Recent results from the NA62 experiment at CERN SPS

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Laboratoire de Physique des Hautes Energies (LPHE), EPFL
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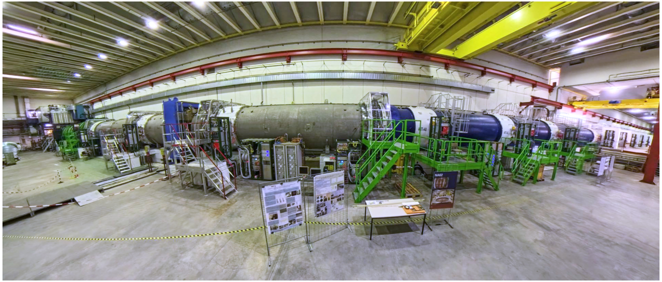
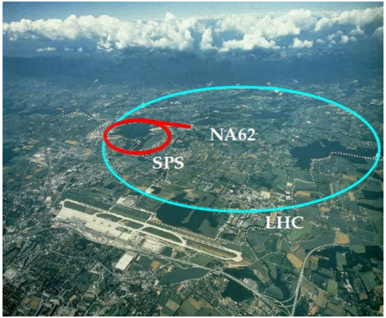
The NA62 experiment

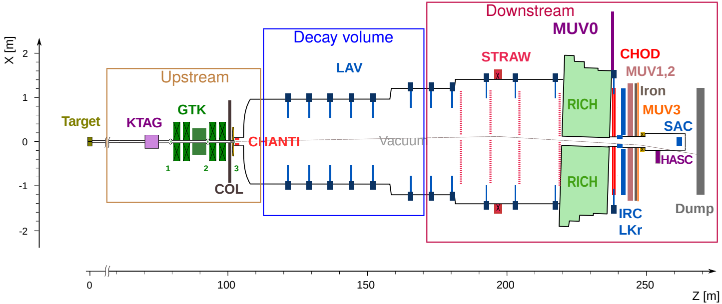
- Fixed target experiment at CERN North Area;
- $400\ \mathrm{GeV/c}$ proton beam from SPS;
- Main goal: measure the very rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay.
- Physics run: $2016 - 2018$ (Run 1), $2021-$ongoing (Run 2).





The NA62 experiment

Detector overview

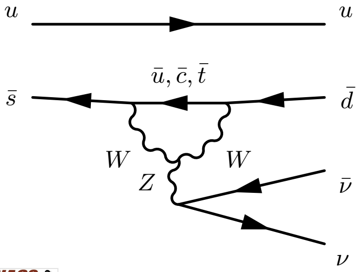


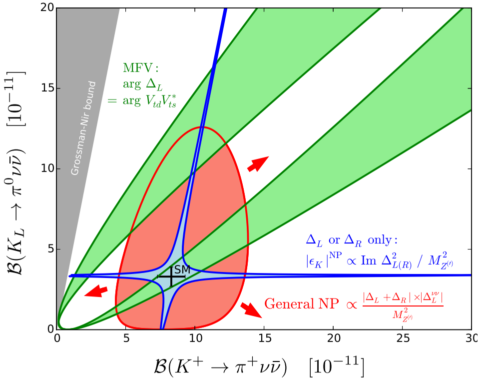
- $400\ \mathrm{GeV}/c$ proton beam on beryllium target;
- Secondary beam at $75\ \mathrm{GeV}/c$ with $6\%\ K^+$;
- K^+ tagging: KTAG;
- K^+ tracking: GTK;
- Beam interaction veto: CHANTI;

- Tracking: STRAW;
- PID: RICH, MUV3 (muon);
- Trigger: CHOD;
- Calorimeters: LKr & MUV1,2;
- Hermetic photon veto: LAV, LKr, IRC, SAC;
- Other vetos: MUV0 (multiplicity), HASC (photon conversion).

$K^+ \to \pi^+\nu\bar{\nu}$: a golden channel in flavor physics

- The $K^+ \to \pi^+\nu\bar{\nu}$ (PNN) decays is a Flavor Changing Neutral Current (FCNC) process;
- Highly suppressed in Standard Model: $Br^{SM}(K^+ \to \pi^+\nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$ [EPJC82(2022)615]
- Dominated by short distance dynamics (t, c quarks). Low intrinsic theoretical uncertainty.
- Sensitive to various New Physics models: new source of flavor violation, new heavy neutral gauge boson, supersymmetry, leptoquarks, etc.





[JHEP11(2015)166]

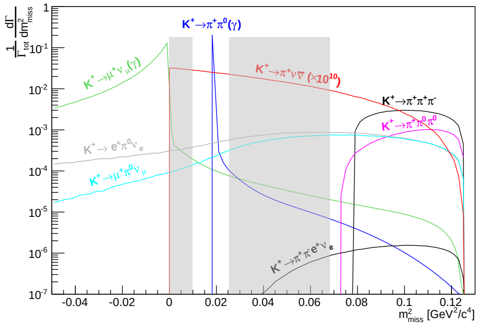
$K^+ \to \pi^+ \nu \bar{\nu}$ analysis

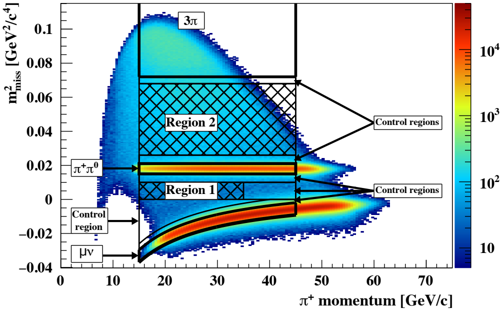
Analysis Strategy

- Reconstruct the 4-momenta of the final state pion and the initial state kaon.
- Compute the squared missing mass:

$$m_{miss}^2 = (p_K - p_\pi)^2.$$

- Define signal region away from peaking backgrounds.
- Use $K^+ \to \pi^+ \pi^0$ as the normalization channel





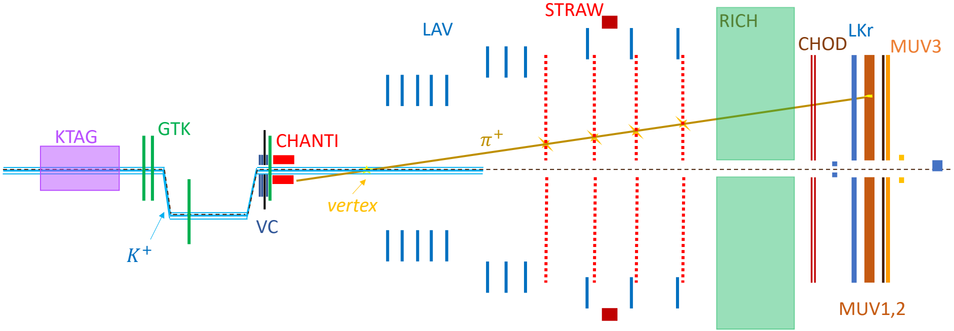
$K^+ \to \pi^+ \nu\bar{\nu}$ analysis

Analysis Strategy

- Selections: vertex, timing, PID, photon veto, and multiplicity veto, etc.
- Normalization channel: Same selections but no photon veto and relax multiplicity veto.
- The branching fraction is computed as

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = N_{SR}^{\pi\nu\bar{\nu}} \cdot SES = (N_{SR}^{tot} - \boxed{N_{SR}^{bg}}) \cdot \boxed{SES}.$$

- The analysis is done in bins of pion momentum.



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

Single Event Sensitivity

$$SES = \frac{Br(K^+ \to \pi^+ \pi^0) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\bar{\nu}} \cdot \epsilon_{RV} \cdot \epsilon_{trig}}$$

- $D = 400$: downscaling factor;
- $N_{\pi\pi}$: number of events in normalization sample;
- $A_{\pi\pi}$, $A_{\pi\nu\bar{\nu}}$: acceptances of the normalization and PNN selection;
- ϵ_{RV}: random veto efficiency;
- ϵ_{trig}: trigger efficiency, $\epsilon_{trig} = \epsilon_{trig}^{PNN} / \epsilon_{trig}^{norm}$;
- Branching ratio of $K^+ \to \pi^+ \pi^0$: $Br(K^+ \to \pi^+ \pi^0) = (20.67 \pm 0.08)\%$ (from PDG).

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

Background estimation

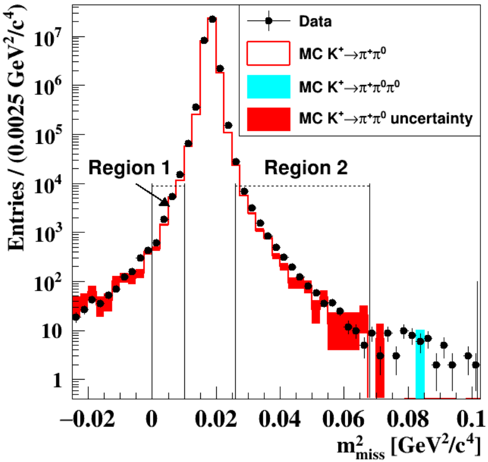
- $N_{bg}^{\pi\pi}$, $N_{bg}^{\mu\nu}$, $N_{bg}^{3\pi}$, & N_{bg}^{ups}: tail fraction method ($K^+ \to \pi^+\pi^0$ background as an example):

$$f_{tail}^{\pi\pi} = N_{SR}^{ctrl_{\pi\pi}} / N_{BGR}^{ctrl_{\pi\pi}},$$

  with $N_{BGR}^{ctrl_{\pi\pi}}$ and $N_{SR}^{ctrl_{\pi\pi}}$ the numbers of events in the background region and signal region in the corresponding control sample (simulation sample for $f_{tail}^{3\pi}$). Then

$$N_{bg}^{\pi\pi} = N_{BGR}^{data} \cdot f_{tail}^{\pi\pi}.$$

- $N_{bg}^{\pi\pi e\nu}$, $N_{bg}^{\pi\gamma\gamma}$, & $N_{bg}^{\pi l\nu}$: Use a large simulation sample to pass signal selection and estimate N_{bg} with the acceptance and branching ratio from PDG.



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

Run 1 result [JHEP06(2021)093]

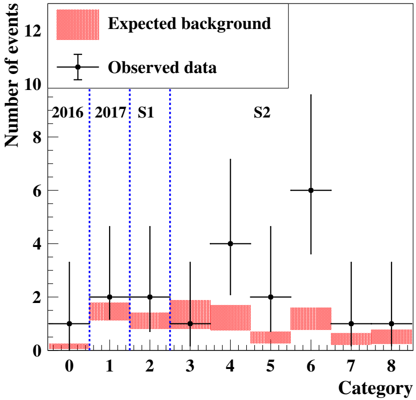
Full Run 1 dataset:

- $SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$;
- $N_{bg}^{exp} = 7.03^{+1.05}_{-0.82}$;
- **20** candidate events observed.

The measured branching fraction:

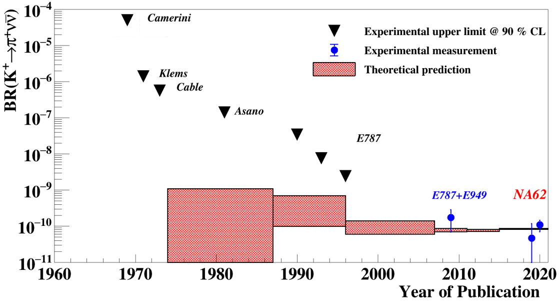
$$\boldsymbol{Br(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}}.$$

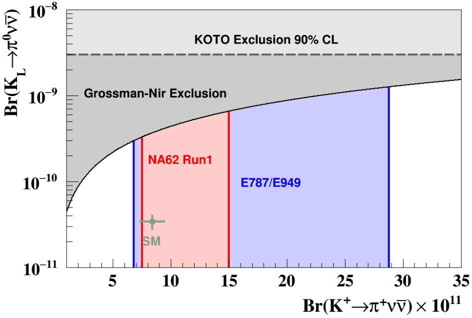
An **evidence** of $K^+ \to \pi^+\nu\bar{\nu}$ decay with $\mathbf{3.4\sigma}$ significance.



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

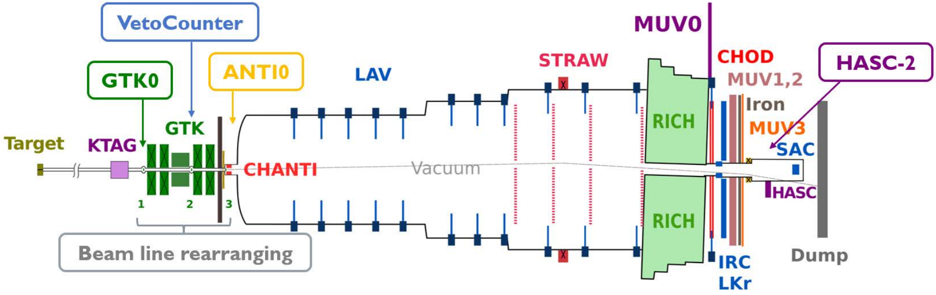
Theory and experiments





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

Run 2 updates [CERN-SPSC-2024-012]



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

Run 2 updates (2021+2022 dataset) [CERN-SPSC-2024-012]

	2021+2022	2018
$N_{\pi\pi}$ $[\times 10^7]$	20.087	
$A_{\pi\pi}$ $[\%]$	13.525 ± 0.005	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}}$ $[\%]$	7.7 ± 0.2	6.37 ± 0.64
ϵ_{trig} $[\%]$	85.8 ± 1.4	89 ± 5
ϵ_{RV} $[\%]$	63.6 ± 0.5	66 ± 1
SES $[\times 10^{-11}]$	0.83 ± 0.03	
$N^{exp\star}_{\pi\nu\bar{\nu}}$	10.07 ± 0.31	
$< N^{exp}_{\pi\nu\bar{\nu}} >_{per\ burst}$	2.3×10^{-5}	1.7×10^{-5}

Background	2021+2022
$\pi^+\pi^0$	0.86 ± 0.06
$\mu^+\nu_\mu$	0.93 ± 0.20
$\pi^+\pi^+\pi^-$	0.11 ± 0.03
$\pi^+\pi^-e^+\nu_e$	$0.84^{+0.35}_{-0.28}$
$\pi^0 l\nu$	$< 10^{-3}$
$\pi^+\gamma\gamma$	0.01 ± 0.01
Upstream	$8.0^{+2.2}_{-1.8}$
Total	$10.8^{+2.2}_{-1.9}$

- 2021+2022 dataset size comparable to full Run 1.
- Most of the selections optimized. Signal yield increased.
- Overall sensitivity ($\sqrt{S+B}/S$) improved.
- **New exciting results at the end of September!**
- Analysis of 2023 onwards data ongoing.

* assuming SM branching ratio $Br^{SM}(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ [JHEP11(2015)033].

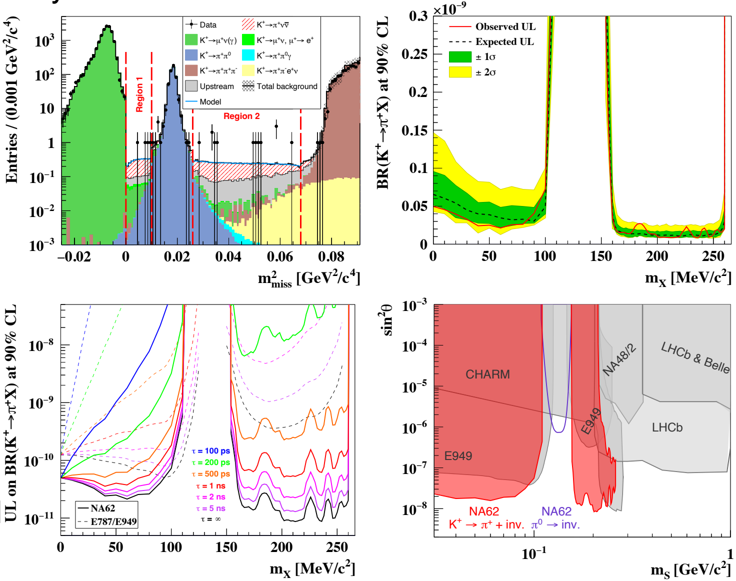
Conclusion

- The $K^+ \to \pi^+ \nu\bar{\nu}$ measurement with NA62 Run 1 data is a major milestone for flavor physics.
- Significant improvements of the signal yield in Run2.
- New results expected at the end of this month!
- NA62 will continue to collect data until CERN LS3.
- Significant improvement of the sensitivity to charged kaon physics observables and new physics.

More physics programs at NA62

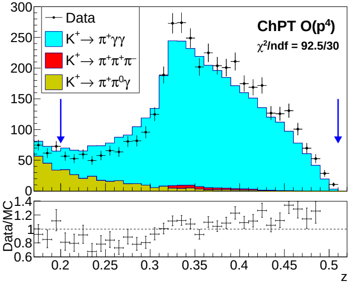
Search for $K^+ \to \pi^+ X$ decay

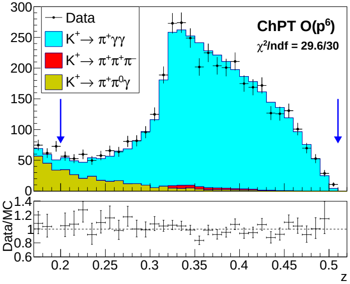
- Search for a peak at m_X^2 in the m^2_{miss} distribution;
- Main background is $K^+ \to \pi^+ \nu \bar{\nu}$;
- Upper limits are set with different X lifetimes, assuming X only decays to SM particles which are always detected once in acceptance;
- The limit are also interpreted within the BC4 model [J.Phys.G47,010501(2020)] as a dark scalar.

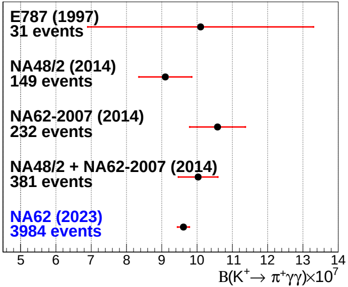


$K^+ \to \pi^+\gamma\gamma$ analysis [PLB850(2024)138513]

- Test of Chiral Perturbation Theory (ChPT);
- $Br(K^+ \to \pi\gamma\gamma)$ parametrized in ChPT by an unknown real parameter $\hat{c}$;
- Main kinematic variable: $z = m^2_{\gamma\gamma}/m^2_K$;
- $N^{obs} = 3984$, $N^{exp}_{bg} = 291 \pm 14$;
- Consistent with the ChPT description to the next-to-leading order ($\mathcal{O}(p^6)$).
- $\hat{c} = 1.144 \pm 0.069_{stat} \pm 0.034_{syst}$, $Br = (9.61 \pm 0.15_{stat} \pm 0.07_{syst}) \times 10^{-7}$.



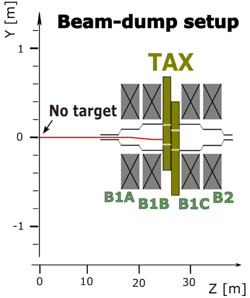


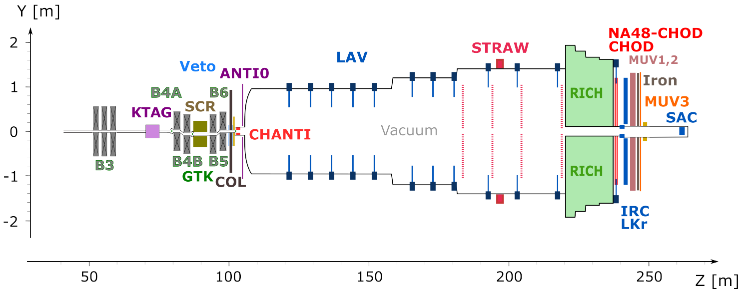


Exotic decays in beam-dump mode

Beam-dump mode

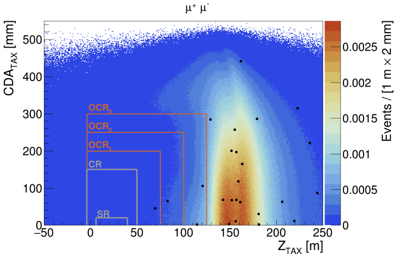
- Remove the target and dump beam on a collimator (TAX);
- Searches for long lived particles (heavy neutral leptons, dark photons, dark scalars, axion-like particles, etc.).
- $(1.4 \pm 0.28) \times 10^{17}$ protons on target (POT) collected in 2021. Expecting 10^{18} in full Run 2;

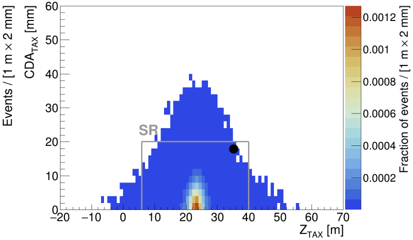


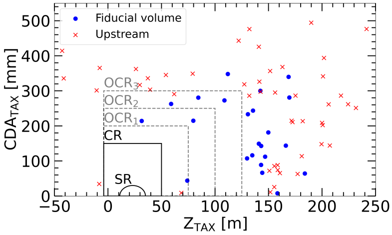


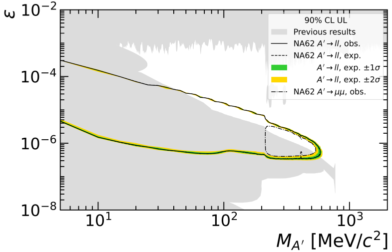
Search for $A' \to l^+l^-$ [JHEP09(2023)035, arXiv:2312.12055]

- Reconstructed vertex in decay region;
- Reconstructed A' pointing to proton beam interaction point at the TAX.
- $N^{\mu\mu}_{bg,exp} = 0.016 \pm 0.002$, $N^{ee}_{bg,exp} = 0.0094^{+0.0206}_{-0.0072}$.
- $N^{\mu\mu}_{obs} = 1$, $N^{ee}_{obs} = 0$.









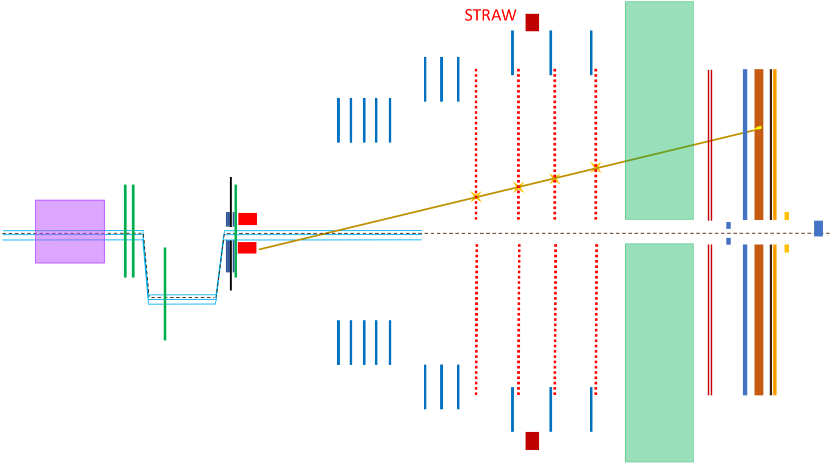
More physics programs at NA62

More physics results are coming:

- $\pi^0 \to e^+e^-$;
- Searches for exotic decays in hadron modes;
- Etc.

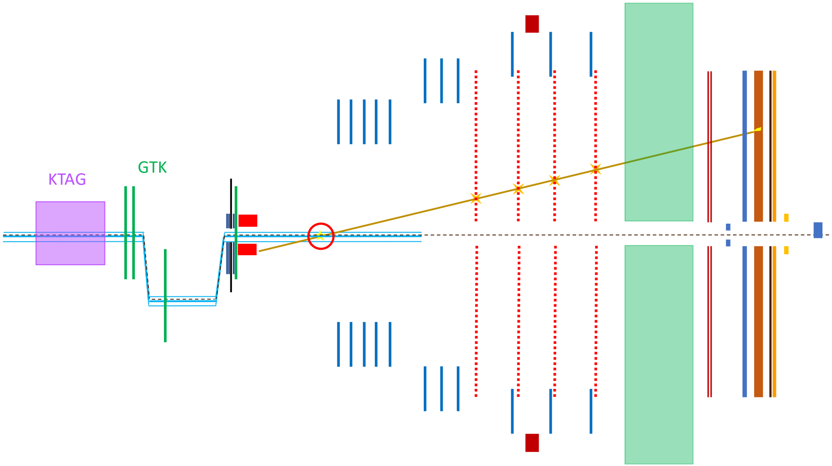
Backup slides

Event reconstruction



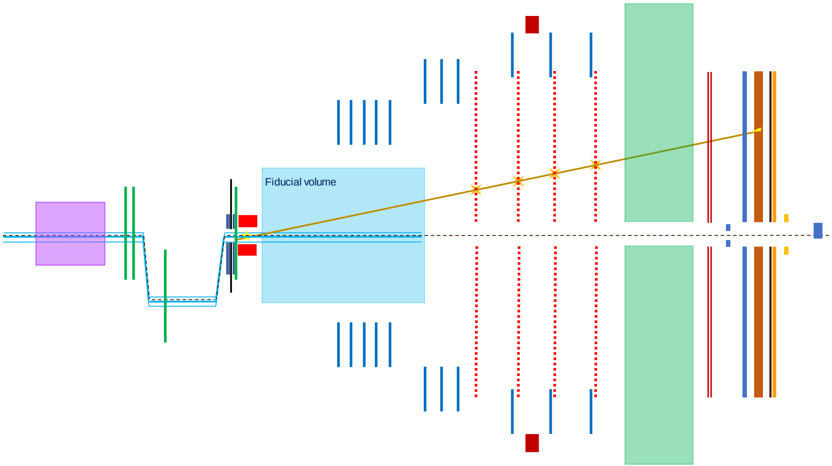
- Reconstruct a track in downstream.

Event reconstruction



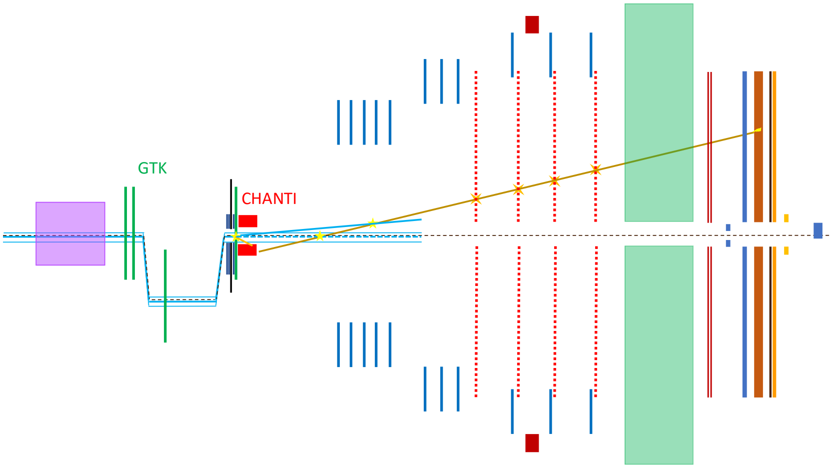
- Find a best matched upstream kaon, which is reconstructed from GTK.
- Build decay vertex.

Selections



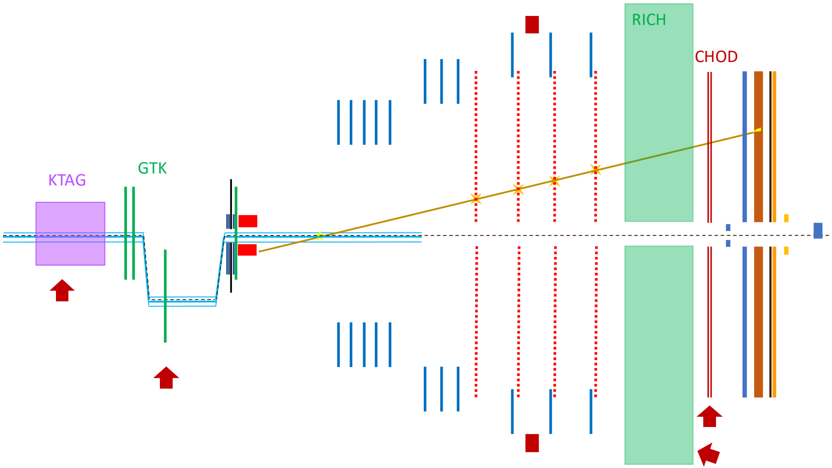
- Reject events with a decay vertex outside the decay region (fiducial volume).

Selections



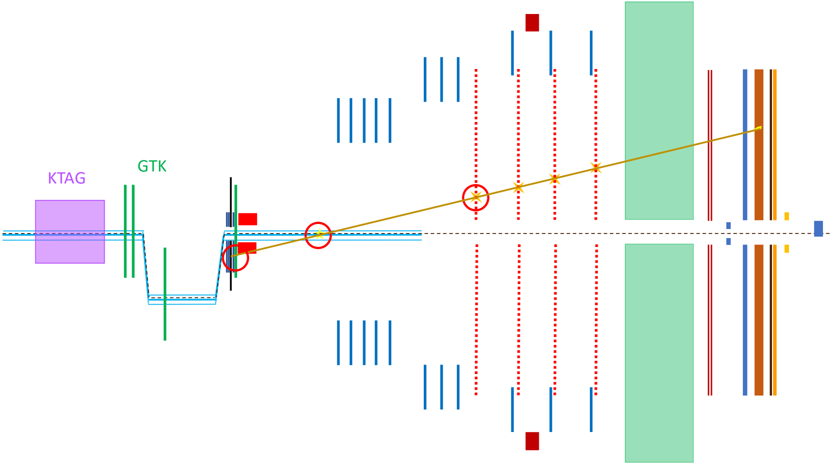
- Reject events with bad beam conditions (bad signals from upstream).

Selections



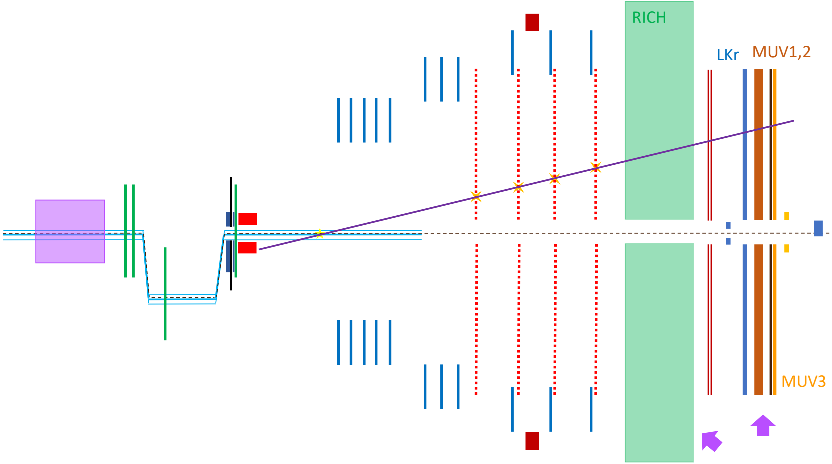
- Reject events with bad time matching in KTAG, GTK, RICH, and CHOD.

Selections



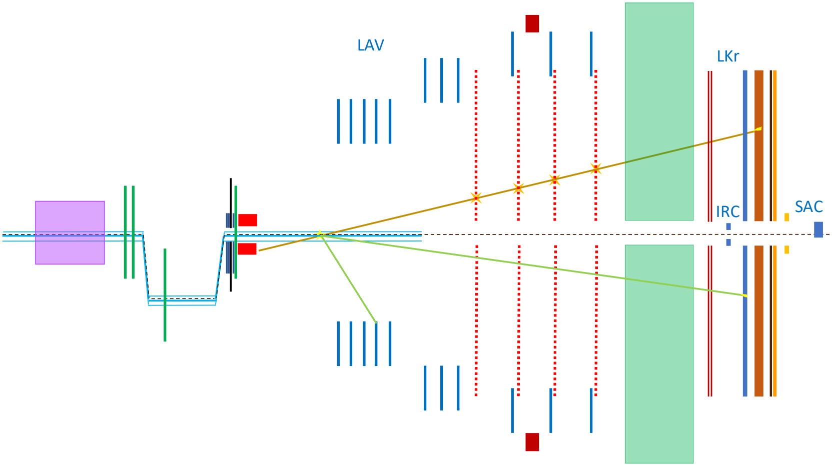
- Reject events with bad matching between up and downstream track, as well as the events looks like upstream background.

Selections



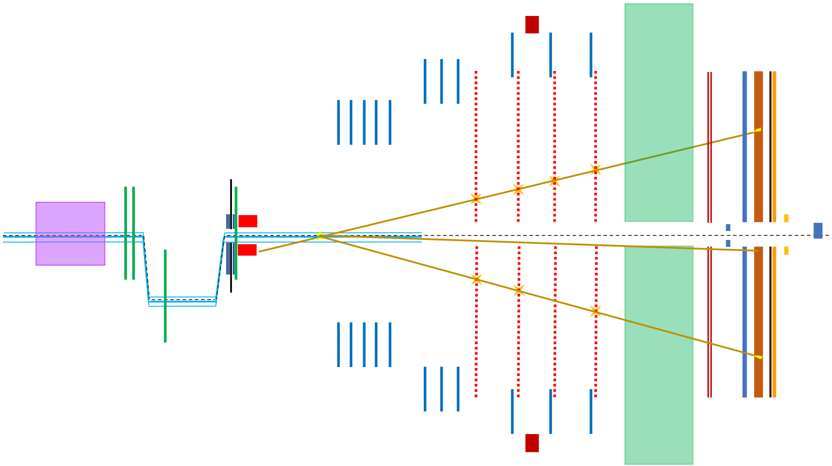
- Downstream track identified as a pion.

Selections



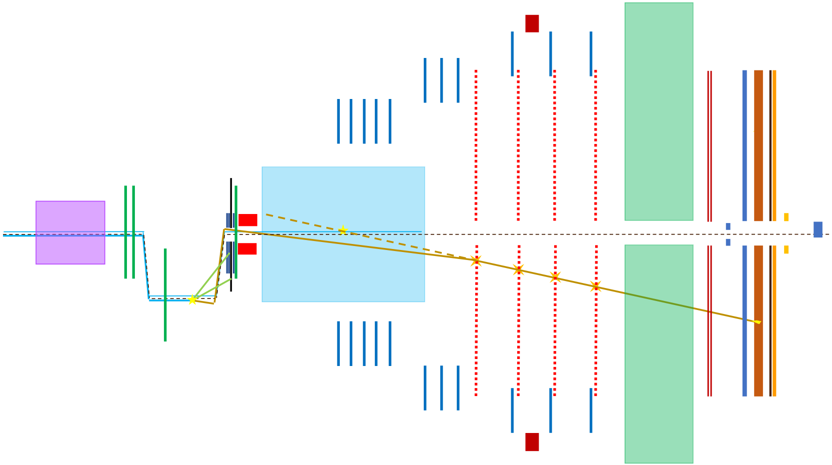
- No photon detected in the event.

Selections



- No any other tracks in downstream.

Selections



- Reject events with signal in the first or second veto counter station but no signal in the third station.

Trigger efficiency

- PNN trigger (mask1):

$$\epsilon_{\pi\nu\bar{\nu}}^{trig,1} = \underbrace{\epsilon_{RICH} \cdot \epsilon_{UTMC} \cdot \epsilon_{!Qx} \cdot \epsilon_{!MUV3} \cdot \epsilon_{!LKr}}_{\epsilon_{L0}^{1}} \cdot \underbrace{\epsilon_{KTAG} \cdot \epsilon_{!LAV} \cdot \epsilon_{STRAW}}_{\epsilon_{L1}^{1}} \cdot$$

- Normalization trigger (mask0):

$$\epsilon_{norm}^{trig,0} = \underbrace{\epsilon_{RICH} \cdot \epsilon_{Q1} \cdot \epsilon_{!MUV3}}_{\epsilon_{L0}^{0}} \cdot \underbrace{\epsilon_{KTAG} \cdot \epsilon_{STRAWOT}}_{\epsilon_{L1}^{0}} \cdot$$

- When entering Single Event Sensitivity, several terms cancel:

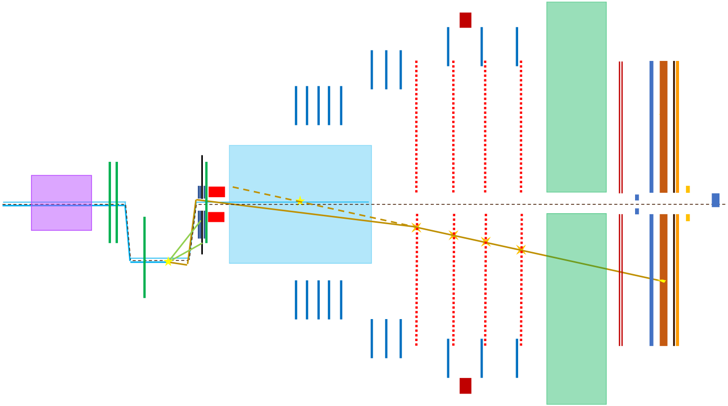
$$\epsilon_{trig} = \frac{\epsilon_{\pi\nu\bar{\nu}}^{trig,1}}{\epsilon_{norm}^{trig,0}} = \frac{\epsilon_{UTMC} \cdot \epsilon_{!Qx} \cdot \epsilon_{!LKr} \cdot \epsilon_{!LAV} \cdot \epsilon_{STRAW}}{\epsilon_{Q1} \cdot \epsilon_{STRAWOT}}$$

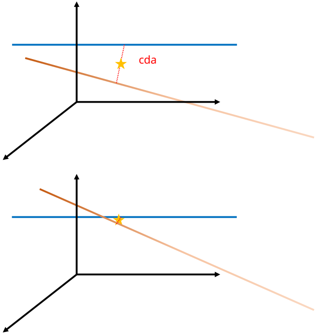
- Evaluation: Checking the L0(L1) trigger flags of normalization(Kmu2) events and compute the fraction of events with flag = true.

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

Background estimation: upstream

Upstream background: the π^+ selected in downstream is originated from the upstream instead of a kaon decay in the decay region, and it's matched with an accidental beam K^+.





- Estimation of upstream background relies on the distribution of the Closest Distance Approach (CDA) of the pion track and the kaon track.

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

Background estimation: upstream

- Use the principle of the tail fraction method, but "tail" in the CDA distribution.
- Control sample: PNN selections but invert the cut on CDA;
- Fit CDA distribution to obtain f_{cda}; Generate a set of upstream-like events to evaluate the probability of upstream background events passing K-π matching (P_{mistag}).

$$N_{ups} = f_{cda} \cdot N^{ctrl_{ups}} \cdot P_{mistag}.$$