Rare kaon decays at the FCC injectors

Matthew Moulson
NA62 Frascati/CERN

FCC Working Group on Physics with the Injectors
CERN, 29 September 2014

Outline

1. Kaon physics and rare decays
2. Current and planned experiments for rare kaon decays
3. Studies for future experiments at the SPS
4. Rare kaon decays at the FCC injectors

NB: **1 sly** (standard live year) ≡ **10^7 s**

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 neutral leptons in K decays

Other topics:

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

Rare kaon decays

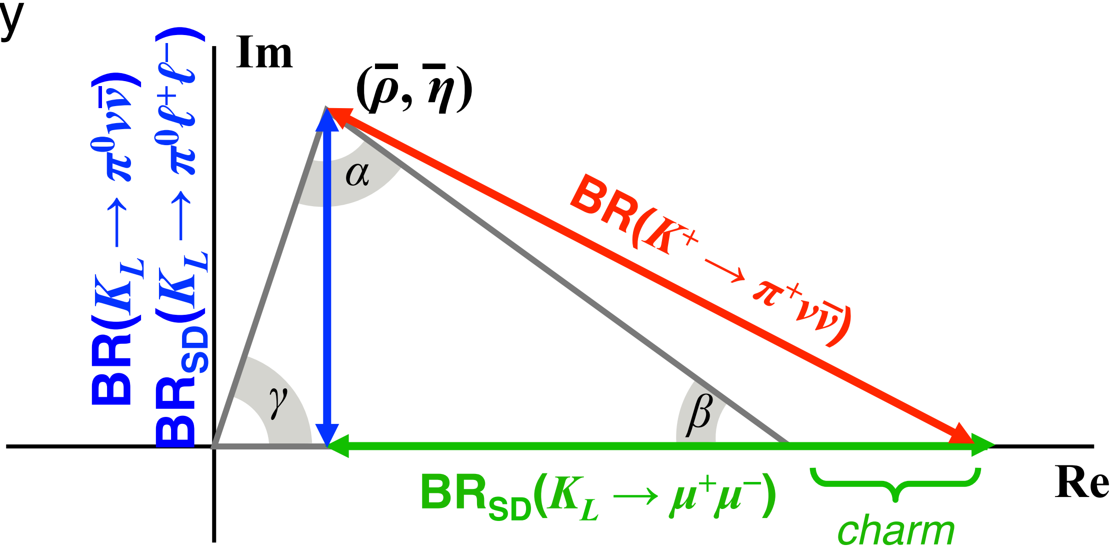
Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{-11}	Exp. BR × 10^{-11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	35 ± 10	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	14 ± 3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	7.8 ± 0.8	17 ± 11
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.4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

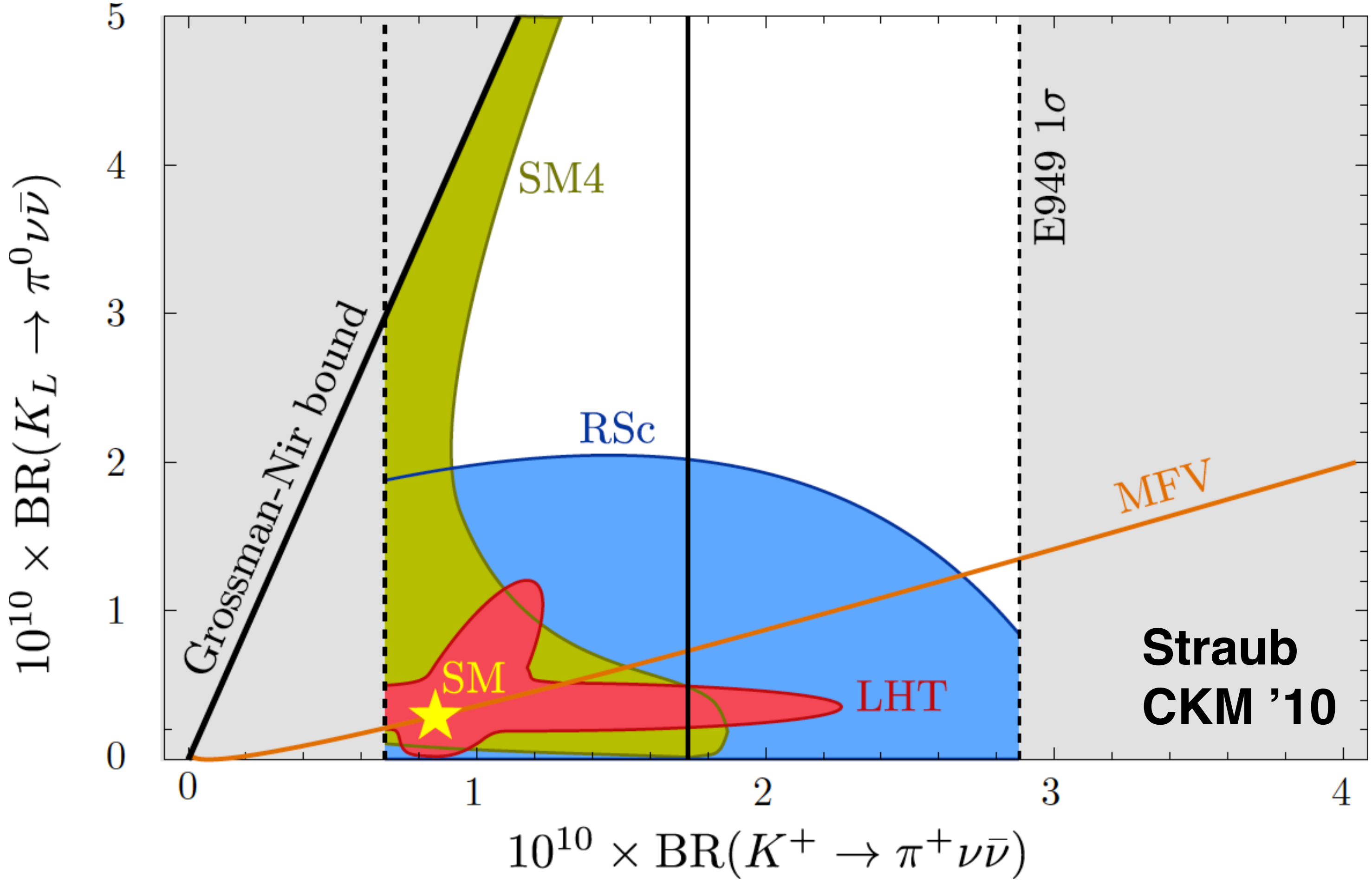
V_{CKM} overconstrained: look for NP in specific channels



$K \to \pi\nu\bar{\nu}$ 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)

RSc: Custodial Randall-Sundrum (Blanke '09)

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

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

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

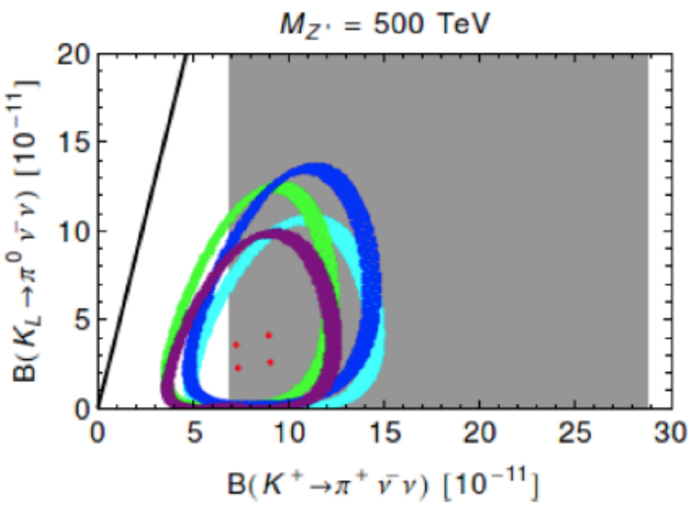
Hors d'Oeuvre | New Physics Reach of Flavour Physics

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**!

6 | M. Blanke | Flavour Physics Beyond the Standard Model

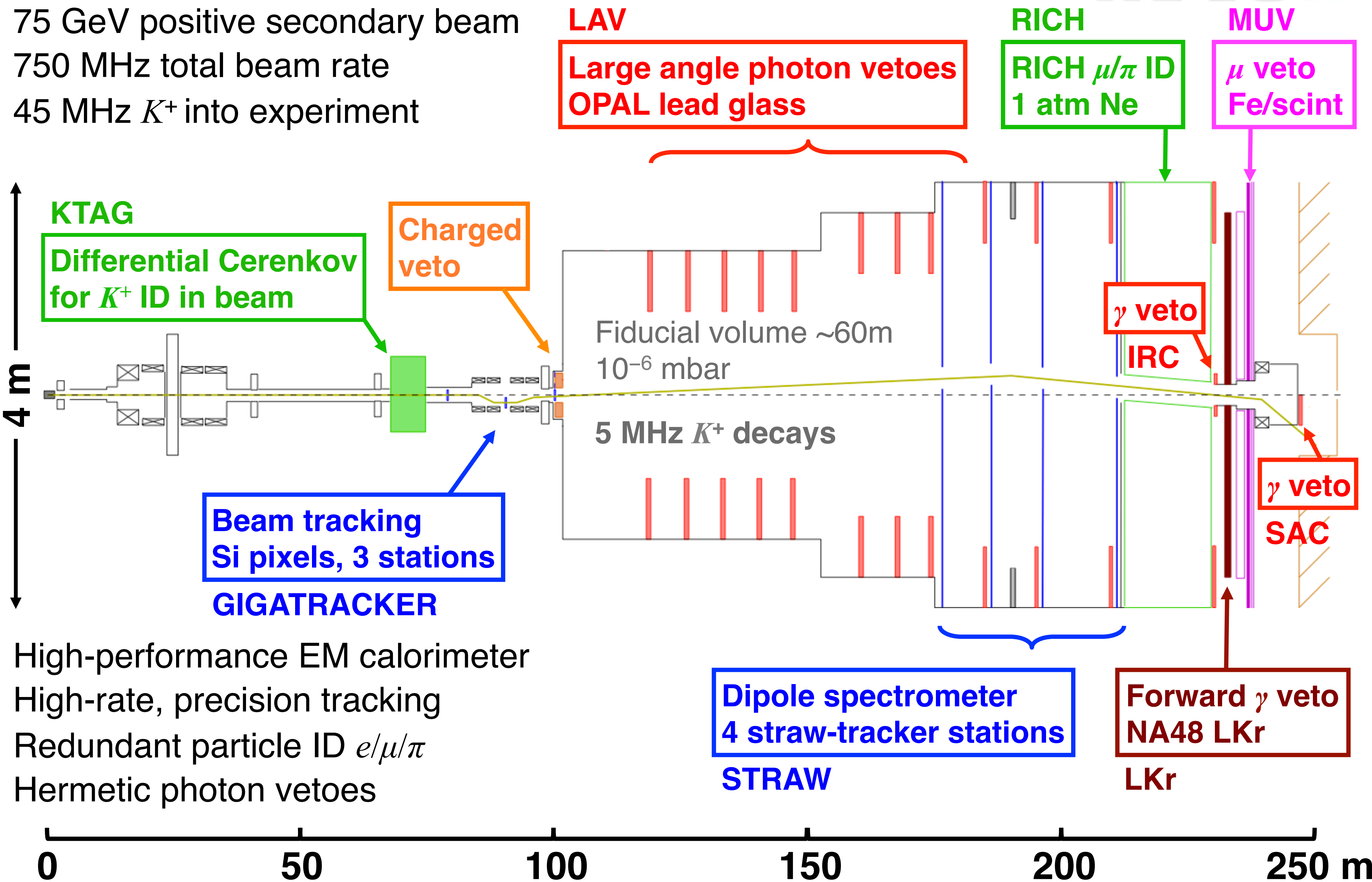
Rare K decays: World outlook

Expt.	Primary beam (E GeV)	Secondary beam (E GeV)	Start date + run years	SM evts	Status
NA62	**SPS (400)**	**positive (75)**	**2014+3** (1 sly)	**100**	**Ready**
ORKA	FNAL MI (95)	K^+ (0.6, stopped)	2020+5 (9 sly)	1000	Proposed
KOTO	**JPARC-I (30)**	**neutral (2 peak)**	**2014+3** (3 sly)	**~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

- ORKA effectively canceled with release of P5 report on 22 May
- NA62 is the only experiment looking at $K^+ \to \pi^+ \nu\bar{\nu}$
- KOTO is the only experiment looking at $K_L \to \pi^0 \nu\bar{\nu}$
- No experiment is looking at $K_L \to \pi^0 \ell^+ \ell^-$

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: Status and future

2014-2017 run (0.8 sly):
Intensity: **3×10^{12} p/16.8 s**
K^+ decays in FV: **10^{13}**
Signal acceptance: **10%**
Background rejection: **10^{-12}**

Start of NA62 running: 6 October 2014

Goal: Measure BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) to 10%
Collect ~100 signal events with S/B > 10

Other elements of physics program:
- Measurement of R_K to ~0.2%
- Searches for LFV K^+ and π^0 decays, heavy neutral leptons, dark photons
- ChPT tests & precision BR measurements

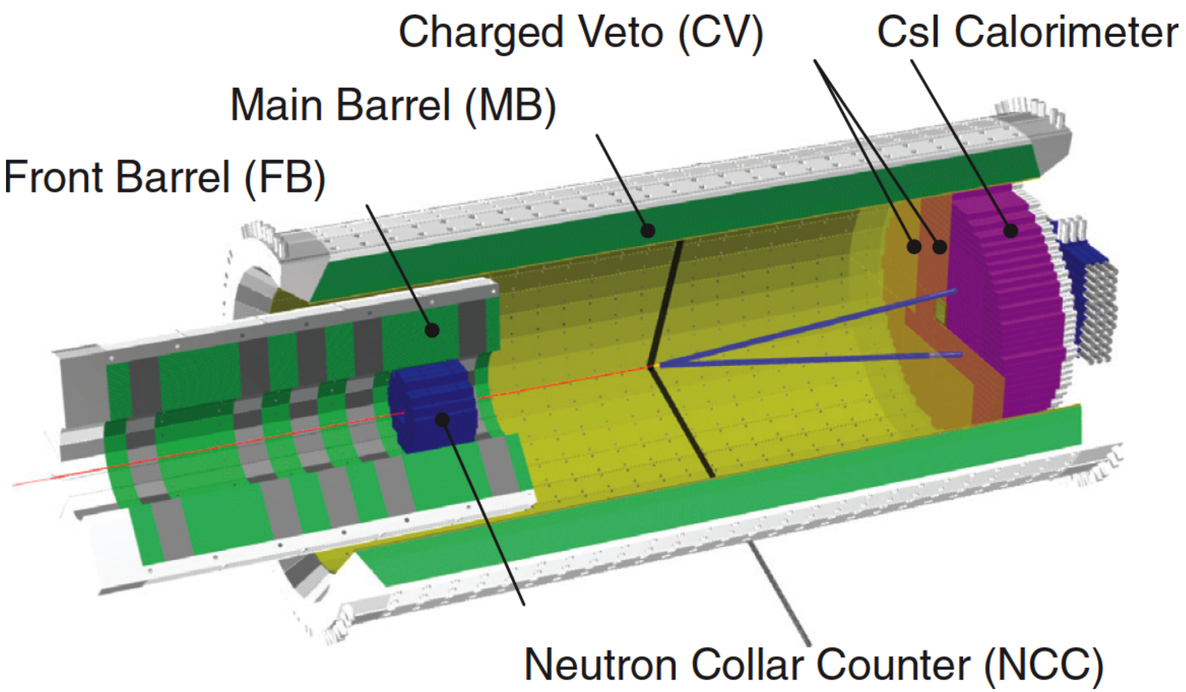
Longer-term future: NA62 could be a 1000-event experiment
- 100 events/sly → 1000 events, with minor upgrades + extra running time
- Incremental upgrades to trigger and readout are in the pipeline
- Potential for additional upgrades will become apparent when data arrive

Suppose in 2022 NA62 has measured BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) to < 5% ?

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

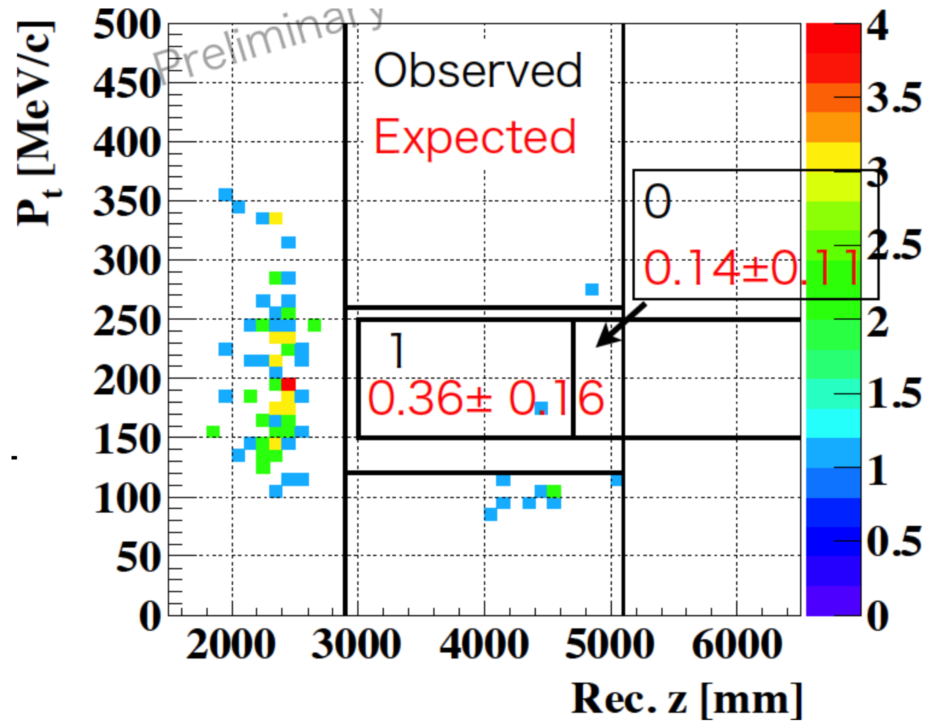
KOTO: Status and future

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
- Indicative timescale: data taking starting 2025?
- No proposal at this time (chapter on Step 2 in original proposal)

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

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

PRIN grant – Italian Ministry of Education

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
- Real work started Fall 2013
- Currently ~ 7 people working part time, phone meetings every 2-3 weeks

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

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?

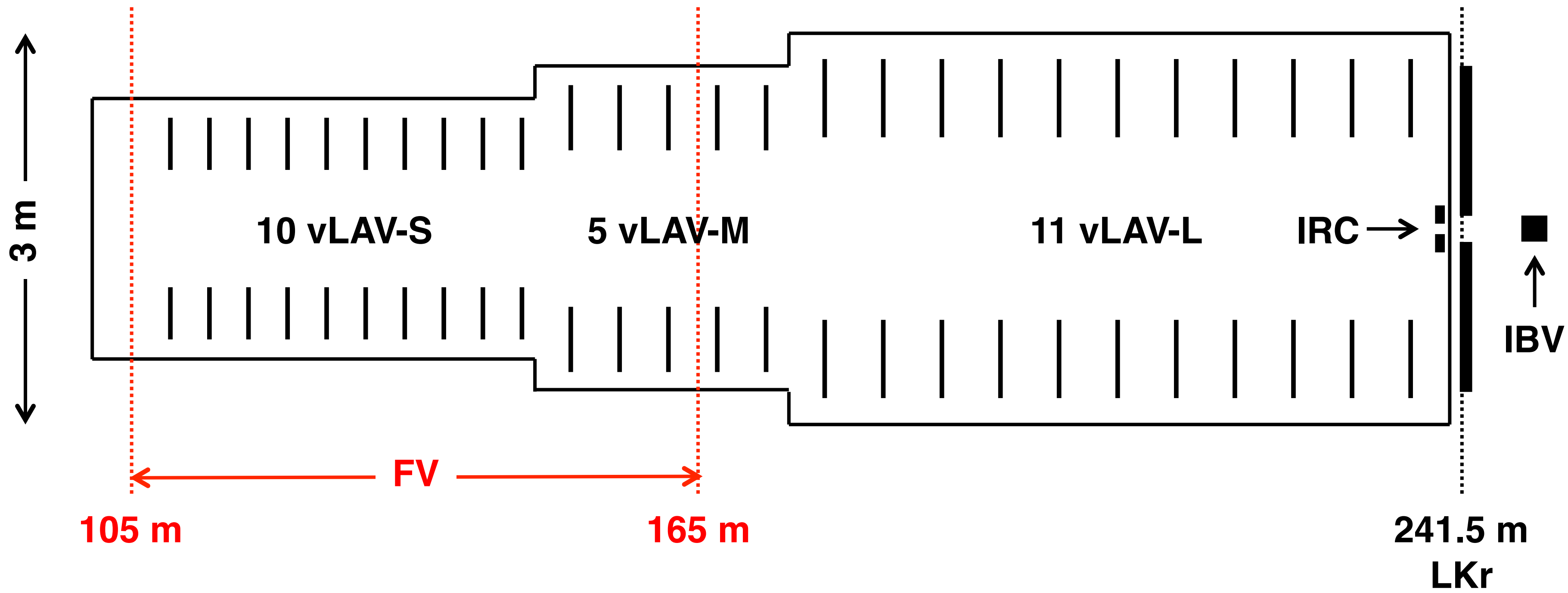
PRIN studies: Assumed beam parameters

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 $\pi^0 \ell^+\ell^-$ requires substantial intensity increase!

	NA62 K^+ beam	PRIN 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	0.125
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 60 K_L
K decays in FV	4.5 MHz **10^{13}/sly**	1.7 MHz **3×10^{12}/sly**

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



Roughly same vacuum tank layout and fiducial volume as NA62

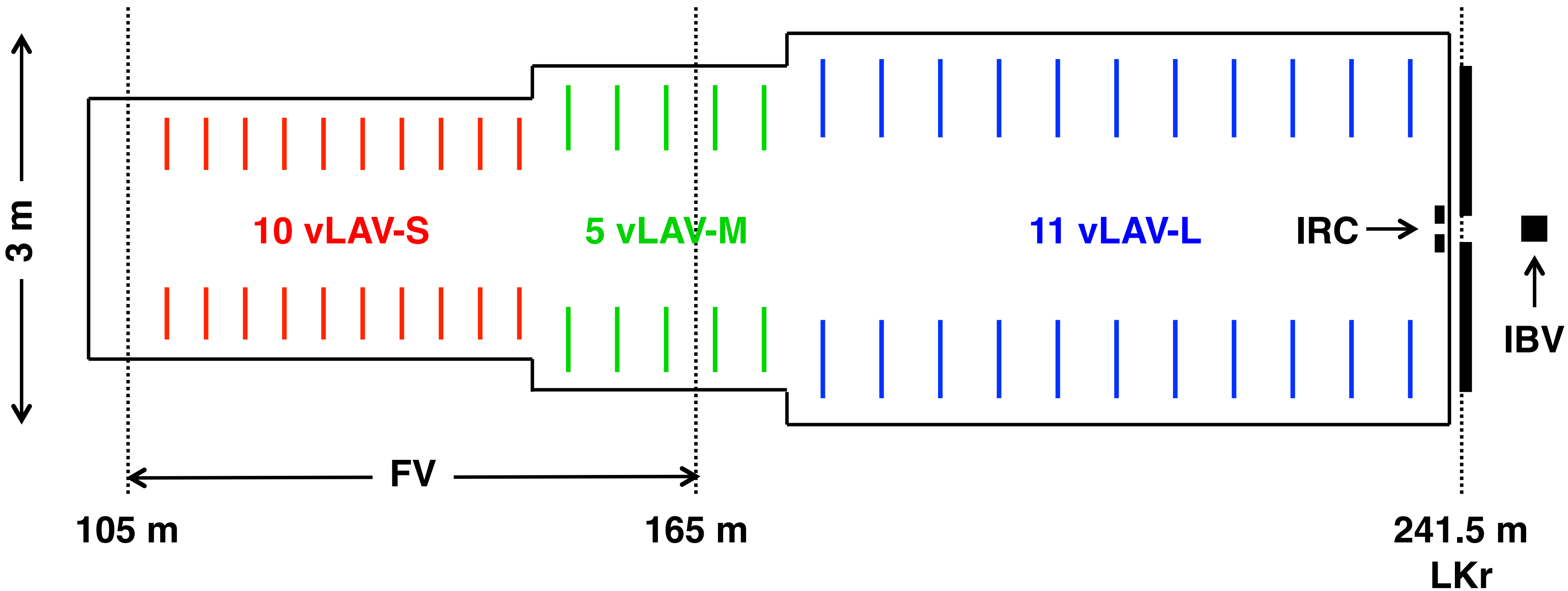
FV starts ~105 m downstream of target – decay away hyperons

About 2.7% of K_L in beam decay in FV

~2 GHz of photons from target: Need beam sweeper to reduce > 10×

May require innovative approach: Iridium monocrystal?

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



26 new large-angle photon veto stations (vLAV)

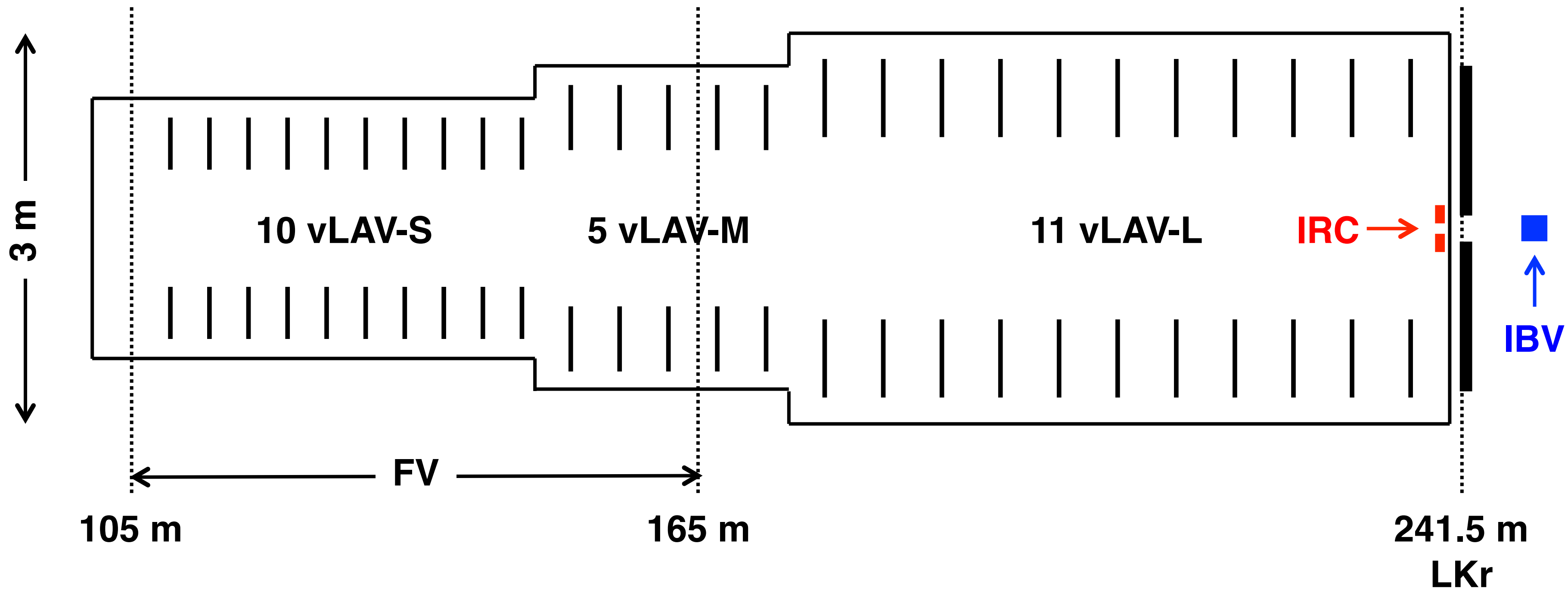
3 sizes, radii similar to NA62, at intervals of 4 to 6 m

Hermetic coverage out to 100 mrad for E_γ down to 20 MeV

Baseline technology: Scintillator/tile with WLS readout, like CKM VVS

- Assumed inefficiency based on E949 and CKM VVS experience

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



New small-angle photon veto systems (IRC, IBV)

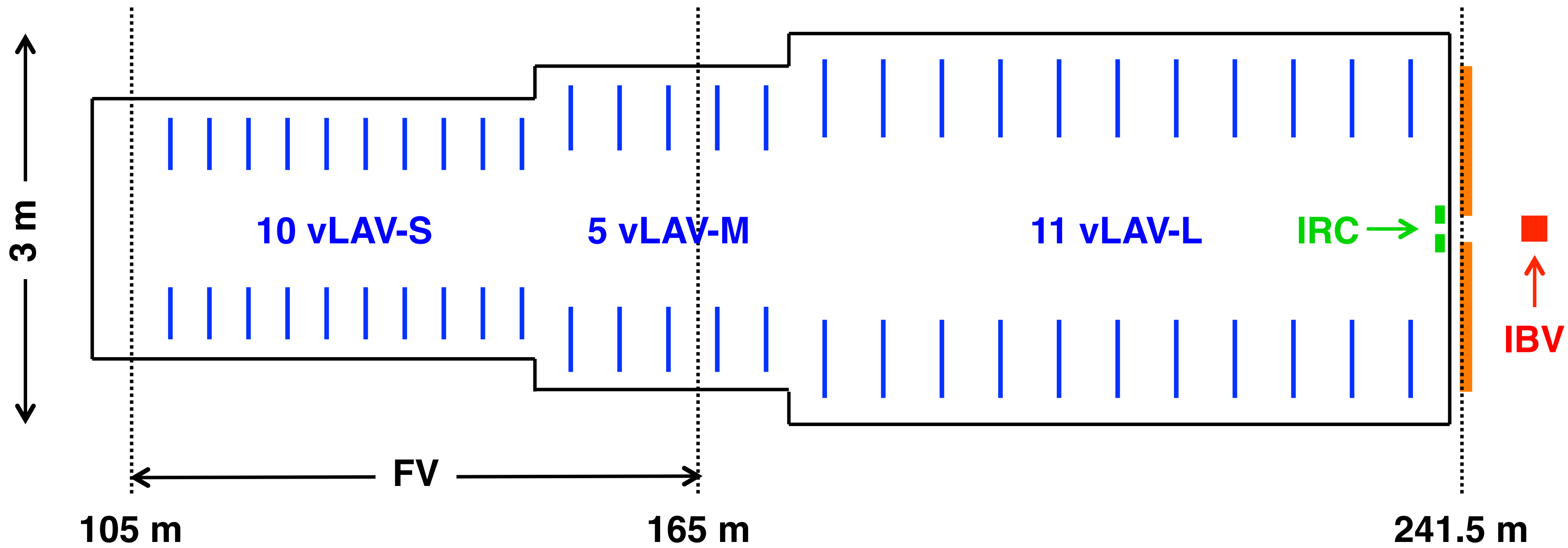
Must be relatively insensitive to 800 MHz of beam neutrons

Amdist this background, must reject γ from $\pi^0\pi^0$ to 10^{-3} level: $\sigma_t < 300$ ps

Possible solutions:

- Dense inorganic Cerenkov crystal veto (NBWO, PbF_2, PWO)
- Converter + NA62 Gigatracker (Si pixel)-based veto

Photon veto efficiencies for simulation



Simulated 1 – ε for indicative values of E_γ

vLAV		LKr		IRC		IBV	
From E949, CKM VVS		Standard NA62 values		Required performance		Required performance	
< 20 MeV	1	< 1 GeV	1	< 1 GeV	1	< 1 GeV	1
200 MeV	0.5%	1 GeV	0.1%	> 1 GeV	3×10^{-5}	> 1 GeV	3×10^{-4}
>0.5 GeV	5×10^{-6}	>10 GeV	8×10^{-6}				

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 $z_{rec}(m_{\gamma\gamma} = m_{\pi 0})$ in FV and $p_{\perp rec}(\pi^0) > 0.1$ 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)

$K_L \to \pi^0 \nu\bar{\nu}$ beyond the PRIN paradigm

Main handle on a better measurement is increased intensity:
3 × 10^{12} K_L decays in FV = 70 SM events before efficiencies

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?

Rethink the basic idea of a $K_L \to \pi^0 \nu\bar{\nu}$ experiment at high energy?

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

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

Outlook: Rare kaon decays at the SPS

The Present: NA62 in Run 2

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

Various possibilities for Run 3

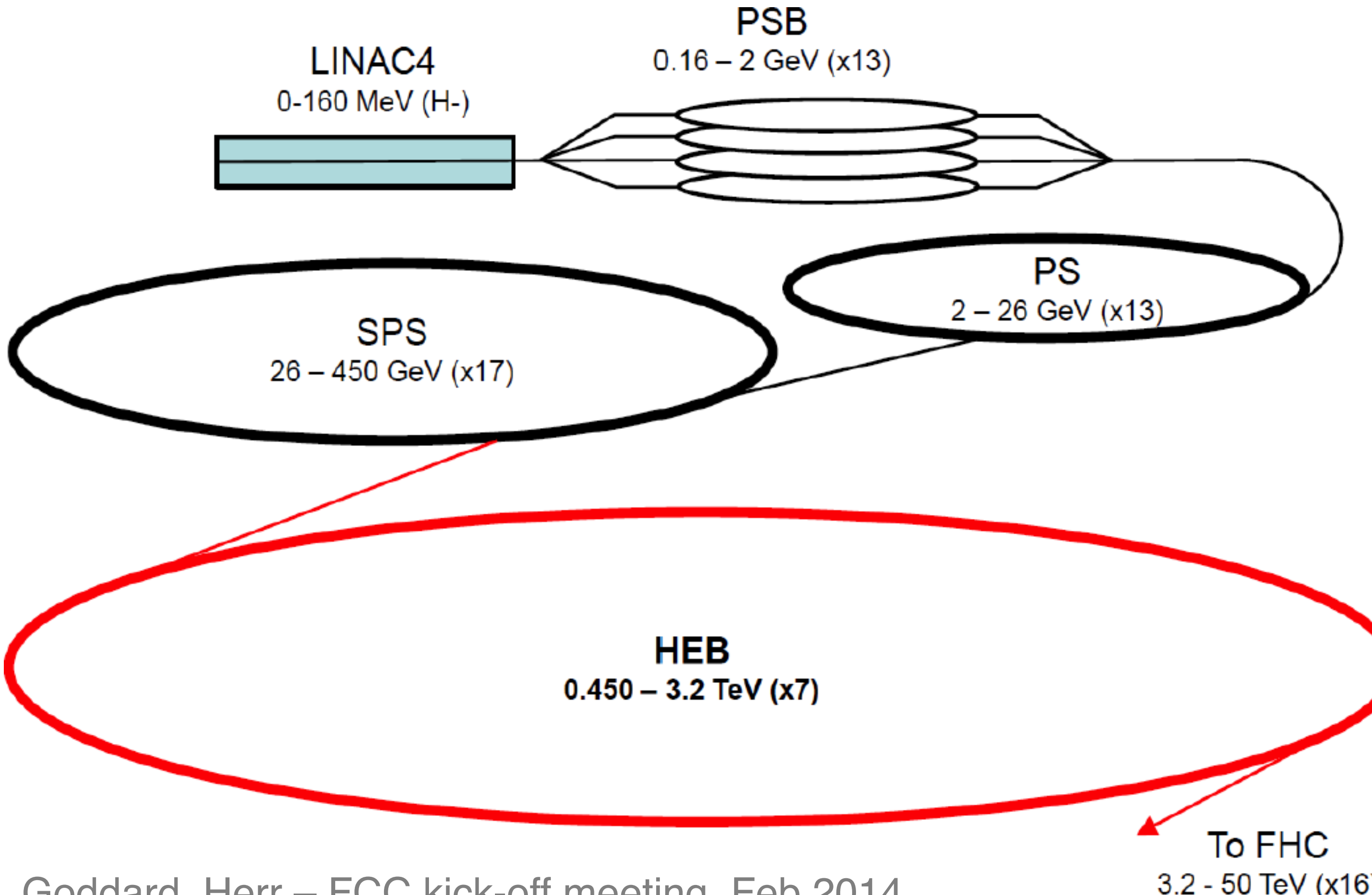
- Upgrades to NA62 to improve precision on $K^+ \to \pi^+ \nu\bar{\nu}$
- Switch to neutral beam; pursue $K_L \to \pi^0 \ell^+ \ell^-$ and prototype studies for $\pi^0 \nu\bar{\nu}$
- Data also useful for LFV, heavy neutral lepton searches, etc.

Long-Term Future: Run 4

- Best time to run a next-generation $K_L \to \pi^0 \nu\bar{\nu}$ experiment
- $K_L \to \pi^0 \nu\bar{\nu}$ requires ambition and will have a long development time

Rare kaon experiments at FCC injectors

Which injector?



Goddard, Herr – FCC kick-off meeting, Feb 2014

$K_L \to \pi^0 \nu\bar{\nu}$ at the LEB (PS)

Most $K_L \to \pi^0 \nu\bar{\nu}$ experiments discussed to date have $p(K_L)$ ~ 1 GeV

Classic design for a PS experiment would be similar to KOTO:

- Pencil beam
- Hermetic coverage of decay volume with high-efficiency vetoes

What slow-extracted beam (SEB) intensity possible at PS now?

Assume PS can supply p to fixed target at same rate as SPS

This limit is from SPS magnet power consumption:

Maybe PS can do a little better

1. **At present: 4.5 × 10^{13} p/10 s**

   About equal to KOTO now – about 10× less than J-PARC goal

2. **After (hypothetical) HL-LHC upgrade: 7 × 10^{13} p/10 s**

Significant work on PS needed for high-intensity SEB

- Need new beamline and experimental facility
- Need work on PS itself for the HL-LHC upgrade

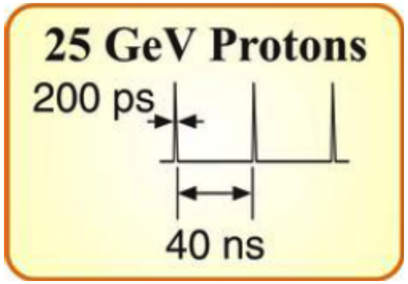
Could it be possible to implement new features?

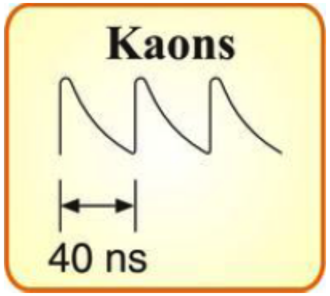
KOPIO: Extra constraints for $K_L \to \pi^0 \nu\bar{\nu}$

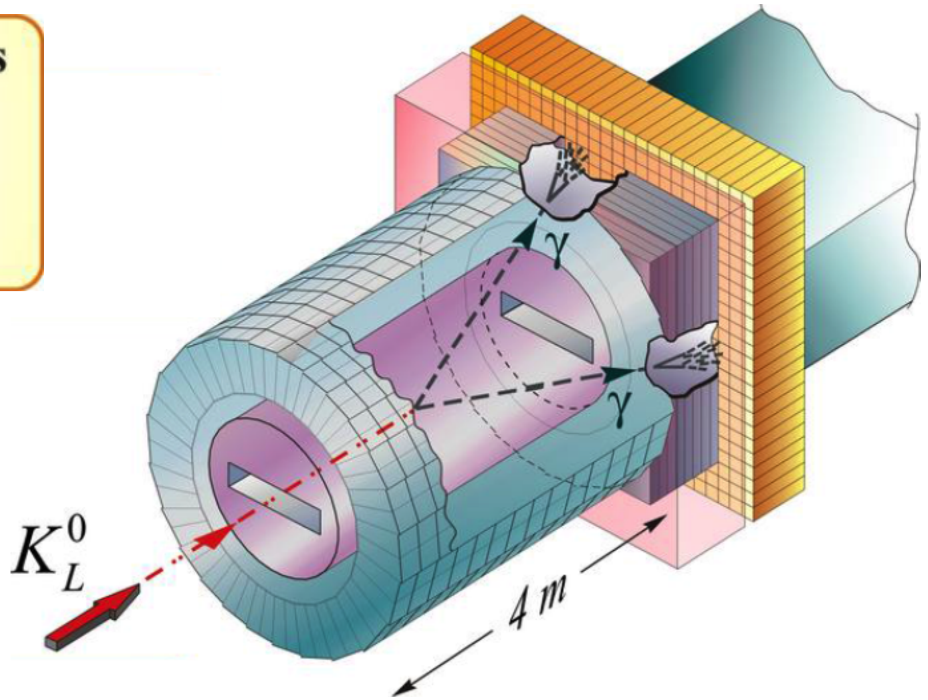
Brookhaven AGS
Cancelled 2005

Primary: 26 GeV p
10^{14} p/7.2 s

Neutral beam (43°)
$\langle p(K_L) \rangle$ = 0.9 GeV
50% of K_L have 0.5-1.2 GeV







Microbunched beam from AGS: Measure $p(K_L)$ by time of flight
200 ps every 40 ns with 10^{-3} extinction between microbunches

Flat beam: Increase solid angle bite to 360 μsr to increase K_L flux

Preradiator before calorimeter: Reconstruct angle of incidence for γs

Sensitivity: 180 SM evts in 12000 hrs (~4 sly)

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

A North-Area high intensity facility?

SHiP
Search for Hidden Particles

SHiP: Search for heavy neutral leptons from D decays in target

Proposal includes new high-intensity facility in North Area:
Beamline, target bunker, and experimental area

Preliminary project study and cost estimate for infrastructure done by CERN-EN (EN-DH-2014-007):

Beam intensity:

- **Initially > 4.5 × 10^{13} ppp**
- **Up to 7 × 10^{13} ppp if PS-SPS upgraded for HL-LHC**

Physics start: Run 4

Infrastructure costs: 113 MCHF

Is 7 × 10^{13} ppp a reasonable assumption for fixed-target at FCC-MEB?

Could it become available sooner than rest of FCC (e.g., Run 4)?

$K_L \to \pi^0 \nu\bar{\nu}$ at the HEB

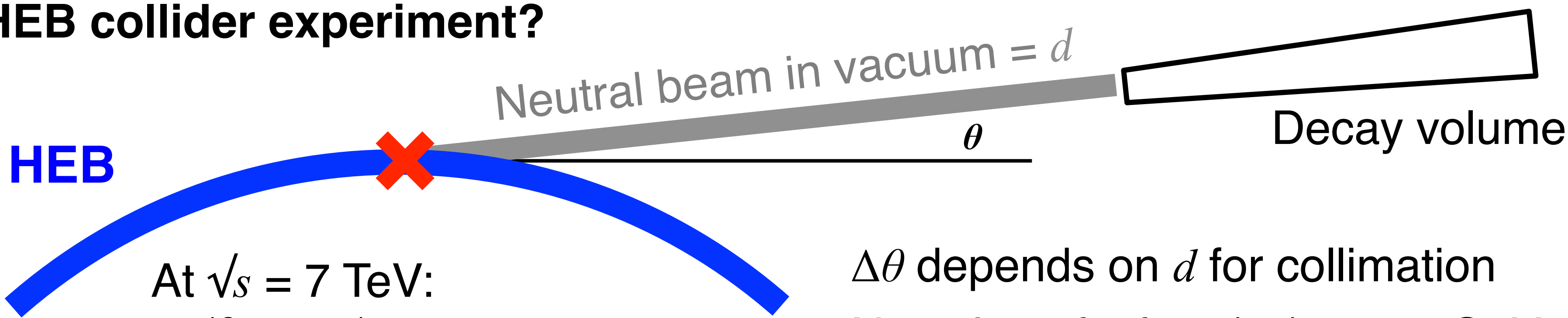
Acceptance for K_L decays in 60-m FV at SPS is 2.6%
Challenge is to obtain a K_L beam with $p_{\text{peak}} < 100$ GeV

HEB fixed-target experiment?

3 × 10[18] pot/year at 3.3 TeV?

Need to go to large angle to get right K_L momentum spectrum

HEB collider experiment?



At $\sqrt{s}$ = 7 TeV:
10^{13} K/fb^{-1}/($\Delta\eta$ = 3)
LHCb $K_S \to \mu\mu$ analysis

$\Delta\theta$ depends on d for collimation

No value of θ for $p(K_L) \sim 100$ GeV and $\Delta\theta$ large enough for good yield

HEB collider experiment with K_S?

$K_S \to \pi^0 \nu\bar{\nu}$ not CP violating — measures base of kaon triangle

- Like $K_L \to \mu\mu$ but with fewer complications from LD effects
- BR($K_S \to \pi^0 \nu\bar{\nu}$) ~ 10^{-14}: Experimentally impossible to isolate in a jet

Summary: Outlook in 2025

New physics at LHC Explore flavor structure of "new" SM	**No new physics at LHC** Explore extremely high mass scales with indirect probes

Either way, $K_L \to \pi^0 \nu\bar{\nu}$ will still be quite interesting!

In 2025, the experimental situation will have progressed:

- NA62 may have BR($K^+ \to \pi^+ \nu\bar{\nu}$) to < 5%
- KOTO will have evidence for $K_L \to \pi^0 \nu\bar{\nu}$ events
- KOTO-2 will be starting up with 10 event/sly sensitivity

Will a 100-event $K_L \to \pi^0 \nu\bar{\nu}$ experiment at CERN be in the works?

- At an upgraded T10 facility using NA62 infrastructure?
- At a new high-intensity facility at PS or SPS?
- As part of an FCC injector upgrade?

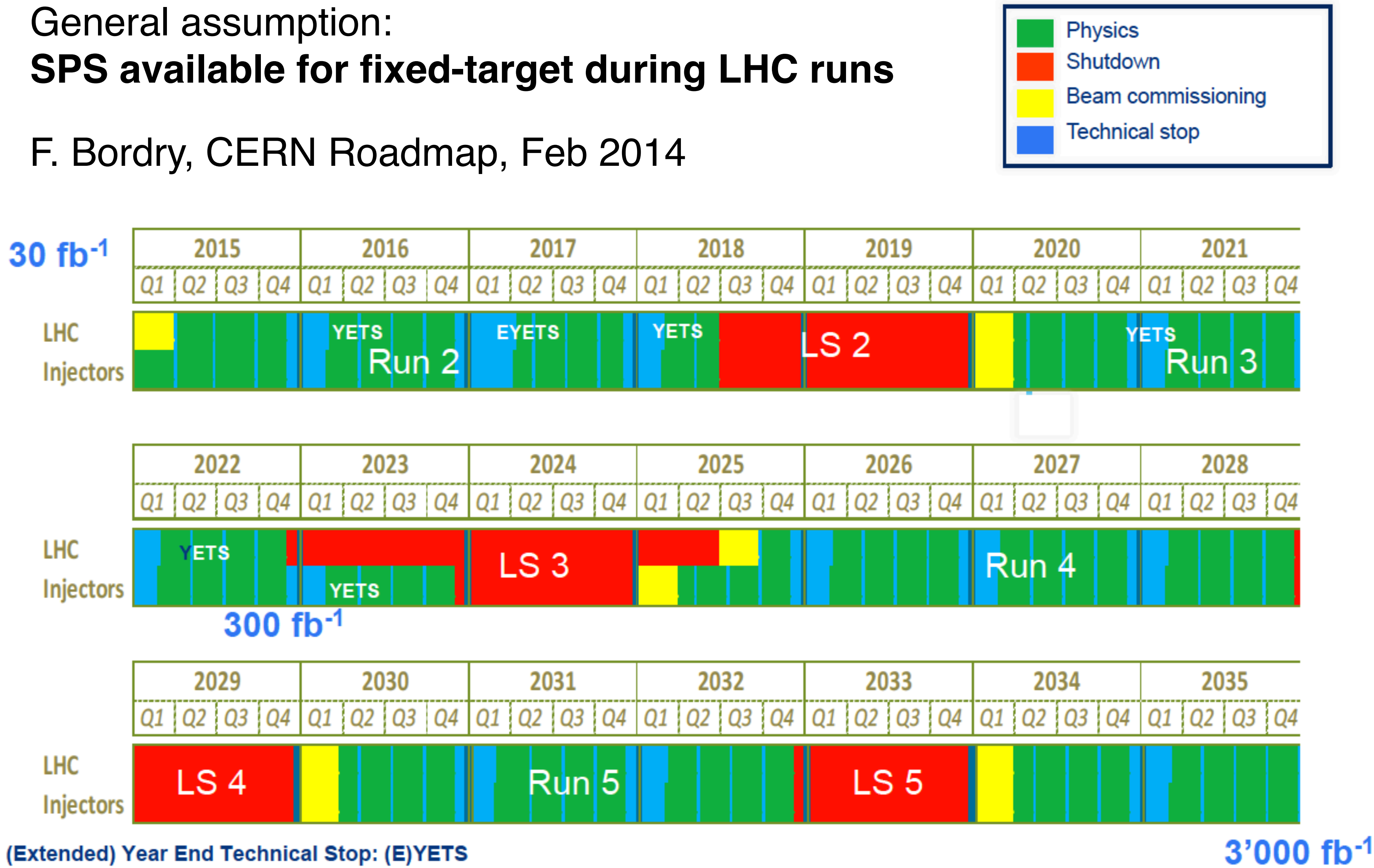
More questions than answers, but a 100 event $K_L \to \pi^0 \nu\bar{\nu}$ experiment is surely a worthwhile endeavor!

Additional information

Fixed target runs at the SPS

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

F. Bordry, CERN Roadmap, Feb 2014



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 ($K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \ell\ell$)

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

Exclusive search for HNL with NA62 setup

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

5 years of data at SHiP intensity (2×10^{20} pot = 20 sly at 2.4×10^{13} p/16.8 s)