Update on the high-intensity Kaon programme at the SPS

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Physics Beyond Colliders General WG meeting – 03/12/2021

High-intensity Kaon programme @ SPS

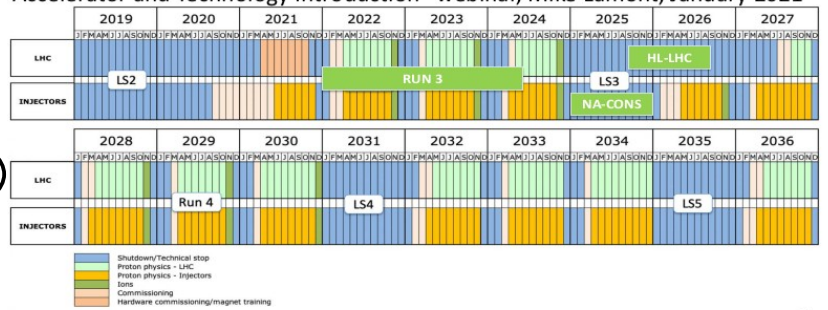
C. Lazzeroni, PBC Annual Workshop, March 2021

Integrated high-intensity Kaon programme at the SPS

EU Strategy deliberation document: **CERN-ESU-014**
"rare kaon decays at CERN" mentioned in Sec4
"Other essential activities for particle physics"

Long-term Physics Programme in NA-ECN3 to extend to FCC-ee (~2039)

"Accelerator and Technology Introduction" webinar, Mike Lamont, January 2021



Integrated programme with multiple phases, synergies with LHC programme
K^+ and K_L beams for precision measurement of $K \to \pi\nu\nu$
Study of other rare kaon decays, including K_L beam with tracking detector for $K_L \to \pi^0 l^+ l^-$
Data taking in dump mode to reach 10^{19} POT to search for FIPs

Advantage of integrated approach: common upgrades for intensity and detectors between projects, more flexibility on schedule.
Phase order depends on factors like civil engineering and detector readiness.
($K_L \to \pi^0\nu\nu$ phase KLEVER probably involves civil construction, see later pages)
Dump mode schedule integration to be finalised

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Experiments to measure $K \to \pi\nu\nu$ BRs at the SPS would require:

- **$K^+ \to \pi^+\nu\nu$**
  ~7×10^{18} pot/year
  4x increase
- **$K_L \to \pi^0\nu\nu$**
  1×10^{19} pot/year
  6x increase

Target/TAX upgrade for high intensity

Considered configurations:

- **Charged beam** ($K^+ \to \pi^+\nu\bar{\nu}$) ~ 7×10^{18} POT/year [4x wrt NA62]
- **Neutral beam**
  - with tracking ($K_L \to \pi^0\ell^+\ell^-$)
  - without tracking ($K_L \to \pi^0\nu\bar{\nu}$)

  ~ 10^{19} POT/year [6x wrt NA62]
- **Beam dump** (ALPs, HNLs, dark scalars, etc) ~ 10^{19} POT by LS4, up to 5×10^{19} POT by 2039
  ~ 10^{19} POT/year [6x wrt NA62]

Updates since March 2021

NA62 news:

- **NA62 officially approved up to LS3**
- NA62 2021 data taking completed
  - Reached 100% nominal intensity
  - ~ 1 week of beam dump: > 10^{17} POT collected

Beam dump data taking @ NA62:

- Crucial source of information for **post-LS3 dump** programme
  - Physics reach: backgrounds, muon rates
  - Operation: TAX stress test, first time at > 150% of NA62 nominal intensity

Post-LS3 programme - Main activities:

Detectors R&D:

- Test beam for KLEVER Small-angle calorimeter
- K^+ phase:
  - New STRAW spectrometer pre-production tests
  - New Si detector project, possible upgrade of NA62 Gigatracker

Sensitivity studies:

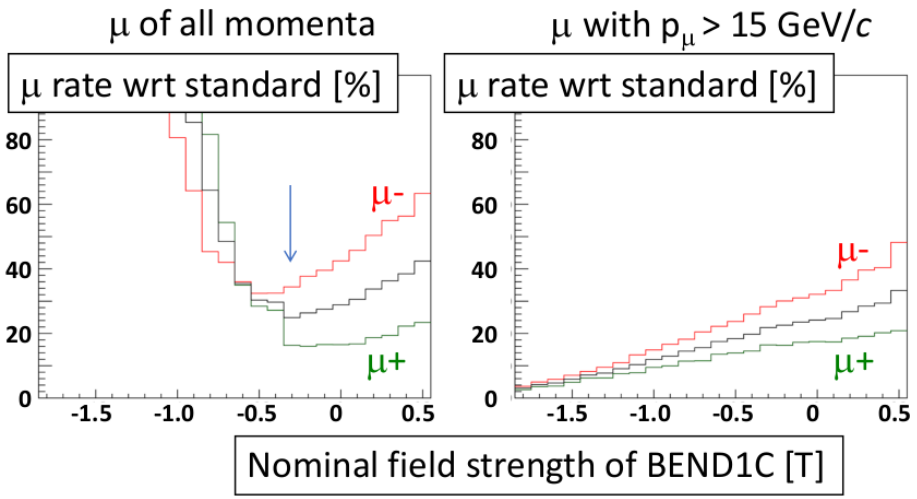
- Feasibility study for a measurement of interference between $K_S \to \mu^+\mu^-$ and $K_L \to \mu^+\mu^-$

NA62-dump: 2021 data taking

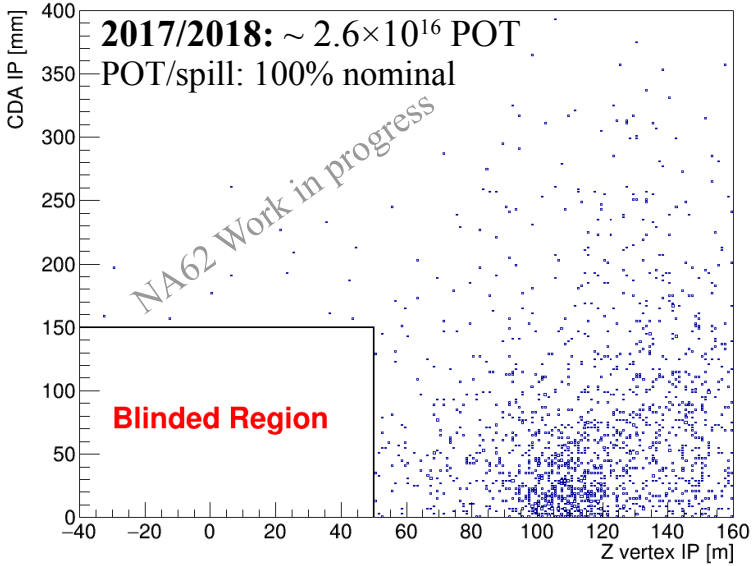
From previous PBC mandate:

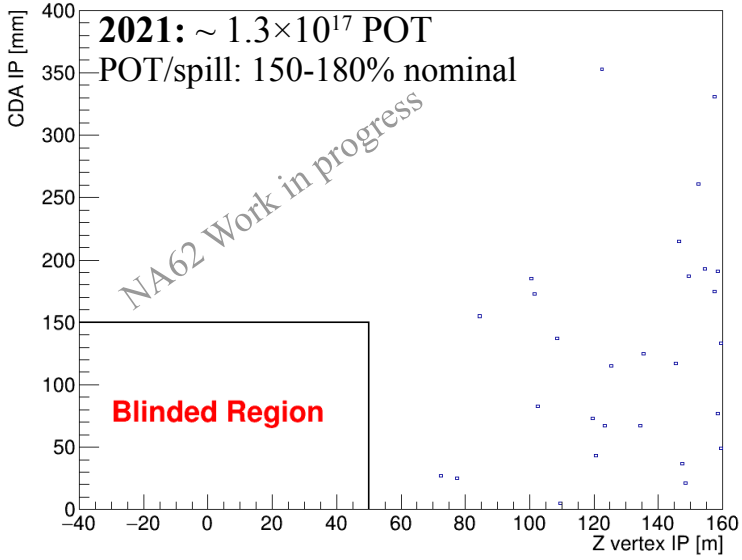
Beam-line tuning for improved beam-dump operation

Optimised sweeping:
~ 4x reduction of single μ rate
IMPLEMENTED in 2021



Preliminary $\mu^+\mu^-$-pair analysis:

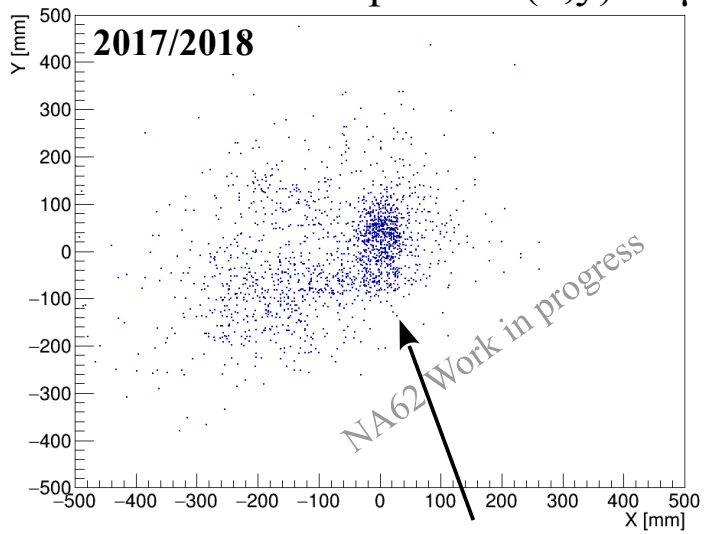


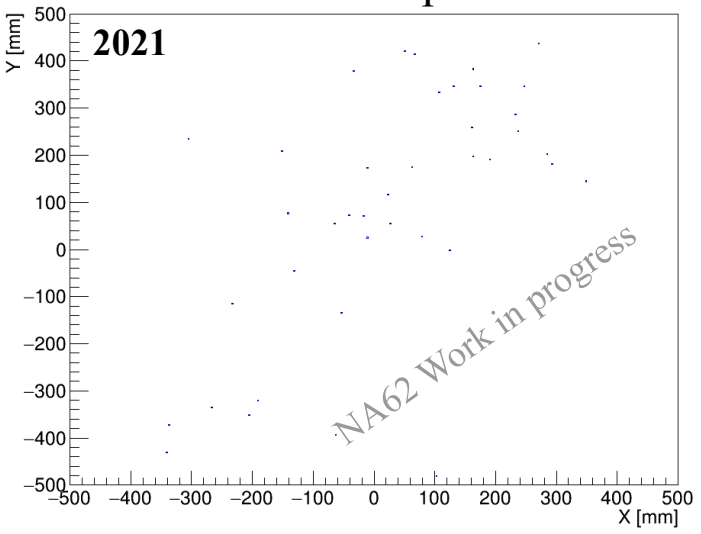


O(200) background reduction, despite higher intensity!

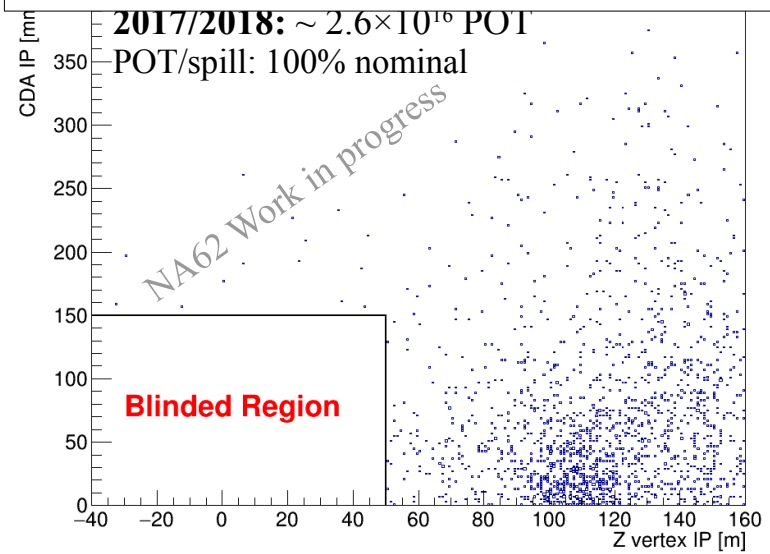
NA62-dump: 2021 data taking

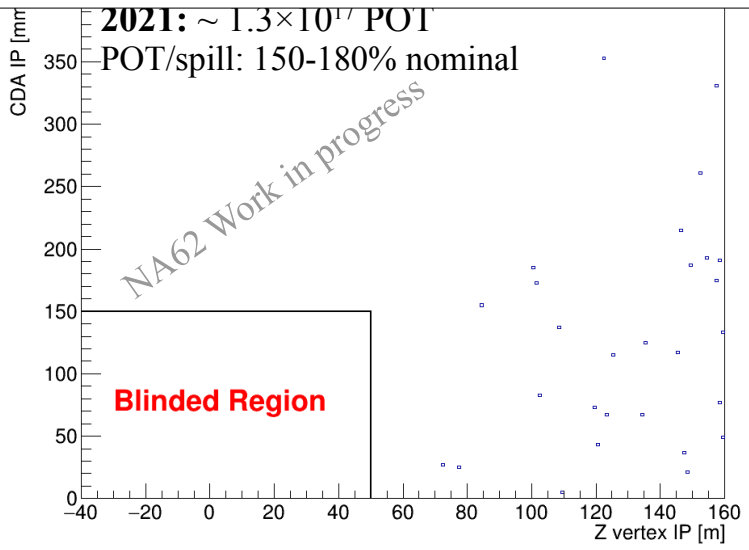
Extrapolated (x,y) of $\mu^+\mu^-$-pair at final collimator z plane





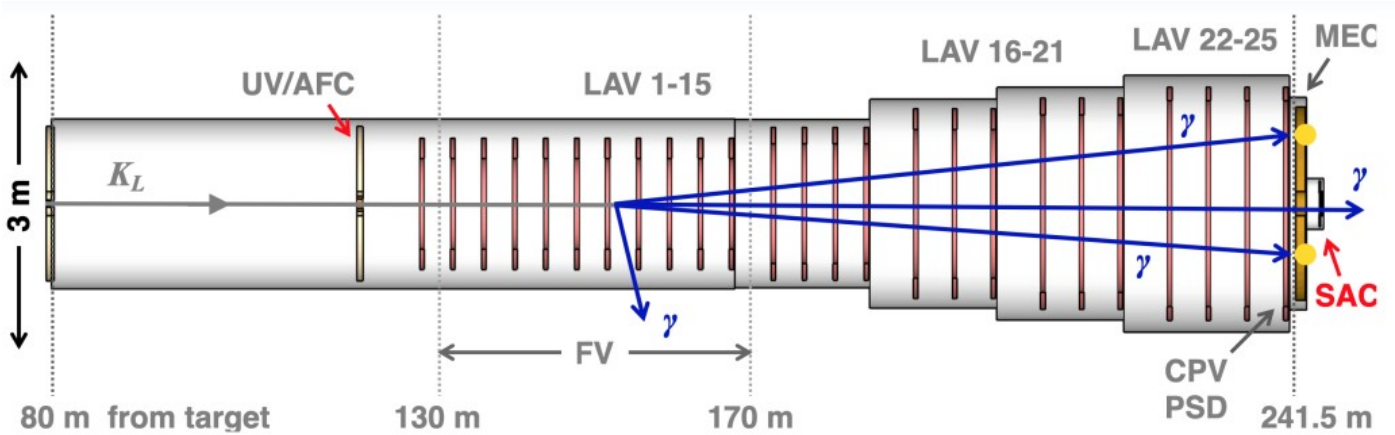
Residual beam-related component now removed!





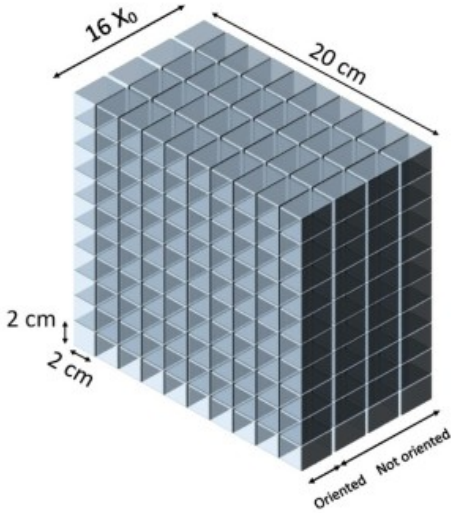
→ Excellent prospects for post-LS3 beam dump

KLEVER: Small-angle calorimeter



Small-angle calorimeter system (SAC) operates inside neutral beam

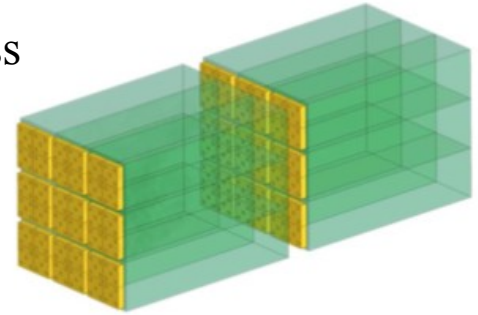
- Rejects γs from $K_L \rightarrow \pi^0\pi^0$ escaping through beam hole
- As insensitive as possible to 430 MHz of beam neutrons



Baseline solution:

Ultra-fast, heavy Cerenkov calorimeter

- $\sigma_t < 100$ ps, 2-pulse separation at ~ 1 ns
- Possibly exploiting coherent interactions in crystals to reduce thickness



Specific implementation:

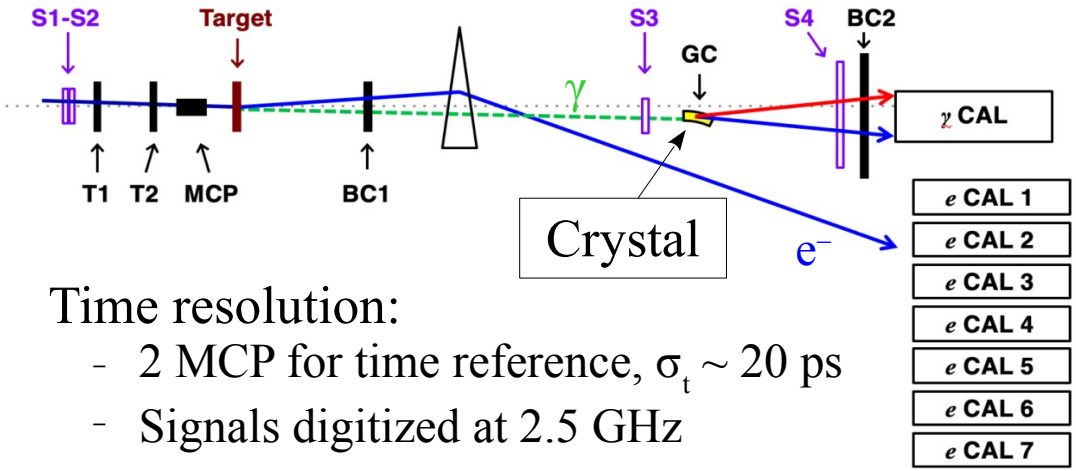
CRYLIN - R&D proposal for muon collider ECAL

- 10×10×40 mm^3 crystal cells
- 4 SiPMs per crystal, read out in pairs

KLEVER: Test beam at SPS H2 (Aug 2021)

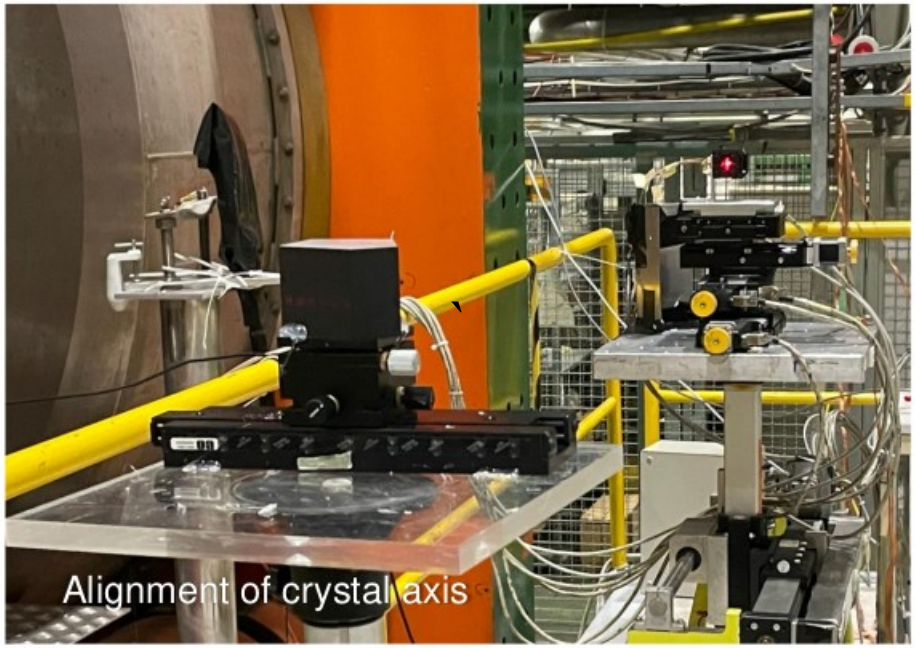
Test beam setup:

- **PbF_2 with CRYLIN module 0**
  - e^- 20-120 GeV (6 points)
  - γ tagged from 120 GeV e^-
  - μ 150 GeV, parallel
- **PWO III, standalone**
  - γ tagged from 120 GeV e^-

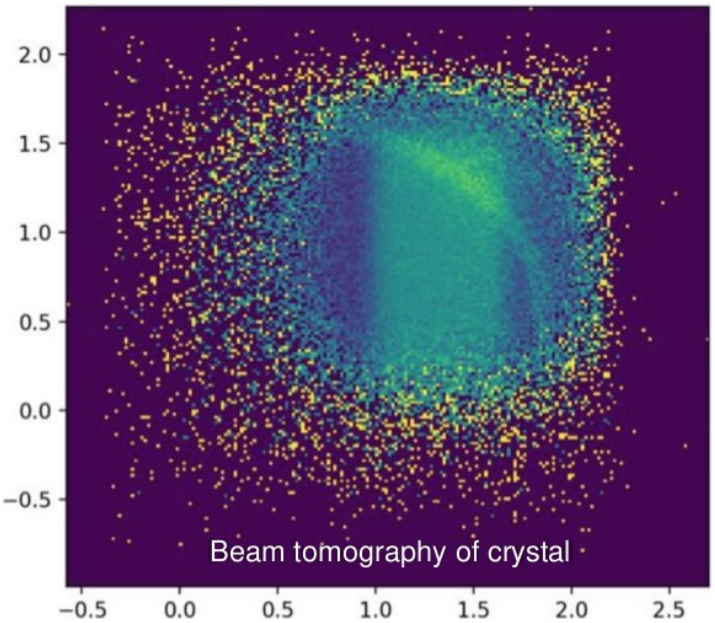


Time resolution:
- 2 MCP for time reference, $\sigma_t \sim 20$ ps
- Signals digitized at 2.5 GHz

Light yield vs angular alignment
→ Full study with tagged γ for each crystal



Joint participation in test beam by KLEVER, MUCOL & STORM



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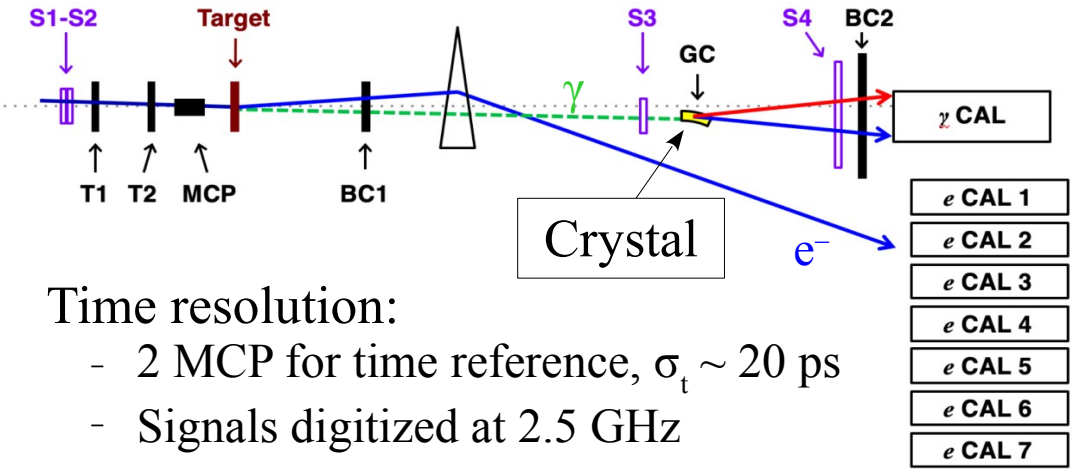
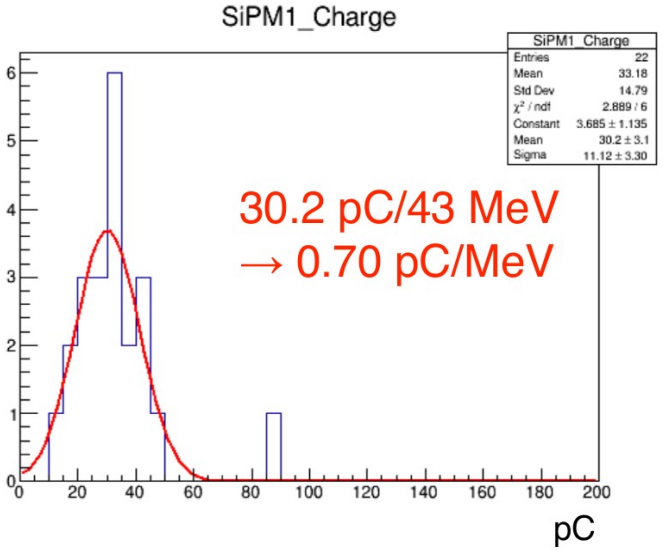


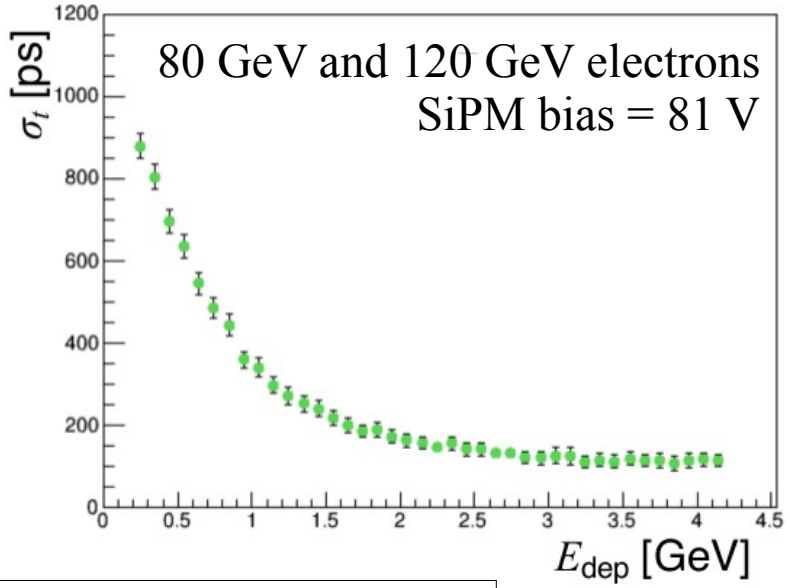
Charge/Energy calibration
using parallel 150 GeV muons



43 MeV = energy released by MIPs
in 4 cm material (verified with MC)

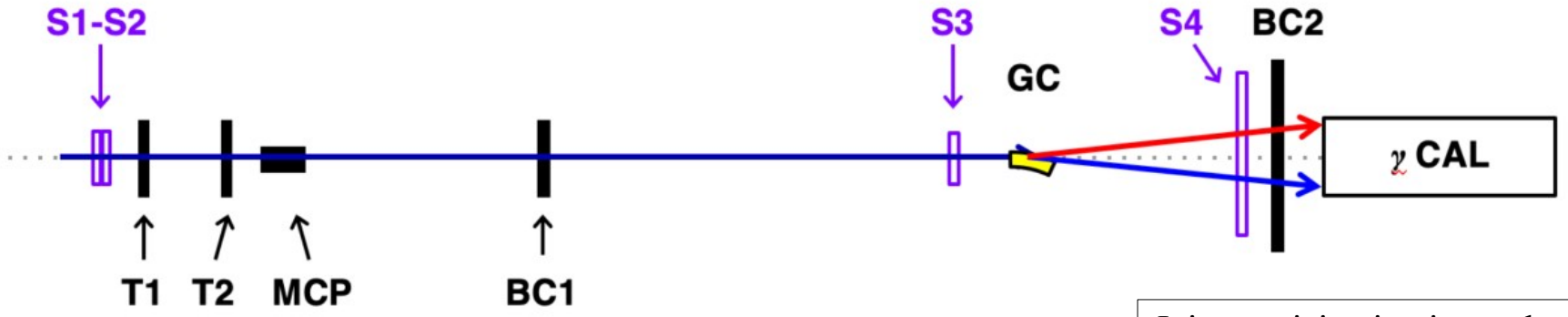
Time resolution:

- 2 MCP for time reference, $\sigma_t \sim 20$ ps
- Signals digitized at 2.5 GHz



Preliminary results:
Stochastic term < 100 ps at 1 GeV
Full angular study with tagged γ ongoing

KLEVER: Plans for 2022



Joint participation in test beam by KLEVER, MUCOL & STORM

Test setup:

- Simpler setup compared to 2021: only electrons (+ MIPs), no tagged γs
- Faster electronics (10 ns fall time)
- **Two 3×3 CRYLIN test modules**
- Have all needed PbF_2 crystals
- Possibly load one 3×3 module (9 crystals, 10×10×40 mm^3) with PWO-III instead of PbF_2

Test objectives:

1) Perform **complete operational test**, possibly including cooling
2) Test **cluster reconstruction** capability, especially for time resolution
3) Conceptual test of **longitudinal segmentation**
4) Possible to study **angular effects** by aligning beam with axis of central crystal

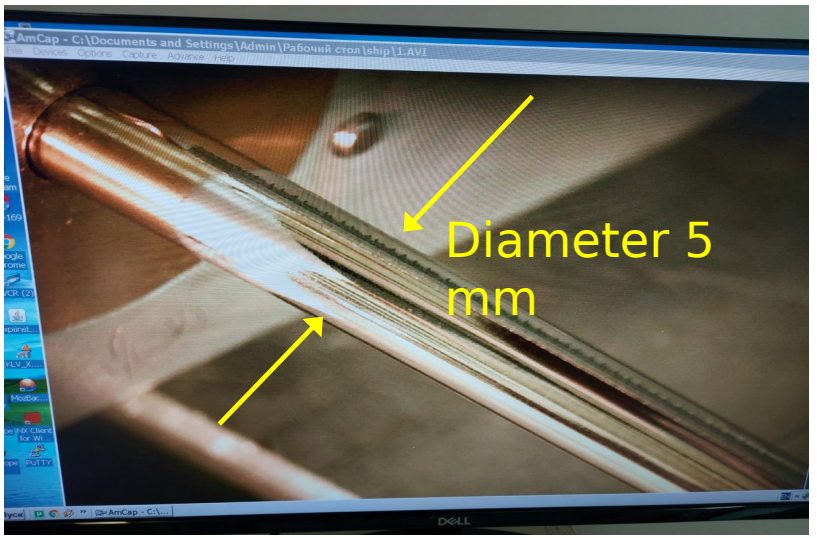
Beam time request (1 week, H2/H4 @ SPS) submitted

K^+ phase: STRAW spectrometer upgrade

- **Main differences wrt NA62 STRAW spectrometer:**
  - **Smaller straw diameter**: 5 mm (instead of 9.8 mm)
    → Improved trailing time resolution:
    ~ 6 ns (single straw), < 1 ns (track)
    → Rate capability increased by factor 6-8, due to geometry and shorter drift time
  - **Reduced straw wall thickness:**
    12 μm or 19 μm (instead of 36 μm)
    → Total material budget:
    1.1%X_0 or 1.5%X_0 (instead of 1.7%X_0)
    → less multiple scattering

NA62 straw chamber

- **Pre-production tests:**
  - Au/Cu coated Mylar film of 12 μm and 19 μm have been procured
  - 5 m long straws with a 19 μm wall thickness **have successfully been produced through ultrasonic welding**



K^+ phase: New Si detector project

- **Current NA62 beam spectrometer – GTK:**
  - 4 stations of Si pixel detectors:
    planar pixel sensor 300×300×200 μm^3
  - Using TDCpix readout chip
  - Time resolution per hit: σ_t ~130 ps

- **New project at TRIUMF:**
  Combine
  NA62 test station (TDCpix Telescope)
  with ~70 ps time resolution
  &
  EUDET pixel telescope
  with < 5 μm spatial resolution

  - Tests of **advanced new Si pixel sensors**
  - <u>Possible short-term impact:</u>
    Identify a new sensor that would improve the GTK time resolution using the existing TDCpix ASIC
    → opportunity to test in NA62 before LS3

NA62 TDCpix Telescope

$K_S \to \mu^+\mu^-/K_L \to \mu^+\mu^-$ feasibility study

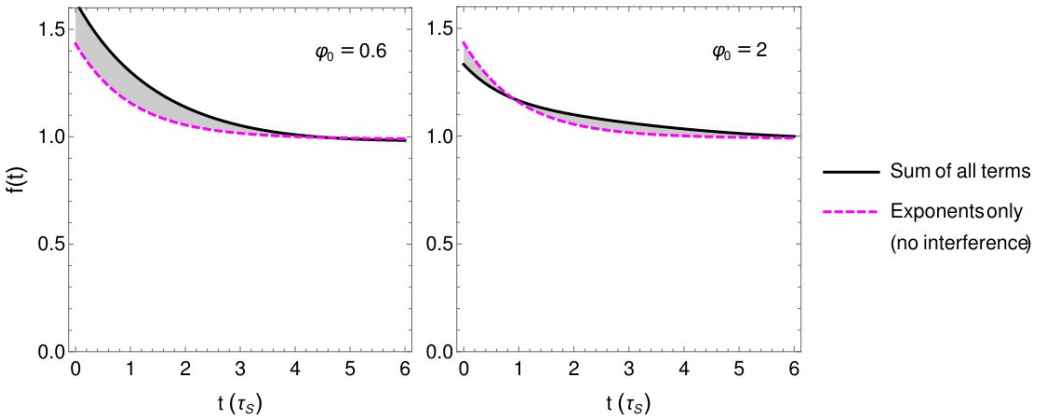
Measurement of interference between $K_S \to \mu^+\mu^-$ and $K_L \to \mu^+\mu^-$:
feasibility study started, triggered by a recent publication by A. Dery et al. [JHEP07(2021)103]

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\ell=0} = \mathcal{B}(K_L \to \mu^+\mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{int}}{C_L}\right)^2$$

SM computation:

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\ell=0} \approx 1.64 \cdot 10^{-13} \times \left|\frac{V_{ts}V_{td}\sin\theta_{ct}}{1.33 \cdot 10^{-4}}\right|^2$$

Measurement of C_{int} = clean measurement of
$|V_{ts}V_{td}\sin\theta_{ct}| = |V_{ts}V_{td}\sin(\beta+\beta_s)| \approx A^2\lambda^5\bar{\eta}$



- <u>Considerations for the required kaon flux:</u>
  - K_L production from previous studies for KLEVER
  - $BR(K_L \to \mu^+\mu^-) \sim 7\times10^{-9}$
  - Interference term ~ 12% of the K_L rate (theory estimate)
  - Fraction of useful $K \to \mu^+\mu^-$ decays (first 6 K_S lifetimes) ~ 1%

→ **Requirements on POT similar to KLEVER**

- <u>Preliminary considerations based on Toy MC:</u>
  - Present NA62 STRAW spectrometer satisfies momentum and angular resolution requirements
  - <u>Main challenges:</u>
    - Design of the target area and the collimation system (synergy with KLEVER)
    - High particle rates at detectors

Conclusions

- **Integrated high-intensity kaon programme at the SPS**
  - Common upgrades for intensity and detectors between projects
  - Long term physics programme in NA-ECN3, from LS3 to ~ 2039
  - Future high-intensity kaon programme strongly relies on K12 target/TAX upgrade

- **NA62-dump 2021 data taking:**
  - $>10^{17}$ POT collected in 2021 by NA62-dump
  - Optimised sweeping leads to O(200) background reduction
    → Excellent prospects for post-LS3 beam dump

- **Detectors R&D:**
  - Test beam for KLEVER small-angle calorimeter
    → Promising preliminary results, further beam tests in 2022
  - K^+ phase:
    - New STRAW spectrometer: promising pre-production tests
    - New Si detector project, possible upgrade of NA62 GigaTracker

- **Sensitivity studies:**
  - Feasibility study of $K_S \to \mu^+\mu^-/K_L \to \mu^+\mu^-$ interference started