Possibilities for future kaon experiments at the SPS

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Disclaimers

Discussion about the future of NA62 after $K^+ \to \pi^+ \nu\bar{\nu}$ is just getting started.

Many different ideas are under development.

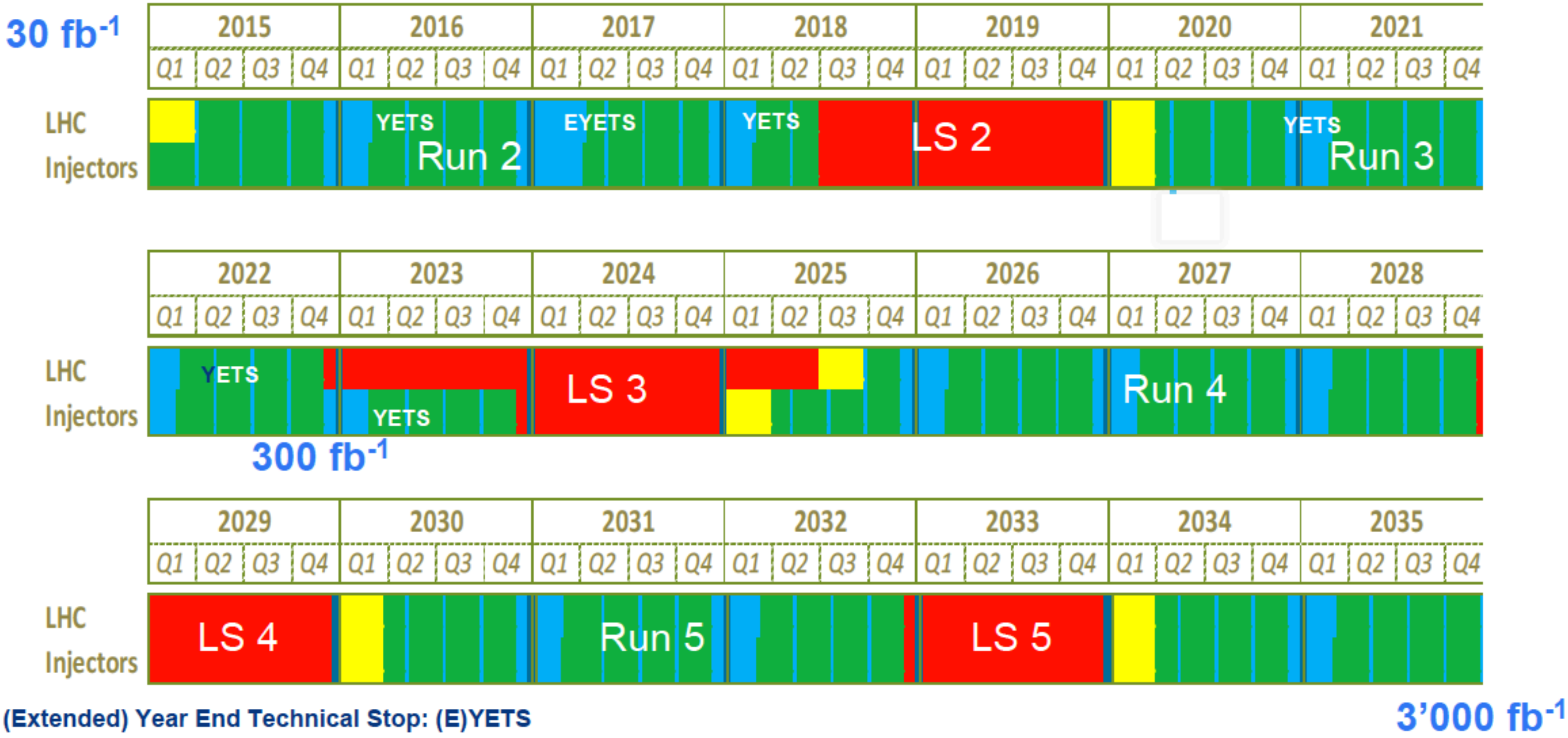
For the purposes of discussion, I will try to survey some of them.

I am not presenting official NA62 perspectives.

Preface: Fixed target runs at the SPS

General assumption:
SPS available for fixed-target during LHC runs

F. Bordry, CERN Roadmap, Feb 2014



(Extended) Year End Technical Stop: (E)YETS

Current topics in kaon physics

Traditional observables: CP violation in $K_S K_L$ (ε, ε'/ε), Δm_K

Much progress on lattice, but likely to remain theory-limited for several years

Precision observables: V_{us}, $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$

Not theory limited, but experimental results hard to improve upon

K decays with explicit LFV

K_L: Excellent experimental limits, tight model constraints, further progress hard

K^+: Searches can be improved by 1-2 orders of magnitude to catch up to K_L

FCNC decays: Clean short-distance probes

$\pi\nu\bar{\nu}$: SD dominated, SM intrinsic theory uncertainties at the few % level

$\pi^0\ell^+\ell^-$: Nominally easier experimental signatures, some irreducible backgrounds
Larger theoretical uncertainties, need progress on ancillary measurements

Searches for heavy, sterile neutrinos in K decay

Other topics:

CPT limits, $K_S K_L$ interferometry, T-odd μ polarization in $K_{\mu 3}$

Kaon experiments: World outlook

$K \to \pi\nu\bar{\nu}$ experiments running, planned, or proposed

Expt.	Primary beam (E GeV)	Secondary beam (E GeV)	Start date + run years	SM evts	Status
NA62	**SPS (450)**	**positive (75)**	**2014+2**	**50/yr***	**Ready**
ORKA	FNAL MI (95)	K^+ (0.6, stopped)	2020+5	200/yr*	Proposal
KOTO	**JPARC-I (30)**	**neutral (2 peak)**	**2013+3**	**~3**	**Running**
KOTO/2	JPARC-II (30)	neutral (~2 peak)	2025?	>100	Concept
FNAL K_L	Project X (3)	neutral (0.7 peak)	2030?	1000	Concept

Prospects for $K^+ \to \pi^+\nu\bar{\nu}$ much more solid than for $K_L \to \pi^0\nu\bar{\nu}$

No experiments looking at $K_L \to \pi^0\ell^+\ell^-$

Other "kaon" experiments

Expt.	Facility	K source	Program
TREK	JPARC	K^+ stopped	R_K, T-odd μ polarization in $K_{\mu 3}$
KLOE/2	DAΦNE	$\phi \to KK$	Continued analysis of KLOE K_S, K_L, $K^\pm$ data
LHCb	LHC	K_S in flight	Good stat. reach for $K_S \to \mu^+\mu^-$, $K_S \to \pi^0\mu^+\mu^-$

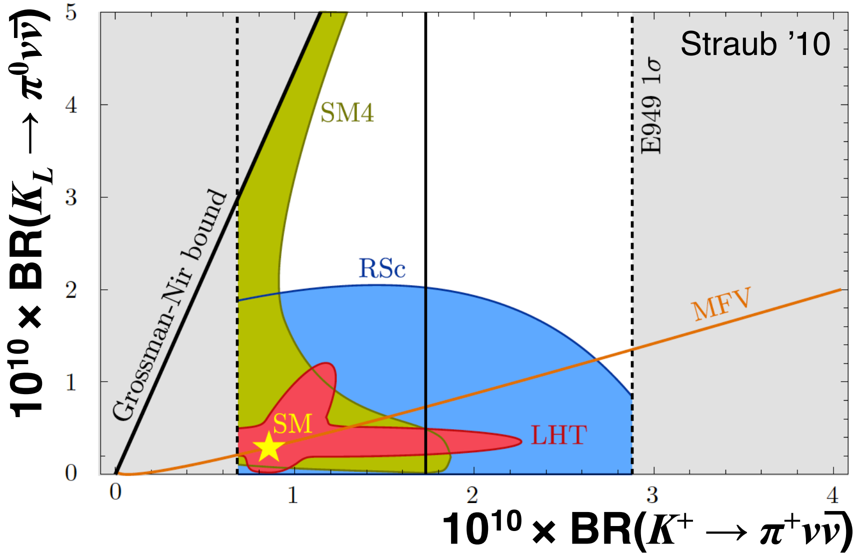
Rare kaon decays

Some modes more important than others, but best to measure as many as possible

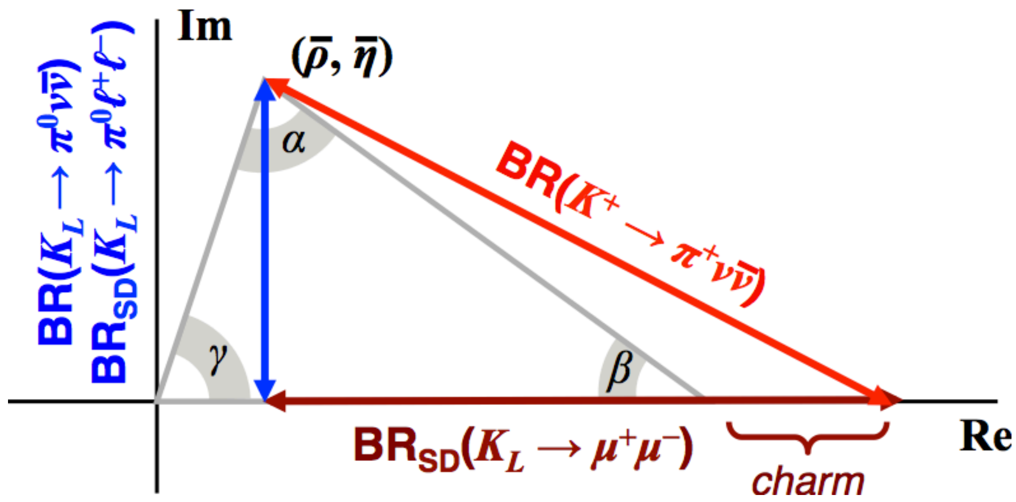
Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{-11}	Exp. BR × 10^{-11}
$K_L \to \mu^+\mu^-$	40%	20%	681 ± 32	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	35 ± 10	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	14 ± 3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	7.8 ± 0.8	17 ± 12
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.4 ± 0.4	<26000†

*Approx. error on LD-subtracted rate excluding parametric contributions †90% CL

New physics affects channels differently

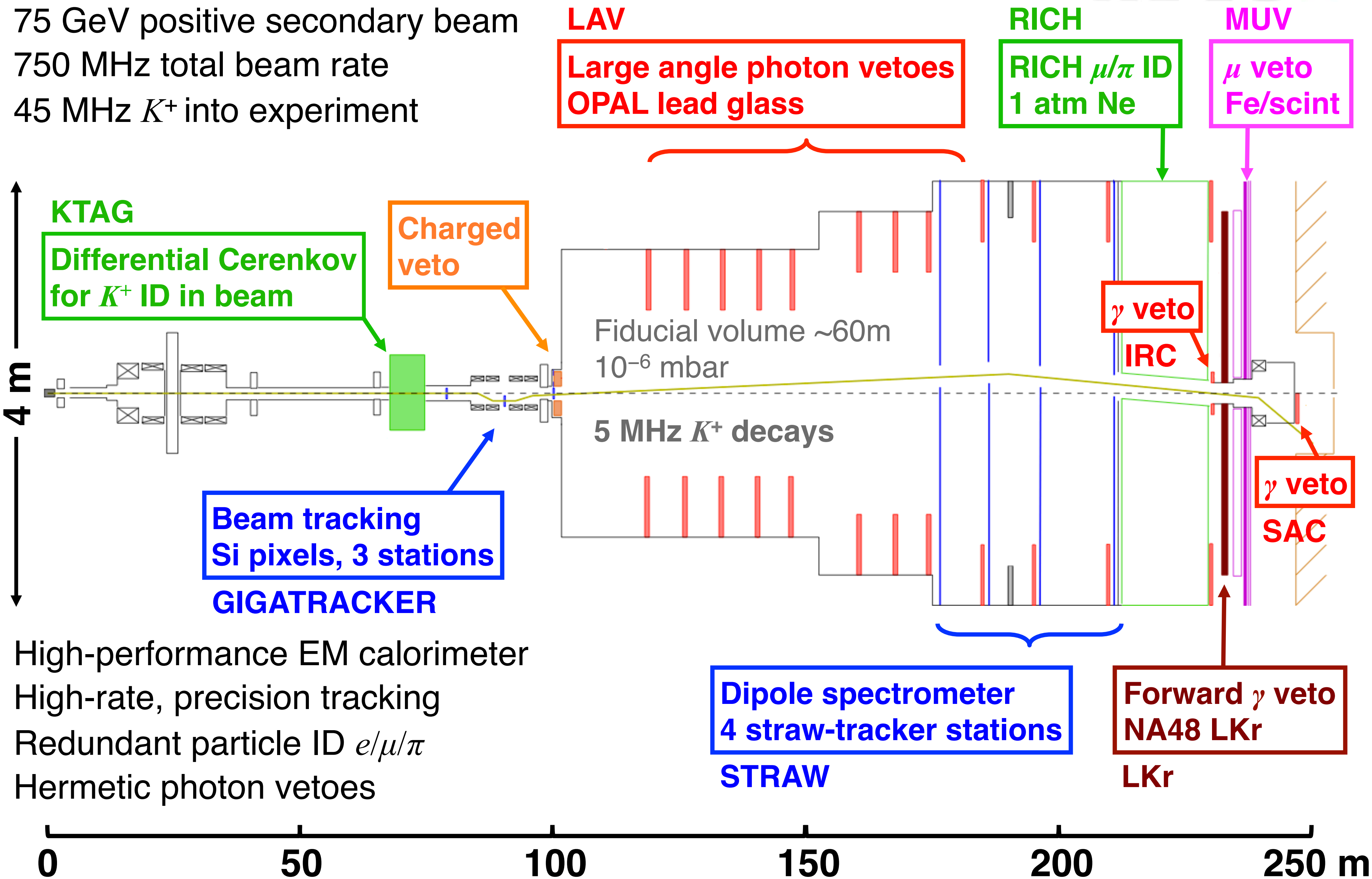


Overconstrain unitarity triangle



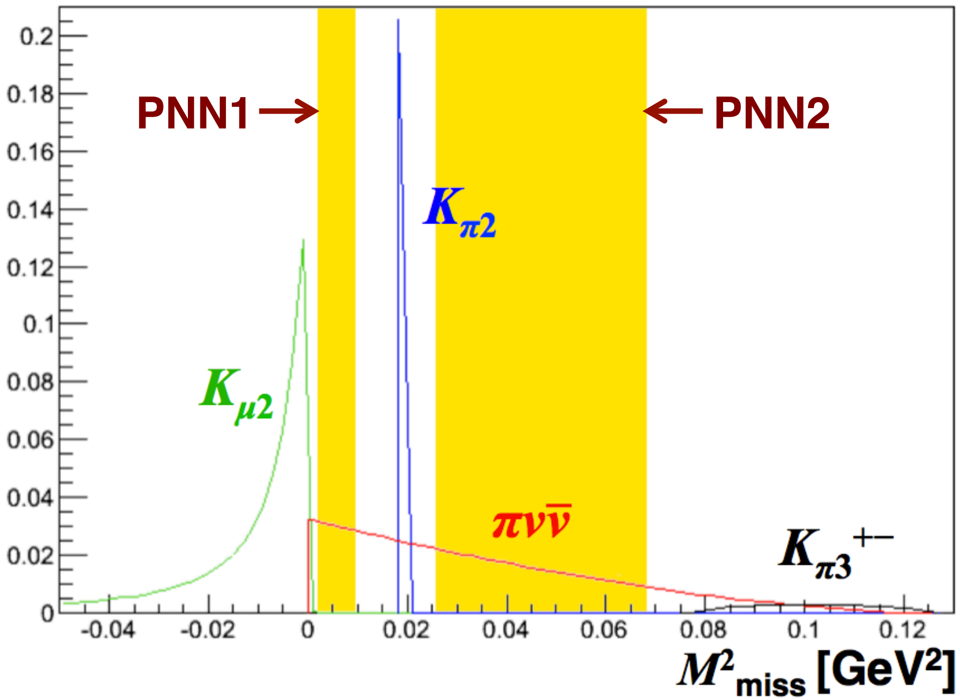
The NA62 experiment at the SPS

75 GeV positive secondary beam
750 MHz total beam rate
45 MHz K^+ into experiment



High-performance EM calorimeter
High-rate, precision tracking
Redundant particle ID $e/\mu/\pi$
Hermetic photon vetoes

NA62 performance for $K^+ \to \pi^+ \nu \bar{\nu}$



- 1 track with $15 < p_\pi < 35$ GeV and π PID in RICH
- No γs in LAV, LKr, IRC, SAC
- No μs in MUVs
- 1 beam particle in Gigatracker with K PID by KTAG
- z_{vtx} in 60 m fiducial volume

Acceptance: ~12%

3% in PNN1 region

9% in PNN2 region

50% loss from momentum cut

Detector inefficiencies included

45 signal events/year

Expected backgrounds	
$K^+ \to \pi^+ \pi^0$	10%
$K^+ \to \pi^+ \pi^0 \gamma_{IB}$	3%
$K^+ \to \mu^+ \nu$	2%
$K^+ \to \mu^+ \nu \gamma_{IB}$	1%
$K^+ \to \pi^+ \pi^+ \pi^-$	< 1%
K^+_{e4}, other 3 track decays	< 1%
K^+_{e3}, $K^+_{\mu 3}$	negligible
Total	**< 20%**

NA62 sensitivity vs. ORKA

Official sensitivity estimates can be misleading due to differences in assumptions for run time, etc.

Is ORKA really 10× more sensitive than NA62?

	NA62	**ORKA**
SM signal events	~100	~1000
Years of data taking	2	5
Data-taking per year	4×10^6 s “100 days, 50% uptime”	18×10^6 s “5000 hours”
Total data taking	8×10^6 s	90×10^6 s
SM events/NA62 year	**~50**	**~50**

Most of the difference just from time scheduled for data taking!

DOE P5 panel report released at 16:00 CEST today
P5 “cannot recommend moving ahead at this time” on ORKA

NA62 in the near future

Goal: Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) to 10%

Collect ~100 signal events with S/B > 10 in 2-years' equivalent data taking

Other elements of physics program:

- Measurement of R_K to ~0.2%
- Searches for LFV K^+ and π^0 decays
- ChPT tests & precision BR mmts.

Start of NA62 running: October 2014

Possible to request more running during Run 2 to improve sensitivity!

Planned and potential upgrades:

- New trigger hodoscope
- Small changes to level-0 architecture to allow more restrictive triggering
- Continuous WFD readout for critical detectors (e.g. LAVs)?

Ambitious upgrades to justify running in Run 3?

None proposed yet, but NA62 just starting up: First need to get experience

NA62: From K^+ to K_L

Possibility of a neutral beam forseen in the NA62 Technical Proposal:

- Slight changes to production angle and upstream beam optics
- Running for $\pi^0 \nu\bar{\nu}$ and $\pi^0 \ell^+\ell^-$ will require a substantial increase in primary intensity, but **well within** what the SPS can provide

	NA62 K^+ beam	Future NA62 K_L beam
Primary intensity (ppp)	3×10^{12}	2.4×10^{13}
Production angle for secondary (mrad)	0	2.4
Angular acceptance (μsr)	12.7 μsr	0.125 μsr
Momentum	75 GeV ±1%	97 GeV (mean) 40-140 GeV (50% peak)
Rates into FV	750 total 525 π 170 p 45 K^+	3000 total 2000 γ 800 n 90 K_L
K decays in FV	4.5 MHz **4.5×10^{12}/year**	0.9 MHz **9×10^{11}/year**

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

NA62 Italy subset has **PRIN funding** for feasibility studies for a K_L experiment

FERRARA, FIRENZE, FRASCATI, NAPOLI, PERUGIA, PISA, TOR VERGATA, TORINO

Estimate cost, timescale, performance for an SPS $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment

Questions to address:

- **What are the pros and cons of a $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment at high energy?**
- What is the intensity and composition of the neutral beam?
  What can we do to suppress beam photons?
- What performance will be required for large-angle photon vetos?
- Is the performance of the NA48 LKr calorimeter suitable?
- Can a preshower detector in front of LKr provide useful geometrical constraints?
- What will be required in terms of charged-particle vetos?
- What technology is needed for the in-beam veto to stop photons from escaping downstream through the beam pipe?
  How to cope with GHz fluxes of beam photons and neutrons?
- What baseline architecture to adopt for triggering/data acquisition?

PRIN studies: $K_L \to \pi^0 \nu \bar{\nu}$ at the SPS

Beam sweeper: Reduce 2 GHz of beam photons by at least 10×
May require innovative approach: Iridium monocrystal?

Large angle photon vetoes: Hermetic coverage out to 100 mrad for E_γ down to 20 MeV
26 new LAV stations with scintillator/tile design

Small angle photon vetoes: Be relatively insensitive to 800 MHz of beam neutrons
Amdist this background, reject γ from $\pi^0\pi^0$ to 10^{-3} level
Prototypes under development:
- Converter + NA62 Gigatracker (Si pixel)-based veto
- Dense inorganic Cerenkov crystal veto

Expected results with 2 yrs of data:
$\pi^0 \nu \bar{\nu}$ cand. with 2γ on LKr, nothing else
Vertex in FV with $p_\perp(\pi^0) > 0.1$ GeV

~10 signal evts
~10 $\pi^0\pi^0$ background evts

Nominally 2× better than KOTO (JPARC)

A $K_L \to \pi^0 \nu \bar{\nu}$ experiment will require long lead time
- Significant construction work, R&D, prototyping necessary
- Aim for turn-on in Run 3 or for a more ambitious measurement in Run 4?

$K_L \to \pi^0\ell^+\ell^-$ at NA62?

$K_L \to \pi^0\ell^+\ell^-$ vs $K \to \pi\nu\bar{\nu}$:

- Measurements are complementary and can help to discriminate among NP models
  Different operators contribute to $K_L \to \pi^0\ell^+\ell^-$ and $K \to \pi\nu\bar{\nu}$
- Nominally easier experimental signatures for $\pi^0\ell^+\ell^-$, but some irreducible backgrounds (esp. for $\pi^0e^+e^-$)
- Larger theoretical uncertainties, need progress on ancillary measurements such as BR($K_S \to \pi^0\ell^+\ell^-$)

Modifications to NA62 needed for $K_L \to \pi^0\ell^+\ell^-$ are straightforward

- Removal of CEDAR, Gigatracker
- Realignment of straws, RICH; new IRC
- Possibly new SAC to handle higher rates

Potential for $K_L \to \pi^0\ell^+\ell^-$ experiment was studied by NA48

- Good basis for extrapolation to NA62

$K_L \to \pi^0 \ell^+ \ell^-$ at NA62?

Extrapolated from studies for NA48

1.8 × 10[12] K_L decays in FV (2 year run, 0.9 × 10[12] K_L/year)

	$K_L \to \pi^0 e^+ e^-$	$K_L \to \pi^0 \mu^+ \mu^-$
SM BR	3.5×10^{-11}	$1.4\ 10^{-11}$
Acceptance	3%	18%
SM signal events	~2	~5
S/B	~1/10	~1/6

$K_L \to \pi^0 e^+ e^-$ channel is plagued by $K_L \to e^+ e^- \gamma\gamma$ background

- Like $K_L \to \gamma\gamma$ with internal conversion + bremsstrahlung
- 3% acceptance for $K_L \to \pi^0 e^+ e^-$ reflects tight cuts on Dalitz plot to reject
- Need to explore other strategies: statistical separation, kinematic fitting
- NA62 has better 2-3× better mass resolution on $\ell\ell$ vertex than NA48

Needs further study, but $K_L \to \pi^0 \ell^+ \ell^-$ could be an interesting part of early-stage K_L running at NA62

NA62 potential for heavy neutrino searches

SM needs extension to address:
- Neutrino masses
- Baryon asymmetry
- Dark matter

Example: Neutrino minimal SM (νMSM)
3 new heavy, sterile RH Majorana νs: $N_{1,2,3}$
$m_1 \sim 10$ keV → DM candidate
$m_2 \sim m_3 \sim 1$ GeV → Observable in $\boldsymbol{K, D \to N\ell}$

NA62 can perform an exclusive search for $N \to e\pi$ or $\mu\pi$

***K* decays**

Upstream: K decays in space between Be target and RP shield wall

Beam: K decays in 100 m downstream of KTAG, upstream of Straw 1

***D* decays**

Fully analogous to SHiP experiment; lower intensity

NA62 can carry out such a search during $K^+ \to \pi^+\nu\bar{\nu}$ running

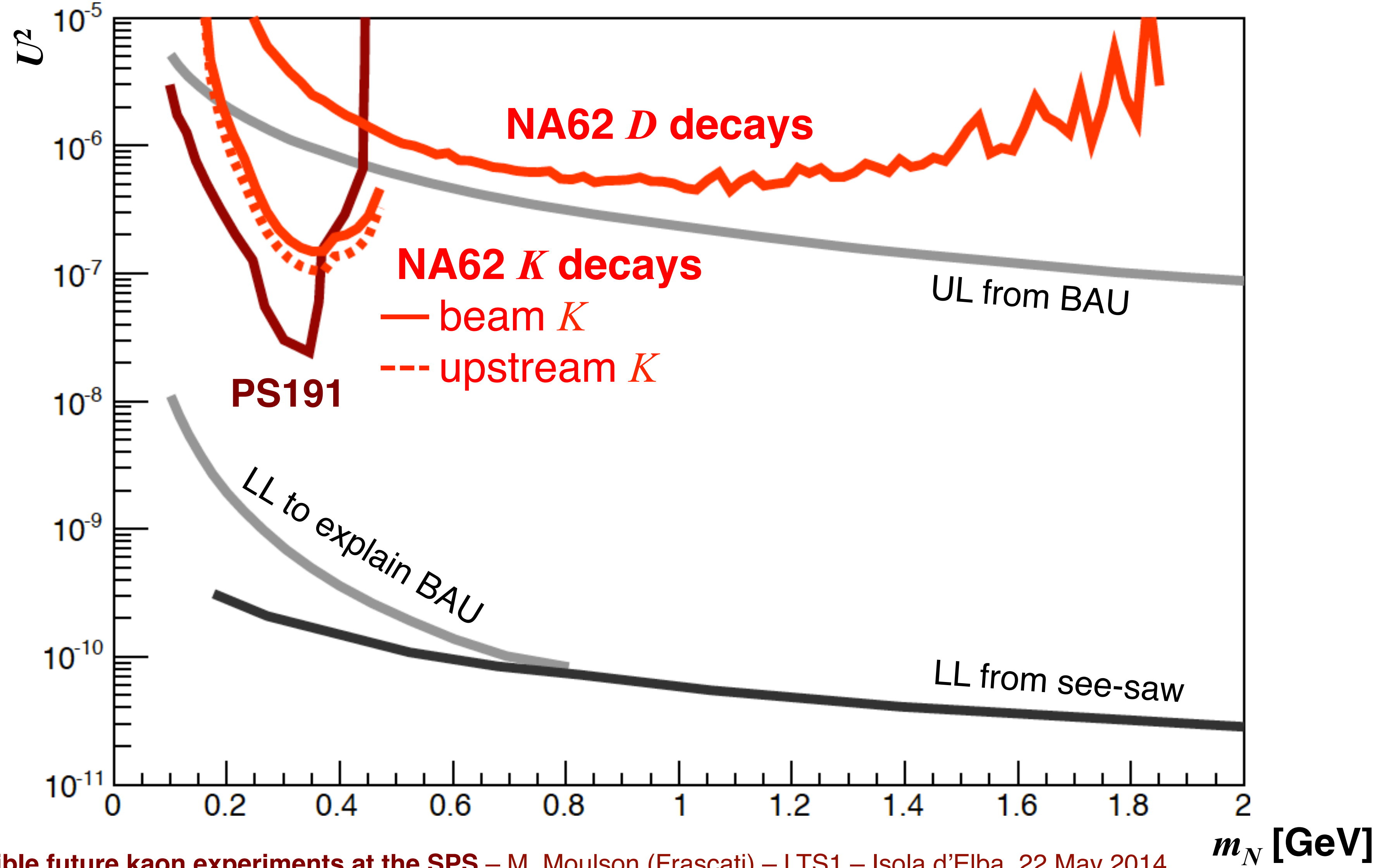
No substantial hardware modifications needed
- May need some small hardware modifications to the NA62 level-0 trigger
- Subject of a SIR proposal (VISHNU); feasibility studies ongoing

Heavy neutrino search also possible with K_L beam
- Slight reduction in sensitivity (only upstream K decays)
- Need to futher explore compatibility with K_L physics program

Exclusive search for $N \to \ell\pi$ at NA62

Sensitivity for exclusive search for $N \to e\pi$ or $\mu\pi$

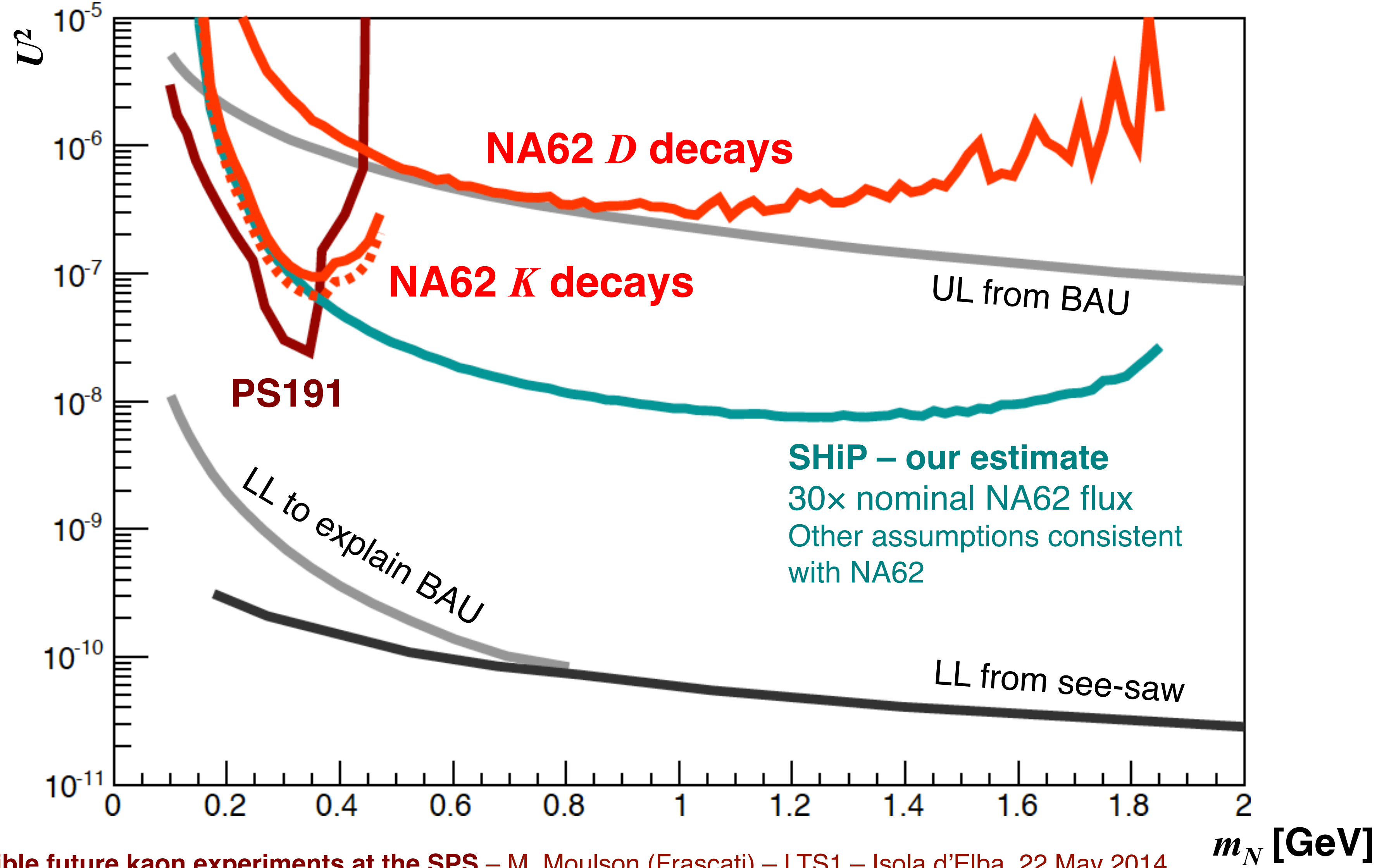
2 years of data at nominal NA62 K^+ run intensity (3×10^{12} ppp)



Exclusive search for $N \to \ell\pi$ at NA62

Sensitivity for exclusive search for $N \to e\pi$ or $\mu\pi$

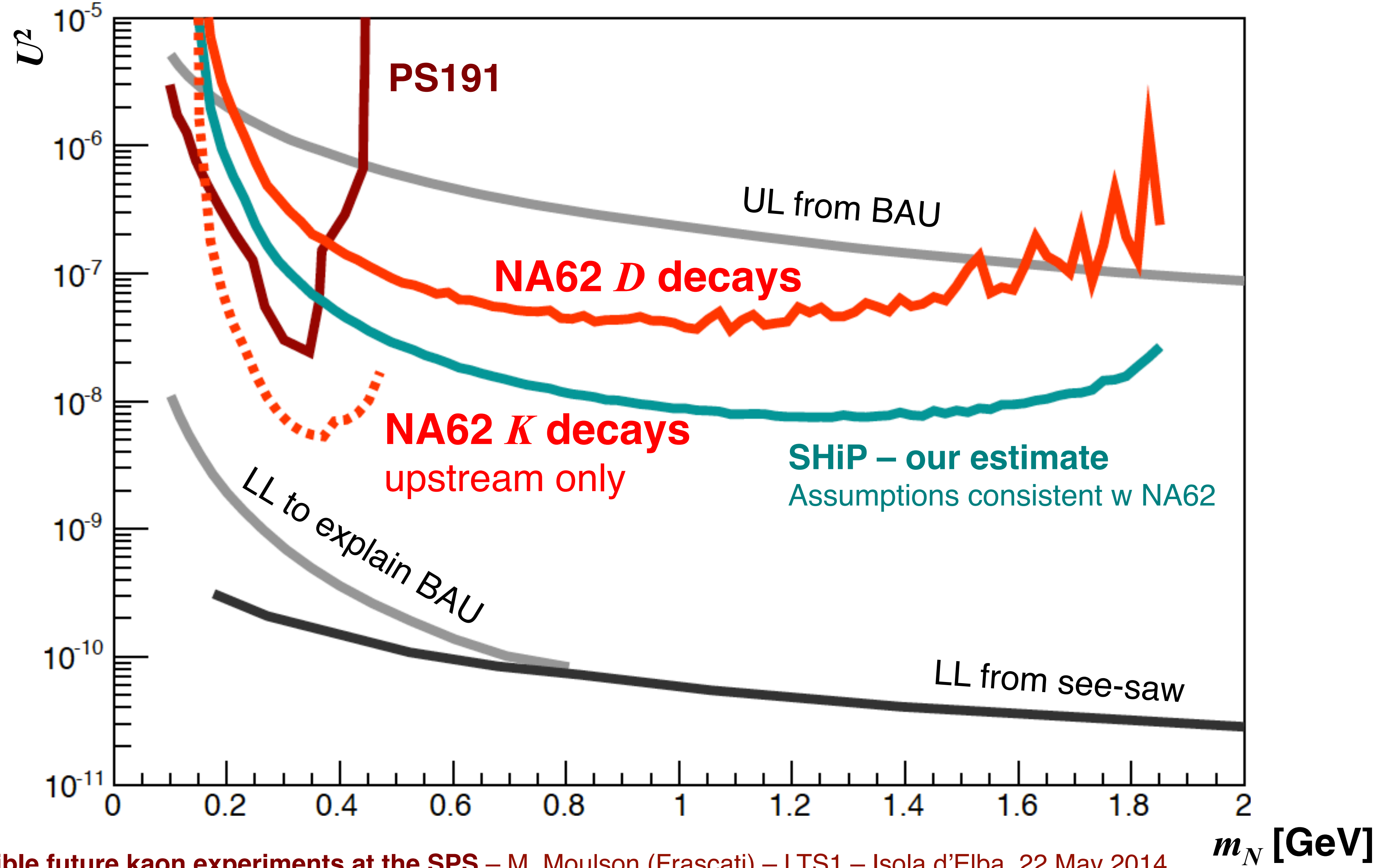
5 years of data at nominal NA62 K^+ run intensity (3×10^{12} ppp)



Exclusive search for $N \to \ell\pi$ at NA62

Sensitivity for exclusive search for $N \to e\pi$ or $\mu\pi$

5 years of data at SHiP intensity (4.5×10^{13} ppp)



Heavy neutrinos: Prospective NA62 results

2 years:

- Fortify PS191 limit, particulary for 350 < m_N < 450 MeV
- Full compatibility with NA62 Run 2 program

5 years, nominal NA62 intensity:

- Largely reproduce and extend PS191 limits for N from K decays
- Begin to test νMSM as an explanation for BAU
- Compatible with Run 3 K decay program ($K^+ \to \pi^+ \nu\nu$, $K_L \to \pi^0 \ell\ell$)

5 years, SHiP-like intensity:

- Substantial improvement on PS191 and SHiP for 200 < m_N < 450 MeV
- Significant test of νMSM as an explanation for BAU by end of Run 3
- Less sensitive than ultimate SHiP result by ~10×
- Possibly compatible with K_L physics program in Run 3 but needs study

Summary and (rather personal) outlook

The Present: NA62 in Run 2

- Assume dedicated to $K^+ \to \pi^+ \nu\nu$ and related studies until LS2 in 2018

Various possibilities for NA62 in Run 3

- Upgrades to improve precision on $K^+ \to \pi^+ \nu\nu$
- Switch to neutral beam; pursue $K_L \to \pi^0 \ell^+ \ell^-$ and prototype studies for $\pi^0 \nu\nu$
- Add shielding and make additional modifications for heavy neutrino search?

Long-term future: NA62 in Run 4

- Likely the best time to run a next-generation $K_L \to \pi^0 \nu\nu$ experiment
- $K_L \to \pi^0 \nu\nu$ is ambitious and will have a long development time
    - Re-uses several elements of the NA62 apparatus, but R&D necessary for new, critical detectors

Monitor developments in physics and experiment over next 5 years

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