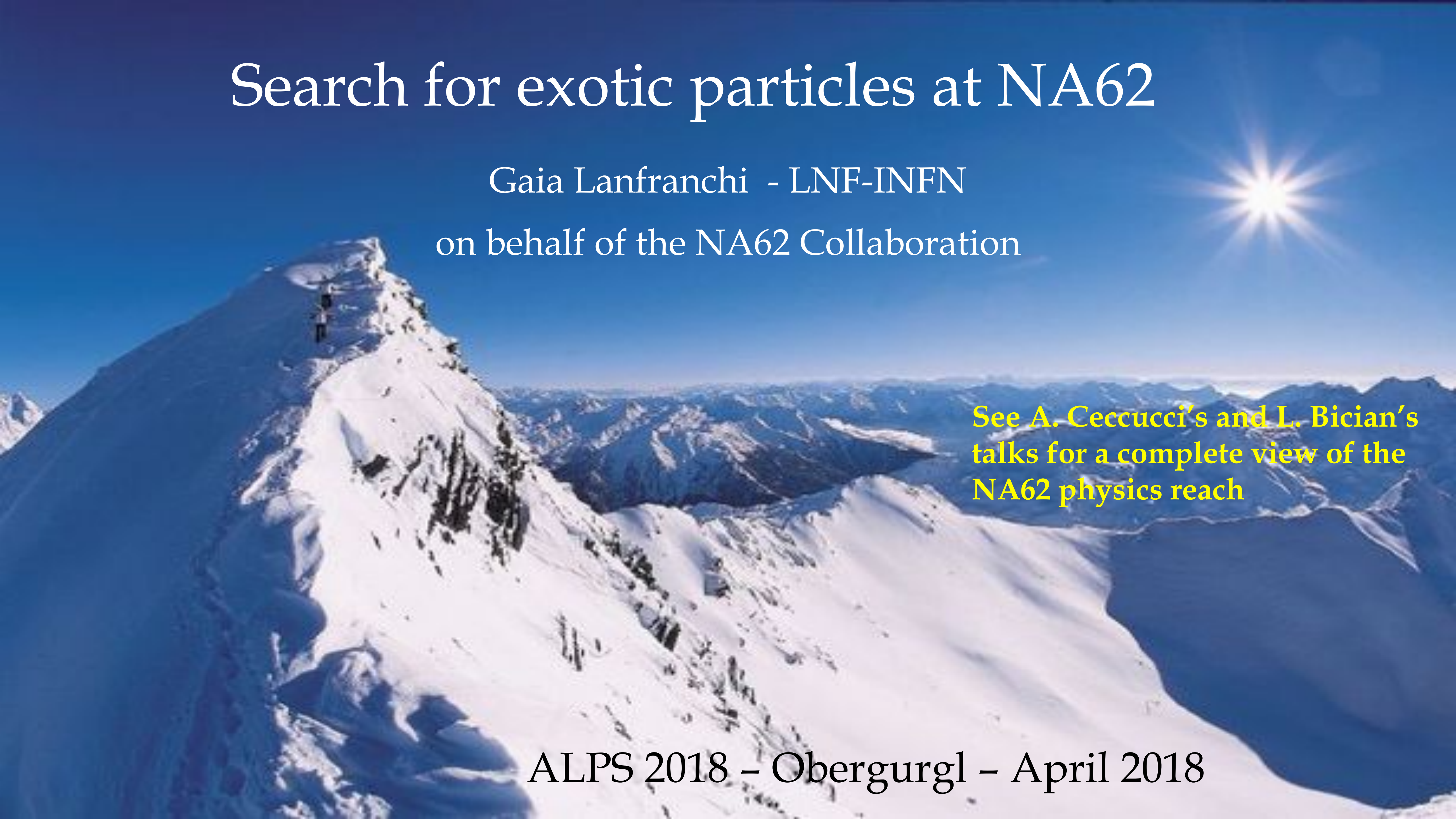


Search for exotic particles at NA62

Gaia Lanfranchi - LNF-INFN

on behalf of the NA62 Collaboration

See A. Ceccucci's and L. Bician's talks for a complete view of the NA62 physics reach

ALPS 2018 – Obergurgl – April 2018

Preamble

With the **discovery at the LHC** of the Higgs boson, the main missing block for the experimental validation of the Standard Model is now in place.

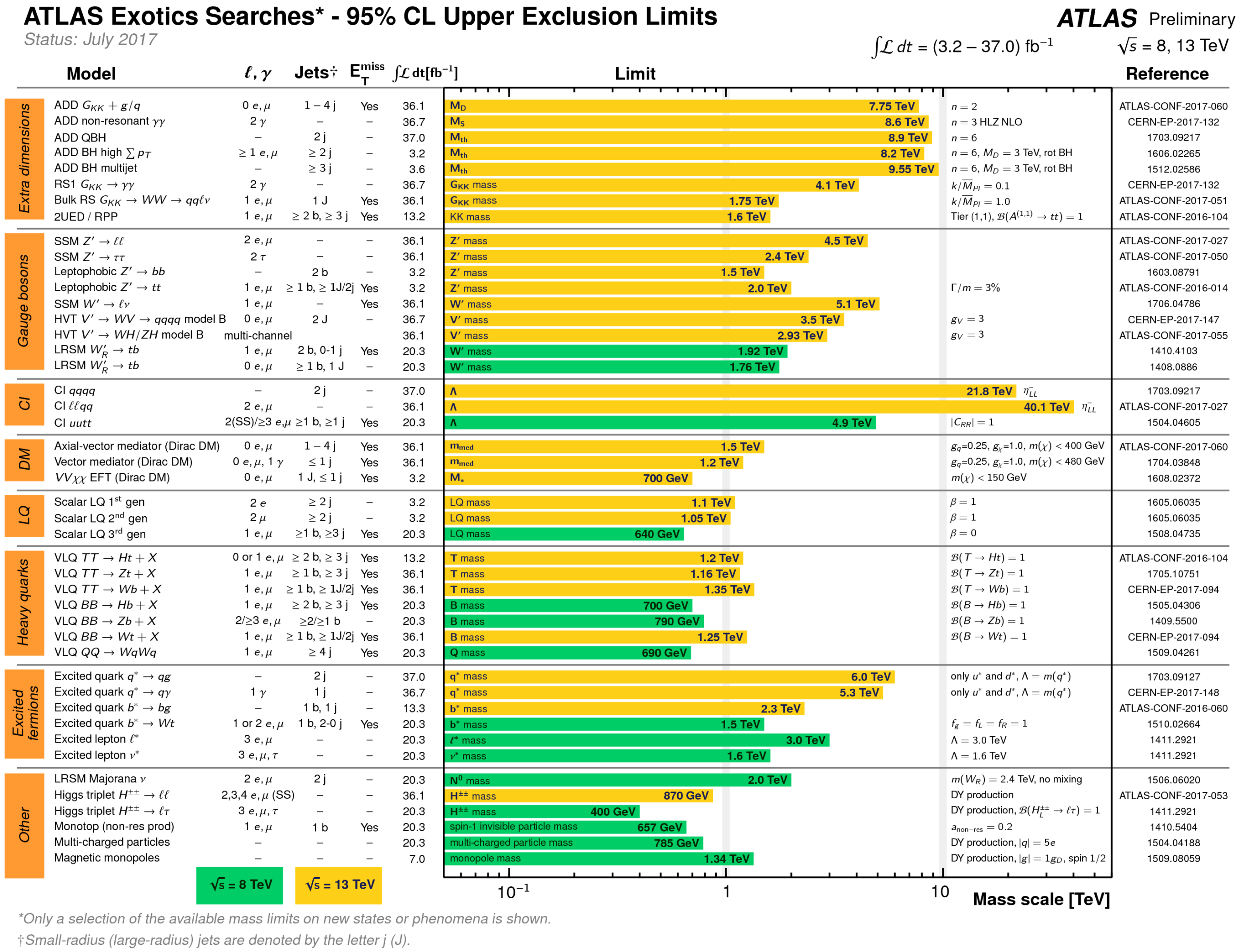
An additional **LHC result of great importance (and totally unexpected) is that a large new territory has been explored and no unambiguous signal of New Physics has been found**.

After ~7 years of excellent running of the LHC and its experiments some conclusions can be drawn.

No New Physics in direct searches

(almost all the limits are above the TeV scale)

CERN DG's New Year speech, Jan 2018



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	🟨 G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	🟨 Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	3.2	🟨 Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	36.1	🟨 W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	36.7	🟨 V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV	η_{LL}^{-}	1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ 40.1 TeV	η_{LL}^{-}	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0\ e, \mu, 1\ \gamma$	≤ 1 j	Yes	36.1	🟨 m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	36.1	🟨 T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	🟨 T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	🟨 B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	🟨 b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

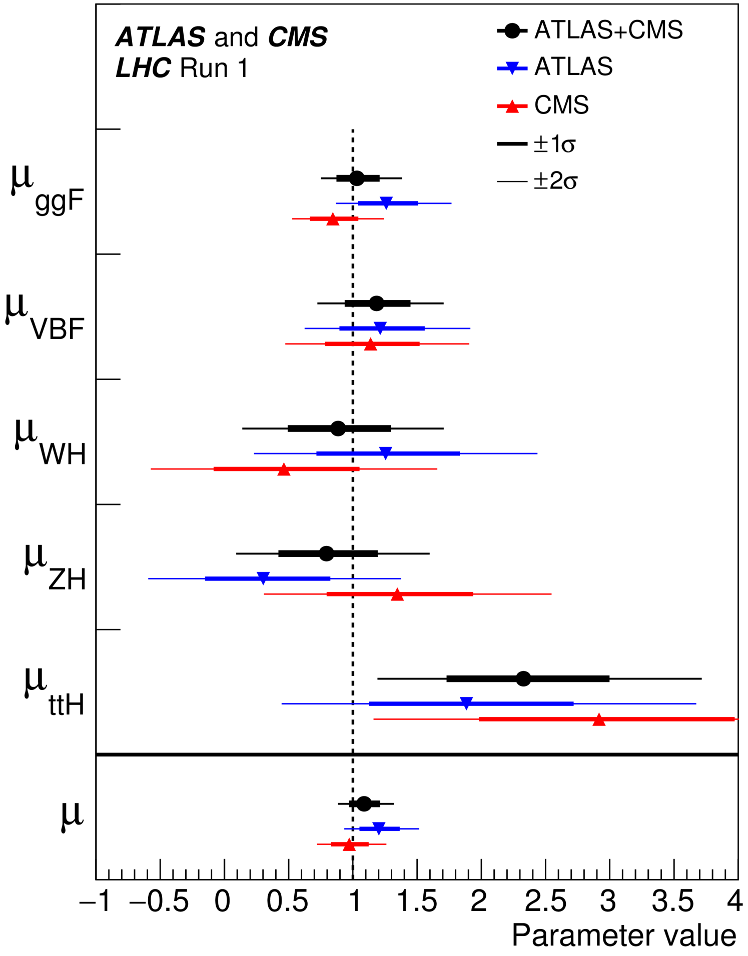
**Only a selection of the available mass limits on new states or phenomena is shown.*

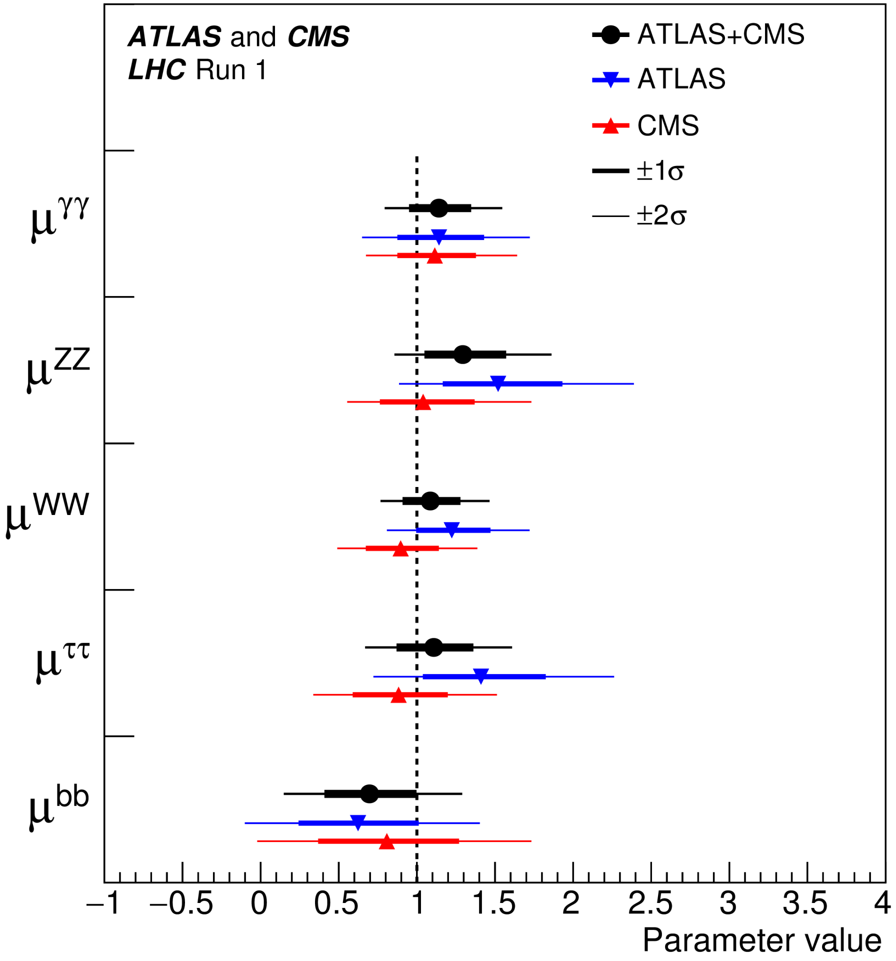
†Small-radius (large-radius) jets are denoted by the letter j (J).

No New Physics in Higgs couplings

Production and decay rates compatible with the SM Higgs at 20-60 % accuracy

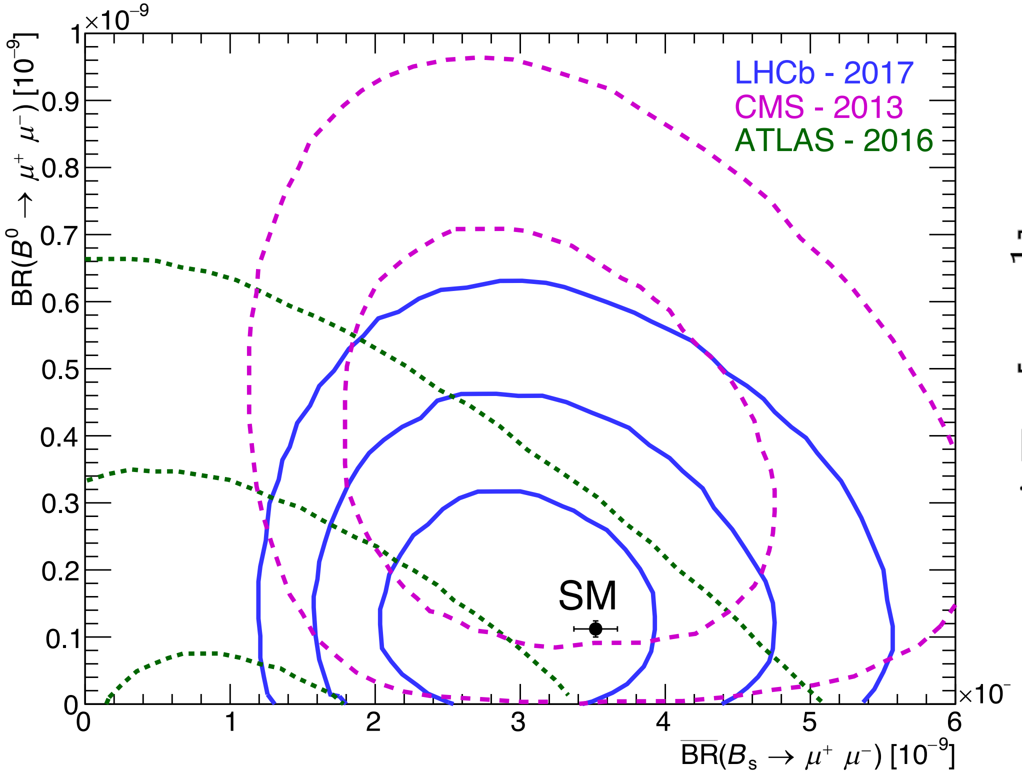
P. Meridiani EPS conference 2017

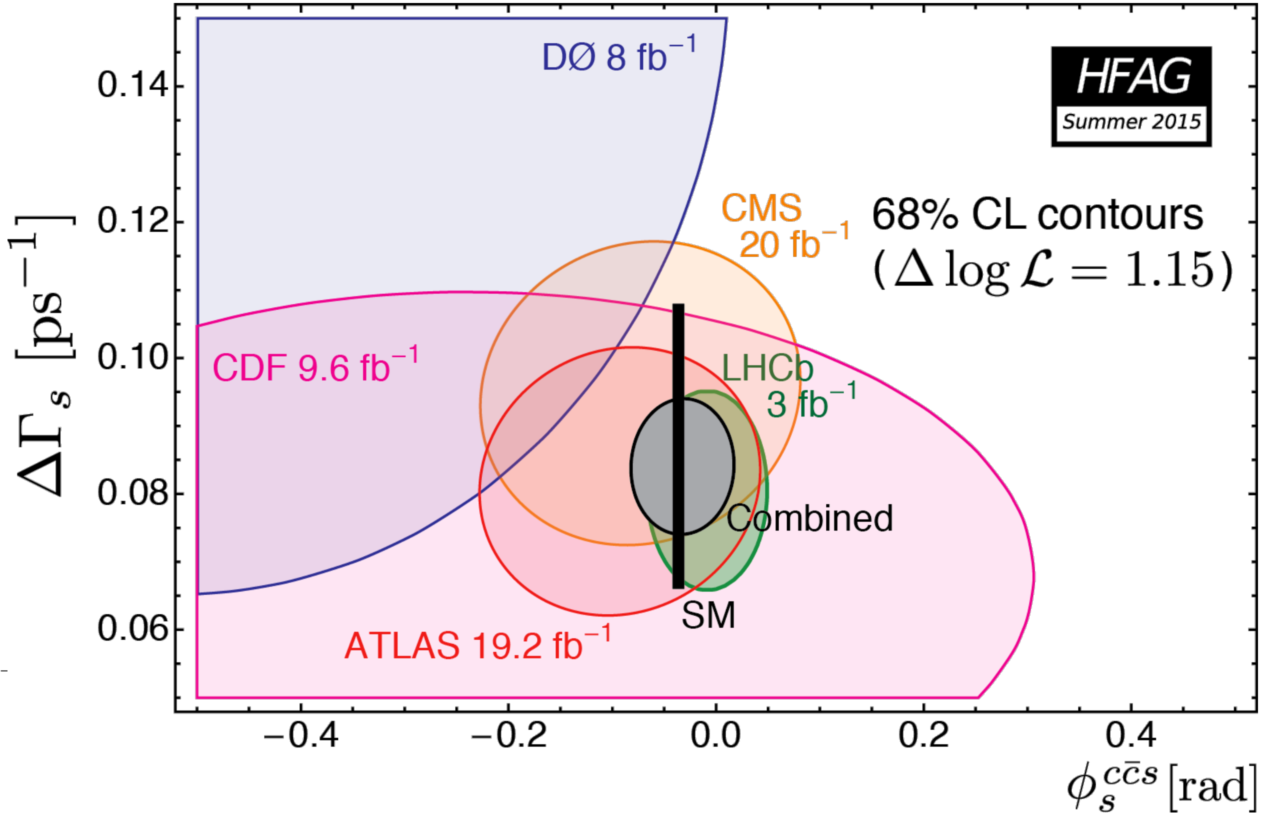




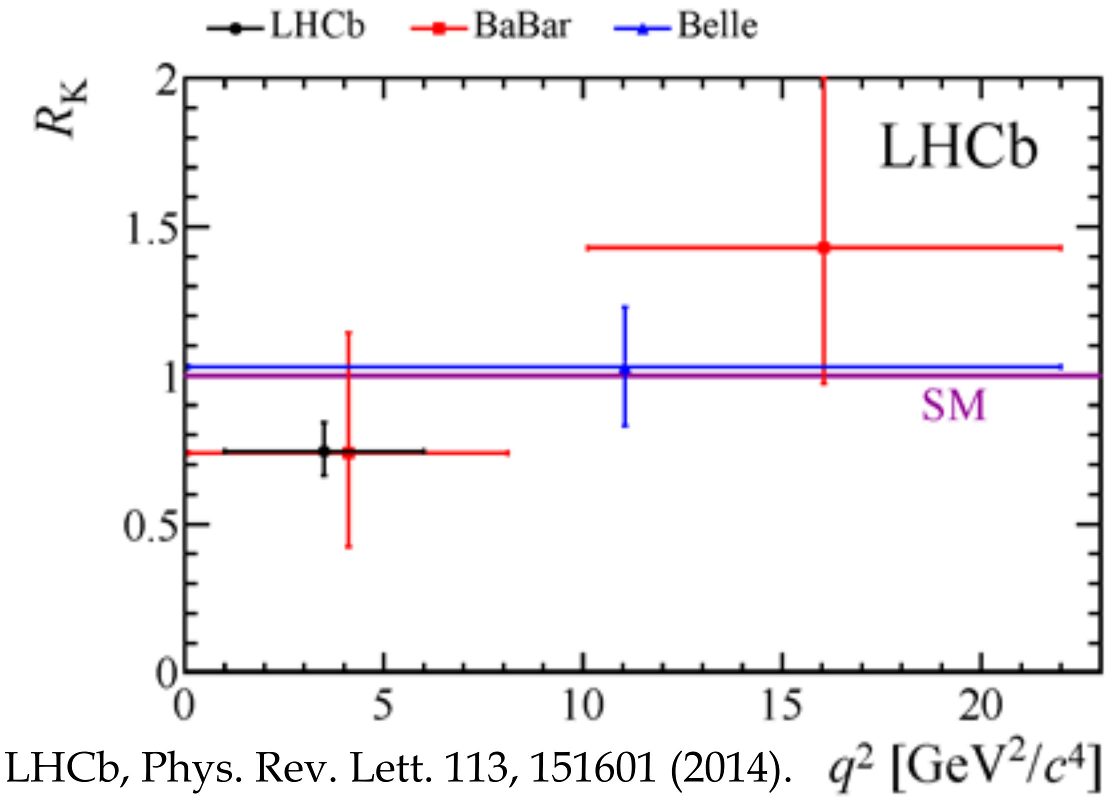
No New Physics in Flavour ?

The $B^0_{(s)} \longrightarrow \mu\,\mu$ branching fractions and Bs mixing phase in excellent agreement with SM predictions

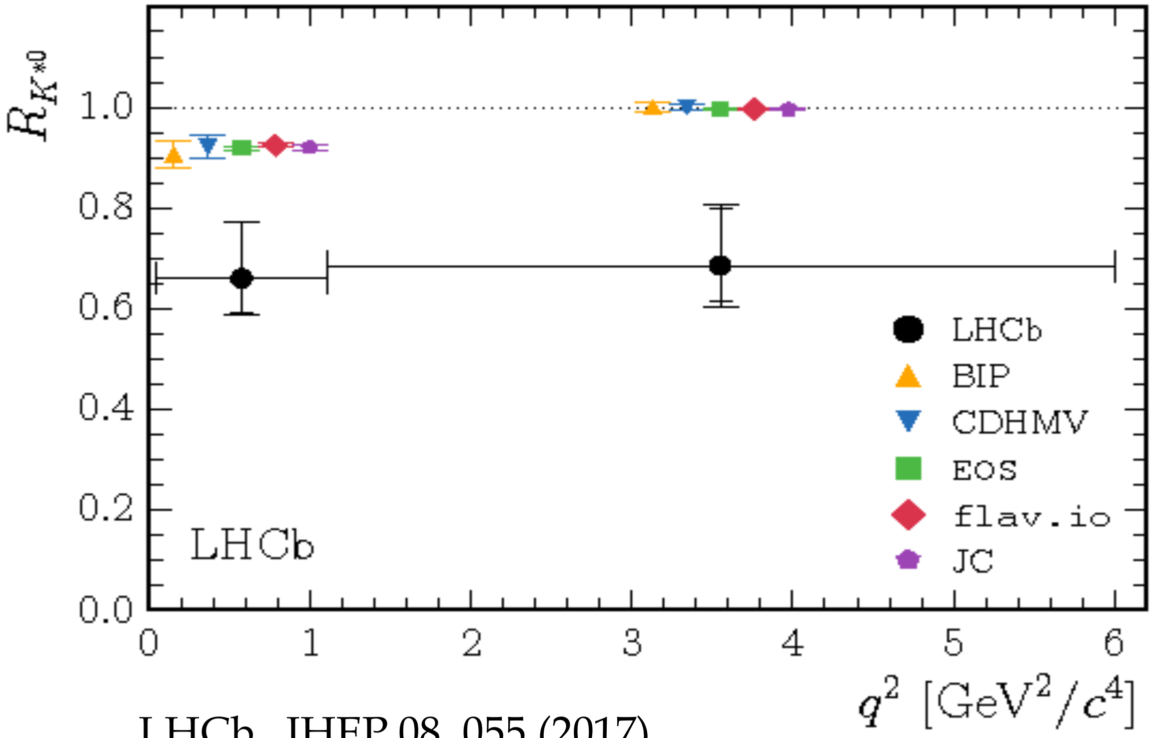




Lepton Flavor Universality anomalies from LHCb



LHCb, Phys. Rev. Lett. 113, 151601 (2014).

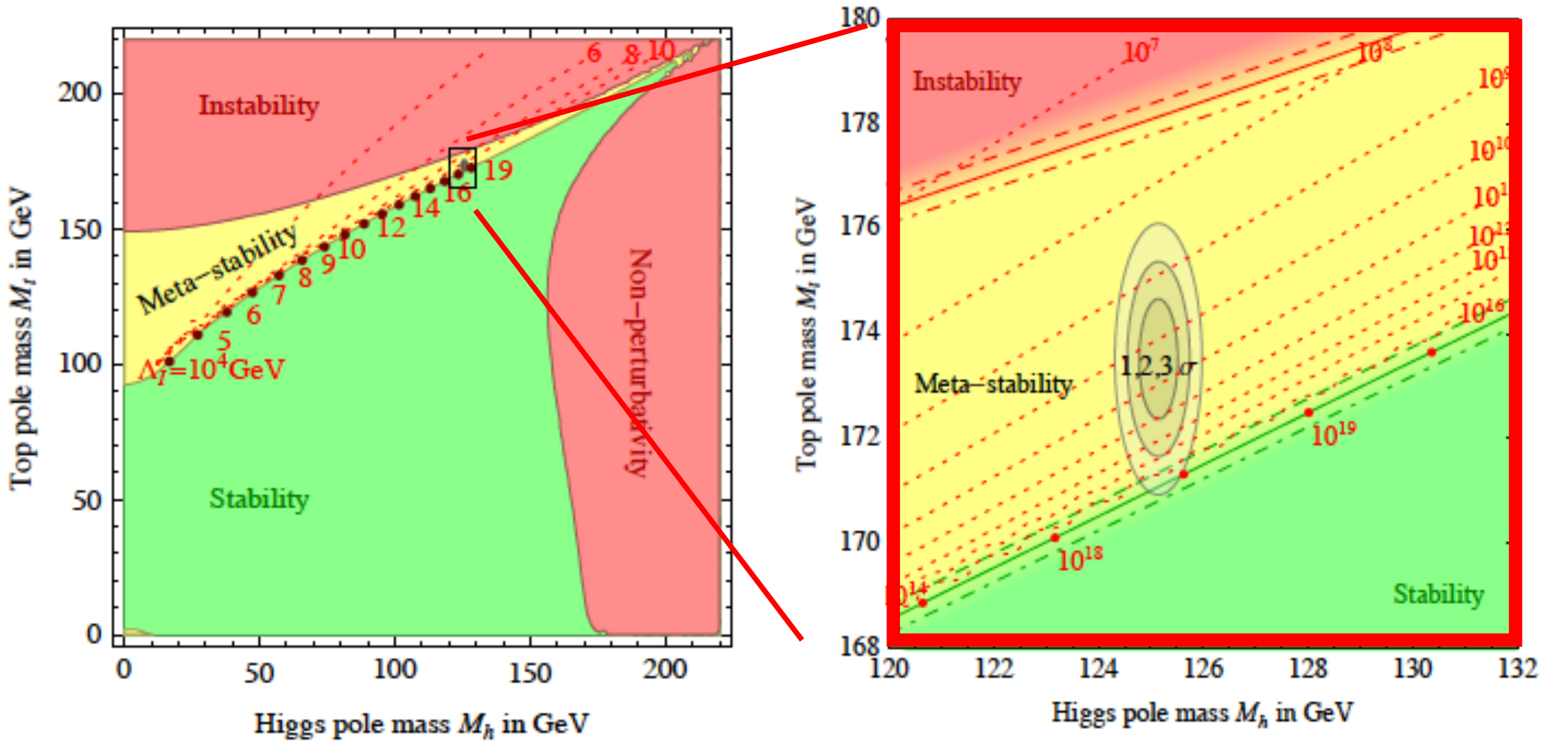


LHCb, JHEP 08, 055 (2017).

An open issue, yet.

A "metastable" world

The main reason for NP at the TeV scale was to solve the fine tuning problem of the mass of the Higgs…



Buttazzo et al.
JHEP 1312 (2013) 089;

A.V. Bednyakov,
Phys.Part.Nucl. 48
(2017) no.5, 698

…..However **the values of the Higgs (m_H ~125.1 GeV) and top mass (m_{top} = 173.1 GeV) the Nature has chosen make the Standard Model a self-consistent (effective field) theory all the way up to the quantum gravity Planck scale**, **even in absence of NP at the TeV scale.**

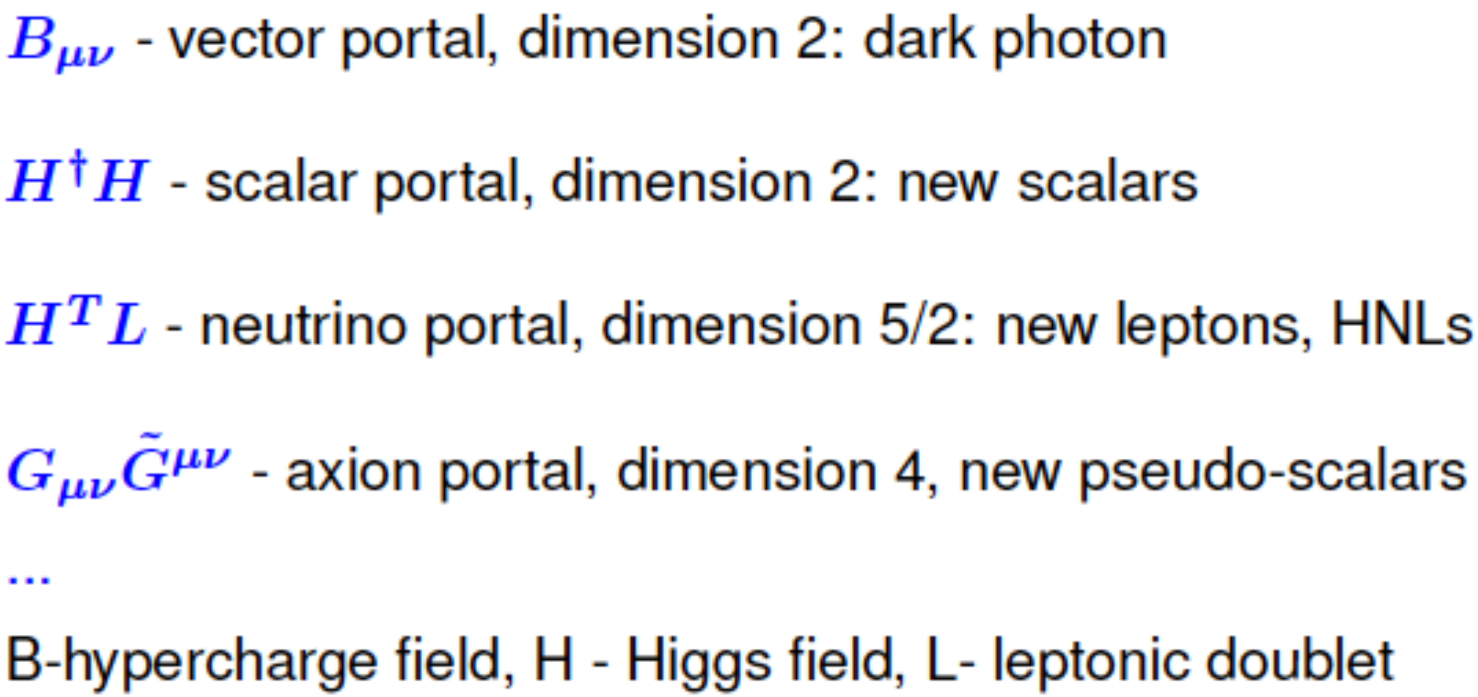
An attractive possibility

- **The Standard Model, as it is, is renormalizable and predictive up to the Planck scale.**

- **However we do have experimental evidence of physics beyond SM:**
  - Dark Matter
  - Neutrino masses and oscillations;
  - Baryogenesis
  - Cosmological inflation
  - Accelerated expansion of the Universe

- **An attractive possibility:**
  there could be no new scale between the EW and the Planck scale:
  - **all the unresolved problems could be explained by NP below the EW scale, that does not perturb the smooth running of the Higgs self-coupling.**

Interaction between DM and SM mediated by Gauge-invariant operators



$B_{\mu\nu}$ - vector portal, dimension 2: dark photon

$H^\dagger H$ - scalar portal, dimension 2: new scalars

$H^T L$ - neutrino portal, dimension 5/2: new leptons, HNLs

$G_{\mu\nu}\tilde{G}^{\mu\nu}$ - axion portal, dimension 4, new pseudo-scalars

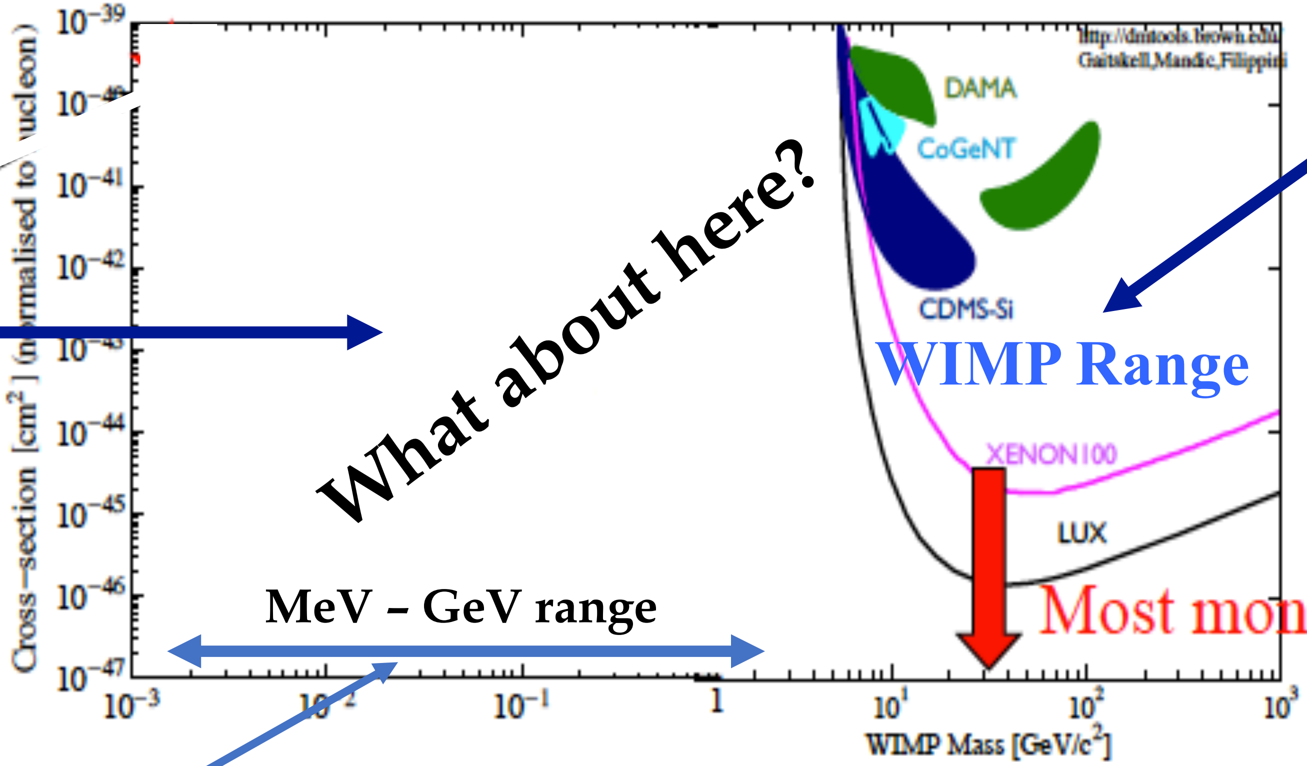
...

B-hypercharge field, H - Higgs field, L- leptonic doublet

MeV-GeV region for Light Dark Matter with thermal origin

Light Dark Matter with **light mediators (hence new forces) that couple very weakly to SM and are therefore *hidden* or *dark***

traditional WIMP at TeV scale **with Z mediator** (excluded by current limits)



What about here?

WIMP Range

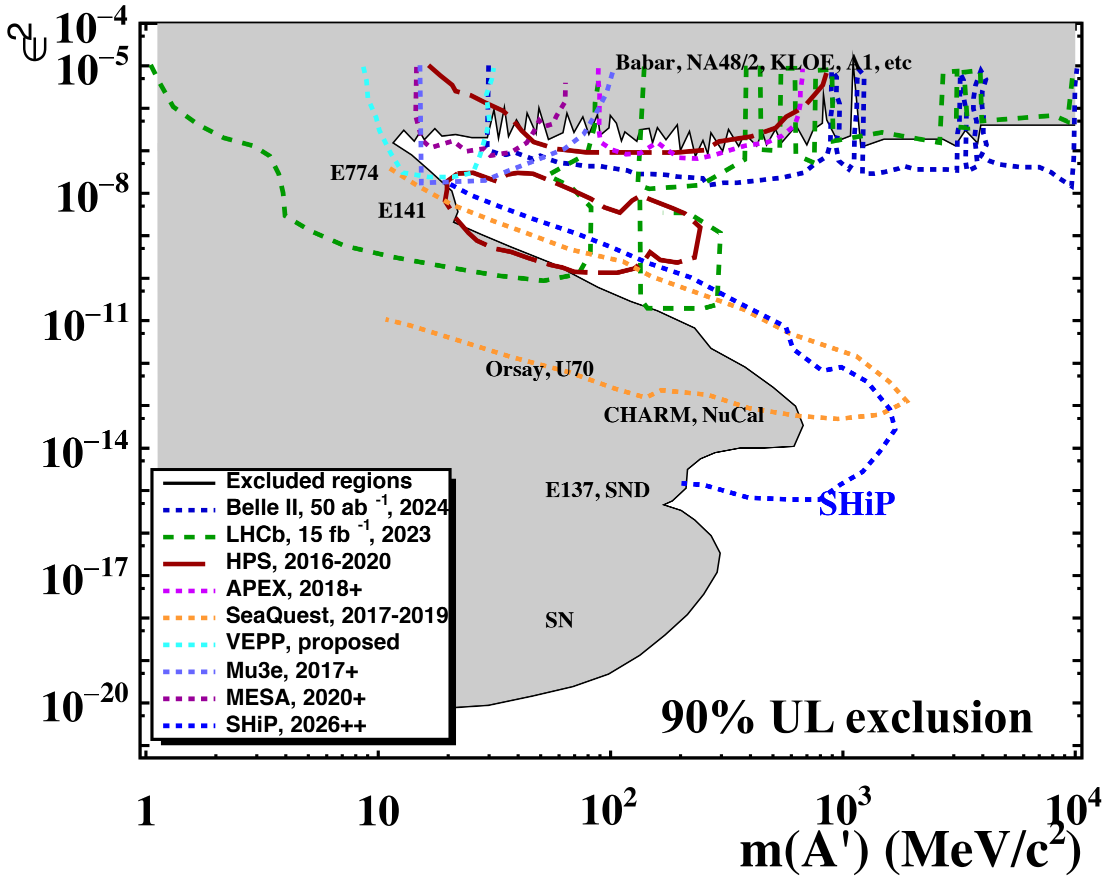
MeV – GeV range

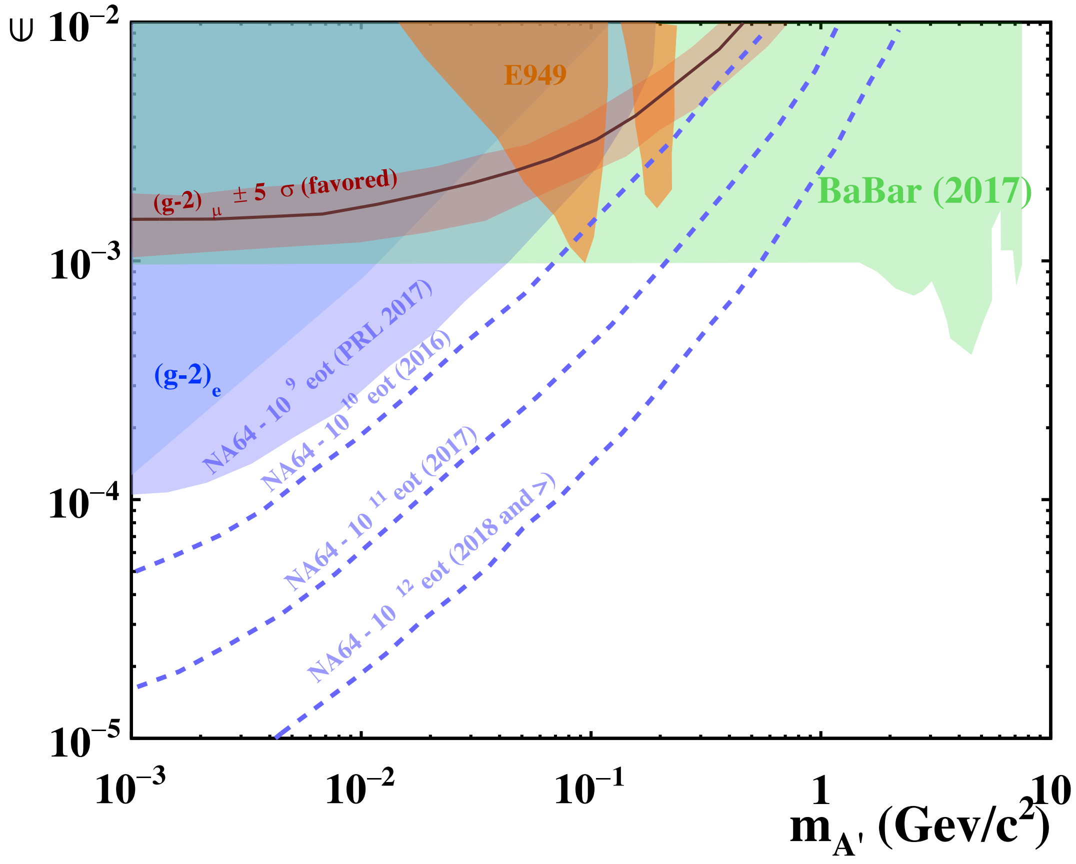
Most money spent

Courtesy of M. Pospelov

Range compatible with the relic density

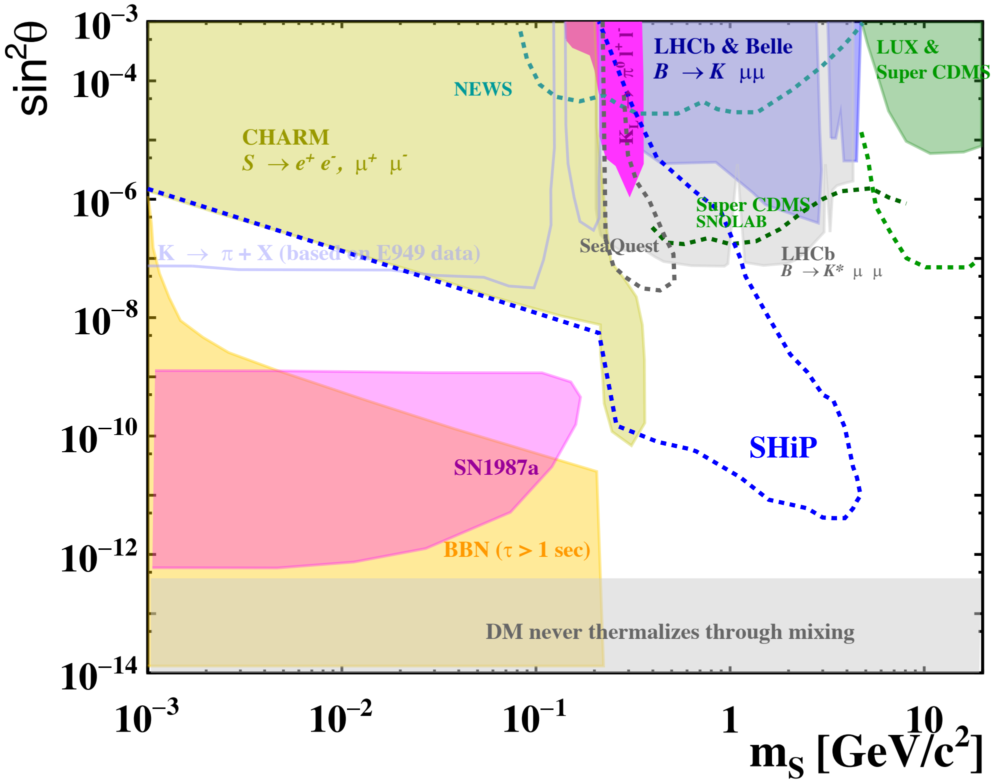
Current exclusion limits and prospects for Dark Photon into visible and invisible (DM) decays

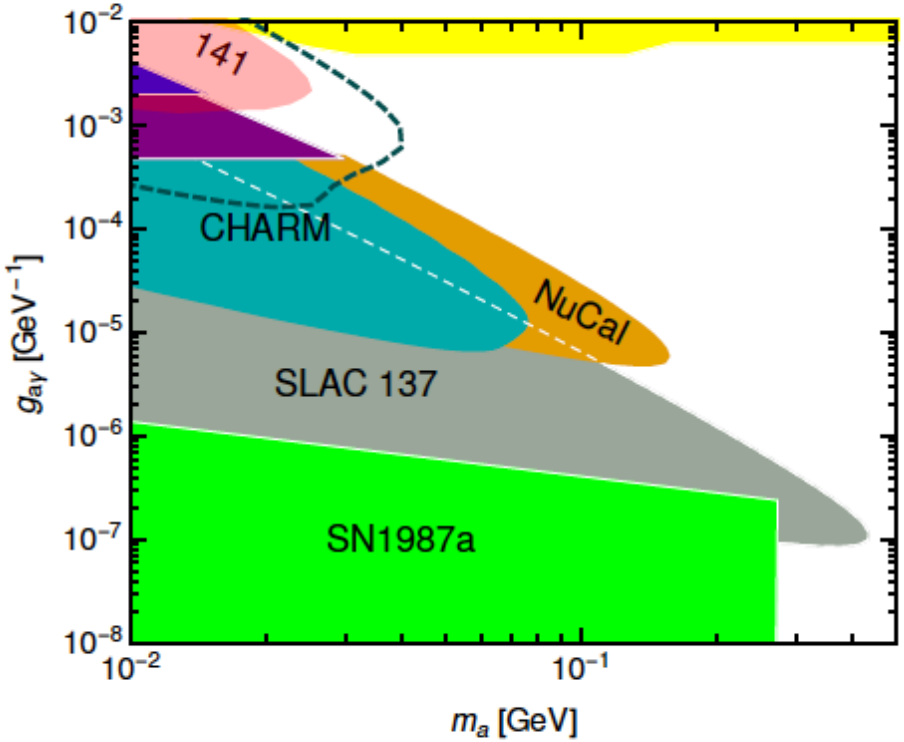




Dark Photon produced via kinetic mixing with ordinary photons

Current exclusion limits and prospects for Dark Scalar and ALPS with photon coupling



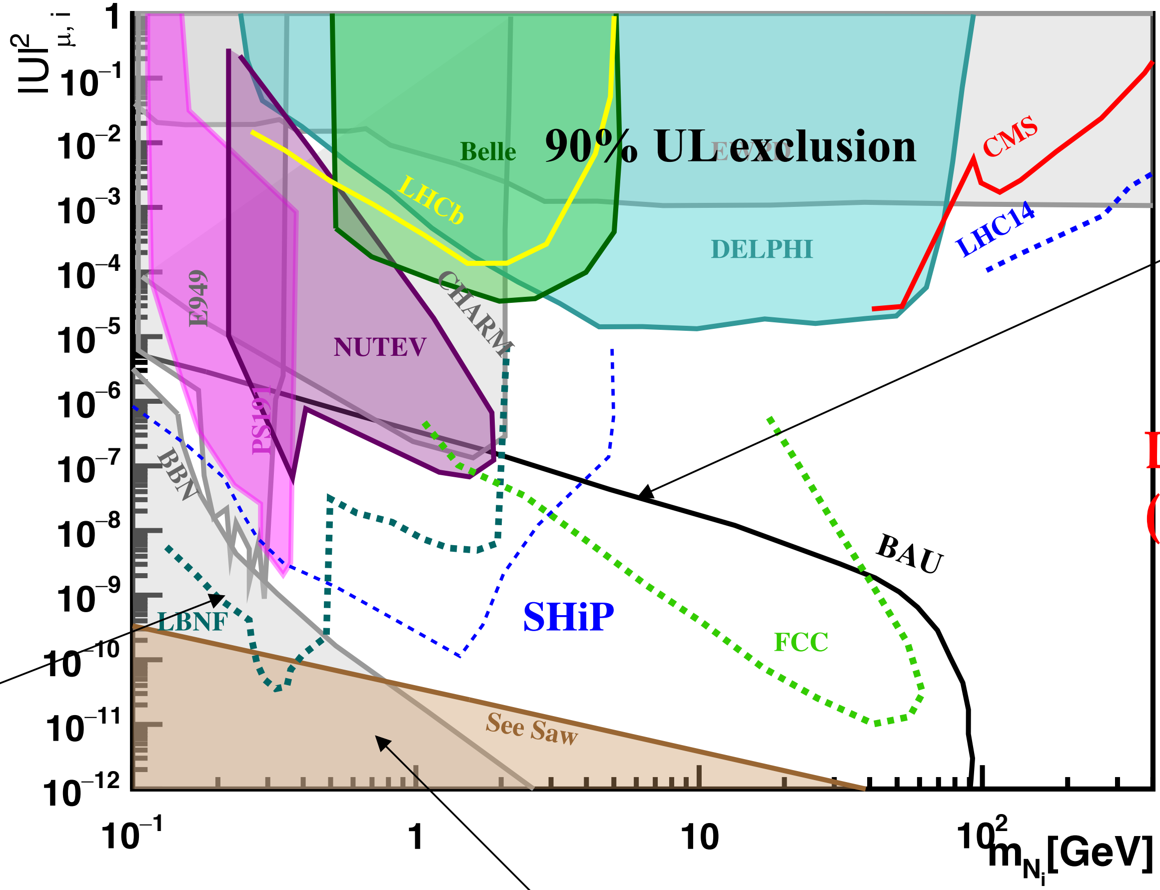


arXiv:1708.05776

Scalars produced via kinetic mixing with the Higgs, either real or virtual
(via FCNC loops in kaon and b decays)

Current exclusion limits and prospects for Heavy Neutral Leptons

$U_e^2:U_\mu^2:U_\tau^2 = 1:16:3.8$
Normal hierarchy of active
neutrino masses



BAU generation requires
out of equilibrium:
mixing angle of $N_{2,3}$ to active
neutrinos cannot be too large

Low couplings: very long lifetimes (10-10000 km at the SPS energies)

BBN:
decays of $N_{2,3}$
must not spoil
Big Bang
Nucleosynthesis
(T ~ 1 MeV)

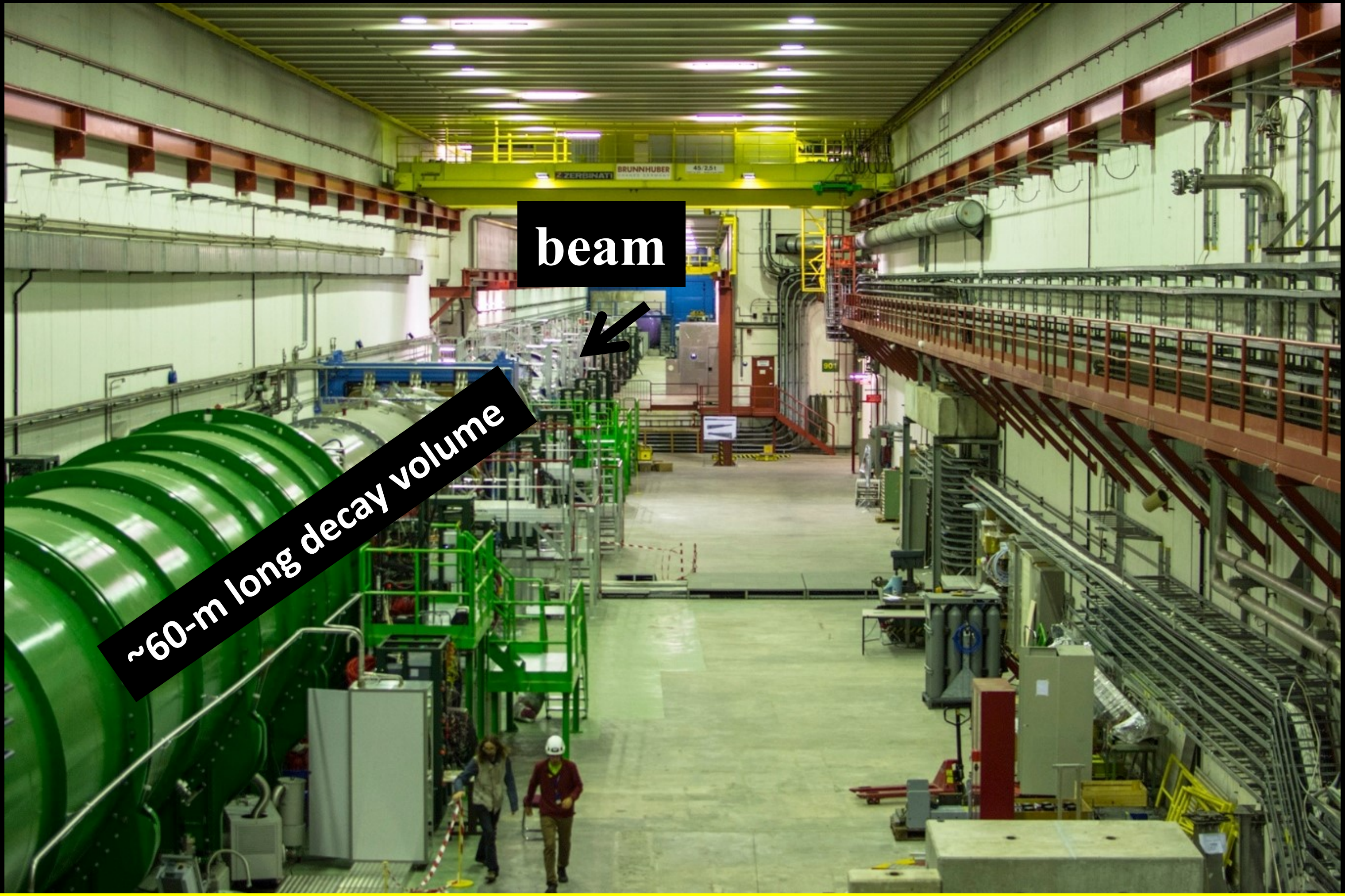
See-saw: mixing angle of $N_{2,3}$ to active neutrinos cannot be too small

How to produce Hidden Particles in the MeV-GeV range?

1) 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**. 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 .

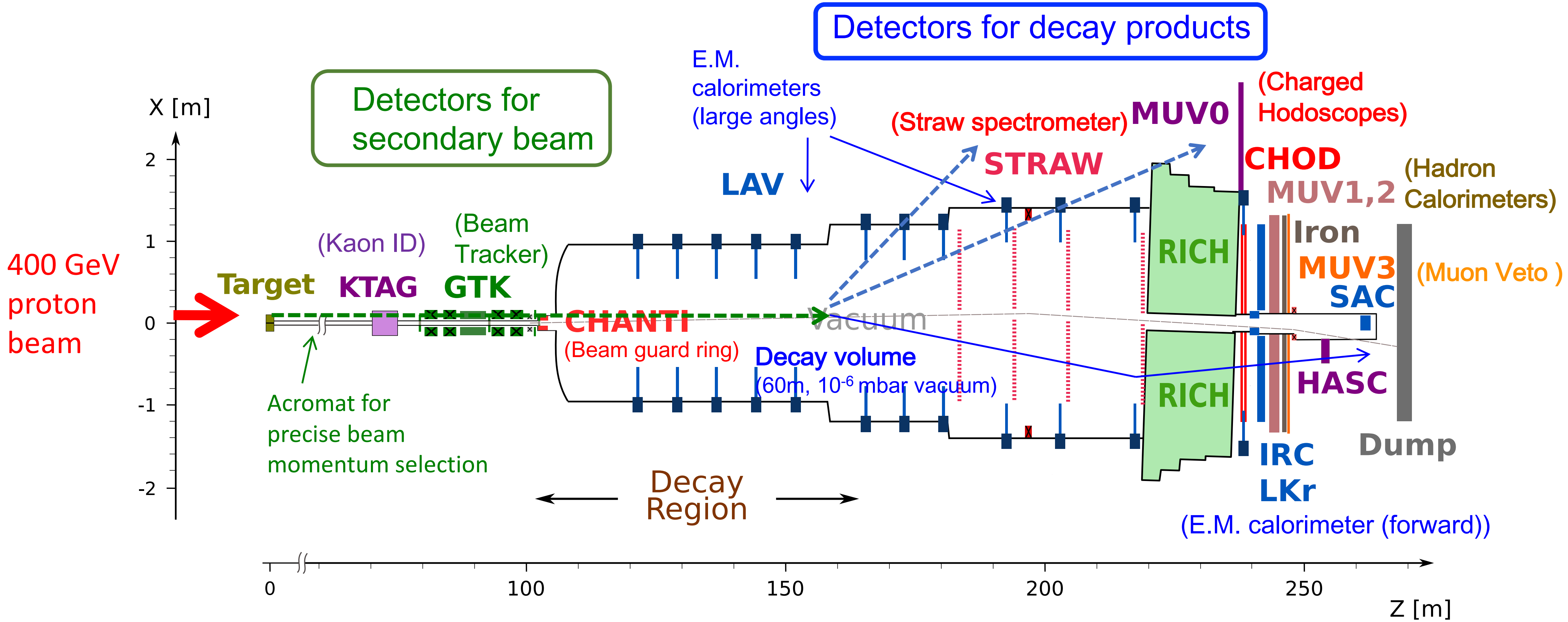
2) The smallness of the couplings implies that the hidden sector mediators are also **very long-lived (up to several km at the SPS energies) compared to the bulk of the SM particles**:
→The decays to SM particles can optimally be detected only using an experiment with decay volume tens of meters long followed by a spectrometer with particle identification capabilities.

The NA62 experiment in the ECN3 experimental hall



The NA62 detector, served by the P42 400 GeV proton line and designed to measure the branching fraction of the rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, is perfectly suited to search for hidden particles

The NA62 experiment: conceptual scheme

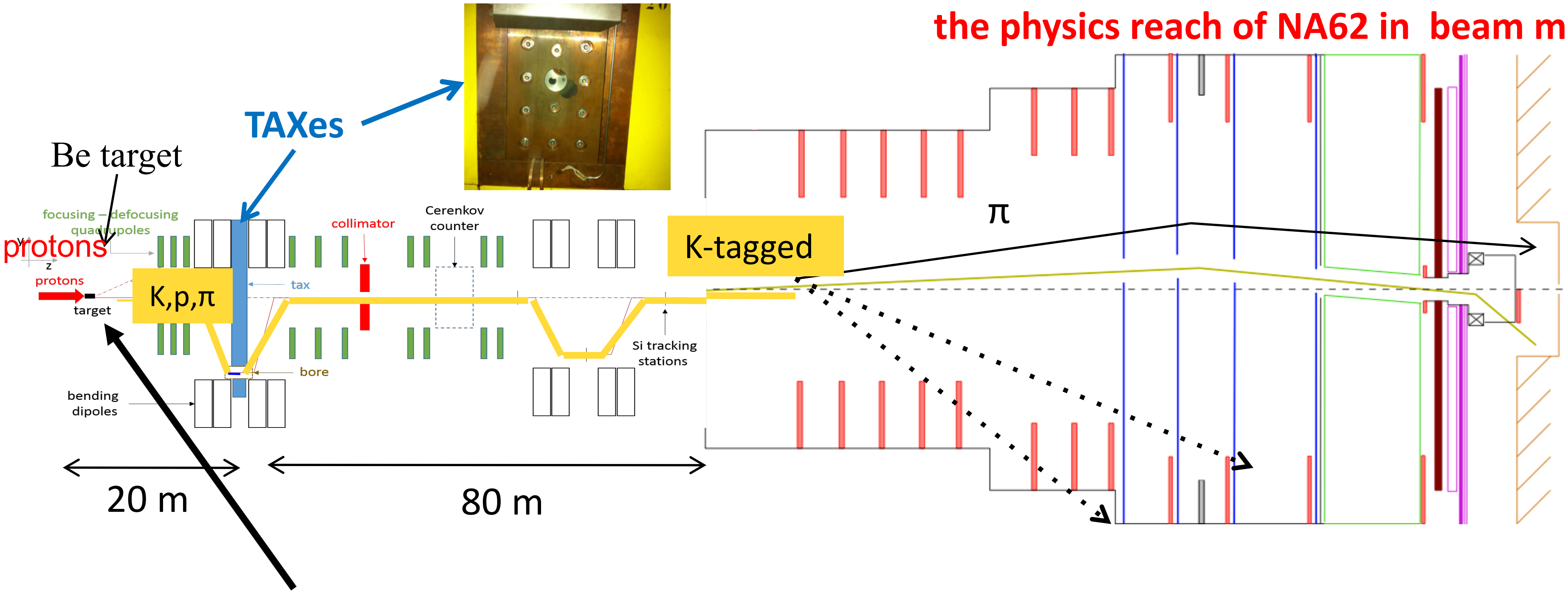


NA62 ~ (2.0-3.0)x10^{18} protons-on-target/year @ 400 GeV/c

NA62 Detector Paper, JINST 12 (2017), P05025

NA62 in beam operation mode

See A. Ceccucci and L. Bician's talks for a wide view of the physics reach of NA62 in beam mode



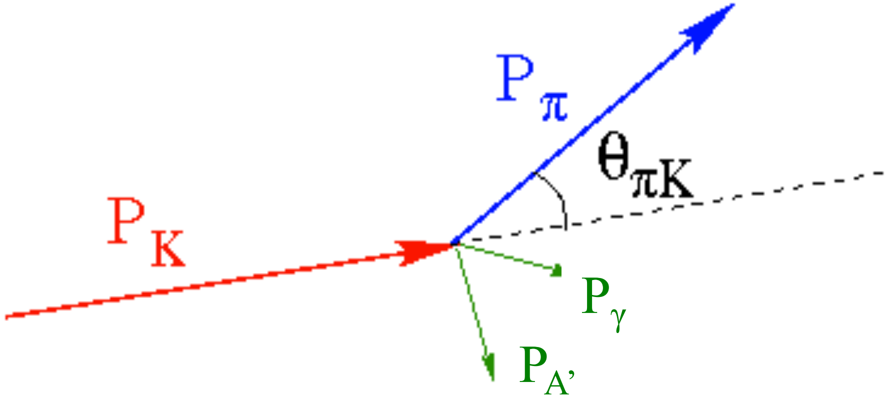
The 400 GeV/c proton beam impinges on a Be-target producing a mixed beam of K, pions, protons. A magnetic system and two 1.6-m long, water-cooled, copper collimators (TAXes) select a monochromatic beam of 75 GeV/c momentum. Kaon are tagged via a Cerenkov detector.

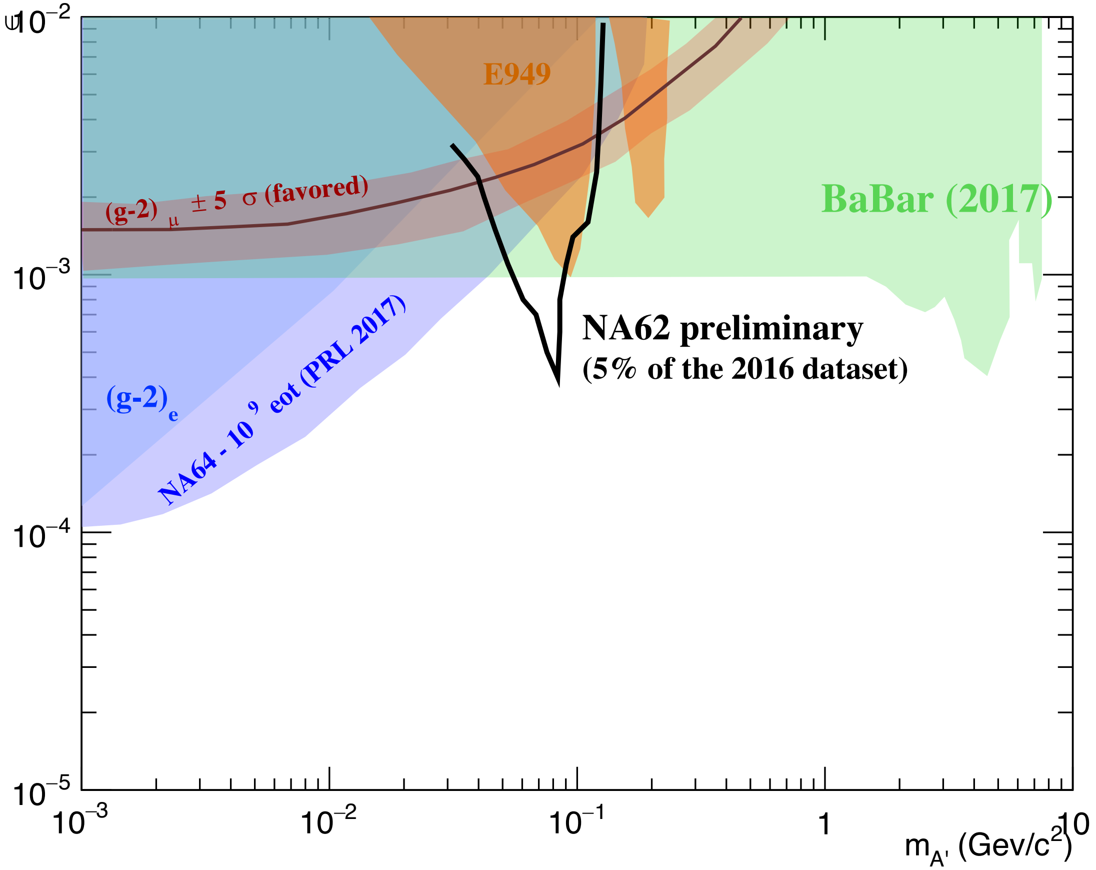
Search for Hidden Particles from kaon decays: Dark Photon⟶ invisible

Use the decay $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \gamma A'$ BR~20%

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

- Limit improves linearly with $N(K^+)$;
- Analysis with the full data set in progress.



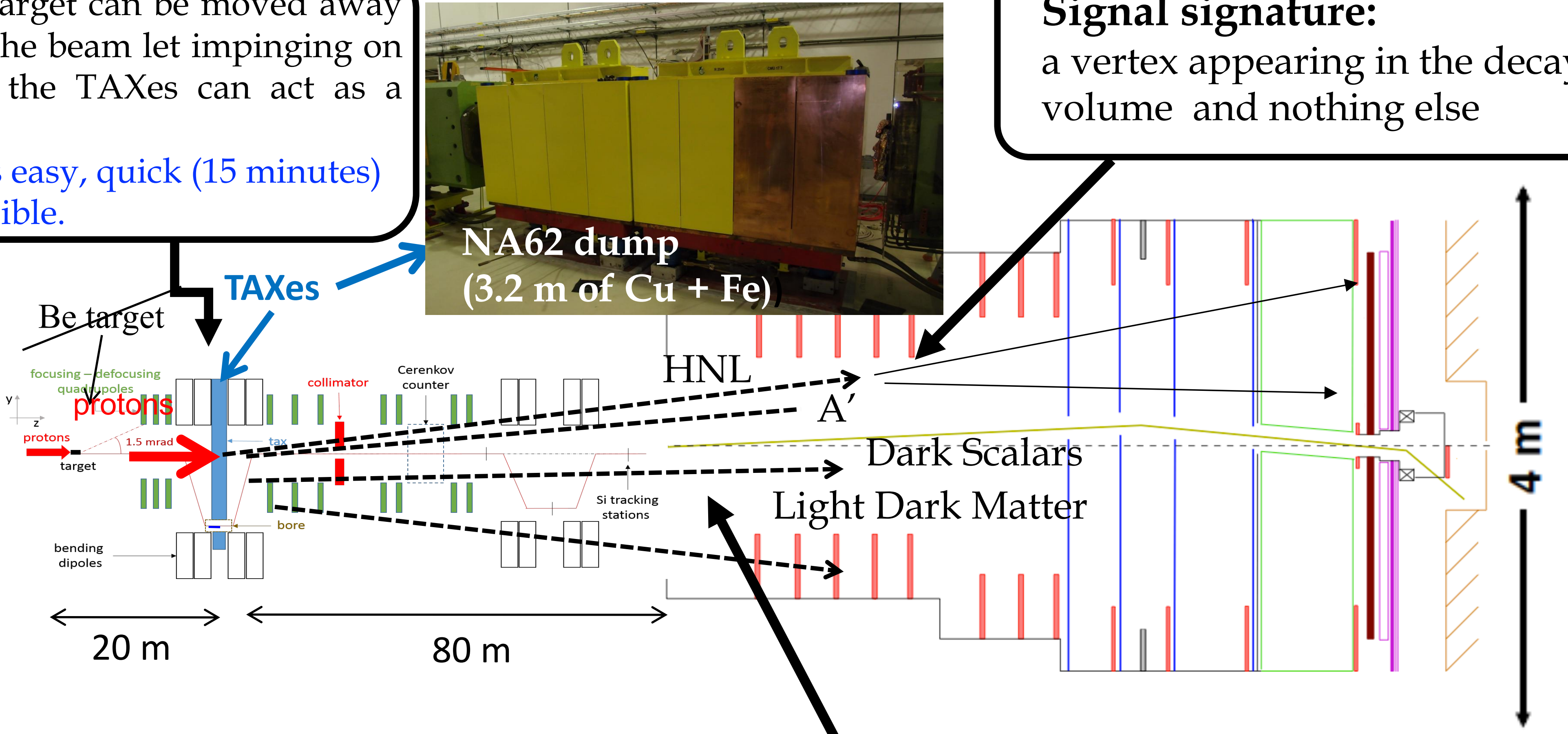


Search for Hidden Particles from Kaon decays limits the reach below the kaon mass

NA62 in "dump" operation mode

In dump mode the target can be moved away from the beam and the beam let impinging on the copper. Hence: the TAXes can act as a dump (2x10.7 λ_I).

→ this operation is easy, quick (15 minutes) and fully reversible.



NA62 dump (3.2 m of Cu + Fe)

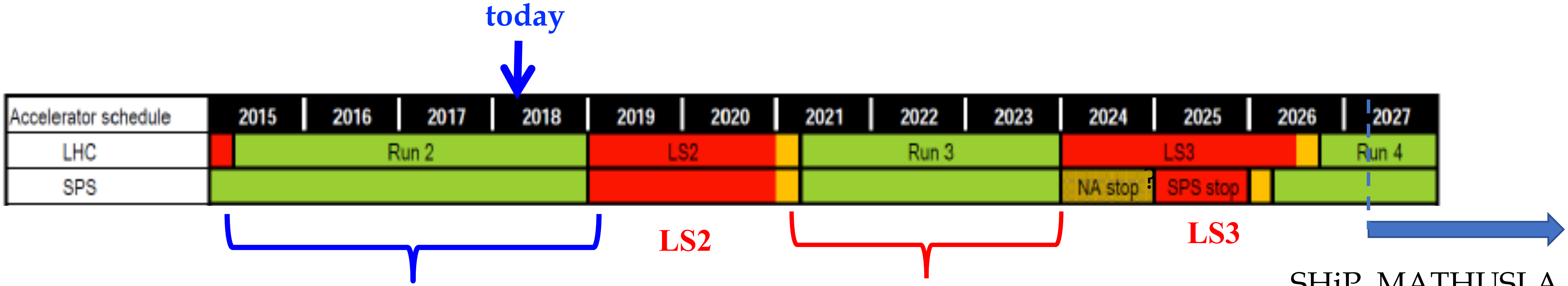
Signal signature:
a vertex appearing in the decay volume and nothing else

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

NA62 in kaon and dump modes: scientific scheduling

NA62 has the main goal of measuring the BR($K^+ \to \pi^+ \nu \bar{\nu}$) with 10% accuracy;

- **Before LS2 (2017-2018)** many searches in the hidden sector will be performed using the kaon beam.
- **After LS2 (2021++)** there is a window of opportunity to run NA62 in beam-dump mode to collect at least 10^{18} pot to search for hidden particles from charm and beauty decays, and photons.



today

Accelerator schedule	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
LHC	Run 2				LS2		Run 3			LS3			Run 4
SPS										NA stop ?	SPS stop		

LS2

LS3

NA62: $K^+ \to \pi^+ \nu \nu$, LFV/LFU modes
Hidden sector from K decays

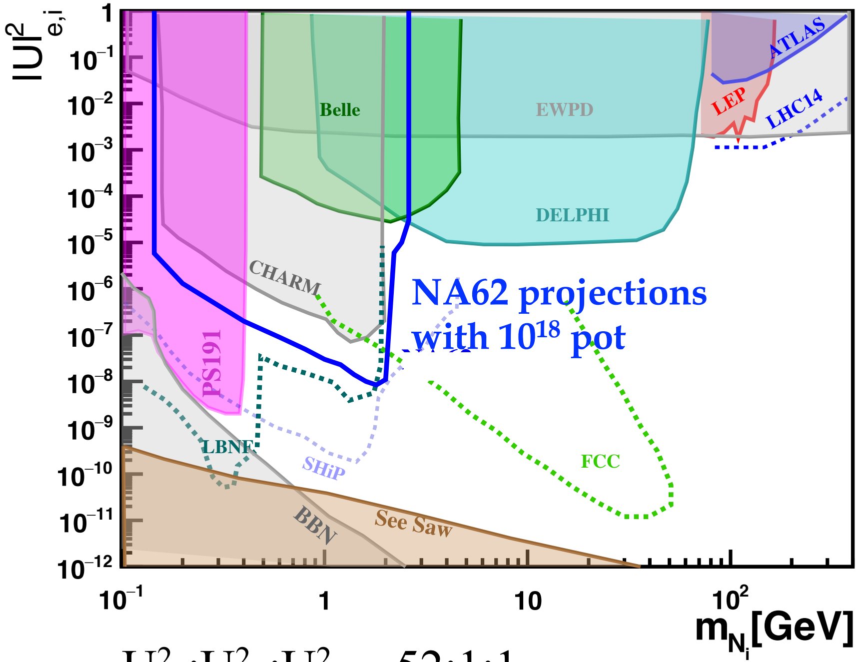
NA62 in dump mode
and kaon physics

SHiP, MATHUSLA,
Codex-b, FASER,
DUNE, etc.

Goal: integrate at least ~10^{18} pot in dump mode by 2023
(corresponding to ~ 3 months of dedicated data taking in 2021-2023)

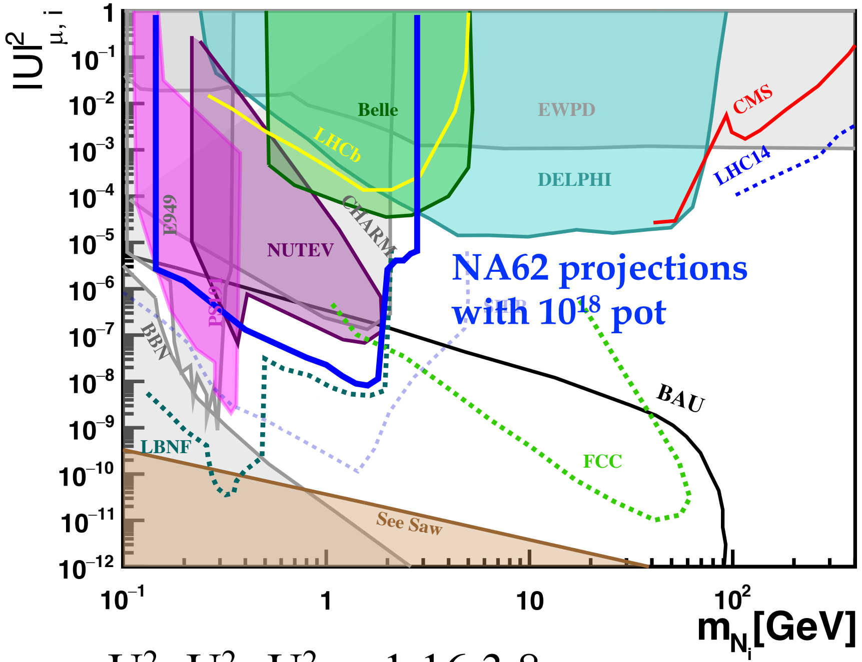
NA62 sensitivity with 10^{18} pot in dump mode: Heavy Neutral Leptons

Scenario 1



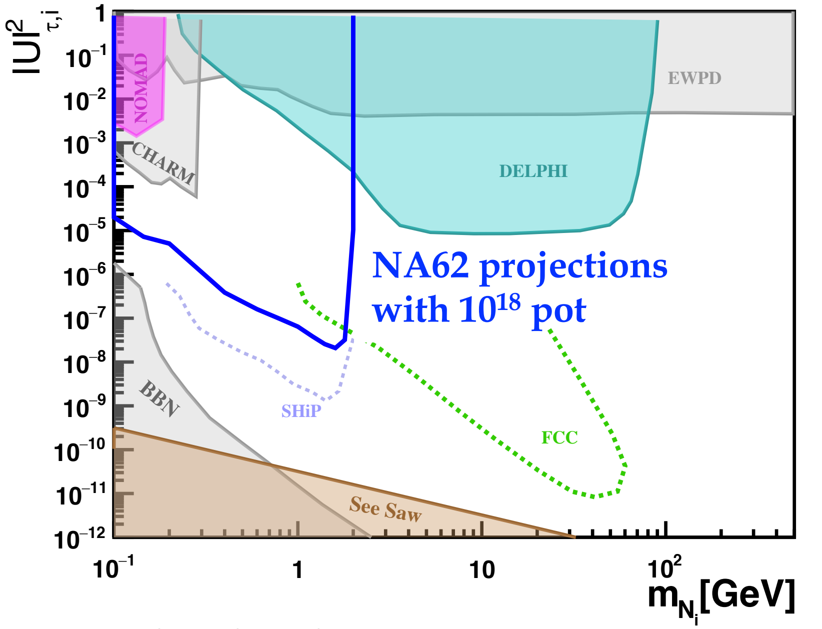
$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active **ν** masses

Scenario 2



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

Scenario 3

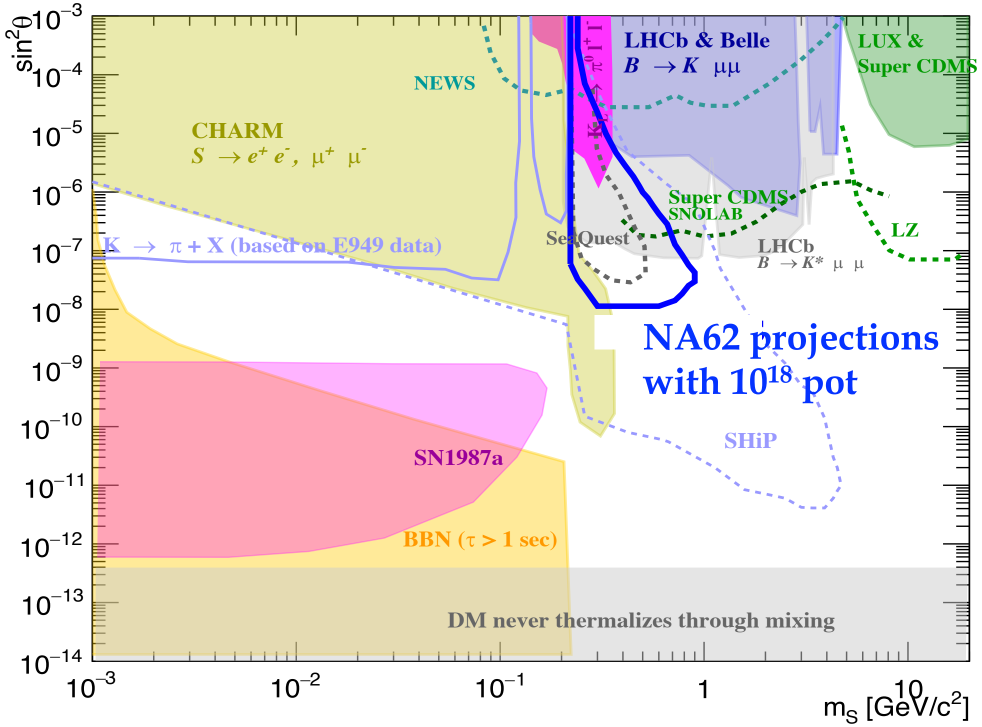


$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active **ν** masses

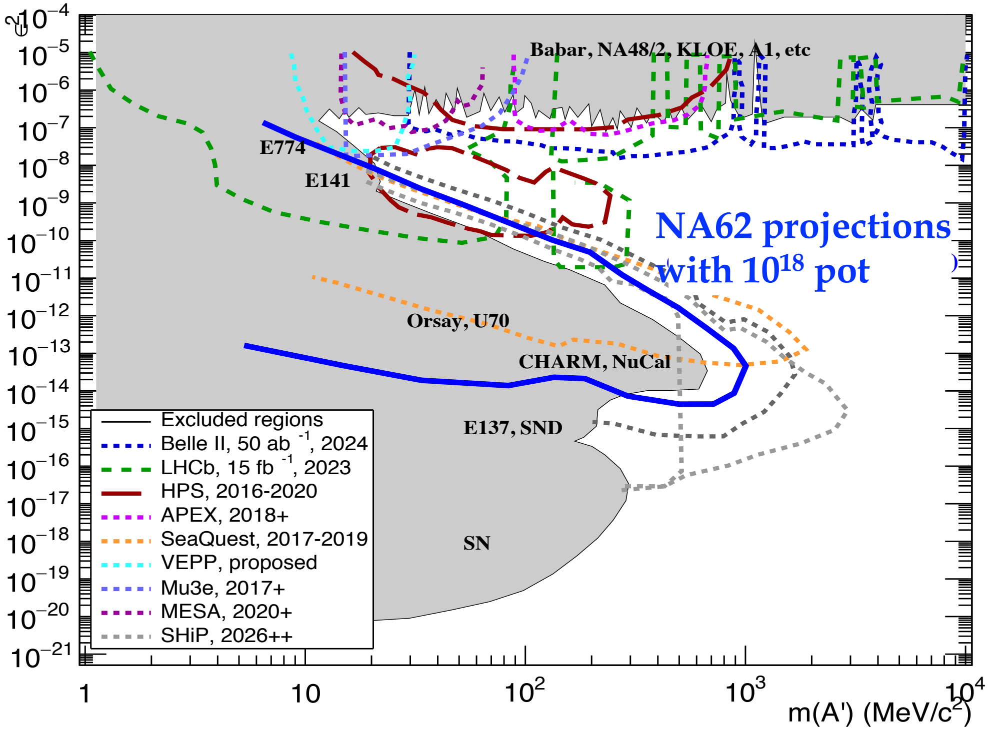
These sensitivities assume to detect all 2-track final states, including open channels, and zero background.

NA62 sensitivity with 10^{18} pot in dump mode

Dark Scalar:



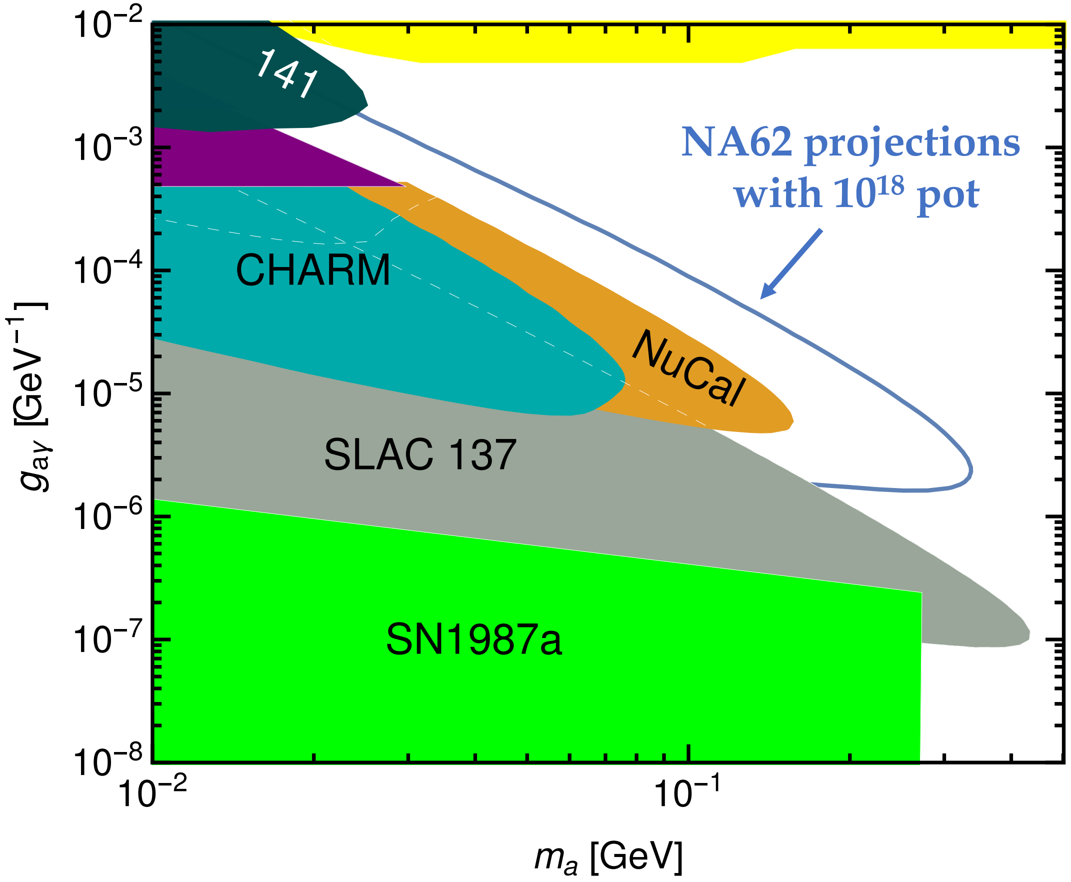
Dark Photon:



The Dark Scalar sensitivity plot assume all 2-track final states, with zero background
The Dark Photon projections are for di-muon final state only and (still) miss the inclusion of the two dominant production processes (QED, QCD): the curve is very conservative!

NA62 sensitivity for ALPs→ γγ in dump mode

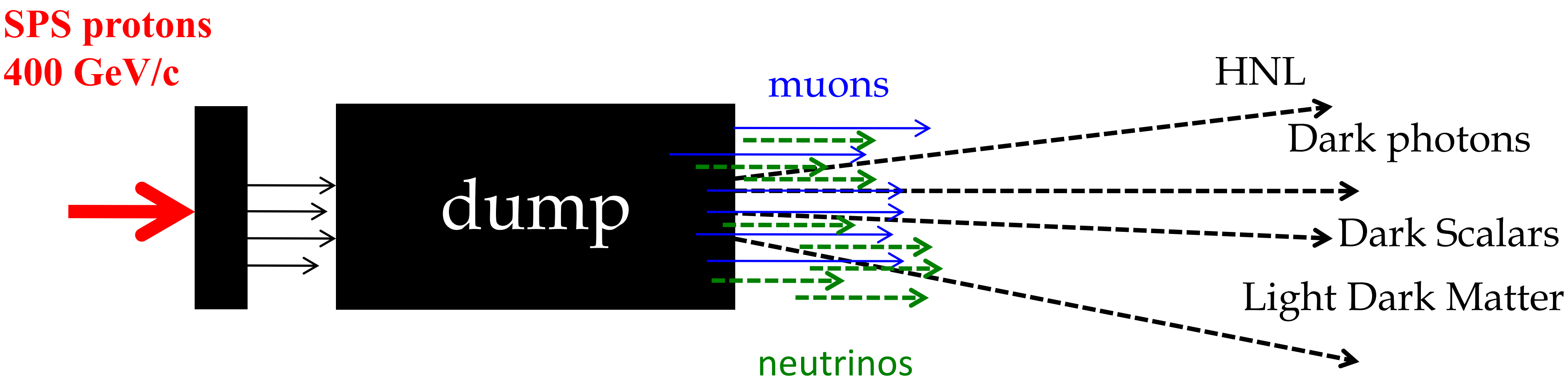
- study ALP production via Primakoff effect (JHEP 1602 (2016) 018) at target;
- search for ALP → γγ in NA62 fiducial volume, account for geometrical acceptance
- assume zero-background, evaluate expected 90%-CL exclusion plot



See also Dobrich et al., JHEP 02 (2016) 018 for details.

….Background, background, background…..

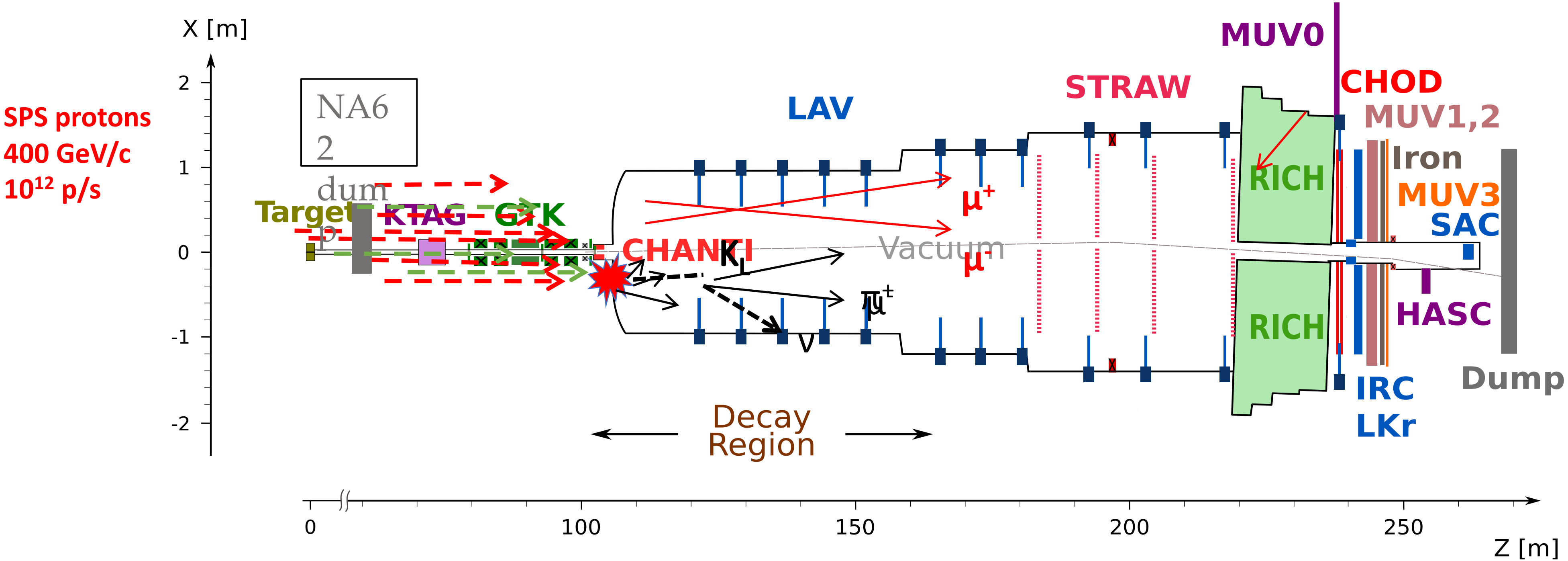
A dump with suitable length stops all beam-induced backgrounds but neutrinos and muons:



Any kind of feebly-interacting
long-lived particle or LDM
(put here your favored model);

Background is the name of the game.

Main Backgrounds in dump mode



Muon halo & neutrino halo

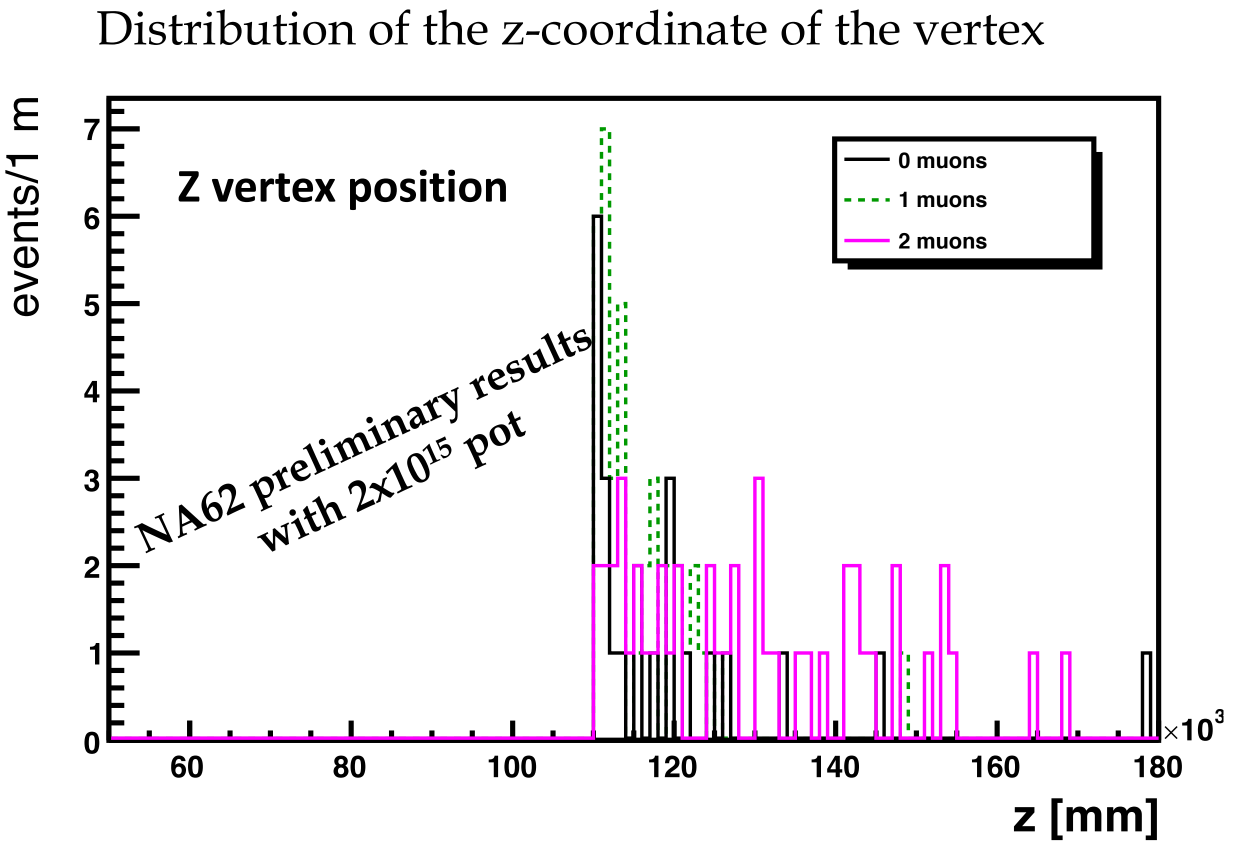
- In *beam mode* about ~ 5 MHz of μ^+ and 150 kHz μ^- are present due to early decays in flight of K and π in the beam;
- **In *dump mode*, the muon halo is reduced by (at least) 2 orders of magnitudes**
- **Muons produce inelastic interactions and combinatorial background**
  Neutrinos can produce inelastic interactions in the material surrounding the FV.

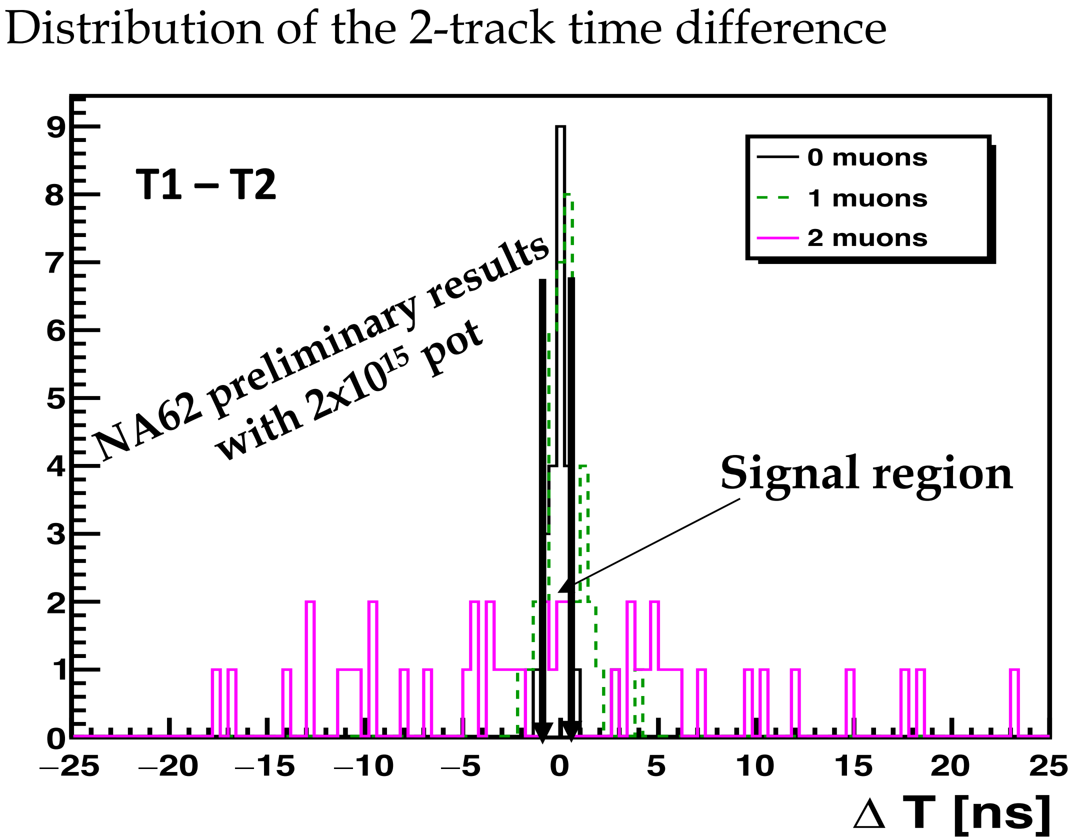
NA62-DUMP: data driven background estimate

In November 2016, few hours long run taken in dump mode, ~2x10^{15} pot collected for ALPs search and in preparation for the longer physics runs in dump mode in 2021-2023:

- ✓ - This small dataset already provides crucial information on the background level;
- ✓ - About x5 more data in dump mode has been collected in 2017 and is currently being analyzed.
- ✓ - Further runs planned for 2018 to complete the study of beam-dump operation before LS2.

NA62-DUMP: data driven background estimate


Distribution of the z-coordinate of the vertex


Distribution of the 2-track time difference

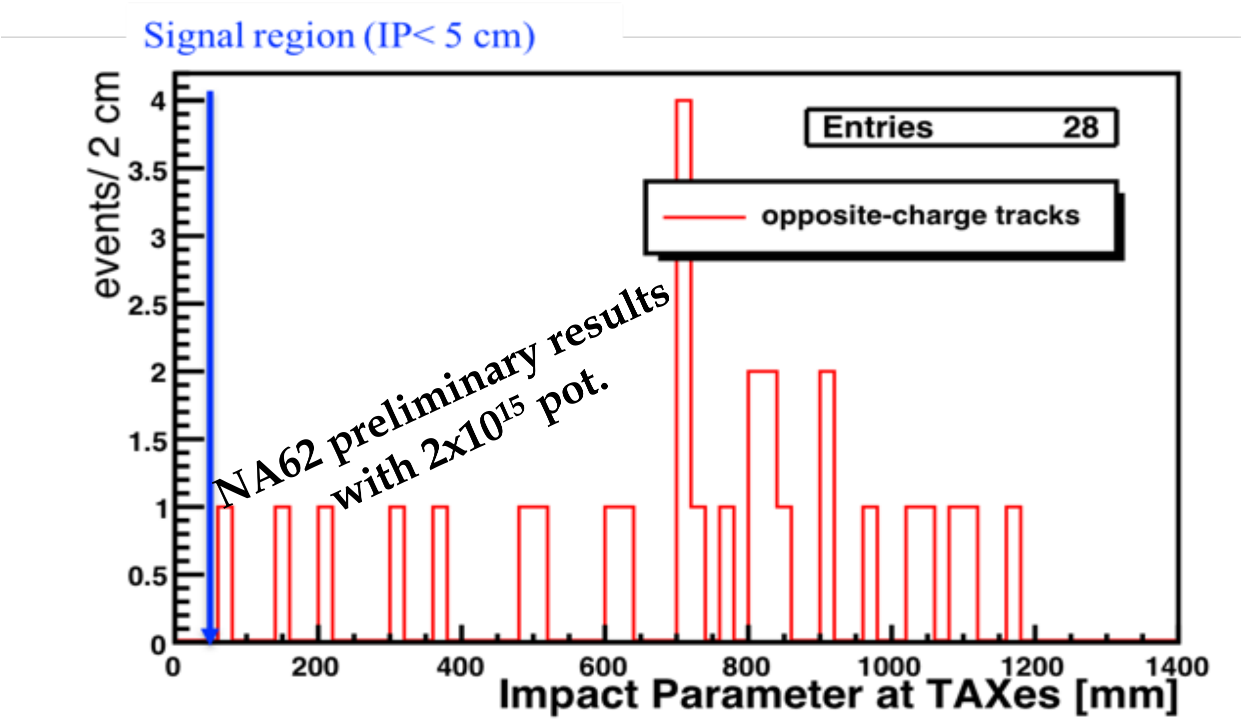
Sample divided in 2-, 1- and 0-muon categories:

- 2-μ sample has vertices spread along the FV and tracks mostly out-of-time:
  ⟶ combinatorial background
- 0- or 1-μ samples are concentrated at the beginning of the FV, and tracks are mostly in-time:
  ⟶ background from inelastic interactions in the last $\boldsymbol{\lambda}_I$ of the final collimator

NA62-DUMP: data driven background estimate

Consider only opposite charge events with two tracks in time within 1 ns:

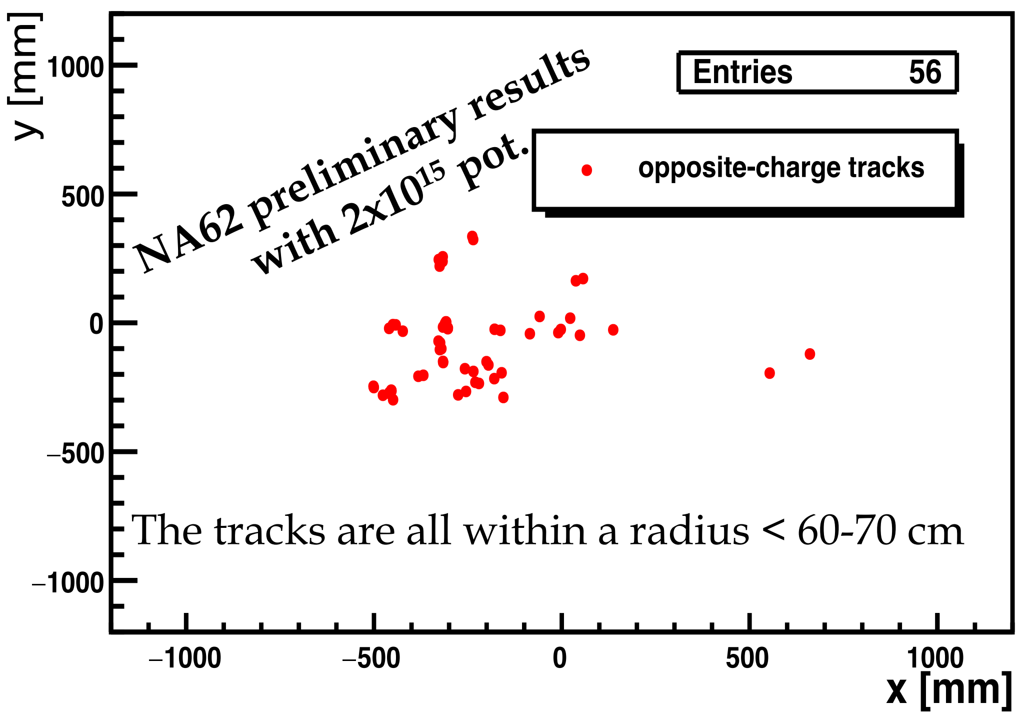
- 28 events are left out of 2×10^{15} pot
- All of them do not point backwards to TAXes (as expected)
- Requiring a mild pointing cut IP < 5 cm we can easily reject all of them……

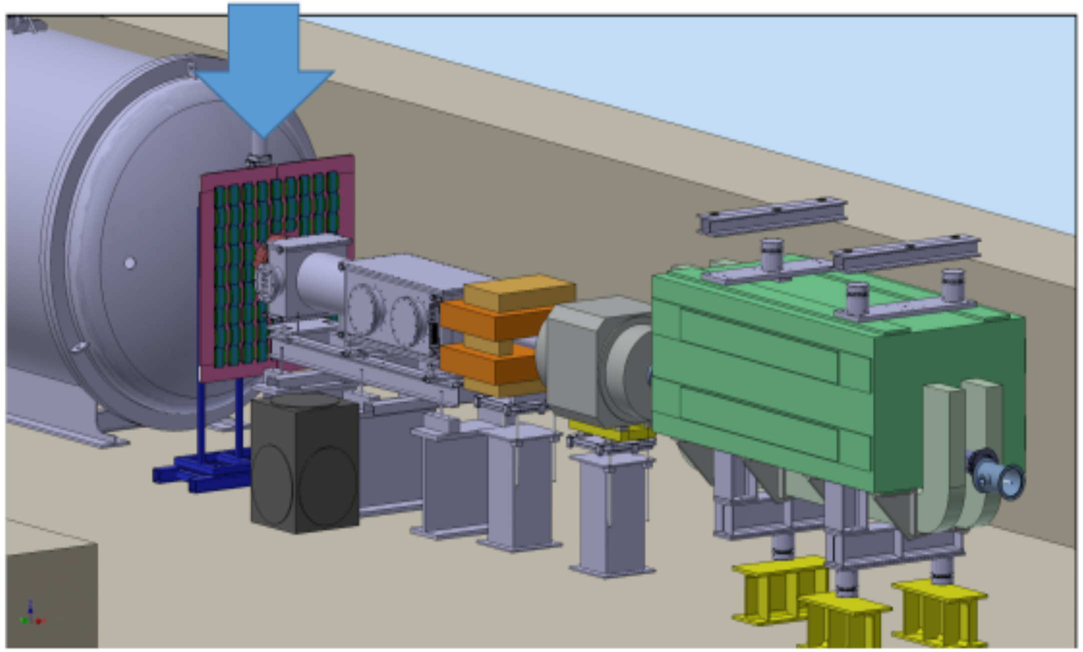


…... but this implies we reject also partially reconstructed final states (eg: most of HNL decays)

NA62-DUMP: extrapolation in front of the decay vessel

Extrapolation of the 2-tracks of the remaining 28 events at the beginning of the decay vessel:
⟶ they are all concentrated either in the "empty" zone not covered by any detector in NA62





An Upstream Veto in front of the decay vessel with < 10^{-4} detector inefficiency
(currently missing in the current setup) could veto most (all) of them,
and largely broaden the physics reach of NA62.

Conclusions

- ☐ **NA62 is successfully running in ECN3 with the main goal of measuring the BR($K^+ \longrightarrow \pi^+ \nu\ \nu$bar) with 10% accuracy.**

- ☐ **NA62 can be a major player in the search for hidden sector particles in Run 3**:
  - in Run 2 & 3: by searching for hidden particles in kaon decays;
  - in Run 3 : by collecting (at least) 10^{18} pot in dump mode by 2023.

- ☐ **Preliminary studies with data taken in beam-dump modes show that the background can be kept under control.**
  More data collected in 2017 and 2018 will allow us to consolidate this result.
  Further improvements in the setup are currently being investigated.

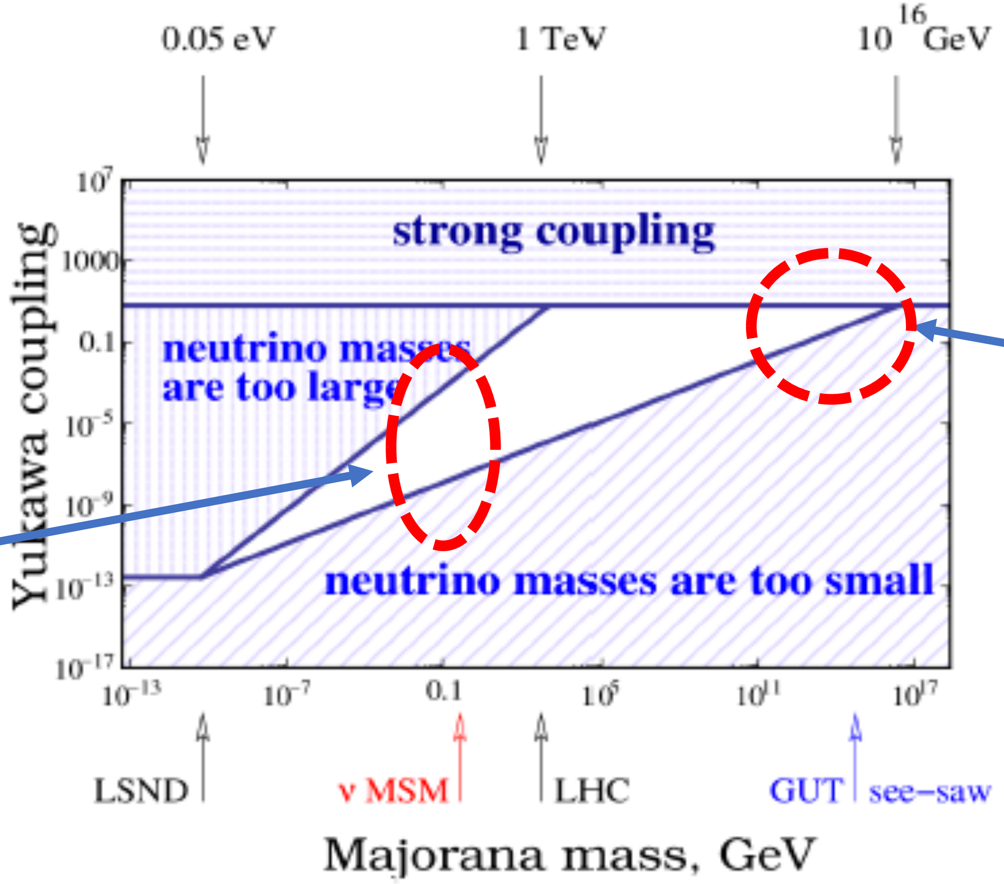
Thank you for your attention!

SPARES

Heavy neutrino Yukawa couplings versus Majorana mass

It is “natural” to assume that the masses of RH neutrinos are similar to all the other masses (~EW scale) :

$$F \sim \frac{\sqrt{m_{atm} M_N}}{v} \sim (10^{-6} - 10^{-13}),$$



It “natural” to assume that the Yukawa couplings of the RH neutrinos are similar to top Yukawa:

$$M_N \simeq \frac{F^2 v^2}{m_{atm}} \simeq 6 \times 10^{14}\ \mathrm{GeV}$$

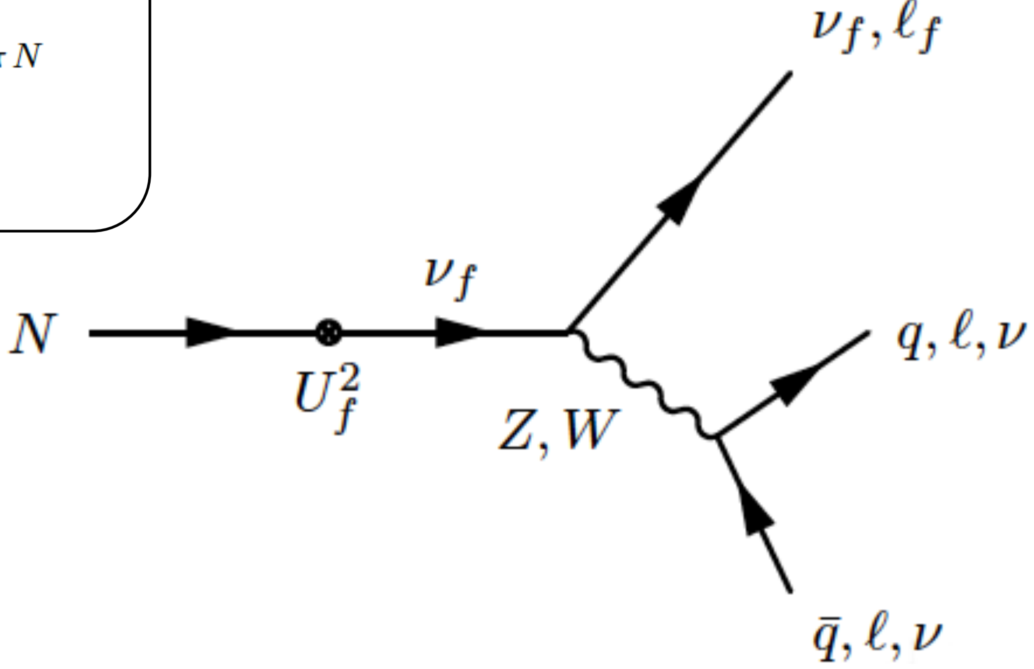
Any number in the white area works to be consistent with the observed pattern of neutrino masses and oscillations

Production and decay of HNLs with mass in the MeV - GeV range

HNLs can be produced in decays where a neutrino is replaced by a N (kinetic mixing, U^2);
Main neutrino sources at the SPS energies: c and b mesons.

Production processes

- $D \to K \ell N$
- $D_s \to \ell N$
- $D_s \to \tau \nu_\tau$ followed by $\tau \to \mu \nu N$ or $\tau \to \pi N$
- $B \to \ell N$
- $B \to D \ell N$
- $B_s \to D_s \ell N$



Decay channels

$N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$
$N \to H^\pm \ell^\mp$, with $H = \pi, \rho$
$N \to 3\nu$
$N \to \ell_i^\pm \ell_j^\mp \nu_j$
$N \to \nu_i \ell_j^\pm \ell_j^\mp$

They can then decay again to SM particles through mixing (U^2) with a SM neutrino. This (now massive) neutrino can decay to a large amount of final states through emission of a Z^0 or W boson