KAON EXPERIMENTS AT CERN

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NA62

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PSI

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2013

Introduction +

R_K (recent results) +

Rare kaon decays (prospects) +

Kaon physics

Minimal Flavour Laboratory

- Kaons are the **simplest system** in which flavour physics effects can be studied. Historically, many discoveries have been made in the kaon sector:
- **Indirect CP violation** (K0 mixing)
- **GIM mechanism** (charm quark prediction)

Clean environment

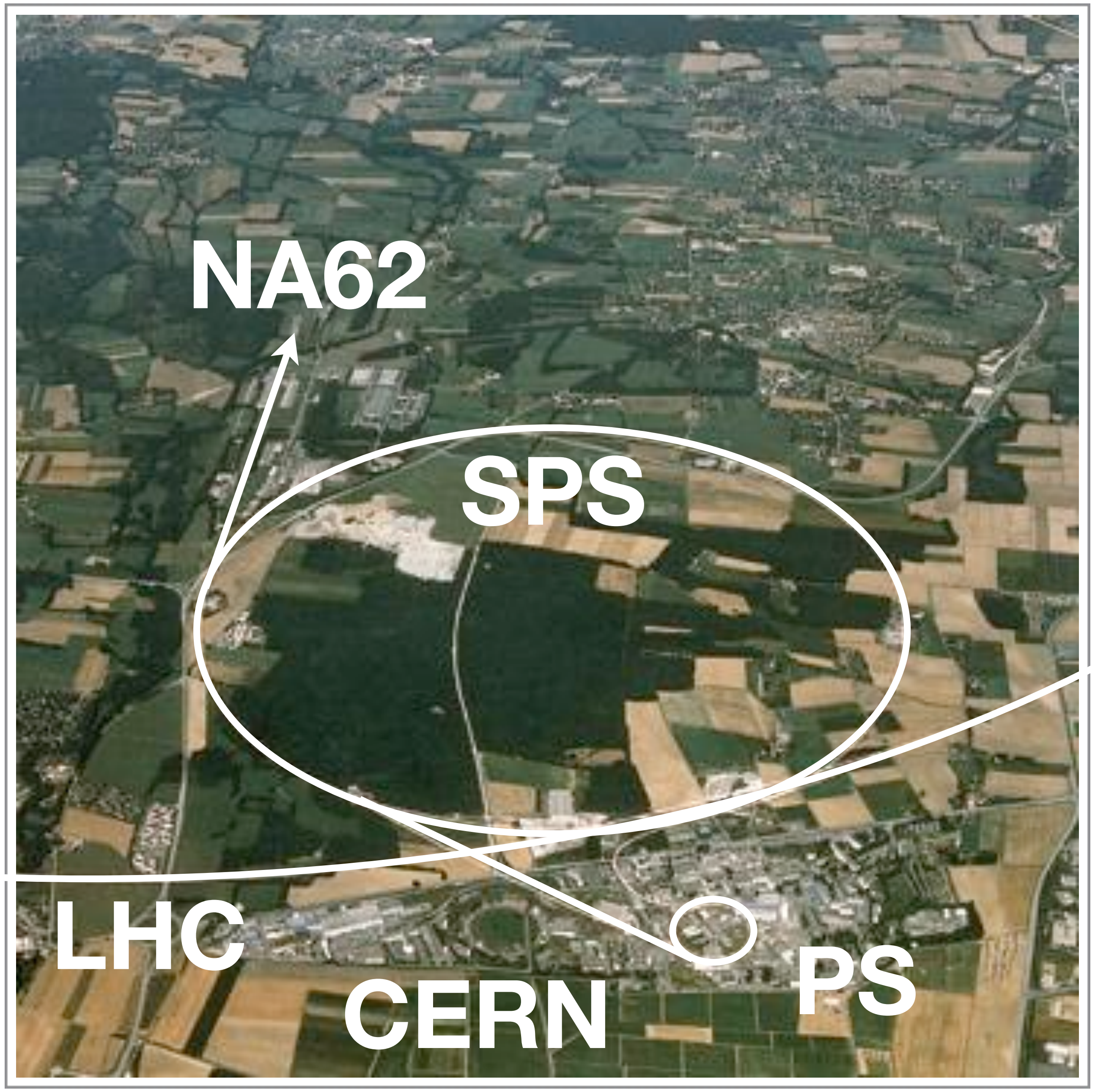
- Kaon have simple decay topologies → **clean experimental signatures**
- Rare decay modes dominated by short distance contributions allow very **accurate theoretical predictions**

Sensitive to new physics

- **GIM suppression** and **hierarchical CKM matrix** → flavour changing neutral current (FCNC) transitions in the kaon sector are most suppressed (effects due to $b \to d$ and $b \to s$ transitions are larger)
- New physics (NP) **may not be hierarchical** so effects would be **most visible in the kaon sector**


FNAL
KTeV
ORKA
BNL
E865
E77
E787
E949
CERN
NA31
CPLEAR
NA48
NA62
LNF
KLOE
KLOE2
IHEP
ISTRA+
OKA
KEK/
J-PARC
E391a
KOTO
TREK
around the world
Stopped kaons
Decay in flight
Collider φ Factory

Kaons at CERN



NA31 1979 - 1991
Direct CP violation in neutral Kaons

NA48 1997 - 2004
Direct CP violation in neutral Kaons
/1 Rare K_S and hyperon decays
/2 $K^{\pm}$ decays, K_{e4}, Rare K studies

NA62-R_K 2007
R_K: lepton universality

NA62 2014
Golden mode $\pi\nu\nu$

NA62 today: **>10** countries **27** institutions **~200** participants

R_K : Lepton universality

K_{e2}

$$R_K = \frac{\Gamma\left(K^{\pm} \to e^{\pm}\nu_e\right)}{\Gamma\left(K^{\pm} \to \mu^{\pm}\nu_\mu\right)}$$

$K_{\mu 2}$

R_K lepton universality

Standard Model

- The Standard Model process is **helicity supressed.**

-4% radiative corrections

$$R_K^{SM} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_K^{\text{rad.corr.}}\right) = 2.477(1) \times 10^{-5}$$

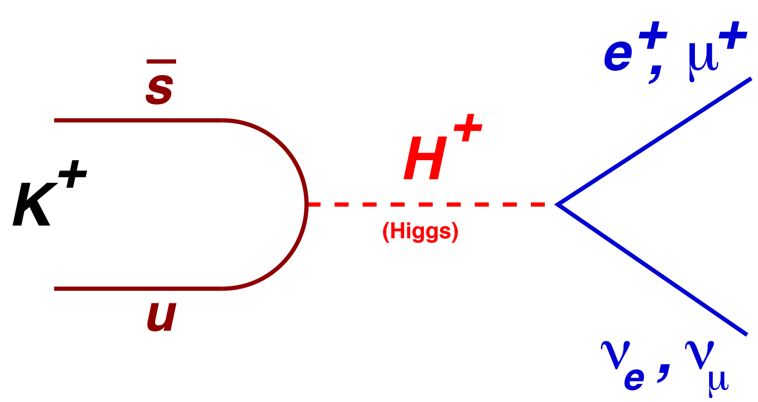
[Cirigliano, Rosell, PhysRevLett 99 (2007) 231801]

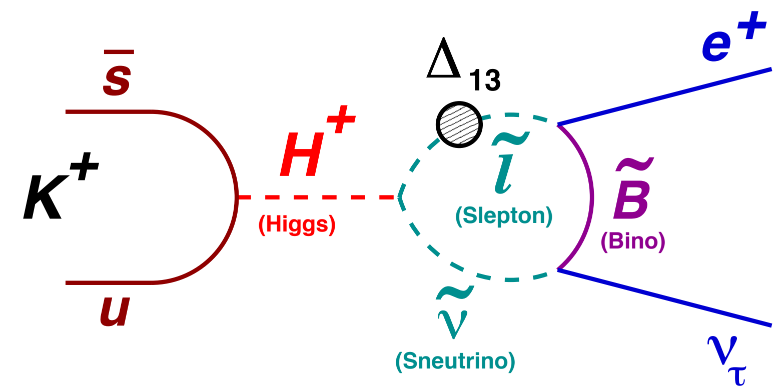
Beyond the Standard Model

- Loop effects are predicted to lead to **lepton flavour violating coupings** $lH^+\nu_\tau$ which give dominant contribution to ΔR_K

$$R_K^{LFV} \approx R_K^{SM}\left[1 + \left(\frac{m_K^4}{M_{H\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2 \tan^6\beta\right]$$

[Masiero, Paradisi, Petronzio PhysRevD 74 (2006) 011701]





- At tree level, decay via **charged Higgs, H^+** instead of W^+ leaves R_K unchanged
- Loops with SUSY particles can modify R_K by up to ~1%

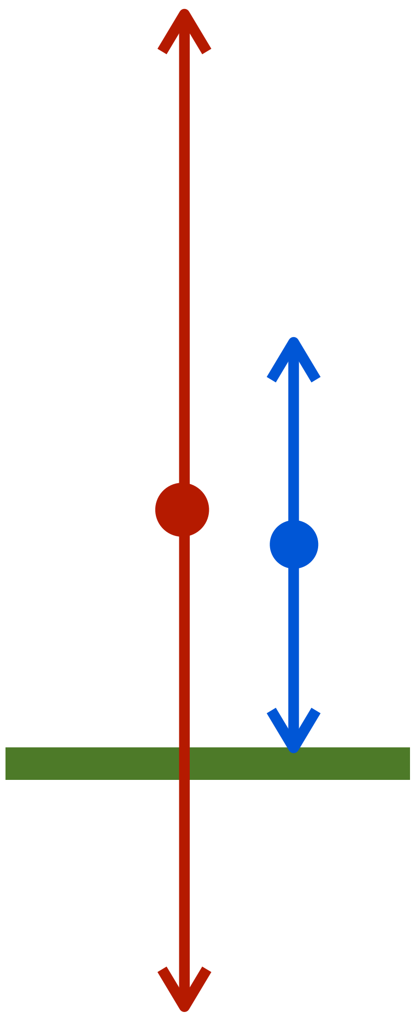
R_K numbers

0.04% relative error on Standard Model prediction

O(1%) enhancement from New Physics

1.2% relative error on World Average before NA62-R_K

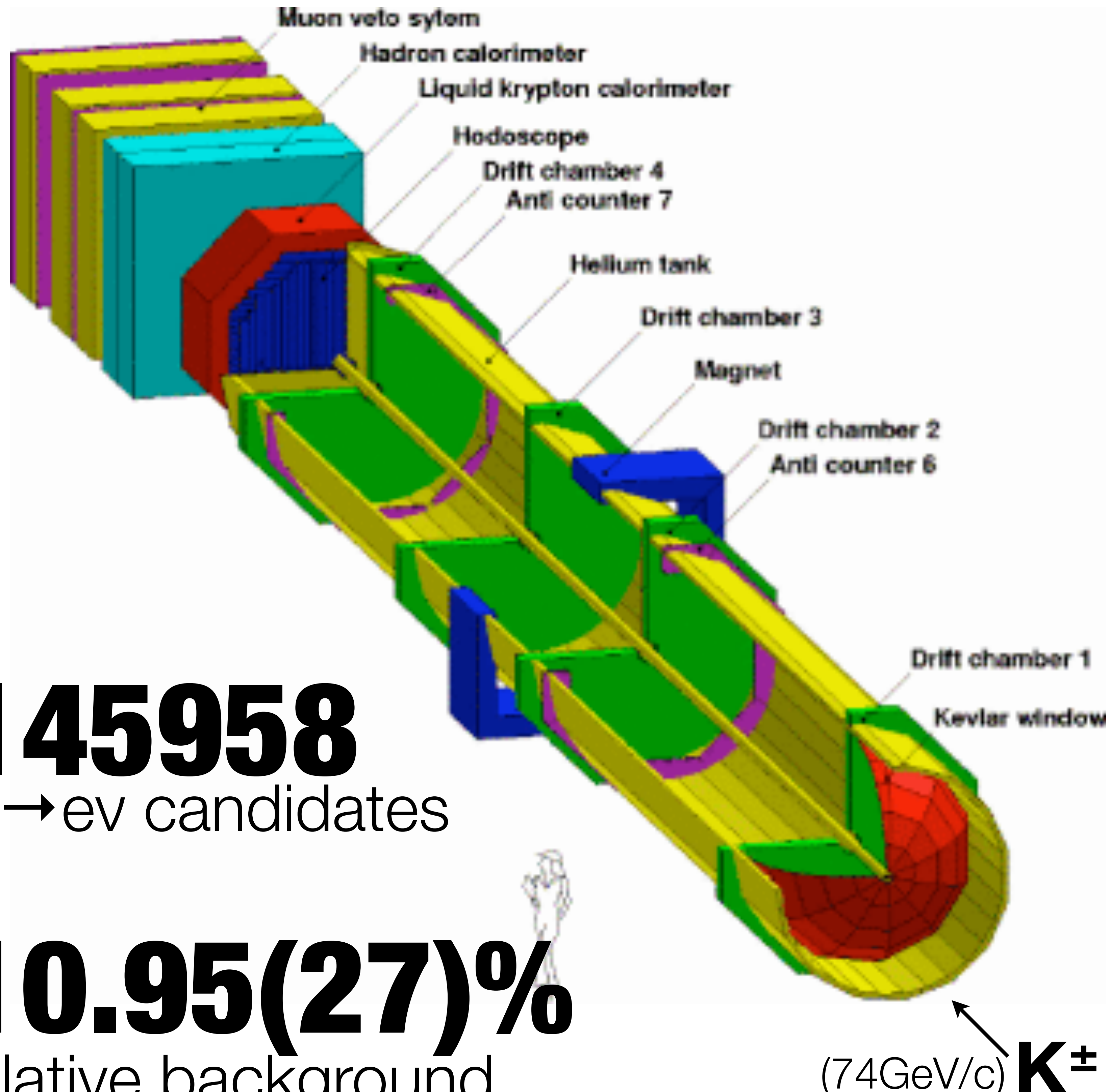
0.5% relative error on NA62-R_K measurement



2010 PDG Average: $R_K = (2.493 \pm 0.031) \times 10^{-5}$

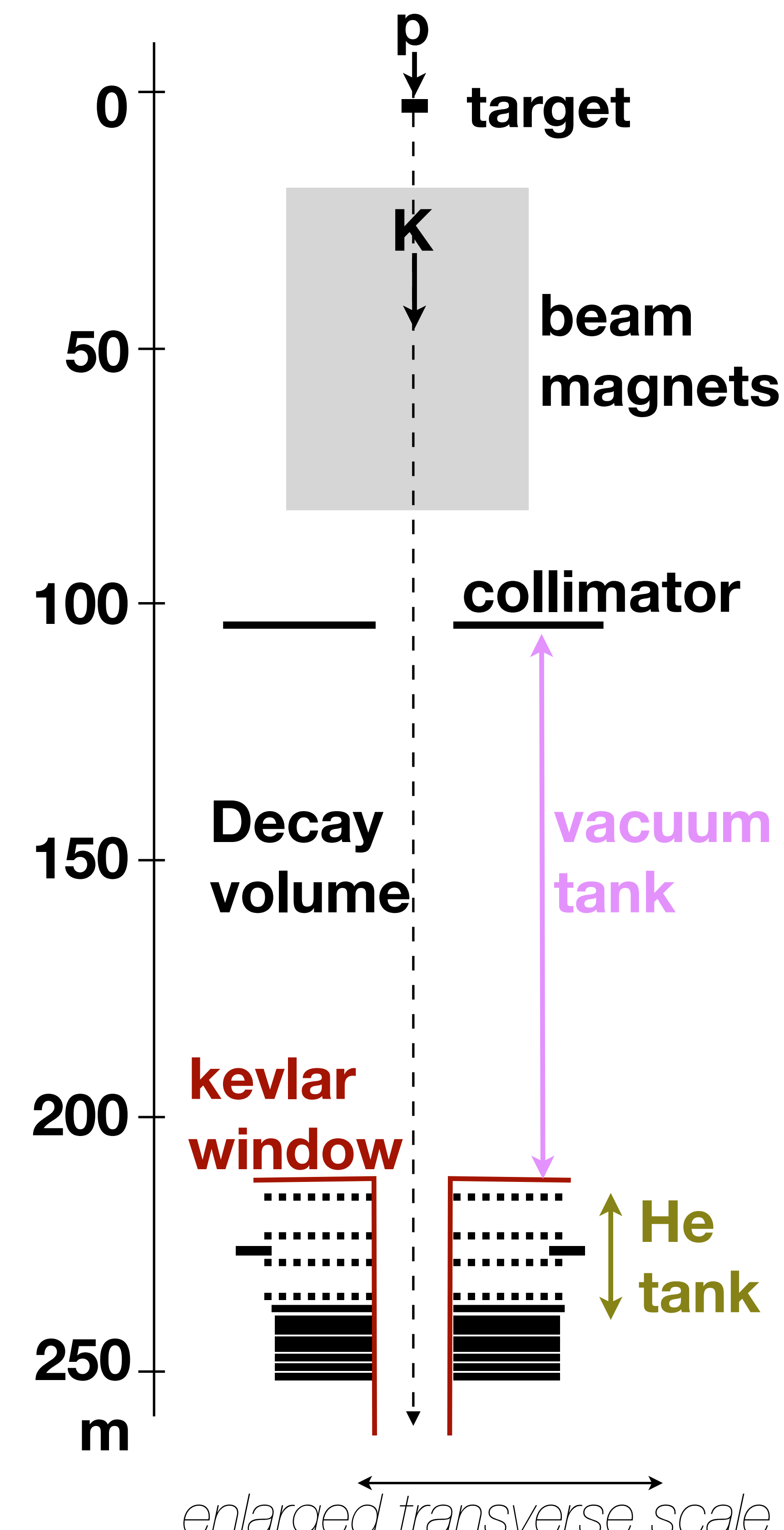
[JPhys G 37 (2010) 075021]

NA48 & NA62-R_K detector



145958
K→eν candidates

10.95(27)%
relative background



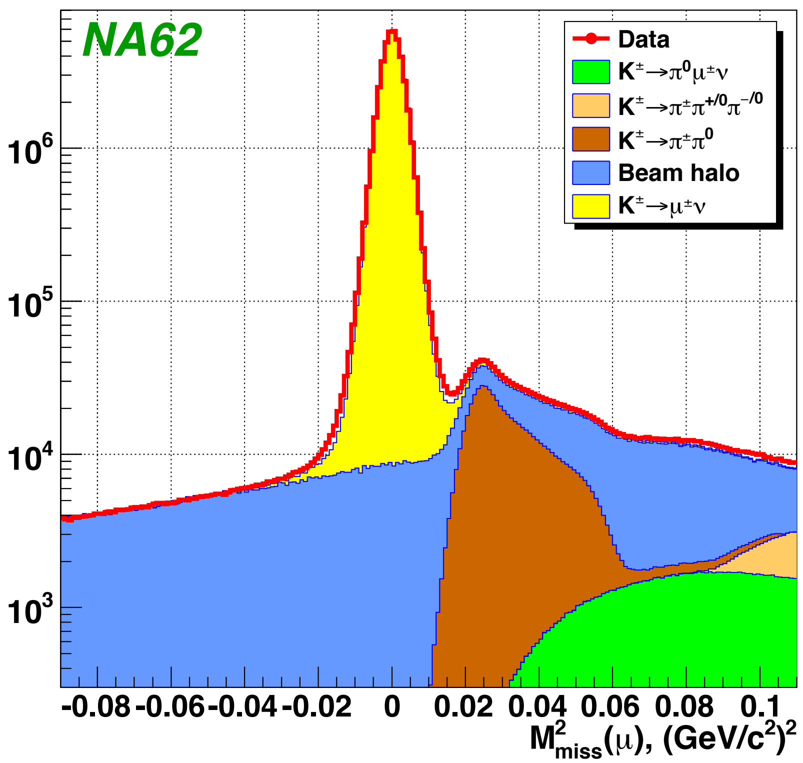
Measurement

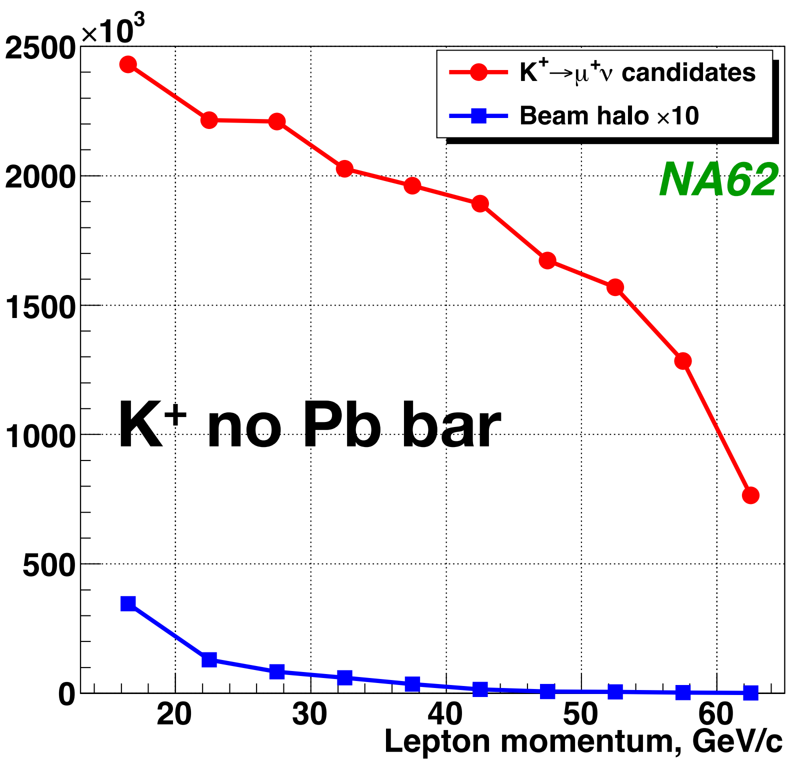
$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2})}{A(K_{e2})} \cdot \frac{f_\mu \times \epsilon(K_{\mu 2})}{f_e \times \epsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}$$

- $1/D$: **$K_{\mu 2}$ trigger downscaling**
- $N(K_{e2})$: **selected candidates**
- $N_B(K_{e2})$: **background events** — **dominant systematic (from $K_{\mu 2}$)**
- A: **geometric acceptance**
- f_μ, f_e: **Particle ID efficiency**
- ϵ: **Trigger efficiency**
- f_{LKr}: **LKr readout efficiency**

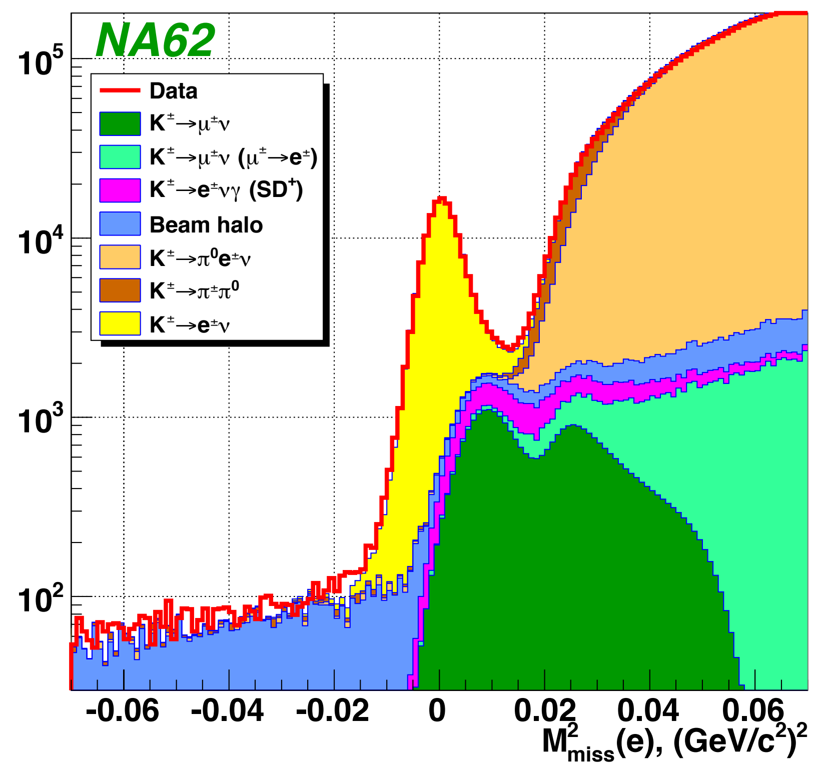
Signal and background

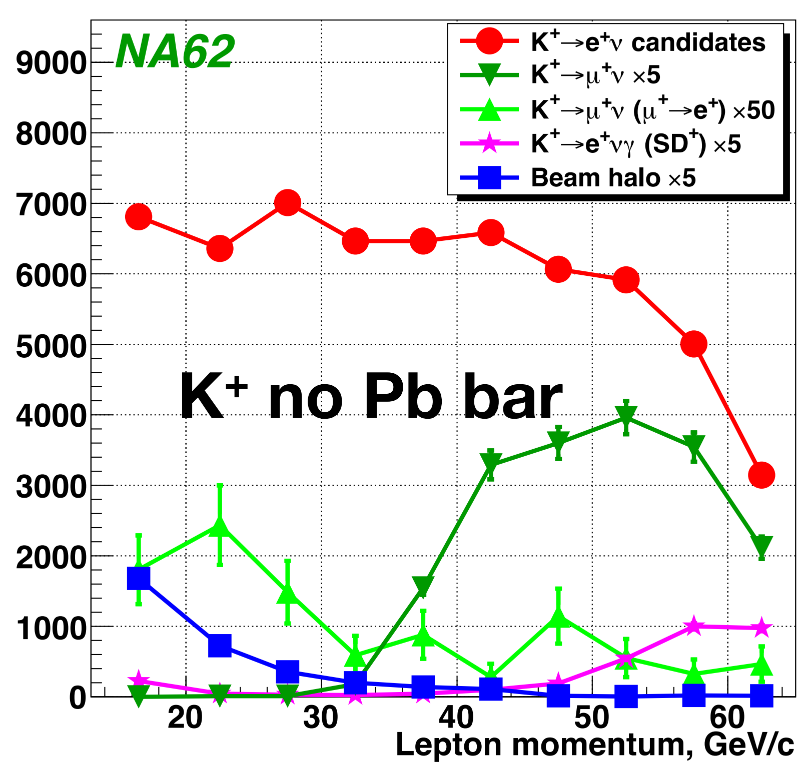
$K_{\mu2}$ selection





K_{e2} selection

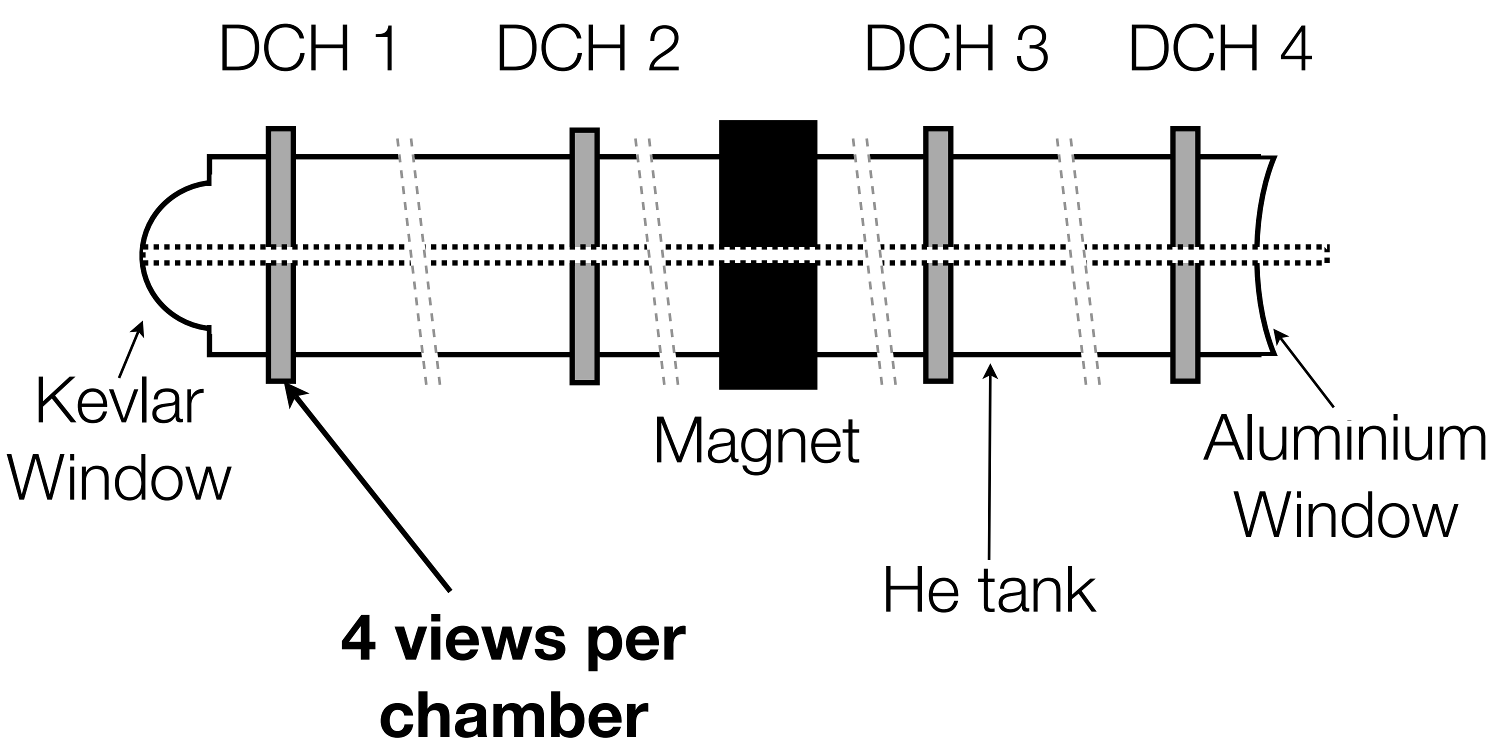


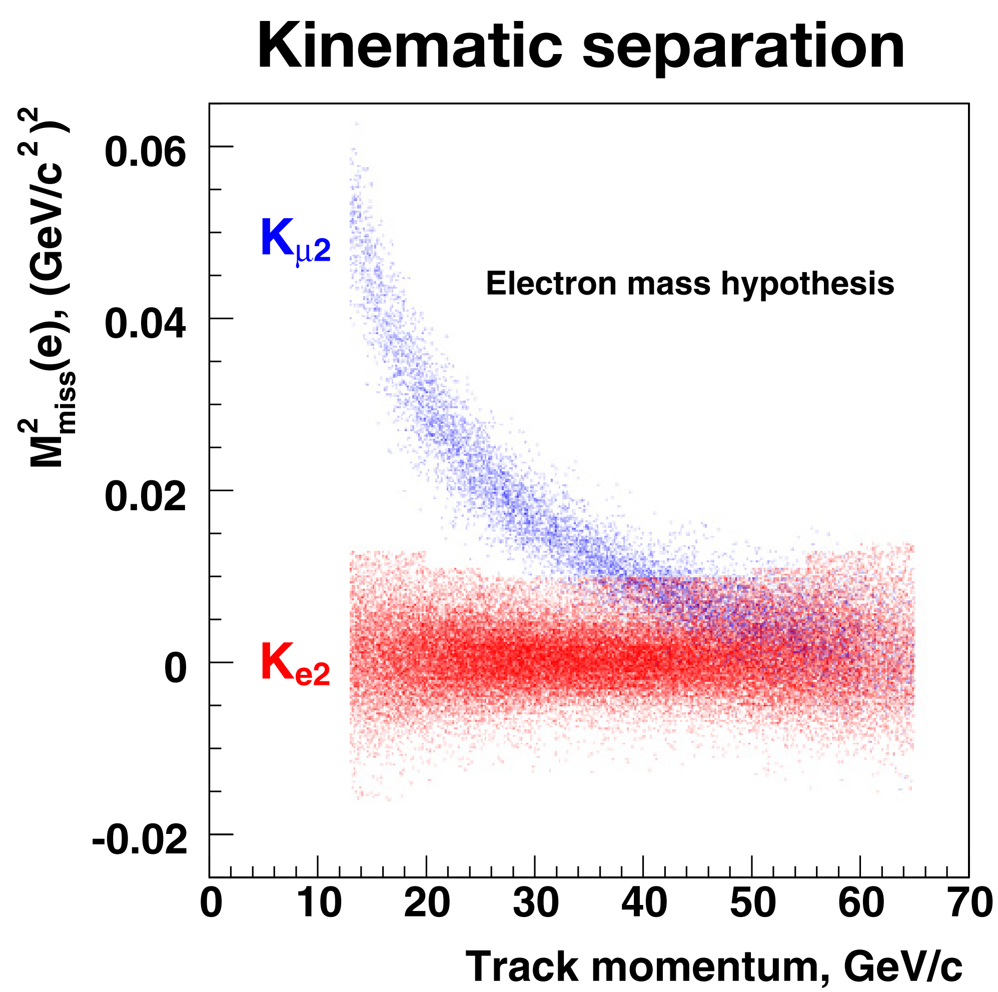


K_{e2} backgrounds

Source	%
$K_{\mu2}$	5.64(20)
$K_{\mu2}$ ($\mu \to e\nu\nu$)	0.26(3)
$K_{e2\gamma}$ (SD^+)	2.60(11)
K_{e3}	0.18(9)
$K_{2\pi}$	0.12(6)
$K^{\mp}$	0.04(2)
μ halo	2.11(9)

Drift chambers



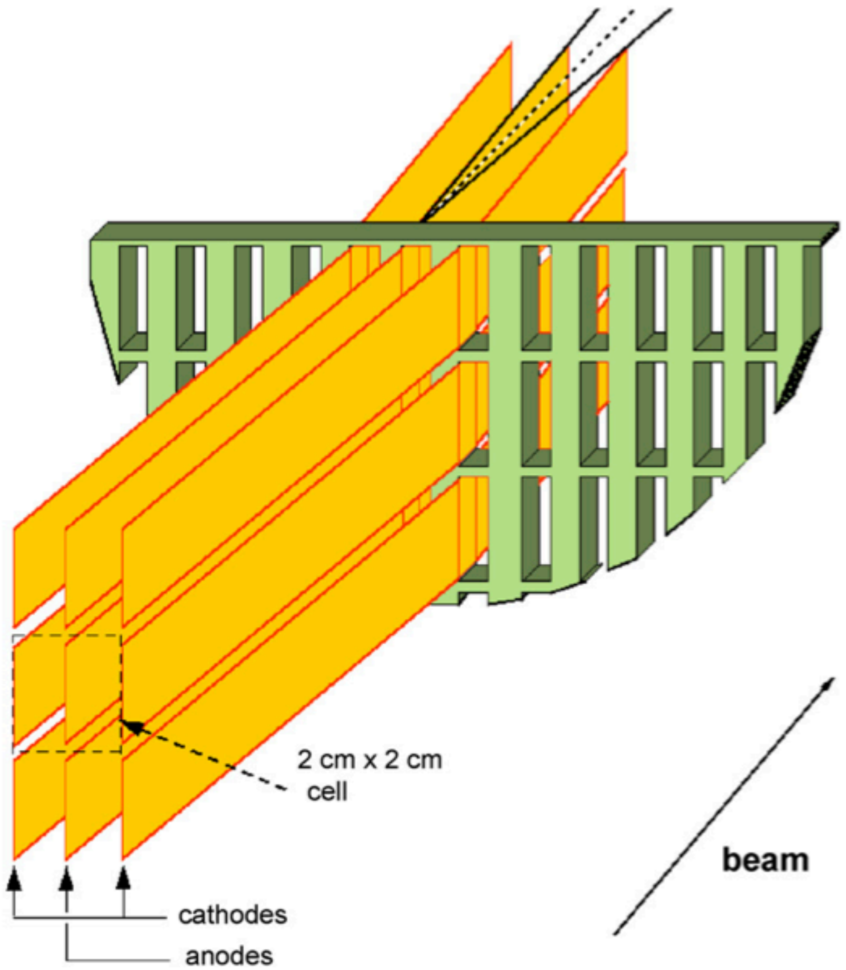


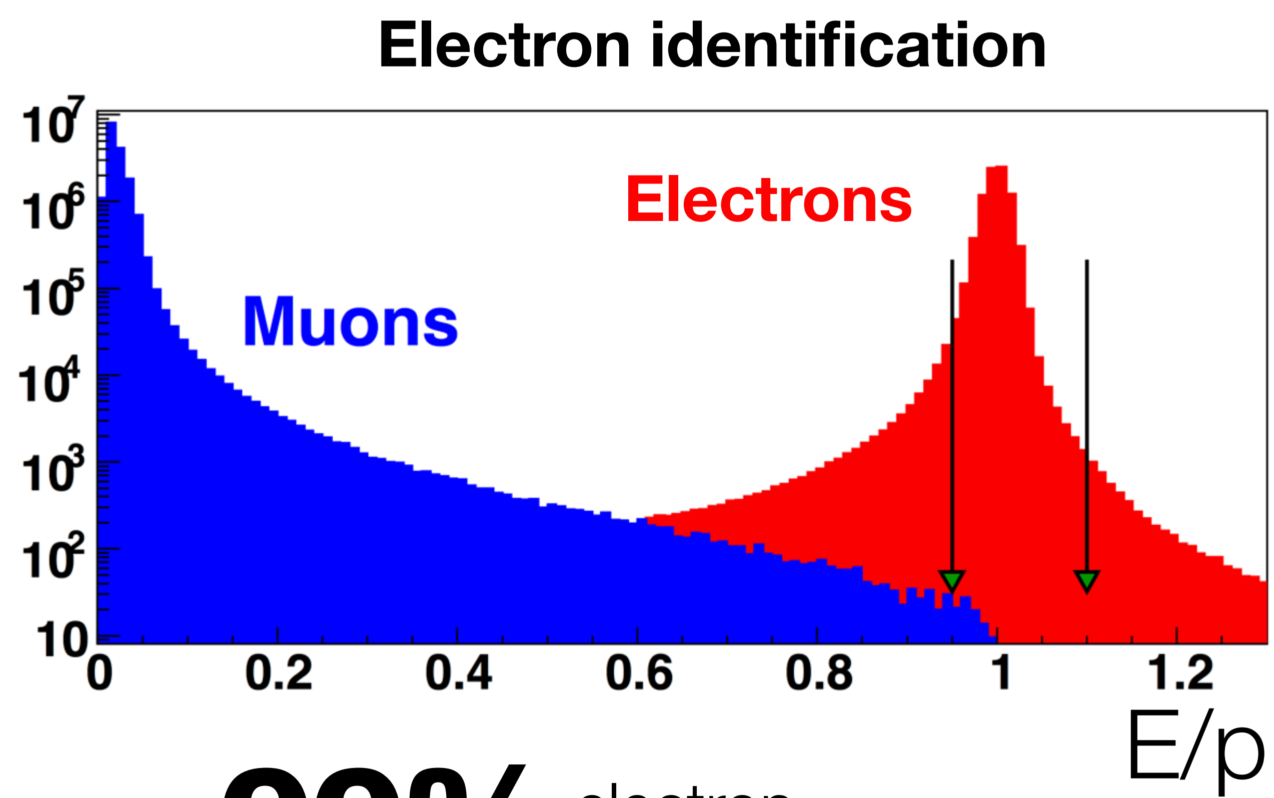
<100µm Average space point resolution in x and y

Spectrometer resolution

$$\sigma_p/p = 0.48\% \oplus 0.009\% p \ [GeV/c]$$

Liquid krypton calorimeter





>99% electron identification efficiency

Lkr Resolution (GeV, cm, ns)

$$\frac{\sigma_E}{E} = \frac{0.032}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.0042$$

$$\frac{\sigma_{X,Y}}{E} = \frac{0.42}{\sqrt{E}} \oplus 0.06$$

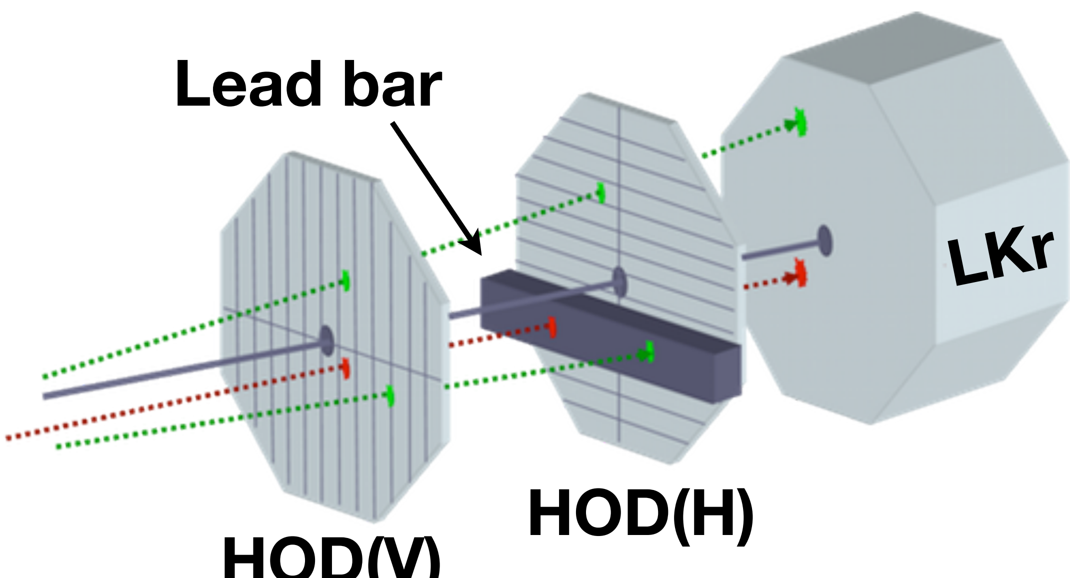
$$\sigma_t = \frac{2.5}{\sqrt{E}}$$

Muon Misidentification

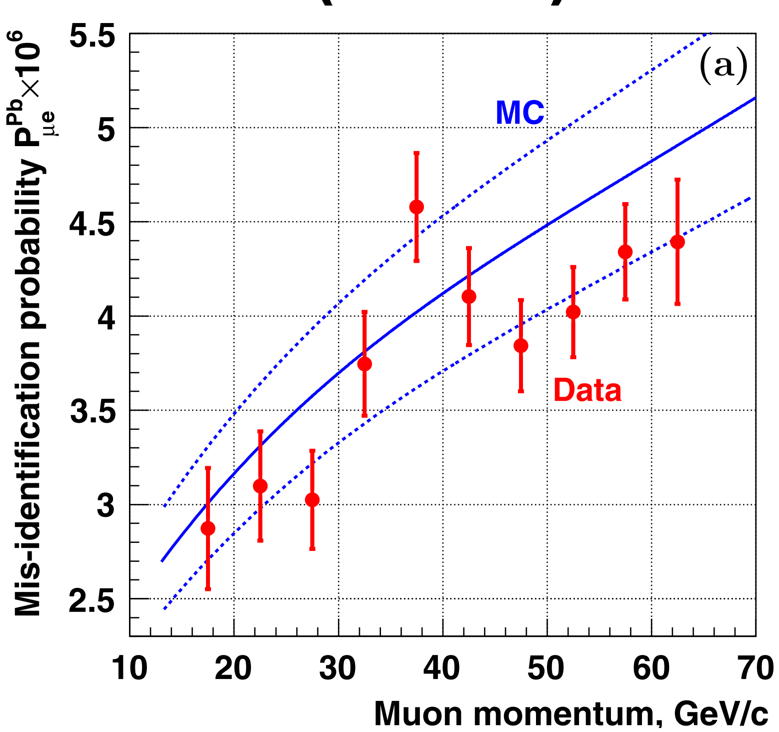
Catastrophic bremsstrahlung in or in front of LKr ➡ **E/p > 0.95 Muon ID'd as electron**

- Subsample of data taken with a 9.2 X_0 Pb bar between HOD's
- Allows collection of electron free samples
- Correct method bias (ionization loss at low **p**, bremsstrahlung at high **p**) with GEANT 4

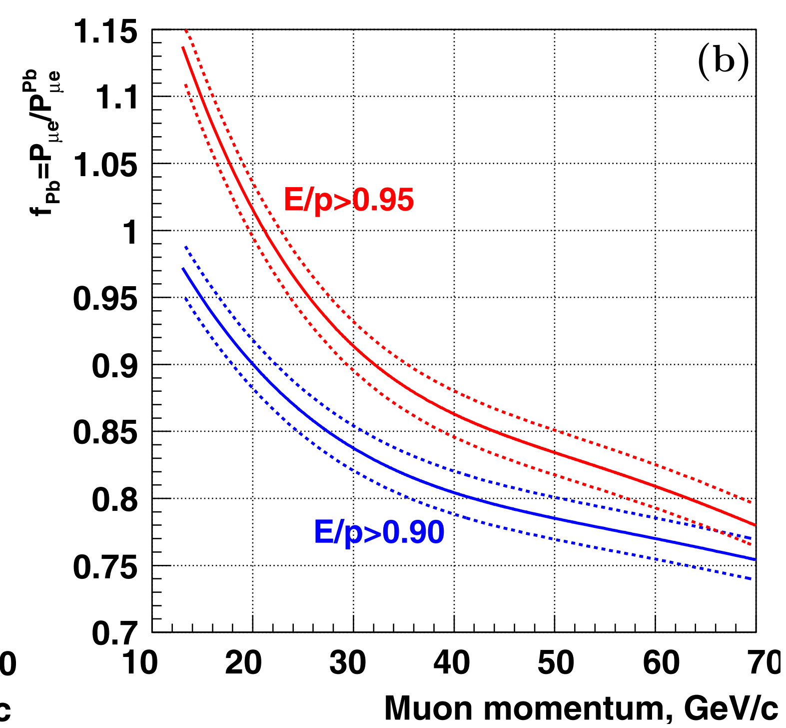
Lead bar excluded geometrically from data taking samples



P(Mis-ID)



GEANT4 Correction Factors



Data samples

4 detector configurations

K^+/K^- lead bar / no lead bar

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10 momentum bins

Acceptance and background depend on the lepton momentum

13-65 GeV/c

To ensure high efficiency in E_{LKr} trigger

background contributions increase at high **p**

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40 independent measurements

Result

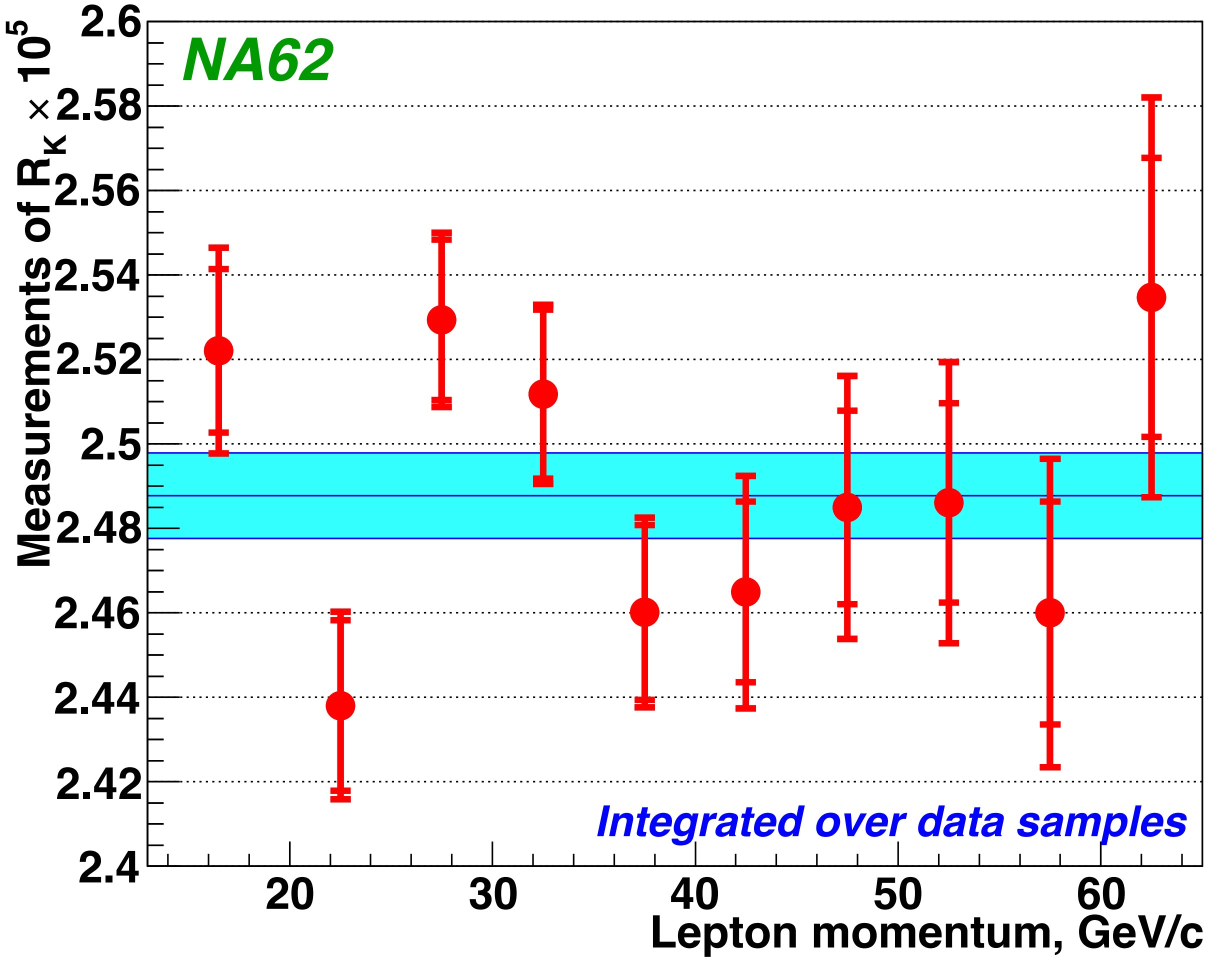
$$R_K = (2.488 \pm 0.010) \times 10^{-5}$$

Source	$\delta R_K (10^{-5})$
Statistics	0.007
$K_{\mu 2}$ bkg	0.004
$K_{e2\gamma}$ SD$^+$ bkg	0.002
K_{e3}, $\pi\pi^0$ bkg	0.003
Muon halo bkg	0.002
Material budget	0.002
Acceptance corr	0.002
DCH alignment	0.001
Electron ID	0.001
LKr readout eff	0.001
Total	**0.010**

$$R_K = (2.488 \pm 0.007_{\mathrm{stat.}} \pm 0.007_{\mathrm{syst.}}) \times 10^{-5}$$

[PhysLettB 719 (2013) 326]

$$\frac{\chi^2}{N_{D.O.F}} = \frac{47}{39} \quad (P = 18\%)$$



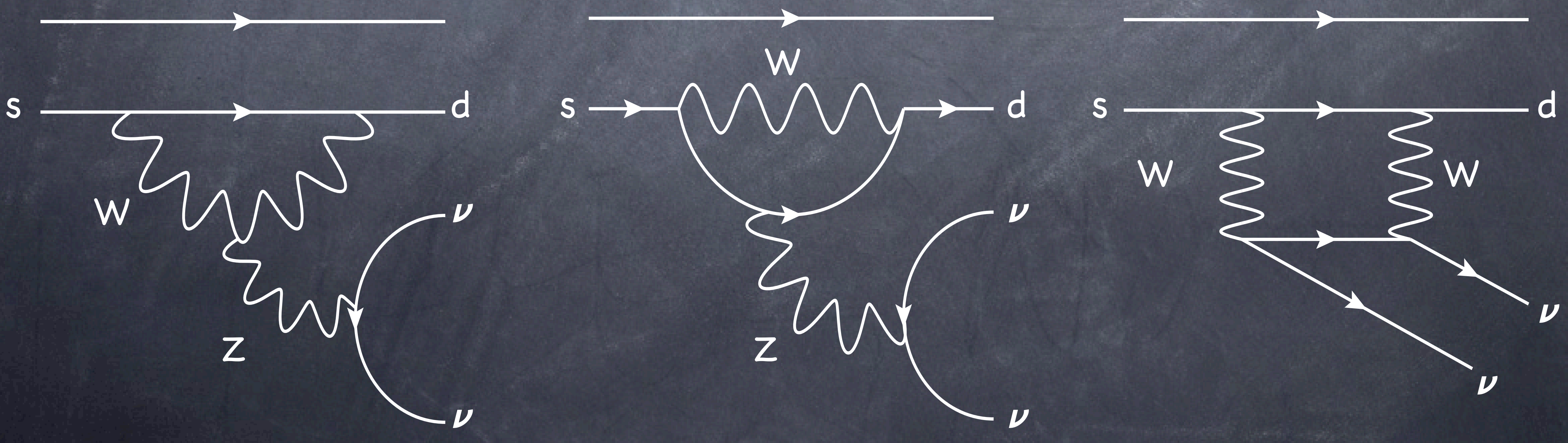
The golden modes

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

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

FCNC

Dominated by box and penguin diagrams



The golden modes

- Theoretically clean handle on CKM matrix unitarity:

$$K^+ \to \pi^+ \nu\nu \longleftrightarrow |V_{ts}^* V_{td}|$$

$$K_L \to \pi^0 \nu\nu \longleftrightarrow \mathrm{Im}(V_{ts}^* V_{td})$$

- Standard Model predictions:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$$

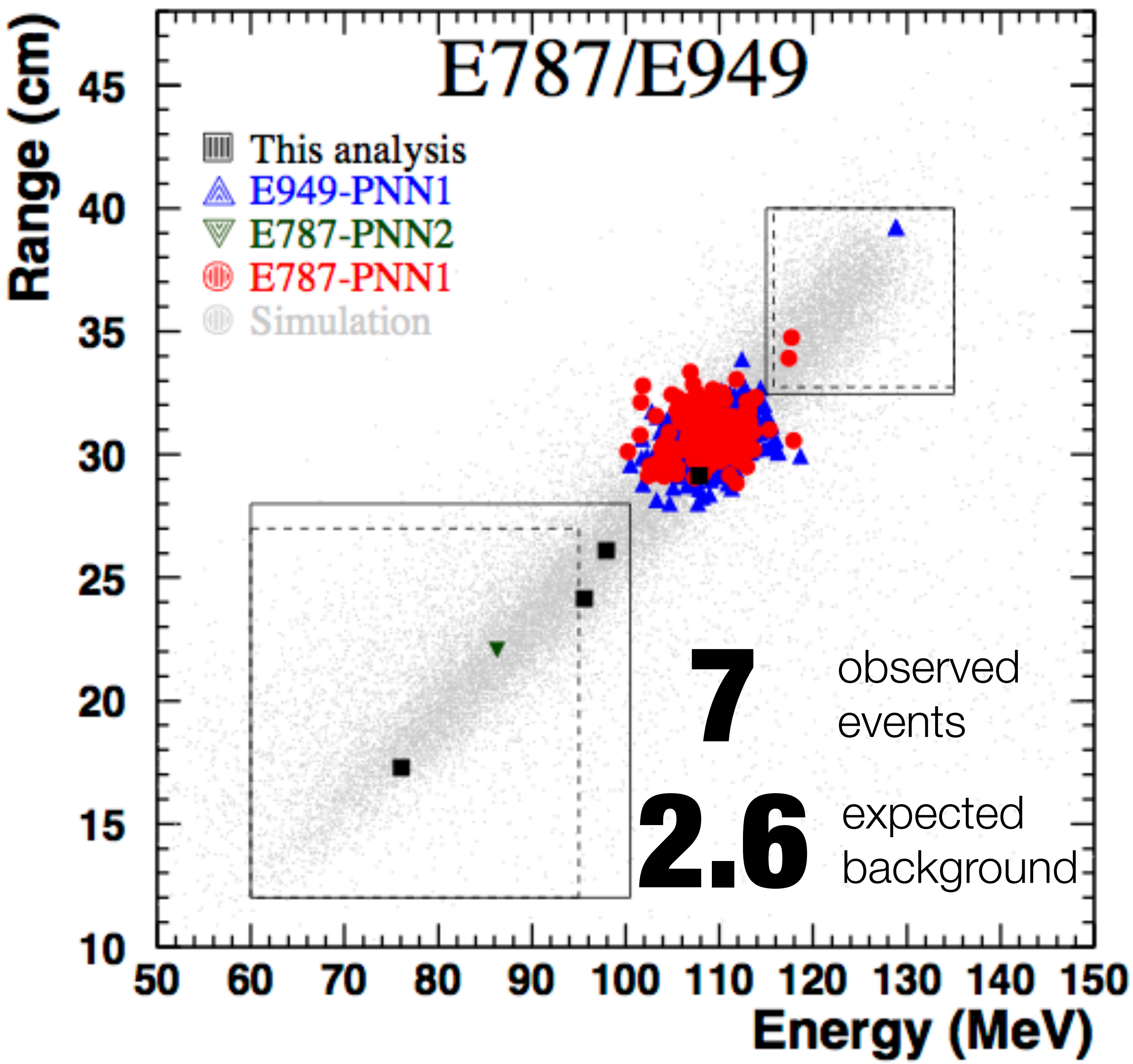
Error on input parameters **'Pure theory' errors**

[Brod, Gorbahn, Stamou, PhysRevD 83 (2011) 034030]

- New physics: large (O(10%)) deviations from SM possible in many NP models

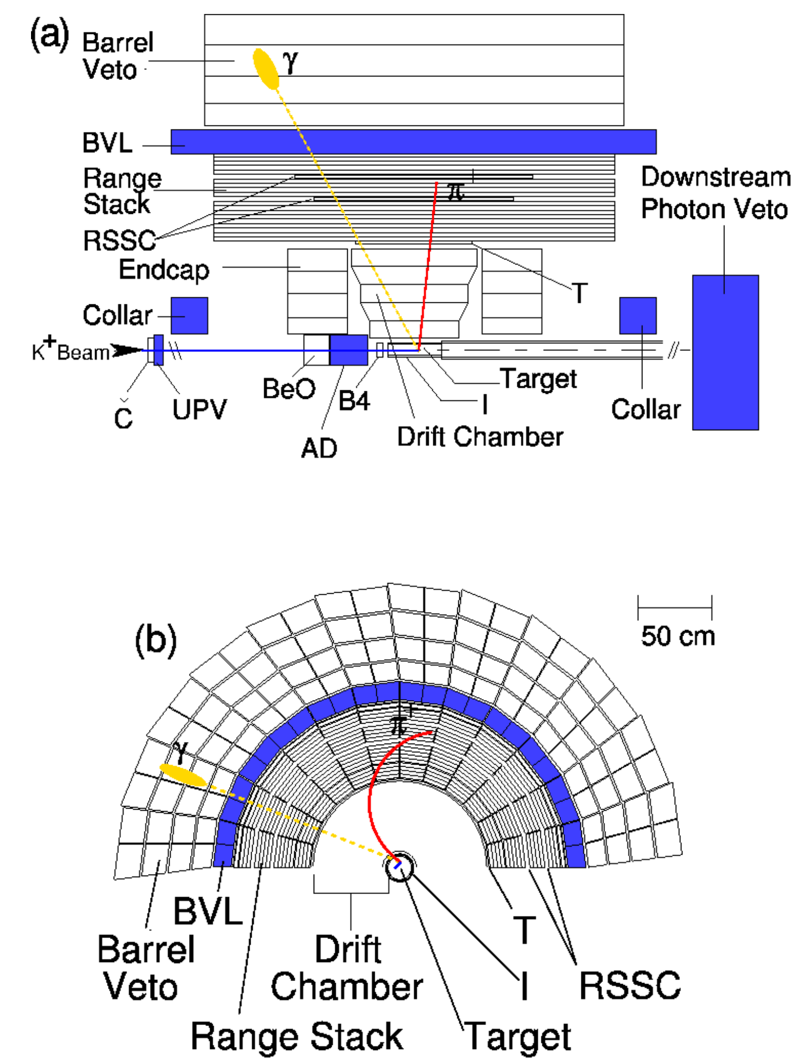
Existing measurement

[PhysRevLett 101 (2008) 191802]



7 observed events

2.6 expected background



[PhysRevD 77 (2008) 052003]

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

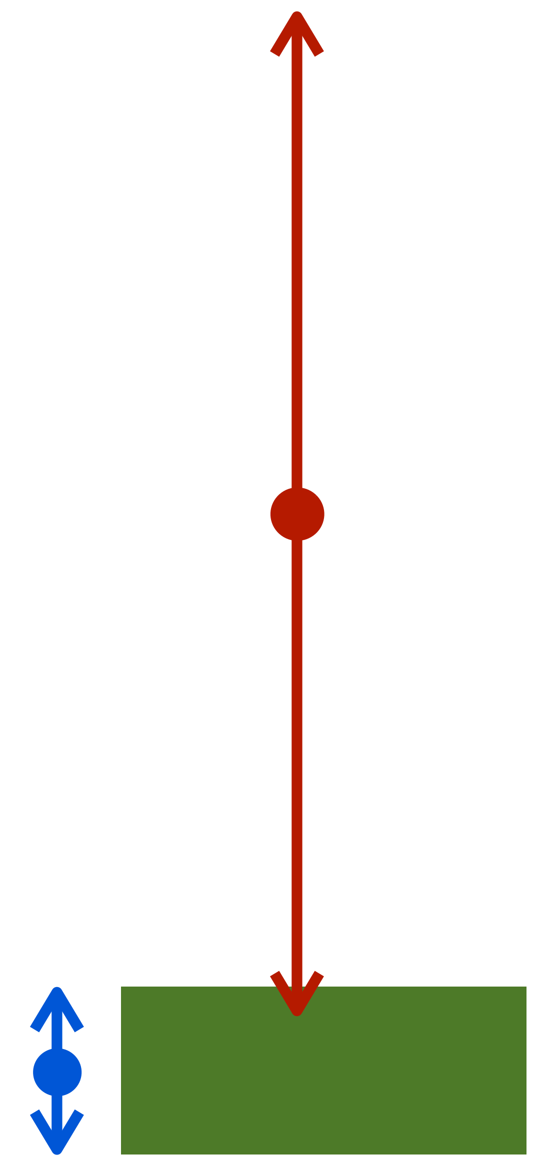
NA62 numbers

10% relative error on Standard Model prediction

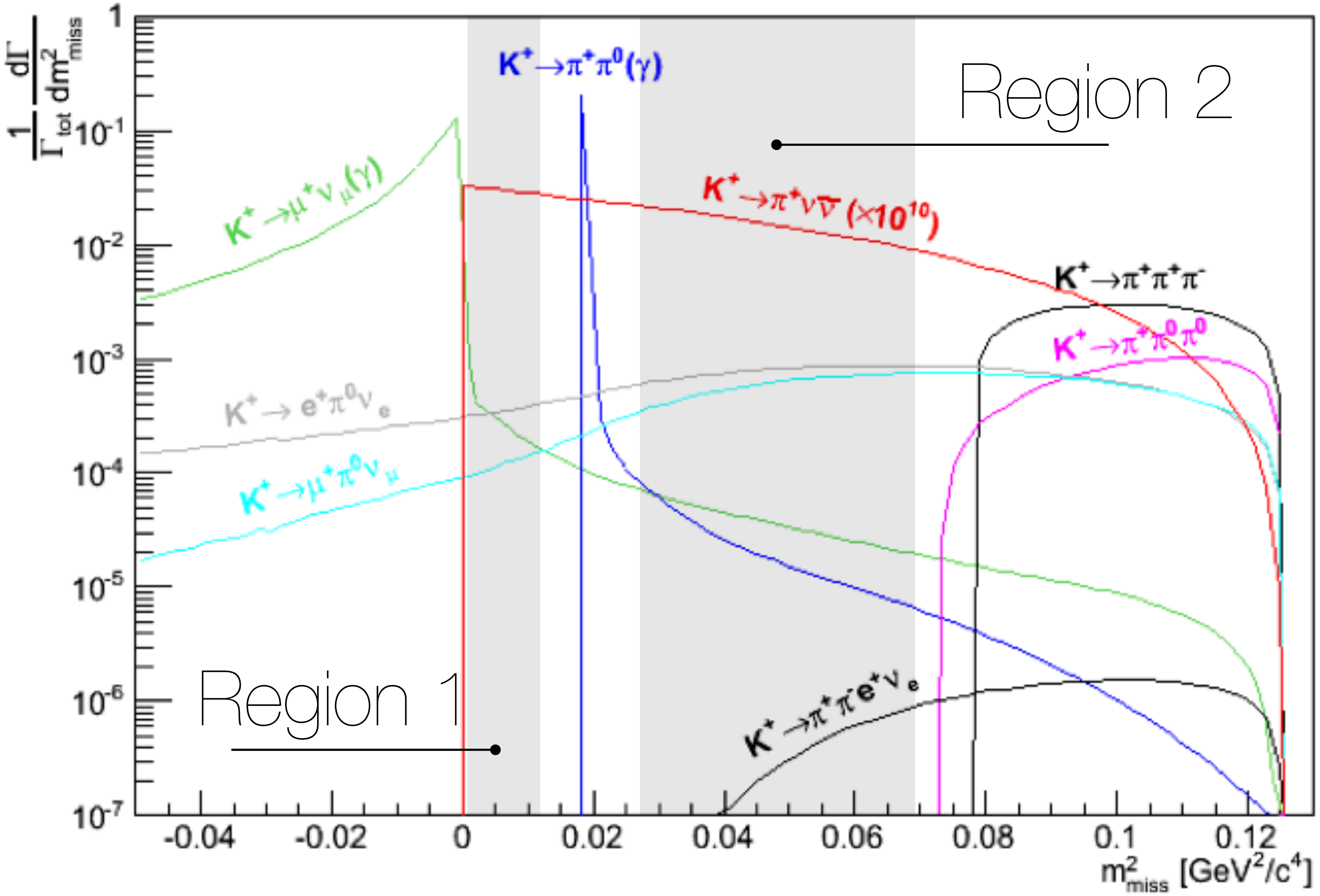
O(10%) enhancement from New Physics

60% relative error on measurement by E787/E949

10% relative error on NA62 measurement (SM)



The challenge



Signal region split by $K^+\to\pi^+\pi^0$

92% of BR(K^+) outside of signal kinematic region

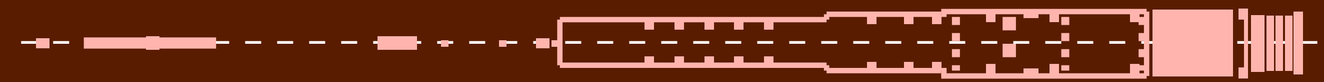
high rate

kinematic rejection
(low mass tracking)

hermetic μ, γ veto

particle identification

The beamline



Primary SPS Beam

400 GeV/c proton momentum

0.3 duty cycle

High intensity, unseparated secondary beam

75 GeV/c kaon momentum

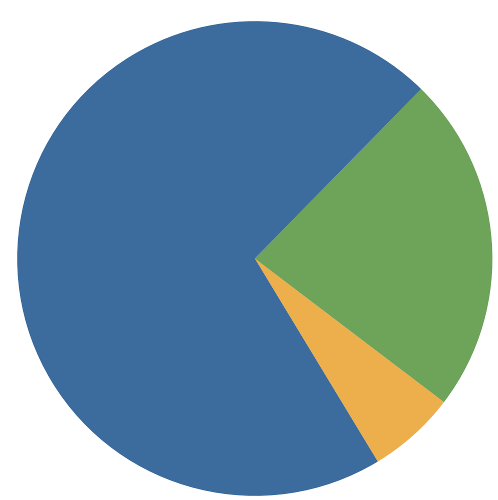
1% momentum bite ($\Delta p/p$)

Decay volume

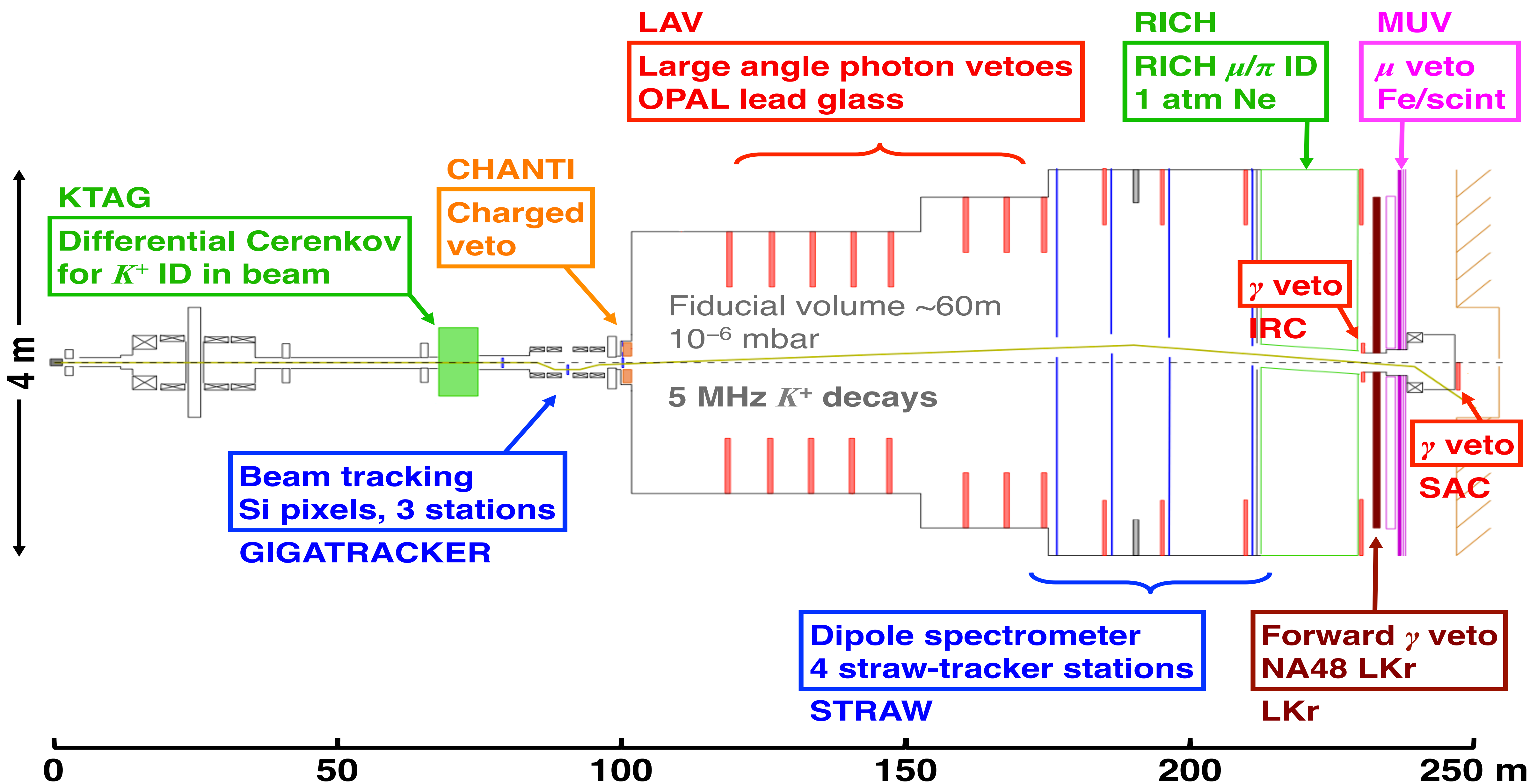
60m decay volume length ($\beta\gamma c\tau$ = 560 m)

10% K^+ decaying in fiducial volume

750 MHz total rate



NA62 detector



$\sim 10^{13}$ K+ decays → **~100** signal events **<20** BG events

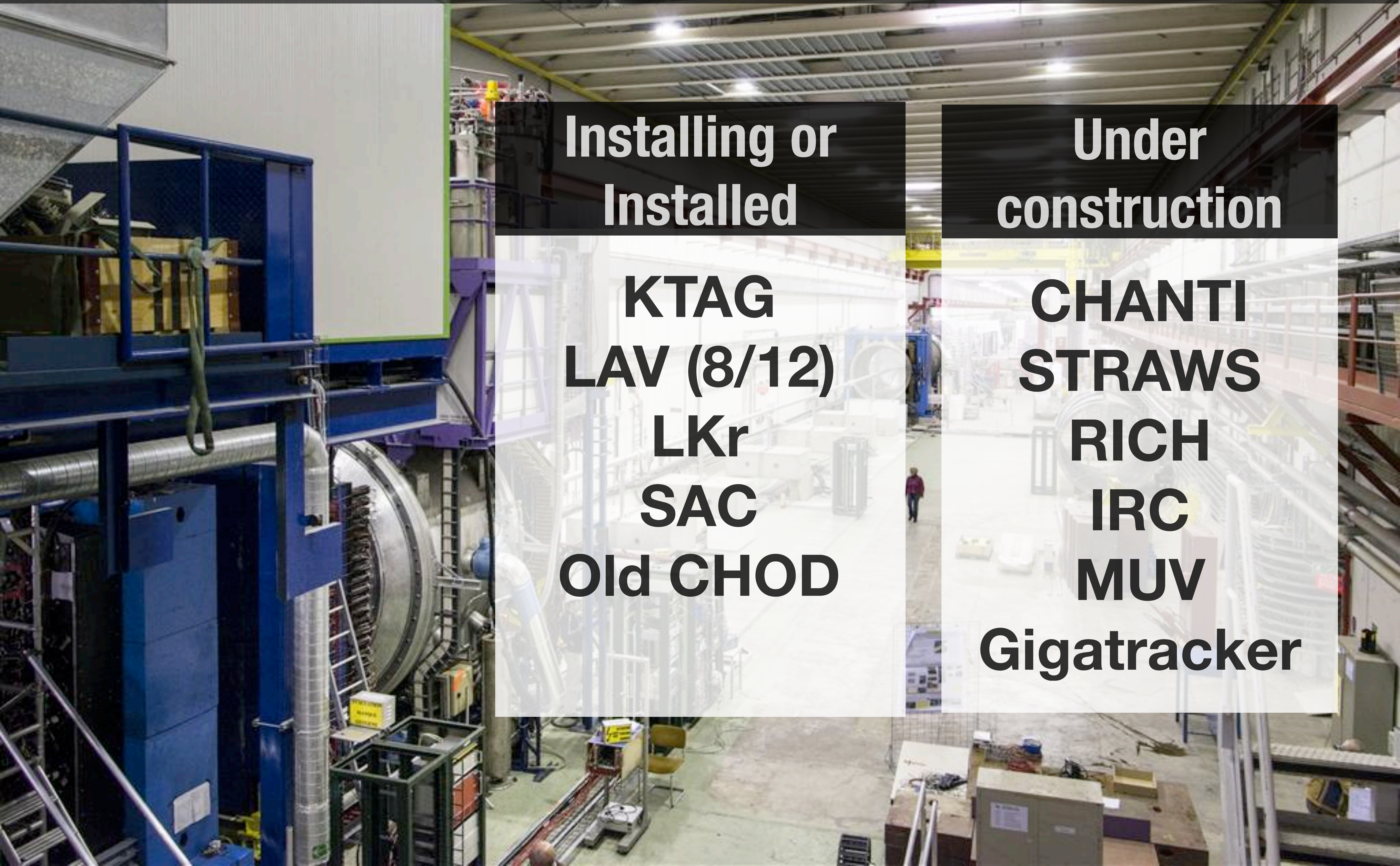
Signal selection

Stage	Criteria		
Beam	K^+ ID'd in KTAG	Track matched in GTK	No veto from CHANTI
Track	1 track reconstructed in STRAW		
Particle ID	π^+ ID'd in RICH	Calorimeter signals (CHOD, LKr, MUV1-3) compatible with π^+	
Photon veto	No γ like clusters in LKr	No γ like signals in LAVs, IRC, SAC	
Kinematics	Decay vertex in first 60m of decay volume	Pion momentum $15 < p_\pi < 35$ GeV/c	

Background levels

Decay	*events / year*
$K^+ \rightarrow \pi^+ \nu\nu$ [SM]	**45**
$K^+ \rightarrow \pi^+ \pi^0$	5
$K^+ \rightarrow \mu^+ \nu$	1
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	< 1
other 3 track decays	< 1
$K^+ \rightarrow \pi^+ \pi^0 \gamma$ (IB)	1.5
$K^+ \rightarrow \mu^+ \nu \gamma$ (IB)	0.5
$K+ \rightarrow \pi^0 e^+(\mu^+)\nu$, others	negligible
Total background	**< 10**

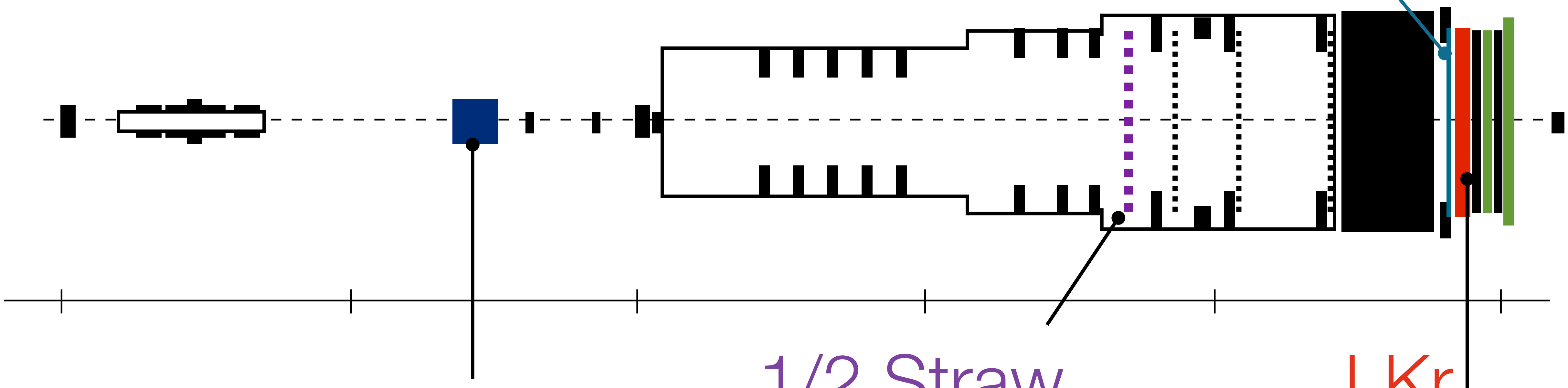
Experimental status



Installing or Installed	Under construction
KTAG	CHANTI
LAV (8/12)	STRAWS
LKr	RICH
SAC	IRC
Old CHOD	MUV
	Gigatracker

2012 Technical Run

Partially equipped detector



$K^+ \to \pi^+\pi^0$ studies

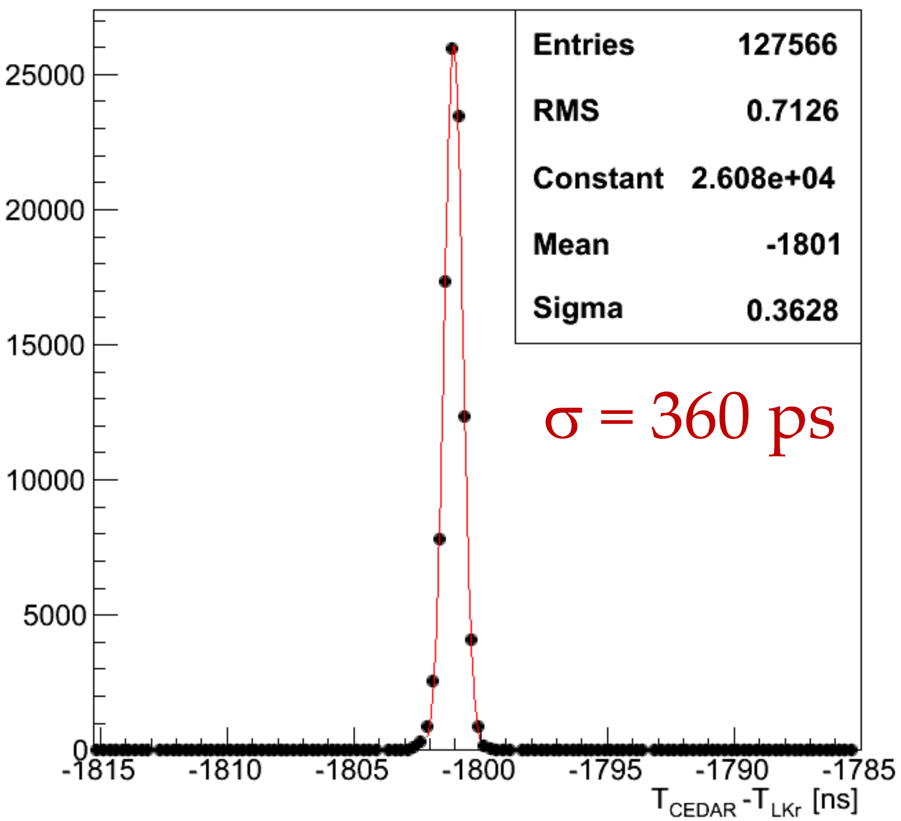
subdetector correlation

timing resolutions

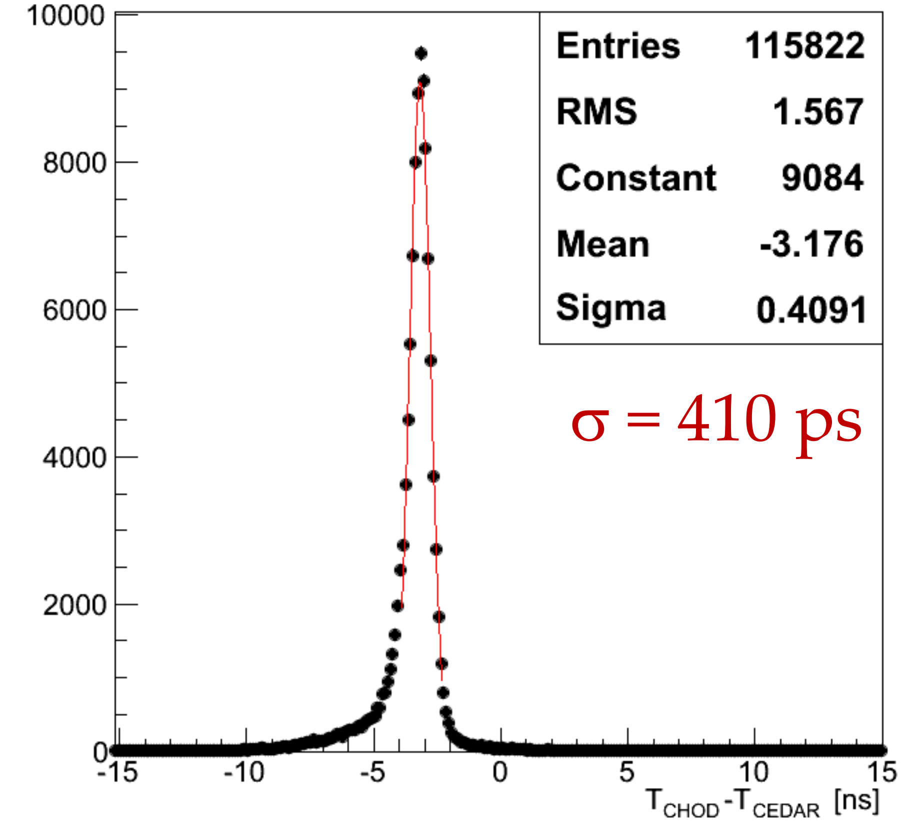
efficiencies

Timing correlations

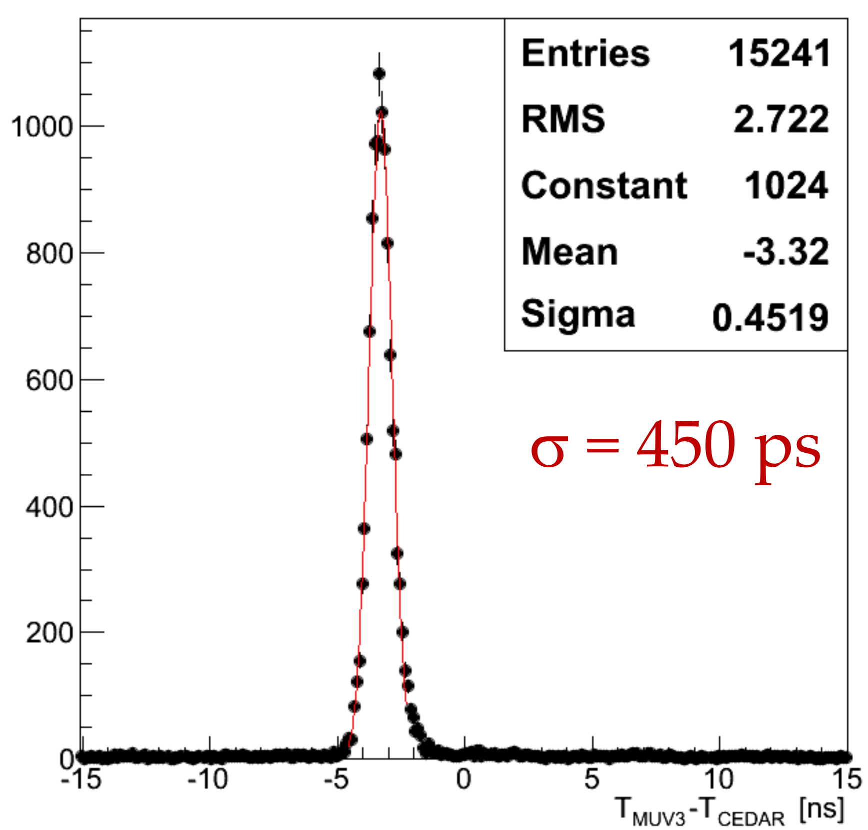
T_{KTAG} - T_{LKr}



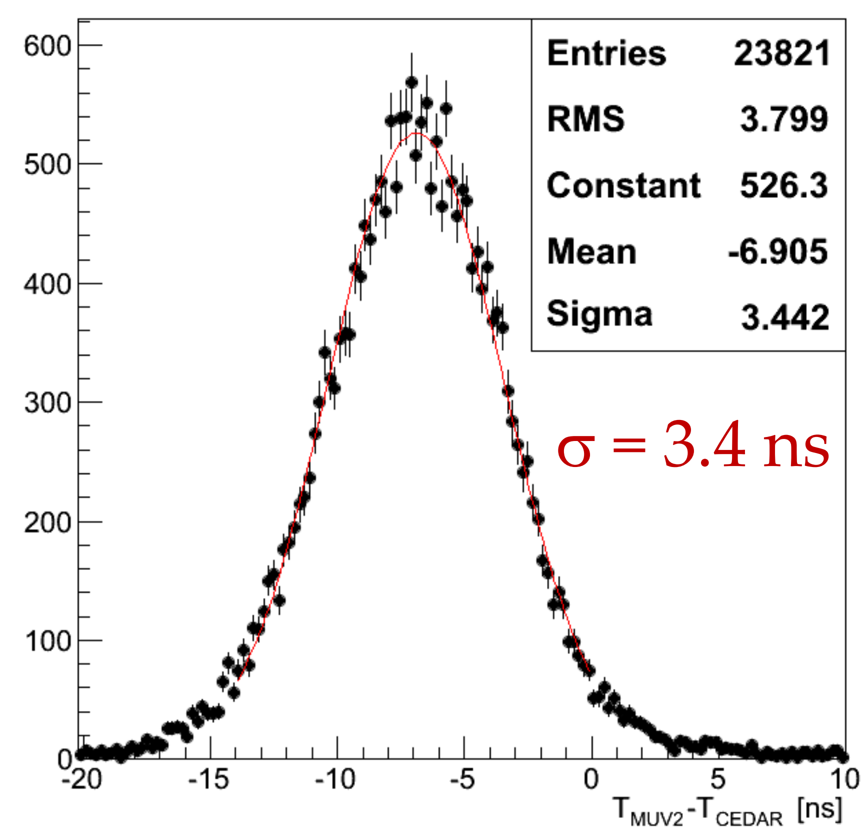
T_{CHOD} - T_{KTAG}



T_{MUV3} - T_{KTAG}

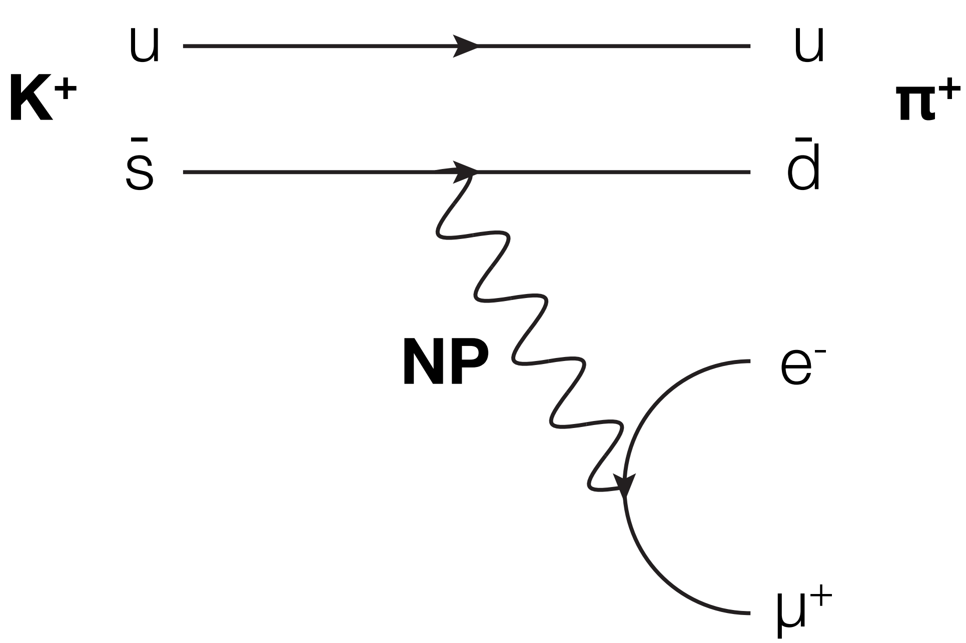


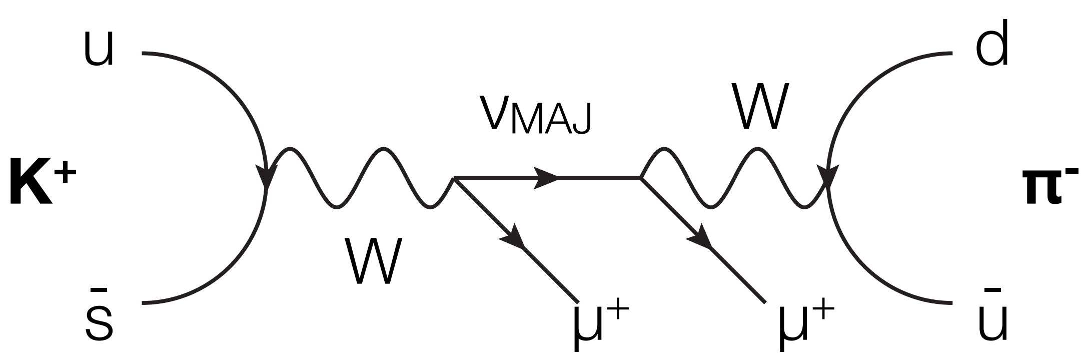
T_{MUV2} - T_{KTAG}

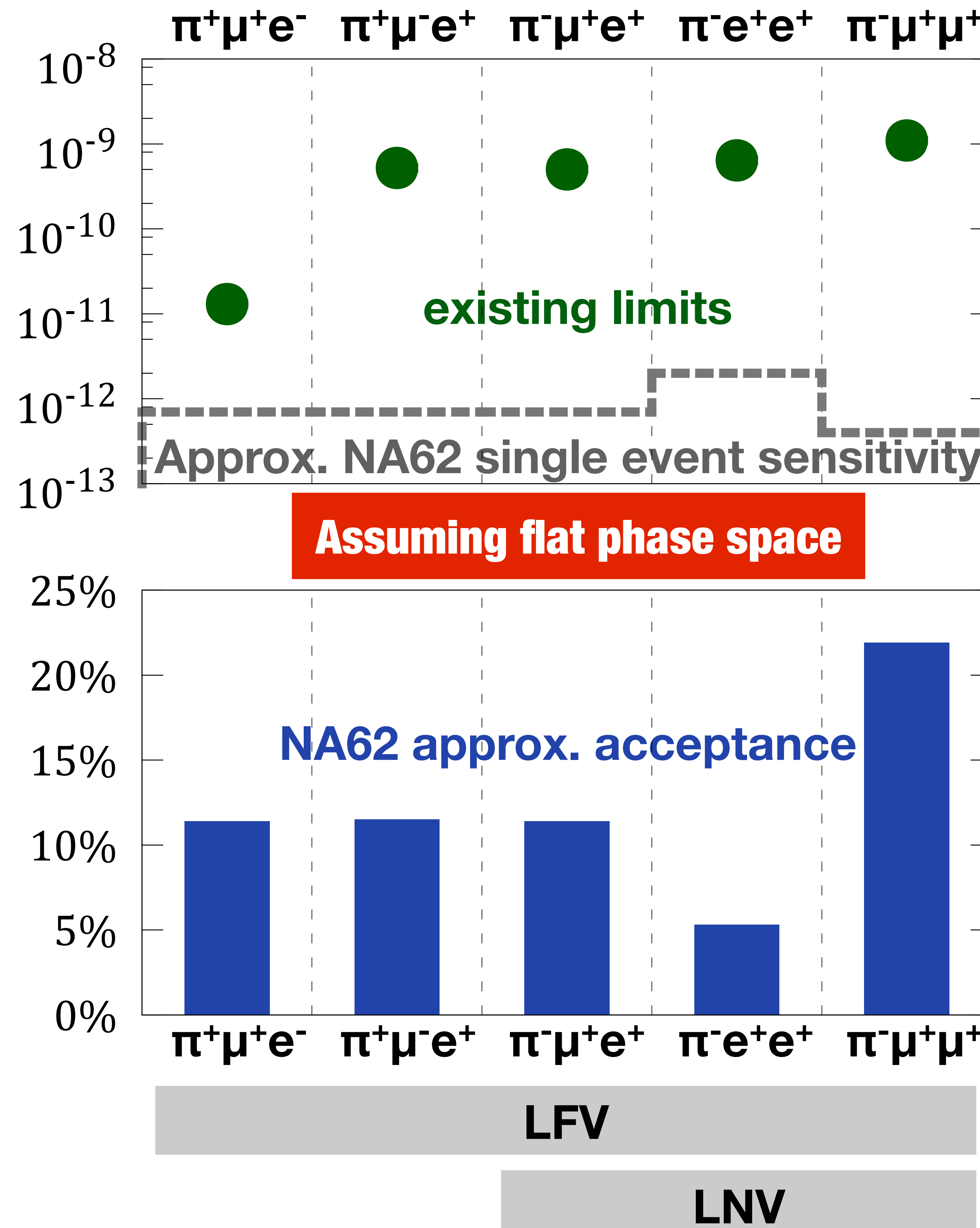


L (F|N) V sensitivity

Examples:





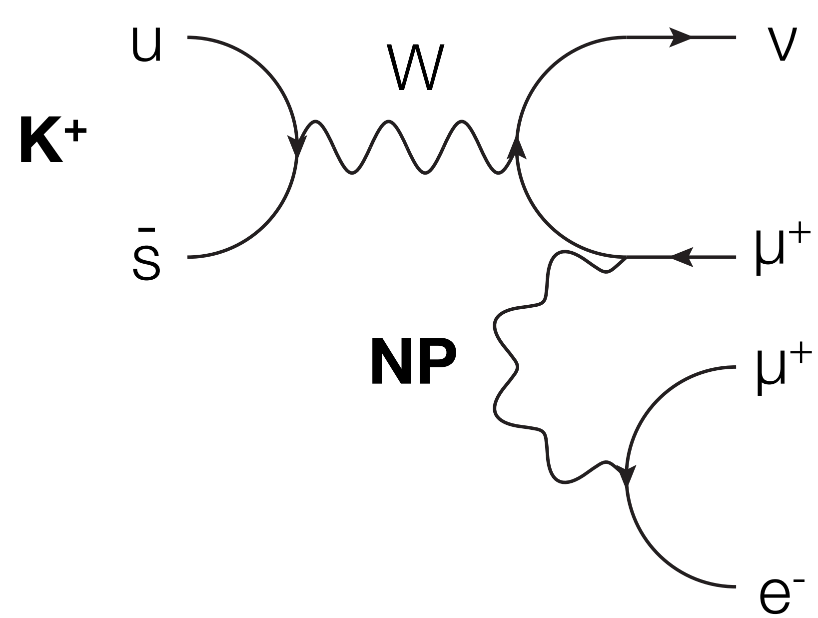


Di-lepton triggers

any charge : any flavour

L (F|N) V sensitivity

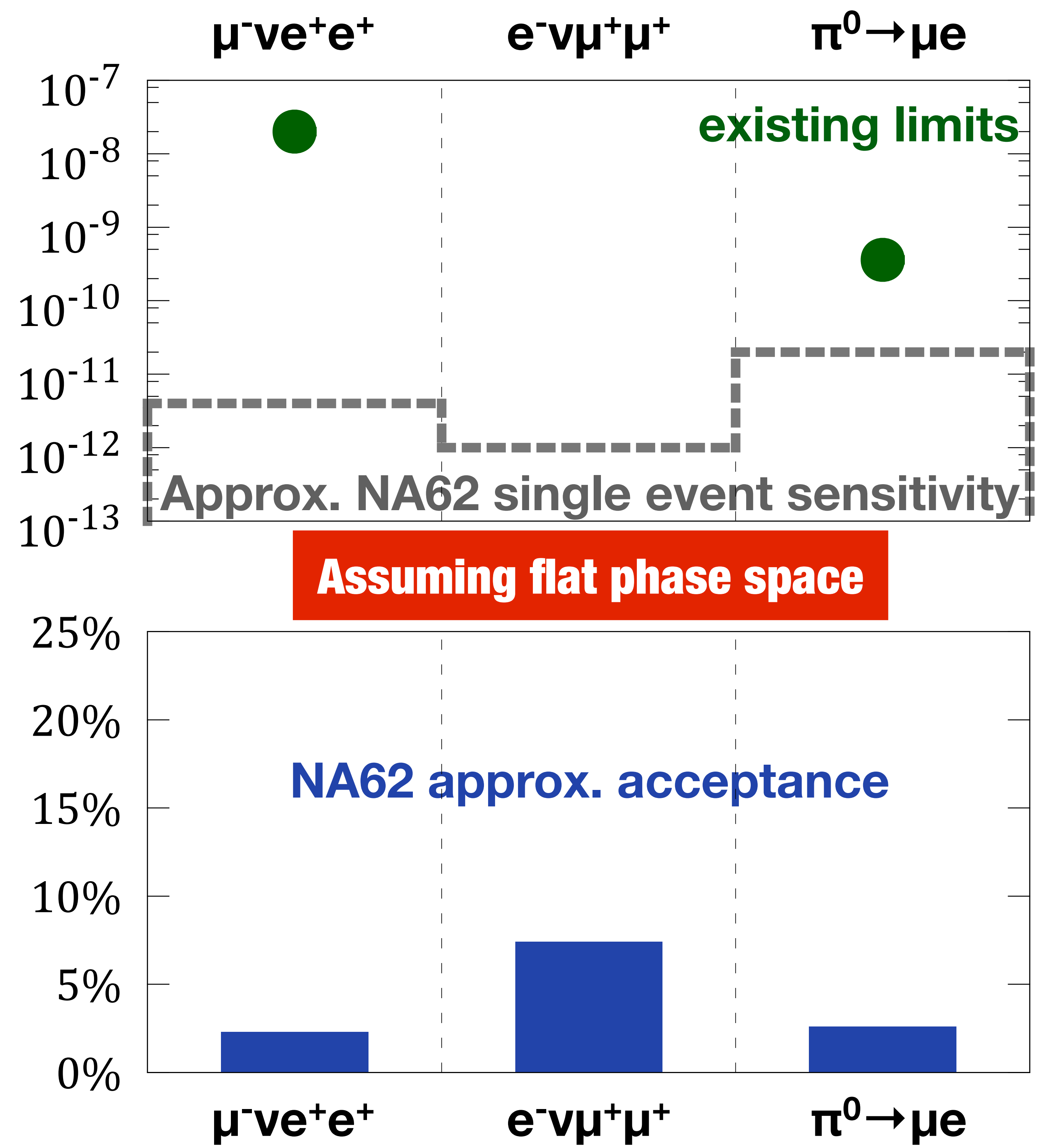
4 lepton events



π^0 decays

From $K^+ \to \pi^+\pi^0$

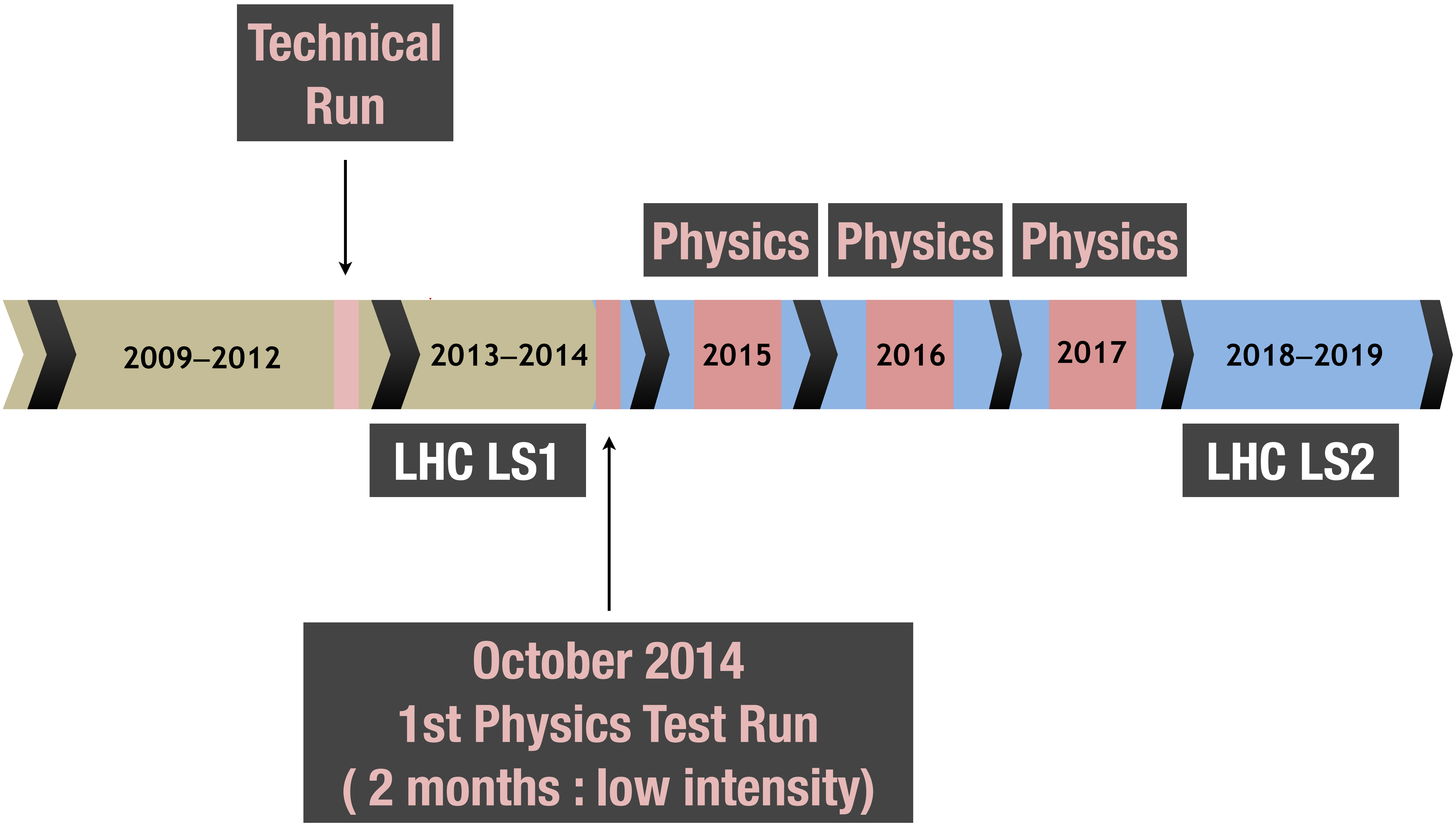
21% Branching Fraction



L (F|N) V limits summary

Mode	UL at 90% CL	Experiment	Reference	NA62 SES
$K^+ \rightarrow \pi^+ \mu^+ e^-$	1.3×10^{-11}	E777 / E865	[PhysRevD 72 (2005) 012005]	4×10^{-13}
$K^+ \rightarrow \pi^+ \mu^- e^+$	5.2×10^{-10}	E865	[PhysRevLett 72 (2005) 2877]	7×10^{-13}
$K^+ \rightarrow \pi^- \mu^+ e^+$	5.0×10^{-10}	E865	[PhysRevLett 72 (2005) 2877]	7×10^{-13}
$K^+ \rightarrow \pi^- e^+ e^+$	5.0×10^{-10}	E865	[PhysRevLett 72 (2005) 2877]	2×10^{-12}
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	1.1×10^{-9}	NA48/2	[PhysLettB 697 (2011) 107]	4×10^{-13}
$K^+ \rightarrow \mu^+ \nu e^+ e^+$	2×10^{-8}	Geneva-Saclay	[PhysLett 62B (1976) 485]	4×10^{-12}
$K^+ \rightarrow e^- \nu \mu^+ \mu^+$	-	-	-	1×10^{-12}
$\pi^0 \rightarrow \mu e$	3.6×10^{-10}	KTeV	[PhysRevLett 100 (2008) 131803]	2×10^{-11}

Timetable


Technical Run
Physics
Physics
Physics
2009–2012
2013–2014
2015
2016
2017
2018–2019
LHC LS1
LHC LS2
October 2014
1st Physics Test Run
(2 months : low intensity)

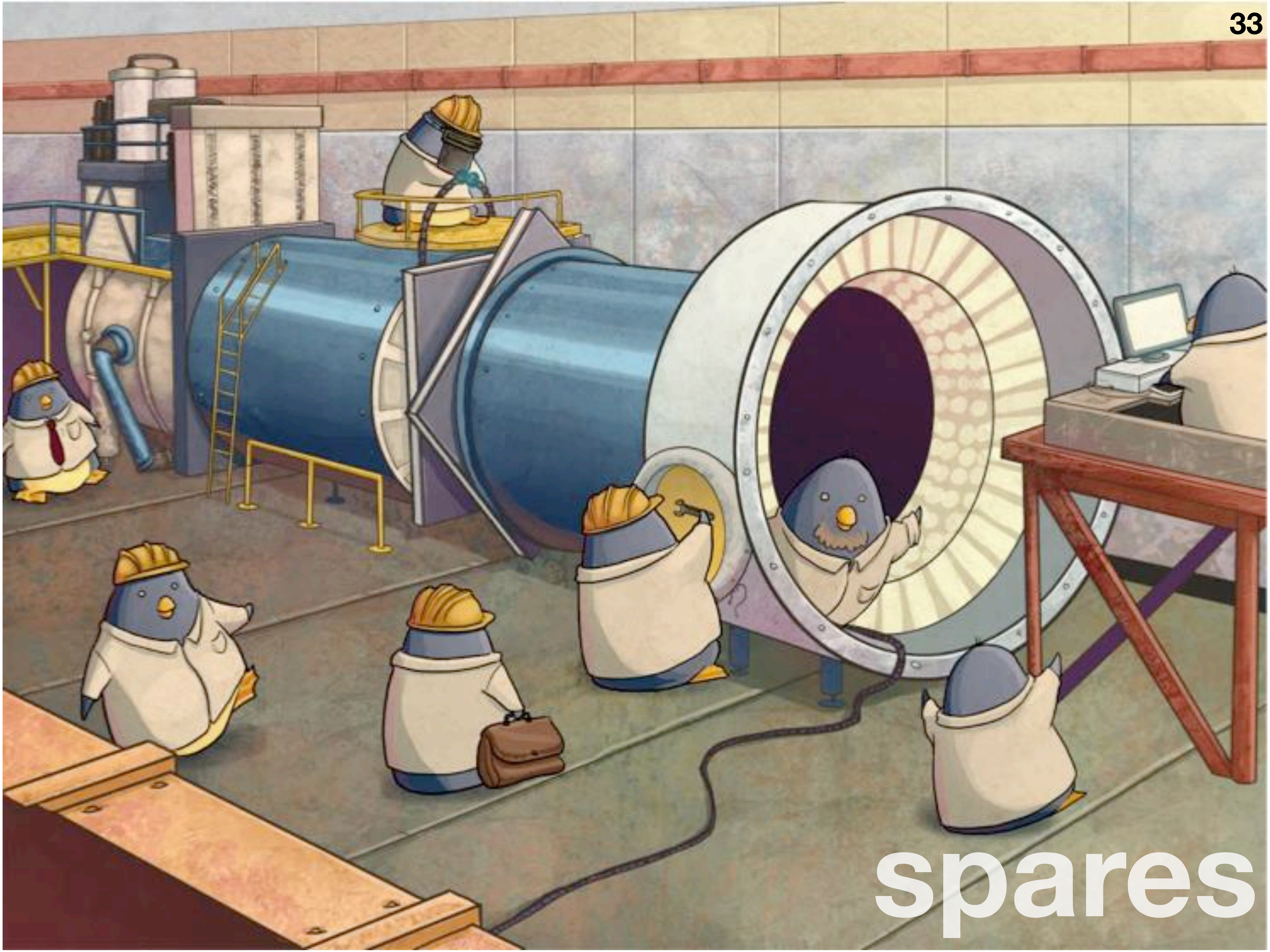
Conclusions

2007 R_K analysis

New measurement consistent with Standard Model
Further studies possible: sterile ν, medium-rare decays

2014 $K^+ \to \pi^+ \nu\nu$

On track for 10% measurement of branching ratio
Prospects for a wide rare and forbidden decay programme
Kaon flux in 2014 ~ few % of nominal flux



spares

NA62-R_K

Previous R_K measurements

- **1972 Bevatron:** $R_K = (2.42 \pm 0.42) \times 10^{-5}$ [PhysRevLett 29 (1972) 1274]
- **1975 CERN PS:** $R_K = (2.37 \pm 0.17) \times 10^{-5}$ [PhysLett B 55 (1975) 327]
- **1976 CERN PS (improved):** $R_K = (2.51 \pm 0.15) \times 10^{-5}$ [PhysLett B 60 (1976) 302]

2008 PDG Average: $R_K = (2.447 \pm 0.109) \times 10^{-5}$

[PhysLett B 667 (2008) 1]

- **2009 KLOE:** $R_K = 2.493 \pm 0.025_{stat} \pm 0.019_{syst} \times 10^{-5}$ [EurPhysJ C65 (2010) 703]

2010 PDG Average: $R_K = (2.493 \pm 0.031) \times 10^{-5}$

[JPhys G 37 (2010) 075021]

Kaon facilities : highlights

KTeV

Measured **direct CP violation** parameters in **2π decays** of neutral kaons [PhysRevD 82 (2011) 092001]

Orka

Upcoming experiment to measure **$K^+ \to \pi^+ \nu\nu$** from stopped kaons. Aiming for 5% measurement [arXiv:1305.7245v1]

E949

Made the first observation of **$K^+ \to \pi^+ \nu\nu$** using stopped kaons [PhysRevLett 101 (2008) 191802]

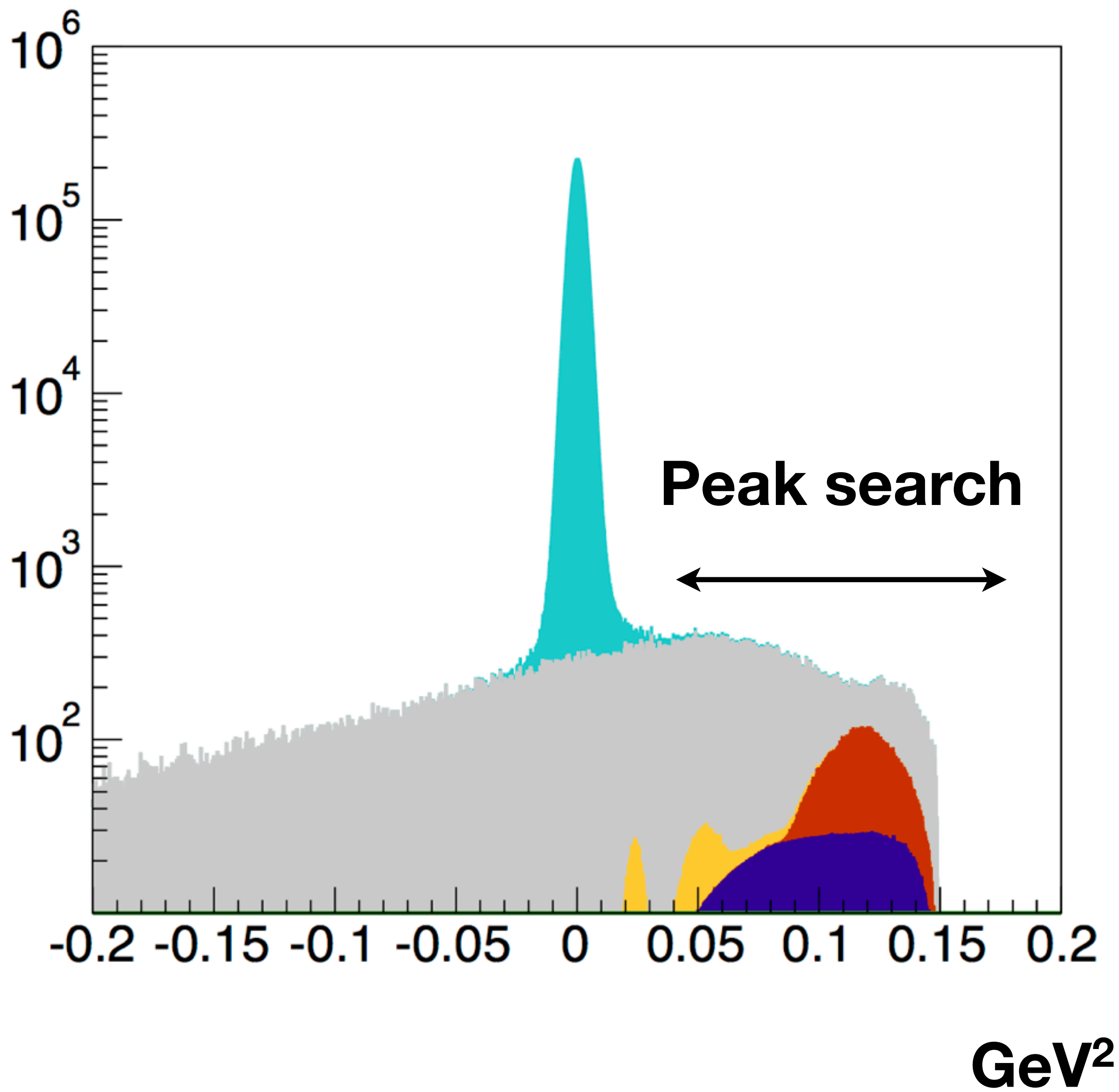
KLOE (2)

Studies kaon physics at a ϕ factory at the DAϕNE e+e= collider [arXiv:1002.2572]

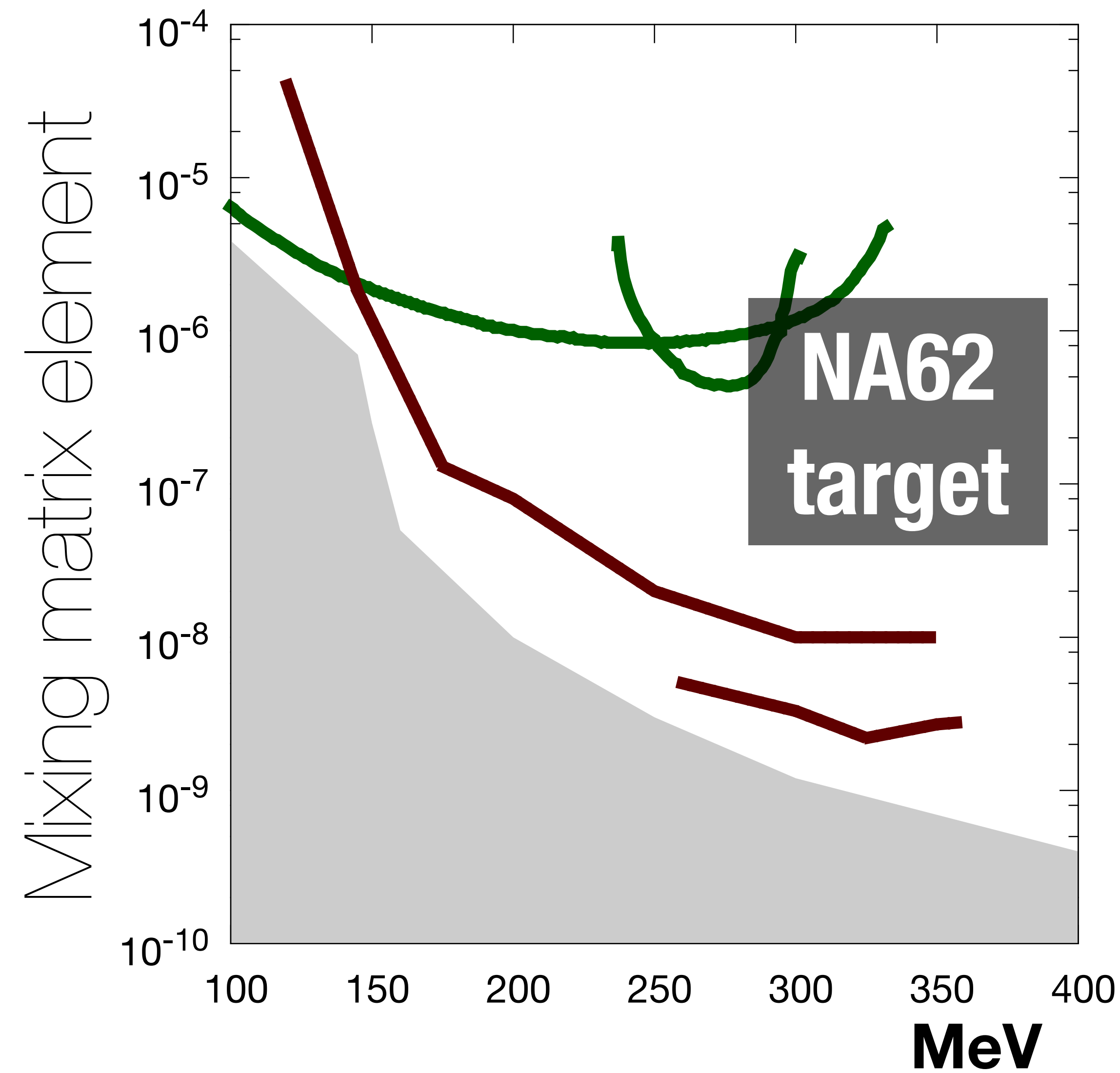
Sterile neutrinos

ONGOING STUDY

$K^+ \rightarrow \mu^+ \nu$ reconstructed m_ν^2



Existing limits



$\mu^+\nu$ | beam halo

$\pi^0\pi^+$ | $\pi^0\mu^+\nu$ | $\pi^+\pi^+\pi^-$

Peaks | Decays

Big bang nucleosynthesis

Golden Mode Theory

K→πνν theory

Standard Model

- Theoretical cleanness comes from **hard** (power like) GIM suppression.
- Theoretical error is now dominated by parametric errors, after a complete analysis of two-loop electroweak contributions. [Brod, Gorbahn, Stamou, PhysRevD 83 (2011) 034030]

long distance EM corrections

charm quark contributions: short distance (P_c), long distance ($\delta P_{c,u}$)

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ (1 + \Delta_{EM}) \left[\left(\frac{\mathfrak{Im}(\lambda_t)}{\lambda^5} X_t \right)^2 + \left(\frac{\mathfrak{Re}(\lambda_t)}{\lambda^5} X_t + \frac{\mathfrak{Re}(\lambda_c)}{\lambda} (P_c + \delta P_{c,u}) \right)^2 \right]$$

hadronic matrix element from BR(K_{e3}) via isospin rotation

top loop contributions dominate (maximum CKM suppression)

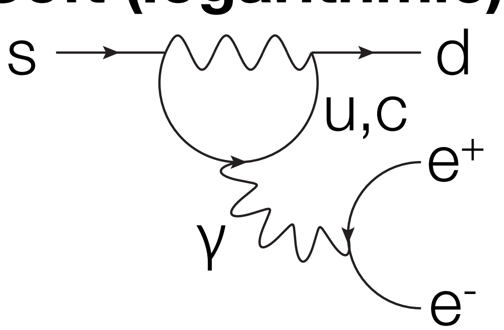
$$\lambda = V_{us}$$

$$\lambda_c = V_{cs}^* V_{cd}$$

$$\lambda_t = V_{ts}^* V_{td}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathfrak{Im}(\lambda_t)}{\lambda^5} X_t \right)^2$$

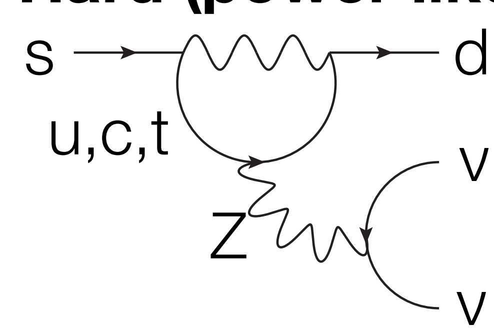
Soft (logarithmic) GIM



$$\sim \ln \frac{M_W}{m_i}$$

- Large long distance up quark contributions

Hard (power like) GIM

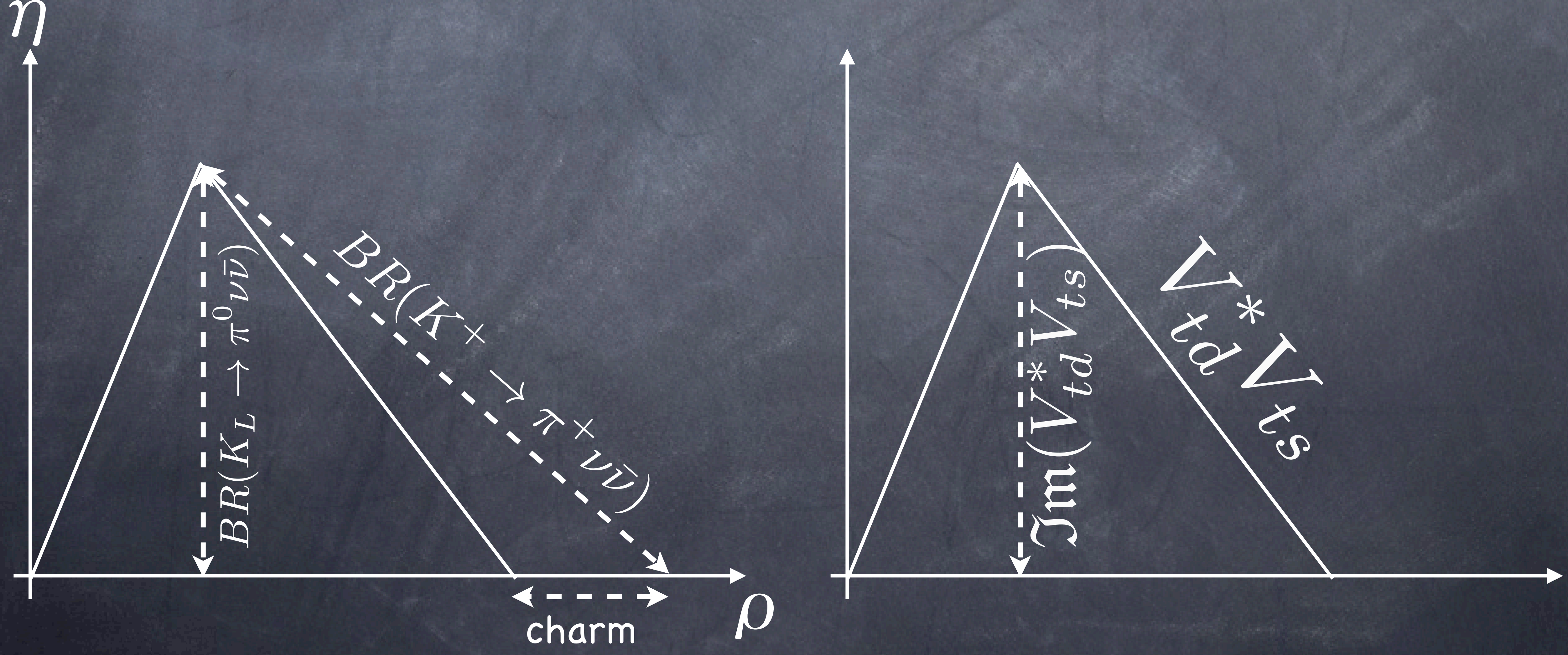


$$\sim \frac{m_i^2}{M_W^2} \ln \frac{M_W}{m_i}$$

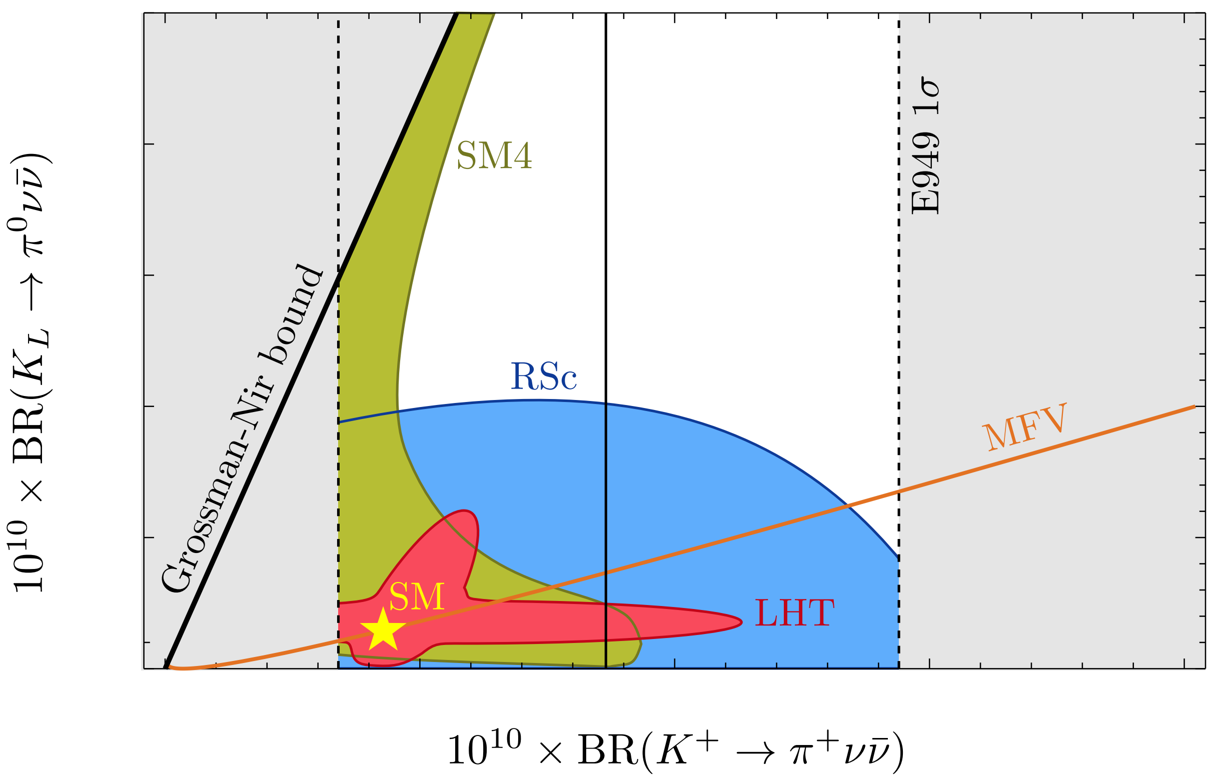
- Up quark contributions suppressed.

CKM and CPV

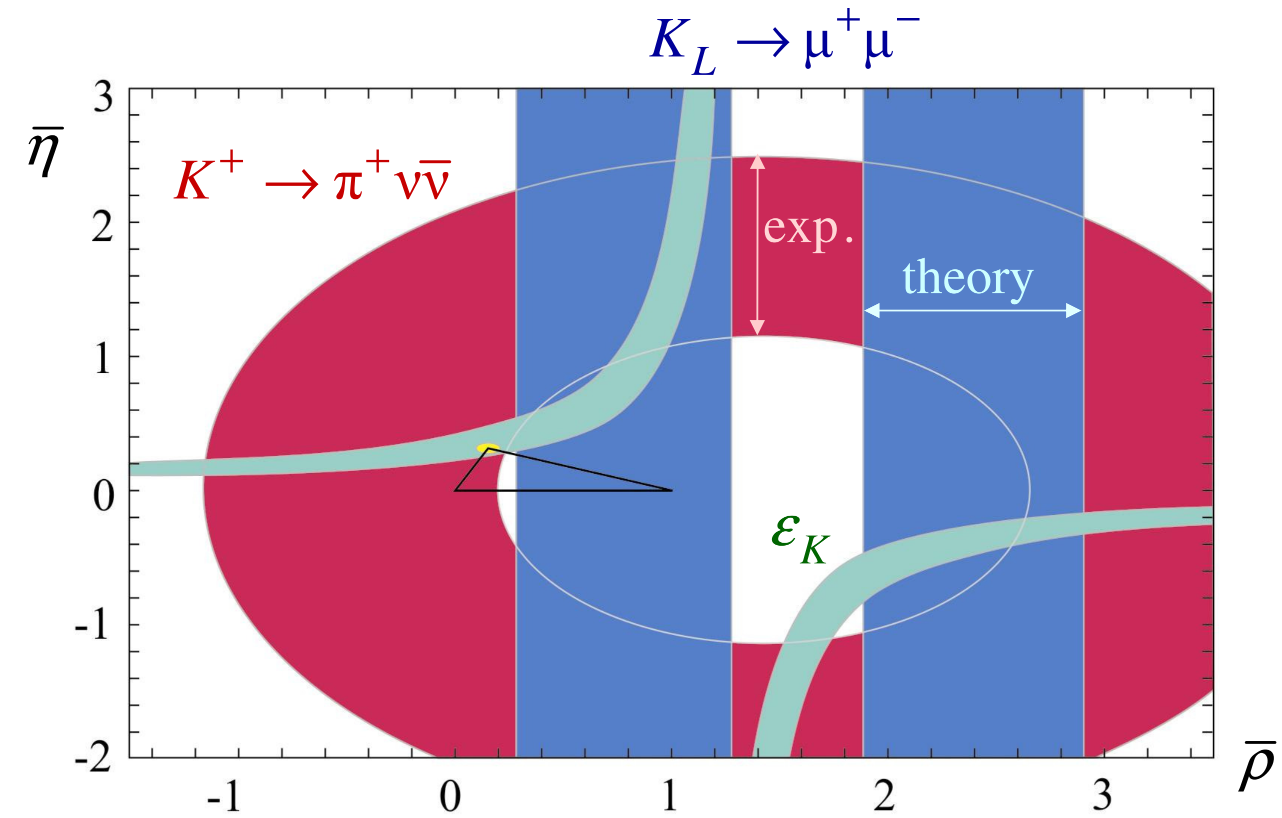
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho+i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



Experiment vs theory



D. Straub
[CKM2010 arXiv:1012.3893]



C. Smith
[CKM2008]

MFV *Minimal Flavour Violation* → All CPV from CKM matrix

[Buras, Andrzej ActaPhysPolonB B34 (2003) 5615]

Standard Model
Two Higgs Doublet Models
MSSM with minimal flavour violation

Beyond MSM

Buras et al **SM4** [JHEP 1009 (2010) 106] — *Standard Model with extra generation*

Albrecht et al **RSc** [JHEP 0903 (2009) 108] — *Randall-Sundrum with custodial protection*

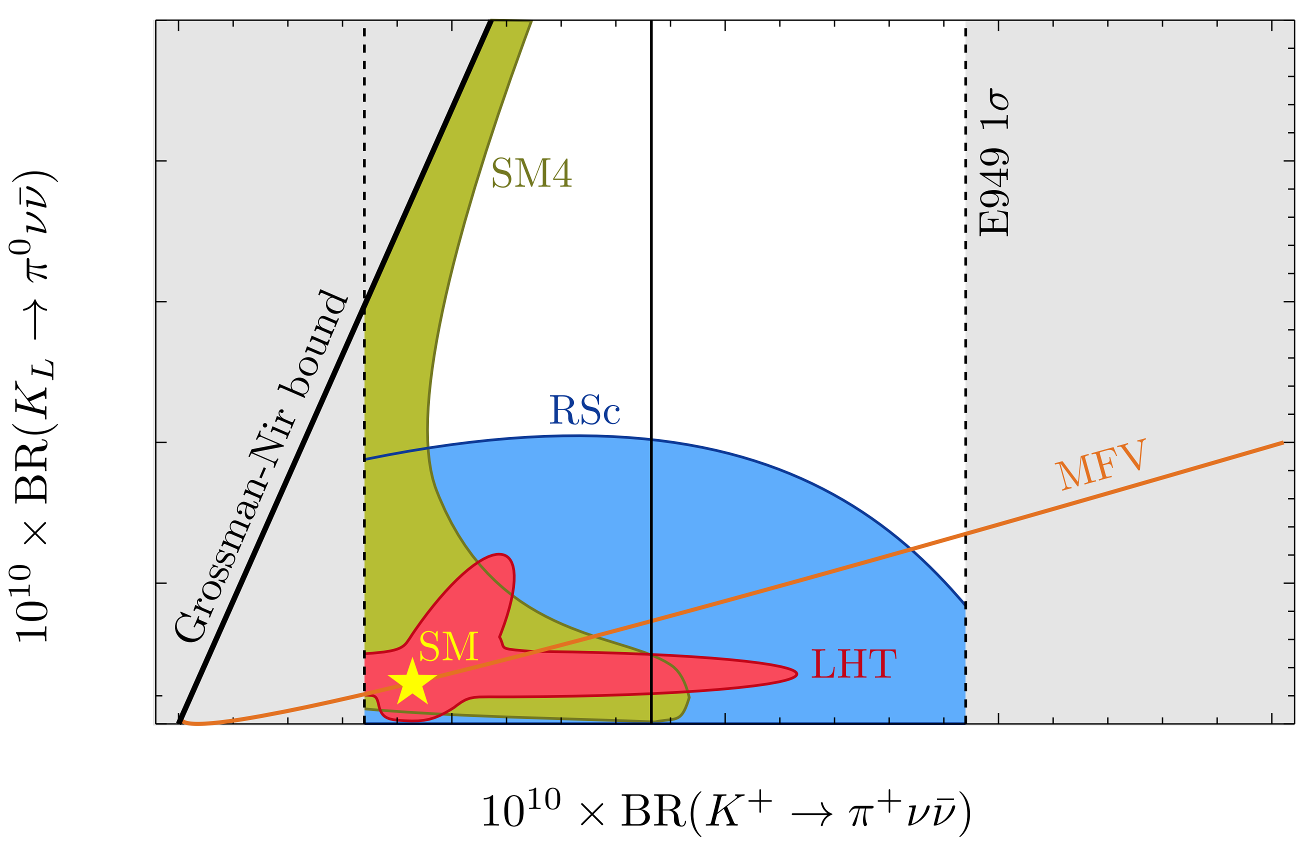
Blanke et al **LHT** [ActaPhysPolonB 41 (2010) 657] — *Little Higgs model with T-Parity*

Grossman-Nir Bound

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ |\xi X - P_{(u,c)}|^2$$

$$BR(K^L \to \pi^0 \nu\bar{\nu}) = \kappa_L \, \mathfrak{Im}(\xi X)^2$$

One complex number: X



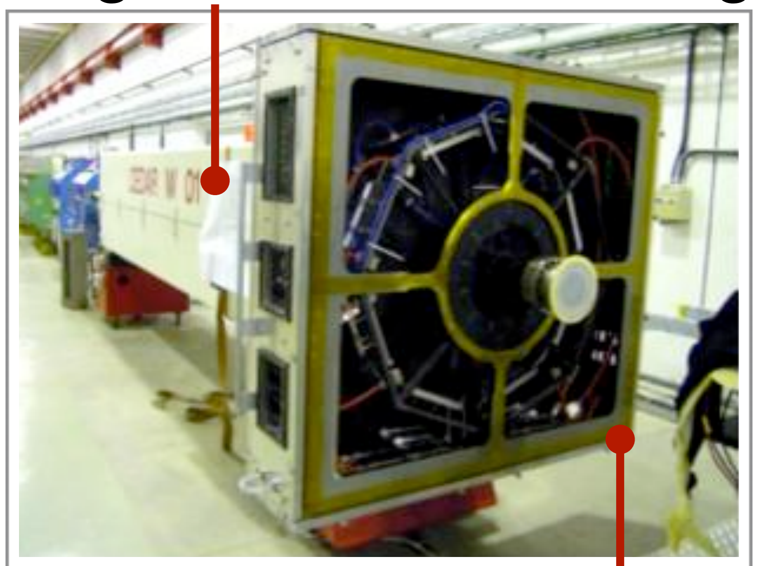
For all complex numbers:

$$\mathfrak{Im}\, z \leq |z|$$

After corrections, this gives an upper limit on the ratio

NA62 Detector

Original CEDAR-W design



New readout

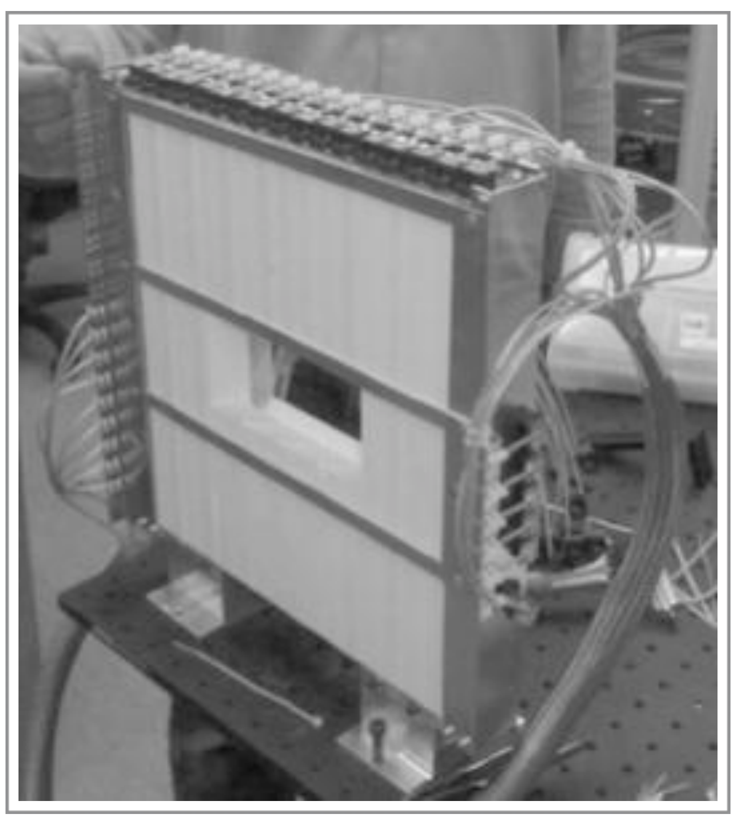
KTAG
Differential Cherenkov counter

Suppress beam-gas interaction backgrounds

Non destructive PID

100 ps timing resolution

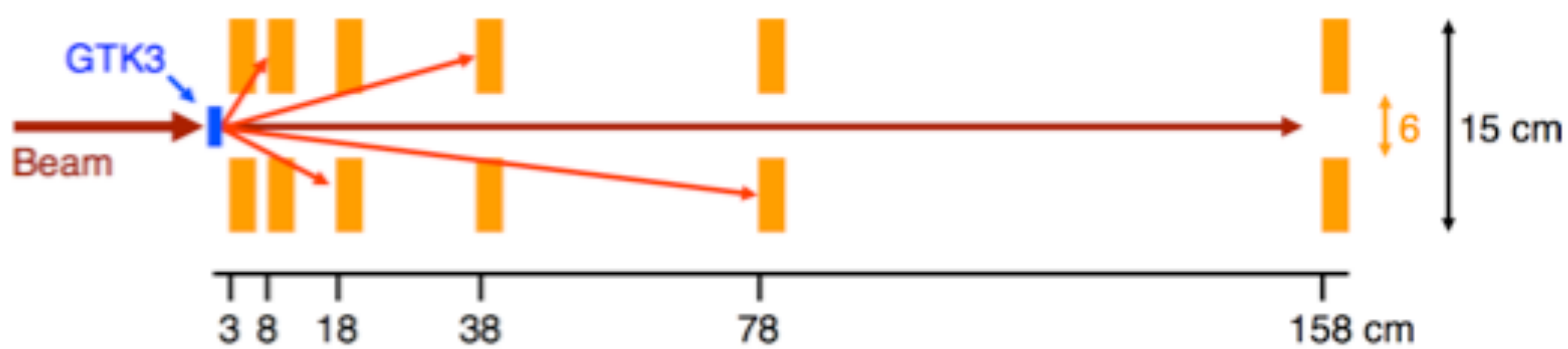
50 MHz kaon rate



CHANTI
Charged anti-particle counter

Reject events with inelastic scattering in the GTK

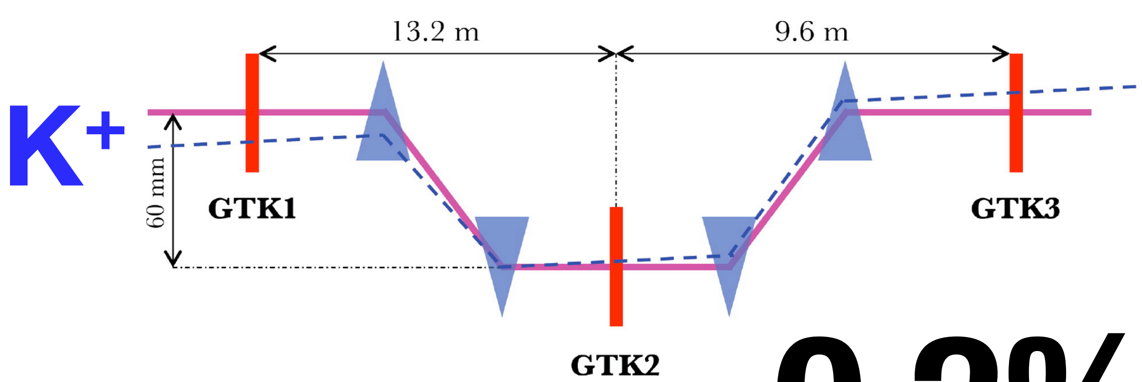
Tag beam halo muons near beam axis



Tracking detectors

5×10^3 $K^+\rightarrow\pi^+\pi^0$ kinematic rejection factor
(via a cut on m^2_{miss})

Limited by:
multiple scattering tails
Pile up in Gigatracker



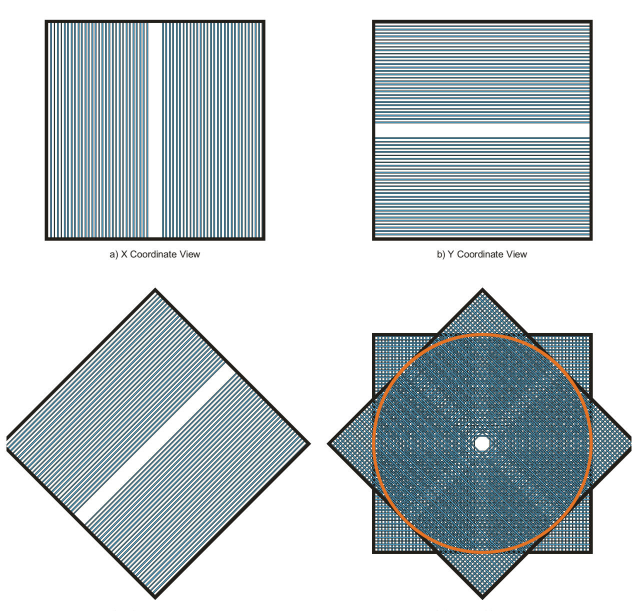
Gigatracker

hybrid pixel detector

Match downstream pions to incoming kaons

0.2% momentum resolution

15 μrad angular resolution



STRAW

vacuum operated straw tracker

Measure momentum of secondaries

$0.32\% \oplus 0.008\%p$
momentum resolution [GeV]

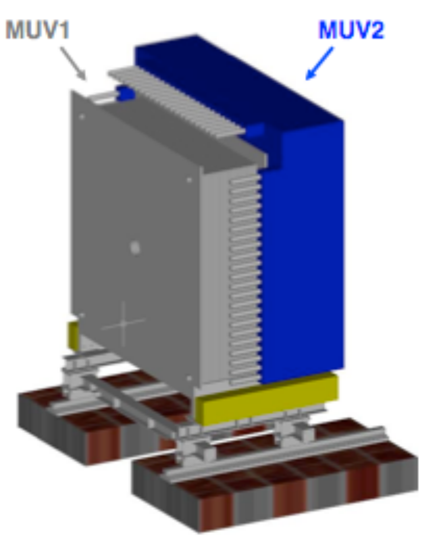
20-50 μrad
$\theta_{K\pi}$ angular resolution

4 views per chamber

2 staggered planes per view to resolve L/R ambiguity

Particle identification

10^{-7} μ/π separation required to suppress K→μν background



MUV1-2

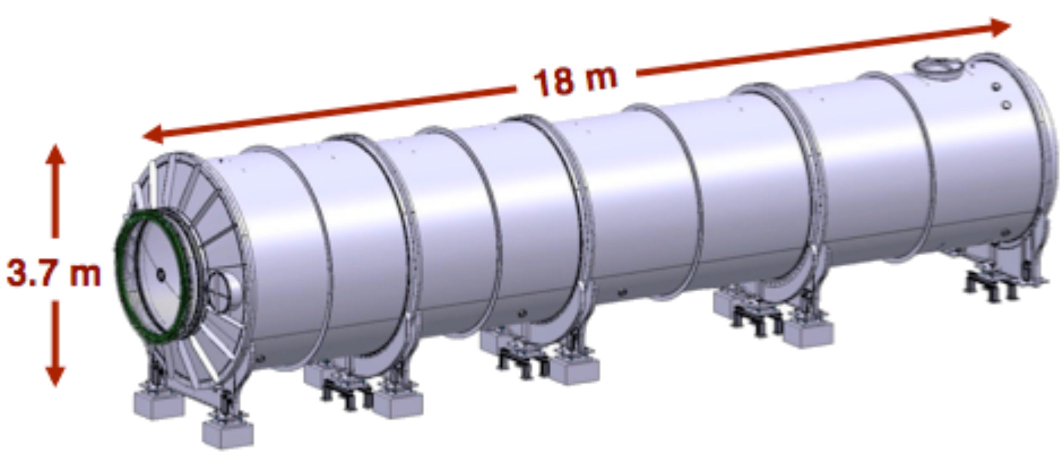
Fe/scintillator hadron calorimeter

10^{-5} μ rejection inefficiency

LKr

Liquid Krypton calorimeter

EM / hadronic clusters discrimination



RICH

Ring imaging Cherenkov detector

Neon radiator

2000 single anode PMTs

100 timing resolution **pico seconds**

10^{-2} π/μ separation inefficency for $15 < p_\pi < 35$ GeV

10^{-2} μ rejection (for K→μν)

Hermetic Photon vetoing

10^8 $\pi 0$ rejection required to suppress $K^+ \to \pi^+\pi^0$

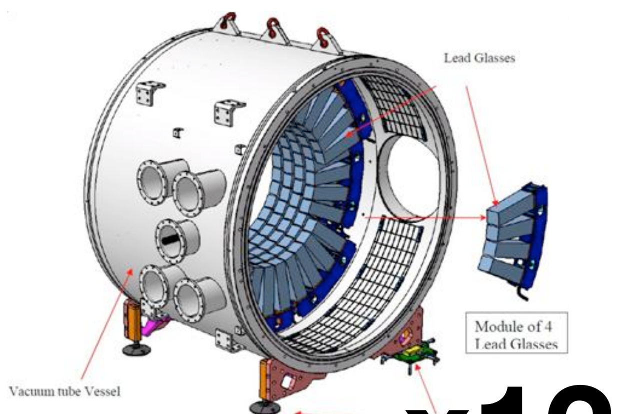
$p_{\pi+}$ $\longrightarrow$ **$E_{\pi 0}$**

< 35 GeV/c > 40 GeV

81.2% 2γ in forward vetoes

18.6% 1γ in forward vetoes, 1γ in LAVS

0.2% 1γ in LAVS, 1γ out of geometrical acceptance



x12

LAV

Large angle vetoes

Lead glass block EM calorimeter

10^{-4} maximum inefficiency at 200 MeV

LKr

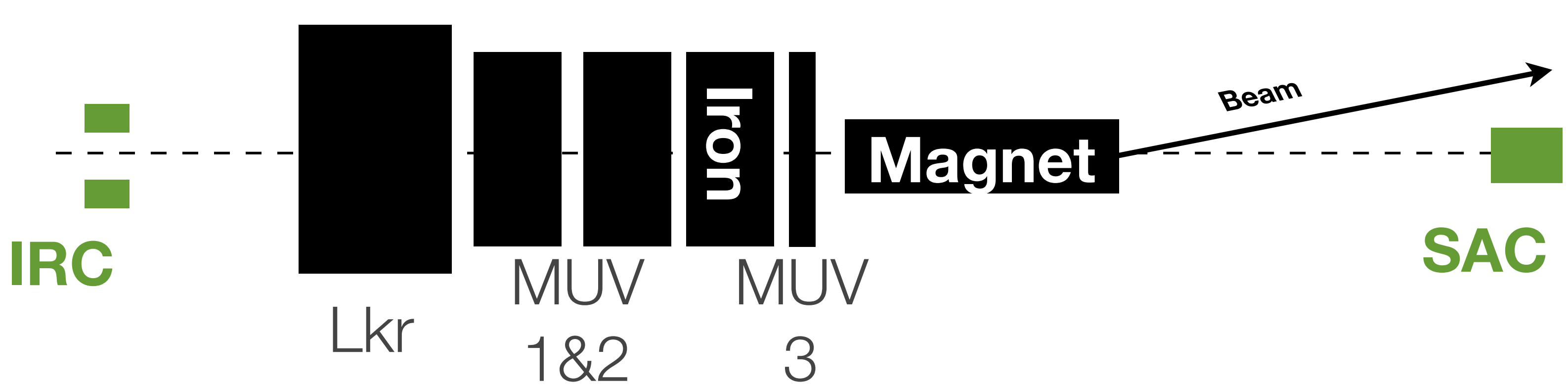
Liquid krypton as a photon veto

E_γ (GeV)	2.5-5.5	5.5-7.5	7.5-10	>10
1-ε (90% CL)	$< 10^{-3}$	$< 10^{-4}$	$< 5\times10^{-5}$	$< 8\times10^{-6}$

Inner **R**ing **C**alorimeter

Small **A**ngle **C**alorimeter

$1-\varepsilon < 10^{-4}$ at 5 GeV



The NA62 Detector Information

NA62

Proposal: CERN-SPSC-2005-013

Technical design: NA62-10-07

RICH

AIPConfProc 1412 (2011) 161

NSS/MIC 2012 IEEE 2053

KTAG

CEDAR: CERN-82-13

STRAW

JINST 5 (2010) C12053

NSS/MIC 2010 IEEE 1914

GigaTracker

JINST 7 (2012) C03030

PoS VERTEX (2010) 40

LAV

JINST 8 (2013) C01020

NSS/MIC 2010 IEEE 852

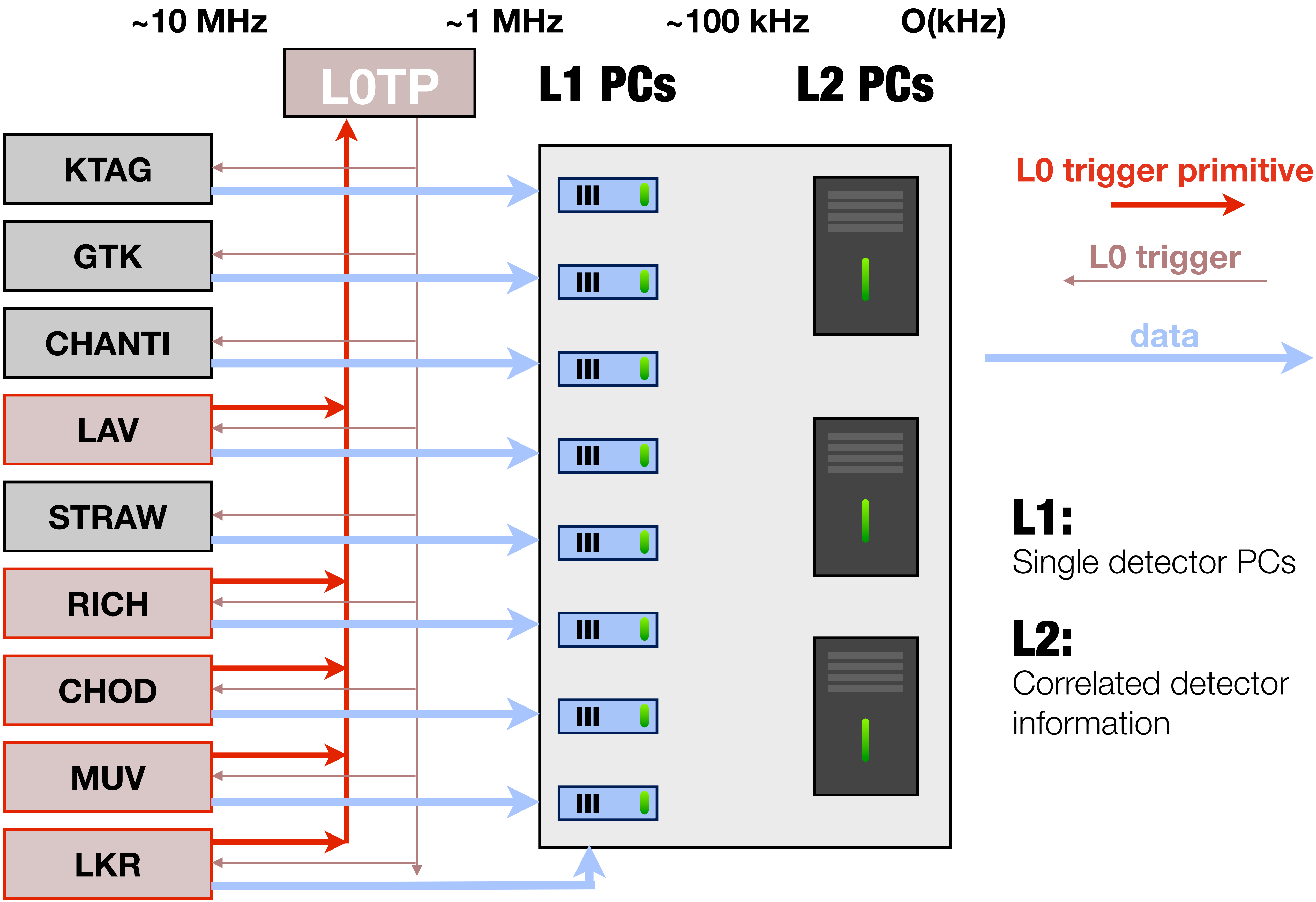
Lkr

JINST 6 (2011) C12017

NA48: NuclInstMeth A 574 (2007) 433

NA62 Trigger Data Acquisition

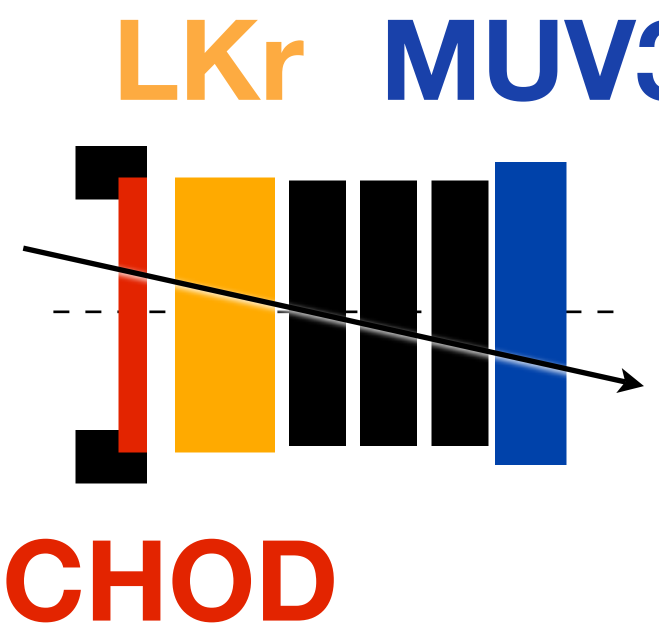
Trigger and data acquisition



L1:
Single detector PCs

L2:
Correlated detector information

$K^+ \rightarrow \pi^+ \nu\nu$ trigger



Q_N at least N CHOD quadrants

MUV_N hits in a least N MUV3 pads

$LKR_N(x)$ at least N Lkr clusters with E > x GeV

L0 trigger:

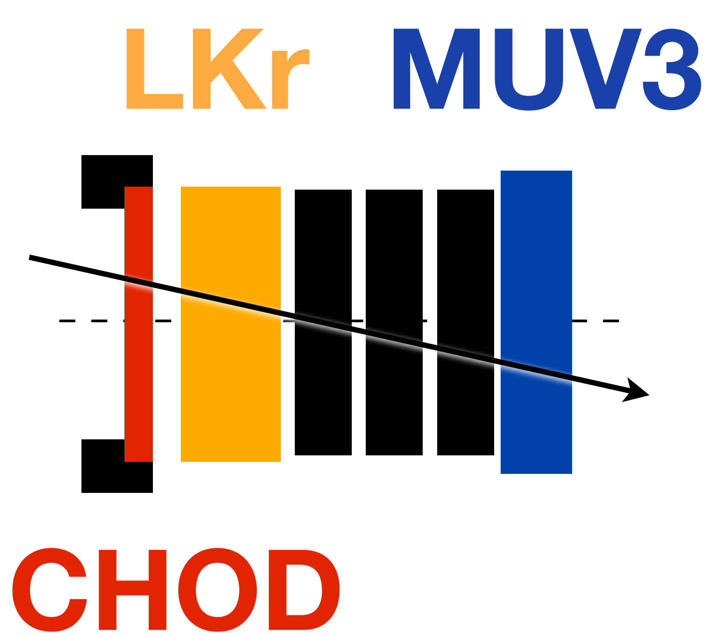
$$Q_1 \cap !(MUV_1) \cap LKr_1$$

Important to reject $K_{\mu 2}$ events

Di-lepton Triggers

640 kHz total 3-track rate — can't collect all three track decays → **10's kHz** lepton pair L0 rate

Dominated by $K^+ \rightarrow \pi^+\pi^+\pi^-$



Q_N at least N CHOD quadrants

MUV_N hits in a least N MUV3 pads

$LKR_N(x)$ at least N Lkr clusters with E > x GeV

ee pair

Q_2

$LKR_2(15)$

μ e pair

Q_2

$LKR_1(15)$

MUV_1

μ μ pair

Q_2

MUV_2