Prospects for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ observation at CERN-NA62

Cristina Biino * - INFN Torino

***SUSY 2015 – Lake Tahoe**, 23-29 August 2015*

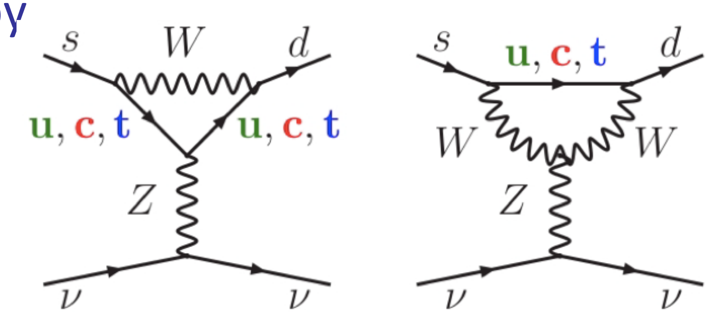
*On behalf of the NA62 Collaboration:
CERN, Ferrara, Firenze, LNF, Napoli, Perugia, Pisa, Roma1, Roma2, Torino, UC Louvain, Sofia, Bucharest, Prague, Mainz, Birmingham, Bristol, Glasgow, Liverpool, TRIUMF, UBC, IHEP, INR, JINR, George Mason, SLAC, UC Merced, BU, BNL, San Luis Potosi

SM theoretical framework

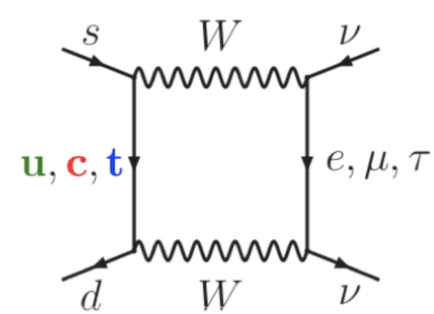
The $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay is a FCNC process, in the SM is forbidden at tree level and dominated by short distance dynamics.

- Very clean theoretical scenario
  - No hadronic uncertanties
  - Electroweak amplitude is largerly dominated by **top quark loops**
  - Dependence on the product of CKM matrix elements $\mathbf{V_{ts}^{*}V_{td}}$
- SM prediction takes into account:
  - 1 loop contributions at the leading order
  - NLO QCD correction to top quark contributions
  - NLO electroweak corrections to both top and charm contributions
  - NNLO QCD corrections to charm contributions
  - Isospin breaking and non-perturbative effects

Box and penguin, one loop diagrams at leading order



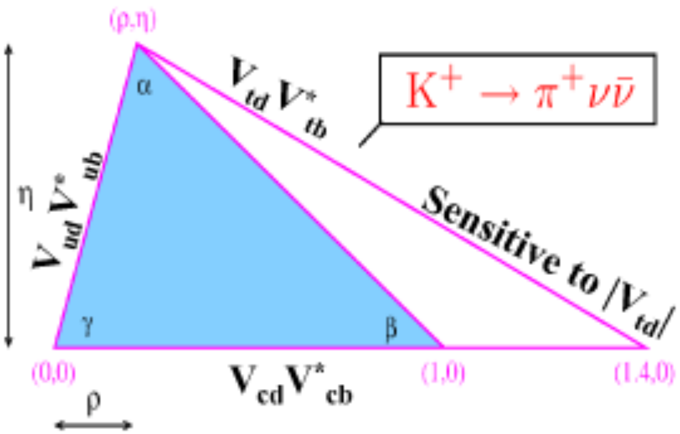
Z-penguin



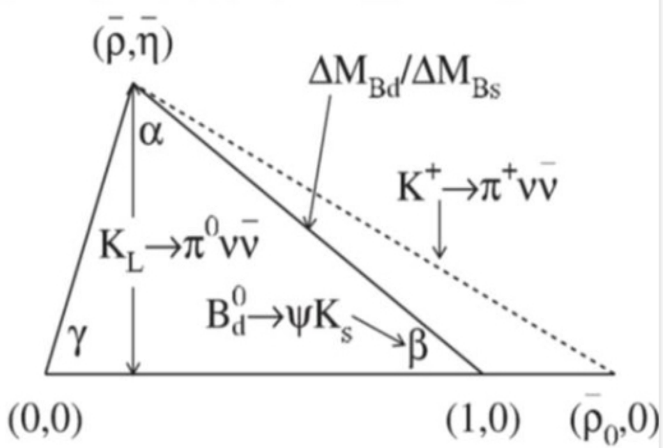
W-box

SM theoretical framework

Short-distance contribution (top quark) dominance → theoretically clean dependence on the product of CKM matrix elements **$V_{ts}{}^{*}V_{td}$**



$K \to \pi \nu\bar{\nu}$ is one of the few processes that can be used to verify accurately the SM Unitary.



SM suppression and proportionality to powers of $V_{ts}{}^{*}V_{td}$ allows:

- stringent test of the SM
- high sensitivity to New Physics (NP)

Complementary to LHC

Theoretical prediction

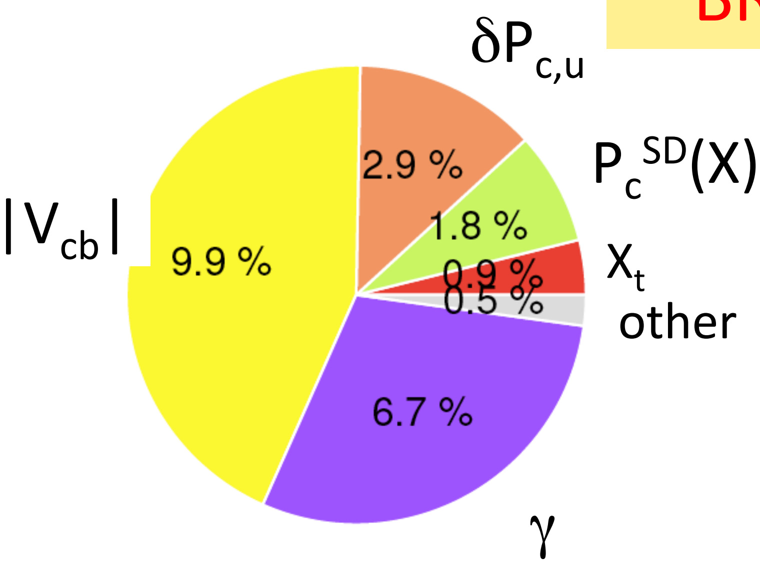
[A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R.Knegjens, arXiv:1503.02693]

Golden modes: $K \longrightarrow \pi\nu\bar{\nu}$

$BR(K_L \to \pi^0\nu\bar{\nu}) = (3.00 \pm 0.30)\times10^{-11}$

$BR(K^+ \to \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72)\times10^{-11}$

$BR(K^+ \to \pi^+\bar{\nu}\nu)$

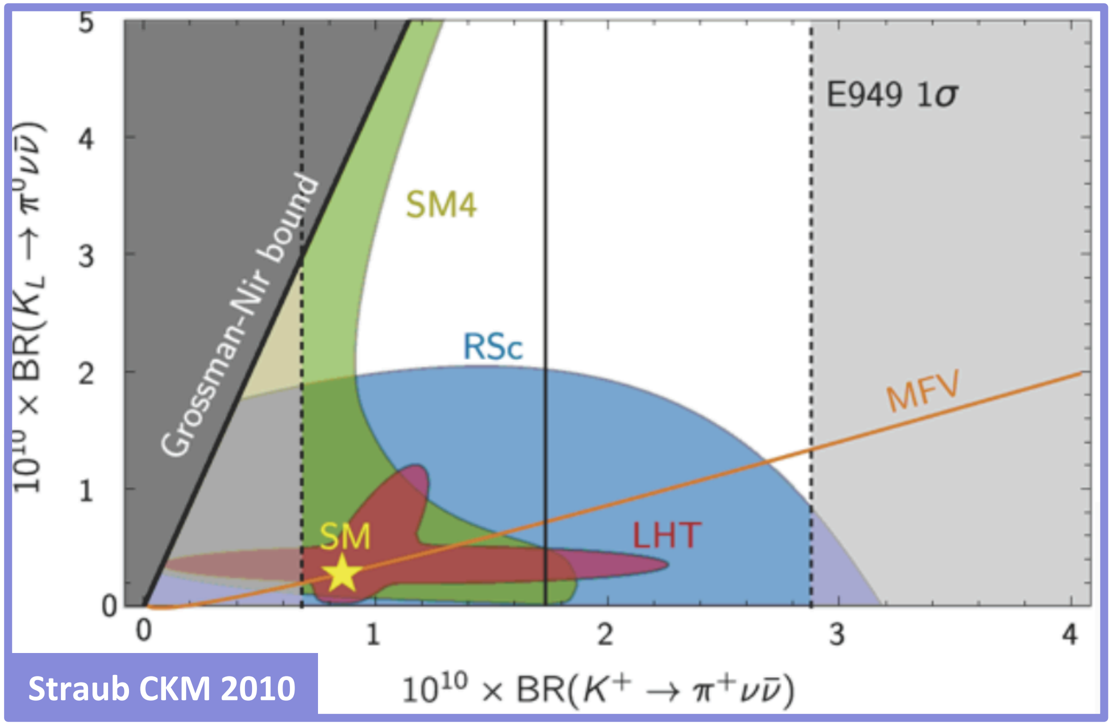


Error budget

	Short-distance contrib	Irreducible theory err. on amplit.	Total SM BR
$K^0_L \to \pi^0 \nu \bar{\nu}$	>99%	1%	3×10^{-11}
$K^+ \to \pi^+ \nu \bar{\nu}$	88%	3%	9×10^{-11}
$K^0_L \to \pi^0 e^+e^-$	38%	15%	3.5×10^{-11}
$K^0_L \to \pi^0 \mu^+\mu^-$	28%	30%	1.5×10^{-11}

New Physics Sensitivity

Measurement of charged $K^+ \to \pi^+ \nu\bar{\nu}$ decay and neutral $K_L \to \pi^0 \nu\bar{\nu}$ modes can discriminate different NP scenarios.



Straub CKM 2010

SM4: *SM with 4th generation* *[AJ.Buras et al. arXiv:1002.2126, 2010]*

RSc: *Randall-Sundrum mechanism* *[M.Blanke et al., JHEP 0903 (2009) 108]*

LHT: *Littlest Higgs with T-parity* *[M.Blanke et al, Acta Phys.Polon. B41 (2010) 657]*

MFV: *Minimal Flavor Violation* *[W.Altmannshofer et al., Nucl.Phys. B830]*

Z' gauge boson mediating FCNC at tree level *[AJ.Buras et al., JHEP 1302 (2013) 116; AJ.Buras et al., Eur.Phys.J. C74 (2014) 039]*

Probe of MSSM non-MFV, not yet excluded by LHC *[G. Isidori et al., JHEP 0608 (2006) 088]*

AJ.Buras et al., arXiv:1507.08672

Measurement of $|V_{td}|$ complementary to measurements from B-B mixing

$\delta(BR)/BR = 10\%$ implies $\delta(|V_{ts}|)/|V_{td}| = 7\%$

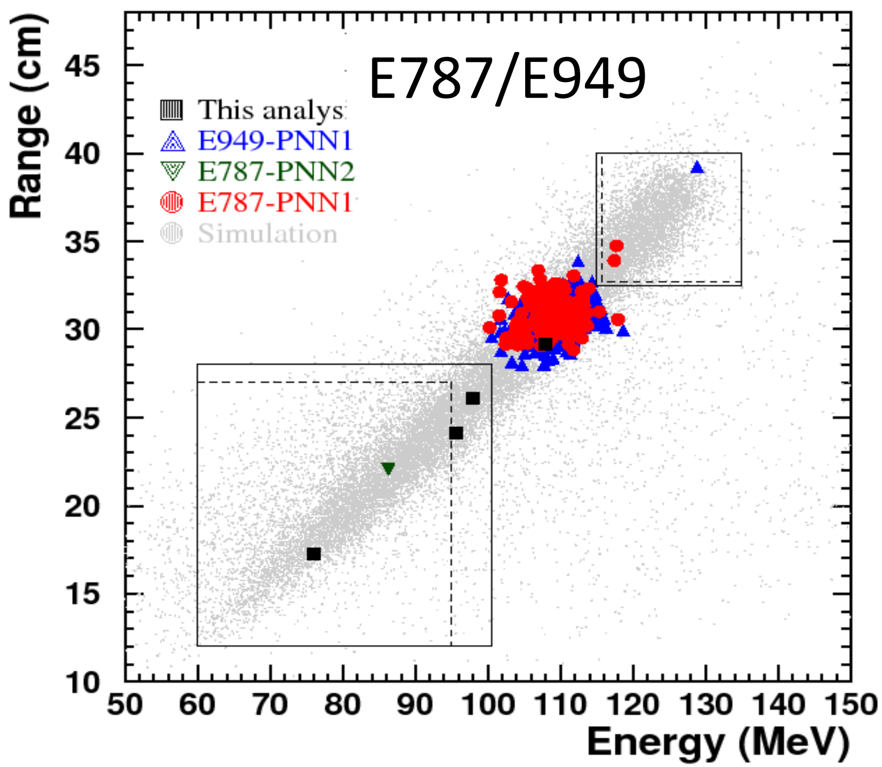
Experimental Status

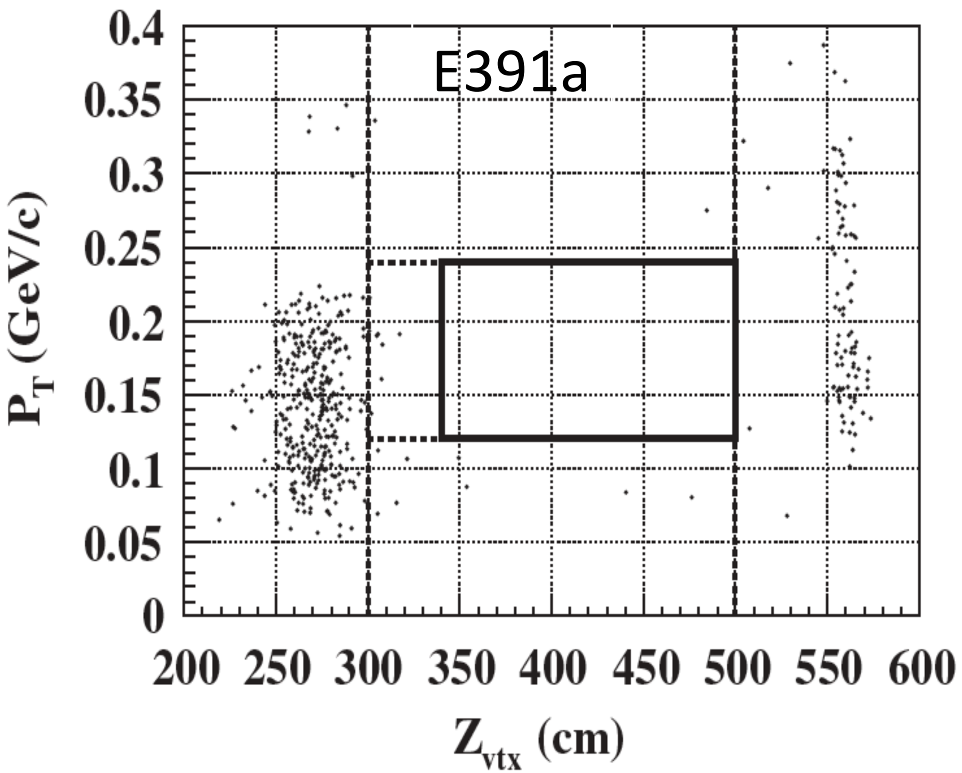
- $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ (from 7 events)

E787/E949 collaborations: Phys.Rev.D77.052003(2008), Phys.Rev.D79.092004 (2009)

- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 2600 \times 10^{-11}$

E391a Collaboration: Phys. Rev. 100, 201802 (2008); PhysRevD.81.072004 (2010)





Experimental vs. Theoretical Status

	SM prediction	Experiment
$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$(9.11 \pm 0.72)\times 10^{-11}$	$(17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$
$B(K^0_L \rightarrow \pi^0 \nu \bar{\nu})$	$(3.00 \pm 0.30)\times 10^{-11}$	$< 2600 \times 10^{-11}$

Gap between theoretical precision and large experimental errors!

NA62 aims at ~10% precision measurement of the $BR(K^+ \rightarrow \pi^+\nu\bar{\nu})$ in 2 years of data taking

Experimental requirements

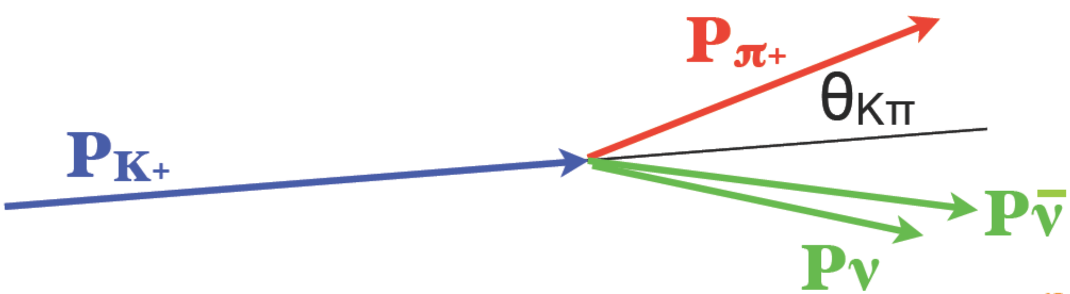
NA62 goal: measure BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) with 10% accuracy

➔ O(100) SM events + systematics control at % level

- Assuming a 10% signal acceptance and a BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) ~$10^{10}$ at least 10^{13} Kaon decays are required
- Rejection factor for dominant kaon decays of the order of 10^{12} (for background <20%)
- Systematics: <10% precision background measurement

NA62 design criteria: Kaon beam intensity, signal acceptance, background suppression

- Technique: high momentum Kaons and in flight decay



★ Signal signature: one beam K^+ track fully matched with one final state π^+ track

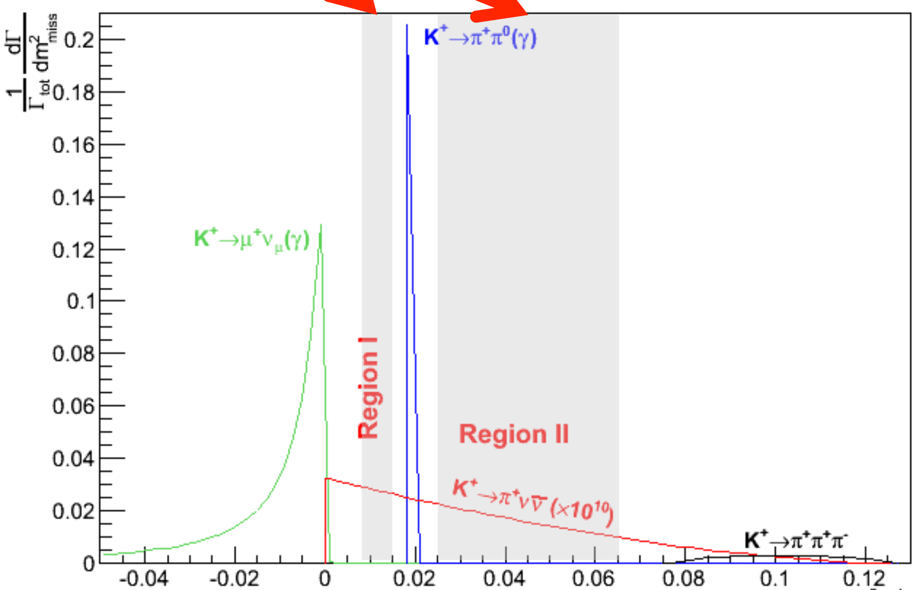
★ Basic ingredients: precise timing & kinematic cuts

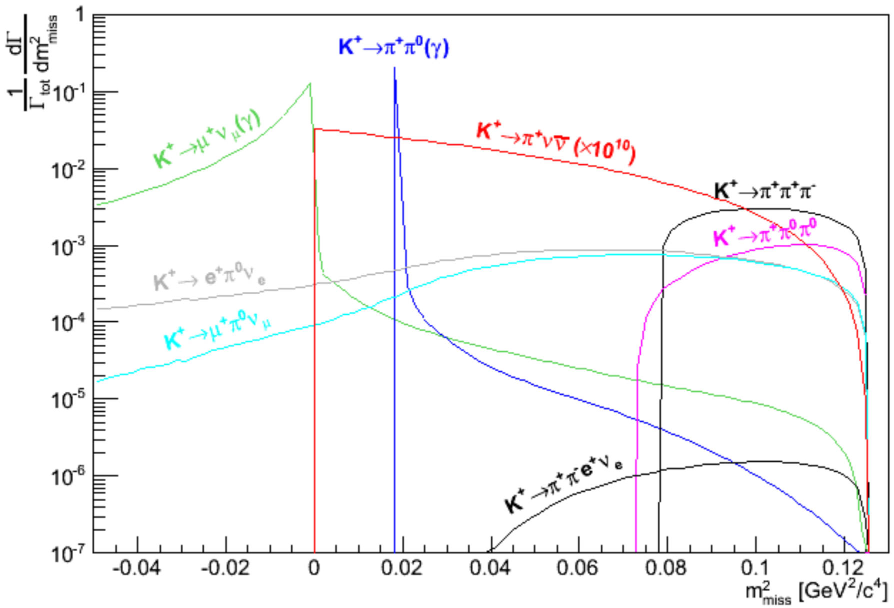
NA62 analysis strategy

Kinematically discriminating variable: $m_{miss}^2 = (P_K - P_\pi)^2$
where the particle from the decay is assumed to be a pion.

2 signal regions, on each side of the $K^+ \to \pi^+\pi^0$ peak, are used to remove contributions from more than 90% of main K^+ background decays.

2 kinematical regions





m_{miss}^2 [GeV^2/c^4]

Background suppression:

K decay background	BR	Rejection tools
$K^+ \rightarrow \mu^+ \nu$	0.6355	μ-ID + kinematics
$K^+ \rightarrow \pi^+ \pi^0$	0.2066	γ-veto + kinematics
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.0559	π^--ID +multi-track + kinematics
$K^+ \rightarrow \pi^+ \pi^0 \pi^0$	0.0176	γ-veto + kinematics
$K^+ \rightarrow \pi^0 e^+ \nu$	0.0507	e-ID + kinematics + γ-veto
$K^+ \rightarrow \pi^0 \mu^+ \nu$	0.0335	μ-ID + kinematics + γ-veto
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	4.257×10^{-5}	

- Beam tracking
- Photon veto
- Muon veto
- π/μ/e identification

Background suppression factors required $O(10^{12})$:

Kinematics	$O(10^4\text{-}10^5)$
Charged Particle ID	$O(10^7)$
γ detection	$O(10^8)$
Timing	$O(10^2)$

$P_{\pi+} < 35$ GeV/c to ensure $P_{\pi 0} > 40$ GeV/c

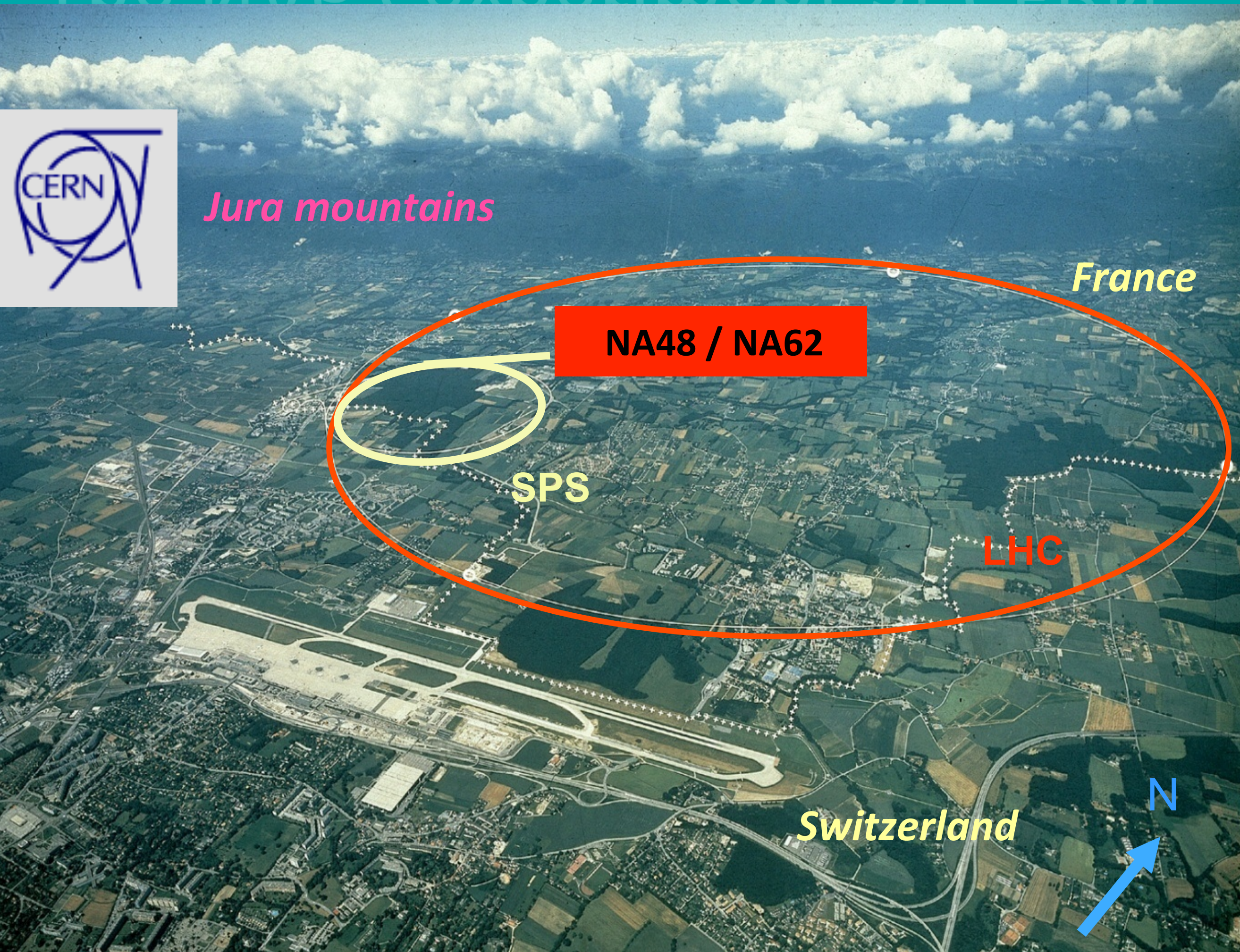
~92% → ~8%

The Analysis Sensitivity

Decay	event/year
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (*)	**45**
$K^+ \rightarrow \pi^+ \pi^0$	5
$K^+ \rightarrow \mu^+ \nu$	1
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	< 1
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ + 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**

(*) [SM] (flux 4.5×10^{12} K^+ decay/year)

The NA62 experiment at CERN

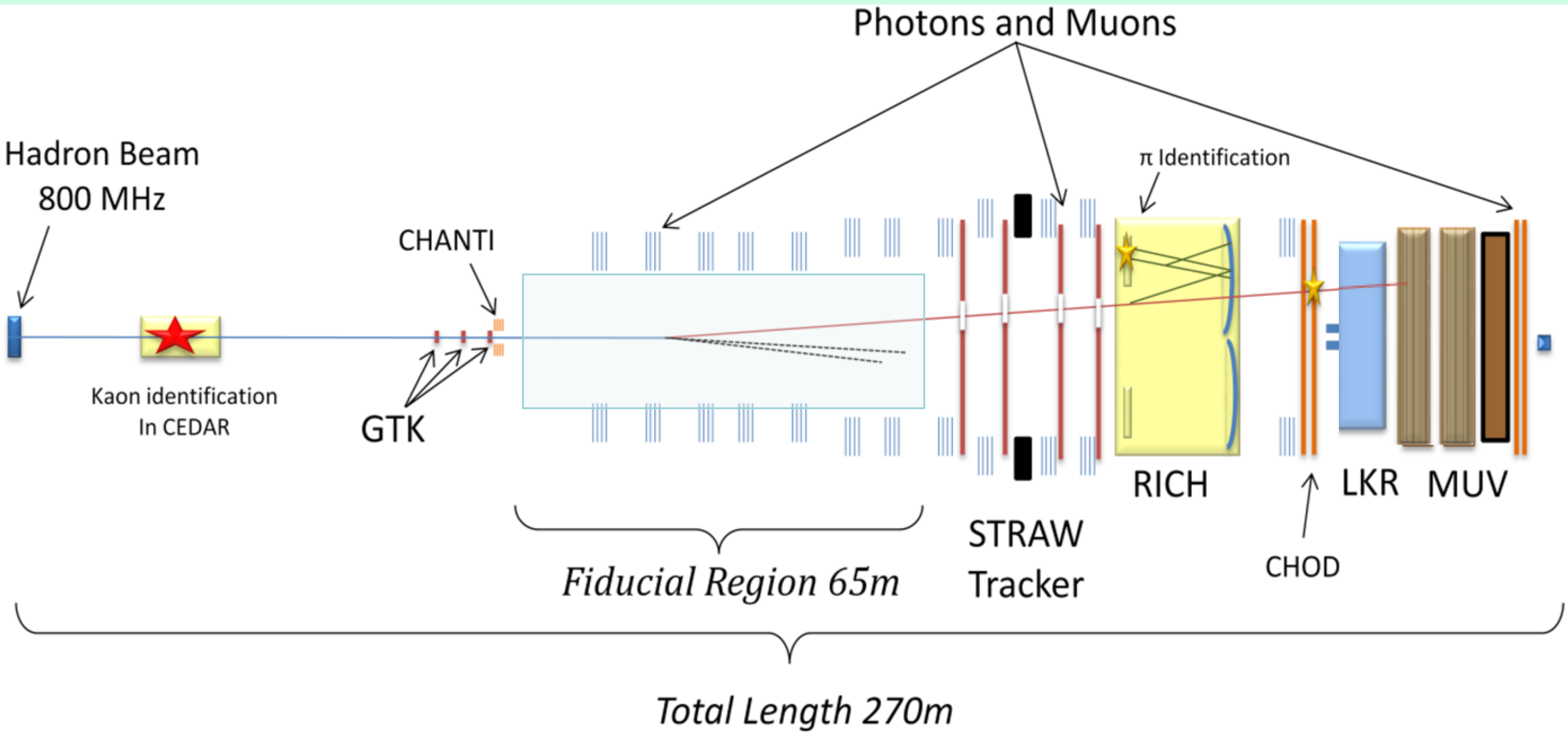


2005	Proposal
2009	Approved
2010	Technical design
2012	Technical run (partial layout)
2014	Pilot Run
2015-18	**Physics Runs**

~200 participants from 30 institutions

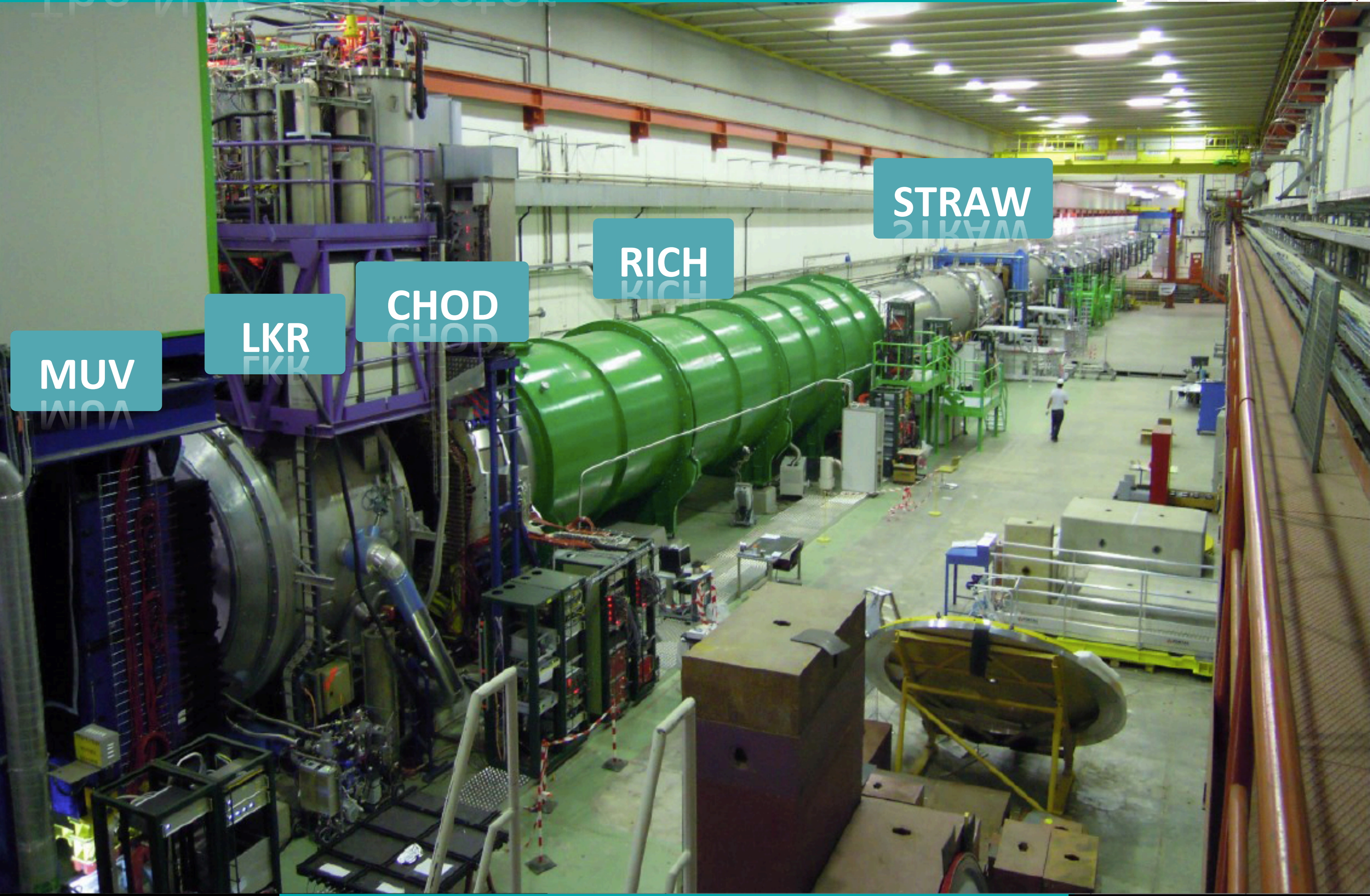
The NA62 beam and detector

- CERN SPS 400 GeV/c primary proton beam on a Be target
- Secondary un-separated positive hadron beam (6% K^+); momentum 75 (±1%) GeV/c
- Nominal beam intensity: 750 MHz (~45 MHz K^+ decays in the fiducial volume)



<u>High intensity and fast timing</u>
High performance e.m. calorimeter
High rate precision and low mass tracking
Redundant particle ID
Hermetic photon veto

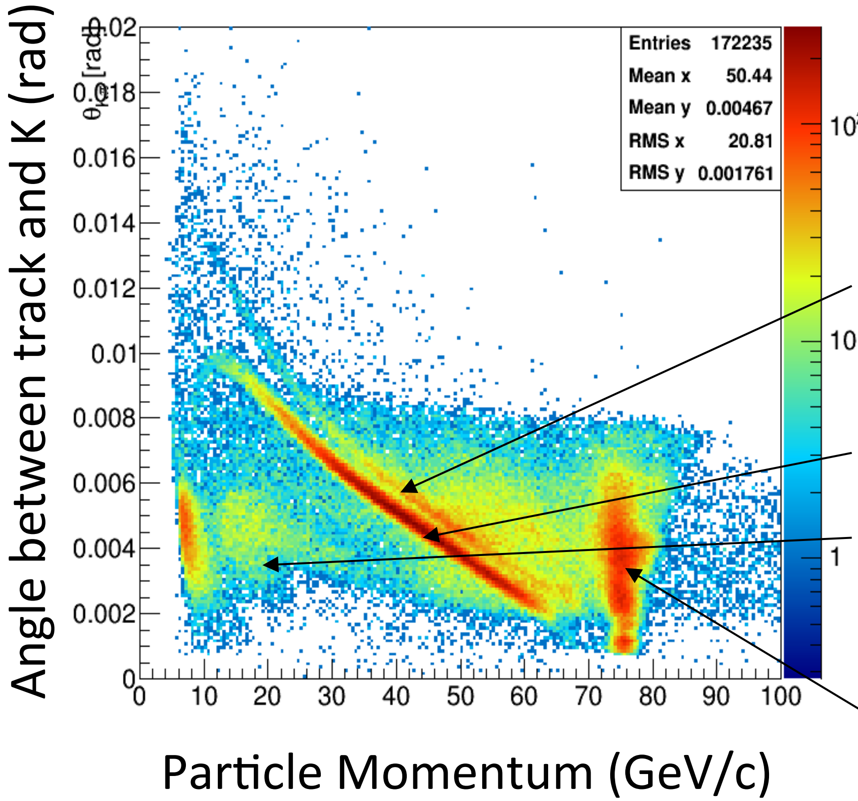
The NA62 detector

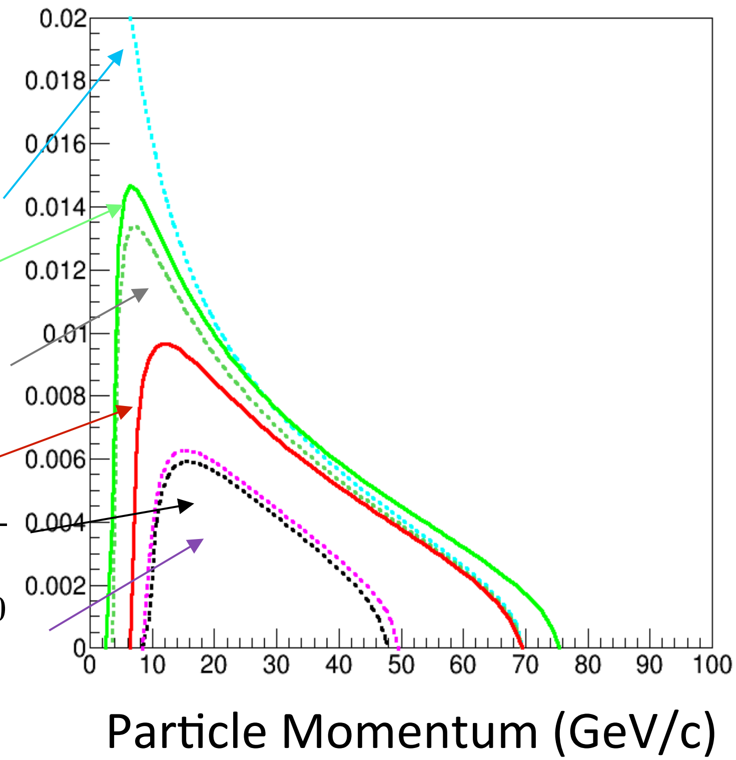


First Look at 2014 Data Quality

(no GTK, 3 out of 4 Straw ch., no RICH mirror alignment, no photon rejection)

- Events with only 1 track in the straw detector (40ns time window)
- 10^2 muon rejection at trigger level

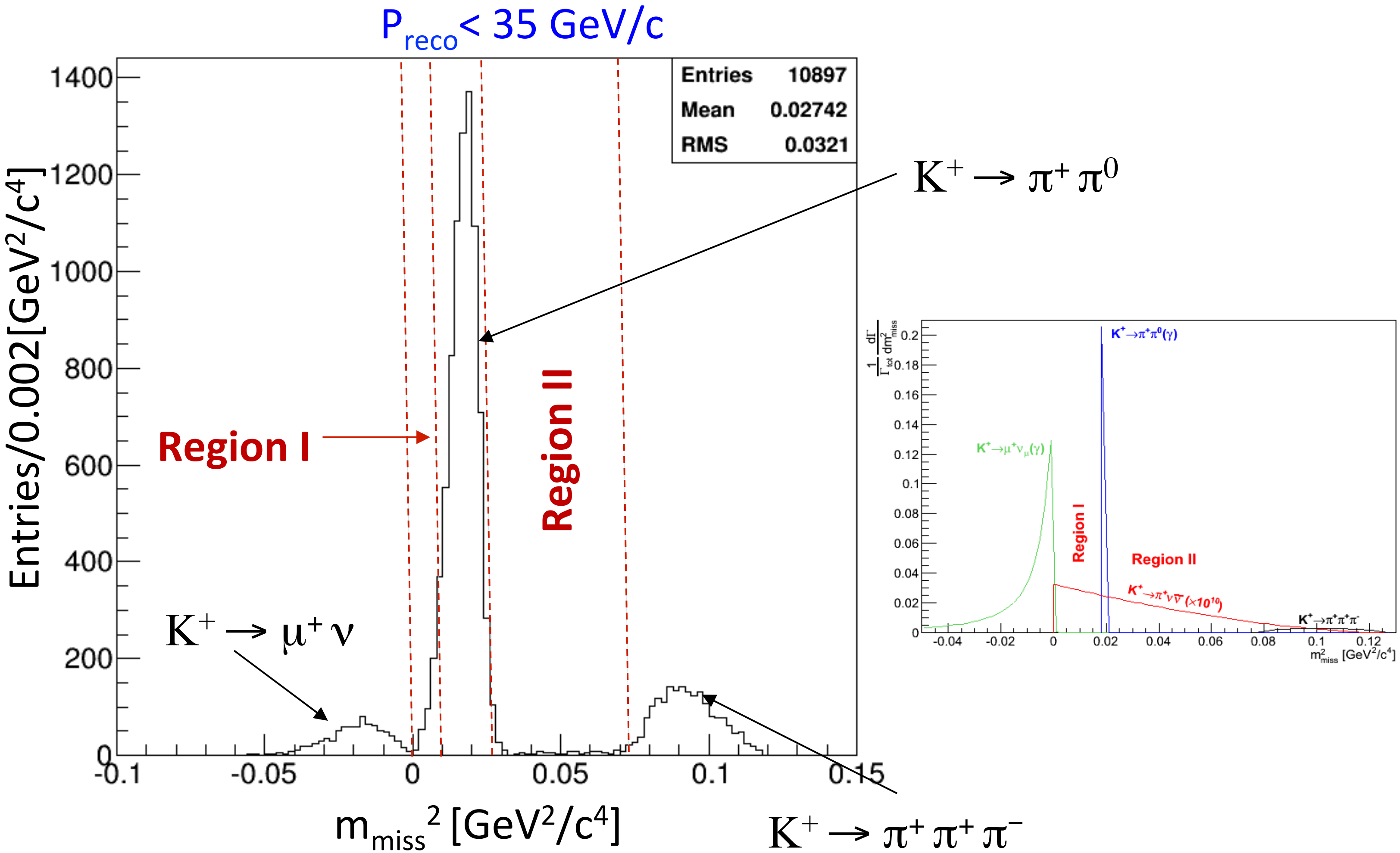




First Look @2014 Data: Missing Mass

Requiring K-ID from KTAG in time with the spectrometer track

Requiring decay vertex in fiducial region



Summary & prospects at NA62

The rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay

$BR_{theor} = (9.11 \pm 0.72) \times 10^{-11}$ $BR_{exp} = (17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$

- ★ **Gap between theoretical precision and large experimental error**
- ★ **Sensitive probe to New Physics**
- ★ **Motivations for a strong experimental effort**

- ★ **NA62: a substantial upgrade of the previous CERN experiments, designed to measure the BR with 10% precision**
- ★ **NA62 successful pilot run in 2014**
- ★ **Data taking starting: NA62 ready for physics and planning to collect the world largest sample of K^+**

NA62 marks CERN's return to the exploration of the Standard Model using high-intensity Kaon beams.

Kaons are partner of LHC in the quest for physics beyond the SM.

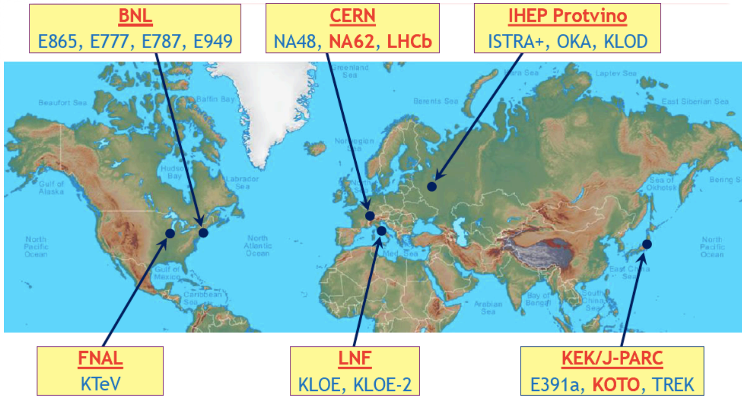
★ Extra material

Kaon physics facilities

Charged Kaon Beams: different exp. techniques.

"Stopped" → work in Kaon frame, high Kaon purity (electromagneto-static-separators); compact detectors

"In-Flight" → decays in vacuum (no scattering, no interactions) ; RF separated or unseparated beams; extended decay regions



Exp	Machine	Meas. or UL 90% CL	Notes
	Argonne	$< 5.7 \times 10^{-5}$	Stopped, HL Bubble chamber
	Bevatron	$< 5.6 \times 10^{-7}$	Stopped, Spark chamber
	KEK	$< 1.4 \times 10^{-7}$	Stopped, $\pi^+ \mu^+ e^+$
E787	AGS	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	Stopped
E949	AGS	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	Stopped
NA62	SPS		In-Flight, unseparat.

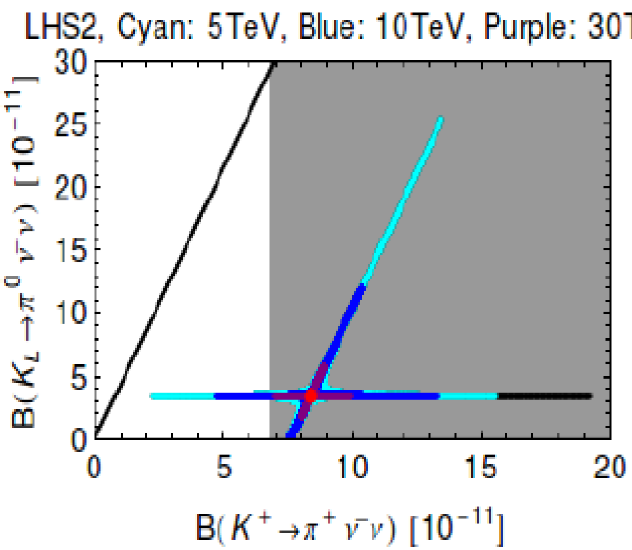
Beyond the baseline

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	5.9×10^{-11} $m_{X^0} = 0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S \neq \Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S \neq \Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h, \nu_h \to \nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h} = 350\ MeV$	
R_K	LU	$(2.488 \pm 0.010) \times 10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$

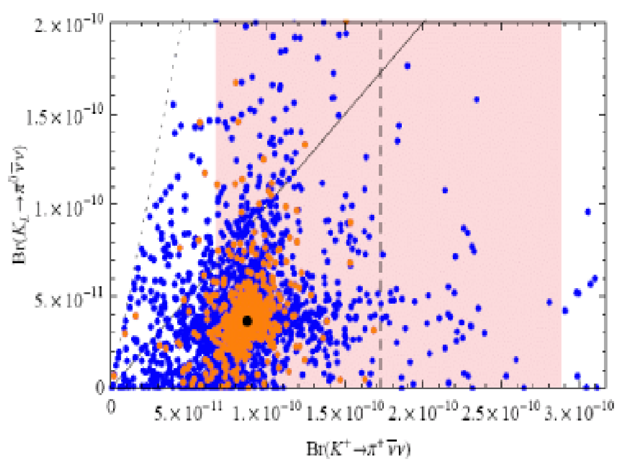
New Physics Sensitivity

- Z' gauge boson mediating FCNC at tree level
  [A.J.Buras et al., JHEP 1302 (2013) 116; A.J.Buras et al. Eur. Phys. J. C74 (2014) 039]
- Littlest Higgs with T-parity
  [M. Blanke et al., Acta Phys. Polon. B 41 (2010) 657]
- Custodial Randall-Sundrum
  [M. Blanke et al., JHEP 0903 (2009) 108]
- Best probe of MSSM non-MFV (still not excluded by LHC)
  [G. Isidori et al., JHEP 0608 (2006) 088]

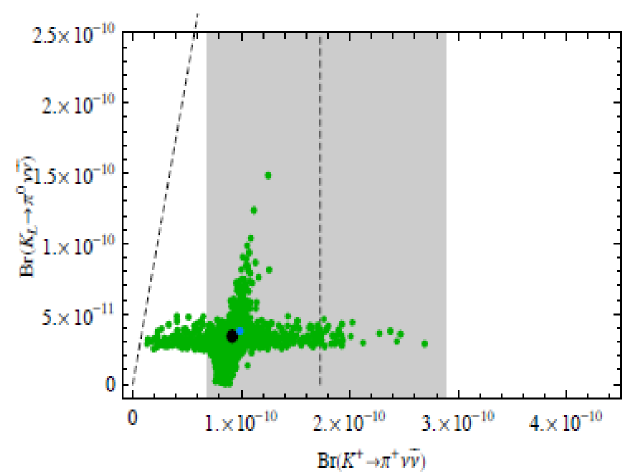
Z' model



Randall - Sundrum



Littlest Higgs



Recent $K^{\pm}$ experiments at CERN

Experiment	NA48/2 ($K^{\pm}$)	NA62-R_K ($K^{\pm}$)	*NA62* (K^{+}; starting)
Data taking period	2003–2004	2007–2008	*2014–2017*
Beam momentum, GeV/c	60	74	75
RMS momentum bite, GeV/c	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV/c	120	265	270
$M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/c^2	1.7	1.2	0.8
$K^{\pm}$ decays in fiducial volume	2×10^{11}	2×10^{10}	1.2×10^{13}
Main trigger	multi-track; $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$	$e^{\pm}$	$K_{\pi\nu\nu}$ + ...

Kaon beams: sources of large clean tagged π^0 samples.

- In a $K^{\pm}$ beam, ratio of number of decays $\pi^0/K^{\pm} \approx 1/3$.
- Principal π^0 source: $K^{\pm}\to\pi^{\pm}\pi^{0}$ (known as $K_{2\pi}$).
- Best data on many rare/forbidden π^0 decays come from K experiments.