Perspectives on future kaon experiments at the SPS

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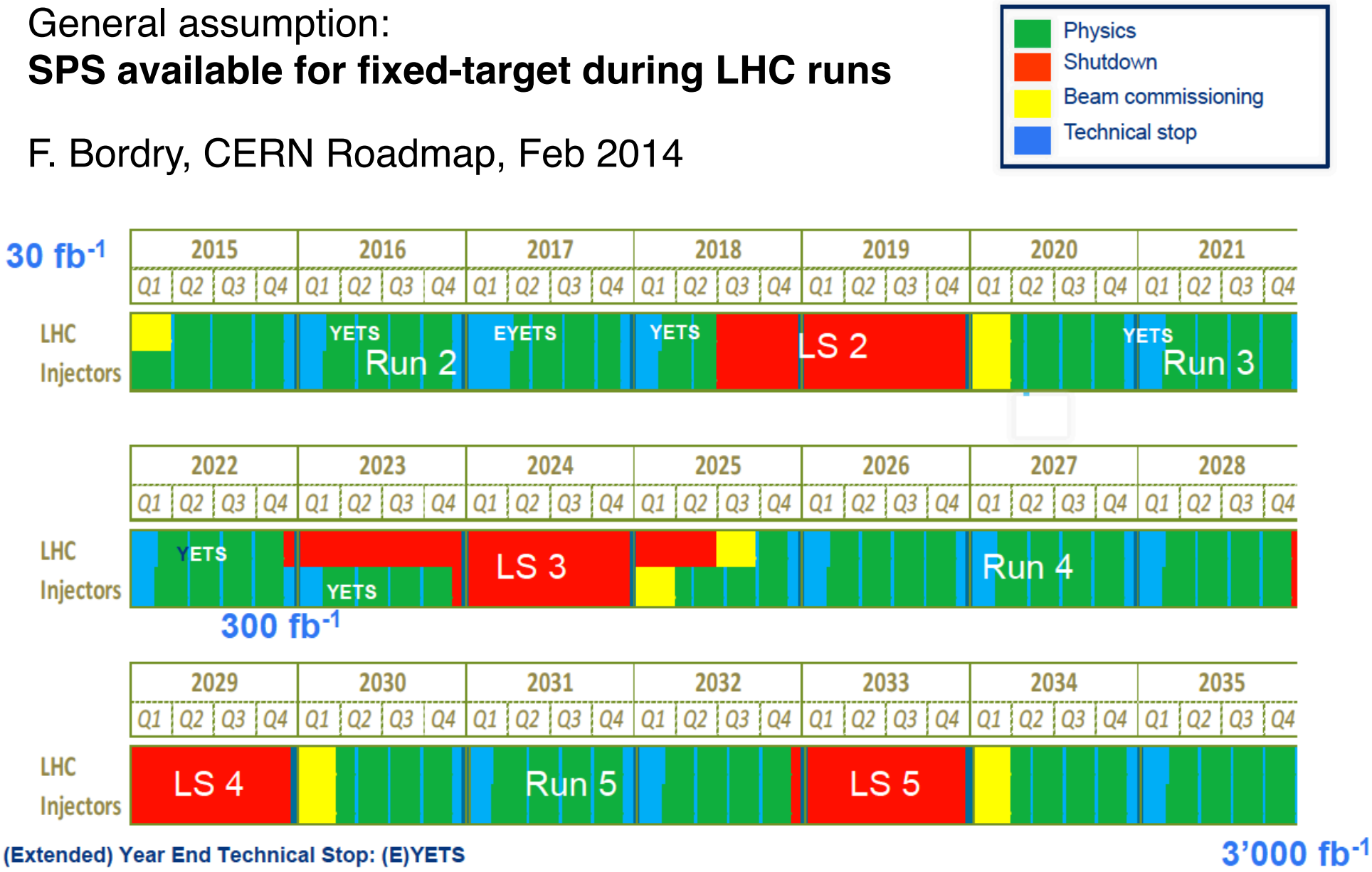
NA62 Collaboration Meeting
Ferrara, 1 September 2014

Preface: Fixed target runs at the SPS

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

F. Bordry, CERN Roadmap, Feb 2014



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 (400)**	**positive (75)**	**2014+2**	**50/yr***	**Ready**
ORKA	FNAL MI (95)	K^+ (0.6, stopped)	2020+5	200/yr*	Proposed
KOTO	**JPARC-I (30)**	**neutral (2 peak)**	**2014+3**	**~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 $K^+ \to \pi^+\bar{\nu}\nu$
- KOTO is the only experiment looking at $K_L \to \pi^0\bar{\nu}\nu$
- No experiment is looking at $K_L \to \pi^0\ell^+\ell^-$

Remarks on NA62 sensitivity

NA62 sensitivity estimates based on **extremely conservative** assumptions in terms of running time

Most of ORKA's claim to greater sensitivity came **only from running time:**

	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**

NA62 has the potential to be a 1000-event experiment

NA62 has an excellent case for additional data taking throughout Run 2

With continuing improvements, NA62 might consider running in Run 3

NA62: From K^+ to K_L

Possibility of a neutral beam forseen in the NA62 Technical Proposal

Substantial increase in primary intensity needed to study $\pi^0\nu\bar{\nu}$ and $\pi^0\ell^+\ell^-$

	NA62 K^+ beam	Future NA62 K_L beam
Primary intensity (ppp)	3×10^{12}	**2.4×10^{13} assumed**
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**

Can we get 2.4×10^{13} ppp in ECN3?

My summary of a conversation with Lau and Niels

Barely possible to get 2.4×10^{13} ppp on T10:

- Max. intensity into TT20 (SPS to North Area): 4×10^{13} ppp
- Max. combined intensity on T2 + T4 + T6: 3.6×10^{13} ppp
  - Have to divide this among users
  - Assumed limit on T4 with 9.6s flat top: 2.4×10^{13} ppp
- Transmission losses from T4 to T10?

2.4×10^{13} ppp on T10 would require various upgrades:

- Minimization of consequences of beam loss in T4-to-T10 line
- Additional shielding against continuous, small losses
- Study issues of equipment survival, e.g. TAX motors
- TCC8 ventilation: plug air leaks, zone segmentation

Preliminary conclusions:

- **2.4×10^{13} is probably impractical: 1.5×10^{13} may be possible**
- Time = “years”; Cost = “many MCHF”

Multiply sensitivity estimates for PRIN studies by 0.6!

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** ($\log_{10}$ € ~ 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?

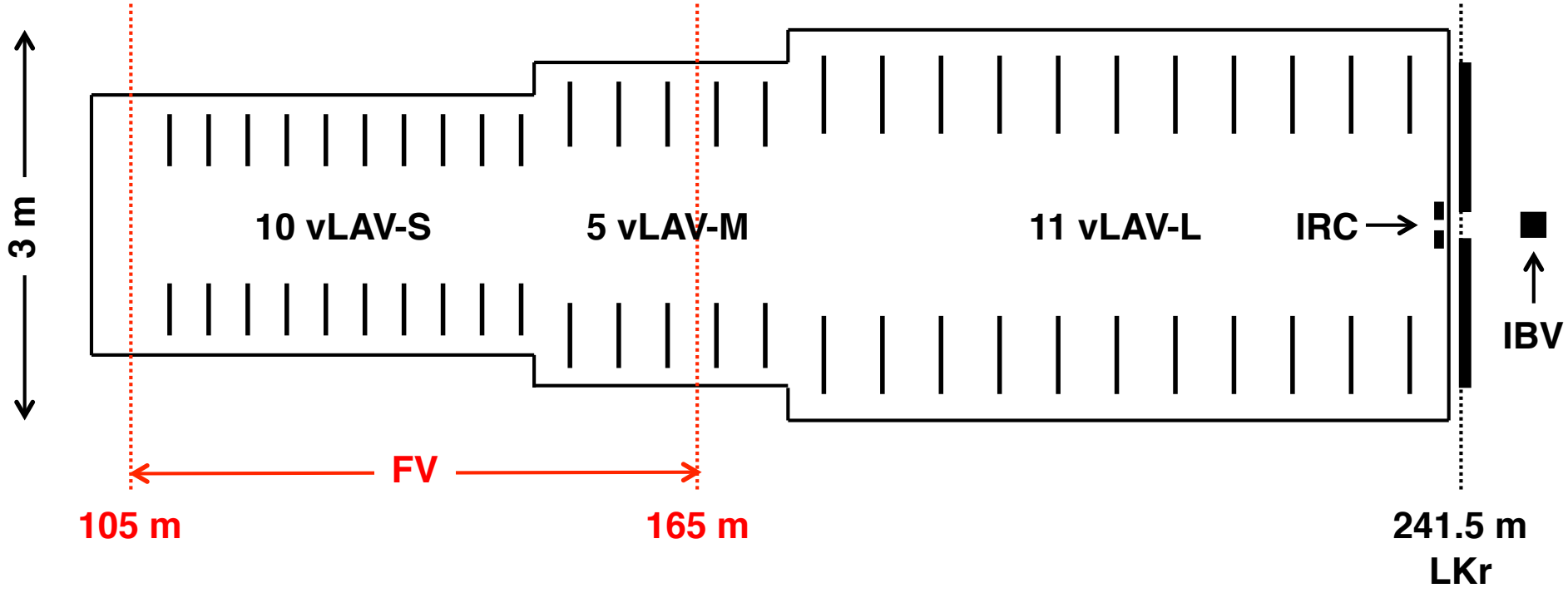
What will be required in terms of charged-particle vetos?

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



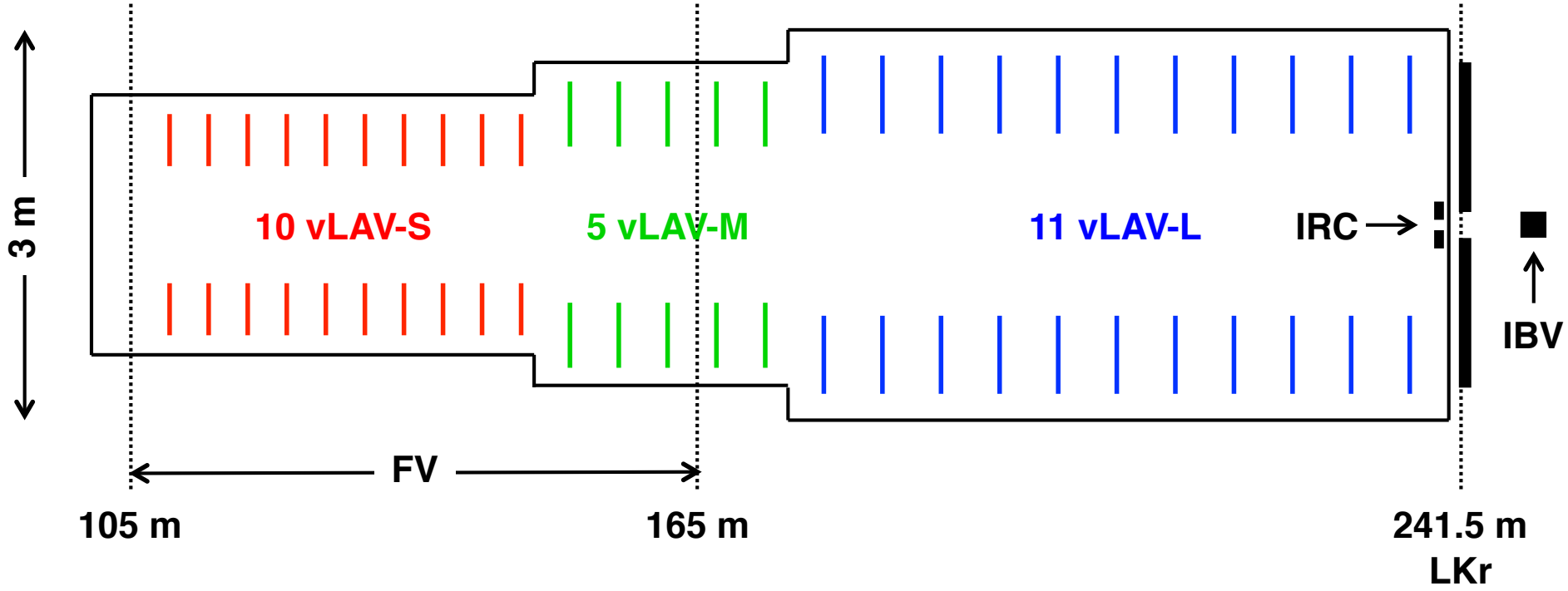
Roughly same vacuum tank layout and fiducial volume as NA62

FV starts ~105 m downstream of target

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

May require innovative approach: Iridium monocrystal?

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



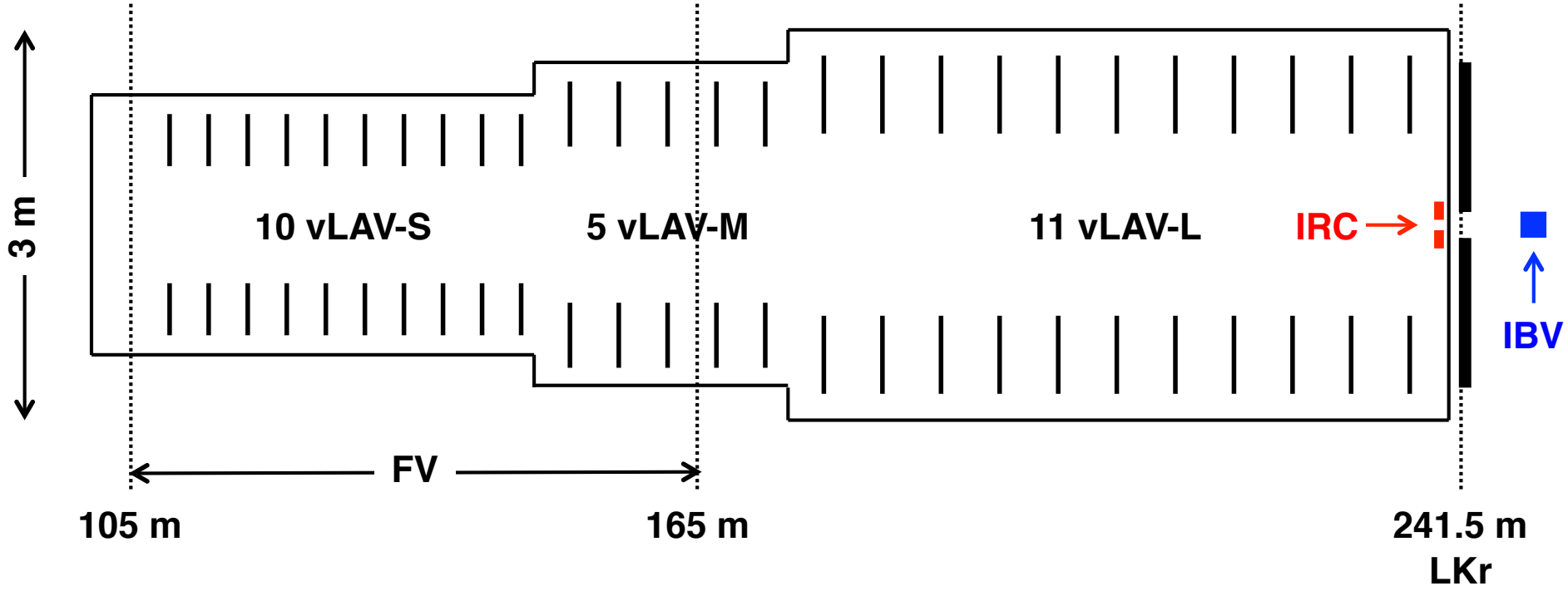
26 new large-angle photon veto stations (vLAV)

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)

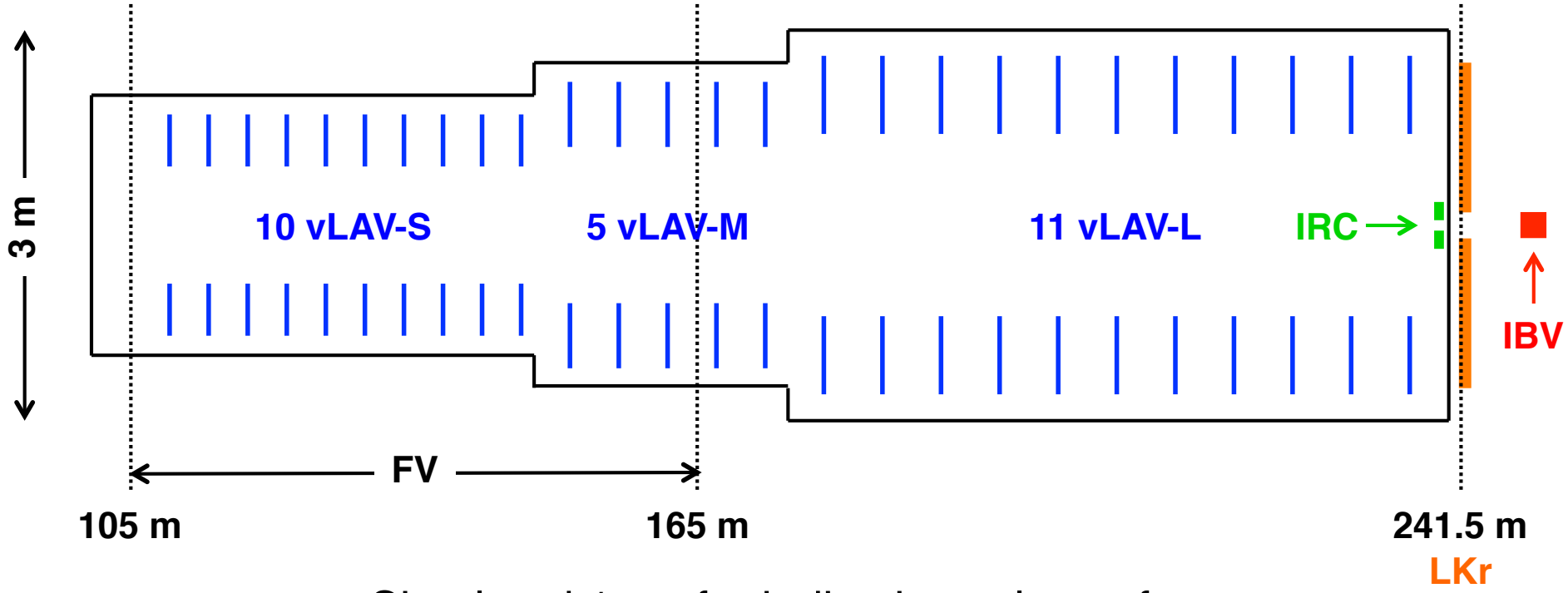
Must be relatively insensitive to 800 MHz of beam neutrons

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 results

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

- Simulate K_L beam and decay in free space (102.8 m < z < 241.5 m)
- Decay each π^0 and track γs – simulate detection efficiencies
- Accept only events with 2 γs in LKr and no hits in LAV, IRC, SAC
- Impose $m_{\pi 0}$ on 2γ and reconstruct z_{rec}
- Accept events with 105 m < z_{rec} < 165 m and $p_{\perp \text{rec}}(\pi^0)$ > 0.1 GeV

Expected results with 2 standard NA62 years of data:
1.8×10^{12} K_L decays in FV (2 year run, 0.9×10^{12} K_L/year)

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

Nominally ~2× better than KOTO (J-PARC)

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?

PRIN work in progress for $K_L \to \pi^0 \nu\bar{\nu}$

Florence	Background from beam-gas interactions
F. Bucci	Background from additional decay channels
R. Volpe	Design of charged vetoes
Frascati	Optimization of photon-veto layout
S. Martellotti	Photon-veto efficiency requirements
M. Moulson	Effects of finite two-hit resolution
	Development of IRC & IBV design
Perugia	Utility of preradiator for LKr
E. Imbergamo	- Extra constraints for background rejection?
	- Increase signal acceptance to large angles?

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

- 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

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

PRIN work in progress for $K_L \to \pi^0 \ell^+ \ell^-$

Naples M.B. Brunetti D. Di Filippo	Inserted $K_L \to \pi^0 \ell^+ \ell^-$ generator in NA62 MC Moved straw chambers along x to reposition holes for K_L beam Rotated RICH to accomodate K_L beam

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

- Data taking with incrementally modified NA62 setup in Run 3?
- Concurrently study detector prototypes for $K_L \to \pi^0 \nu \bar{\nu}$

NA62 potential for heavy neutrino searches

Not part of PRIN studies

V. Fascianelli (Laurea thesis) – T. Spadaro (advisor)

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

$K \to N\ell$ decays (m_N < 0.5 GeV)

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

$D \to N\ell$ decays (m_N < 1.8 GeV)

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

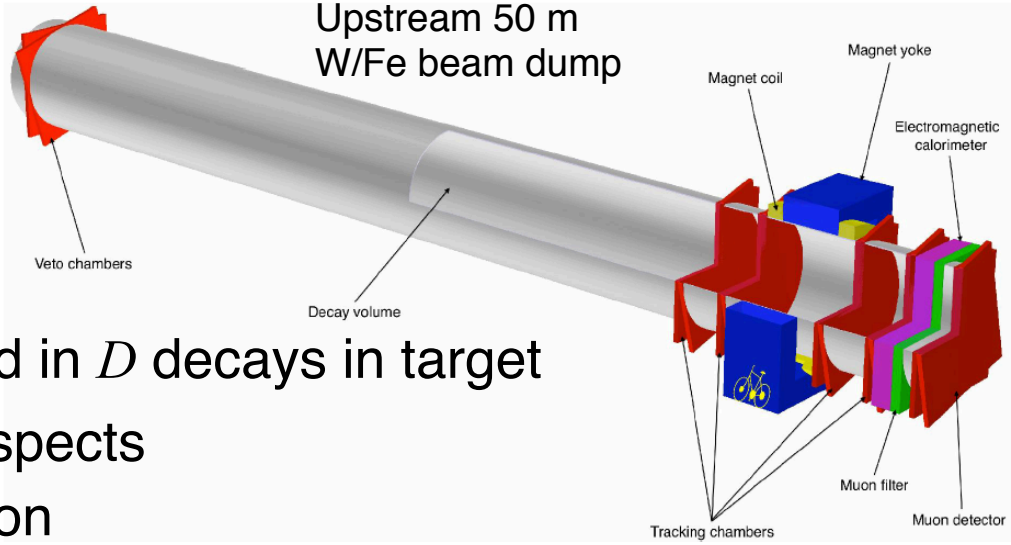
- May need some small hardware modifications to the NA62 level-0 trigger
- Subject of a SIR proposal (F. Gonnella, T. Spadaro); feasibility studies ongoing

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

SHiP

Beam dump experiment for new high-intensity SPS beamline



Search for N up to 1.8 GeV produced in D decays in target

Detector similar to NA62 in many respects

- Much larger: 5 × 5 m^2 cross section
- Straw chambers à la NA62 a possible choice for spectrometer

Completely new North Area beamline, target bunker, and experimental area

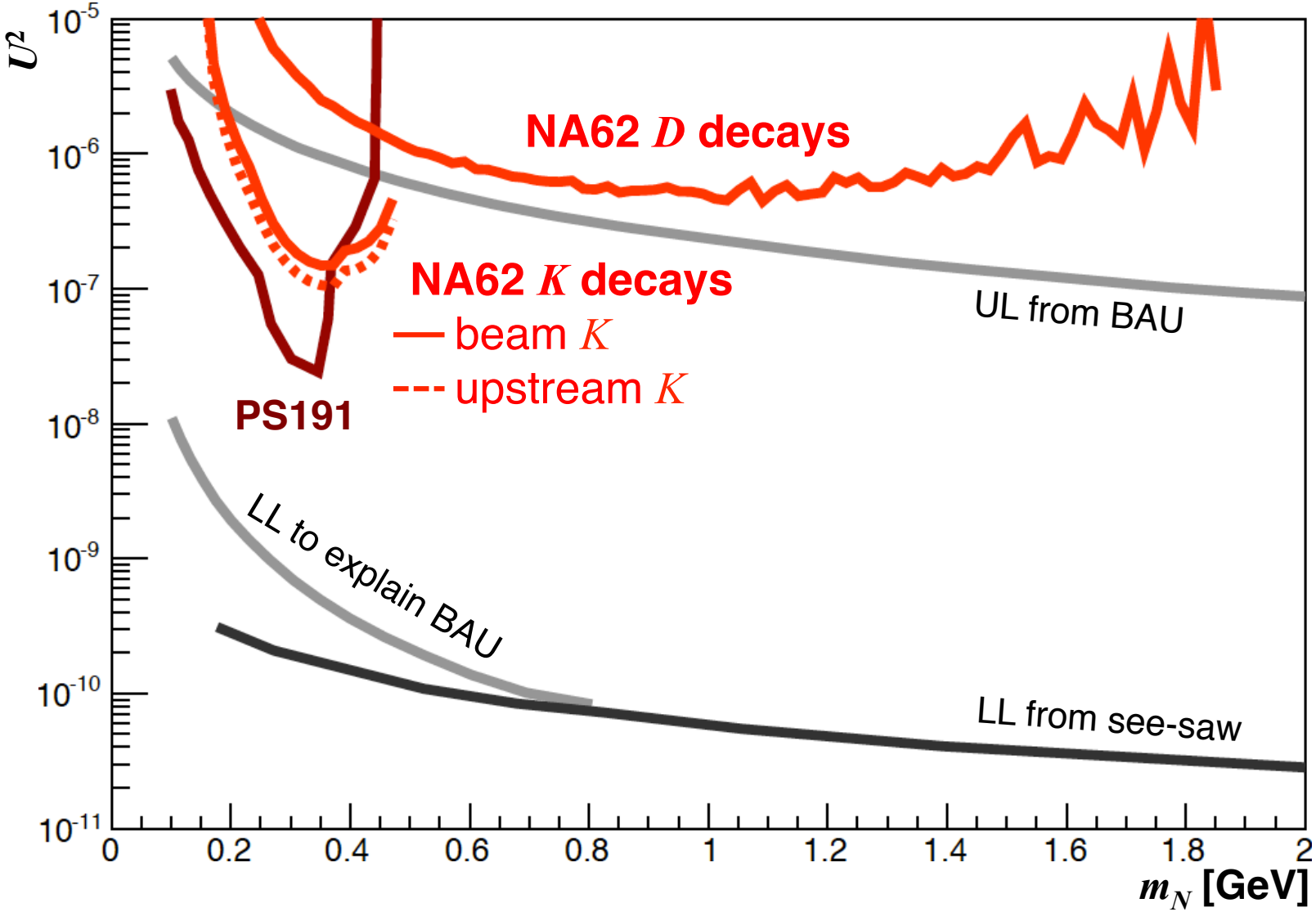
Preliminary project study and cost estimate for infrastructure done by CERN-EN (EN-DH-2014-007):

- **Beam intensity: > 4 × 10^{13} ppp**
- **Infrastructure costs: 113 MCHF**
- **Experiment costs: 45 MCHF**
- **Physics start: Run 4**

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

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

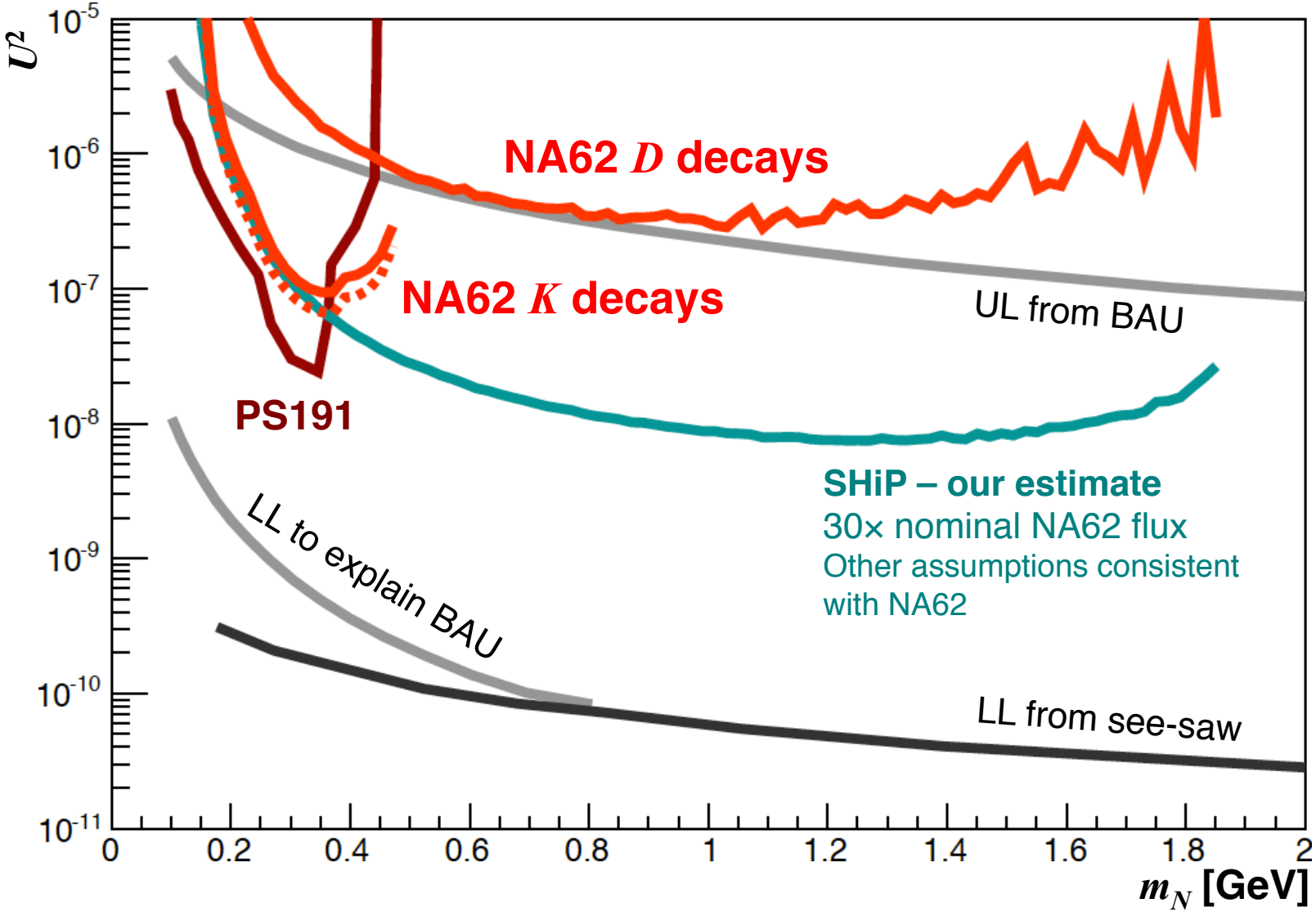
2 years of data at nominal NA62 K^+ run intensity (2.5×10^{18} pot)



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

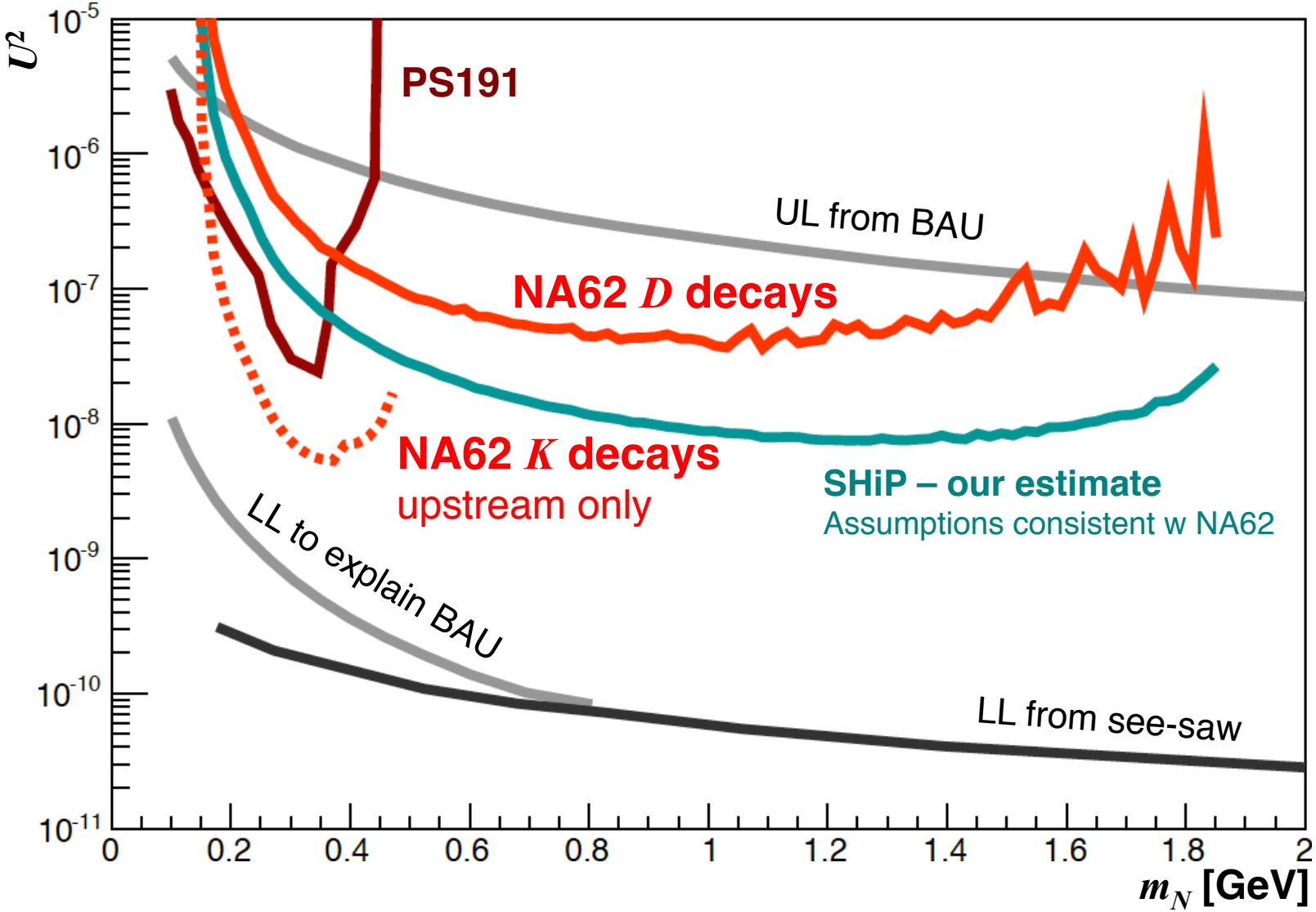
Sensitivity for exclusive search for $N \to e\pi$ or $\mu\pi$

5 years of data at nominal NA62 K^+ run intensity (6×10^{18} pot)



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 (2×10^{20} pot)



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 4
- 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

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

Various possibilities for NA62 in Run 3

- Upgrades 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 $\pi^0 \nu\bar{\nu}$
- 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 $K_L \to \pi^0 \nu\bar{\nu}$ experiment
- $K_L \to \pi^0 \nu\bar{\nu}$ 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

INFN “What Next?” exercise

Workshop on the Long-Term Strategy of INFN-CSN1:
The next 10 years of accelerator-based experiments
Elba, 22-24 May 2014

INFN is currently conducting a long-term strategy exercise called “What Next?” and patterned on the Snowmass process

I presented the perspectives on the future of NA62 from the previous slide at the meeting in Elba in May

How was this message received?

F. Bedeschi, LTS1 workshop summary

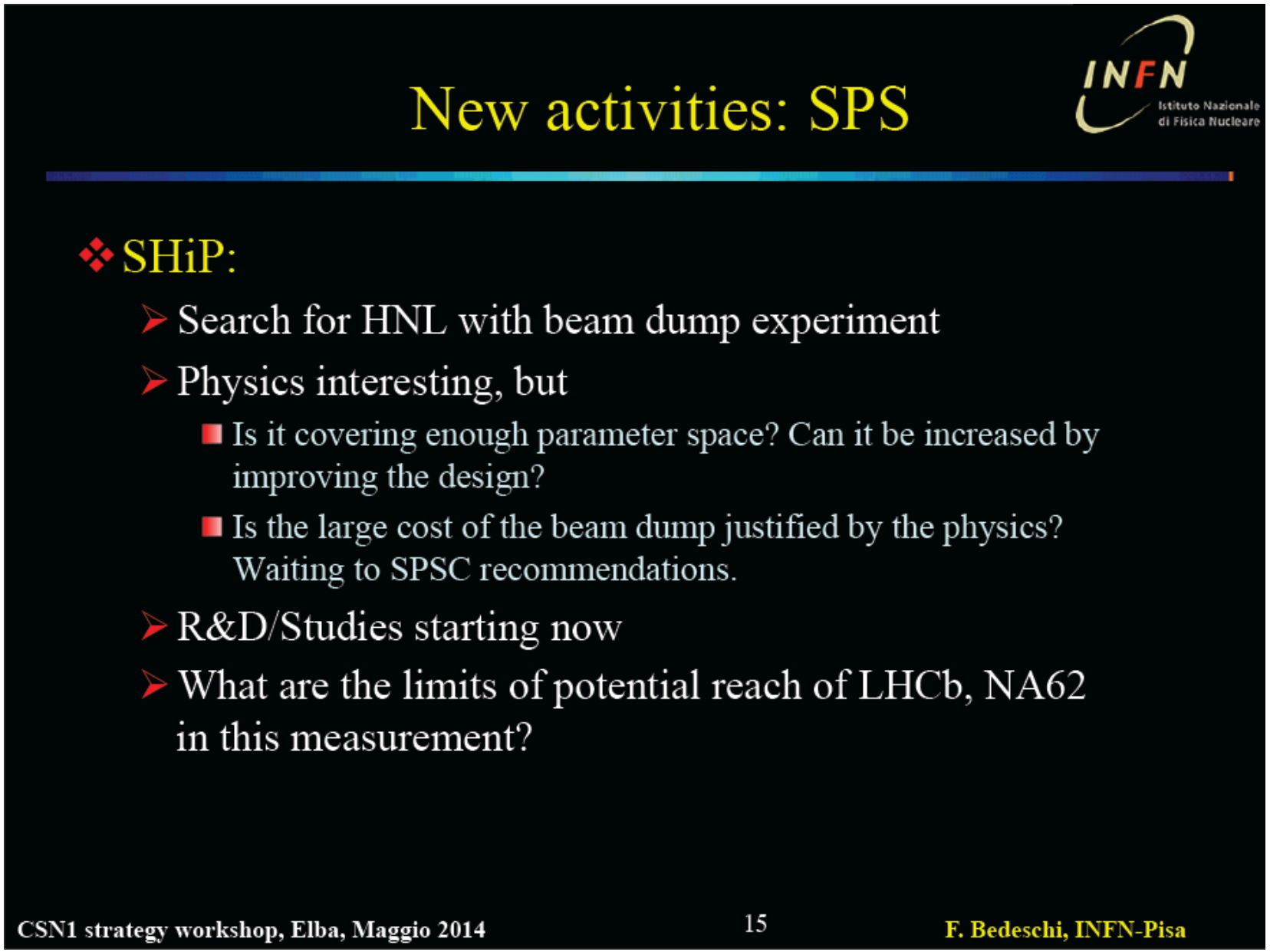
Current activities evolution: SPS fixed target

INFN Istituto Nazionale di Fisica Nucleare

- NA62 (rare charged kaon decay):
  - Completing now, data end 2014 onwards
  - Potential extension to neutral kaon channel
    - On paper x2 KOTO statistics, but
      - Real backgrounds still unknown
      - Starts rather late relative to KOTO
      - Is it worth it?
  - Potential HNL search before SHiP with lower sensitivity
    - Should explore potential?
- COMPASS:
  - Upgrade in progress. Resume data taking end 2014
  - What happens after end of this run 2017-2018?

CSN1 strategy workshop, Elba, Maggio 2014 10 F. Bedeschi, INFN-Pisa

F. Bedeschi, LTS1 workshop summary



A word on KOTO

KOTO status:

- 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 sensitivity:

- **Now:** Expect to see the $K_L \to \pi^0 \nu\bar{\nu}$ decay by 2018: ~3 clean events
- **Future:** Strong intention to upgrade to ~100 event sensitivity
  - With 100 kW of beam power ~10 evts/yr (1 yr = 10^7 s)
  - Exploring possibilities to increase sensitivity
  - Indicative timescale: data taking starting 2025?
  - However, no proposal at this time

NA62 K_L vs KOTO

KOTO does not make NA62 K_L redundant:

- NA62 methodology is complementary to KOTO's (high-energy beam)
- KOTO will not have significantly better sensistivity than NA62 without breakthroughs
- KOTO upgrade plans are far from certain

However:

- Unlikely that NA62 can mount a $\pi^0\nu\bar{\nu}$ experiment before Run 4
- This will be a significant investment
- We should consider playing the long game: Make the proposal ambitious!
  - A signficant next-generation step
  - Need to match KOTO upgrade plans (hopes): ~100 event sensitivity

This has not been the spirit of the PRIN exercise so far!

- We have tried to keep the design modest and affordable
- Do we risk making it not attractive enough to justify a "modest" investment?

NA62 & SHiP

Plan for an experiment with ~100 event sensitivity: Need more protons?

Get involved in design of the SHiP facility? (Neils's suggestion)
Push to design in the possibility for a K_L/neutral beam experiment

Advantages:	3-5× higher primary beam intensity
	Easier to justify than P42/T10 intensity upgrade if SHiP goes ahead?
Problems:	Run serially or in parallel with SHiP?
	Running in ECN3 at 1.5×10^{13} ppp may lead to less complicated interplay between experiments
More exotic ideas:	Extract 2nd beam at SHiP facility at large angle and do a "low-energy" K_L experiment like KOTO or KOPIO
	Full-integration with SHiP detector: Use SHiP tracking and PID detectors to measure photon detection efficiencies for K_L experiment; remove if needed during main measurement.

Right now just speculation, but may want to develop these ideas!

NA62 & SHiP

What would a move to the SHiP facility buy us in terms of intensity?

	Primary intensity	Rep rate	Uptime/year	Years requested	Total flux
NA62	1.5×10^{13}	0.06	1200	2	8×10^{18}
SHiP	4.3×10^{13}	0.095 avg	3700	5	2.7×10^{20}
SHiP/ NA62	**2.9**	**1.6**	**3.1**	**2.5**	**34**

This part is intrinsic
4.6×

This part is run time
7.8×

30× increase in flux at SHiP is largely a statement about running time

Whither the PRIN project?

Current status:

- Focused on a moderate-cost $\pi^0\nu\bar{\nu}$ experiment with ~10-event sensitivity
- Beginning to explore $\pi^0\ell^+\ell^-$ although not originally in proposal
- There is also interest in heavy neutral lepton searches at NA62, not currently a part of the PRIN project, but obviously relevant to it
- Even a ~10-event experiement has a long lead time: Run 4

Evolutionary pressures:

- External competition? KOTO?
- Perception that a ~10-event experiment isn't ambitious enough
- Current window of opportunity to get in on design of the SHiP facility

Do we want to take the PRIN in a significantly new direction?

Concluding remarks

The PRIN WG is currently a small subset of NA62

If we want to be more ambitious about the future of kaon experiments at CERN, we need a larger WG

Some non-Italian collaborators have expressed interest in working on the project

Lots of possibilities for strong contributions from new collaborators and groups that arrived too late to have strong roles in the design and construction of NA62

More questions than answers in this talk
Lots of need for discussion – lots of work to do!

First step: Open future PRIN WG meetings to the whole collaboration