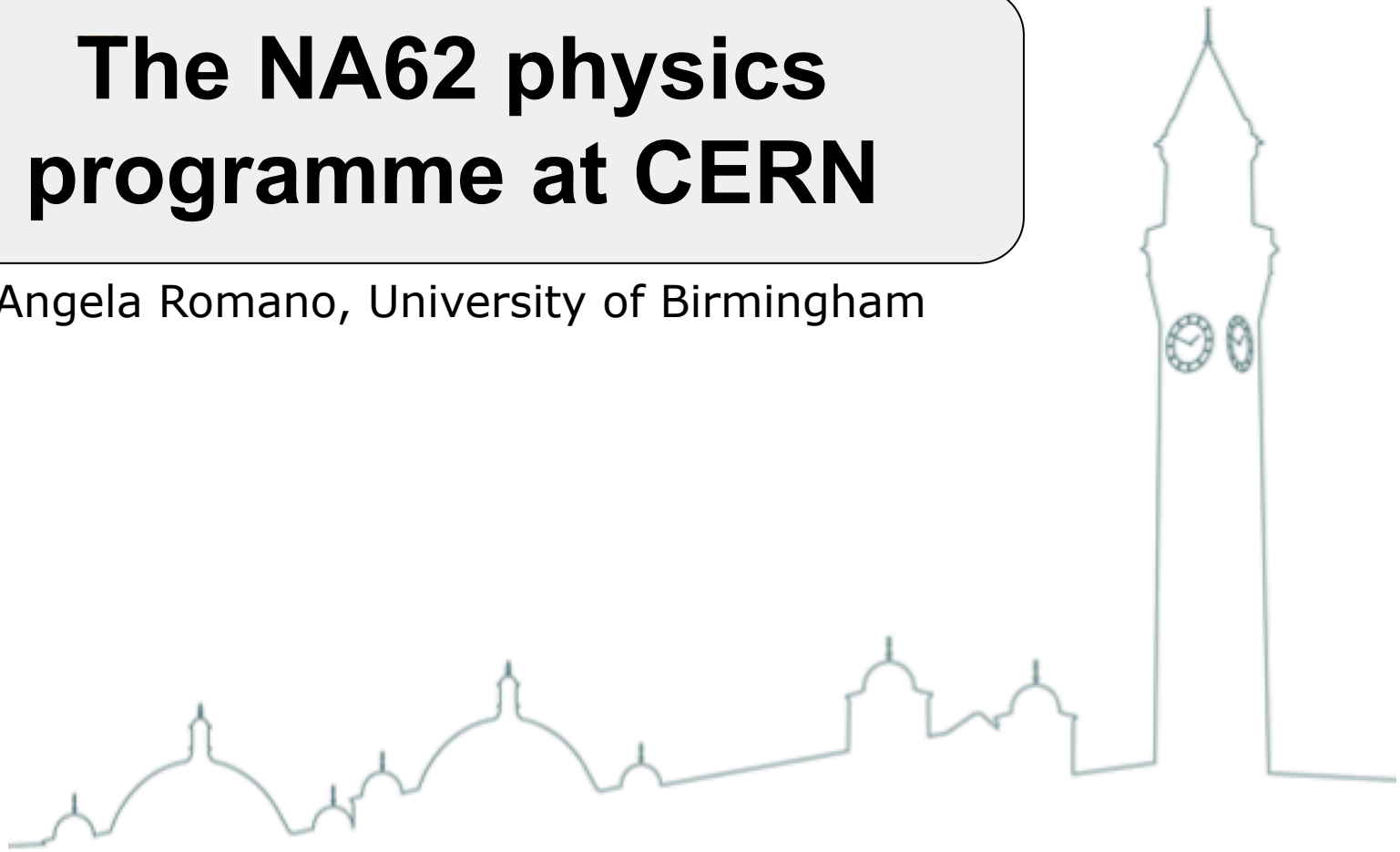
New physics in kaon and beam-dump experiments

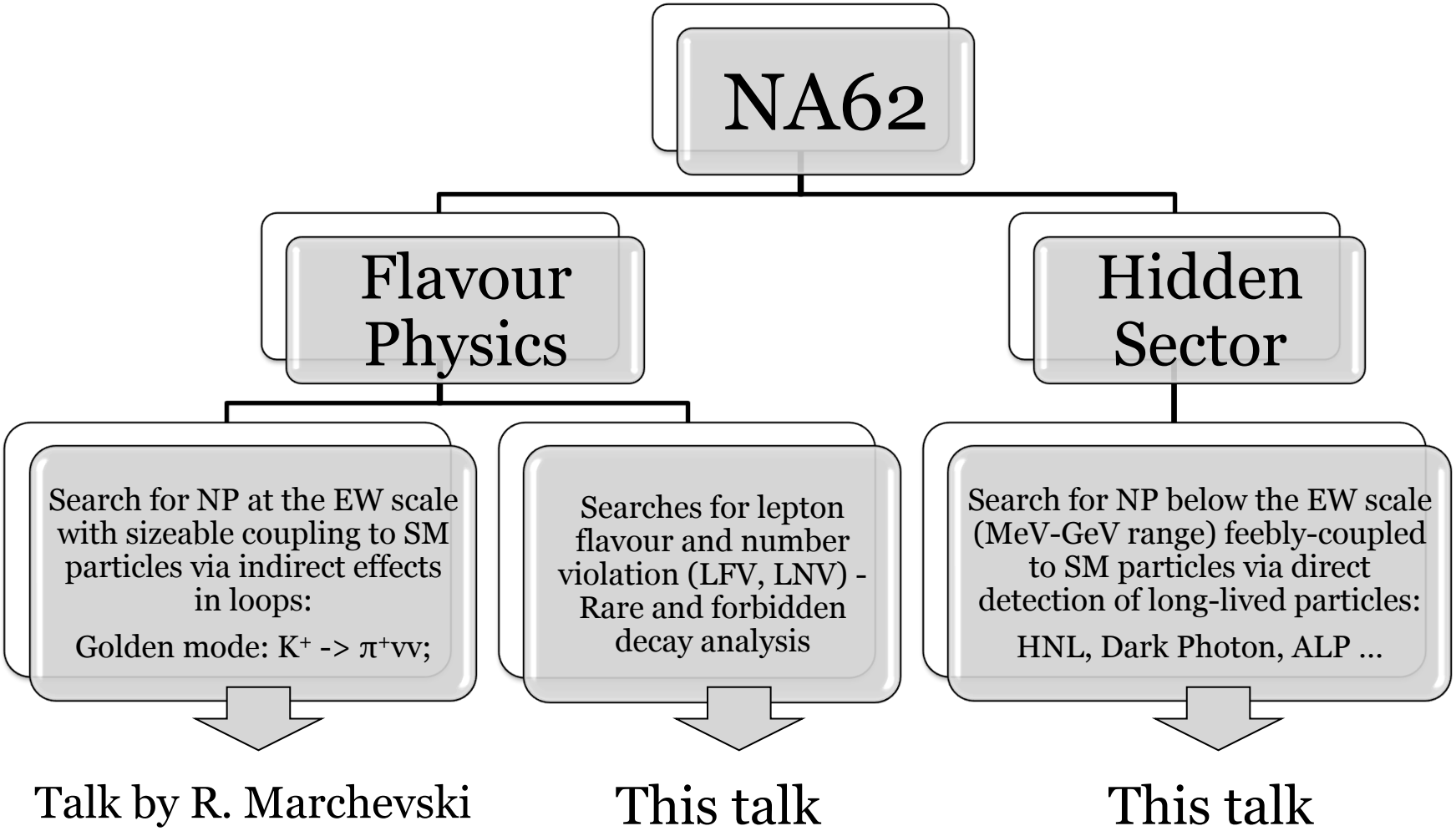
3rd December 2018, University of Birmingham

The NA62 physics programme at CERN

Angela Romano, University of Birmingham



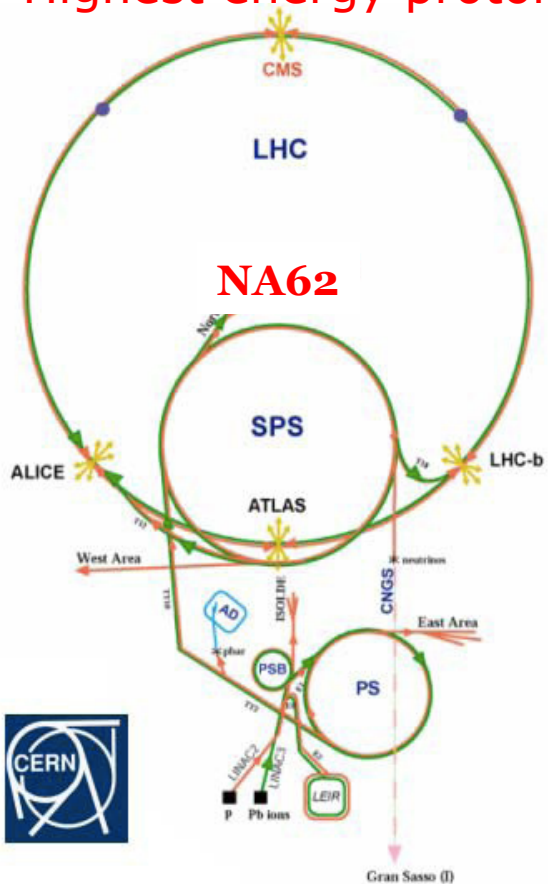
NA62: a general purpose experiment



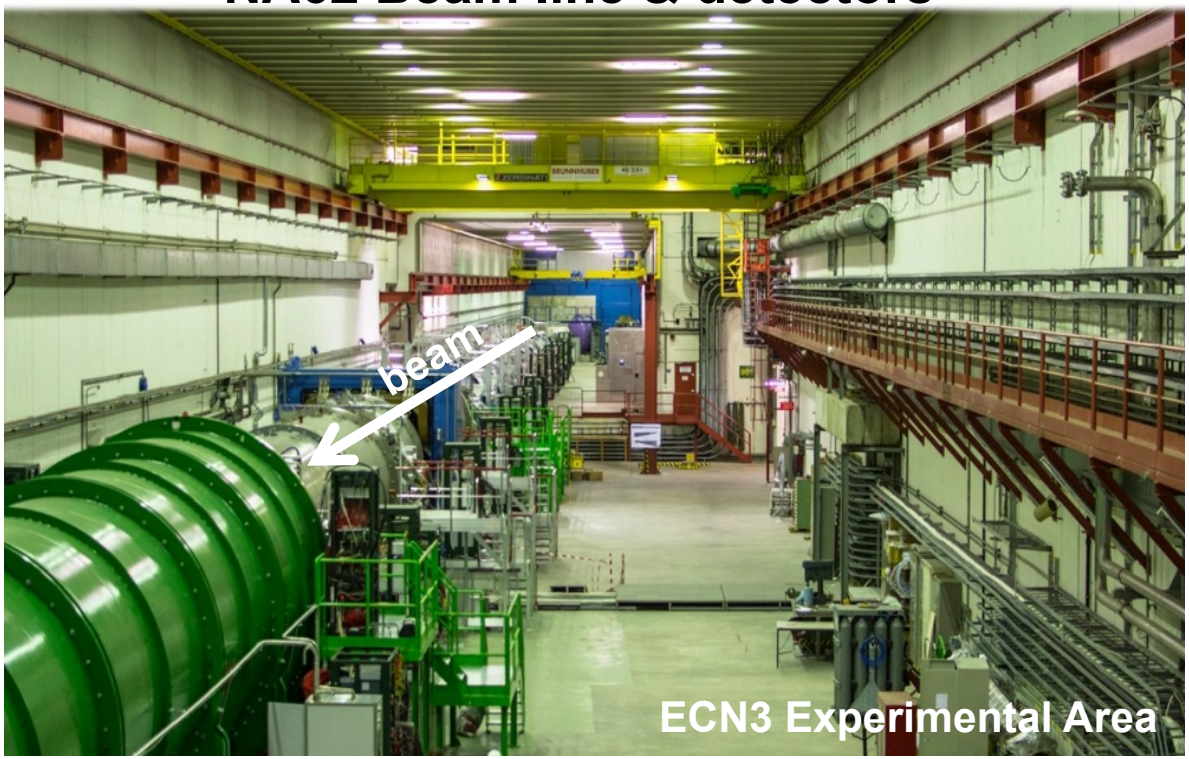
The NA62 experiment

High precision fixed-target Kaon experiment at CERN SPS

Highest energy proton beam delivered for fixed-target exp in the world



NA62 Beam line & detectors

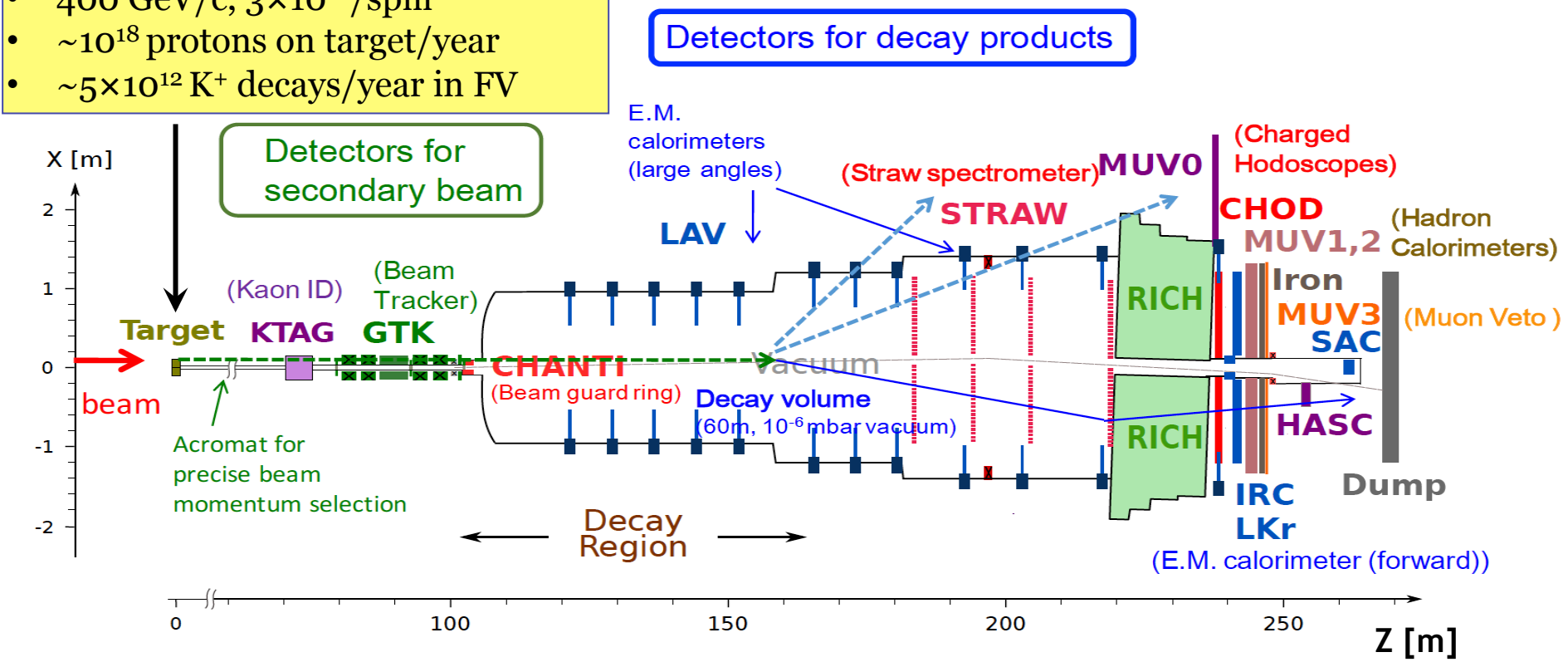


Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Louvain-la-Neuve, Mainz, Merced, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin, Vancouver (UBC)

The NA62 Detector

SPS proton beam on Be target:
- 400 GeV/c, 3×10^{12}/spill
- ~10^{18} protons on target/year
- ~5×10^{12} K^+ decays/year in FV

[NA62 Detector Paper, 2017 JINST 12 P05025]



- Secondary **un-separated hadron ($\pi^+/K^+/p$) beam**
- **800MHz** beam rate @GTK (45MHz K^+ component)
- **K^+: 75GeV/c** (±1%), divergence < 100μrad
- ~10% of K^+ decays in **~60m Fiducial Volume (FV)**

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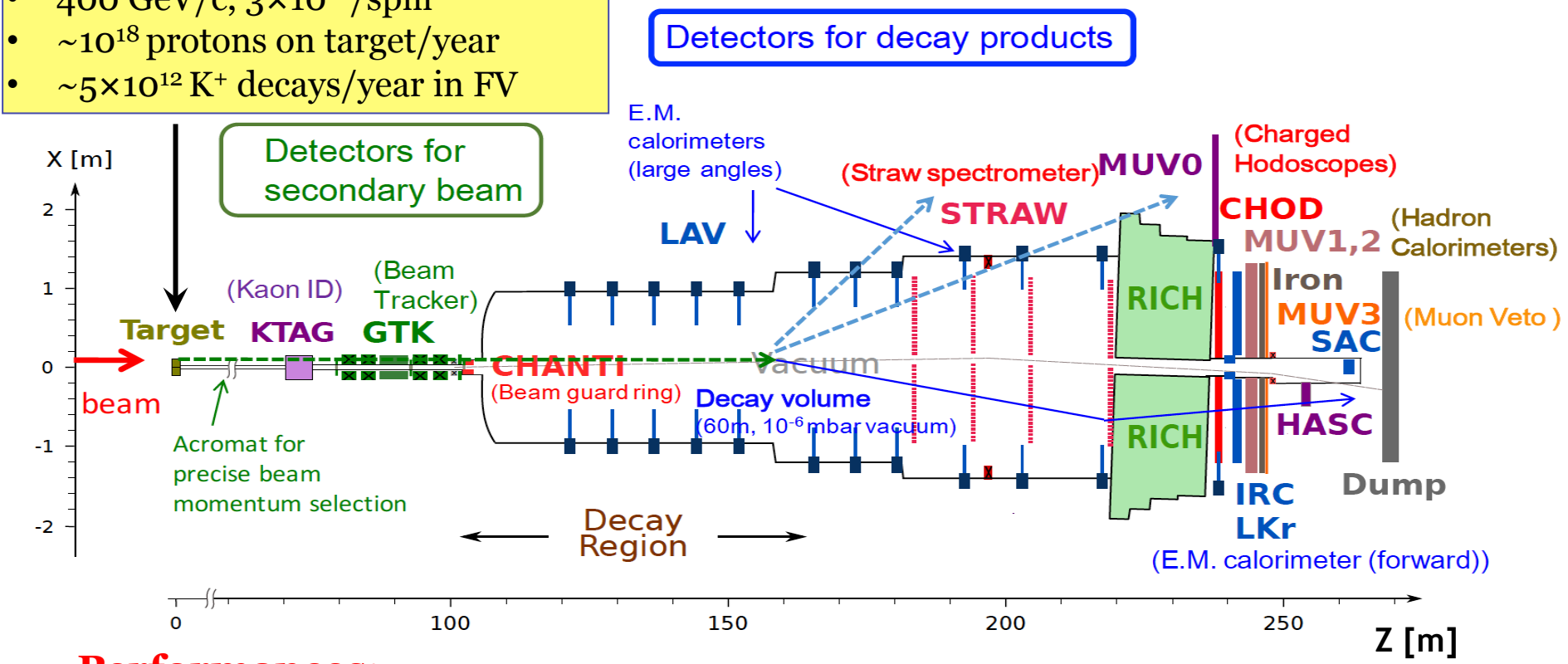

Performances:

- Excellent time resolution **O(100 ps)** to match beam/daugther particle info
- Kinematic rejection factors: **~10^{-4}** for **$K^+\to\pi^+\pi^0$**, **$K\to\mu^+\nu$** bkg channels
- Particle ID: **~10^{-7}** μ suppression for $15 < p(\pi^+) < 35$ GeV/c
- Hermetic photon veto: **~10^{-8}** rejection of **$\pi^0\to\gamma\gamma$** for $E(\pi^0)>40$GeV

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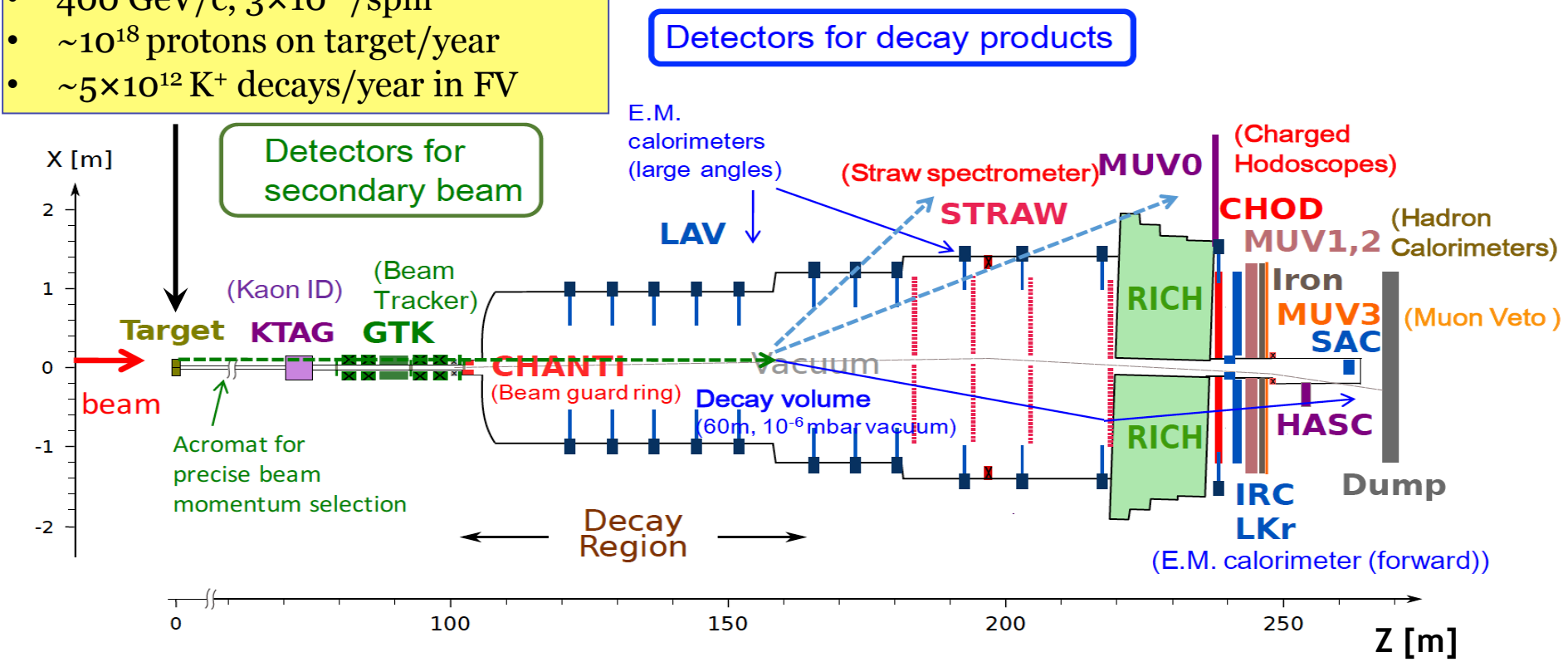


High-intensity setup, trigger system flexibility and detector performances make

NA62 particularly suitable to search for NP effects from different scenarios

NA62 Physics Programme beyond K→πνν

- **Standard Kaon Physics**
  - Measurements of the BR of all the main K^+ decay modes
  - χPT: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+e^-$, $K^+ \to \pi^0(^+)\pi^0(^-)l^+\nu$
  - Lepton Universality: $R_K = \Gamma(K^+ \to e^+\nu_e)/(K^+ \to \mu^+\nu_\mu)$

- **Rare/forbidden K^+ and π^0 decays at SES ~10^{-12}:**
  - **K^+** physics: **$K^+ \to \pi^+\ell^+\ell^-$, $K^+ \to \pi^+\gamma\ell^+\ell^-$, $K^+ \to \ell^+\nu\gamma$,**
  - LFV-LNV searches: $K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^- l^+ l^+$, ...
  - **π^0** physics: $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$, $\pi^0 \to e^+e^-e^+e^-$, $\pi^0 \to \gamma\gamma\gamma(\gamma)$, ...

- **Exotics searches**
  - Heavy Neutral Lepton (HNL) production from $K^+ \to l^+\nu_h$
  - Dark Photon (A') $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma A'$, $A' \to$ invisible

Recent Results

$K^+ \rightarrow e^+\nu$: Lepton Universality

25% 2017 Data: $N_K = 3 \times 10^{11}$, world largest sample of $K^+ \rightarrow e^+\nu$ 4×10^5

- Study of lepton universality in K:

  $R_K \equiv \Gamma(K^+ \rightarrow e^+\nu)/\Gamma(K^+ \rightarrow \mu^+\nu)$

- Theory (SM) :

  $R_K = (2.477 \pm 0.001) \times 10^{-5}$

  [Phys. Rev. Lett. 99 (2007) 231801]

- Experimental Status (2007 NA62):

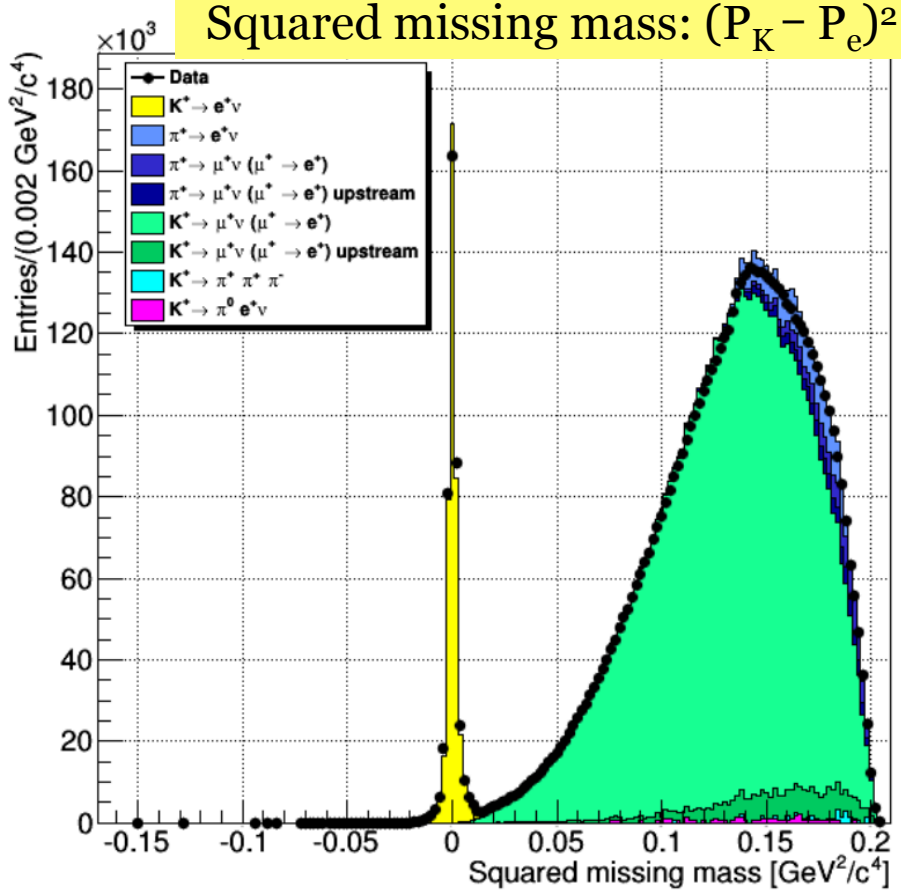
  $R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$

  [Phys. Lett. B 719 (2013) 326]

- NA62 Present: novel method to measure R_K using $\mu^+ \rightarrow e^+\nu\bar{\nu}$ for normalization

- No systematics uncertainties that limited the 2007 NA62 measurement

Squared missing mass: $(P_K - P_e)^2$

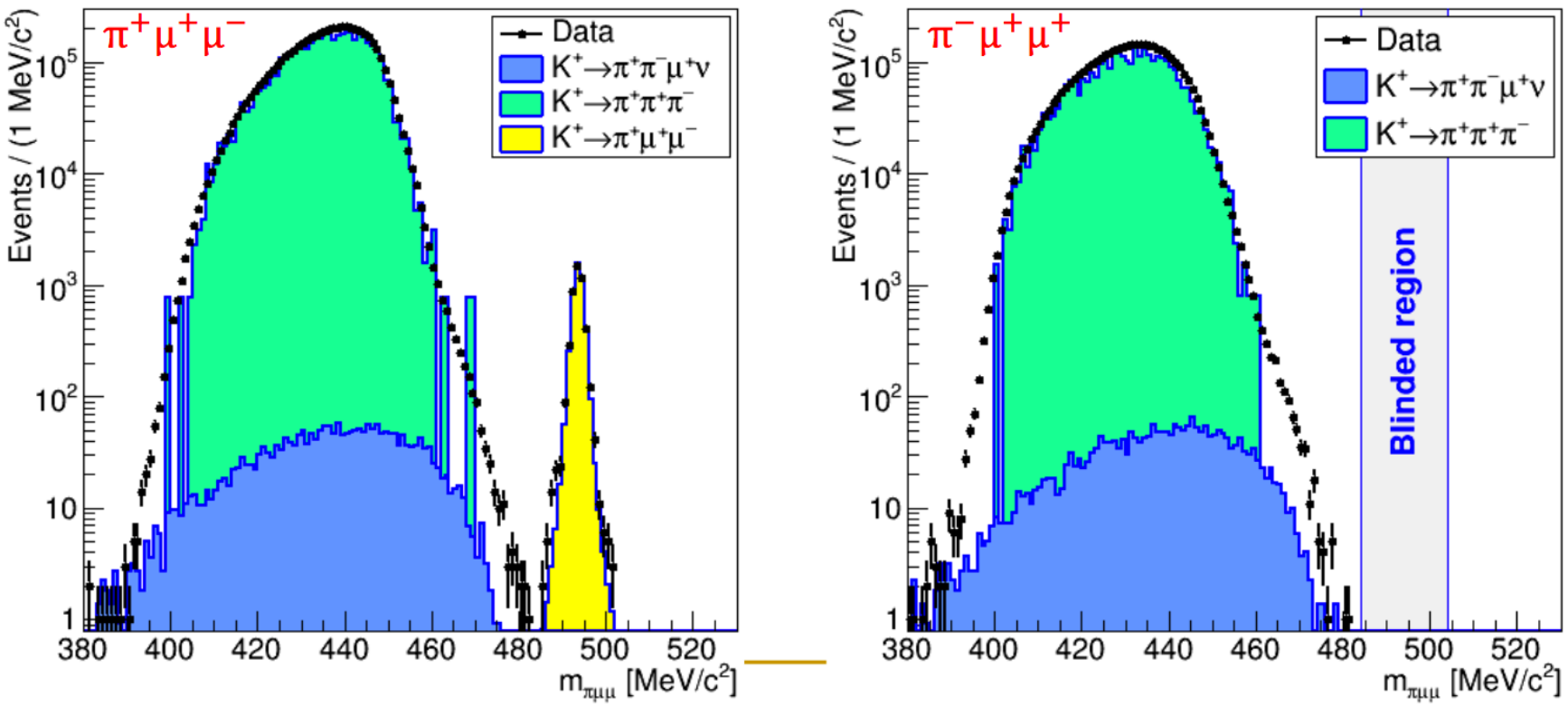


Aim: R_K measurement at sub-percent level precision

$K^+ \rightarrow \pi^+\mu^+\mu^-$

50% 2016 + 25% 2017 Data: $N_K = 6.3 \times 10^{11}$

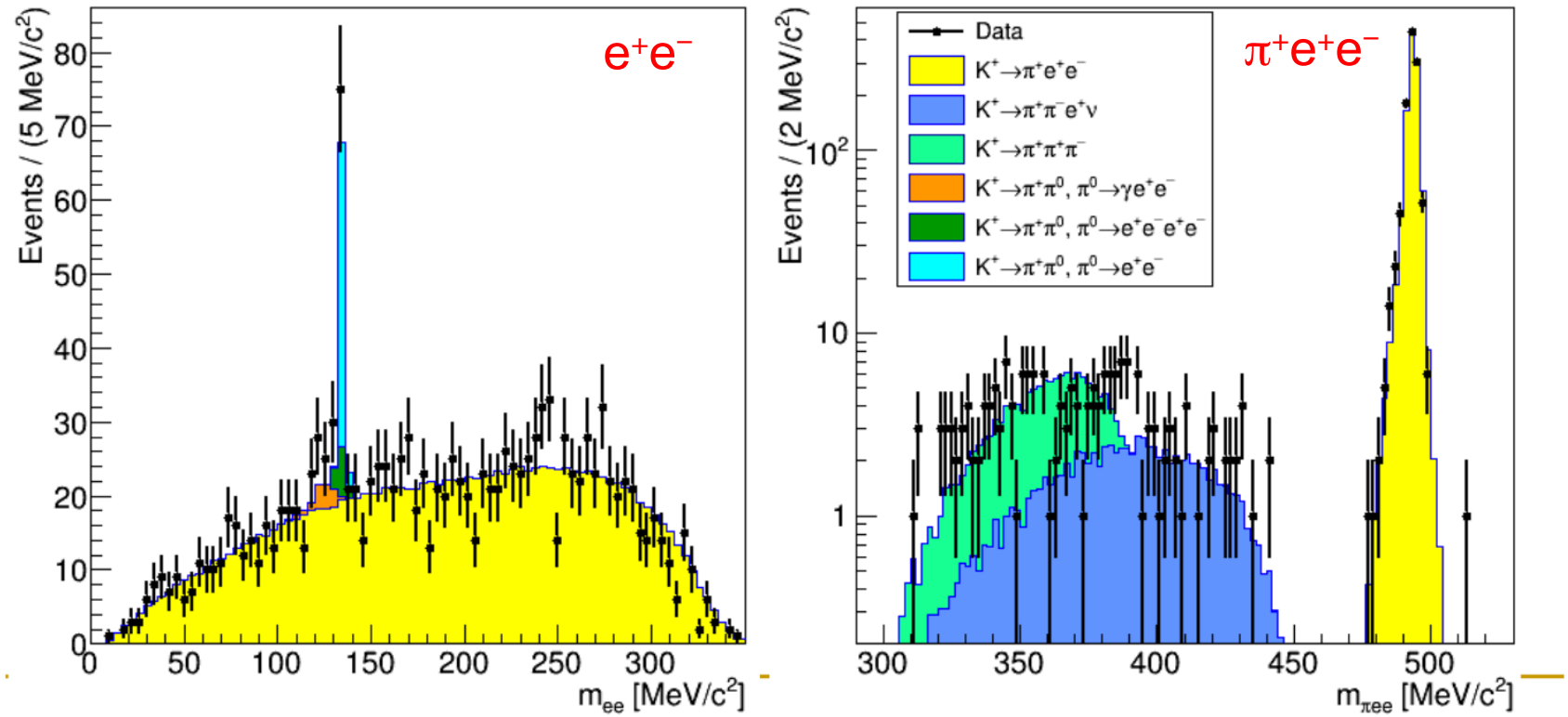
- World-largest $K^+ \rightarrow \pi^+\mu^+\mu^-$: $\sim 4.6 \times 10^3$ events $(BR \sim 10^{-7})$
- Wxpected 10K; competitive measurement
- Search for $K^+ \rightarrow \pi^-\mu^+\mu^+$ is not limited by background: $SES = 2 \times 10^{-11}$
- Sensitivity to $K^+ \rightarrow \pi^+ S, S \rightarrow \mu^+\mu^-$: $SES \sim 10^{-10}$ for lifetimes up to $\mathcal{O}(1\ \mathrm{ns})$



$K^+ \rightarrow \pi^+e^+e^-$

50% 2016 + 25% 2017 Data: $N_K = 1.3 \times 10^{11}$

- Background – free $\sim 1.1 \times 10^3$ events for $m_{ee} > 140\ \mathrm{MeV/c^2}$ ($BR \sim 3 \times 10^{-7}$)
- First observation at $m_{ee} < 140\ \mathrm{MeV/c^2}$
- Sensitivity to $BR(K^+ \rightarrow \pi^+X)BR(X \rightarrow e^+e^-)$, $10 < m_X < 100\ \mathrm{MeV/c^2}$: $\mathcal{O}(10^{-9})$
- Search for $K^+ \rightarrow \pi^-e^+e^+$ is not limited by background: $SES = 2 \times 10^{-10}$



Forbidden K^+ decays at NA62

Goal: improve over most existing limits (mainly from BNL E865, E777).

- Search for the LNV decay $K^+ \to \pi^- \mu^+ \mu^+$ [BR<8.6×10^{-11}, NA48/2@CERN]
- Search for the LNV decay $K^+ \to \pi^- e^+ e^+$ [BR<6.4×10^{-10}]
- Searches for LNV/LFV decays $K^+ \to \pi\mu e$, including $\pi^0 \to \mu e$.
  [BR($\pi^-\mu^+e^+$)<5.0×10^{-10}; BR($\pi^+\mu^-e^+$)<5.2×10^{-10}; BR($\pi^+\mu^+e^-$)<1.3×10^{-11}]
  [BR($\pi^0 \to \mu^\pm e^\mp$)<3.6×10^{-10}, kTeV@FNAL]
- Searches for $K^+ \to \mu^- \nu e^+ e^+$ and $K^+ \to e^- \nu \mu^+ \mu^+$ decays.
  [BR($\mu^-\nu e^+e^+$)<1.9×10^{-8}: Geneva-Saclay, 1976]
- Searches for $\Delta S = \Delta Q$ violating decays $K^+ \to \pi^+\pi^+e^-\nu$ and $K^+ \to \pi^+\pi^+\mu^-\nu$.
  [BR($\pi^+\pi^+e^-\nu$)<1.3×10^{-8}; BR($\pi^+\pi^+\mu^-\nu$)<3.0×10^{-6}: ~50 years old]

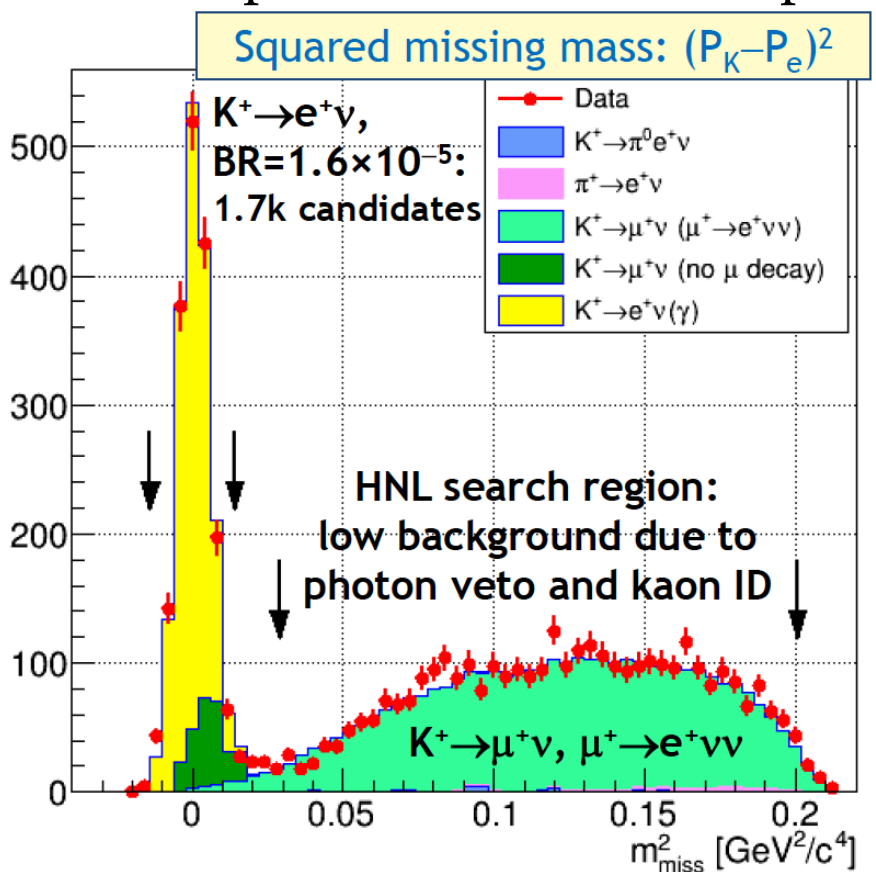
Approximate statistical reach with the 2016–17 data sample:

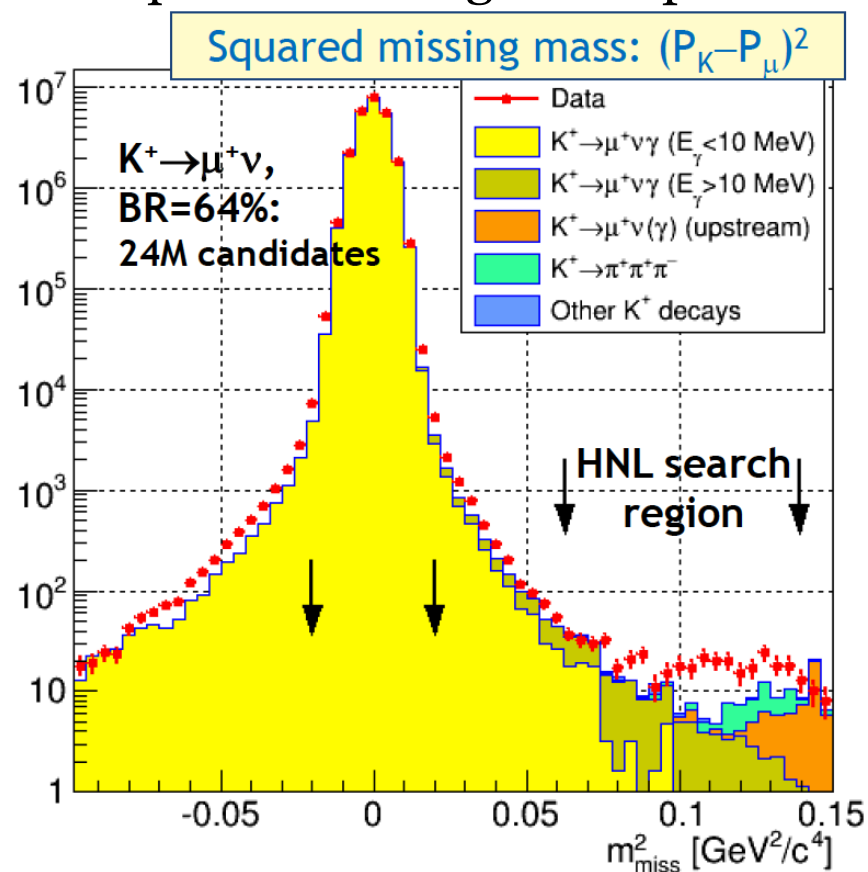
- Di-muon trigger stream: ~2×10^{12} K^+ decays; SES~10^{-11};
- Decays to μe and ee pairs: ~5×10^{11} K^+ decays; SES~10^{-10};
- Other 3-track decays: ~5×10^{10} K^+ decays; SES~10^{-9}.

NA62 is competitive for most of these decay modes

HNL Production @ NA62

- Search for HNL produced in $K^+ \to e^+ \nu_h$ and $K^+ \to \mu^+ \nu_h$ decays
- **NA62 2015 data** (minimum bias @ 1% intensity, 5days)
- Number of K^+ decays in FV: $N_K = (3.01 \pm 0.11) \times 10^8$ in positron case; $(1.06 \pm 0.12) \times 10^8$ in muon case.
- HNL production: search for peaks in squared missing mass spectra

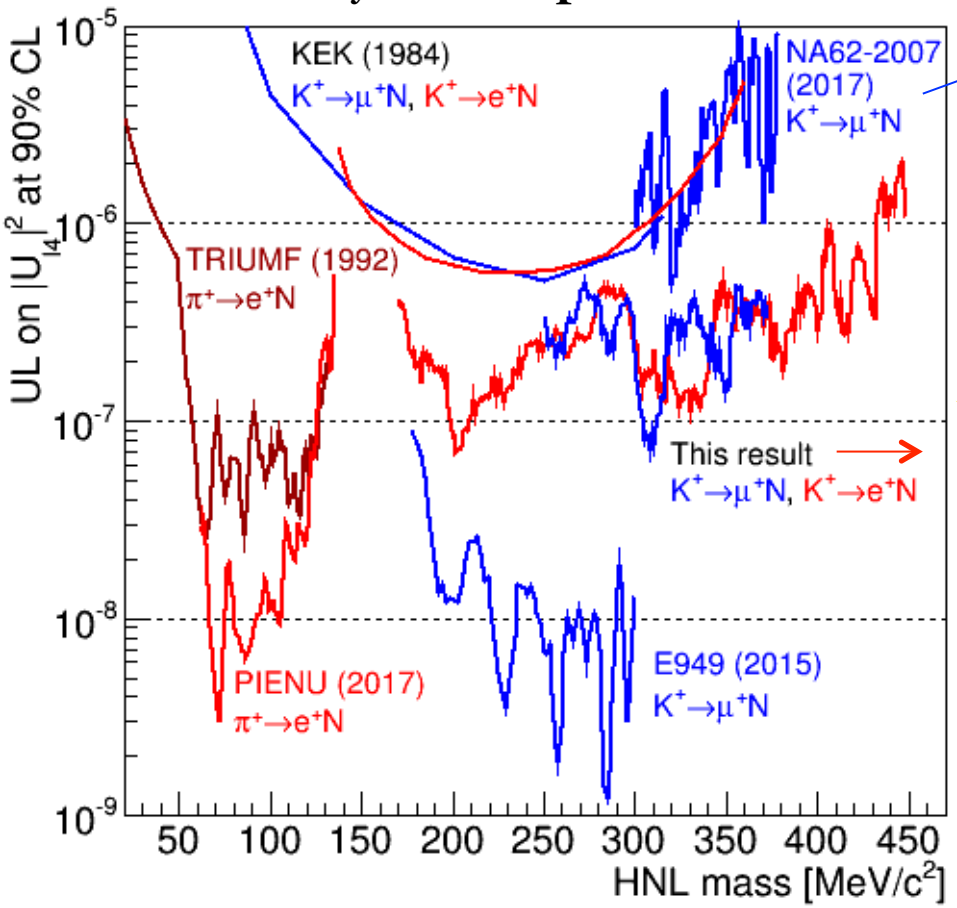




HNL Global Limits

$$|U_{l4}|^2 = \frac{\mathcal{B}(K^+ \to l^+ N)}{\mathcal{B}(K^+ \to l^+ \nu_l)\ \rho_l(m_N)}$$

Limits from heavy neutrino **production** searches



NA62 2007 Data Analysis:

- Extends the mass range for upper limits on $|U_{\mu 4}|^2$

[Phys. Lett. B772 (2017) 712]

NEW

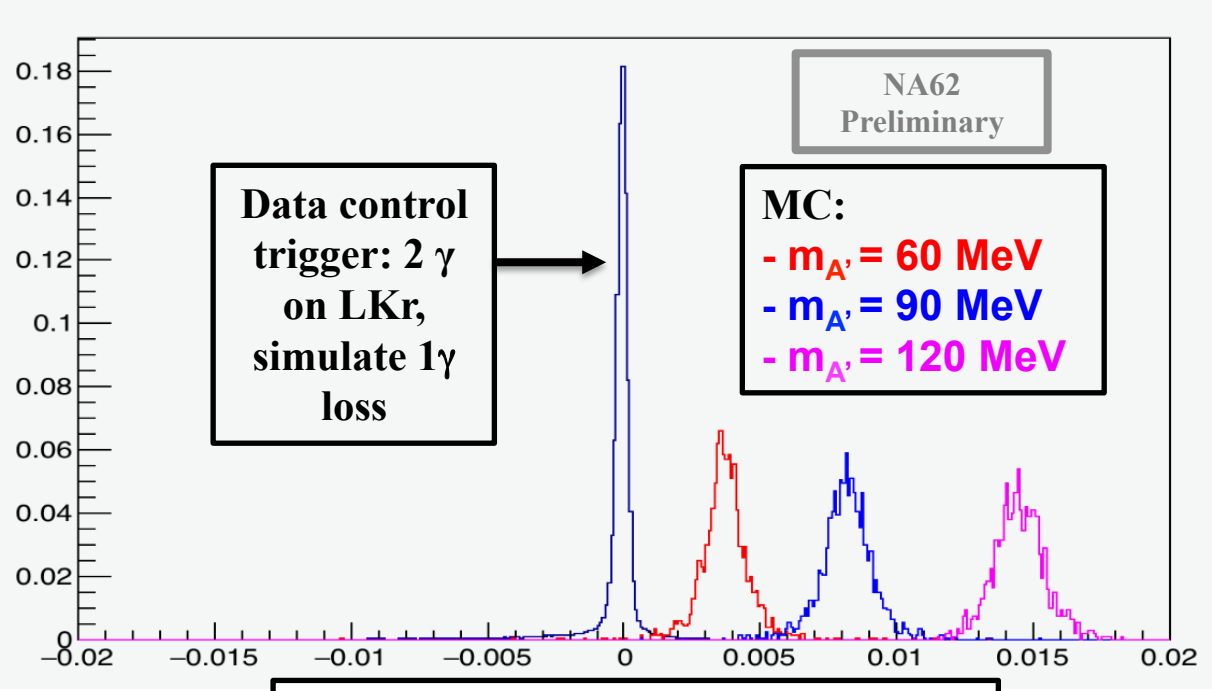
NA62 2015 Data Analysis:

- Reached 10^{-6}-10^{-7} limits for $|U_{l4}|^2$ in HNL **(170,448) MeV/c²** mass range [Phys. Lett. B778 (2018) 137]

Full 2016-2018 data set analysis will esplore $|U_{l4}|^2 \lesssim 10^{-8}$ range

Dark Photon Searches @ NA62

- Search for A' produced via: $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma A'$, $A' \to$ invisible
- Sensitivity to DP for $m(A') < m(\pi^0)$
- **NA62 2016 data** (40% nominal beam intensity)
- NA62 main trigger for $K^+ \to \pi^+\nu\nu$
- Search for peaks in $M^2_{miss}(K^+ \to \pi^+\pi^0) = (P_K - P_\pi - P_\gamma)^2$



$M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$ [GeV²/c⁴]

Signature:

- 1 photon + missing energy

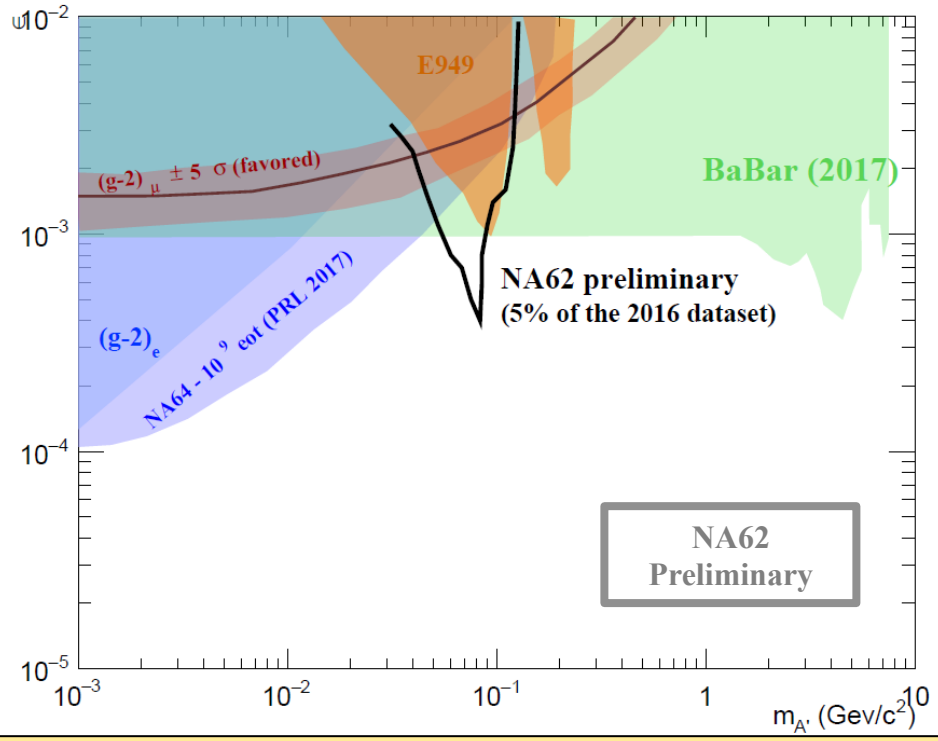
Selection:

- π^+ as in $K^+ \to \pi^+\nu\nu$
- 1 γ in LKr
- Missing momentum in LKr
- Extra γ veto

Dark Photon Searches @ NA62

- Search for A' produced via: $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma A'$, $A' \to$ invisible
- DP mass range: 50 MeV/c² < m(A') < 90 MeV/c²

Expected DP exclusion limits at 90% C.L.



Preliminary results using ~1.5 x 10^{10} K^+ decays [**~5% of 2016 NA62 data**]

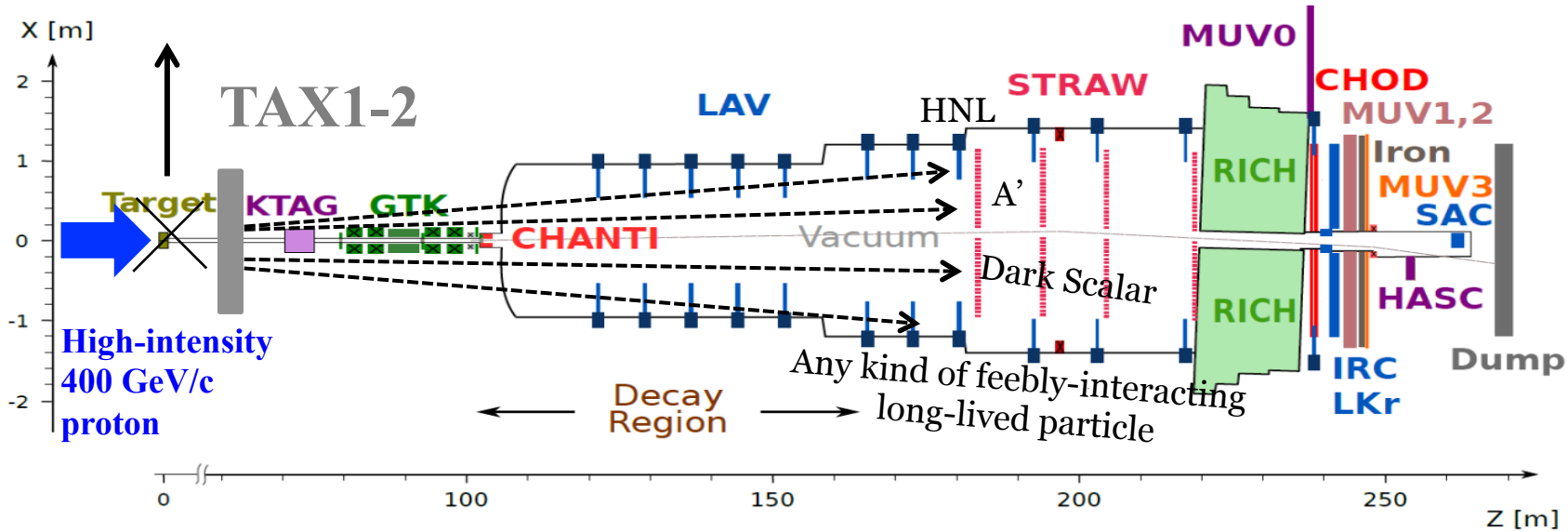
Expect improvement over the world data

Improvement on BR($\pi^0 \to$invisible) over current limit of 2.7×10^{-7} also possible

Hidden Sector searches at NA62 in “Dump” mode

NA62 "Dump" Operation Mode

- Be target can be moved away
- Proton beam impinges on TAX1-2 (PoT)
- **TAX1-2 can act as a beam "dump": 3.2 m of Cu + Fe, ~22λ_I**
- Production of HNL, Dark Photon(DP), Dark Scalar(DS) and ALP from charm, beauty and γs produced in interaction of protons with the dump
- **10^{18} PoT/nominal year**: 10^{12} PoT/sec on spill, 100 days/year



NA62 kaon or proton "dump" modes are easily switchable in current setup

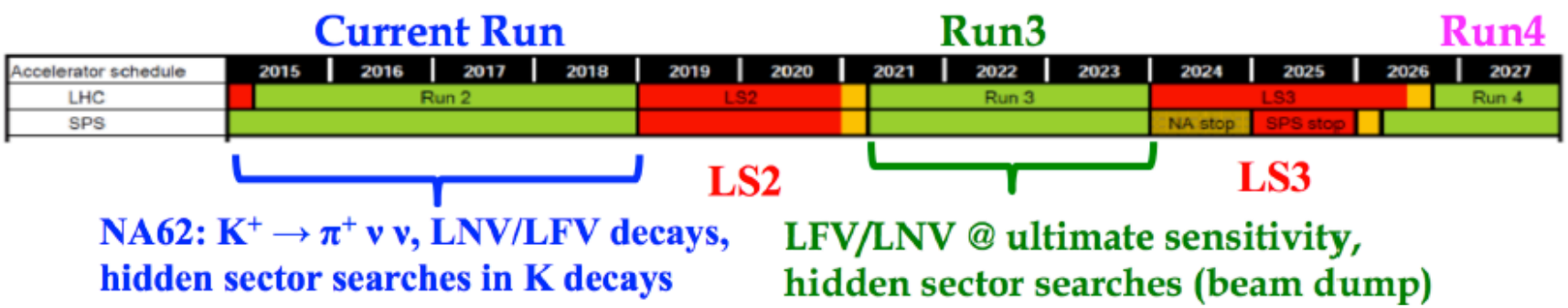
NA62 Timeline

NA62 Data taking in 2021-2023 (Run 3)

A rich field to be explored with minimal upgrades to the present setup:

1. **run for refining $K_{\pi\nu\nu}$ measurement**
2. **present K^+ setup: unprecedented LFV/LNV sensitivities from K^+/π^0**
3. **run in "beam-dump" mode with NP searches for MeV-GeV mass hidden-sector candidates: HNL, DP, DS, ALP, etc.**

Run 3 goal: integrate at least 10^{18} PoT in "dump" operation mode(*)



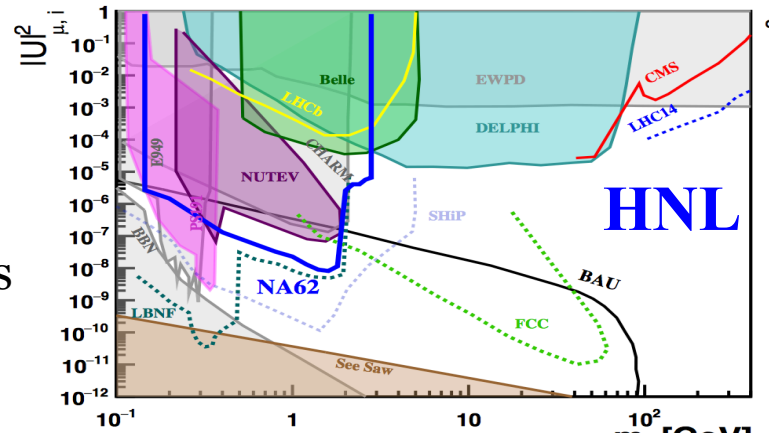
NA62 @ **Physics Beyond Colliders**

(*) "dump" data taking distributed in 3 years, without disruption for the kaon mode operation

NA62 Sensitivity

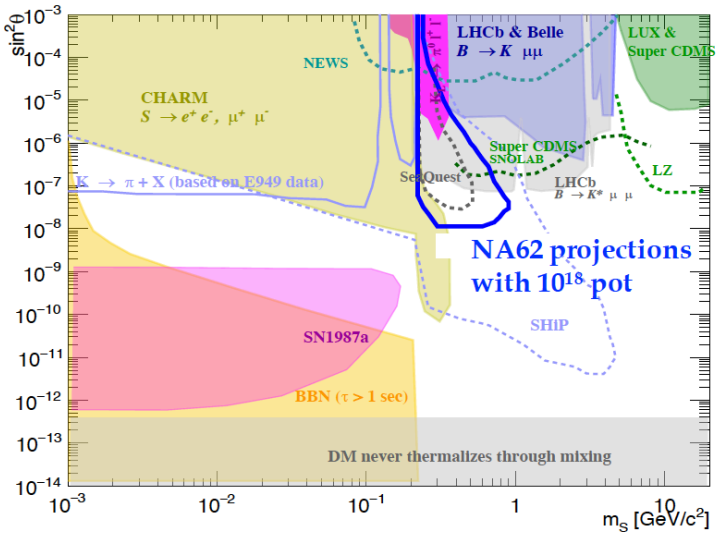
NA62 sensitivity with ~10^{18} **400-GeV PoT** running in "dump" mode

- Fully reconstructed 2-track final states
- Assume zero-background
- Evaluate expected 90% C.L. exclusion plots

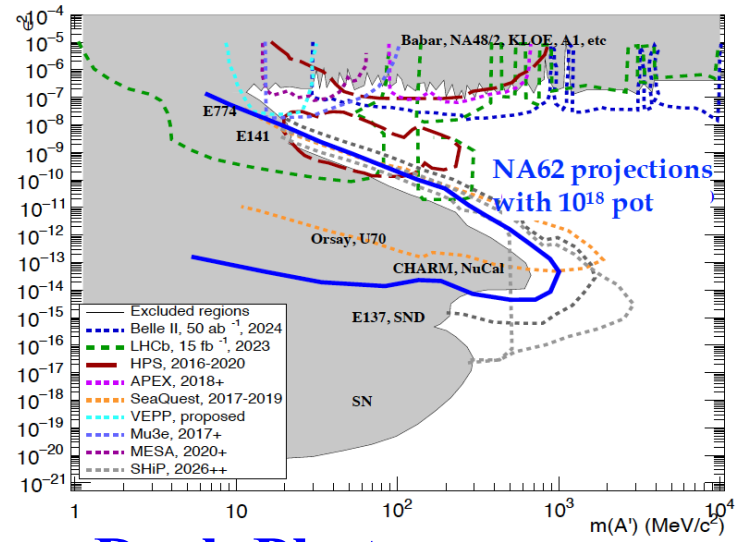


$U^2_e : U^2_\mu : U^2_\tau = 1:16:3.8$

Normal hierarchy of active **ν** masses



Dark Scalar



Dark Photon

Conclusions

The NA62 experiment (aka the CERN kaon factory) has **a vast and unique physics program for the search of NP**, complementary to what can be achieved at colliders.

First results on PNN, HNL and DP searches have been obtained on subsample of data collected during NA62 Run1 (2016-2018)

Running after LS2 (2021-2023) will allow to **fully exploit the NA62 physics reach** with the current detector and setup

There is a window of opportunity to **run NA62 in beam-dump mode to search for hidden sector mediators** from charm and beauty decays and pave the way for the next generation experiments (SHiP....);

New physics in kaon and beam-dump experiments

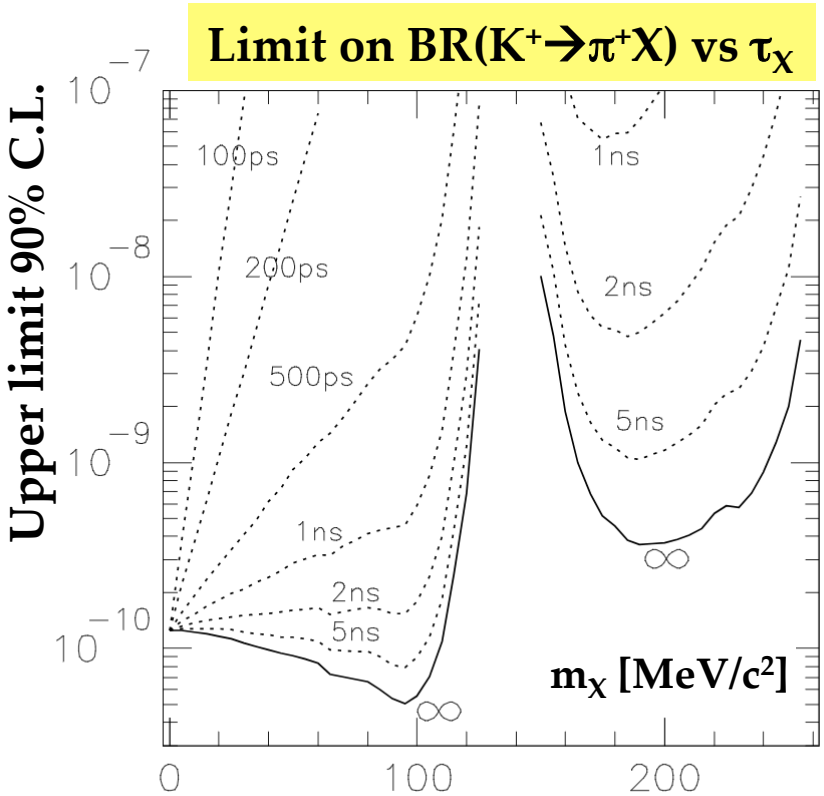
3rd December 2018, University of Birmingham

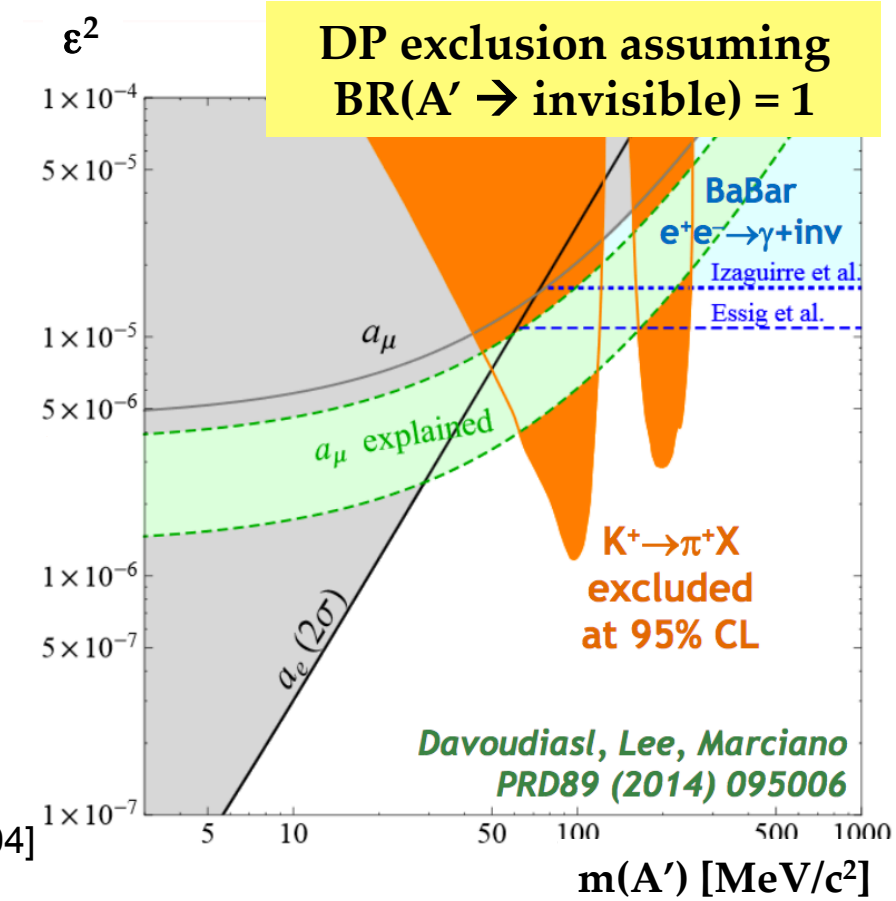
Spares

Angela Romano, University of Birmingham

$K^+ \to \pi^+ A'$, $A' \to$ invisible

NA62 $K^+ \to \pi^+ \nu\nu$ analysis interpreted as $K^+ \to \pi^+ X$ search, X is invisible





BNL-E949 $K^+ \to \pi^+ \nu\nu$ analysis: [PRD79 (2009) 092004] search for $K^+ \to \pi^+ X$, (X is invisible)

BNL-E949 $BR(\pi^0 \to \text{invisible}) < 2.7 \times 10^{-7}$ at 90% CL [PRD72 (2005) 091102]

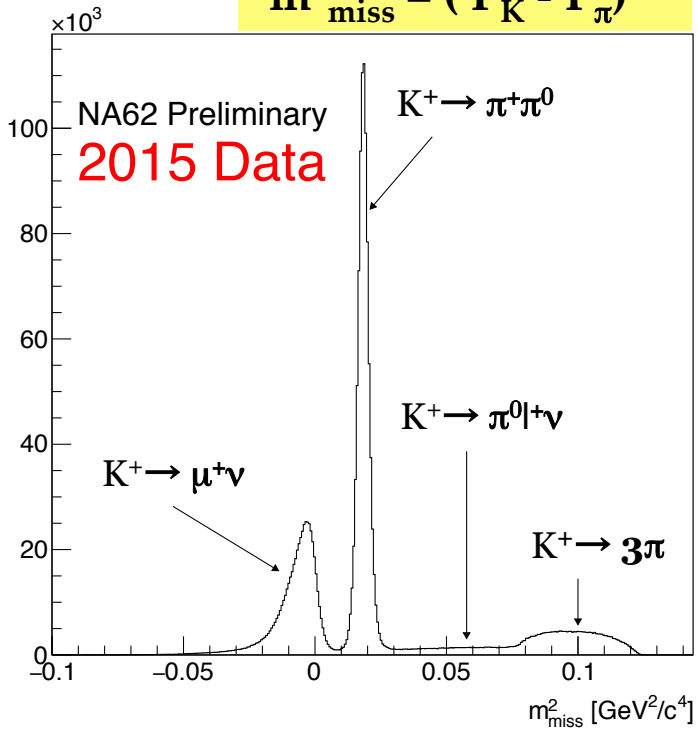
Non-trivial limits on DP phase space including the (g-2)μ favoured band, assuming invisible DP decays.

NA62: expect an order of magnitude improvement

Search for $\pi^0 \rightarrow$ invisible

Search for $\pi^0 \rightarrow$ invisible, NA62 sensitive at 10^{-8} or better…

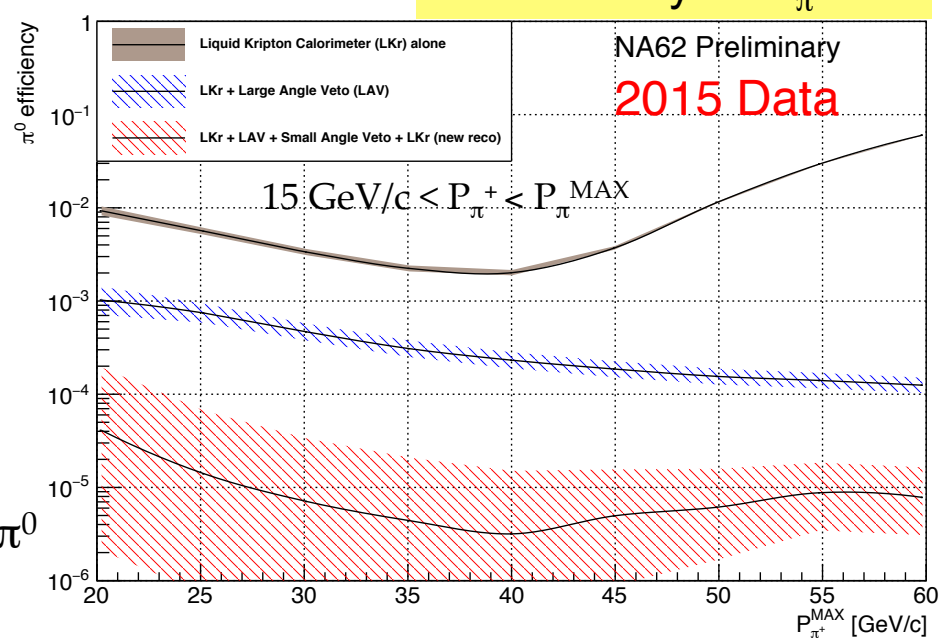
$m^2_{miss} = (P_K - P_\pi)^2$



Photon Rejection (2015 Data):

- Measured $\pi^0 \rightarrow \gamma\gamma$ decay suppression = 1.2×10^{-7} in $K_{\pi\nu\nu}$ signal region
- **Goal: $O(10^8)$ π^0 rejection for $K^+ \rightarrow \pi^+\pi^0$ bkg**
- $E(\pi^0) > 40$GeV for $P_{\pi^+} < 35$ GeV/c

π^0 efficiency vs P_π^{MAX}



Kinematics (2015 Data):

- Measured bkg rejection: 6×10^{-4} for $K^+ \rightarrow \pi^+\pi^0$
- **Goal: $O(10^4)$ for $K^+ \rightarrow \pi^+\pi^0$ and $K^+ \rightarrow \mu^+\nu$**

Search for resonances in $K^+ \to \pi^+ X$ ($X \to \mu^+\mu^-$) decay

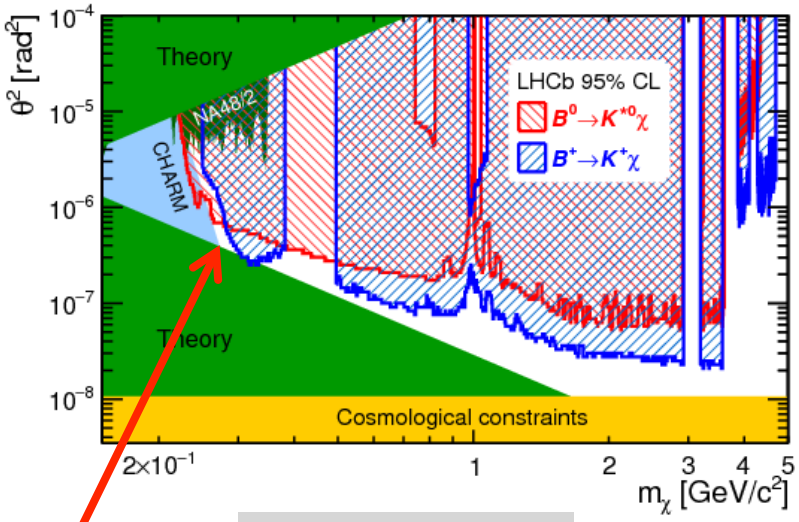
Light inflaton model:

- Inflaton **X** is a new scalar
- 3 parameters in the model, 2 free
- Inflaton production: B and K decays are governed by the same parameters
- Inflaton decays to SM particles

Low energy SUSY models :

- Sgoldstinos **P** (pseudoscalar) and **S** (scalar) are superpartners of goldstino
- No strict limits on the mass and lifetime
- Sgoldstino production: K and $\sum$ decays are driven by the same coupling constants
- P and S can be light and decay to SM particles

Experimental limits:



[arXiv:0612.07818]

Region accessible in $K^+ \to \pi^+ X, X \to \mu^+\mu^-$:
$\theta^2 \sim 4 \cdot 10^{-7}$ (m~270-300 MeV)

Experimental limits:

- Hyperon decays: $\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-$
  HyperCP, LHCb [arXiv:hep-ex/0501014] [arXiv:1712.08606]
- K_L decays: $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$
  kTeV [arXiv:1105.4800]
- $K^\pm$ decays: $K^+ \to \pi^+ S, S \to \mu^+\mu^-$
  NA48/2 [arXiv:1612.04723]

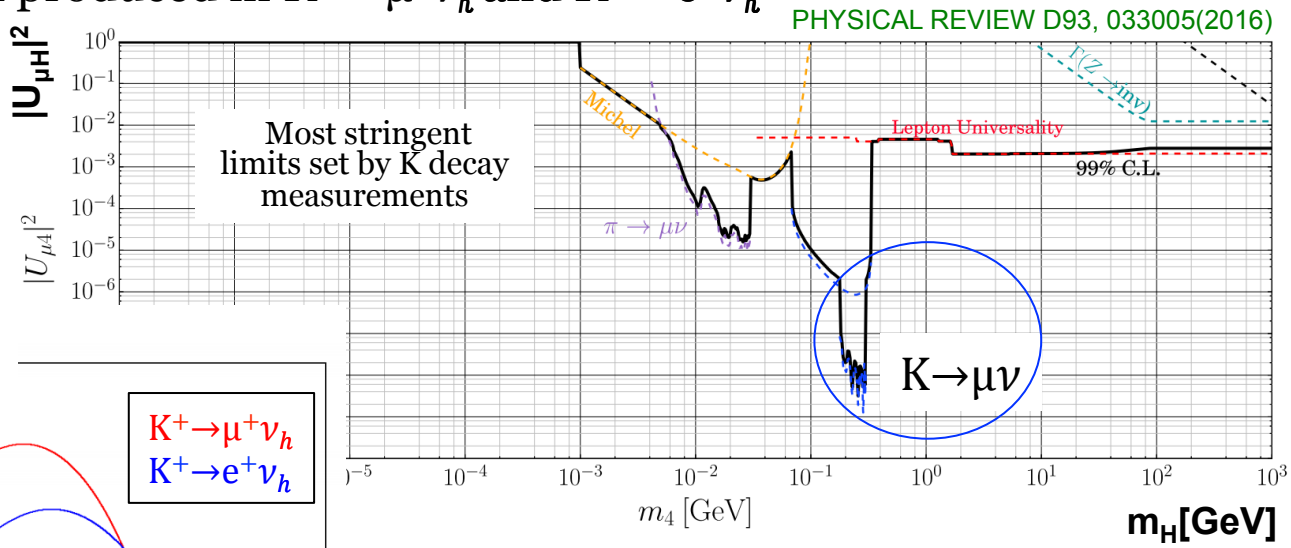
NA62 PROSPECTS:

- $O(10^{12})$ K decays in 2016-2017
- Displaced vertex approach
- Acceptance up to O(10%)
- Almost background free for long-lived particles

HNL Searches in νMSM

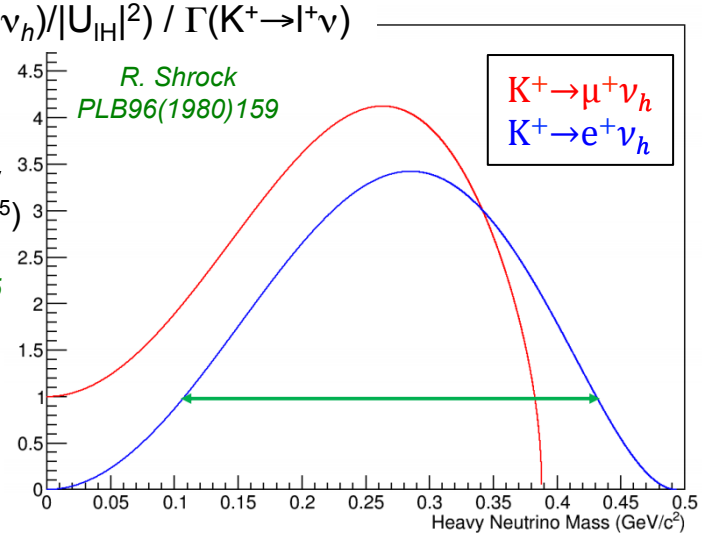
- **νMSM** = **SM** + 3 right-handed HNLs [Asaka et al., PLB 631 (2005) 151]
- Masses: **m_1~10 keV**; **$m_{2,3}$~1 GeV**
- HNLs observable via **production** and **decay**
- Production searches are model-independent
- NA62 searches for HNL produced in $K^+ \to \mu^+ \nu_h$ and $K^+ \to e^+ \nu_h$

Global limits on $|U_{\mu H}|^2$ as a function of HNL mass



HNL production, kinematic factor
$(\Gamma(K^+ \to l^+ \nu_h)/|U_{lH}|^2) / \Gamma(K^+ \to l^+ \nu)$

$K^+ \to e^+ \nu_h$ helicity suppressed (~10^{-5}) for $m(\nu_h) \to 0$
PLB698 (2011) 105



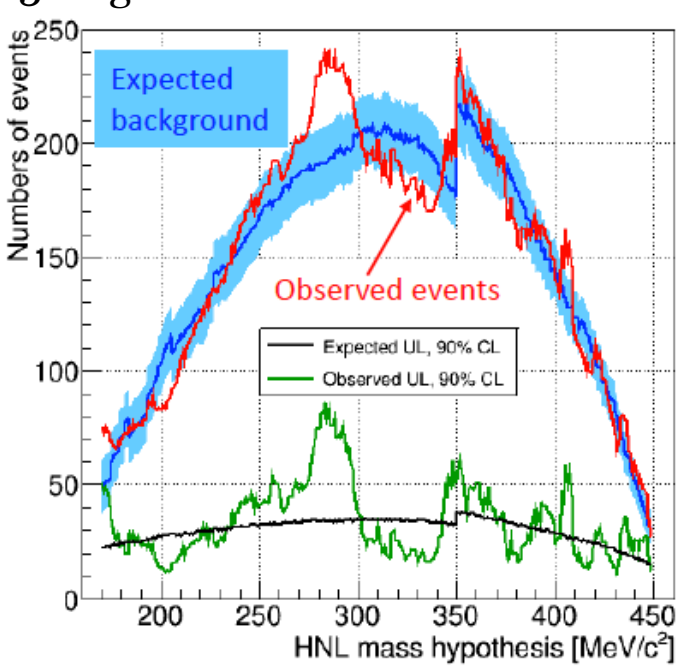
Lifting of the suppression by the HNL (for $m(\nu_h)$ ~0.1GeV) means there could be a similar number of $K^+ \to e^+ \nu_h$ events as $K^+ \to \mu^+ \nu_h$

HNL Production @ NA62

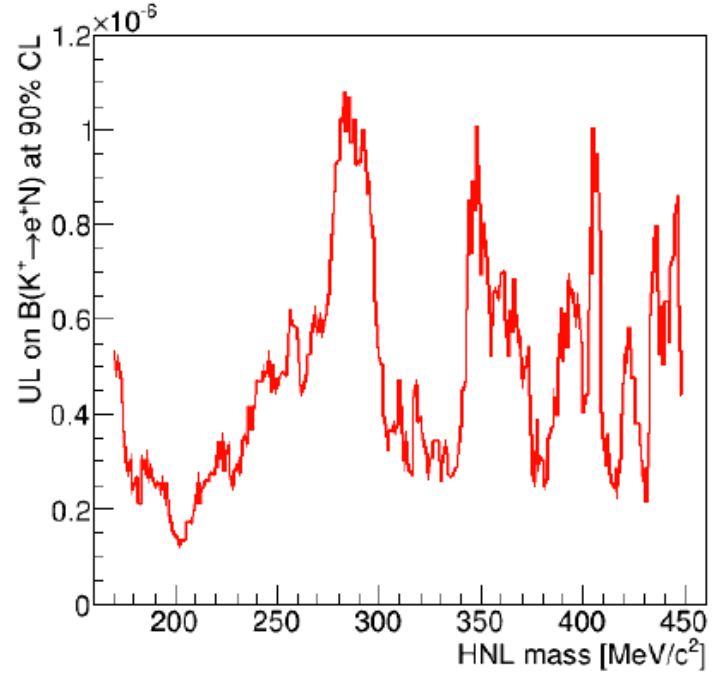
- Rolke-Lopez method used to find upper limits on number of signal events
- Heavy neutrino mass step: 1 MeV/c²
- Search window size for each mass hypothesis: $\pm 1.5\sigma_m$
- Background estimate: polynomial fits to mass spectra outside signal window

No HNL signal observed
~3σ significance

NA62 (2015): $K^+ \to e^+ \nu_h$ search



x $1/A(m_H)*N_K$



Limits on $BR(K^+ \to e^+ \nu_e) \sim 10^{-7}$, limits on $|U_{e4}|^2 \sim 10^{-7}$ for $M_H > 170 MeV/c^2$

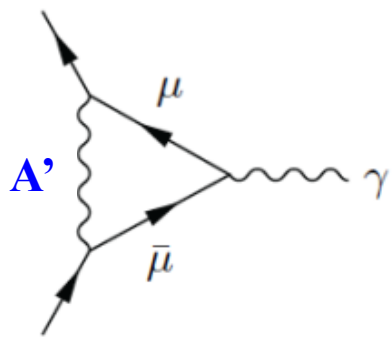
Hidden Sector Motivations

If Dark Matter (DM) is a thermal relic from hot early universe, can hunt for it in particle-physics:
search for non-gravitational interactions DM-SM

- **A mediator of a hidden sector might exist**, inducing DM-SM field **(feeble)** interactions;
- Many possible dynamics: vector (A' dark photon), neutrino (HNL), axial (ALP a), scalar ...

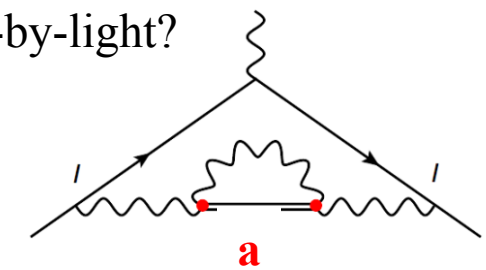
Various experimental hints for hidden sector at MeV-GeV, e.g. a_μ 3.5-σ discrepancy**:**

might be due to a dark photon **A'**...



[*Okun, Holdom*]

…or to an ALP **a** enhancing light-by-light?



[*Marciano et al. arXiv:1607.01022*]

Feeble interaction: ultra-suppressed production rate, **very long-lived states.**
E.g.: 1-GeV mass HNL, $\tau \sim 10^{-5}$-10^{-2} s, decay length ~ 10-10000 Km at SPS energies, suppression at production 10^{-7}-10^{-10}

Hidden Sector at NA62

Feeble interactions: ultra-suppressed production rate, **very long-lived states**

Why searching for hidden sector mediators at NA62?

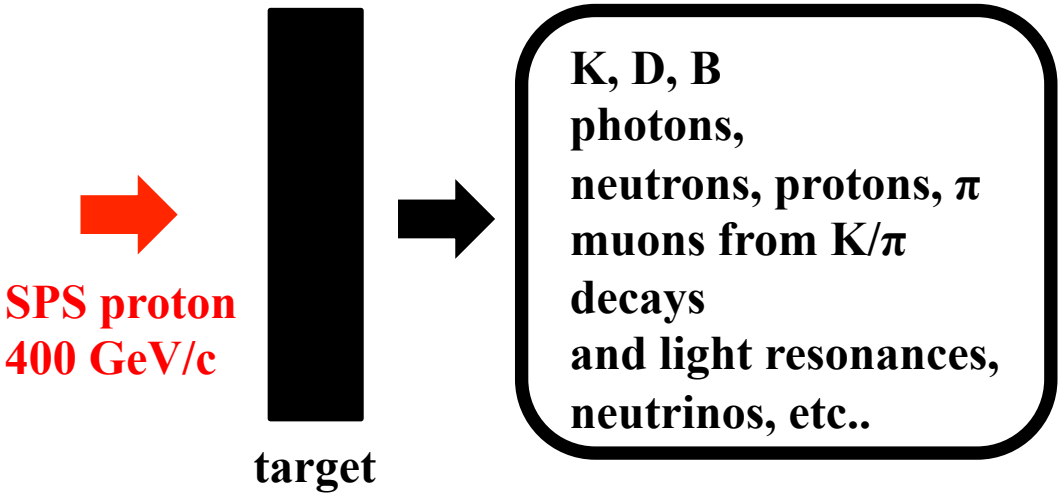
- **High-intensity, high-energy proton beam**
- To date the world best line to produce high intensity fluxes of beauty and charm hadrons and photons through the interactions of protons on a high-Z target is a 400 GeV/c proton beam line extracted from the CERN SPS

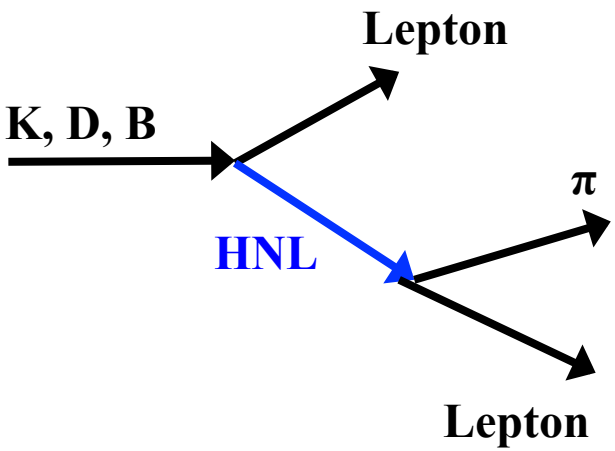
- **Long fiducial decay volume**
- The decays to SM particles can optimally be detected using an experiment with decay volume tens of meters long followed by a spectrometer with particle identification capabilities

The NA62 detector perfectly fits these requirements

Hidden Sector Particle at NA62

K, B, Bs, D, Ds → lepton HNL
K, B, Bs, D, Ds → semi-leptonic modes



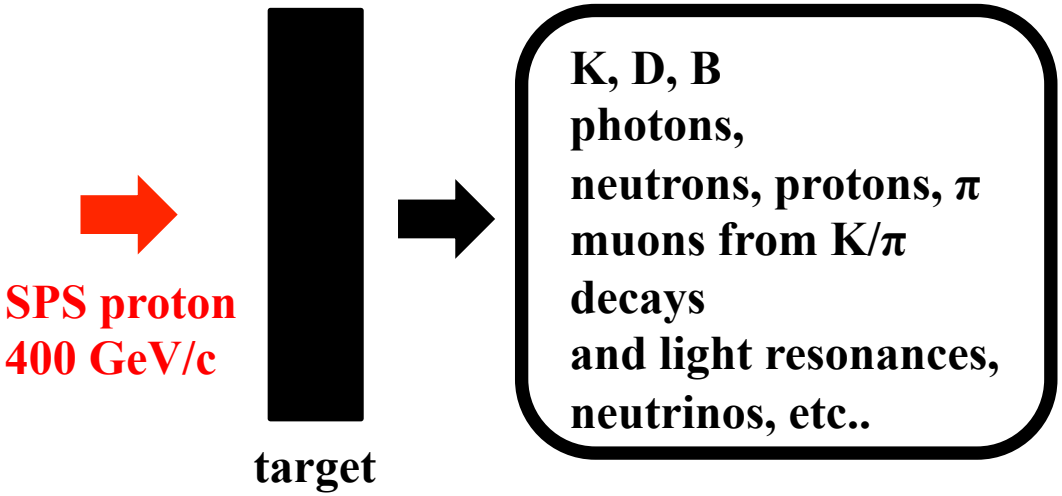


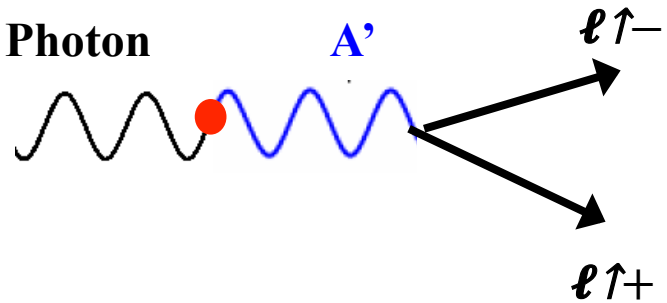
At SPS energies:
σ (pp → s sbar X) ~ 0.15
σ (pp → c cbar X) ~ 2 10^{-3}
σ (pp → b bbar X) ~ 1.6 10^{-7}

Heavy neutrino couplings enter both in production and in decay (~ U^4 process)

Hidden Sector Particle at NA62

Dark photons





At SPS energies:

σ (pp → s sbar X) ~ 0.15

σ (pp → c cbar X) ~ 2 10^{-3}

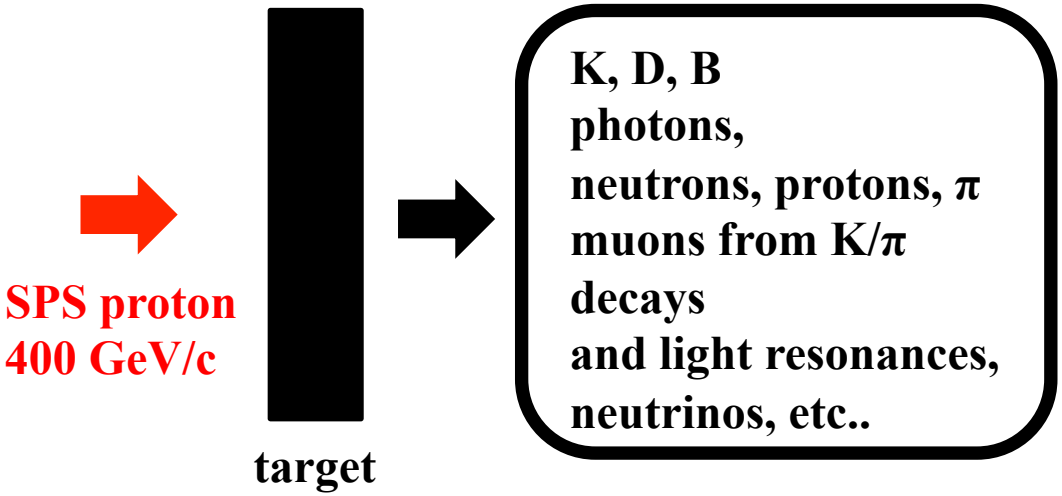
σ (pp → b bbar X) ~ 1.6 10^{-7}

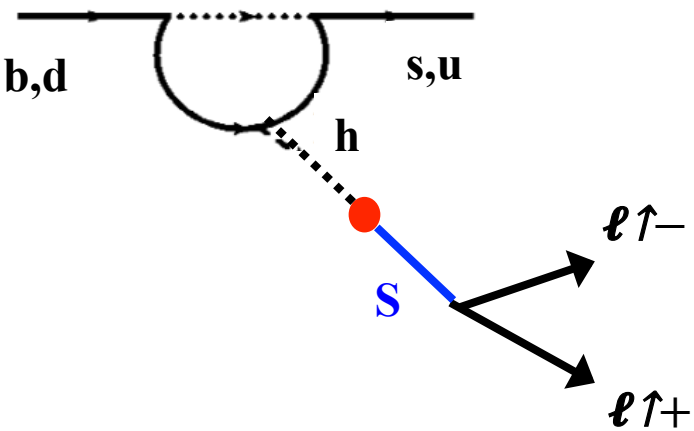
Photon produced in light meson resonances, bremsstrahlung, and QCD processes.

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

Hidden Sector Particle at NA62

Dark scalars: B →K S, K →π S





At SPS energies:

σ (pp → s sbar X) ~ 0.15

σ (pp → c cbar X) ~ 2 10^{-3}

σ (pp → b bbar X) ~ 1.6 10^{-7}

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

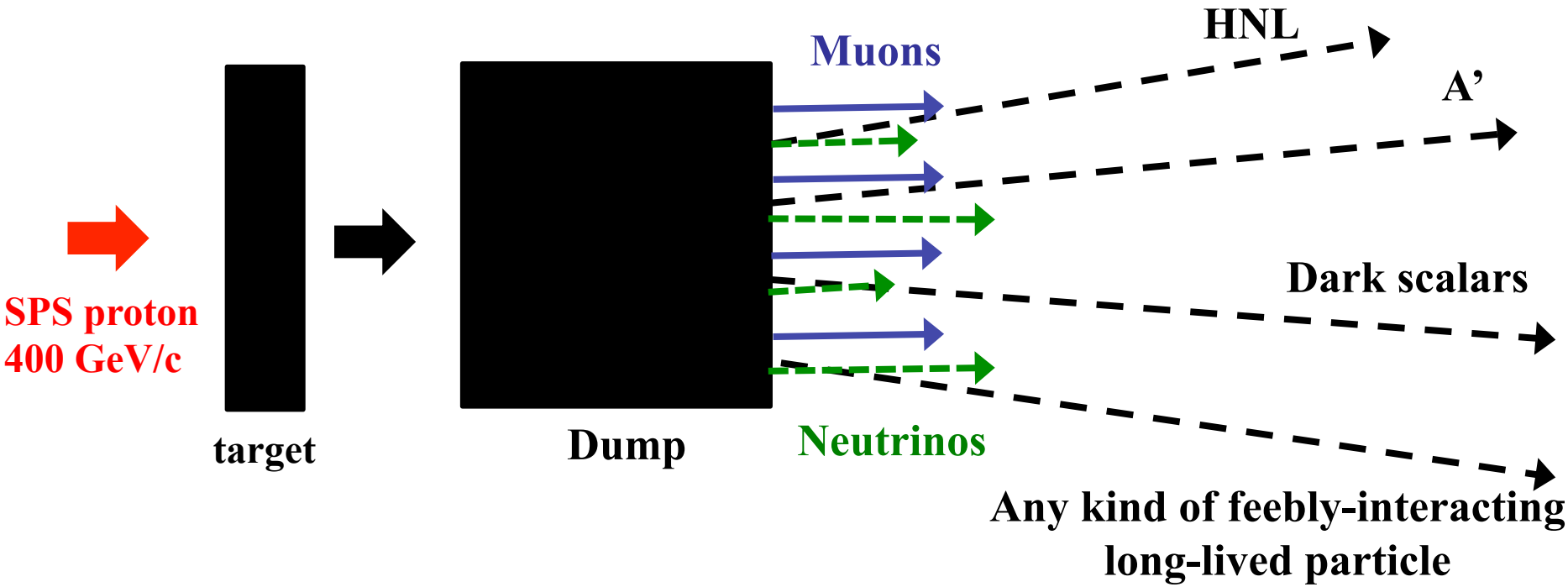
$\Gamma(D \to \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$

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

Hidden Sector Particle at NA62

"Dump" mode

All beam-induced backgrounds are stopped but **muons** and **neutrinos**



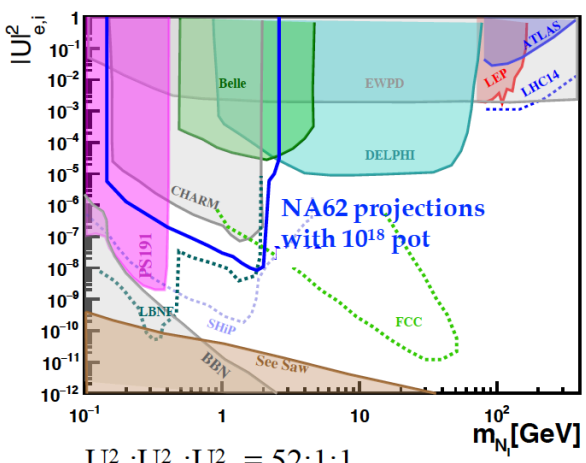
A setup with long decay volume allows for probing low values of couplings (as the lifetime of hidden-sector particles ~ 1/coupling^2)

Heavy Neutral Lepton

NA62 sensitivity with ~10^{18} **400-GeV PoT** running in "dump" mode

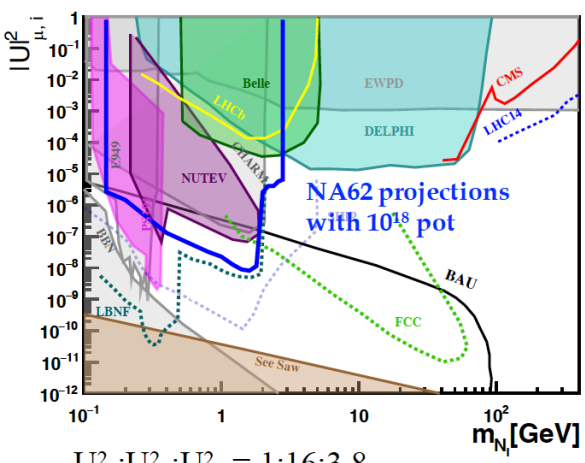
- Fully reconstructed 2-track final states
- All HNL decays, close and open channels
- Include trigger/acceptance/selection efficiency
- Assume zero-background
- Evaluate expected 90% C.L. exclusion plots

Scenario 1



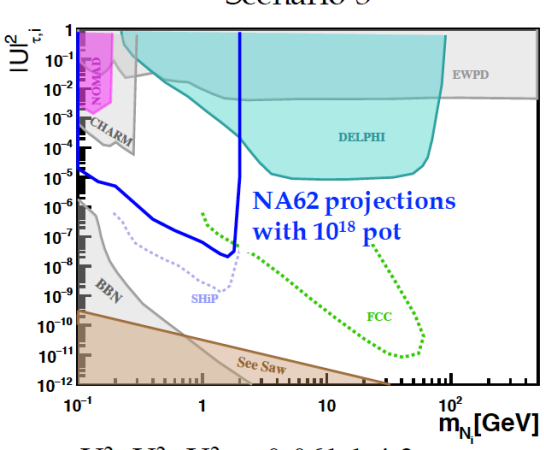
$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active **ν** masses

Scenario 2



$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
Normal hierarchy of active **ν** masses

Scenario 3

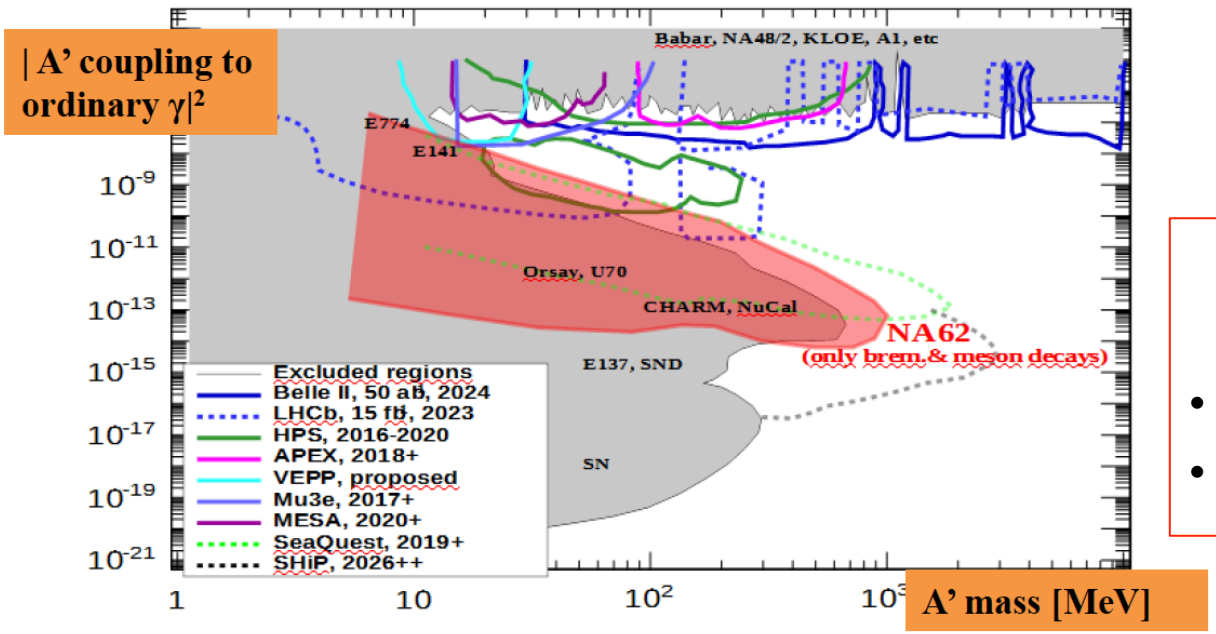


$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active **ν** masses

Dark Photon

NA62 sensitivity with ~10^{18} **400-GeV PoT** running in "dump" mode

- Fully reconstructed 2-track final states
- Search for displaced, di-lepton decays of DP (A' → ee,μμ)
- Include trigger/acceptance/selection efficiency
- Assume zero-background
- Evaluate expected 90% C.L. exclusion plots



Projections consider only A' production in Be target

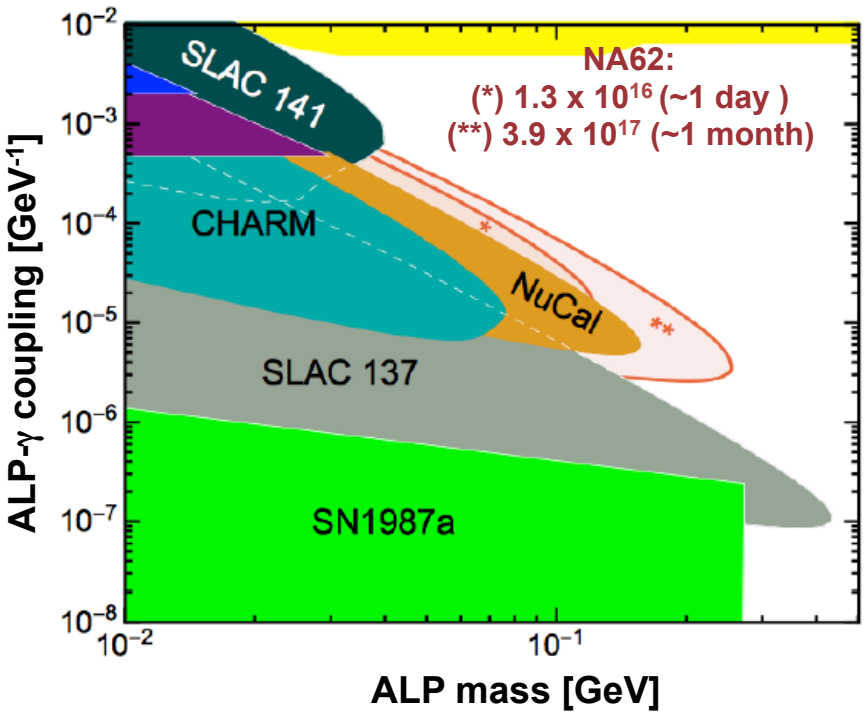
Sensitivity expected to be higher when including:

- Direct QCD production of A'
- A' production in the TAX

Axion-like Particle (ALP)

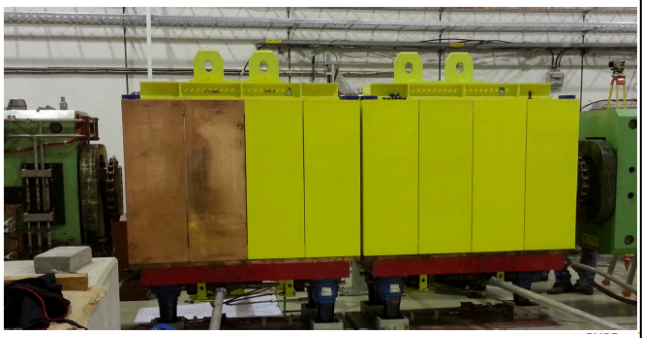
NA62 sensitivity with **1.3 x 10^{16} (3.9 x 10^{17}) 400-GeV PoT** corresponding to 1 day (1 month) of runs in "dump" mode

- study ALP production via Primakoff effect [*JHEP 1602 (2016) 018*] at target
- search for ALP → γγ in NA62 fiducial volume, account for geometrical acceptance
- Assume zero-background, evaluate expected 90% C.L. exclusion contours



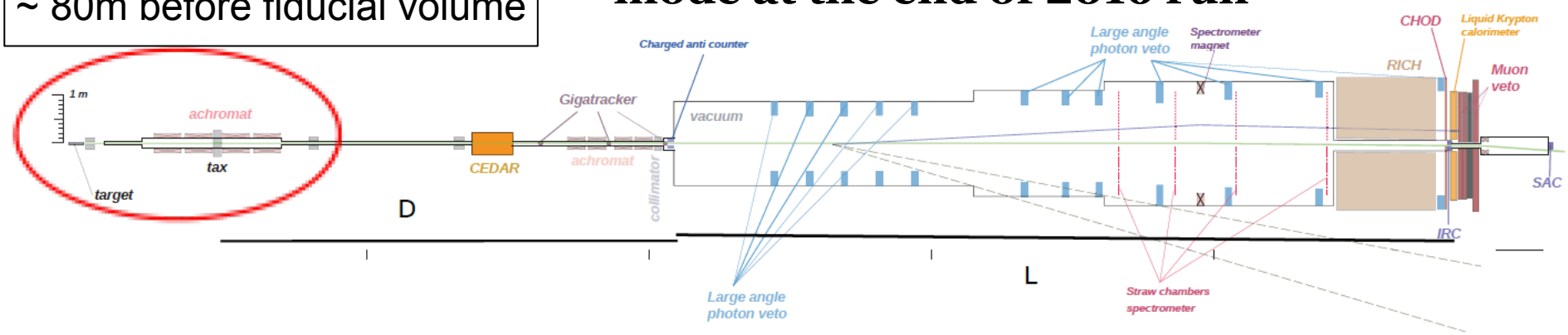
Axion-like particle (ALP) production in NA62

TAX1-2: movable copper + iron made collimators of ~22λ_I total thickness



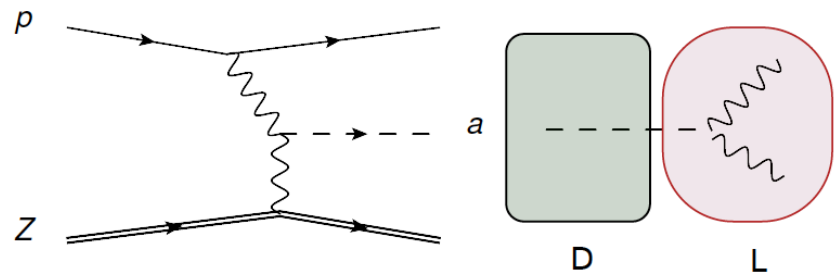
~ 80m before fiducial volume

- K^+ from Be target, large fraction of SPS protons continuously 'dumped'
- long-lived, weakly-interacting particles produced along with nominal beam directly/decay
- possibility to dump entire beam by closing TAX (~ 10^{12} p/sec) and removing Be target
  - Copper TAX → coherent Z^2 enhancement with charge
- **collected ~ 2.5 x 10^{15} PoT in beam "dump" mode at the end of 2016 run**



ALP production from TAX in NA62

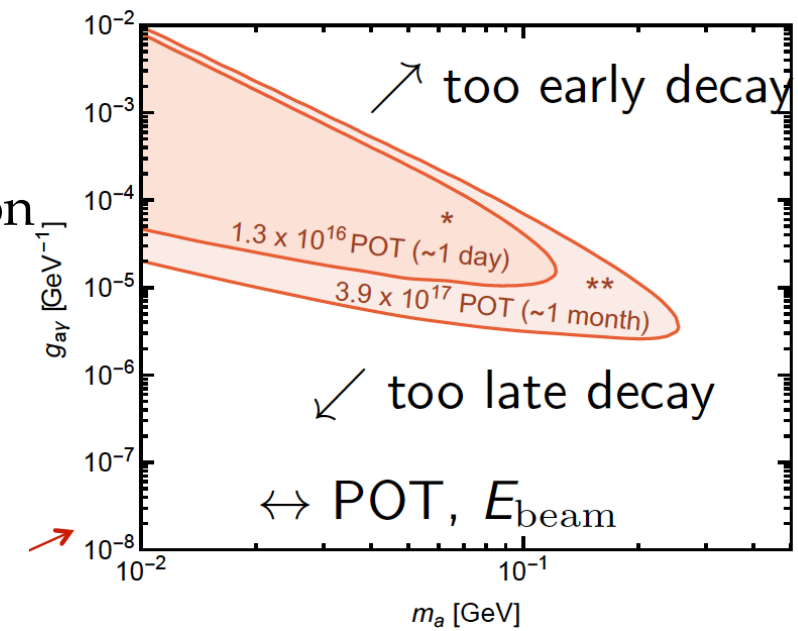
Pseudo-scalar ALP (a) created by photon fusion (Primakoff effect);



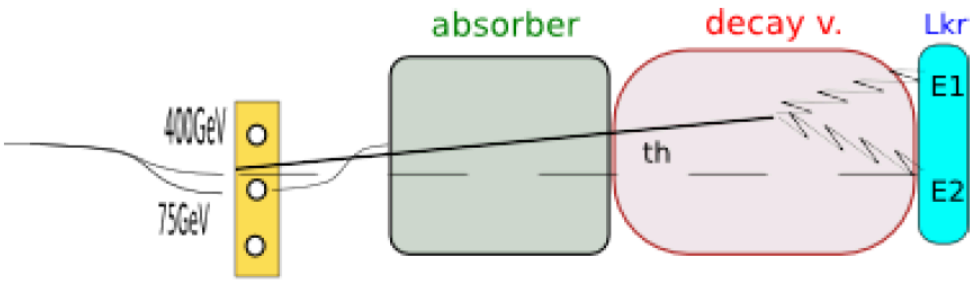
ALP lifetime dependence on its mass and coupling with photon: $t \sim 1/(g_{a\gamma}^2 m_a^3)$

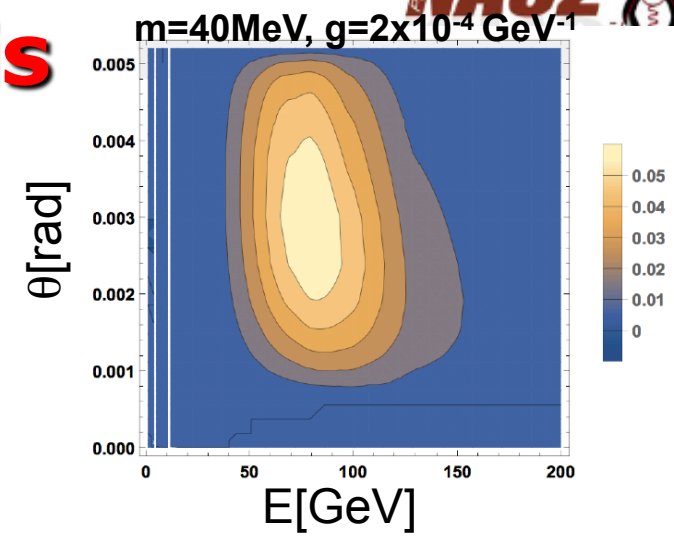
The projected limits fold as input:
1. the differential cross-section for production
2. coincidence and acceptance in EM calo
3. probability to decay within the FV

Expected limits on the mass and coupling assuming (*)1 day/(**)1 month of data taking in "dump" mode



ALP Ongoing Analysis





- **Challenging**:
  - photon is not tracked, know only **E1, E2, d in Ecal** and need to impose mass or decay point to discriminate;
- **Mitigation:**
  - only extend beyond existing limits at small I_d: decay in absorber:

$$\sim \exp(-l_{\rm abs}/l_d),\ l_d = \gamma\beta\tau \sim \frac{E_a}{m}\frac{64\pi}{m^3 g^2}$$

- yields the **ALPs** in reach **highly boosted** $E_a = E(\gamma 1) + E(\gamma 2)$
- their barycenter enclose a (computable) non-zero angle θ
- compare charged sample in side-band, **deduce expected background** in signal region - optimization of signal efficiency for (g,m) in full MC on the way