First thoughts on high-intensity K_S experiment

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High-intensity K_S/K_L experiment

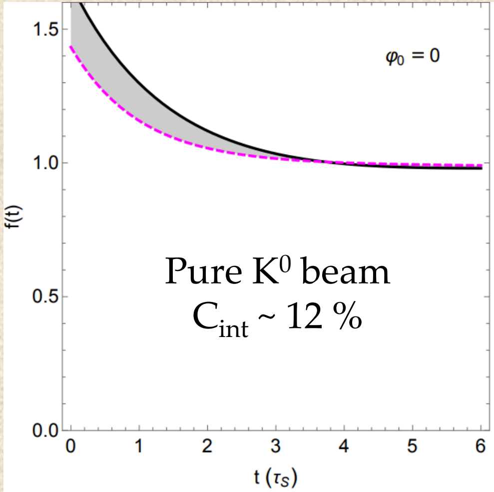
- A **golden** opportunity to get **η** cleanly, with **less than 1% error**
- A possibility in the long-term that should not be overlooked
- Interference mesurement is the main motivation: **[PRL 119 201802(2017), JHEP 07 (2021) 103]**
  - Challenges on intensity, detector performance, background suppression
- **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 the $K_S - K_L \to \mu^+\mu^-$ interference experimentally?
- High-intensity K_S/K_L experiment
  - Thoughts on experimental design
  - Toy MC simulation: signal yield and background contamination
  - Detector challenges
- Areas for future studies
- Conclusions

Experimental considerations: $K \to \mu^+ \mu^-$ interference

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



JHEP07(2021)103

Strong phase

$$C_{int}^2 = C_{sin}^2(D, \varphi_0) + C_{cos}^2(D, \varphi_0)$$

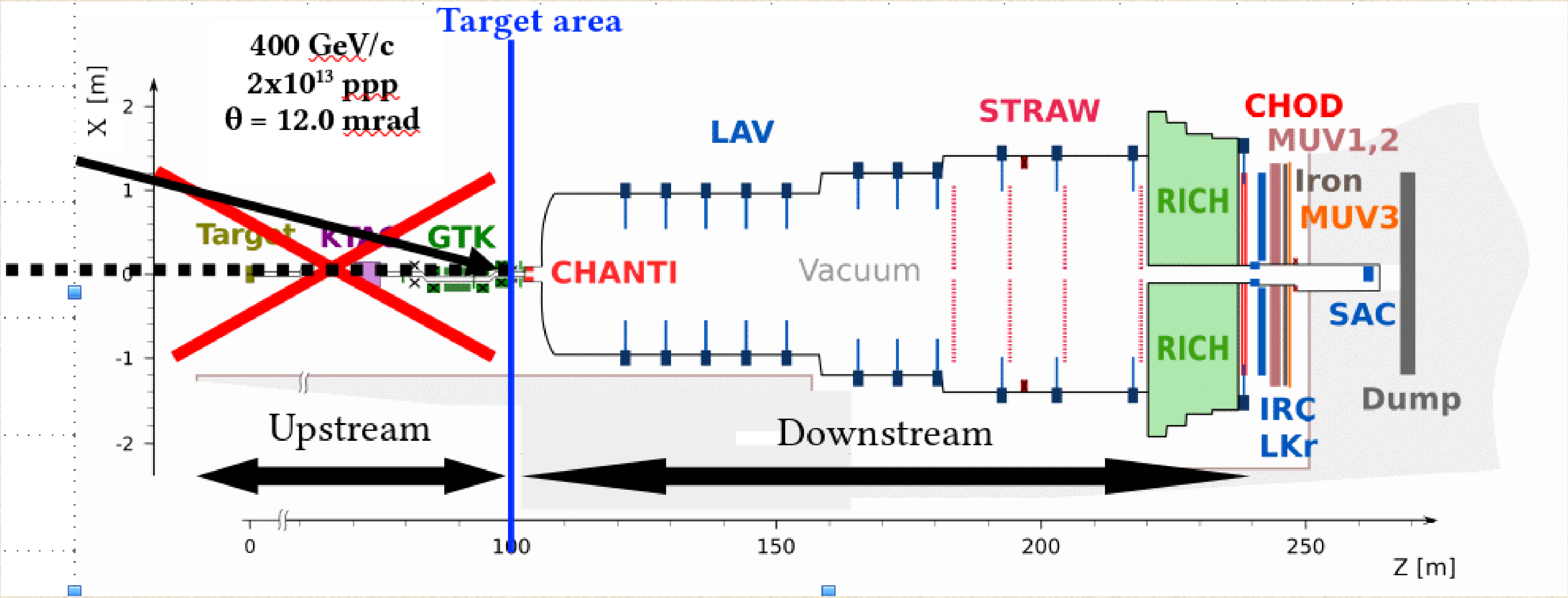
Dilution

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

- Asymmetric K^0 and $\overline{K^0}$ beam required: **fixed-target experiment at the SPS?**
  - QCD production with a $K^0 - \overline{K^0}$ asymmetry (D ~ 0.3 for NA48)
  - Dilution must be measured precisely (~ 1% precision or better) with $K \to \pi\pi$ decays
- At least **O(10^{14}) K decays** needed for a few % measurement (depends on φ_0)

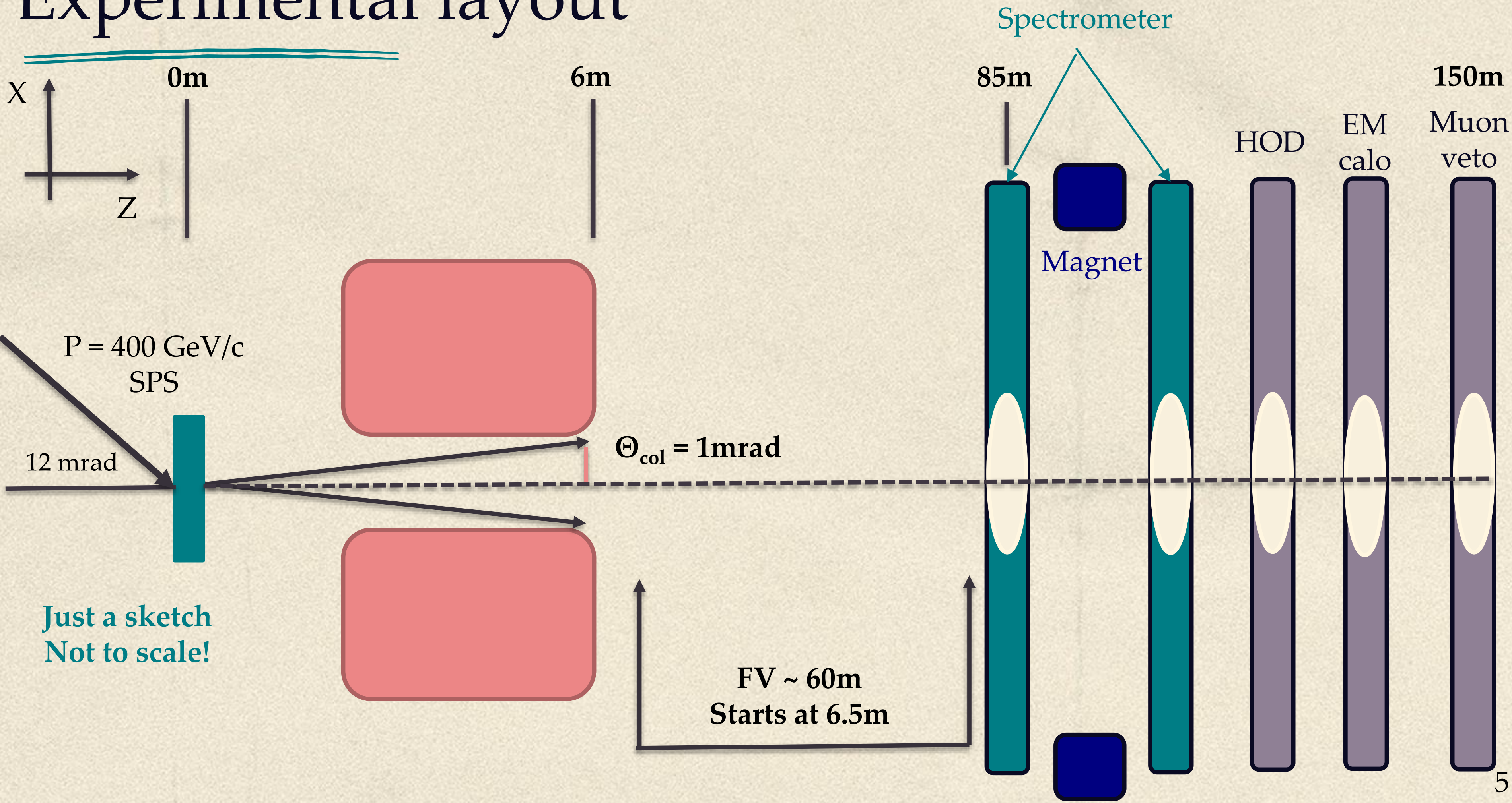
See A. Dery`s talk

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**

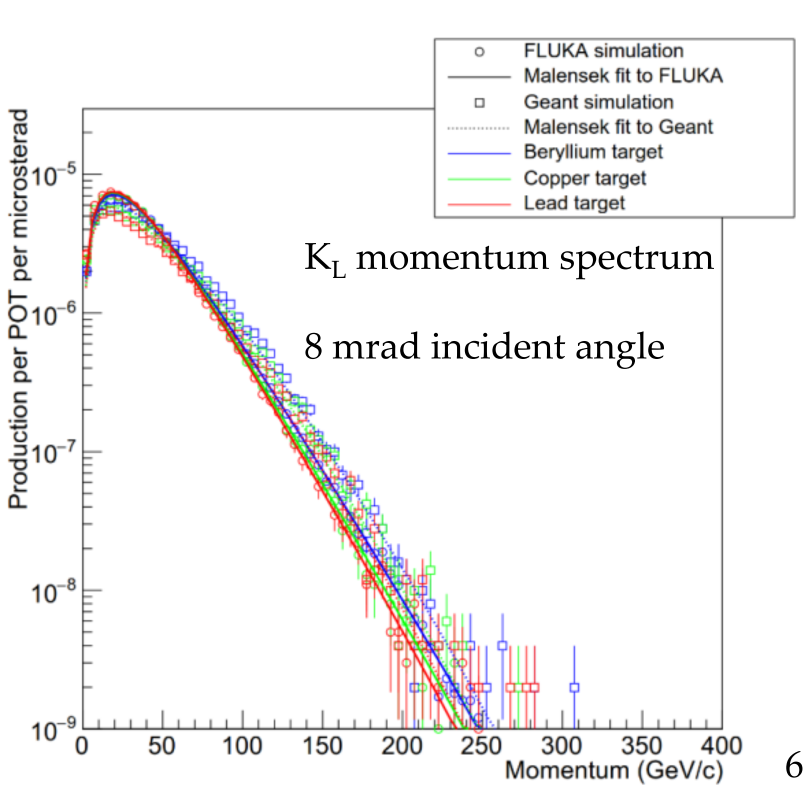
Experimental layout



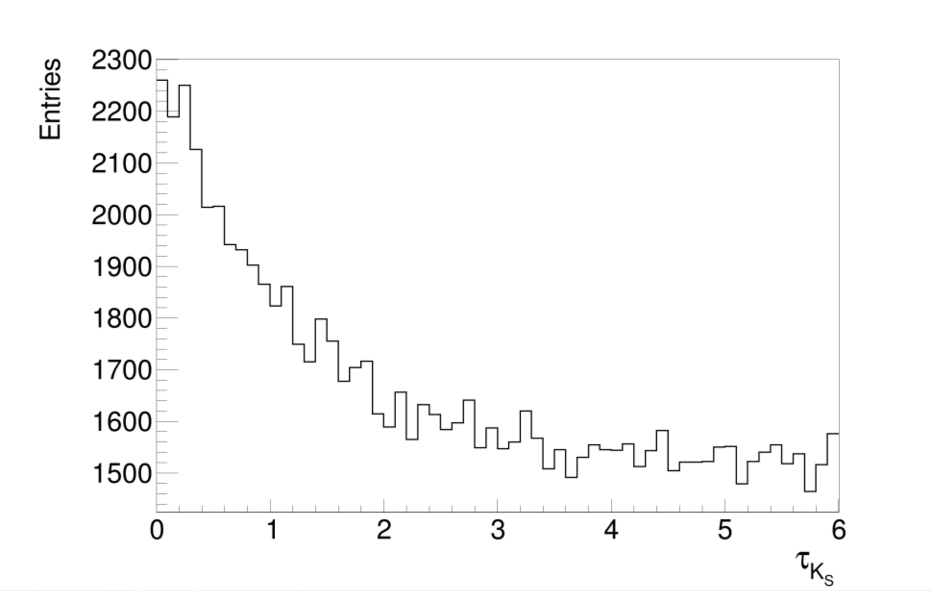
Simulation: Kaon momentum spectrum

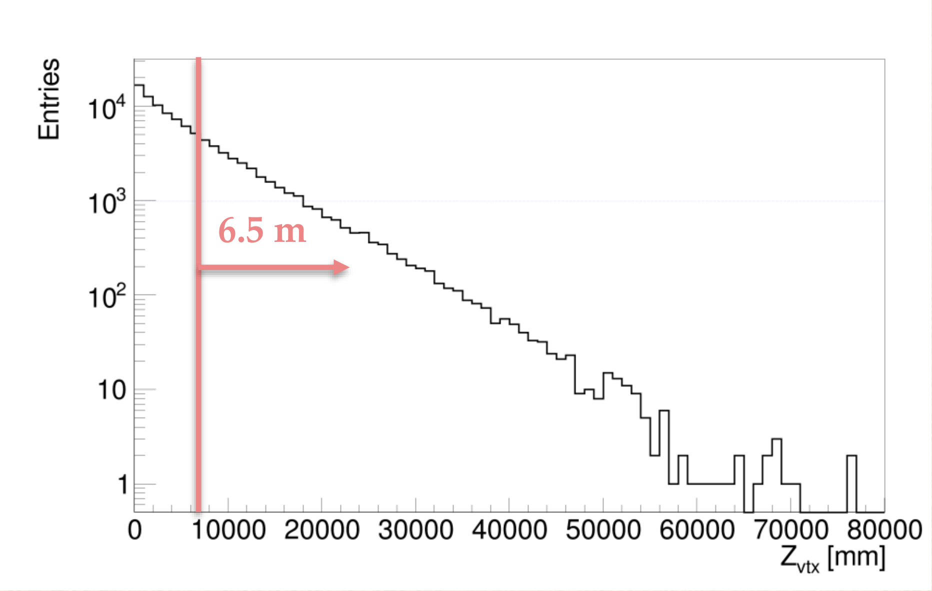
- *Beam simulation:* 400 GeV/c protons on a beryllium target producing K_L
  - $\frac{d^2N}{dp\,d\theta} = BX\frac{(1-X)^A(1+5\,e^{-DX})}{\left(1+{(p\theta)^2}/{C}\right)^4}$ with $X = \frac{p}{E_0}$
  - A, B, C and D taken for 400 mm beryllium target

Ref: M. van Dijk and M. Rosenthal



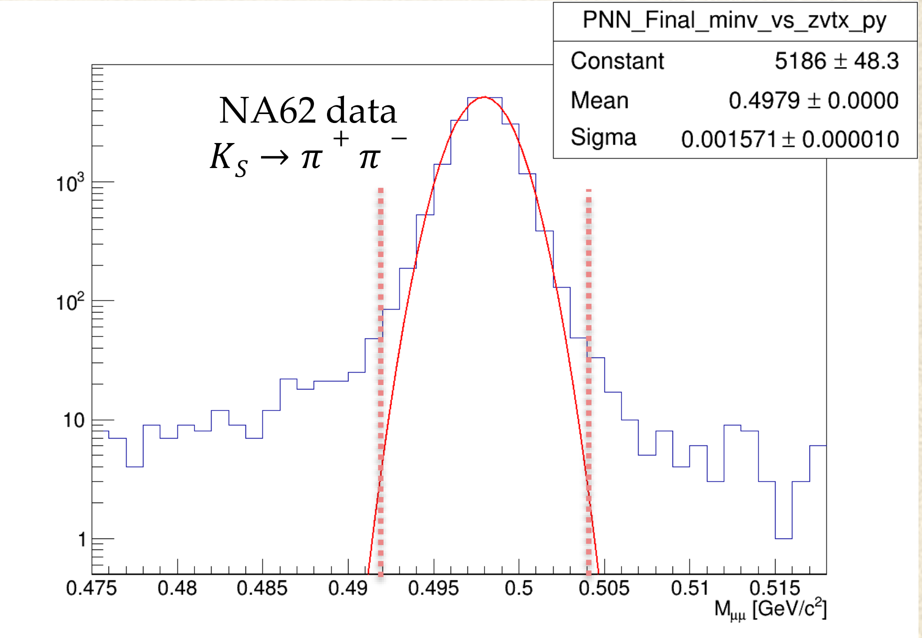
Simulation: Fiducial volume

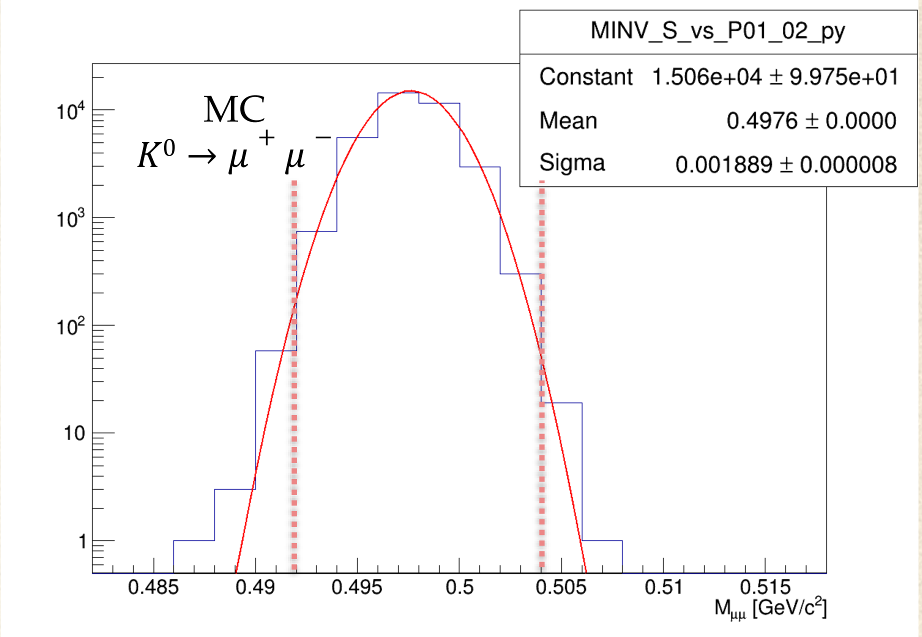




- *Only the first 6 K_S lifetimes produced* (1% of K_L will decay in this region)
- FV starts after the collimator **~ 6.5 m** from the target (might be optimistic)
- Detailed simulation of the beam line required

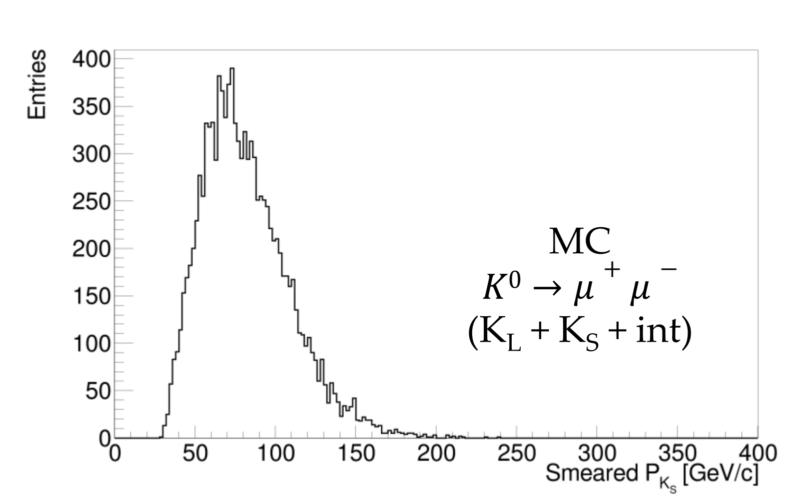
Simulation: Signal mass resolution

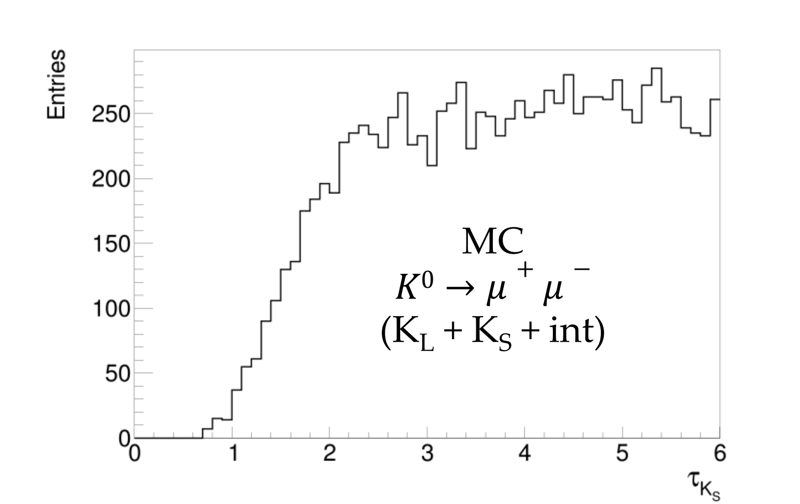




- *Smearing applied based on the NA62 spectrometer momentum and angular resolution*
- Signal region used: **0.492 – 0.504 GeV/c²** (signal efficiency ~ 99%)

Simulation: Signal after geometrical selection





- Signal efficiency **~ 15%** (DAQ+Trigger+Detector efficiency (a la NA62)+full selection)
  - Geometrical acceptance **~ 40%**
- Statistics in the plots correspond to ~2 *years of operation* (10^{19} POT/year), *12mrad* incident angle, *1mrad* collimator opening, and $\varphi_0 = 0$ strong phase

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 φ_0
- A particular experimental setup and φ_0 chosen
  - Expected number of interference decays in 0-6 τ_S **~ 500 – 2000 events/year (no selection)**
  - Signal efficiency ~ 15 % **→ 75 – 300 events/year (after full selection)**
  - Work on the signal extraction is needed to translate the expected statistics to sensitivity
  - **Optimization of the beam line essential to determine if the sensitivity will be sufficient**

Signal yield for 10^{19} POT/year

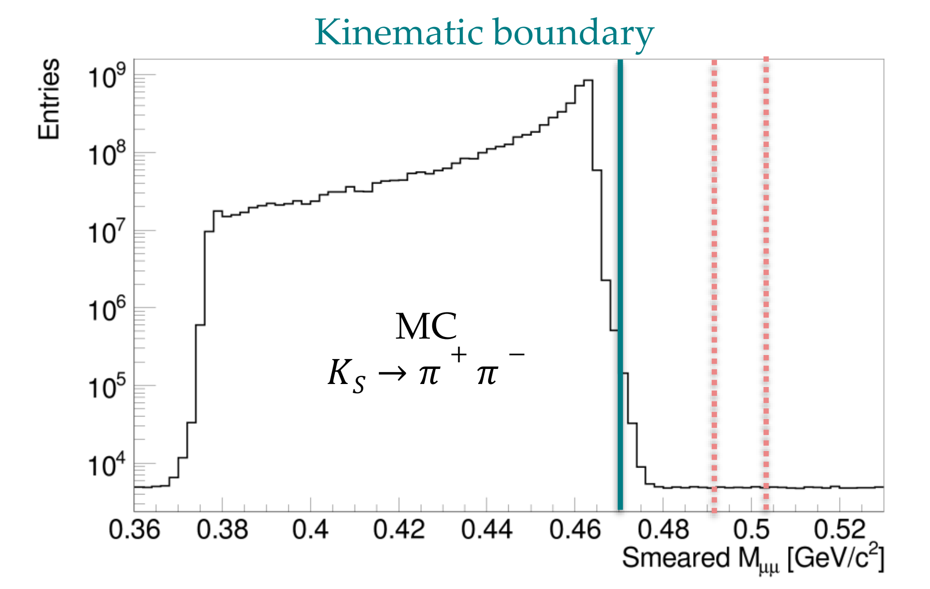
- The fiducial volume for other decay channels is larger than the first $6\tau_{KS}$ (FV ~ 60m)
- Large number of K_S, K_L, Λ decays in the FV
  - K_L ~ 4×10^{13} decays/year
  - K_S ~ 3×10^{13} decays/year
  - Λ ~ 1×10^{13} decays/year
- **O(10^{14}) K_S/K_L decays can be collected over 5 years of data-taking**
  - Opportunities to measure and search for very rare K_L decays ($K_L \to \pi^0 l^+ l^-, K_L \to \mu e$)

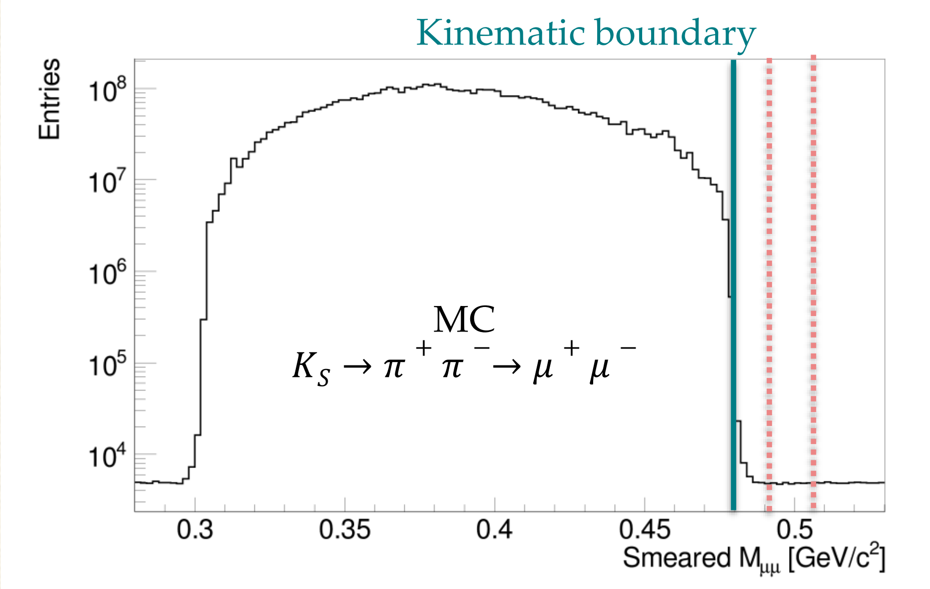
Background from kaon decays

	Effective BR	Suppression mechanism
$K^0 \rightarrow \mu^+ \mu^-$ (Signal)	**~3×10^{-10}**	**-**
$K_S \rightarrow \pi^+ \pi^-$	0.7	PID, Kinematics (wrong mass assignment)
$K_S \rightarrow \pi^+ \pi^- (\rightarrow \mu^+ \mu^-)$	1×10^{-4}	Probability for 2x $\pi \rightarrow \mu$ decays, Kinematics (P_{miss}, Vertex reconstruction, Position at primary target)
$K_L \rightarrow \mu^+ \mu^- \gamma$	3.6×10^{-7}	Branching ratio, Missing momentum, Photon rejection
Accidental muon pairs	-	Kinematic rejection, timing

- **$K^0 \rightarrow \mu^+ \mu^-$ signal signature:** two muons with invariant mass $M_{\mu\mu}$, peaking at the neutral kaon mass
- Complementary challenges as for the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ measurement:
  - **Strong PID, Kinematic, and Photon rejection**

Background: Non-gaussian kinematic tails





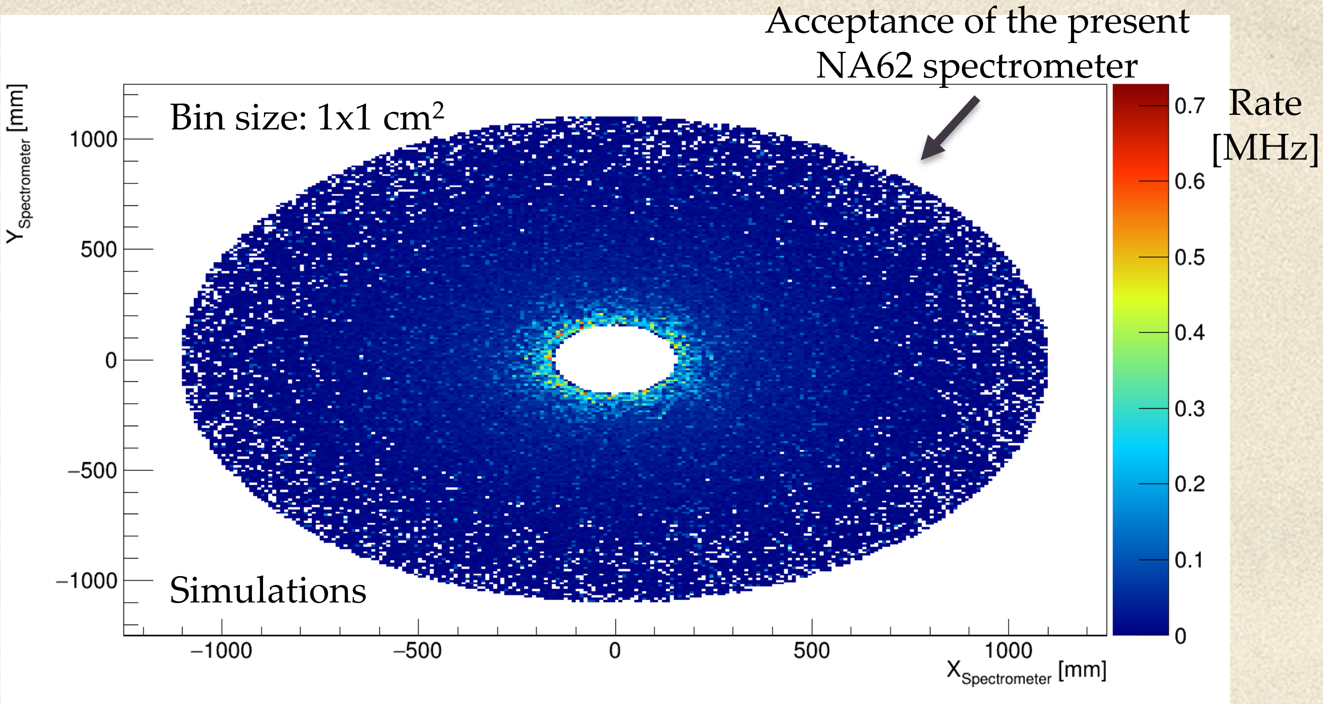
- Kinematic boundary for both backgrounds far from signal region (at least 10 sigma)
- Smearing as for the gaussian + non-gaussian tails from $K^+ \to \pi^+ \pi^+ \pi^-$ in NA62 data
- Expected kinematic tails at the level of **~ 10^{-5}**

Background contamination

	Effective BR	Suppression mechanism	Expected S/B
$K_S \to \pi^+\pi^-$	0.7	PID, Kinematics (wrong mass assignment)	~10
$K_S \to \pi^+\pi^- (\to \mu^+\mu^-)$	1x10^{-4}	Probability for 2x $\pi \to \mu$ decays, Kinematics (P_{miss}, Vertex reconstruction, Position at primary target)	~2
$K_L \to \mu^+\mu^-\gamma$	3.6x10^{-7}	Branching ratio, Missing momentum, Photon rejection	?
Accidental muon pairs	-	Kinematic rejection, timing	?

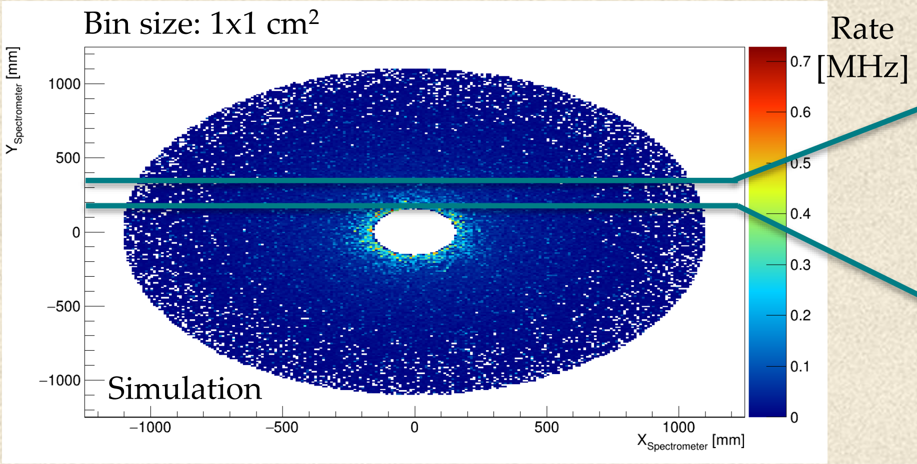
- Work required to estimate the contribution of radiative decays and accidentals
- **Accidental background will be an issue (heavily dependent on the beam line)**

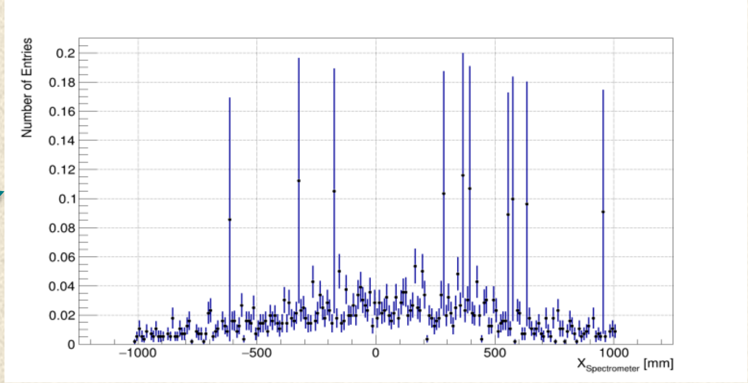
Rate of charged particles

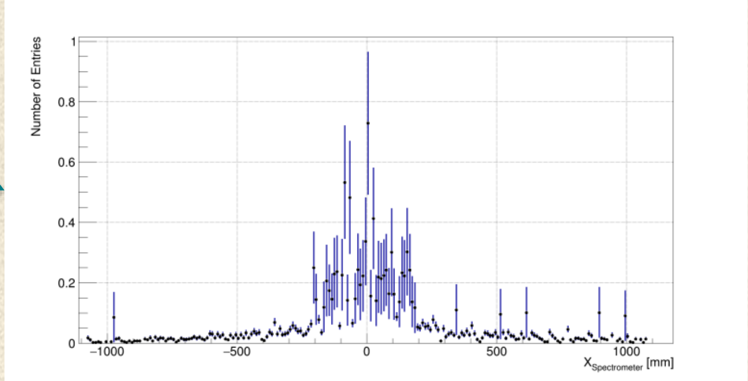


- Primary source of charged particles: **K_S and Λ decays**
  - Large integrated rates **~ 1GHz** (total surface ~ 3.7 m^2)
  - *Non-uniform rate:* hot spots can reach **~ 0.7 – 1 MHz/cm^2**

Rate of charged particles







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

Areas for future study: analysis and simulations

- More serious feasibility study needed to address the $\boldsymbol{K_S - K_L \to \mu^+ \mu^-}$ **interference**

- Important questions:
    - Can we collect O(10^3) interference events in few years of operation
    - Background studies (accidentals and $K_L \to \mu^+ \mu^- \gamma$ background)
    - Impact of background contamination and fit procedure on the extraction of η
    - How is the sensitivity dependent on the strong phase

Areas for future study: beyond $K \to \mu^+\mu^-$

- <u>Large statistics of rare processes will be available</u>
- O(10^{14}) K_S/K_L decays will allow studies of $K_L \to \pi^0 l^+ l^-$ and $K_L \to e\mu$ decays
  - *Translates to ~ 50 (25) $K_L \to \pi^0 e^+ e^-$ ($K_L \to \pi^0 \mu^+ \mu^-$) events/year*
- 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 (muon rate, collimation, target, …)

- Tracking and calorimetry at the GHz regime: **dedicated R&D program required**
  - High-granularity detectors with O(100ps) time resolution
  - High detection efficiency > 95%
  - Hybrid technology (different techniques as a function of R)
  - Calorimetry essential for $K_L \rightarrow \pi^0 l^+ l^-$
  - Excellent momentum and energy resolution
  - Readout challenges

Conclusions

- Opportunity to obtain a clean determination of η from kaon physics
- Interesting prospects to measure $K_S - K_L \to \mu^+ \mu^-$ interference at CERN in the future
- A high-intensity neutral kaon beam will allow a **very broad physics program**
  - Opportunity to **rewrite the PDG for K_S and K_L decays**
  - Sensitivity to broad range of NP scenarios
- *Huge technical challenges:* require O(10) years of development
  - Synergies with detector technology for HL-LHC
- High-intensity kaon experiments, HIKE, at CERN after LS3
  - This implies kaon physics remains in ECN3