Kaon Rare Decays

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Kaon role in SM and beyond (I)

- Associated production of kaons: idea of hadronic flavour
- Strangeness as a quantum number
- Meson-antimeson oscillation
- θ-τ puzzle and parity violation
- Quark model and SU(3)
- Flavour mixing, Cabibbo angle
- CP violation ε
- Suppression of $K^0 \rightarrow \mu^+\mu^-$ and GIM mechanism
- Direct CP violation ε'/ε

↓

Virtual contributions from particles in loop processes:
deviations have often preceded direct observation of new particles

Flavour changing Neutral Currents forbidden at tree-level in SM,
Hence necessary sensitive to New Physics

Kaon role in SM and beyond (II)

Mixing processes ($\Delta F=2$) and rare decays ($\Delta F=1$) :
- Complement each other in search for NP
- Test Minimal Flavour Violation
- Search for forbidden processes

LHC direct searches probe few TeV, or $O(10^{-19})$ m scale
Kaon $\Delta F=2$ and $\Delta F=1$ processes can access $O(10^{-21})$ m scale, the Zeptouniverse

$\Delta F=2$ alone is not enough: for example, to decide if new flavour changing dynamic is left-handed or righ-handed nature, need $\Delta F=1$

Depending on RH / LH couplings play, can reach scale up to 2000 TeV

Courtesy of Nierste's talk

(i) theoretical control of ϵ_K increases steadily (hadronic matrix elements and NNLO QCD under good control, $\epsilon_K \propto |V_{cb}|^4$ issue improving),

(ii) ϵ'_K now tractable with lattice QCD,

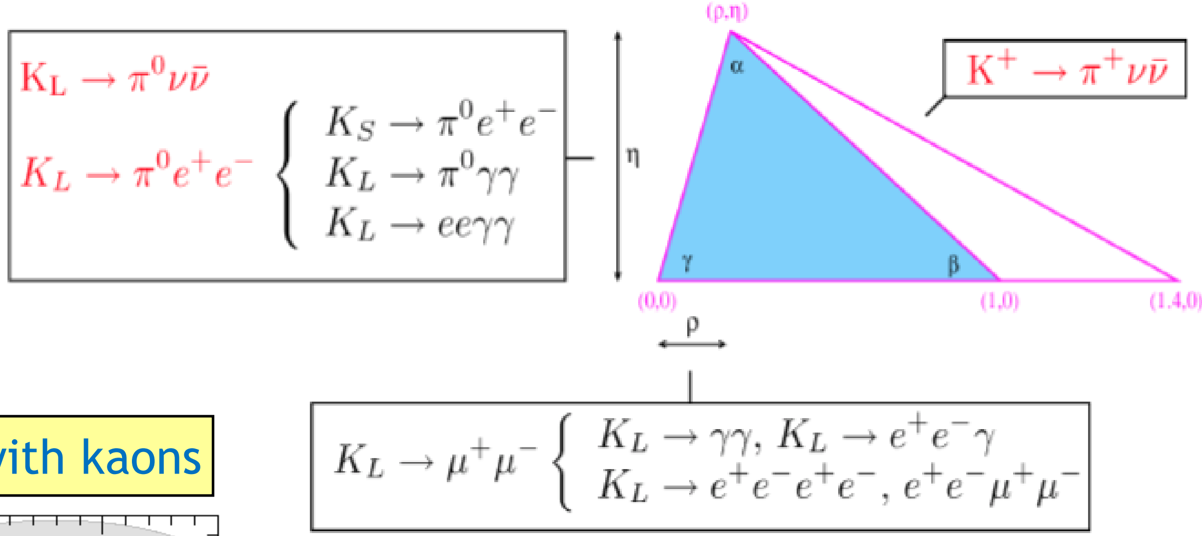
(iii) upcoming measurements of theoretically clean branching ratios $B(K^+ \to \pi^+ \nu\bar{\nu})$ (by NA62) and $B(K_L \to \pi^0 \nu\bar{\nu})$ (by KØTØ),

(iv) no new particles found at LHC:
$\Rightarrow$ weaker rationale for Minimal Flavour Violation (MFV)

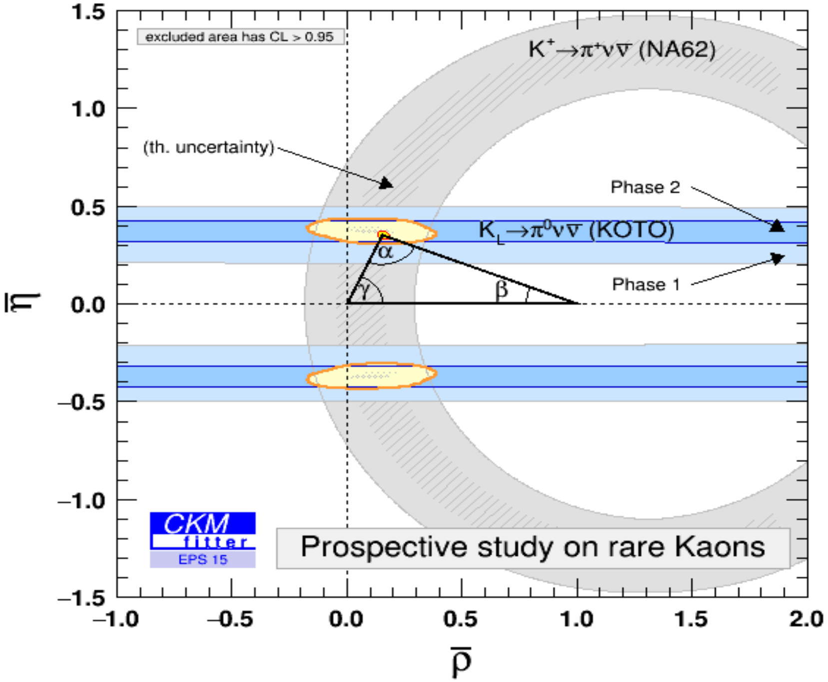
If the flavour structure of new physics is unrelated to the SM Yukawa sector, one expects the largest effects in Kaon (and $\mu \to e$) FCNC processes.

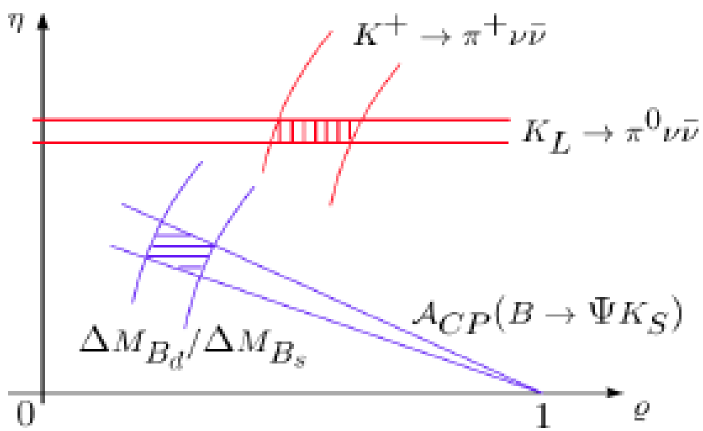
CKM triangle

Kaons alone can fully constrain the CKM triangle



CKM unitarity triangle with kaons





Comparison with B physics can provide hints on NP dynamics

Kaon "anomalies"

$$\frac{\epsilon'_K}{\epsilon_K} = (16.6 \pm 2.3) \times 10^{-4}$$

Experiments: NA48, KTeV

$$\frac{\epsilon'_K}{\epsilon_K} = (1.1 \pm 4.7_{\text{lattice}} \pm 1.9_{\text{NNLO}} \pm 0.6_{\text{isosp. br.}} \pm 0.2_{m_t}) \times 10^{-4} \qquad \text{(SM)}$$

Kitahara,UN,Tremper, JHEP 1612 (2016) 078

The prediction uses the lattice-QCD results from RBC-UKQCD,
Phys. Rev. Lett. **115** 212001 (2015).

Buras, Jäger, Gorbahn (JHEP 1511 (2015) 202) find a 2.9σ deviation:

$$\frac{\epsilon'_K}{\epsilon_K} = (1.9 \pm 4.5) \times 10^{-4} \qquad \text{(SM)}$$

See Nierste's talk for details

See Nierste's talk

- The new lattice results for the matrix element $\langle(\pi\pi)_{I=0}|Q_6|K^0\rangle$ from RBC-UKQCD points to a tension between the experimental value of ϵ'_K and the Standard-Model prediction.
- If new physics enters through loops, a sizable effect in ϵ'_K requires a new source of flavour violation which is much larger then the CKM factor $\mathrm{Im}\,\dfrac{V_{td}V_{ts}^*}{V_{ud}V_{us}^*} \sim 6 \cdot 10^{-4}$. But then the effect on ϵ_K will typically be too big.
- In the MSSM one can simultaneously enhance ϵ'_K and suppress the new-physics contributions to ϵ_K. This requires flavour mixing among left-handed squarks, masses of right-handed up-type squarks different from those of the down-type squarks, and a gluino mass above 1.5 times the mass of the left-handed squarks.

(Buras, KAON2016)

Kaon "anomalies"

Universal Unitarity Triangle 2016 (CMFV)

AJB, Gambino, Gorbahn, Jäger, Silvestrini 0007085

New Results from Fermilab Lattice + MILC 1602.03560

Hadronic matrix elements

$$F_{B_s}\sqrt{\hat{B}_{B_s}} = (274.6 \pm 8.8\ \text{MeV})$$

$$F_{B_d}\sqrt{\hat{B}_{B_d}} = (227.7 \pm 9.8\ \text{MeV})$$

Their ratio

$$\xi = 1.206 \pm 0.019$$

Similar but less precise results from ETM (1308.1851)

Blanke + AJB (1602.04020)

Requiring CMFV to reproduce data for $\Delta M_{s,d}$ favors low value of V_{cb} in agreement with exclusive determination and upper bound on ε_K significantly below data.
Requiring CMFV to reproduce data for ε_K favors high value of V_{cb} in agreement with inclusive determination and lower bound on $\Delta M_{s,d}$ significantly above data.

$\Rightarrow$ Tension between ΔM_s and ε_K

Buras, KAON2016 Conference

Stars of KAON Flavour Physics

$\varepsilon_K, \Delta M_K$ | ε'/ε | $K^+ \to \pi^+ \nu\bar{\nu}$ | $K_L \to \pi^0 \nu\bar{\nu}$

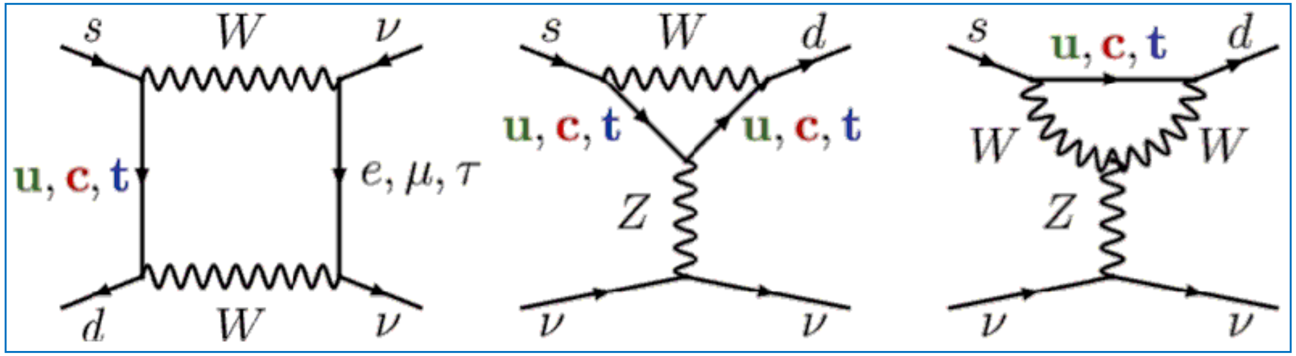
$K_L \to \mu^+\mu^-$ | $K_L \to \pi^0 e^+ e^-$ | $K_L \to \pi^0 \mu^+\mu^-$

They all can give some information about very short distance scales but to identify new physics, correlations with $B_{s,d}$ and D observables, EDMs, Lepton physics crucial

In particular if we want to reach Zeptouniverse without any direct hints from the LHC

Rare kaon decays: $K \to \pi\nu\bar{\nu}$

SM: box and penguin diagrams



Ultra-rare decays with
the highest CKM suppression:

$A \sim (m_t/m_W)^2 |V^*_{ts} V_{td}| \sim \lambda^5$

- Hadronic matrix element related to a measured quantity ($K^+ \to \pi^0 e^+ \nu$).
- Exceptional SM precision.
- Free from hadronic uncertainties.
- Measurement of $|V_{td}|$ complementary to those from $B\text{–}\bar{B}$ mixing or $B^0 \to \rho\gamma$.

SM branching ratios
Buras et al., JHEP 1511 (2015) 033

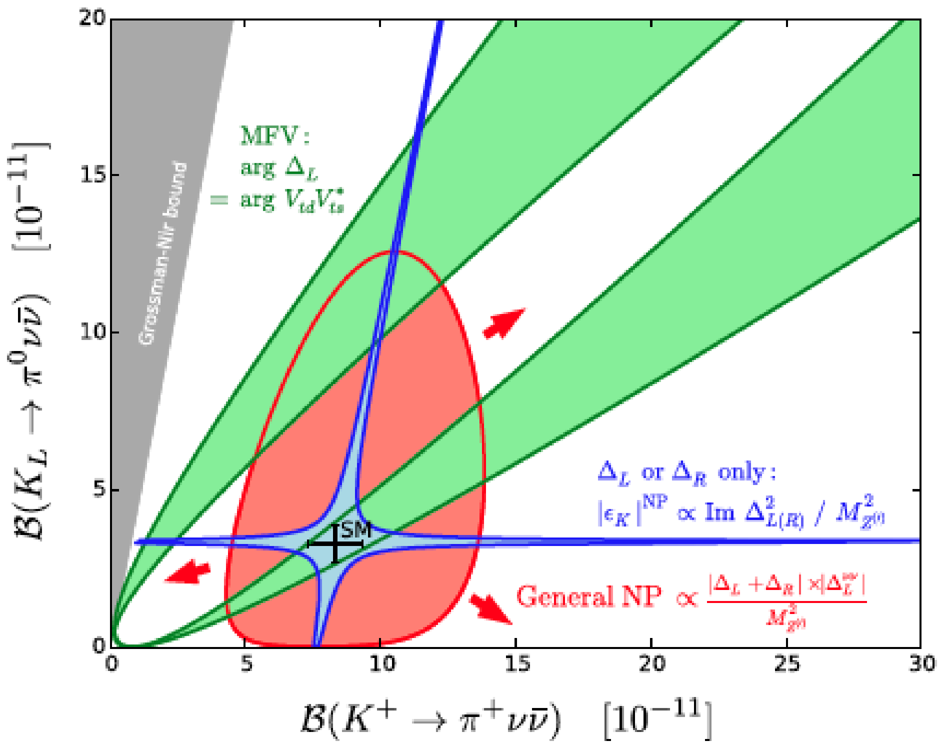
Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	8.4±1.0
$K_L \to \pi^0 \nu\bar{\nu}$	3.00±0.31

The uncertainties are largely parametric (CKM)

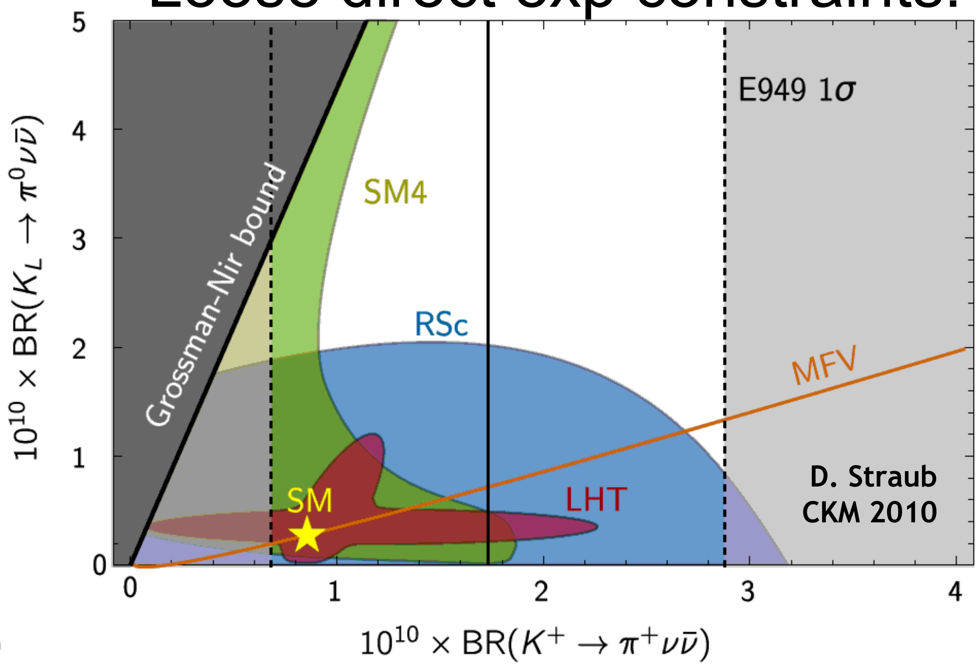
Theoretically clean,
almost unexplored,
sensitive to new physics.

JHEP 1511 (2015) Buras, Buttazzo, Girrbach,Knegjens
EPJ C76 (2016) Blanke, Buras, Recksigel
JHEP 0903 (2009) Blanke, Buras, Duling, Gemmler, Gori
JHEP 0608 (2006) Isidori, Mescia, Paradisi, Smith, Trine

Testing the SM (I)



Loose direct exp constraints:



- General Observables

Br($K^+ \to \pi^+\nu\nu$), Br ($K_L \to \pi^0\nu\nu$)
$K \to \pi\nu\nu$ vs ε'/ε, ΔM_K
$K \to \pi\nu\nu$ vs B decays ($B \to \mu\mu$, R_K, R_{D^*}, etc)
Correlations are model-dependent

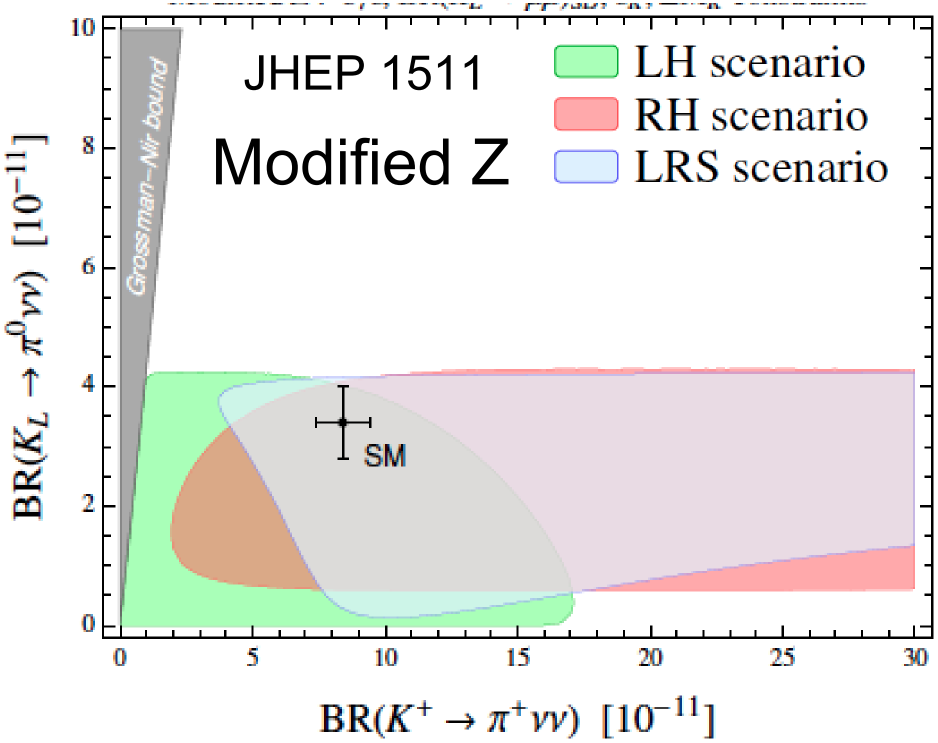
- CMFV or general
- Specific models:

Modified Z'/Z
TeV SUSY
LFV in 3rd generation
Etc….

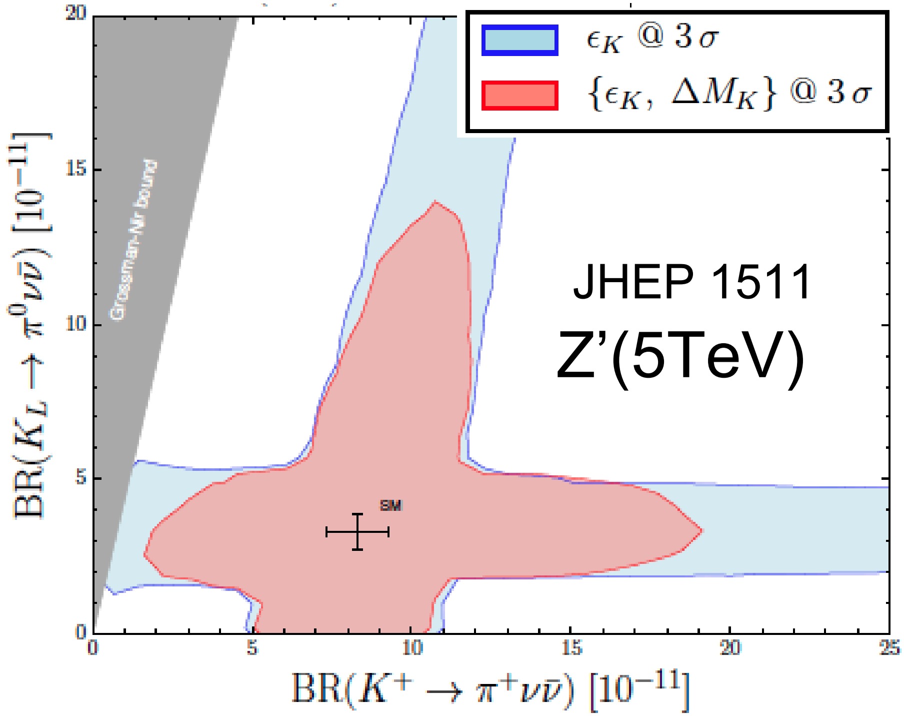
Testing the SM (II)

Modified Z, Z' model used as paradigm:

ε'/ε, $Br(K_L\to\mu\mu)_{SD}$, ε_K , ΔM_K constraints



ε_K , ΔM_K constraints

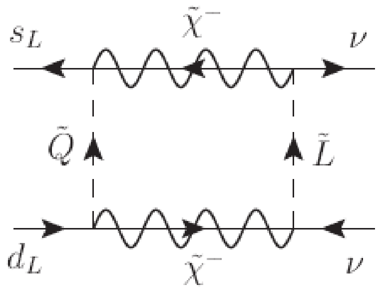


LH and RH couplings allowed:
constraints from other kaon observables

Testing the SM (III)

In our MSSM scenario:
Contributions from wino-like chargino box:

1703.05786
D'Ambrosio, Crivellin, Kitahara, Nierste



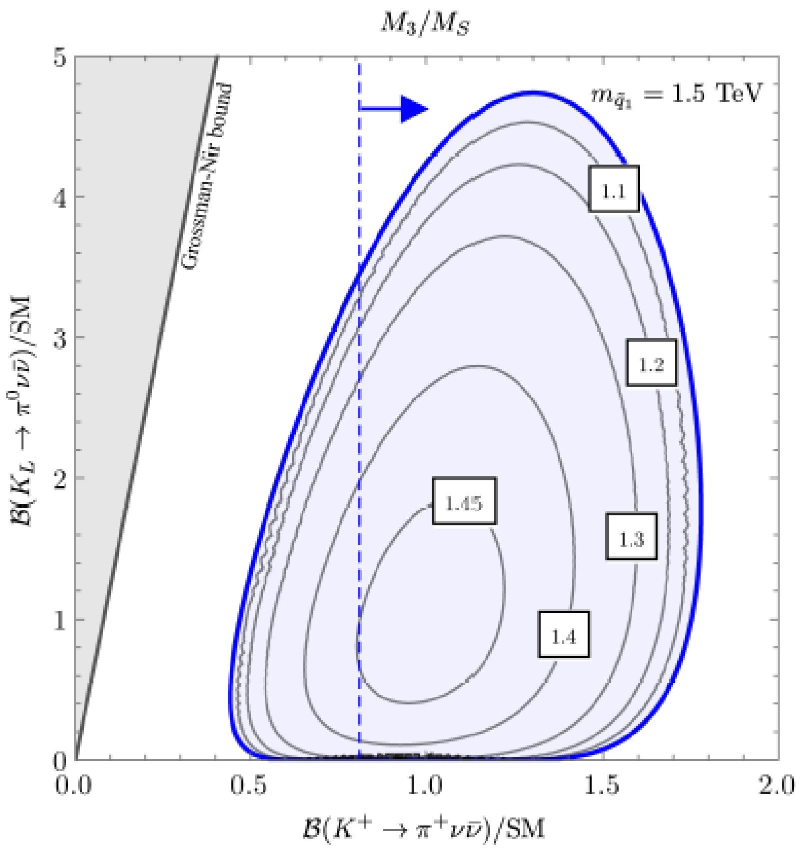
See more details
In Nierste's talk

Our MSSM scenario makes falsifiable predictions for $B(K^+ \to \pi^+\nu\bar{\nu})$ and $B(K_L \to \pi^0\nu\bar{\nu})$:

Allowed region for the two branching ratios:

$m_{\tilde{q}_1} = 1.5\,\text{TeV}$ is the mass of the lightest ($\tilde{s}_L$–$\tilde{d}_L$–mixed) squark,
M_3 is the gluino mass, GUT relations for $M_{1,2}$,
M_S is the mass of all other sparticles.

The number in the squares show the value for M_3/M_S needed to cancel the MSSM contribution to ϵ_K.



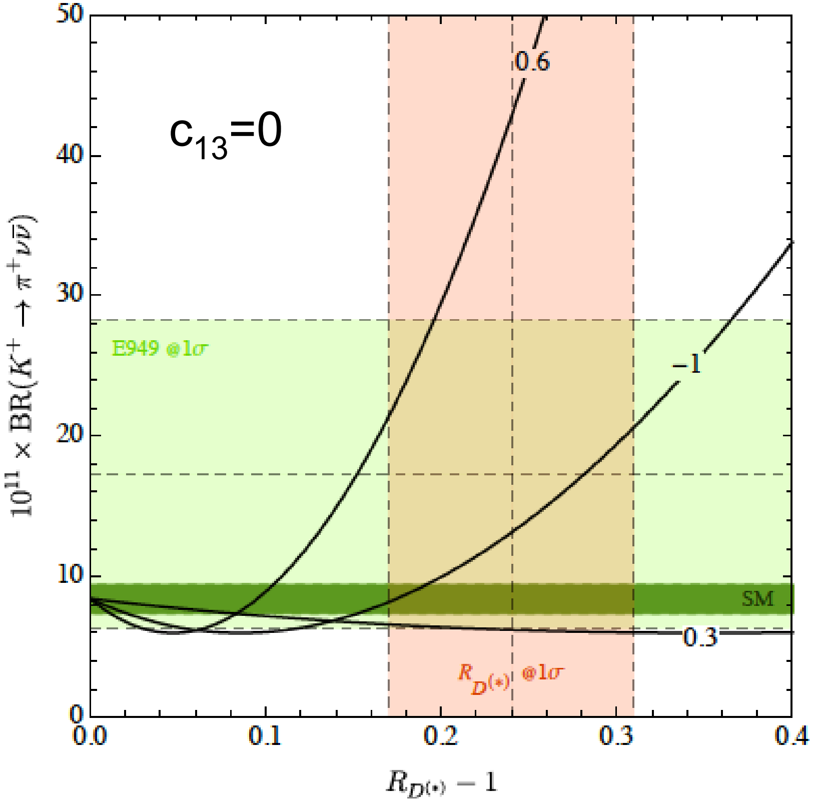
Testing the SM (IV)

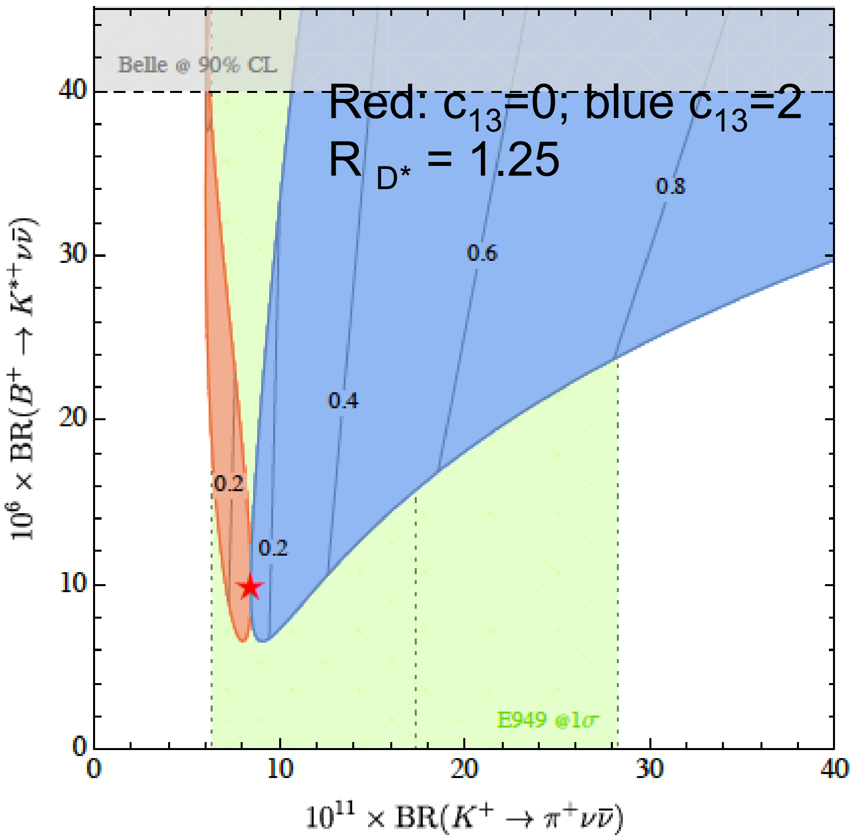
LFU violation in third generation, EFT approach:

$$\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}) = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})_{\rm SM} \left|1 + R_0\left(1 - \theta_q e^{-i\phi_q}\right)\right|^2 \qquad R_0 = \frac{1}{\Lambda^2}\frac{1}{\sqrt{2}G_F}$$

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \;=\; 2\mathcal{B}(K_L \to \pi^0\nu_e\bar{\nu}_e)_{\rm SM} + \mathcal{B}(K_L \to \pi^0\nu_\tau\bar{\nu}_\tau)_{\rm SM}\left|1 - \frac{R_0\,\theta_q^2(1-c_{13})}{(\alpha/\pi)(X_t/s_w^2)}\right|^2$$

Varying θ_q :

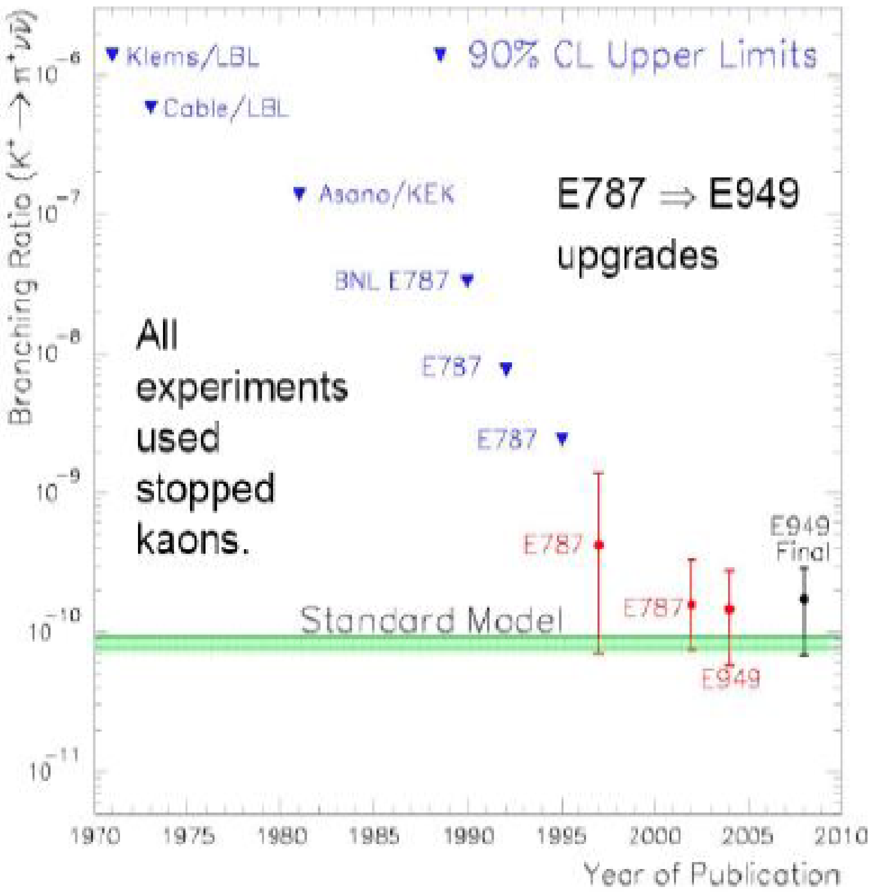




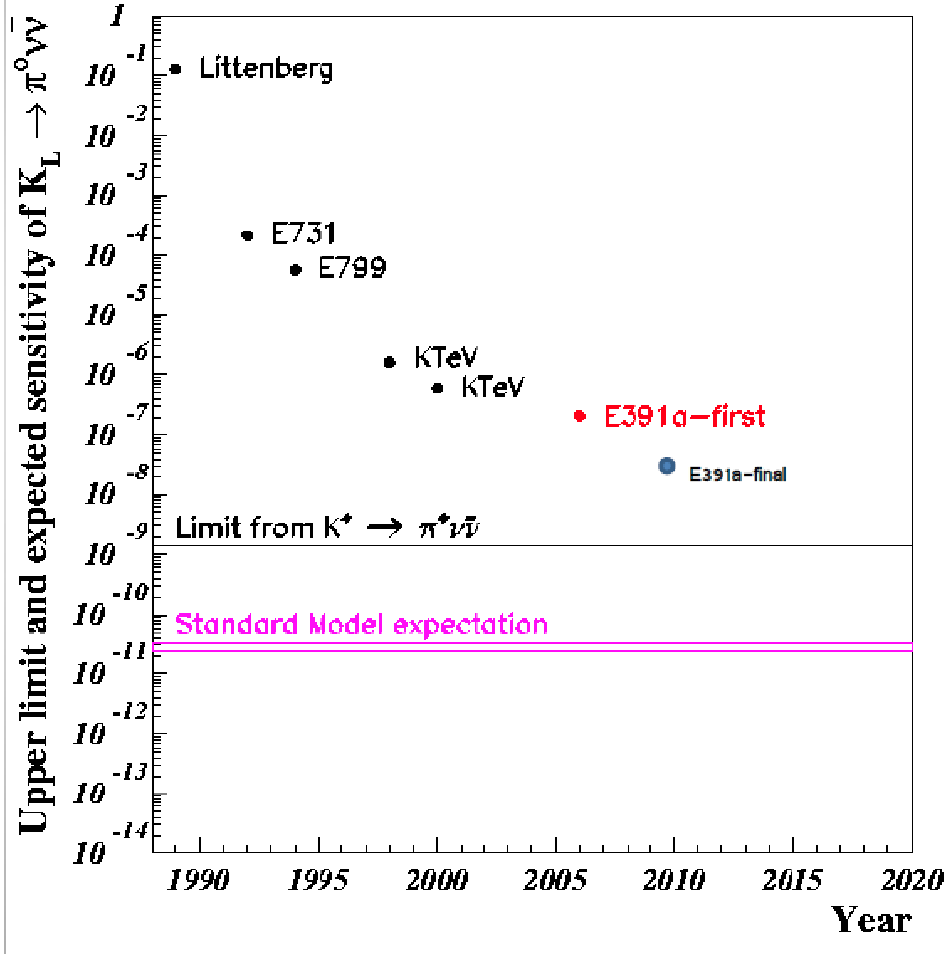
Bordone, Buttazzo, Isidori, Monnard, arXiv:1705.10729v1

$K_{\pi\nu\nu}$ Experimental Status

$K^+ \to \pi^+ \nu\nu$



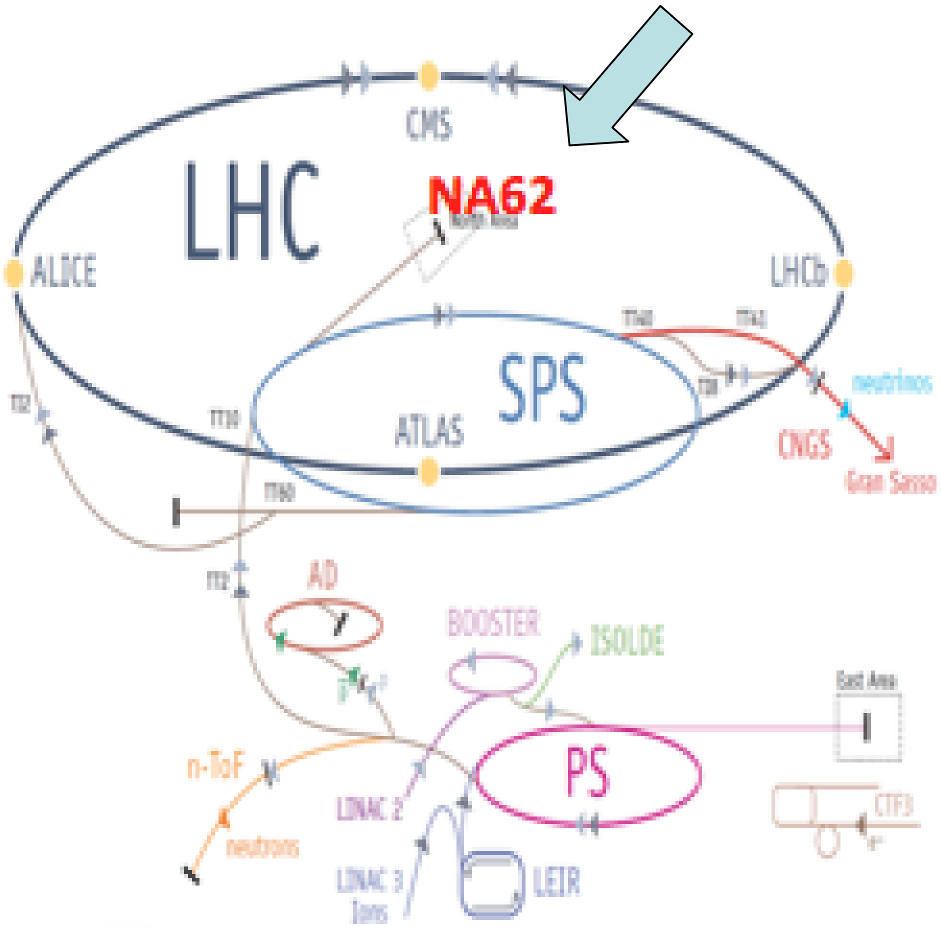
$K^0 \to \pi^0 \nu\nu$



$BR(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

$BR(K_L \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% C. L.) Phys. Rev. D 81, 072004 (2010)

NA62 @CERN-SPS



Primary Goal:
O(10%) precision on
measurement of BR($K^+ \rightarrow \pi^+ \nu\nu$)

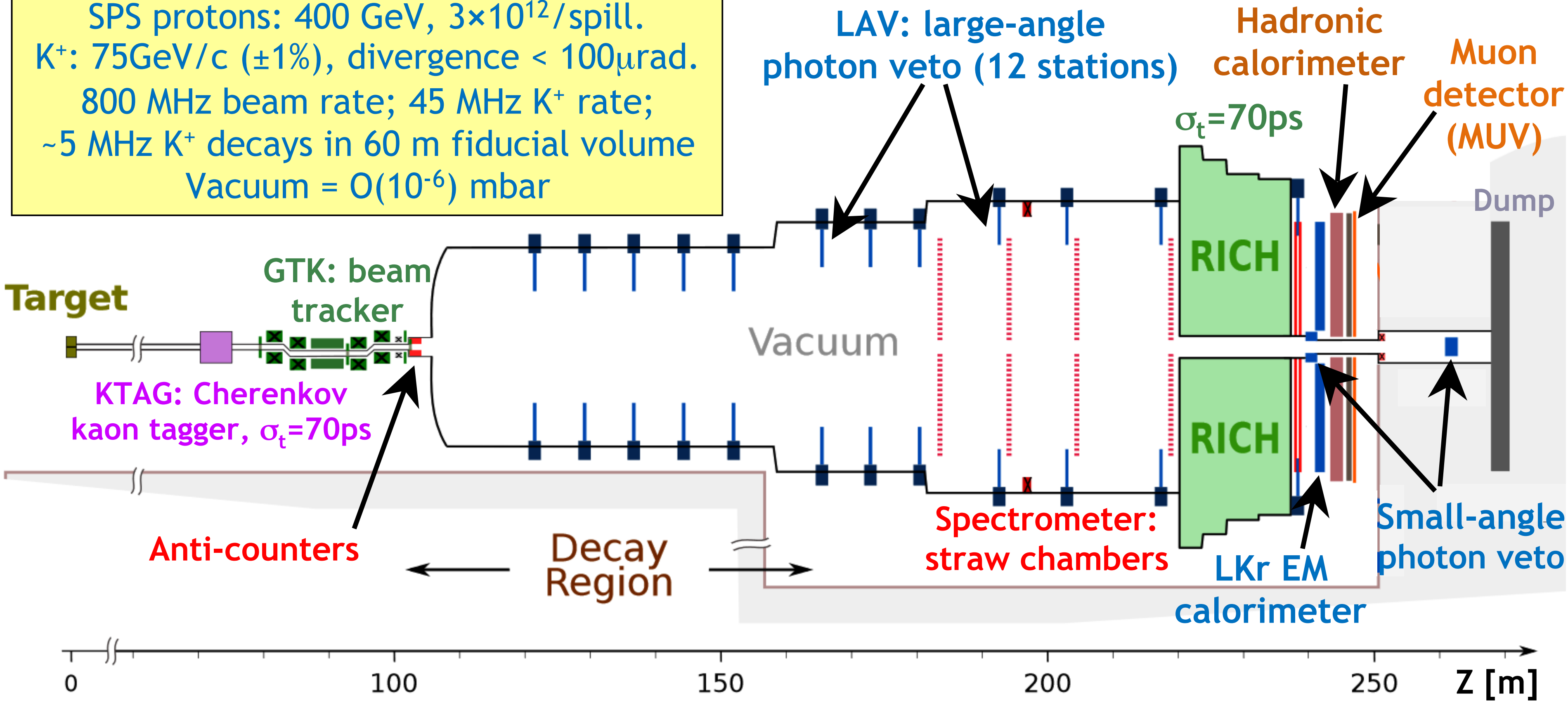
Technique:
Kaon decay-in-flight experiment

NA62: currently **~200** participants, **~30** institutions.

NA62 collaboration,
JINST 12 (2017) P05025

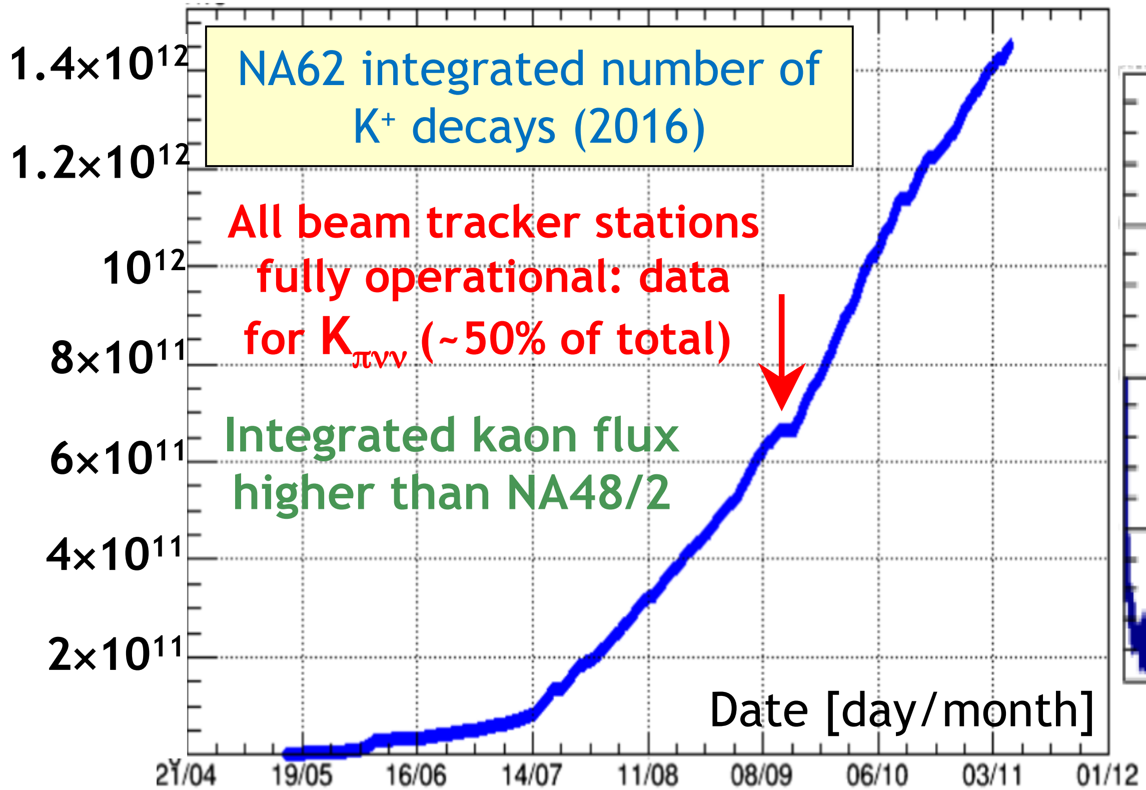
The NA62 detector

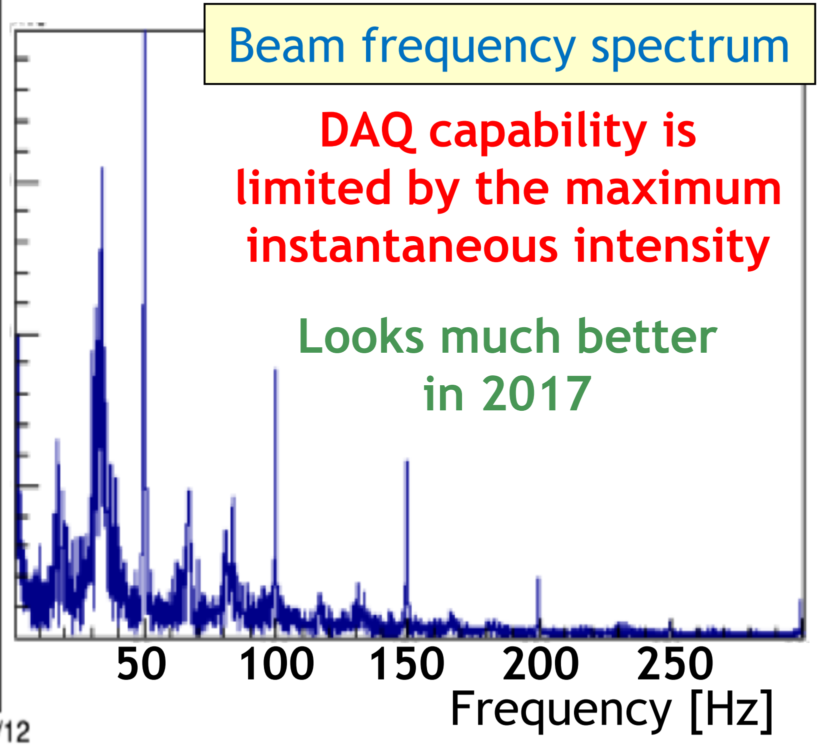
Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, 3×10^{12}/spill.
K^+: 75GeV/c (±1%), divergence < 100μrad.
800 MHz beam rate; 45 MHz K^+ rate;
~5 MHz K^+ decays in 60 m fiducial volume
Vacuum = $O(10^{-6})$ mbar



- ❖ Expected single event sensitivity for K^+ decays: **BR~10^{-12}**.
- ❖ Measured kinematic rejection factors (limited by beam pileup & MCS tails): **6×10^{-4}** for $K^+\to\pi^+\pi^0$, **3×10^{-4}** for $K\to\mu^+\nu$.
- ❖ Hermetic photon veto: measured $\pi^0\to\gamma\gamma$ decay suppression = **1.2×10^{-7}**.
- ❖ Particle ID (RICH+LKr+HAC+MUV): **~10^{-7}** muon suppression.

High intensity run in 2016

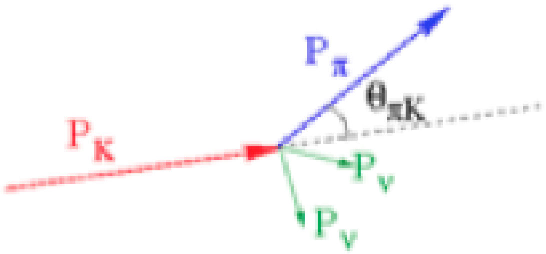


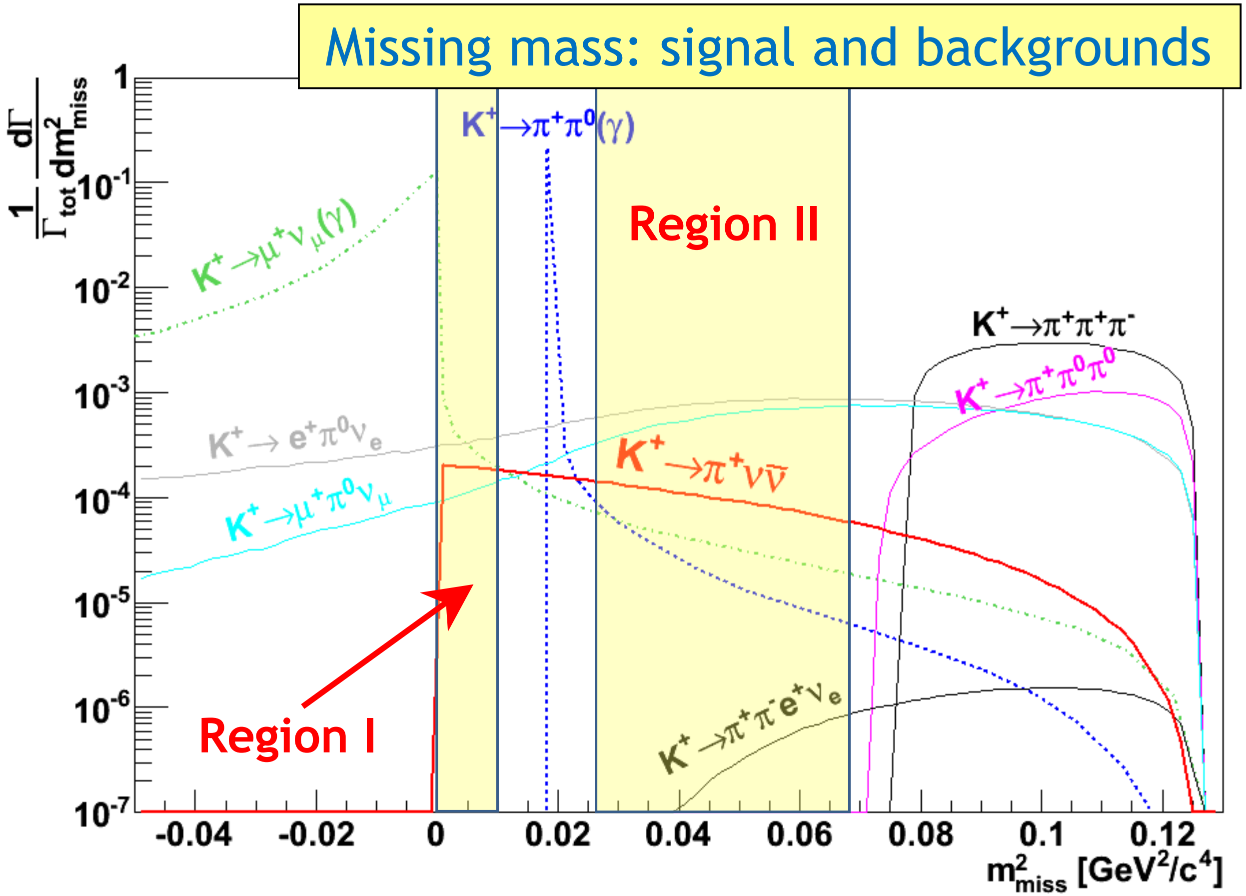


- Stable data collection at ~40% of the nominal intensity; limited by beam structure, including the 50 Hz harmonics.
- Simultaneous data taking for $K_{\pi\nu\nu}$ and **rare/exotic decays**.
- Extrapolation to end of 2018 (12 months of live time): 7×10^{12} K^+ decays.
- With improved extraction and incremental improvements in efficiency, the target of **10^{13} K^+ decays** by end of 2018 is reachable.

$K_{\pi+\nu\nu}$ kinematics

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





92% of total **BR(K^+)**:

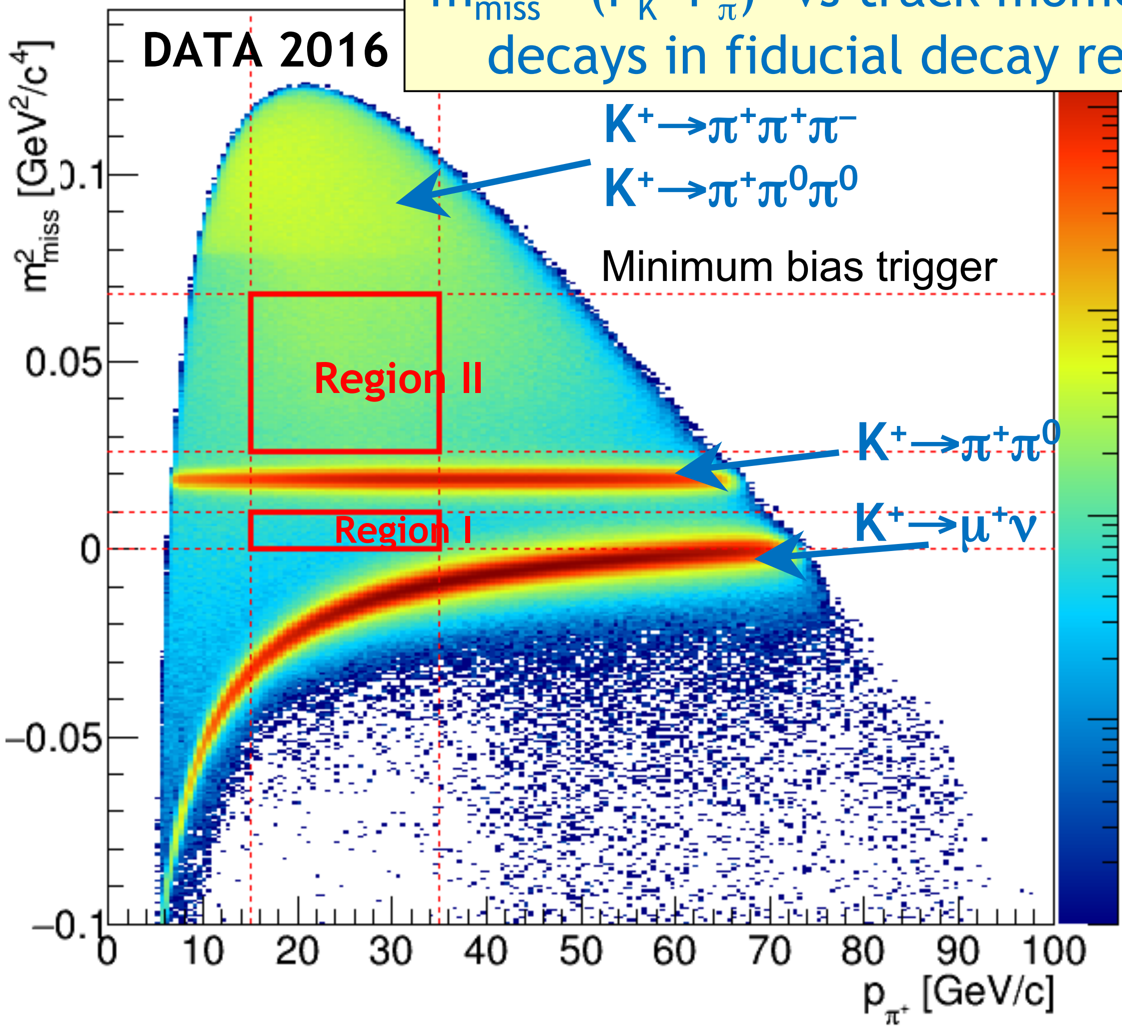
- Outside the signal kinematic region.
- Signal region is split into **Region I** and **Region II** by the $K^+ \to \pi^+\pi^0$ peak.

8% of total **BR(K^+)** including multi-body:

- Span across the signal region (not rejected by kinematic criteria).
- Rejection relies on hermetic photon system, PID, sub-ns timing.

$K_{\pi+\nu\nu}$ signal region definition

$m_{miss}{}^2=(P_K-P_\pi)^2$ vs track momentum; decays in fiducial decay region



Analysis done in 3D space:
m^2_{miss}, m^2_{miss}(RICH), m^2_{miss}(no GTK)

Main K^+ decay modes (>90% of BR) rejected kinematically.

Design kinematical resolution on $m_{miss}{}^2$ has been achieved ($\sigma=1.0\times10^{-3}$ GeV^4/c^2).

Measured kinematical background suppression:

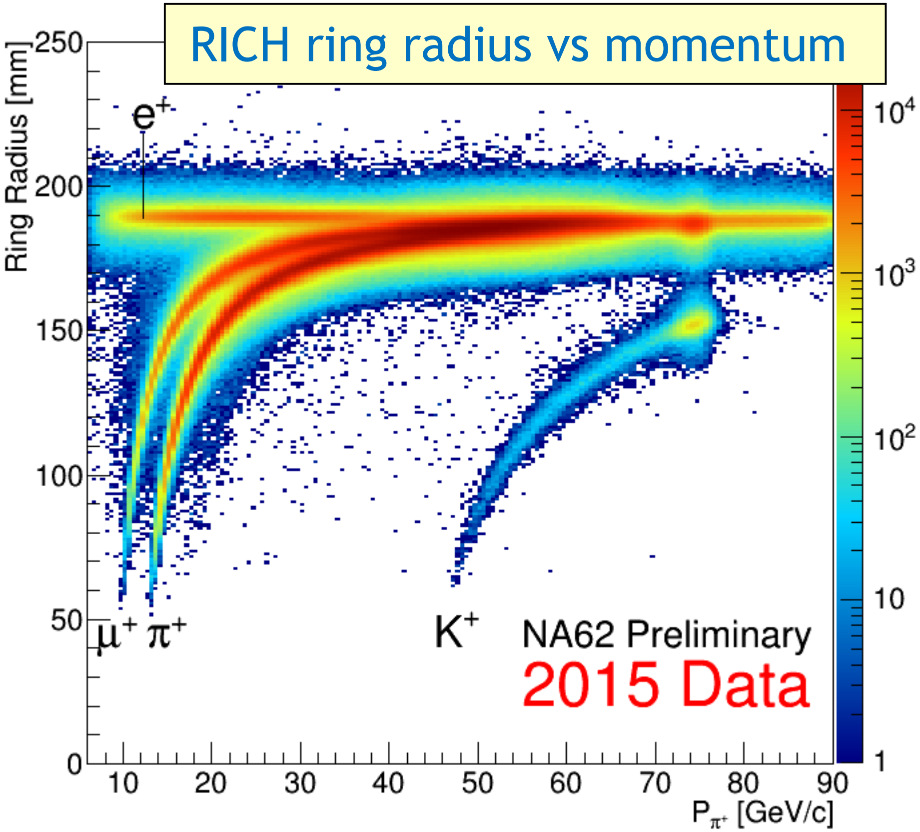
✓$K^+\to\pi^+\pi^0$: 6×10^{-4};
✓$K^+\to\mu^+\nu$: 3×10^{-4}.

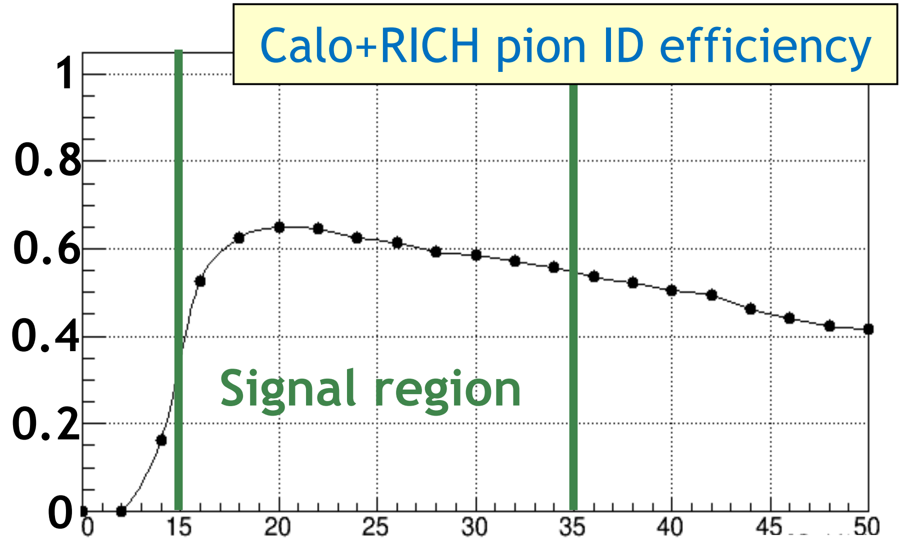
Further background suppression:

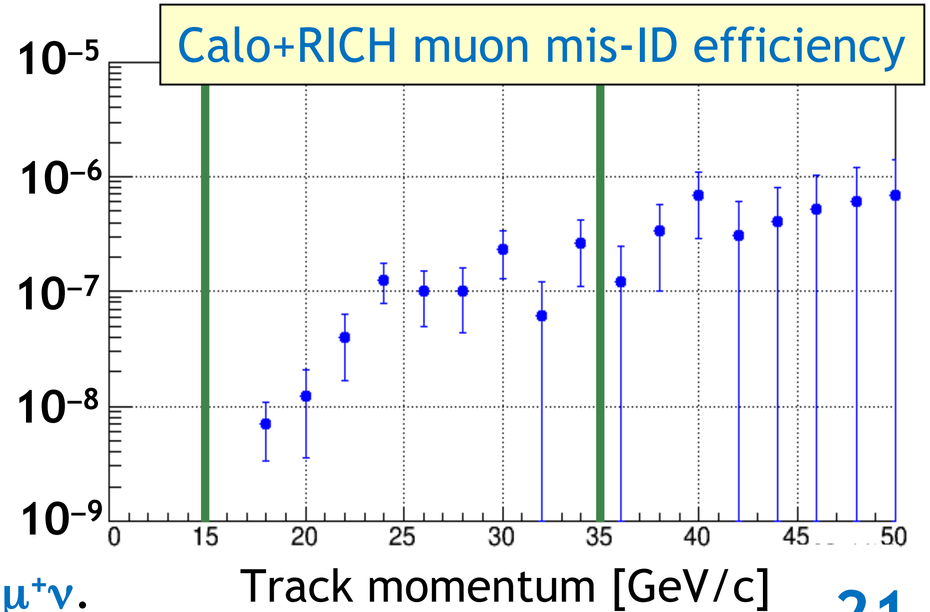
✓PID (calorimeters & Cherenkov detectors): μ suppression $<10^{-7}$.

✓Hermetic photon veto: suppression of $\pi^0\to\gamma\gamma$ decays $<10^{-7}$.

Identification with RICH & HAC





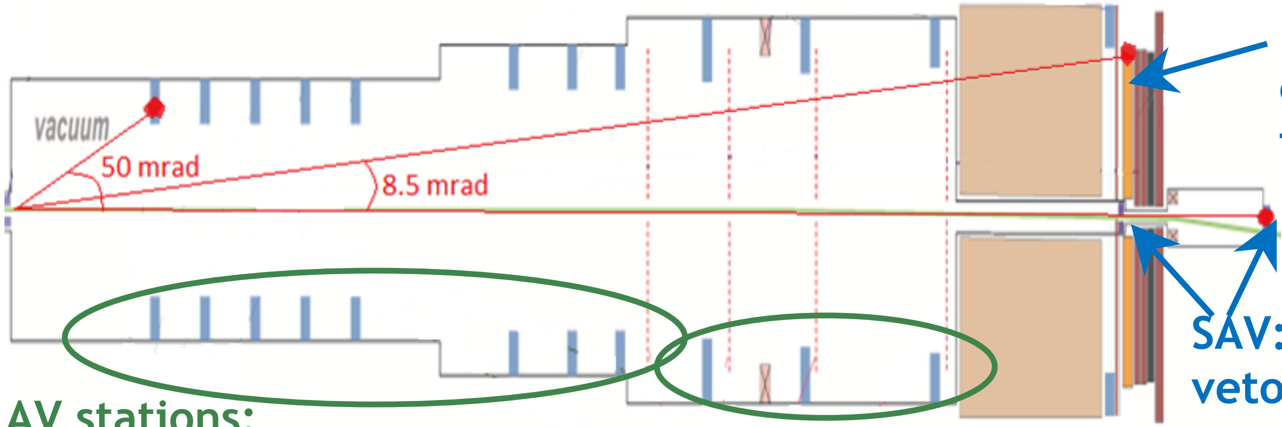


<u>Two independent PID measurements:</u>

1) with calorimeters & muon detector:
MVA technique used; $\varepsilon_\mu \div \varepsilon_\pi = 10^{-5} \div 80\%$,
2) with RICH: $\varepsilon_\mu \div \varepsilon_\pi = 10^{-2} \div 80\%$
in the signal momentum region.

Performance measured with $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$.

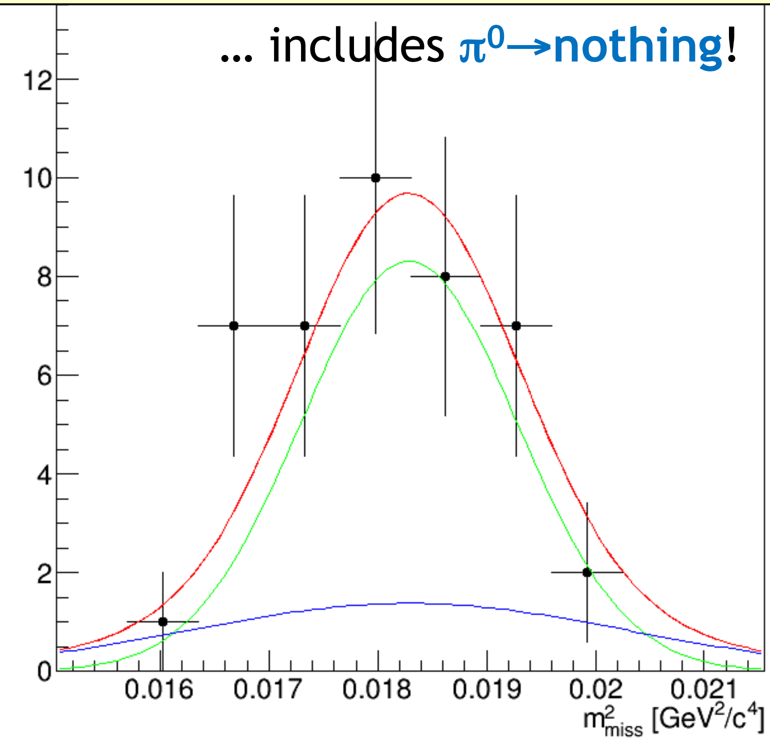
Photon rejection



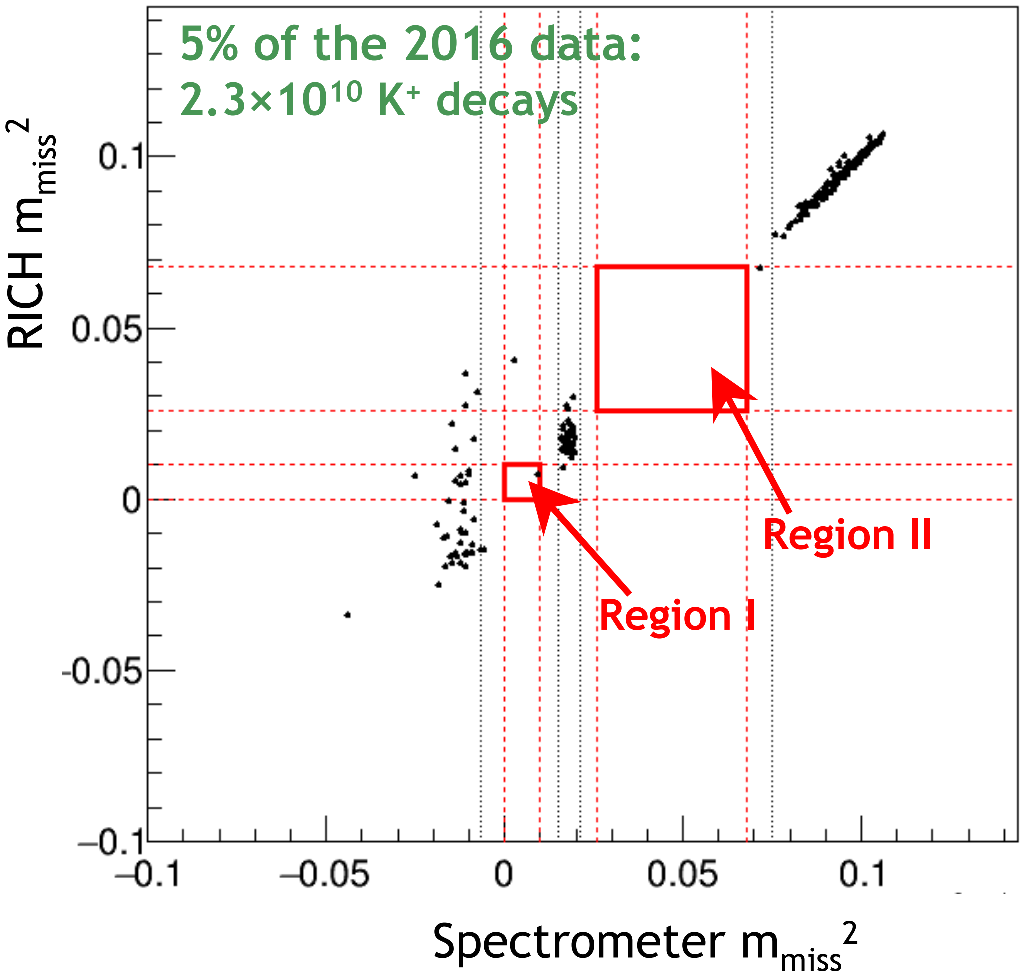
12 Pb glass LAV stations: hermetic up to 50 mrad

- Technique: EM calorimetry exploiting correlations between photons from $\pi^0 \rightarrow \gamma\gamma$ decays.
- Signal region: $p(\pi^+) < 35$ GeV/c, therefore $p(\pi^0) > 40$ GeV/c.
- Goal: $O(10^{-7})$ to $O(10^{-8})$ rejection of π^0 from $K^+ \rightarrow \pi^+\pi^0$ decays.
- Measured π^0 rejection factor with the $K_{\pi\nu\nu}$ selection: $\varepsilon = (1.2 \pm 0.2) \times 10^{-7}$. Accidental loss measured with $K_{\mu 2}$: 16% at 40% intensity, can be improved.

$m_{miss}^2 = (P_K - P_\pi)^2$: full $K_{\pi\nu\nu}$ selection



Data 2016: $K_{\pi+\nu\nu}$ sample



$K^{\pm}\rightarrow\pi^{\pm}\nu\nu$ **decay:**

~**50%** of 2016 data is useful.

Analysis of **5% of this sample**.

No events found in 3D-space.
in $K_{\pi\nu\nu}$ signal region.
(event in box has m^2_{miss}(No GTK) outside signal region)

- Expect **1.3** SM $K_{\pi\nu\nu}$ decays from total 2016 sample.
- Preliminary statement on background: **B/S<0.9**.
- Analysis in progress to increase signal acceptance and improve BKG suppression.

NA62 broad physics programme(I)

NA62 approach allows for a broad physics programme:

Signature: high momentum K^+ (75GeV/c) → low momentum π^+ (15–35 GeV/c).

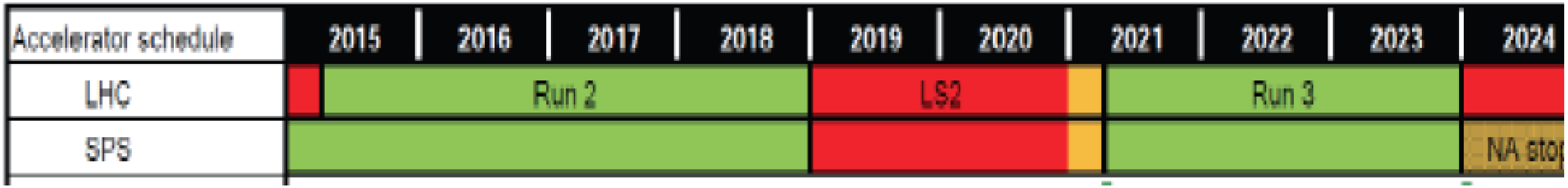
Advantages: max detected K^+ decays/proton ($p_K/p_0 \approx 0.2$);
efficient photon veto (>40 GeV missing energy)

Un-separated beam (6% kaons) → higher rates, additional background sources.

❖ **NA62 Run 2016–2018: focused on the "golden mode" $K^+ \to \pi^+ \nu\nu$.**

- ✓ Several measurements at nominal SES~10^{-12}: $K^+ \to \pi^+ A'$, $\pi^0 \to \nu\nu$.
- ✓ A few measurements do not require extreme SES: $K^+ \to \ell^+ N$, …
- ✓ Sensitivities to most rare/forbidden decays are limited but still often world-leading (~10^{-10} to ~10^{-11}).
- ✓ Proof of principle for a broad rare & forbidden decay programme.

NA62 broad physics programme(II)



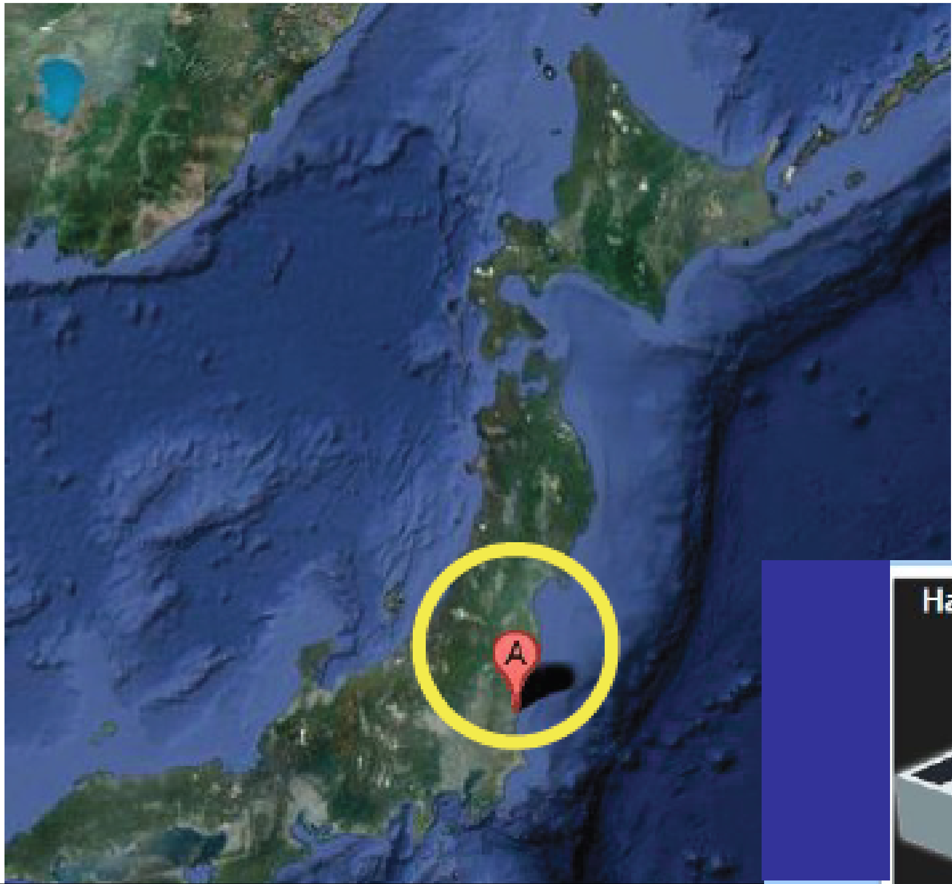
❖ **NA62 Run 2021–2024**:

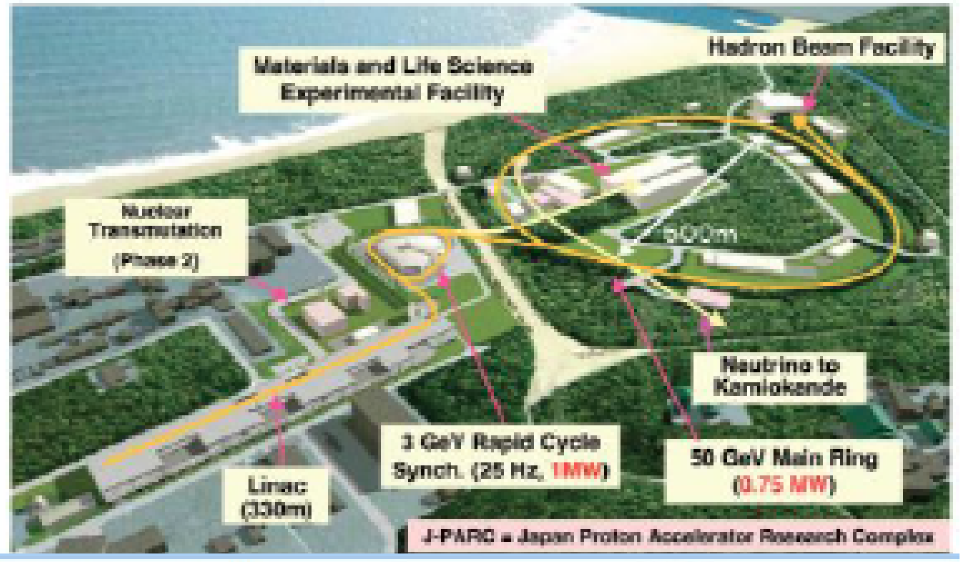
- ✓ Existing apparatus with improved trigger logic.
- ✓ Evaluate incremental changes for optimal efficiency.
- ✓ Further $K^+ \to \pi^+ \nu\nu$ data collection.
- ✓ Rare/forbidden K^+ and π^0 decays at SES~10^{-12}:
  - K^+ physics: $K^+ \to \pi^+ \ell^+ \ell^-$, $K^+ \to \pi^+ \gamma \ell^+ \ell^-$, $K^+ \to \ell^+ \nu\gamma$, $K^+ \to \pi^+ \gamma\gamma$, …
  - π^0 physics: $\pi^0 \to e^+e^-$, $\pi^0 \to e^+e^-e^+e^-$, $\pi^0 \to 3\gamma$, $\pi^0 \to 4\gamma$, …
  - Searches for LFV/LNV: $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi^+ \mu e$, $\pi^0 \to \mu e$, …
- ✓ Beam dump with ~10^{18} POT: hidden sector (long-lived HNL, DP, ALP).

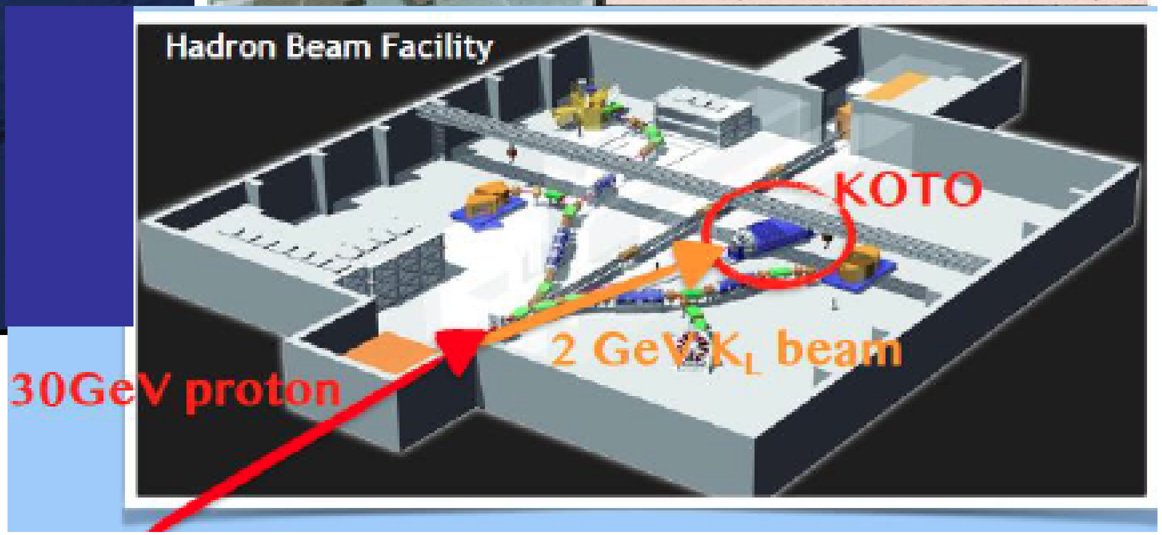
See Soldi’s talk about the wider NA62 programme

KOTO experiment

KOTO @ JPARC



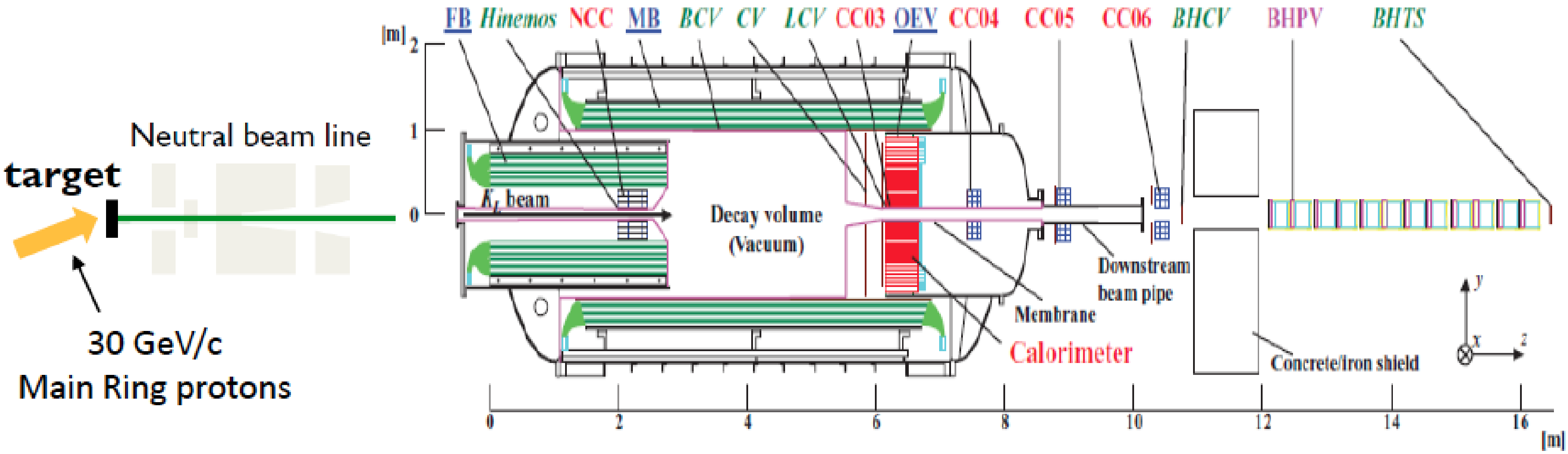




Goal:
Observe few SM $K_L \to \pi^0 \nu\nu$

KOTO detector

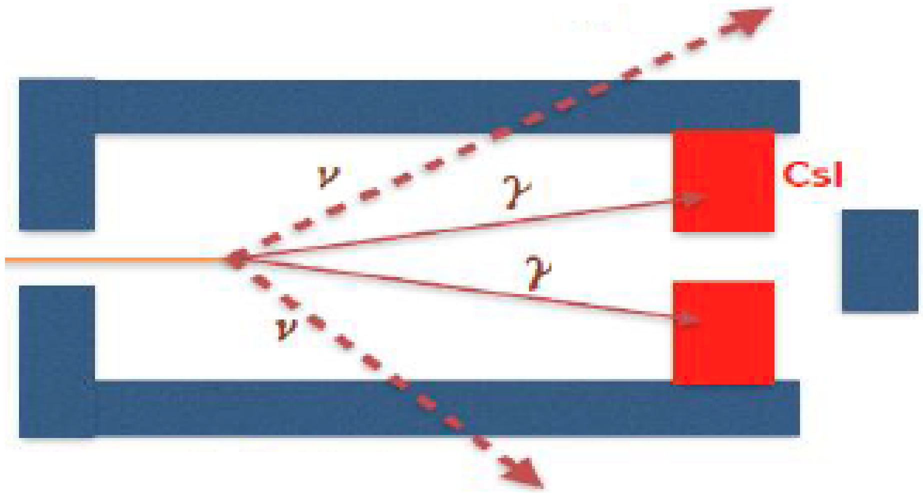
"Stopped kaons" technique:

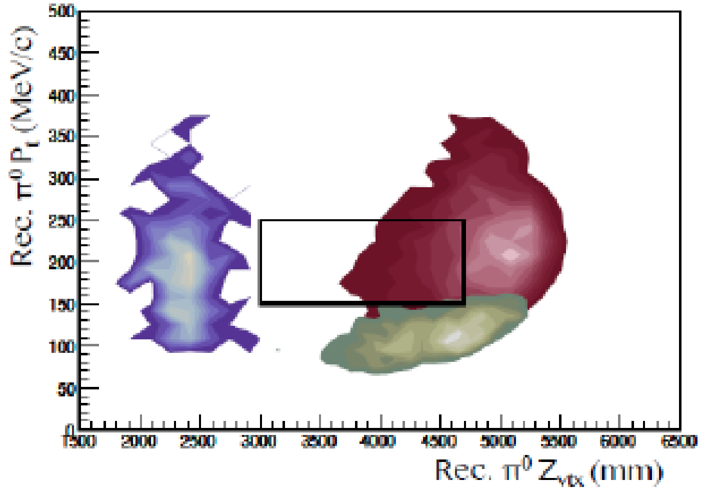


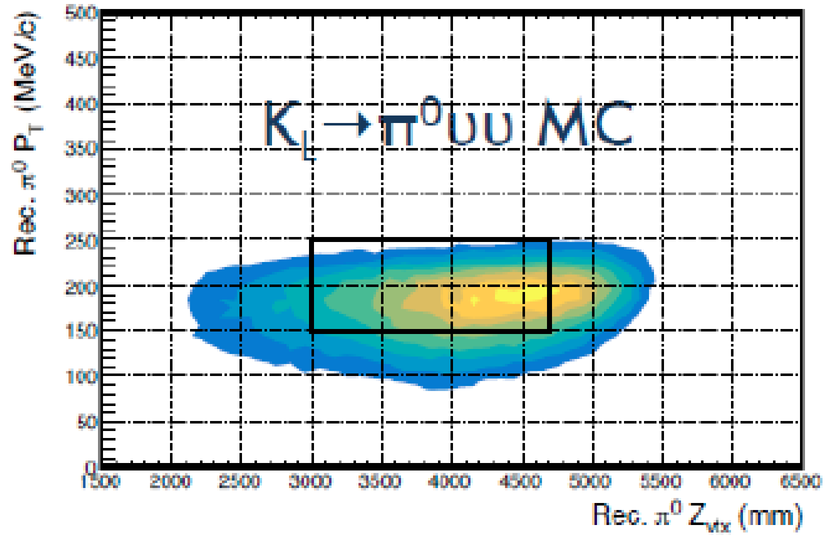
Secondary neutral beam:
Momentum = 1.4 GeV/c peak
Transverse size = 80x80 mm^2
Composition = K_L, neutrons, photons
(high kaon purity)
Intensity (2013) = 3 x10^{13} ppp on target (25 kW)
Intensity (2015-16) = 30/42 kW

Detector:
Fiducial region = ~3m
Vacuum = 5 10^{-7} mbar
CsI calorimeter
Hermetic γ-veto

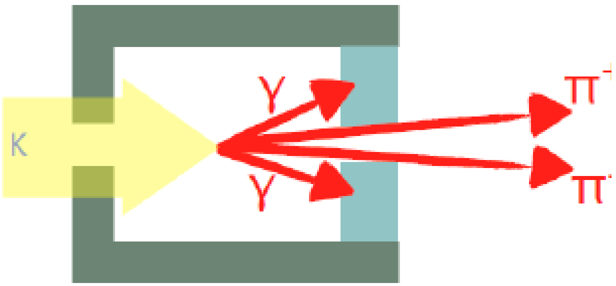
$K_{\pi0\nu\nu}$ selection



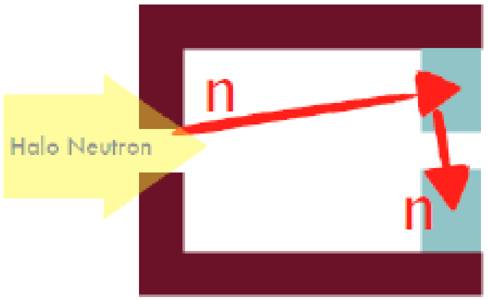




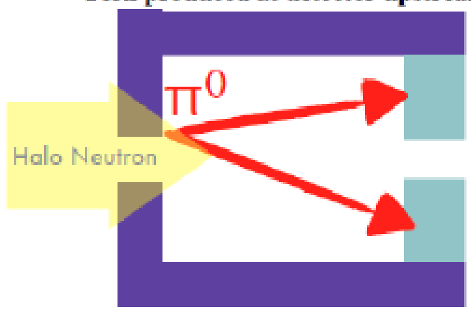
Particles missing in the downstream gap



Neutron directly hit on CsI



Pion produced at detector upstream



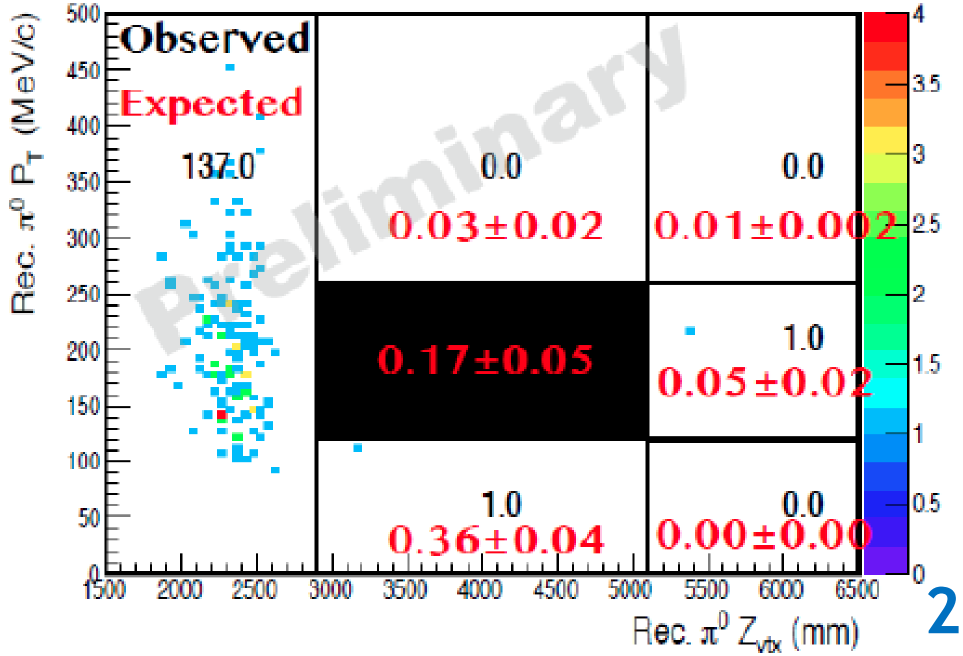
KOTO data

2013: First physics result
N(K_L) =~ 2.4 x 10^{11}
BR($K_L \to \pi^0 \nu\nu$) < 5.1 x 10^{-8} (90% CL) [PTEP 2017, 021C01]
Background in signal region dominated by neutrons

2015-2016: 20 x statistics of 2013
Modified setup: x 5 reduction in neutron background wrt 2013
Small subsample analyzed: N(K_L) =~ 3.8 x 10^{11}
S.E.S =~ 5.9 10^{-9}

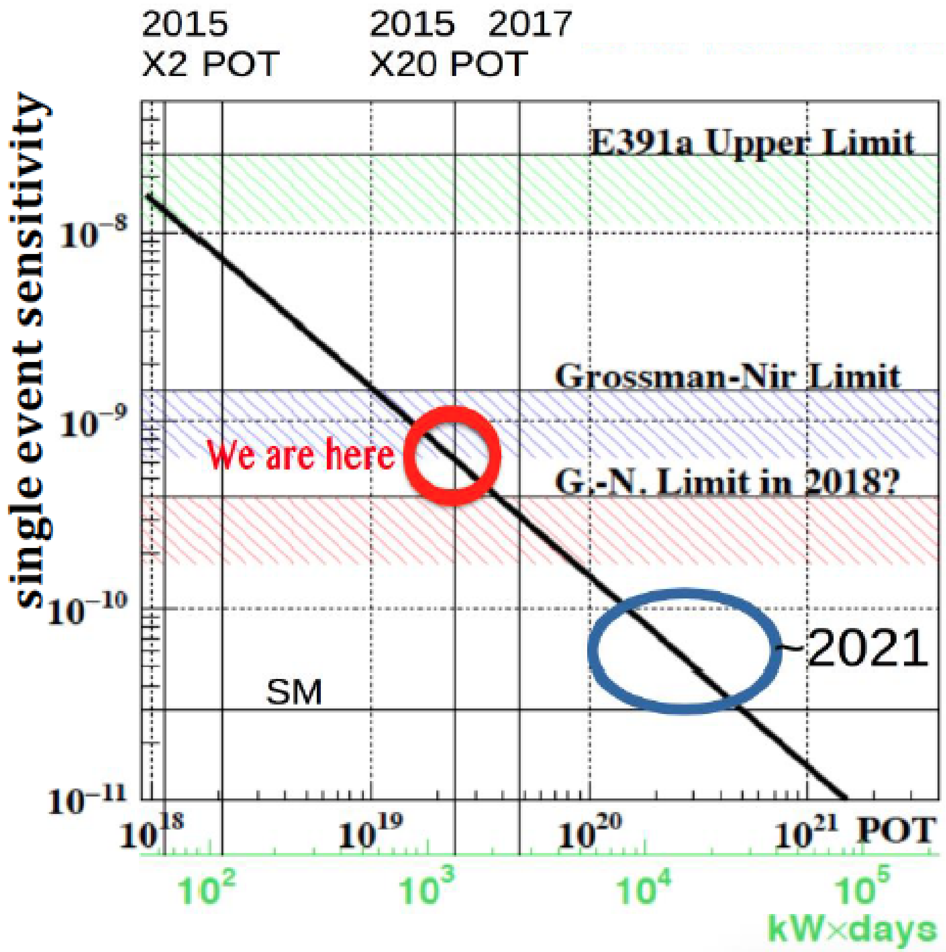
BG in Box	#BG
$K_L \to \pi^0\pi^0$	0.04±0.03
$K_L \to \pi^+\pi^-\pi^0$	0.04±0.01
Upstream Events	0.04±0.04
Neutron Events	0.05±0.02
Other BG	Under Estimation

Preliminary



KOTO prospects

Total 2015-2016: S.E.S < 10^{-9}



Upgrades to reach SM:
- New barrel detector
- Beam pipe modification
- CsI both end readout (2018)
- JPARC 42->100 kW (2019)

$K_{\pi 0 \nu\nu}$ @CERN ?

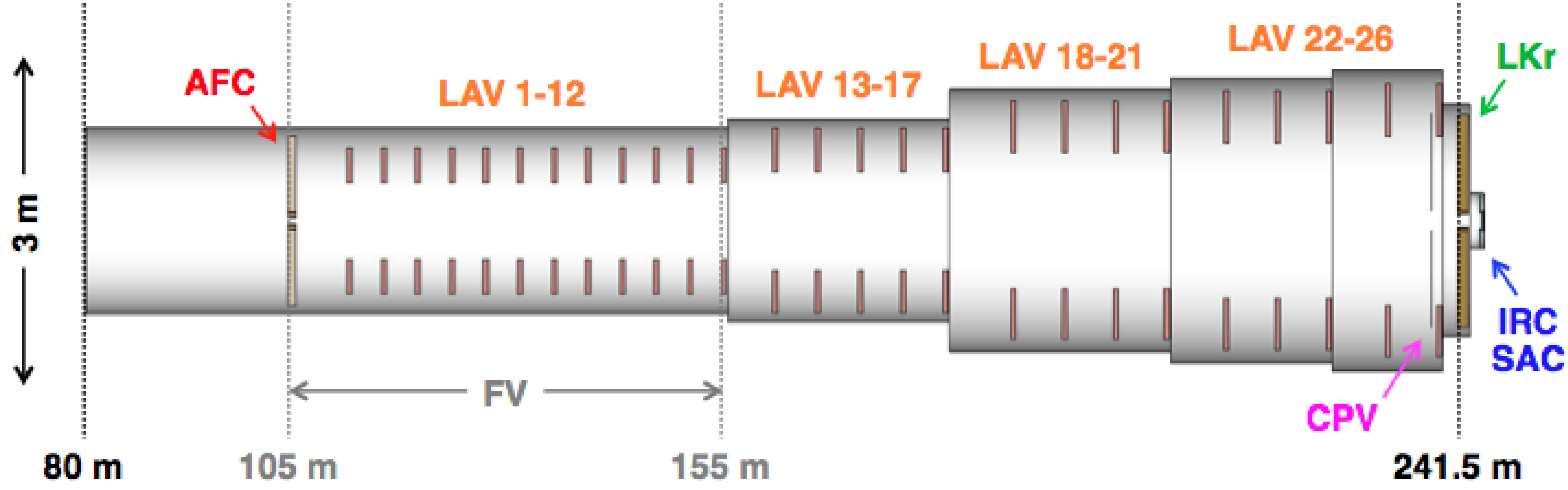
Idea to make the measurement at the SPS:

1) High energy experiment (p_K=70 GeV), complementary
2) Photons from K_L decays boosted forward - makes photon vetoing easier
3) Perhaps possible to reuse NA62 infrastructure

400 GeV protons on 400 mm Be target
Production at 2.4 mrad to optimize K_L versus n
For ~100 events and reasonable acceptance:
Require 2 x 10^{13} protons per pulse/ 16.8 s = 6 x NA62
Currently not available, would require upgrades

Aim to take ~60 SM events in 5 years from 2026 with S/B~1
Project discussed at CERN as part of Physics Beyond Collider

KLEVER $K_{\pi0\nu\nu}$ @CERN



Main detector/veto systems:

AFC	Active final collimator/upstream veto
LAV1-26	Large-angle vetoes (26 stations)
LKr	NA48 LKr calorimeter
IRC/SAC	Small-angle vetoes (SAC in neutral beam)
CPV	Charged-particle veto

Refined background study and detector studies are in progress

Kaon physics at LHCb

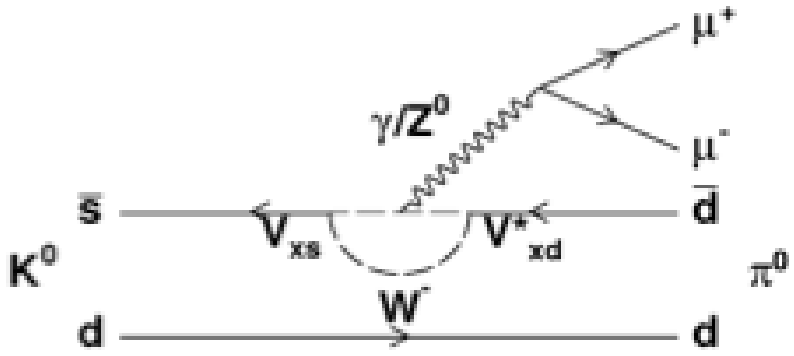
LHCb was designed for heavy flavour physics

This had strong impact on geometry, size of subsystems, acceptance and trigger main mechanism.

The decay length of a kaon is typically much larger than that of a B or a D.
As final states, kaons are present in the vast majority of LHCb programme but kaon decays as a topic of study is difficult: geometry is a limitation, as well as the trigger.
However a flexible software trigger and a full reconstruction can mitigate the problem: Upgrade fully software trigger can reach 100% efficiency for kaon physics

$K_S \to \mu+\mu-$: see Pescatore's talk

$K_S \to \pi^0 \mu^+ \mu^-$ @LHCb



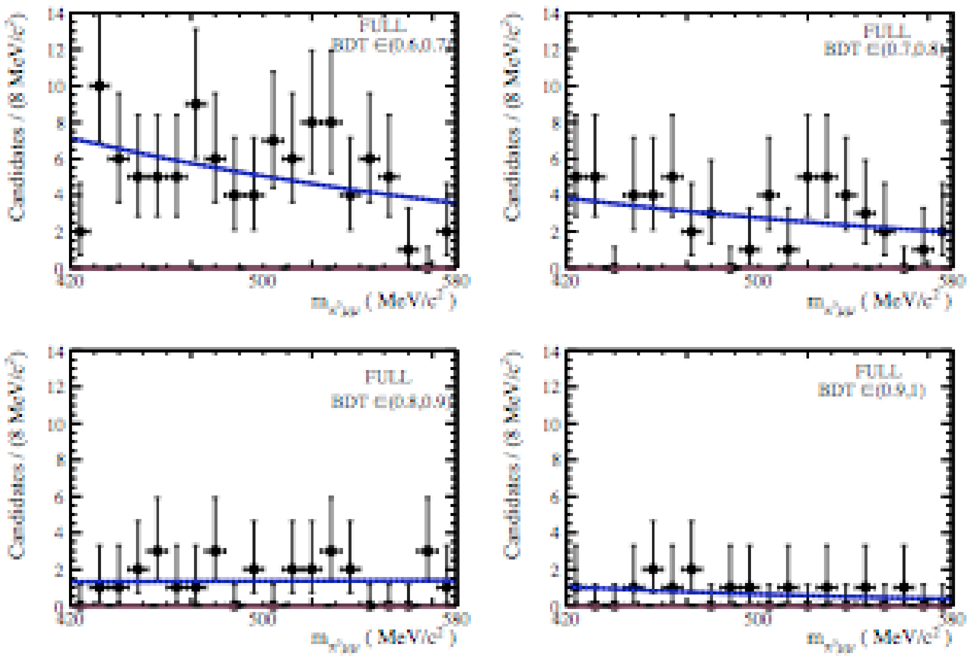
$s \to dll$ decays are potentially sensitive to NP

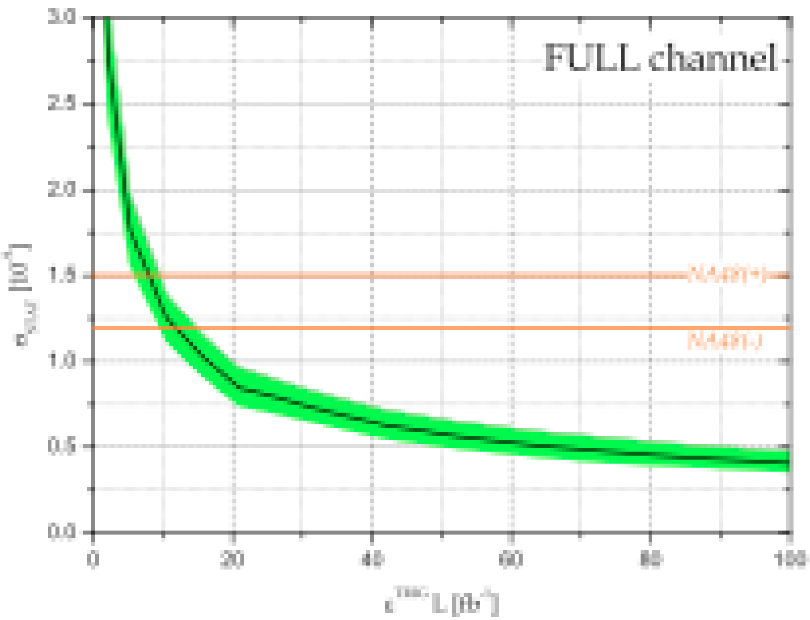
$BR(K_L \to \pi^0 \mu^+ \mu^-)_{EXP} < 3.8\ 10^{-10}$ @90% CL [KTEV, PRL84 5279]
Could be enhanced up to one order of magnitude in NP
(JHEP09 017)

SM prediction for KL is strongly limited by KS measurement by NA48:
$BR(K_S \to \pi^0 \mu^+ \mu^-)_{EXP} = (2.9\ ^{+1.5}_{-1.2} \pm 0.2)\ x10^{-10}$ [PLB599 197]

$K_S \to \pi^0 \mu^+ \mu^-$ @LHCb

Use BDT to suppress combinatorial background
(physics background is negligible)
Use RUN I data to get realistic estimate of background for sensitivity studies





Strongly limited by hardware trigger.
Sensitivity better than NA48 achievable with fully software trigger

Conclusions

Kaon physics has played a large role in establishing the basis of the SM, and now has a fundamental role in the search for NP.

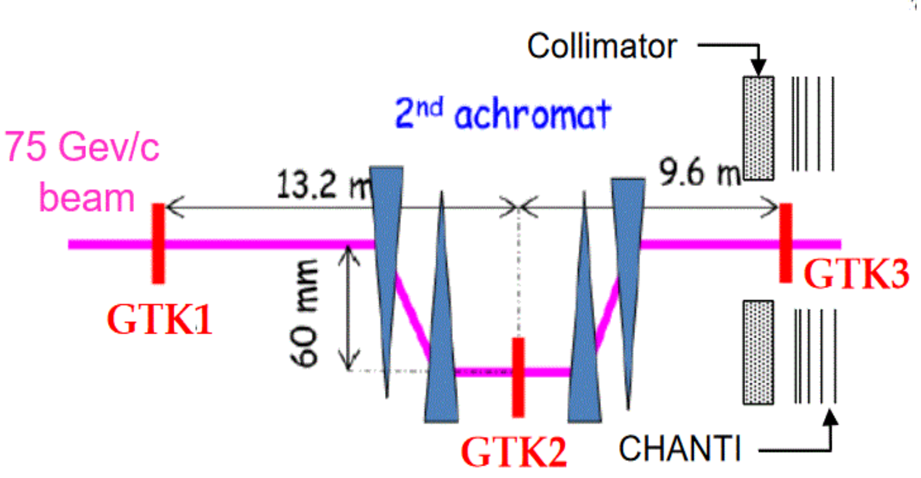
Kaon physics is a broad subject, with several contributing experiments: KLOE2, KOTO, LHCb, NA62, OKA among others. I have concentrated on rare decays.

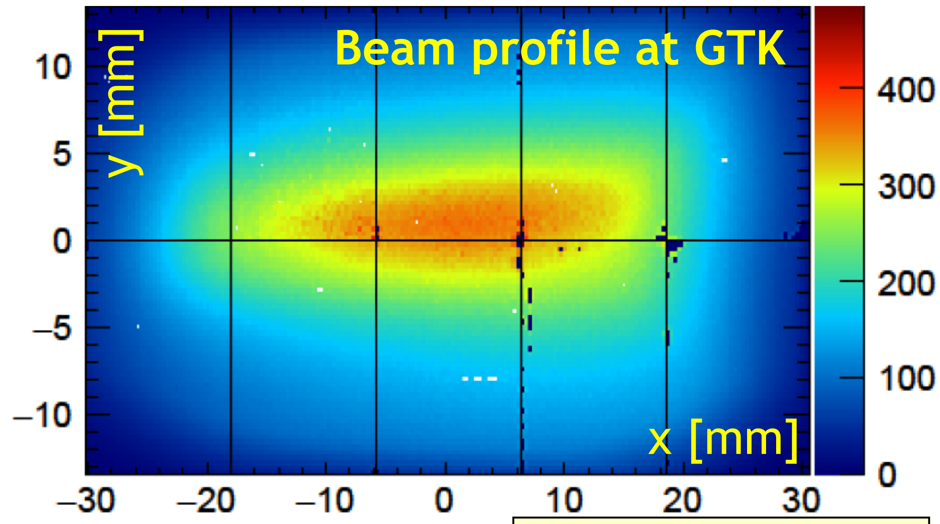
The NA62 and KOTO experiments are exploring physics beyond SM via the ultra-rare decays $K^{+,0} \rightarrow \pi^{0,+} \nu\nu$:
$K^+ \rightarrow \pi^+ \nu\nu$: NA62 expects to reach SM sensitivity soon;
BR measurement expected in the next few years
$K^0 \rightarrow \pi^0 \nu\nu$: KOTO expects to reach $< 10^{-19}$ sensitivity soon;
SM sensitivity expected by 2021

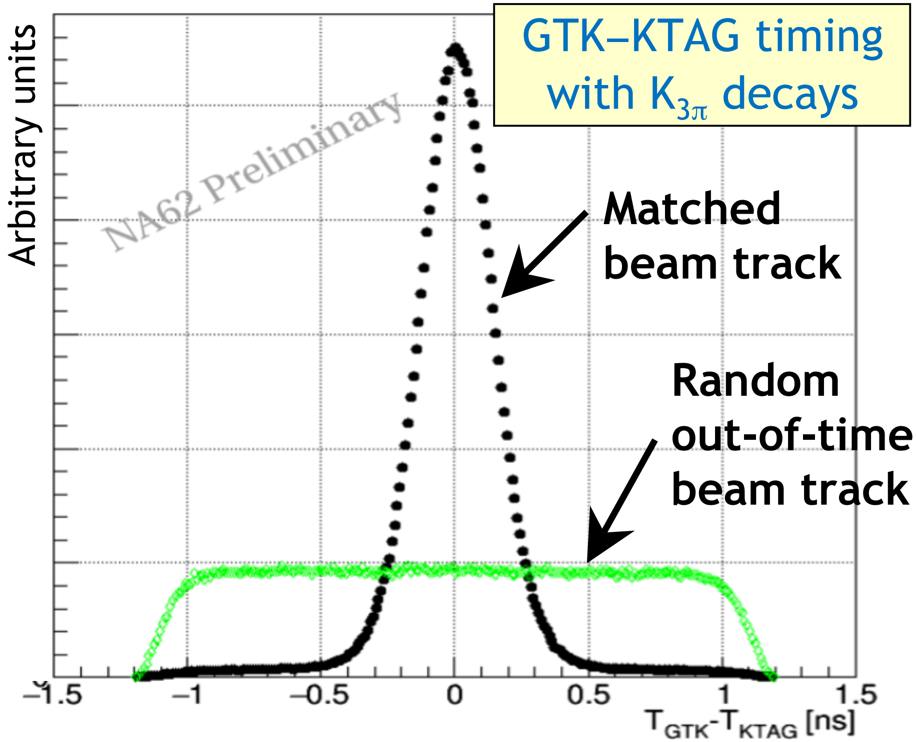
The LHCb experiment is placing limits on K_S rare decays.
Will reach the full potential after fully software trigger is in place

Spares

Beam tracker: the Gigatracker







<u>Tracker design:</u>

❖Three Si pixel stations in the beam.

❖Operation at beam rate up to **800 MHz**.

❖In total, **54k** pixels (**300×300 μm²**).

❖Thickness: **<0.5% X_0** per station.

<u>Performance at 40% beam intensity:</u>

❖Track reconstruction efficiency: **75%**.

❖Time resolution $\sigma(t_{BeamTrack}) \approx 100$ ps.

❖Beam track mis-tagging probability: **1.7%**.

❖Spatial matching: beam/downstream track intersection, $\sigma_{CDA} \approx 1.5$ mm.

$K_{\pi+\nu\nu}$ selection

- PNN trigger: RICH, CHOD signals and LAV, MUV and LKr vetos at L0; KTAG, LAV and STRAW at L1

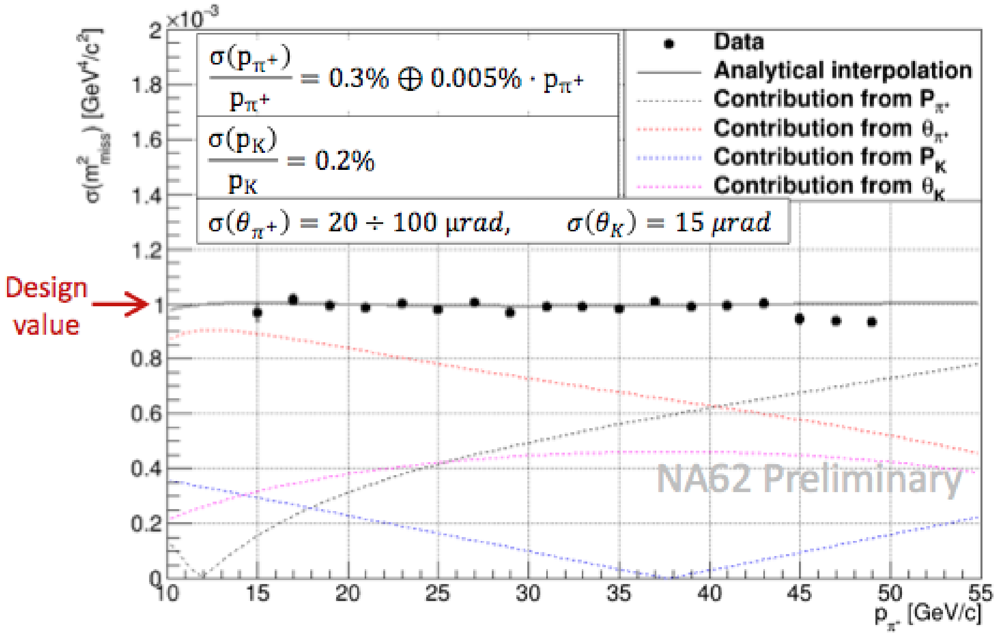
- Single π^+ topology, $15 < P_\pi < 35$ GeV/c
- K/π matching in time (KTAG/GTK vs CHOD/RICH)
- K/π matching in space (GTK and STRAW track)

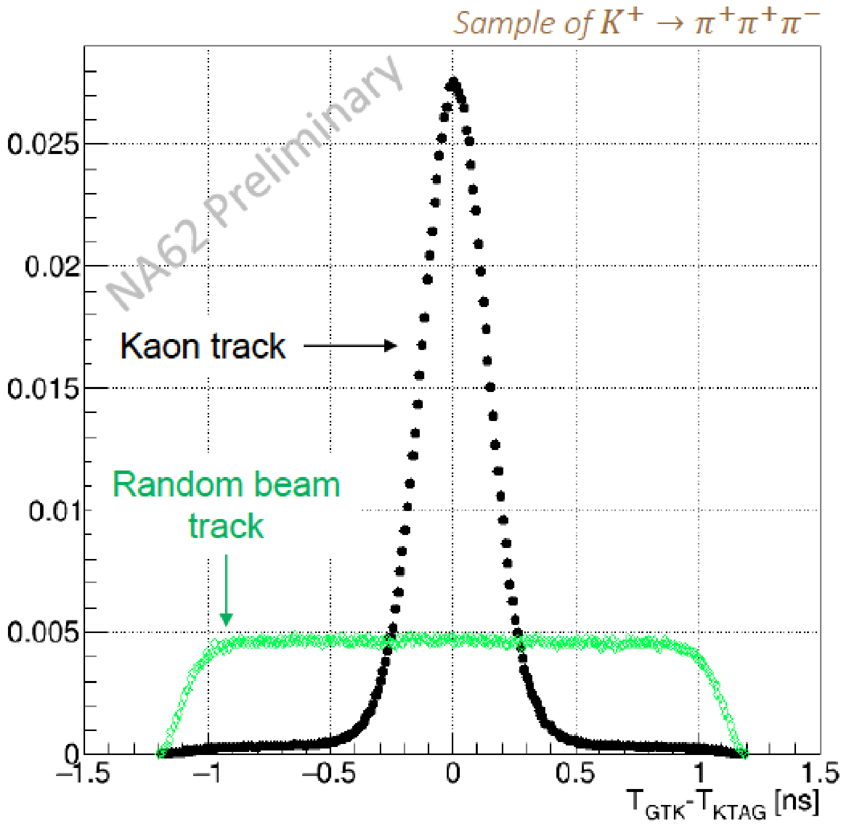
- Fiducial decay region: 110/115 < Z_v < 165 m and Z_v vs π position at STRAW (remove early decays; CHANTI against interactions in GTK3)

- Particle ID (Cherenkov, calorimeters, muon veto)
- Photon veto

- Signal regions: 2 regions in m^2_{miss} vs $P_{\pi+}$ shown on next slide
Analysis done in 3D space: m^2_{miss}, m^2_{miss}(RICH), m^2_{miss}(no GTK)
(kinematical suppression for $\pi^+\pi^0$ and $\mu^+\nu$ measured on data with events selected using calorimeters)

Missing mass resolution, GTK matching





Time and space matching

Mis-tagging probability: ~1.7% (75% efficiency)

$K_{\pi+\nu\nu}$ 5% of 2016 sensitivity

Normalization: $K^+ \rightarrow \pi^+\pi^0$ (in $\pi^+\pi^0$ region before γ rejection on minimum bias events)

5% of 2016 statistics:

N(K decays) ~ 2.3×10^{10}

N(normalization) = 3.3×10^8

Acceptance (normalization) ~ 7%

Acceptance signal ~ 3.3%

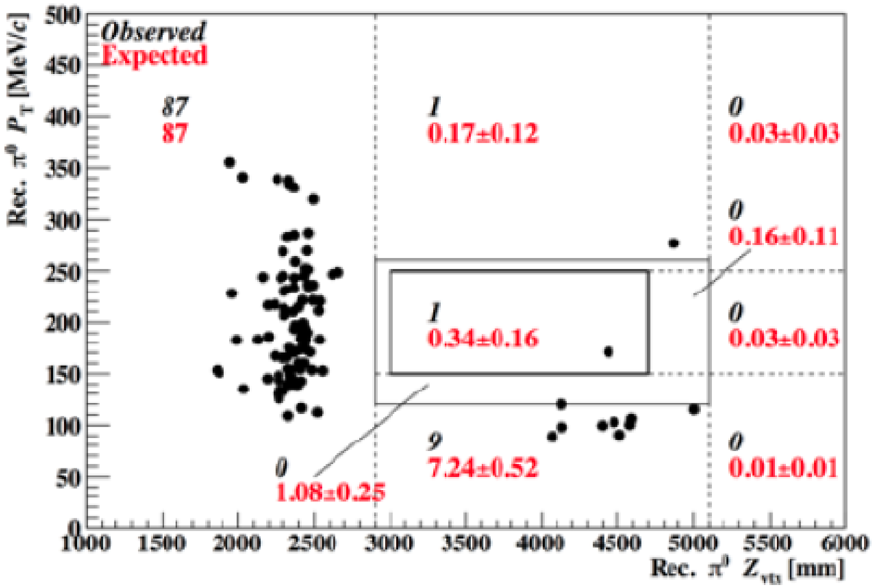
N(Expected $\pi\nu\nu$) ~ 0.064 assuming SM branching ratio

N(K decays) ~ 2.3×10^{10} [5% 2016 statistics]

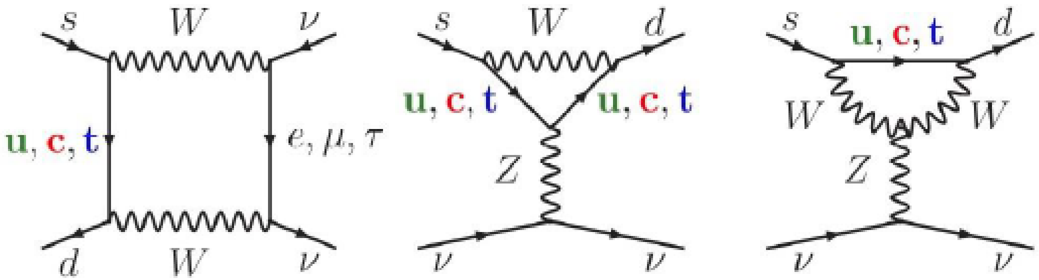
Process	Expected Events	Branching ratio
$K^+ \rightarrow \pi^+\pi^0$	0.024	0.2066
$K^+ \rightarrow \mu^+\nu$	0.011	0.6356
$K^+ \rightarrow \pi^+\pi^+\pi^-$	0.017	0.0558
Early Decays	< 0.005	

KOTO 2013 data

Background source	Number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
Pileup of accidental hits	0.014 ± 0.014
Other K_L background	0.010 ± 0.005
Halo neutrons hitting NCC	0.056 ± 0.056
Halo neutrons hitting the calorimeter	0.18 ± 0.15
Total	0.34 ± 0.16



- FCNC loop processes: s→d coupling and highest CKM suppression



- Very clean theoretically: Short distance contribution. No hadronic uncertainties.

- SM predictions [Buras et al. JHEP 1511 (2015) 33]

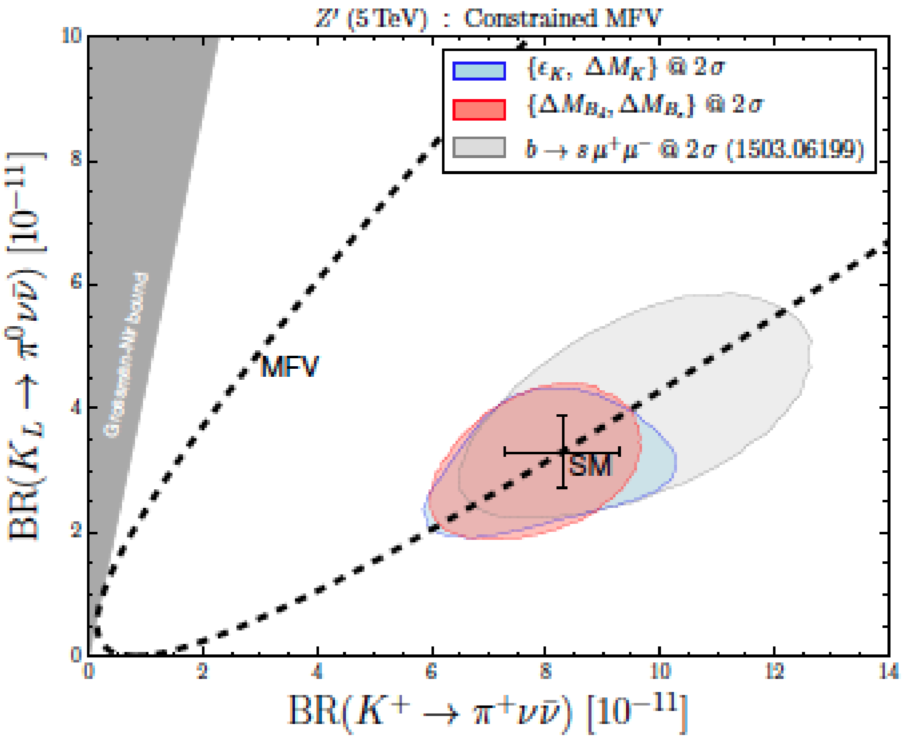
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6) \cdot 10^{-11}$$

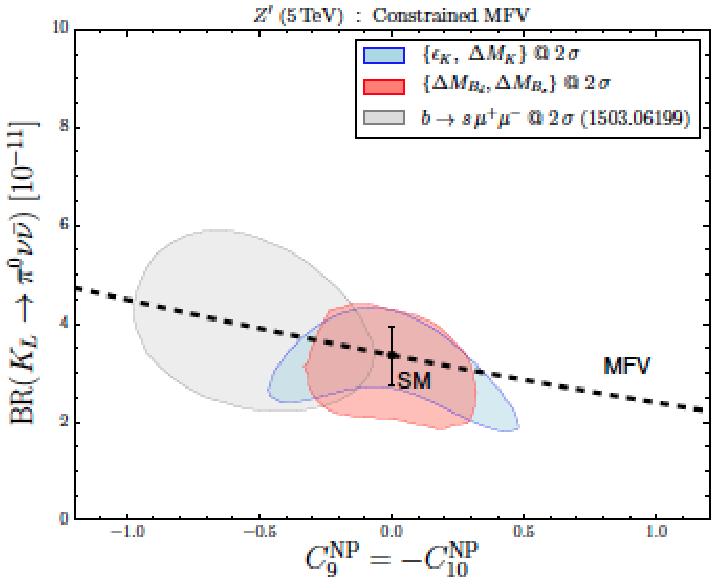
Testing the SM (III)

CMFV with Z' (5 TeV):

JHEP 1511



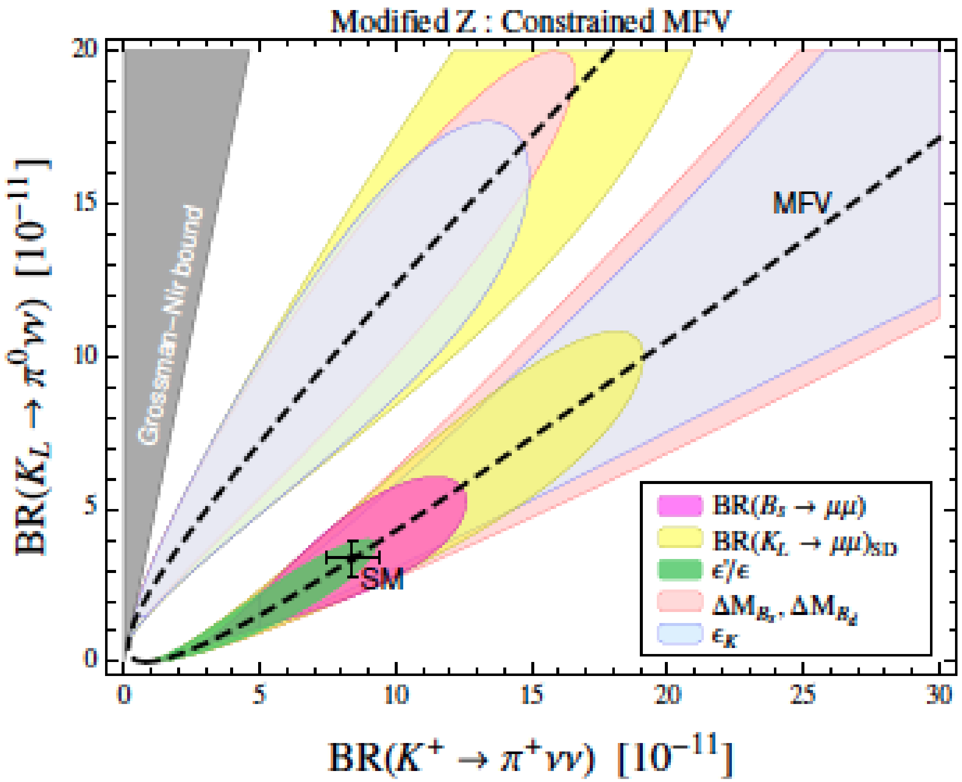
JHEP 1511



Testing the SM (IV)

CMFV with modified Z:

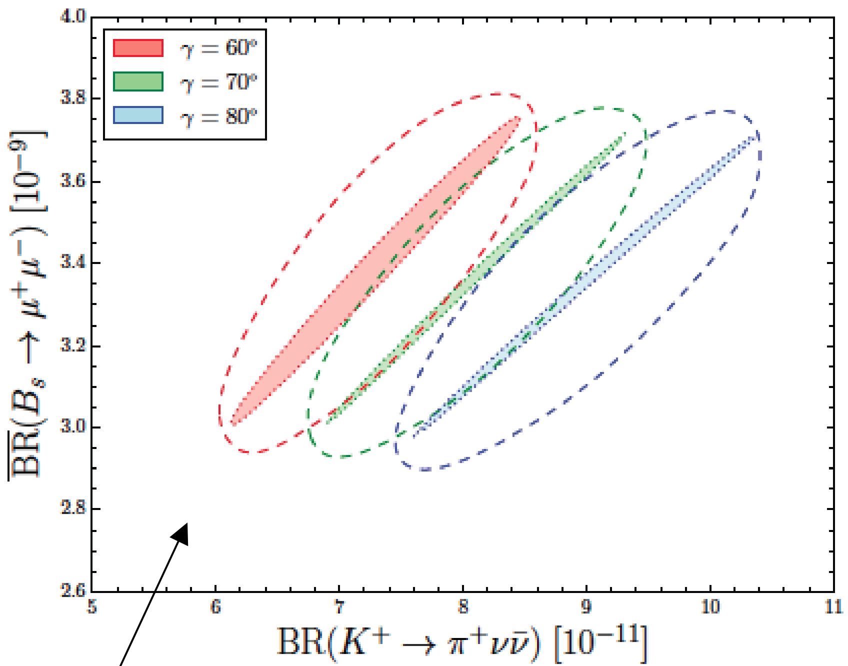
JHEP 1511



Filled regions: uncertainties from V_{ub} , V_{cb} , V_{us}

Dashed regions: uncertainties from all other parameters as well

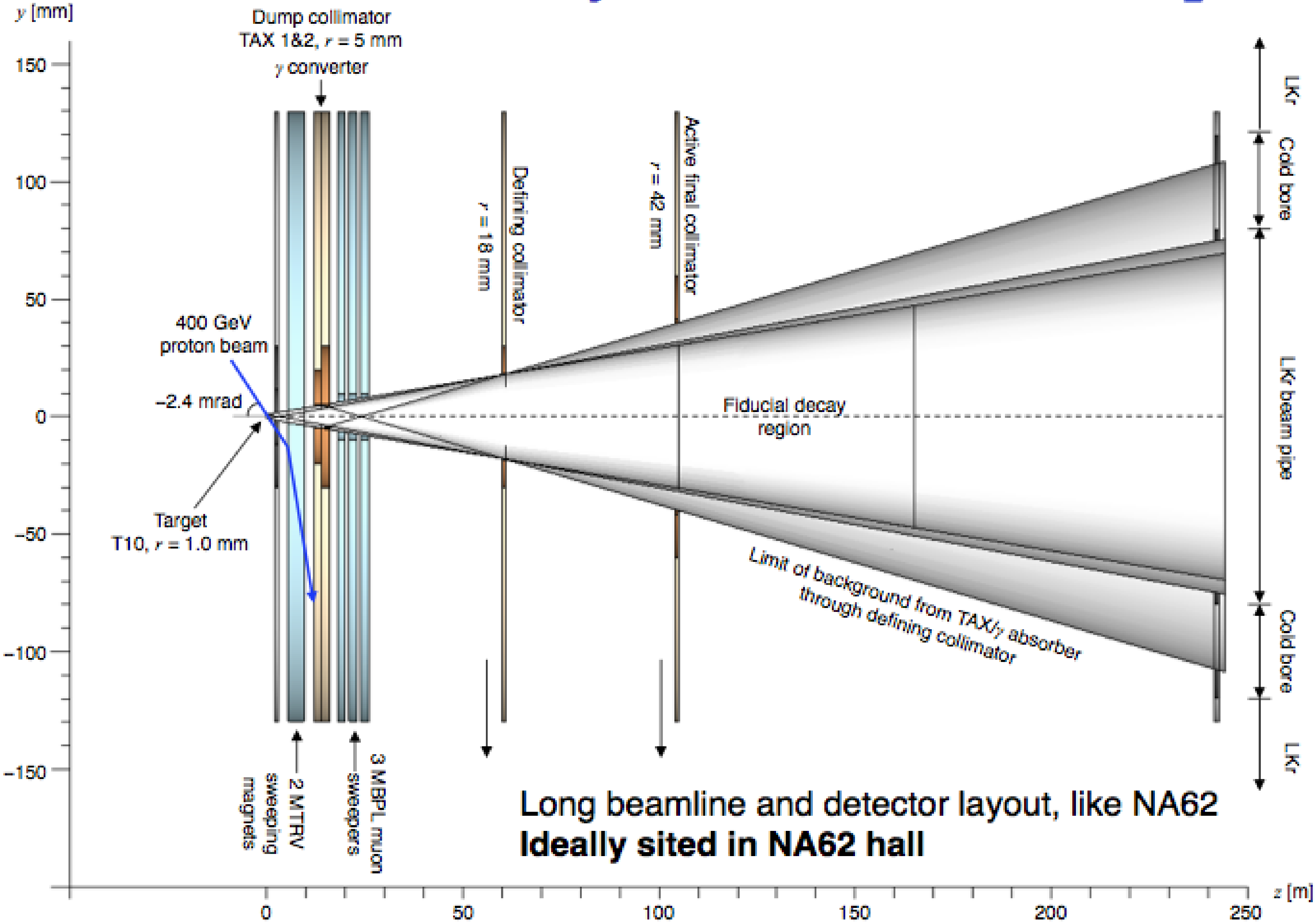
arXiv:1503.02693v2



SM correlations

Could be broken already in CMFV

Neutral beamline layout

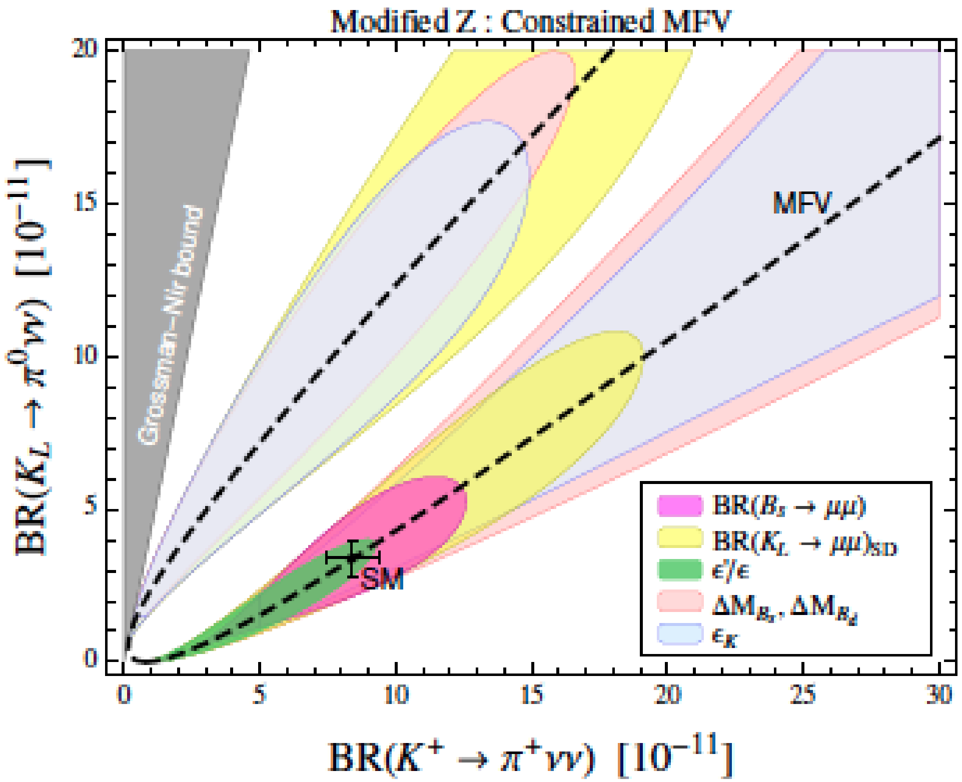


Long beamline and detector layout, like NA62
Ideally sited in NA62 hall

Testing the SM (III)

CMFV with modified Z:

JHEP 1511



CMFV with Z' (5 TeV):

JHEP 1511