

New measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ at NA62

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Riunione Gruppo 1
Napoli, 16/01/2025

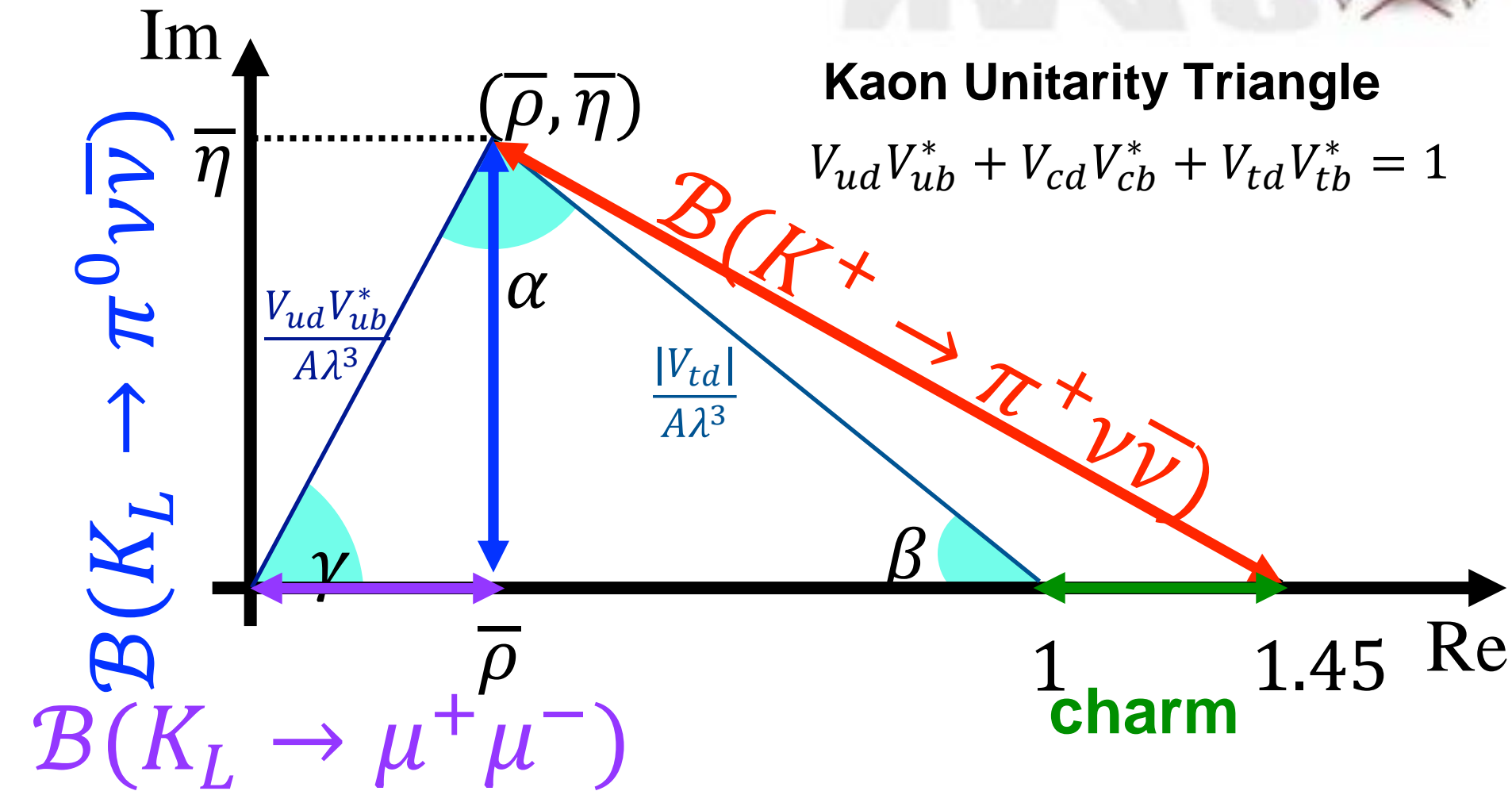
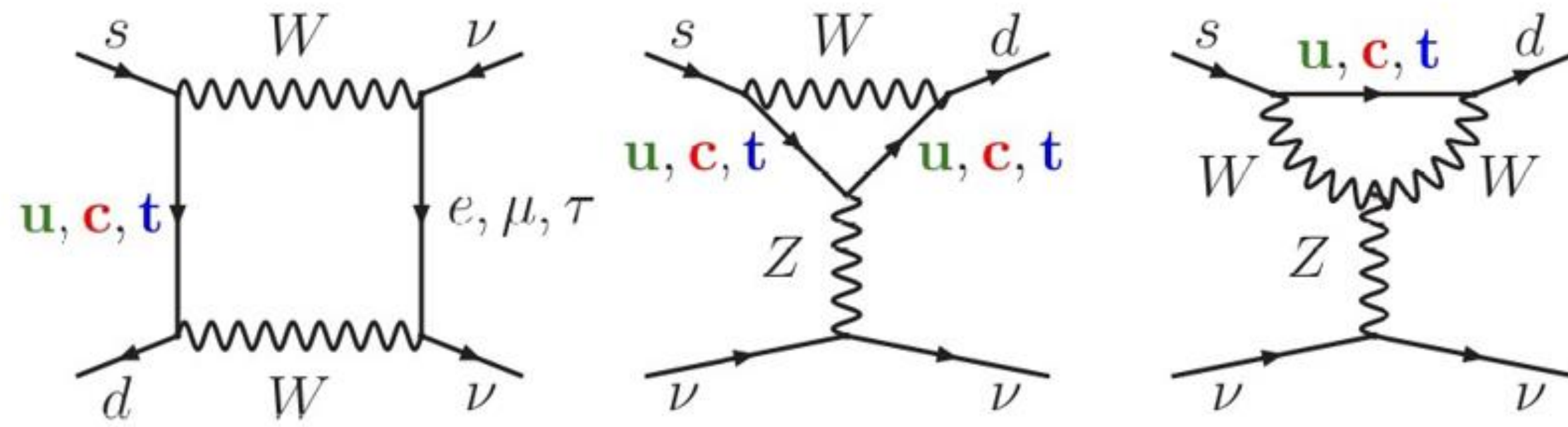
Contents:

- The NA62 experiment
- Signal sensitivity
- Background estimation
- New measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

$K \rightarrow \pi \nu \bar{\nu}$: Precision test of the SM



SM: Z-penguin & box diagrams



- $\mathcal{B}(K \rightarrow \pi \nu \bar{\nu})$ highly suppressed in SM

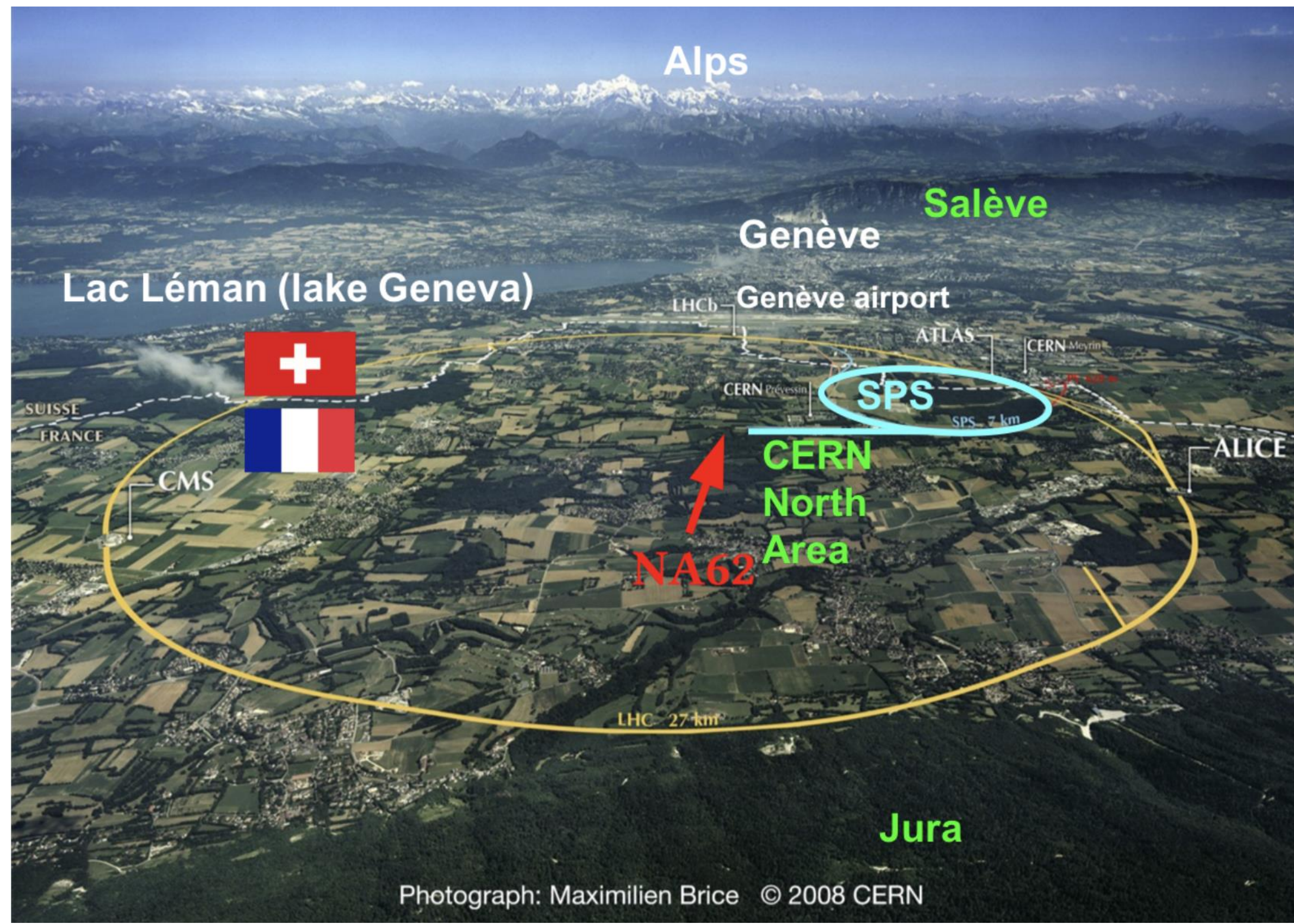
- GIM mechanism & maximum CKM suppression $s \rightarrow d$ transition: $\sim \frac{m_t}{m_W} |V_{ts}^* V_{td}|$
- Theoretically clean \Rightarrow high precision SM predictions, high sensitivity to BSM
 - Dominated by short distance contributions
 - Hadronic matrix element extracted from $\mathcal{B}(K \rightarrow \pi l \nu)$ decays via isospin rotation

Decay Mode BR	SM [Buras et al. EPJC 82 (2022) 7, 615]	SM [D'Ambrosio et al. JHEP 09 (2022) 148]	Experimental Status
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.1}_{-3.5}) \times 10^{-11}$ (NA62)
$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2.2 \times 10^{-9}$ (KOTO)

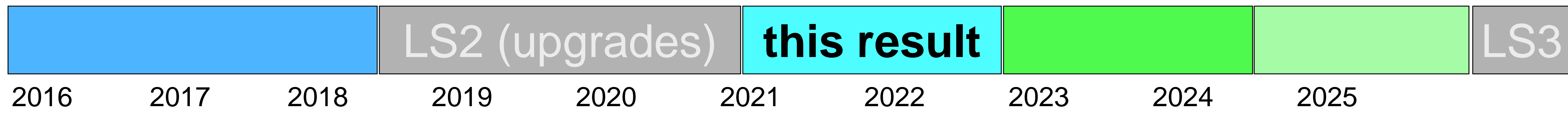
The NA62 Experiment at CERN



~200 collaborators from ~30 institutions.



- Primary goal: measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
- New Technique: K^+ decay-in-flight
- Results: [\[PLB 791 \(2019\) 156\]](#) [\[JHEP 11 \(2020\) 042\]](#) [\[JHEP 06 \(2021\) 093\]](#)
- Broader physics programme:
 - Rare K^+ decays (e.g. $K^+ \rightarrow \pi^+ \gamma \gamma$ [\[PLB 850 \(2024\) 138513\]](#))
 - LNV/LFV decays (e.g. $K^+ \rightarrow \pi^- (\pi^0) e^+ e^+$ [\[PLB 830 \(2022\) 137172\]](#))
 - Exotics (e.g. Dark photon [\[PRL 133 \(2024\) 11, 111802\]](#))
- Data taking
 - 2016 Commissioning + Physics run (45 days).
 - 2017 Physics run (160 days).
 - 2018 Physics run (217 days).
 - 2021 Physics run (85 days [10 beam dump]).
 - 2022 Physics run (215 days).
 - 2023 Physics run (150 days [10 beam dump]).
 - 2024 Physics run ongoing ...

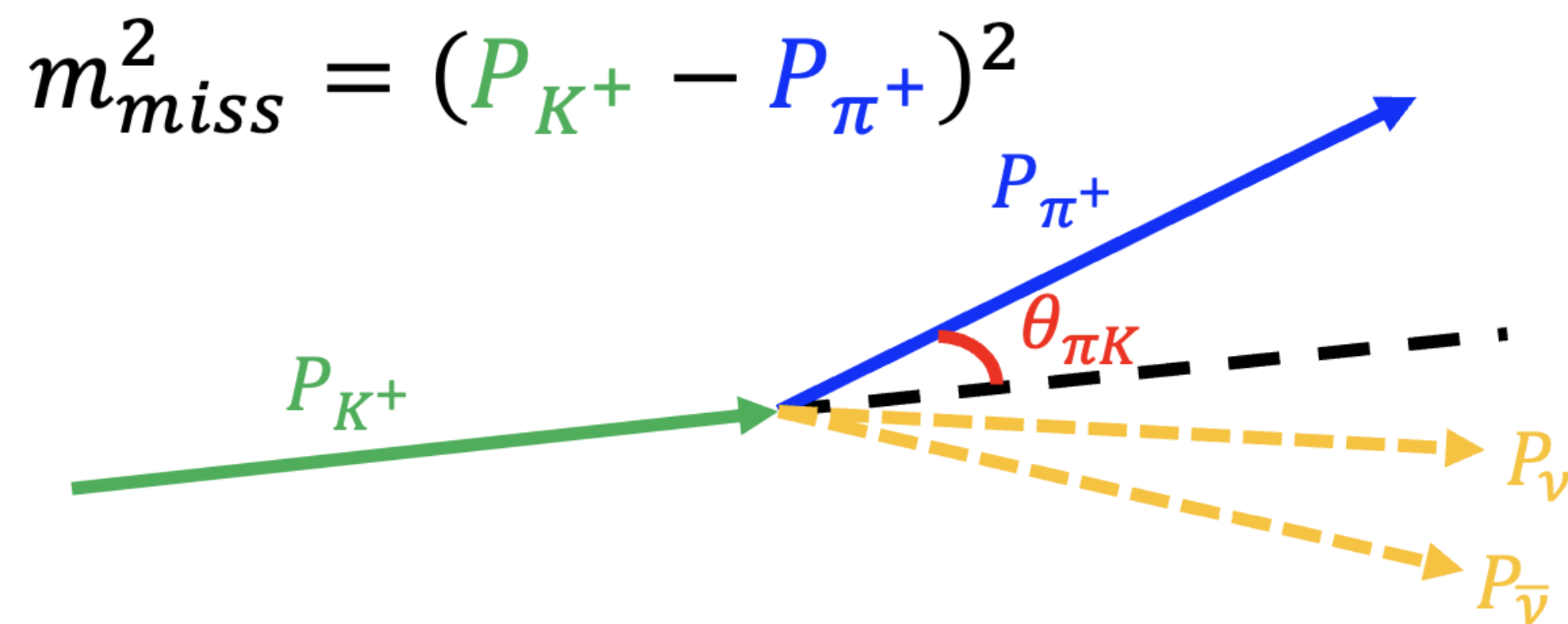


$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: NA62 strategy



Selection strategy:

- Tag K^+ and measure momentum.
- Identify π^+ and measure momentum.
- Match K^+ and π^+ in time & form vertex.
 - Determine $m_{miss}^2 = (P_K - P_\pi)^2$
- Reject any additional activity.



Performance Keystones:

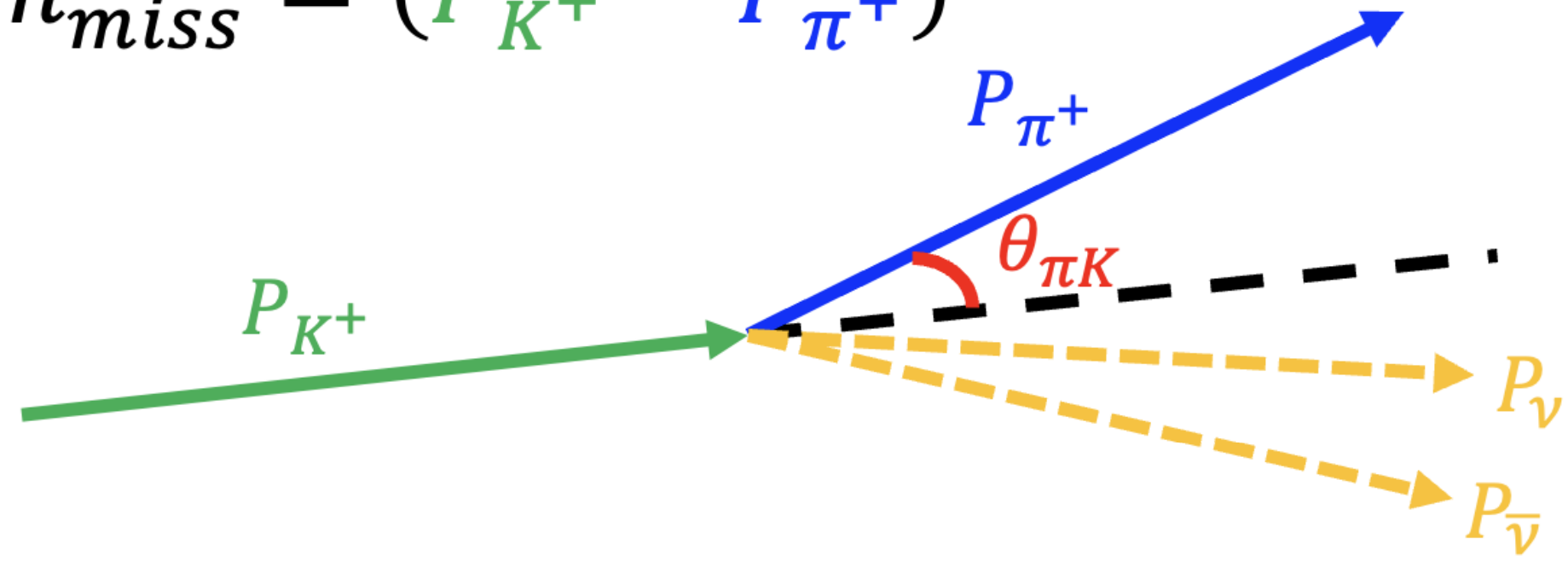
- $\mathcal{O}(100)ps$ timing between detectors
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $> 10^7$ muon rejection
- $> 10^7$ rejection of π^0 from $K^+ \rightarrow \pi^+ \pi^0$ decays

Decay mode	Branching Ratio [PDG]
$K^+ \rightarrow \mu^+ \nu_\mu$	$(63.56 \pm 0.11)\%$
$K^+ \rightarrow \pi^+ \pi^0$	$(20.67 \pm 0.08)\%$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$(5.583 \pm 0.024)\%$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$

$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad \approx 10^{-10}$$

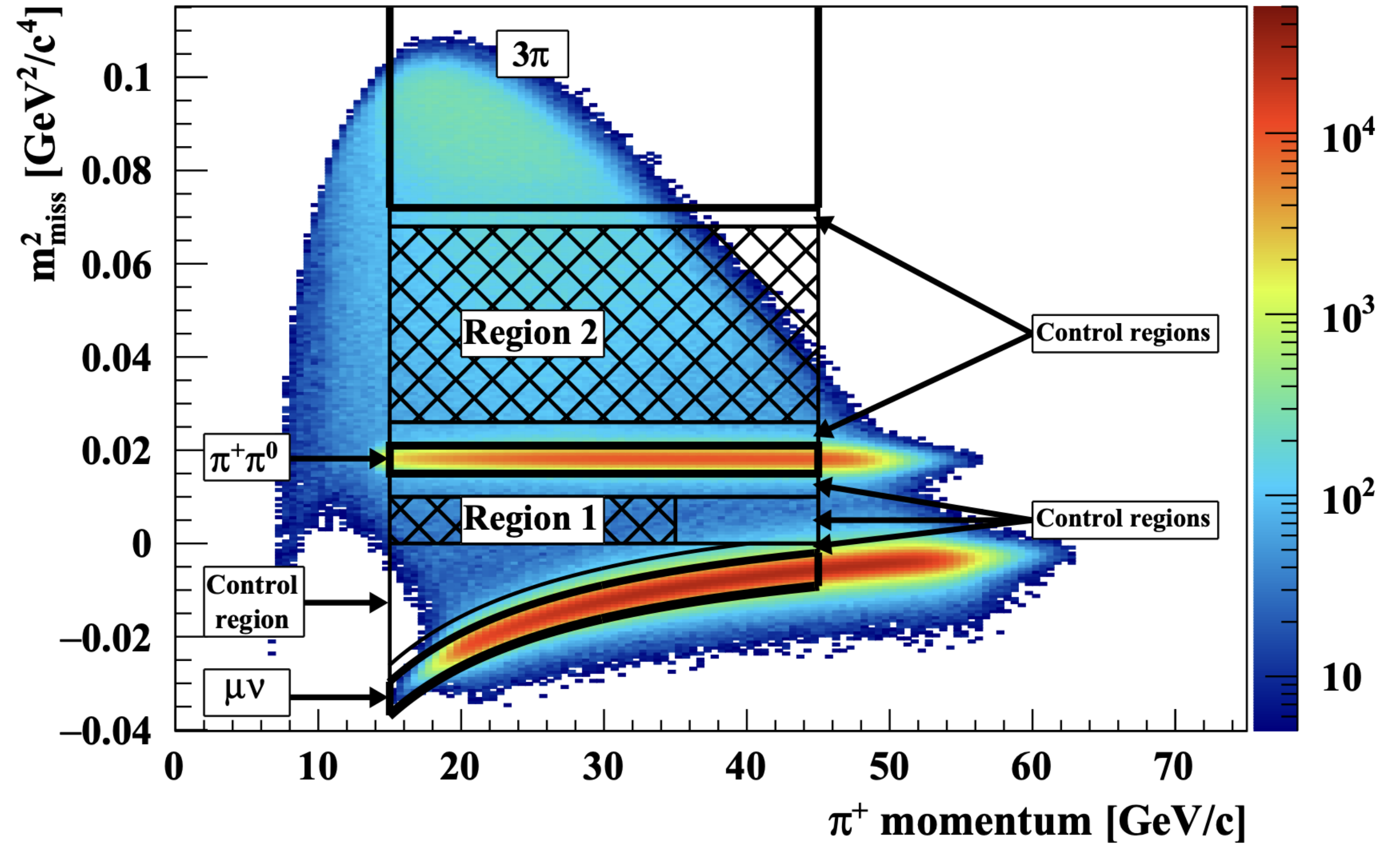
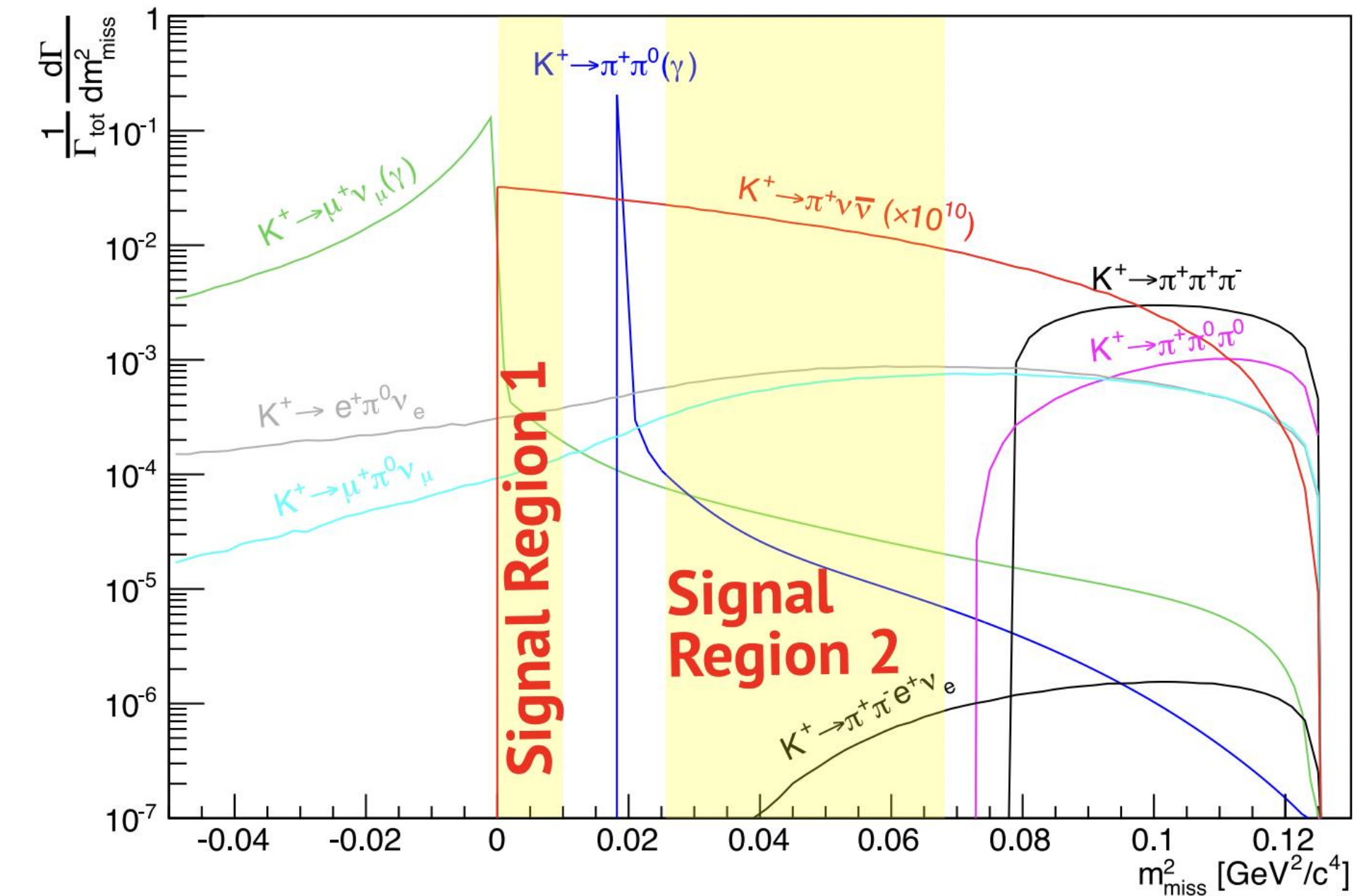
Kinematic constraints & signal regions

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



$\mathcal{O}(10^4)$ background suppression from kinematics

[JHEP 06 (2021) 093]



π^+ momentum range: 15—45 GeV/c

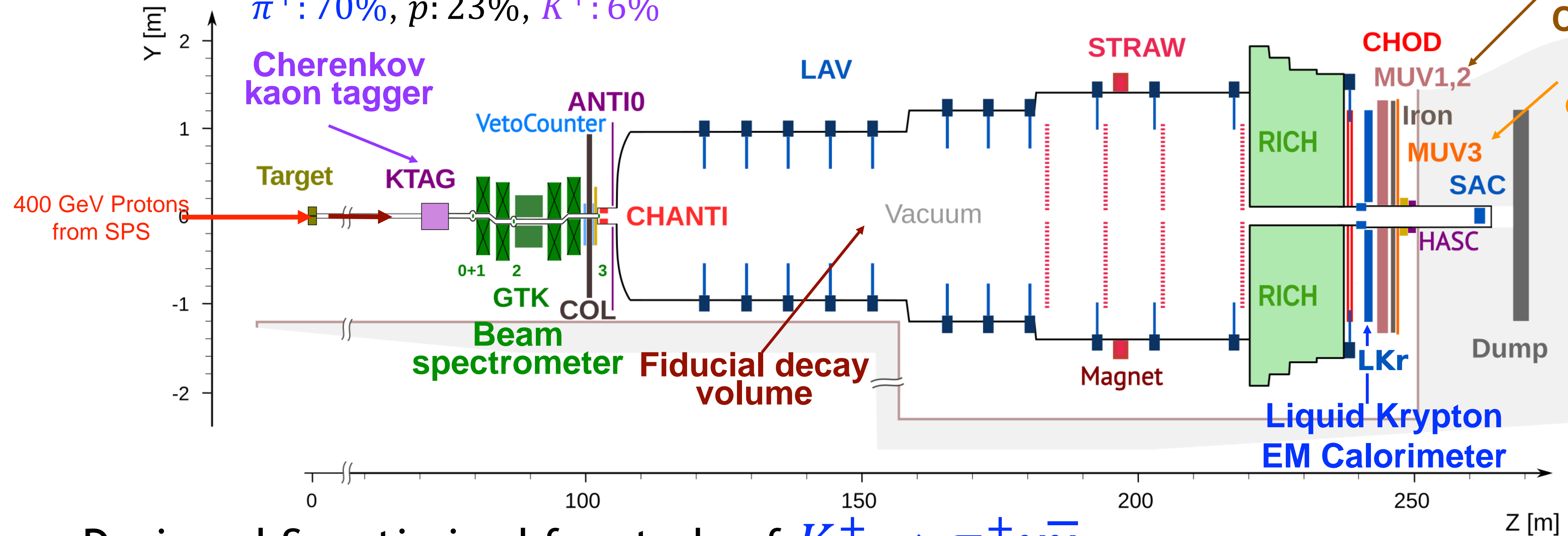
NA62 beamline & detector

[JINST 12 (2017) 05, P05025]



Secondary $75 \text{ GeV}/c$ beam:

π^+ : 70%, p : 23%, K^+ : 6%



- Designed & optimised for study of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:
 - Particle tracking: beam particle (GTK) & downstream tracks (STRAW)
 - PID: K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
 - Comprehensive veto systems: CHANTI (beam interactions), LAV, LKr, IRC, SAC (γ) + new additions since LS2: VetoCounter, ANTI0, HASC2

Signal sensitivity

- Normalisation channel: $K^+ \rightarrow \pi^+ \pi^0$, momentum range $p \in [15, 45] \text{ GeV}/c$ (in $5 \text{ GeV}/c$ bins)

Effective number of K^+ decays, N_K :

$$N_K = \frac{N_{\pi\pi} D_0}{B_{\pi\pi} A_{\pi\pi}}$$

Number of normalisation events $\rightarrow N_{\pi\pi} D_0$
 Downscaling factor of normalisation trigger (generally 400) $\rightarrow D_0$
 Branching ratio of $K^+ \rightarrow \pi^+ \pi^0$ decay $\rightarrow B_{\pi\pi}$
 Acceptance of normalisation selection $\rightarrow A_{\pi\pi}$

Single event sensitivity:

(Branching ratio corresponding to expectation of 1 event)

$$B_{SES} = \frac{1}{N_K \epsilon_{RV} \epsilon_{trig} A_{\pi\nu\bar{\nu}}}$$

Random veto efficiency $\rightarrow \epsilon_{RV}$

Trigger efficiency (ratio) $\rightarrow \epsilon_{trig}$

Signal selection acceptance $\rightarrow A_{\pi\nu\bar{\nu}}$

Number of expected SM events:

(For comparison to previous results use $B_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$ but results are independent of this choice)

$$N_{\pi\nu\bar{\nu}}^{SM} = \frac{B_{\pi\nu\bar{\nu}}^{SM}}{B_{SES}}$$

Signal sensitivity results

Comparison with 2016-18

$N_{\pi\pi}$	Normalisation $K^+ \rightarrow \pi^+\pi^0$	$(1.953 \pm 0.005) \times 10^8$
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective K^+ decays	$(2.85 \pm 0.01) \times 10^{12}$
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.62 \pm 0.22)\%$
ε_{trig}	Trigger efficiency	$(85.9 \pm 1.4)\%$
ε_{RV}	Random veto efficiency	$(63.2 \pm 0.6)\%$
\mathcal{B}_{SES}	Single event sensitivity	$(8.48 \pm 0.29) \times 10^{-12}$

+15% (retuned selection)

+20% (retuned selection)

3x more precise

stable despite intensity increase

Assuming $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$:

$N_{\pi\nu\bar{\nu}}^{SM} = 9.91 \pm 0.34$

cf. 2016-18: 10.01 ± 0.42

- Significant improvement in SES uncertainty:

- old: 6.3% → new: 3.5%. Due to:

- trigger efficiency cancellations (new dedicated norm. trigger)

- improved procedures for evaluation of acceptances and ε_{RV}

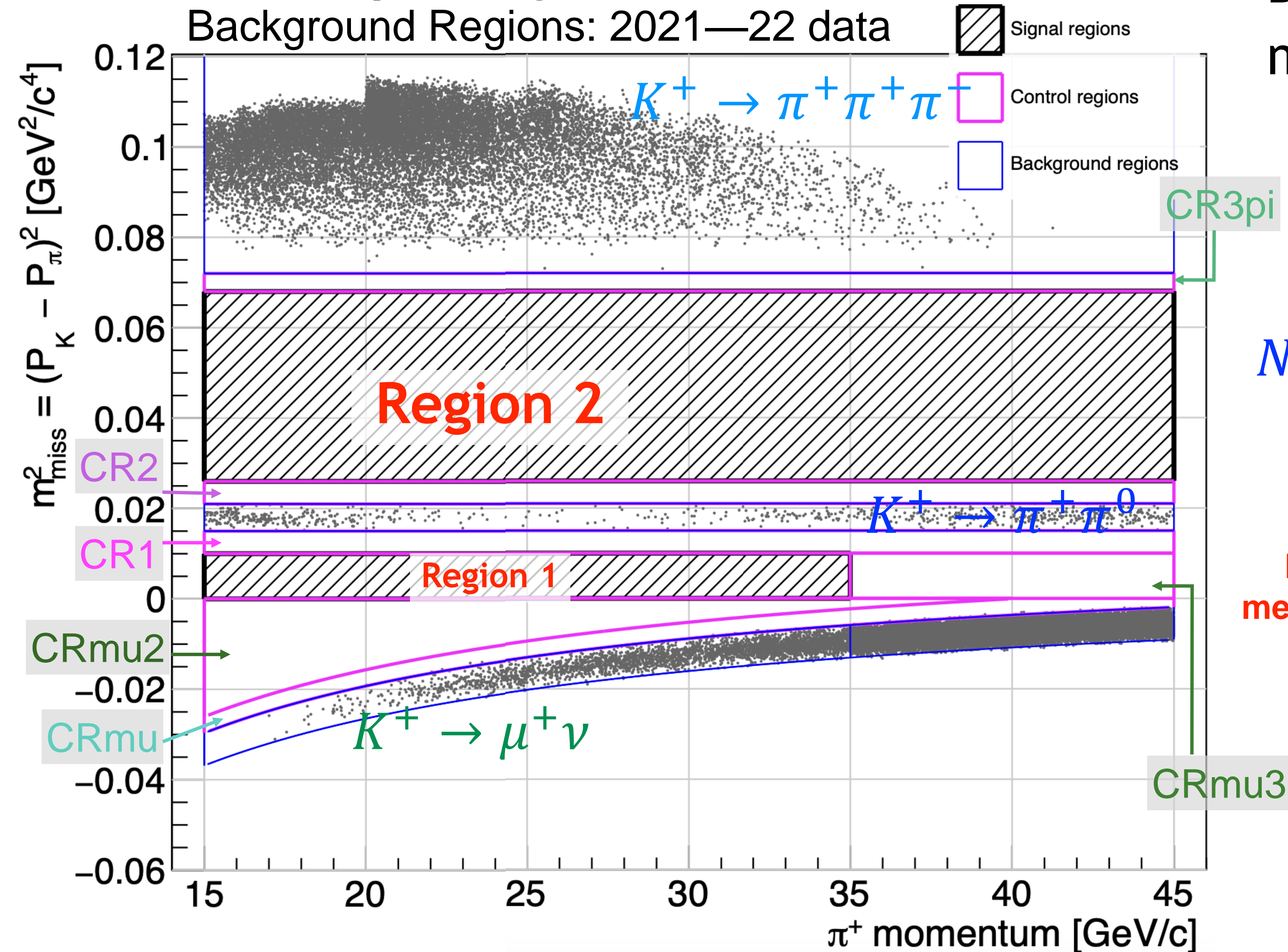


Double expected signal
by including 21–22 data

Background regions & estimations

Events passing $\pi V V$ selection

Background Regions: 2021—22 data



Backgrounds from kinematic misconstruction tails in m_{miss}^2

$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N_{SR}^{CS}}{N_{bkgR}^{CS}}$$

Kinematic tail fraction: measured in control sample

Control sample events in Signal Regions

Control sample events in Background Region

$$N_{bg}(K^+ \rightarrow \pi^+ \pi^0(\gamma)) = 0.83 \pm 0.05$$

$$N_{bg}(K^+ \rightarrow \mu^+ \nu(\gamma)) = 1.70 \pm 0.47$$

$$N_{bg}(K^+ \rightarrow \pi^+ \pi^+ \pi^-) = 0.11 \pm 0.03$$

Upstream background

[New fully data-driven procedure]

Underlying misreconstruction:
 π^+ matching to accidental GTK track



$$N_{ups} = \sum_{(\Delta T, N_{GTK}) \text{ bins}} N_{URS} f_{CDA} P_{match}$$

N_{URS}	Upstream Reference Sample: signal selection but bad CDA (>4mm)	—————>	Contains all known upstream mechanisms Provides normalisation in bins of $(\Delta T, N_{GTK})$
f_{CDA}	Scaling factor : bad CDA \rightarrow good CDA	—————>	Depends only on geometry
P_{match}	Probability to pass $K^+ - \pi^+$ matching	—————>	Depends on $(\Delta T, N_{GTK})$

$$N_{URS} = 51$$

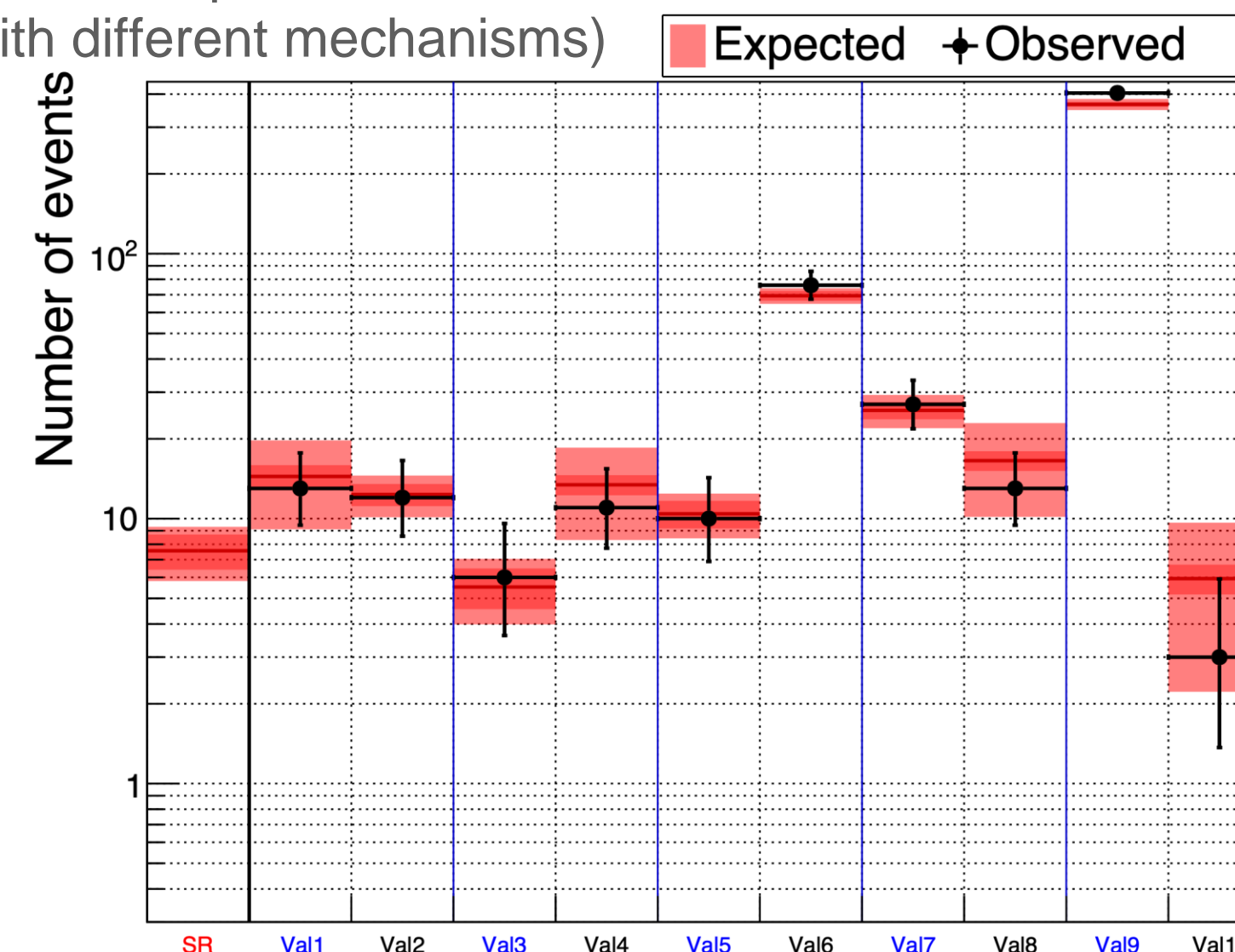
$$f_{CDA} = 0.20 \pm 0.03$$

$$\langle P_{match} \rangle = 73\%$$

$$N_{ups} = 7.4^{+2.1}_{-1.8}$$

Validation samples

invert & loosen upstream vetoes
 (enrich with different mechanisms)



New VetoCounter
 improves rejection
 by a factor 2

Summary of expectations

Backgrounds

$K^+ \rightarrow \pi^+ \pi^0(\gamma)$	0.83 ± 0.05
$K^+ \rightarrow \pi^+ \pi^0$	0.76 ± 0.04
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	0.07 ± 0.01
$K^+ \rightarrow \mu^+ \nu(\gamma)$	1.70 ± 0.47
$K^+ \rightarrow \mu^+ \nu$	0.87 ± 0.19
$K^+ \rightarrow \mu^+ \nu \gamma$	0.82 ± 0.43
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.11 ± 0.03
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \rightarrow \pi^0 \ell^+ \nu$	< 0.001
$K^+ \rightarrow \pi^+ \gamma \gamma$	0.01 ± 0.01
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Signal Sensitivity

$$\mathcal{B}_{SES} = (0.85 \pm 0.03) \times 10^{-11}$$

$$N_{\pi\nu\bar{\nu}}^{SM,exp} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}}$$

Assuming $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$:

$$N_{\pi\nu\bar{\nu}}^{SM} = 9.91 \pm 0.34$$

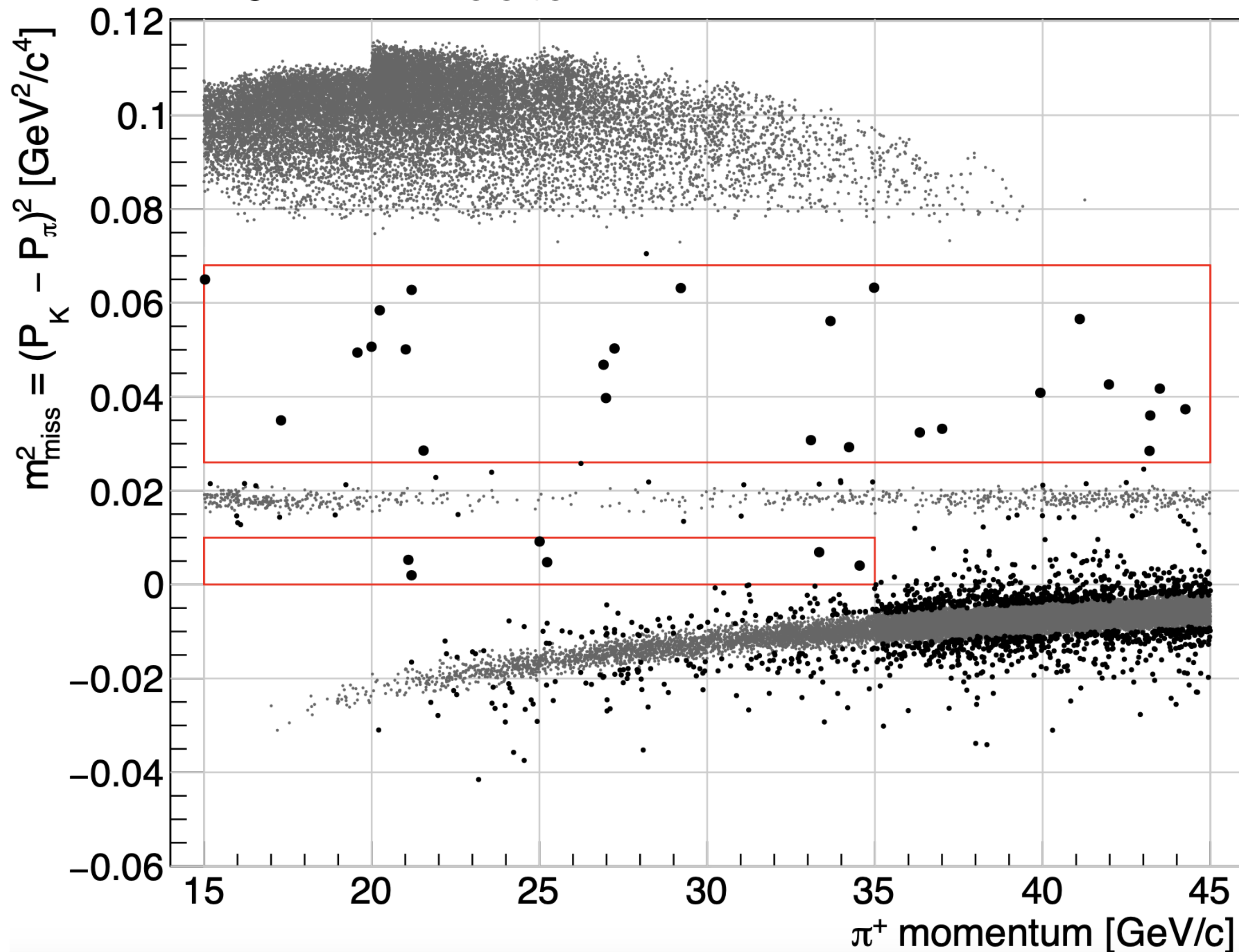
cf. 2016-18: 10.01 ± 0.42

Expected signal doubled by including 2021–22 data

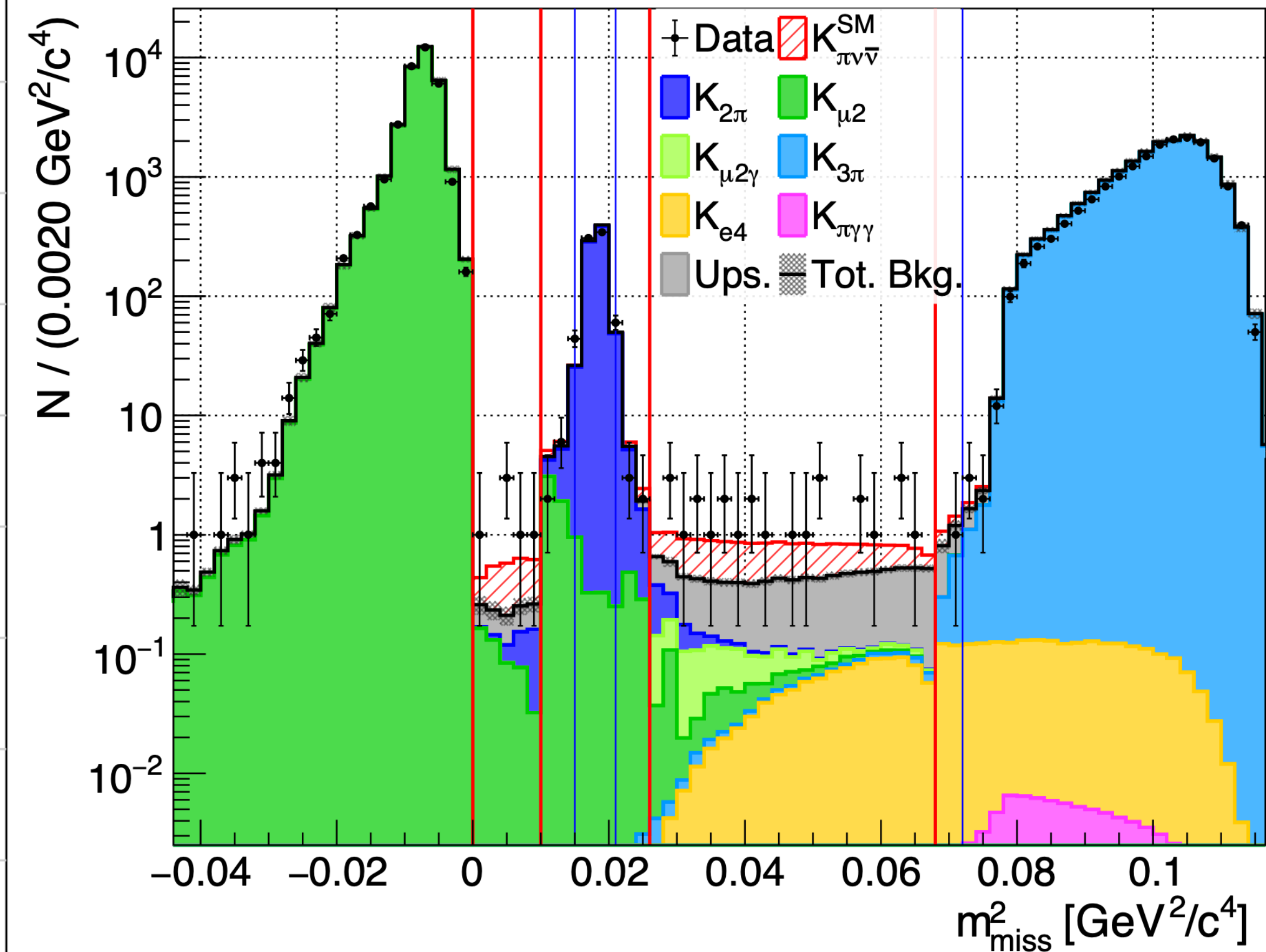
- $N_{\pi\nu\bar{\nu}}^{SM}$ per SPS burst: 2.5×10^{-5} in 2022
 - c.f. 1.7×10^{-5} in 2018. \Rightarrow signal yield increased by 50%
- Sensitivity for BR $\sim \sqrt{S + B}/S = 0.5$
 - Similar but improved with respect to 2018 analysis for same amount of data

Signal regions: 2021–22 Data

2021–22 data



1D projection with differential background predictions & SM signal expectation [not a fit]:



Expected SM signal: $N_{\pi\nu\bar{\nu}}^{SM} \approx 10$

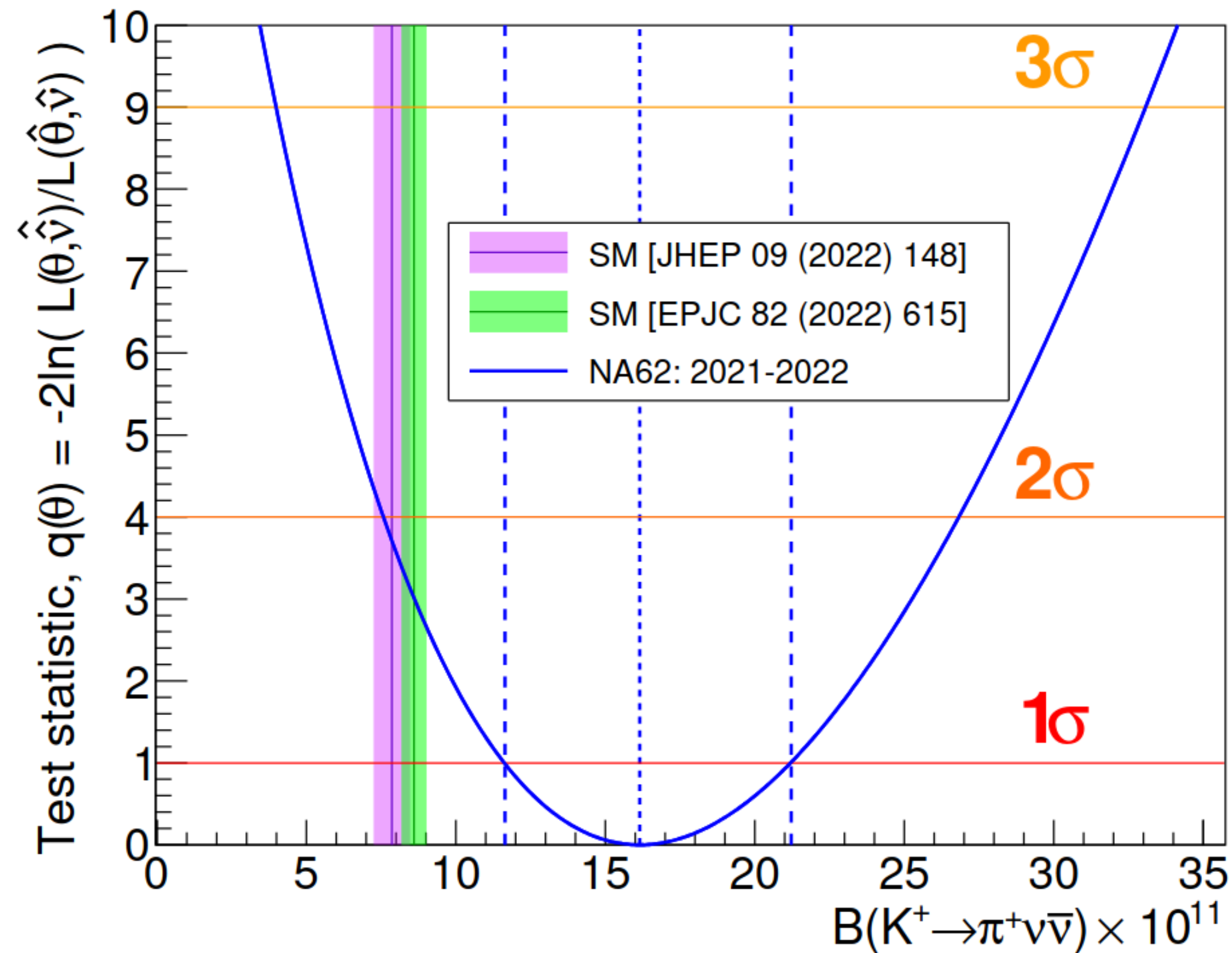
Expected background: $N_{bg} = 11.0^{+2.1}_{-1.9}$

Observed: $N_{obs} = 31$

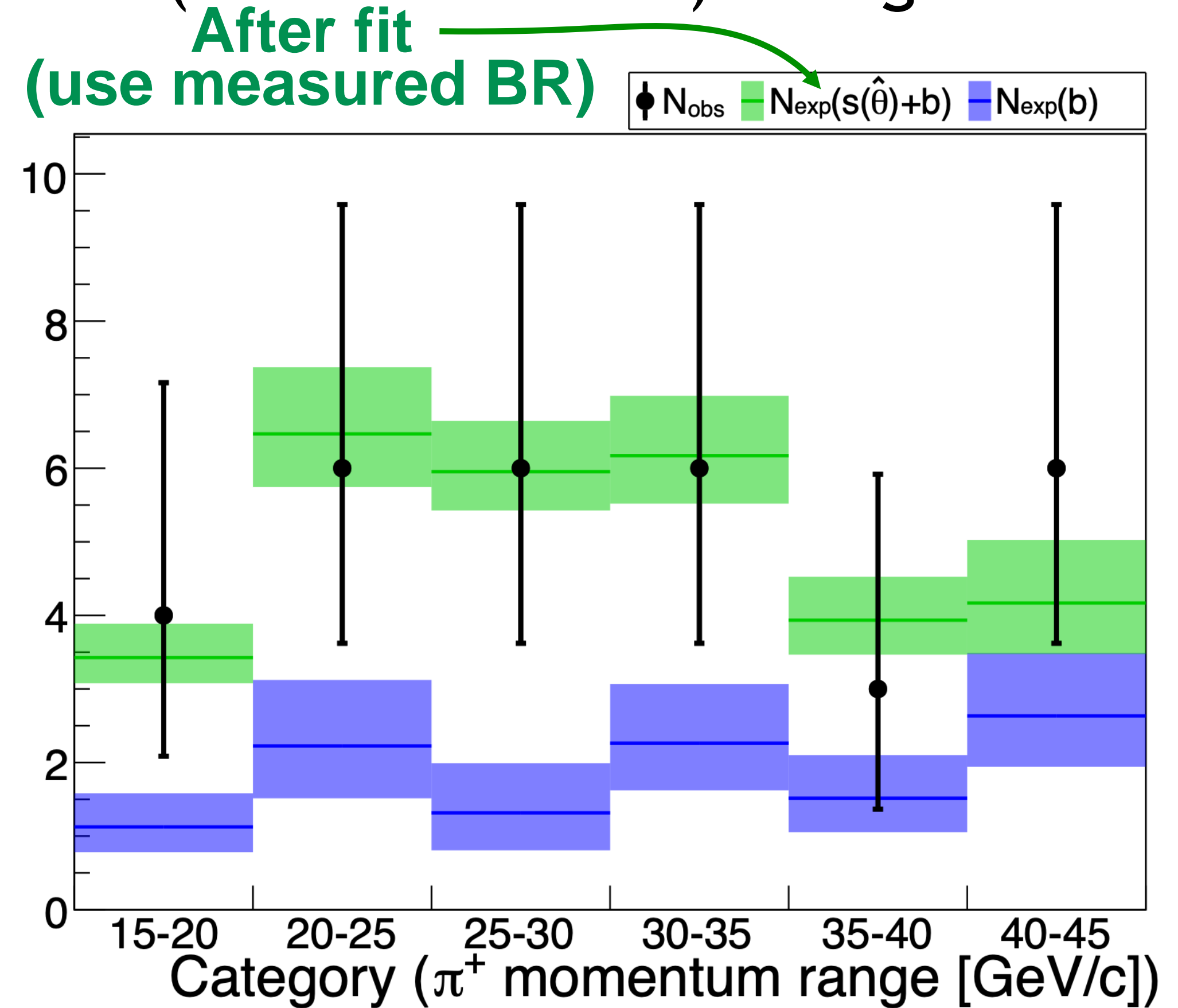
Results: 2021–22 Data



- Measure $\mathcal{B}_{\pi\nu\bar{\nu}}$ and 68% (1σ) confidence interval using a profile likelihood ratio test statistic $q(\theta)$



- Use 6 (momentum bin) categories

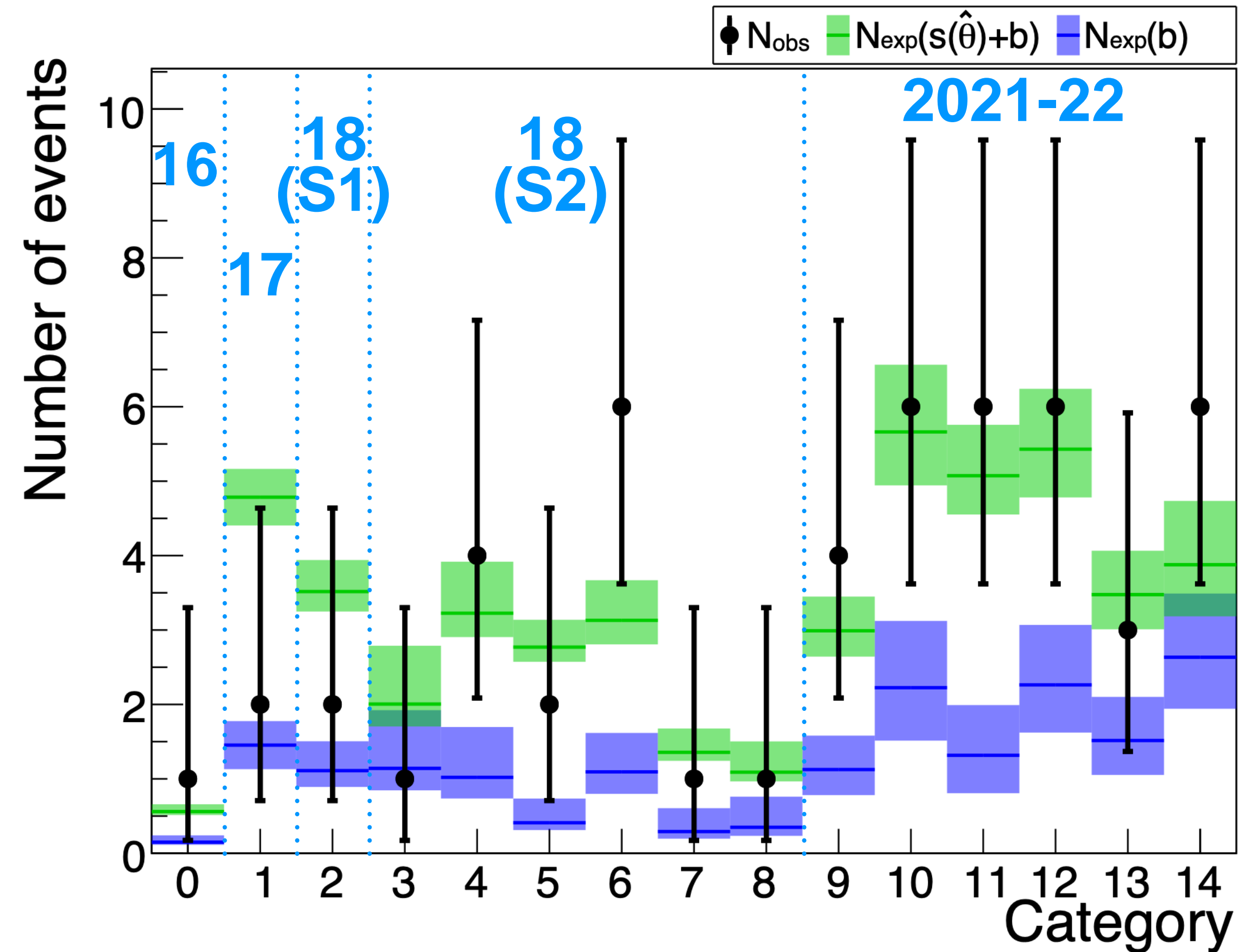
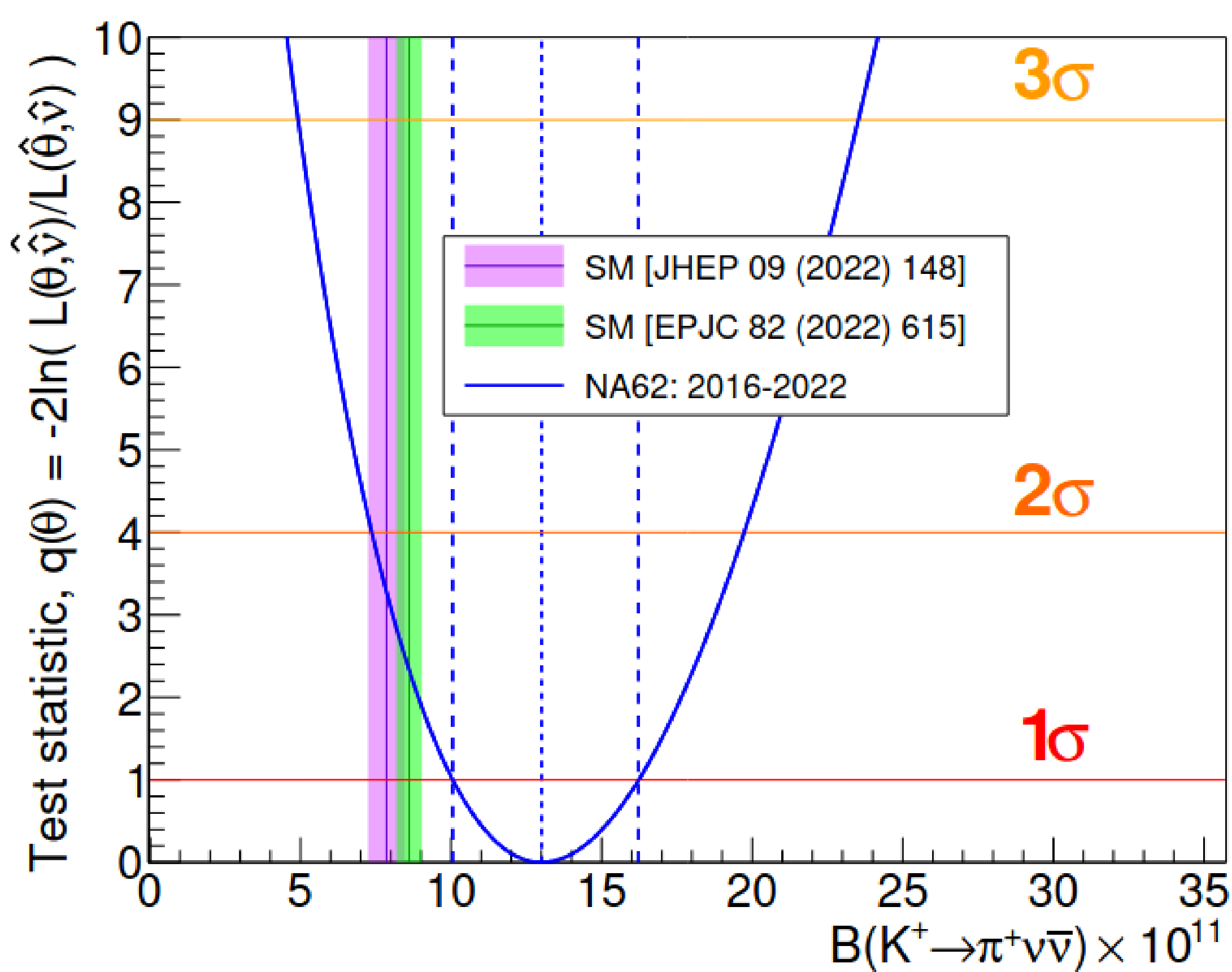


$$\mathcal{B}_{21-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (16.2_{-4.5}^{+5.1}) \times 10^{-11} = (16.2 ({}_{-4.3}^{+4.9})_{\text{stat}} ({}_{-1.4}^{+1.4})_{\text{syst}}) \times 10^{-11}$$

Combining NA62 results: 2016–22



- Integrating 2016–22 data: $N_{bg} = 18_{-2}^{+3}$, $N_{obs} = 51$.
- Background-only hypothesis **p-value** = $2 \times 10^{-7} \Rightarrow$ **significance** $Z > 5$



$$B_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0_{-3.0}^{+3.3}) \times 10^{-11} = (13.0 \begin{pmatrix} +3.0 \\ -2.7 \end{pmatrix}_{stat} \begin{pmatrix} +1.3 \\ -1.3 \end{pmatrix}_{syst}) \times 10^{-11}$$

Conclusion

BNL E787/E949 experiment
[\[Phys.Rev.D 79 \(2009\) 092004\]](#)

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6_{-3.5}^{+4.1}\right) \times 10^{-11}$$

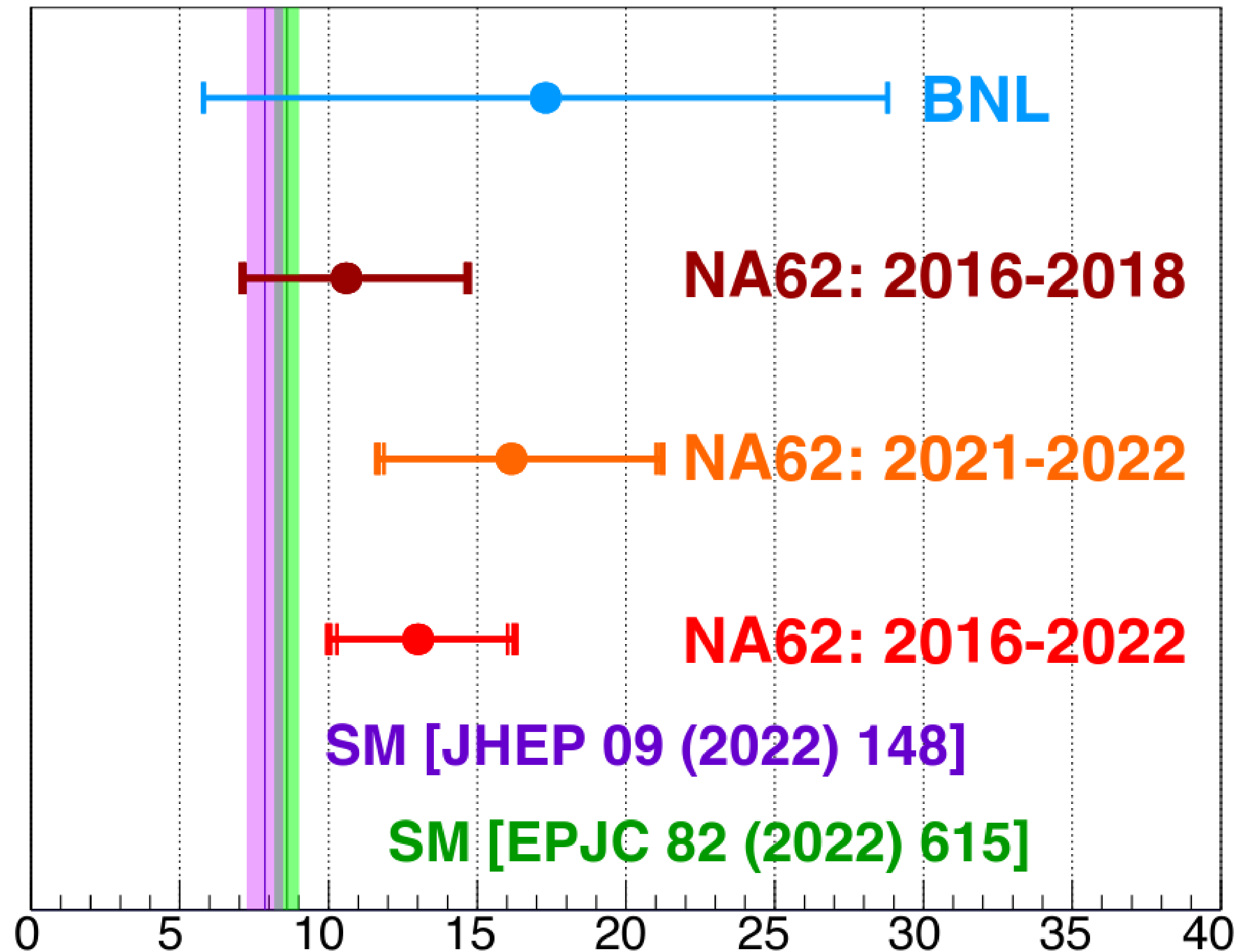
[JHEP 06 (2021) 093]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.2_{-4.5}^{+5.1}\right) \times 10^{-11}$$

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0_{-3.0}^{+3.3}\right) \times 10^{-11}$$

[arXiv:2412.12015](#)

- NA62 results are consistent
- Central value moved up (now 1.5–1.7 σ above SM)
- Fractional uncertainty decreased: 40% to 25%

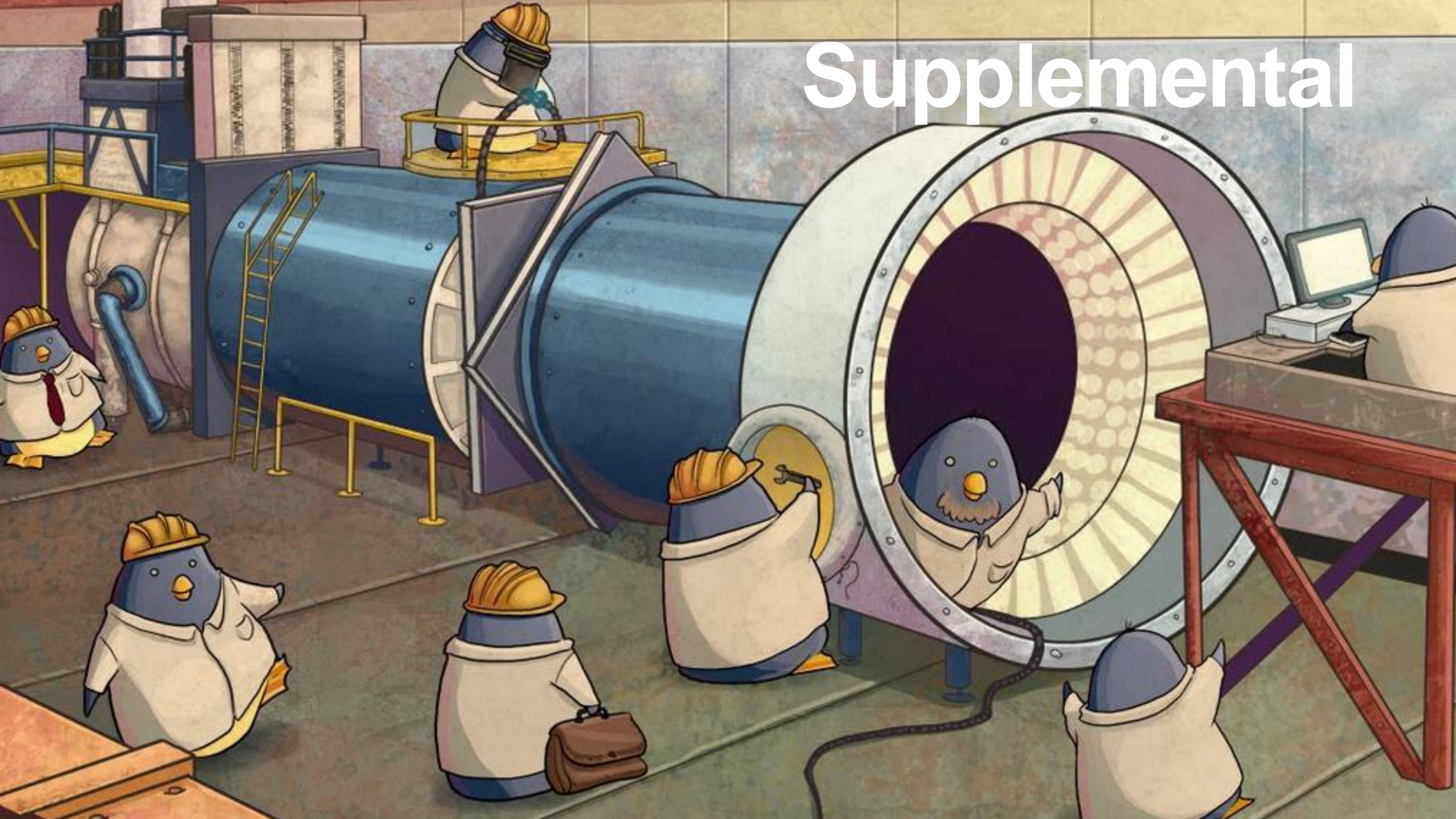


First observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay at 5 σ $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \times 10^{11}$

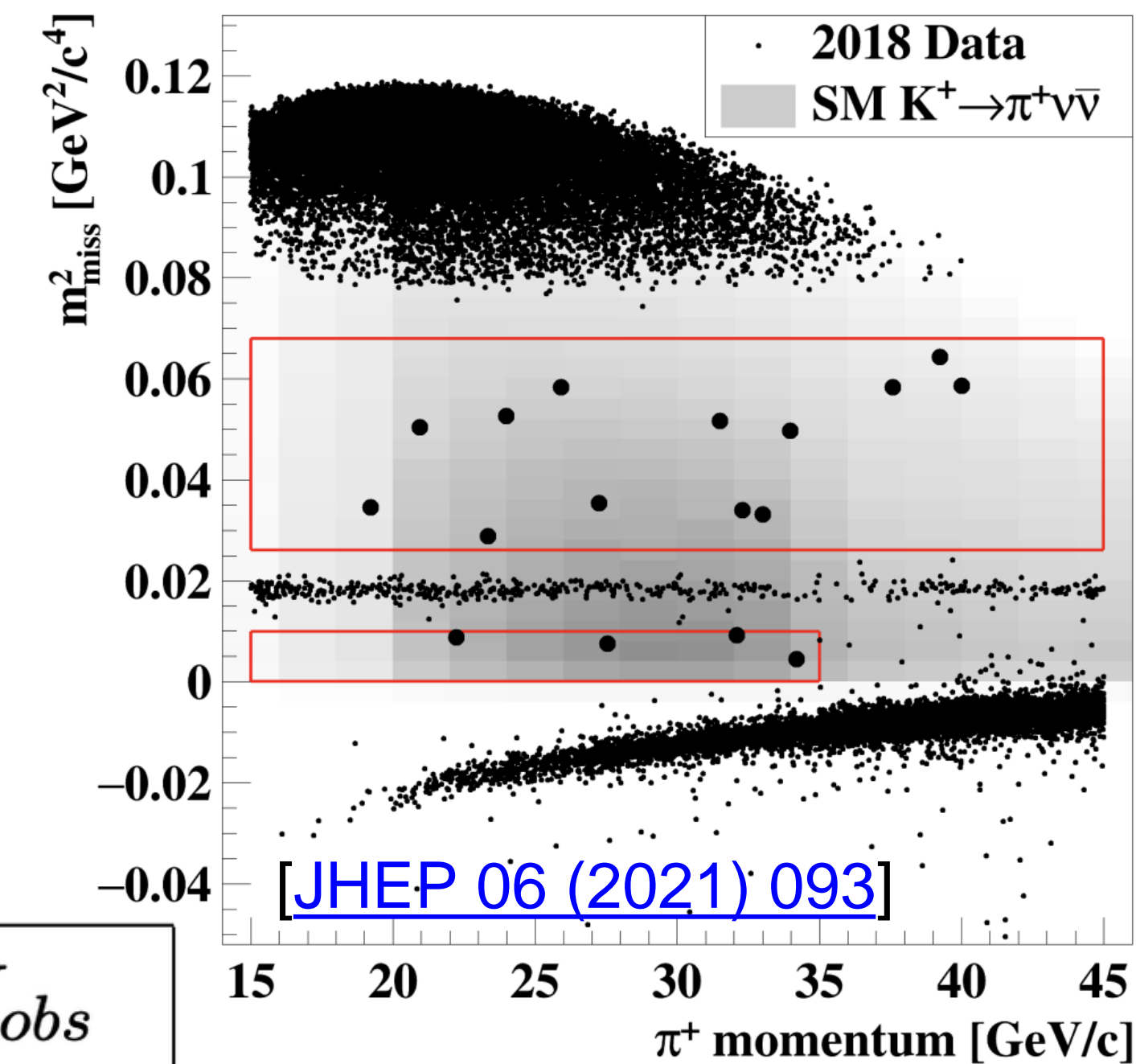
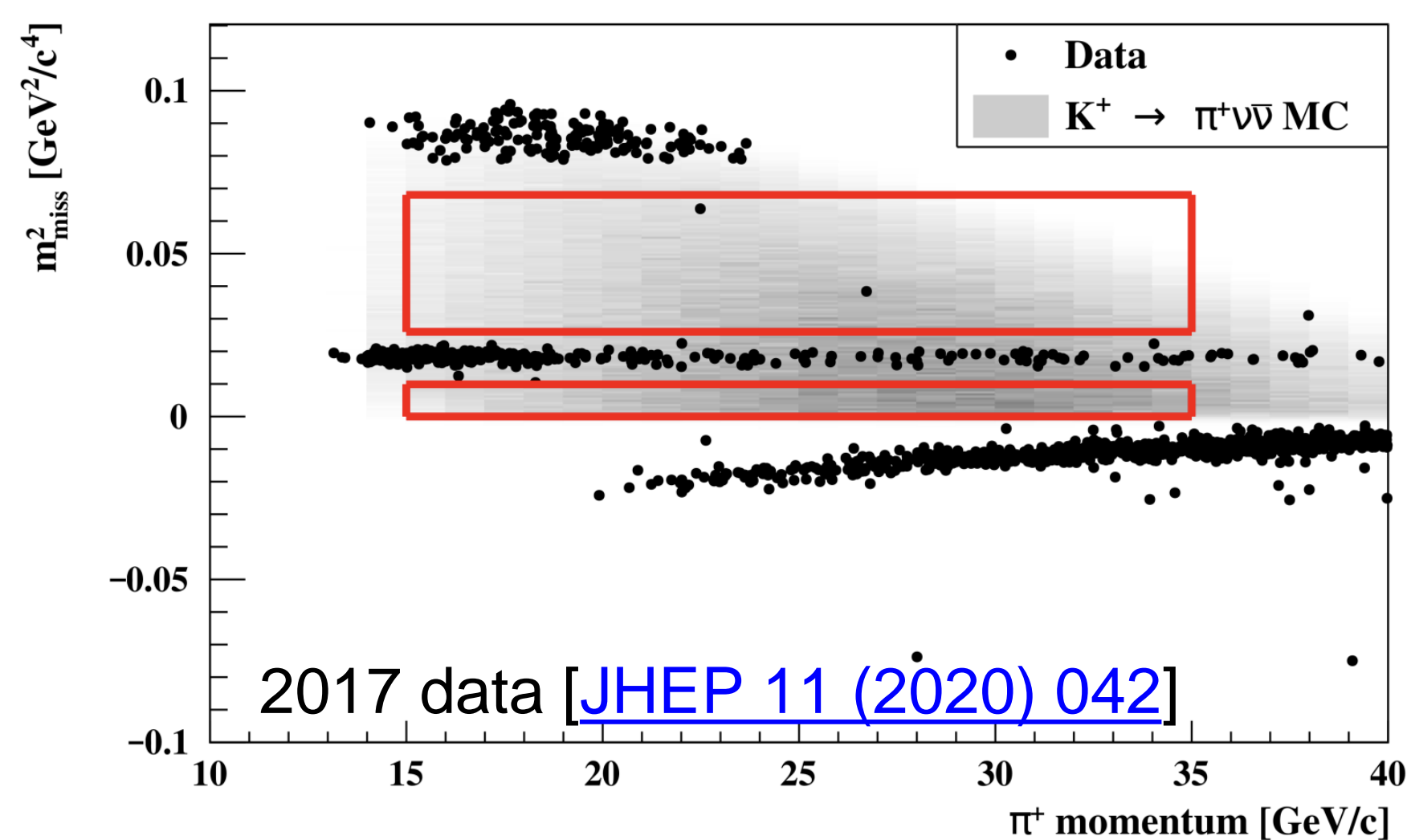
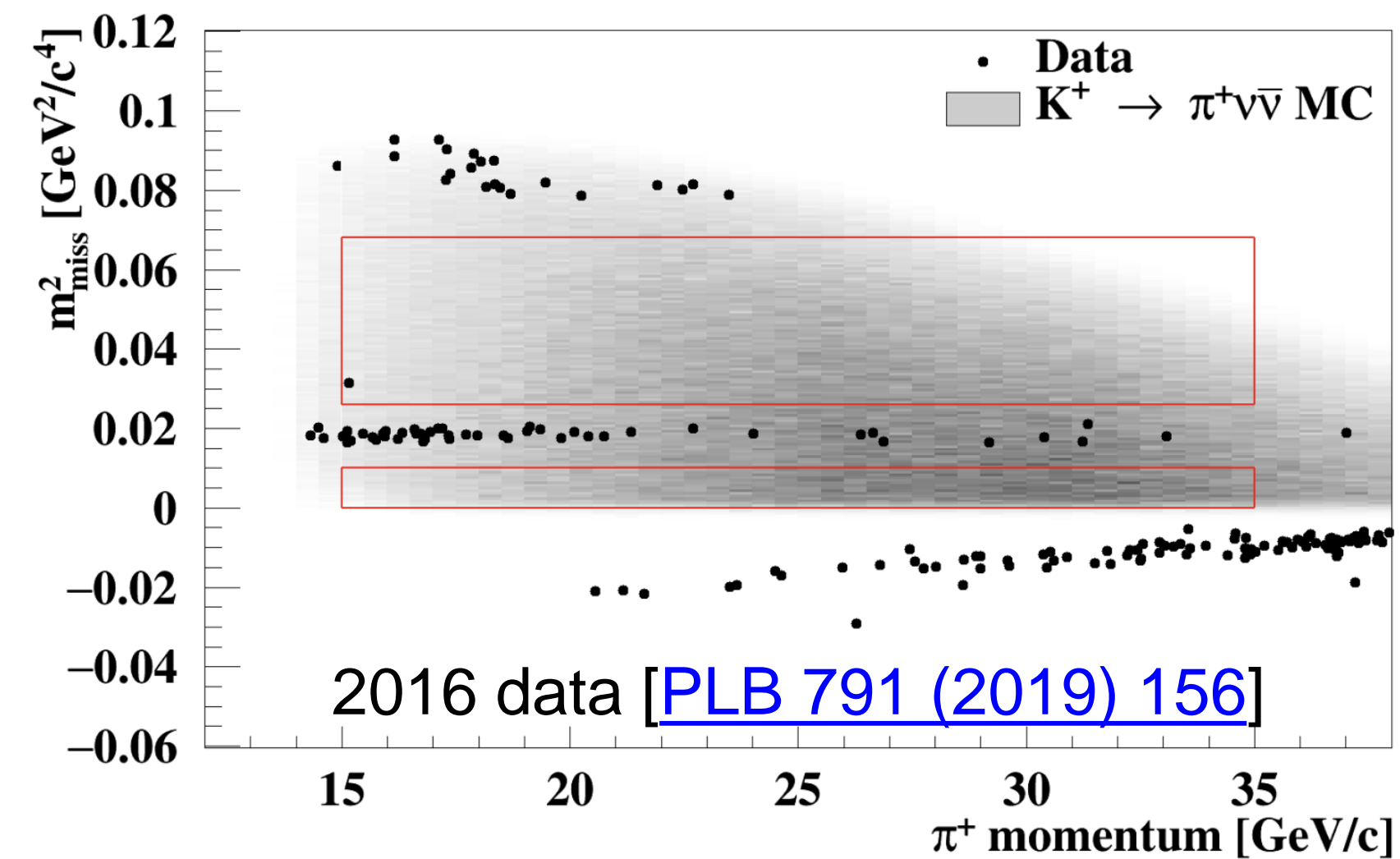
Smallest BR ever measured at this level of signal significance

Need full NA62 data-set to clarify SM agreement or tension

Supplemental



NA62 results: 2016–2018 data



Data-taking year	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{SM,exp}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

$N_{\pi\nu\bar{\nu}}^{SM,exp}$ assumes:
 $B_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$

Statistical combination:

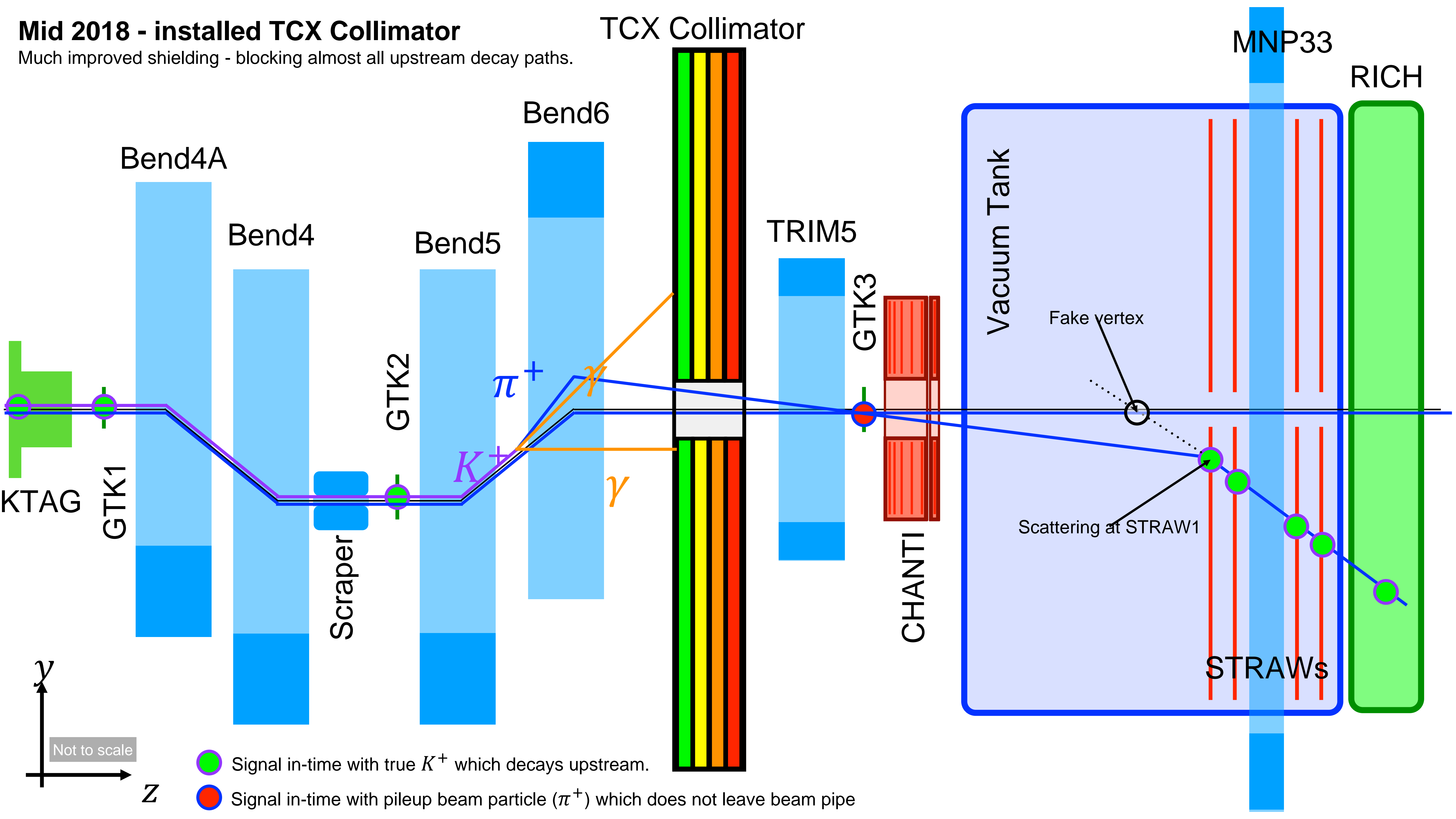
$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11} @ 68\% CL$$

Background-only hypothesis: $p = 3.4 \times 10^{-4} \Rightarrow$ significance = 3.4σ

Mid 2018 - installed TCX Collimator

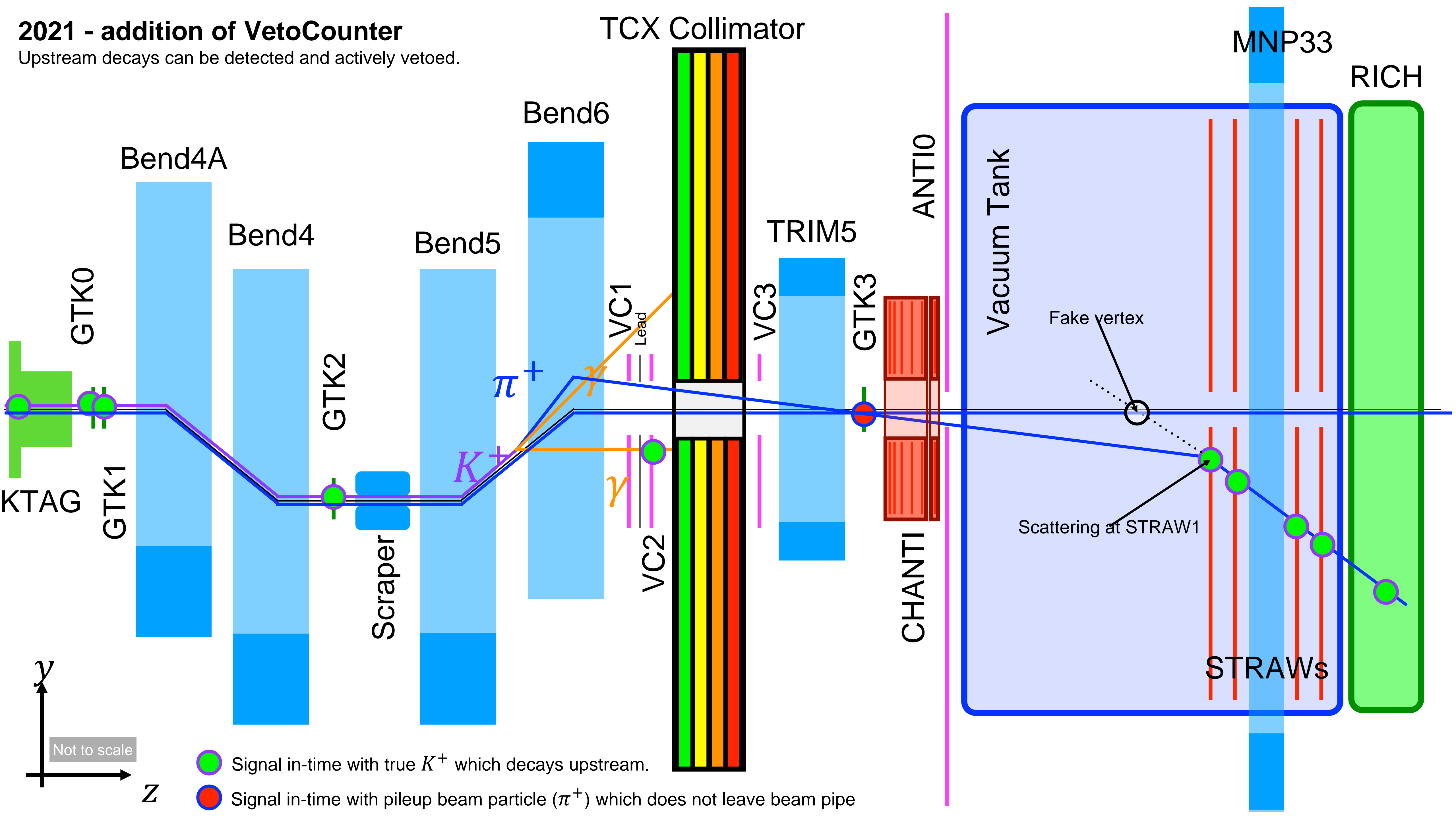
Much improved shielding - blocking almost all upstream decay paths.

TCX Collimator



2021 - addition of VetoCounter

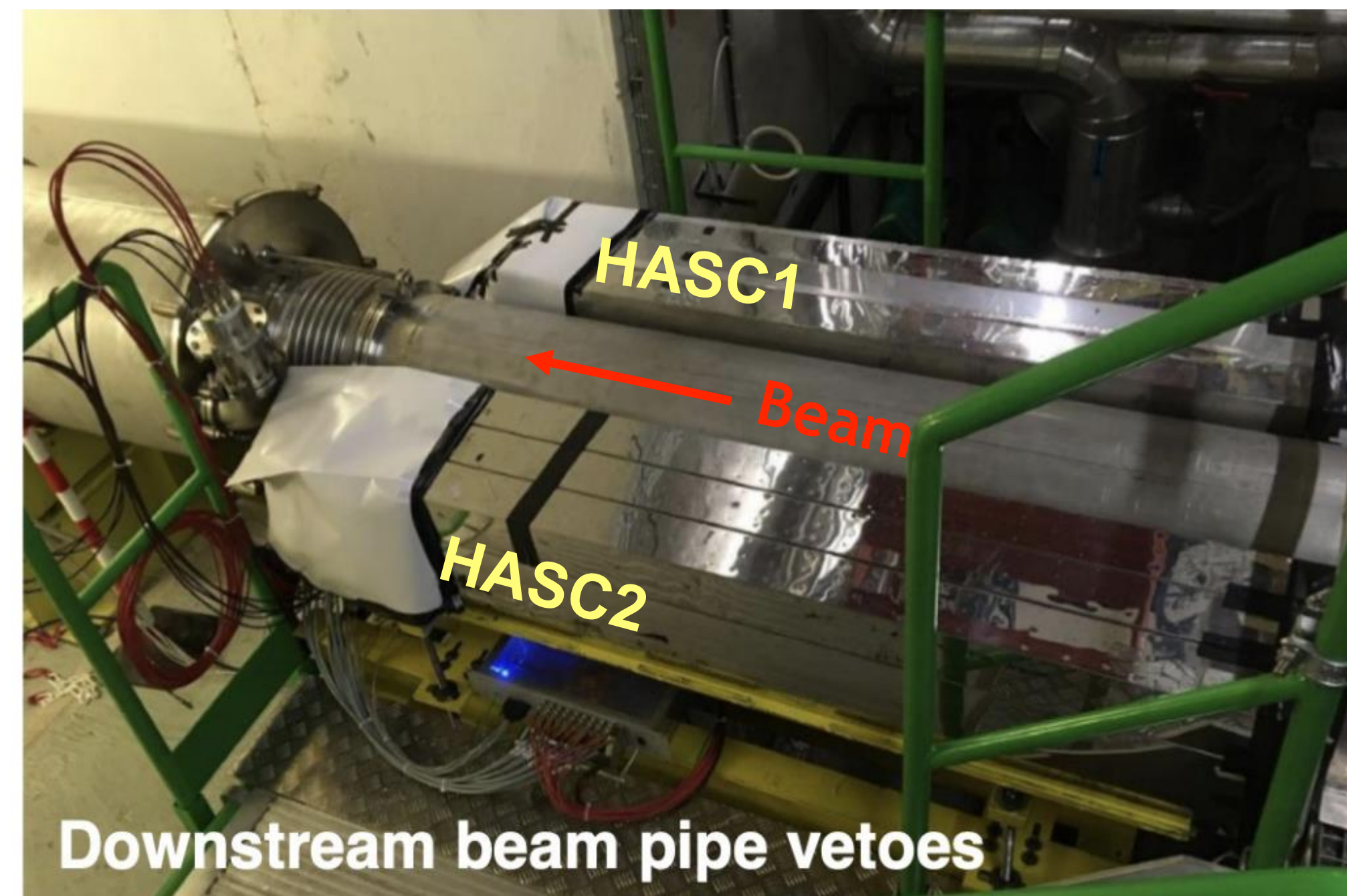
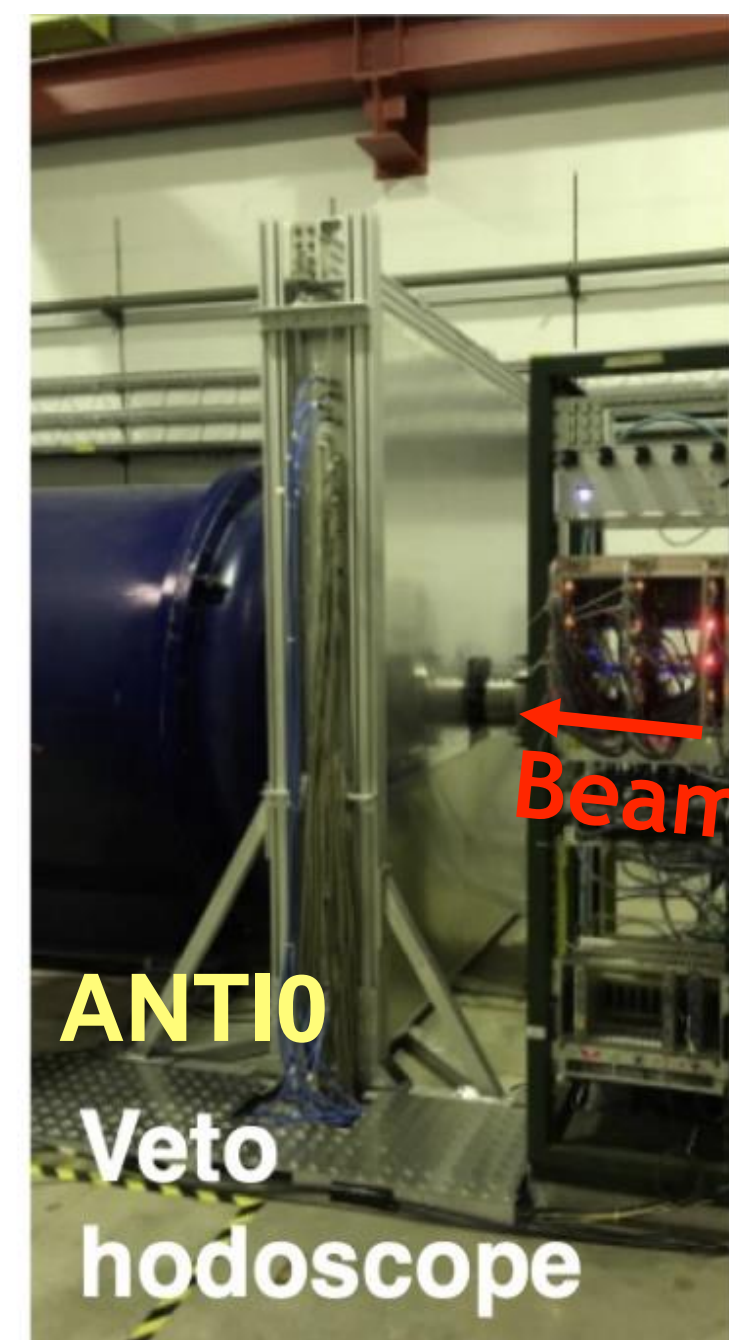
Upstream decays can be detected and actively vetoed.



NA62 upgrades during LS2

- New detectors, installed during LS2:
 - 4th GTK (Kaon beam tracker) & rearrange GTK achromat (GTK2 upstream of scraper).
 - New upstream veto (**VetoCounter**) & veto hodoscope (**ANTI0**) upstream of decay volume.
 - Additional veto detector (**HASC2**) at end of beam-line.
- Improvements to the trigger configuration.
- Intensity increased by $\sim 35\%$ with respect to 2018 [450 \rightarrow 600 MHz].

New detectors installed in 2021:



$K \rightarrow \pi \nu \bar{\nu}$: Beyond the SM

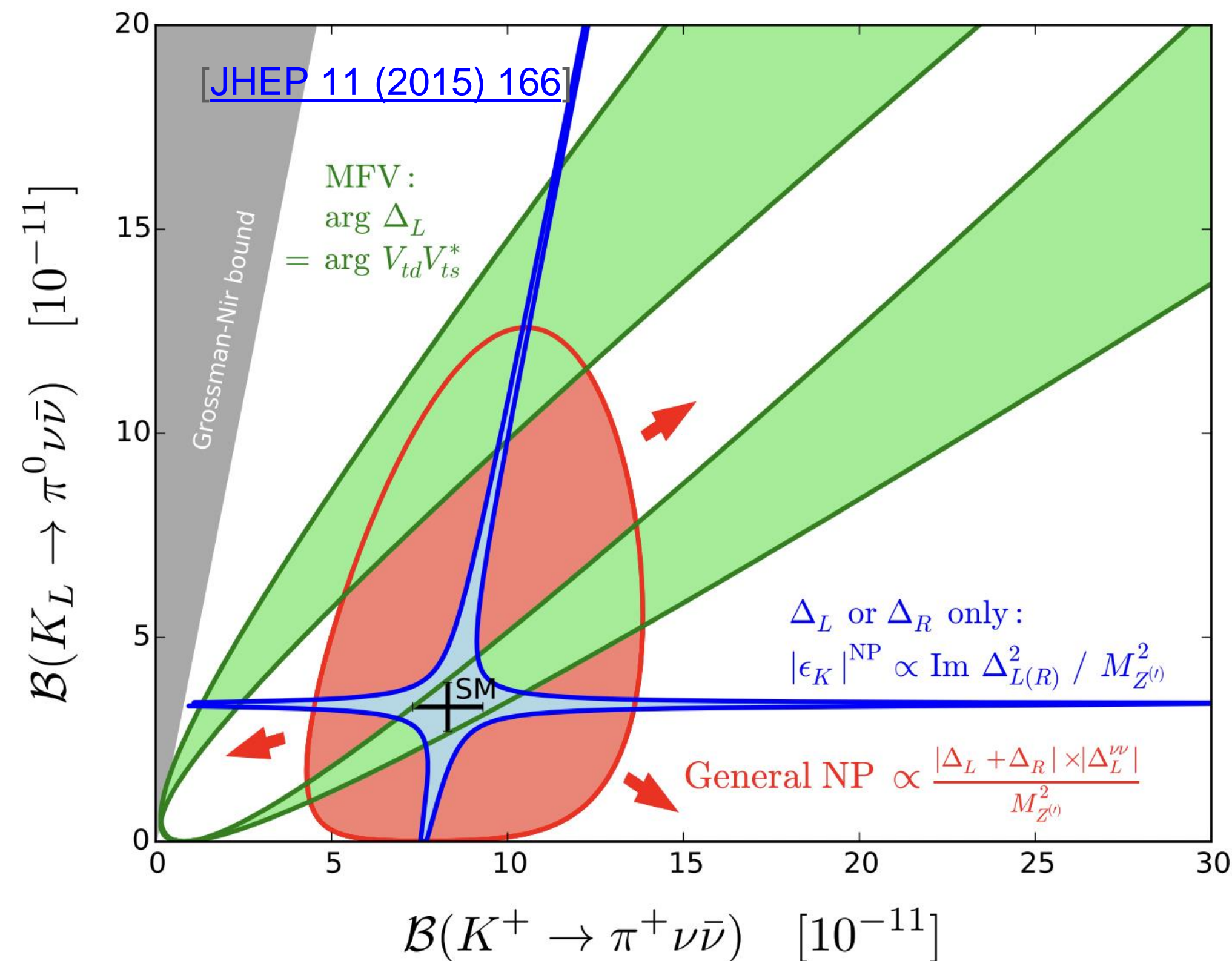
- Correlations between BSM contributions to BRs of K^+ and K_L modes [[JHEP 11 \(2015\) 166](#)].
 - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ϵ'/ϵ , ΔM_B , B-decays) [[JHEP 12 \(2020\) 097](#)][[PLB 809 \(2020\) 135769](#)].
- Leptoquarks [[EPJ.C 82 \(2022\) 4, 320](#)], Interplay between CC and FCNC [[JHEP 07 \(2023\) 029](#)], NP in neutrino sector [[EPJ.C 84 \(2024\) 7, 680](#)] and additional scalar/tensor contributions [[JHEP 12 \(2020\) 186](#)][[arXiv:2405.06742](#)] ...

- **Green:** CKM-like flavour structure
 - Models with Minimal Flavour Violation
- **Blue:** new flavour-violating interactions where LH or RH currents dominate
 - Z' models with pure LH/RH couplings
- **Red:** general NP models without above constraints
- **Grossman-Nir Bound:** model-independent relation

[[PLB 398 \(1997\) 163-168](#)]

$$\frac{\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \tau_{K^+}}{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \tau_{K_L}} \simeq 1$$

$$\Rightarrow \mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \lesssim 4.3 \cdot \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$$



Particle ID performance : 2021–22 data

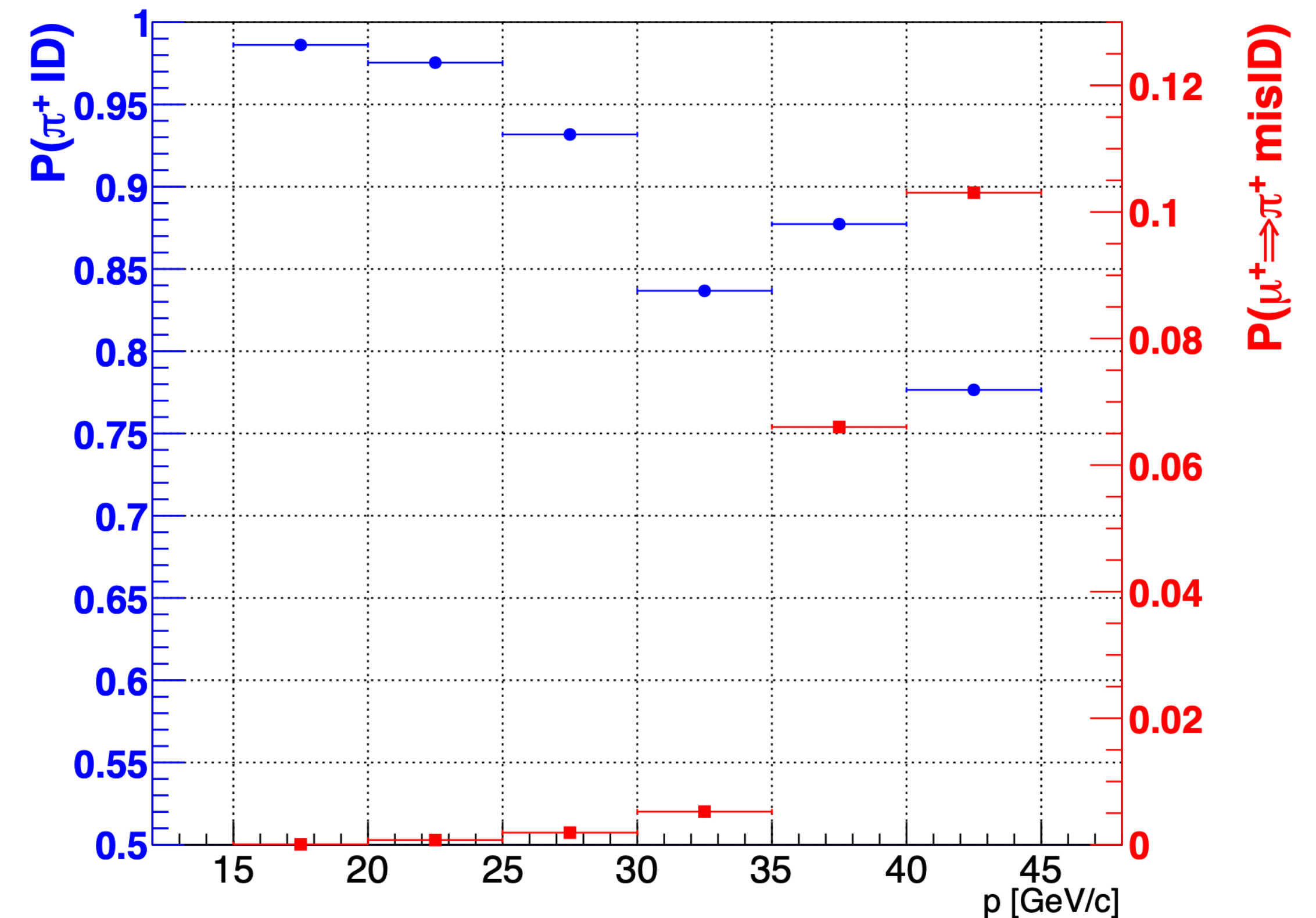
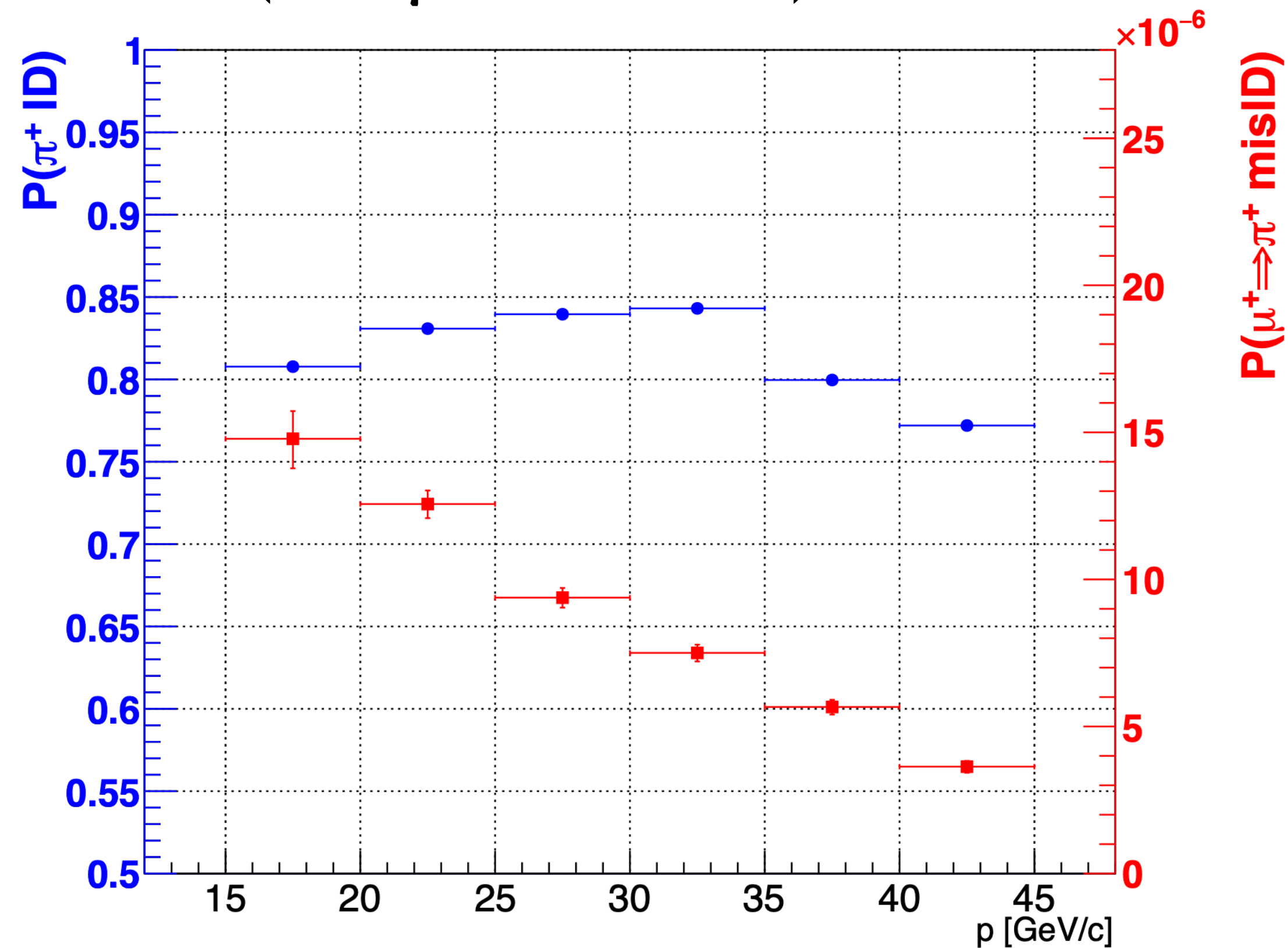


Calorimeters

RICH

- Use BDT classifier for LKr & MUV1,2
- + MUV3 (fast μ^+ detector)

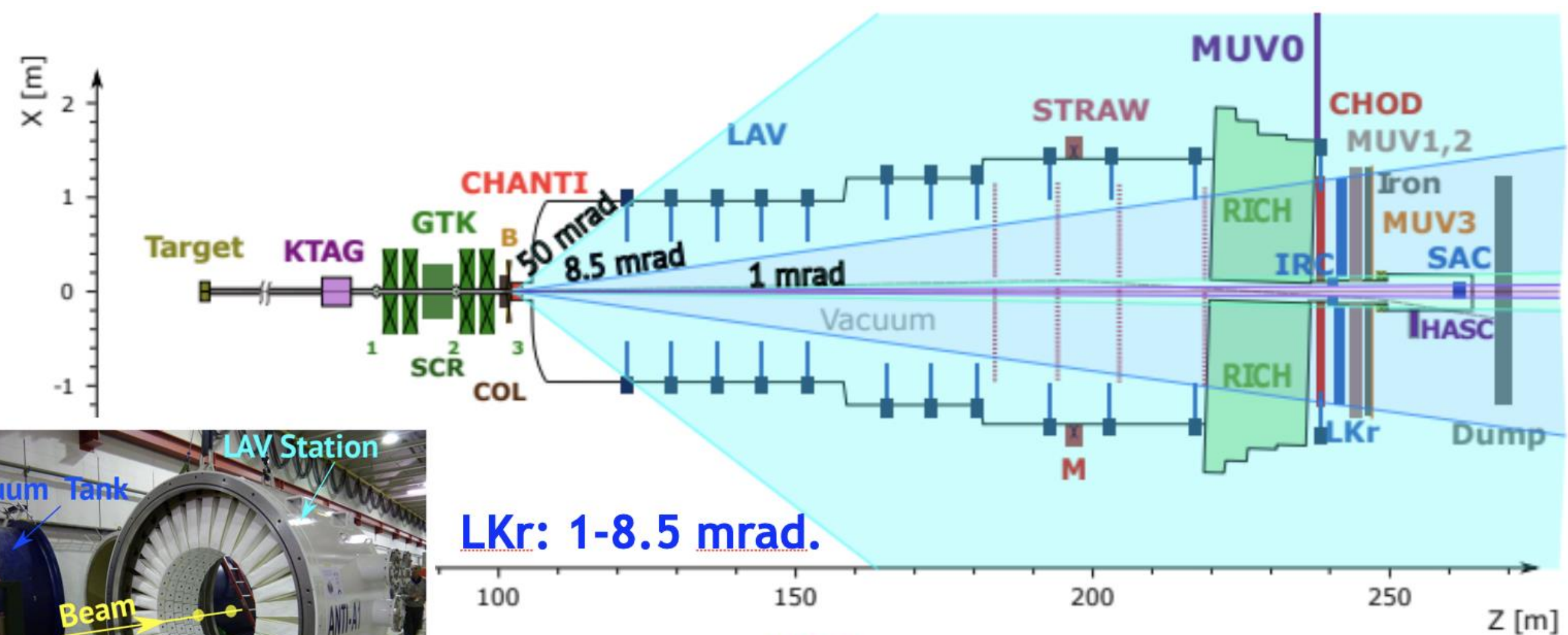
Designed to distinguish between π^+ / μ^+ with 15 – 35 GeV/c



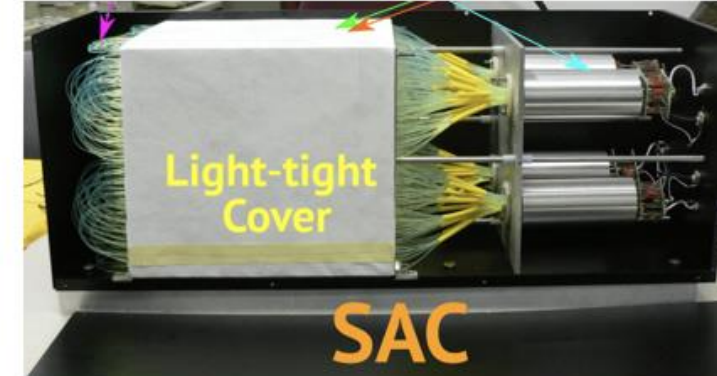
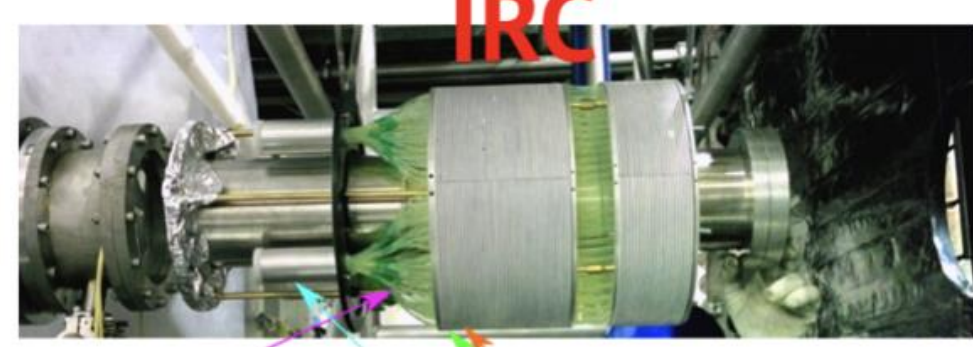
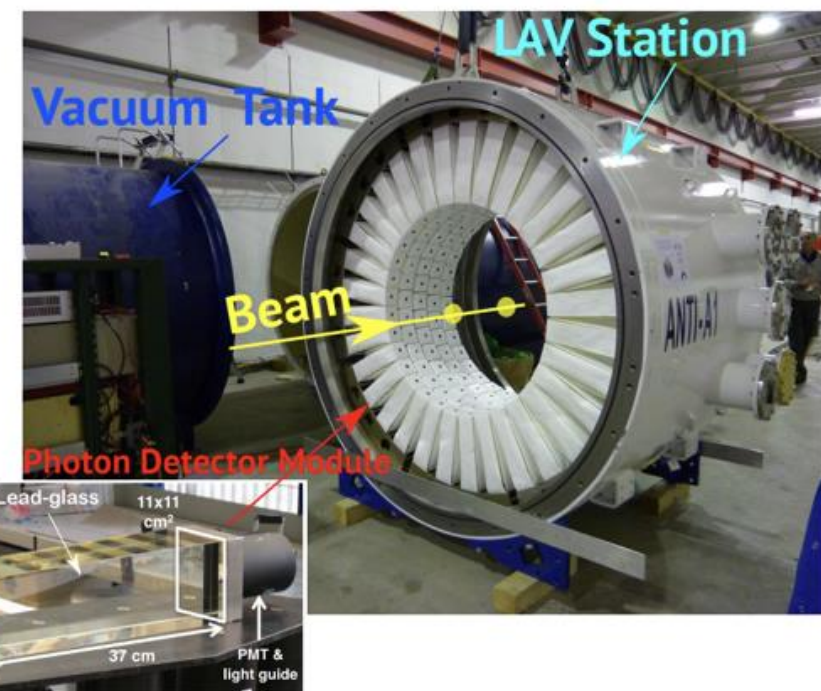
$$P(\pi^+) = 73 \%$$

$$P(\mu^+ \Rightarrow \pi^+) = (1.3 \pm 0.2) \times 10^{-7}$$

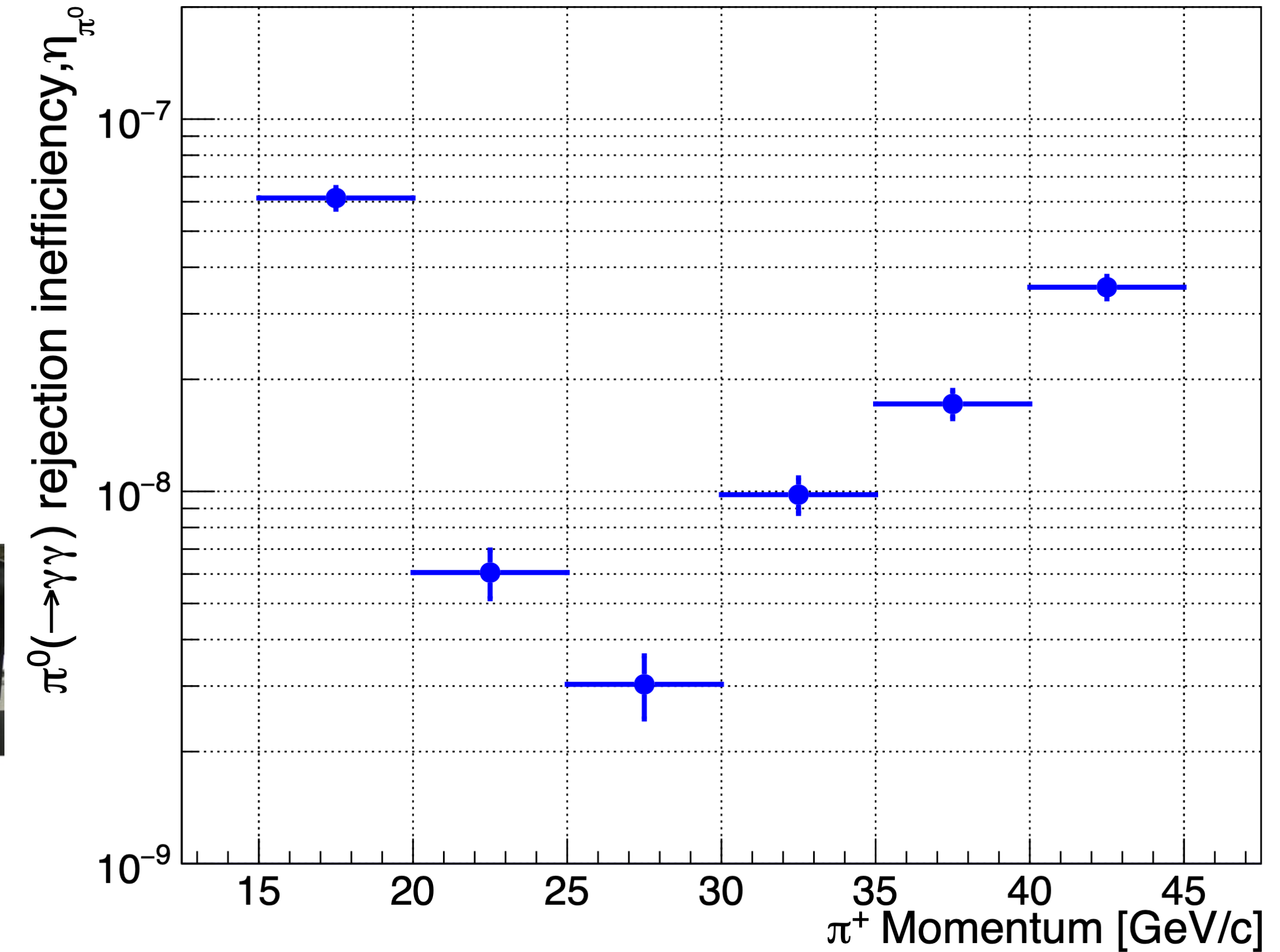
Comprehensive photon veto system: 21–22



LKr: 1-8.5 mrad.



Control sample of $K^+ \rightarrow \pi^+ \pi^0$

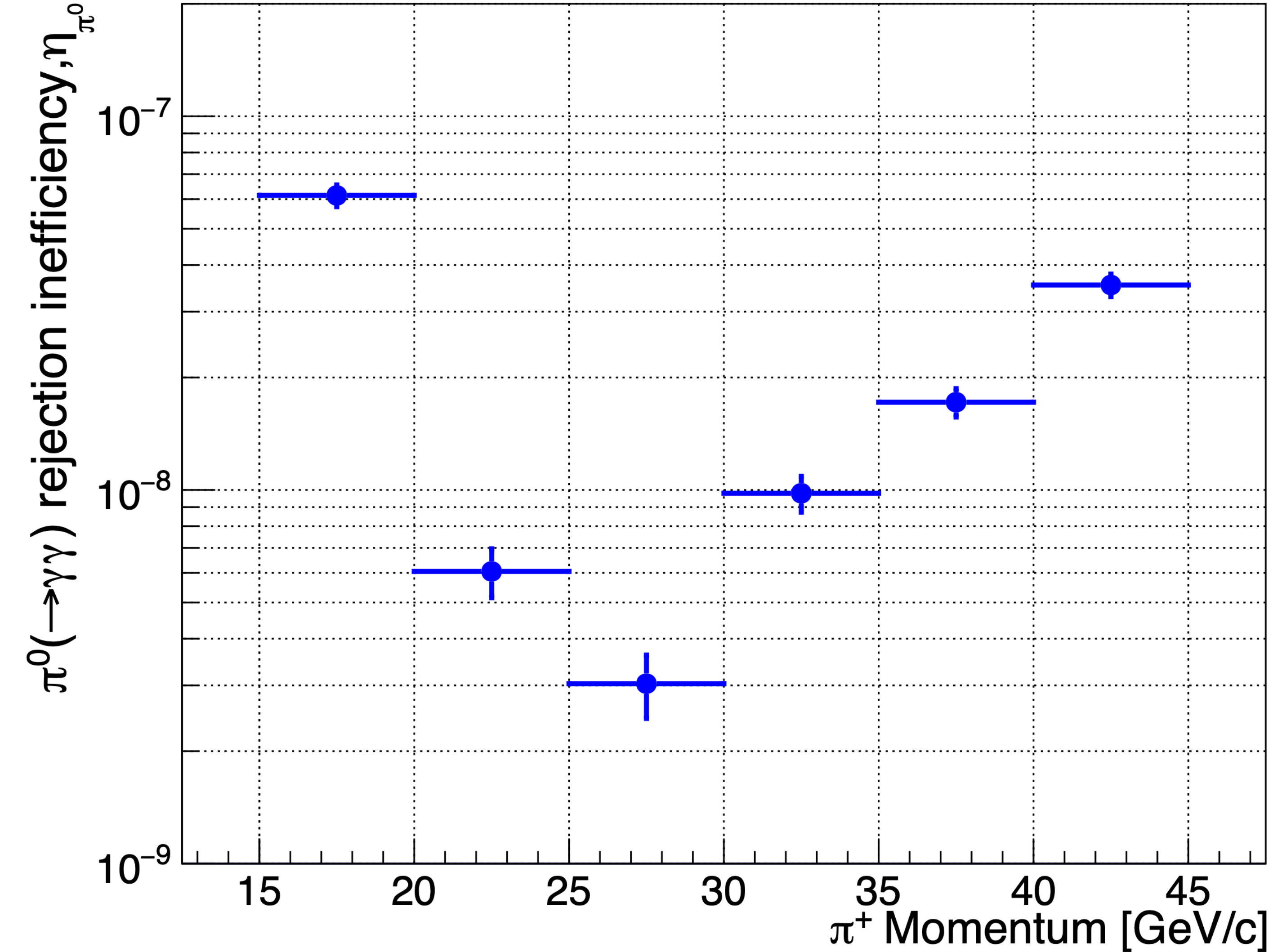


- Probability of $K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \gamma\gamma$ events passing all photon veto conditions:

$$\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$$

• Meets target: combined γ/π^0 rejection of $\mathcal{O}(10^8)$

Photon veto performance



- Probability of $K^+ \rightarrow \pi^+ \pi^0$ events with $\pi^0 \rightarrow \gamma\gamma$ passing full photon vetos:

Number of events passing full $\pi^+ \nu \bar{\nu}$ selection in $\pi^+ \pi^0$ region

$$\eta_{\pi^0} = \frac{N_{sel.}^{\pi^+ \pi^0 R}}{N_{\pi\pi} D_0 \epsilon_{trig} \epsilon_{RV}}$$

Number of selected normalisation events

Normalisation trigger downscaling and efficiency

Random veto efficiency

$$\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$$

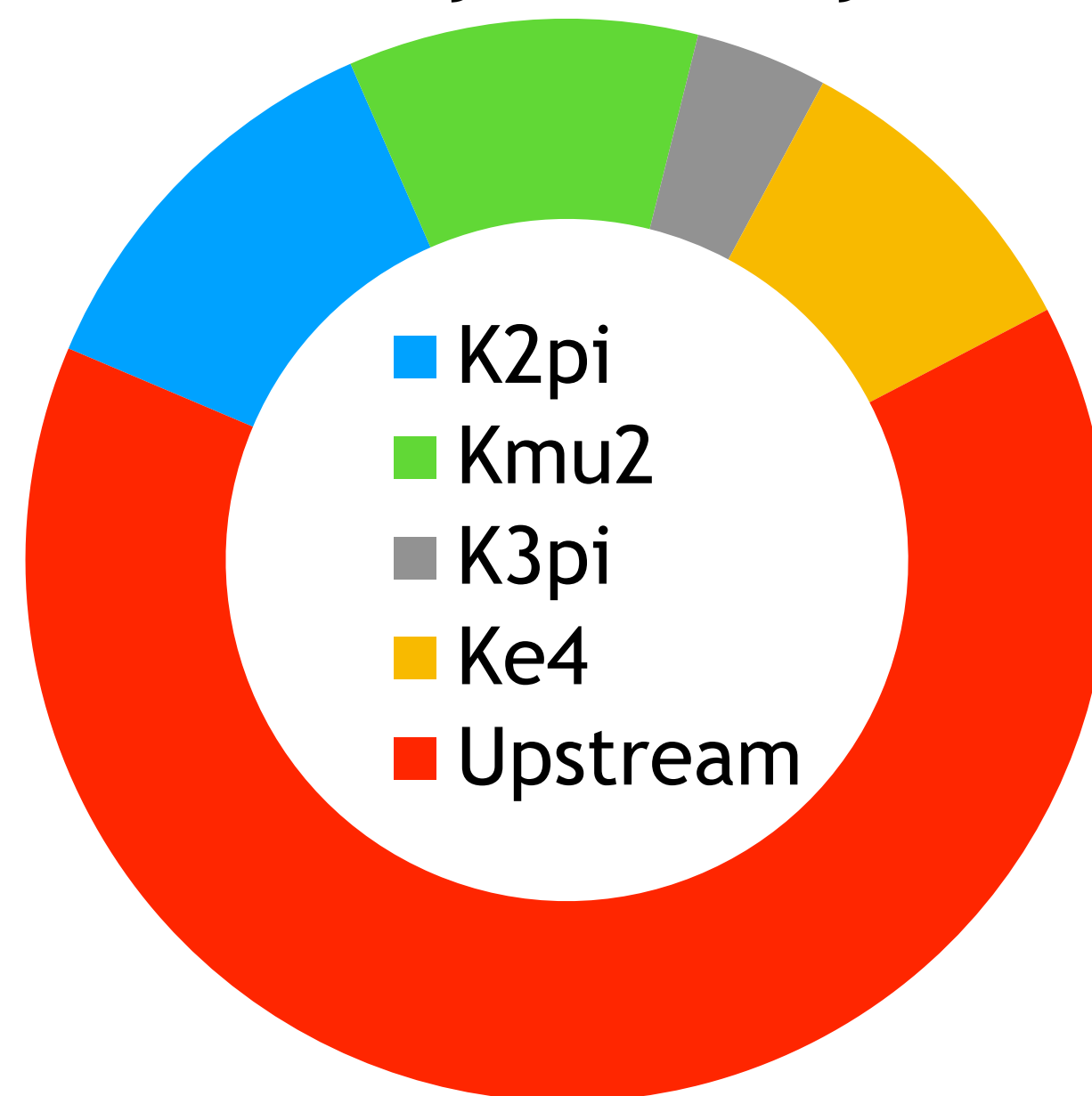
- Combined γ/π^0 rejection of $\mathcal{O}(10^8)$.

Upgrading NA62

- 2016–18 analysis proved NA62 technique.
- Limitation: tight cuts to reject backgrounds \Rightarrow reduces signal efficiency.
- To improve: need new tools to control background.

Background	N(exp) 2018 (S2)
Upstream	$2.76^{+0.90}_{-0.70}$
$K^+ \rightarrow \pi^+ \pi^0$	0.52 ± 0.05
$K^+ \rightarrow \mu^+ \nu$	0.45 ± 0.06
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	0.41 ± 0.10
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.17 ± 0.08
Total	$4.31^{+0.91}_{-0.72}$

K^+ decays in decay tank



Upstream background

Largest backgrounds:

1. Upstream
2. $K^+ \rightarrow \pi^+ \pi^0$

Veto by detecting previously missed particles...

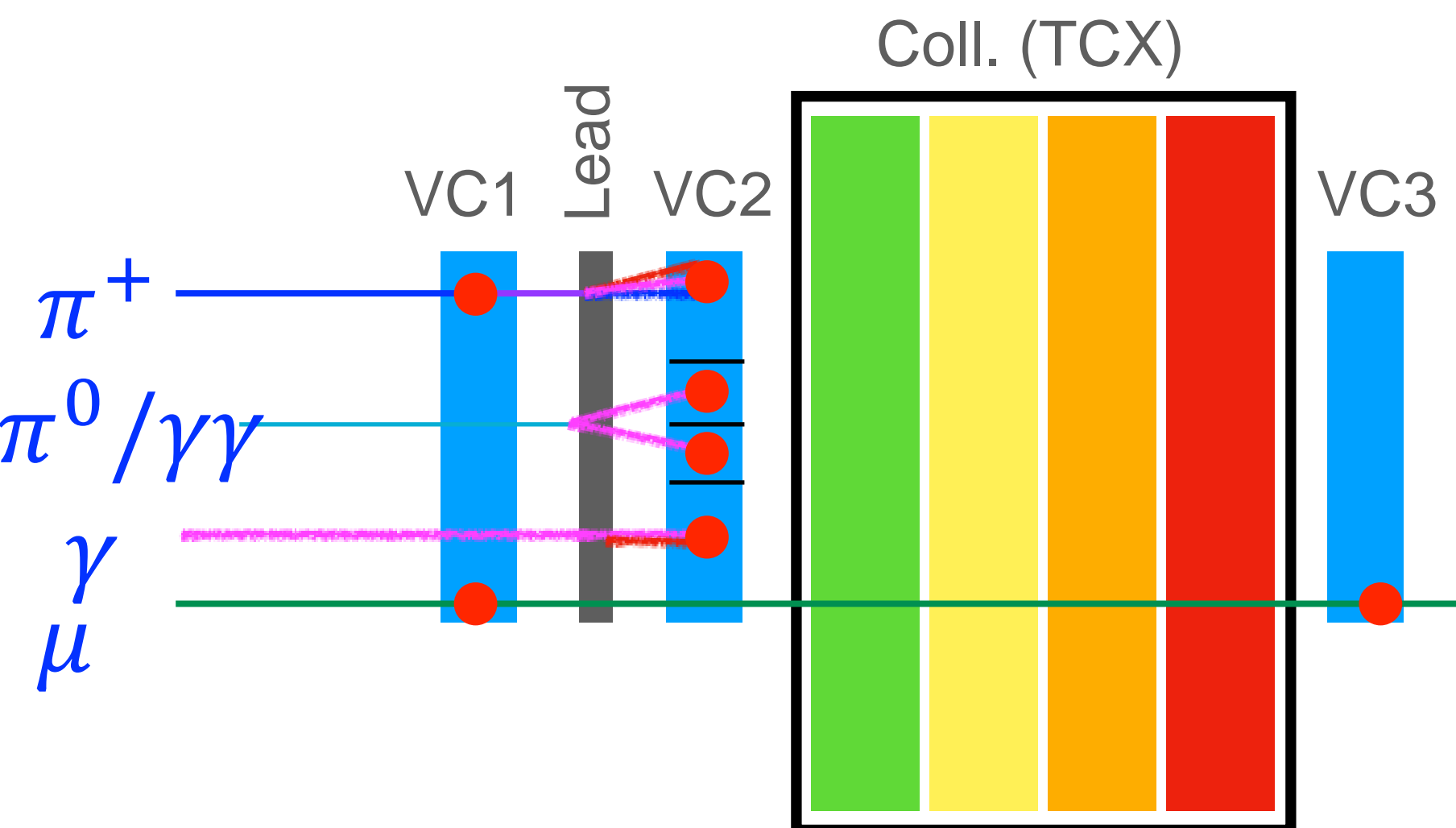
New upstream vetos: VetoCounter & ANTI0



[FELIX readout: [Streaming Readout Workshop talk 2021](#)]

VetoCounter

- Detect particles from decays upstream of final collimator.
- **Factor ~3 rejection** with ~2% accidental veto.



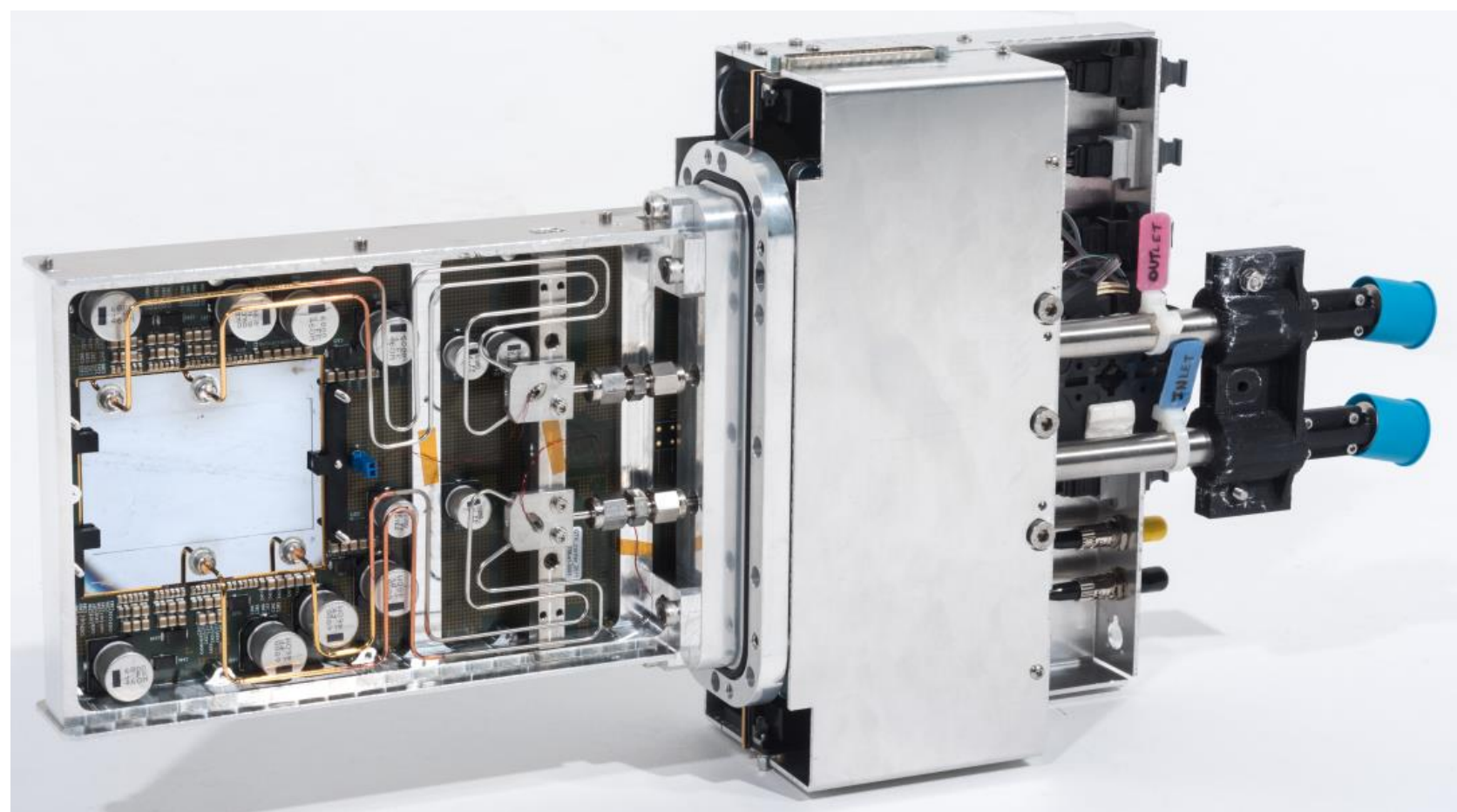
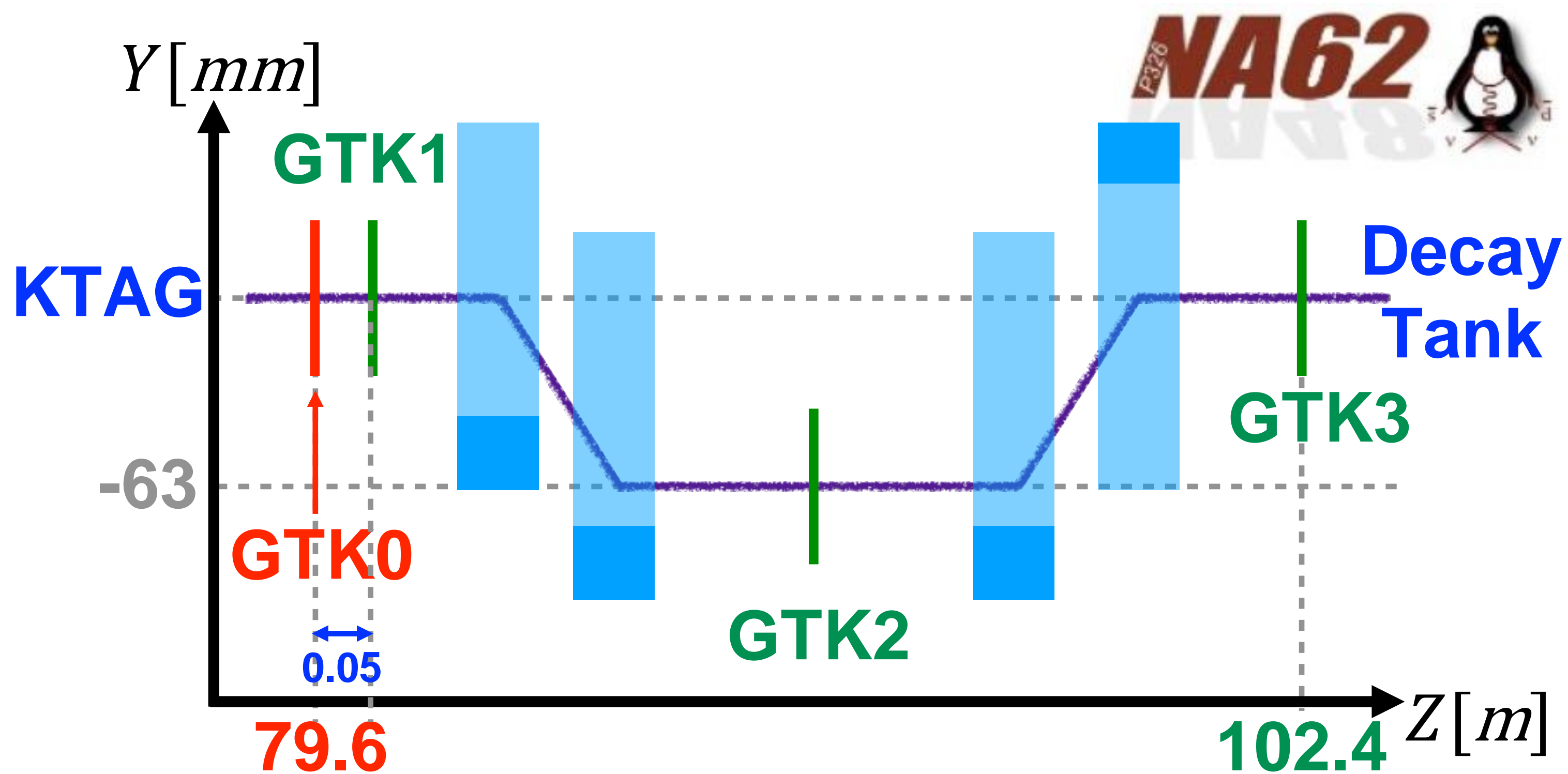
ANTI0

- Detect particles up to ~1 m from beam line.
- **Reject ~20% of upstream background** with <1% signal loss.

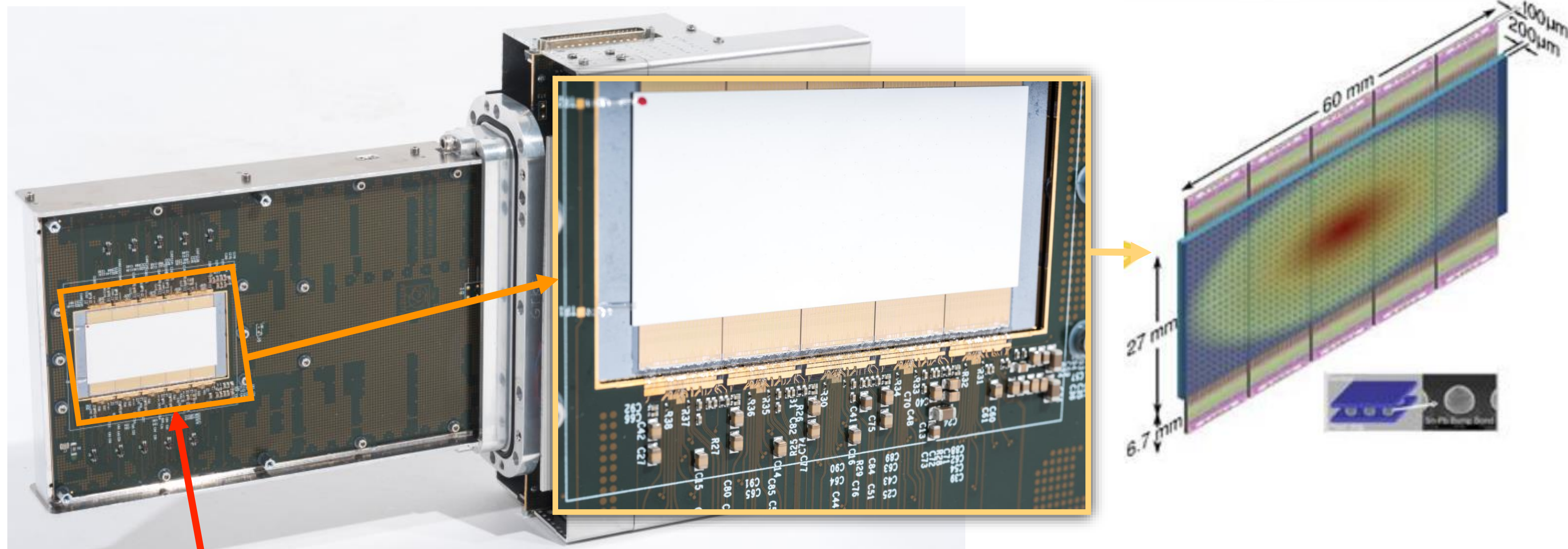
[SPSC report 2023][EP Newsletter, Dec21]

4th GTK station

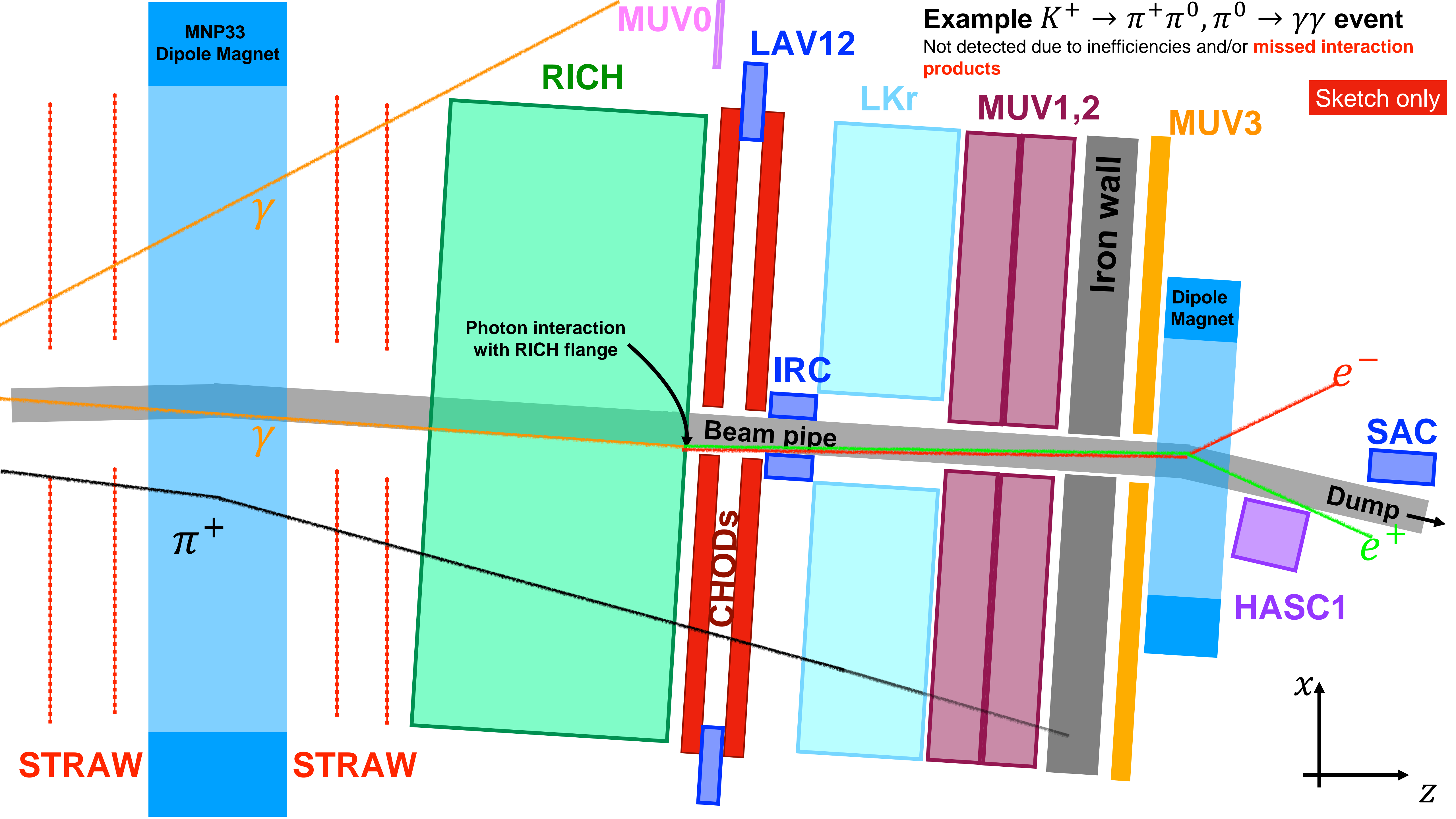
- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
 - Measures K^+ 3-mom. & time
- 4th GTK station improves efficiency & pileup resilience.

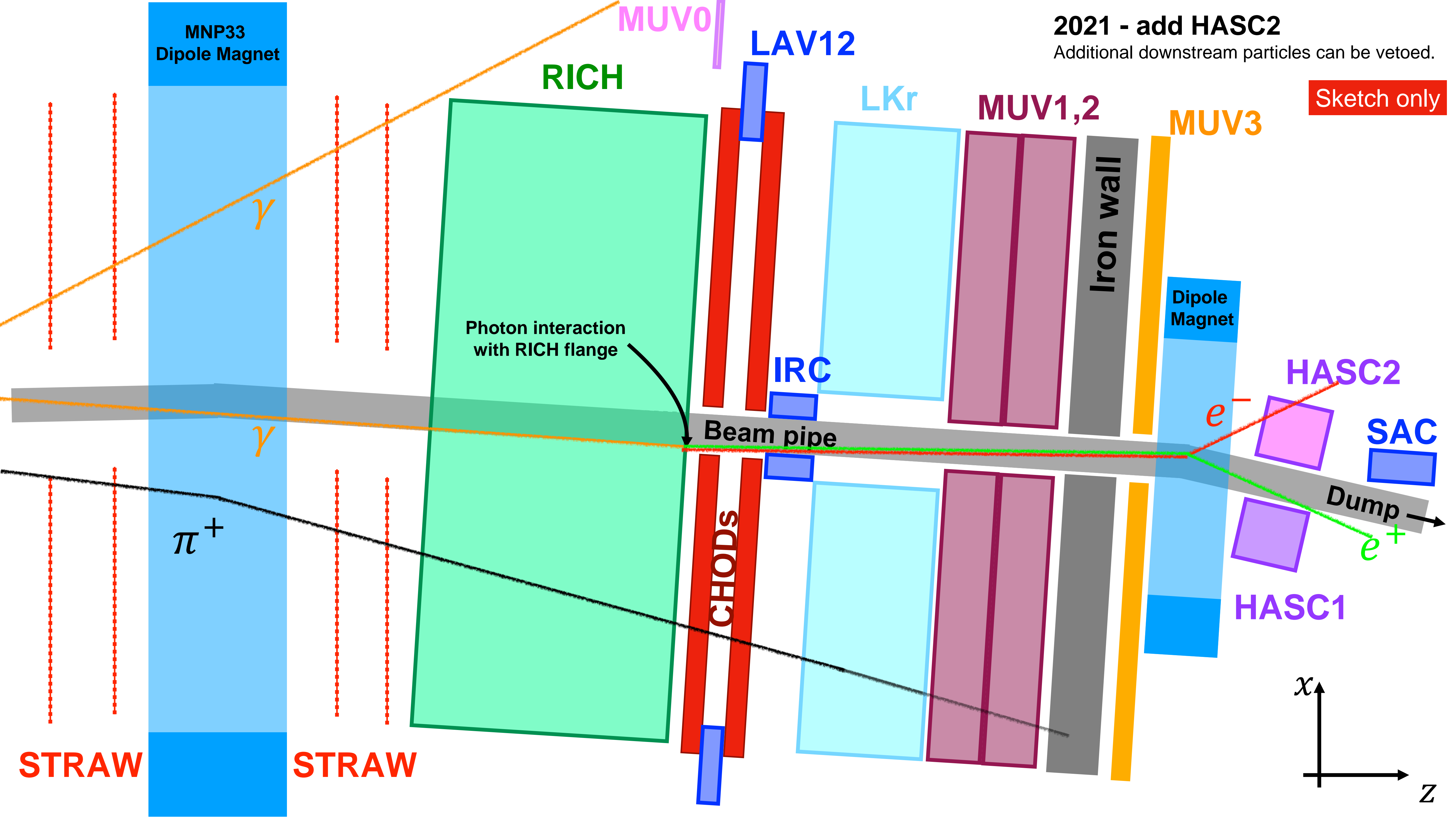


Cooling plate



Si Pixels ~(30x60 mm active area)





HASC2 veto

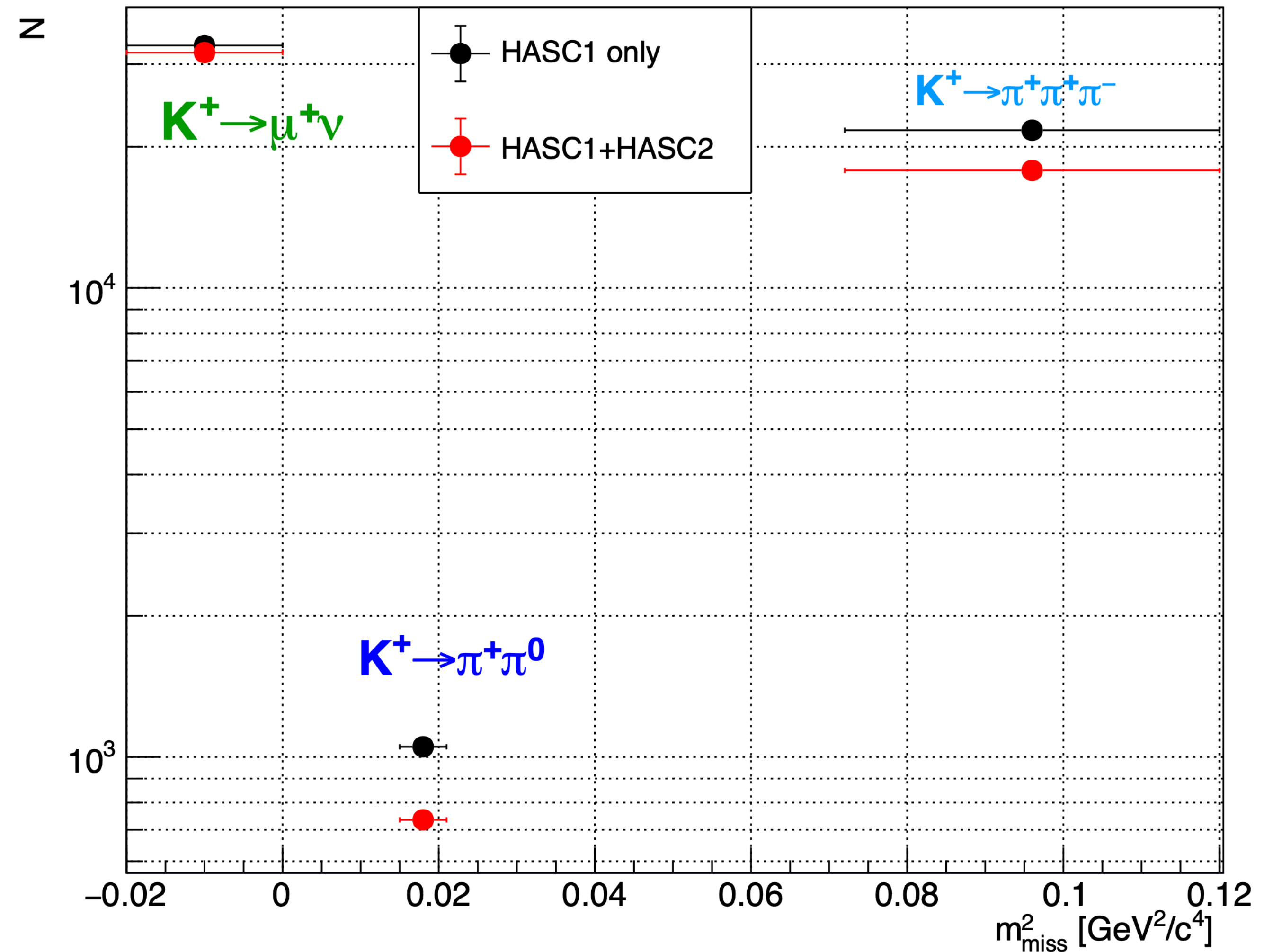
Events passing $\pi^+ \nu \bar{\nu}$ selection

(modifying HASC veto: study integral of background regions)

- $K^+ \rightarrow \pi^+ \pi^0$ was 2nd largest background for 2018 analysis.

- Addition of HASC2:

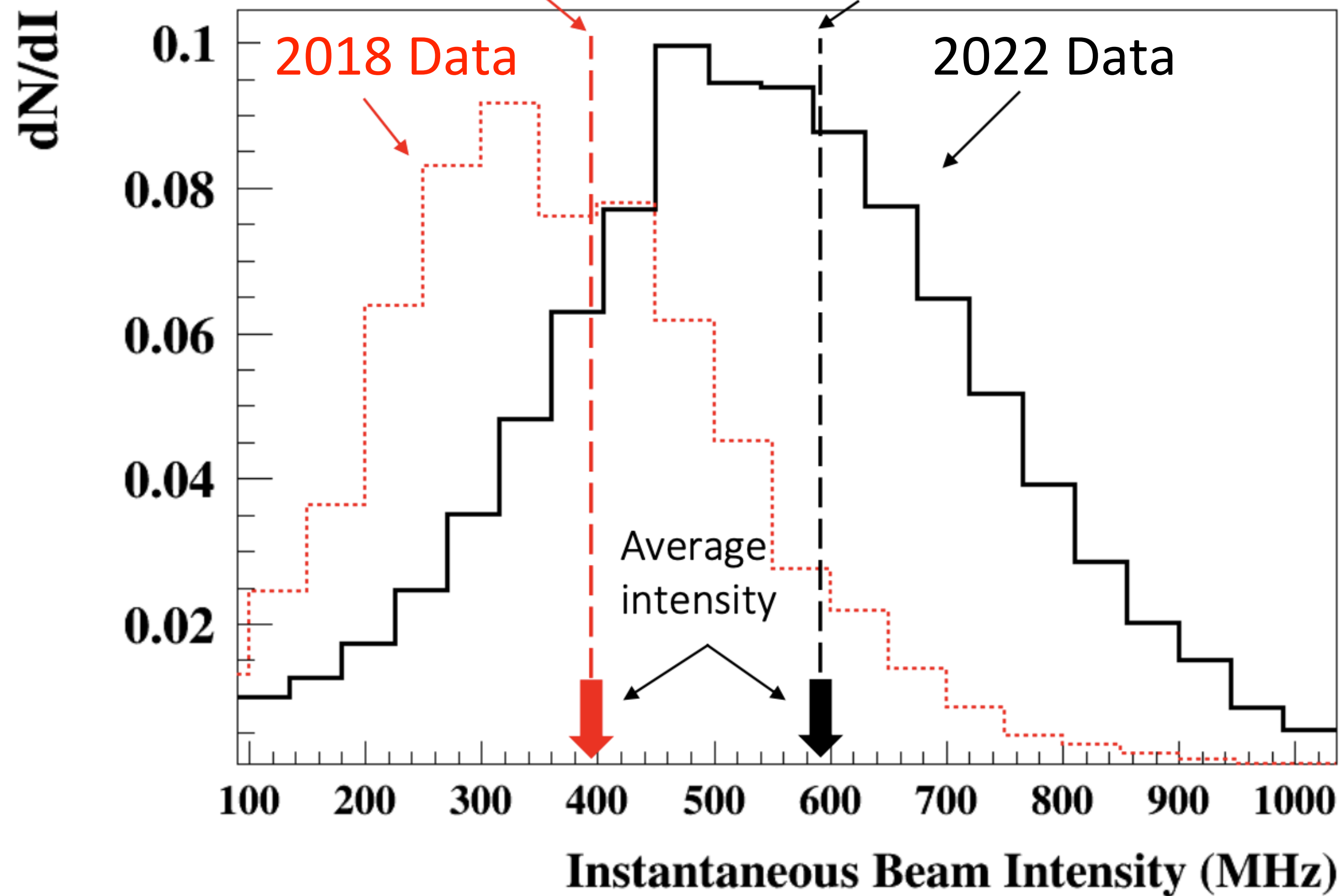
- 30% less $K^+ \rightarrow \pi^+ \pi^0$
- 18% less $K^+ \rightarrow \pi^+ \pi^+ \pi^-$
- 3.5% less $K^+ \rightarrow \mu^+ \nu$
- with only 1.5% signal loss



Beam intensity: 2018 vs 2022

$\sim 20 \times 10^{11}$ ppp on T10

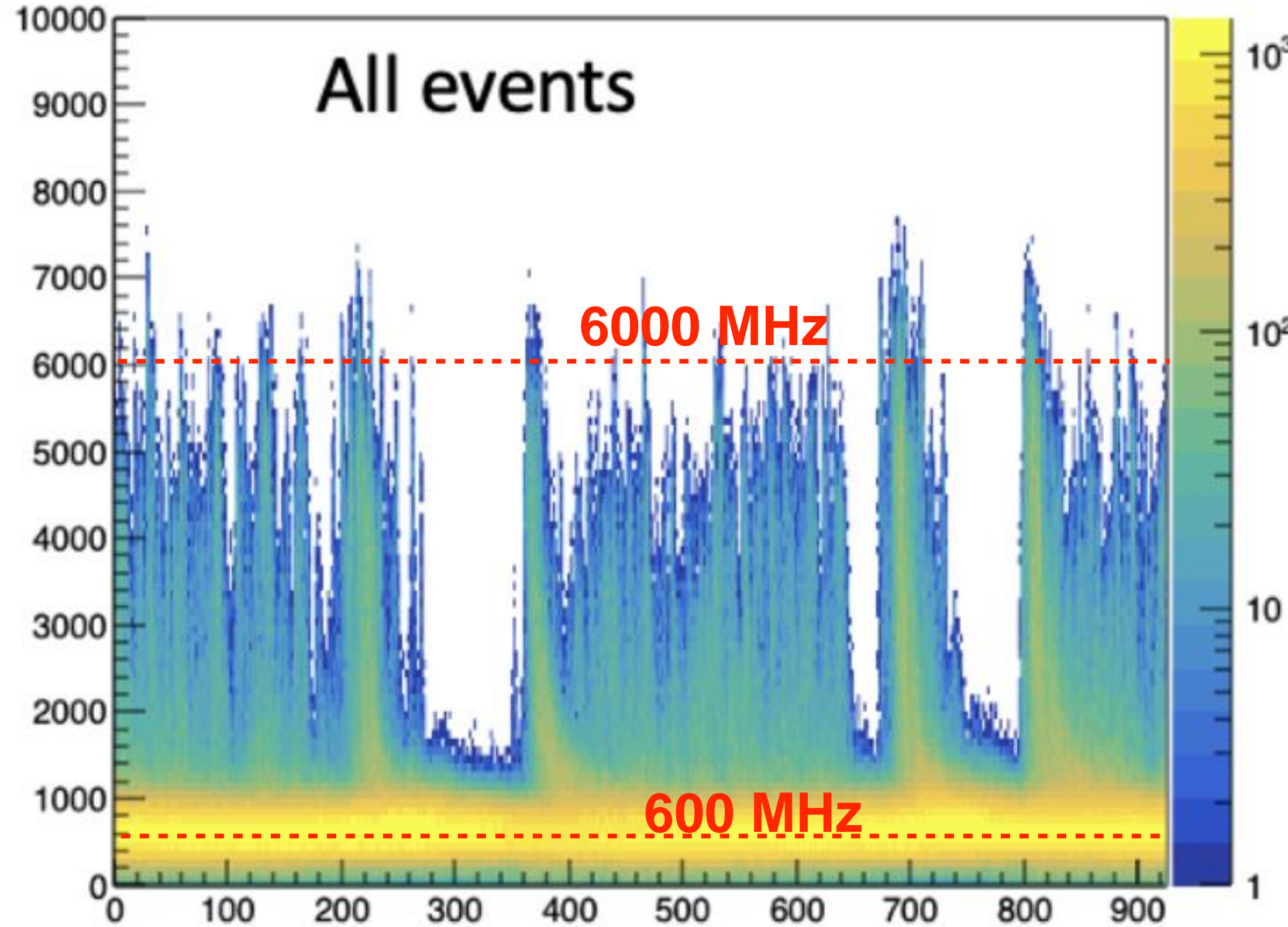
$\sim 30 \times 10^{11}$ ppp on T10



- Average beam intensity increased.
- NA62 “Full intensity” with 4.8s spill = 600 MHz

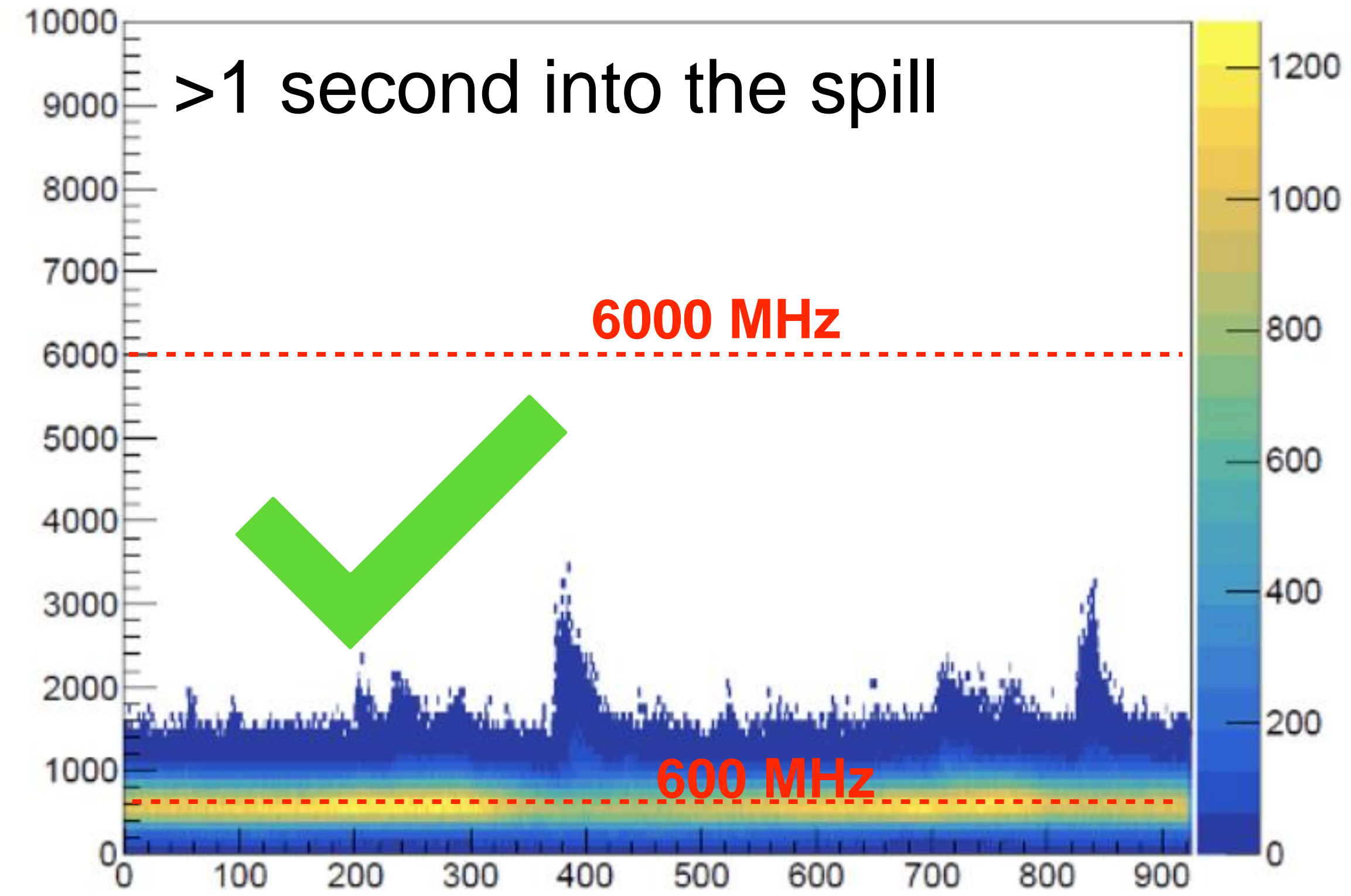
2021 instantaneous beam intensity

Instantaneous beam intensity [MHz]



Folded event timestamp [25ns]

Instantaneous beam intensity [MHz]



Folded event timestamp [25ns]

- Remove events in first 1s of 4.8s spill for 2021 data only.
 - DAQ overwhelmed by instantaneous rates up to 10x higher than design.

Triggers:

- **Minimum Bias:** $K^+ \rightarrow \mu^+ \nu$
- **Normalisation:** $K^+ \rightarrow \pi^+ \pi^0$
- **Signal:** $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates

- RICH multiplicity (reference time)
- Signal in CHODs
- No signal in MUV3 (μ veto)
- Tag K^+ (≥ 5 KTAG sectors)
- < 40 GeV in LKr ($\pi^0 / \gamma / e$ veto)
- LAV veto (downstream of vertex)

Common conditions

+ add more conditions

Selection:

- **Normalisation** $K^+ \rightarrow \pi^+ \pi^0$: 1 downstream track (only); identified as π^+ ; K^+ – π^+ matching (space & time); upstream vetos.
- **Signal** $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates: same as normalisation selection + full photon and detector multiplicity cuts (reject all extra activity).

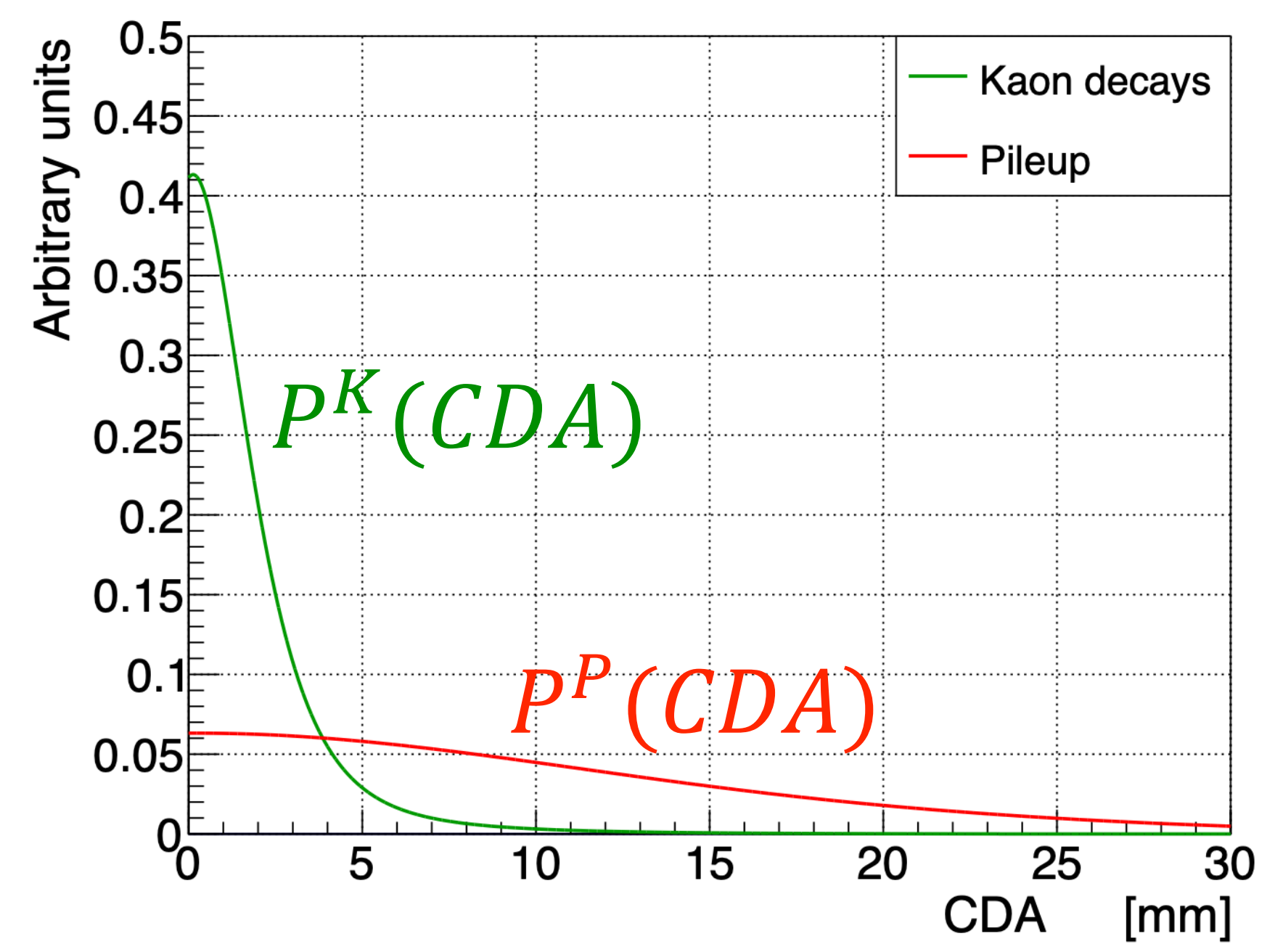
Bayesian classifier for $K^+ - \pi^+$ matching

Example of selection update

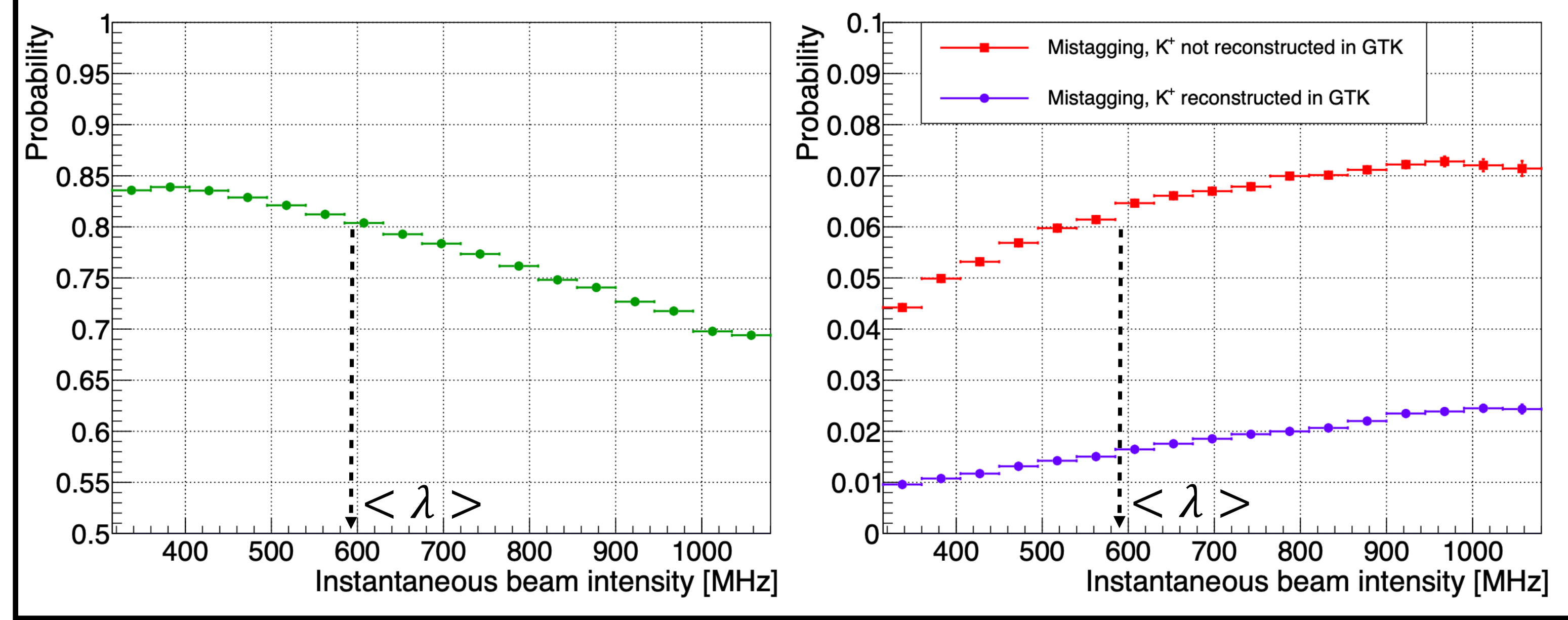


- **Inputs:** matching in space (CDA) & time (ΔT)
- Prior: pileup (N_{GTK})
- Models for PDFs/Prior from $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ data

- **Output:** posterior probability of GTK track = true K^+
 - Use likelihoods of kaons (K) and pileup (P)
 - Likelihood ratio used to select true match when $N_{GTK} > 1$



$\varepsilon = 80\%$ $P^P_{mistag} = 6\%$ $P^K_{mistag} = 2\%$

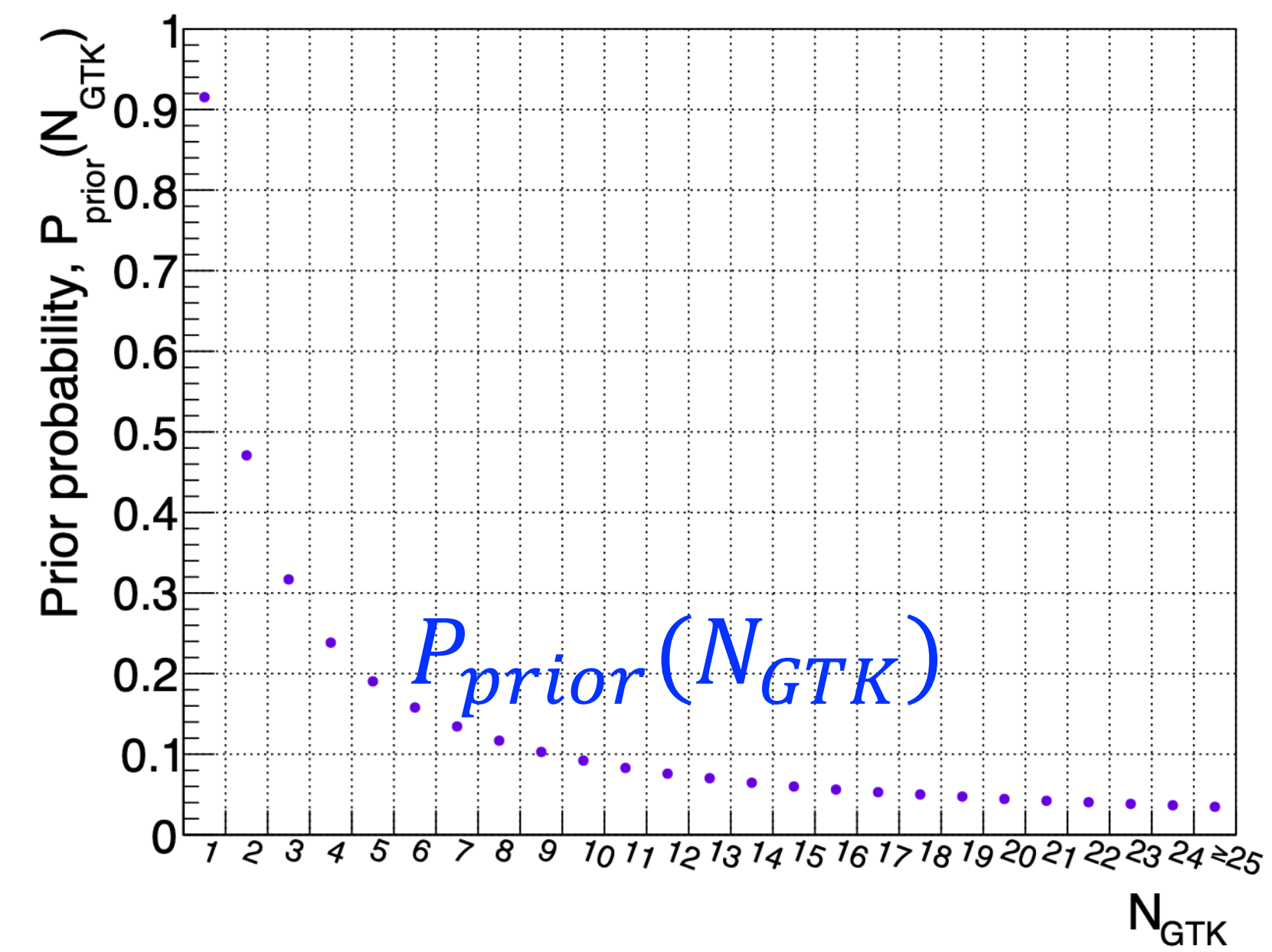
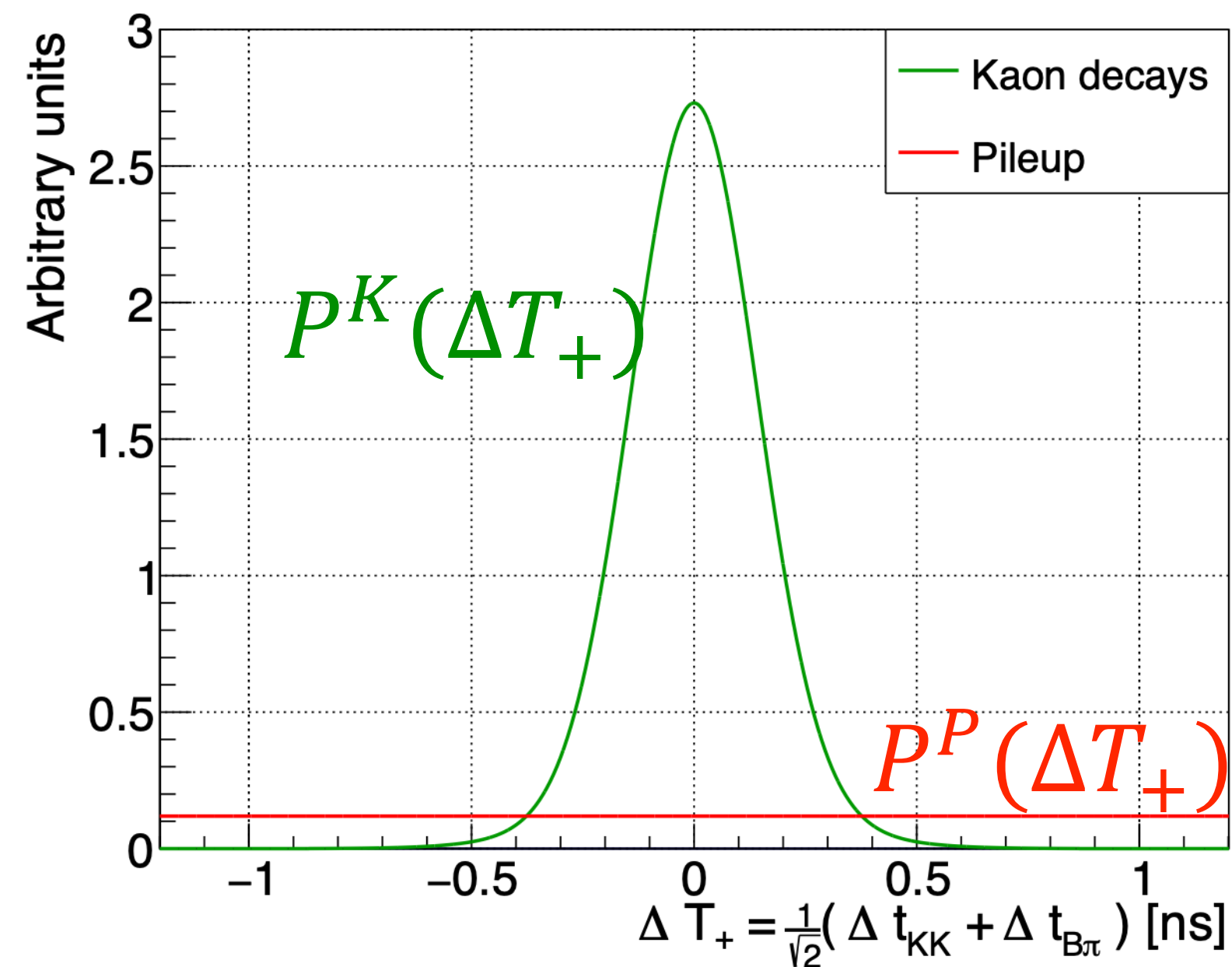
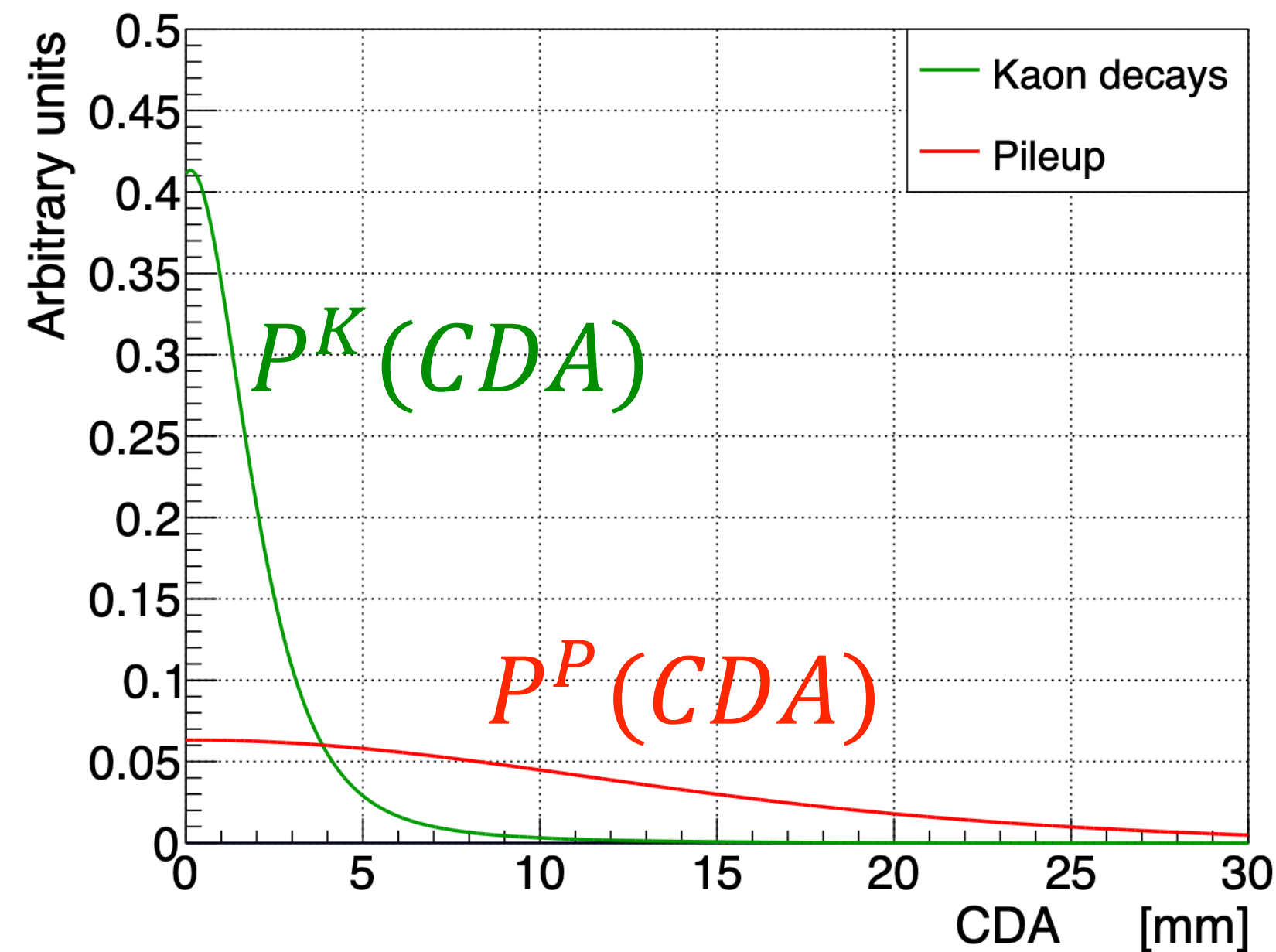


- Efficiency improved (+10%) and mistagging probability maintained.

Bayesian classifier for $K^+ - \pi^+$ matching



- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
 - Models for PDFs/Prior from $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ data.



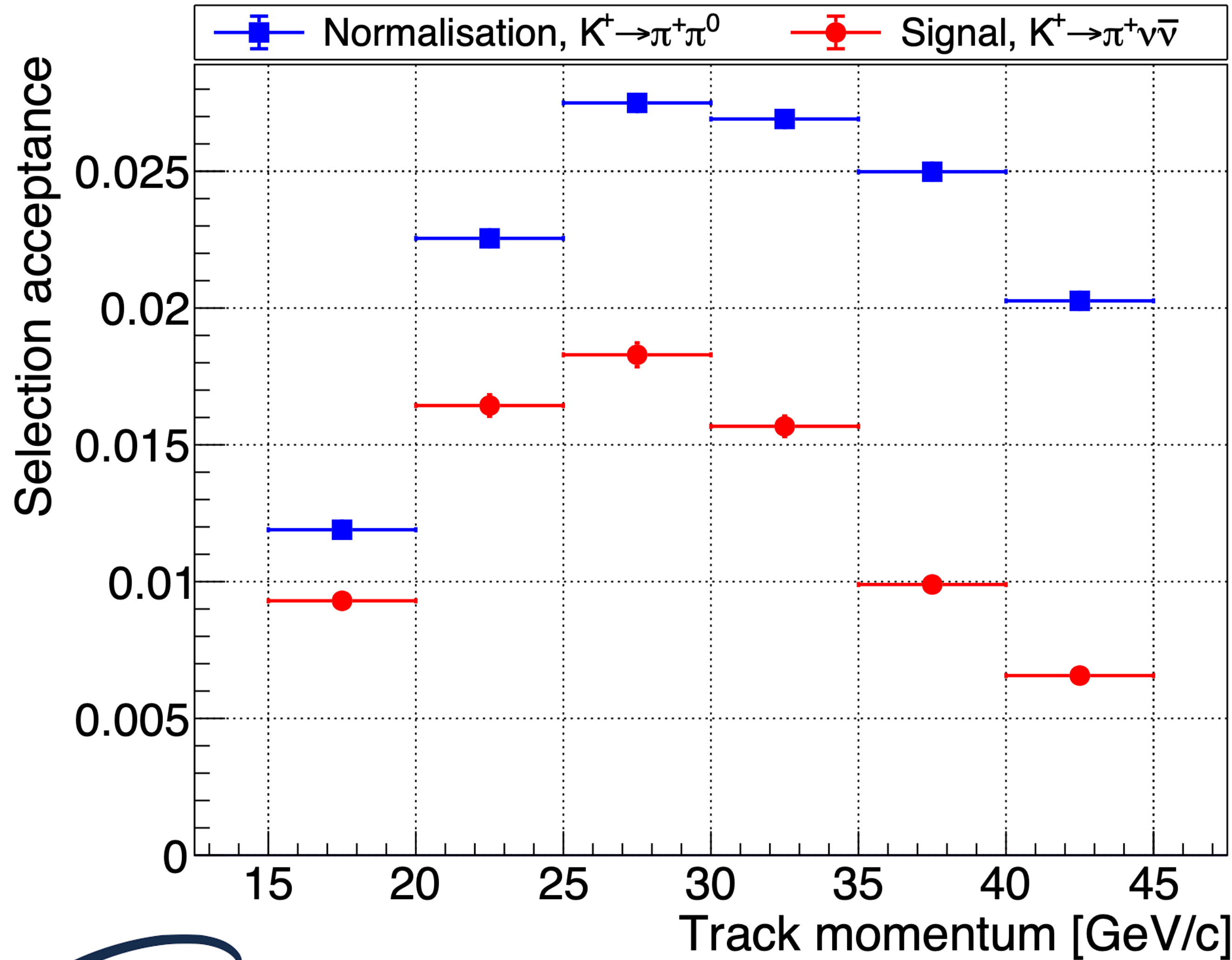
Example of
selection update

- **Output:** posterior probability of GTK track = true K^+
 - Use likelihoods of kaons (K) and pileup (P)
 - Likelihood ratio used to select true match when $N_{GTK} > 1$
 - Efficiency improved (+10%) and mistagging probability maintained.

Acceptances

Analysis is performed in (5 GeV/c) bins of momentum:

$$N_{\pi\nu\bar{\nu}}^{exp}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}(p_i)} = D_0 N_{\pi\pi}(p_i) \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} \varepsilon_{trig}(p_i) \varepsilon_{RV}$$



Case	OLD 2018 (S2)	NEW 2021-22	
Norm.	11.8%	13.4%	+15%
Signal	(6.37±0.64)%	(7.62±0.22)%	+20%

- Increased selection efficiencies.
 - New K-pi matching technique.
 - Re-tuned vertex conditions.
 - Relaxation of some vetos.
- Improved precision (plus improved systematic uncertainty evaluation).

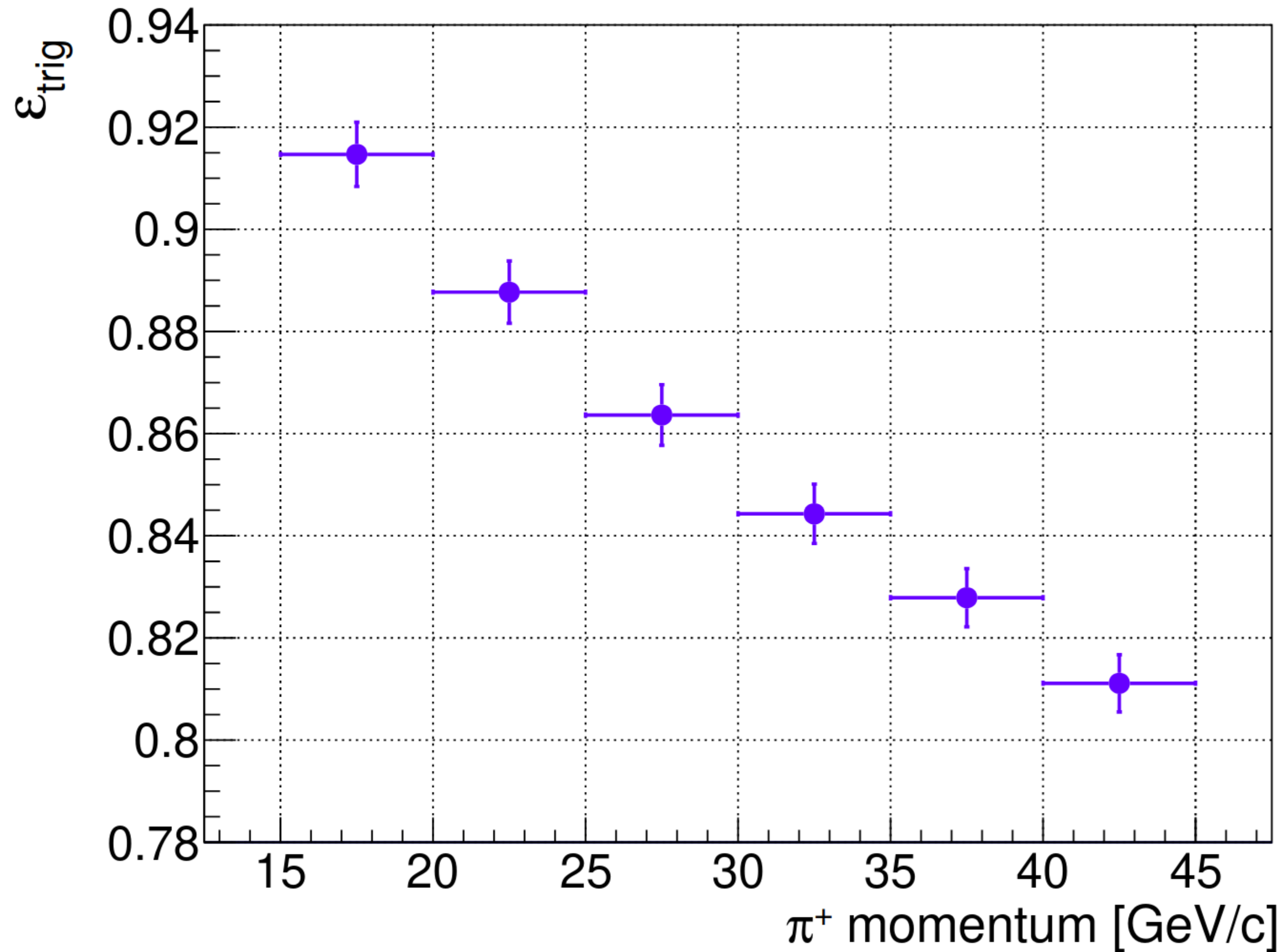
Acceptances evaluated at 0 intensity.
Intensity dependence captured in ε_{RV}

Trigger efficiencies



Analysis is performed in (5 GeV/c) bins of momentum:

$$N_{\pi\nu\bar{\nu}}^{exp}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}(p_i)} = D_0 N_{\pi\pi}(p_i) \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} \boxed{\varepsilon_{trig}(p_i)} \varepsilon_{RV}$$



$$\varepsilon_{trig} = \frac{\varepsilon_{sig}}{\varepsilon_{norm}} \quad \varepsilon_{trig}(new) = (85.9 \pm 1.4)\%$$

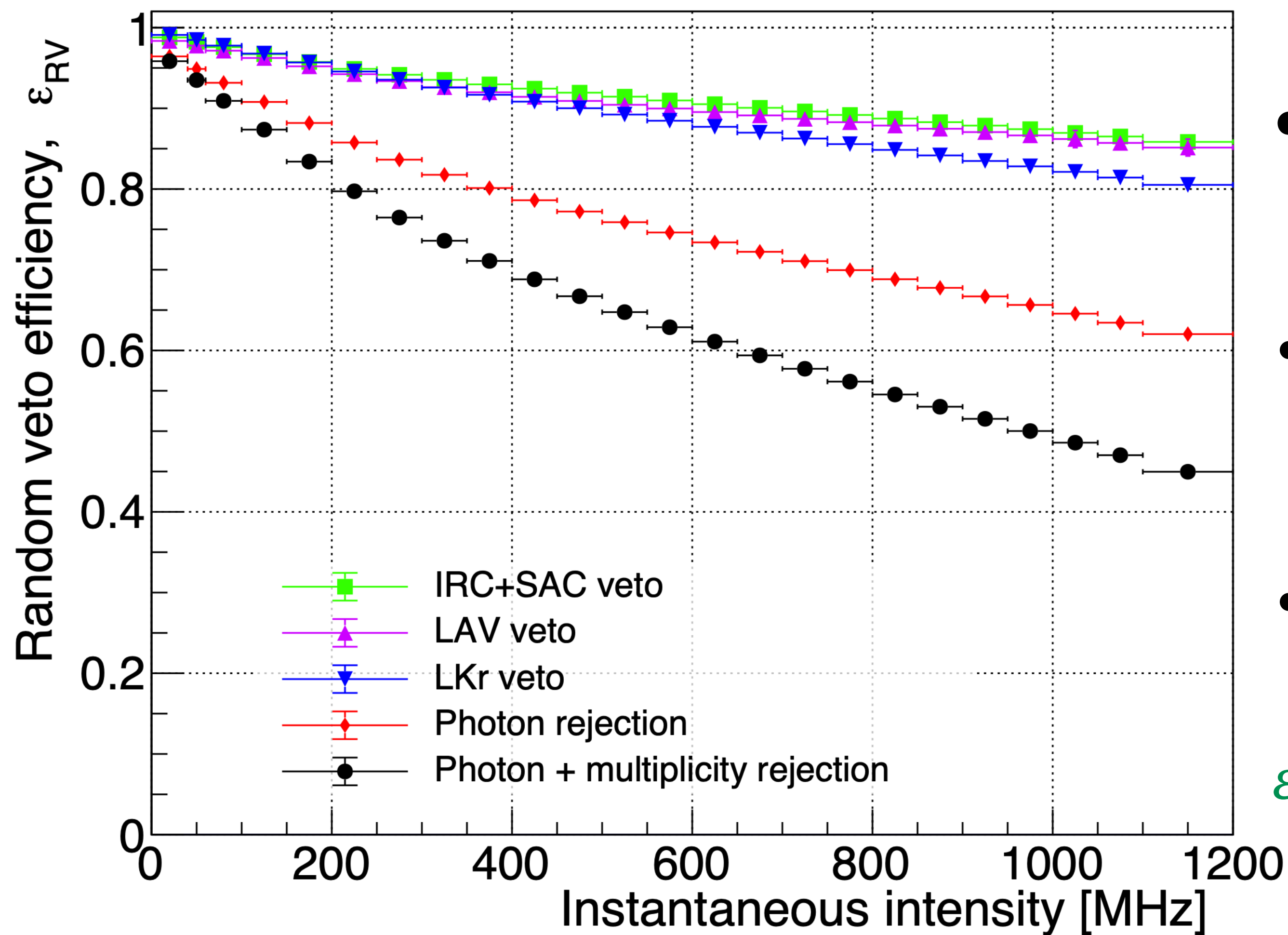
$$\varepsilon_{trig}(2018) = (89 \pm 5)\%$$

- Trigger efficiency ratio:
 - **New:** several components in both normalisation & signal triggers: **partial cancellation.**
 - **Old:** in 2016–18 data normalise with fully independent min bias trigger (**no cancellation**).
- Improved precision by factor 3 with reduced systematic uncertainty.

Random veto

ϵ_{RV} is independent of track momentum
(related to additional activity only)

$$N_{\pi\nu\bar{\nu}}^{exp}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}(p_i)} = D_0 N_{\pi\pi}(p_i) \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} \epsilon_{trig}(p_i) \epsilon_{RV}$$



- ϵ_{RV} = Random Veto Efficiency:
 - $1 - \epsilon_{RV}$ = Probability of rejecting a signal event due to additional activity.
- Balance:
 - Strict vetos \Rightarrow lower efficiency
 - Loose vetos \Rightarrow higher background
- Operational intensity higher but re-tuning vetos means ϵ_{RV} is comparable:

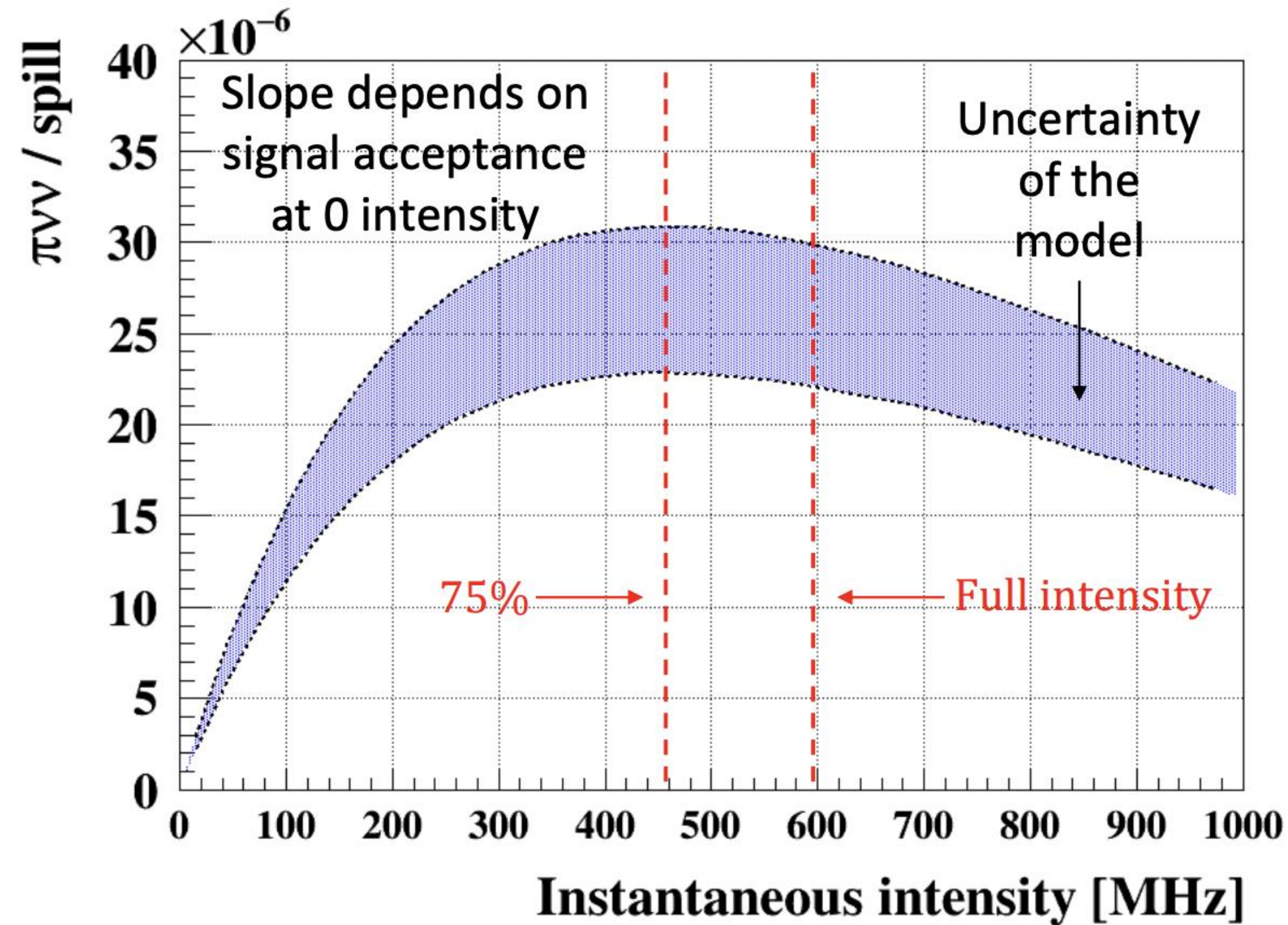
$$\epsilon_{RV}(new, \overline{\lambda_{21-22}} \approx 600 MHz) = (63.2 \pm 0.6)\%$$

$$\epsilon_{RV}(old, \overline{\lambda_{2018}} \approx 450 MHz) = (66 \pm 1)\%$$

Optimum NA62 intensity



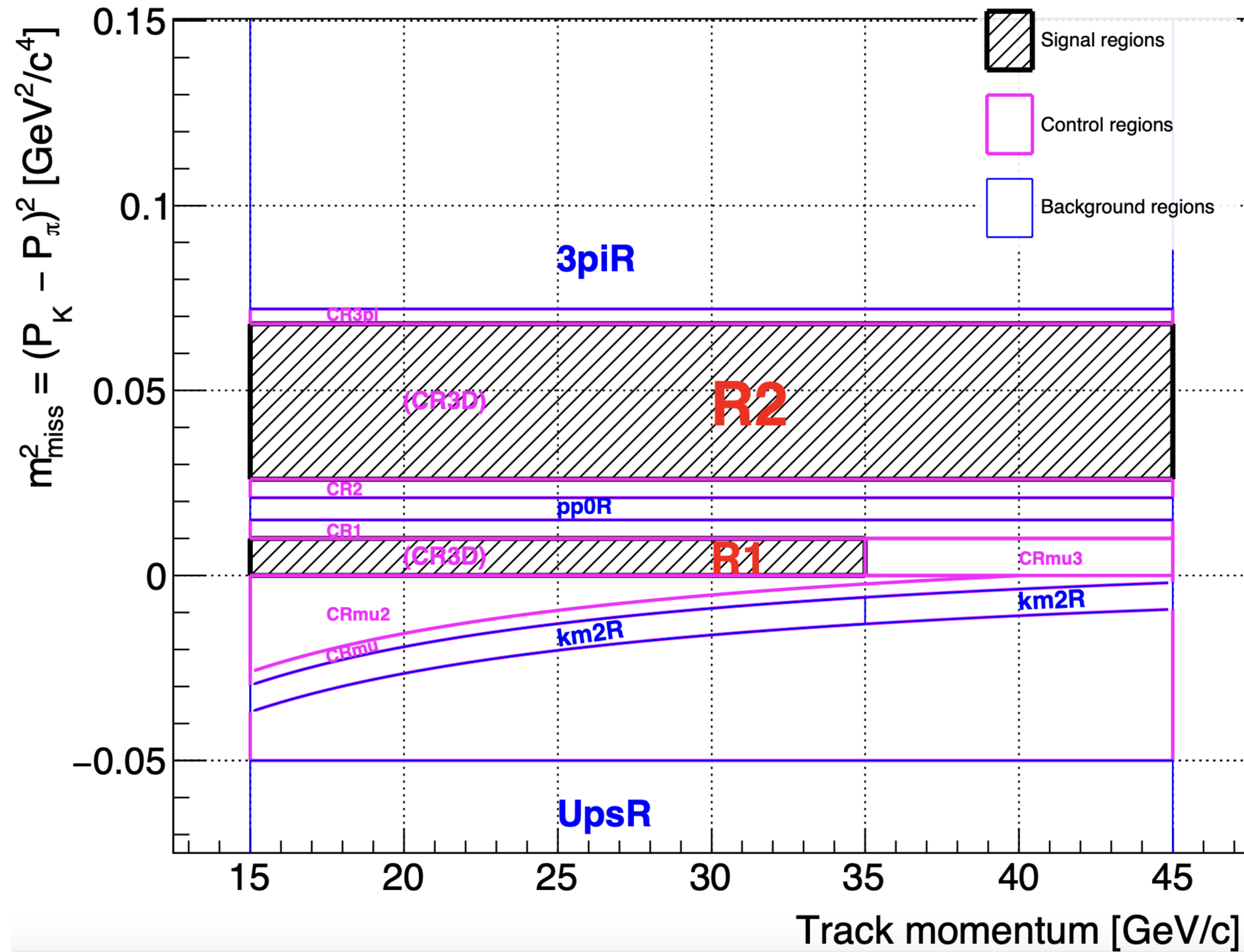
Selected signal yield vs intensity



- Saturation of expected signal yield with intensity. Mainly due to:
 - Paralyzable effects from TDAQ dead time and trigger veto windows.
 - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
 - Online time-dependent mis-calibrations.
 - Fit uncertainty.
- **From August 2023 operate at optimal intensity (~75% of full) to maximise $\pi V V$ sensitivity**
 - Maximise signal yield
 - lower expected background
 - Higher DAQ efficiency

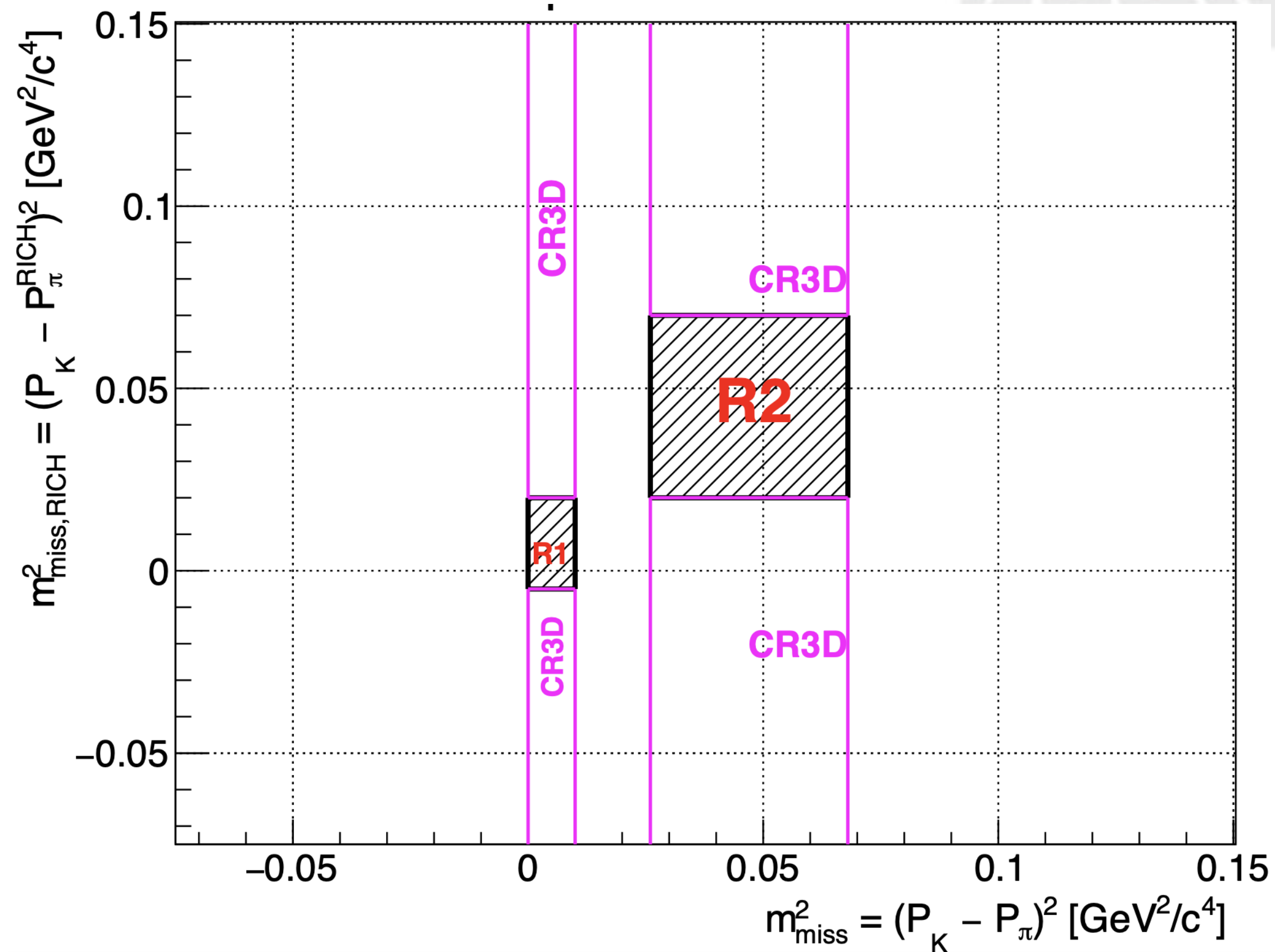
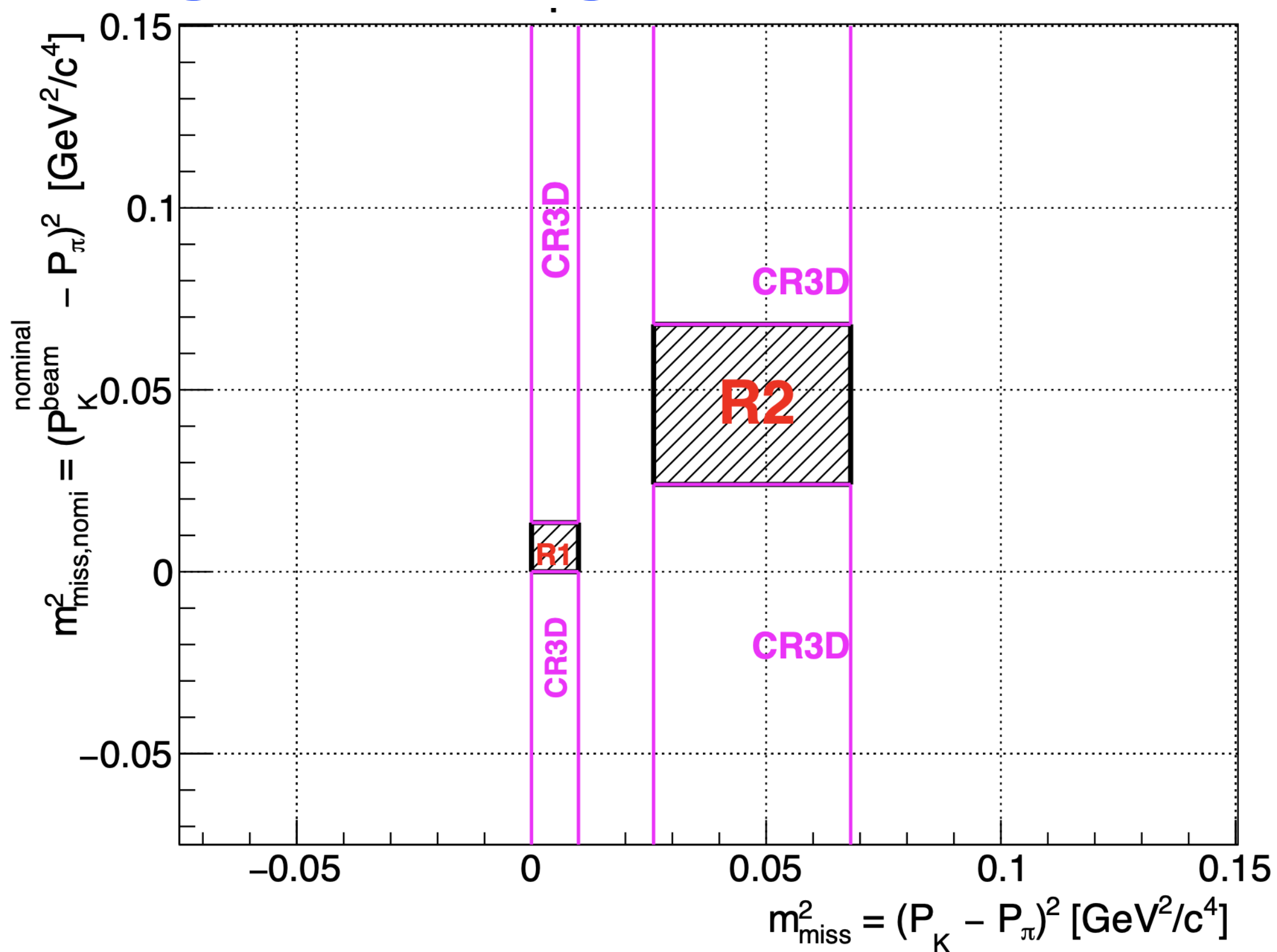
Studies of **2021—22 data** at high intensity **were crucial** to establish optimal intensity

Kinematic regions



- **Signal regions:**
- **Control regions:**
 - Used to validate background predictions.
- **Background regions:**
 - Used as “reference samples” for some background estimates.

3D signal regions definition



CR3D: control region for events in SR in 2 out of 3 dimensions.

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

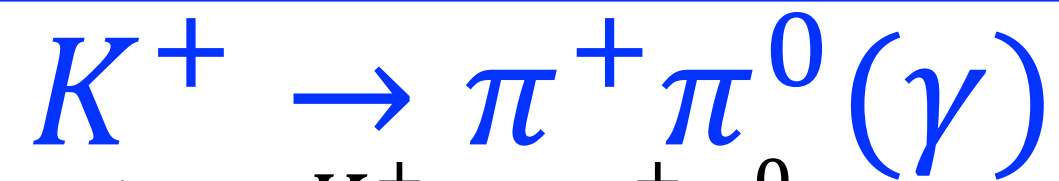
Default: GTK

Alternative: Nominal beam = $m^2_{miss,nom}$

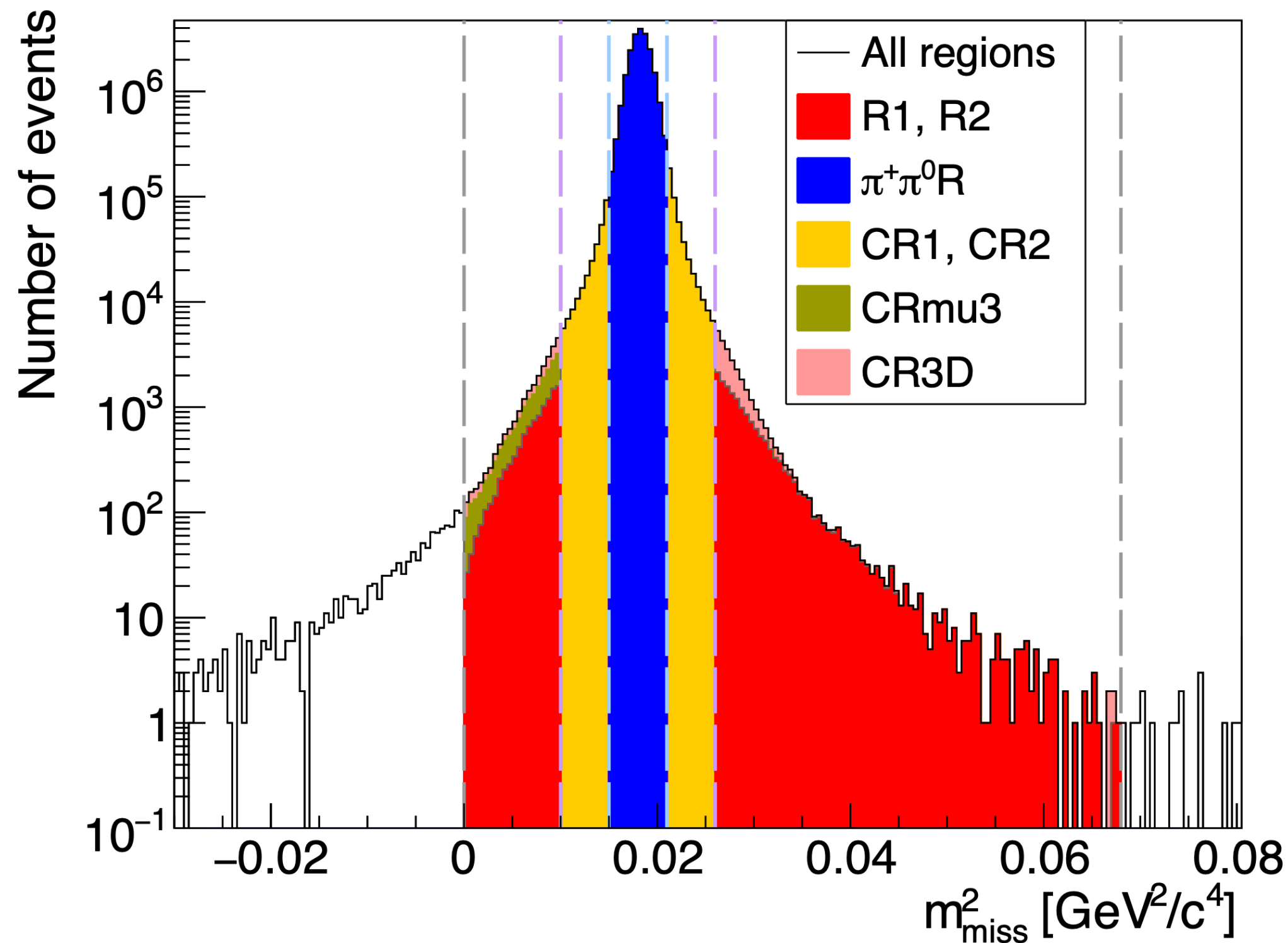
Default: STRAW

Alternative: $|p|$ from RICH (use as a velocity spectrometer) = $m^2_{miss,RICH}$

Backgrounds from kinematic tails



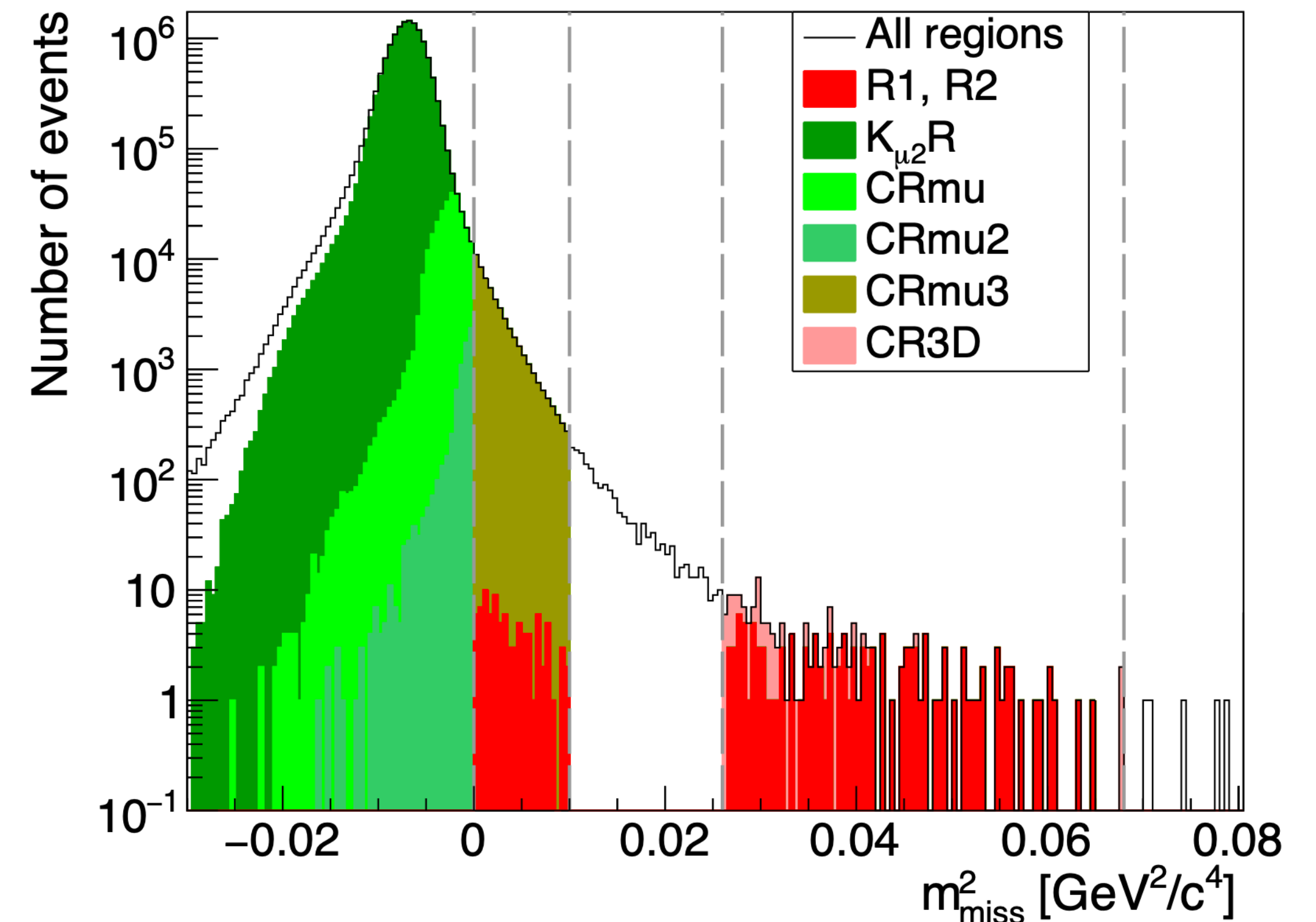
control sample of $K^+ \rightarrow \pi^+ \pi^0$ events with $\pi^0 \rightarrow \gamma\gamma$ and 2 photons detected in LKr:



$$N_{bg}(K^+ \rightarrow \pi^+ \pi^0 (\gamma)) = 0.83 \pm 0.05$$

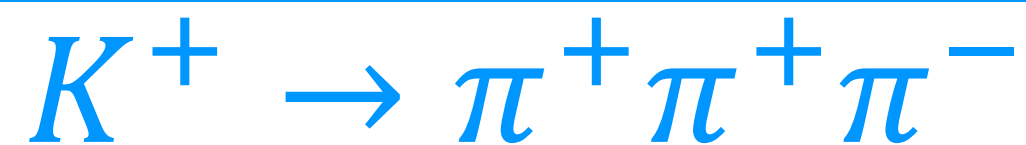


control sample of $K^+ \rightarrow \mu^+ \nu$ events with RICH PID= π^+ and Calo PID= μ^+ :



- <1% contribution from $K^+ \rightarrow \mu^+ \nu$ followed by $\mu^+ \rightarrow e^+ \nu \nu$

$$N_{bg}(K^+ \rightarrow \mu^+ \nu) = 0.9 \pm 0.2$$



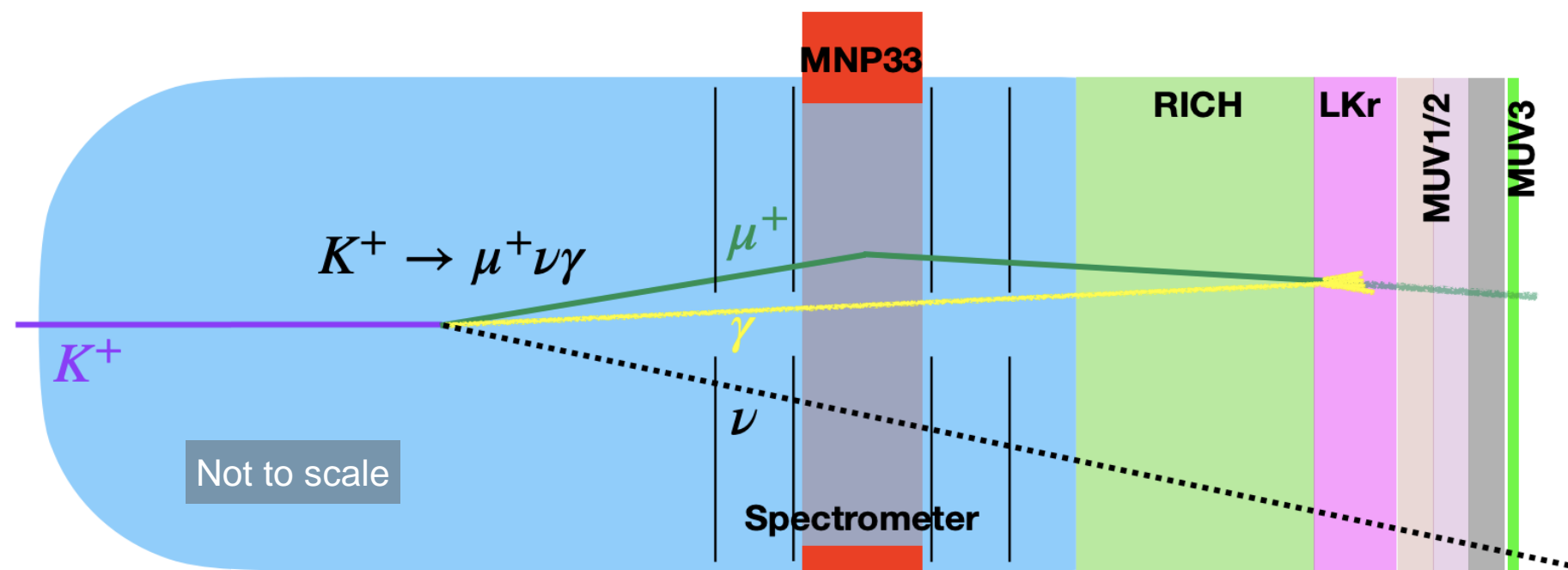
- Use MC to measure f_{tail} :

$$N_{bg}(K^+ \rightarrow \pi^+ \pi^+ \pi^-) = 0.11 \pm 0.03$$

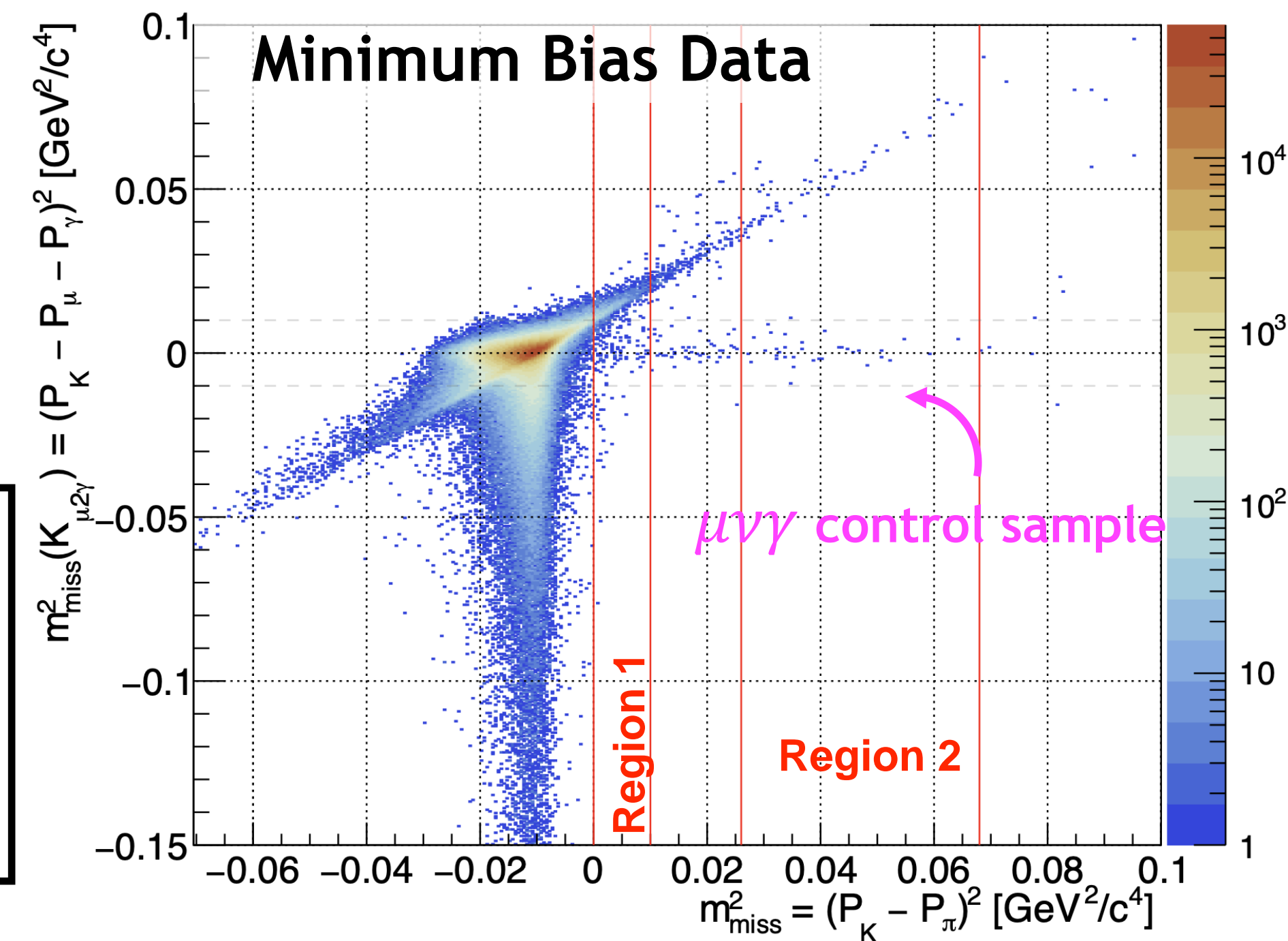
Radiative decays: $K^+ \rightarrow \pi^+ \pi^0 \gamma$ & $K^+ \rightarrow \mu^+ \nu \gamma$



- $K^+ \rightarrow \pi^+ \pi^0 \gamma$: included with “kinematic tails” estimation.
 - Suppression: photon vetos, rejection with additional γ is 30x stronger.
 - Estimation: MC + measured single photon rejection efficiency : $N_{bg}(K^+ \rightarrow \pi^+ \pi^0 \gamma) = 0.07 \pm 0.01$
 - Validation: m_{miss}^2 control regions (CR1,2 - see later)
- $K^+ \rightarrow \mu^+ \nu \gamma$: not included in “kinematic tails” estimation if γ overlaps μ^+ at LKr (leading to misID as π^+)
 - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with $\gamma =$ LKr cluster (mis)associated to muon.
 - Necessary for 2021–22 data, since Calorimetric PID degraded at higher intensities.
 - Estimation: min. Bias data control sample with signal in MUV3 : $N_{bg}(K^+ \rightarrow \mu^+ \nu \gamma) = 0.8 \pm 0.4$
 - Validation: data sample without $K^+ \rightarrow \mu^+ \nu \gamma$ veto and PID = “less pion-like” (Calo BDT bins below π^+ bin).



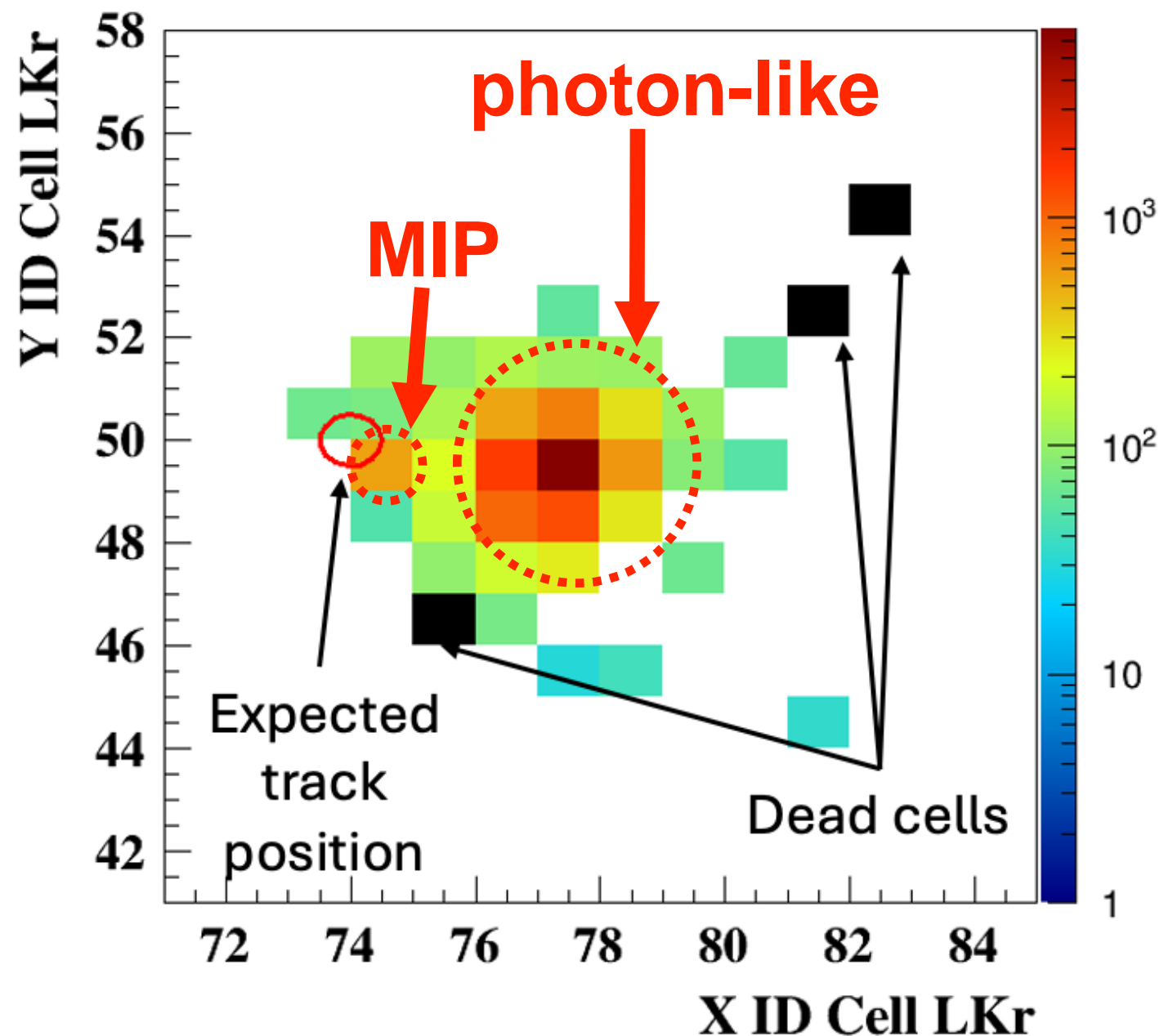
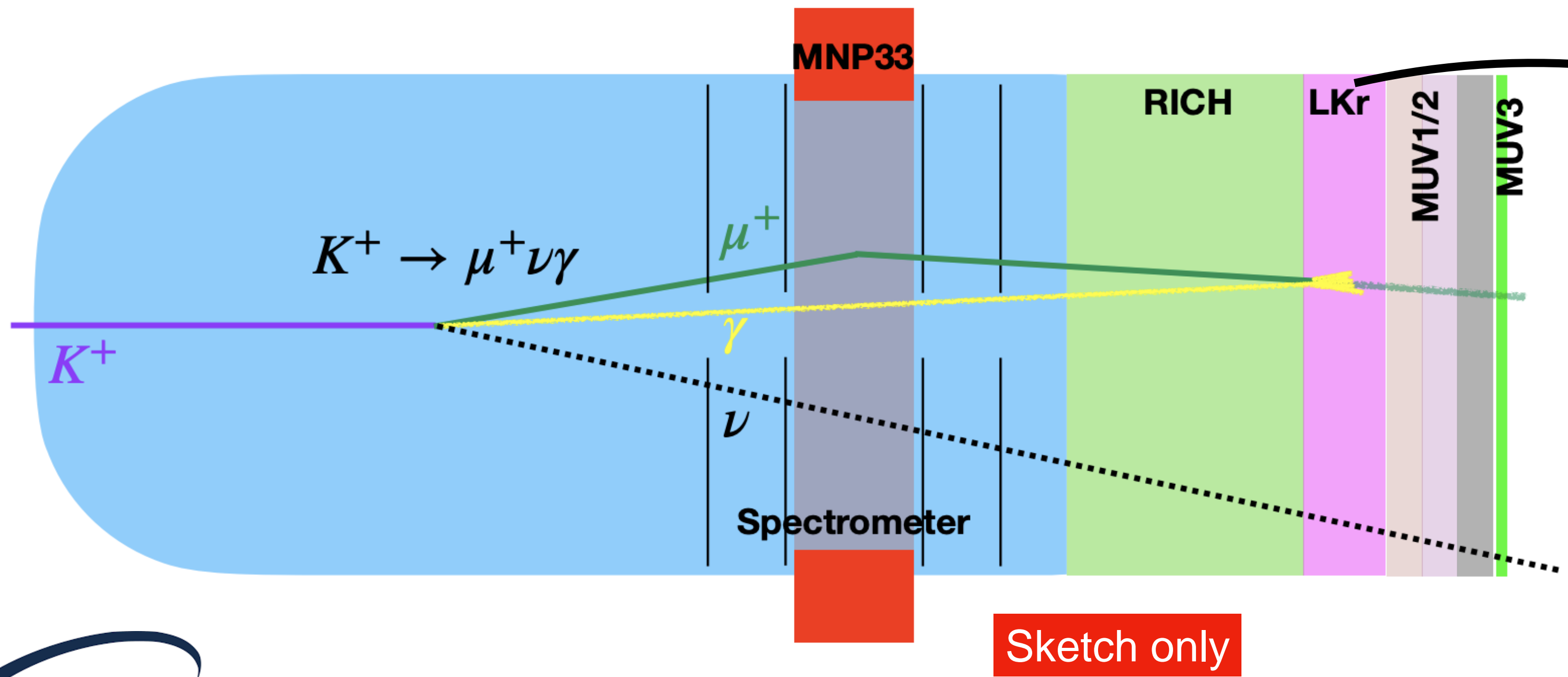
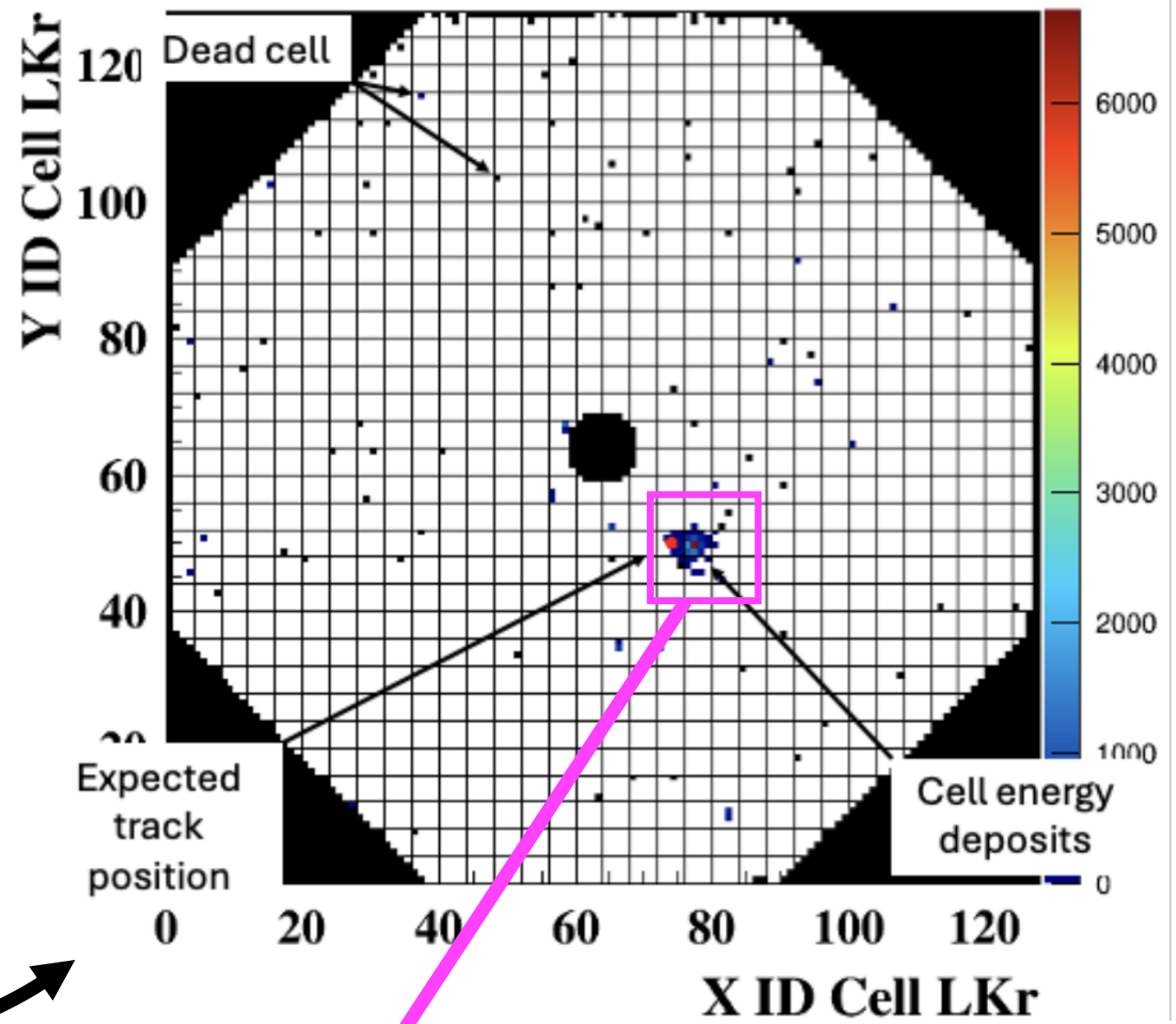
- Before $K^+ \rightarrow \mu^+ \nu \gamma$ veto: found excess of events at $p > 35 \text{ GeV}/c$ in Region 2 relative to 2016–18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \rightarrow \mu^+ \nu \gamma$ veto added to selection criteria for final analysis.



Background mechanism: $K^+ \rightarrow \mu^+ \nu \gamma$

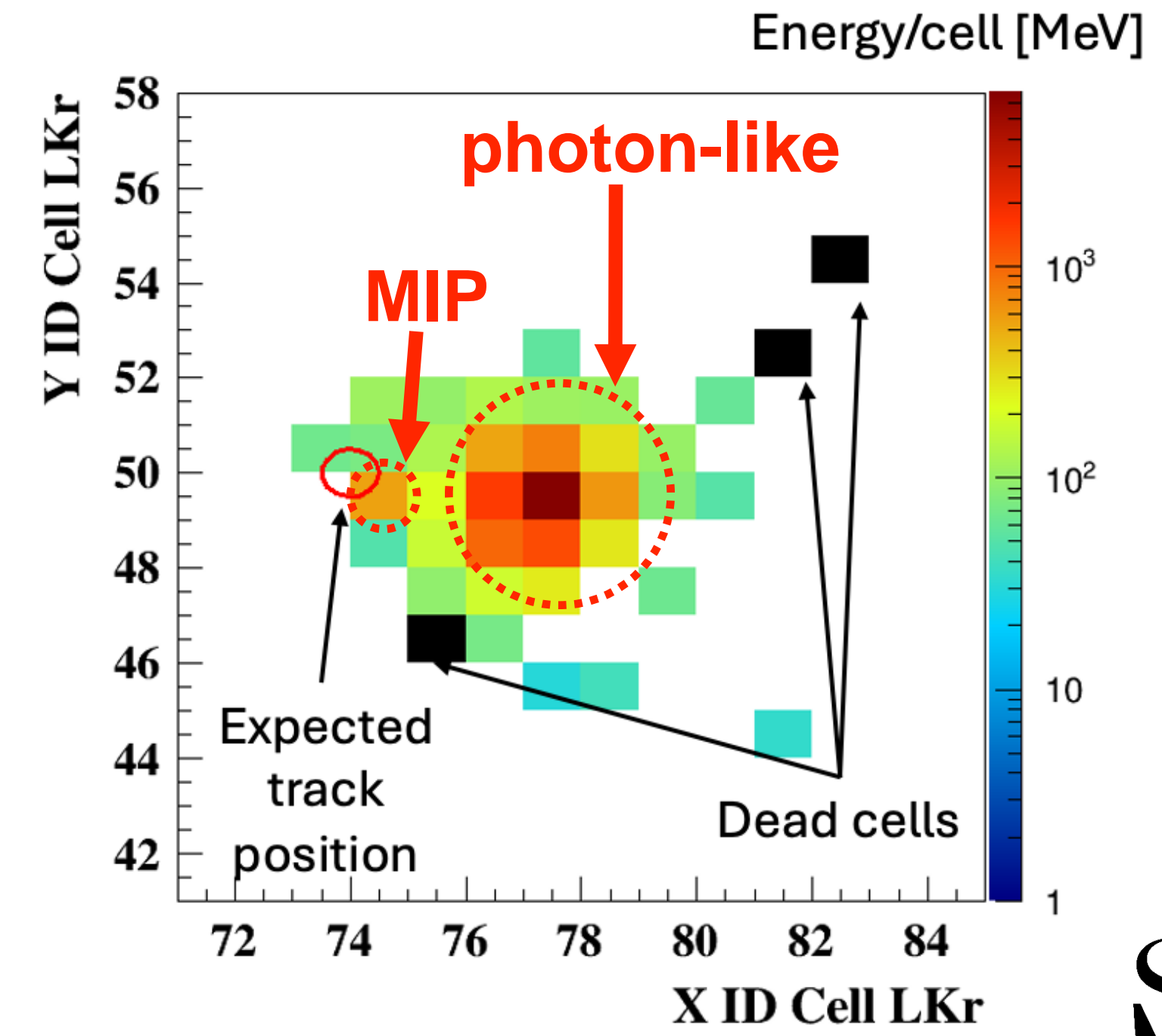
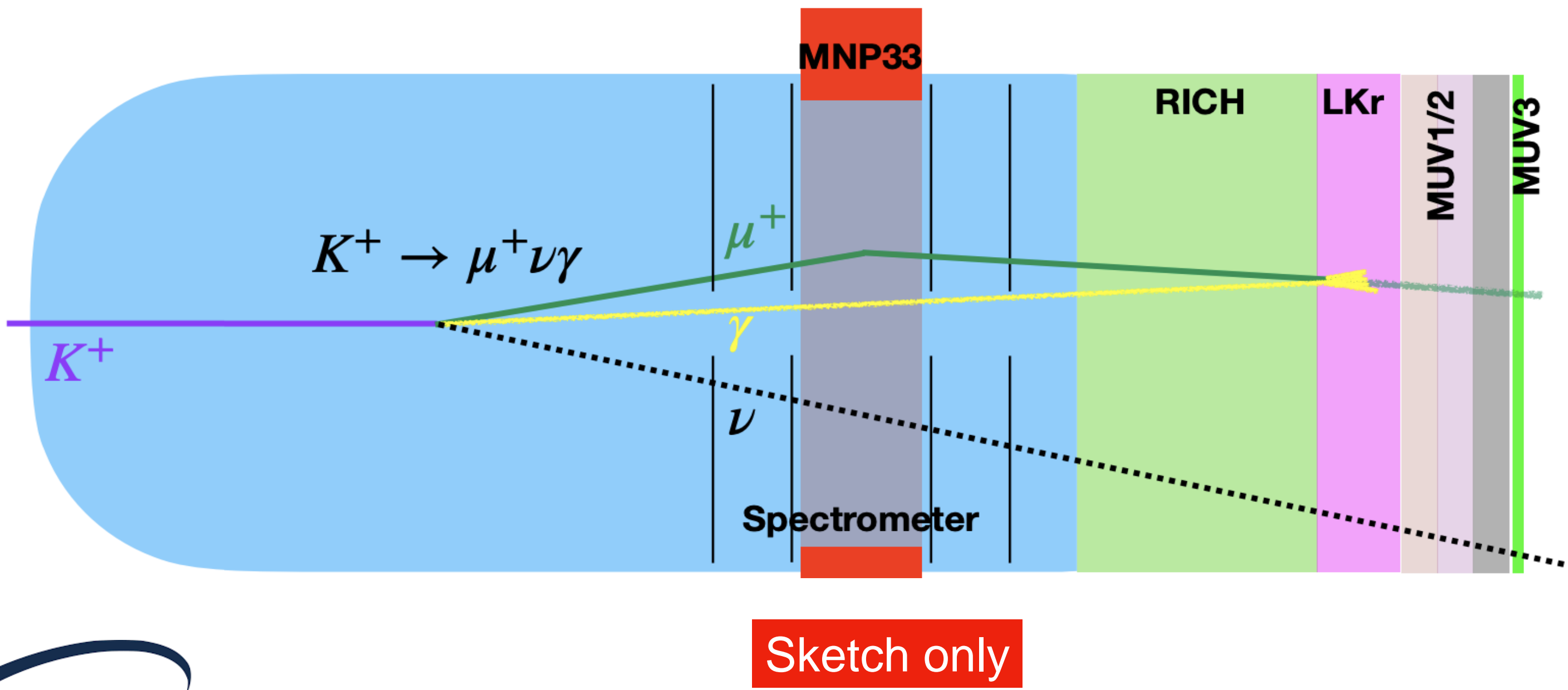
- $K^+ \rightarrow \mu^+ \nu \gamma$ decay with fairly energetic photon ($E_\gamma > 5 \text{ GeV}$) and high momentum μ^+ ($p \gtrsim 35 \text{ GeV}/c$).
- γ and μ^+ hit LKr together and are misidentified as a π^+ .
- No rejection power from photon vetos (LKr γ cluster associated to track).
- Additional γ naturally shifts $m_{miss}^2 = (P_K - P_\pi)^2$ towards higher values (i.e. towards signal regions).

Example event (2022 data):



Radiative decays: $K^+ \rightarrow \pi^+ \pi^0 \gamma$ & $K^+ \rightarrow \mu^+ \nu \gamma$

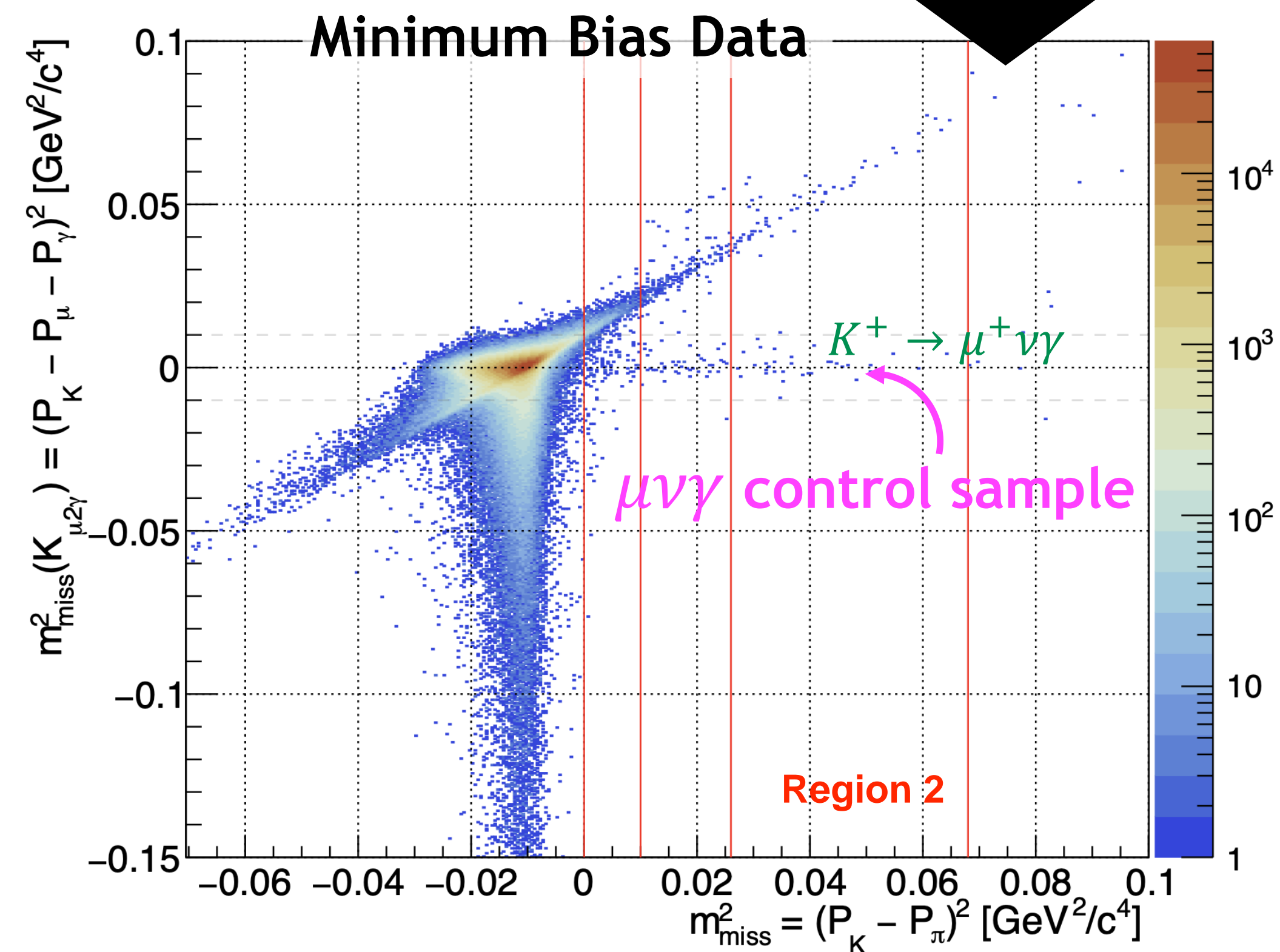
- $K^+ \rightarrow \pi^+ \pi^0 \gamma$: included with “kinematic tails” estimation.
 - Suppression: photon vetos, rejection with additional γ is 30x stronger.
 - Estimation: MC + measured single photon rejection efficiency : $N_{bg}(K^+ \rightarrow \pi^+ \pi^0 \gamma) = 0.07 \pm 0.01$
 - Validation: m_{miss}^2 control regions (CR1,2 - see later)
- $K^+ \rightarrow \mu^+ \nu \gamma$: not included in “kinematic tails” estimation if γ overlaps μ^+ at LKr (leading to misID as π^+)
 - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with $\gamma =$ LKr cluster (mis)associated to muon.
 - Necessary for 2021–22 data, since Calorimetric PID degraded at higher intensities.
 - Estimation: min. Bias data control sample with signal in MUV3 : $N_{bg}(K^+ \rightarrow \mu^+ \nu \gamma) = 0.8 \pm 0.4$
 - Validation: data sample without $K^+ \rightarrow \mu^+ \nu \gamma$ veto and PID = “less pion-like” (Calo BDT bins below π^+ bin).



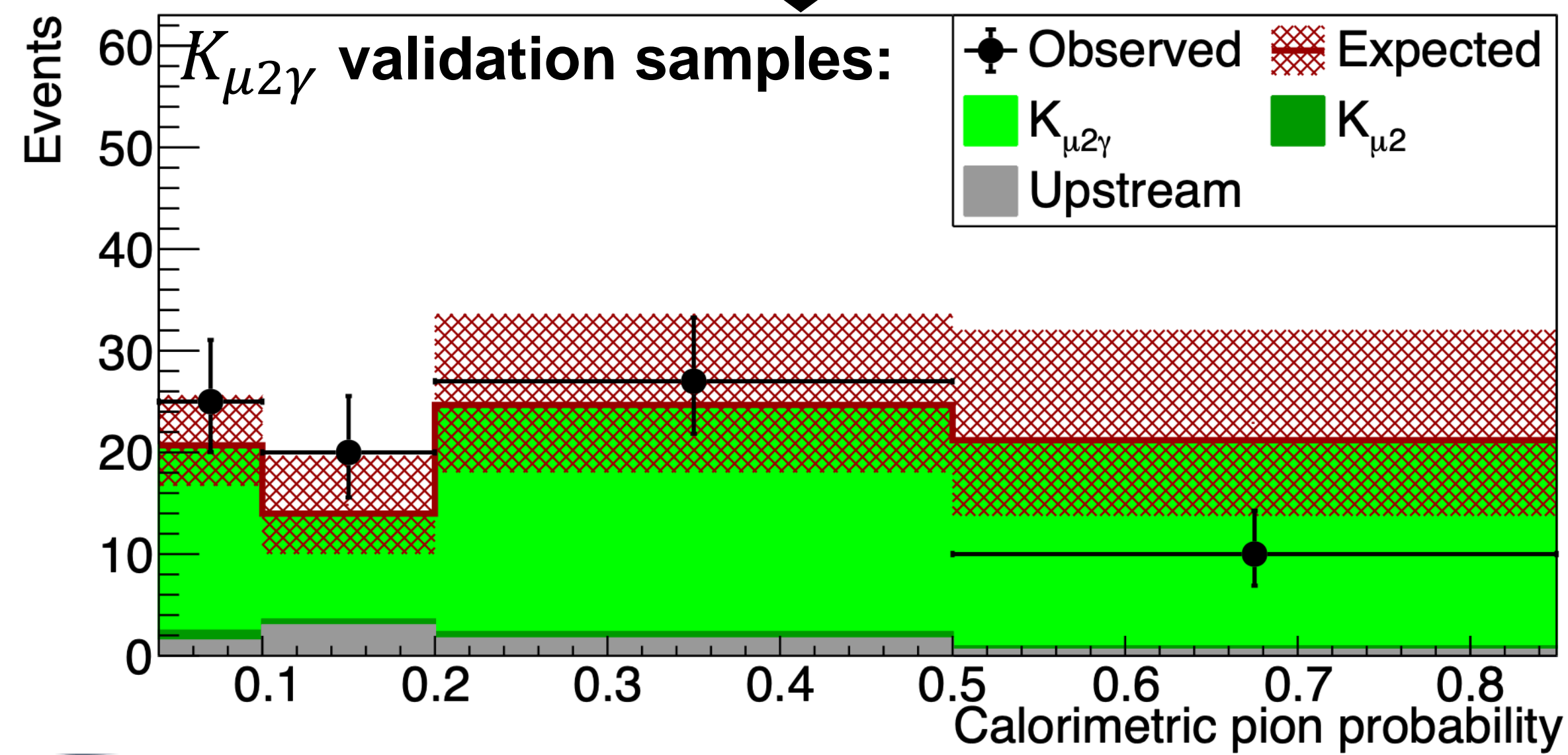
$K^+ \rightarrow \mu^+ \nu \gamma$ Background

- Kinematically select $K^+ \rightarrow \mu^+ \nu \gamma$ events: $m_{miss}^2(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
 - P_K : 4-momentum of K^+ from GTK (as normal)
 - P_μ : 4-momentum of track with μ^+ mass hypothesis.
 - P_γ : reconstructed from energy and position of LKr cluster (and position of $K^+ - \mu^+$ vertex).

Evaluate background expectation using $\mu \nu \gamma$ control sample from MinimumBias trigger, not applying Calorimetric BDT classifier and MUV3 signal:



Validation: data sample with PID = “less pion-like” (Calo BDT bins below π^+ bin).

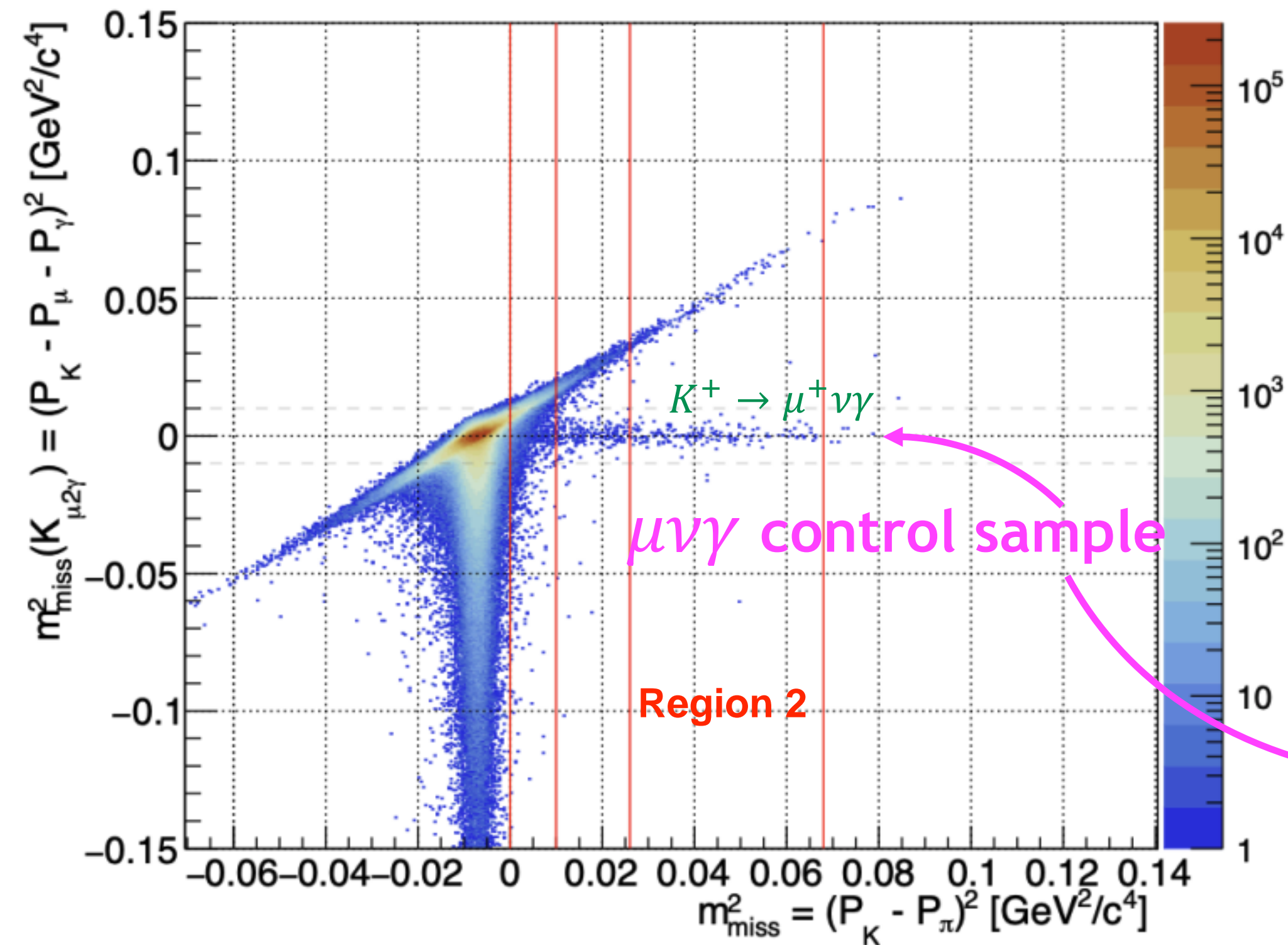


- Before $K^+ \rightarrow \mu^+ \nu \gamma$ veto: found excess of events at $p > 35 GeV/c$ in Region 2 relative to 2016–18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \rightarrow \mu^+ \nu \gamma$ veto added to selection criteria for final analysis.

Background evaluation: $K^+ \rightarrow \mu^+ \nu \gamma$

- Evaluate background expectation using $\mu\nu\gamma$ control sample from MinimumBias (MB) trigger.
 - Not applying Calorimetric BDT classifier and a signal in MUV3.

Minimum Bias Data



- Kinematically select $K^+ \rightarrow \mu^+ \nu \gamma$ events: $m_{miss}^2(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
 - P_K : 4-momentum of K^+ from GTK (as normal)
 - P_μ : 4-momentum of track with μ^+ mass hypothesis.
 - P_γ : reconstructed from energy (subtracting MIP energy deposit) and position of LKr cluster (and position of $K^+ - \mu^+$ vertex).

$$N_{bg}(K^+ \rightarrow \mu^+ \nu \gamma) = N_{\mu\nu\gamma}^{MB} D_{MB} \frac{\epsilon_{signal}}{\epsilon_{MB}} P_{misID}$$

Downscaling of MB trigger

Ratio of $\pi^+ \nu \bar{\nu}$ and MB trigger efficiencies

probability of $\gamma + \mu^+$ being misidentified as a π^+

Not included in kinematic tails calculation because the tails sample imposes Calorimetric PID= μ^+ , while here there is misID of $\mu^+ \gamma \Rightarrow \pi^+$.

Background rejection: $K^+ \rightarrow \mu^+ \nu \gamma$

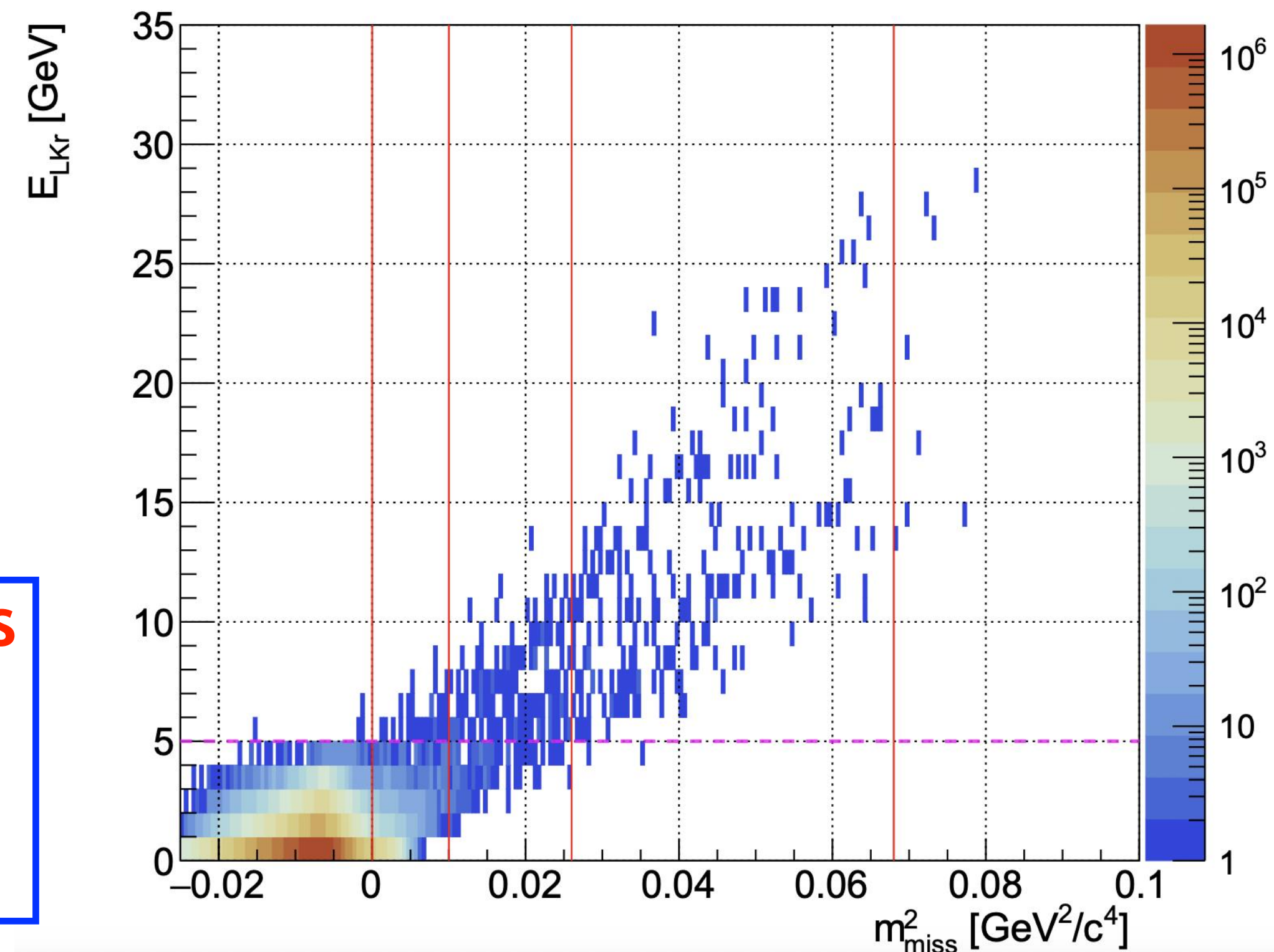
Minimum Bias Data

Events with MUV3 association and $|m_{miss}^2(K_{\mu 2\gamma})|^2 < 0.01 \text{ GeV}^2/c^4$

veto $K^+ \rightarrow \mu^+ \nu \gamma$ events with:

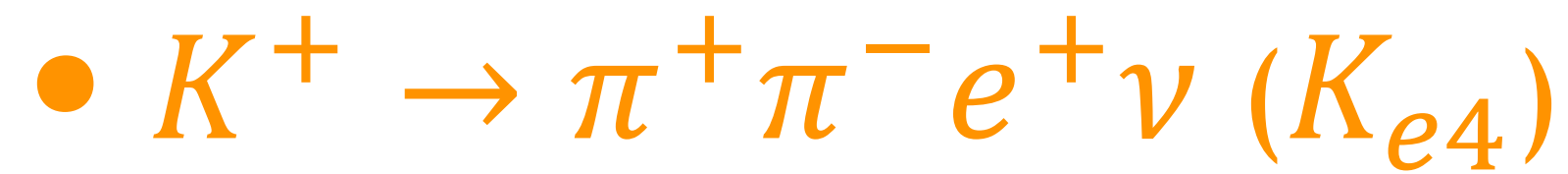
- $|m_{miss}^2(K_{\mu 2\gamma})|^2 < 0.01 \text{ GeV}^2/c^4$ \rightarrow c.f. resolution $\sim 0.0025 \text{ GeV}^2/c^4$
- $E_\gamma > 5 \text{ GeV}$
- μ^+ -like RICH PID.

- Veto conditions established using data control samples and MC.
- $K^+ \rightarrow \mu^+ \nu \gamma$ Veto \Rightarrow 20x background suppression with 0.4% signal loss.



- Why different to 2016–18 analysis?
 - Calorimetric PID degraded:
 - Higher intensity in 2021–22 data (in particular, affects MUV1,2).
 - Training of BDT classifier.

Other backgrounds



- No clean control samples for K_{e4} in data: Use 2×10^9 simulated decays.

Acceptance : $A_{K_{e4}} = \frac{N_{MC}^{sel}}{N_{MC}^{gen}} = (1.3 \pm 0.3_{stat}) \times 10^{-8}$

Effective # of K^+

Random veto & trigger efficiencies

$$N_{bg}(K^+ \rightarrow \pi^+ \pi^- e^+ \nu) = N_K \varepsilon_{RV} \varepsilon_{trig} \mathcal{B}_{K_{e4}} A_{K_{e4}}$$

$$N_{bg}(K^+ \rightarrow \pi^+ \pi^- e^+ \nu) = 0.89^{+0.34}_{-0.28}$$

Branching ratio of K_{e4}
(from PDG)

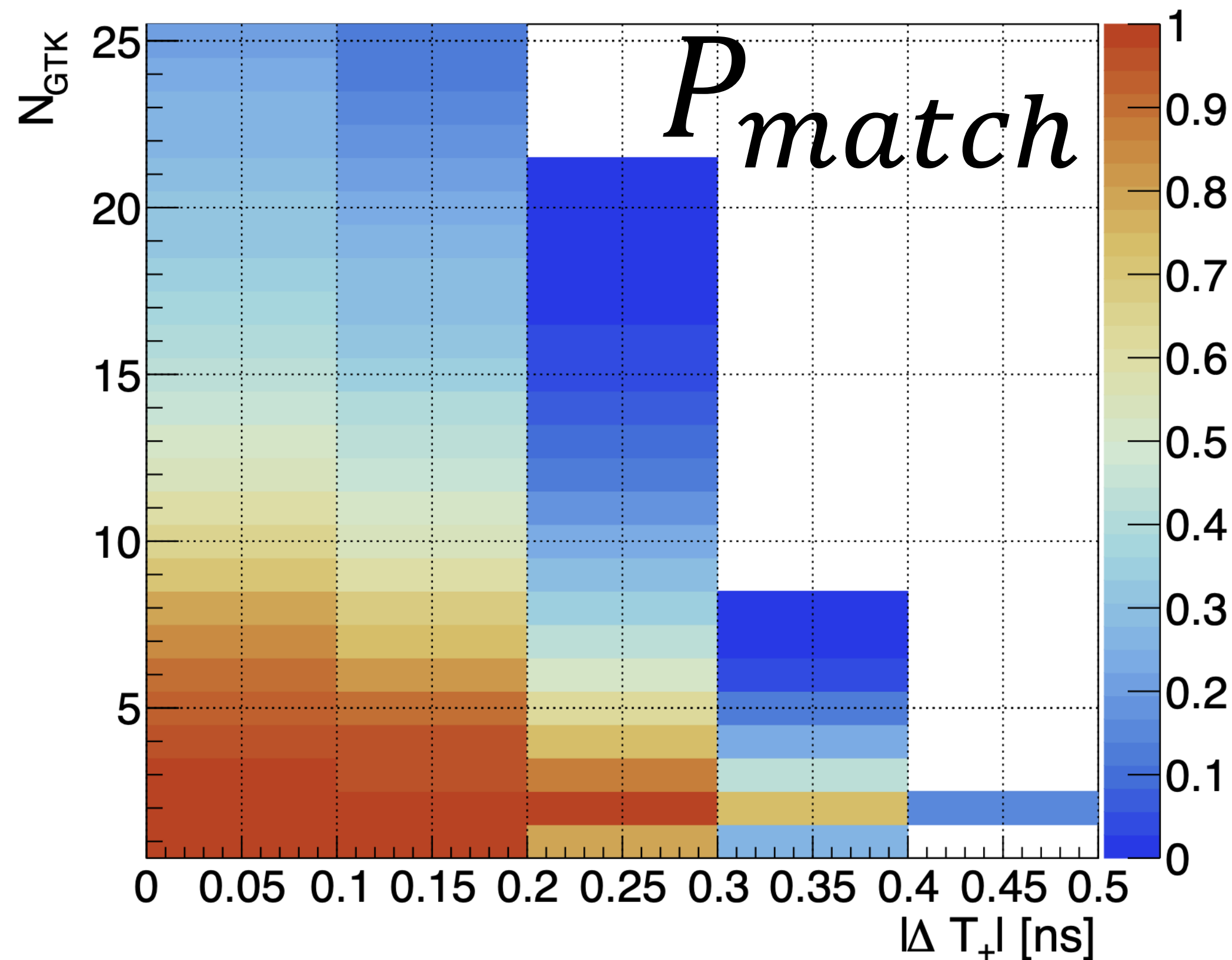


- Evaluated with simulations.
- **Negligible contributions to total background.**

$$N_{bg}(K^+ \rightarrow \pi^0 \ell^+ \nu) < 1 \times 10^{-3}$$

$$N_{bg}(K^+ \rightarrow \pi^+ \gamma \gamma) = 0.01 \pm 0.01$$

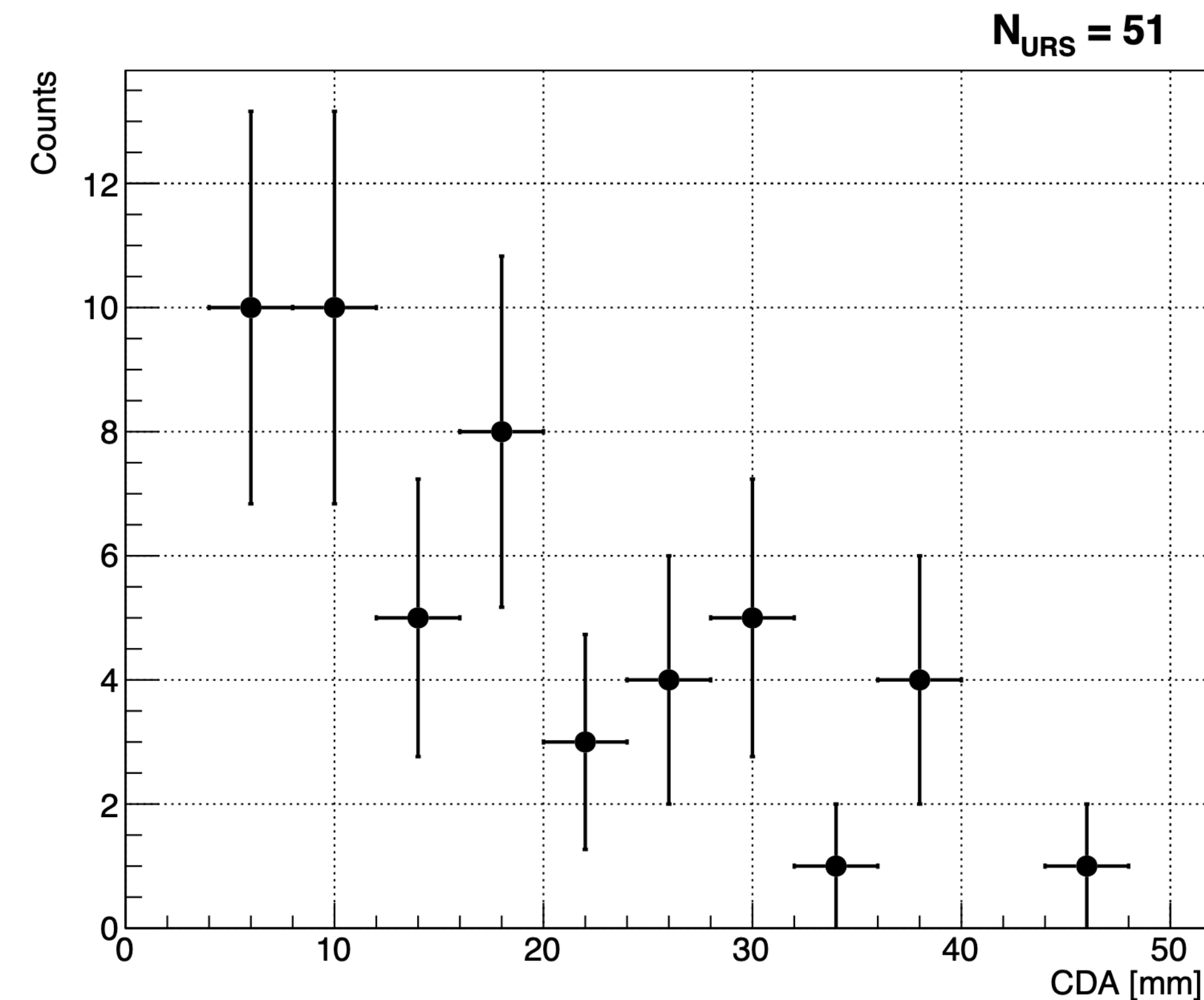
Upstream background evaluation



- Upstream reference sample contains all known upstream mechanisms.
 - N provides normalisation.
- f_{CDA} depends only on geometry.
- P_{match} depends on $(\Delta T_+, N_{GTK})$.

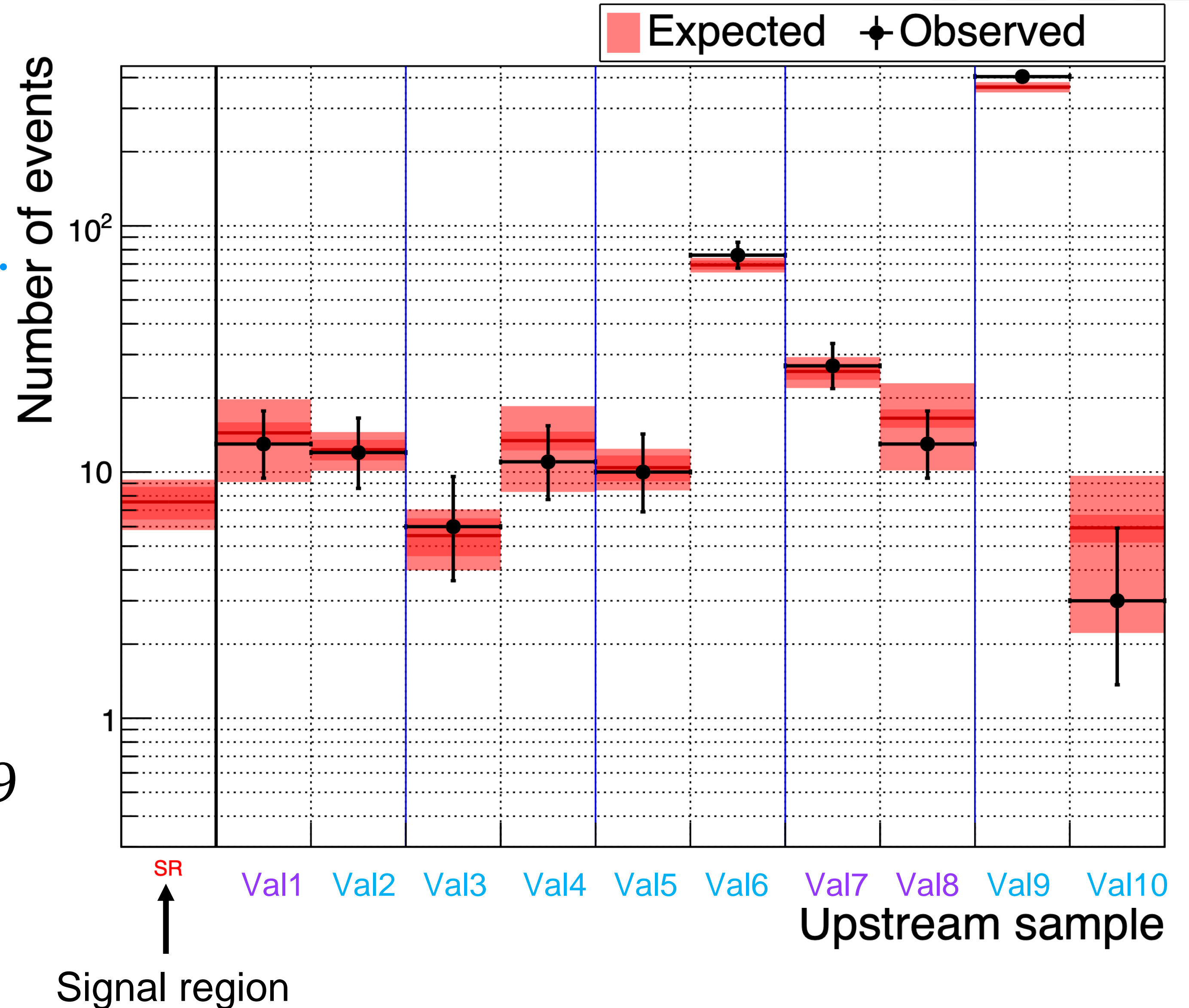
$$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad \langle P_{match} \rangle = 73\%$$

$$N_{bg}(Upstream) = 7.4^{+2.1}_{-1.8}$$



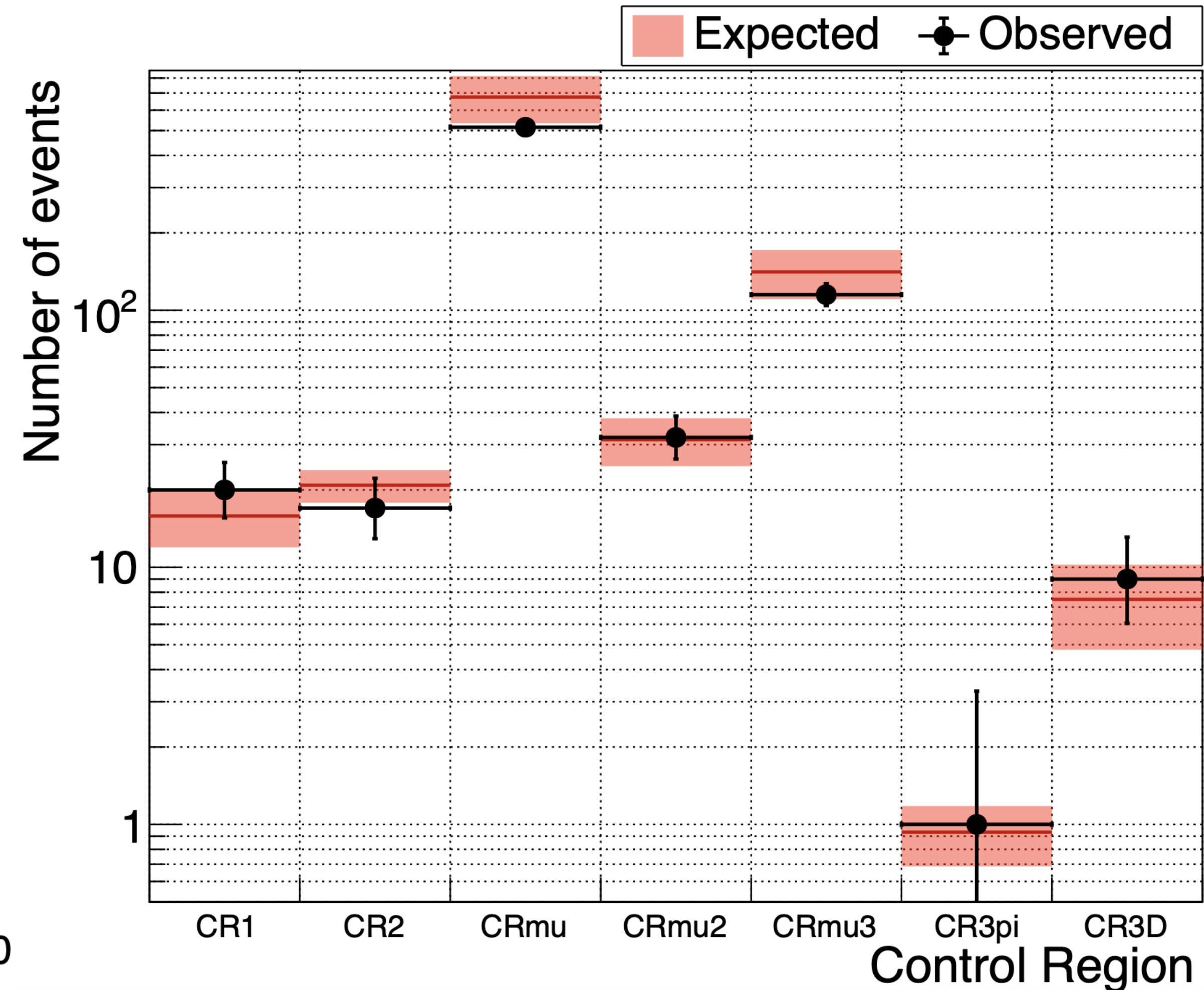
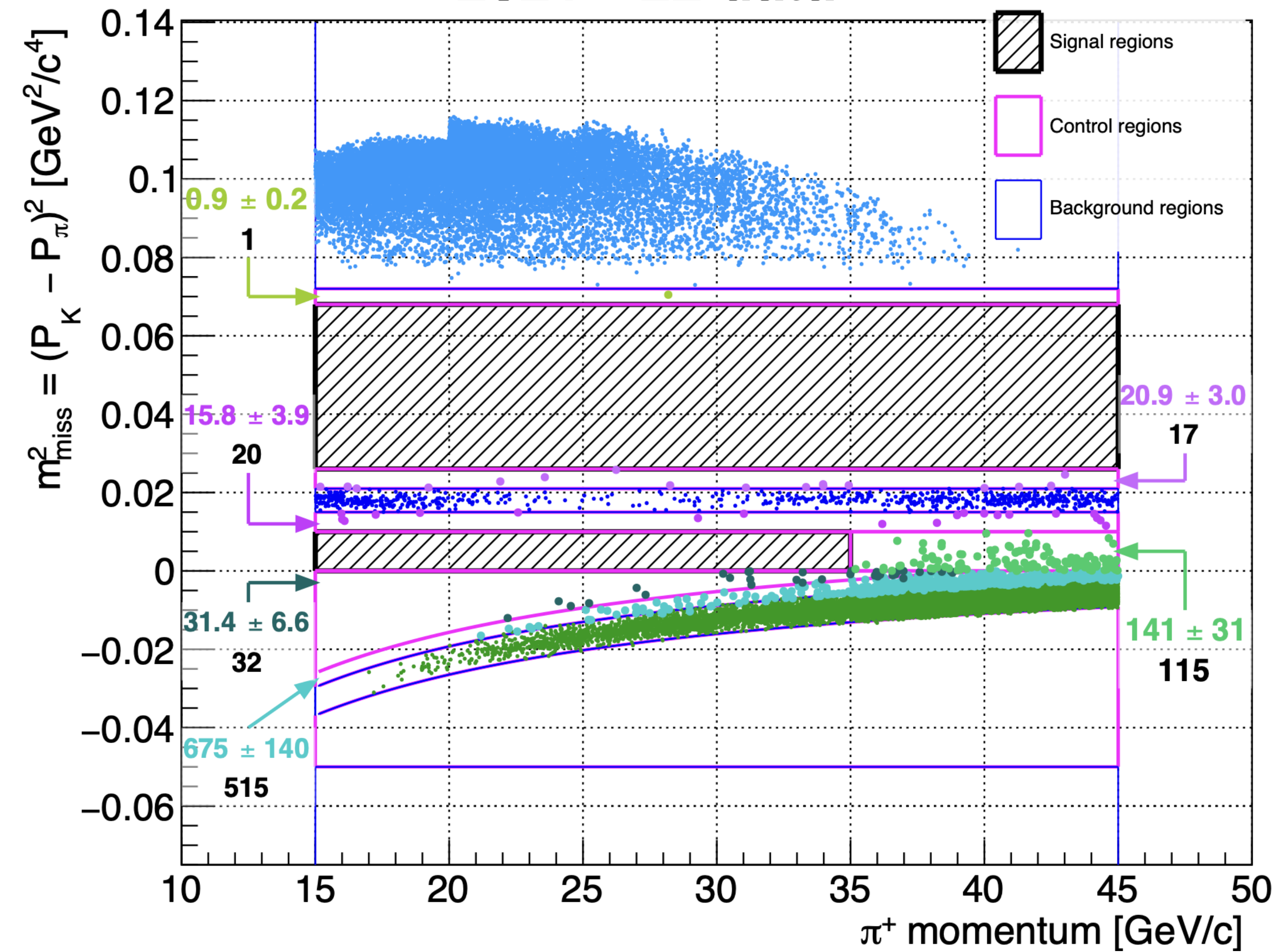
Upstream background validation

- Invert & loosen upstream vetos to enrich with different mechanisms:
 - Interaction-enriched: Val1,2,7,8
 - Accidental-enriched: Val3,4,5,6,9,10.
- All independent.
- Expectations and observations are in good agreement.
- Number of events rejected by VetoCounter:
 - (i.e. events in signal region with associated VC signal)
 - $N_{exp}^{VCrej.} = 6.9 \pm 1.4$, $N_{obs}^{VCrej.} = 9$
- VetoCounter is essential to control upstream background.



Control regions: 2021–22 Data

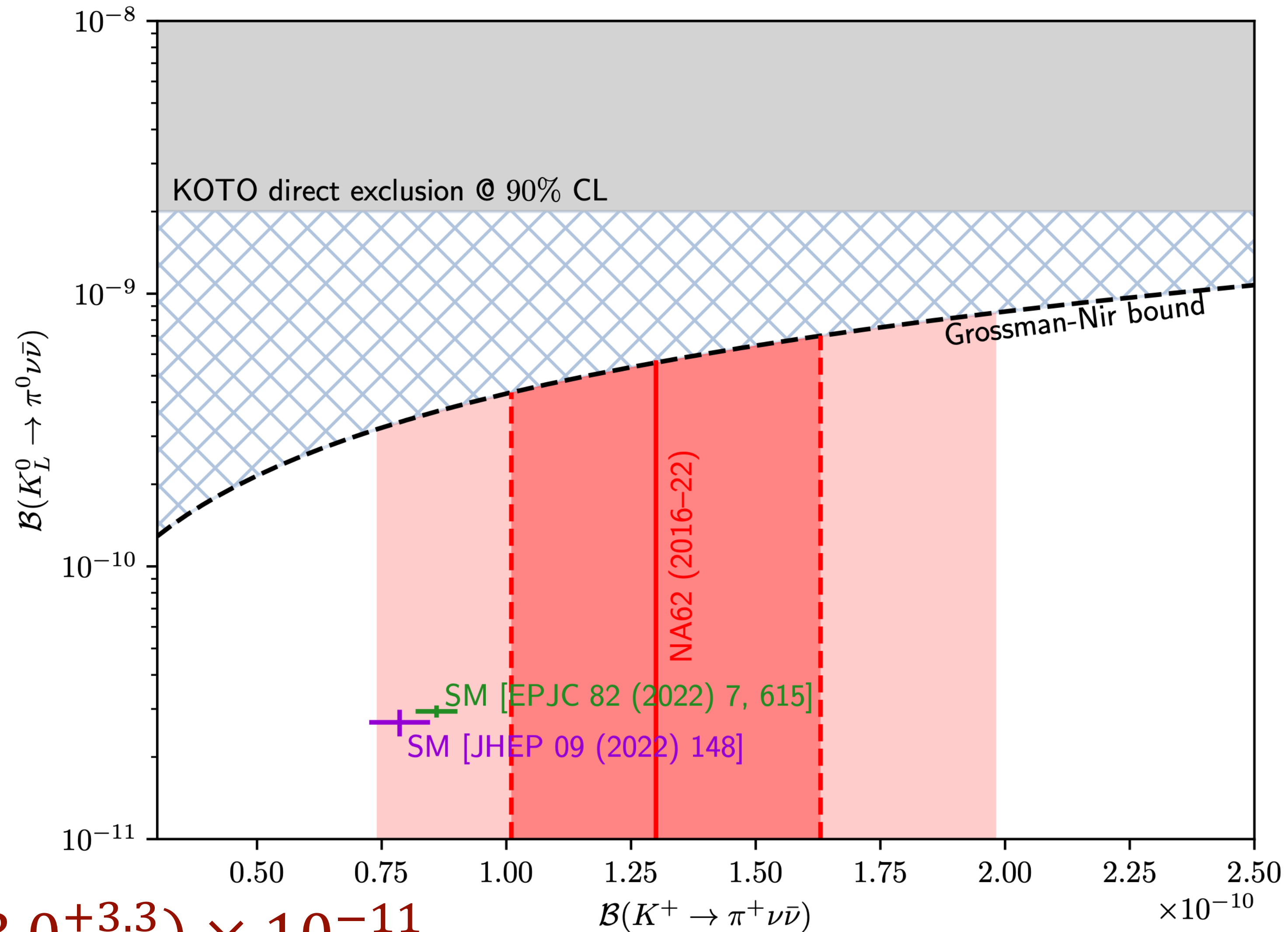
2021–22 data



- Good agreement in control regions validates background expectations.

Results in context

- Fractional uncertainty: 25%
- Bkg-only hypothesis rejected with significance $Z > 5$
- Observation of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay with BR consistent with SM prediction, within 1.7σ
- Need full NA62 data-set to clarify SM agreement or tension



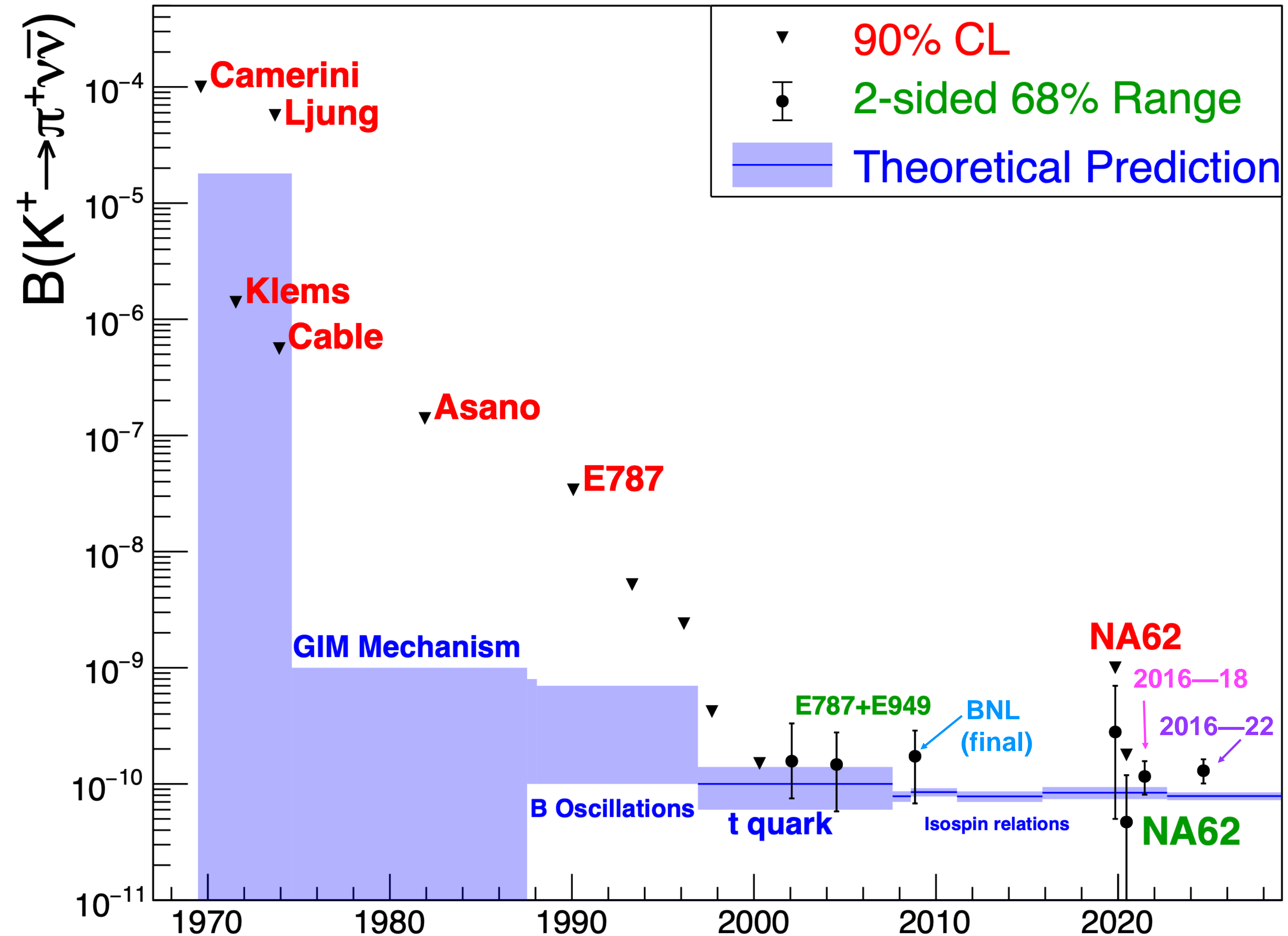
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = (13.0_{-2.9}^{+3.3}) \times 10^{-11}$$

$$2\sigma \text{ range : } [7.4 - 19.7] \times 10^{-11}$$

Results in context: the long story of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



- Experimental measurements:
 - Camerini et al. [[PRL 23 \(1969\) 326-329](#)]
 - Klems et al. [[PRD 4 \(1971\) 66-80](#)]
 - Ljung et al. [[PRD 8 \(1973\) 1307-1330](#)]
 - Cable et al. [[PRD 8 \(1973\) 3807-3812](#)]
 - Asano et al. [[PLB 107 \(1981\) 159](#)]
 - E787 :
 - [[PRL 64 \(1990\) 21-24](#)]
 - [[PRL 70 \(1993\) 2521-2524](#)]
 - [[PRL 76 \(1996\) 1421-1424](#)]
 - [[PRL 79 \(1997\) 2204-2207](#)]
 - [[PRL 84 \(2000\) 3768-3770](#)]
 - [[PRL 88 \(2002\) 041803](#)]
 - E949 (+E787)
 - [[PRL 93 \(2004\) 031801](#)]
 - [[PRL 101 \(2008\) 191802](#)]
 - NA62:
 - 2016 data: [[PLB 791 \(2019\) 156](#)]
 - 2016+17 data: [[JHEP 11 \(2020\) 042](#)]
 - 2016–18 data: [[JHEP 06 \(2021\) 093](#)]
 - 2016–22 data : this result.
- Theory:
 - [[Phys.Rev. 163 \(1967\) 1430-1440](#)]
 - [[PRD 10 \(1974\) 897](#)]
 - [[Prog.Theor.Phys. 65 \(1981\)](#)]
 - [[PLB 133 \(1983\) 443-448](#)]
 - [[PLB 192 \(1987\) 201-206](#)]
 - [[Nucl.Phys.B 304 \(1988\) 205-235](#)]
 - [[PRD 54 \(1996\) 6782-6789](#)]
 - [[PRD 76 \(2007\) 034017](#)]
 - [[PRD 78 \(2008\) 034006](#)]
 - [[PRD 83 \(2011\) 034030](#)]
 - [[JHEP 11 \(2015\) 033](#)]
 - [[JHEP 09 \(2022\) 148](#)]



Conclusions



- New study of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay using NA62 2021–22 dataset:
 - Improved signal yield per SPS spill by 50%.
 - $N_{bg} = 11.0_{-1.9}^{+2.1}$, $N_{obs} = 31$
 - $\mathcal{B}_{21-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (16.0_{-4.5}^{+5.0}) \times 10^{-11} = (16.0 \text{ }_{-4.2}^{+4.8})_{stat} \text{ }_{-1.3}^{+1.4})_{syst} \times 10^{-11}$
- Combining with 2016–18 data for full 2016–22 results:
 - $N_{bg} = 18_{-2}^{+3}$, $N_{obs} = 51$ (using 9+6 categories for BR extraction)
 - $\mathcal{B}_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0_{-2.9}^{+3.3}) \times 10^{-11} = (13.0 \text{ }_{-2.7}^{+3.0})_{stat} \text{ }_{-1.2}^{+1.3})_{syst} \times 10^{-11}$
 - Background-only hypothesis rejected with significance $Z > 5$.
- **First observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay: BR consistent with SM prediction within 1.7σ**
 - Need full NA62 data-set to clarify SM agreement or tension.

2023–LS3 data-set collection & analysis in progress...