IOP 2021 : 12th—15th April 2021

NA62 Measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ Decay

Contents

- The NA62 experiment at CERN
- Study of $K^+ \to \pi^+ \nu\bar{\nu}$ decay
- Future

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On behalf of the **NA62 Collaboration**

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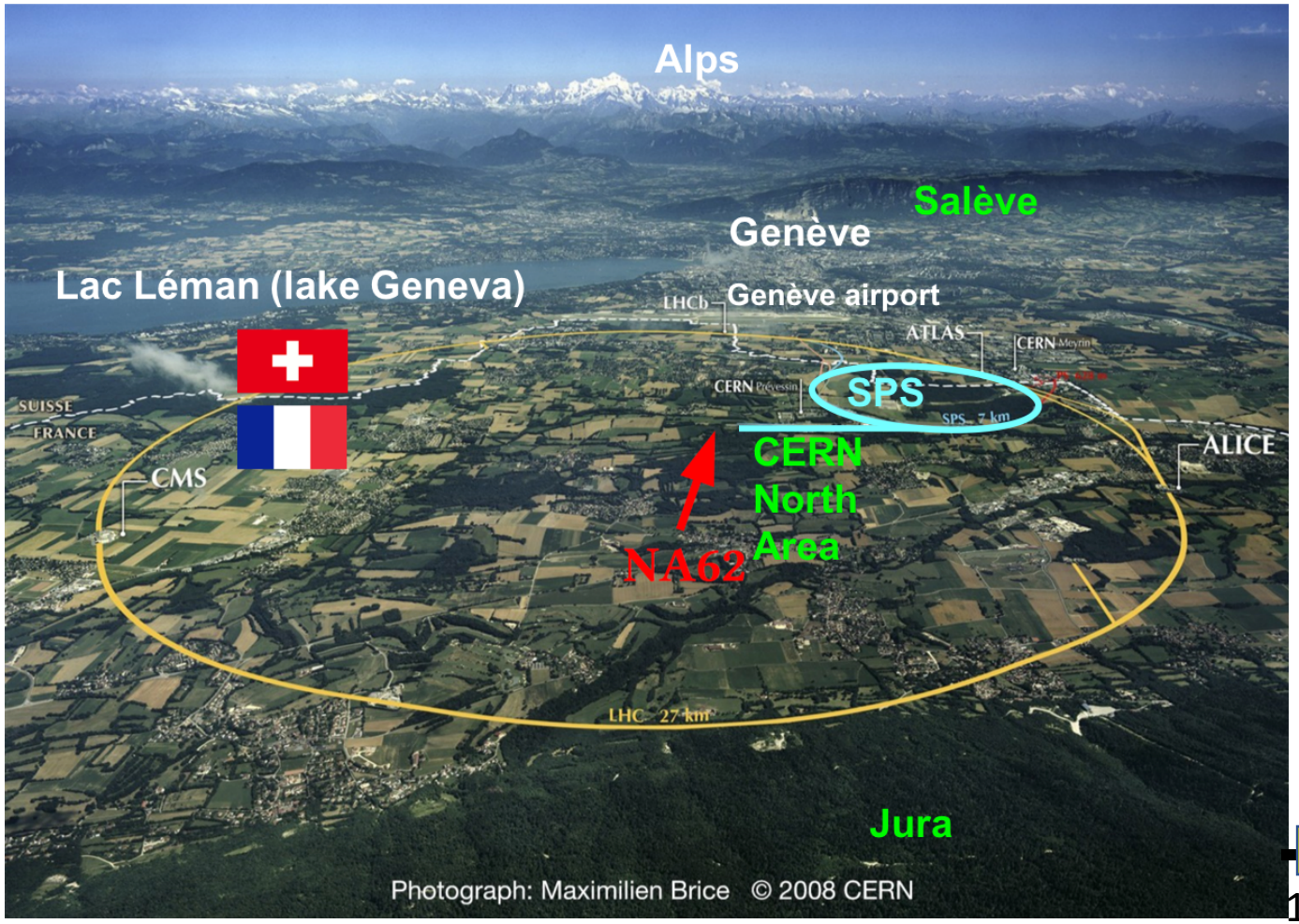
The NA62 Experiment at CERN

~200 collaborators from ~30 institutions :

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP) , Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver (UBC) .



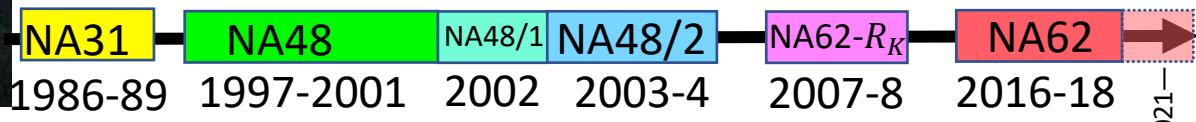
- **Primary goal:** Measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$.
- **New Technique:** K decay-in-flight.
- **$\pi\nu\bar{\nu}$ results** : [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [arXiv:2103.15389]

- **Broader Physics programme: [T. Bache, Tues 15:15]**
  - Rare K^+ decays (e.g $K^+ \to \pi^+ \mu^+ \mu^-$ [ICHEP20]).
  - LNV/LFV K^+ decays (e.g $K^+ \to \pi^\pm l_1^\mp l_2^+$ [ICHEP20]).
  - Exotics (e.g HNL : [PLB 807 (2020) 135599] [ICHEP20]).

- **Data Taking**

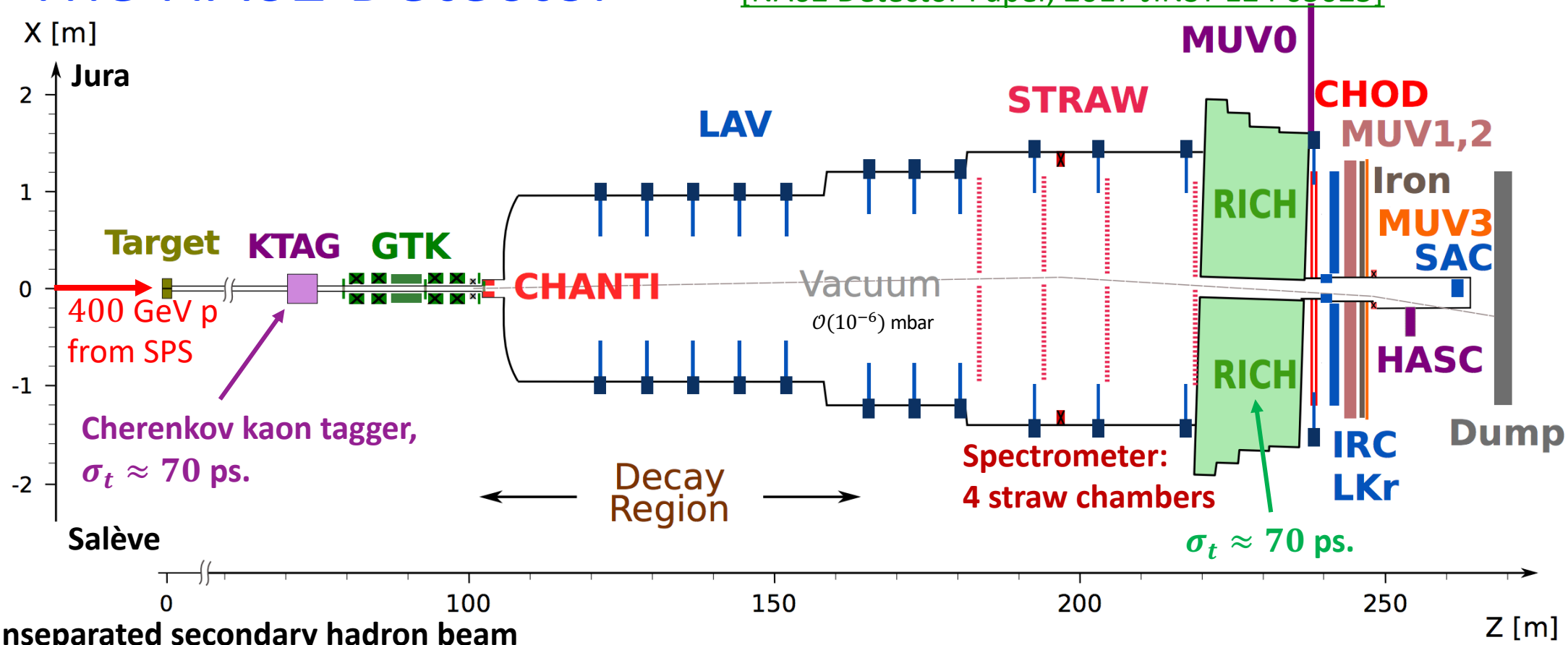
This talk:
- 2016 Commissioning + Physics run (45 days).
- 2017 Physics run (160 days).
- 2018 Physics run (217 days).
- 2021 resuming data taking.

Continues long history of Kaon physics at CERN:



The NA62 Detector

[NA62 Detector Paper, 2017 JINST 12 P05025]



Unseparated secondary hadron beam

- Composition : 70% π^+, 24% p , 6% K^+
- $p_{K^+} = 75$ GeV.
- Nominal intensity : 33×10^{11} protons/SPS spill.
  - ~5 MHz K^+ decays in ~60 m decay region.
- Average instantaneous beam Intensity [MHz]: ~300,~500, ~600 (in 2016,17,18).

Detector Systems

- **Spectrometers:** GTK (upstream) and STRAWs (downstream).
- **PID (1):** Cherenkov detectors: KTAG (K^+), RICH (π/μ separation).
- **PID (2):** Calorimeters (ECAL = LKr , HCALs = MUV1&2).
- **Photon vetos:** (hermetic for $0-50$ mrad) 12LAVs, 2SAVs (IRC&SAC), LKr.
- **Muon veto:** MUV3.
- **Additional detectors:** NA48-CHOD, CHOD, CHANTI, MUV0, HASC.

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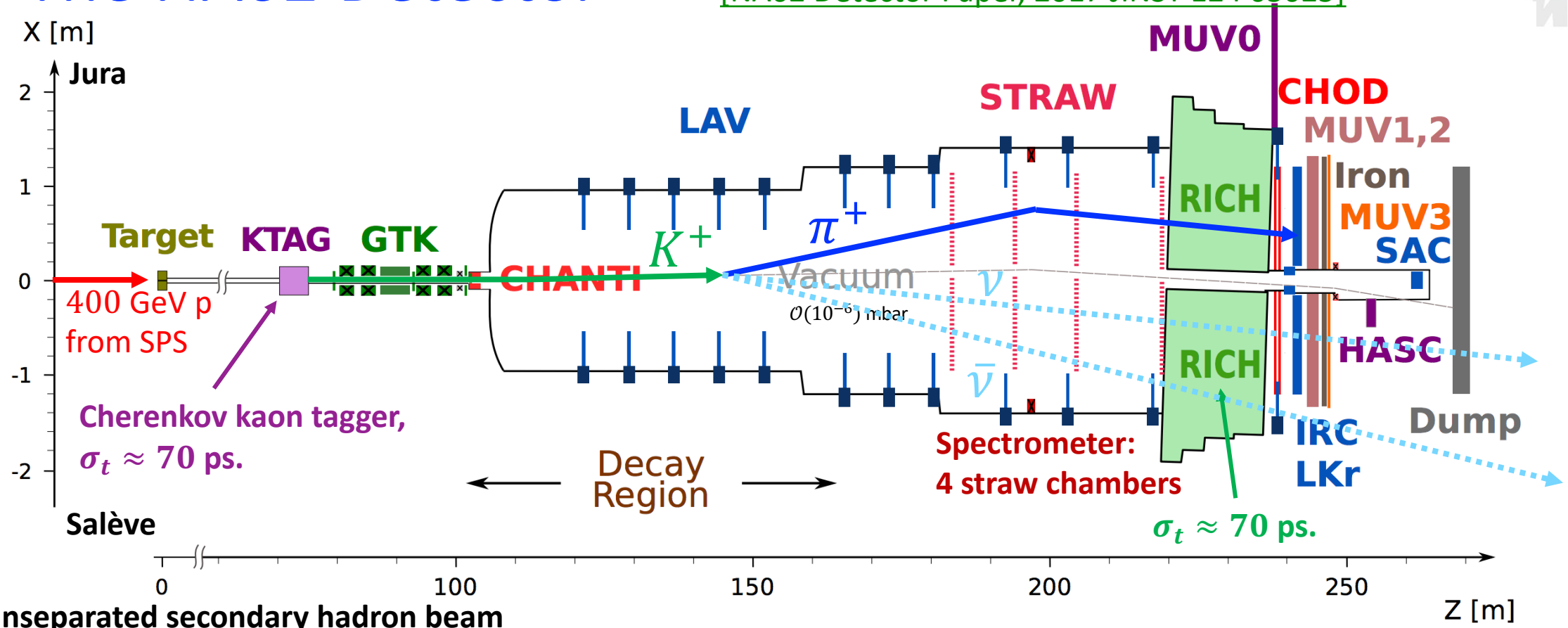

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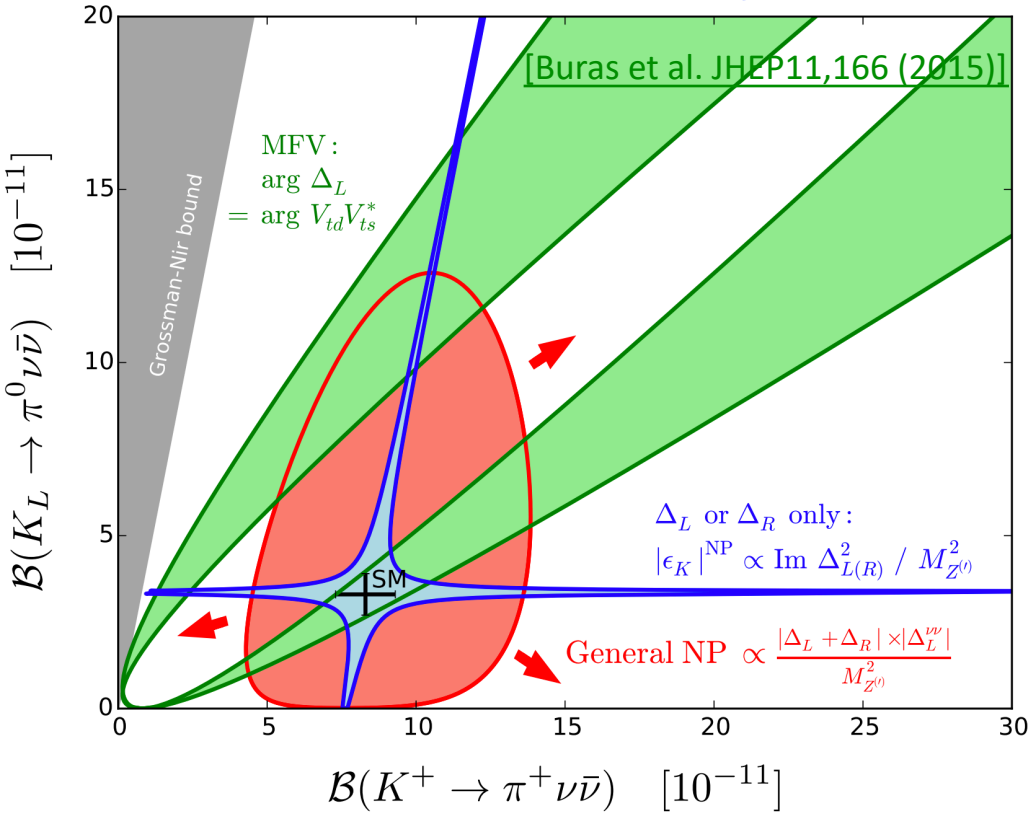
$K^+ \to \pi^+ \nu\bar{\nu}$: Precision test of the SM

- SM BR highly suppressed: $BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$
- Precise theoretical prediction [Buras et al. : JHEP 1511 (2015) 033]
  - NLO (NNLO) QCD corrections to top (charm) contributions, NLO EW corrections.
  - Hadronic matrix elements precisely measured from $BR(K^+ \to \pi^0 e^+ \nu_e)$ decay.

$K^+ \to \pi^+ \nu\bar{\nu}$ Beyond the Standard Model



- Spot BSM contributions in deviation from SM prediction of $Br(K \to \pi\nu\nu)$:
  - sensitive to high mass scales.
- Correlations between BSM contributions to K^+& K_L BRs [JHEP 1511 (2015) 166].

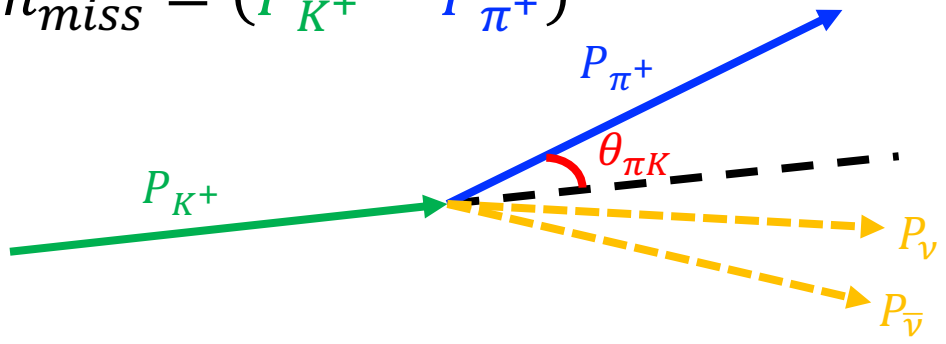
$K^+ \to \pi^+ \nu\bar{\nu}$ Analysis Strategy at NA62

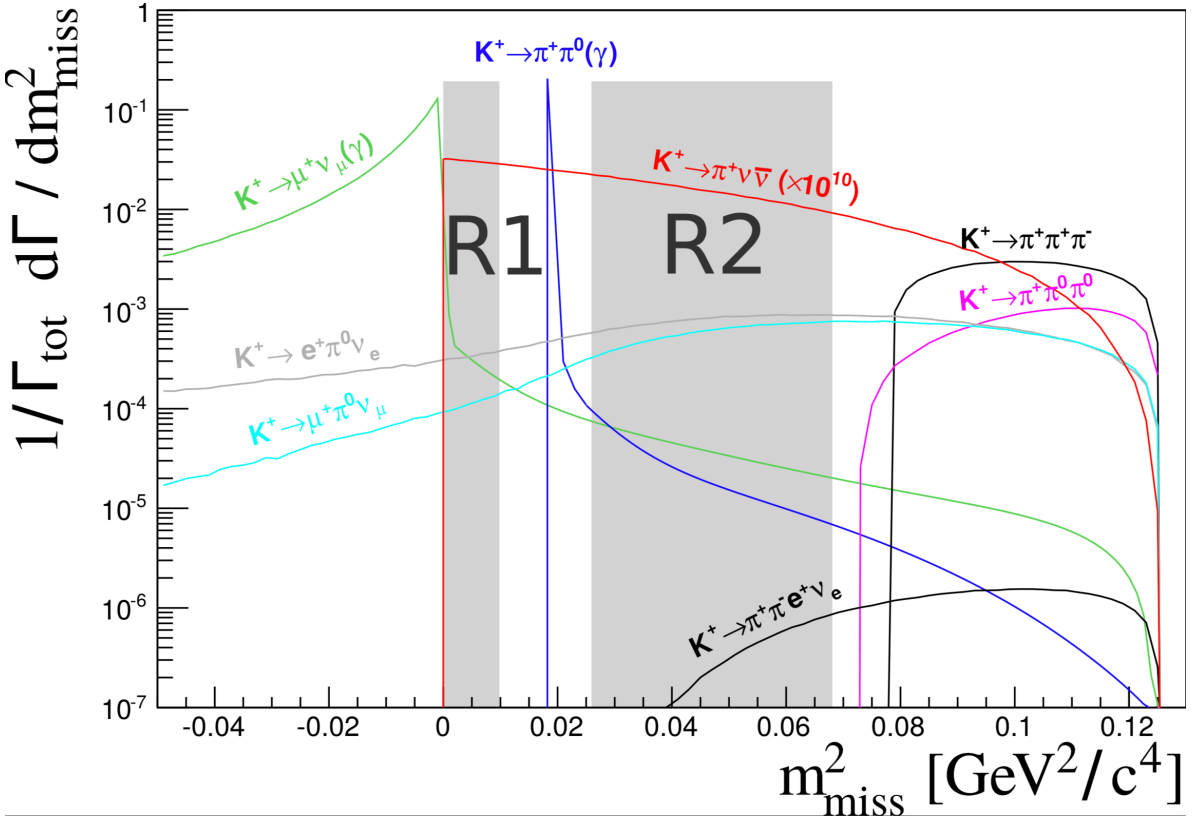
NA62 Performance Keystones

- $\mathcal{O}(100)$ ps timing between sub-detectors.
- $\mathcal{O}(10^4)$ background suppression from kinematics.
- $> 10^7$ muon rejection.
- $> 10^7$ rejection of π^0 from $K^+ \to \pi^+\pi^0$.

Process	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	0.6356 ± 0.0011
$K^+ \to \pi^+\pi^0$	0.2067 ± 0.0008
$K^+ \to \pi^+\pi^+\pi^-$	0.05583 ± 0.00024
$K^+ \to \pi^+\pi^- e^+\nu_e$	$(4.247 \pm 0.024)\times10^{-5}$
$\boldsymbol{K^+ \to \pi^+\nu\bar{\nu}}$	[SM] $\boldsymbol{(8.4 \pm 1.0)\times10^{-11}}$

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

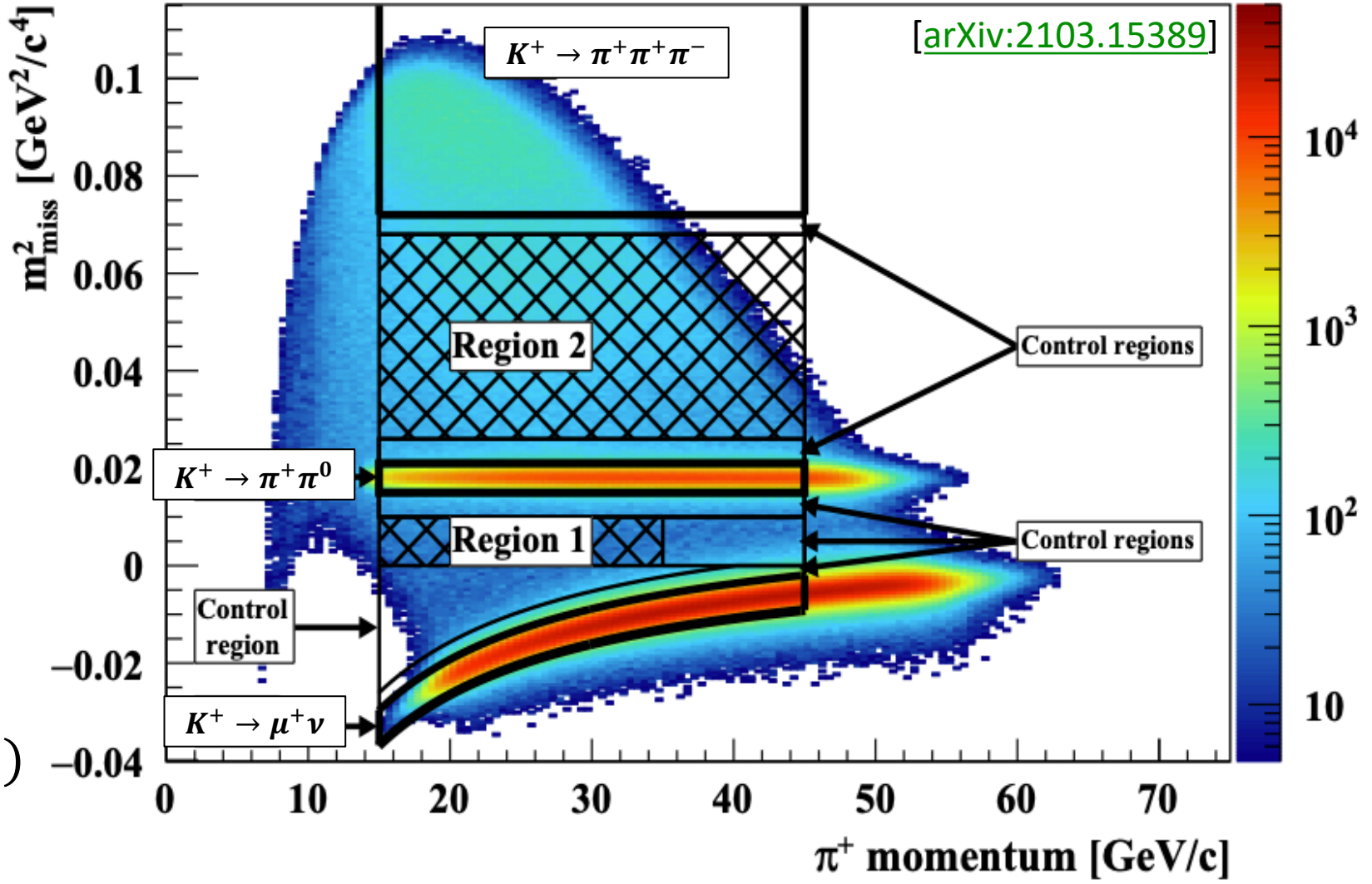




Signal Selection

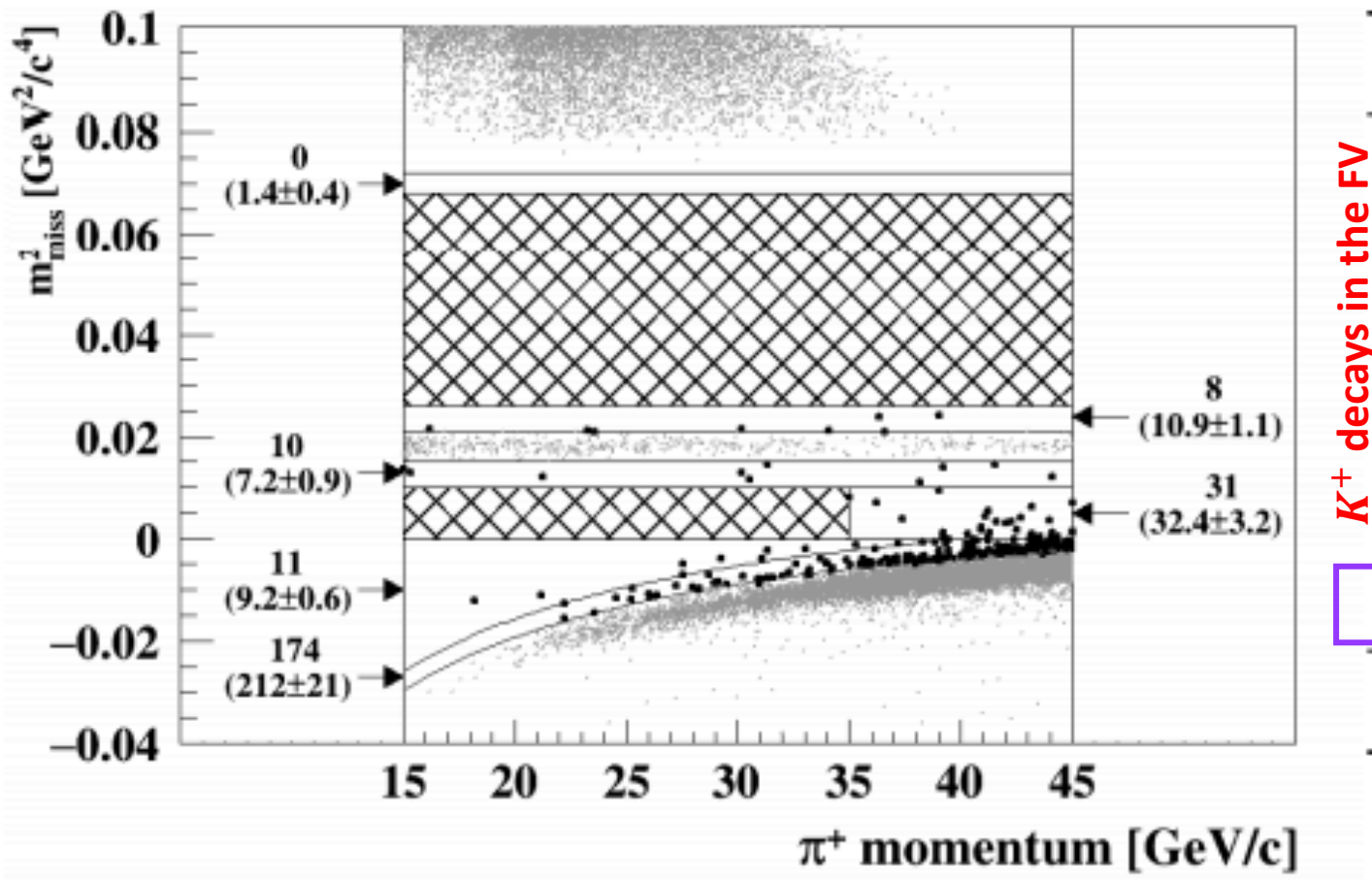
- **Reconstruct K^+ and π^+**
- **$K^+ - \pi^+$ matching & reconstruct vertex**
  - CDA & timing, vertex in FV.

- **π^+ identification (μ^+ rejection)**
  - RICH (Calorimeters) performance: $\varepsilon(\pi^+ \text{ ID}) \approx 0.85(0.82)$ with $P(\mu^+ \Rightarrow \pi^+ \text{ misID}) \approx 3\times10^{-3}(10^{-5})$
- **Photon vetos**
  - $\pi^0(\rightarrow \gamma\gamma)$ rejection inefficiency $\sim 10^{-8}$



- **Multi-track rejection**
- **Kinematics (m^2_{miss} vs p_{π^+})**
  - Selection optimized in bins of p_{π^+}.

Background Studies

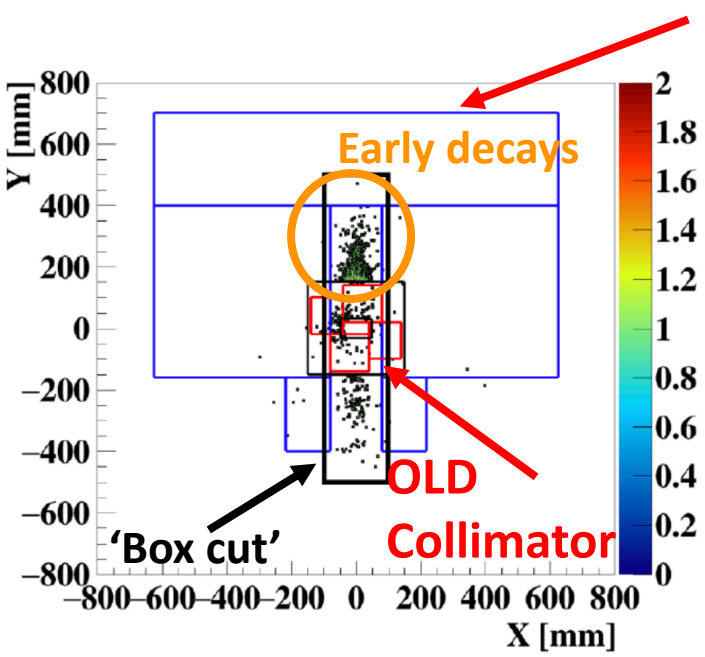


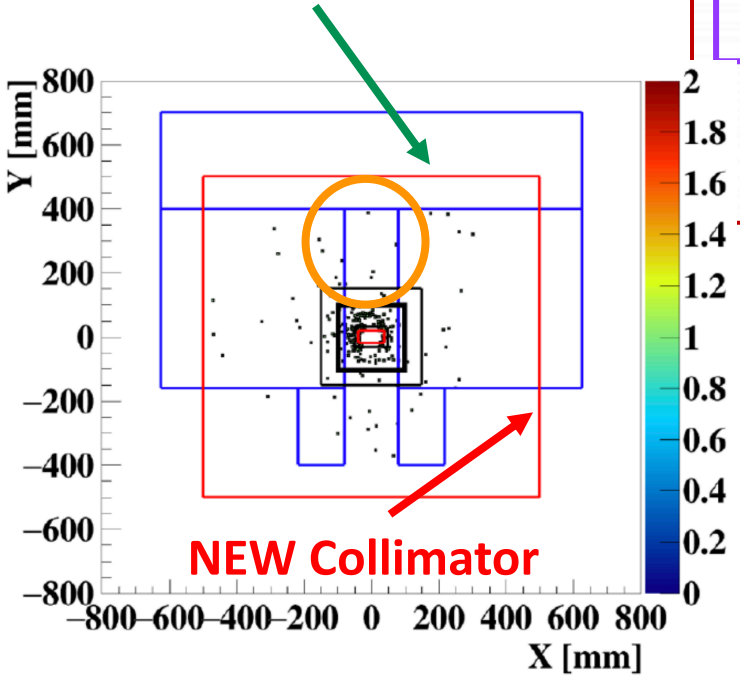
K^+ decays in the FV

Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Background Studies: Upstream Background

- Upstream background:
  - Early decays in upstream region
  - Interactions with GTK stations
  - + beam pileup & scattering in STRAW1
- During 2018 collimator was replaced – removing an early decay mechanism.
  - Split data into S1 (before) S2 (after)





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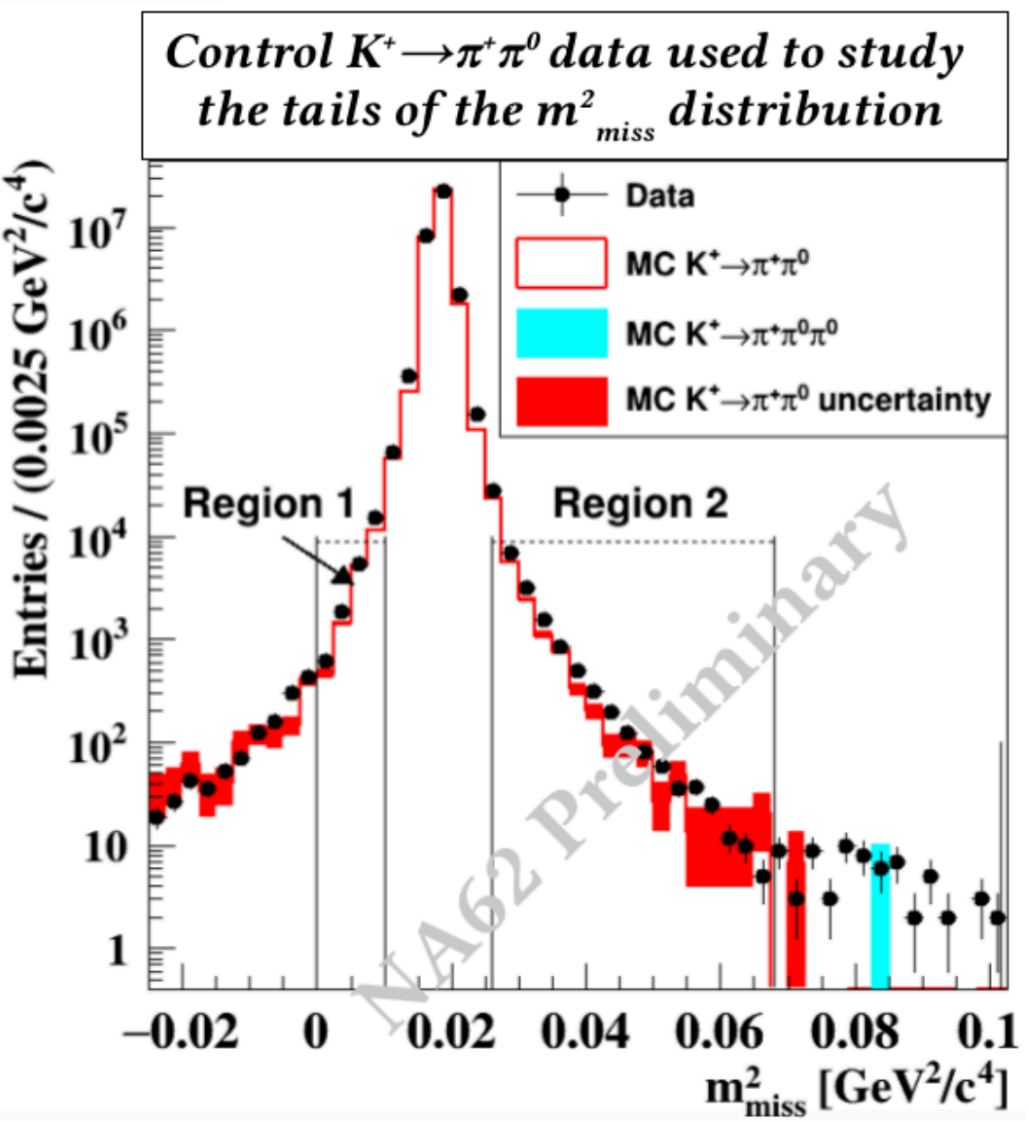
Background Studies: K^+ decays in the FV (1)



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Data-driven background evaluation:

Data events in $\pi^+\pi^0$ region after $K_{\pi\nu\bar{\nu}}$ selection

$$N_{bkg} = N(\pi^+\pi^0) f_{kin}$$

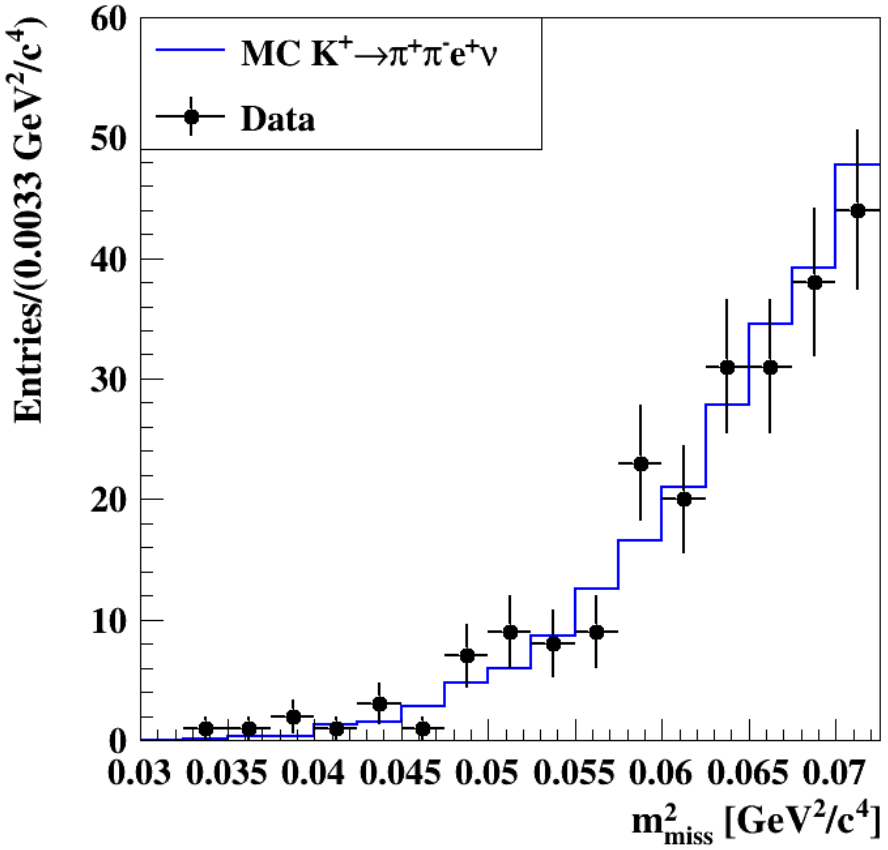
Expected numbers of $K^+ \to \pi^+\pi^0$ events in signal regions after $K_{\pi\nu\bar{\nu}}$ selection

Fraction of $K^+ \to \pi^+\pi^0$ events in signal regions measured from control data.

Background Studies: K^+ decays in the FV (2)

Study background with simulations

e.g. $K^+ \to \pi^+\pi^- e^+ \nu_e$: Validate using samples obtained inverting at least one selection criteria.



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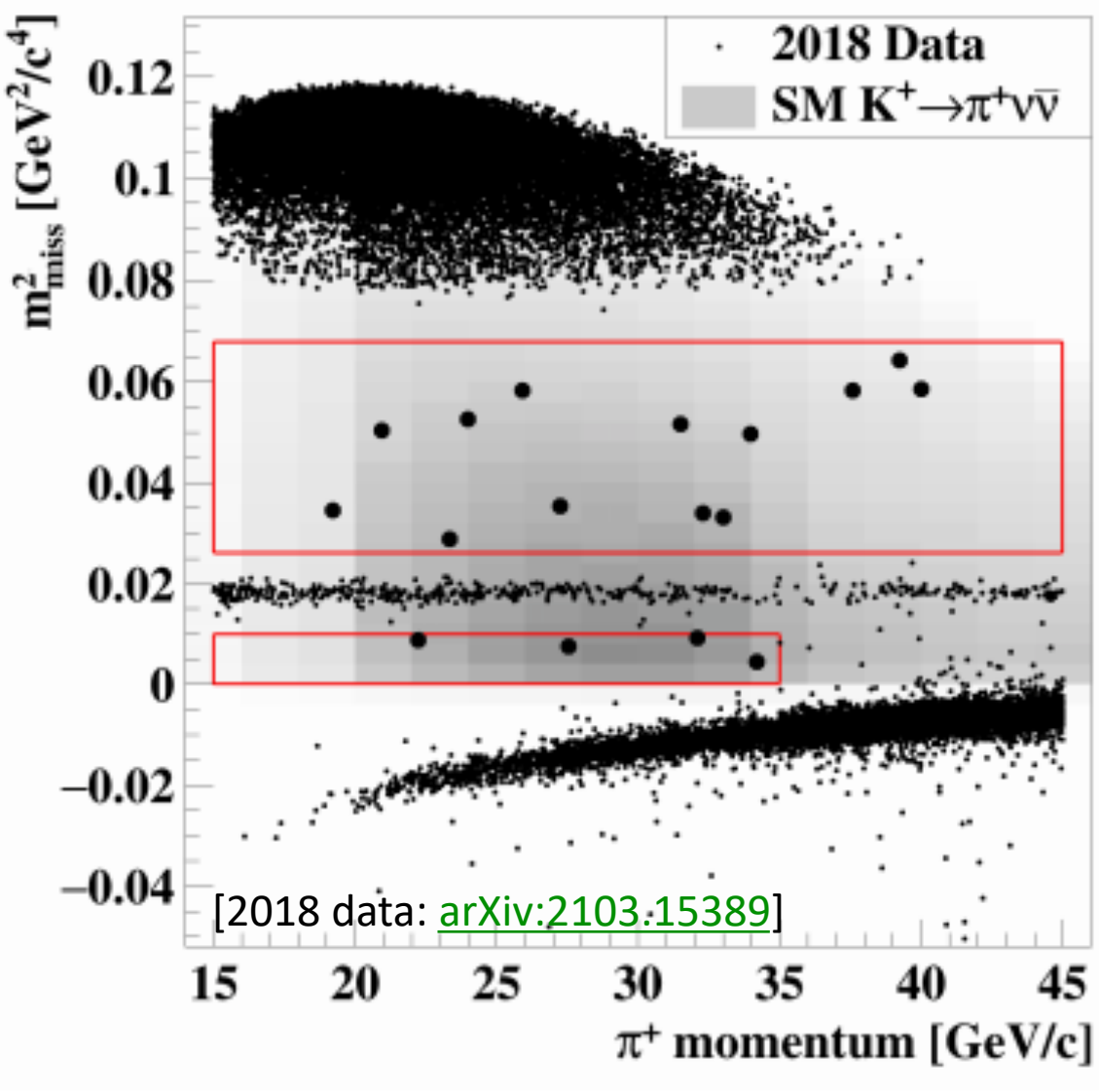
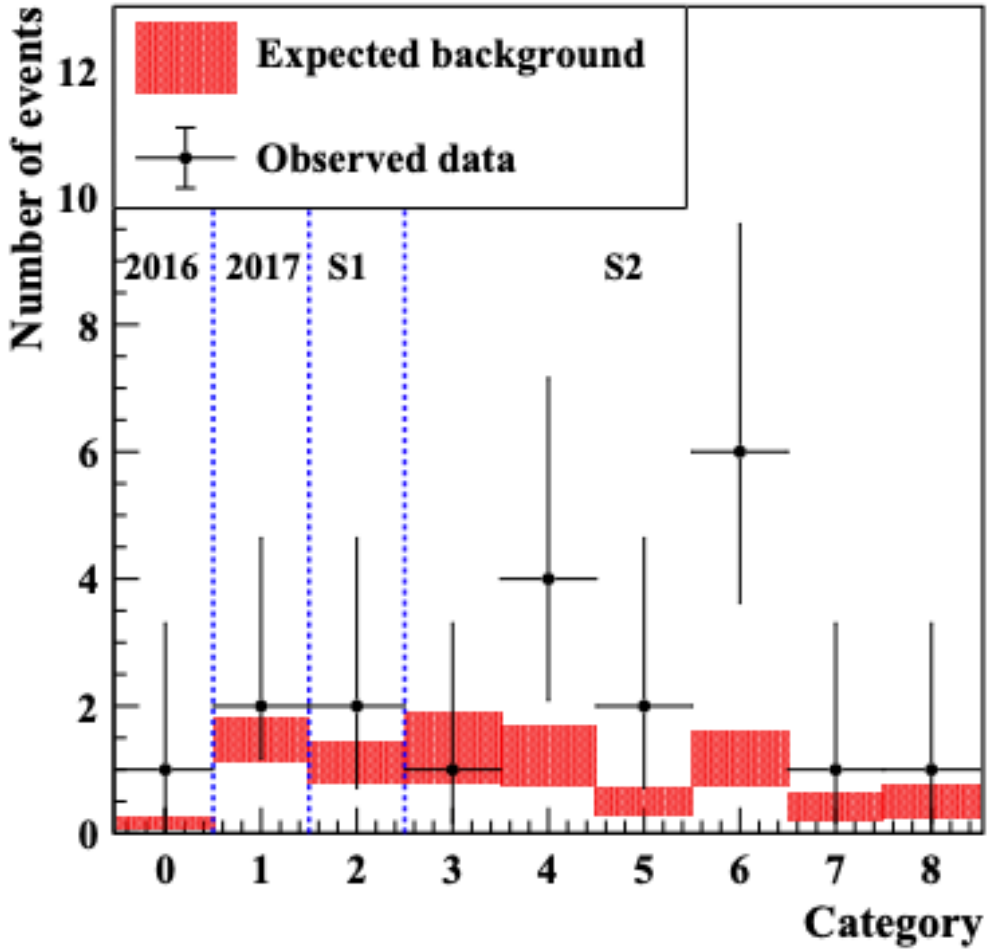
Result : 2016+17+18 data





$$SES = (0.839 \pm 0.053_{\text{syst}}) \times 10^{-11},$$

$$N^{\text{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}},$$

$$N^{\text{exp}}_{\text{background}} = 7.03^{+1.05}_{-0.82}.$$

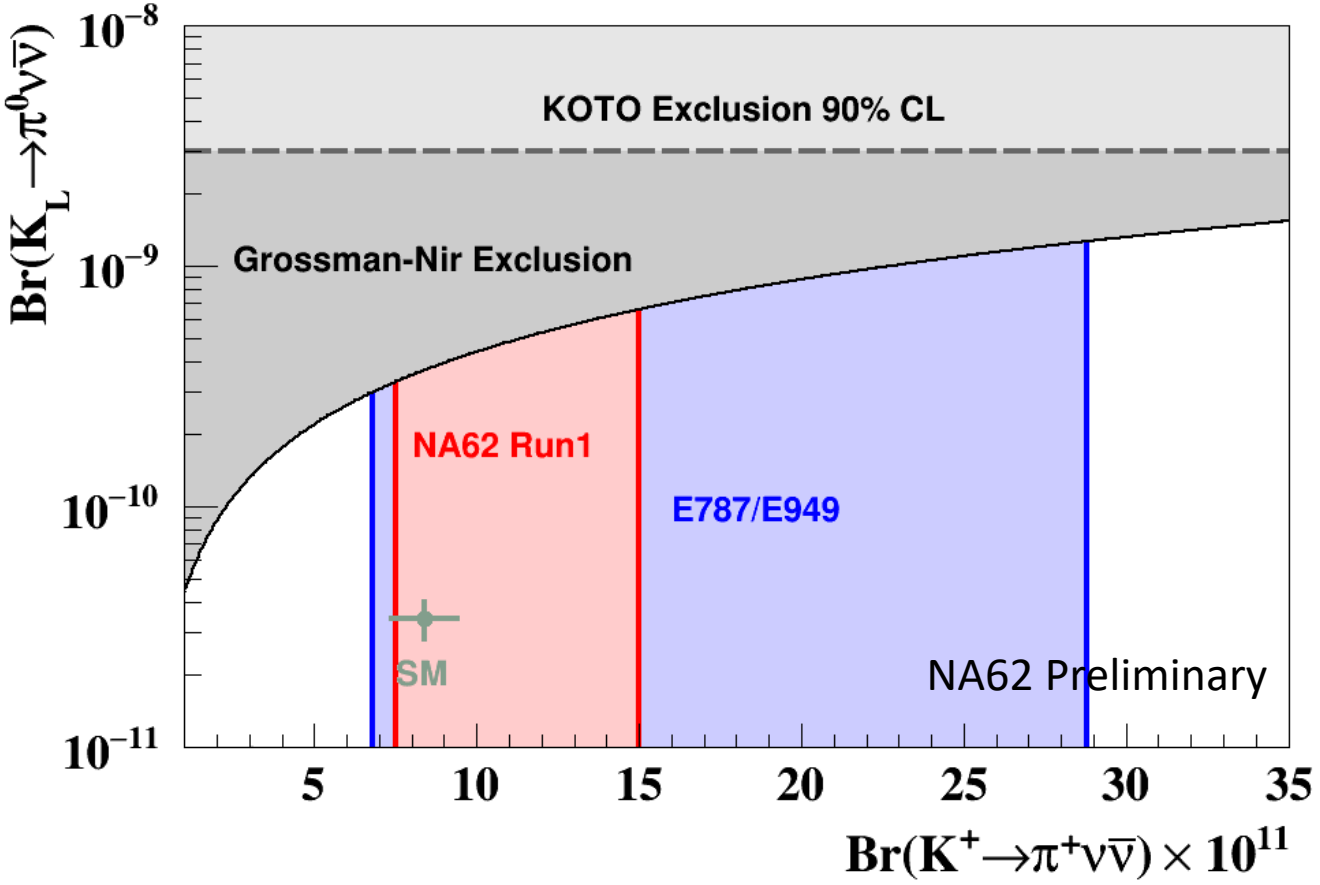
$N_{obs} = 20$

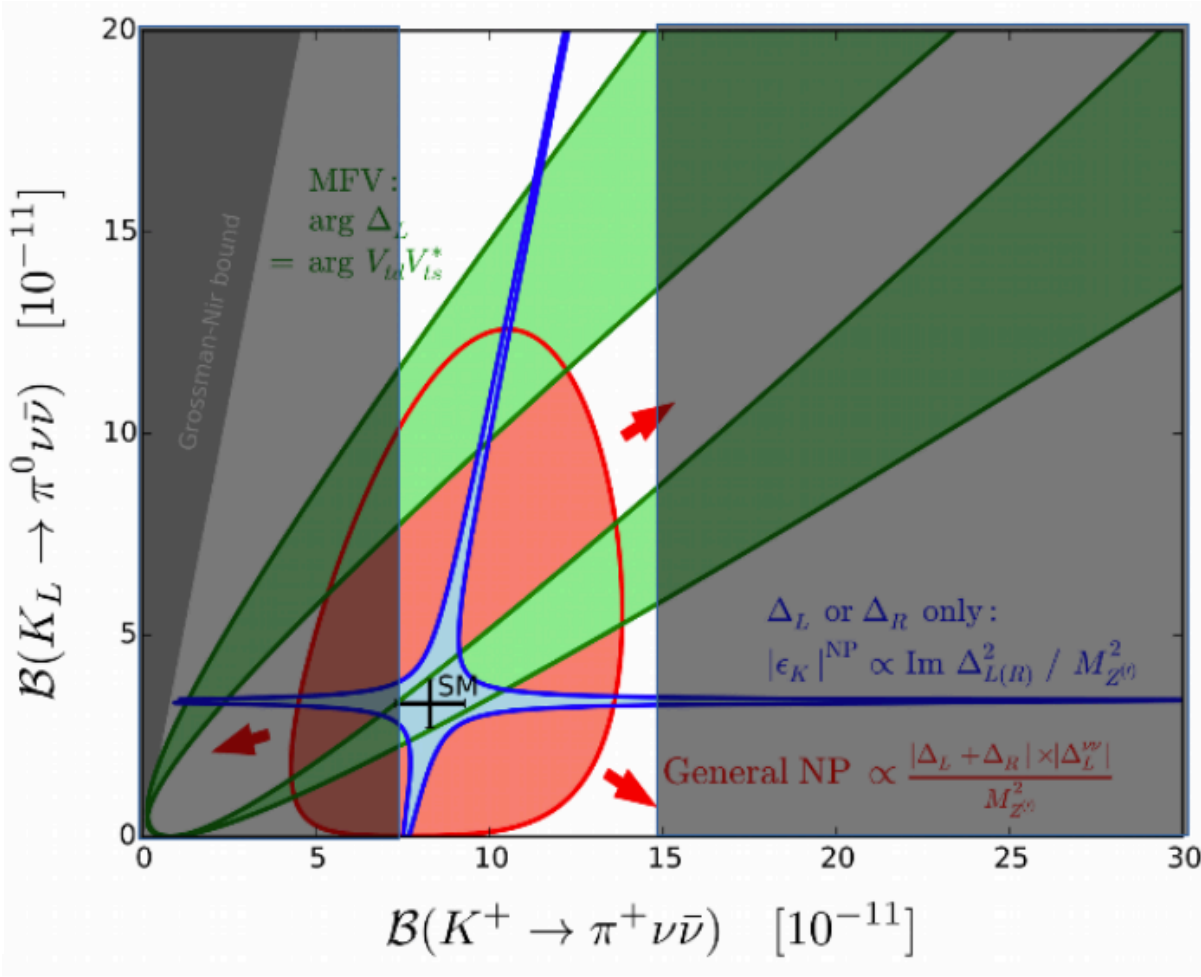
$$\text{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

3.4σ significance

Interpretation of Result (1) & Future

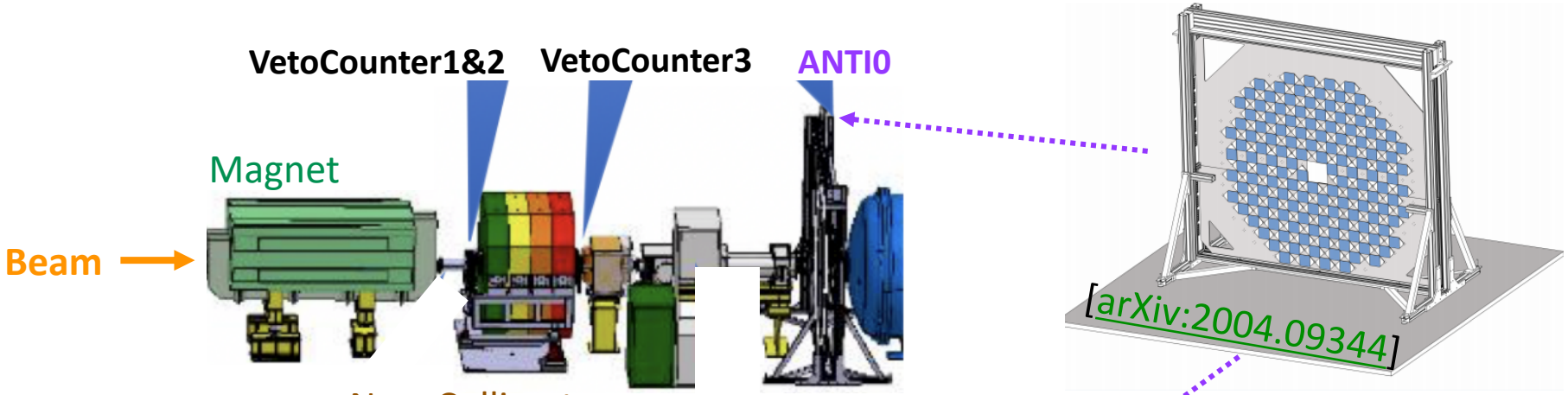
- Large deviations from SM already ruled out – next target : high precision measurement.

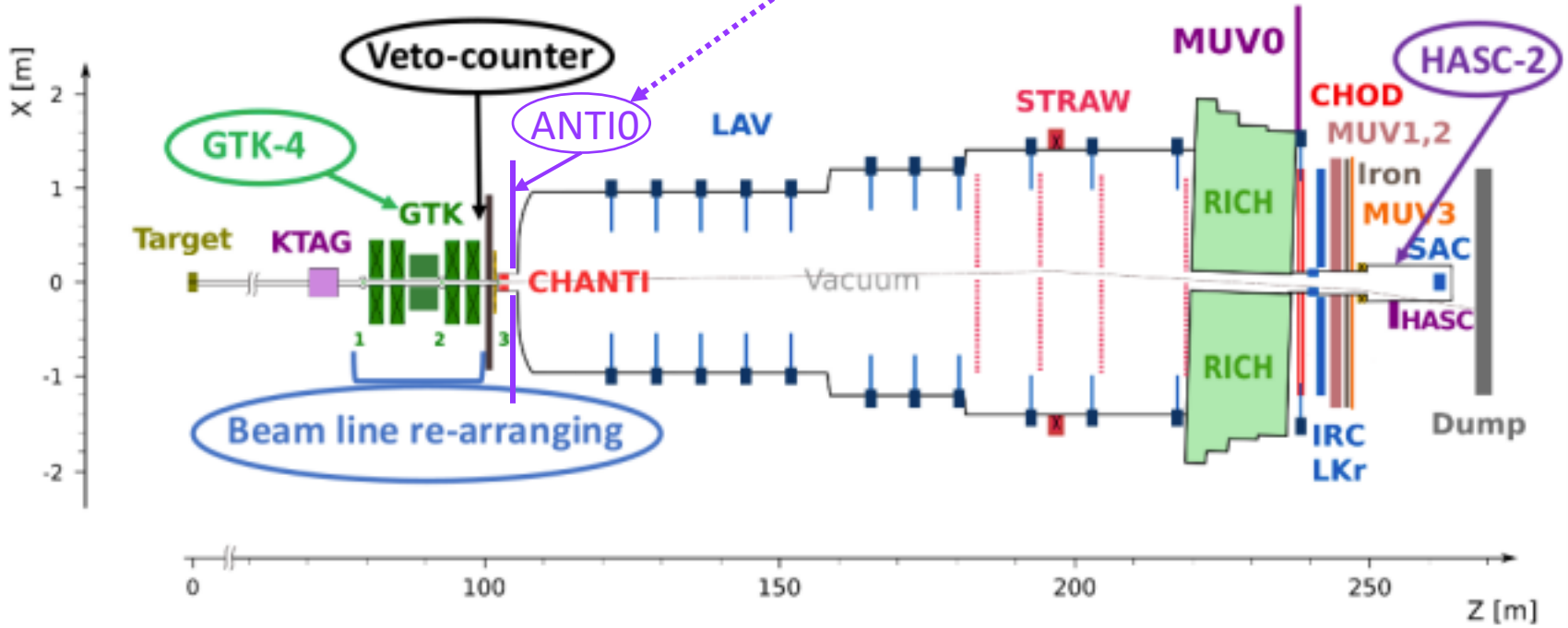




Future

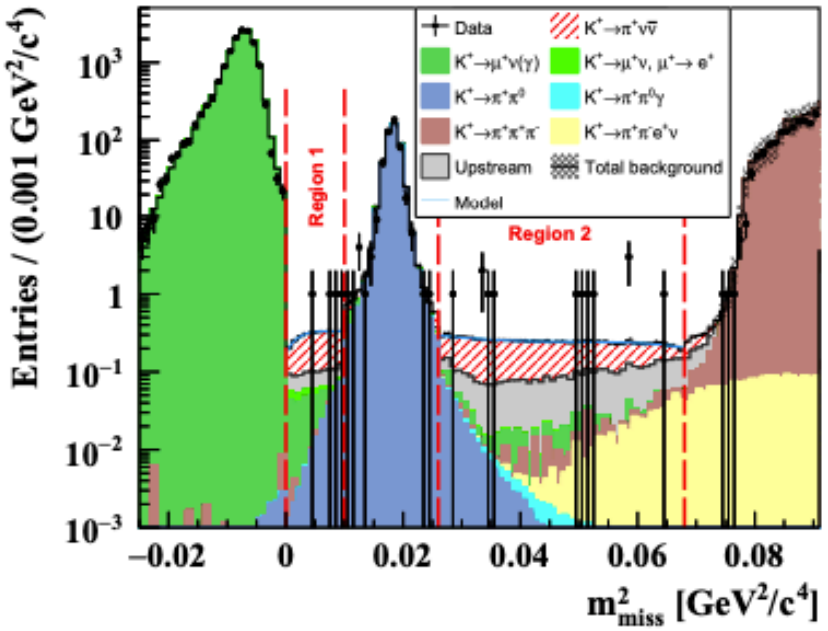
- Data-taking to resume in 2021 at higher intensity with updated detector:
  - Enhanced upstream rejection (additional vetos), reconstruction (GTK4) …

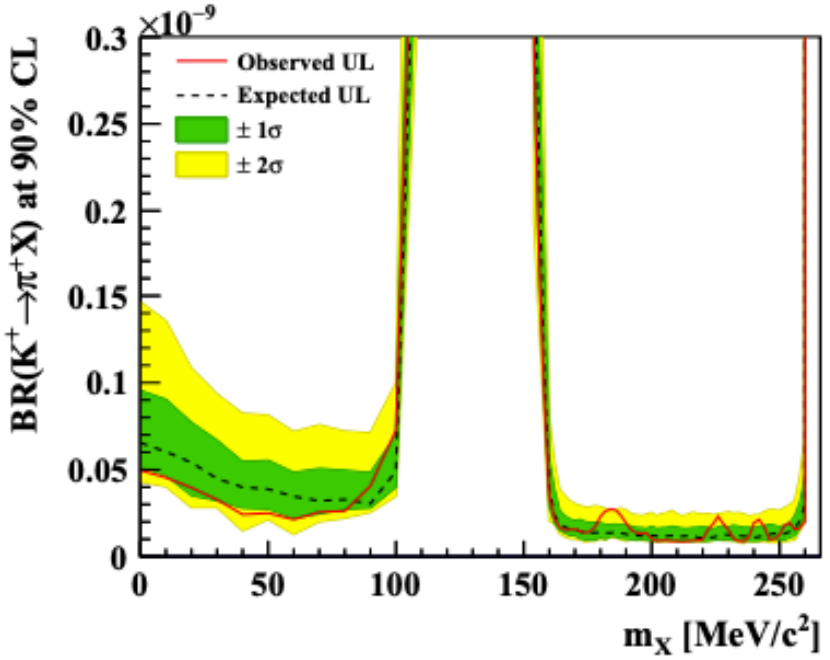


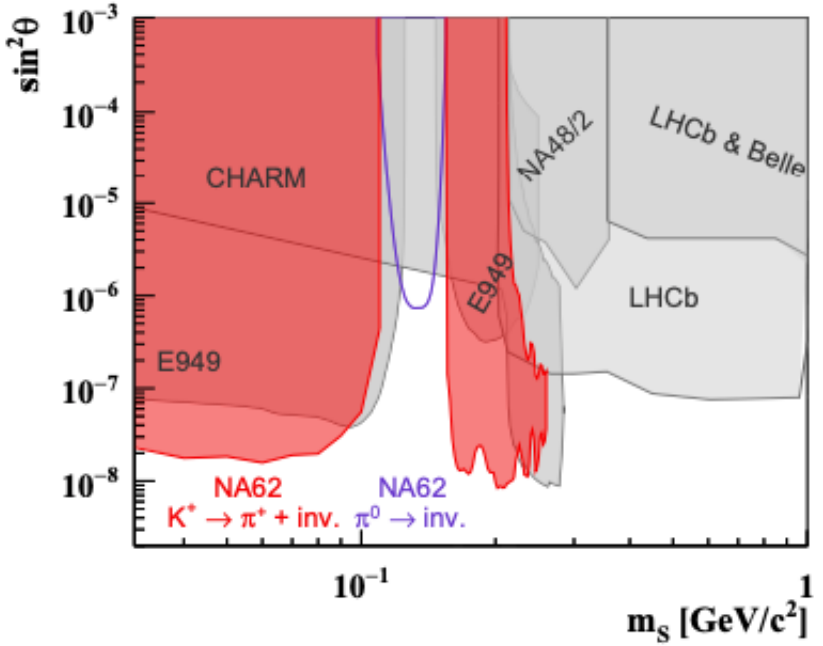


Interpretation of Result (2) Search for $K^+ \to \pi^+ X$

- Search for e.g. Dark Scalar ($X = S$), production & decay driven by mixing with Higgs boson (mixing parameter $sin^2\theta$).
- Perform a peak search considering SM $K^+ \to \pi^+ \nu\bar{\nu}$ as a background.
- Improve on recent NA62 limits from 2017 analysis [JHEP 03 (2021) 058] by factor ~ 4.







Summary

- NA62 has used 2016+17+18 data to study the ultra-rare decay $K^+ \to \pi^+ \nu\bar{\nu}$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

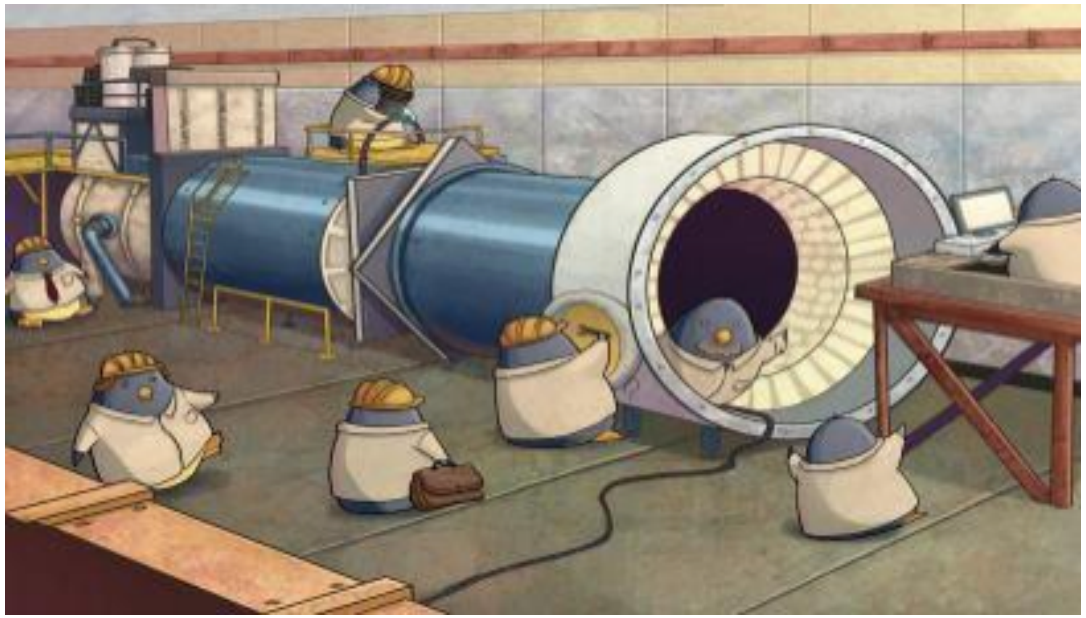
3.4σ significance

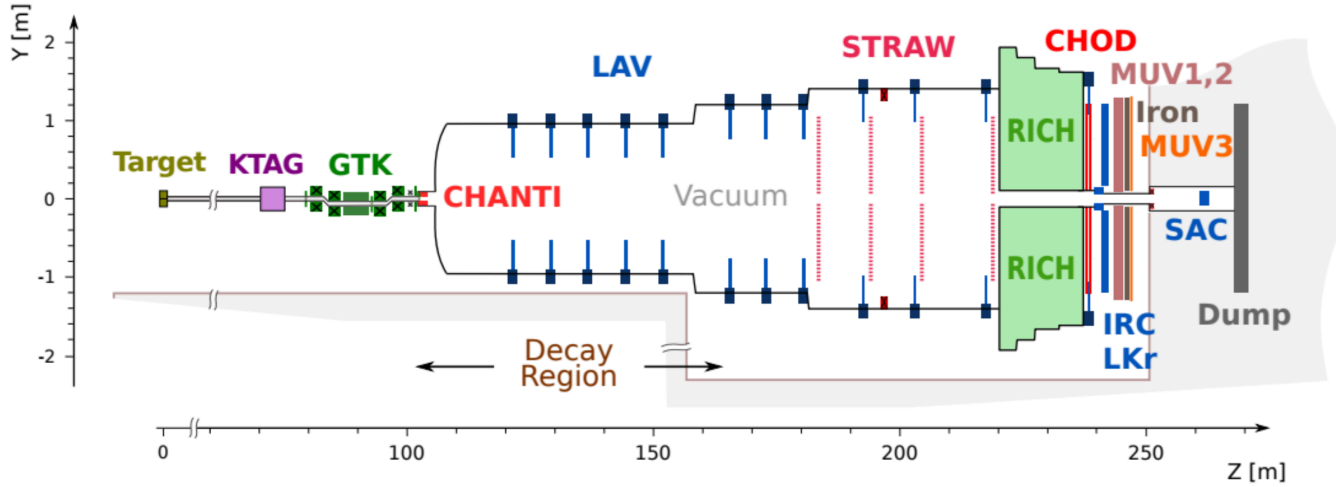
- Starting to constrain BSM scenarios: need high precision measurement + measurement of $K_L \to \pi^0 \nu\bar{\nu}$.
- Use same data to search for $K^+ \to \pi^+ X$ where X is e.g. a Dark Scalar.

Outlook

- NA62 data-taking scheduled to resume in July 2021:
  - New detector systems, will improve upstream rejection & high intensity performance
  - Run at higher intensities
- Target $\mathcal{O}(10\%)$ precision measurement of $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$.

Supplemental



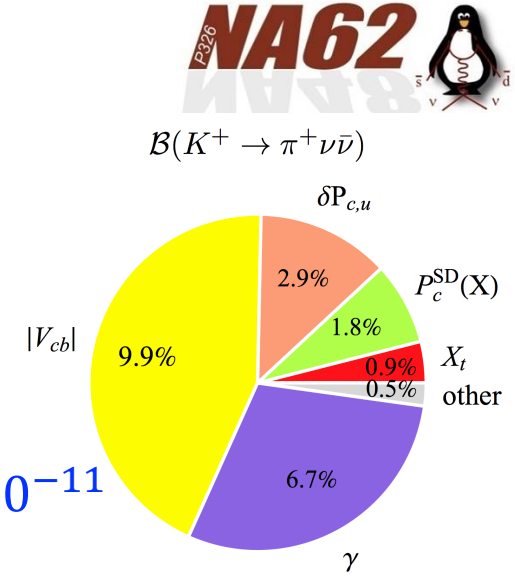


$K^+ \to \pi^+ \nu\bar{\nu}$: Precision test of the SM

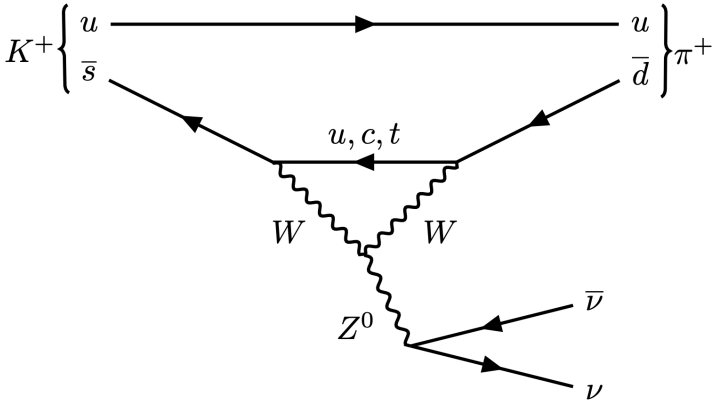
- **SM BR highly suppressed:** $BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$
  - Precise theoretical prediction: [Buras et al. : JHEP 1511 (2015) 033]
- **FCNC loop process:** $\bar{s} \to \bar{d}$ transition, dramatic CKM & GIM suppression.

$$\therefore BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.38 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2°}\right]^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

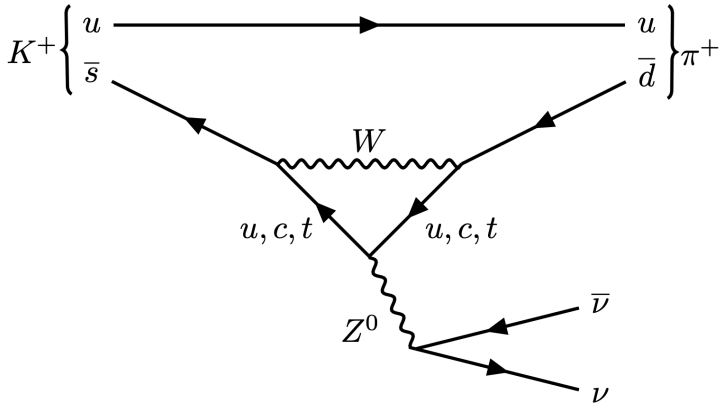
- **Intrinsic theory uncertainty ~2%**
  - Short-distance dominated – only small contributions from (non-perturbative) long-distance effects.
  - NLO (NNLO) QCD corrections to top (charm) contributions, NLO EW corrections.
  - Hadronic matrix elements precisely measured from $BR(K^+ \to \pi^0 e^+ \nu_e)$ decay.



Uncertainty budget



$K^+ \to \pi^+ \nu\bar{\nu}$ SM Z^0 penguin diagram.



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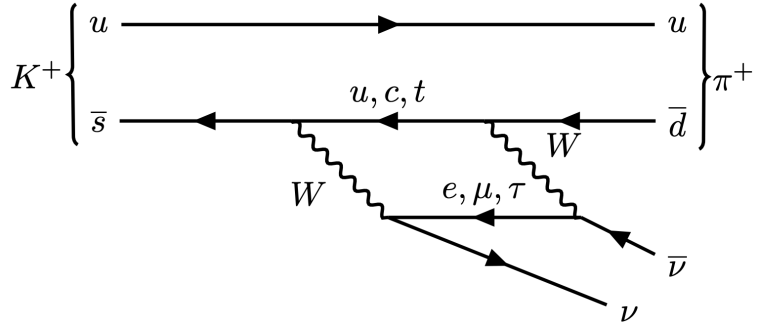
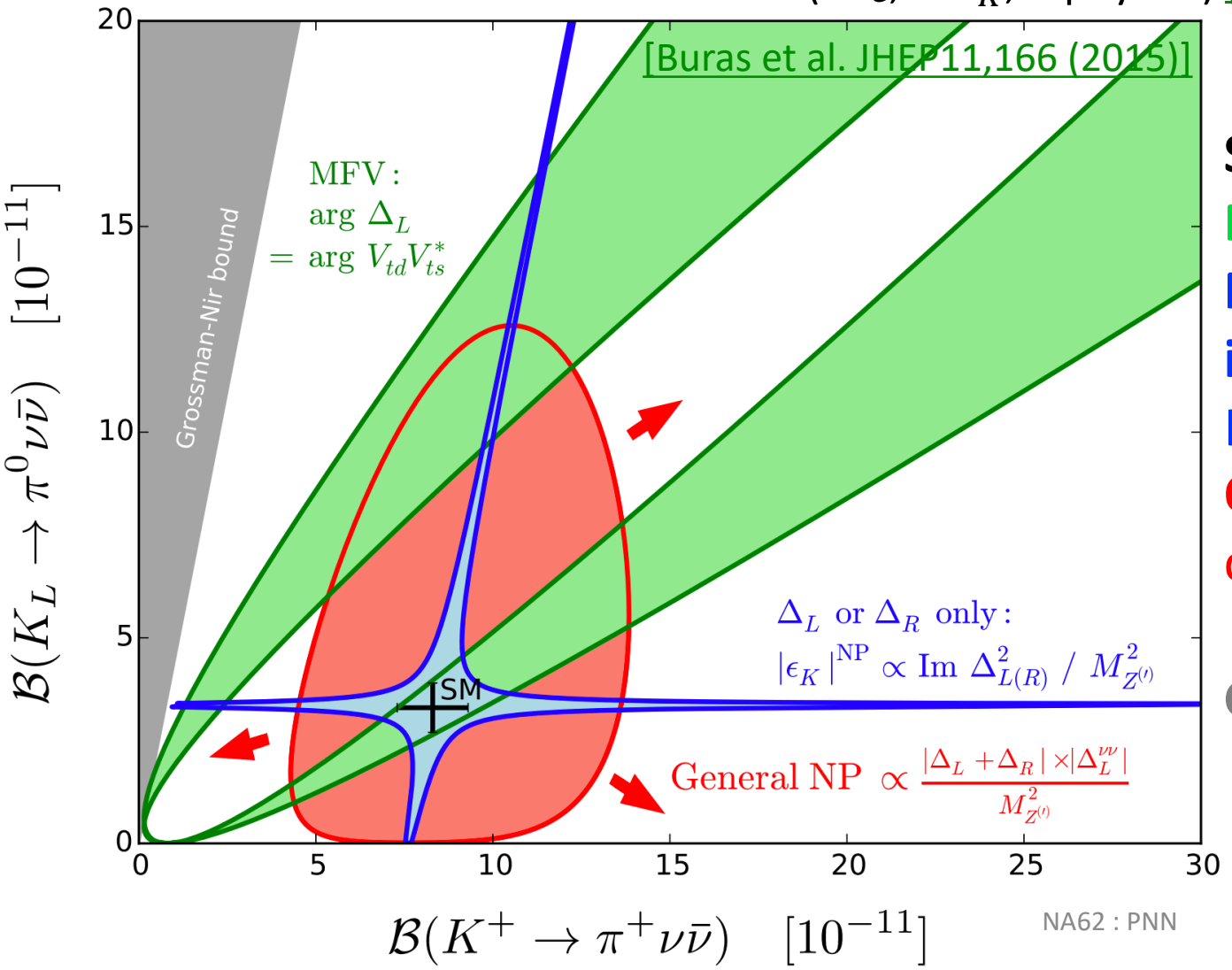


$K^+ \to \pi^+ \nu\bar{\nu}$ SM W box diagram.

$K^+ \to \pi^+ \nu\bar{\nu}$ Beyond the Standard Model

- Spot BSM contributions in deviation from SM prediction of $Br(K \to \pi\nu\nu)$: sensitive to high mass scales.
- Correlations between BSM contributions to K^+& K_L BRs [JHEP 1511 (2015) 166].
- Correlations with other observables (ε'/ε, ΔM_K, B physics) [arXiv:2006.01138]



SM

Minimal Flavour Violation

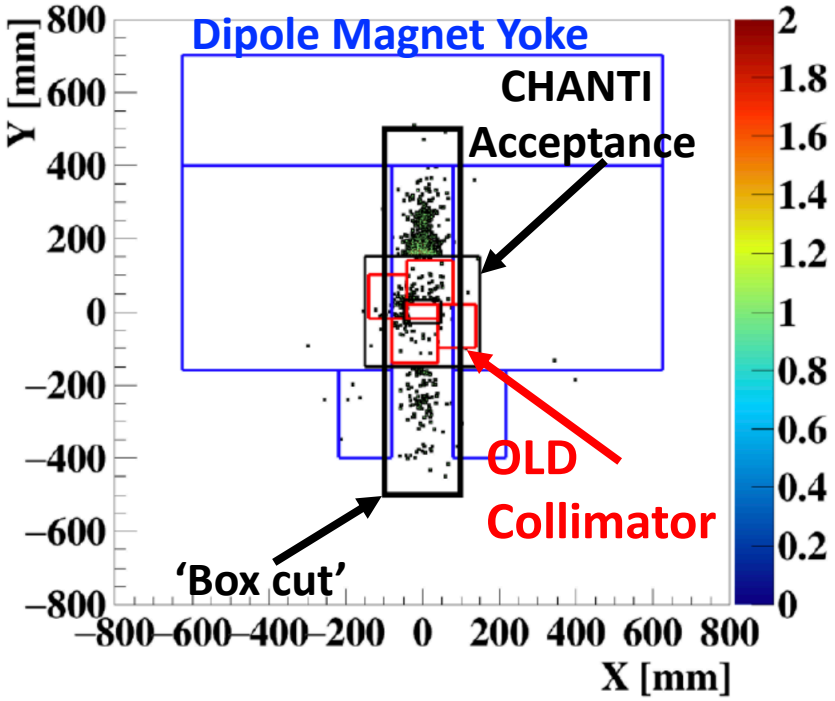
Models with new flavour violating interactions (e.g. Z/Z' models, or Littlest Higgs with T-parity)

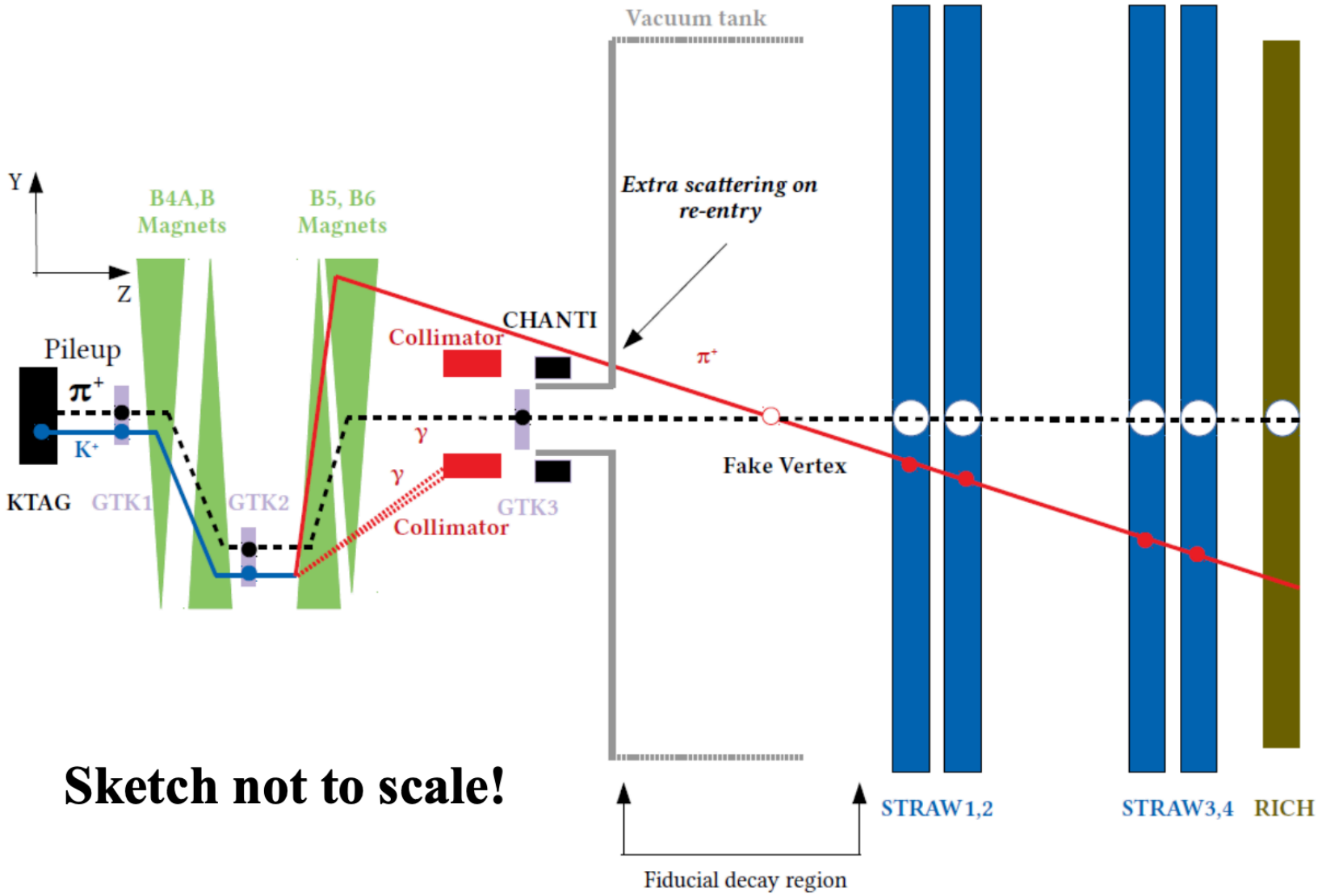
Other NP without flavour constraints (e.g. custodial Randall-Sundrum)

Grossman-Nir bound:

$$\frac{BR(K_L \to \pi^0\nu\bar{\nu})}{BR(K^+ \to \pi^+\nu\bar{\nu})} = \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\sin^2\theta}{r_{is}} \leq 4.3$$

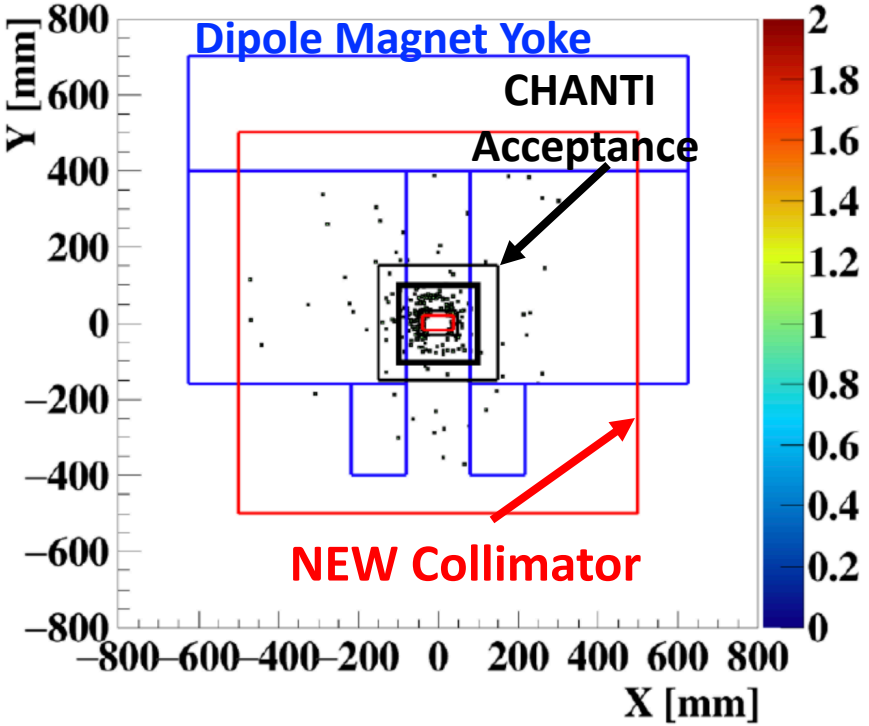
Upstream background [Old Collimator: Sample S1]

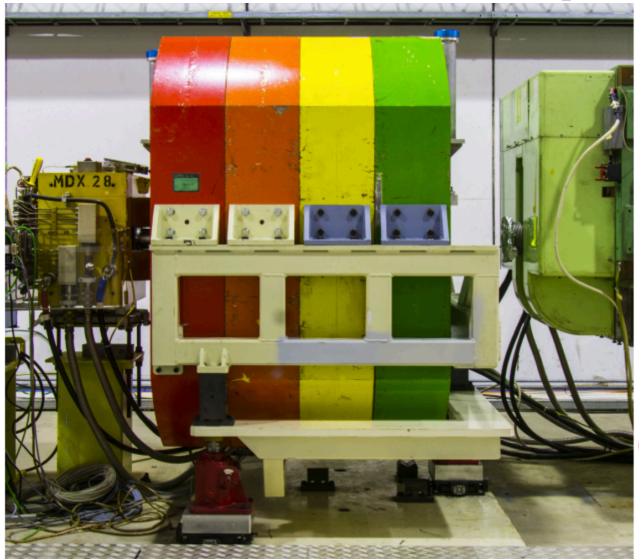


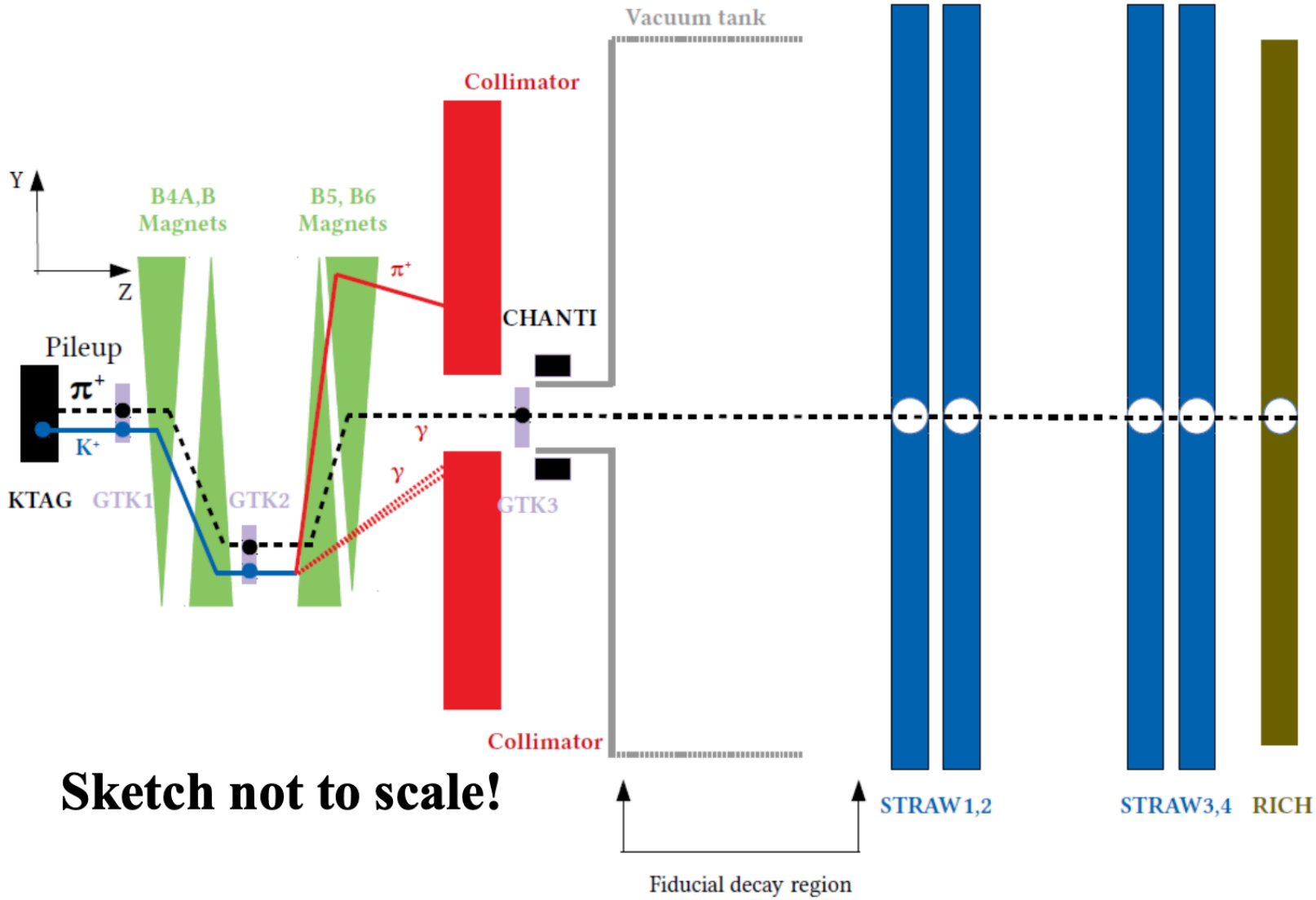


Upstream background [New Collimator: Sample S2]

[~70% of 2018 data taken with new collimator]



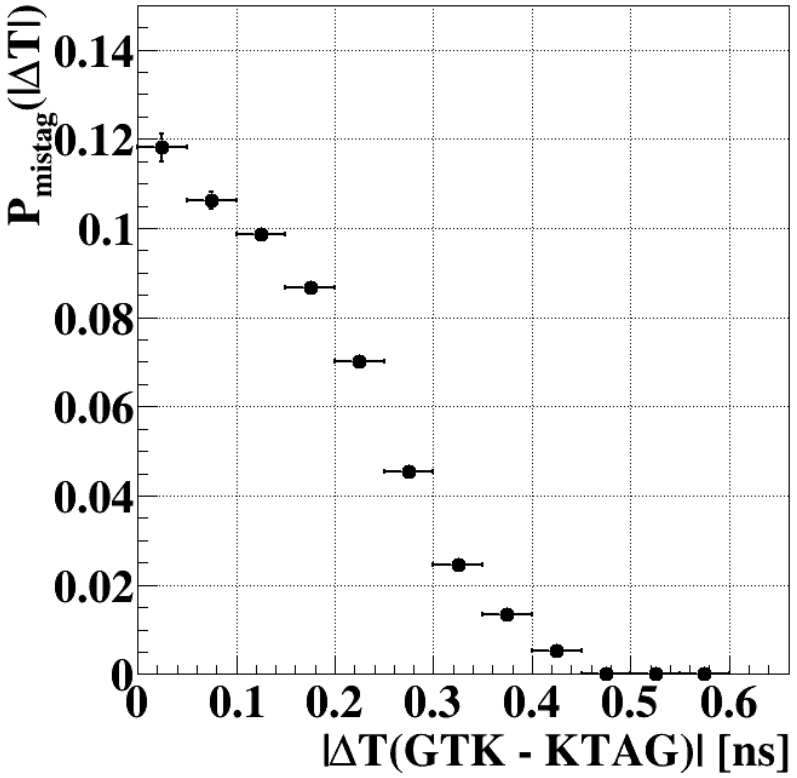


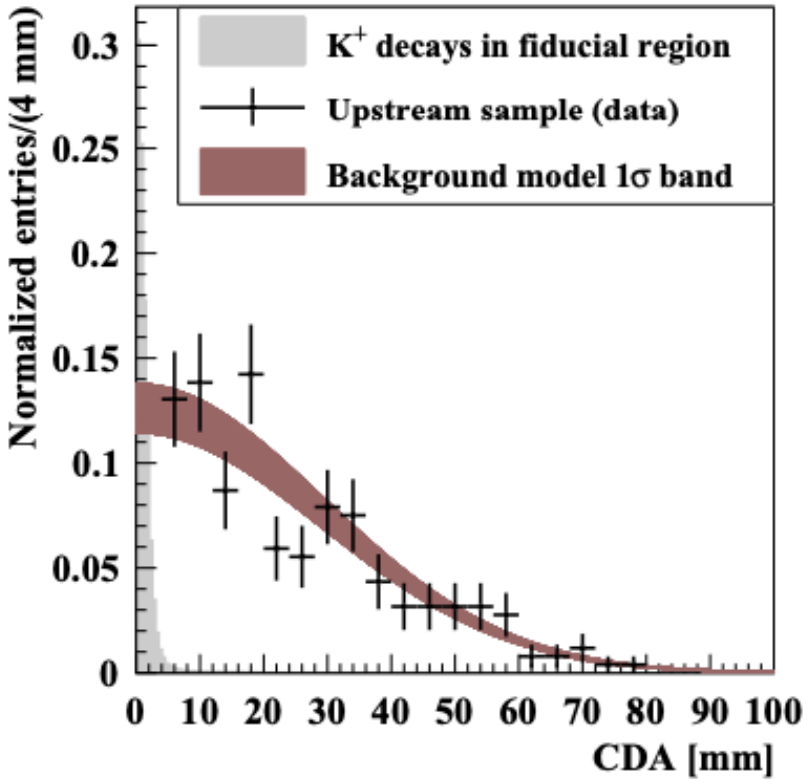


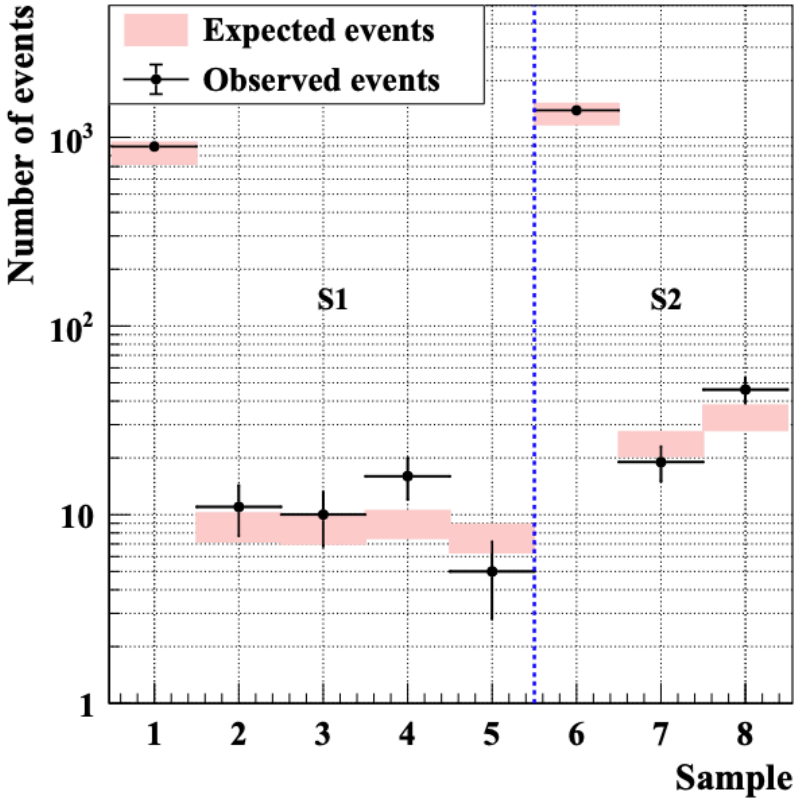
Can relax 'box cut' and gain signal acceptance $(4.0\% \rightarrow 6.4\%)$ keeping S/B to same level.

Upstream Background

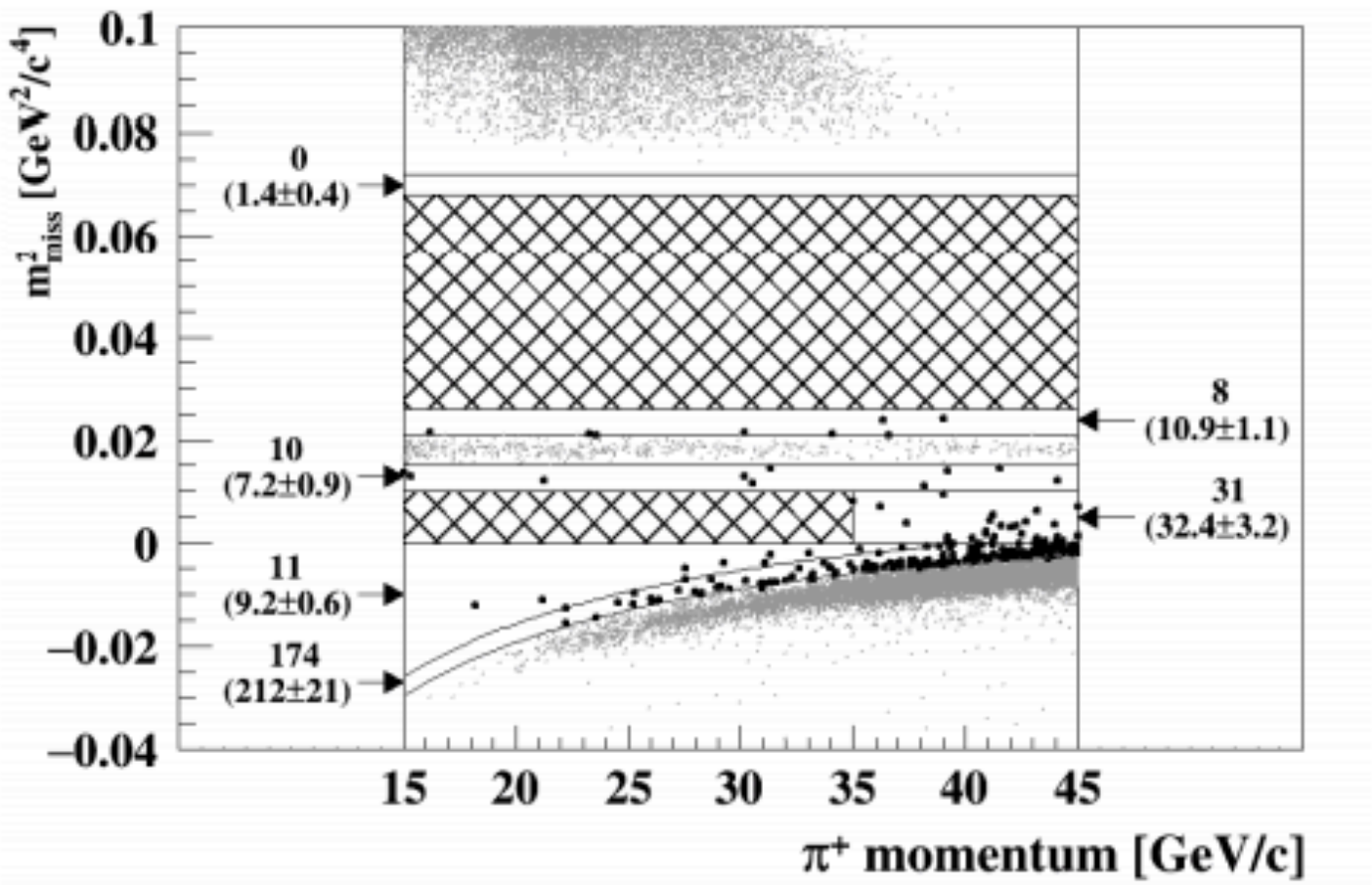
- Data-driven procedure:
  - Use a control sample without time and K-pi matching requirements: N_{up}
  - $N_{bg} = N_{up} P_{mistag}$, where P_{mistag} depends on ΔT and CDA distributions.
- Validate using inverted data samples enriched with upstream events.







Summary : 2018 Analysis

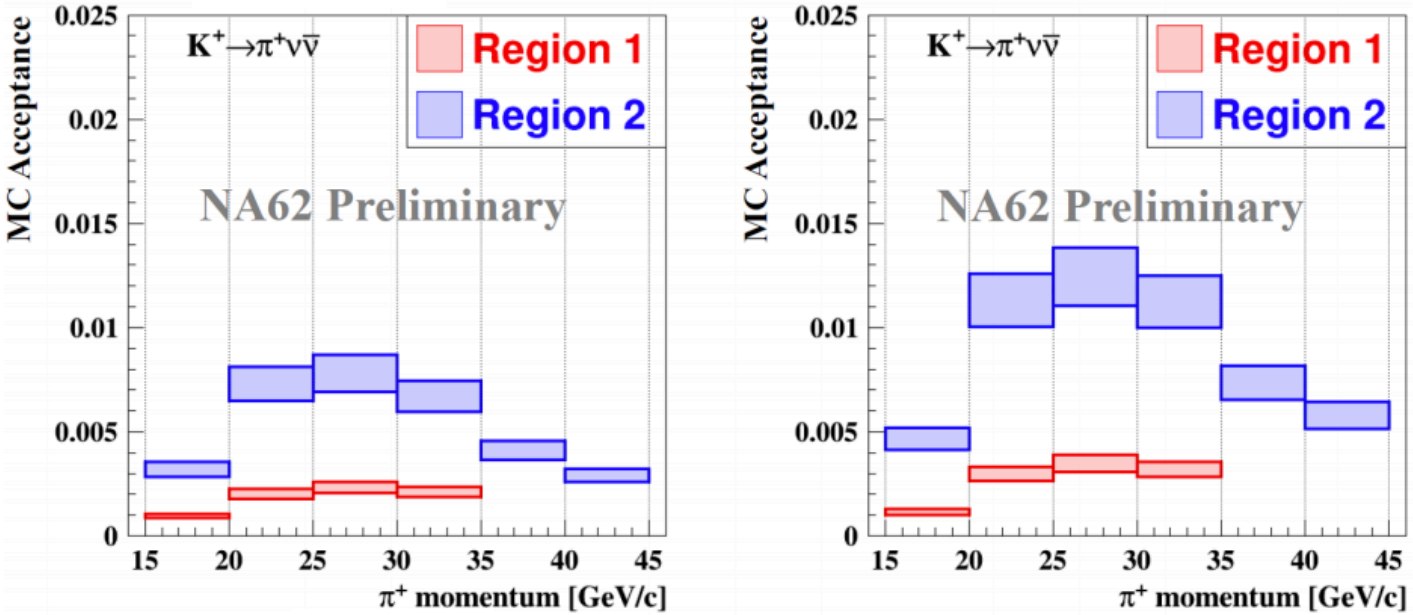


Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

	Subset S1	Subset S2
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N^{exp}_{\pi\nu\bar{\nu}}$	$1.56 \pm 0.10 \pm 0.19_{ext}$	$6.02 \pm 0.39 \pm 0.72_{ext}$

Summary : 2018 Analysis

S1 S2



$A_{\pi\nu\nu}$(S1) $\simeq 4.0\%$, $A_{\pi\nu\nu}$(S2) $\simeq 6.4\%$

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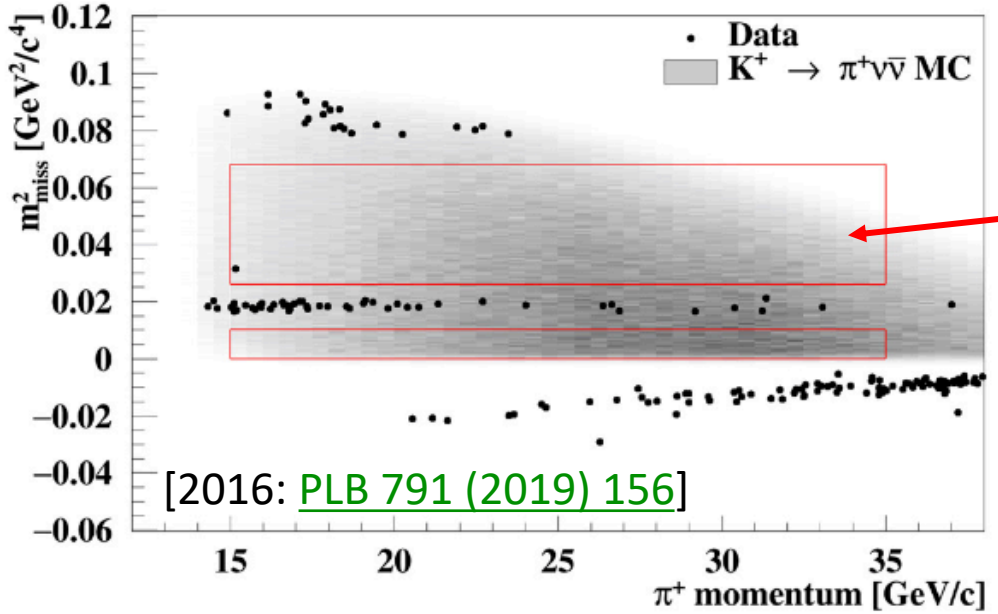
Combine 2016,17,18 data



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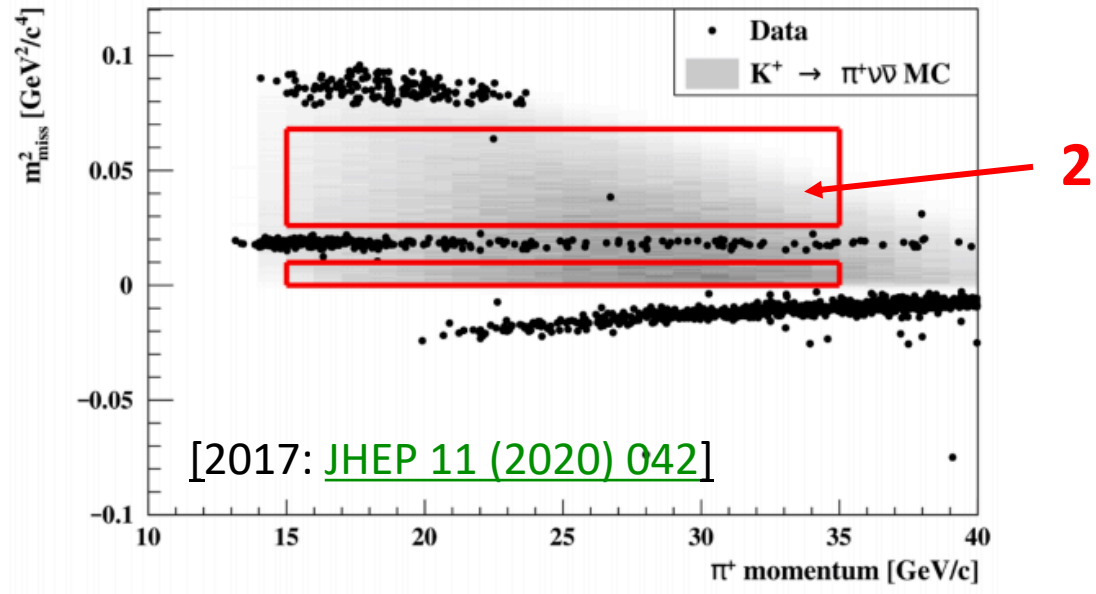
20 Events in signal regions



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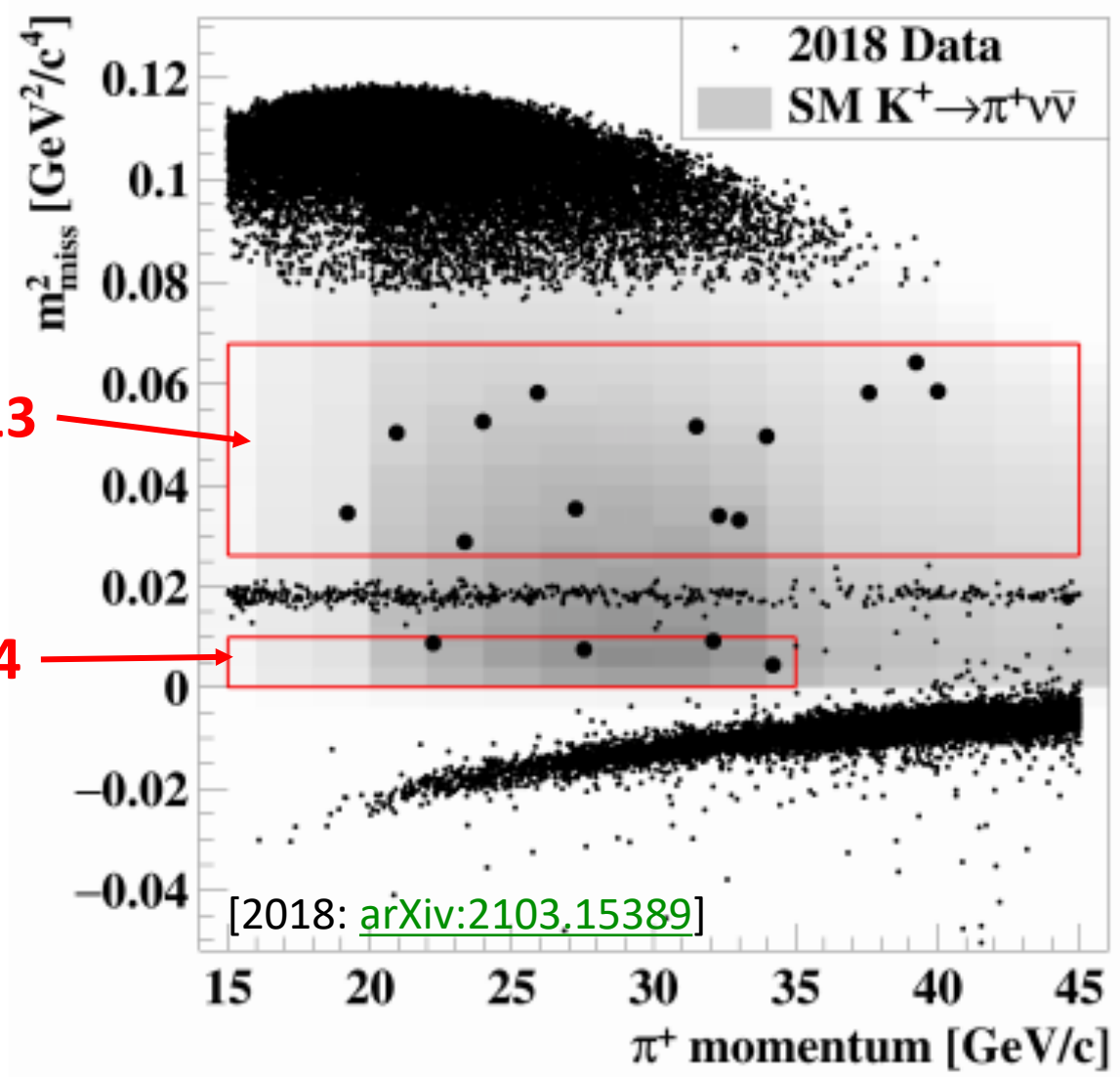

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4

$$SES = (0.839 \pm 0.053_{\text{syst}}) \times 10^{-11},$$

$$N^{\text{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}},$$

$$N^{\text{exp}}_{\text{background}} = 7.03^{+1.05}_{-0.82}.$$