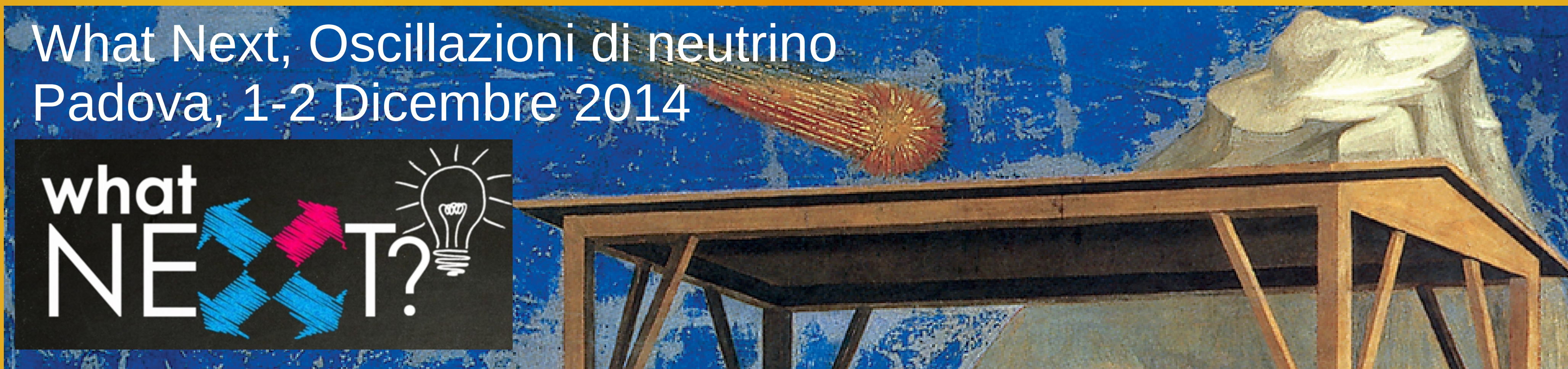
Tagged ν_e beams, a novel technique to measure $\sigma(\nu_e)$



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- Tagged ν beams
- Applications: ν_e cross section
- Beamline and decay tunnel instrumentation
- Rate and dose at the tagger station
- Background, efficiencies, rates at the neutrino detector
- Perspectives and conclusions

Tagged neutrino beams

The "forbidden dream" of ν physicists: detect simultaneously both the neutrino at the far detector and the associated lepton at production → unique tag of flavor at production

> 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 ($\pi \to \mu\nu$, $K \to \mu\nu$,

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

Literature:
- L. Hand, 1969, V. Kaftanov, 1979 ($\pi/K \to \nu_\mu$)
- G. Vestergombi, 1980, R. Bernstein, 1989 ($K \to \nu_e$)
- S. Denisov, 1981, R. Bernstein, 1989 (K_{e3})
- L. Ludovici, P. Zucchelli, hep-ex/9701007 (K_{e3})
- L. Ludovici, F. Terranova, EPJC 69 (2010) 331 (K_{e3})

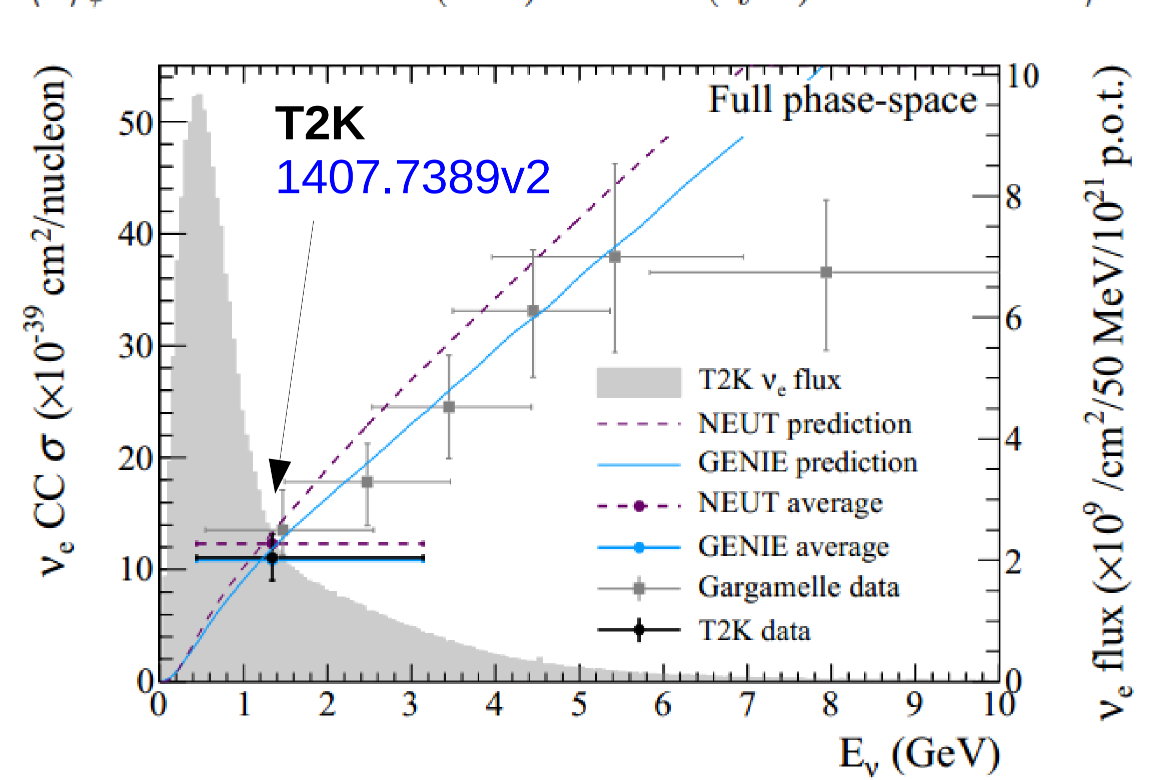
What's new here: a beam design optimized for $\sigma(\nu_e)$

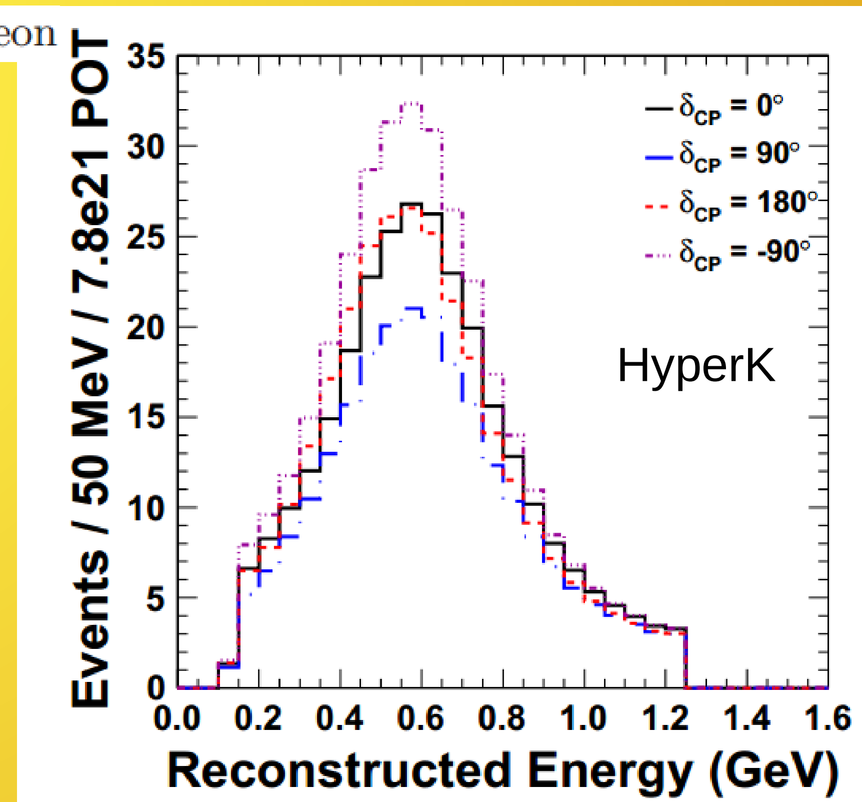
- using $\mathbf{K^+ \to e^+ \pi^0 \nu_e}$ (K^+_{e3} decays)
- taking advantage of the progress in **fast and radiation-hard detectors** at the LHC

Importance and status of $\sigma(\nu_e)$

- Despite lepton universality in weak interactions the ν_μ/ν_e ratio suffers from uncertainties related to nuclear effects (Phys. Rev. D86 (2012) 052003).
- Current mesurements (Gargamelle, T2K) are limited by systematics.
  - T2K recent measurement: σ_{sys} = 16% (12% from the ν flux)
- Measurement of leptonic CP violation: modulations in the energy spectrum of ν_e from $\nu_\mu \rightarrow \nu_e$: knowing well the ν_e cross section is extremely valuable for future experiments planned worldwide (HyperK, LBNF/O).

$$\langle\sigma\rangle_\phi = 1.11 \pm 0.09 \text{ (stat)} \pm 0.18 \text{ (syst)} \times 10^{-38} \text{ cm}^2/\text{nucleon}$$





Tagging e^+ from $K^+ \rightarrow e^+\pi^0\nu_e$

BR(K_{e3}) = (5.07 ± 0.04) %

"SINGLE TAG" = count "all" prompt e^+ instrumenting the decay tunnel

$$N(e^+_{prompt}) = \alpha\, N(\nu_e)_{Produced} = \alpha'\, N(\nu_e)_{Detector}$$

α,α' geometrical acceptances of tagger and ν detector (K decay kinematics)

1) could **measure $\sigma(\nu_e)$** removing the largest uncertainty related to the flux (driven by hadro-production in the target)

$$\sigma^{CC}(\nu_e) \propto N(\nu_e^{CC,\ Observed}) / N(\nu_e)_{Detector}$$

"DOUBLE TAG" prompt e^+ in time coincidence with ν_e^{CC} at ν detector

...

2) could **veto the intrinsic ν_e background** in conventional neutrino beams

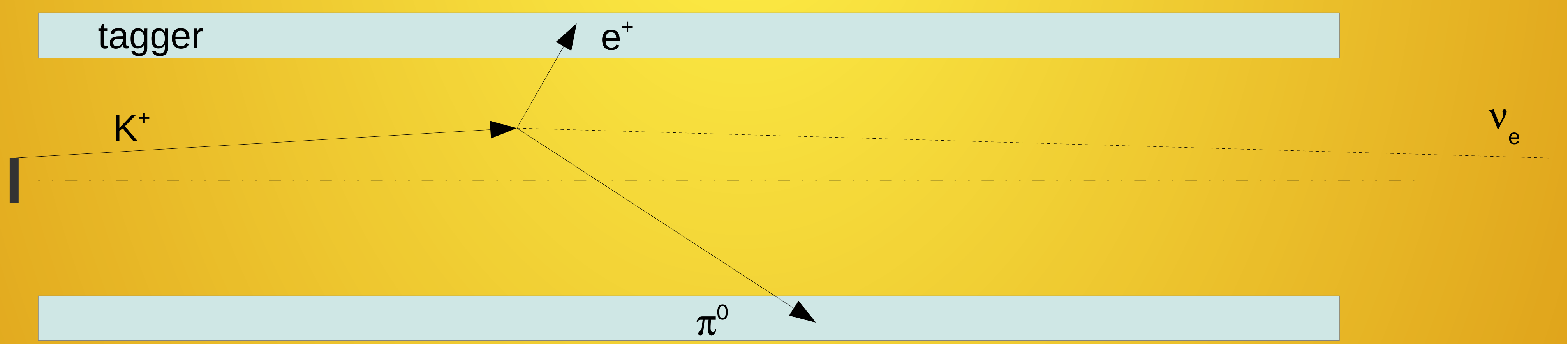
3) could **measure $E(\nu_e)$ event-by-event** from the energies of e^+ and π^0

Concept for the tagger

Let's assume **a beam of collimated pions and kaons selected in sign and momentum**.

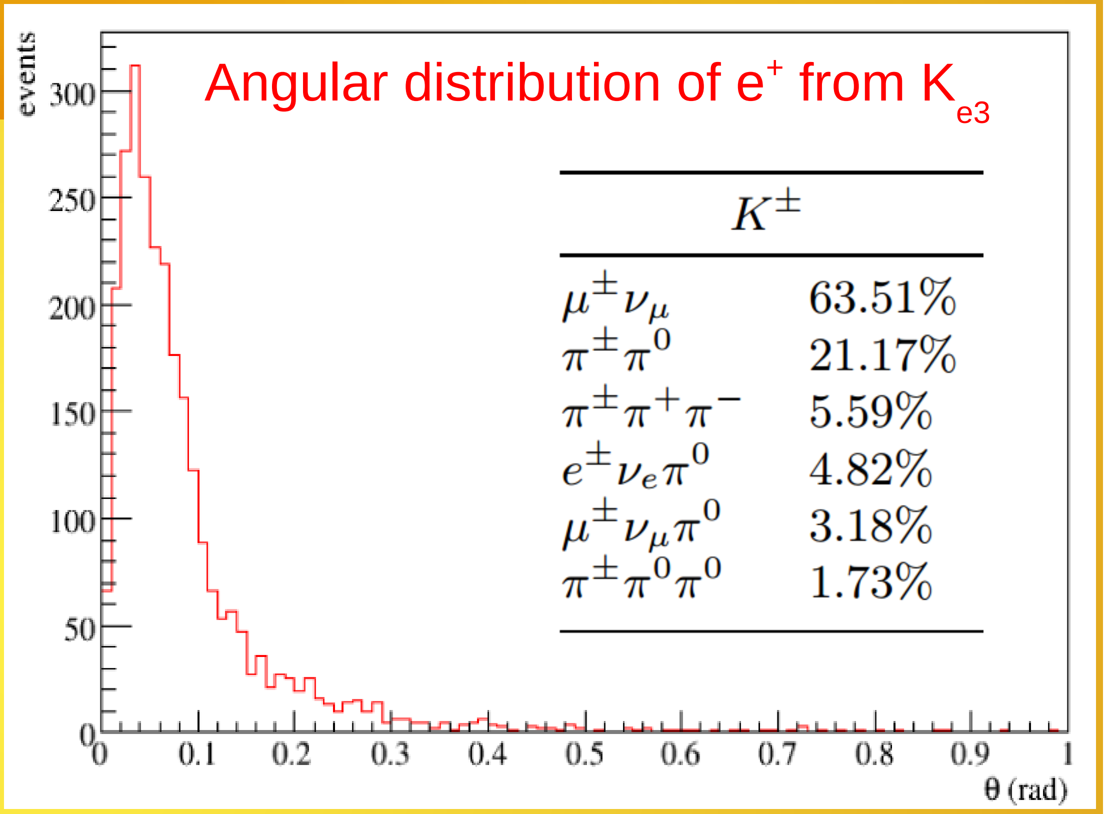
Channel	*ν at far detector*	*Angular spread (*)*	*kinematics*
$\pi^+ \rightarrow \mu^+\nu_\mu$	Bulk of ν_μ	μ^+ ~ 4 mrad	2-body
$\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu}_\mu\nu_\mu$	ν_e from μ decay in flight (DIF)+(anti)ν_μ	e^+ ~ 28 mrad	3 body (low mass)
$K^+ \rightarrow \pi^0 e^+ \nu_e$	ν_e from K_{e3}	**e^+ ~ 88 mrad**	3 body (high mass)
Undecayed π,K/p	/	O(3 mrad)(**)	
Other K^+ decays	ν_μ		No prompt e^+

(*) RMS assuming p = 8.5 GeV (see below)
(**) depends on the focusing system



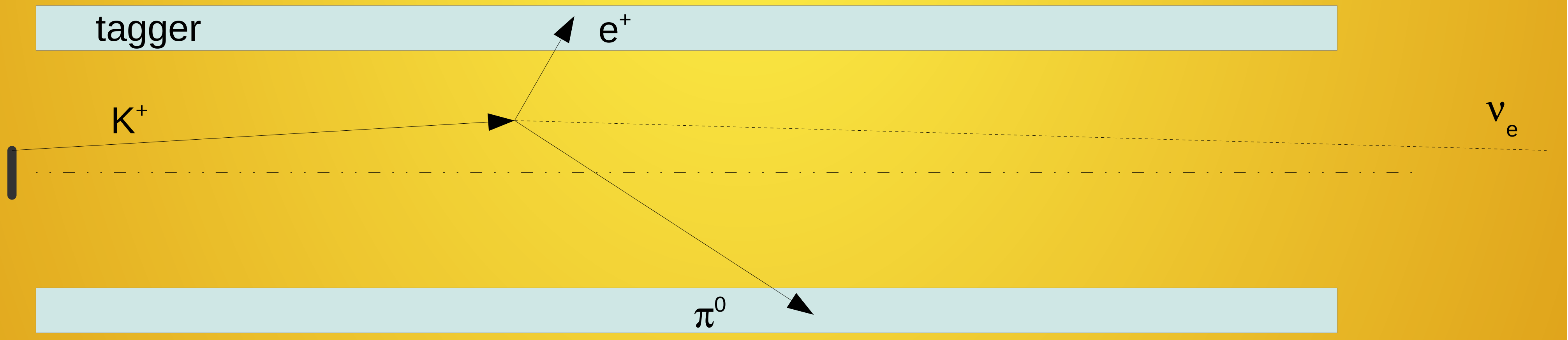
Concept for the tagger

- Good tagging efficiency for e^+ from K_{e3} thanks to the high emission angle
- e^+ from μDIF suppressed by $L_\mu << L$ and low emission angle (28 vs 88 mrad)



What else hits the tagger ?

- hadrons and γ from K, π decays (mostly at low angle). **Must be efficiently discriminated from e^+**
- μ from K and π decays: easy to discriminate
- undecayed π/K/p. Very few/none if the incoming beam is collimated enough.



Beam design considerations

K^+ decay "earlier":
$(\tau/m)_{K+} = 0.13\ (\tau/m)_{\pi}$

The ν_e/ν_μ ratio roughly scales as:
(neglecting ν_μ from K^+ w.r.t. ν_μ from π^+)

~ 10 % (see later)

$$R_{K/\pi} \cdot BR(K_{e3}) \cdot \frac{\left[1 - e^{-L/\gamma_K c\tau_K}\right]}{\left[1 - e^{-L/\gamma_\pi c\tau_\pi}\right]}$$

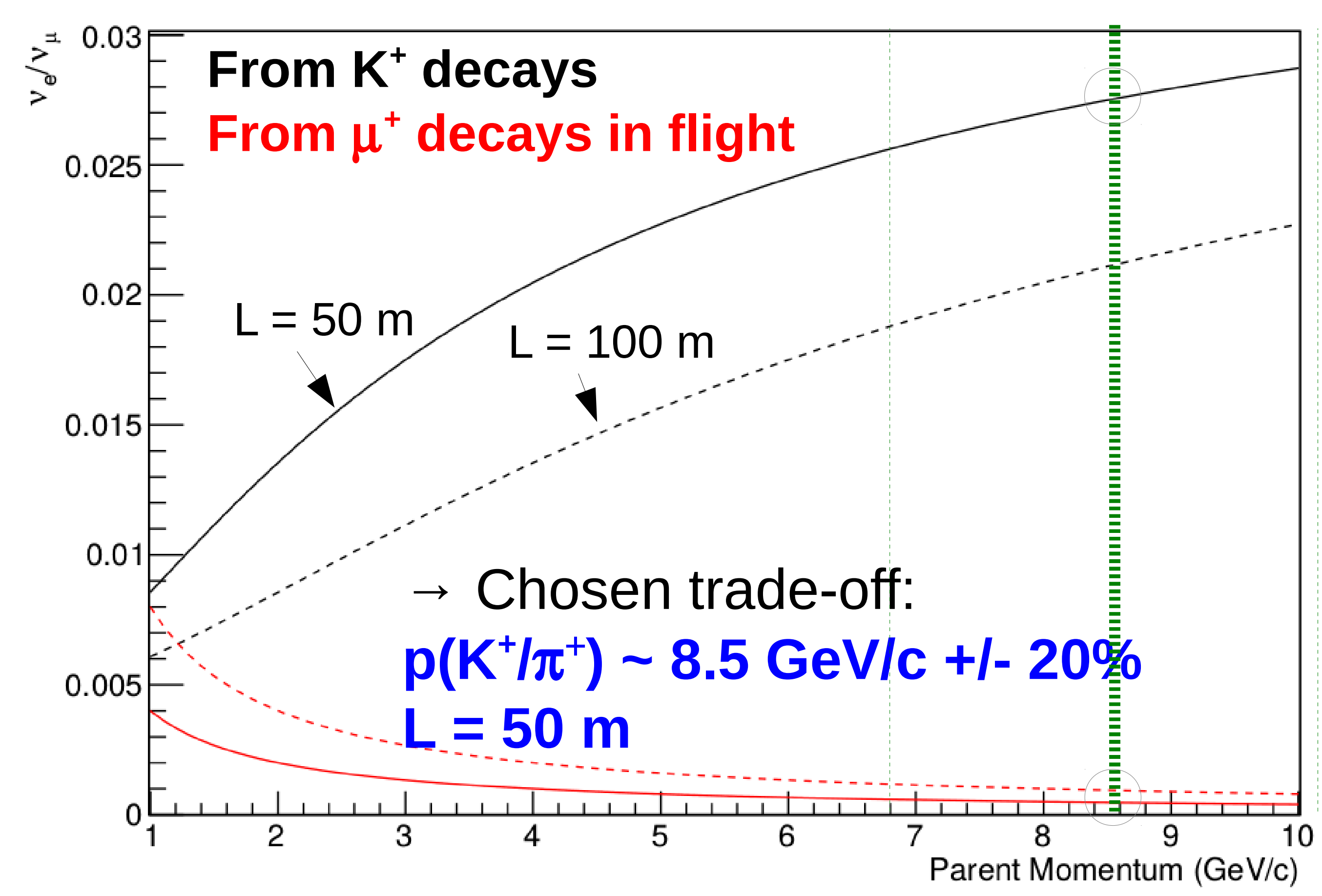
5.07 %

To get a sizeable ν_e from K_{e3} with reduced ν_e from μDIF:
1) keep the tunnel "short" (L)
2) increase the parent energy (γ)

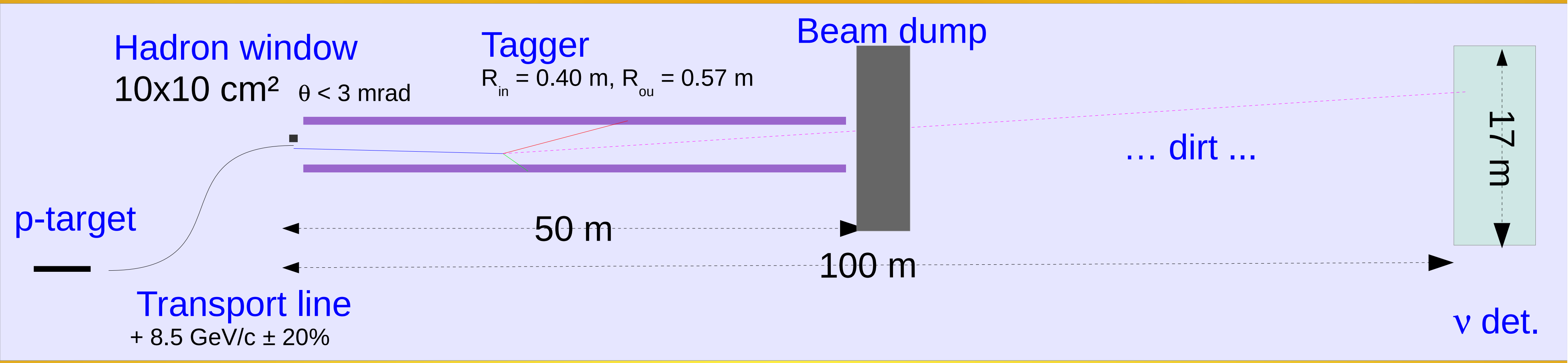
→ ν_e at far proportional to the decaying $K^+ \rightarrow e^+$

Increasing E(K,π) ~ γ

* increased $R_{K/\pi}$ ☺
* < loss in the transport line ☺
* better e/π separation ☺
* $E(\nu_e)$ higher than the R.O.I. ☹
* longer decay (tunnel) ☹

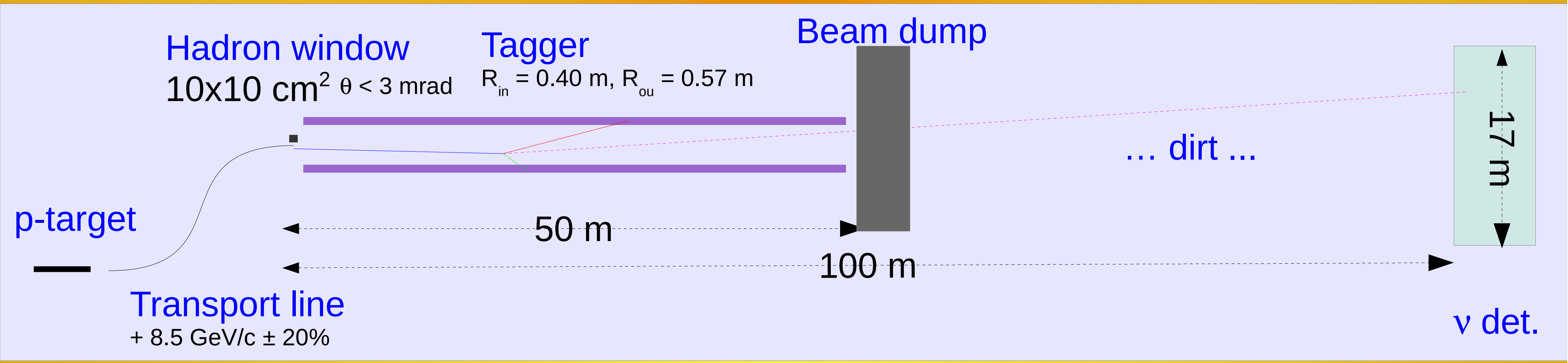


Setup and simulation tools

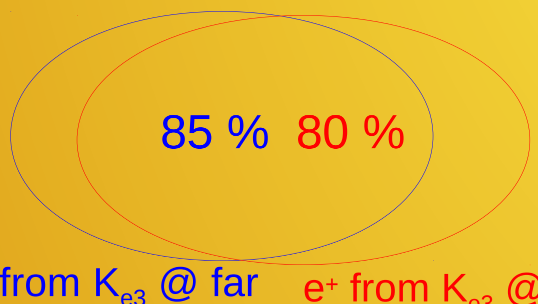


- p-target interactions: **FLUKA 2011** (cross-checked w. **BMPT** param.)
  Be target: L= 1.1 m ∅ 3 mm. Energies: **30, 50, 60, 70, 120, 450 GeV/c**
  (*JPARC, U-70 at Protvino, NUSTORM 1ry beamline, FNAL-MI, CERN-SPS*)
- K^+/π^+ charge selection, focusing, transport: **not simulated in detail** (horns for fast extraction, quad/solenoid focusing for slow extraction. See next →)
- K^+/π^+ decays and propagation in the tunnel (**GEANT4**, two independent)
- e^+/π^+ interactions with the fast calorimeter (**GEANT4**, up to hits level)
- e^+ energy reconstruction: smearing with a realistic **parametrisation**
- ν detector at 100 m: **not sim**. σ_t ~1-10 ns, good NC-π^0 rejection, **500 t**

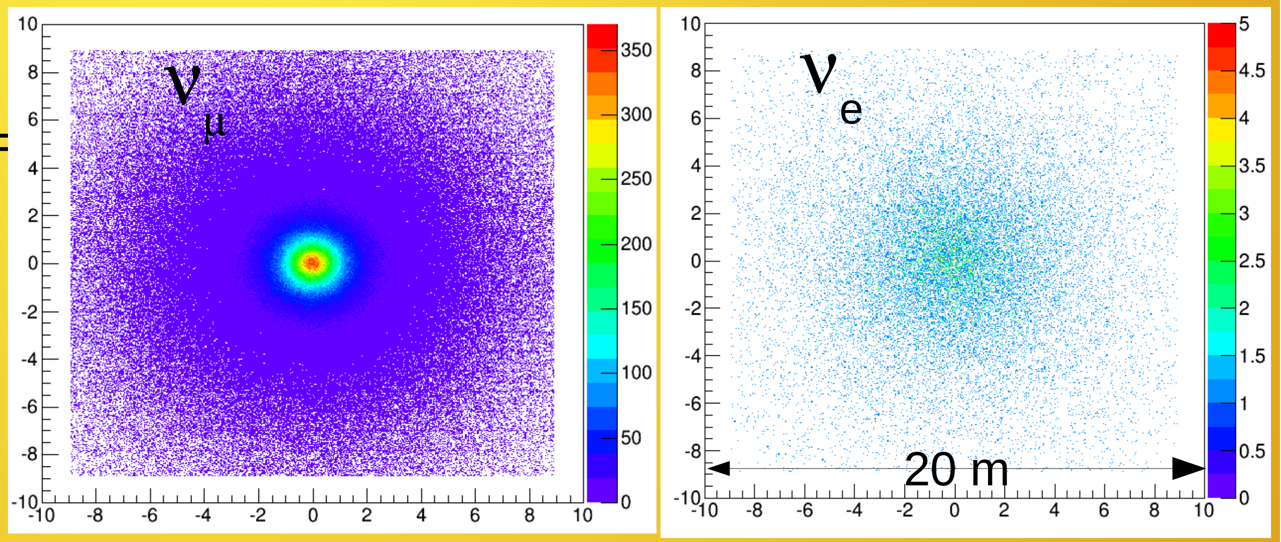
Geometrical acceptance



- % of ν_e at ν-detector with a tagged e^+ = 85% (tagger geometrical acceptance – forward "hole")
- % of tagged e^+ with a ν_e at far = 80% (far det. geometrical acceptance)

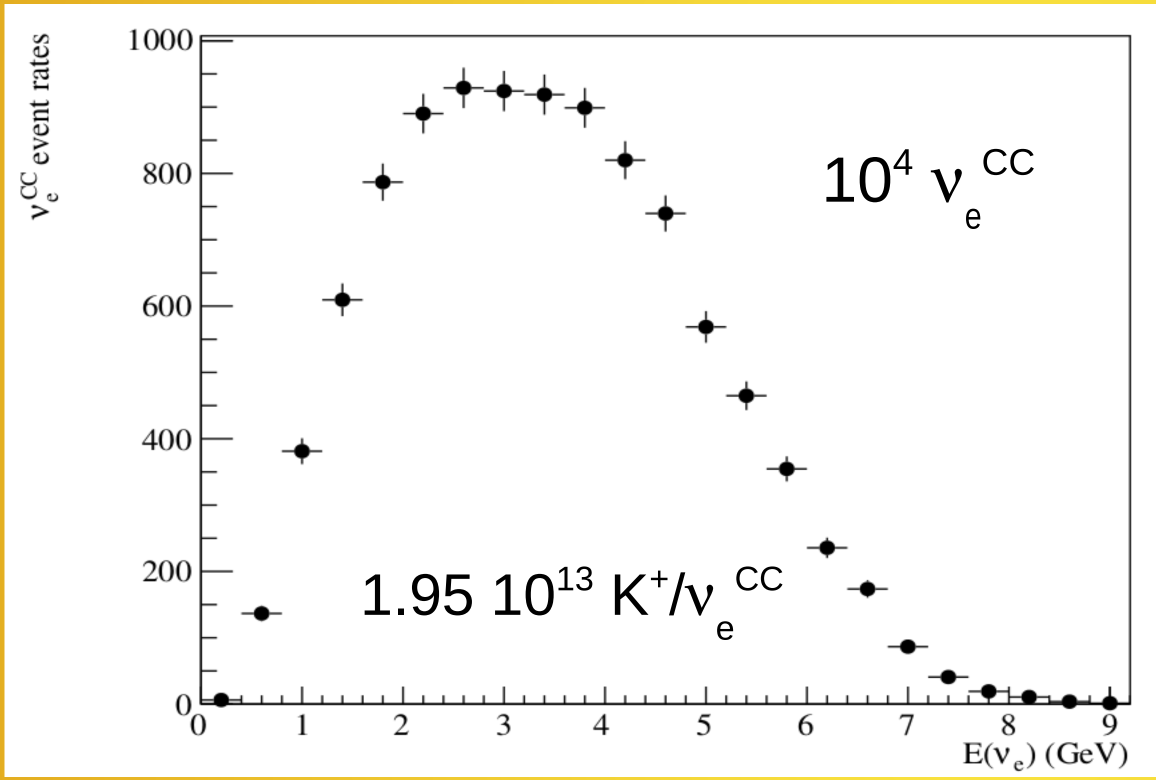


Radial profiles at the ν detector (z = 100m)



Neutrinos at the ν detector

Detector at 100 m from the hadron window with a cross sectional area of 17.7 x 17.7 m². Mass = **500 t** (isoscalar)



$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8\ \%\ (\nu_e \text{ from } K_{e3})$$

$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 0.06\ \%\ (\nu_e \text{ from DIF})$$

- Only 3.3 % of ν_e from μDIF (low-E)
- <E> = 3 GeV, FWHM = 3.5 GeV

Interesting region of long baseline projects is well covered.

- A good rejection power for NC π^0 is still necessary (large ν_μ flux).

The ν_e flux is proportional to the e^+ flux measured in the CAL.

It does NOT depend on:

hadroproduction, $R_{K/p}$, PoT, 2^{ry} beamline transport efficiency

It depends on:

geometrical efficiency of far detector, e^+ efficiency in the CAL and backgrounds

Transport line/focusing system

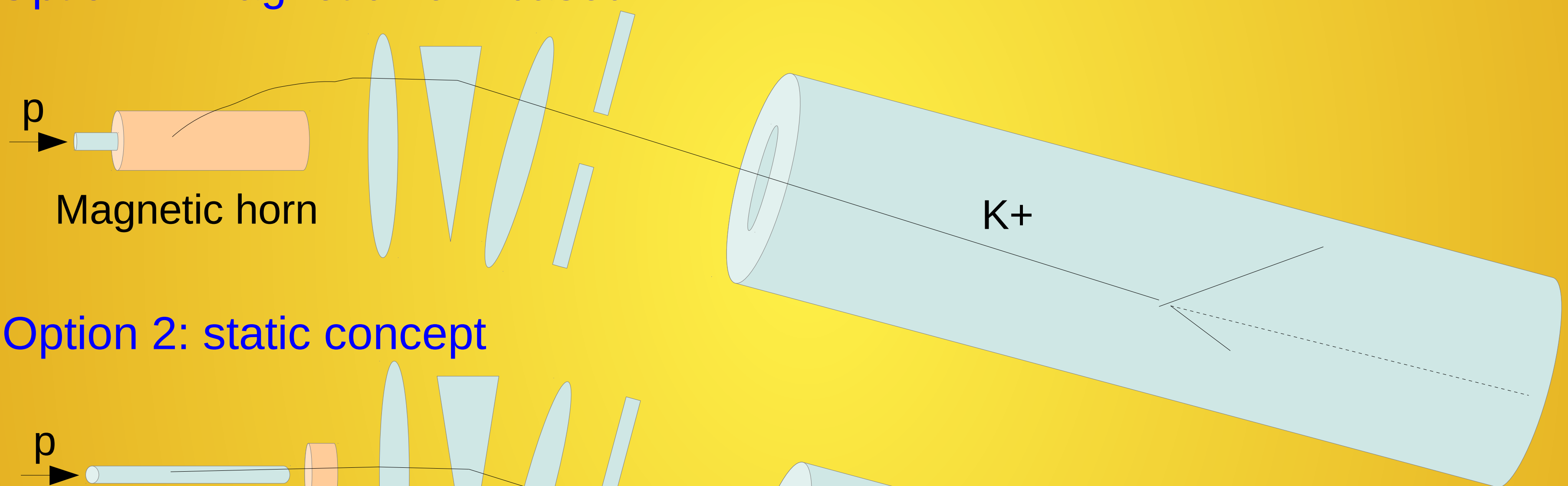
- The secondary hadrons have to be captured, sign-selected and transported to the instrumented decay tunnel
- Requirements at the tagging station:
  - K^+ and π^+ in a 8.5 GeV/c ± 20 % momentum bite
  - distributed over a 10 x 10 cm^2 window
  - dN/dθ uniform in [0, 3] mrad

  Not decayed hadrons do not intercept the tagger → acceptable rates

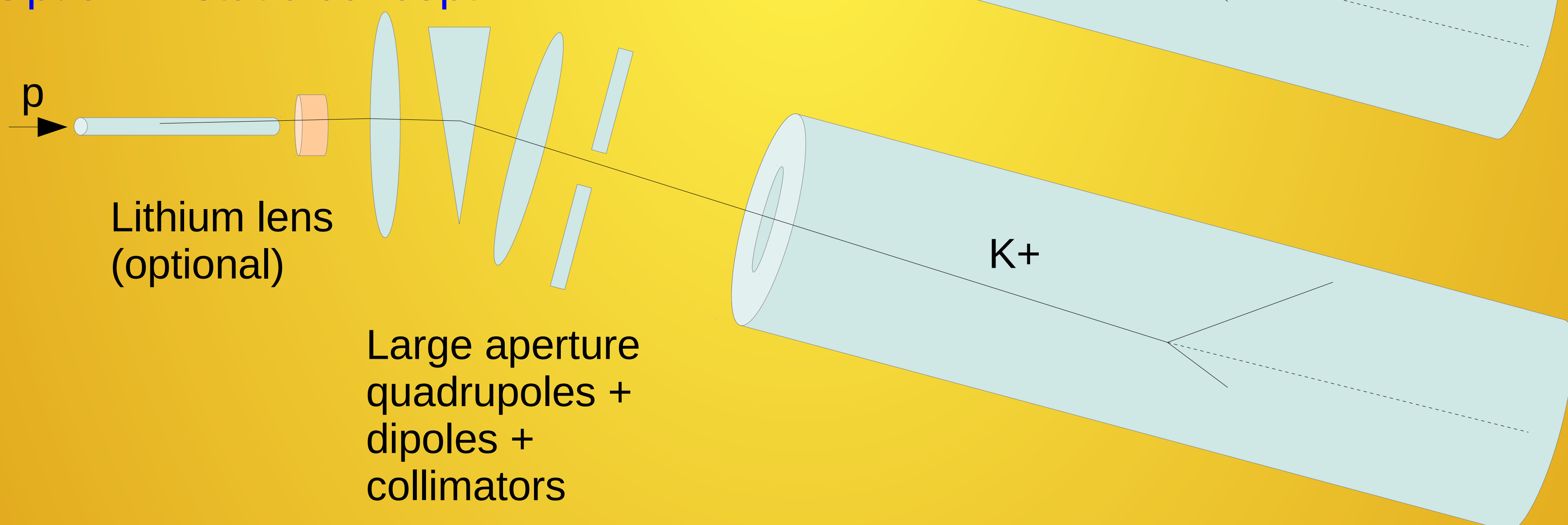
  - Geom. acceptance of the dec. tunnel,
    - $A = 4\varepsilon_{xx'} = 4\varepsilon_{yy'} = 4 \times (5 \text{ cm}) \times (3 \text{ mrad}) = 0.6$ mm rad
  - Time structure: a 2 ms extraction
    - Used for example in the past at the CERN WANF.
    - Horn pulses have this typical time development even for beams with O(10 μs) extractions (NOvA, T2K).
  - Length: ~10 m induces a 16% loss from early decays

Options for the focusing system

- No detailed simulation/optimization. Considered two focusing schemas based on realistic figures (literature, e.g. the NUSTORM proposal)
- Option 1: magnetic horn based



- Option 2: static concept



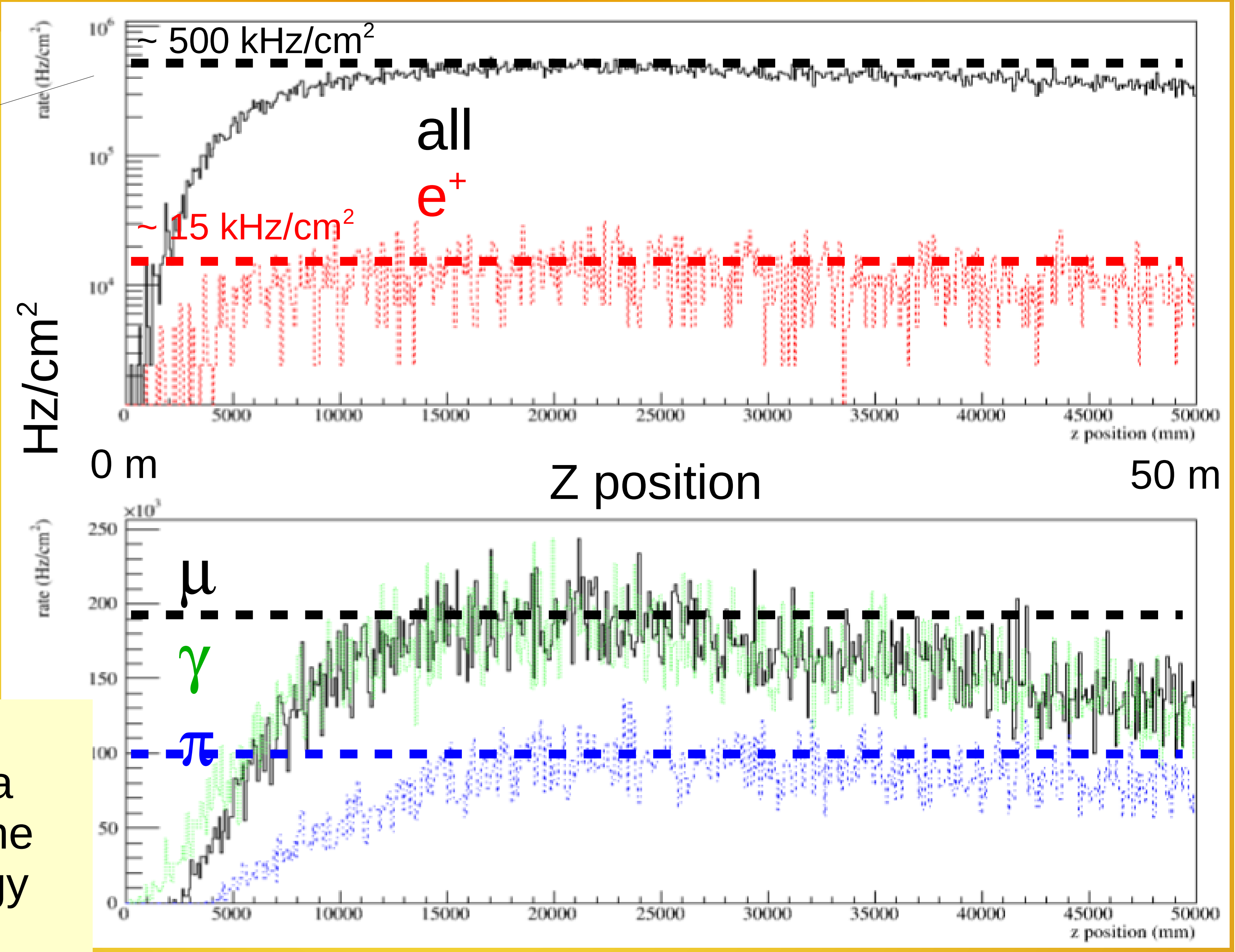
Particle rates along the tagger

Assuming to have 10^{10} π^+ in a 2 ms spill at the tunnel entrance →

Maximum rates at about 20 m from the target (broad)

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

These rates are manageable with a proper choice of the detector technology → see later



Transport line/focusing system: option 1

- Adopts a magnetic pulsed horn (compatible with a 2 ms extraction)
- We assume a 85% collection efficiency (from NUSTORM) in the momentum bite.
- For each proton energy (E_p) we have considered the (x,x',y,y') phase space 5 cm downstream of the target
- We have figured out in this space the ellipse with emittance ($\varepsilon_{xx'} = \varepsilon_{yy'} = 0.15$ mm rad) maximizing the π^+ rate → figure out the maximal collectable π^+/PoT (see below)
- 1.94 x 10^{13} K^+ are needed per ν_e^{CC} with a 500 t detector and the given setup (does not depend on E_p) → count how many PoT are needed to get 10^4 ν_e^{CC} (= 1% stat. err. measurement).

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})
30	4.0	0.39	2.5	5.0
50	9.0	0.84	1.1	2.4
60	10.6	0.97	0.94	2.0
70	12.0	1.10	0.83	1.76
120	16.6	1.69	0.60	1.16
450	33.5	3.73	0.30	0.52

Simple conversion → (PoT for a 10^{10} π^+ spill)

Simple conversion 1.94 x 10^{13} K^+ / ν_e^{CC} → (PoT for 10^4 ν_e CC)

Needed spills

~2 x 10^8

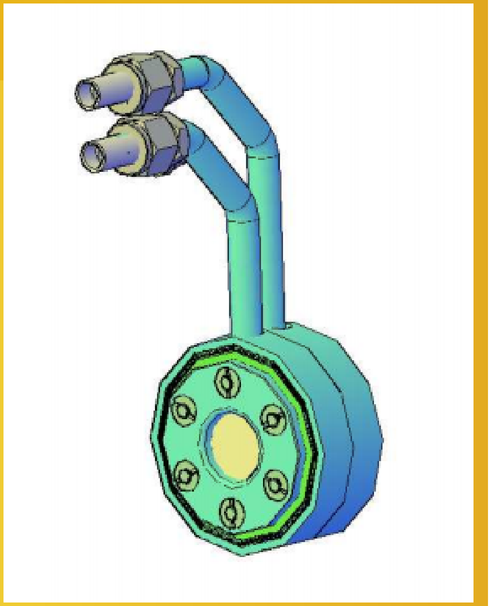
Integrated PoT: achievable(*)!
Number of spills: might be challenging (depend on realistic repetition rates, need Hz. Multi-turn extraction ?)

FLUKA simulation + emittance optimization in the phase space

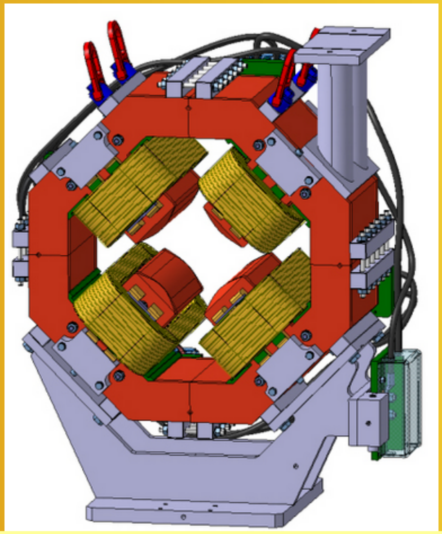
* JPARC > 6.6 x 10^{20} PoT
CNGS = 1.8 x 10^{20} PoT
2.4x10^{13} pot/spill every 6s
NuMI = 10.7 x 10^{20} PoT

Transport line/focusing system: option 2

- We assume to be able to focus only those pions and kaons emitted in the momentum bite and in a 80 μSr cone centered in the forward direction (a small angular forward acceptance like the one achievable with a purely static focusing and bending channel). Large aperture quadrupoles might eventually be replaced by a Lithium lens device →)
- This option implies a loss of acceptance of ~ x 10 (and correspondingly more PoT for a given neutrino rate).
- Could sustain longer proton pulses.



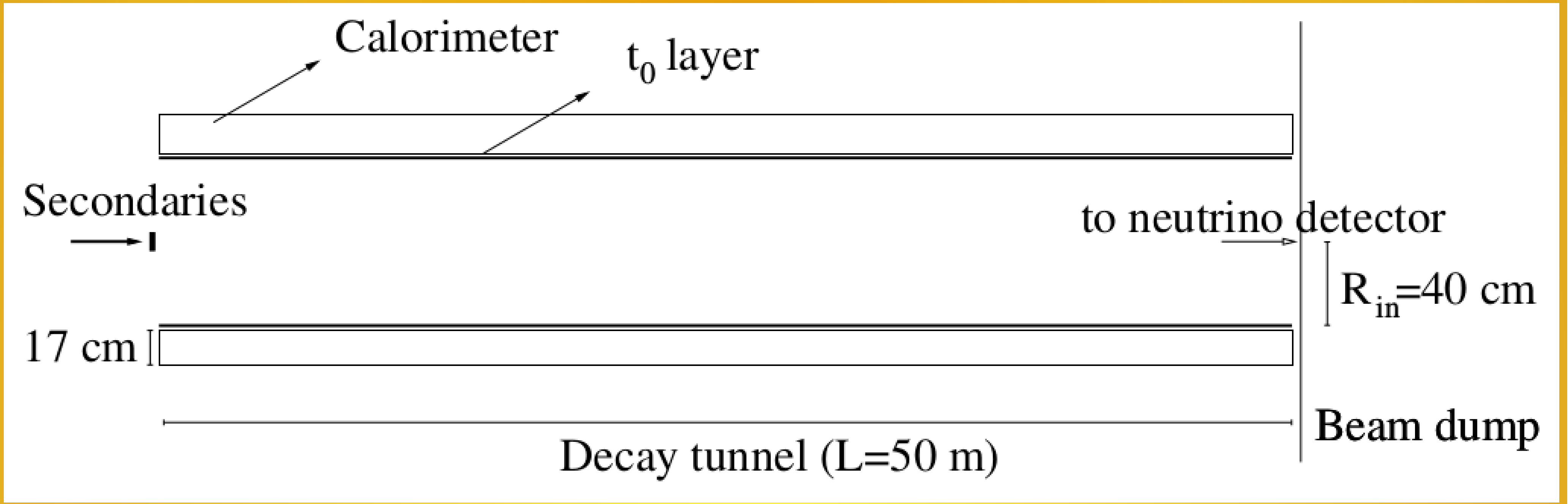
http://www.lns.cornell.edu/public/CBN/2012/CBN12-1/CBN12-1.pdf



E (GeV)	π^+/PoT (10^{-3})	K^+/PoT (10^{-3})	PoT for a 10^{10} π^+ spill (10^{13})	PoT for 10^4 ν_e CC (10^{21}) ←
30	0.24	0.027	4.2	7.2
50	0.58	0.069	1.7	2.8
60	0.73	0.091	1.4	2.2
70	0.80	0.095	1.3	2.0
120	1.25	0.16	0.80	1.22
450	3.65	0.43	0.27	0.46

* JPARC > 6.6 x 10^{20} PoT
CNGS = 1.8 x 10^{20} PoT
NuMI = 10.7 x 10^{20} PoT

Layout of the e^+ tagger



t_0 layer: a **pre-shower** providing absolute timing of arrival of the charged particle → rejects neutral background (π^0).

Calorimeter: Copper absorber (X_0 = 1.436 cm, λ_π = 18.5 cm).**Thickness (17 cm)**: > $3\lambda_\pi$ for particles at 88 mrad. Longitudinally **segmented tiles**. **Area = 10 cm²**.

Vacuum chamber: 1.5 mm Be or 1 mm Al (to reduce conversion prob. before the t_0 layer)

Instrumenting z = 10-50 m, m(CAL) = 185 t. Area ~ 100m^2 → ~ **4 x 10^5** channels (including t_0)

e^+/π^+ separation

Defining $E_{1,2}$ as the E deposited in a cylinder w.

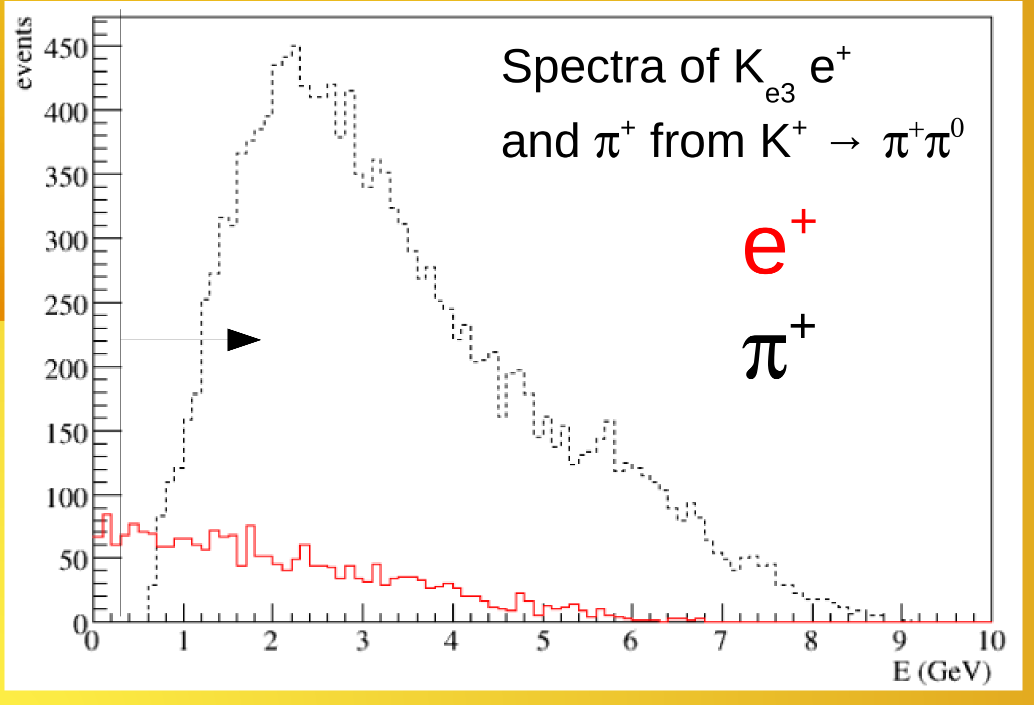
- $r = 2R_{Moliere}$ (3.2 cm for Cu)
- $h = 5n\ X_0$ (7.2 and 14.4 cm)

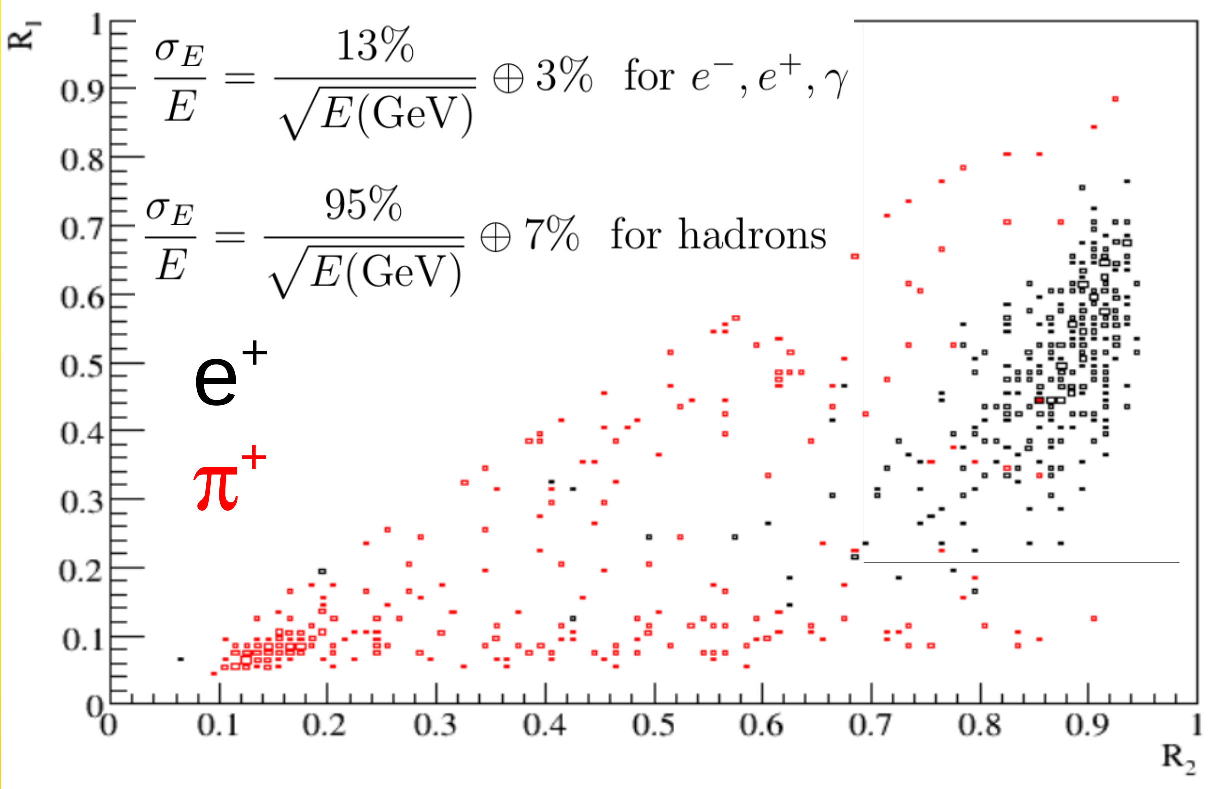
Selection:

- **Coincidence with hits in t_0 detector**
- **E_{tot} > 300 MeV**
- **$R_1 = E_1 / E_{tot} > 0.2$**
- **$R_2 = E_2 / E_{tot} > 0.7$**

the smearing is done on E_{tot}

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





Pile-up and radiation

Pile-up mostly from the overlap of a $K_{\mu 2}$ muon with a candidate e^+ (N.B. not decayed pions and kaons do not intercept the CAL)

Recovery time, Δt_{cal} = 10 ns
Rate, R = 0.5 MHz/cm^2
Tile surface, S ~ 10 cm^2

→ 5% pile-up probability (= $RS\Delta t_{cal}$)

Possible mitigation: veto (also offline) mip-like and punch-through particles using the longitudinal segmentation of the CAL and eventually a muon catcher (Fe + μ–chambers)

Radiation

150 MJ (but 64% into muons) from 1.94 x 10^{17} K^+ decays (~ 10^4 ν_e^{CC})

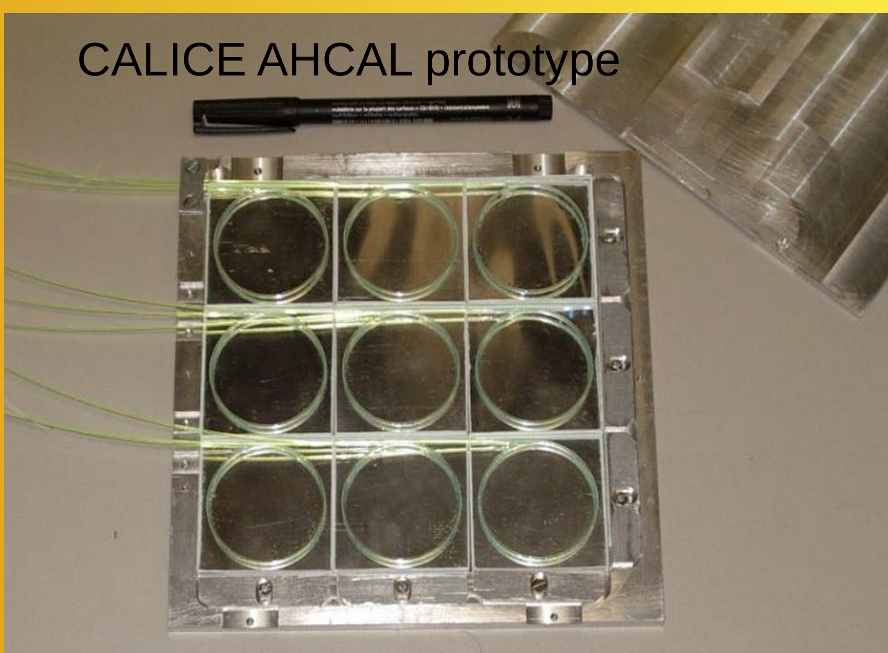
Mass: $3X_0$ (4.3cm) for 40 m of length (Cu) → 38 t → integrated dose < 1.26 kGy (~100 kGy for CMS forward ECAL)

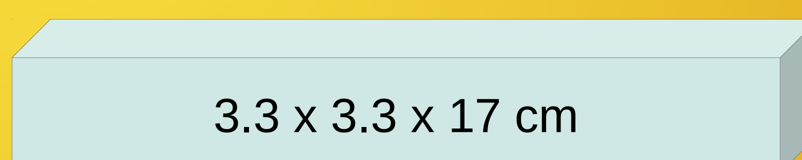
→ Both issues not critical

Possible technology for the CAL

- Scintillator tile calorimeter developed for the ILC (CALICE AHCAL)
- Readout: SiPM + WLS fibers
- but with a much coarser longitudinal segmentation.
- Copper could be used as absorber

NA62 LAV llayout
(10 x 10 x 37 cm crystals)


CALICE AHCAL prototype



Background budget after selection

Signal K_{e3} ~ 5% of all K^+ decays. Bulk: μ from $K_{\mu2}$ (63%), $\pi^+\pi^0$ from $K^+ \rightarrow \pi^+\pi^0$ (21%)

- e^+/μ^+ mis-id ~10^{-3} adding $K_{\mu2}$, $K_{\mu3}$ and π DIF
- π^+/e^+ dominates (e.m. component of hadronic shower):
  $\varepsilon(\pi^+ \rightarrow e^+)$ = 2.2 % → 18 % of fake e^+
- π^0/e^+ Mis-id if the γ converts in the t_0 detector or in the vacuum chamber in front
  1.5 mm Be → $\varepsilon(\pi^0 \rightarrow e^+)$ = 3 x 10^{-3} → < 2 % of fake e^+ from π^0 (6% with 1 mm Al)
  CAL in vacuum region as for NA62 Large-Angle-Veto → 0

NB. fake e^+ from $K^+ \rightarrow \pi^+\pi^+\pi^+$ (5%) and π^0 in $K^+ \rightarrow \pi^+\pi^0$ (2-6%) could be removed vetoing π^+ from the decay vertex. Requires t_0-detector with σ_t O(100 ps) ~ σ_z O(1m): not used here.

Source	BR	Misid	$\epsilon_{X\to e^+}$	Contamination
$\pi^+ \to \mu^+\nu_\mu$	100%	$\mu \to e$ misid.	<0.1%	neglig. (outside acceptance)
$\mu^+ \to e^+\bar{\nu}_\mu\nu_\mu$	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

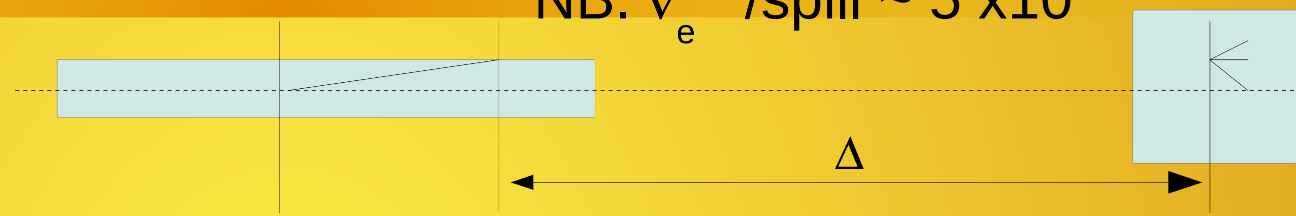
Systematics

- The number of reconstructed positrons is proportional to the ν_e flux.
- The dependence of the ν_e flux from hadron yield, kaons/pions ratio, secondary transport efficiency and number of PoT is thus by-passed.
- The geometrical efficiency of the neutrino detector and of the tagger need to be known (tipically not critical). Residual dependence from:
  - the K_{e3} decay kinematics (very well studied, experimentally)
  - the divergence of the beam at the entrance of the decay tunnel (could be measured in situ with low-intensity runs)
  - The slope of the momentum distribution of K^+ in the momentum bite (quite flat)
- Test beam characterisation of the calorimeter before installation.
- ~1 % systematics looks possible (even tough only a full simulation might give a more precise answer)

"Double tag" mode?

NB. ν_e^{CC}/spill ~ 5 x10^{-5}

Time coincidence between ν_e^{CC} and e^+ $|\delta t-\Delta/c| < \delta$



δt : the difference between the e^+ and the ν_e^{CC} time (~100 ns).

δ the linear sum of the timing resolutions of the e^+ tagger and neutrino detector

measured e^+ from K_{e3} per extraction   fake e^+ per extraction

Accidental tag probability

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

- **With T_{extr} = 1s (1 obs. e+ / 30 ns) and δ = 1 ns → A = 2 %**

NB. Previous beam parameters (T_{extr} = 2 ms spill) not suitable (1 e^+ / 70 ps observed). Even assuming δ = 50 ps (→ A = 50%), the intrinsic limit related to the imperfect knowledge of the decay point transverse position starts to play a role (~80 ps uncertainty).

"Double tag" mode?

Associating a single neutrino interaction to a tagged positron with a low probability of having picked up a fake coincidence would allow to know "a priori" the energy of that neutrino (event by event).

Tagger acceptance for K_{e3} ($e^+ + \pi^0$) pairs = ~ 70%

(→ still high even adding the π^0 requirement)

E_ν resolution: mainly limited by the ignorance of the parent K^+ energy (momentum bite Δ_p = 20%) besides the energy resolution on the e^+:

For 3 GeV ν_e: [K^+ (8.5 GeV) → ν_e (3 GeV) + {$e^+\pi^0$}(5.5 GeV)]

$$\frac{\sigma_E}{E} = \frac{13\%}{\sqrt{E(\mathrm{GeV})}} \oplus 3\% \quad \text{for } e^-, e^+, \gamma$$

$\sigma_{E\nu} = \sigma_{em} \oplus (\Delta_p/\sqrt{12}) = 0.35 \oplus 0.49 = 0.6$ GeV (i.e. ~20 %)

This could of course be combined with direct measurement at the far detector.

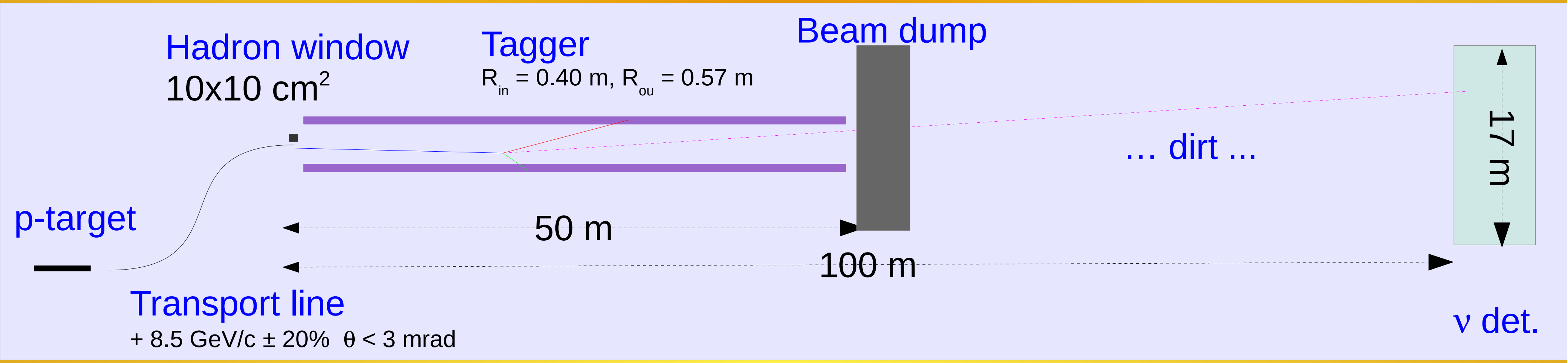
Present "double tag" mode challenges

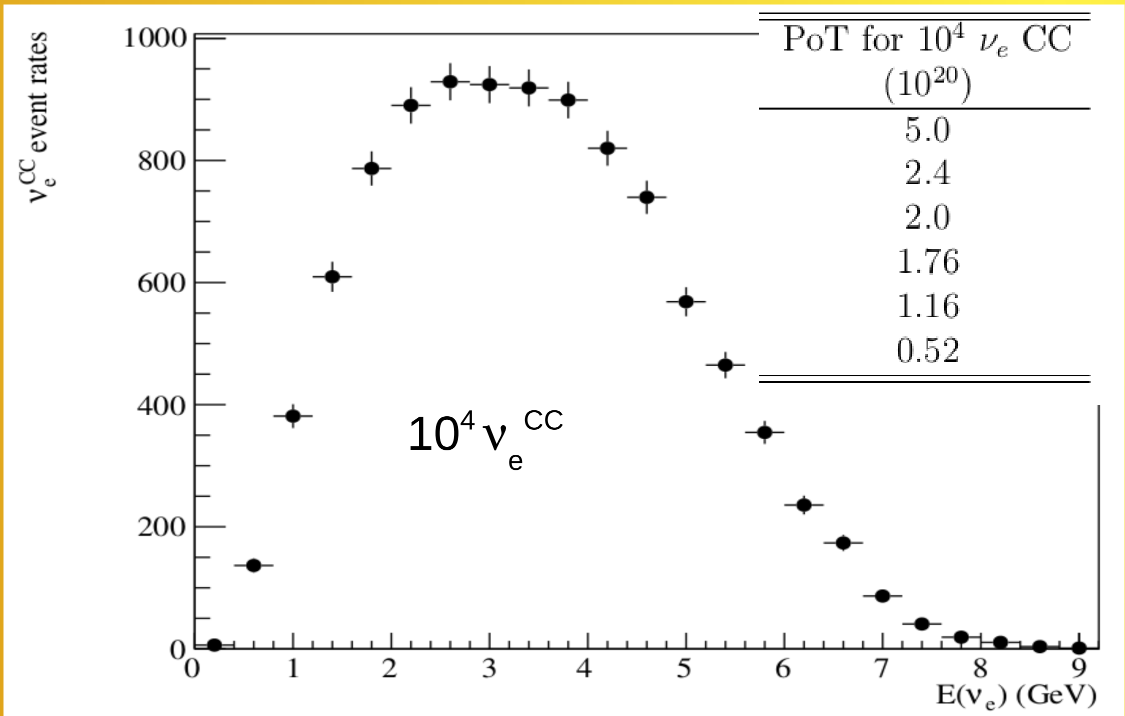
- 1 s beam extraction is needed to cope with accidental coincidences and reasonably standard time resolutions
  - BUT magnetic horns cannot be pulsed at ~100 kA for so long (Joule heating) → should rely on static focusing components (or high-duty cycle Lithium lenses) at the expense of a lower collection efficiency
  - Cosmic ray background increase
    - O(10x) larger than in single tag mode
- Momentum bite → reflects directly on the achievable neutrino energy resolution. Being more selective → drop in statistics, PoT cost.

Conclusions

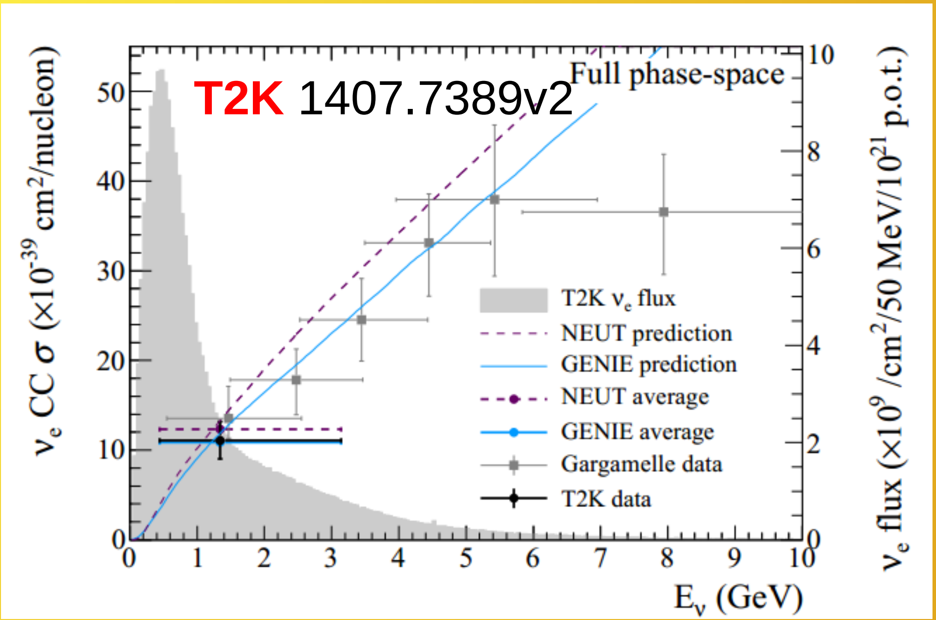
- The development of fast, radiation hard detectors allows for a reconsideration of the old idea of tagged neutrino beams.
- Tagging efficiencies: 59%. Background contamination ~ 18%. 85% of e^+ with a ν_e crossing the far detector.
- Single tag mode:
  - can be employed to reduce systematics in the determination of the initial flux (flux depends on kinematic corrections) and measure the ν_e cross-section
  - 1 % precision (10^4 ν_e^{CC}) achievable with a 0.5 kt detector and a reasonable amount of PoT ($0.5\text{-}5 \times 10^{20}$ PoT depending on the proton energy). Large number of spills (~2×10^8) might pose restrictions (to be better investigated).
- Double tag mode can be implemented to veto ν_e intrinsic component of the beam and reconstruct the ν energy at source.
- Challenged by high accidental rates requiring long proton extractions (1 s)

Thank you !



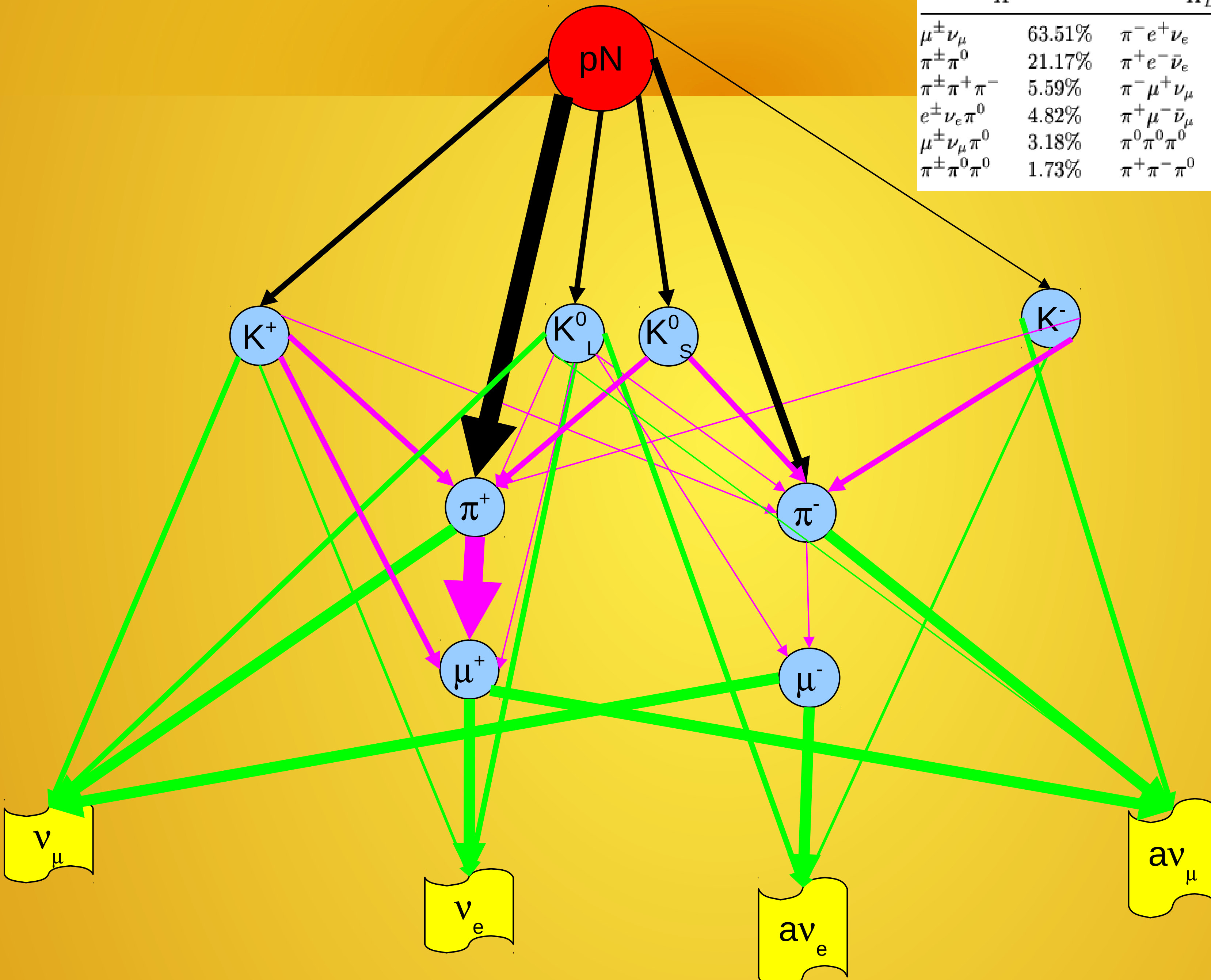


PoT for 10^4 ν_e CC (10^{20})
5.0
2.4
2.0
1.76
1.16
0.52



Neutrinos from protons

$K^{\pm}$		K^0_L		K^0_S	
$\mu^{\pm}\nu_\mu$	63.51%	$\pi^- e^+ \nu_e$	19.35%	$\pi^+\pi^-$	68.61%
$\pi^{\pm}\pi^0$	21.17%	$\pi^+ e^- \bar{\nu}_e$	19.35%	$\pi^0\pi^0$	31.39%
$\pi^{\pm}\pi^+\pi^-$	5.59%	$\pi^- \mu^+ \nu_\mu$	13.5%		
$e^{\pm}\nu_e\pi^0$	4.82%	$\pi^+ \mu^- \bar{\nu}_\mu$	13.5%		
$\mu^{\pm}\nu_\mu\pi^0$	3.18%	$\pi^0\pi^0\pi^0$	21.5%		
$\pi^{\pm}\pi^0\pi^0$	1.73%	$\pi^+\pi^-\pi^0$	12.38%		



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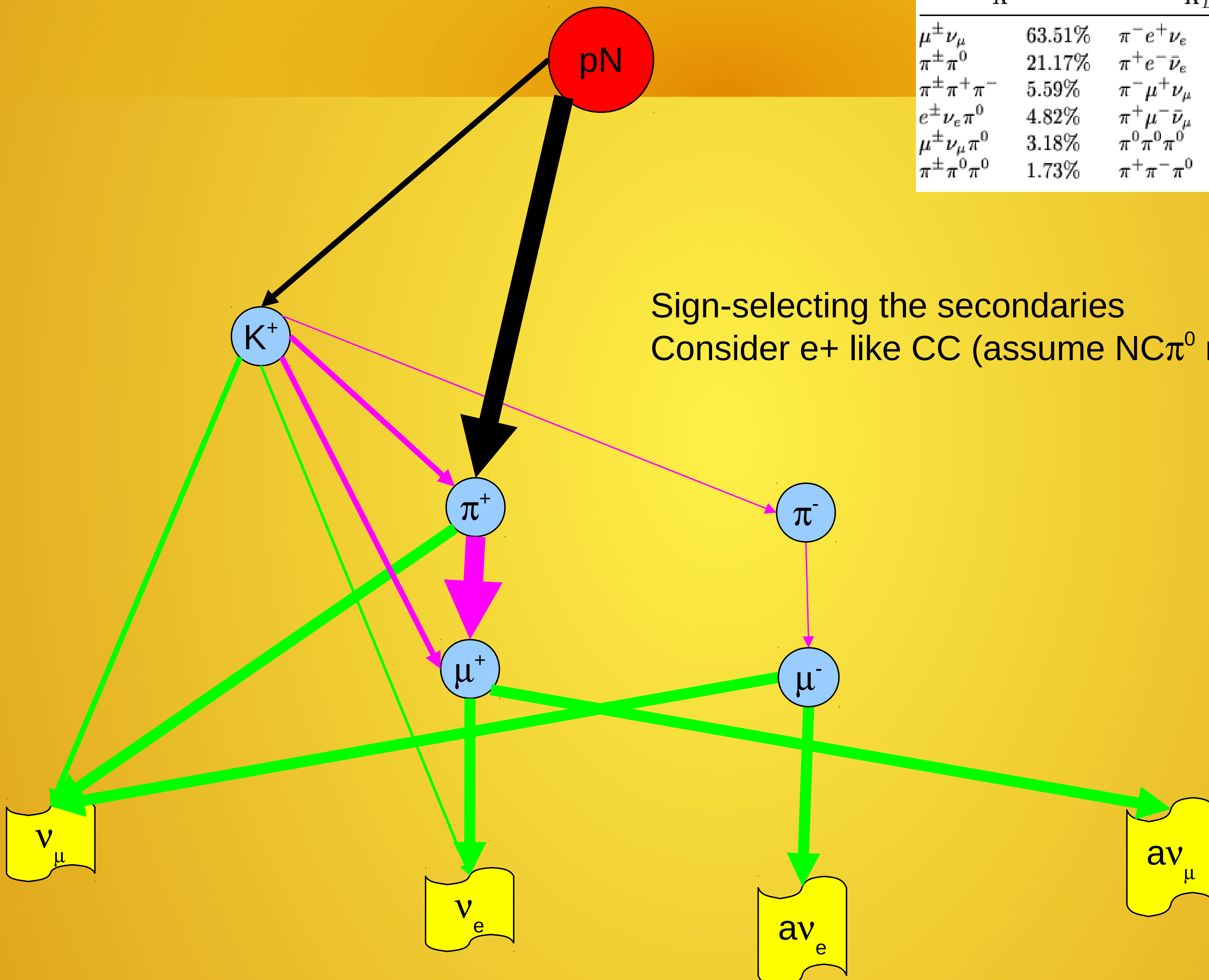

Sign-selecting the secondaries
Consider e+ like CC (assume NCπ^0 rejection)

Neutrinos from protons

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$\mu^{\pm}\nu_{\mu}$	63.51%	$\pi^{-}e^{+}\nu_{e}$	19.35%	$\pi^{+}\pi^{-}$	68.61%
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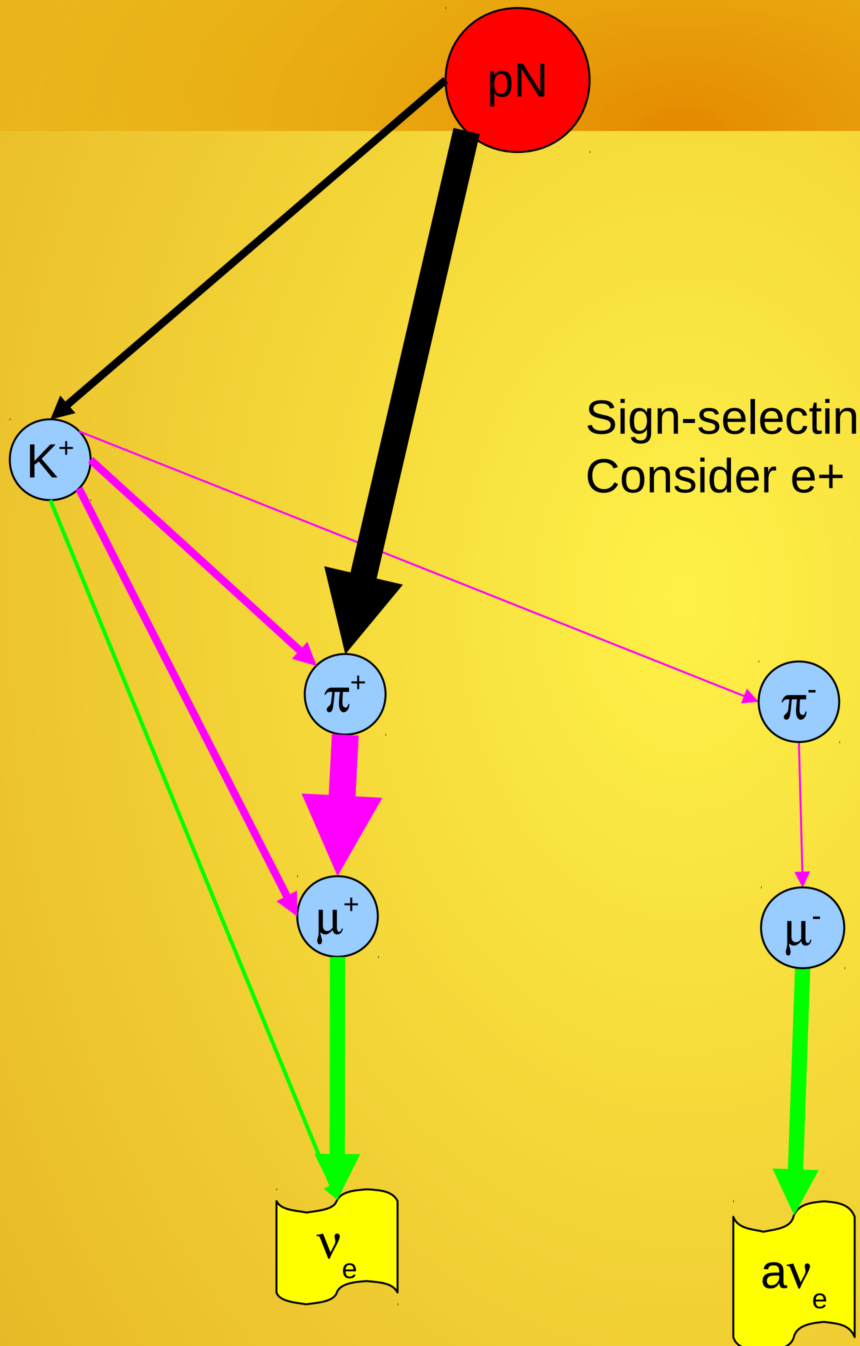

Sign-selecting the secondaries
Consider e+ like CC (assume NCπ^0 rejection)

Neutrinos from protons

$K^{\pm}$		K_L^0		K_S^0	
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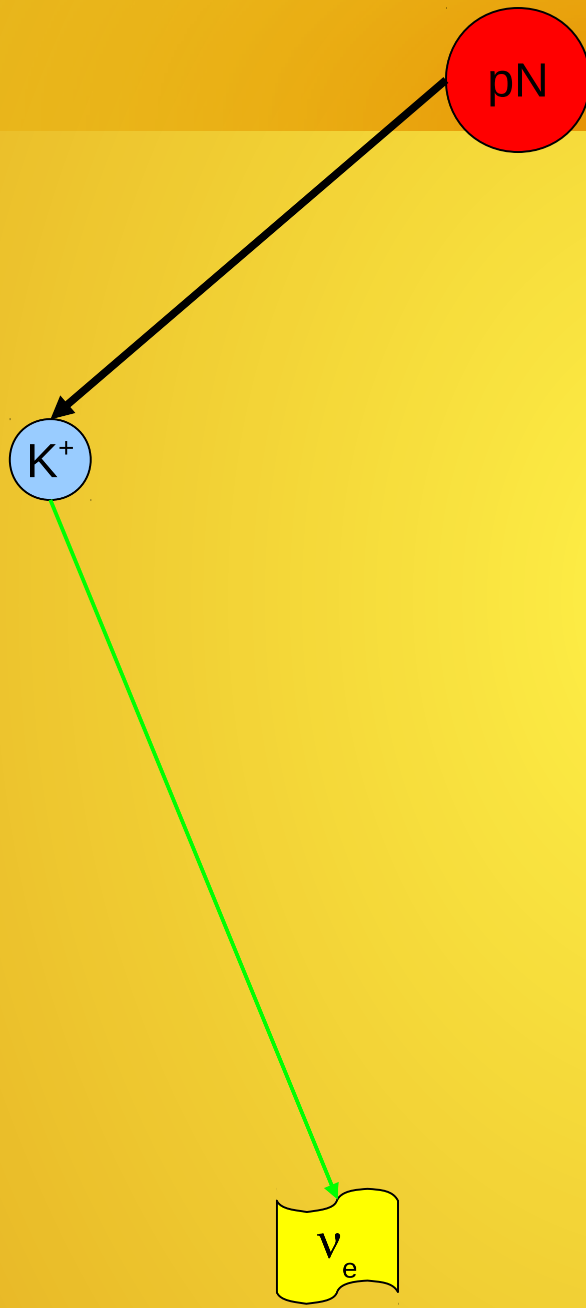
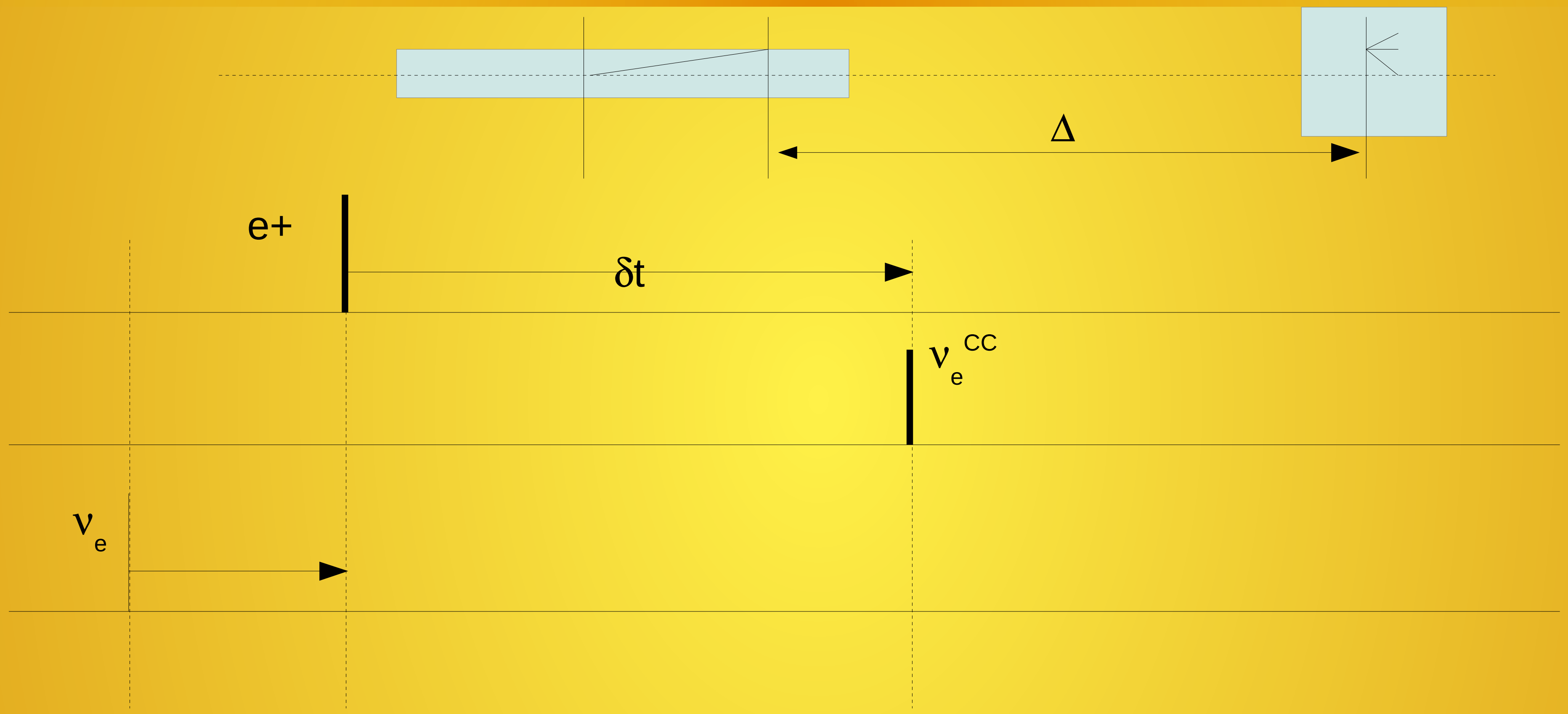


Sign-selecting the secondaries
Consider e+ like CC (assume NCπ^0 rejection)
Consider large angle e+ only and shorten tunnel

Intrinsic uncertainty



$\delta t \sim 50\text{-}100$ m/c = 170-330 ns. The difference between the e+ and the ν_e CC time.

Realistic σ_t of 50 ps (contribution from tagger and neutrino detector timing resolution)

Coincidence $|\delta t - \Delta/c| < \sigma_t$

This assumes that the e+ and the neutrino are isocronous which is not perfectly true due to the e+ emission angle. The correction is of $O(R_{in}\theta/2c) \sim 80$ ps