First thoughts on a high-intensity neutral experiment

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Introduction

- Running experiments in the kaon sector
  - K^+ physics: NA62 ($K^+ \rightarrow \pi^+ \nu\nu$)
  - K_L physics: KOTO ($K_L \rightarrow \pi^0 \nu\nu$)
  - K_S physics: LHCb ($K_S \rightarrow \mu^+\mu^-$)

- Fixed–target experimental program after LS3 described in Snowmass White Paper in preparation
- Medium–term: high–intensity K^+ experiment
- Long–term: neutral beam
- Opportunity for the development of a broad kaon physics program
  - Rare decays, LFV/LNV searches, Feebly interacting particles, QCD

High-intensity K_S/K_L experiment

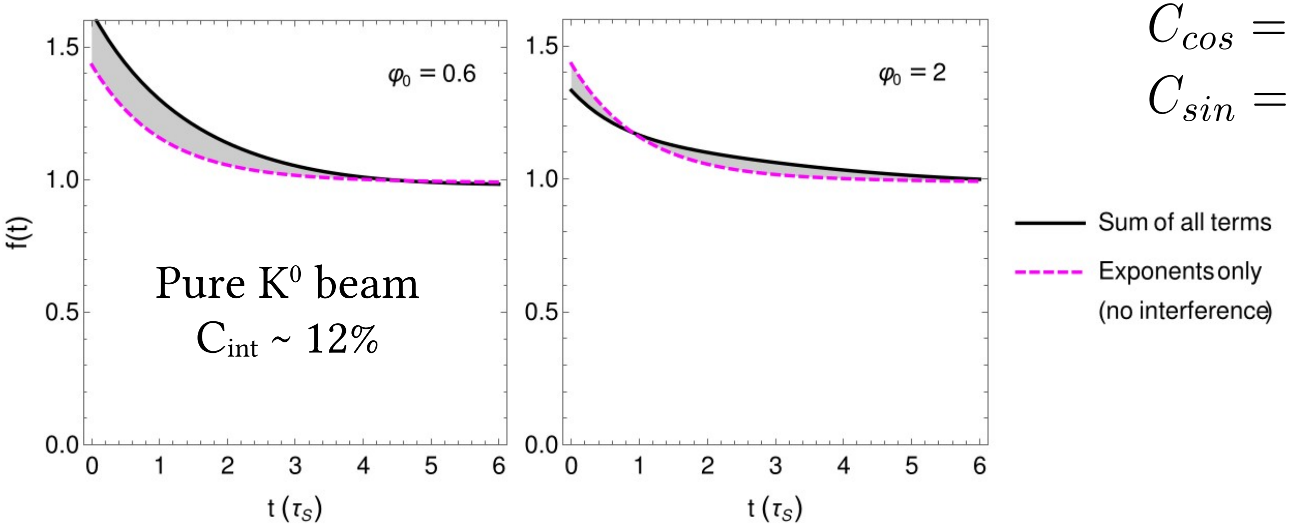
- One of the possibilities in the long term
- $K \rightarrow \mu^+\mu^-$ interference measurement is the main motivation
  - Challenges on intensity, detector performance, background suppression
- A high-intensity kaon factory that could address the interference requires a much more generic machine
- Rewrite the PDG for K_S and K_L decays

Outline

- How to address K_S–$K_L \rightarrow \mu^-\mu^+$ interference experimentally?
- High–intensity K_S/K_L experiment
  - Thoughts on experimental design
  - Toy MC: signal yield and background contamination
  - Detector challenges
- Areas for future studies
- Conclusions

Experimental considerations: K→μ⁺μ⁻ interference

$$\left(\frac{d\Gamma}{dt}\right) \propto f(t) = C_L e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t} + 2\left[C_{sin}\sin(\Delta m t) + C_{cos}\cos(\Delta m t)\right] e^{-\Gamma t}$$



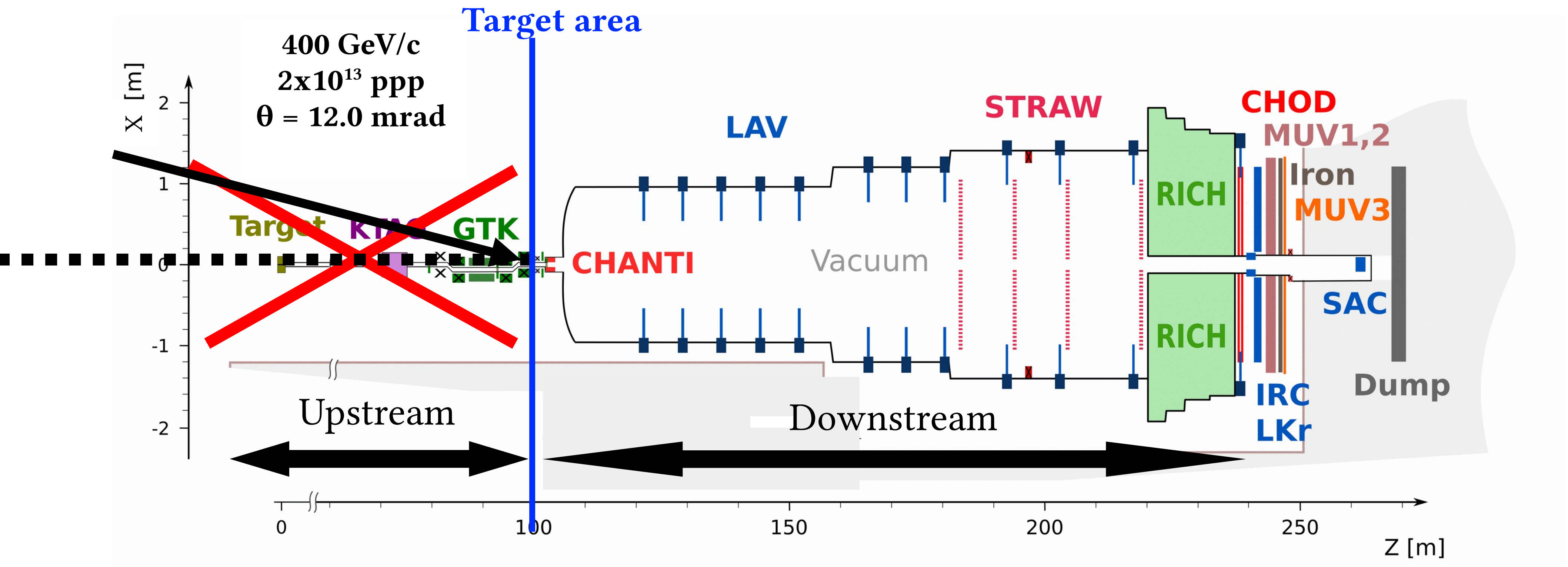
$$C_{cos} = D \cdot \left|A(K_S)_{l=0} \times A^*(K_L)_{l=0}\right| \cdot \cos\varphi_0$$

$$C_{sin} = D \cdot \left|A(K_S)_{l=0} \times A^*(K_L)_{l=0}\right| \cdot \sin\varphi_0$$

$$D = \frac{N_{K^0} - N_{\bar{K}^0}}{N_{K^0} + N_{\bar{K}^0}}$$

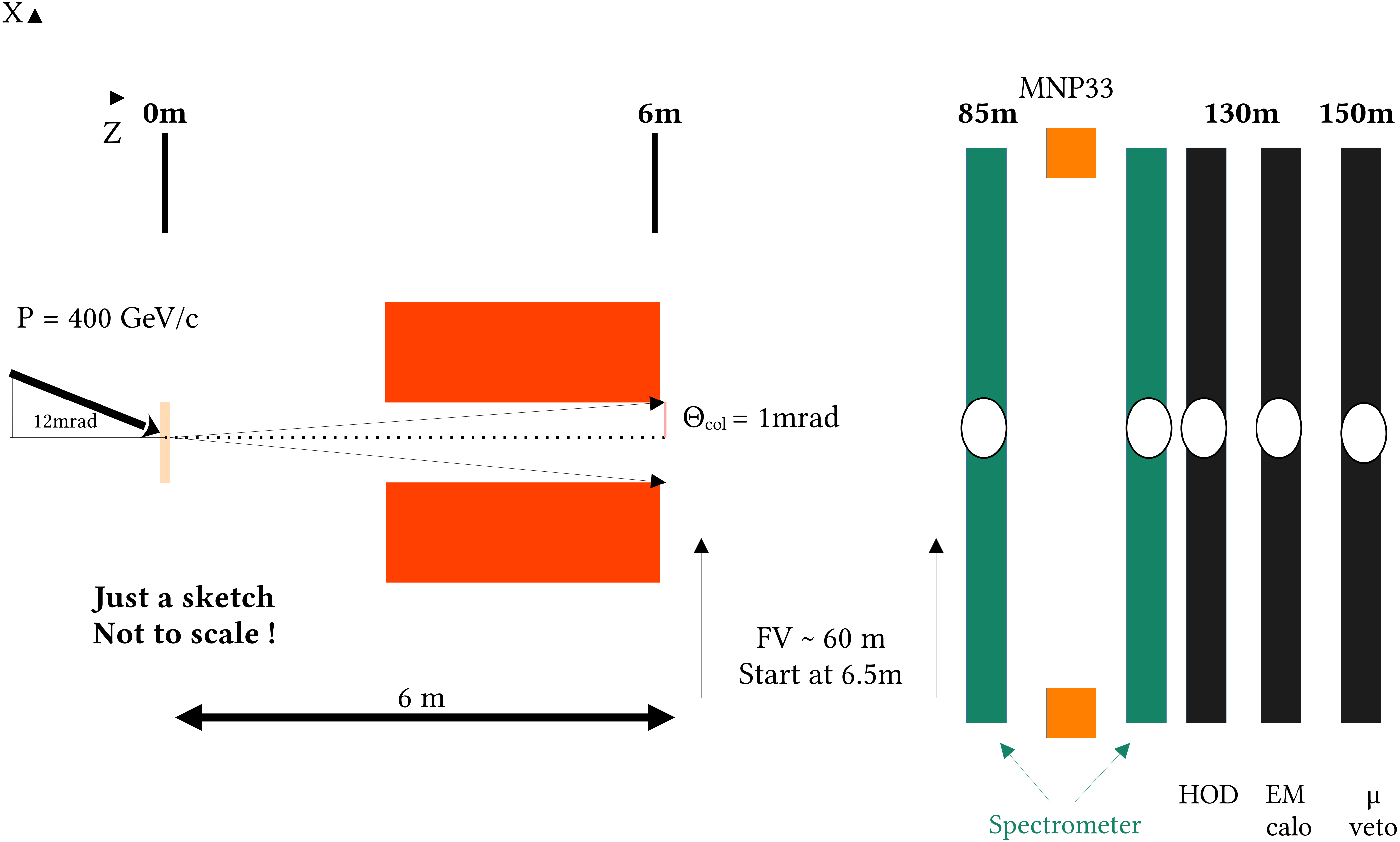
- We need asymmetric K^0 and $\bar{K}^0$ beam: fixed–target experiment at the SPS?
  - QCD production with a $K^0 - \bar{K}^0$ asymmetry (D ~ 0.3 for NA48)
  - Dilution must be measured precisely (~ 1% precision) with K → ππ decays
- Effective branching ratio for K → $\mu^+\mu^-$ interference ~ $3\text{x}10^{-10}$
- O(10^{14}) K decays are needed for a O(1%) measurement (~10% signal efficiency)
- Precise background control + good τ_S resolution

Thoughts on experimental design



- Similar setup to NA62 but switch to neutral beamline: 6xNA62 intensity → 10^{19} POT/year
- Beam much closer to the detectors: high event rate
- First few meters after the target will be needed for collimation
- Large incident angle → soft kaon momentum spectrum → 30–40% geometrical acceptance

Experimental layout used



Just a sketch
Not to scale !

Signal yield for 10^{19} POT/year

- Yield for interference events can`t reliably be computed
  - Depends heavily on the beam setup (incident angle + collimation) and the strong phase
  - Expected number of interference decays in 0 – $6\tau_S$ ~ 500 – 2000 events/year (no selection)
  - Signal efficiency ~ 15% ⟶ 75 – 300 events/year (after full selection)
  - Optimization of the beam line essential to determine if the sensitivity is sufficient

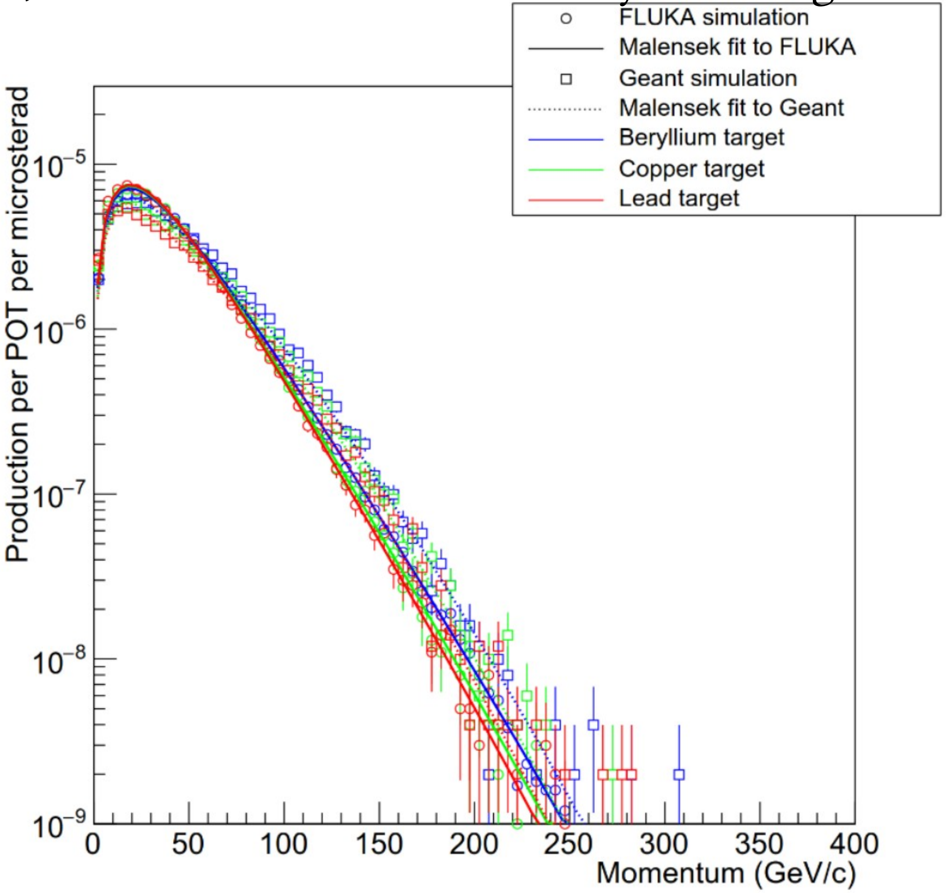
- The fiducial volume of the experiment is larger than the first $6\tau_S$ (FV ~ 60m)
- Large number of K_S, K_L and Λ decays in the 60m FV (setup from previous slide):
  - K_L ~ $4\text{x}10^{13}$ decays/year
  - K_S ~ $3\text{x}10^{13}$ decays/year
  - Λ ~ $1\text{x}10^{13}$ decays/year
- $O(10^{14})$ K_S/K_L decays can be collected over 5 years of data–taking
  - Opportunities to measure and search for very rare K_L decays ($K_L \to \pi^0 l^+ l^-$, $K_L \to \mu e$)

Simulation: Kaon momentum spectrum

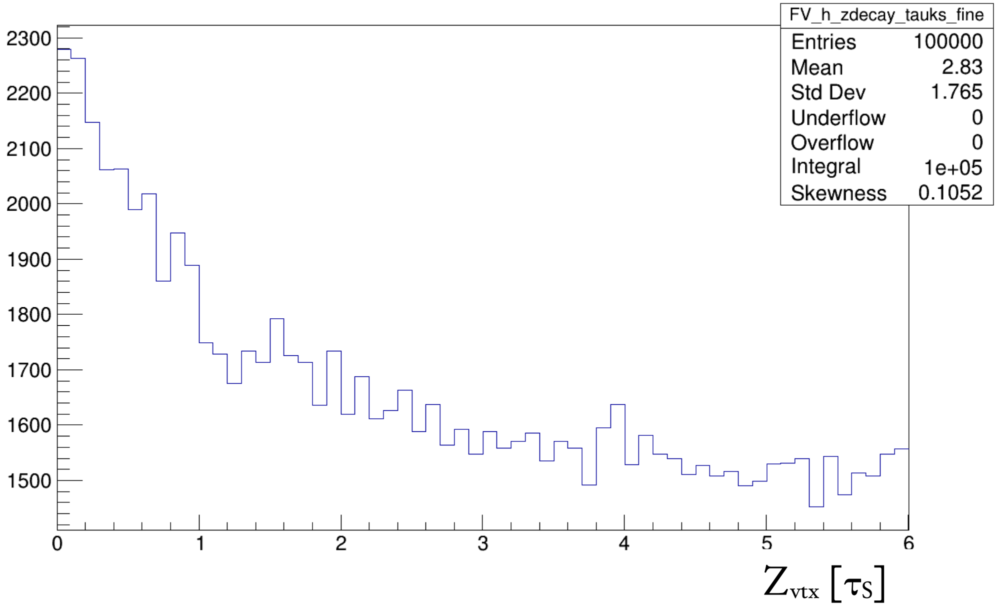
- Beam simulation
  - 400 GeV/c protons on a beryllium target producing K_L according to the Aetherton formula

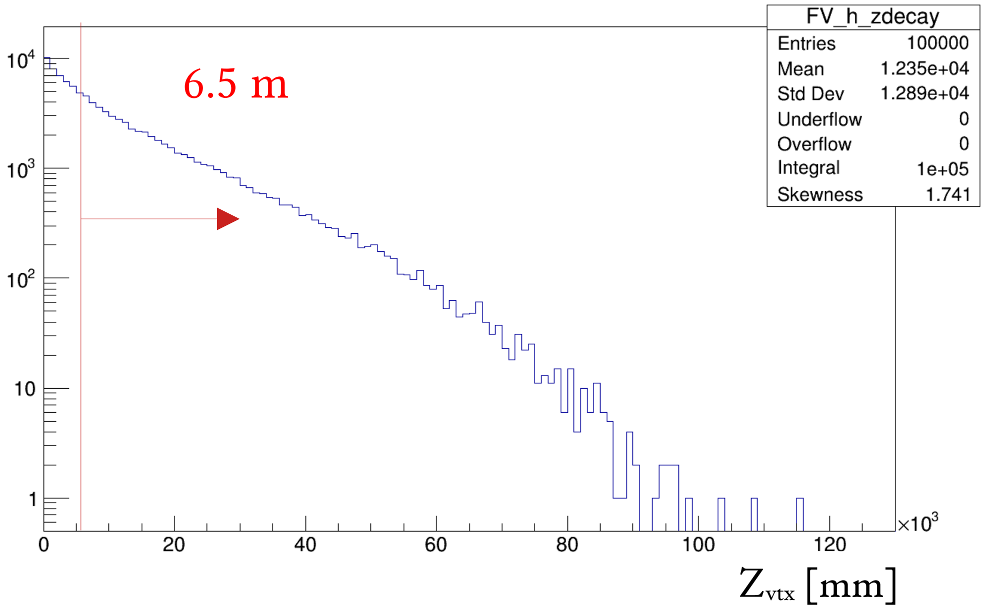
$$\frac{d^2N}{dpd\Omega} = BX\frac{(1-X)^A(1+5e^{-DX})}{\left(1+{(p\theta)^2}/{C}\right)^4} \quad \text{with} \quad X=\frac{p}{E_0}$$

  - The coefficients A,B,C and D taken for 400mm beryllium target from M. van Dijk, KLEVER target studies



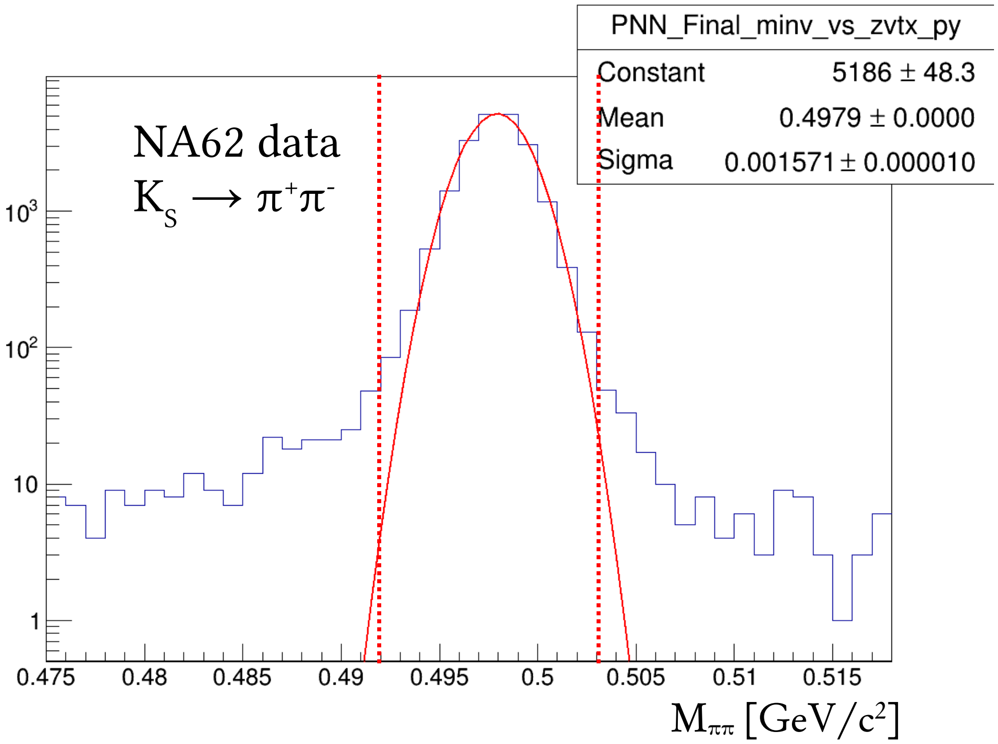
Simulation: Fiducial volume

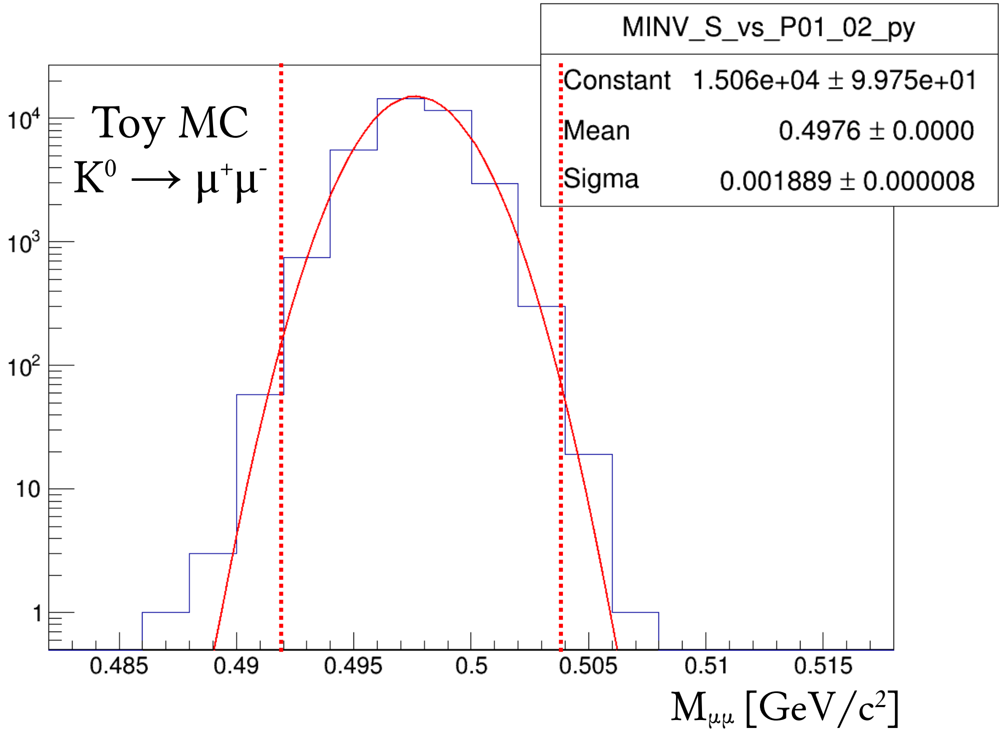




- Only the first 6 K_S lifetimes generated (1% of K_L decay in this region)
- FV starts after the collimator: ~ 6.5 m
  - Not much improvement possible
  - Collimation in 6 – 6.5m might also be optimistic
  - Feasibility studies required

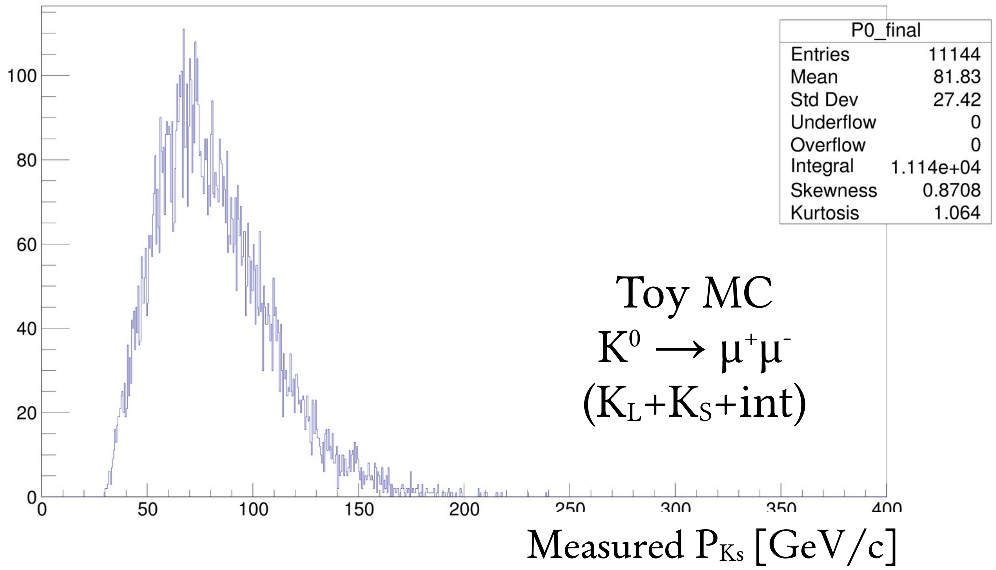
Simulation: Signal mass resolution

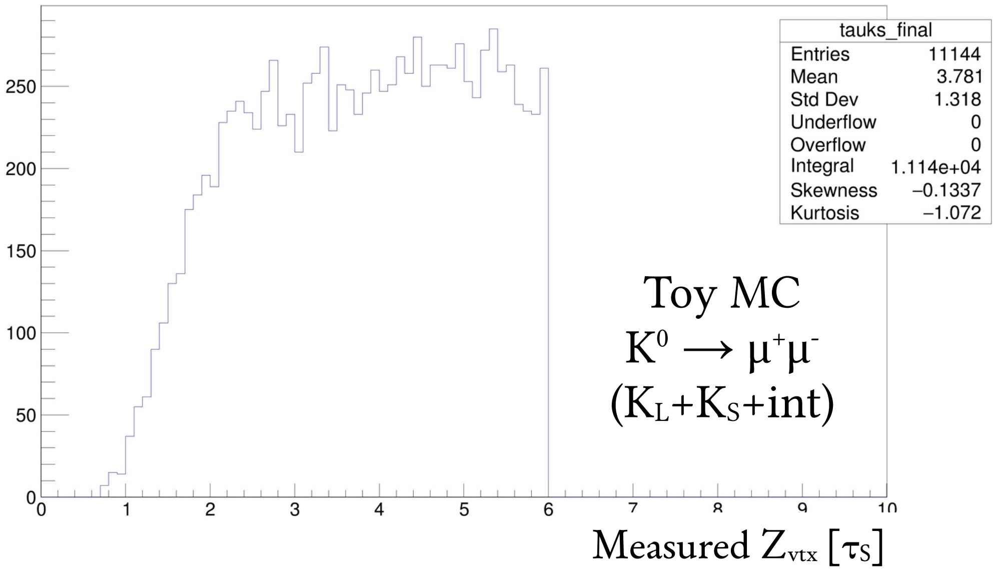




- Smearing applied to the toy MC based on measured NA62 spectrometer momentum and angular resolution
- Signal region used: 0.492 – 0.504 GeV/c² (10 MeV/c² – wide)
    - Signal efficiency ~ 99%

Simulation: Signal after geometrical selection



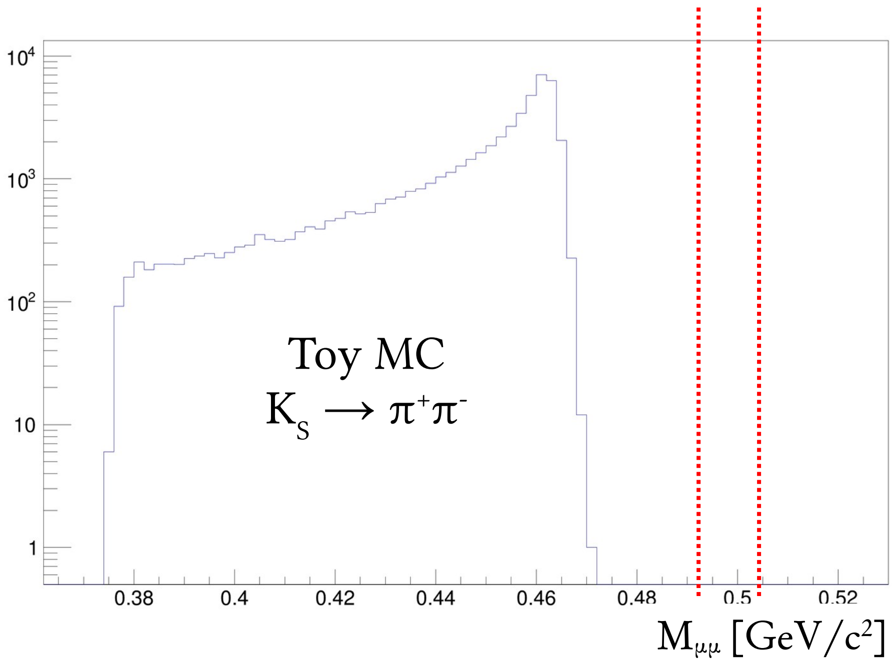


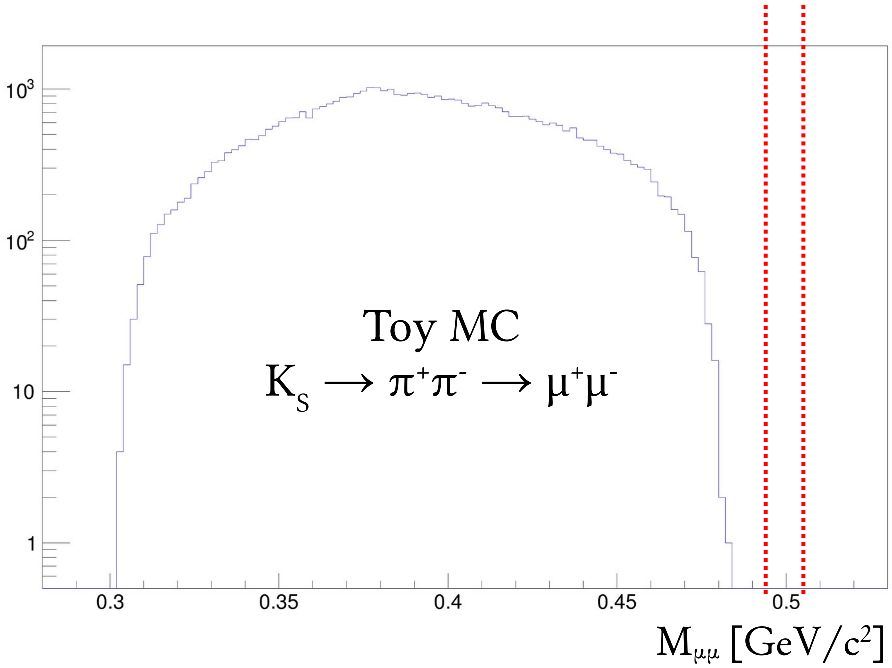
- Total geometrical acceptance: **Acc ~ 40%**
  - After corrections (DAQ+Trigger+Detector efficiency+Full selection) ~ 15%
  - Similar to other experiments looking at the same channel and to efficiency loss in NA62
  - Extending the FV closer to the target can lead to significant gains but quite complicated
- The above plots represent statistics, corresponding to ~ 2 years of operation at 10^{19} POT/year, 12mrad incident angle, and 1mrad collimator opening

Backgrounds from kaon decays

- $K \rightarrow \mu^+\mu^-$ signal signature ($BR_{eff} \sim 3\times10^{-10}$): Two muons with invariant mass $M_{\mu\mu}$ peaking at the neutral kaon mass
- $K_S \rightarrow \pi^+\pi^-$ decays (BR ~ 0.7)
  - PID suppression
  - Kinematic suppression (wrong mass assignment)
  - Can be used for normalization
- $K_S \rightarrow \pi^+\pi^- \rightarrow \mu^+\mu^-$ ($BR_{eff} \sim 1\times10^{-4}$)
  - Probability for 2x $\pi \rightarrow \mu$ decays (momentum dependent)
  - Kinematic suppression
    - Missing momentum
    - Vertex reconstruction
    - Extrapolated position at the primary target
- $K_L \rightarrow \mu^+\mu^-\gamma$ ($BR \sim 3.6\times10^{-7}$)
  - Kinematics (missing momentum)
  - Photon rejection

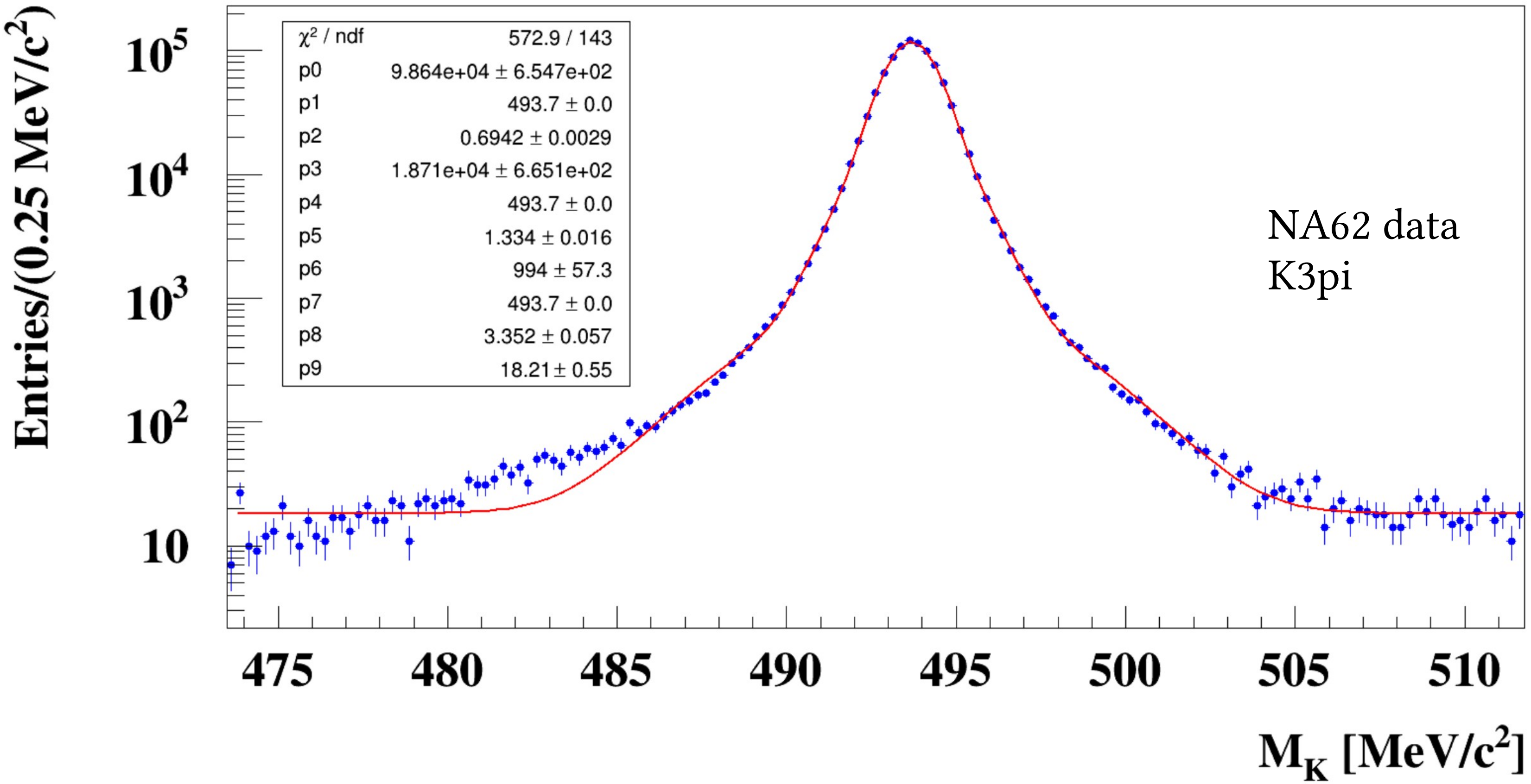
Background: Kinematic tails





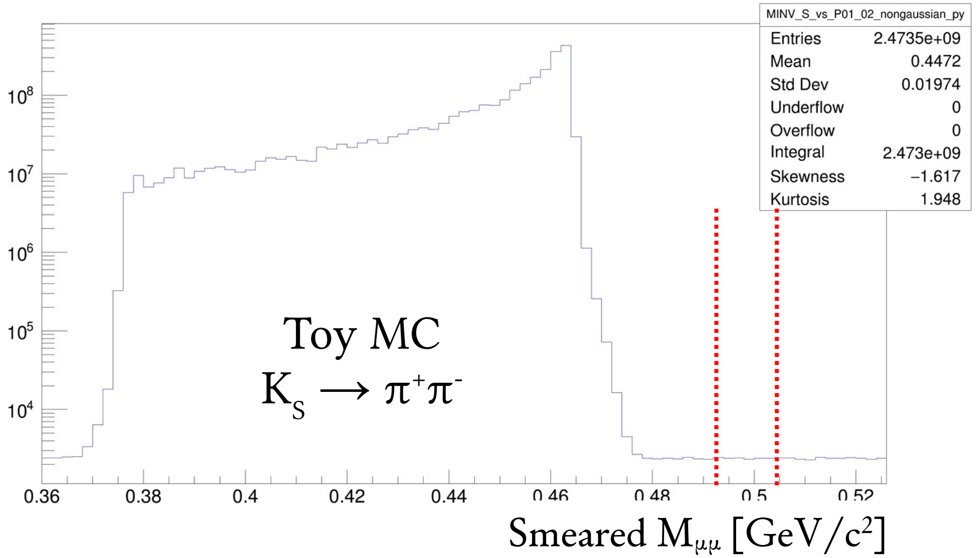
- Muon mass assumed for both tracks
- Kinematic boundary for both backgrounds far from the signal region
  - For $K_S \rightarrow \pi^+\pi^-$ both tracks have with wrong masses
  - For $K_S \rightarrow \pi^+\pi^- \rightarrow \mu^+\mu^-$ correct masses but a lot of missing energy due to the two neutrinos
  - Gaussian tails not a problem
  - Main issue will be the non-gaussian tails as is the case for the $K^+ \rightarrow \pi^+\nu\nu$ measurement

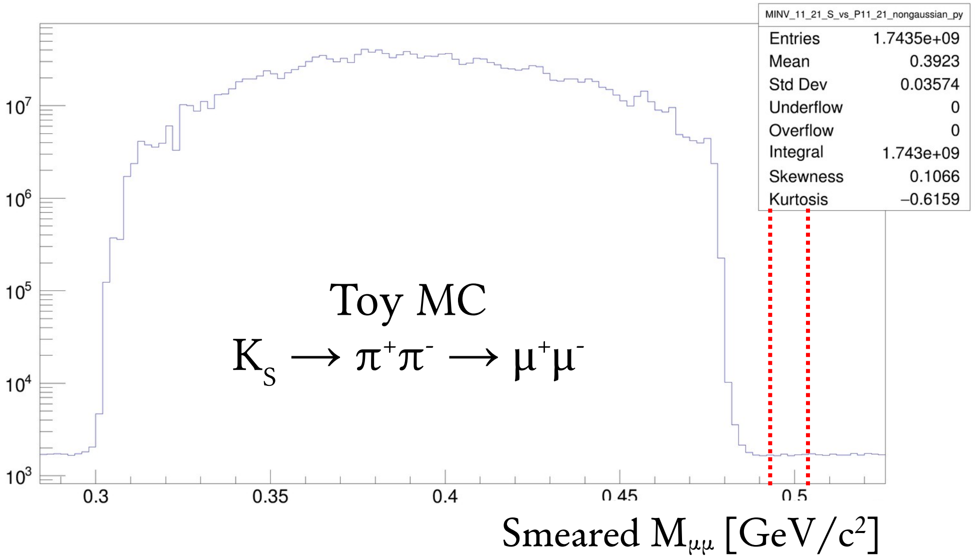
Background: Non-gaussian kinematic tails



- Assuming the same smearing as for the non-gaussian tails of k3pi
  - Caveat: three pion tracks instead of two
  - Can be used as a first order proxy for the tails of the invariant mass distribution
- Smearing the invariant mass of the $K_S \rightarrow \pi^+\pi^-$ ($\rightarrow \mu^+\mu^-$) decays in the toy MC

Background: Non-gaussian kinematic tails



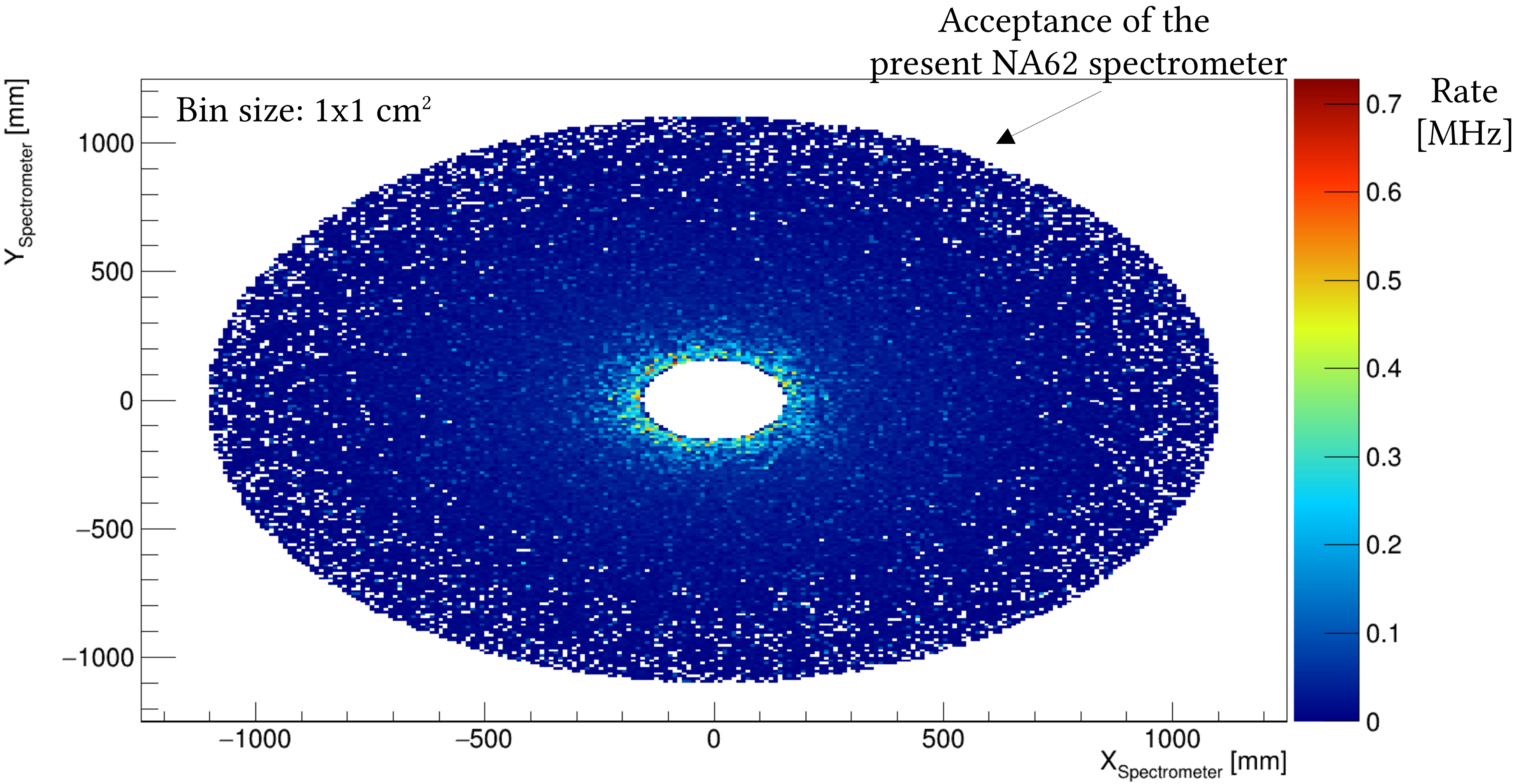


- Non-gaussian tails estimate
  - $K_S \rightarrow \pi^+\pi^- \sim 1\text{x}10^{-5}$
  - $K_S \rightarrow \pi^+\pi^- \rightarrow (\mu^+\mu^-) \sim 1\text{x}10^{-5}$
- Safety factor 2 applied because the accidental rate will be higher than NA62
  - Requires more studies

Background contamination

- $K_S \to \pi^+\pi^-$ decays
  - BR ~ 0.7
  - PID suppression ~ 10^{-4}/track (calo + muon detector)
  - Kinematic suppression (wrong mass assignment + nongaussian tails) ~ 10^{-5}
  - Expected S/B ~ 10
- $K_S \to \pi^+\pi^- \to \mu^+\mu^-$ decays
  - BR_{eff} ~ $1\text{x}10^{-4}$ (2x pion decays)
  - Kinematic suppression ~ 10^{-5}
  - CDA + extrapolating the K_S to the primary target ~ $3\text{x}10^{-3}$
  - Expected S/B ~ 2
- $K_L \to \mu^+\mu^-\gamma$ (BR ~ $3.6\text{x}10^{-7}$): **TODO**
  - Kinematics (missing momentum)
  - Photon rejection
- Accidental muon pairs: **TODO**

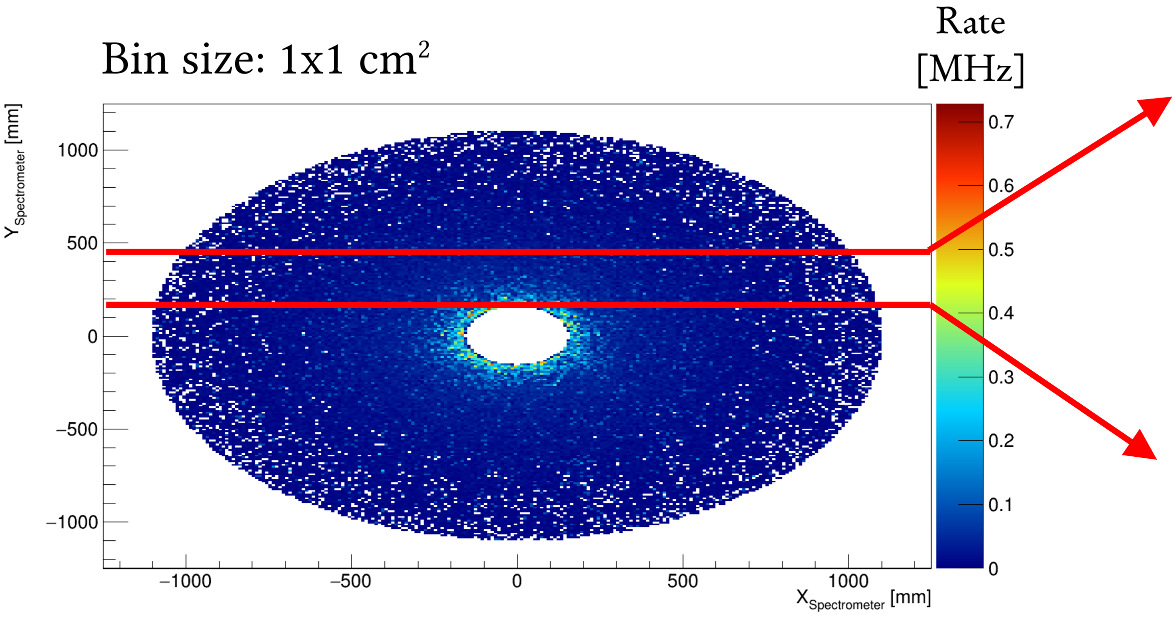
Rate of charged particles


Acceptance of the present NA62 spectrometer

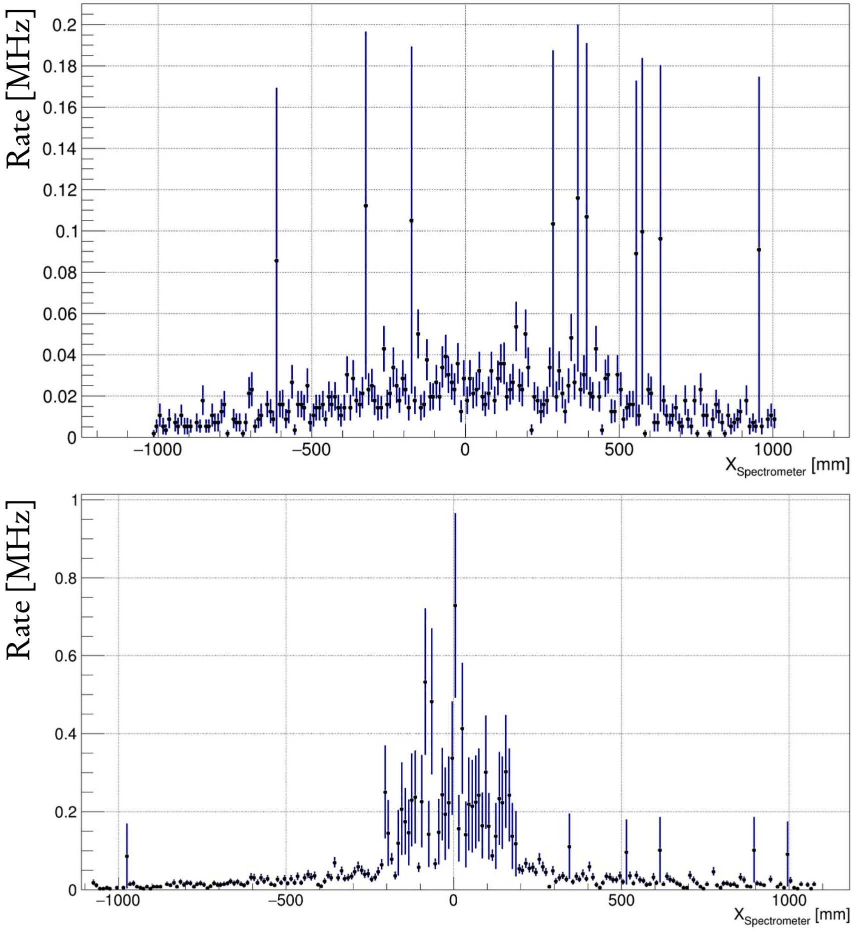
Bin size: 1x1 cm^2

- Primary source of charged particles: K_S and Λ decays
  - Large integrated rates ~ 1 GHz (total surface ~ 3.7m^2)
  - Non–uniform rate: hot spots can reach ~ 700 kHz/cm^2

Rate of charged particles



Bin size: 1x1 cm^2



- Affordable rates but technically challenging
  - High granularity + different technology as a function of radius
  - Interface between different detector materials
  - Solid state detectors should be the solution
- Similar to the solution required for detectors at the HL–LHC

Areas for future study: analysis and simulations

- Feasibility: K_S–$K_L \rightarrow \mu^+\mu^-$ interference measurement
  - Can we collect O(10^3) interference events in few years of operation (yes?)
  - Background studies (accidentals and $K_L \rightarrow \mu^+\mu^-\gamma$ backgrounds)
  - Impact of background and fit procedure on the extraction of η?
- Going beyond $K \rightarrow \mu^+\mu^-$
  - Large statistics for rare processes will be available
  - O(10^{14}) K_S/K_L decays → allow studies of $K_L \rightarrow \pi^0 l^+ l^-$, $K_L \rightarrow e\mu$
  - O(10^{13}) Λ decays
- Sensitivity studies for a wide range of rare processes must be performed
  - New ideas for observables are welcome
  - Understand better the experimental requirements for a broad program!

Areas for future study: beam and detector

- Beam line for a future high–intensity K_S experiment
  - Different options must be studied in detail (see L. Gatignon's talk)
  - Muon rate, collimation, target, …
- Tracking and calorimetry at the GHz regime: dedicated R&D program required
  - High–granularity detectors
  - Fast detectors: O(100ps)
  - High detection efficiency > 95%
  - Hybrid technology (different techniques as a function of R)
  - Calorimetry essential for $K_L \to \pi^0 l^+ l^-$
  - Excellent momentum/energy resolution
  - Readout challenges

Conclusions

- Interesting prospects to measure K_S–$K_L \to \mu^+\mu^-$ interference at CERN in the future
- A high–intensity neutral kaon experiment will have a very broad physics reach
  - Opportunity to rewrite the PDG for K_S and K_L decays
  - Sensitivity to broad NP scenarios
- Huge technical challenges → require O(10) years to be overcome
  - Synergies with detector technology for HL–LHC
- NA62 will take $K^+ \to \pi^+\nu\nu$ data until LS3
- Plan for high–intensity kaon experiments at CERN after LS3 is being formed
  - This implies kaon physics remains in ECN3 (presently in competition with BDF)