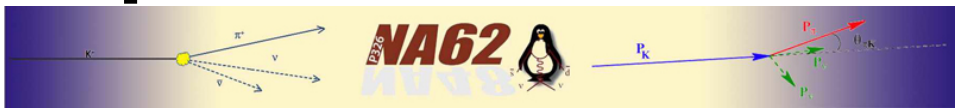
Bundesministerium für Bildung und Forschung

PRISMA

The Future of the NA62 Experiment at CERN



Gia Khoriauli

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

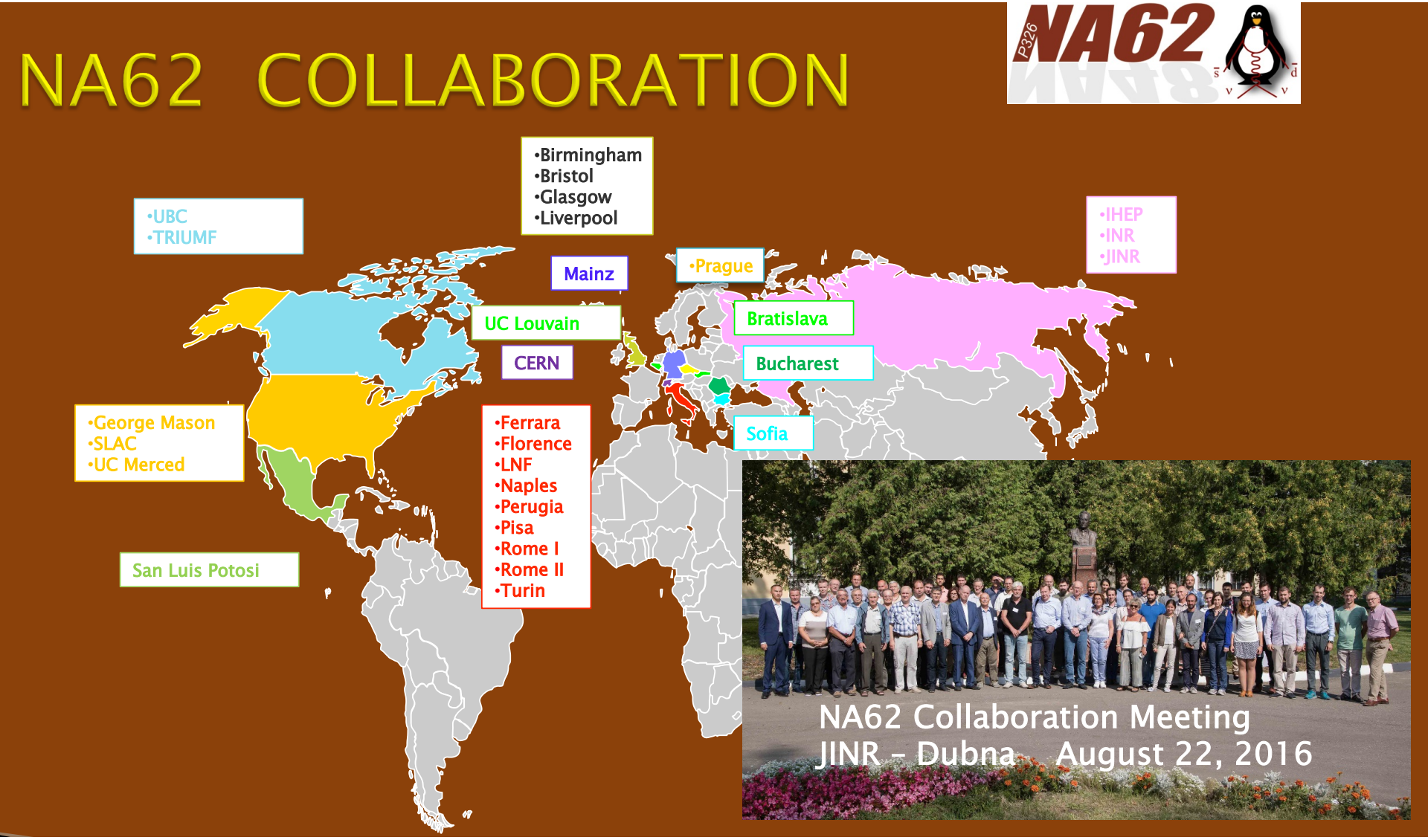
JG|U

Flavour and Dark Matter
25-28 September 2017
Heidelberg

Content

- The NA62 experiment, its main goal and the detector
  - Kaon rare decays → test of the SM
  - Status of the $K^+ \to \pi^+\nu\bar{\nu}$ measurement
    - Highlights of the detector and its performance
- The NA62 beam operation modes
  - K^+ beam and dump
- NA62 searches of New Physics at MeV-GeV scale
  - Dark Photons, Axion-Like Particles, Heavy Neutral Leptons
    - Present status & future prospects
- Long term future: prospects of a $K_L \to \pi^0\nu\bar{\nu}$ measurement

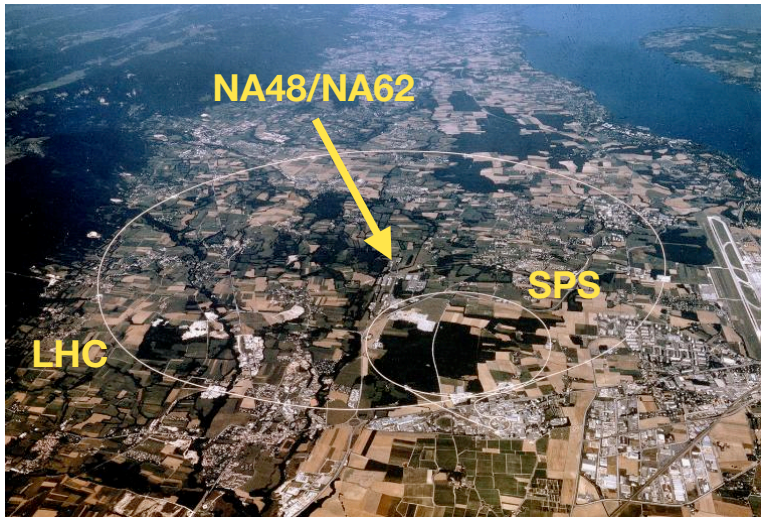
The NA62 Collaboration



29 institutes, more than 200 members

The NA62 Experiment

- **62**nd proposed experiment in the CERN **N**orth **A**rea
  - Successor of the NA48 experiment
  - Fixed target (Beryllium)
  - 400 GeV/c proton beam from SPS



- K^+ from secondary beam
  - p_{Kaon} = 75±1 GeV/c
  - Kaons decaying in flight
- 2014: first pilot run, 2015: commissioning/physics run
- 2016 physics run → the SM sensitivity for $K^+ \to \pi^+ \nu\bar{\nu}$
- Data taking until the LHC long shutdown 2 in 2018
  - ~10^{13} K^+ decays to be recorded in total

Golden Rare Kaon Decays

- $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$: very clean FCNC processes
  - SM branching ratios **~10^{-10}**
  - $K_L \to \pi^0\nu\bar{\nu}$: completely CP-violating decay

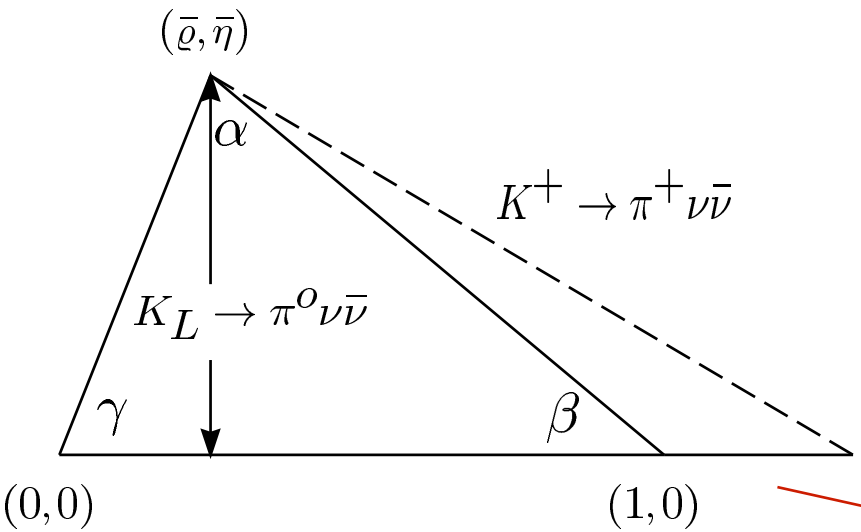
$$K^+ \to \pi^+\nu\bar{\nu}$$

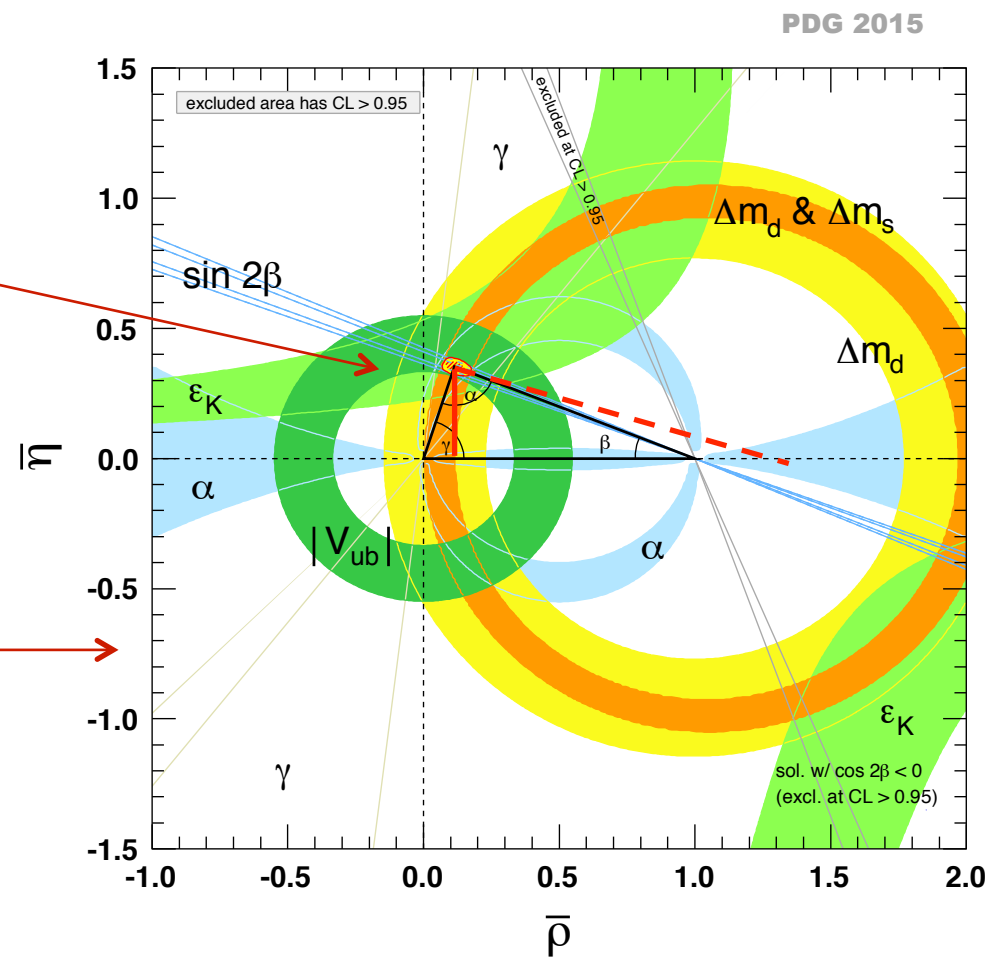
$$K_L \to \pi^0\nu\bar{\nu}$$

@ CERN

@ J-PARC

Relation with Unitarity Triangle

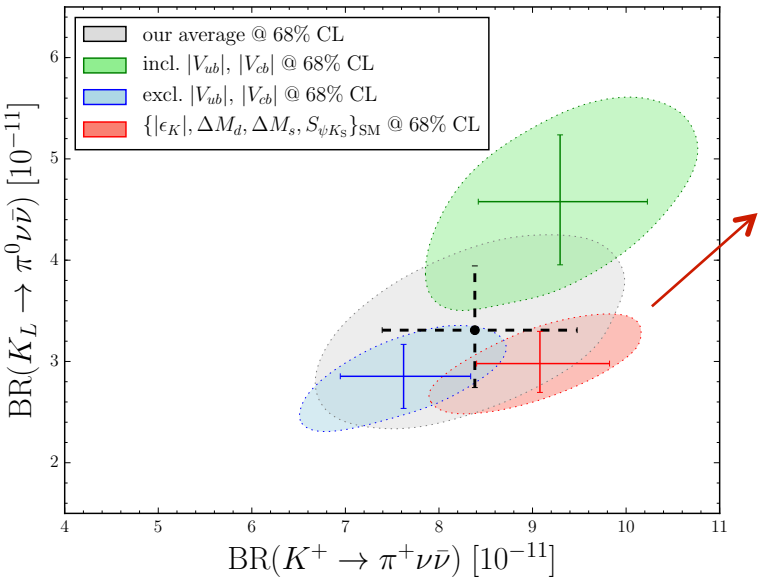




- New Physics models predicting different ways of violating this harmony in the two rare decays

BR($K^{+,0}_L \to \pi^{+,0}\nu\bar{\nu}$) SM Predictions

Buras et al., JHEP11 (2015) 033



$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.00 \pm 0.31) \times 10^{-11}$$

- BR($K^+ \to \pi^+\nu\bar{\nu}$) and BR($K_L \to \pi^0\nu\bar{\nu}$) uncertainties: **8%** and **10%**
  - Theory uncertainty: **only 2%** !
    - Excellent precision in flavour physics

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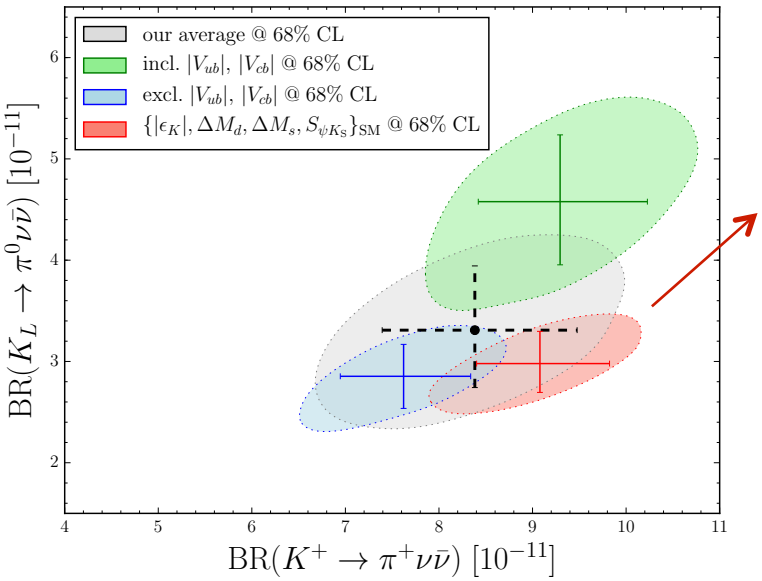

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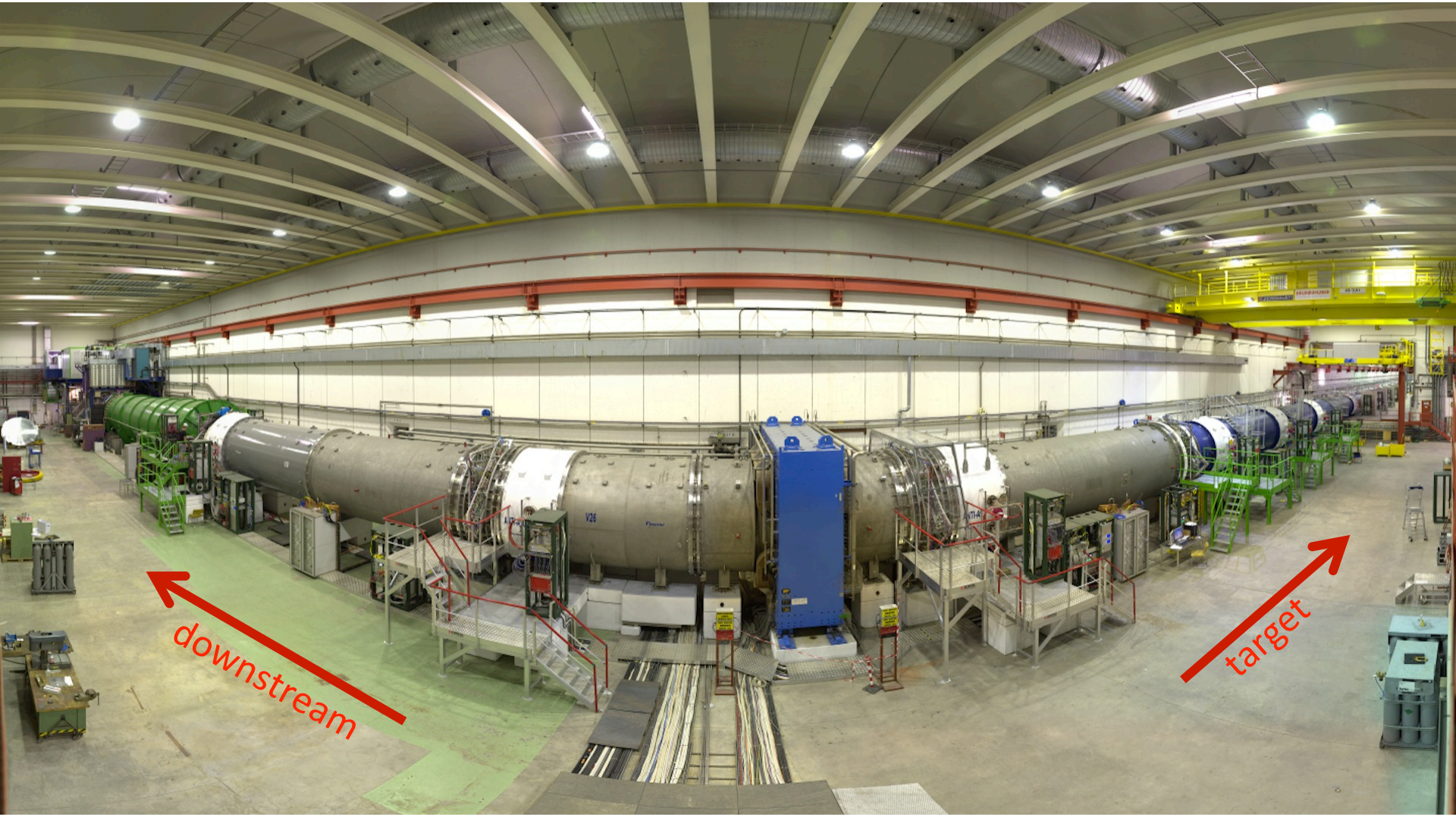
- The NA62 goal: BR($K^+ \to \pi^+\nu\bar{\nu}$) with **10%** precision
  - 10^{12} background rejection factor to be achieved

- Experimental status: E787/E949 experiments at BNL

$$\mathrm{BR}_{\mathrm{exp}}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$$

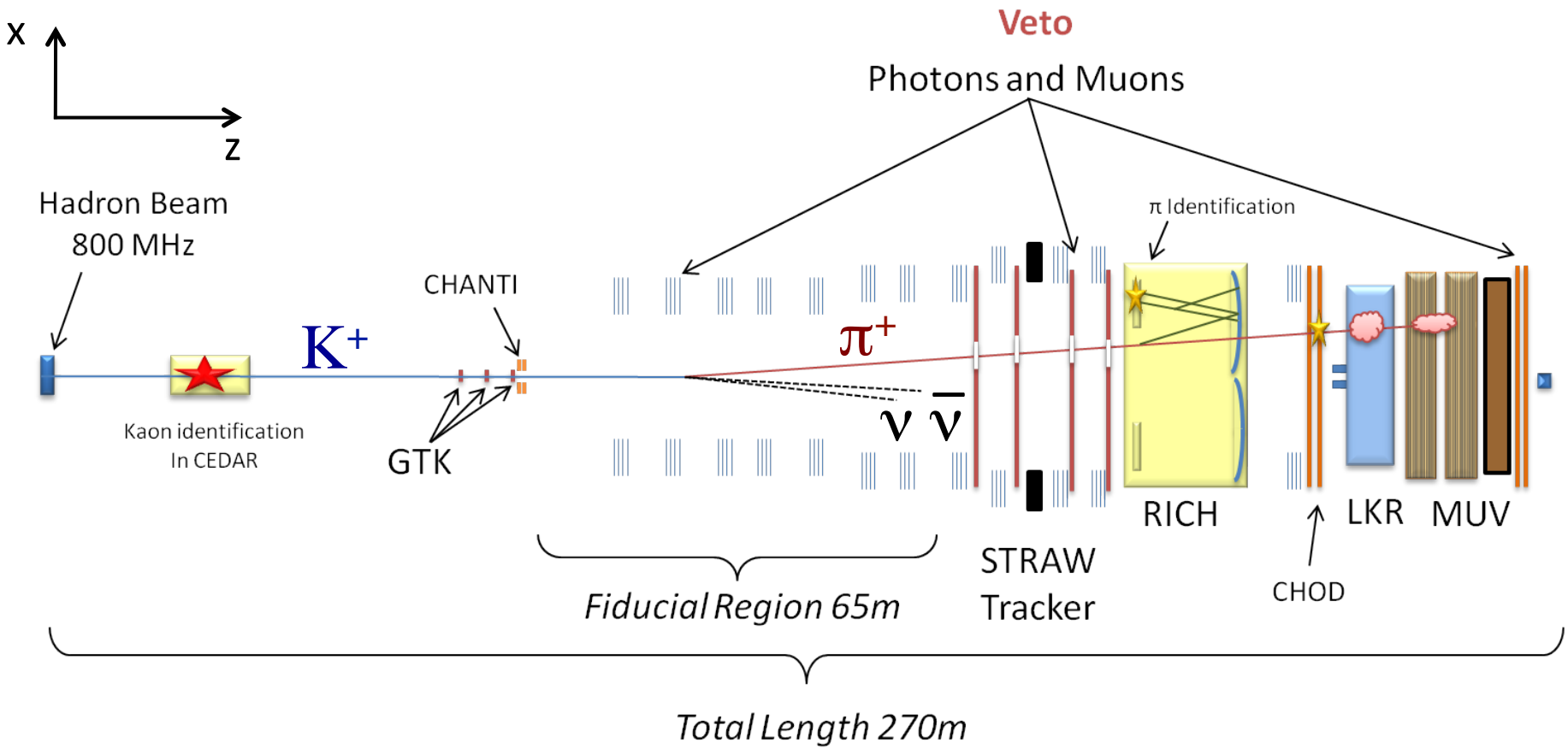
BNL E787/E949 PRL 101 (2008) 191802

The NA62 Detector Hall



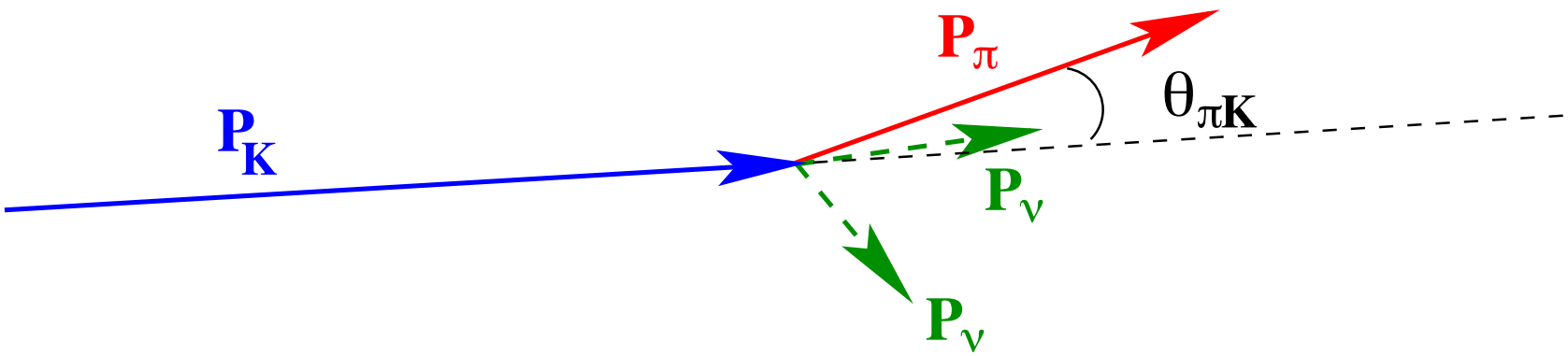
Detector hall + target hall = 270 m

The NA62 Detector



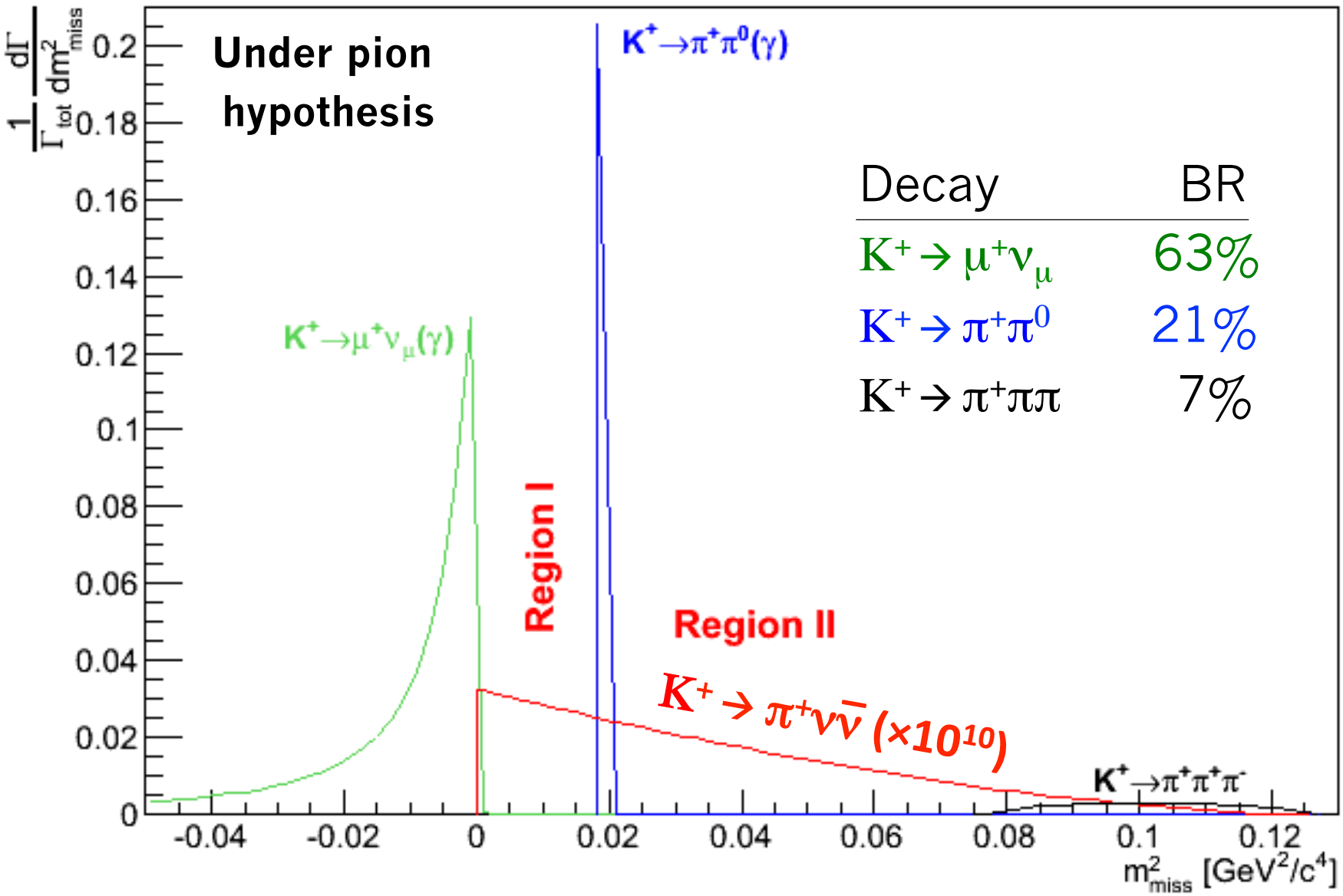
- 4.5 x 10^{12} K^+ decays in the fiducial region per year
  - @ nominal intensity of the primary proton beam: 3 x 10^{12}/pulse

NA62 Strategy of Measurement



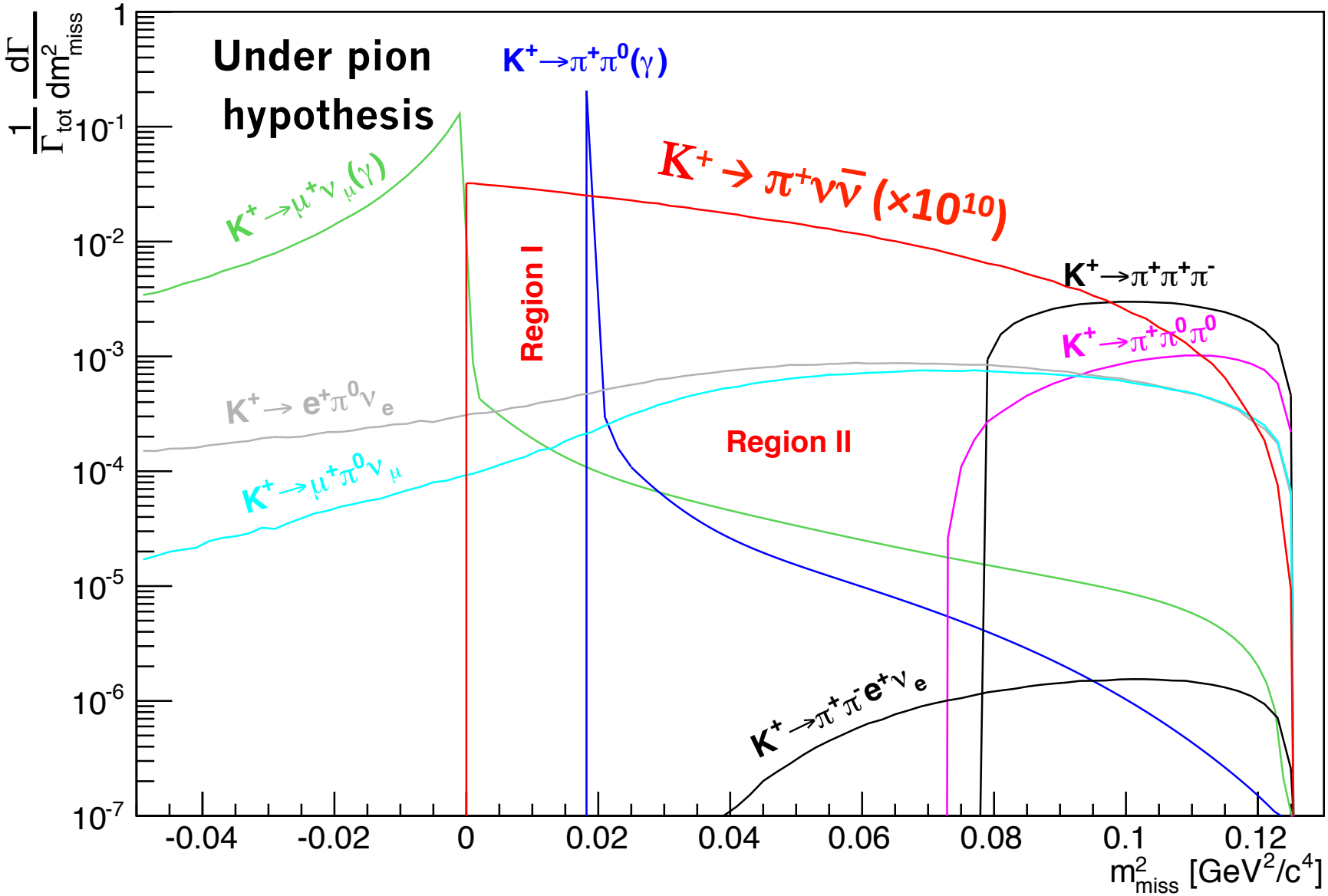
$$m^2_{miss} = \left(P_{K^+} - P_{\pi^+} \right)^2$$

NA62 Strategy of Measurement

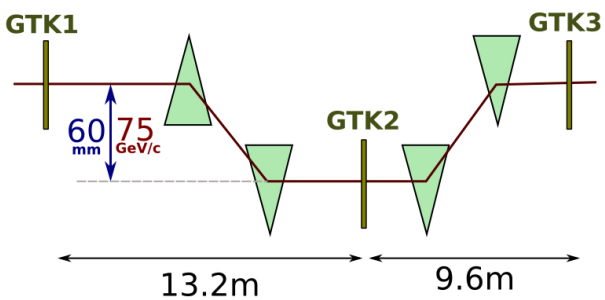


Decay	BR
$K^+ \to \mu^+\nu_\mu$	63%
$K^+ \to \pi^+\pi^0$	21%
$K^+ \to \pi^+\pi\pi$	7%

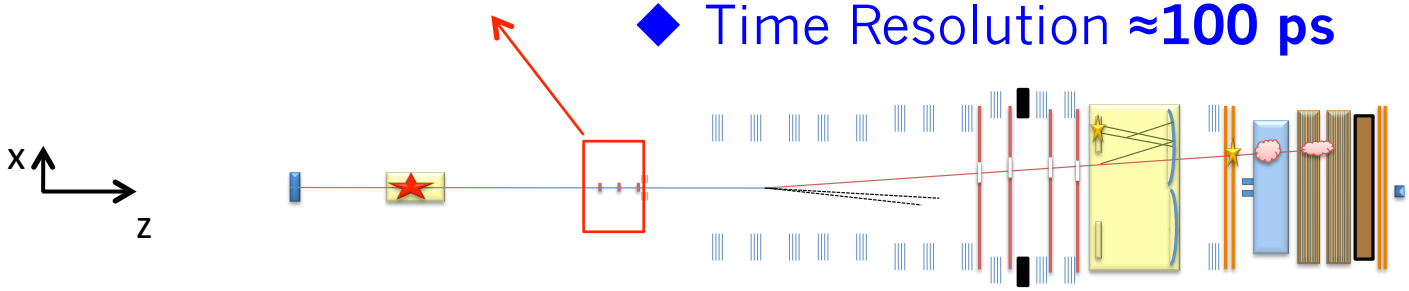
NA62 Strategy of Measurement



NA62 Tracking



- Silicon Pixel detector, 3 stations
  - **750 MHz** total particle rate
  - Track momentum & angle resolutions: **0.2%** & **16 μrad**
  - Time Resolution **≈100 ps**



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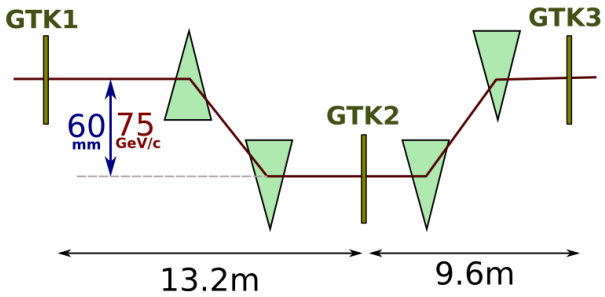

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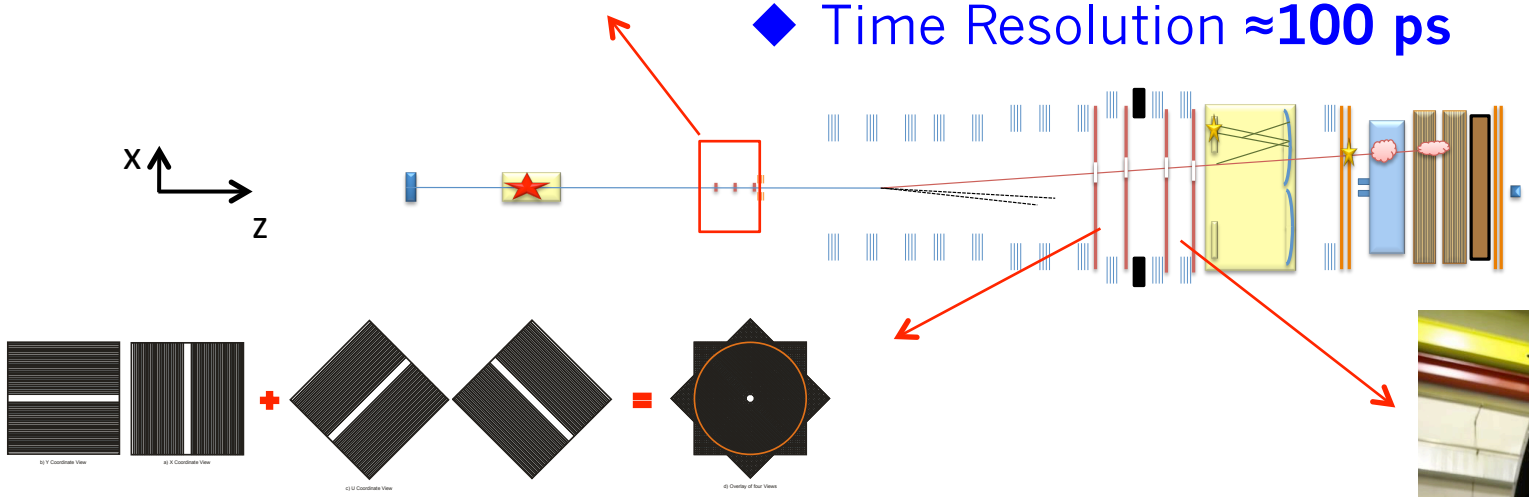
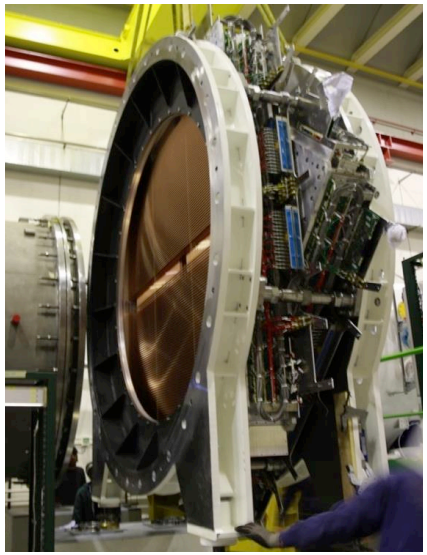
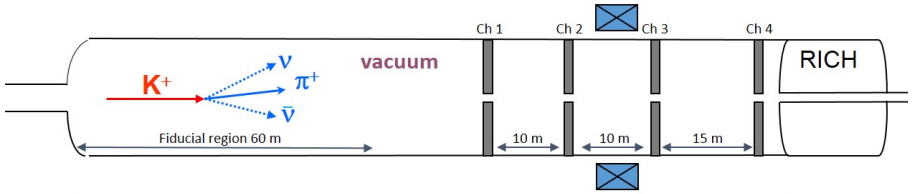


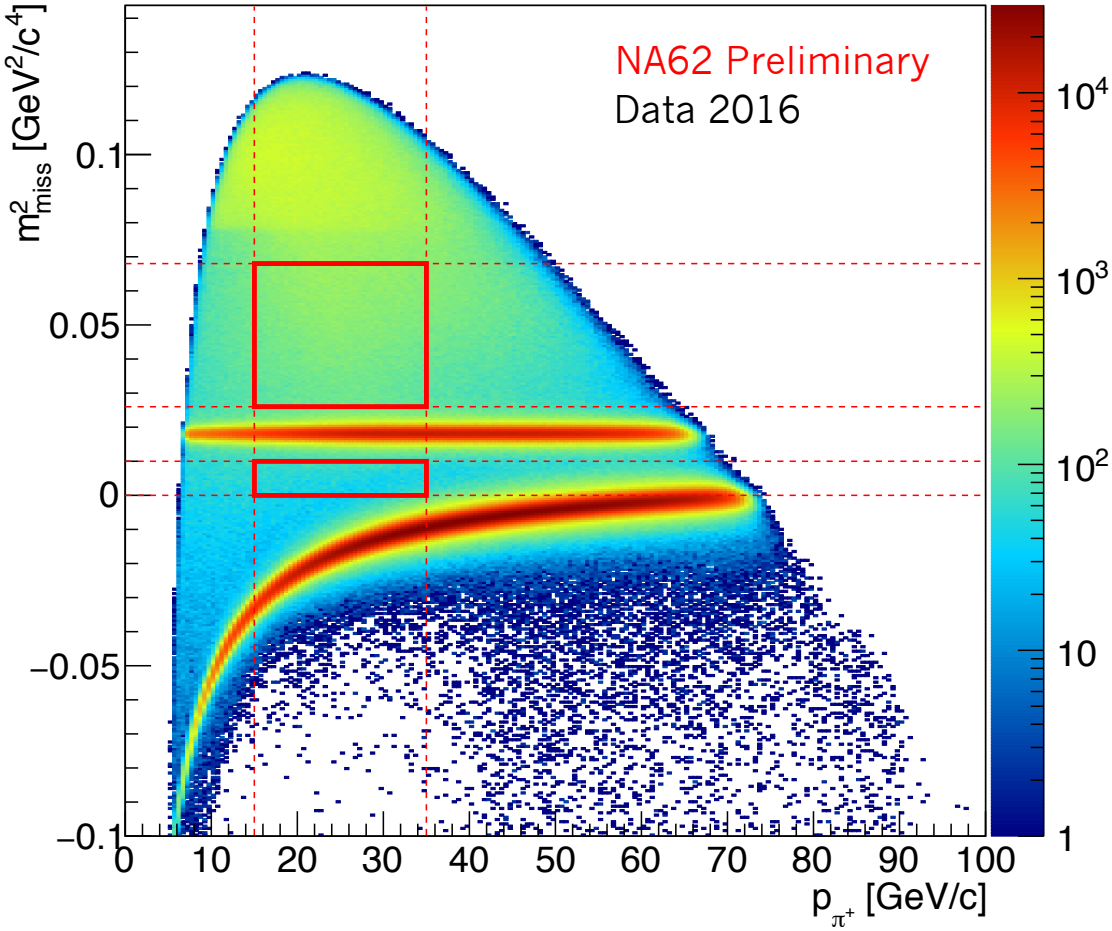


- 4 STRAW stations with ≥3-coordinates **operating in vacuum** – only **0.018**X_0 (total)



$K^+ \rightarrow \pi^+\nu\bar{\nu}$ Analysis in Data 2016

- 1-track selection
  - Good track originated from a Kaon decay in the fiducial volume
    - Pion track hypothesis



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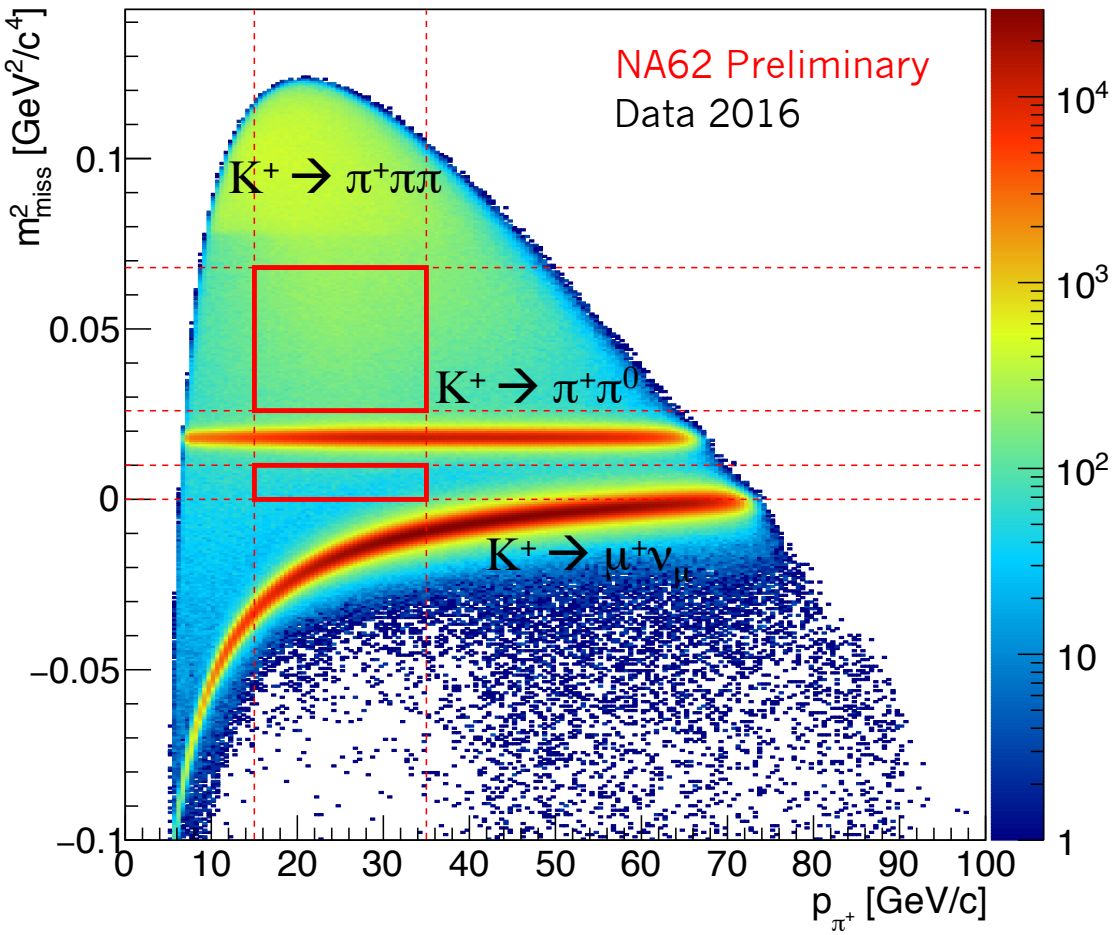
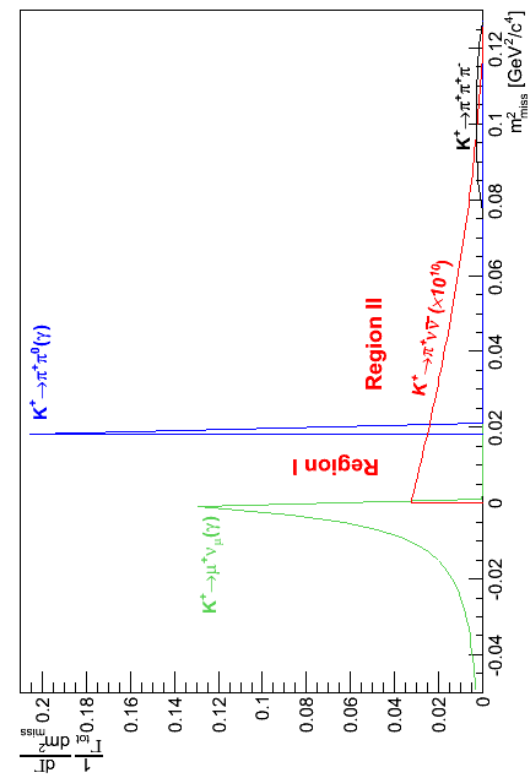




Summary of the Performance

- ~10^4 kinematic suppression of the background
  - GTK, STRAW

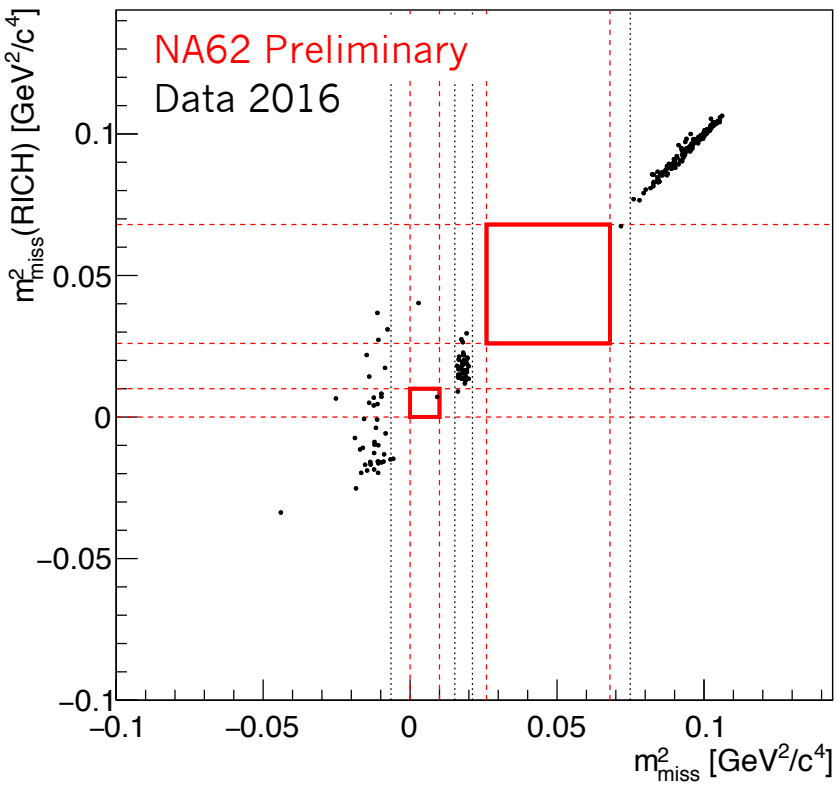
- Highly effective photon veto system, ~10^8 π^0 – rejection
  - LAV (large angle vetos), LKr (as a medium angle veto), IRC and SAC (small angle vetos, down to 0 radian)

- ~10^7 muon suppression from particle identification with calorimeters, fast muon veto (MUV3) and RICH
  - LKr+MUVs: 10^5 muon rejection @ ~80% pion efficiency
  - RICH: ~10^2 muon rejection in range 15 GeV/c < p_{track} <35 GeV/c

- Good time resolution: ~100 ps

$K^+ \to \pi^+\nu\bar{\nu}$ Analysis in Data 2016

- After particle ID and photon veto cuts
  - 2.3×10 K^+ decays (5% of 2016 data) used



- Expected signal: 0.064, expected background: 0.057, observed: 0 events
  - (The event in the box fails m^2_{miss}(w/o GTK) cut)
  - Signal acceptance: 3.3%
    - Will be improved

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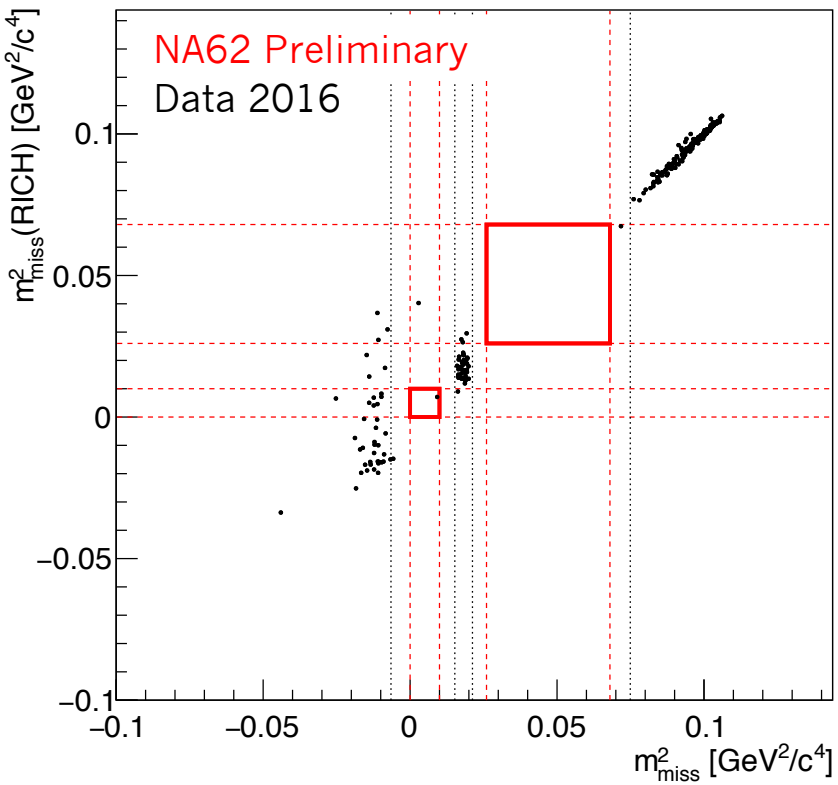

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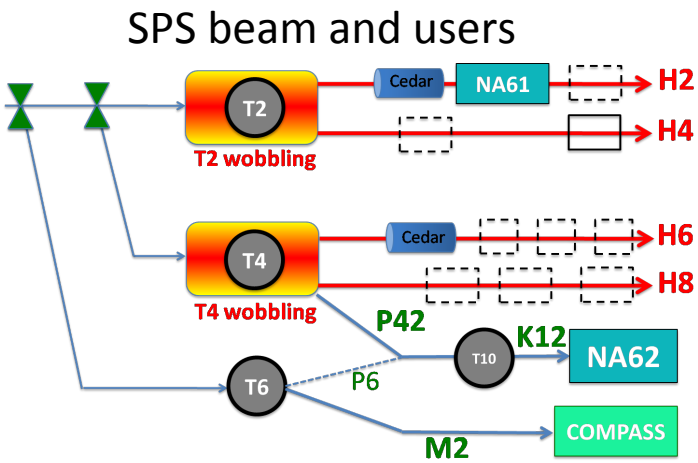
- The SM sensitivity, BR<10^{-9}, expected to be reached using the ~full 2016 data

- Expected **~15** signal events in 2017 data

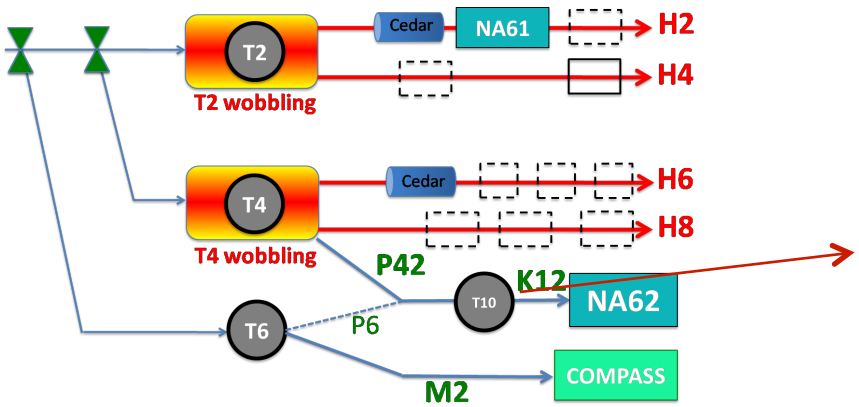
NA62 Beam Operation Modes



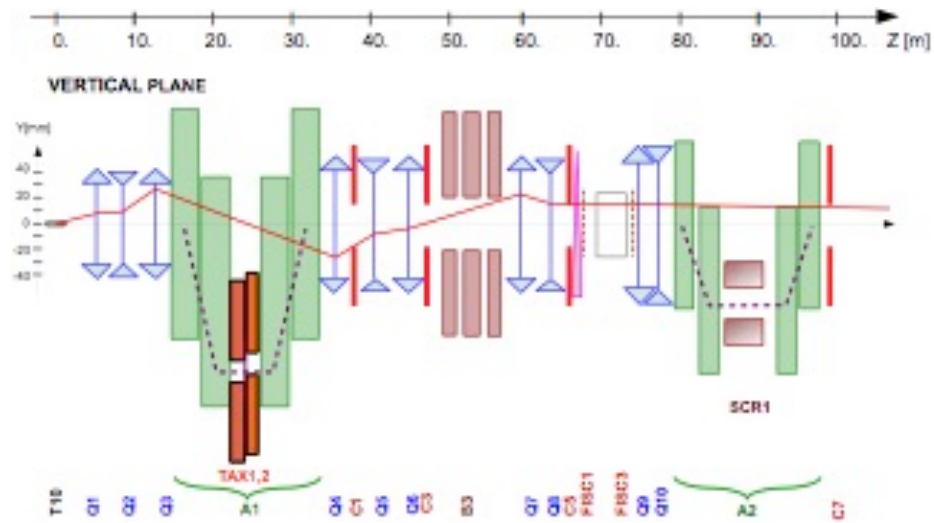
NA62 Beam Operation Modes

- 75 GeV/c K^+ beam or proton dump modes using "TAXes"
  - Easily switchable modes in the current beam setup of NA62

SPS beam and users



NA62 beam-line from target to decay volume



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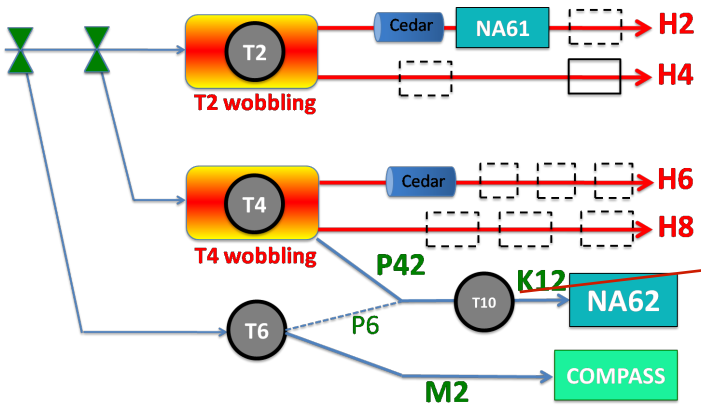

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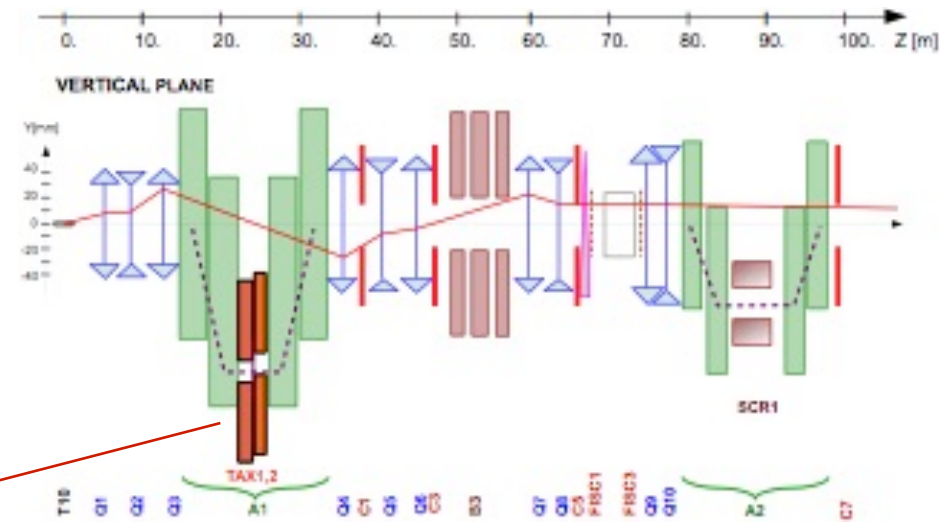
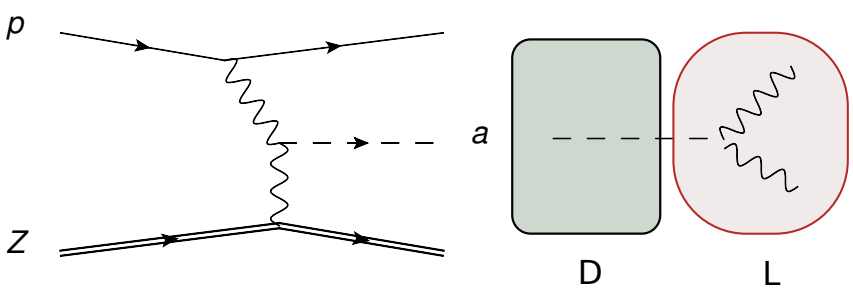


TAX1&2

- TAXes: movable copper + iron made collimators of ~22λ_I total thickness

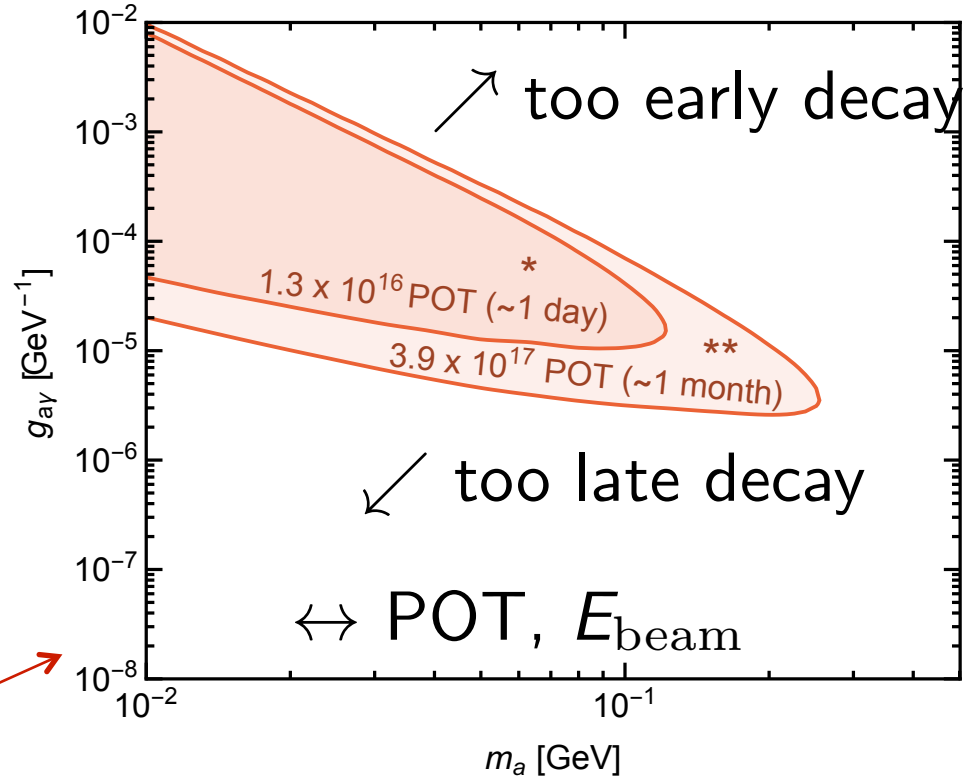
NP Searches in Dump Mode: ALP

- Long-lived Axion-like particles created by photon fusion
  - Copper TAX → coherent Z^2 enhancement of production rate



- ALP lifetime dependence on its mass and coupling with photon

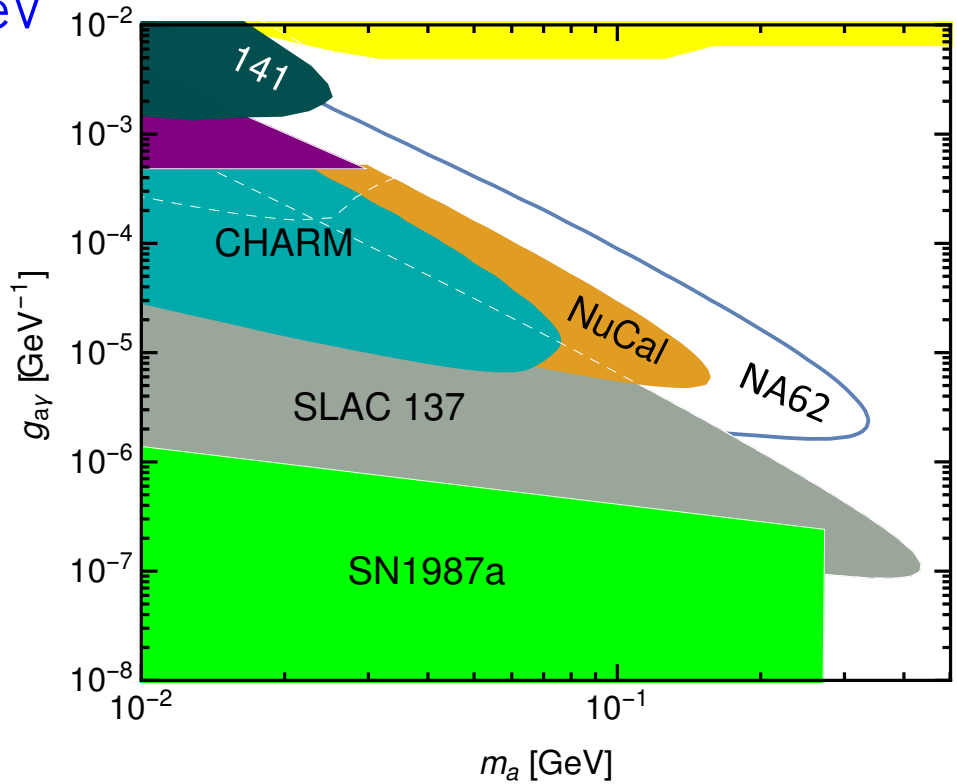
$$\tau \sim 1/(g_{a\gamma}^2 m_a^3)$$



- Expected limits on the mass and coupling assuming 1 day/1 month of data taking in the dump mode

NP Searches in Dump Mode: ALP

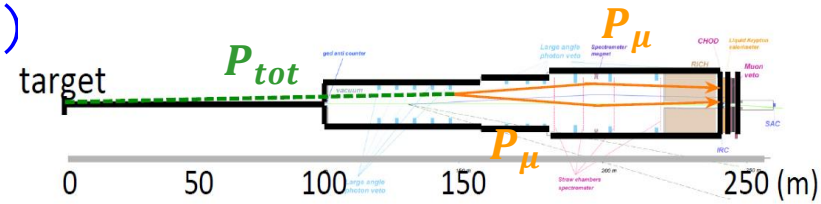
- ~1 day NA62 data from running in dump mode already sensitive to ALPs at 90% CL
  - Large proton energy, 400 GeV
  - Long decay volume, 65 m
  - Assume 0 background
    - Rather realistic

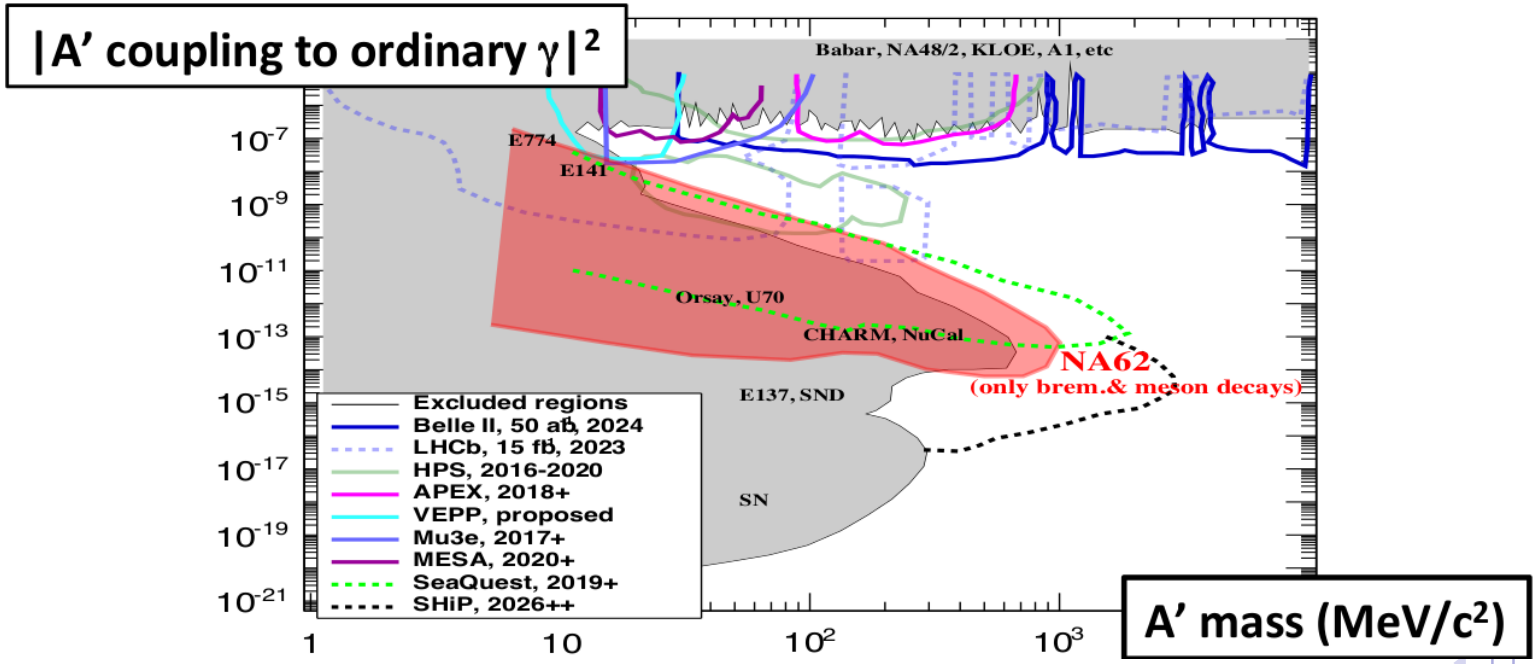


- Dependence of the projected limits on
  - Production differential cross section of ALPs and lifetime
  - Acceptance photons in the LKr electromagnetic calorimeter

NP Searches in Dump Mode: A'

- Search for displaced di-lepton decays: $A' \rightarrow e^+e^-$, $A' \rightarrow \mu^+\mu^-$
  - 2×10^{18} protons on target (~2 years)
  - Limits at 90% CL, 0 background
    - Production only in target, no TAXes

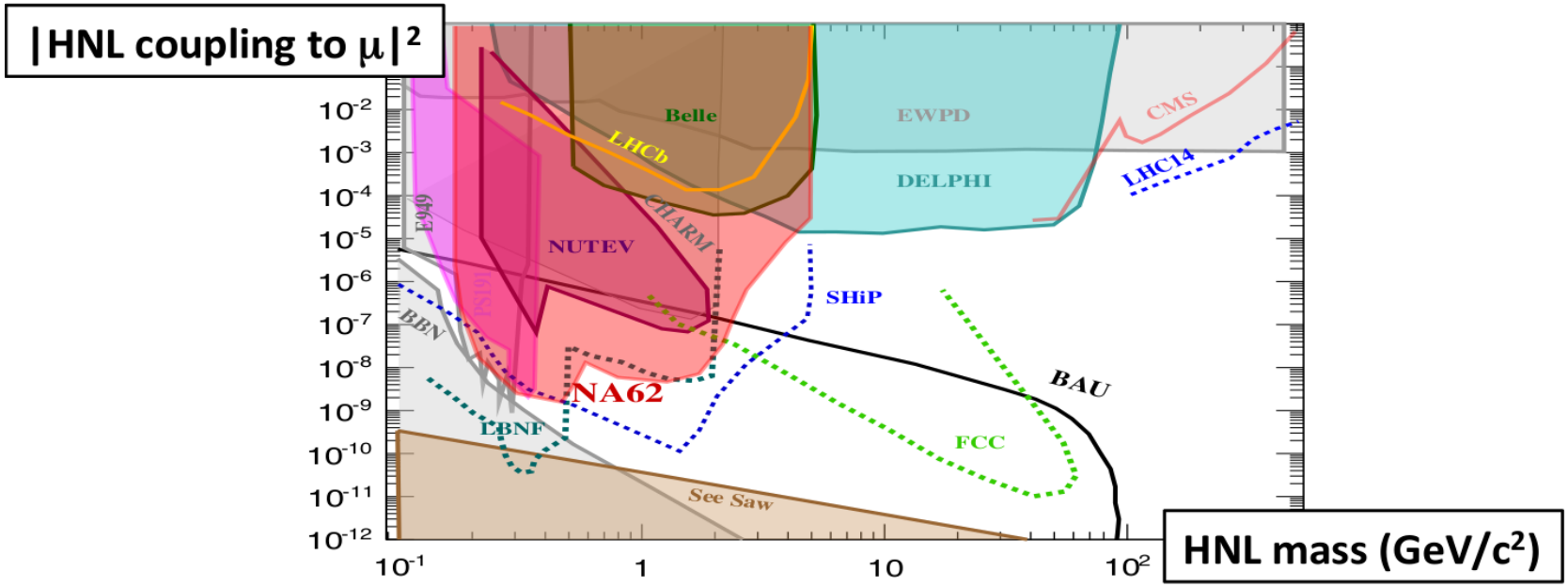




- Higher sensitivity is expected considering direct QCD production of A' and dump on TAXes

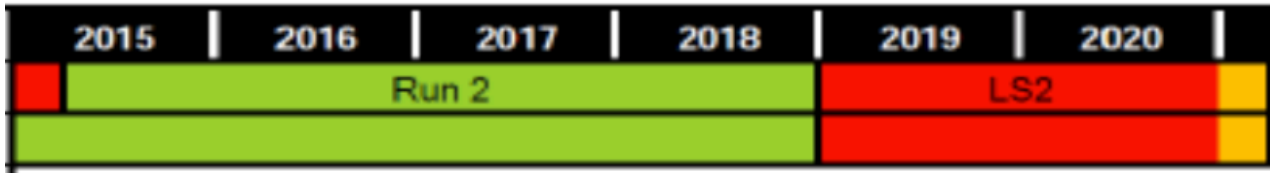
NP Searches in Dump Mode: HNL

- Search for visible decays of long-lived HNL → πe, $\pi\mu$
  - Limits depend on the relation of HNL couplings with the SM leptons, $U_e:U_\mu:U_\tau$
  - 2×10^{18} protons on target (~2 years)
  - Limits at 90% CL, 0 background

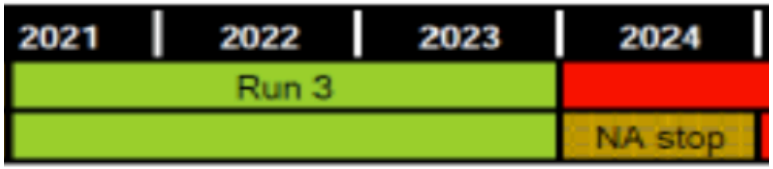


NA62 in Run 2, 3 and 4

- Run 2: K^+ beam for $K^+ \to \pi^+ \nu\bar{\nu}$, dark photon, HNL, LNV/LFV decays



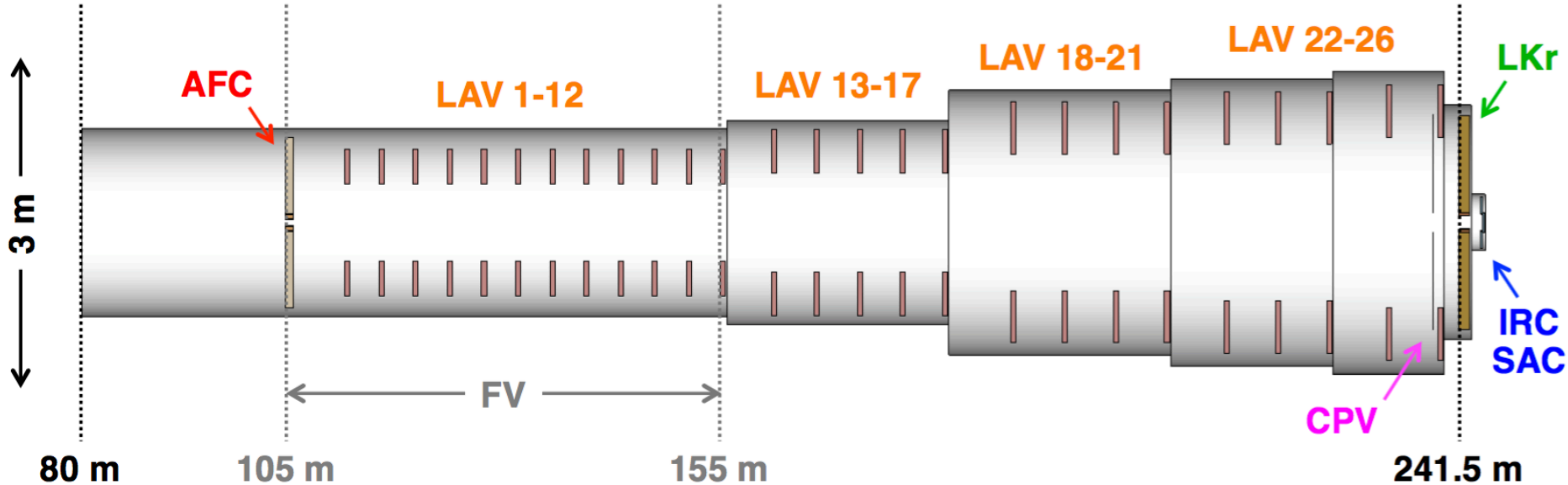
- Run 3: many interesting fields to be studied with minimal (or no upgrades at all) of the existing setup
  - In K^+ beam mode:
    - If needed improve $K^+ \to \pi^+ \nu\bar{\nu}$, A'→invisible, HNL single track decays
      - All benefit from the same trigger signature
  - In proton dump mode:
    - ALPs, A'→visible, HNL



- Run 4: there are some ideas...

K_L EVER for $K_L \to \pi^0 \nu\bar{\nu}$ Measurement

- Complementary search of KOTO with the high energy of π^0, $p_{\pi 0}$ = 70 GeV/c
  - ~60 Standard Model events in 5 years of running
    - 5×10^{19} protons on target
  - Boosted photons from $K_L \to \pi^0\pi^0$ decays (main background), easy for vetoing

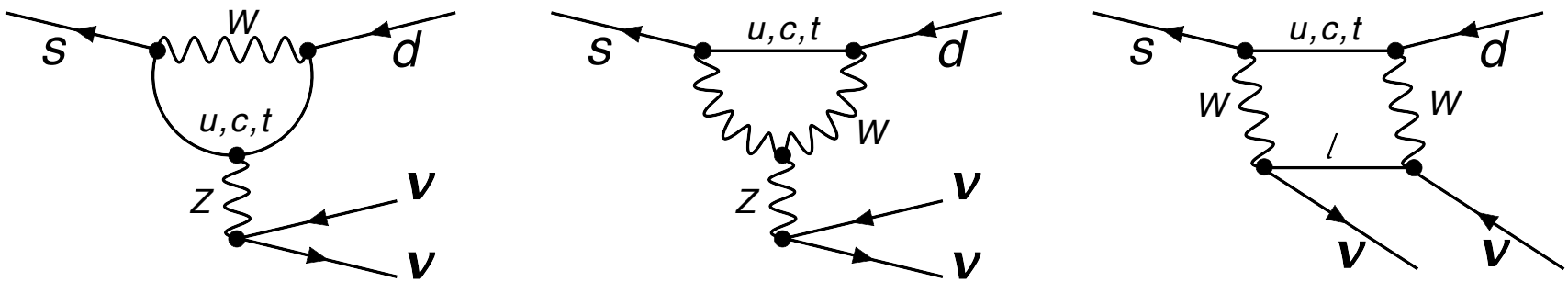


- New large angle photon veto (LAV) detectors

Summary

- NA62 experiment at CERN to measure K^+ rare (BR ~10^{-11}) decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- High energy & intensity proton beam + long decay volume & advanced detector system → NA62 as a very powerful tool to search for hidden sector particles
  - Dark photon, Axion-like particles, Heavy neutral leptons
  - MeV to GeV mass range, weak coupling with the SM
  - Visible and invisible decays
- Operation in K^+ beam or proton beam dump mode
  - Easy to switch between the modes
  - Both modes considered after the long shutdown 2 (2021)
- Possible long term future: measurement of $K_L \rightarrow \pi^0\nu\bar{\nu}$
  - *K_LEVER*: modified beam-line, upgraded detector
    - After long shutdown 3 (2027)
    - The experiment logo will be changed

FCNC Decay $K^+ \to \pi^+ \nu\bar{\nu}$



- Amplitude ~ $m^2_{u,c,t} / m^2_W$ → short-distance dynamics
  - Negligible up-quark contribution
  - Effective theory framework for calculation of the decay amplitude

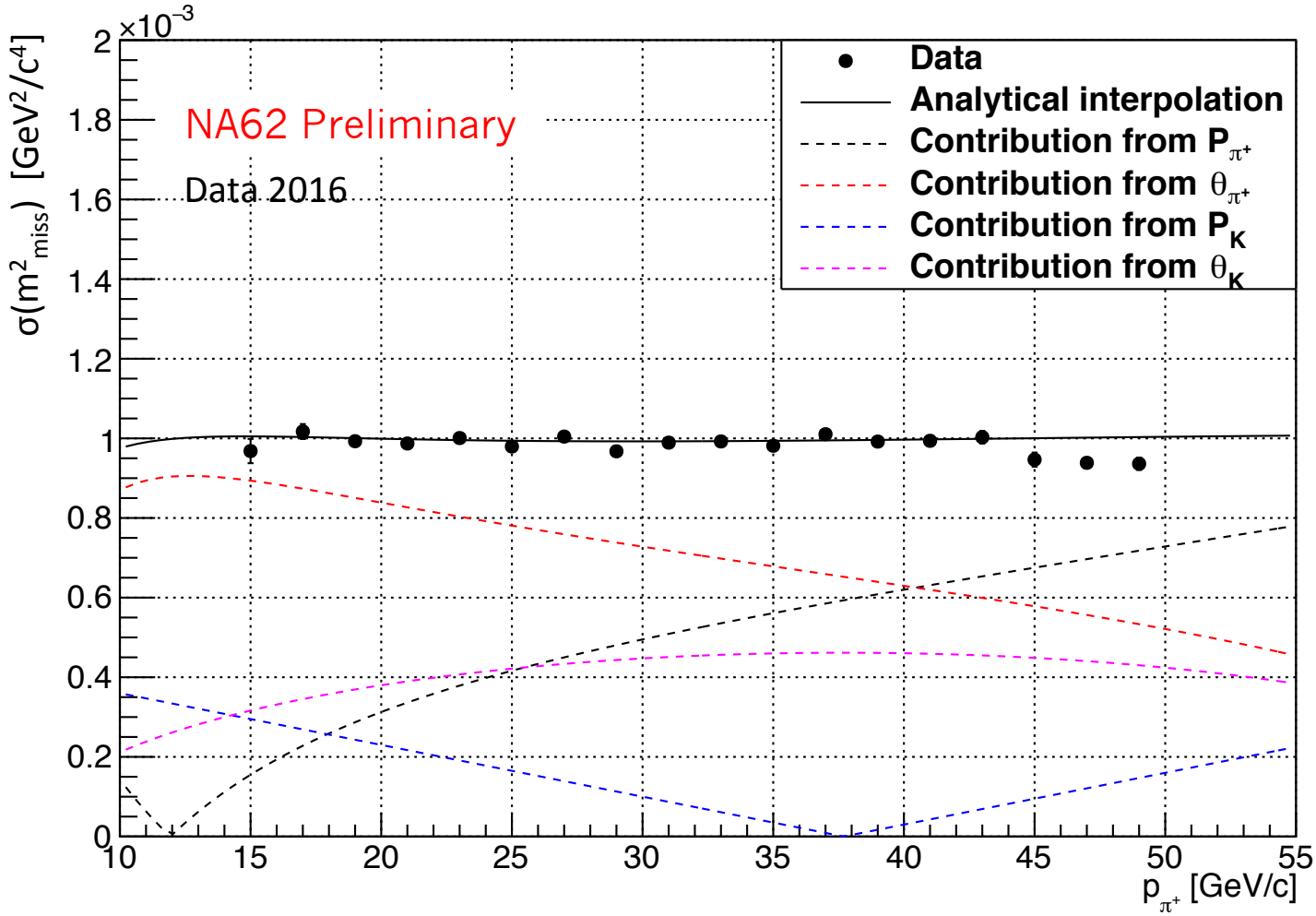
Buras et al., hep-ph/0405132 (2007)

$$\mathcal{H}_{\rm eff}^{\rm SM} = \frac{G_{\rm F}}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_{\rm w}} \sum_{l=e,\mu,\tau} \left(V_{cs}^* V_{cd} X_{\rm NL}^l + V_{ts}^* V_{td} X(x_t) \right) (\bar{s}d)_{V-A} (\bar{\nu}_l \nu_l)_{V-A}$$

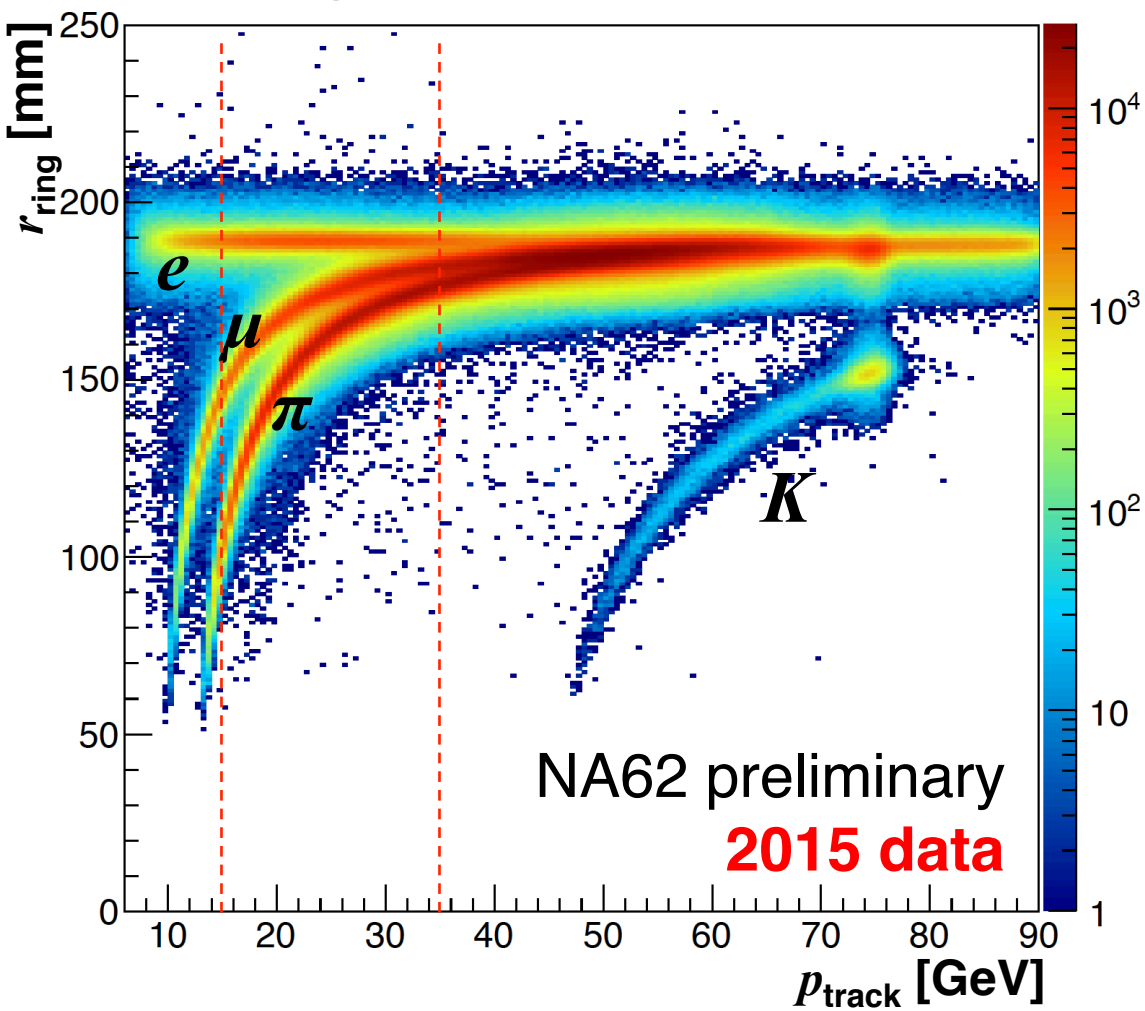
- Theoretically calculable X^l_{NL} and $X(x_t)$ loop functions
  - Remarkable progress over the last decade

Photon Rejection with Vetos

- $K^+ \rightarrow \pi^+\pi^0$ selection requiring 2γ in LKr compatible with π^0
  - No photons in other sub-detectors



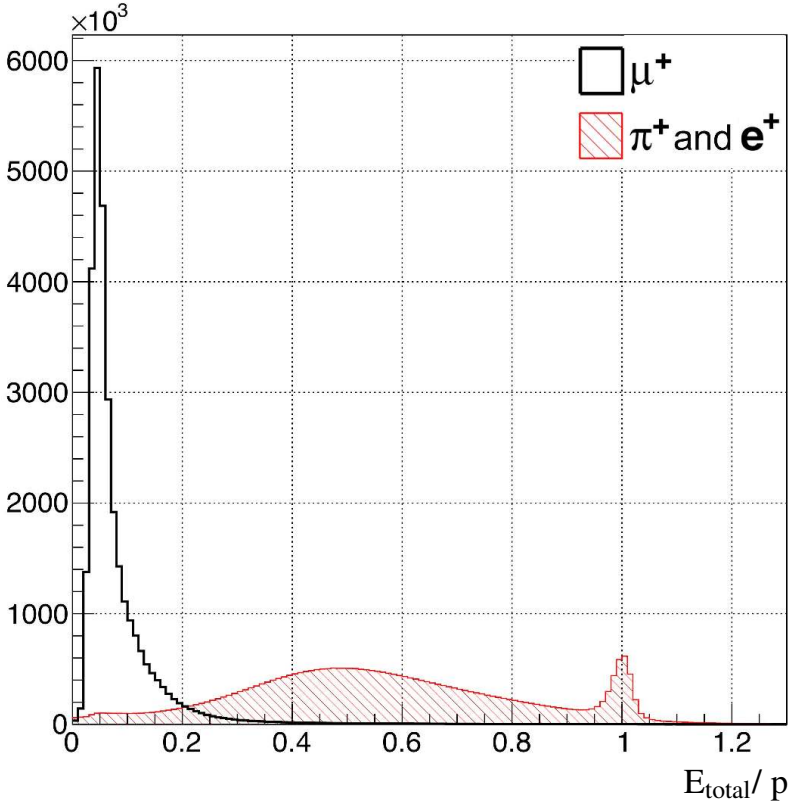
Performance of RICH



- ~10^2 muon suppression factor
  - 15 GeV/c < p_{track} <35 GeV/c

Calorimeter Performance

- Total energy = LKr + MUV1 + MUV2



- 10^5 muon rejection is reached at 80% pion efficiency
  - On-going study to increase the efficiency up to 90%

NA62 Sensitivity to BR($K^+ \to \pi^+\nu\bar{\nu}$)

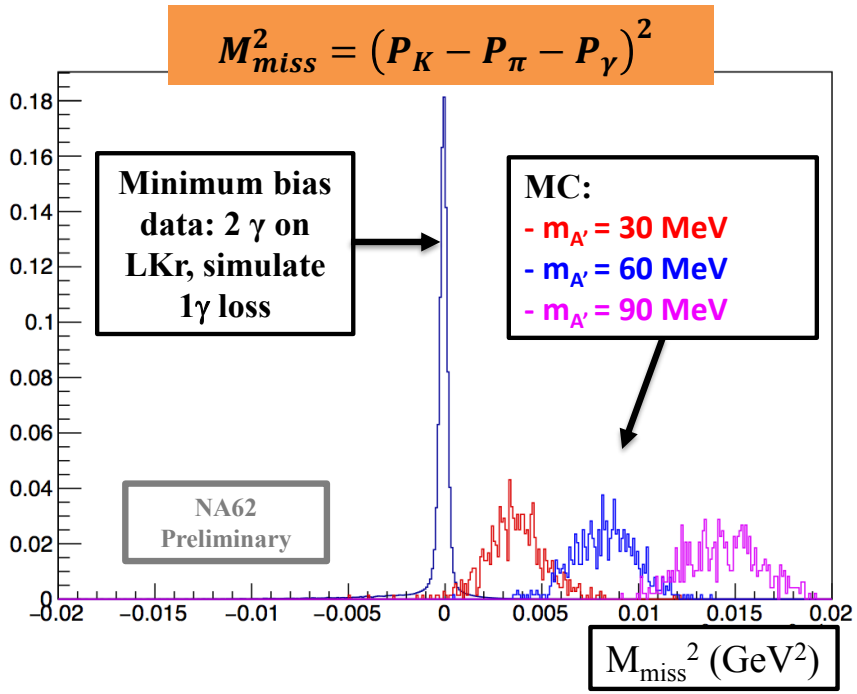
- Monte-Carlo simulation
  - 10% signal acceptance

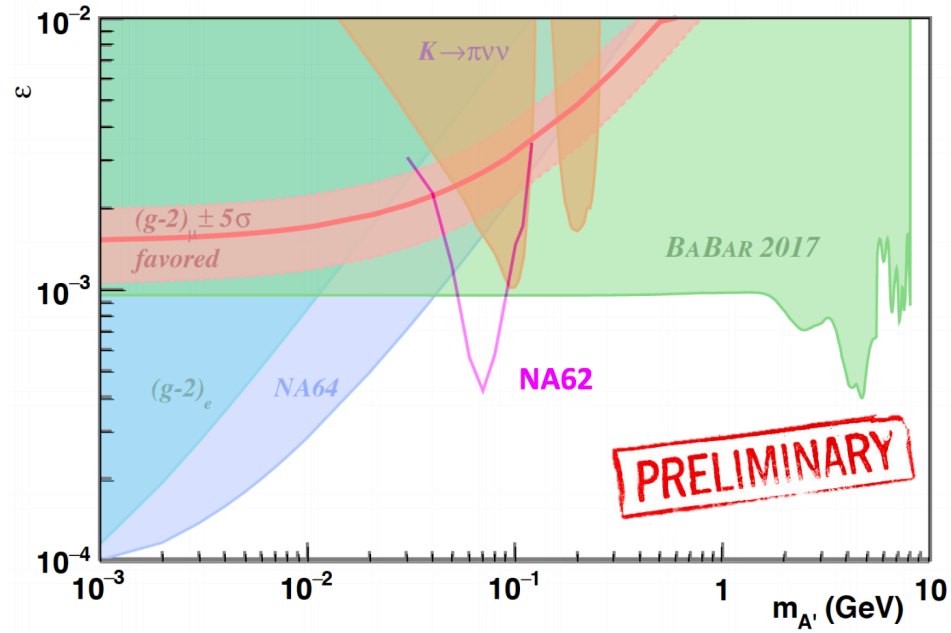
Decay	SM events/year
$K^+ \to \pi^+\nu\bar{\nu}$	**45**
$K^+ \to \mu^+\nu_\mu(\gamma)$	1.5
$K^+ \to \pi^+\pi^0(\gamma)$	7.5
$K^+ \to \pi^+\pi^+\pi^-$	<1
Others	<1
Σ background	**<10**

- 10% precision after 2 years of data taking

NP Searches with K+ Beam: A'

- Dark Photon: $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma A'$ and $A' \to \chi\ \chi$
  - Same trigger signature as the $K^+ \to \pi^+ \nu\bar{\nu}$ decays





- Improved limits at 90% CL (preliminary) in DP mass range: ~ 50 MeV/c² < $m_{A'}$ < 90 MeV/c²
  - Data used: 1.5×10^{10} K+ decays (small fraction of 2016 sample)

NP Searches with K+ Beam: HNL

- Heavy Neutrino from Neutrino Minimal SM (νMSM)
  - Three right-handed neutrinos: the lightest N_1 – dark matter candidate

See Letizia Peruzzo's talk on Monday

$$|U_{l4}|^2 = \frac{\mathcal{B}(K^+ \to l^+ N)}{\mathcal{B}(K^+ \to l^+ \nu_l)\ \rho_l(m_N)}$$

- $K^+ \to \mu^+ N$: NA62 2007 data (arXiv:1705.07510)

- $K^+ \to e^+ N$: NA62 2015 data (paper in preparation)
  - Improved limits on $|U_{e4}|^2$ in the m_N range ~ 170 MeV/c^2 – 450 MeV/c^2