

NA62 and the Hidden Sector

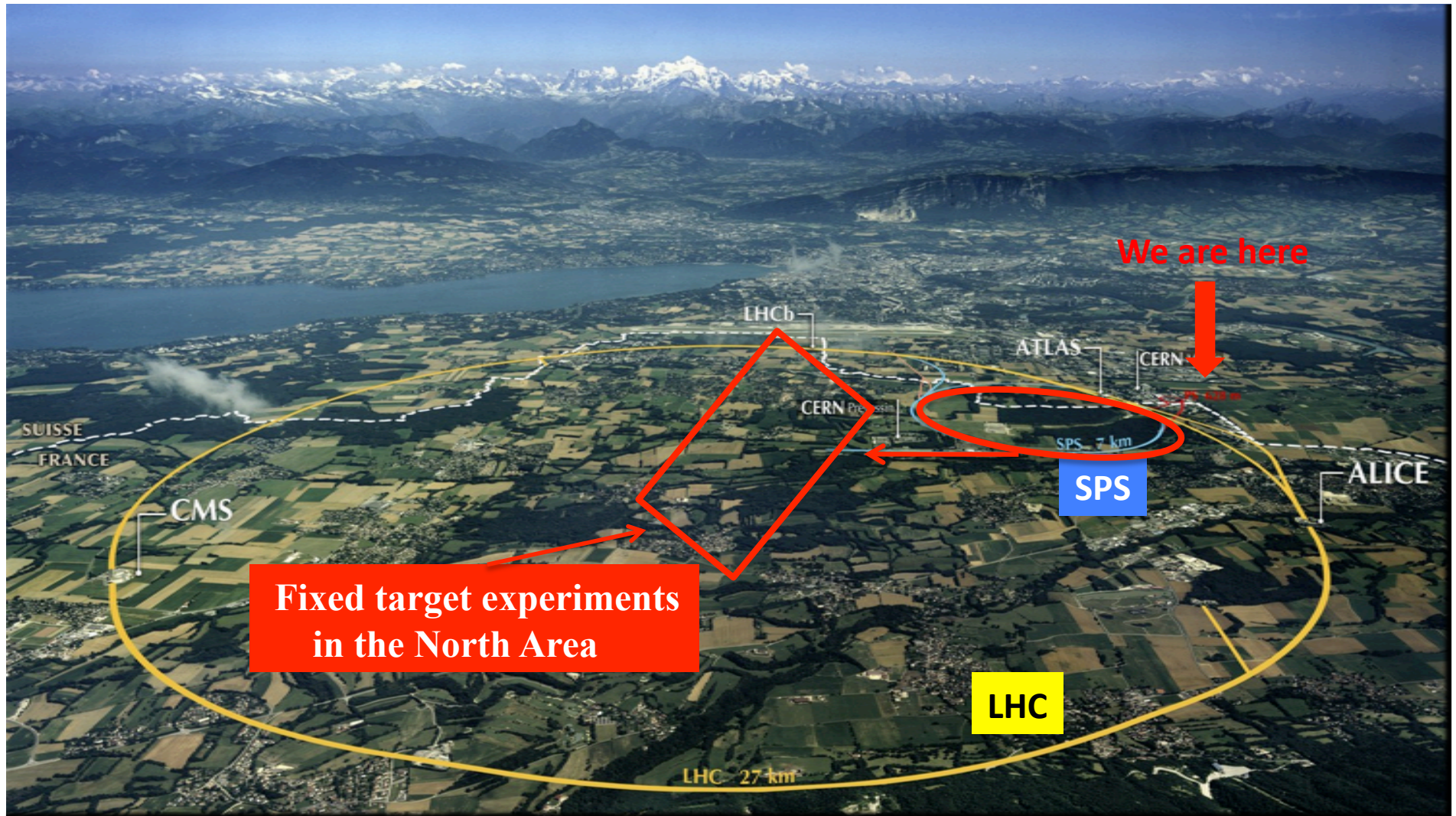


Gaia Lanfranchi

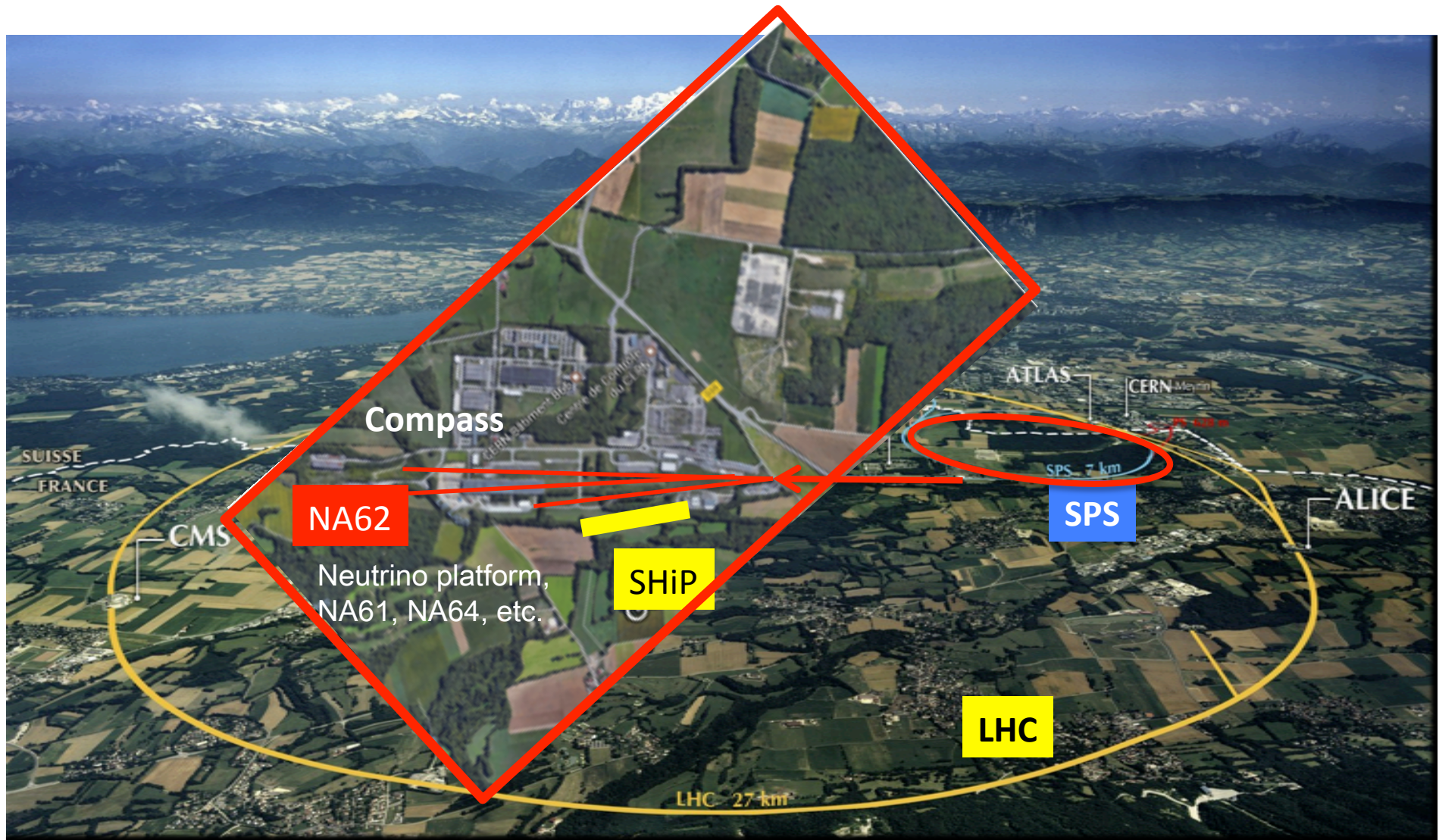
LNF-INFN

on behalf of the NA62 Collaboration

The CERN accelerator complex



Fixed Target Experiments @ CERN



2015: $2\text{--}3 \times 10^{19}$ pot delivered to the North Area.

Highest energy proton beam delivered for fixed target experiments in the world 2

How to search for Hidden Particles?

Light and feebly-interacting particles can be **originated by the decay of beauty, charm and strange hadrons and by photons produced in the interaction of protons with a target**. Their couplings to SM particles are very suppressed leading to expected production rates of 10^{-10} or less. As the charm and beauty cross-sections increase steeply with the energy, **a high-intensity, high-energy proton beam is required to improve over the current results**:

→ To date the world best line to produce high intensity fluxes of beauty and charm hadrons and photons through the interactions of protons on a high-Z target is a 400 GeV/c proton beam line extracted from the CERN SPS

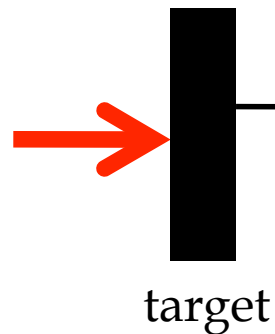
The smallness of the couplings implies that the hidden sector mediators are also very long-lived compared to the bulk of the SM particles:

an HNL with $m=1$ GeV has $\tau \sim 10^{-5}$ sec and an average flight distance of >10 km at the SPS energies.

→ The decays to SM particles can optimally be detected only using an experiment with decay volume tens of meters long followed by a spectrometer with particle identification capabilities.

Production of Hidden Sector Particles at the SPS

SPS protons
400 GeV/c



K, D, B
photons,
neutrons, protons, π
muons from K/ π decays
and light resonances,
neutrinos, etc..



Use K, D, B decays and photons
to search for hidden particles in
various portals

At SPS energies:

$$\begin{aligned}\sigma(pp \rightarrow s\bar{s} X) / \sigma(pp \rightarrow X) &\sim 0.15 \\ \sigma(pp \rightarrow c\bar{c} X) / \sigma(pp \rightarrow X) &\sim 2 \cdot 10^{-3} \\ \sigma(pp \rightarrow b\bar{b} X) / \sigma(pp \rightarrow X) &\sim 1.6 \cdot 10^{-7}\end{aligned}$$

Production of Hidden Sector Particles at the SPS: [HNL](#)

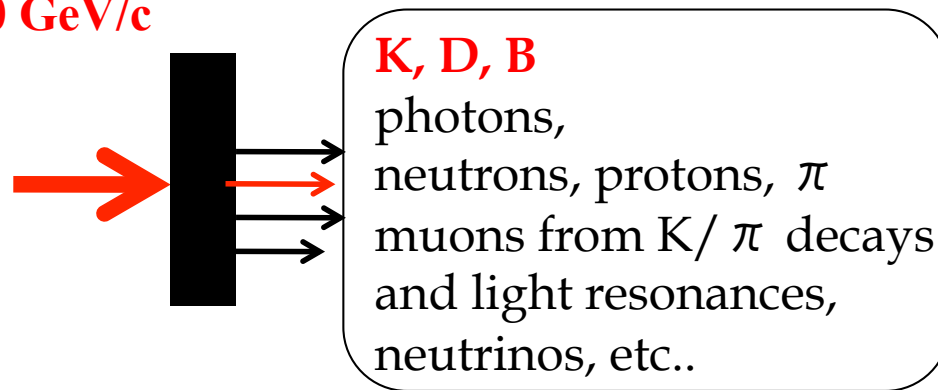
Production of HNL:

$K, B, B_s, D, D_s \rightarrow \text{lepton} + \text{HNL}$

$K, B, B_s, D, D_s \rightarrow \text{semi-leptonic modes}$

SPS protons

400 GeV/c

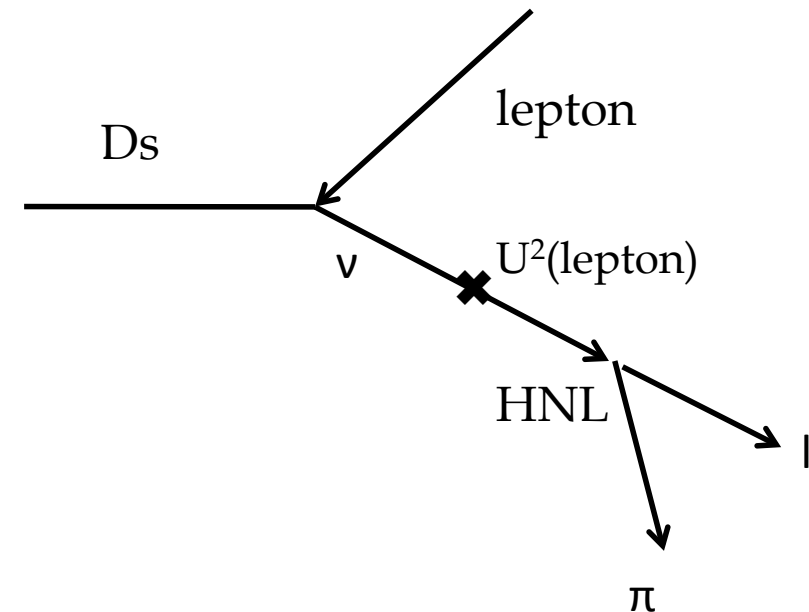


At SPS energies:

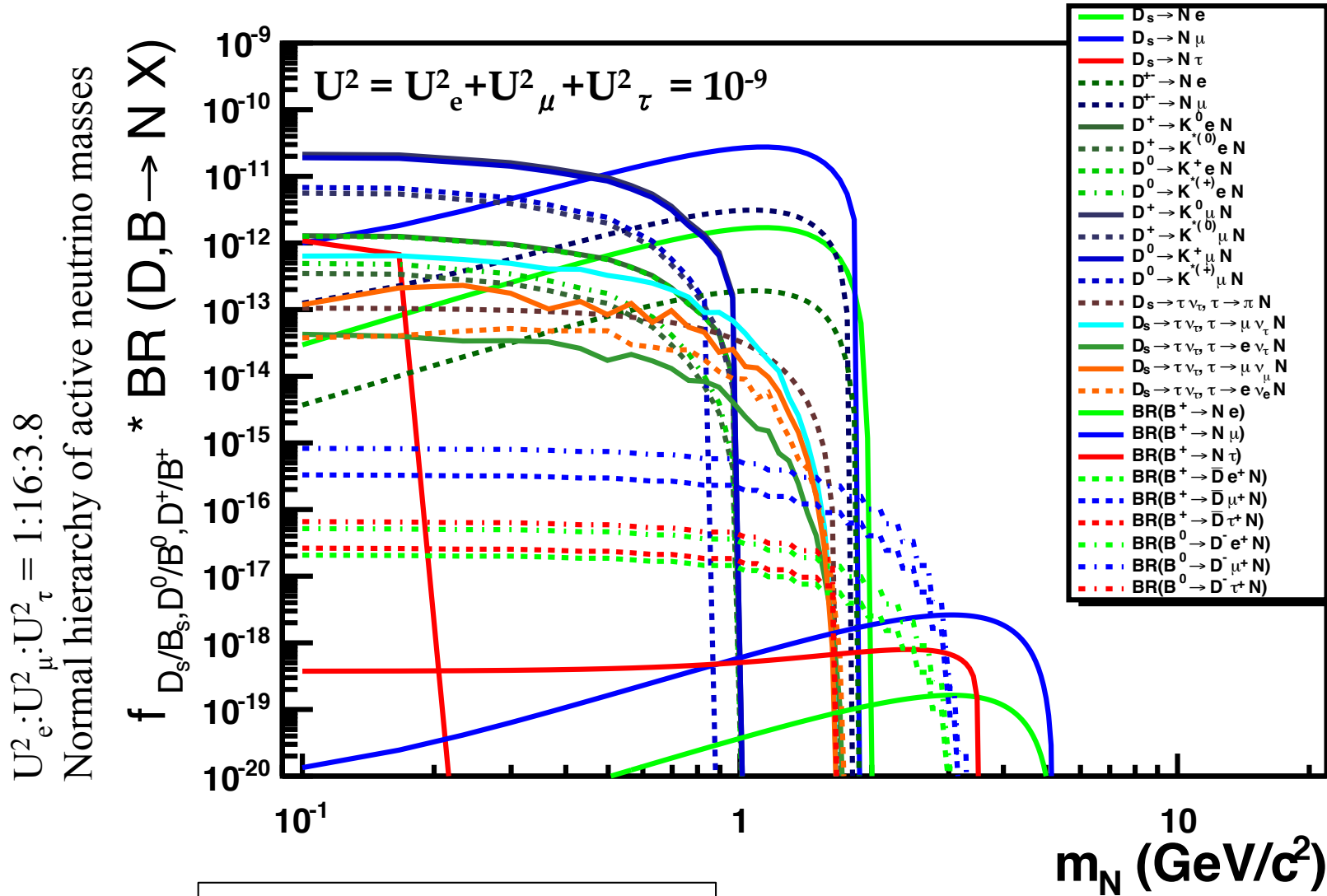
$$\sigma(pp \rightarrow s\bar{s} X) / \sigma(pp \rightarrow X) \sim 0.15$$

$$\sigma(pp \rightarrow c\bar{c} X) / \sigma(pp \rightarrow X) \sim 2 \cdot 10^{-3}$$

$$\sigma(pp \rightarrow b\bar{b} X) / \sigma(pp \rightarrow X) \sim 1.6 \cdot 10^{-7}$$



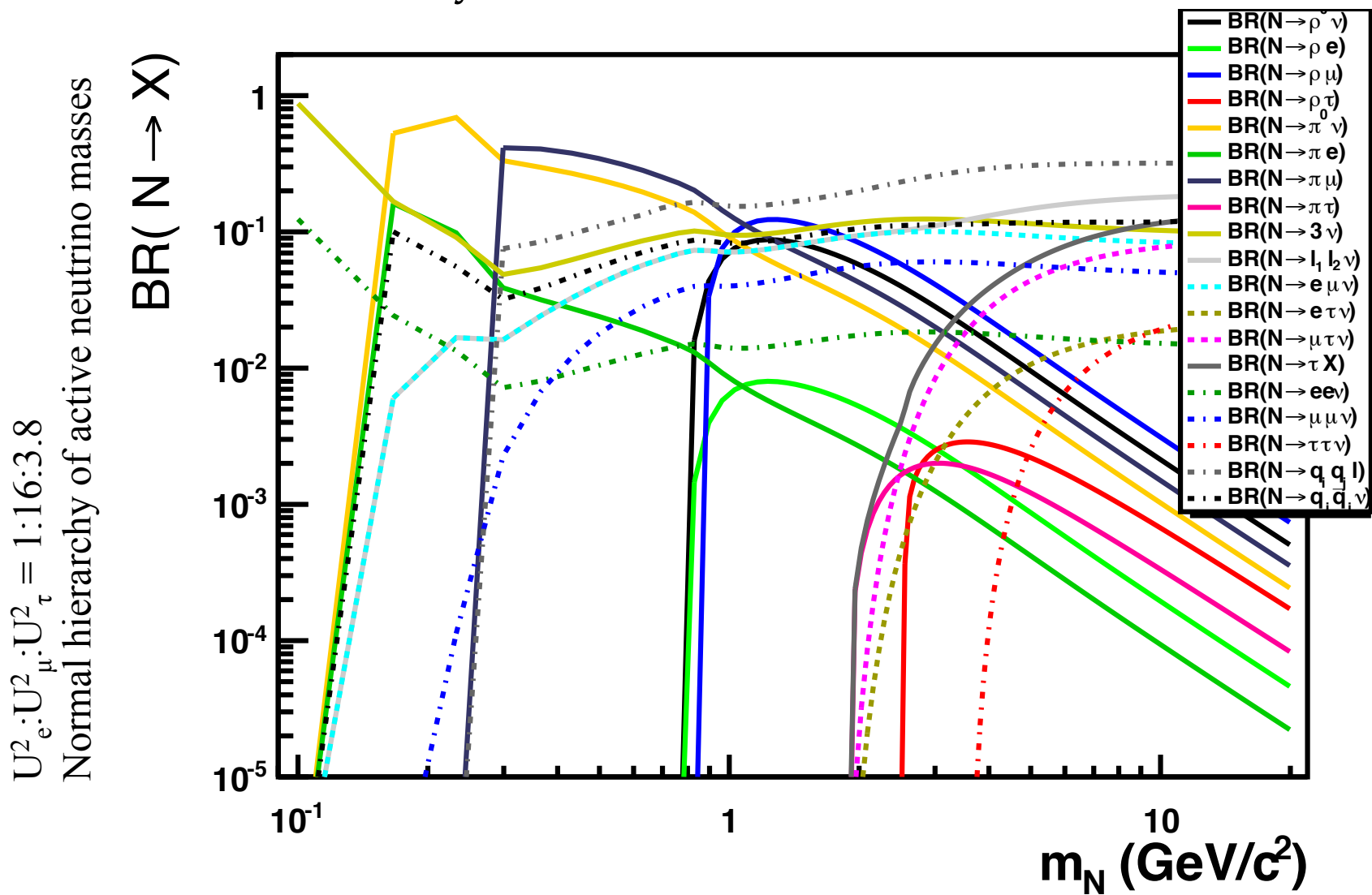
Eg: HNL production modes in a beam-dump (mostly D,B)



Green-ish: U_e^2 dominated
Blue-ish: U_μ^2 dominated
Red-ish: U_τ^2 dominated

See M. Shaposhnikov, D. Gorbunov,
arXiv:0507.1729

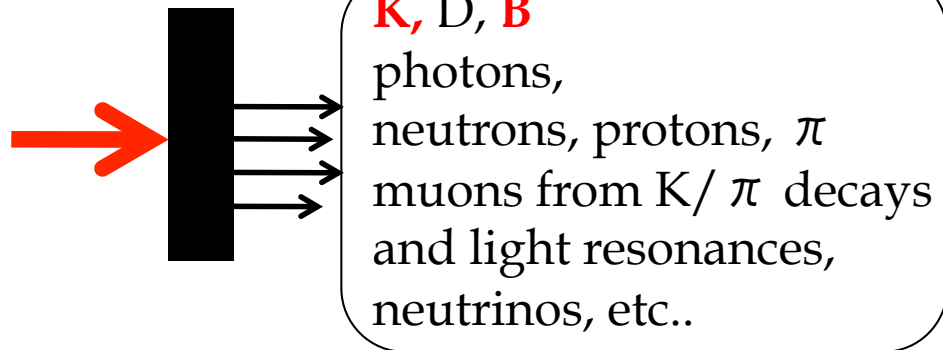
HNL decay modes:



See M. Shaposhnikov, D. Gorbunov,
arXiv:0507.1729

Production of Hidden Sector Particles at the SPS: Dark Scalars

SPS protons
400 GeV/c



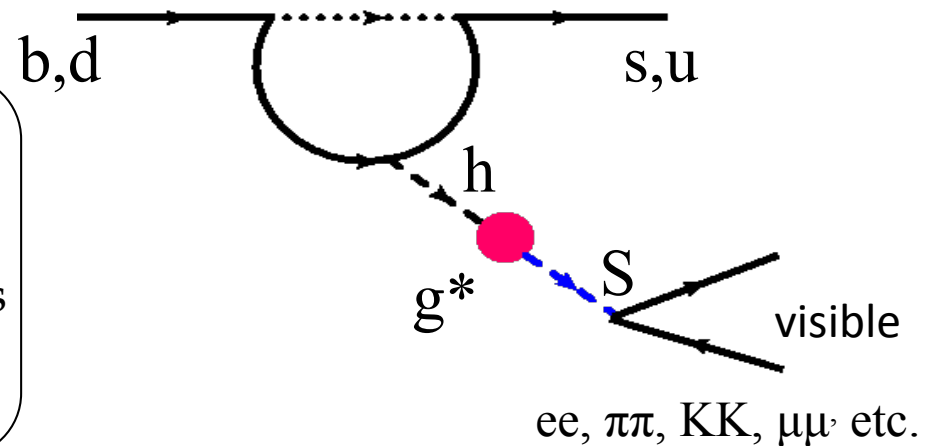
At SPS energies:

$$\begin{aligned}\sigma(pp \rightarrow s\bar{s} X) / \sigma(pp \rightarrow X) &\sim 0.15 \\ \sigma(pp \rightarrow c\bar{c} X) / \sigma(pp \rightarrow X) &\sim 2 \cdot 10^{-3} \\ \sigma(pp \rightarrow b\bar{b} X) / \sigma(pp \rightarrow X) &\sim 1.6 \cdot 10^{-7}\end{aligned}$$

Production of Dark Scalars:

$$B \rightarrow K S$$

$$K \rightarrow \pi S$$



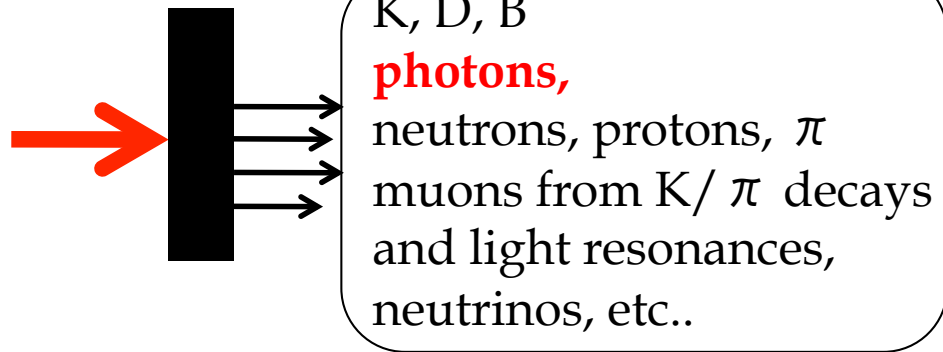
$$\rightarrow \Gamma(K \rightarrow \pi\phi) \sim (m_t^2 |V_{ts}^* V_{td}|)^2 \propto m_t^4 \lambda^5$$

$$\Gamma(D \rightarrow \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$$

$$\rightarrow \Gamma(B \rightarrow K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$$

Production of Hidden Sector Particles at the SPS: Dark Photons

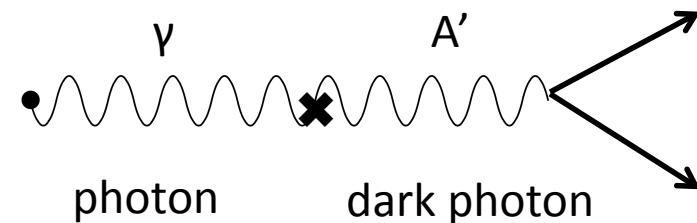
SPS protons
400 GeV/c



Production of Dark Photons:

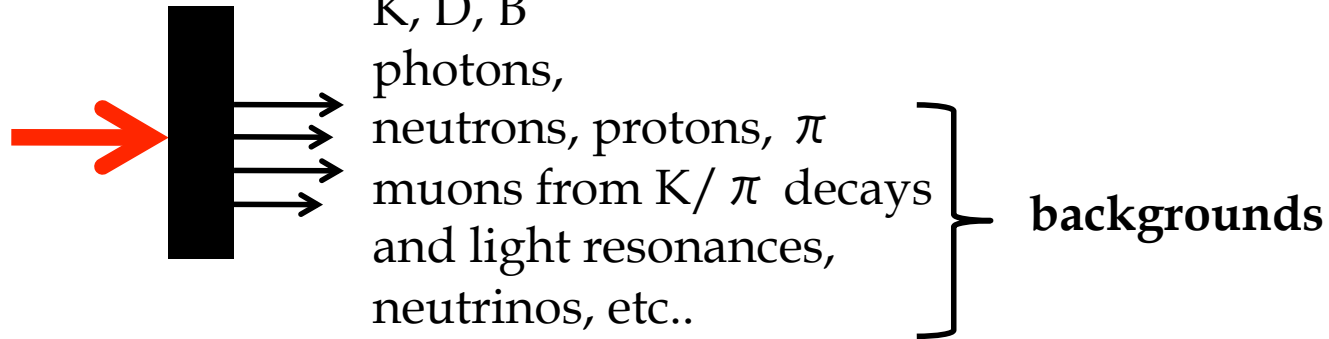
Photon produced in light meson resonances, bremsstrahlung, and QCD processes.

Search for massive particle mixing with the photon and decaying to visible final states ($e^+ e^-$, $\mu^+ \mu^-$, etc.)



Background, background, background.....

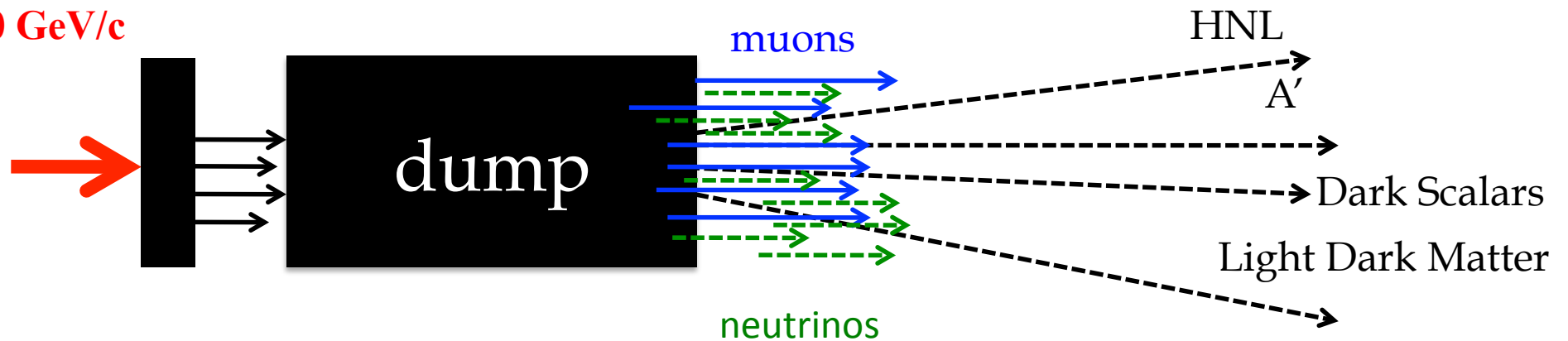
SPS protons
400 GeV/c



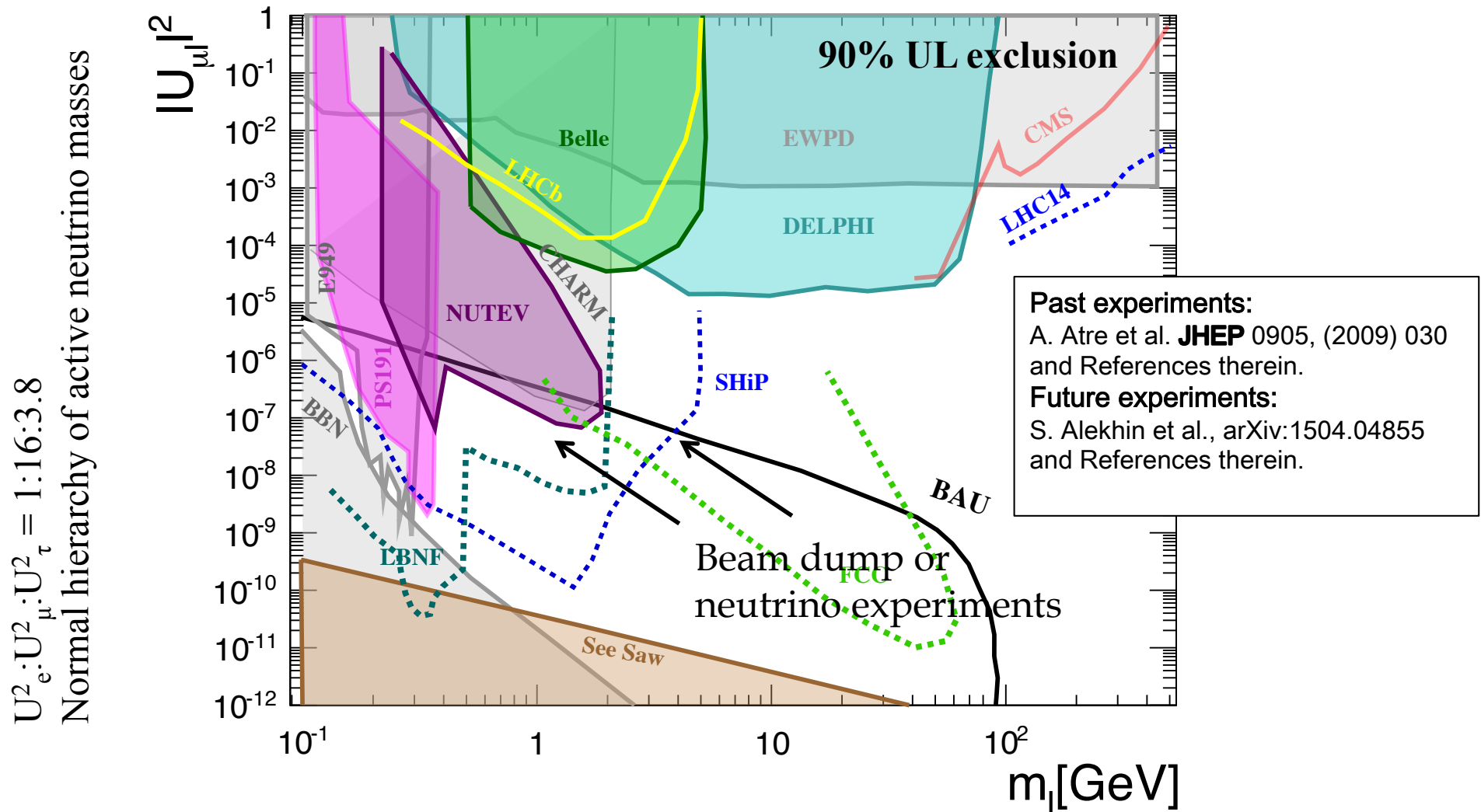
Background, background, background.....

A dump with suitable length stops all beam-induced backgrounds but neutrinos and muons:

SPS protons
400 GeV/c



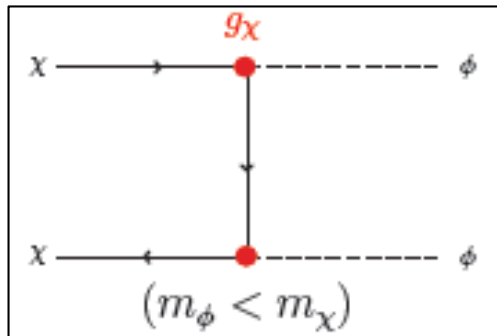
Heavy Neutral Leptons: past and future sensitivities



From CHARM (1988), PS191, NUTEV (1998+) to SHiP, LBNF (2026++):
a big gap in sensitivity (2-3 orders of magnitude in coupling)

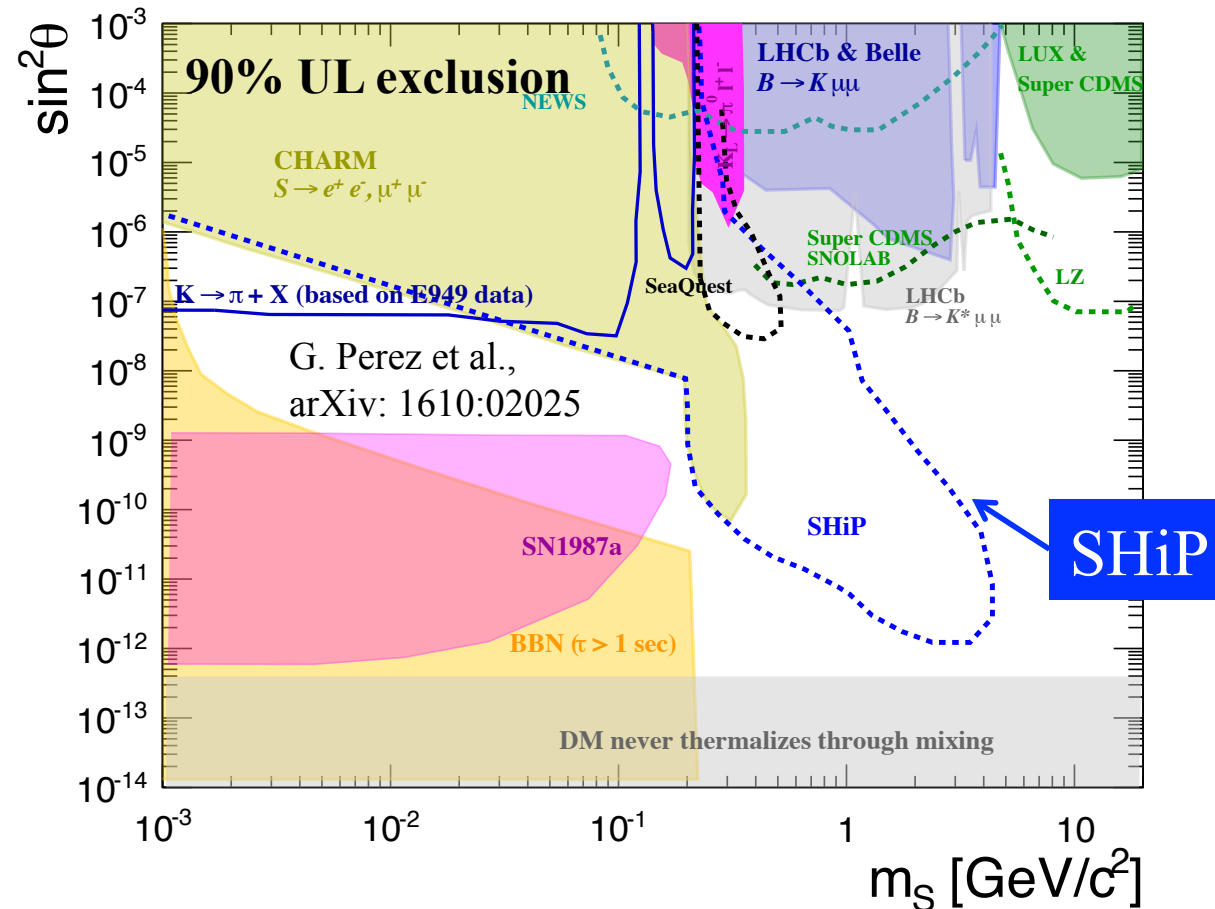
Dark Scalars in **visible** modes: past and future sensitivities

Secluded annihilation via mediators (only possibility compatible with CMB and rare mesons decays constraints), mediators decay to SM particles



$$g_X = \sin \theta$$

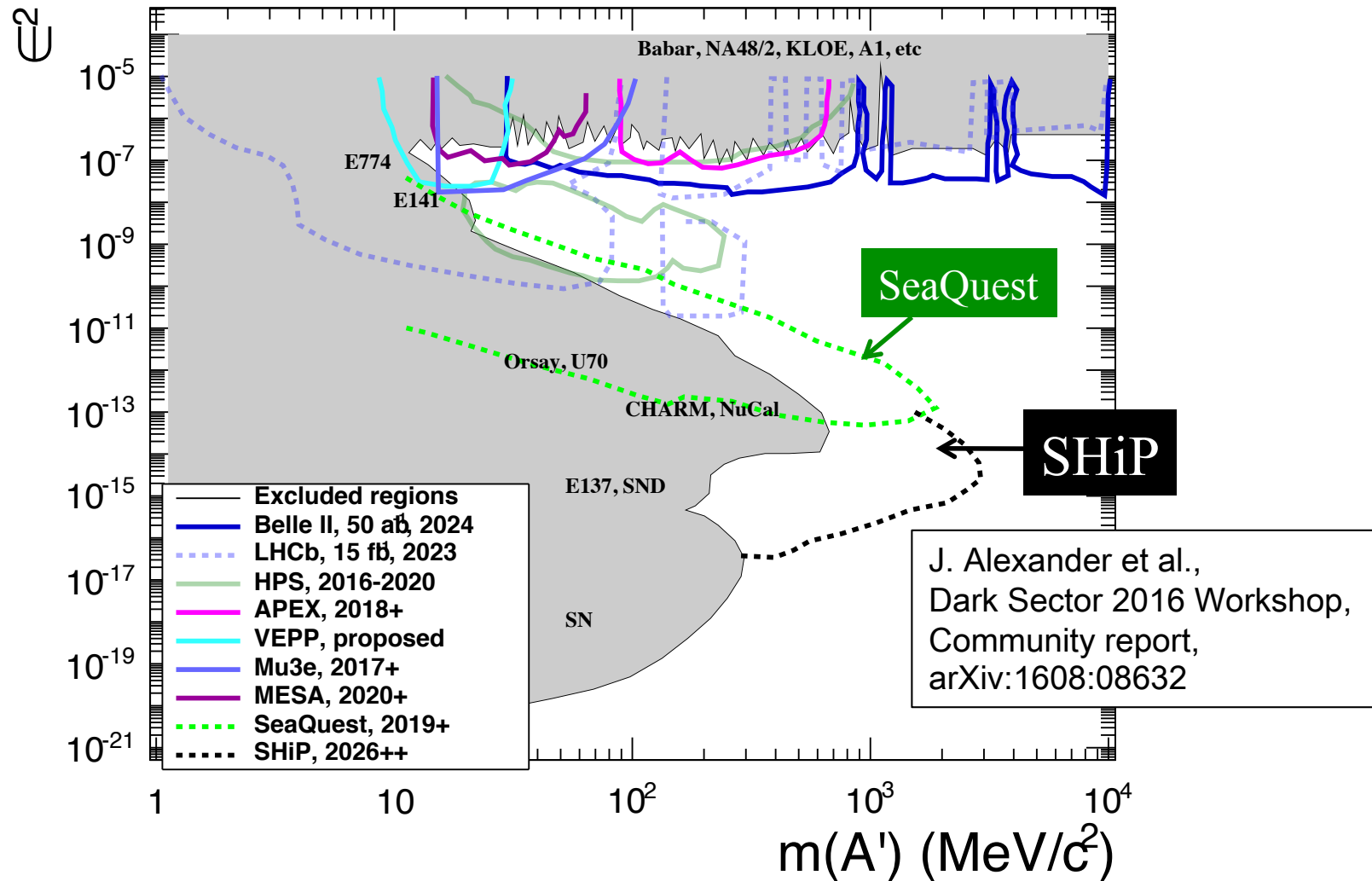
See G. Krnjaic's talk,
arXiv:1512.04119v1,
and references therein



From CHARM (1980+) to SHiP (2026++):

A huge gap in sensitivity (several orders of magnitude in coupling & mass) 13

Dark Photons in visible modes: past and future sensitivities



From CHARM, NuCal to SHiP (2026++):
a big gap in sensitivity in mass & coupling



.... and SHiP, LBNF (2026++)

...a big gap to cover in the Hidden Space...



Between CHARM, NuTeV (1980++)....



.... and SHiP, LBNF (2026++)



NA62 (now)

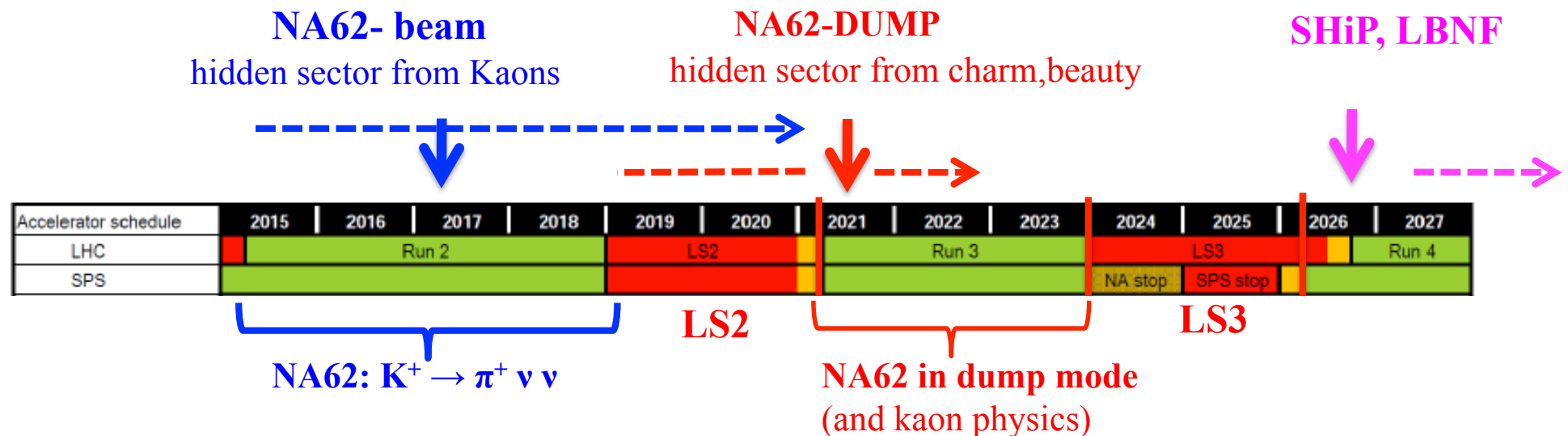
an intermediate step between
the past and the future



Between CHARM, NuTeV (1980++)....

NA62: the intermediate step between the past and the future

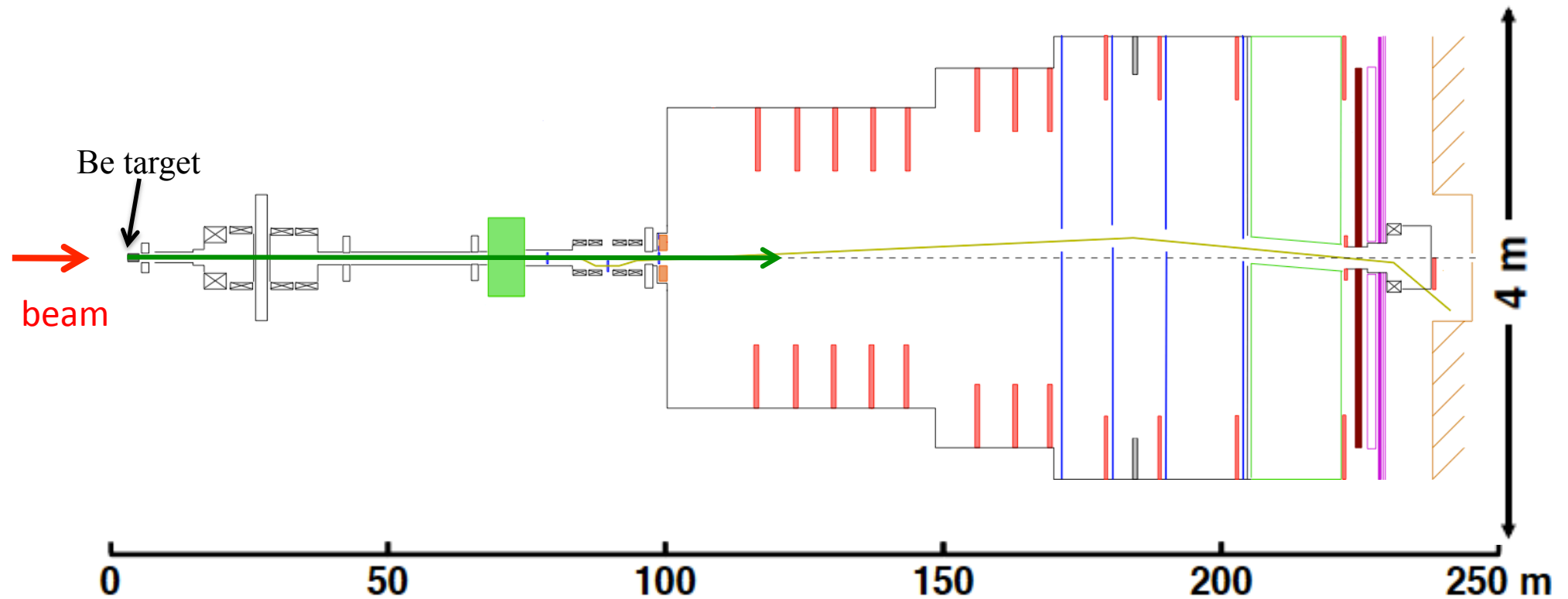
- NA62 is officially approved to run until LS2 with the main goal of measuring the $\text{BR}(\text{K}^+ \rightarrow \pi^+ \nu \text{ anti-}\nu)$ with 10% accuracy;
- **Before LS2 (2018)** many searches in the hidden sector will be performed using the kaon beam.
- **After LS2 (2020+)** there is a window of opportunity to run NA62 in beam-dump mode to search for hidden particles from charm and beauty decays and pave the way for next generation experiments (SHiP/LBNF).



The NA62 experiment in the ECN3 experimental hall



The NA62 experiment



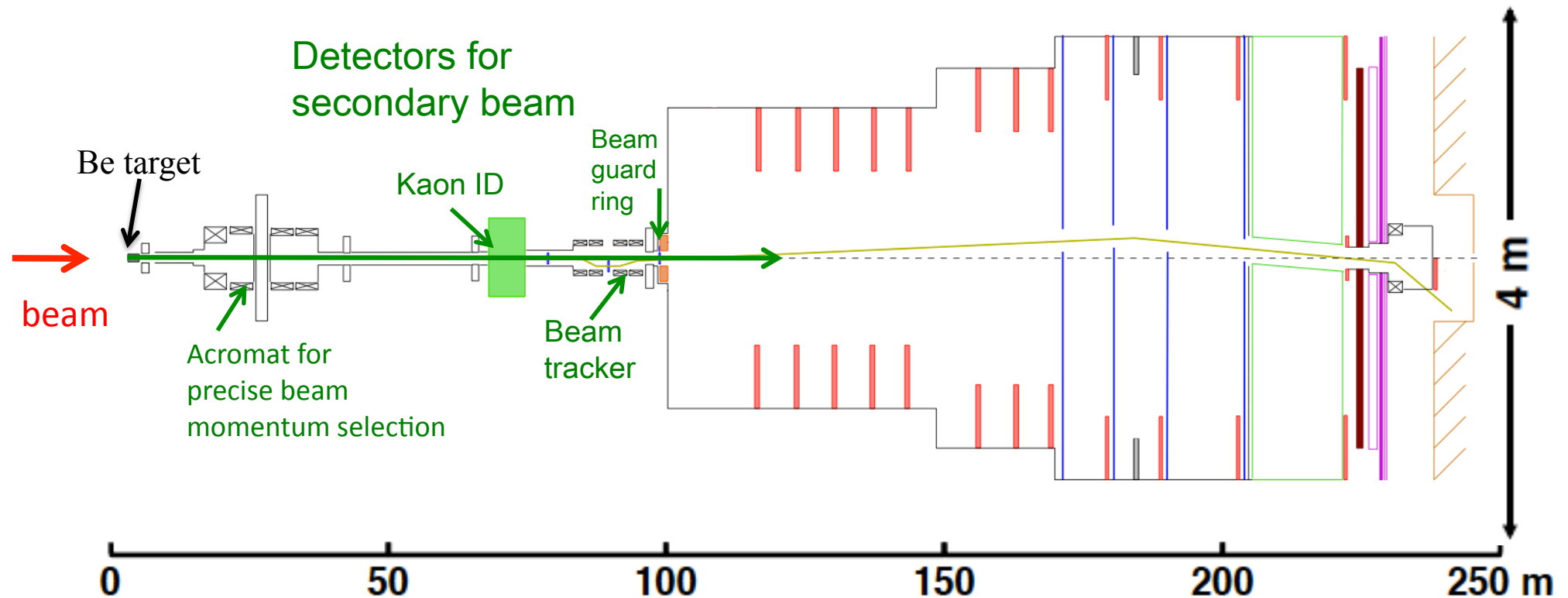
SPS protons

400 GeV/c

10^{12} p/sec

3.5 sec spill

The NA62 experiment

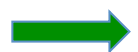


SPS protons

400 GeV/c

10^{12} p/sec

3.5 sec spill



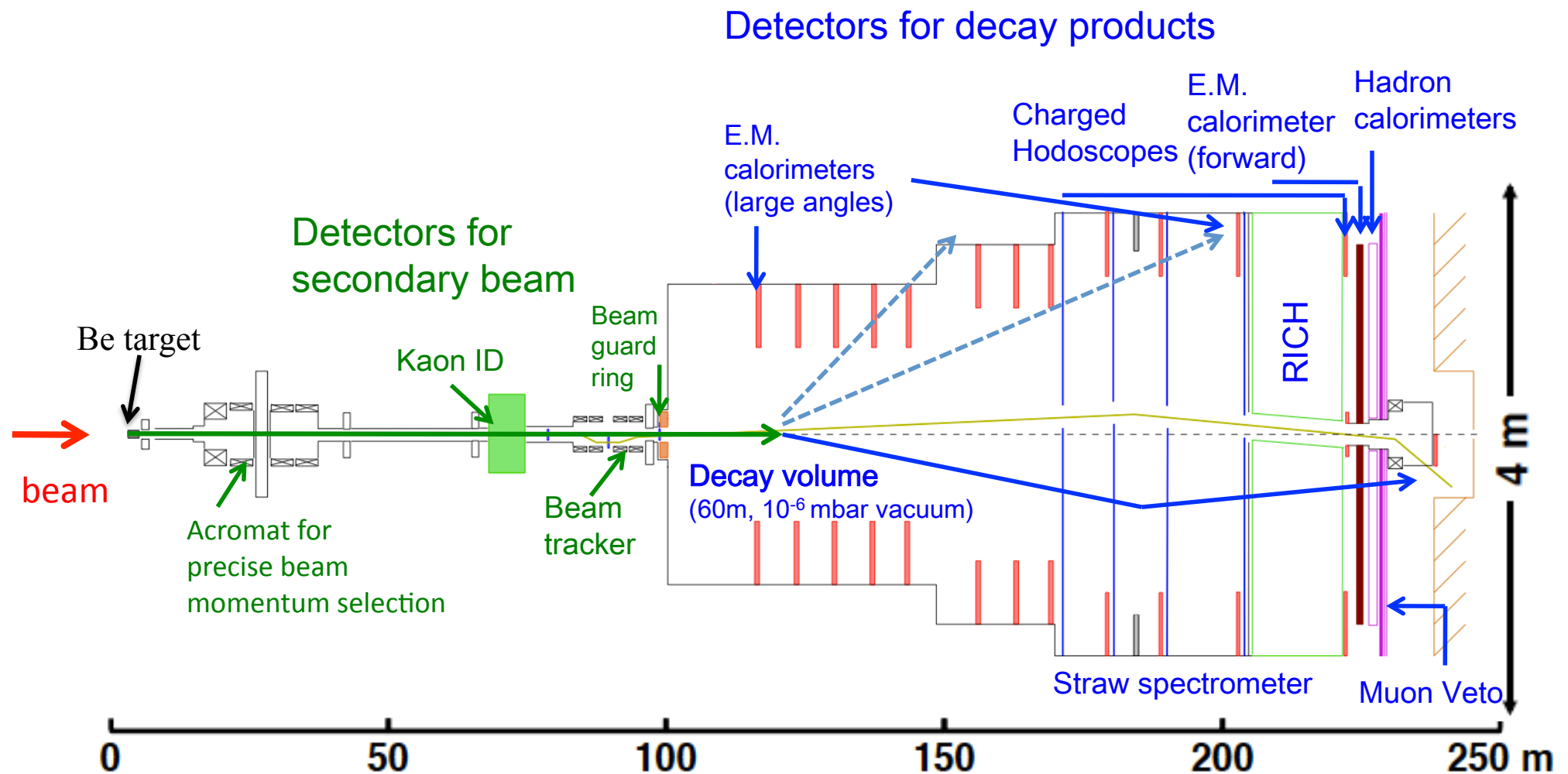
Secondary beam

K(6%), π (70%), p(23%)

Total rate: 750 MHz

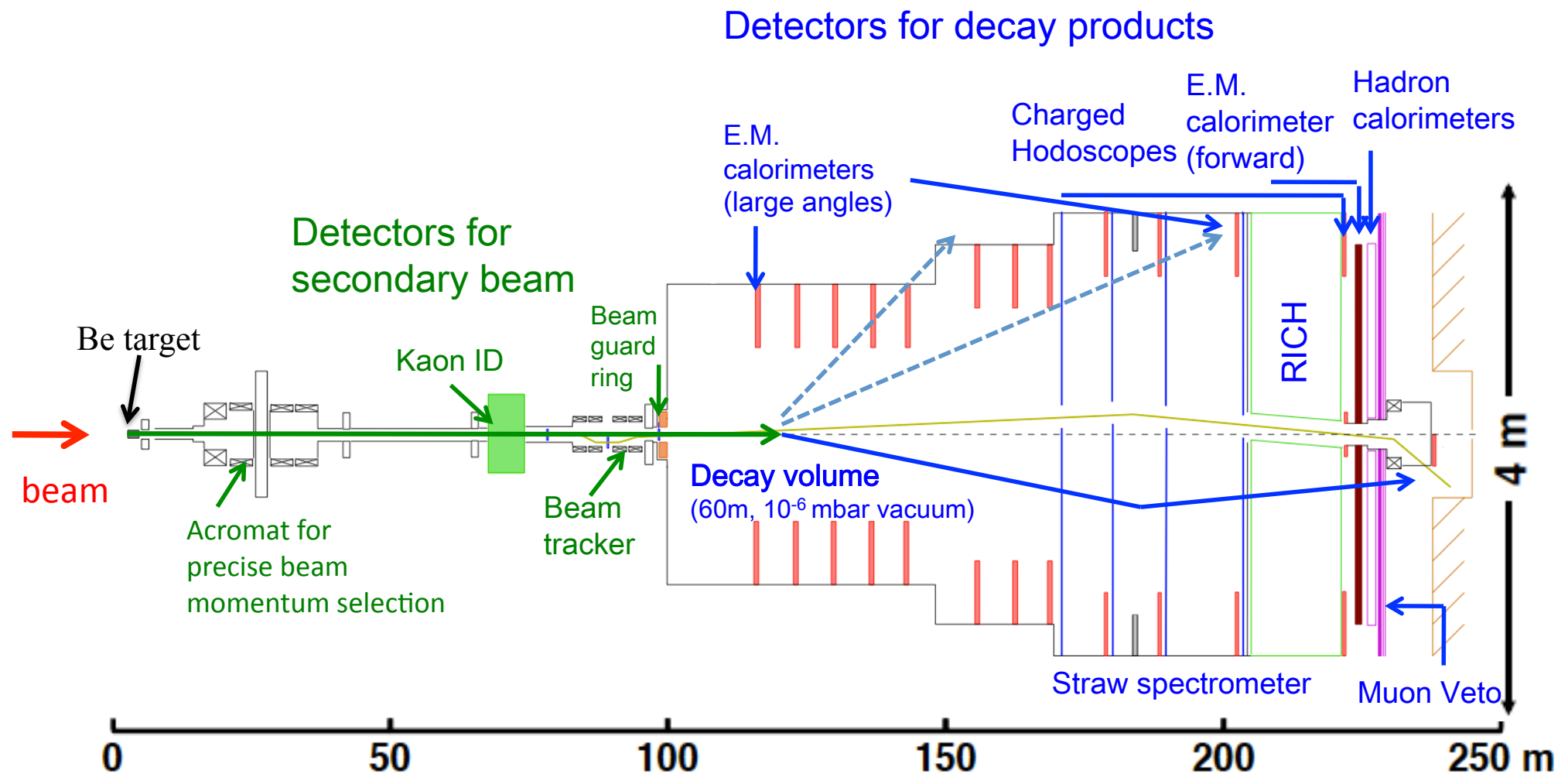
$\delta p/p \sim 1\%$

The NA62 experiment



SPS protons	Secondary beam	Kaon decays
400 GeV/c	K(6%), π (70%),p(23%)	~ 5 MHz
10^{12} p/sec	Total rate: 750 MHz	4.5×10^{12} /year
3.5 sec spill		

The NA62 experiment

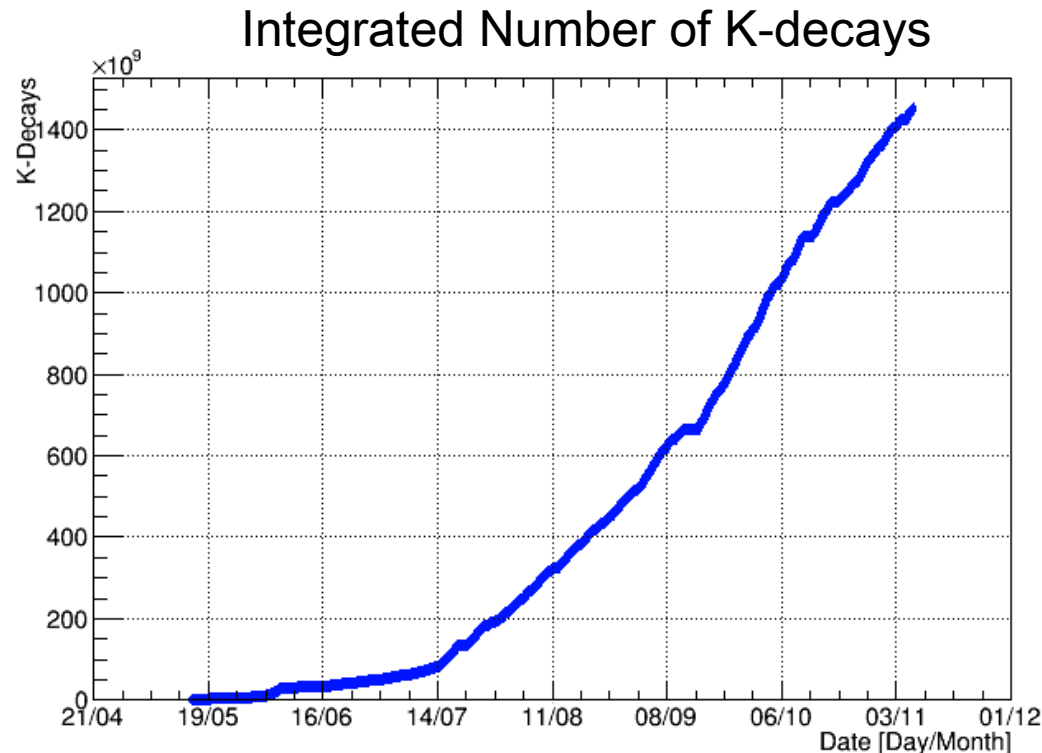


NA62 $\sim (1.0-2.0) \times 10^{18}$ pot/year @ 400 GeV/c

[10^{12} p/s $\times 2 \times 10^7$ sec (~ 200 days) $\times 20\%$ (duty cycle) $\times 50\%$ (SPS efficiency)]

SHiP: 4×10^{19} pot/year @ 400 GeV/c, LBNF: $\sim 10^{21}$ pot/year @ 120 GeV/c

NA62 Data Taking in 2016



Running consistently at about 40% of nominal intensity, hence 0.4×10^{12} pot/sec

→ limited by beam “structures” in the spill (e.g. 10-30 Hz, 50 Hz, etc.)

→ reached 5×10^{11} kaon decays/ month

Extrapolation to end of 2018:

→ 5×10^{11} decays/month $\times 12$ months = 6×10^{12} K-decays

With better beam and incremental improvements possible to reach the design goal of 10^{13} K decays before LS2, equivalent to $\mathcal{O}(100)$ signal events.

The “known” face of NA62...

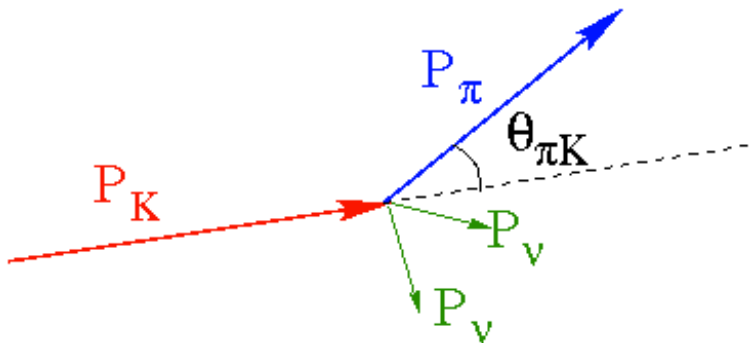


Kaon physics

NA62: from an “impossible” decay mode....

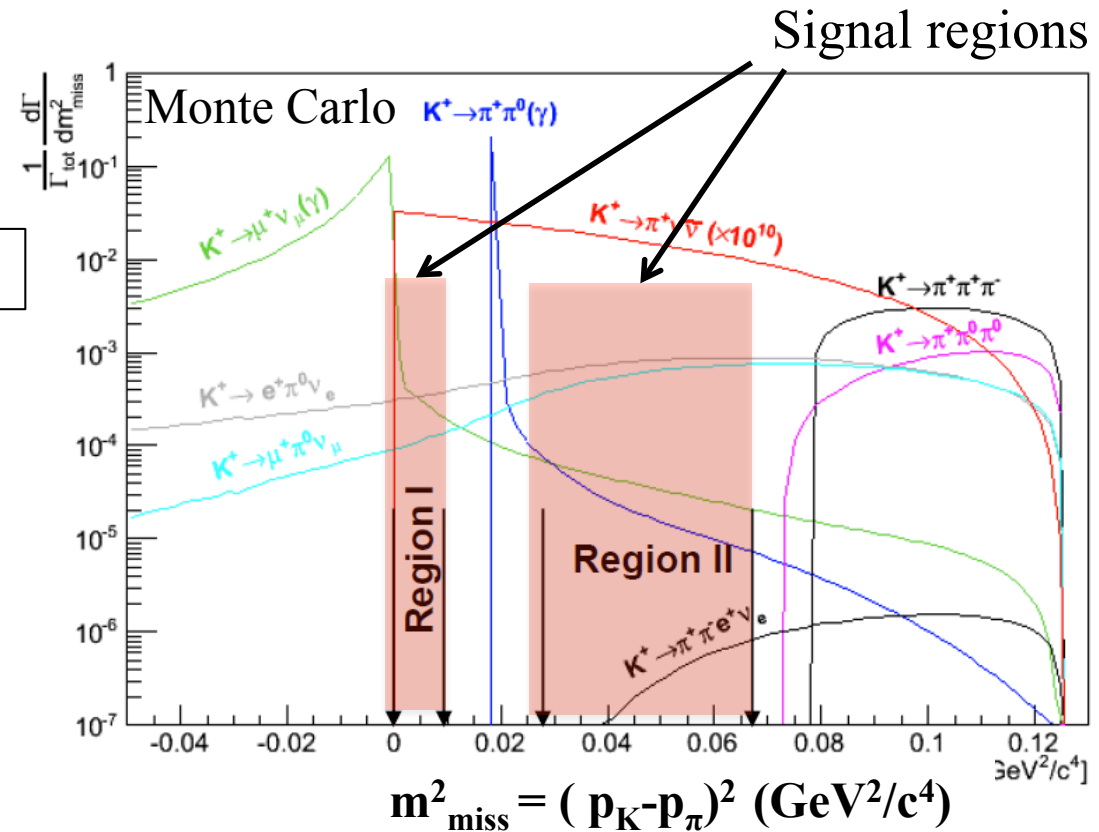
Signal:

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11}$$



Background:

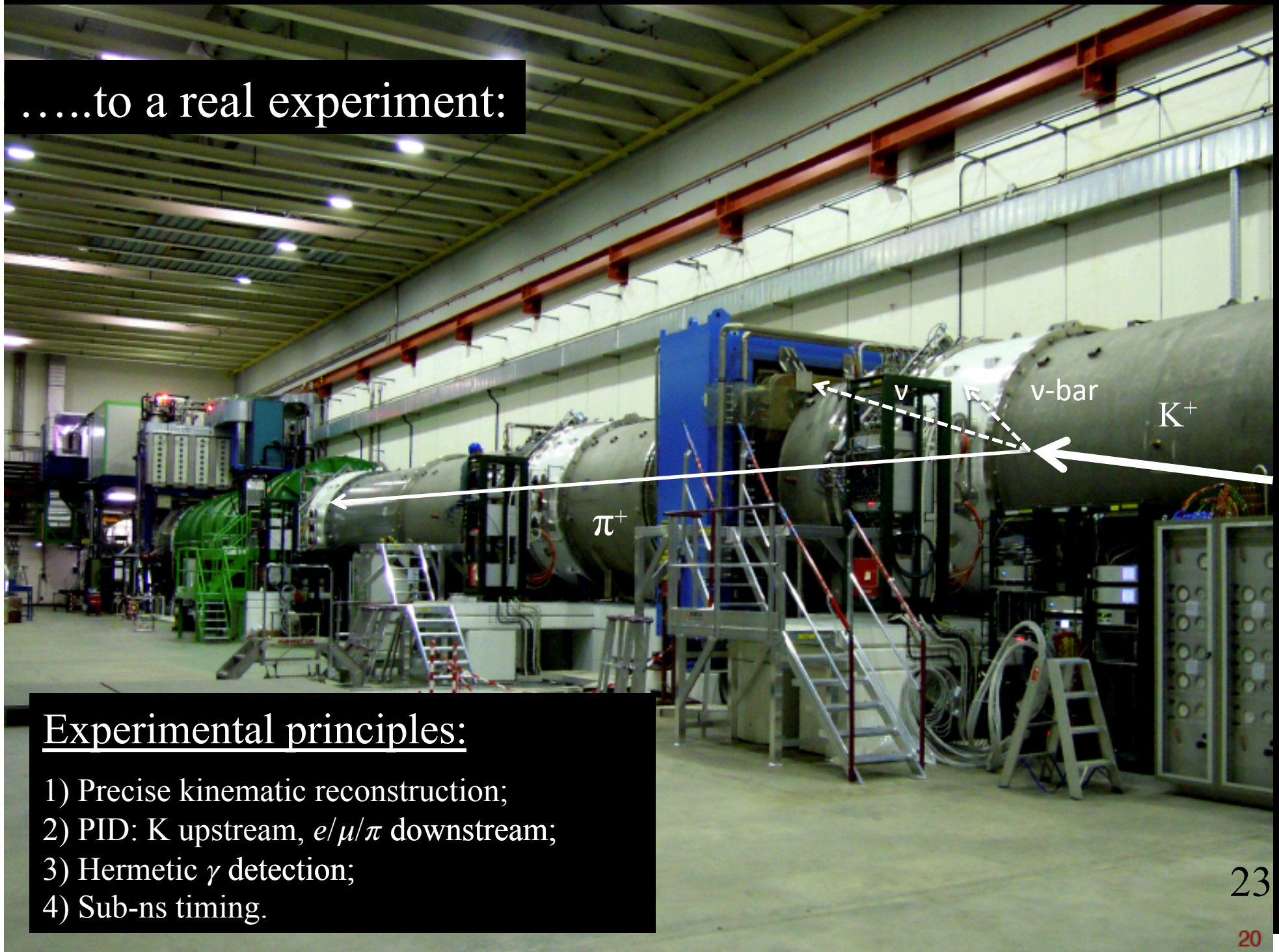
K^+ decays ($\sim 70\%$),
beam activity (30%)



Expected 45 SM signal events / year with < 10 background [$\sim 10^{-12}$ SES]

10^{12} background rejection, 10% signal acceptance

.....to a real experiment:



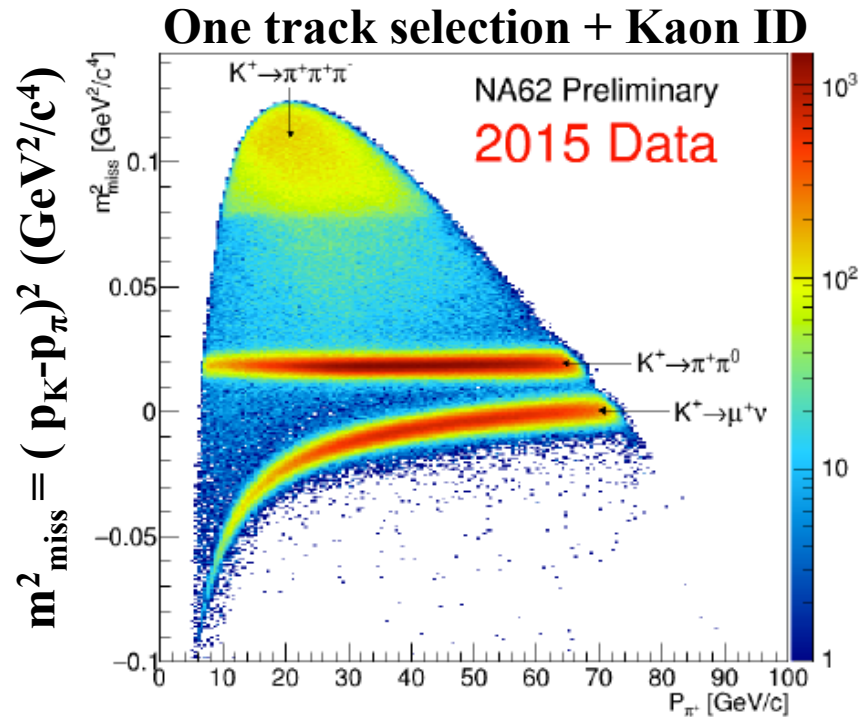
Experimental principles:

- 1) Precise kinematic reconstruction;
- 2) PID: K upstream, $e/\mu/\pi$ downstream;
- 3) Hermetic γ detection;
- 4) Sub-ns timing.

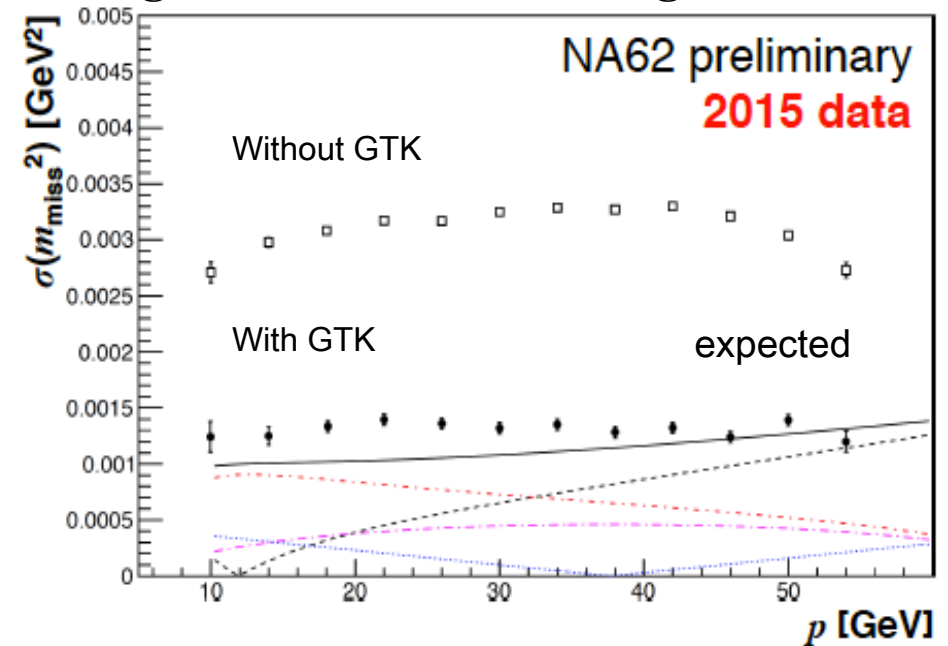
1) Precise kinematic reconstruction

24

Goal: 10^4 - 10^5 rejection for 2-body decays



Missing mass resolution for single-track event



Excellent mass resolution:

- ~ 15 - 20 MeV missing mass resolution (from $K^+ \rightarrow \pi^+ \pi^0$ events)
- ~ 1.5 MeV for $K_S \rightarrow \pi^+ \pi^-$, < 1 MeV for $\Lambda \rightarrow p \pi^-$

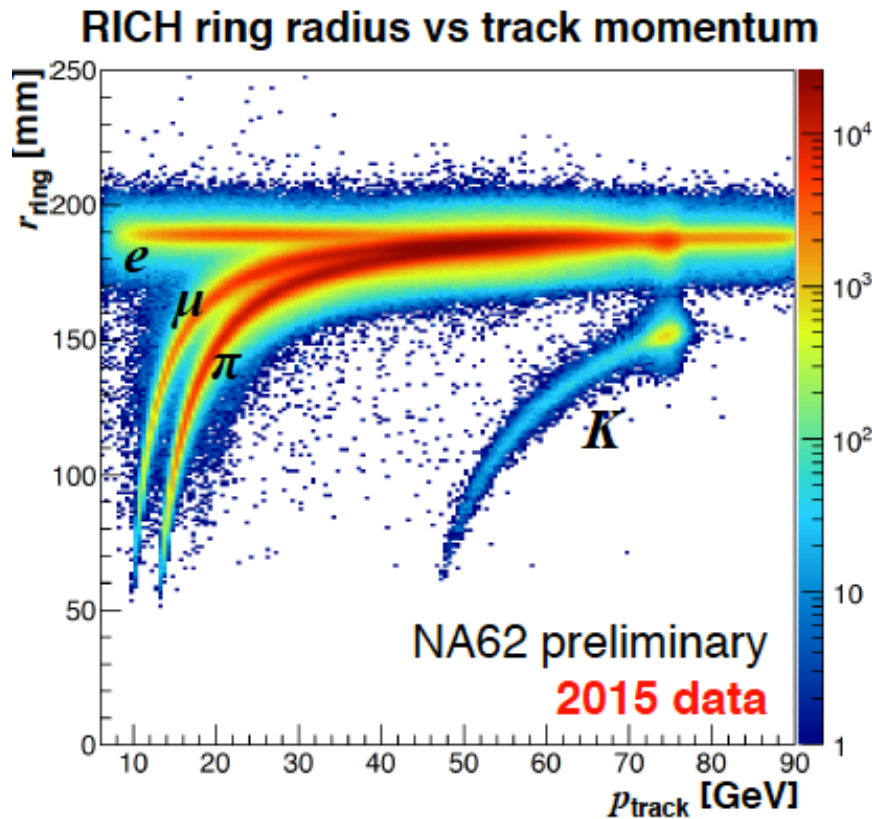
But also (for free) excellent vertex and IP resolutions:

- ~ 1 - 2 cm vertex resolution for 2-track vertices over 60 m long decay volume
- \sim few cm IP resolution with respect to the target

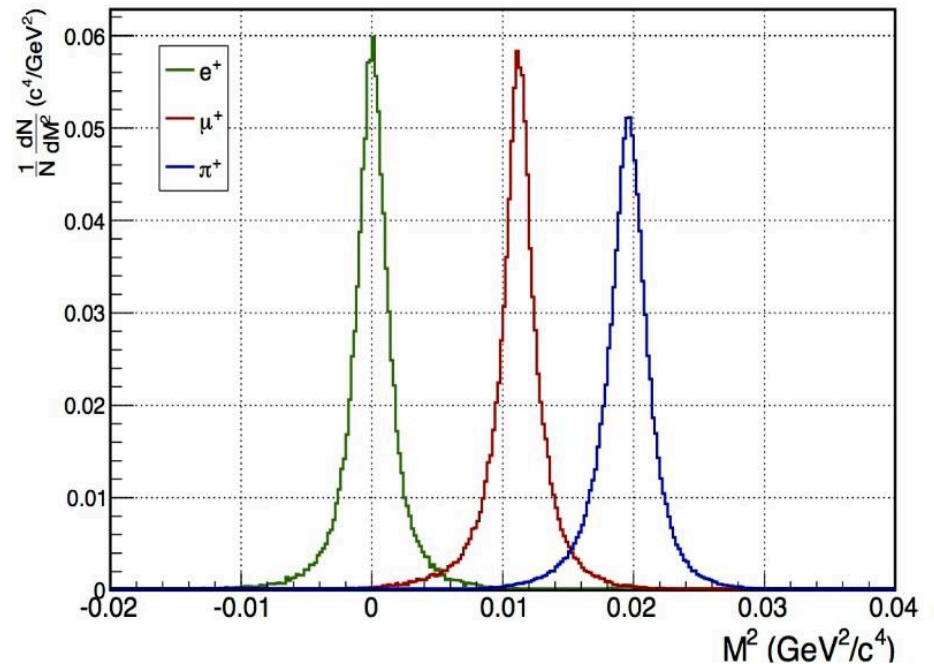
Crucial features for Hidden sector searches with fully reconstructed final states

2) Charged Particle Identification

Goal: 10^7 μ/π separation, mainly for rejection of $K_{\mu 2}$



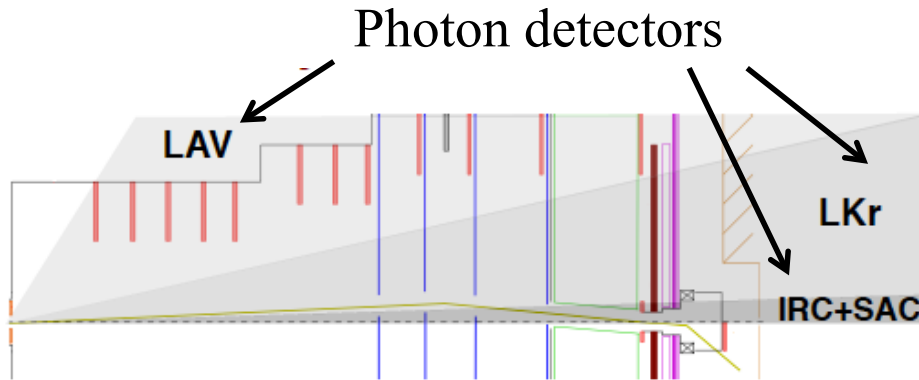
Separation $e/\mu/\pi$ with $15 < p < 35$ GeV/c



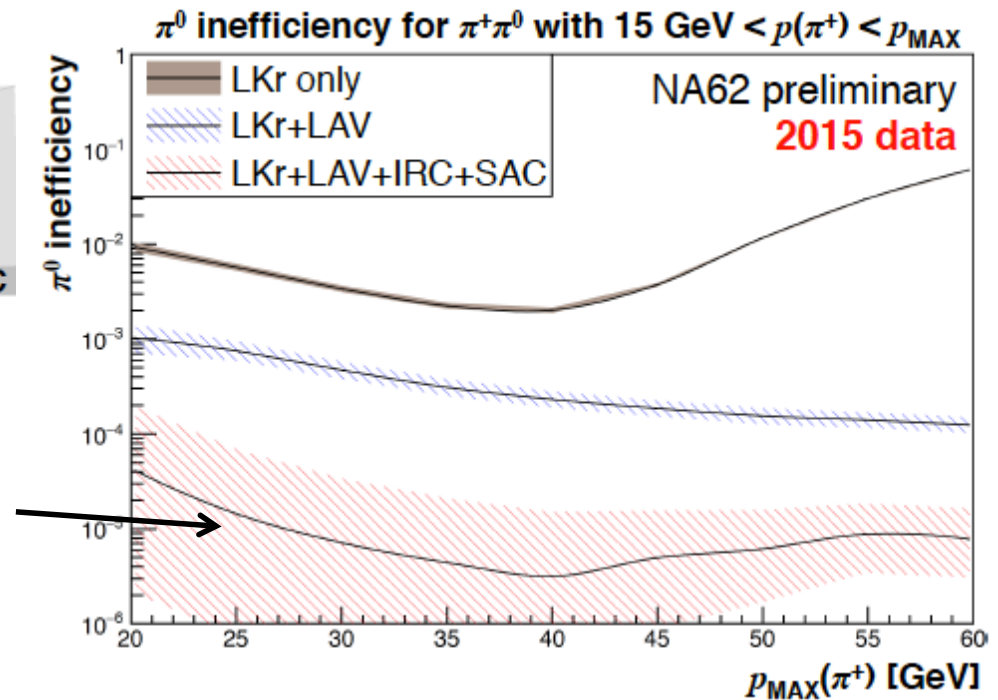
Hidden sector: excellent PID for all possible hidden sector final states
(10^7 μ/π separation important for rejection of the muon halo)

3) Hermetic γ detection

Goal: 10^8 rejection of $\pi^0 \rightarrow \gamma\gamma$, from $K \rightarrow \pi^+ \pi^0$



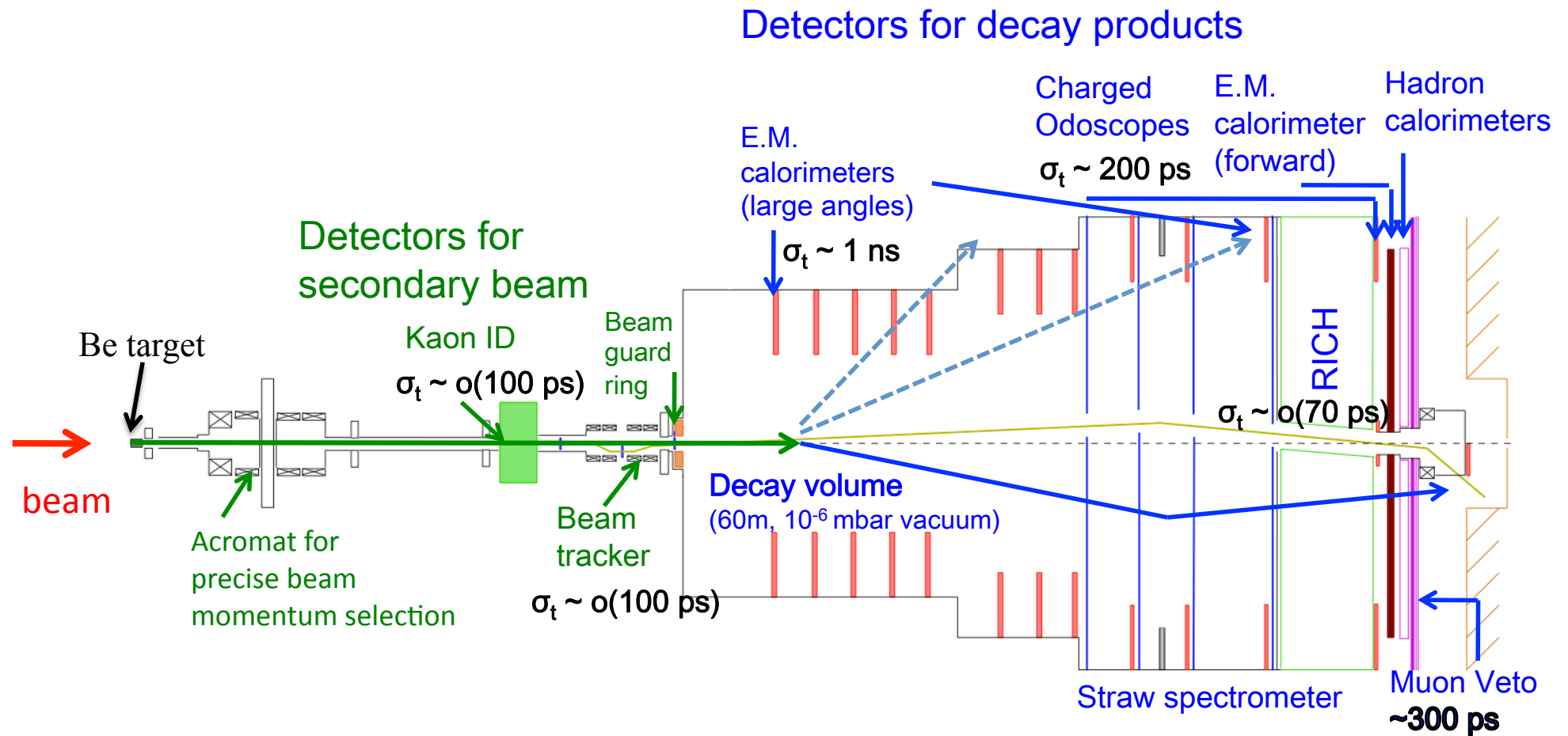
$O(10^6)$ rejection obtained in 2015
(measurement with minimum bias data
limited by statistics)



Hidden sector:

perfectly suited to study $A' \rightarrow$ invisible mode from $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow \gamma A'$

4) Sub-ns timing:



Hidden sector:

Important to reject combinatorial background from muon or neutrino halos 27
which is spread along the spill length (3.3 s)

The “double” face of NA62

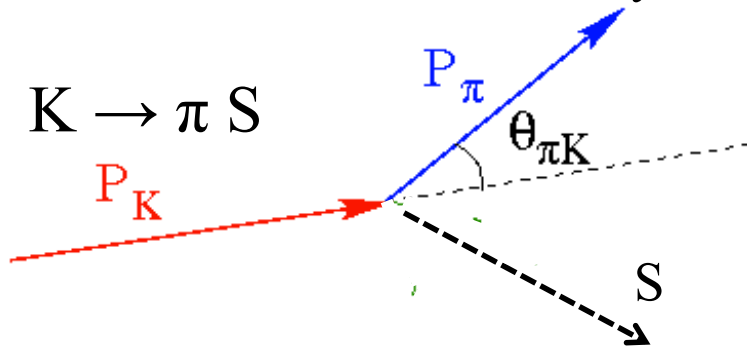


Kaon physics

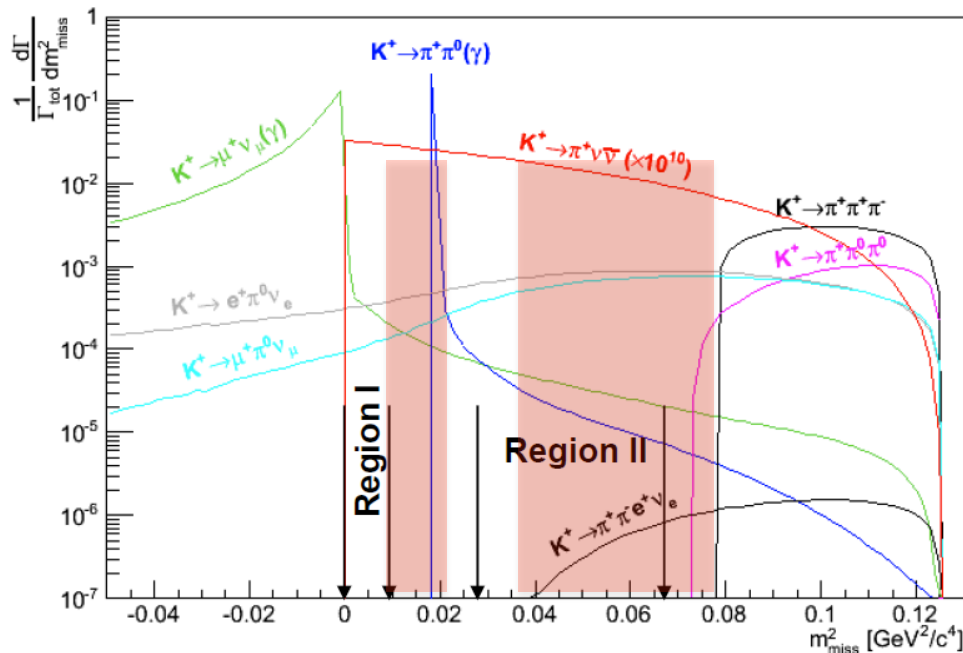
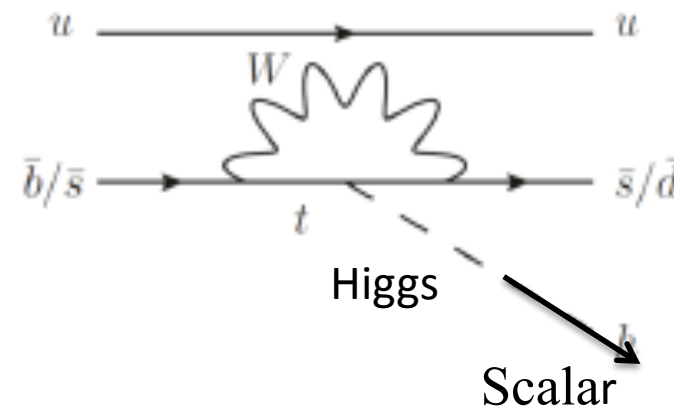
Hidden Sector physics
(in beam mode)

NA62 Sensitivity to Dark Scalars in Kaon decays

Dark Scalars in Kaon decays:



Relevant diagram:



“Simple” by-product of the $K \rightarrow \pi \nu \bar{\nu}$ analysis:

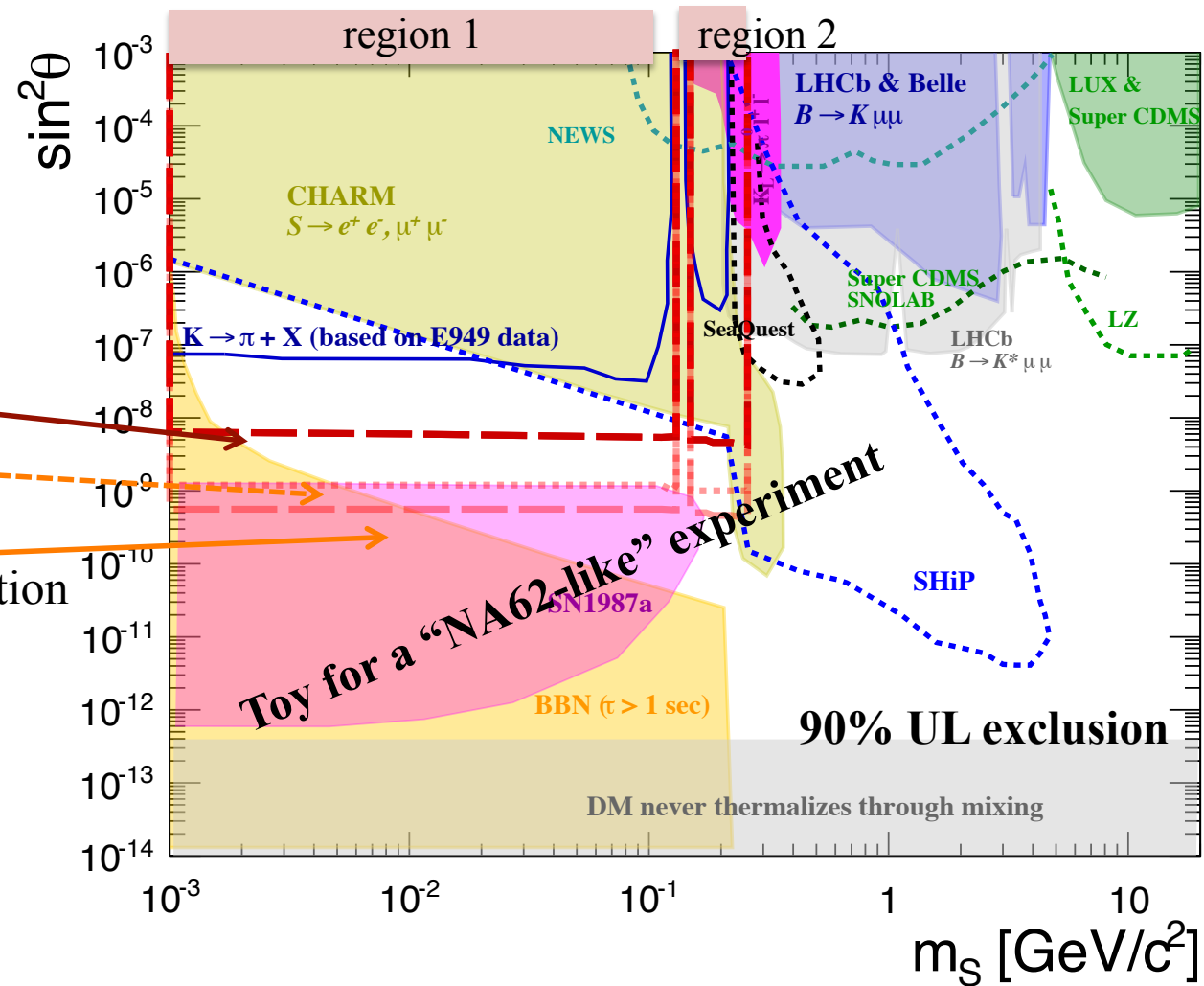
- search for bumps in region 1&2, where background is (will be) under control
- main background will be the $K \rightarrow \pi \nu \bar{\nu}$ signal itself (!).

NA62 Sensitivity to Dark Scalars in Kaon decays

Toy for a “NA62-like” experiment:

- $\sim 10^{12}$ K^+ decays, 0 bkg
- $\sim 10^{13}$ K^+ decays, 200 bkg
- $\sim 10^{13}$ K^+ decays, 0 bkg

Acceptance, trigger and selection efficiencies included.
Limit improves linearly with $N(K^+)$



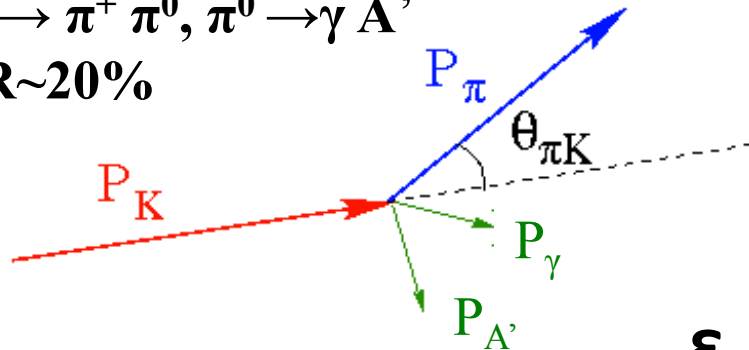
NA62 can fill the gap between E949 and SN1987 before LS2 (2019)

NA62 Sensitivity for Dark Photons to invisible final states

Use the decay

$$K \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \gamma A'$$

BR~20%



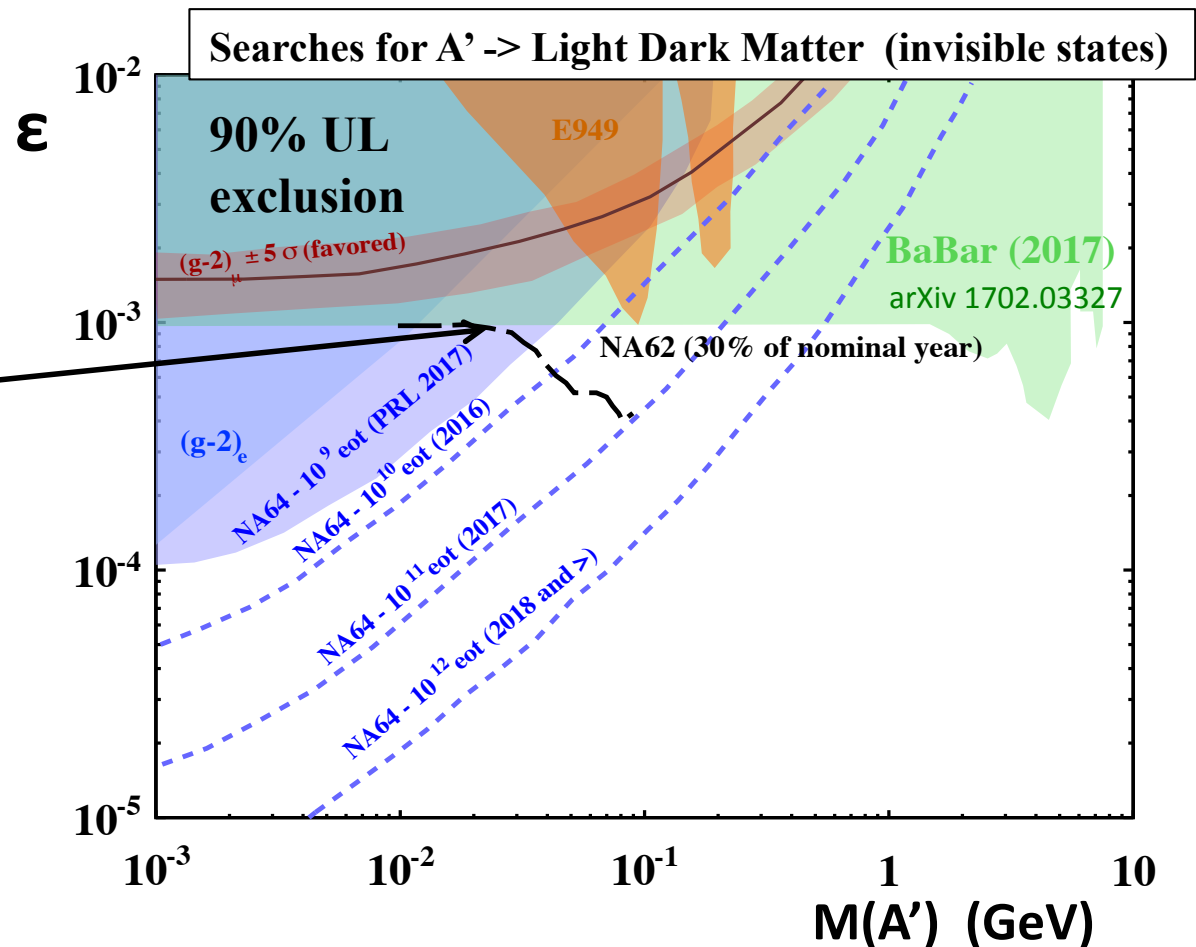
By-product of the study of the

$$K^+ \rightarrow \pi^+ \pi^0 \text{ background for } K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

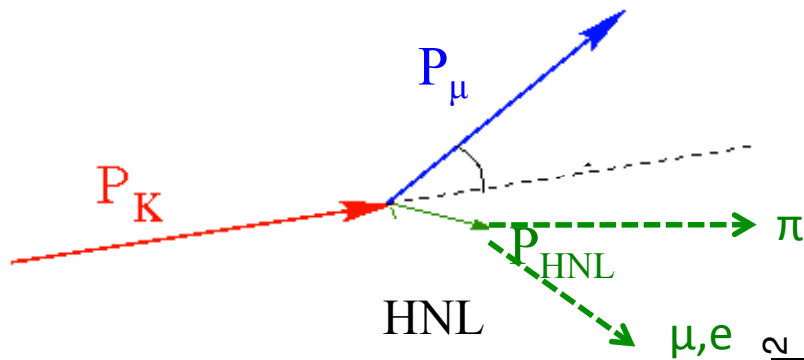
- Reconstruct K^+ , π^+ , one photon
- Constrain A' using the π^0 mass

Limit improves linearly with $N(K^+)$

Improve over NA64 result
with 100k spills (~30% of a
nominal year)



Sensitivity to Heavy Neutral Leptons from Kaon decays



Use $K^+ \rightarrow \mu^+ \nu$ (BR~64%),

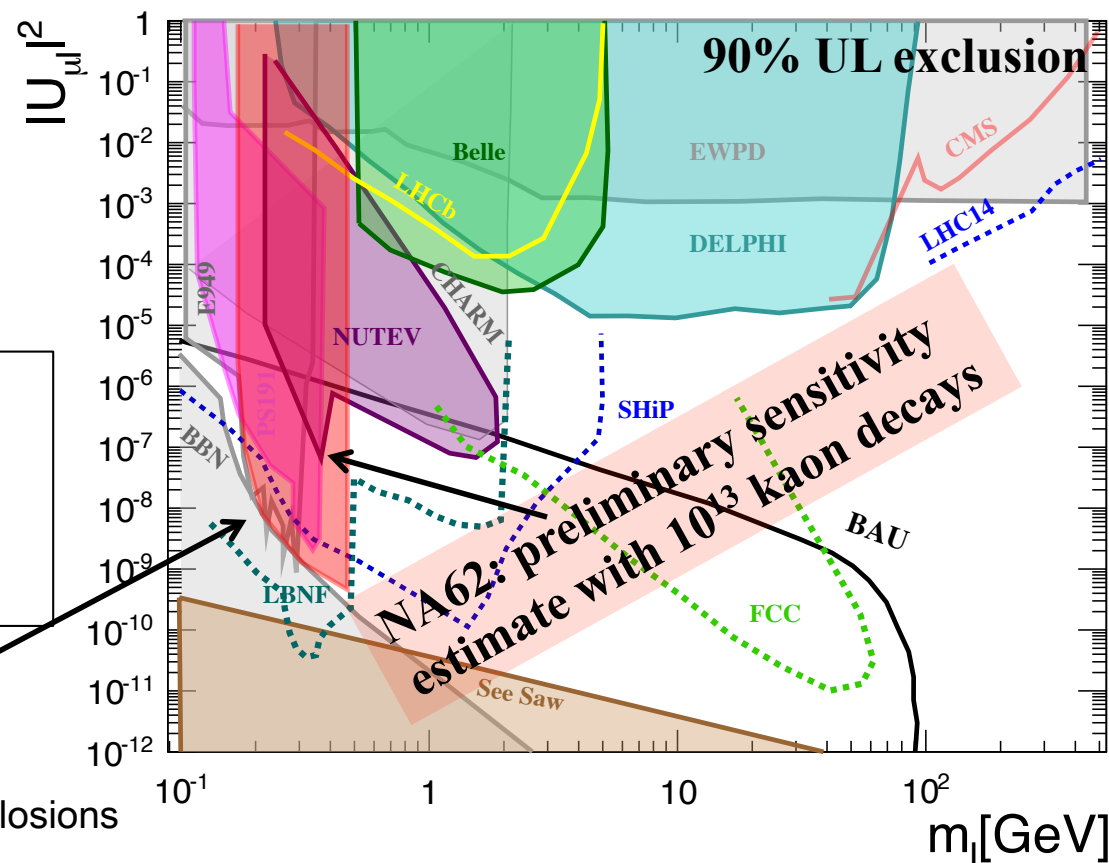
$\nu_\mu \rightarrow N, N \rightarrow \pi\mu, \pi e$

- 3-tracks final state

- 2-track displaced vertex

-Limit improves with $\sqrt{N(K^+)}$

Expect to improve the world best limit below the kaon mass with 10^{13} kaon decays (2018) and go beyond the BBN limit.



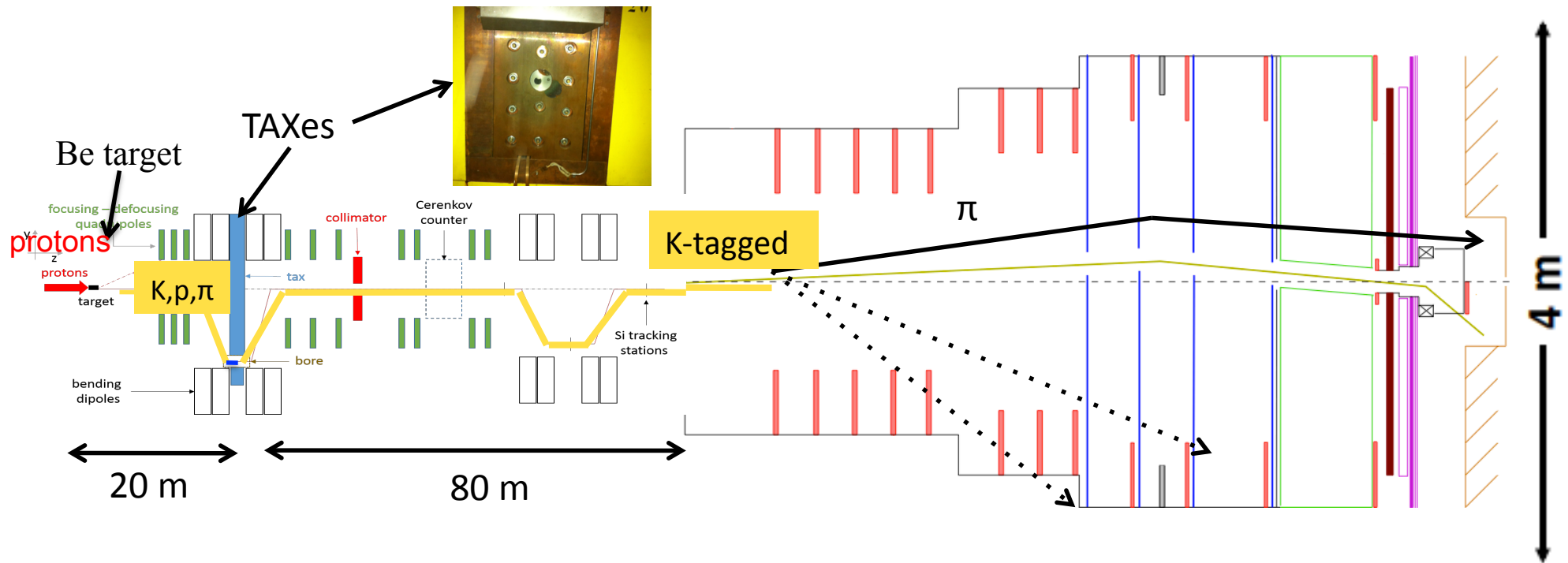
See A. Kusenko's talk last Wednesday
Heavy sterile neutrinos and supernova explosions
Physics Letters B 670 (2009) 281–284

The “hidden” face of NA62



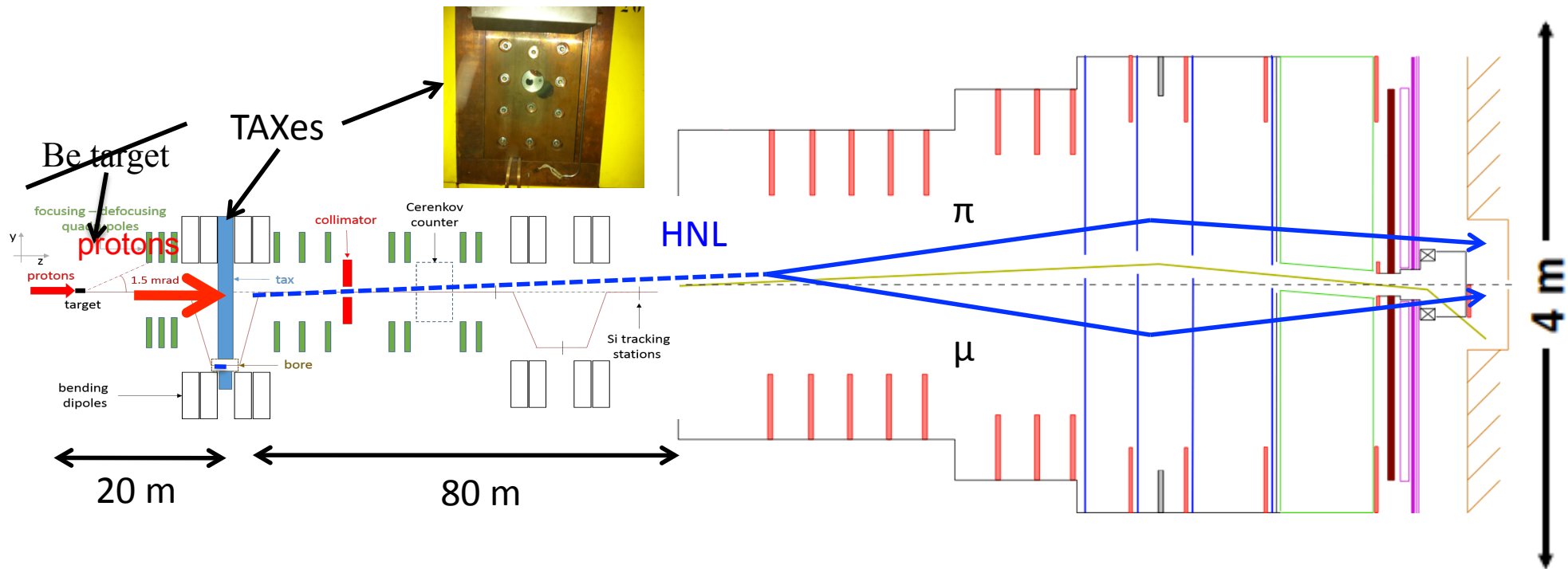
Hidden Sector physics
(in dump mode)

NA62-DUMP: NA62 operated in DUMP-mode



The NA62 target is followed 20-m downstream by 1.6-m long, water-cooled, copper collimators, 'Target Attenuator eXperimental areas' (TAXes) offering a choice of bores of different apertures for momentum selection.

NA62-DUMP: NA62 operated in DUMP-mode

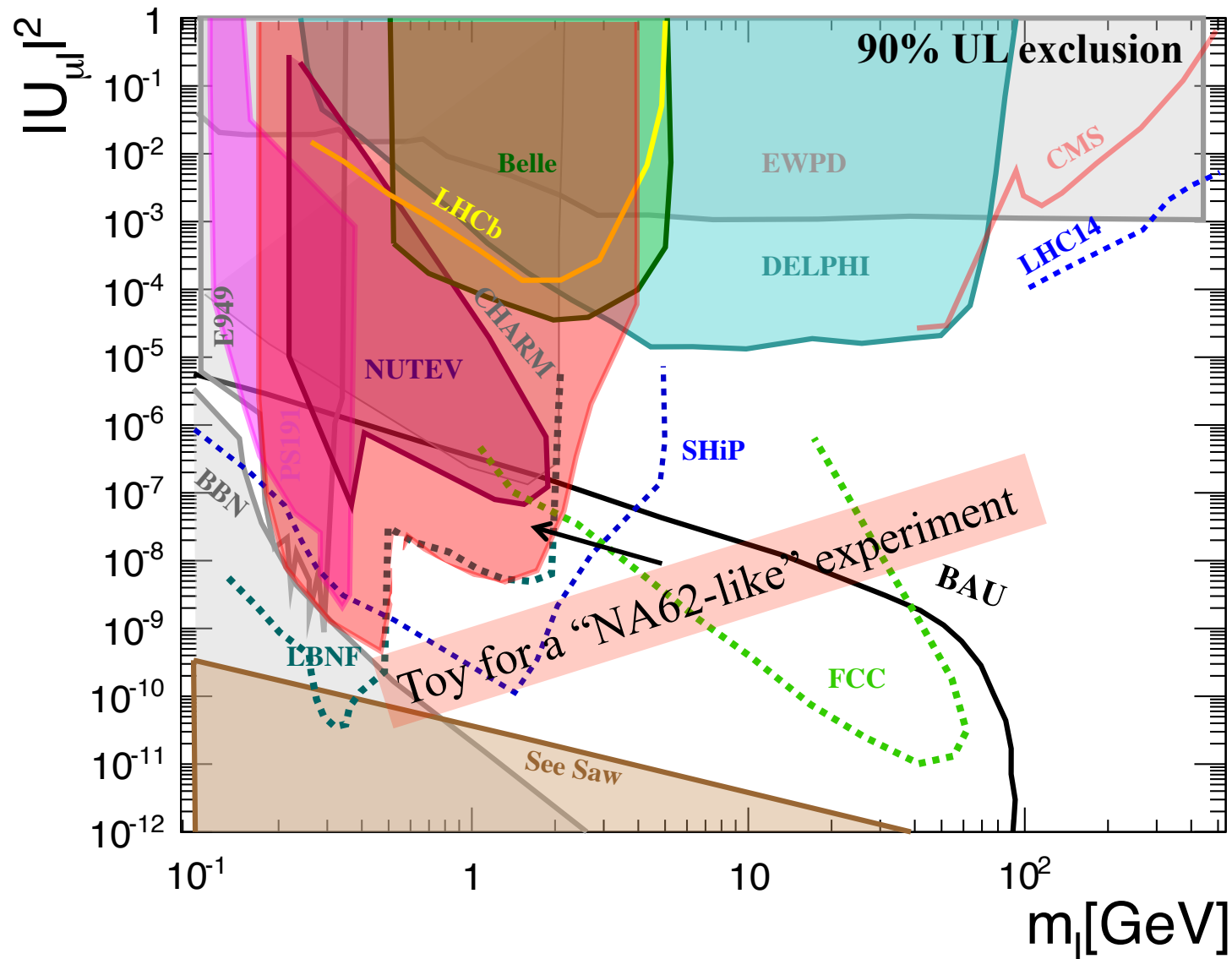


In dump mode the target can be moved away from the beam and the beam let impinging on the copper. **The TAXes can act as a dump ($10.7 \lambda_I$).**

Heavy Neutral Leptons, Dark Photons, and Dark scalars can be originated by charm, beauty and photons produced in the interaction of protons with the dump.

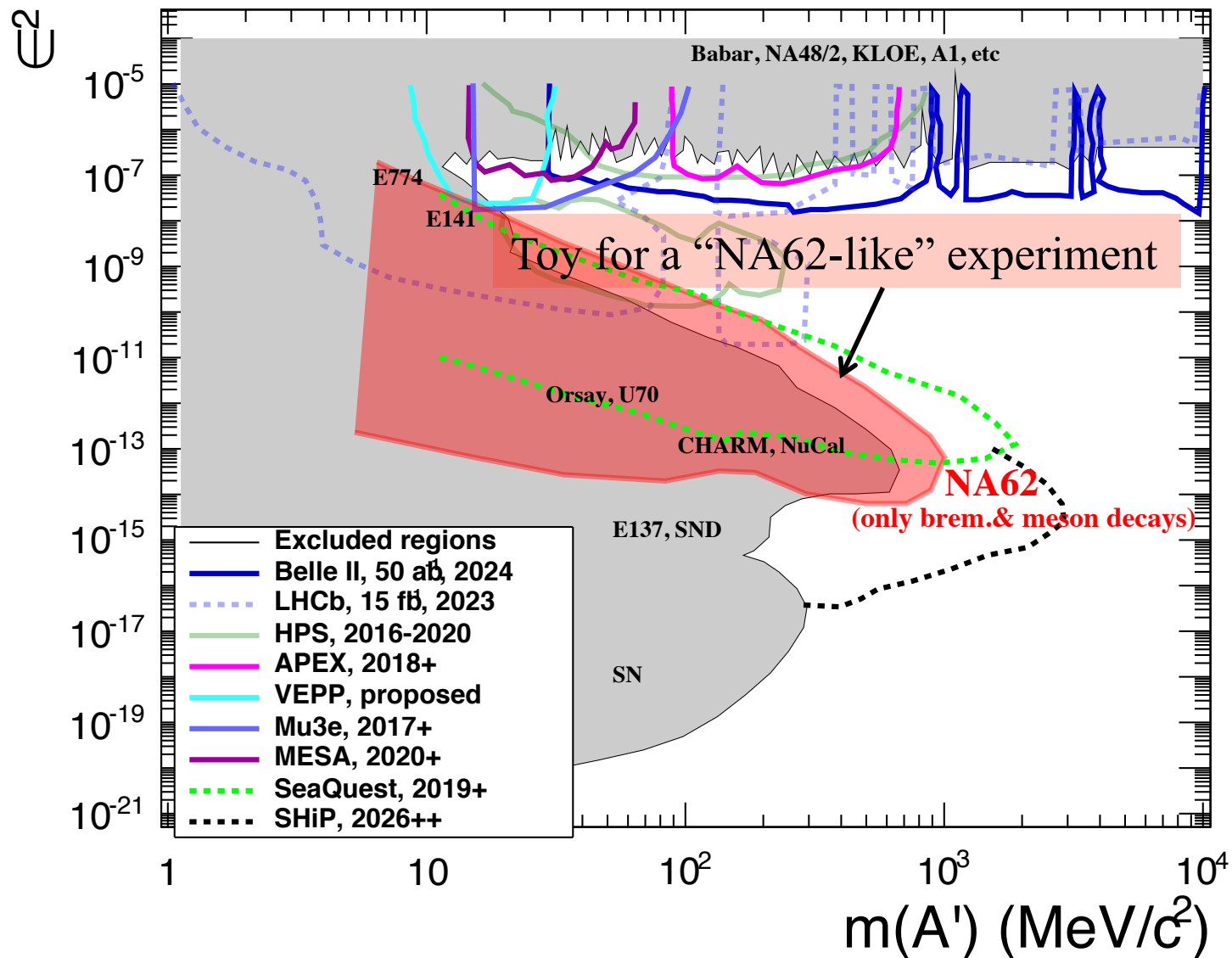
PS: already in beam mode $\sim 40\%$ of protons do not interact with the target and are dumped onto the TAXes....

Sensitivity for HNL in dump mode



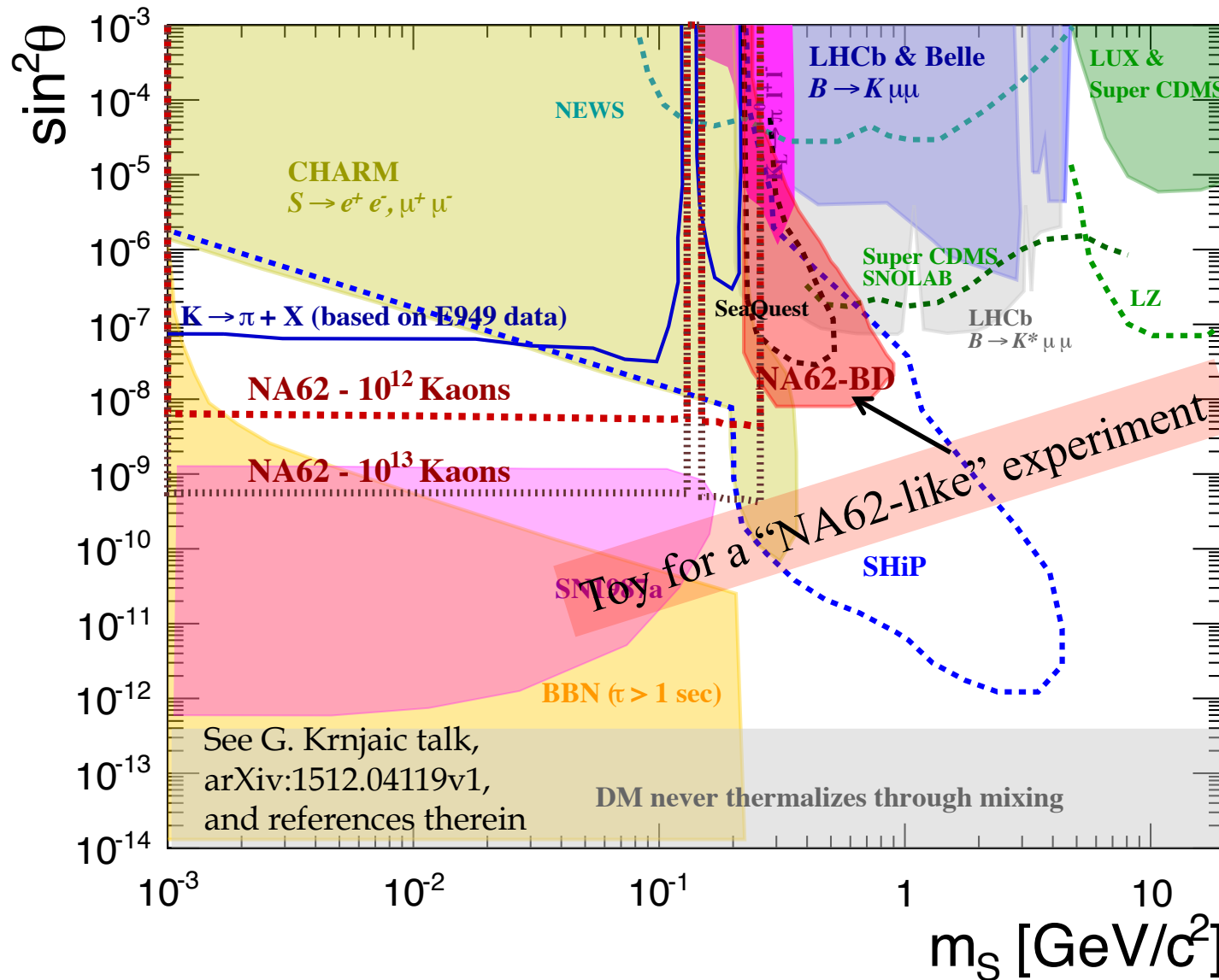
Assume: 2×10^{18} pot, $\text{HNL} \rightarrow \pi\mu/\pi e$ decays,
trigger/acceptance/selection efficiencies, zero background

Sensitivity for Dark Photons in dump mode



Assume: 2×10^{18} pot, $A' \rightarrow \mu\mu$ decays,
trigger/acceptance/selection efficiencies, zero background

Sensitivity for Dark Scalars in dump mode

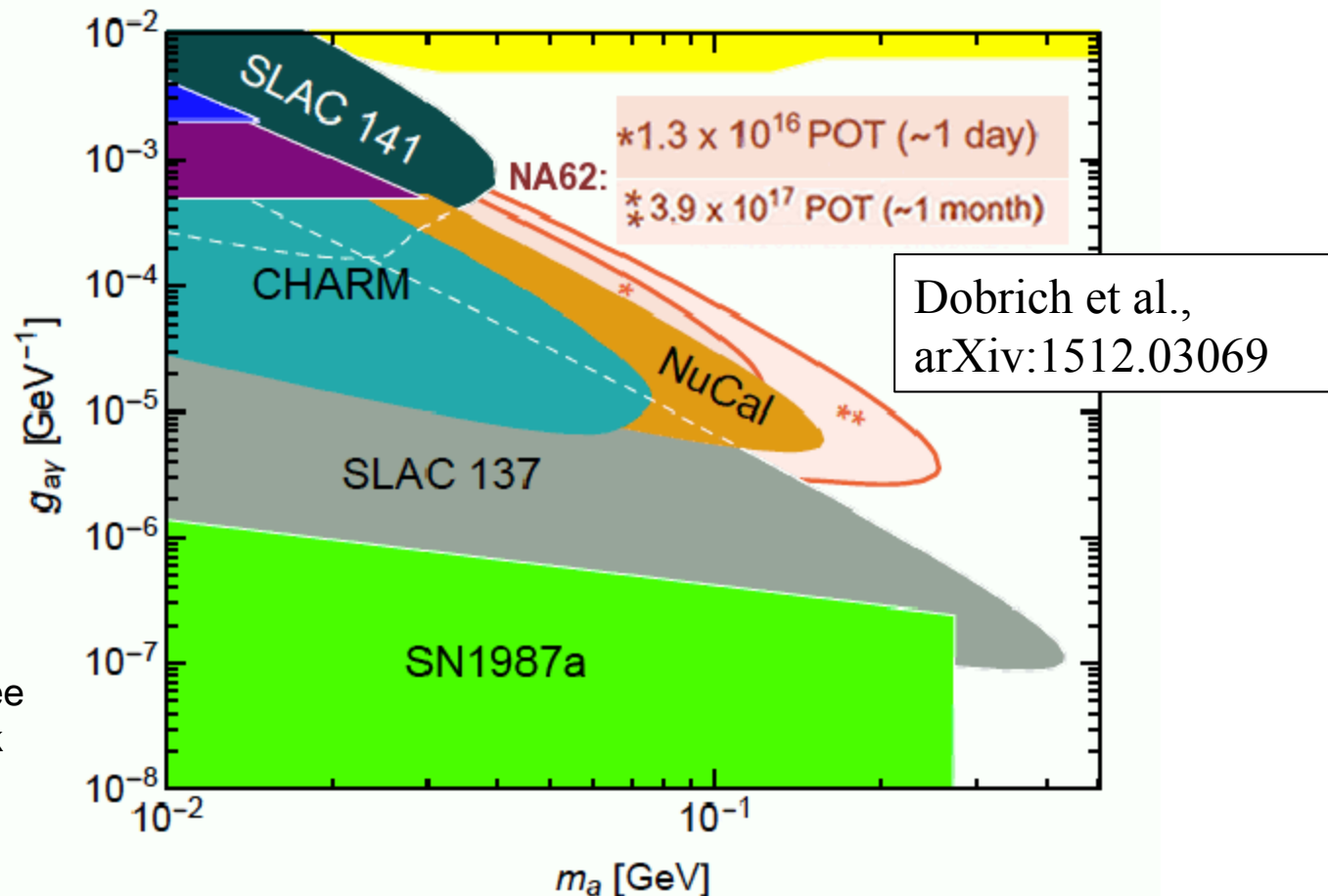


Assume: 2×10^{18} pot, $S \rightarrow \mu \mu$ decay, trigger/acceptance/selection efficiencies.
Assume zero background (see later).

NA62 Sensitivity for ALPs $\rightarrow \gamma\gamma$ in dump mode

Assume $1.3 \cdot 10^{16}$ ($3.9 \cdot 10^{17}$) pot corresponding to 1 day (1 month) of data taking.

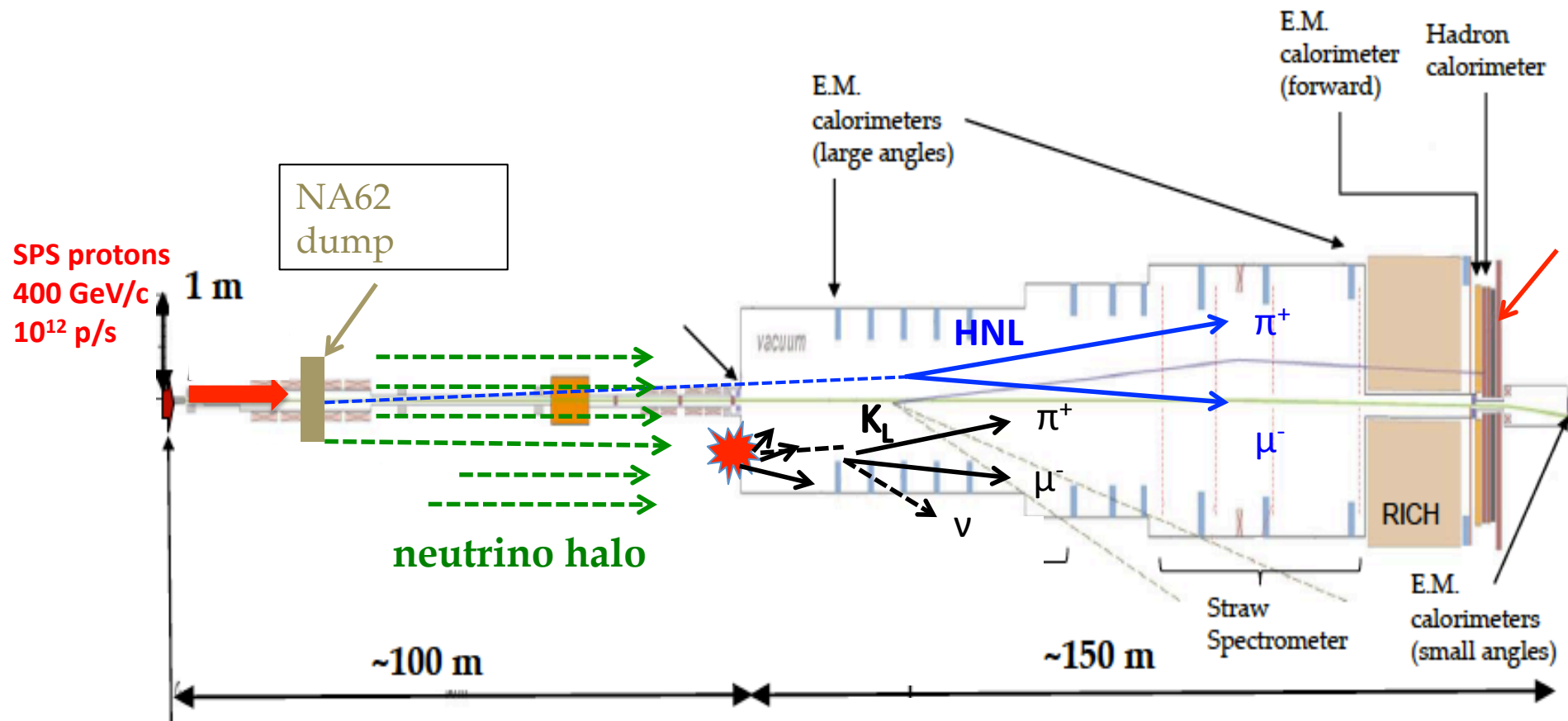
- study ALP production via Primakoff effect (JHEP 1602 (2016) 018) at target;
- search for $\text{ALP} \rightarrow \gamma\gamma$ in NA62 fiducial volume, account for geometrical acceptance
- assume zero-background, evaluate expected 90%-CL exclusion plot





.....About the zero background approximation.....

Main Backgrounds for NA62 in dump mode

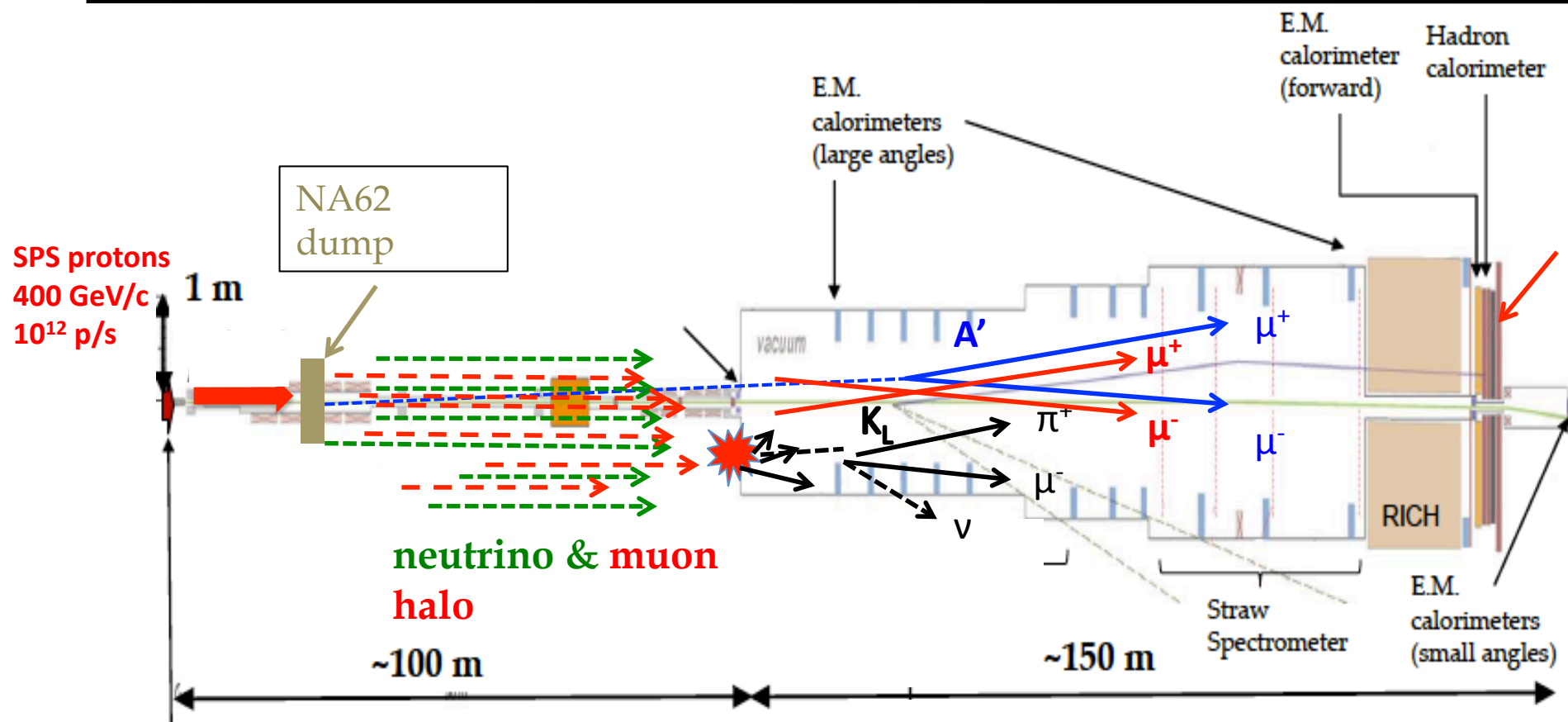


Neutrino halo:

~ 10 GHz of active neutrinos from the dump are expected in nominal conditions which can make inelastic interactions in the material of the decay vessel creating V^0 s and other tracks that can mimic signal signature.

--- In general this background does not point to the target.

Main Backgrounds for NA62 in dump mode



Muon halo:

- In *beam mode* about ~ 5 MHz of μ^+ and 150 kHz μ^- are expected due to early decays in flight of K and π in the beam;
- **In *dump mode*, the muon halos is reduced by 2 orders of magnitude (2016 data).**
- Muons can produce inelastic interactions and combinatorial background.
- An upstream veto (currently missing in the setup) could reduce further this background by about 3-4 orders of magnitude. Additional handle: timing with muon PID system

Facing the background with real data: di-muon bkg

Assume the worse case:

1) Search for $A' \rightarrow \mu^+ \mu^-$, main background: muon halo

→ In presence of the beam (100x muon halo in dump mode)

→ Without an upstream veto

2) Use 10^{15} pot from 2016 dataset (<0.1% of a nominal year)

3) Exploit the performance of the current setup:

→ precise kinematic reconstruction, highly efficient veto systems, sub-ns timing;

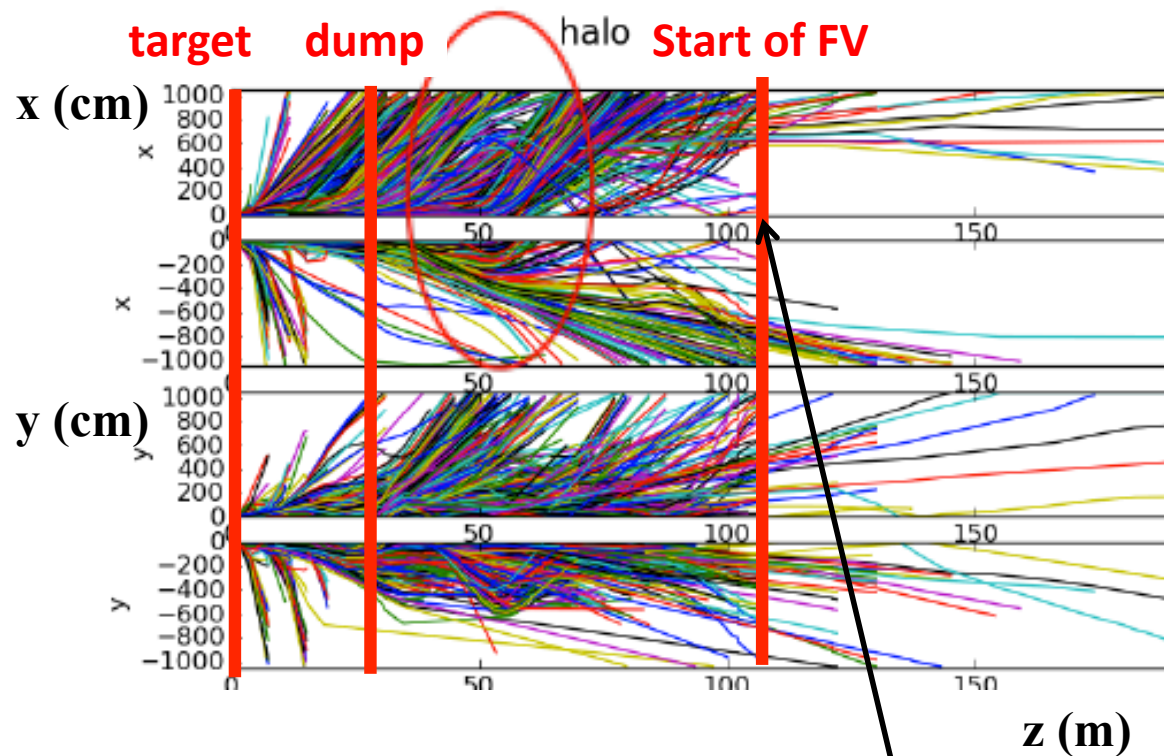
→ require two muon tracks of opposite charge, in the acceptance of the apparatus, forming a vertex in the fiducial volume, in time each other and no other activity in the veto systems.

Simulation of the muon halo from Kaon Decays

In *beam mode* about ~ 5 MHz of μ^+ and 150 kHz μ^- are expected due to early decays in flight of K and π in the beam;

A reduction of 2 orders of magnitude has been measured with 1 day data in dump mode

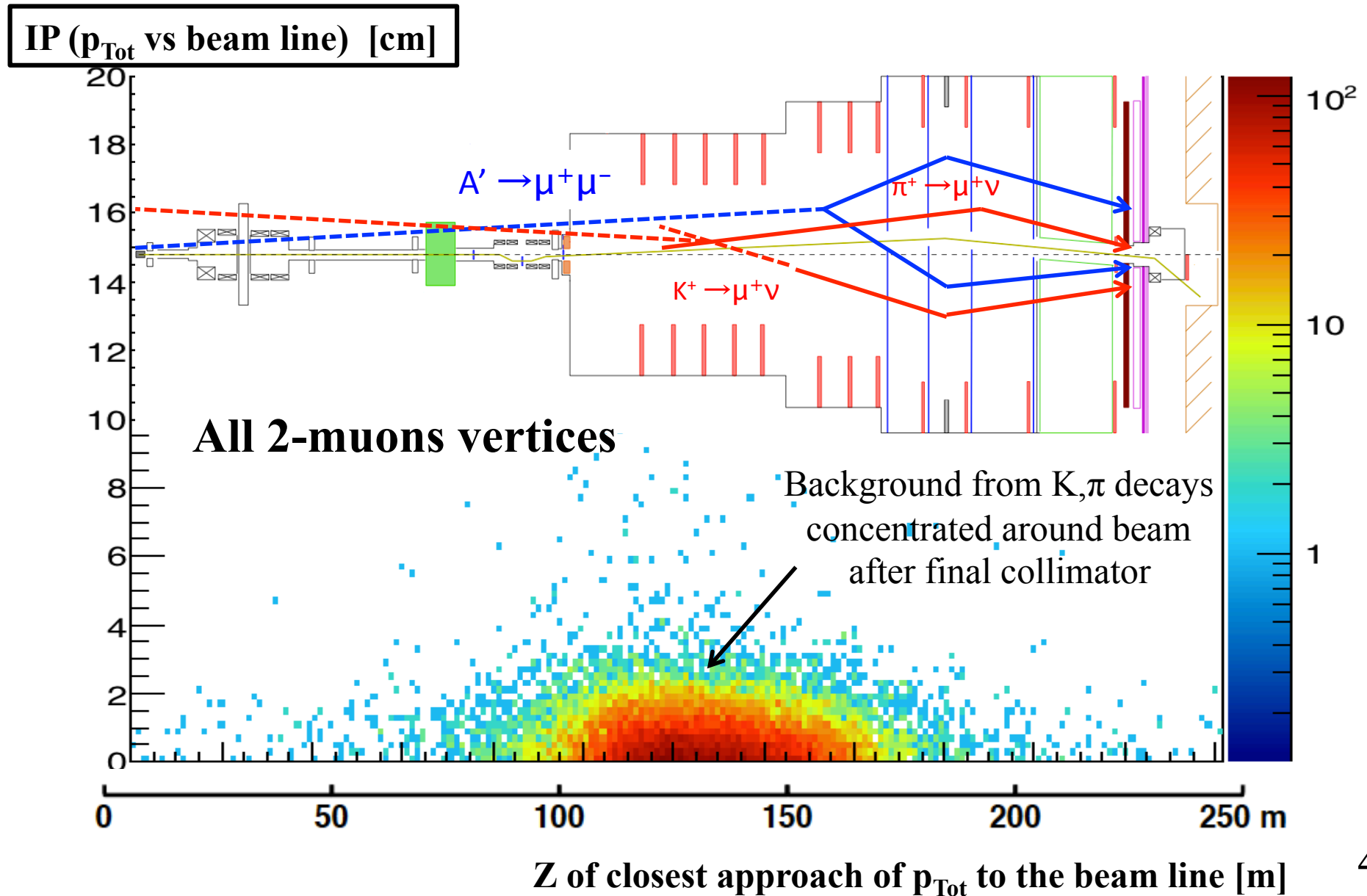
K^+ muon/halo tracks from target to spectrometer



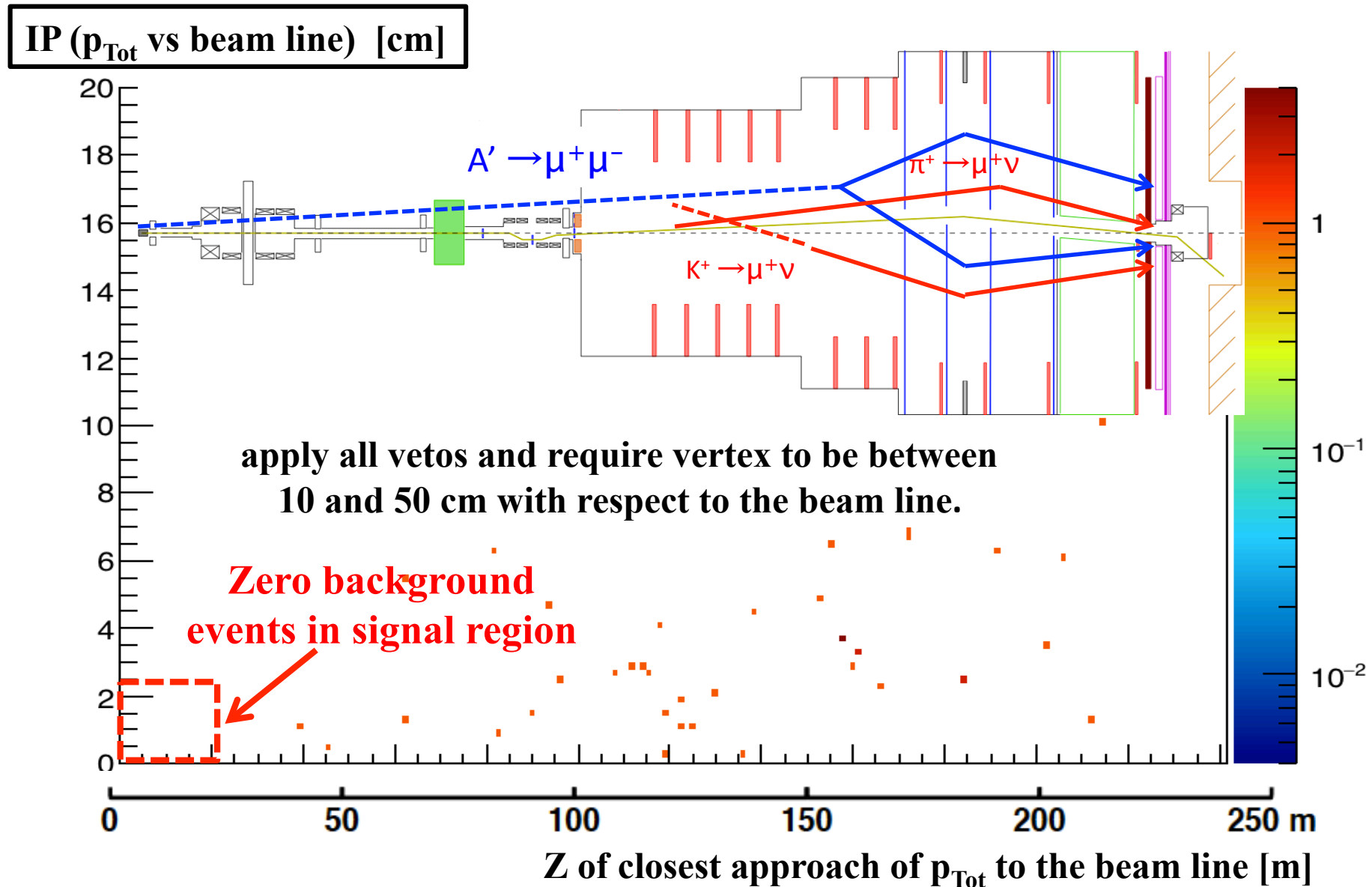
- BEND3 @ ~ 50 m sweeps muons close to the beam axis away
- return field of BEND3 puts some μ^+ back into acceptance

Muons interacting with material are not tracked any longer

Facing the background with real data: di-muon bkg



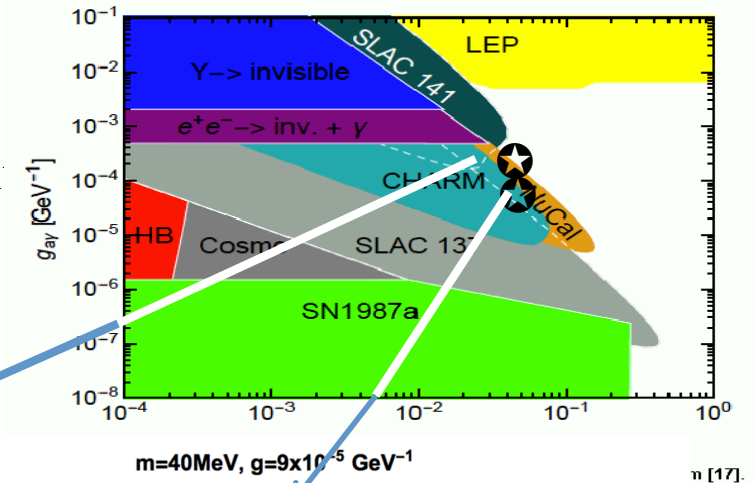
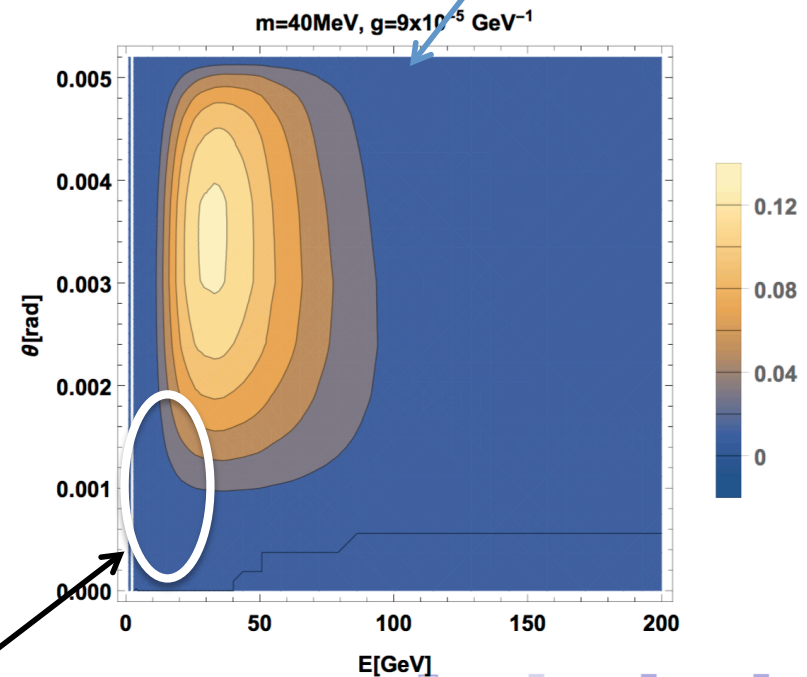
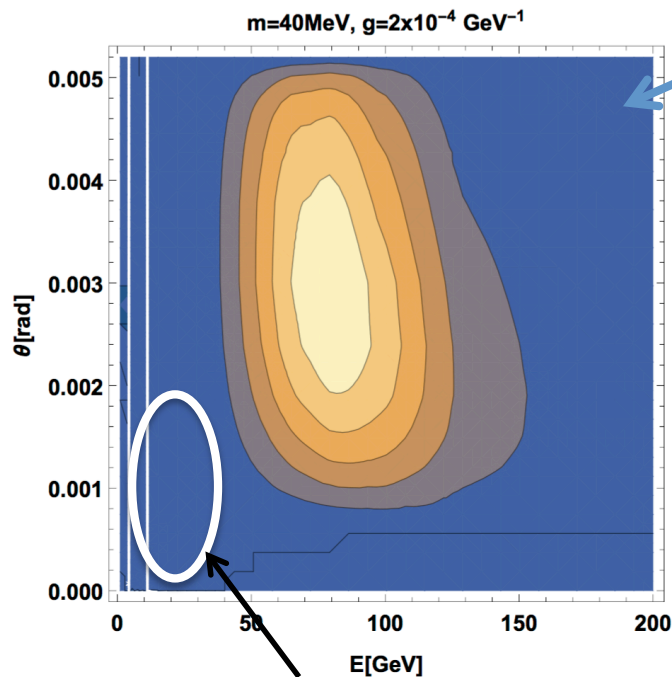
Facing the background with real data: di-muon bkg



Facing the background with real data: di-photon bkg

Search for $\text{ALP} \rightarrow \gamma \gamma$:

- Data from a few-hours run with closed tax at full intensity $\sim 10^{14}$ pot;
- Use correlation of ALP energy and θ angle for background rejection.



Background tends to be concentrated at low E , low θ
(more studies ongoing with 1 full day of data taking in dump mode)

Conclusions

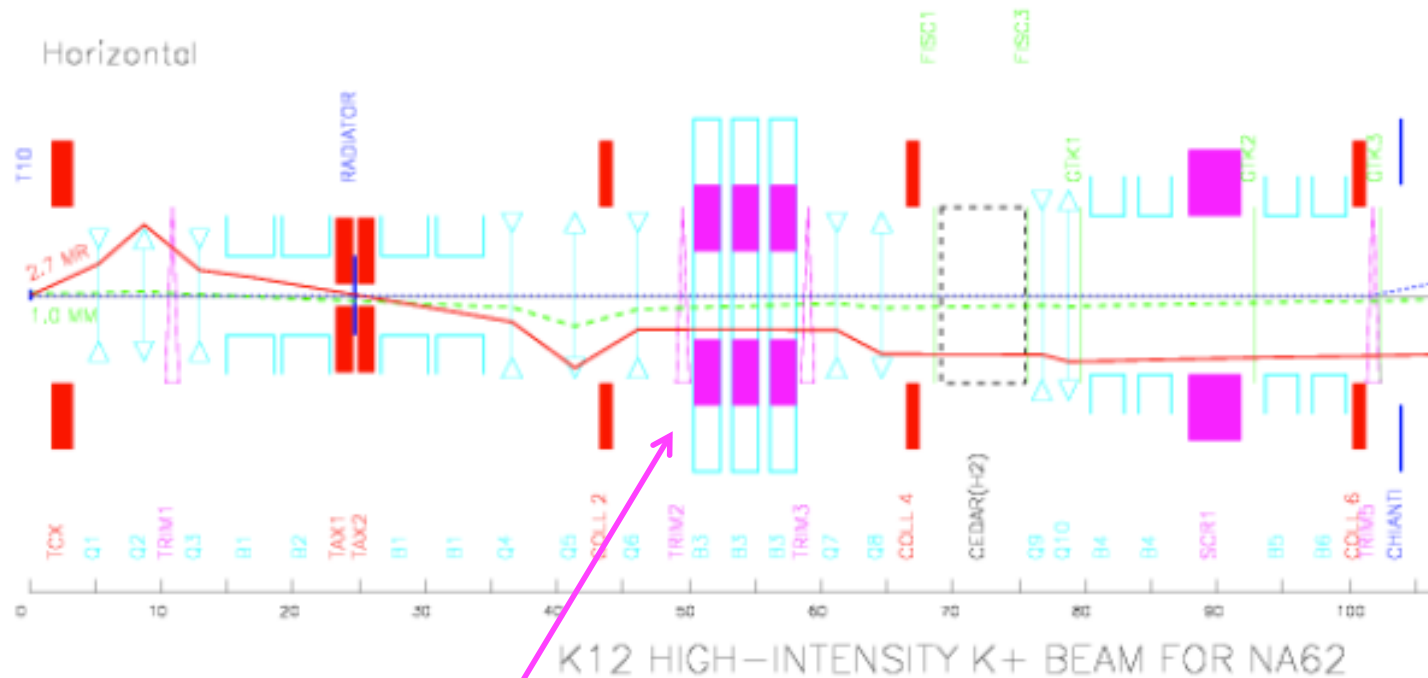


- NA62 is officially approved to run until 2018 with the main goal of measuring the $\text{BR}(\text{K}^+ \rightarrow \pi^+ \nu \text{ anti-}\nu)$ with 10% accuracy;
- Before LS2 (2018): many searches in the hidden sector will be performed using the kaon beam. Short periods in dump mode are also scheduled.
- After LS2 (2021++) there is a window of opportunity to run NA62 in beam-dump mode for o(1) year to search for hidden particles from charm/beauty decays and pave the way for the next generation experiments (SHiP/LBNF).
- Preliminary studies with data taken in beam and beam-dump modes show that the background can be kept under control. Further improvements in the setup (upstream veto, better timing) are currently under study.

**A lot of results expected in the coming years.
(and any help from the theory community will be more than welcome)**

SPARES

The sweeping system of NA62:



After the TAXes, the beam passes through a 40mm diameter, almost field-free bore, drilled in iron slabs, which are inserted to fill the 200mm high gaps **in three, 2m-long, dipole magnets**. The vertical magnetic field in the iron surrounding the beam serves to sweep aside muons of both signs.

Muon flux reduced by a factor ~ 10 .