Physics Beyond Colliders
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NuTAG

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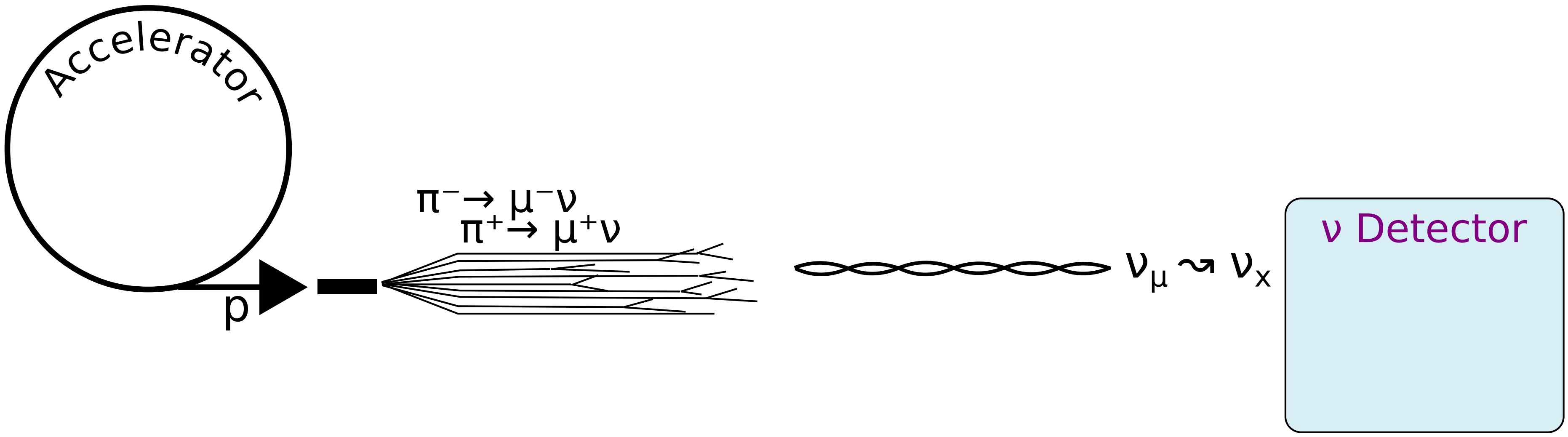
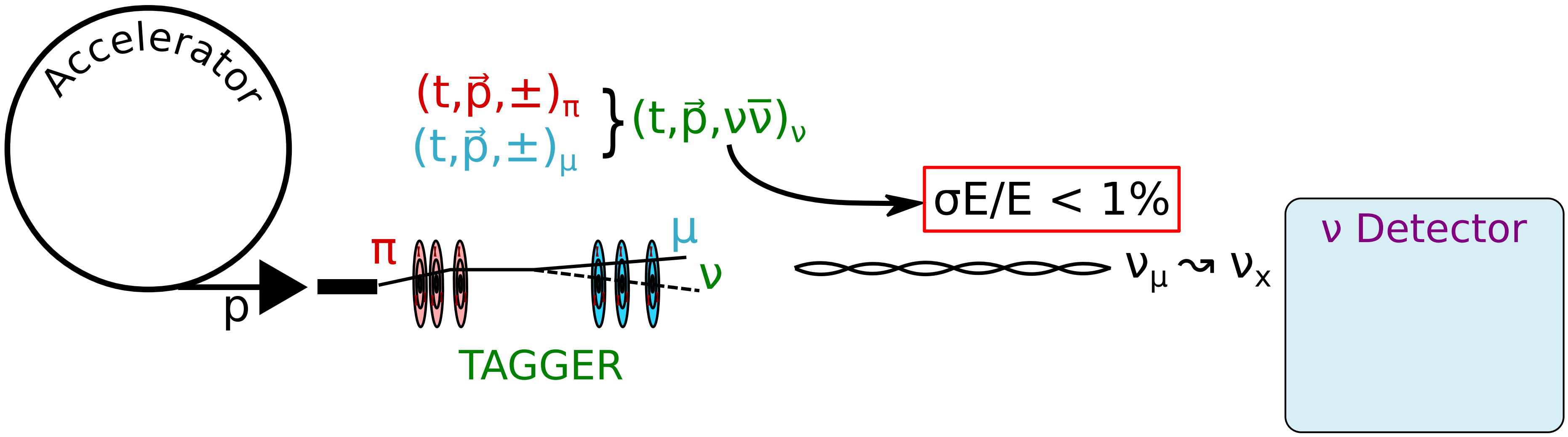
Outline

- Concept Description
- Feasibility
- Physics Potential
  - Case study: CP violation in ν

Conventional Neutrino Experiments



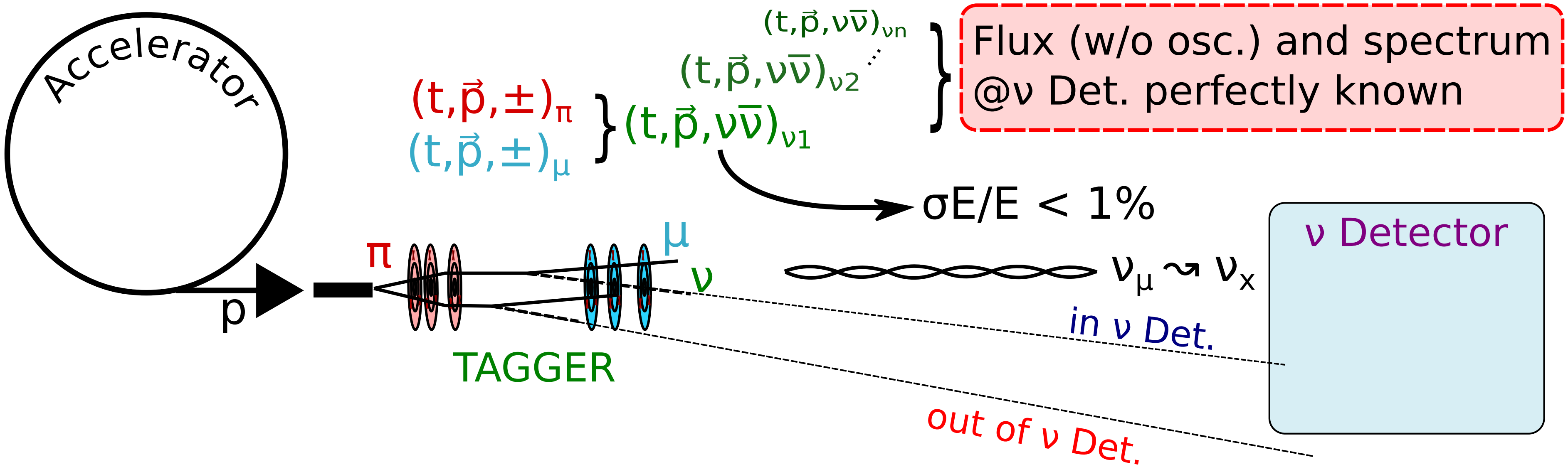
ν tagging – Beam Instrumentation



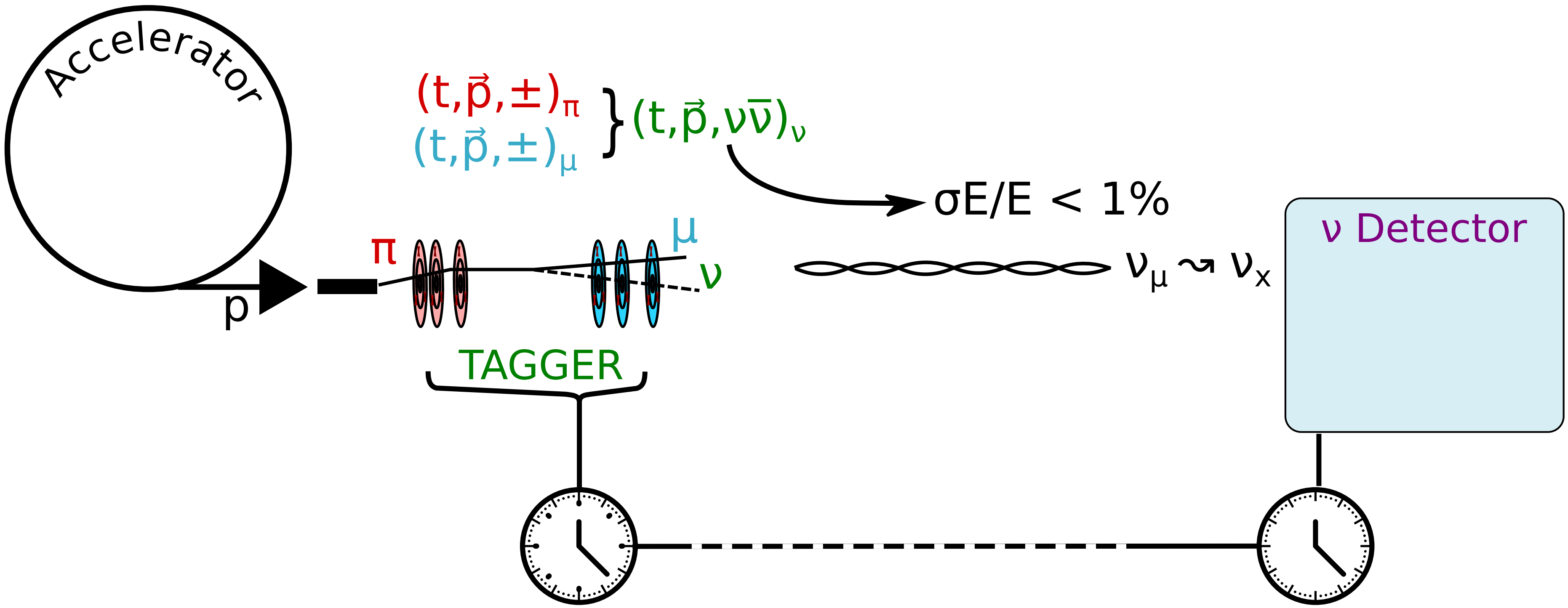
- Each neutrino is fully & precisely **characterised from its decay partners**
- Similar to old ideas [1,2,3] that the **progress on Silicon Trackers** (see next) makes now feasible

[1] B. Pontecorvo, Lett. Nuovo Cim.25(1979) 257
[2] S. P. Denisov et al., preprint IHEP 80-158, Serpukhov, 1980 Tagged Neutrino Facility at Protvino
[3] R.H. Bernstein et al., FERMILAB-Proposal-0788, 1989.

ν tagging – 1. Flux Determination



ν tagging – 2. Reco. Improvement



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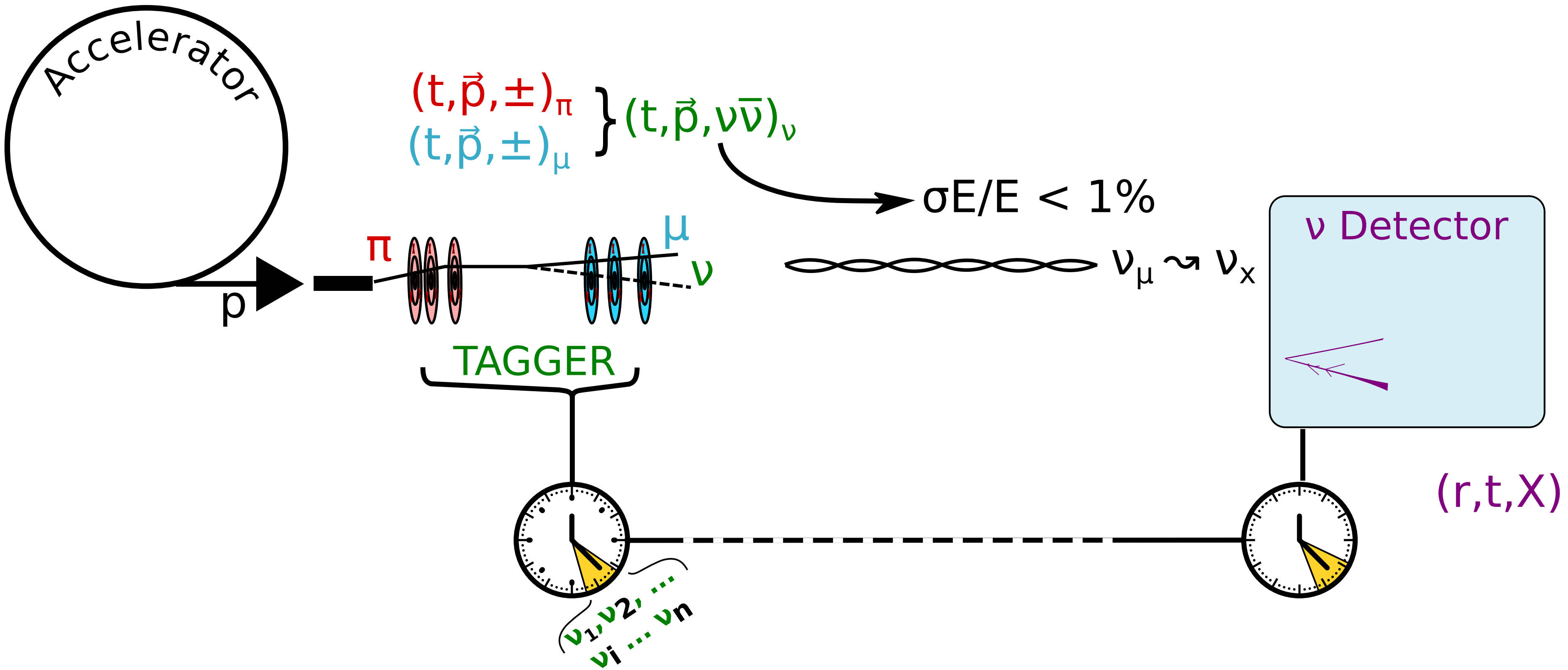

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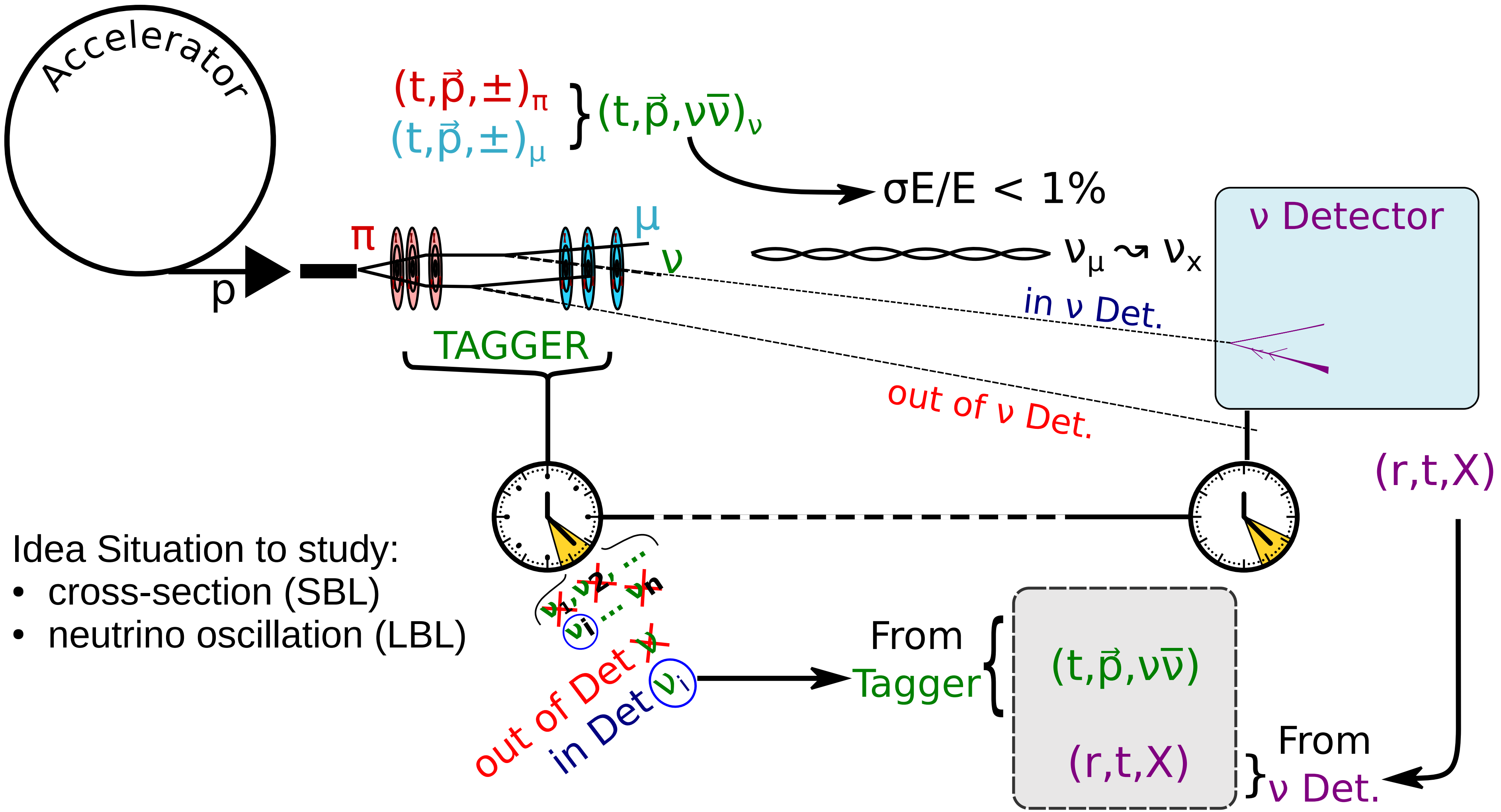

Idea Situation to study:

- cross-section (SBL)
- neutrino oscillation (LBL)

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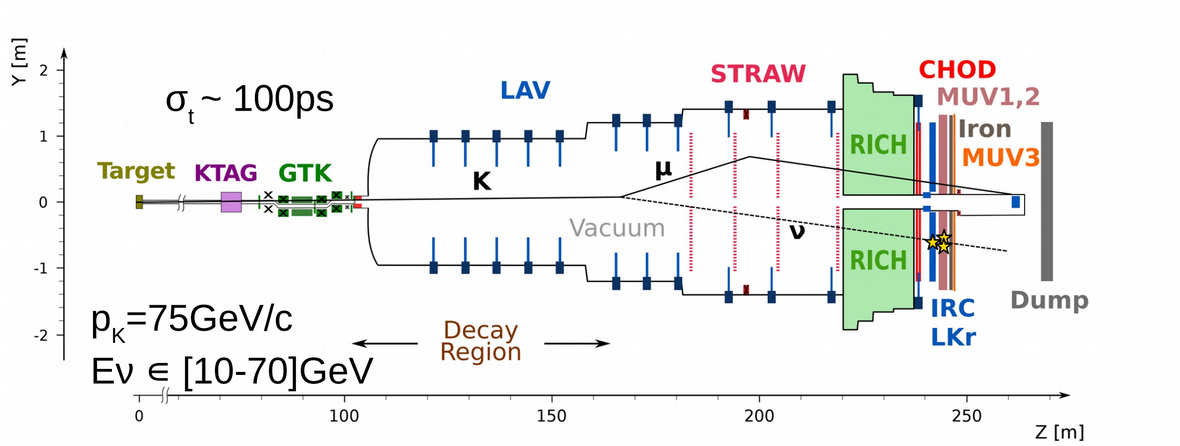
Feasibility: NA62 as demonstrator

- **ν tagging implemented at NA62 (rare K decays)** as a by-product
- **Calorimeters act also as ν detectors** and with O(10^{13}) K decays:

  ~1700ν from K→μν + Kμ3 interact in Lkr+MUV (20 + 66 ton)

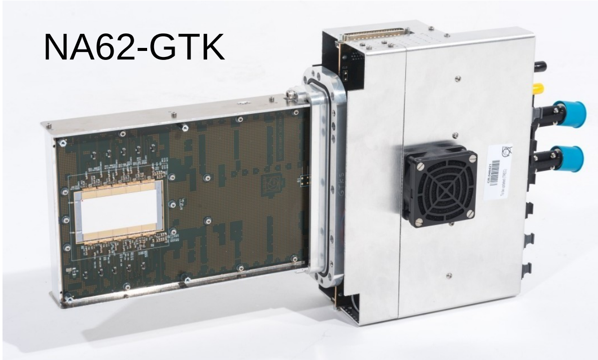
- K and μ properties (p,θ) precisely measured thanks to GTK (Si-Pixel) and STRAW trackers
- Dedicated **trigger line** collecting these data…



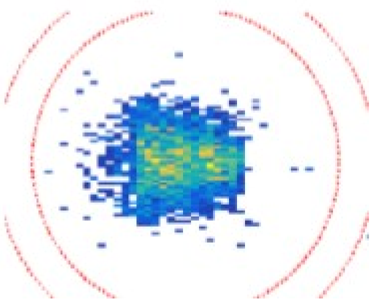
Toward a Dedicated Tagged Neutrino Beam

- Difference between NA62 and a ν-beam: **beam particle rate**
- Rate is limited by **trackers irradiation and occupancy**

	Available	Max. Radiation	Max. Flux
NA62-GTK	since 2015	$10^{14\text{-}15}$ n_{eq}/cm^2	200 MHz/cm²
HL-LHC	before 2028	$10^{16\text{-}17}$ n_{eq}/cm^2	2000 MHz/cm²



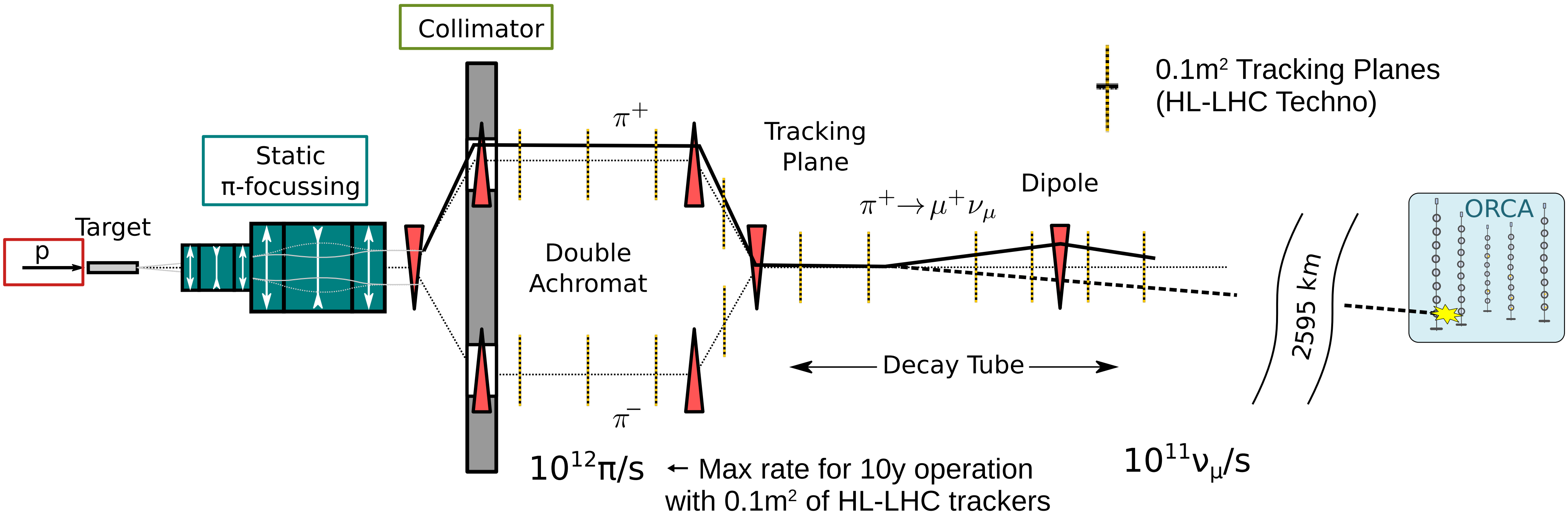
- Handles to **limit particle flux**:
  - spread particles in **time** (slow extraction) and **space** (beam size)
  - select only relevant π **momentum range**
- **ENUBET** beam line was optimized with **~similar concerns**
  - expected rate [1] is ~10^{12} part/s on ~1m radius surf. at pipe end:
    ➔ already matches the capabilities of the GTK technology!



[1] Pupilli, NeuTel 2019

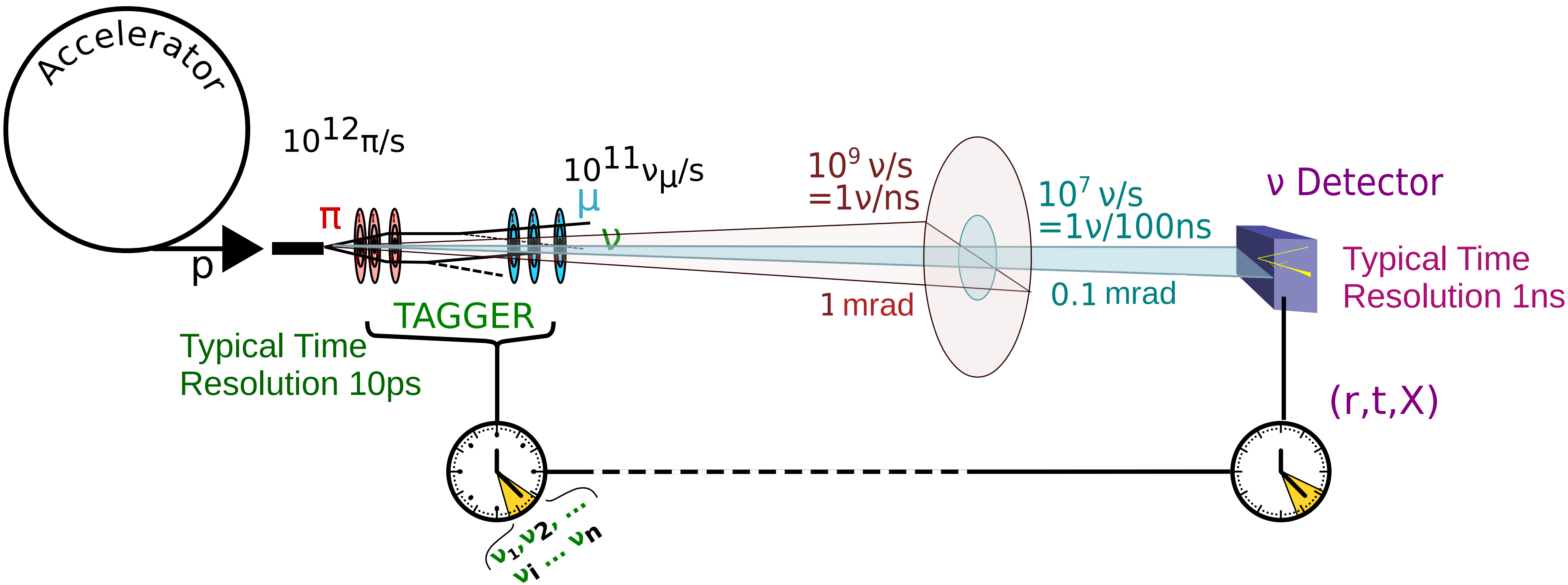
NuTAG Beam Line Sketch

- **Slow extraction (few sec.)** & **beam cleaning** to reduce π rate
- **Static π+ <u>and π-</u> Focussing Devices** replace conventional horns
- **Beam size** around **0.1 m²** to match HL-LHC trackers specs.
- Challenging beam line design: **CERN expertise** would be more than welcomed!



How to match $\pi \rightarrow \mu\nu$ to ν-interaction?

- **Rates** matching specs for HL-LHC type trackers of about $0.1 m^2$
- **Association $\nu_\mu \leftrightarrow \nu_X$** relies on **time** and **direction** matching
  - with **1ns & 1mrad** ν_μ ang. reso (10x det. accep): $\nu_\mu \leftrightarrow \nu_X$ is done w/o ambiguity



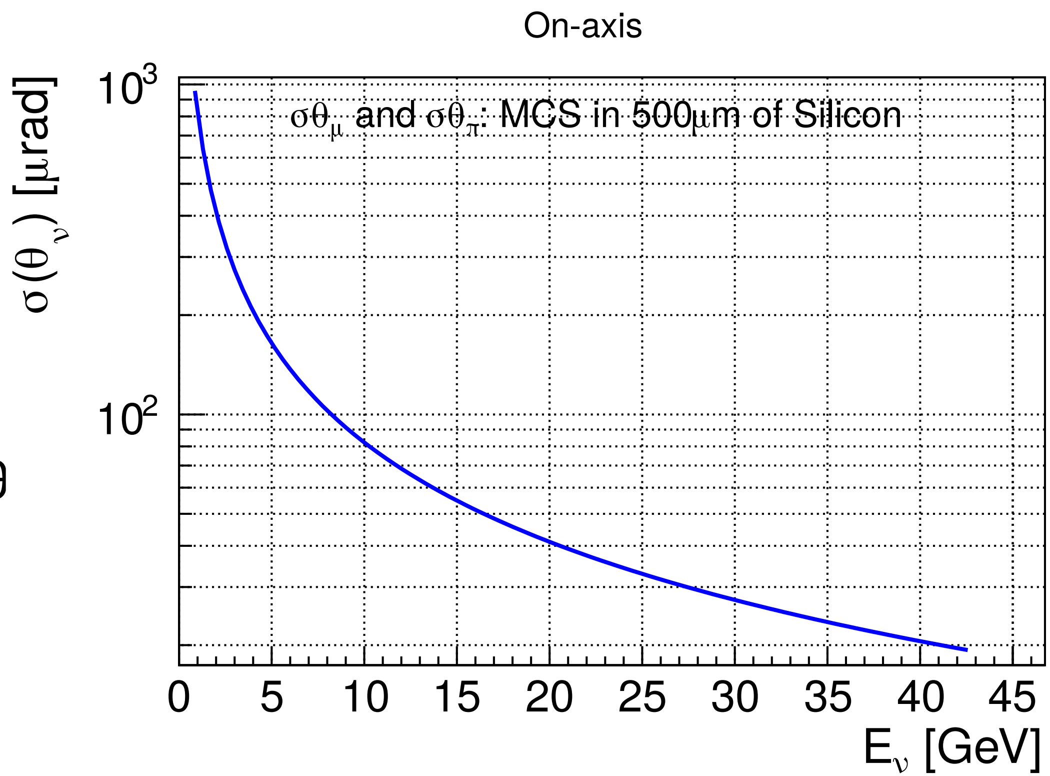
Is 1mard ν ang. resolution achievable? YES

- When $\theta\nu\pi \rightarrow 0$ (i.e **on axis**):

  $\theta\nu\pi \rightarrow 1.3 \cdot \theta\mu\pi$

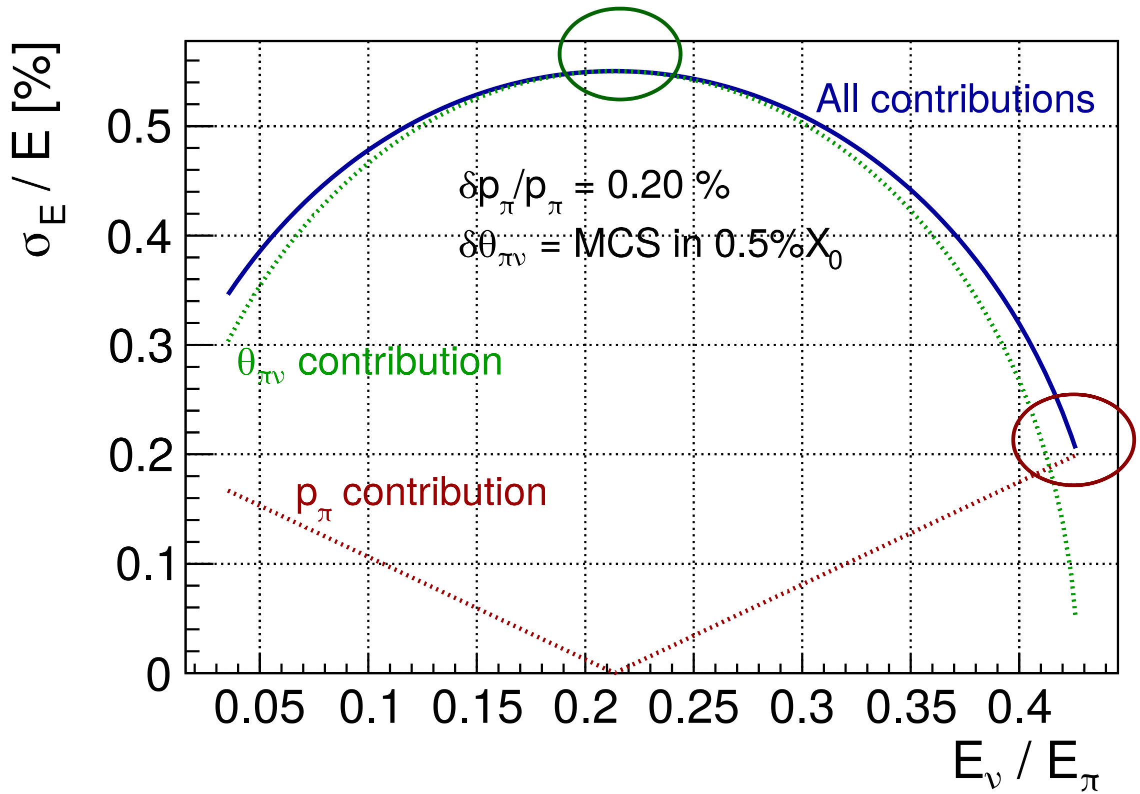
- Assume that **multiple coulomb scattering** (in 0.5% X_0 like at NA62) dominates the resolutions on $\theta\mu\pi$ & θ

- **Sub-mrad prec. on θ_ν can be achieved**



What about Energy Resolution ? 0.2% !

- ν energy obtained from p_π and θ_ν as $E_\nu = \frac{(1 - m_\mu^2/m_\pi^2)\, p_\pi}{1 + \gamma^2 \theta_\nu^2}$
- Energy resolution **between 0.2% (on axis) and 0.6 %** (independent of p_π)!



Relevant Region for LBLNE
(Emax = on axis)

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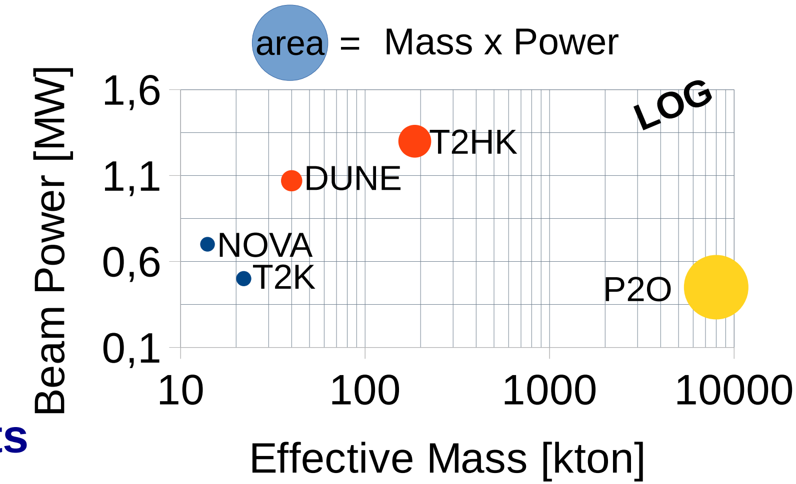
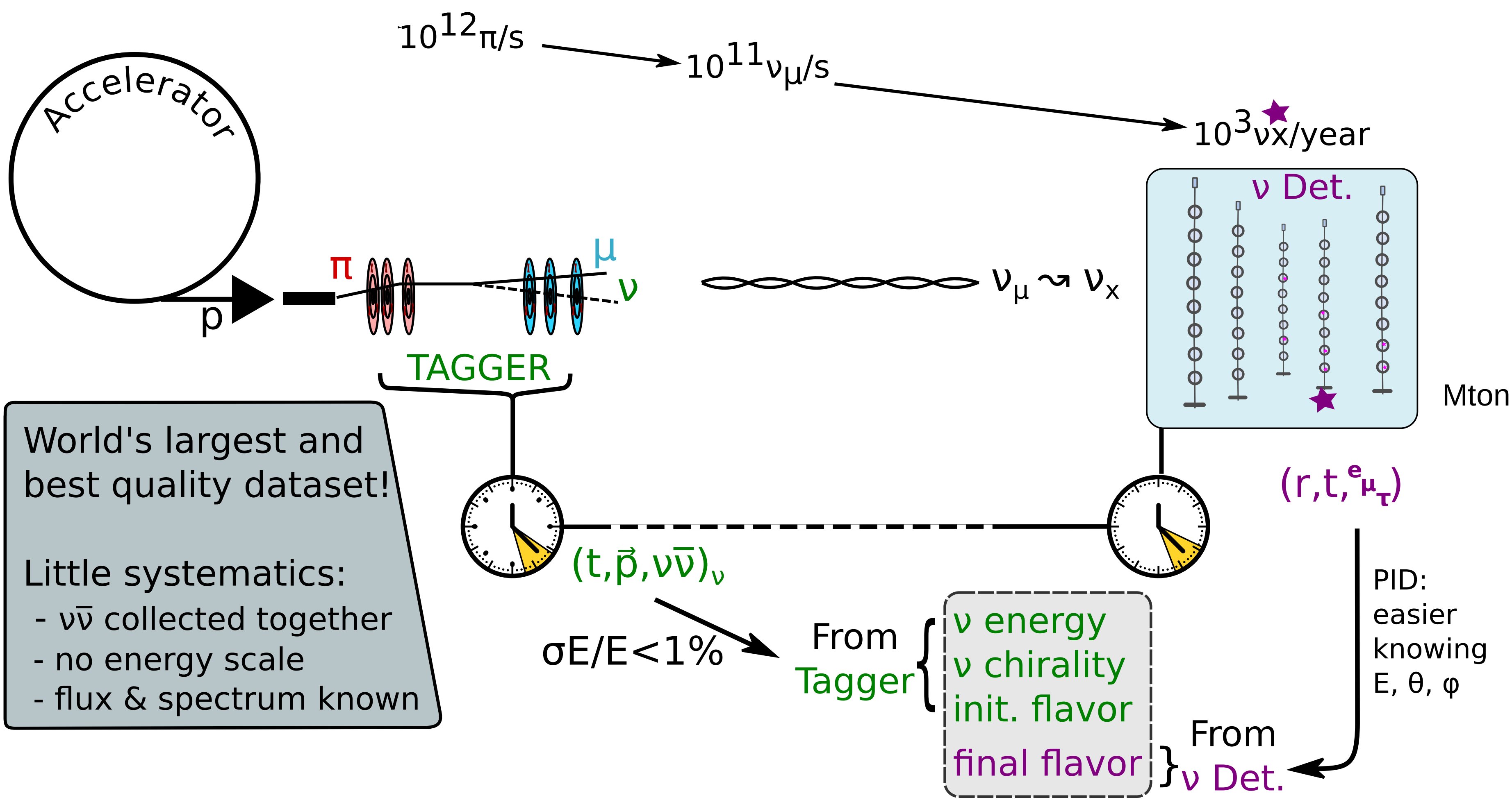
NuTag for δ_{CP} Precison Measurement

- **Future** measurements require **high statistics** and **low systematics**
- Very challenging for **conventional LBLNE**:
  - higher **power** beam
  - **larger** underground high granularity **far detector**
  - more **precise near det. + dedicated experiments**

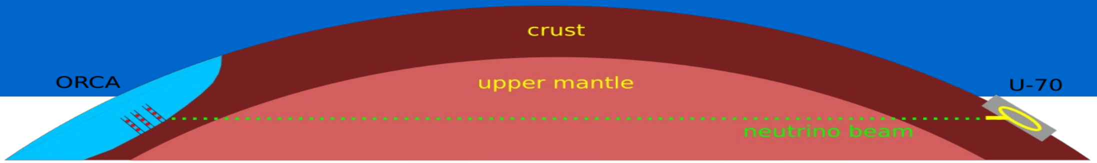


- **Alternative**:
  « ***low*** **» power tagged-beams + huge (>Mton) natural water Cerenkov detectors**
  - natural water detectors **size has virtually no limits**
  - detectors **poor granularity** (more than) **compensated by tagging**, ($\delta E/E<1\%$)
  - little or **no systematics** thanks to the tagging

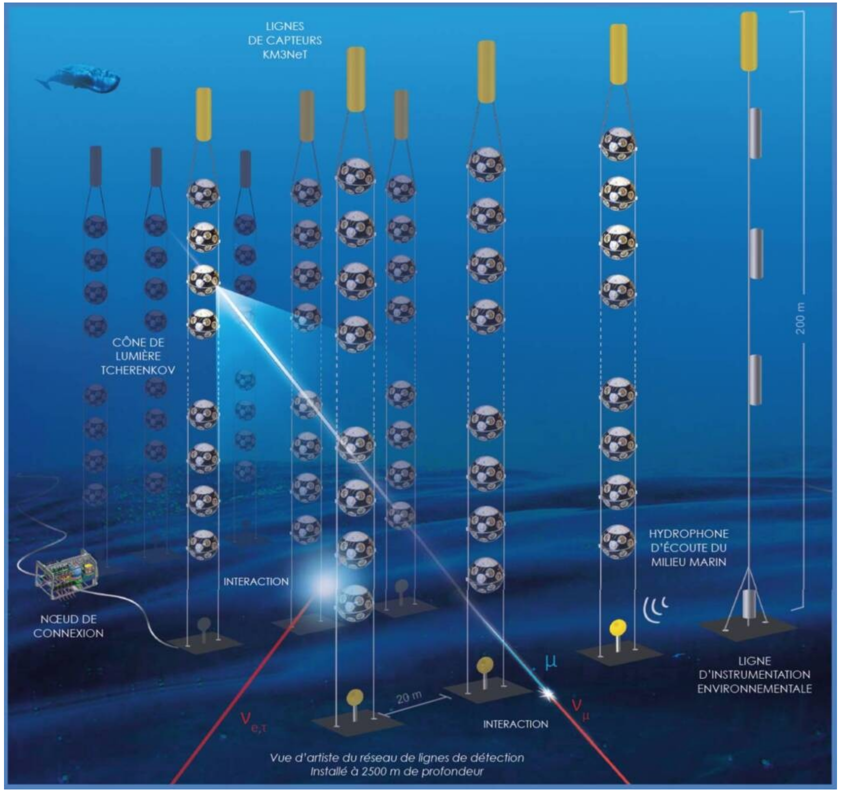
NuTAG for LBLNE

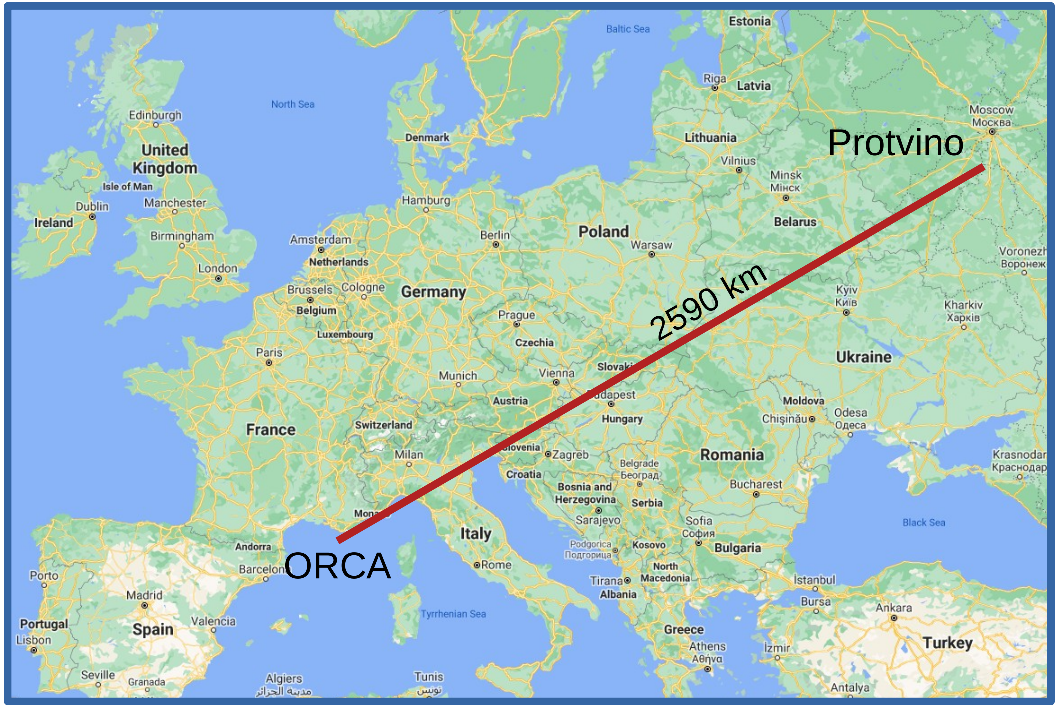


A case study P2O



- LBLNE from **U70-Protvino** (Russia) **to KM3NeT-ORCA [1]**





- U70 could provide 450kW beam
- ORCA will instrument 5Mton of sea water

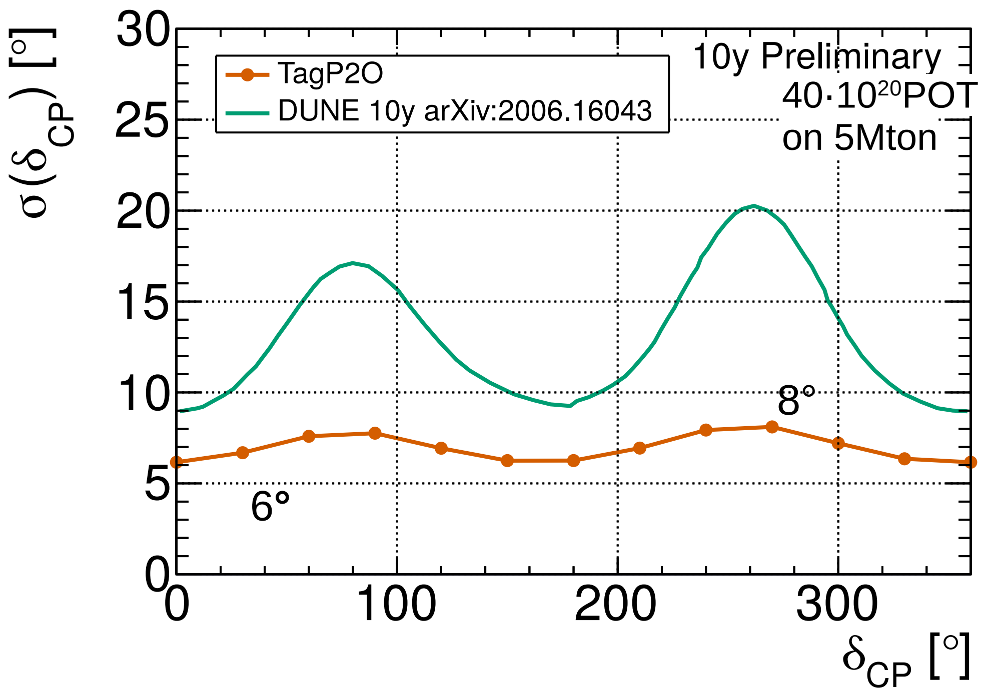
[1] Letter of Interest (EPJ-C)

Precision to δ_{CP} at P2O

- **Systematics** on oscillation parameters, cross section & normalisation (free)

θ13 ± 0.15°	ντ ± 10%
θ23 ± 2°	NC ± 5%
Δm^2_{31} ± 5e-3eV²	νe=νμ ± 5%

- **Conservative** estimates:
  no PID improvement with respect to atmospheric ν was considered
- δ_{CP} precision **stable** over all values
- **<8° precision** can be achieved!



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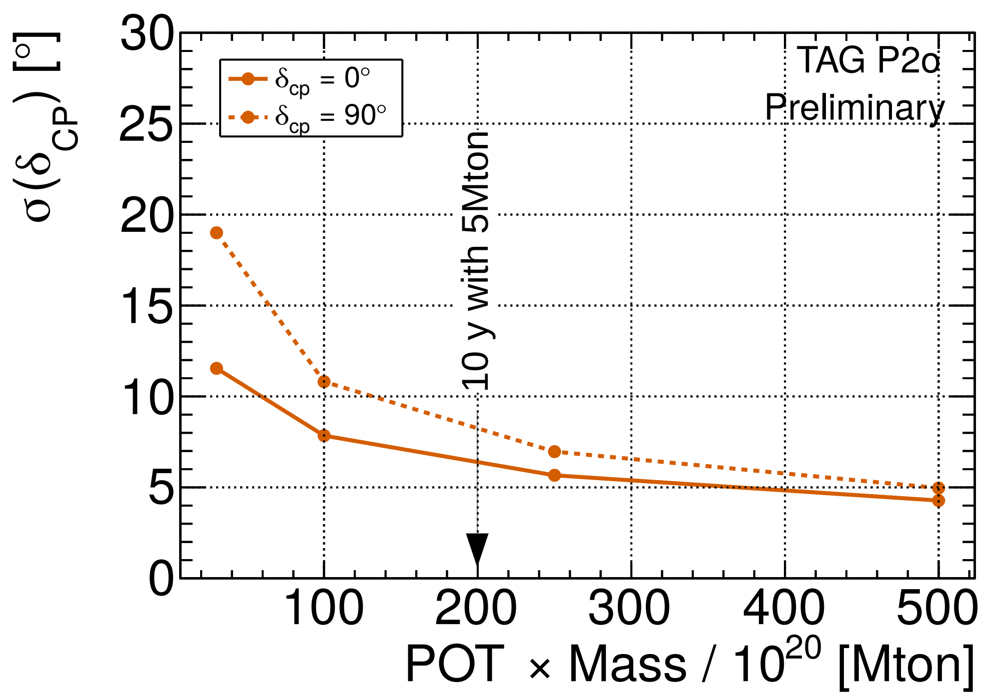
- **<5°** achievable with larger detectors



Summary and Conclusions

- **Neutrino tagging**: follow ν from creation to detection
  - reconstruct each and **every π➔μν decay** to precisely characterize ν
  - **associate** ν seen in ν-detector to its π➔μν genitor

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- **Technological** challenge is the beam particle rate and addressed by
  - dedicated **beam line studies** (efficient static focusing, large beam)
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  - dedicated **beam line studies** (efficient static focusing, large beam)
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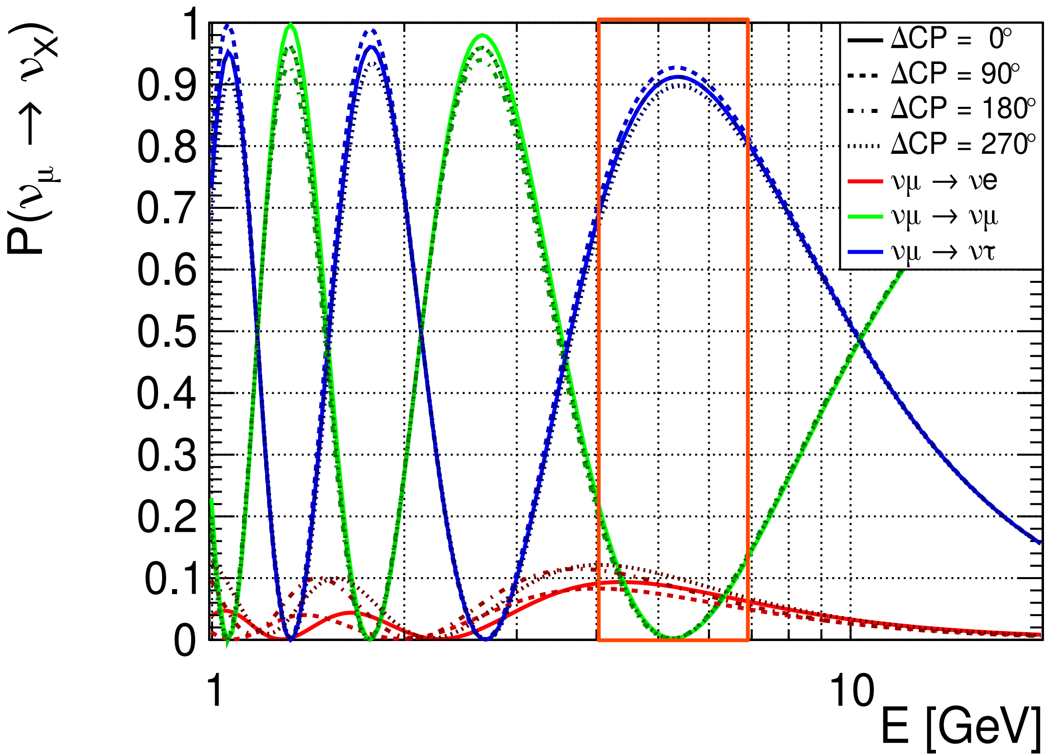
- **Applications:** x-section (synergy with ENUBET), ν-oscillation

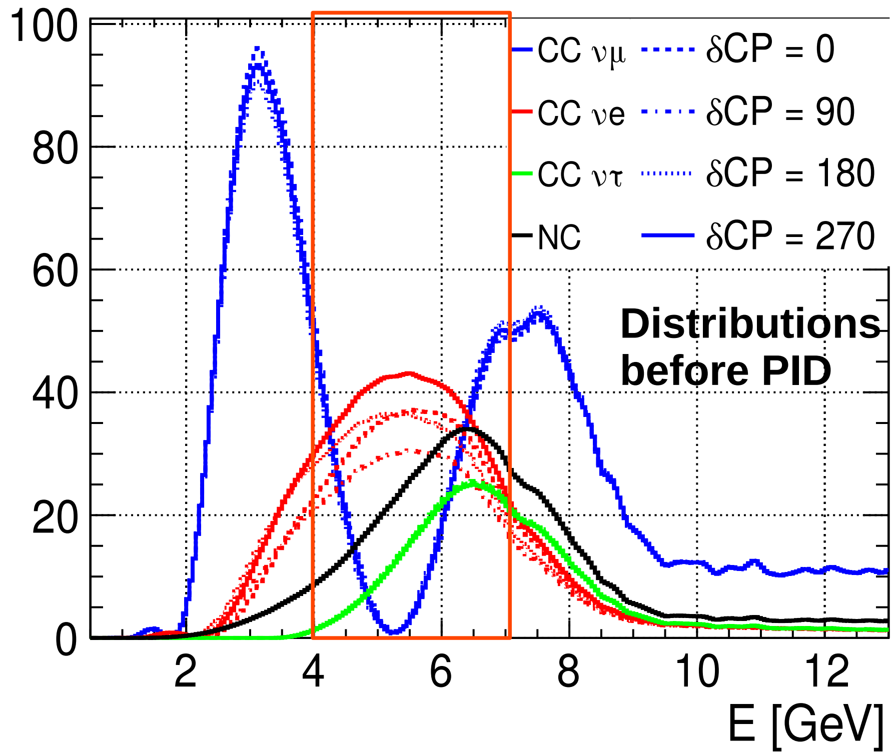
  LBLNE with **NuTAG** and mega-ton **natural water Cerenkov** ν detector
  - large **statistic** obtain from detector mass
  - **lower beam intensity** allows ν tagging
  - tagging brings **unprecedented energy resolution** and remove **systematics**

Thank you for your attention

How to measure δ_{CP} with P2O

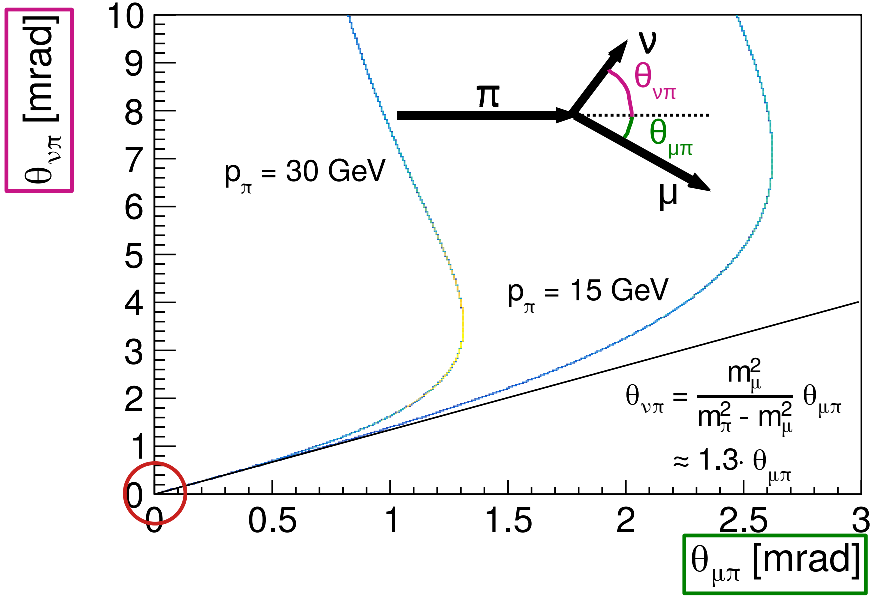
- δ_{CP} measured using νe-CC energy distribution around 5GeV (1rst osc max)
  - **ORCA threshold ~3.5GeV**
  - **NC pollution** in νe-CC reduced comparing **visible energy vs tag-energy**

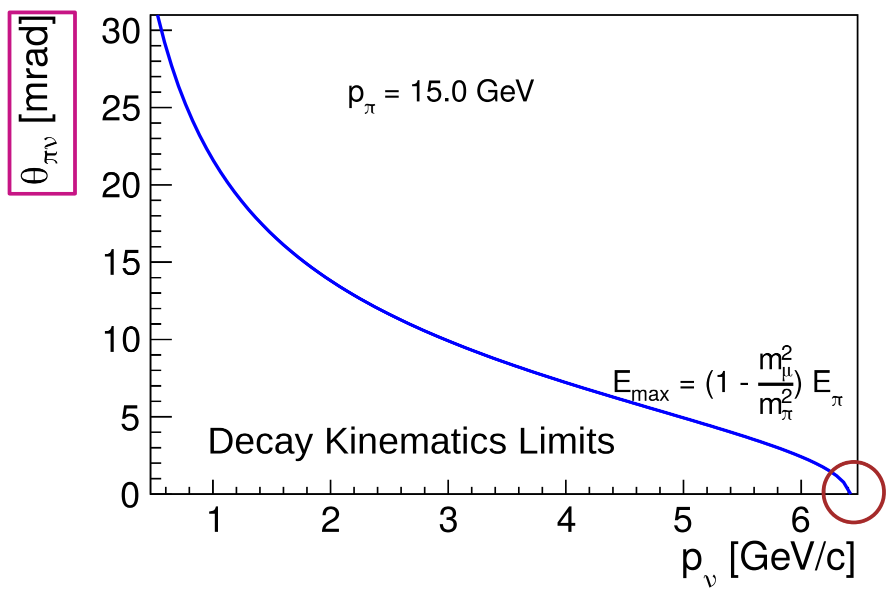




Angular Resolution for on-axis ν

- Assuming $\theta_{\pi,\mu}$ prec. is dominated by MCS (0.5%X_0 as for NA62), **sub-mrad prec. on θ_ν can be achieved**





Asymptotically: $\theta_\nu = 1.3\ \theta_\mu$

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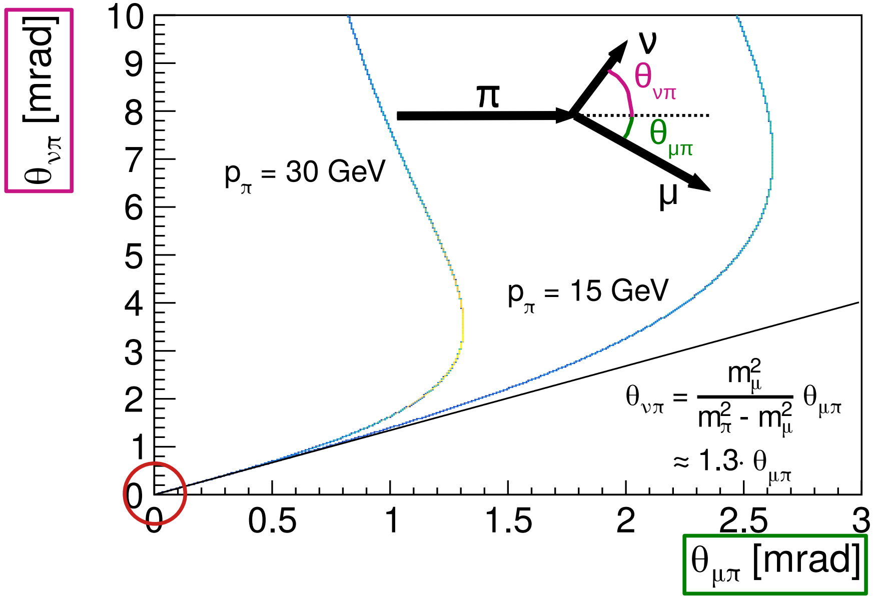

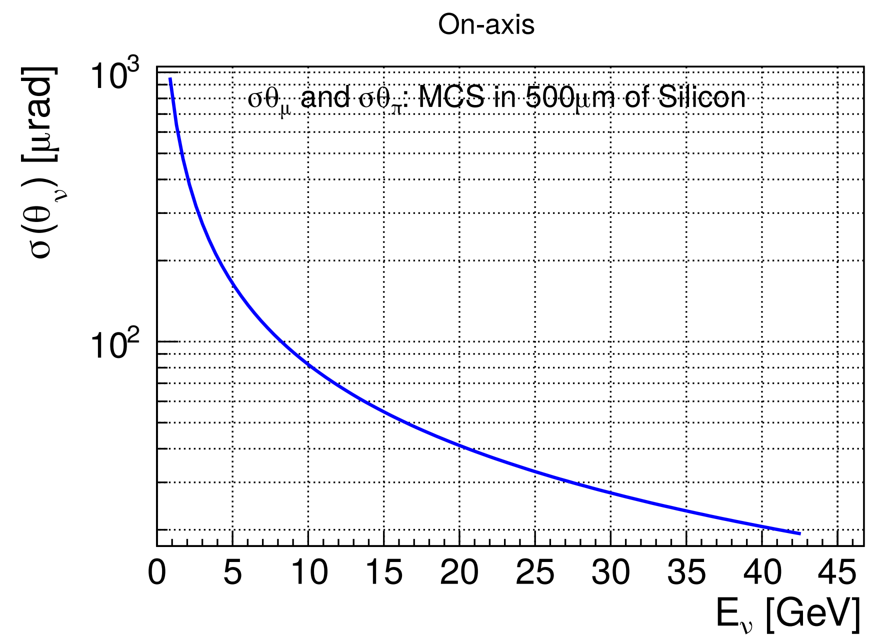

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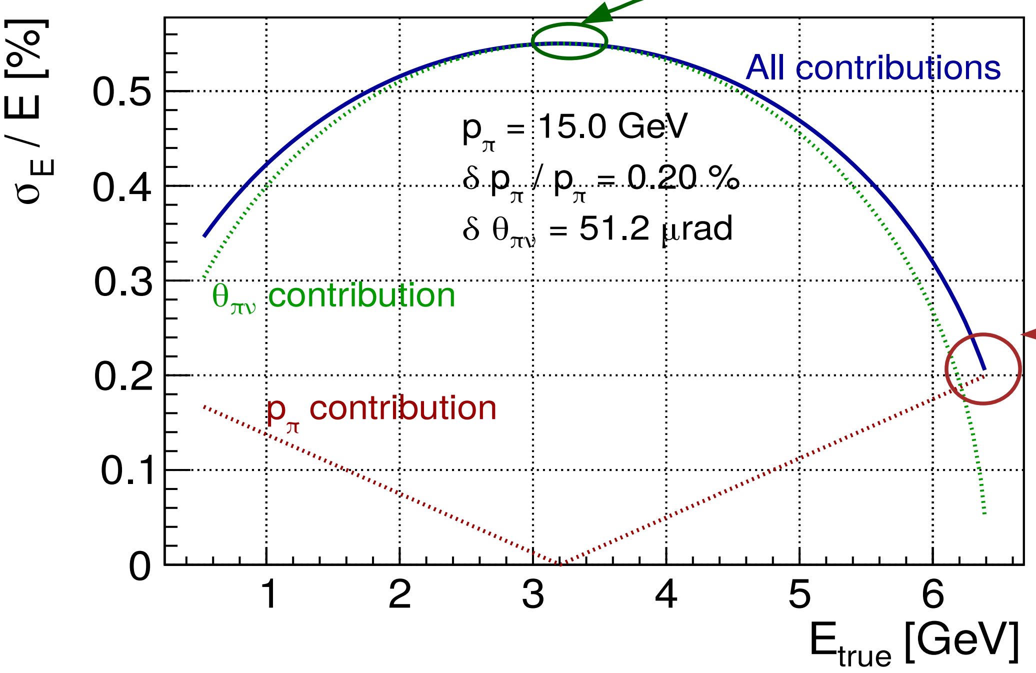
- Energy resolution **between 0.2 and 0.6 %** (independent of p_π)!



Worse reso. is at ~0.22 E_π and determined by π MCS

$$\left.\frac{\sigma_E}{E}\right|_{worse} = \frac{p_\pi}{m_\pi}\sigma\theta_{\pi\nu} = 0.55\,\%$$

Best reso. is **on axis,** and determined by p_π reso., as (E=0.43Eπ):

$$\left.\frac{\sigma_E}{E}\right|_{best} = \frac{\sigma_{p_\pi}}{p_\pi} = 0.2\,\%$$