# Rare kaon decay experiments at CERN

Snowmass 2021 - Rare and Precision Frontier
Virtual Town Hall Meeting, 02 October 2020

Matthew Moulson – INFN Frascati

**For the NA62 Collaboration and KLEVER Project**

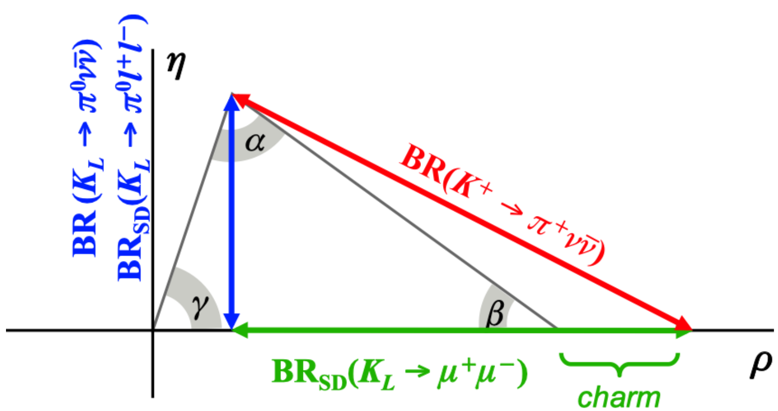
# New physics in $K \to \pi\nu\bar{\nu}$ decays

**Extremely rare decays with rates very precisely predicted in SM:**

| | SM predicted rates* | Experimental status (Sep 2019) |
|---|---|---|
| $K^+ \to \pi^+\nu\bar{\nu}$ | **BR = (8.4 ± 1.0) × 10$^{-11}$** | 7 evts from BNL787, 3 evts from **NA62**<br>Goal: BR to 20% from **NA62** by end of Run 3 |
| $K_L \to \pi^0\nu\bar{\nu}$ | **BR = (3.4 ± 0.6) × 10$^{-11}$** | Only limits at present<br>**KOTO** (JPARC): ~ few SM events by 2025 |

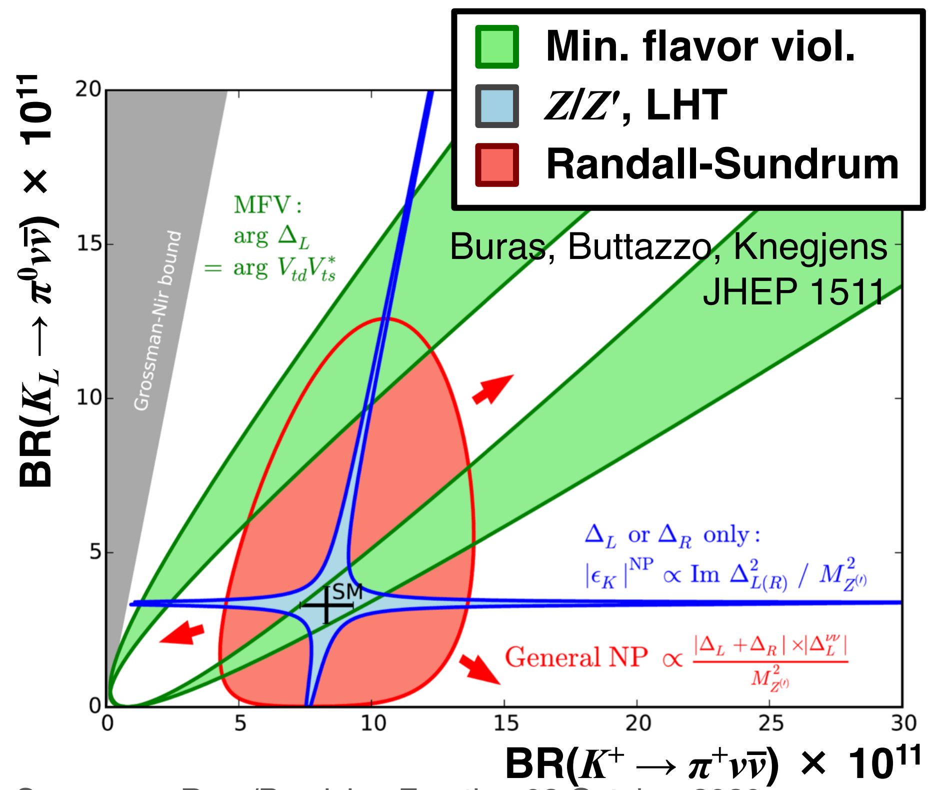
Buras et al, JHEP 1511*

**$K^+$ and $K_L$ BRs completely determine unitarity triangle:**




**New physics affects $K^+$ and $K_L$ BRs differently**

Can discriminate among different models



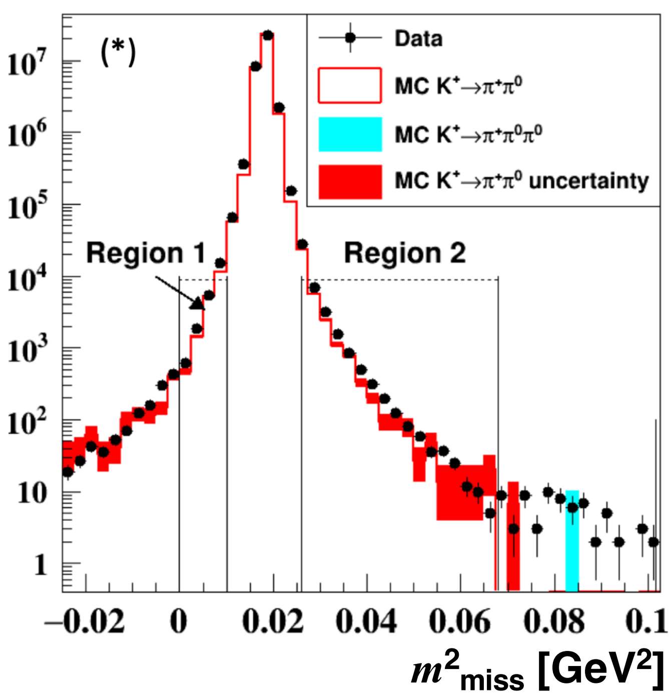
# Analysis of 2018 data

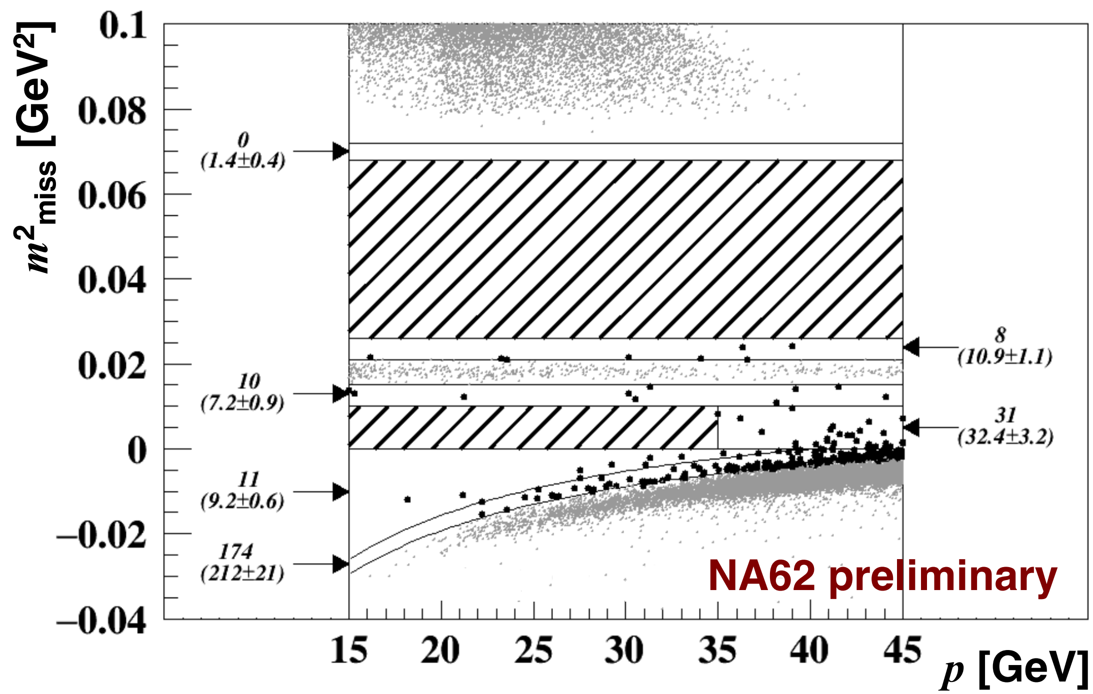
## Preliminary (ICHEP 2020)

**SES: (1.11 ± 0.07) × $10^{-11}$**

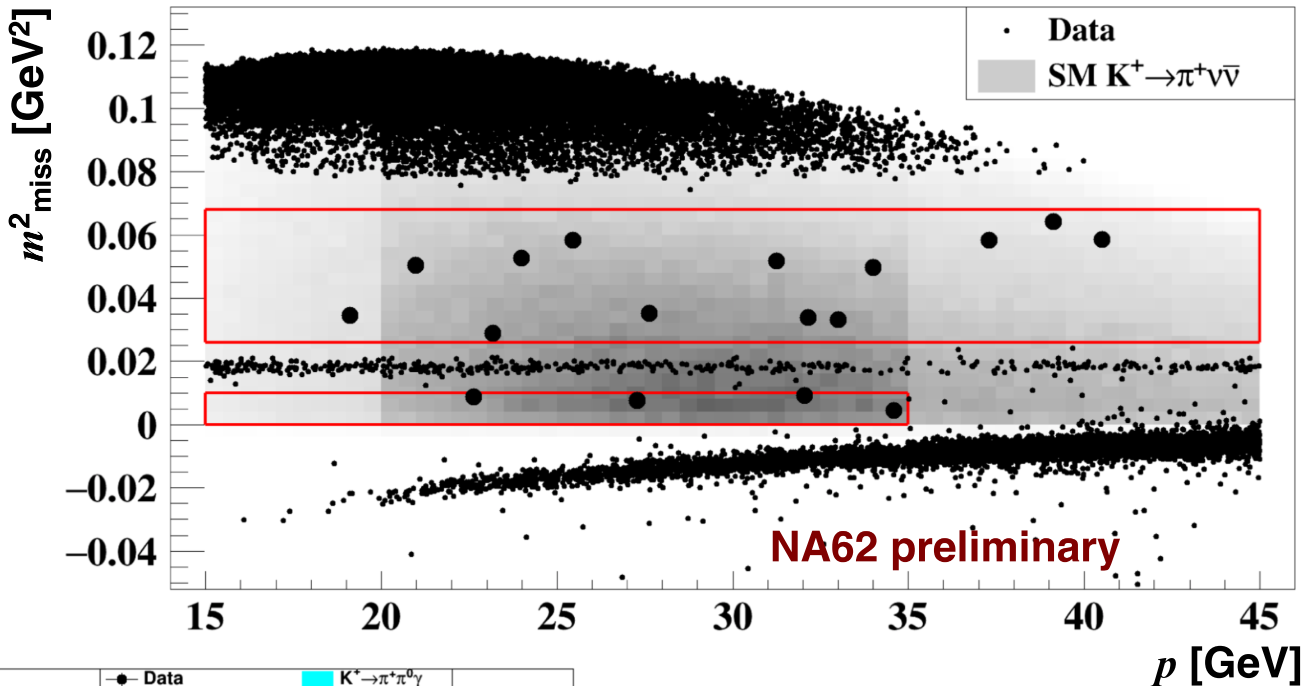
- $\pi^+\pi^0$, $\mu^+\nu$, $\pi^+\pi^-\pi^+$ backgrounds estimated from tails of $m^2_{\text{miss}}$ distribution
- Upstream background estimated by inverting $K^+ \to \pi^+$ matching cuts

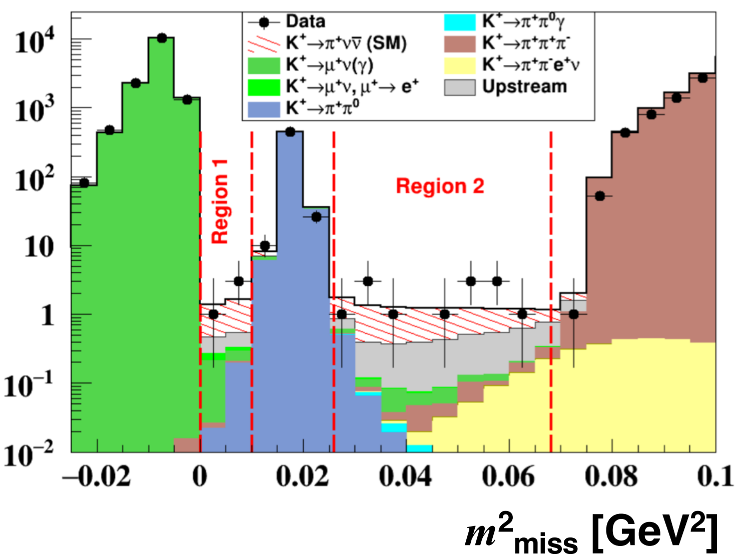
| Source | Expected events |
|---|---|
| **$K^+ \to \pi^+\nu\nu$ (SM)** | **$7.58(40)_{\text{sys}}\,(75)_{\text{ext}}$** |
| $K^+ \to \pi^+\pi^0(\gamma_{\text{IB}})$ | 0.75(4) |
| $K^+ \to \mu^+\nu(\gamma_{\text{IB}})$ | 0.49(5) |
| $K^+ \to \pi^+\pi^-e^+\nu$ | 0.50(11) |
| $K^+ \to \pi^+\pi^-\pi^+$ | 0.24(8) |
| Upstream background | $3.30^{+0.98}_{-0.73}$ |
| **Total background** | **$5.28^{+0.99}_{-0.74}$** |



# Preliminary results from 2018 data




**Preliminary (ICHEP 2020):**

- SES: $(1.11 \pm 0.07) \times 10^{-11}$
- Expected signal: $7.6 \pm 0.9$ evts
- Expected bkg: $5.3^{+1.0}_{-0.7}$ evts
- **17 events observed!**

# NA62 through 2024

## Summary of NA62 Run 1 (2016-2018):

- **Expected signal (SM): 10 events**
- **Expected background: 7 events**
- **Total observed: 20 events**
- $3.5\sigma$ signal significance
- Most precise measurement to date

$$\mathbf{BR}(K^+ \to \pi^+ \nu\nu) = (11.0\ ^{+4.0}_{-3.5\ \mathrm{stat}} \pm 0.3_{\mathrm{syst}}) \times 10^{-11}$$

## Plans for NA62 Run 2 (from LS2 to LS3):

NA62 to resume data taking in July 2021

Key modifications to reduce background from upstream decays and interactions:

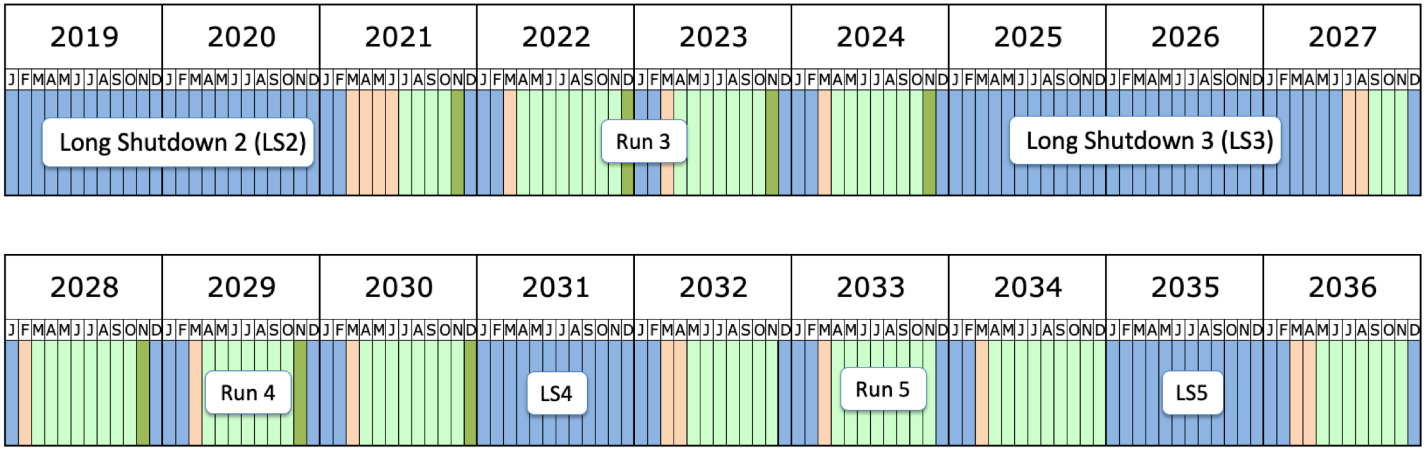
- Rearrangement of beamline elements around GTK achromat
- Add $4^{th}$ station to GTK beam tracker
- New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

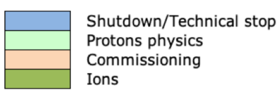
Run at higher beam intensity (70% → 100%)

**Expect to measure BR($K^+ \to \pi^+ \nu\nu$) to better than 20%**

# Fixed target runs at the SPS

Fixed target runs planned to accompany LHC running through 2036

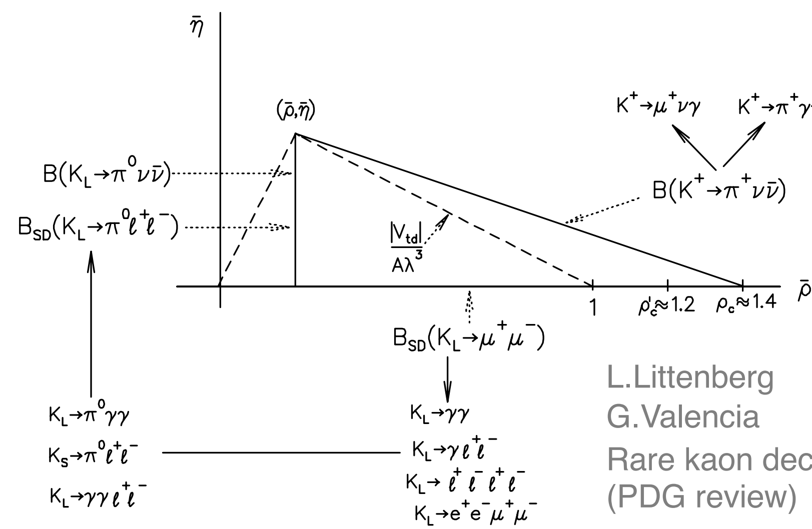



https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

There is an opportunity at the SPS for an integrated program to pin down new physics in kaon decays

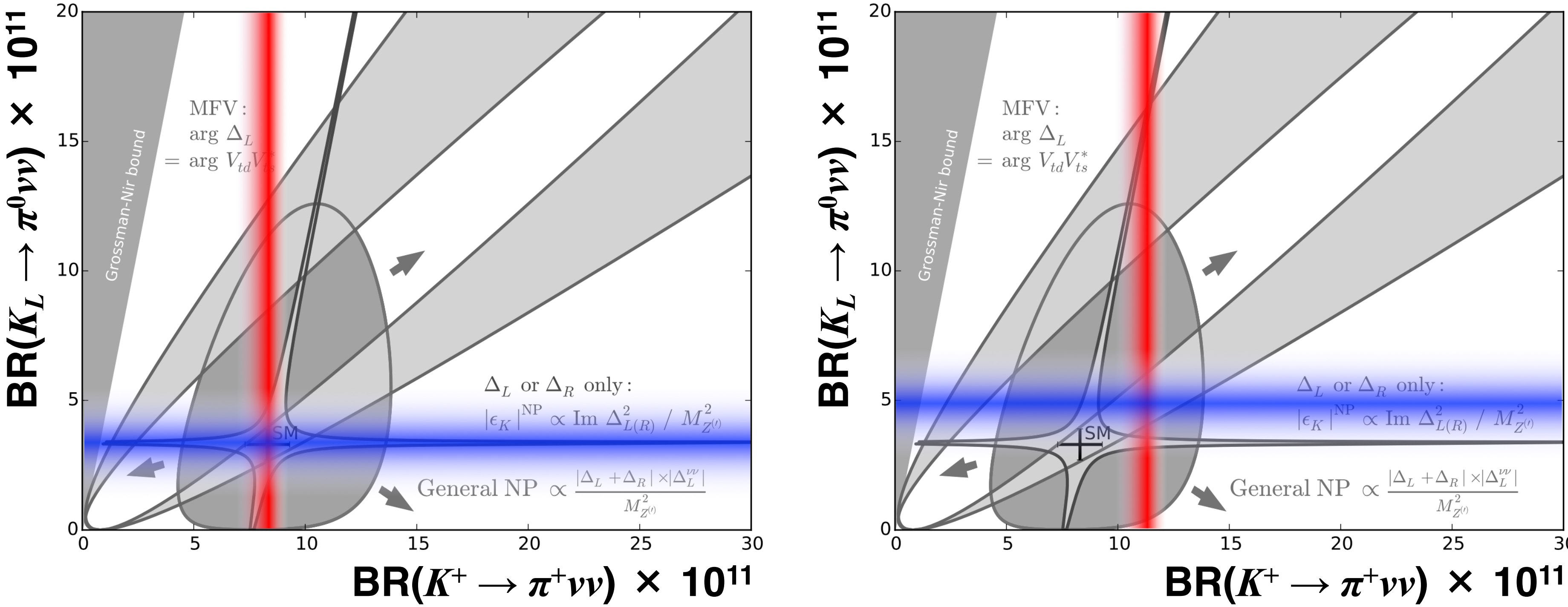
Measurement of all rare kaon decay modes—charged and neutral—to give clear insight about the flavor structure of new physics




L.Littenberg
G.Valencia
Rare kaon decays
(PDG review)

# Physics opportunities in the kaon sector

Precision measurements of $K \to \pi\nu\nu$ BRs can provide model-independent tests for new physics at mass scales of up to O(100 TeV)




- BR($K^+ \to \pi^+\nu\nu$) = **$BR_{SM}$** with $\delta$BR = **5%**
- BR($K_L \to \pi^0\nu\nu$) = **$BR_{SM}$** with $\delta$BR = **20%**

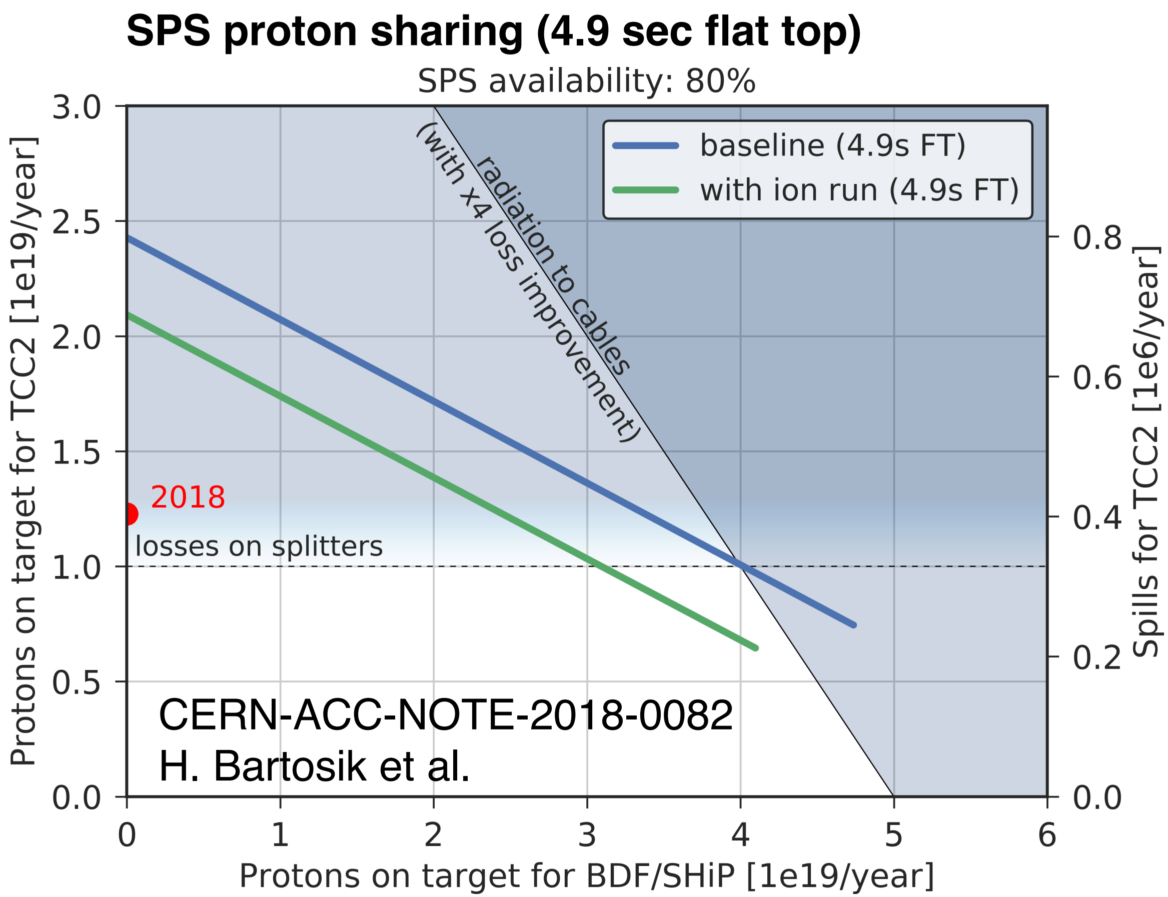
- BR($K^+ \to \pi^+\nu\nu$) = **1.33 $BR_{SM}$** with $\delta$BR = **5%**
- BR($K_L \to \pi^0\nu\nu$) = **1.50 $BR_{SM}$** with $\delta$BR = **20%**

# High-intensity kaon beams at the SPS

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

- $K^+ \to \pi^+\nu\nu$
  **4x increase**
- $K_L \to \pi^0\nu\nu$
  **6x increase**

with respect to present primary intensity




- **A kaon experiment at 6x present intensity is compatible with a robust North Area program**
- **With small compromises, BDF + a high intensity kaon experiment + North Area test beam program can run simultaneously**

# High-statistics $K^+ \to \pi^+ \nu\nu$ at CERN

**The NA62 decay-in-flight technique is now well established!**

- Background estimates validated by in-depth study with data and MC
- Lessons learned in 2016-2018 will be put in action in 2021-2024

**Possible next step:**

**An experiment at the SPS to measure BR($K^+ \to \pi^+ \nu\nu$) to within ~5%!**

Requires 4x increase in intensity → equal to present limit with charged secondary beam (after major upgrades)

**Key challenges:**

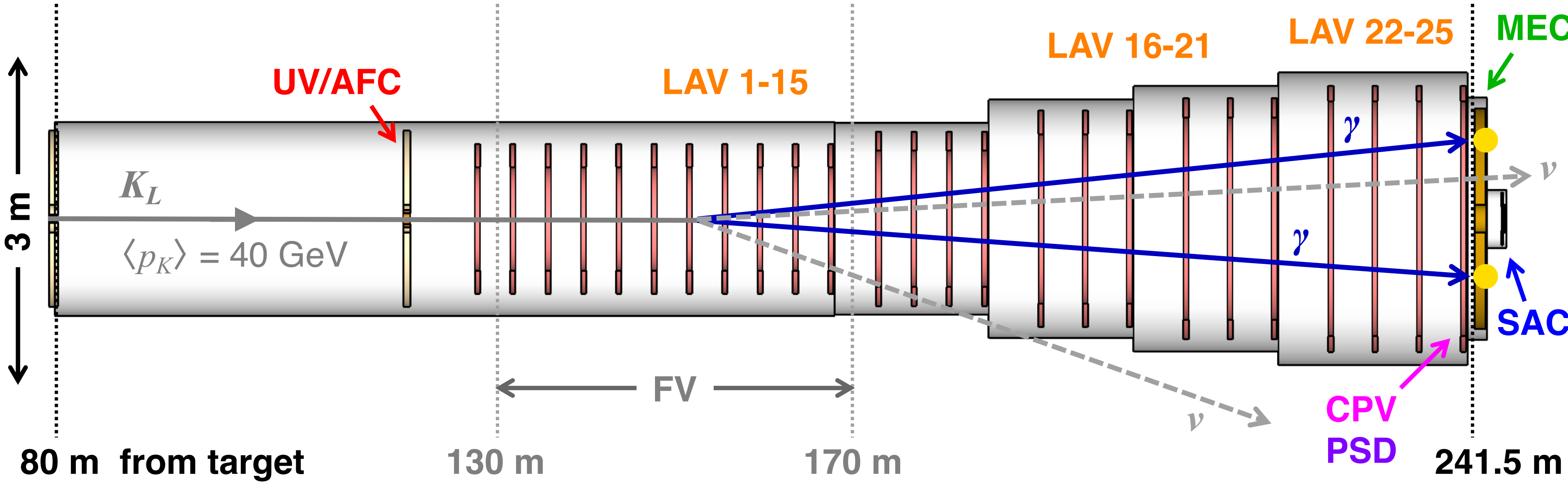
- Require much improved time resolution to keep random veto rate under control
- Must maintain other key performance specifications at high-rate:
  - Space-time reconstruction, low material budget, single photon efficiencies, control of non-gaussian tails, etc.
- For example: $\sigma_t$ ~20 ps time resolution for Cerenkov detectors for beam tagging and secondary PID

**Synergies to be explored:**

- Challenges often aligned (sometimes more stringent than) to High Luminosity LHC projects and next generation flavor/dark matter experiments

# A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS? KLEVER

400-GeV SPS proton beam on Be target at $z$ = **0 m**




**KLEVER target sensitivity:**
**5 years starting Run 4**

**~60 SM $K_L \to \pi^0 \nu\nu$**
**$S/B$ ~ 1**

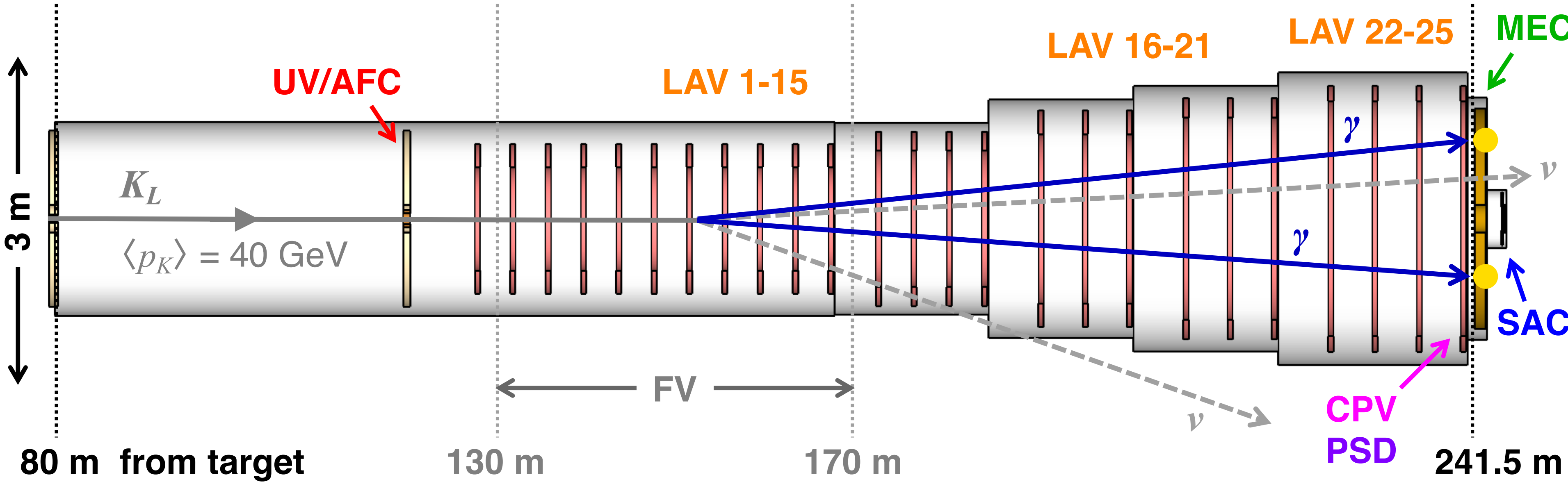
**$\delta$BR/BR($\pi^0 \nu\nu$) ~ 20%**

- High-energy experiment: Complementary to KOTO
- Photons from $K_L$ decays boosted forward
  - Makes photon vetoing easier - veto coverage only out to 100 mrad
- Roughly same vacuum tank layout and fiducial volume as NA62

# A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS

KLEVER

400-GeV SPS proton beam on Be target at $z$ = **0 m**

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**Main detector/veto systems:**

| | |
|---|---|
| **UV/AFC** | Upstream veto/Active final collimator |
| **LAV1-25** | Large-angle vetoes (25 stations) |
| **MEC** | Main electromagnetic calorimeter |
| **SAC** | Small-angle vetoes |
| **CPV** | Charged particle veto |
| **PSD** | Pre-shower detector |

# Integrated program with $K^+$ and $K_L$ beams

Availability of high-intensity $K^+$ and $K_L$ beams at the SPS:
Important physics measurements at boundary of NA62 and KLEVER!

**Example: Experiment for rare $K_L$ decays with charged particles**

- $K_L$ beamline, as in KLEVER
- Tracking and PID for secondary particles, as in NA62

**Physics objectives:**

- $K_L \to \pi^0 \ell^+ \ell^-$
  Excellent $\pi^0$ mass resolution – look for signal peak over Greenlee background
- Lepton-flavor violation in $K_L$ decays
- Radiative $K_L$ decays and precision measurements
- $K_L$ decays to exotic particles

**Will provide valuable information to characterize neutral beam**

- Example: Measurement of $K_L$, $n$, and $\Lambda$ fluxes and halo
- Experience from KOTO and studies for KLEVER show this to be critical!

**Just getting started!**

# Outlook

**There is an opportunity at the SPS for an integrated program to pin down new physics in kaon decays**

**We are working towards a proposal for a high-intensity kaon facility with three phases, with same primary beamline and interchangeable detectors**

1. "NA62x4": $K^+ \to \pi^+ \nu\nu$
2. KLEVER: $K_L \to \pi^0 \nu\nu$
3. Intermediate stage: $K_L$ beam + charged-particle tracking/PID:
   $K_L \to \pi^0 \ell^+ \ell^-$; LFV and radiative $K_L$ decays

**We plan to submit a contributed paper as input to the Snowmass meeting**

**We hope that participation in the Snowmass process will help to consolidate the community interested in rare kaon decay experiments**

- CERN, J-PARC, USA: Highlight importance of kaon next-generation kaon experiments in respective communities
- Examples of opportunities for discussion and high-level cooperation:
  - Detector ideas and R&D: Calorimeters with photon vectoring; in-beam vetoes; signal processing and readout
  - Simulation: Benchmarking for MC and event generators; techniques for generation of large samples

# Additional information

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# Preliminary results: 2016-2018 data

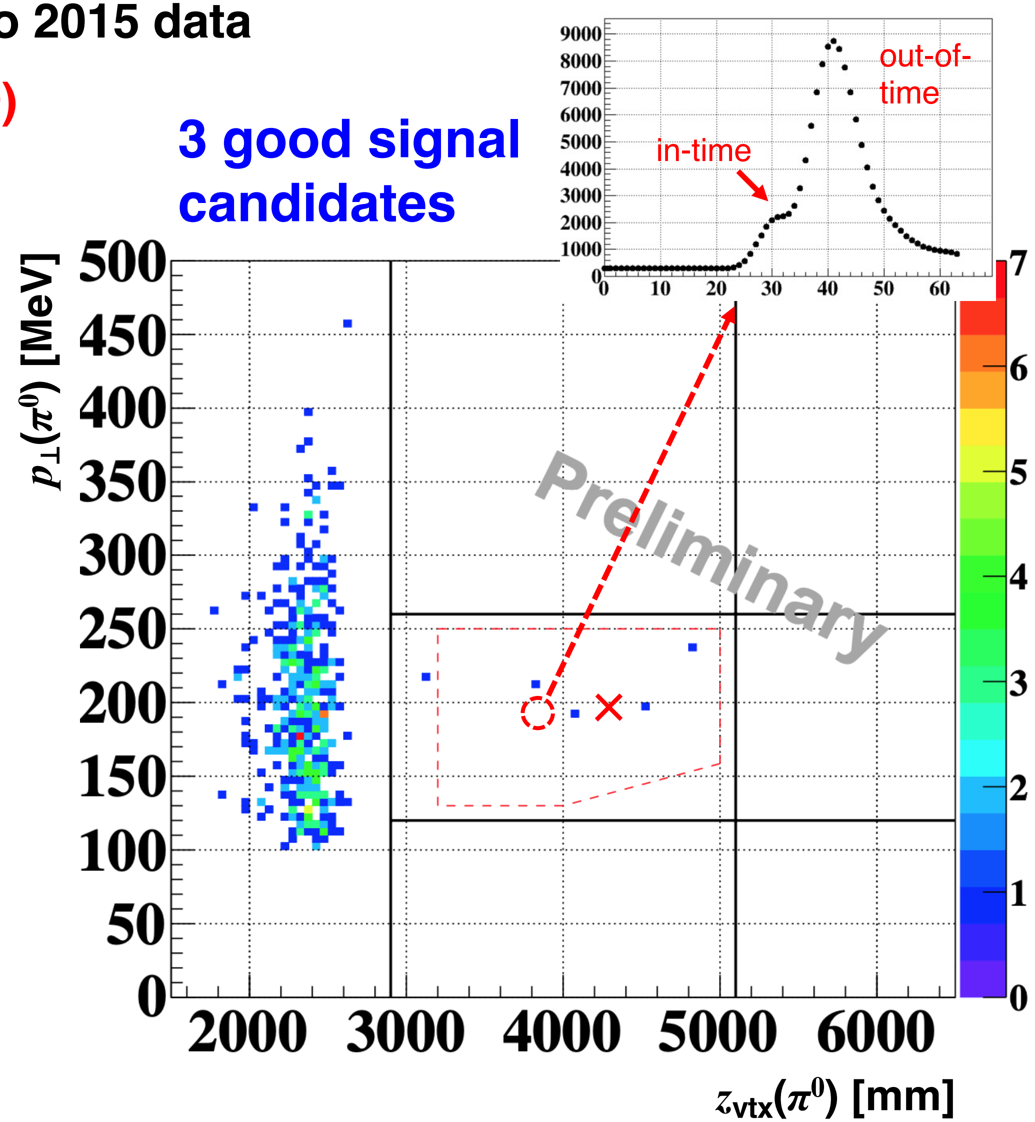
**Several important detector upgrades and analysis improvements compared to 2015 data**

**KOTO preliminary (KAON, Sep 2019)**
**SES: 6.9 × $10^{-10}$** (0.05 SM evts)
**Expected bkg: 0.05 ± 0.02 evts**

**New background estimates**
Preliminary (ICHEP 2020)

| Source | Expected (68%CL) |
|---|---|
| $K_L \to \pi^0\pi^0$ | < 0.05 |
| $K_L \to \pi e \nu$ overlap pulse | < 0.05 |
| $K_L \to ee\gamma$ | < 0.05 |
| $K_L \to \gamma\gamma$ core | < 0.06 |
| $K_L \to \gamma\gamma$ halo | < 0.10 |
| $K^+ \to \pi^0 e^+ \nu$ | 0.90 ± 0.27 |
| $K^+ \to \pi^+ \pi^0$ | 0.09 ± 0.09 |
| $K^+ \to \pi^0 \mu^+ \nu$ | < 0.12 |
| $\pi^0$ from $n$ in CV | < 0.05 |
| **Total** | **1.05 ± 0.28** |

**3 good signal candidates**




**KOTO will reach SM SES by mid-decade: Step-2 required for BR mmt**

# High-intensity proton beam study

**Conclusions from PBC Conventional Beams working group**

| Issue | Approach |
|---|---|
| **Proton availability** | SHiP supercycle = $4 \times 10^{19}$ pot/yr with $1 \times 10^{13}$ ppp for users<br>KLEVER requires $1 \times 10^{19}$ pot/yr (25% of SHiP) |
| **Extraction losses** | Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) workshop, 9-11 November 2017:<br>https://indico.cern.ch/event/639766/ |
| **Beam loss on T4** | Vertical by-pass to increase T4 → T10 transmission to 80% |
| **Equipment protection** | Interlock to stop SPS extraction during P0Survey reaction time |
| **Ventilation in ECN3** | Preliminary measurements indicate good air containment<br>Comprehensive ventilation system upgrade not needed |
| **ECN3 beam dump** | Significantly improved for NA62<br>Need to better understand current safety margin |
| **T10 target & collimator** | Thermal load on T10 too high → Use CNGS-like target?<br>Dump collimator will require modification/additional cooling |
| **Radiation dose at surface above ECN3** | 8 mrad vertical targeting angle should help to mitigate<br>Preliminary results from FLUKA simulations<br>Proposed target shielding scheme appears to be adequate<br>Mixed mitigation strategy may be needed for forward muons |

# Experimental challenges: STRAW

## NA62 straw chambers

- Straw diameter: 9.8 mm
- Tungsten wire, 30 μm diameter:
- Mylar straws: 36 wall μm thickness
- Hit leading-time resolution: 3-4 ns
- Hit trailing-time resolution: ~30 ns
- Maximum drift time: ~150 ns
- Gas: Ar+$CO_2$ (70:30)
- 4 chambers, 7168 straws
- Operation in vacuum
- Material budget: 1.7% $X_0$


**Design effort started at CERN**

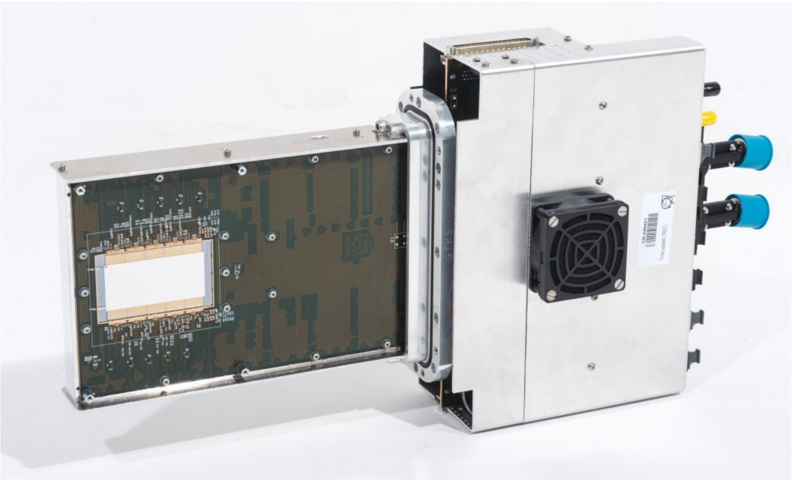
## Straw chambers for 4x intensity

- **Main feature: Straw diameter ~5 mm**
- **Improved trailing-time resolution: ~6 ns (per straw)**
- **Smaller maximum drift time: ~80 ns**
- Layout: 4 chambers, ~21000 straws
- Decreased straw wall thickness: ~20 μm, with copper and gold plating
- Material budget: 1.5% $X_0$

# Experimental challenges: GTK

## NA62 Gigatracker

- Strict requirements on material budget: 0.5% $X_0$ per tracking plane
- Use minimum number of planes, with time mmts to constrain event reconstruction
- 200 μm planar silicon sensors
- TDCPix readout chips
- Cooled with silicon micro-channel plates
- Time resolution with beam = 120 ps @250V



$$\sigma_t = \sqrt{\sigma^2_{\text{elec+TDC}} + \sigma^2_{\text{field}} + \sigma^2_{\text{straggling}}}$$

## GTK for 4x intensity

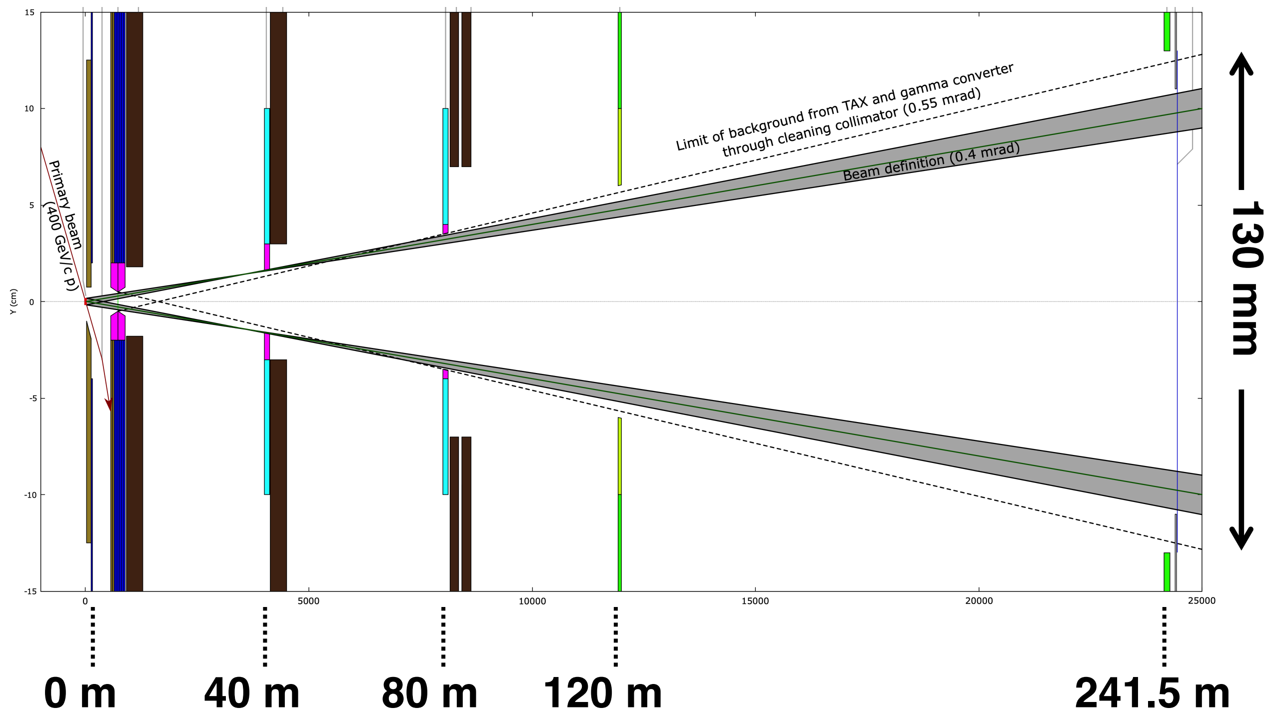
- **Time resolution < 50 ps per plane**
  **No non-gaussian tails!**
- Pixel size: < 300 × 300 μm$^2$
- Efficiency: > 99% (incl. fill factor)
- Material budget : 0.3-0.5% $X_0$
- Beam intensity : 3 GHz over ~3x6 cm$^2$
- Maximum local intensity : 8 MHz/mm$^2$
- Radiation resistance: 2.3x10$^{15}$ $n$ eq/cm$^2$/yr (200 days)

- **Continue to improve planar sensors**
- **Possible synergies with USFD (LGAD) and TimeSpot (3D trench) projects**

# Neutral beam and beamline

$K_L$EVER

- **400 GeV $p$ on 400 mm Be target**
- **Production angle $\theta$ = 8.0 mrad**
- **Solid angle $\Delta\theta$ = 0.4 mrad**
- **2.1 × $10^{-5}$ $K_L$/pot in beam**
- **$\langle p(K_L) \rangle$ = 40 GeV**
- Probability for decay inside FV ~ 4%
- Acceptance for $K_L \to \pi^0 \nu\nu$ decays occurring in FV ~ 5%




- **4 collimation stages** to minimize neutron halo, including beam scattered from absorber
- **Photon absorber** in dump collimator

NB: Choice of higher production angle under study to decrease rate of $\Lambda \to n\pi^0$ decays in detector:

Possible changes to beamline configuration and experimental layout

# Shashlyk calorimeter with spy tiles

**Main electromagnetic calorimeter (MEC):**

**Fine-sampling shashlyk based on PANDA forward EM calorimeter produced at Protvino**

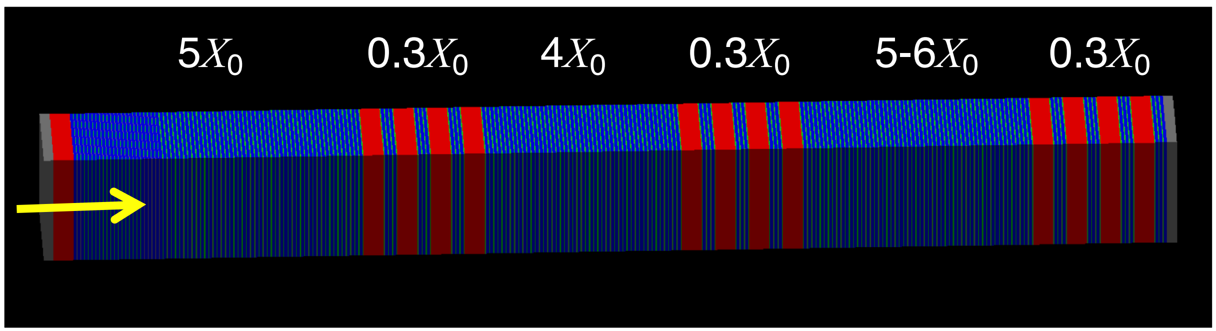
0.275 mm Pb + 1.5 mm scintillator

**PANDA/KOPIO prototypes:**

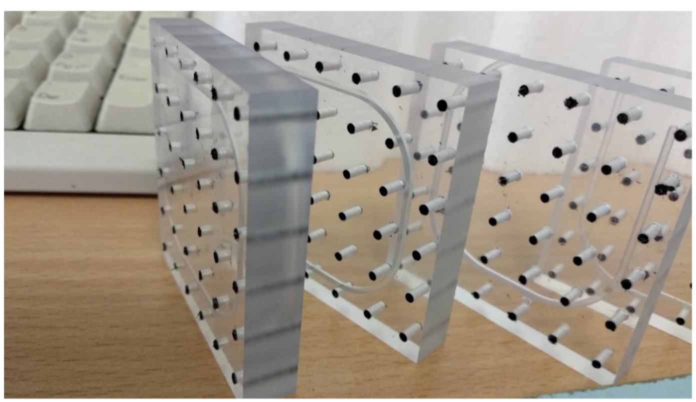
- $\sigma_E/\sqrt{E}$ **~ 3%** $/\sqrt{E}$ (GeV)
- $\sigma_t$ **~ 72 ps** $/\sqrt{E}$ (GeV)
- $\sigma_x$ **~ 13 mm** $/\sqrt{E}$ (GeV)

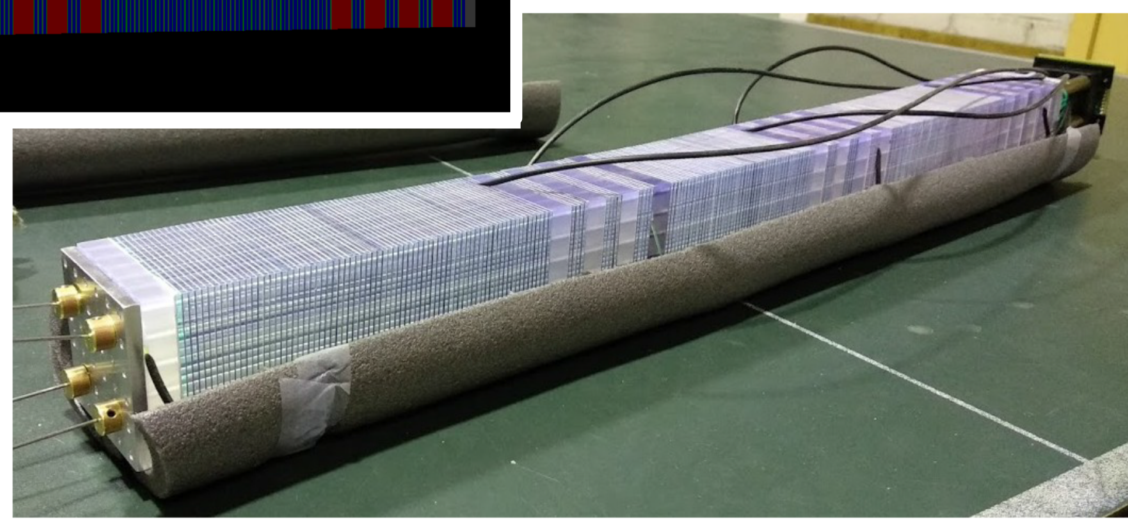
**New for KLEVER: Longitudinal shower information from spy tiles**

- PID information: identification of $\mu$, $\pi$, $n$ interactions
- Shower depth information: improved time resolution for EM showers

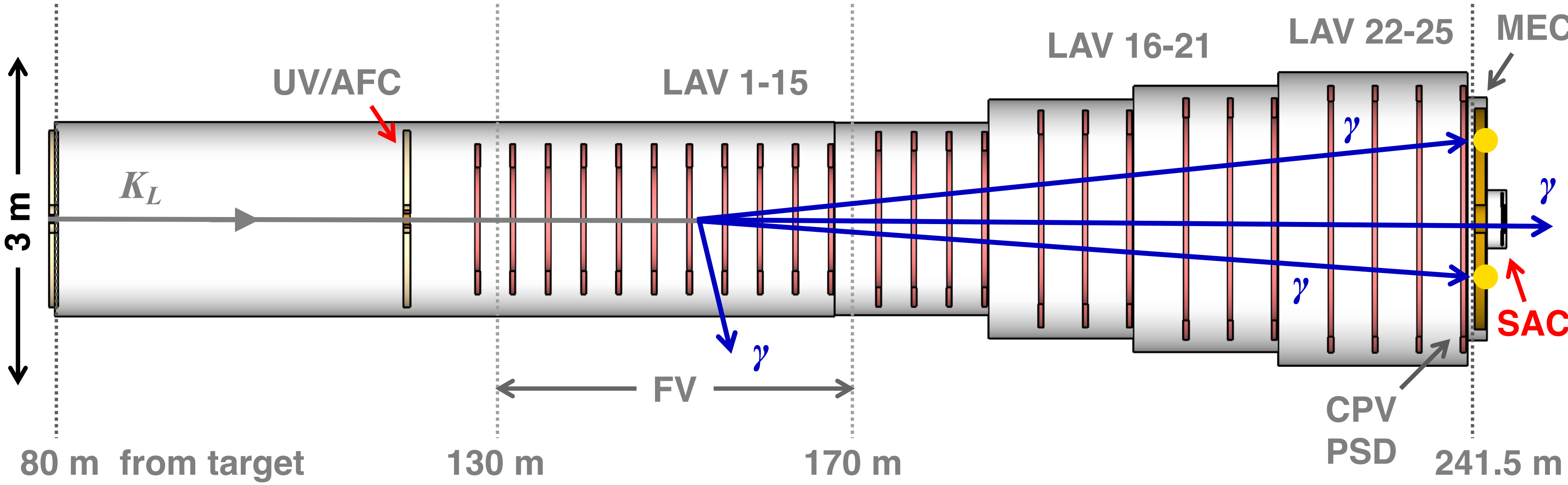



**1st prototype assembled and tested at Protvino and DESY**





# Small-angle photon veto




**Small-angle photon calorimeter system (SAC)**

- Rejects high-energy $\gamma$s from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

| Beam comp. | Rate (MHz) | Req. $1 - \varepsilon$ |
|---|---|---|
| $\gamma$, $E > 5$ GeV | **50** | **$10^{-2}$** |
| $\gamma$, $E > 30$ GeV | **2.5** | **$10^{-4}$** |
| $n$ | **430** | **–** |

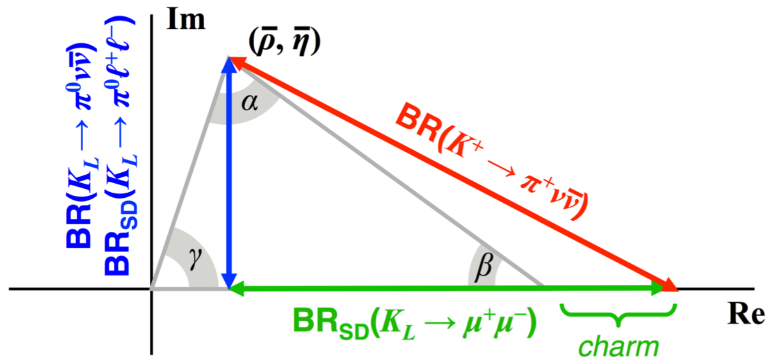
**Possible solutions:**

- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber to exploit enhancement of photon conversion by coherent interaction with lattice
- Compact Cerenkov calorimeter with oriented crystals

# What about $K_L \to \pi^0 \ell^+ \ell^-$?

**$K_L \to \pi^0 \ell^+ \ell^-$ vs $K \to \pi \nu\nu$:**

- Somewhat larger theoretical uncertainties from long-distance physics
  - SD CPV amplitude: $\gamma/Z$ exchange
  - LD CPC amplitude from $2\gamma$ exchange
  - LD indirect CPV amplitude: $K_L \to K_S$
- $K_L \to \pi^0 \ell^+ \ell^-$ can be used to explore helicity suppression in FCNC decays




**$K_L \to \pi^0 \ell^+ \ell^-$ CPV amplitude constrains UT in same way as BR($K_L \to \pi^0 \nu\nu$)**

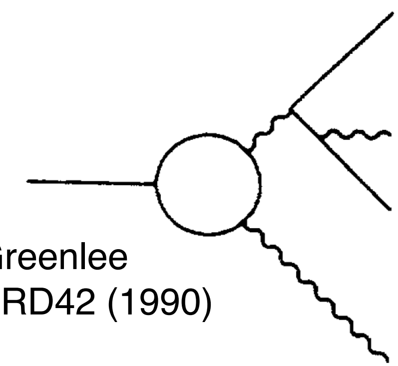
**Experimental status:**

**BR($K_L \to \pi^0 e^+ e^-$) < 28 × $10^{-11}$** — Phys. Rev. Lett. 93 (2004) 021805

**BR($K_L \to \pi^0 \mu^+ \mu^-$) < 38 × $10^{-11}$** — Phys. Rev. Lett. 84 (2000) 5279–5282

**Main background:** $K_L \to \ell^+ \ell^- \gamma\gamma$

- Like $K_L \to \ell^+ \ell^- \gamma$ with hard bremsstrahlung



Greenlee PRD42 (1990)

**BR($K_L \to e^+ e^- \gamma\gamma$) = (6.0 ± 0.3) × $10^{-7}$** $\quad E_\gamma^* > 5$ MeV

**BR($K_L \to \mu^+ \mu^- \gamma\gamma$) = $10^{+8}_{-6}$ × $10^{-9}$** $\quad m_{\gamma\gamma} > 1$ MeV