Rare kaon decays at the SPS: SWOT analysis

Matthew Moulson
NA62 Frascati/CERN

Prepared for INFN What Next Mid-Term Review
Frascati, 2 April 2015

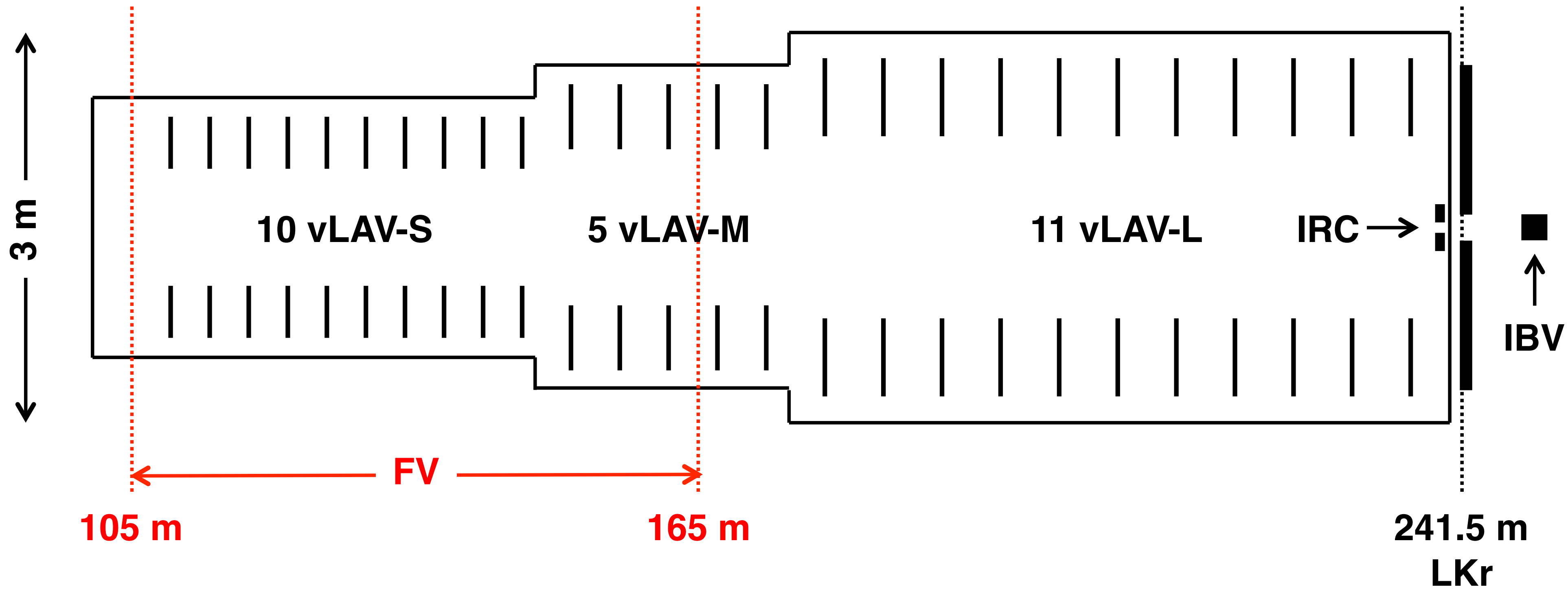
PRIN project: $K_L \to \pi^0 \nu\bar{\nu}$ at the SPS

NA62 Italy subset has PRIN funding for feasibility studies for a K_L experiment
36 months (2/2013 – 2/2016) – 7 university/INFN groups
FERRARA, FIRENZE, FRASCATI, NAPOLI, PERUGIA, PISA, TOR VERGATA, TORINO

Estimate cost, timescale, and performance for an experiment to measure BR($K_L \to \pi^0 \nu\bar{\nu}$) at the SPS

- Initially hoped to reuse much of the existing NA62 apparatus
- Early simulations indicated that a substantial redesign would be needed
- However, PRIN project still focused on a **moderate cost** ($\log_{10}$ CHF ~ 7.5) experiment that can operate in **ECN3** and make use of the **NA48 LKr** as the primary veto
- Ideas for more ambitious (and costly) designs beyond the baseline are still under consideration

Baseline PRIN simulation for $K_L \to \pi^0 \nu\bar{\nu}$



- **400 GeV primary beam 5-8x of higher intensity than NA62**
- **Secondary neutral beam with $\langle p \rangle$ ~ 97 GeV and GHz total rate**
  ~1.7 MHz K_L decays in FV
- **Roughly same vacuum tank layout and fiducial volume as NA62**
  FV starts ~105 m downstream of target
- **26 new large-angle photon veto stations (vLAV)**
- **New small-angle photon veto systems (IRC, IBV)**

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

FCNC decays are the cleanest indirect probes of short-distance physics

- SM rates highly suppressed (GIM mechanism) and known very precisely
- Intrinsic uncertainty ~2% (other components almost entirely parametric)

Together, K and B decays overconstrain unitarity triangle → look for NP

Multiple measurements can discriminate among NP scenarios

- New physics affects BRs differently for different channel

$K_L \to \pi^0 \nu\nu$ in particular gives access to extremely high mass scales

- In some scenarios, up to 10x higher than B decays
- Potentially orders of magnitude higher than LHC

PRIN baseline sensitivity for 3 × 10[12] K_L decays in FV (for 10[7] s live = sly)

~10 signal evts

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

Goal: Turn this into a **100-event experiment** (> 30 events/sly)

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

Expt.	Primary beam (E GeV)	Secondary beam (E GeV)	Running	SM evts	Status
NA62	**SPS (400)**	**positive (75)**	**2014-18**	**100**	**Ready**
ORKA	FNAL MI (95)	K^+ (0.6, stopped)	2020-25	1000	**Cancelled**
KOTO	**JPARC-I (30)**	**neutral (2 peak)**	**2014-18**	**~3**	**Ready**
KOTO/2	JPARC-II (30)	neutral (~2 peak)	2025?	100	Concept
FNAL K_L	Project X (3)	neutral (0.7 peak)	2030?	1000	Concept?

No experiments are looking at $K_L \to \pi^0 \nu\bar{\nu}$ with a high-energy beam

- Photon vetoing is substantially easier at high energy

The CERN SPS can provide a neutral beam with $\langle p \rangle$ ~ 100 GeV

A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS could use the NA62 infrastructure

- NA62 hall and LKr calorimeter could be used for $K_L \to \pi^0 \nu\bar{\nu}$
- The NA62 experiment could be used in Run 3 with a neutral beam as an R&D platform and to measure $K_L \to \pi^0 \ell^+ \ell^-$

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

Main handle on a better measurement is increased intensity:

3×10^{12} K_L decays in FV = 70 SM events before efficiencies

- Baseline solution: 3×10^{12} K_L in FV implies 2.4×10^{13} ppp (8x NA62)
- 2.4×10^{13} ppp not currently available in North Area
- Use of full SPS intensity (4×10^{13} ppp) requires new North Area facility
  E.g. SHiP facility, CHF 140M?
- Is it possible to increase intensity at NA62?
  To 1.5×10^{13} ppp? To 2.4×10^{13} ppp? How much will it cost?

Other technological challenges:

- Reduced acceptance for high-energy K_L decays
- In-beam veto to handle GHz fluxes of beam photons & neutrons
- Life expectancy of NA48 LKr calorimeter?

Timescale: After LS3 – 2025 at the earliest

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

LHC: What if BSM physics already discovered and explored in 2025?

- $K \to \pi\nu\bar{\nu}$ and other key flavor observables still useful for exploration of the CP/flavor structure of the new physics

KOTO/2: Upgrades foreseen in original KOTO proposal

- Original KOTO/2 estimate: 100 SM events in 3 years
  - Assumes 450 kW – currently at 25 kW with prospects for 100 kW
  - New idea: increase angular acceptance 2 → 8 μsr at cost of increased background
  - Back of the envelope: 350 SM events in 3 years at 100 kW, but nothing official yet
- New target, extension of hadron hall, completely rebuilt experiment
  - Timescale and costs similar to SPS experiment

Scientific policy issues:

- Competition from other fixed-target users
- Changes in spending profile

Conclusions and outlook

Critical to achieve at least 100 SM event sensitivity

Infrastructure investment needed to obtain at least 2.4×10^{13} ppp

- Coordination with other fixed-target experiments at CERN?

Can we do better with the experiment?

- **Increase angular acceptance of beam**
  Present beam divergence = 5 cm at LKr → new small-angle vetoes?
- **Increase FV acceptance**
  Total length is important for background rejection (buffer zones)
  Decrease beam energy?
- **Increase forward calorimeter acceptance**
  New calorimeter with diameter 2x larger than NA48 LKr?
- **Increase background rejection**:
  Better efficiency for LKr in range 1-10 GeV?
    LKr efficiency as a photon veto will be studied well in NA62!
  Increase coverage of large-angle photon vetoes?
  Explore use preradiator to provide additional constraints?

Additional information: Strengths

Rare kaon decays

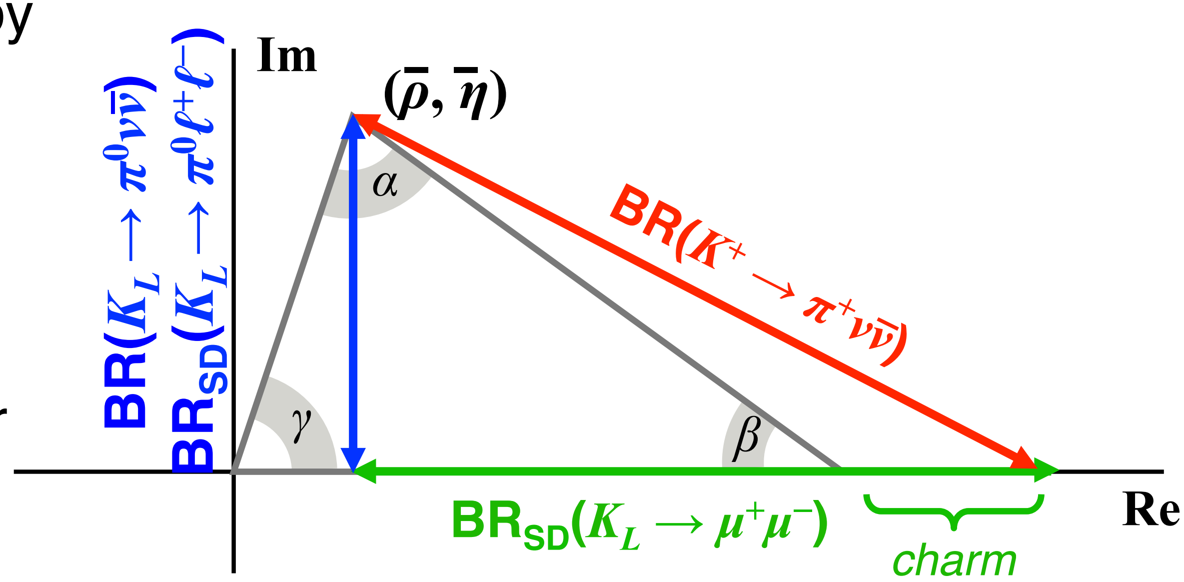
Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{-11}	Exp. BR × 10^{-11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	35 ± 10	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	14 ± 3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	7.8 ± 0.8	17 ± 11
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.4 ± 0.4	< 2600†

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

FCNC processes dominated by Z-penguin and box diagrams

Rates related to V_{CKM} with minimal non-parametric uncertainty

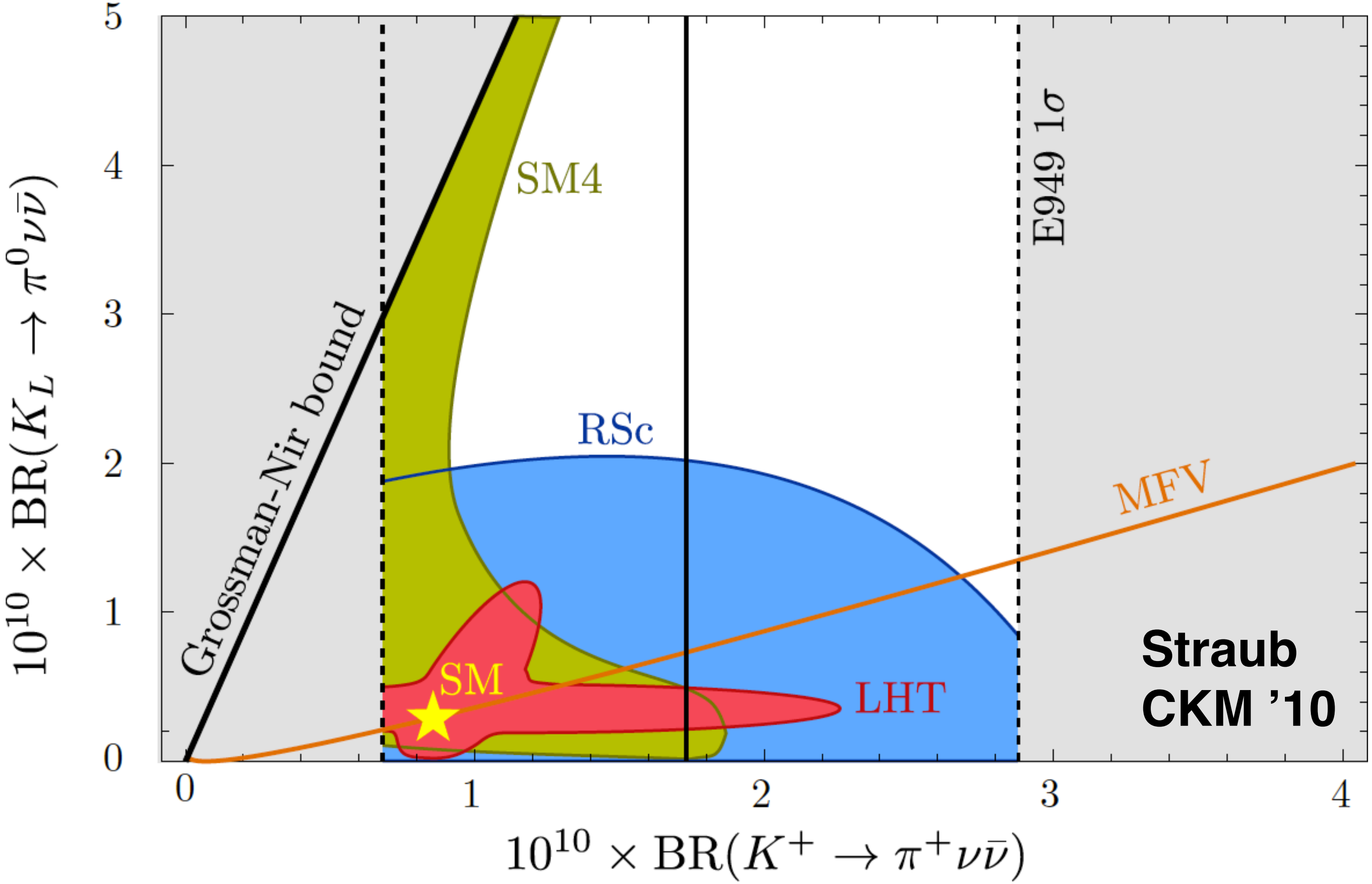
V_{CKM} overconstrained: look for NP in specific channels



$K \to \pi\nu\bar{\nu}$ and new physics

New physics affect BRs differently for different channels

Multiple measurements can discriminate among NP scenarios



SM4: SM with 4th generation (Buras et al. '10)

LHT: Littlest Higgs with T parity (Blanke '10)

RSc: Custodial Randall-Sundrum (Blanke '09)

MFV: Minimal flavor violation (Hurth et al. '09)

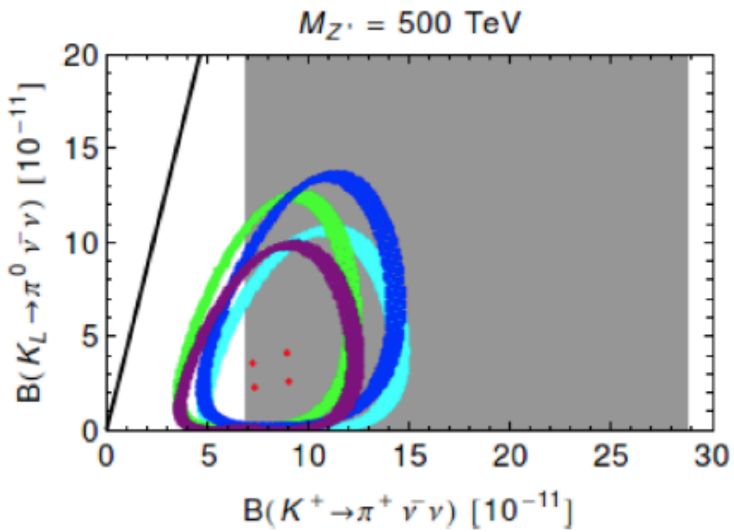
$K \to \pi\nu\bar{\nu}$ and new physics

A Glimpse at the Zeptouniverse

M. Blanke, CKM 2014

recent analysis of tree level flavour changing Z': Buras et al. (2014)

- $K \to \pi\nu\bar{\nu}$ decays sensitive to scales up to 2000 TeV if left- and right-handed FV couplings are present
- (fine-tuned) cancellation of effects in $K^0 - \bar{K}^0$ mixing required
- new physics reach of B decays lower by an order of magnitude ($\sim$ 100 TeV!)



➢ **high precision** in rare K and B decays is **crucial**!

PRIN simulation: Current status

Only $K_L \rightarrow \pi^0\pi^0$ background seriously studied to date:

- Accept only events with 2 γs in LKr and no hits in LAV, IRC, SAC (ε_{sig} = 19%)
- Select events with $z_{\text{rec}}(m_{\gamma\gamma} = m_{\pi 0})$ in FV and $p_{\perp\text{rec}}(\pi^0) > 0.1$ GeV (ε_{sig} = 87%)

Expected results/1 sly: 3 × 10^{12} K_L decays in FV

~10 signal evts

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

What does this imply?

- Sensitivity about same as KOTO Step 2 at 100 kW beam power
- However, acceptance estimate is far from final!
- Experiment has significant cost (50 MCHF?) and long lead time (Run 4)
  Extensive R&D, prototyping, construction work necessary

Should aim for a 100-event experiment (> 30 events/sly)

Physics in addition to $K_L \to \pi^0 \nu\bar{\nu}$

Transitional phase: $K_L \to \pi^0 \ell^+ \ell^-$

Operational phase:

- **Exotics (P, S, V):** $K_L \to \pi^0 X,\ \pi^0\pi^0 X$
- **Radiative decays:** $K_L \to \gamma\gamma,\ \gamma\gamma^*,\ \gamma^*\gamma^*,\ \gamma\gamma\gamma$

  $K_L \to \gamma\gamma$ useful for isolating SD component of $K_L \to \mu^+\mu^-$
- **Other decays interesting in ChPT:** $K_L \to \pi^0\gamma\gamma,\ \pi^0\pi^0\gamma\gamma$

  $K_L \to \pi^0\gamma\gamma$ useful for isolating SD component of $K_L \to \pi^0 \ell^+ \ell$

See KOPIO 2005 proposal for more information

PRIN studies: $K_L \to \pi^0 \ell^+ \ell^-$

$K_L \to \pi^0 \ell^+ \ell^-$ 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 $\pi^0 e^+ e^-$)
- 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

Additional information: Weaknesses

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

What are the pros and cons of a $K_L \to \pi^0 \nu\bar{\nu}$ 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?

$K_L \rightarrow \pi^0 \nu\bar{\nu}$ at the MEB (SPS)

Conclusion of PRIN studies:

2.4×10^{13} p/16.8 s → 10 events/sly with S/B = 1

Better performance would require substantial intensity increase

2.4×10^{13} ppp not currently available in North Area*

Max. intensity from SPS to North Area (TT20): 4×10^{13} ppp

- Must be divided among users: T2 + T4 + T6

Target areas and transfer lines would require upgrades

- Minimization of consequences of beam loss
- Additional shielding against continuous small losses
- Study issues of equipment survival, e.g., TAX motors
- Ventilation, zone segmentation, etc.

1.5×10^{13} may be possible on T10 (NA62)

Time = “years”; Cost = “many MCHF”

*Conversations with L. Gatignon, N. Doble

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

Extrapolated from studies for NA48

Assuming 1 sly at 2.4 × 10^{13} → 3 × 10^{12} K_L decays in FV

	$K_L \to \pi^0 e^+e^-$	$K_L \to \pi^0\mu^+\mu^-$
SM BR	3.5 × 10^{-11}	1.4 × 10^{-11}
Acceptance	3%	18%
SM signal events	~3	~8
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

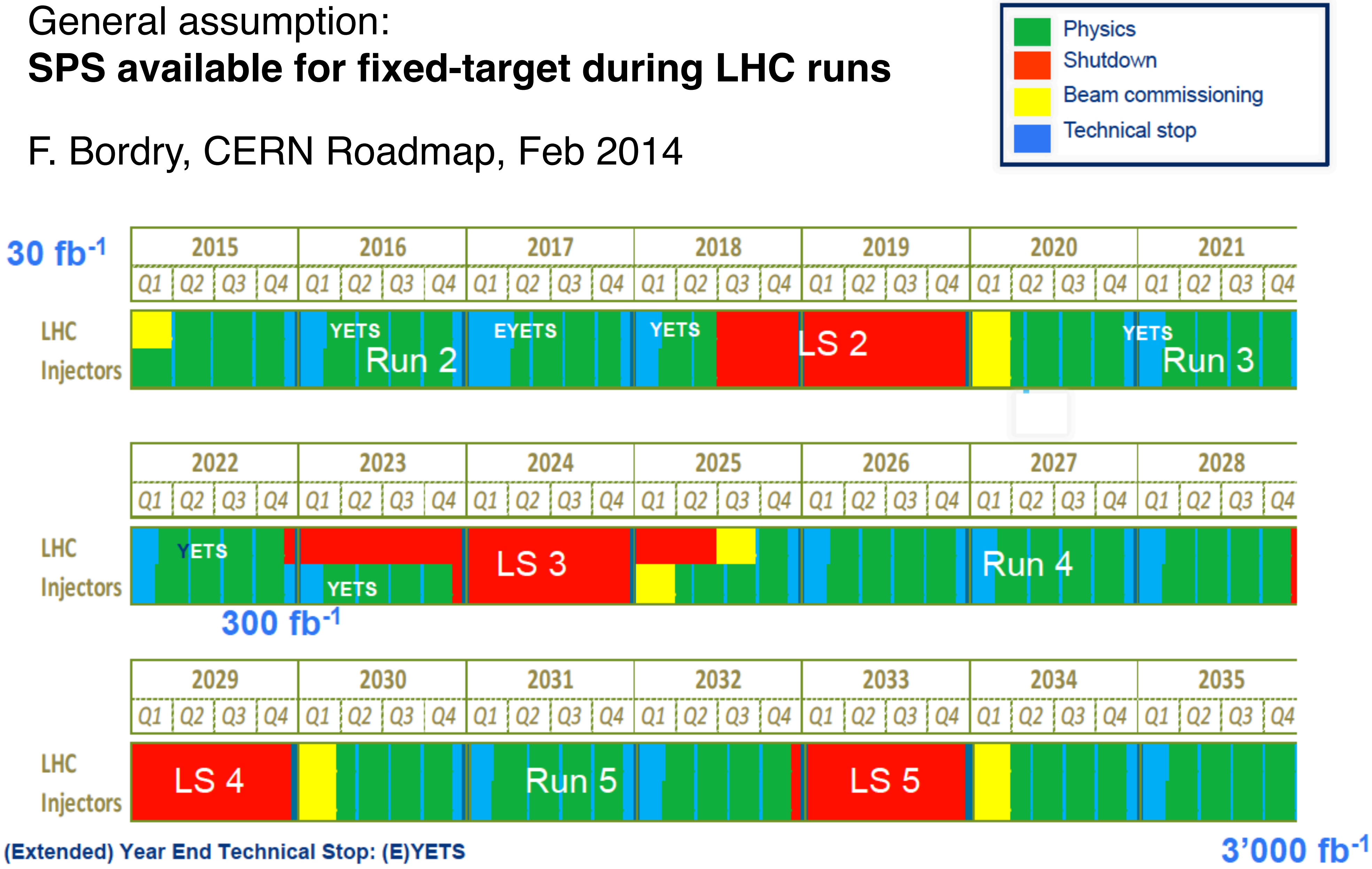
Continuing to study in context of PRIN project

Additional information: Opportunities

Fixed target runs at the SPS

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

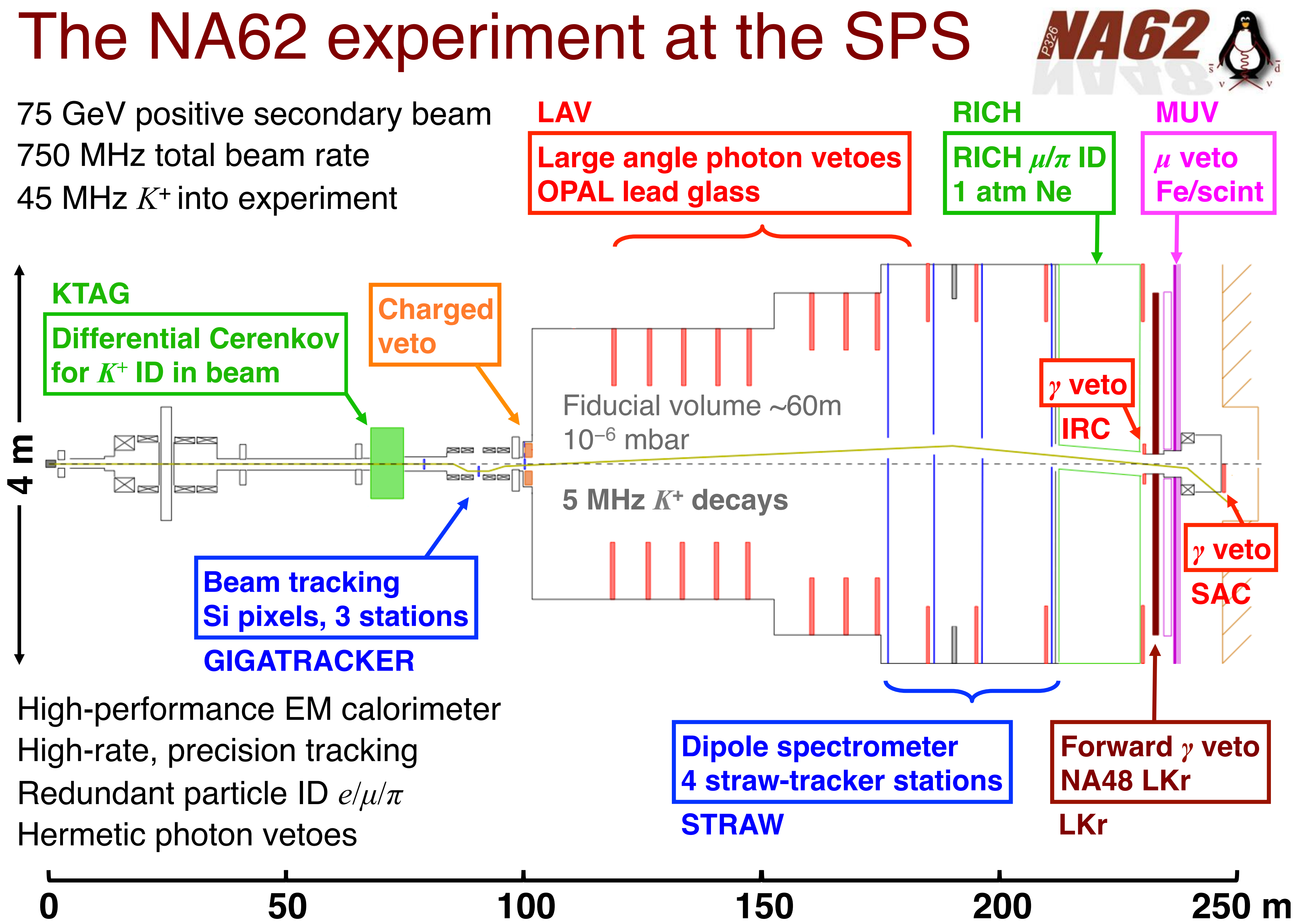
F. Bordry, CERN Roadmap, Feb 2014



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

The NA62 experiment at the SPS

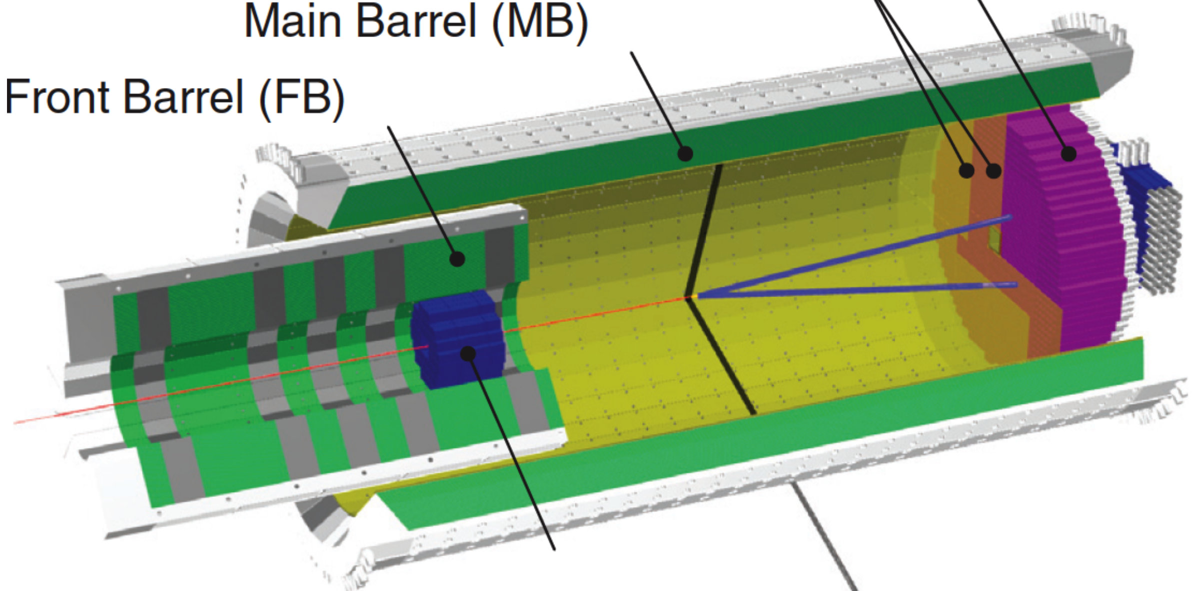
75 GeV positive secondary beam
750 MHz total beam rate
45 MHz K^+ into experiment



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

Additional information: Threats

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC



Primary beam: 30 GeV p
2×10^{14} p/3.3 s = 300 kW

Neutral beam (16°)
$\langle p(K_L) \rangle$ = 2.1 GeV
50% of K_L have 0.7-2.4 GeV
9 μsr "pencil" beam

- Started data taking in May 2013
- Halted right after startup due to an accident in the Hadron Hall
- Operations expected to resume in late 2014/early 2015
- Intensity now ~2×10^{13} p per 3.3 sec (25 kW)
- Upgrade path to increase intensity by 4× "within a few years"

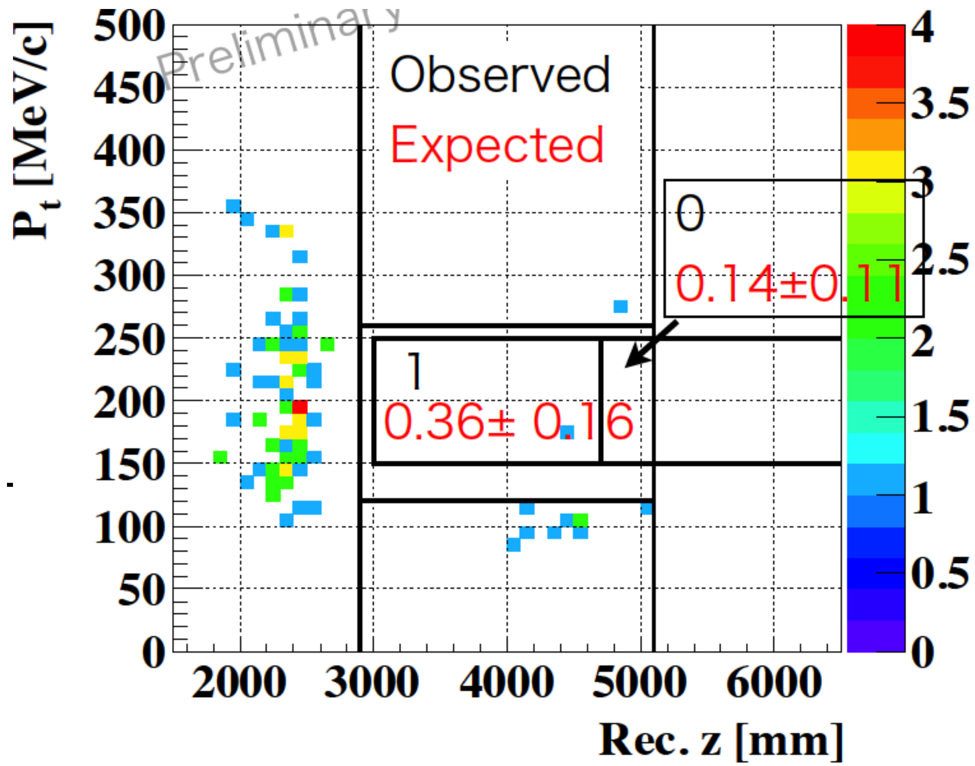
KOTO: Status and future

Proposal:
300 kW × 3 sly
SES 8 × 10^{-12} (3.5 SM evts)
S/B = 1.4

Current status:
25 kW x 100 hrs
SES 1.3 × 10^{-8}
1 event (0.36 expected)

- Beam power will gradually increase to 100 kW
- Meet original goal by 2018?

Shiomi, CKM 2014



Future: Strong intention to upgrade to ~100 event sensitivity

- Exploring upgrade possibilities to increase sensitivity
- Hope to get to ~10 SM evts/sly for 100 kW of beam power (2 μsr)
- Indicative timescale: data taking starting 2025?
- No proposal at this time (chapter on Step 2 in original proposal)