max. rate (kHz/cm^2)
μ^+	190
γ	190
π^+	100
e^+	20
all	**500**



Tagger Technology

Shashlik calorimeter
~3x3 cm2 tiles, 1.5 cm thick Cu absorber, 0.5cm thick plastic scintillator tiles, read by 9 WLS fibers directly coupled to 9 SiPM, digitized by a single waveform digitizer



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The direct, bundle-free matching of the fibers to the SiPM is an elegant solution to the problem of longitudinally segmenting the shashlik calorimeters

Original application of a shashlik calorimeter to a diffuse, non-projective particle source

SCENTT (Shashlik Calorimeter for Electron Neutrino Tagging and Tracing) approved R&D in gruppo V (2016-17) to test on prototypes the solutions for the tagging detector and prove their scalability

Pile-Up and Radiation dose

PILE-UP

mostly overlap of a muon from $K^+ \rightarrow \mu^+ \nu_\mu$ with a candidate positron

Recovery time, Δt_{cal} = 10 ns

Rate, R = 0.5 MHz/cm^2

Tile surface, S ~ 10 cm^2

→ 5% pile-up probability (= RS Δt_{cal})

RADIATION DOSE

For the full statistic (10^4 ν_e CC events), 150 MJ are deposited into the tagger (64% into muons)

→ Integrated dose < 1.3 kGy (cfr. CMS forward ECAL ~100 kGy)

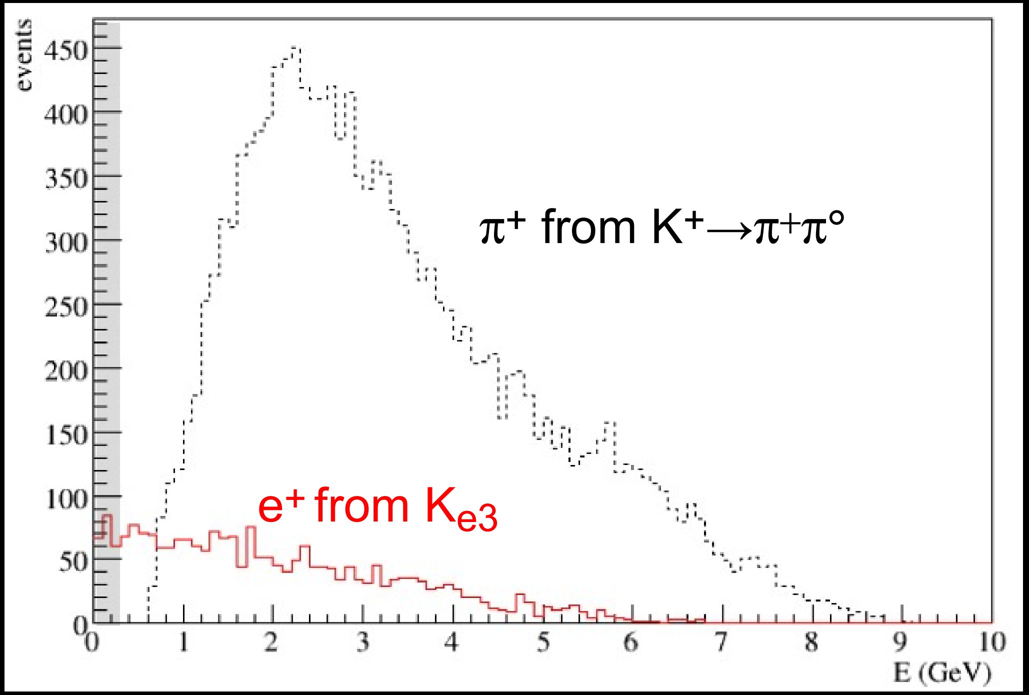
Tagger e/π separation

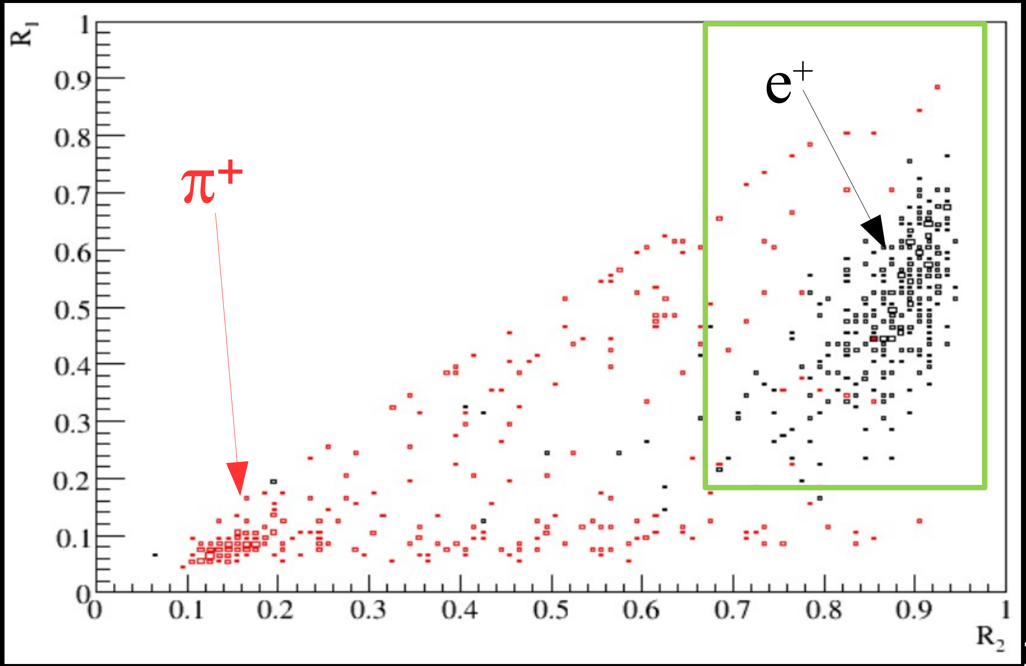
$E_1(E_2)$ defined as the energy deposited in a cylinder of $2R_{Molière}$ and 5(10) X_o length

Requires

$E_{TOT} > 300$ MeV
$R_1 = E_1 / E_{TOT} > 0.2$
$R_2 = E_2 / E_{TOT} > 0.7$

Cut	Efficiency
K_{e3} decay	100%
e^+ in calorimeter	85%
R_1,R_2 cuts	67%
$E_{tot} > 300$ MeV	59%





Backgrounds

Source	BR	Misid	$\epsilon_{X\to e^+}$	Contamination
$\pi^+ \to \mu^+\nu_\mu$	100%	$\mu \to e$ misid.	<0.1%	neglig. (outside acceptance)
$\mu^+ \to e^+\bar{\nu}_\mu\nu_e$	DIF	genuine e^+	<0.1%	neglig. (outside acceptance)
$K^+ \to \mu^+\nu_\mu$	63.5%	$\mu \to e$ misid.	<0.1%	negligible
$K^+ \to \pi^+\pi^0$	20.7%	$\pi \to e$ misid.	2.2%	13%
$K^+ \to \pi^+\pi^+\pi^-$	5.6%	$\pi \to e$ misid.	3.8%	5%
$K^+ \to \pi^0\mu^+\nu_\mu$	3.3%	$\mu \to e$ misid.	<0.1%	negligible
$K^+ \to \pi^+\pi^0\pi^0$	1.7%	$\pi \to e$ misid.	0.5%	negligible

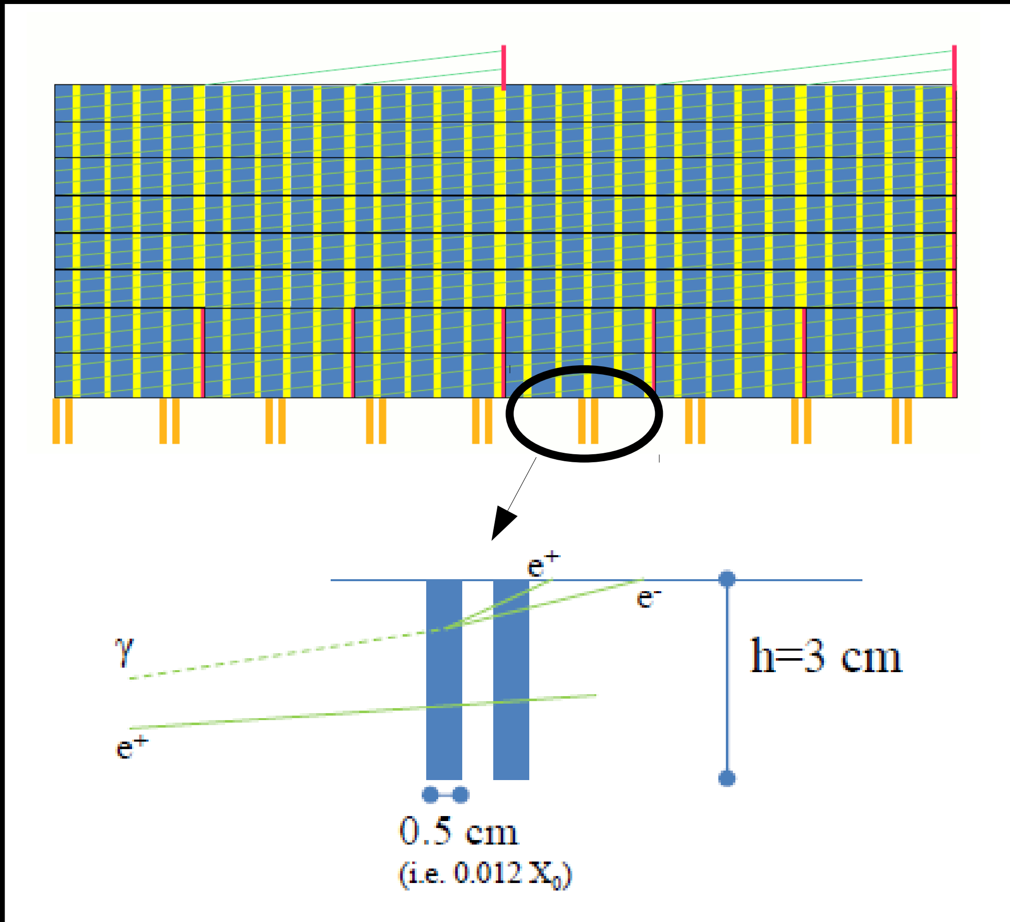
π/e mis-identification is the dominant background: 18% for 59% efficiency
(down to 7% for tighter R2>0.8 cut, with 36% efficiency)

μ/e mis-identification accounts for ~0.1% adding all sources together

γ/e mis-identification : the largest contribution comes from $K^+ \to \pi^+\pi^\circ$
Photon conversion rate ~3 10^{-3} in a 1mm Be pipe → 2% background (6% for an Al pipe)
Negligible if the tagger is inside the evacuated (<~1mbar) pipe.

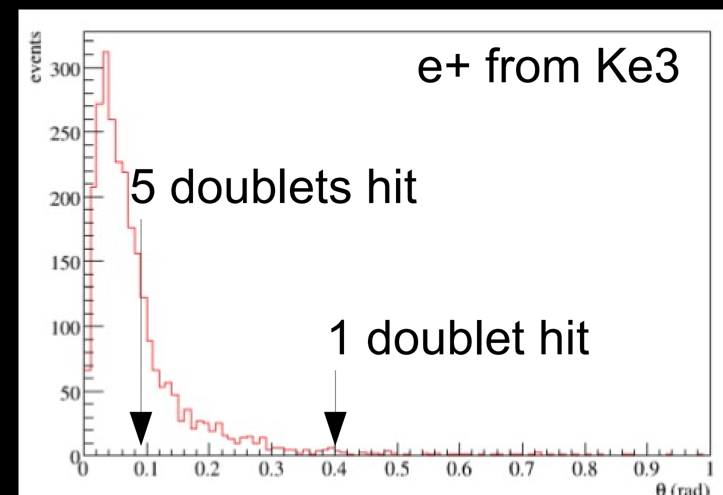
NB. fake e^+ from $K^+ \to \pi^+\pi^+\pi^-$ (5%) and π° in $K^+ \to \pi^+\pi^\circ$ (2-6%) could be removed vetoing additional π^+ from the same decay vertex. Requires tagger tracking capability and good timing from a t_0-layer detector in front. To be studied, not used for now.

t_o-layer



3x3 cm^2 scintillator tiles read by WLS fibers
0.5 cm ($0.012X_o$) thick

one doublet every 7cm in Z



Time resolution requirements: ~10 ns (matching tagger recovery time for cross-section)
~1 ns (for event by event tagging)
~100 ps (further background rejection)

Alternative technologies

Si counters: less material, less channels, better 1 vs 2 mips separations (time resolution ?)

Low-Gain Avalanche detectors → very good timing, (large surface ?)

Beam requirements

PoT/spill required to have 10^{10} p+ /spill (2ms spill length)
Integrated PoT required for 10^4 νe (in a 500t detector, 100m from decay tunnel entrance)

	E (GeV)	π^+/PoT (10^{-3})	K^+/PoT (10^{-3})	PoT for a 10^{10} π^+ spill (10^{12})	PoT for 10^4 ν_e CC (10^{20})
JPARC/PS	30	4.0	0.39	2.5	5.0
	50	9.0	0.84	1.1	2.4
Protvino/U70	60	10.6	0.97	0.94	2.0
	70	12.0	1.10	0.83	1.76
Fermilab/MR	120	16.6	1.69	0.60	1.16
CERN/SPS	450	33.5	3.73	0.30	0.52

The integrated PoTs are well within reach of existing facilities (except Protvino, currently a 10kW accelerator)

The number of protons per extraction is quite small

A large number of extractions of protons to target (~2 10^8 spills) is needed, challenging for higher energy/low-rep accelerators

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	70	12.0	1.10	0.83	[illegible]
Fermilab/MR	120	16.6	1.69	0.60	[illegible]
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1.5 10^{11} PoT/ms

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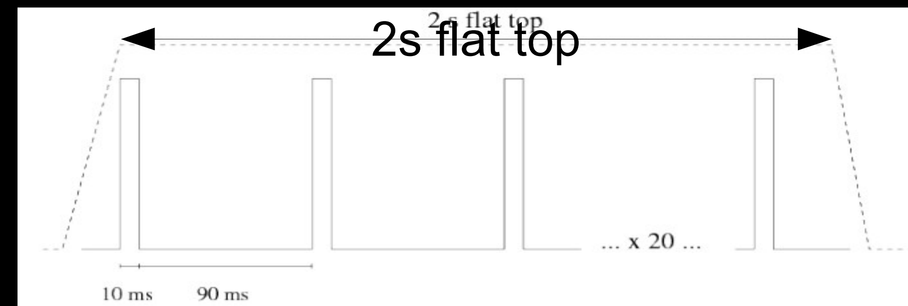
Extraction scheme(s) (the CERN/SPS case)

1. Multiple Slow Resonant Extraction

10ms 3rd integer SR extractions, repeated 20 times on the 2s flat top of the 15s super-cycle

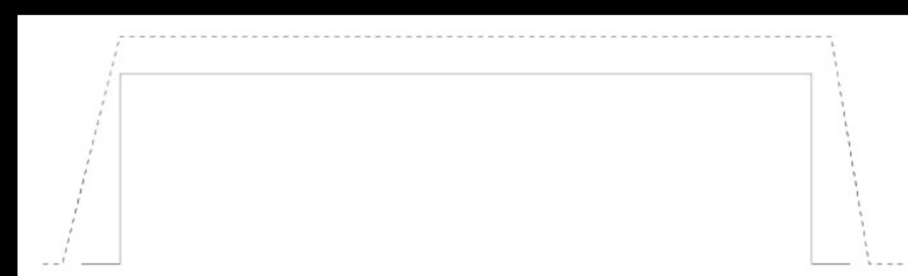


1.2 $\cdot 10^{12}$ protons extracted per spill
Extracted for each super-cycle ~half of the protons available (4.5 10^{13})

MSRE never tried before. To be tested

2. Conventional slow resonant extraction

A single SE, 2s long
(scheme proposed for SHiP)



Requires static focusing
large aperture, rad-hard quadrupoles, reduced rate (~10%) w.r.t. horn
4.5 $\cdot 10^{13}$ protons extracted per super-cycle

Allow event-by-event time coincidence tagging for spill lengths O(1s)

ν_e CC Spectrum

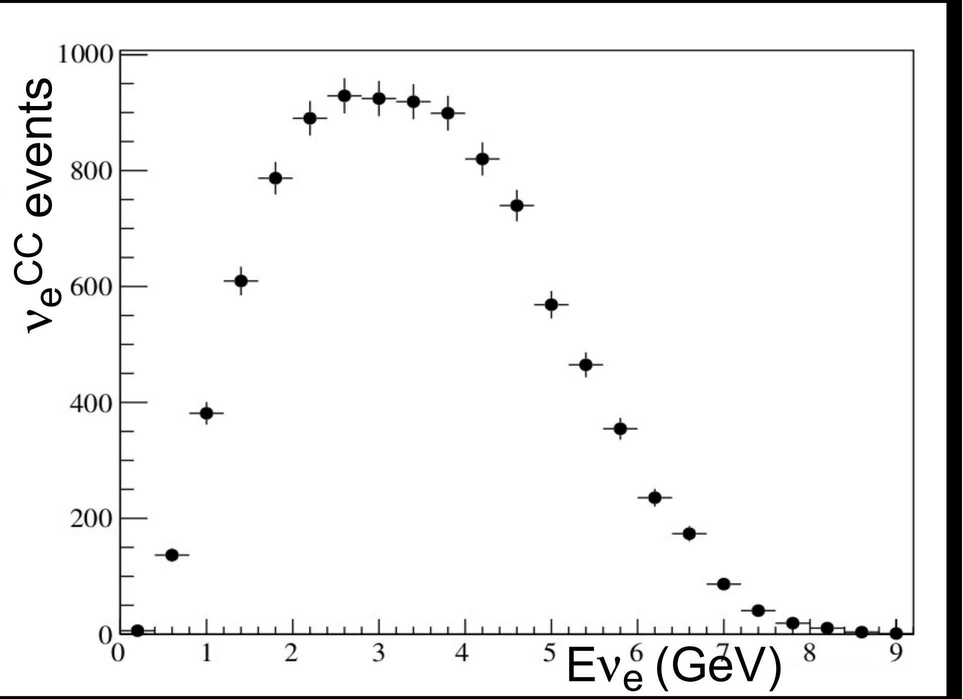
1.95 1013 K+/ν_eCC

96.7% ν_e from Ke3 (μ DIF contamination)

500 t detector 100m from tunnel entrance

Good rejection of NC $\pi°$ needed

Covers energy range of future experiments



ν flux → directly proportional to the positrons detected by the tagger
→ independent from PoTs, hadro-production, collection and focusing efficiency
→ only depend on tagger efficiency and background subtraction

High intensity mode (x10) for exclusive and differential cross-section (additional systematic for flux extrapolation from low intensity

Anti-neutrino runs

large angle $\nu\mu$ come from kaon decays → $\nu\mu$ cross section measurement

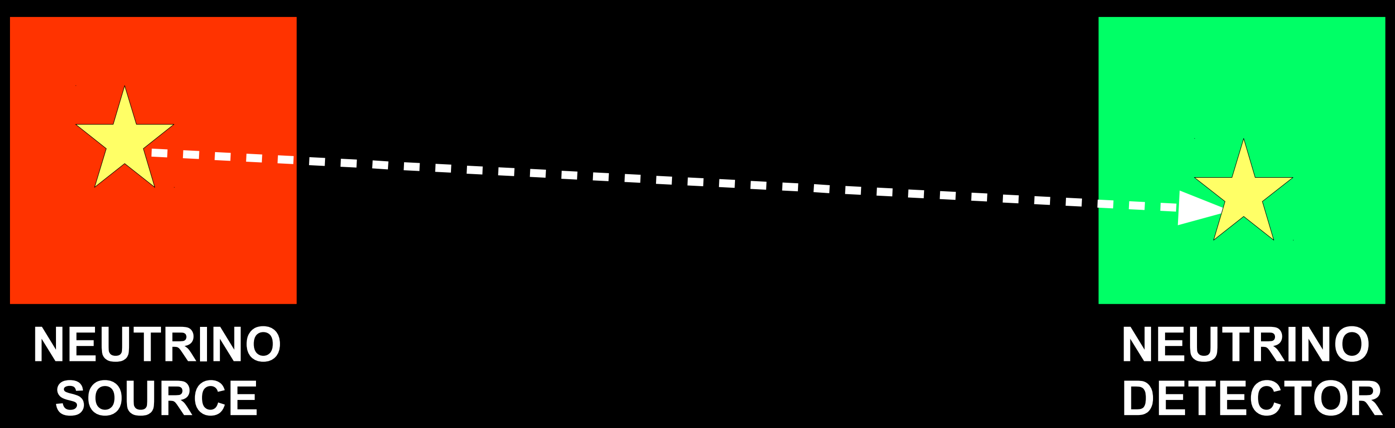
Error budget evaluation

Is 1% really feasible?
Not demonstrated yet, but from a preliminary discussion:

Source of uncertainties	Size and mitigation
statistical error	<1%
kaon production and collection efficiency	**irrelevant (positron tag)**
uncertainty on integrated pot	**irrelevant (positron tag)**
geometrical efficiency and fiducial mass	<0.5% PRL 108 (2012) 171803 [Daya Bay]
uncertainty on 3-body kinematics and mass	<0.1% Chin. Phys. C38 (2014) 090001 [PDG]
uncertainty on phase space at entrance	**can be checked directly with low intensity pion runs**
uncertainty on Branching Ratios	**irrelevant (positron tag)** except for background estimation (<0.1%)
tagger e/π^+ separation	**can be checked directly at test-beams**
detector background from NC π^0 events	<1% uncertainty EPJ C73 (2013) 2345 [ICARUS]
detector efficiency	**large cancellations if the target/technology is the same as for the CPV experiment**

Tagged neutrino beams principle

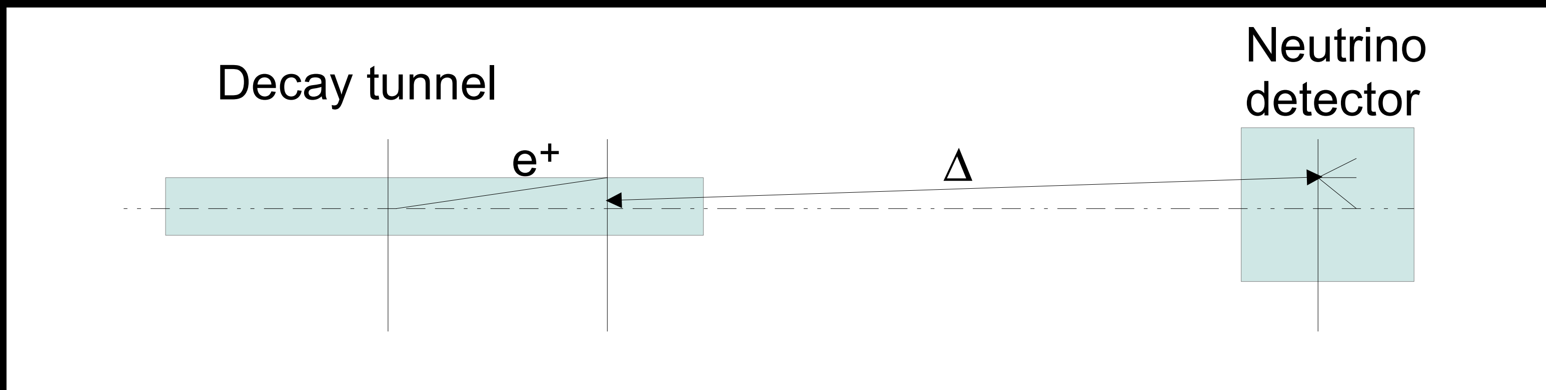
Detects **simultaneously** the neutrino interaction at the neutrino detector and the associated lepton at the neutrino source



Event-by-event tagging

Simultaneous observation of the positron and the neutrino interaction

Direct tag of the neutrino flavor, veto beam ν_e, reconstruct ν_e energy



Delayed time coincidence: $|\delta t - \Delta/c| < \delta$

The double tag mode can work if we **can beat the number of accidentals**:

$$\mathcal{A} \equiv \left[N_K \cdot \mathrm{BR}(K_{e3})(1 - e^{-\frac{\gamma_K c \tau_K}{L}})\epsilon + \mathrm{bkg} \right] \cdot \delta \simeq 2 \times 10^7 \frac{\delta}{T_{extr}}$$

positron rate per extraction — fake e+ per extraction — extraction time

For $\delta \sim 1$ns, requires $T_{extr} \sim 1$s

Close, but still not ready to fly

The proton extraction time must be ~1s	Must rely on static focusing (Li lenses?) Reduction of flux (by a factor of ~10)
The tagger and neutrino detector time resolution must be ~1ns	At the limit of current technologies for neutrino detectors (sync OK: direct optical link at ~100m baseline)
Cosmic background at the neutrino detector increases	Can be a problem at small overburden (active veto ?)
Small kaon momentum bite to improve the neutrino energy reconstruction	Can imply further reduction of the flux

Conclusions

The next generation of CPV experiments will have to deal with a level of control of systematics O(1%), unprecedented for neutrino physics

Facing the cost of these facilities, new approaches to reduce the systematic budget are extremely cost effective to extend their physics reach

A "positron monitored" Ke3 source of ν_e

- can be built using today detector technology and accelerators available at CERN, Fermilab and JPARC

- offers a O(1%) cross-section measurement with a neutrino detector of moderate mass (~500t)

- is a first step toward a flavor tagged beam