Probing Extremely Weakly Interacting Particles in Gamma Factory

Based on Phys. Rev. D **104**, no.5, 055023 (2021)

Sreemanti Chakraborti

LAPTh, Annecy

March 29, 2022

in collaboration with

Jonathan L. Feng	James K. Koga	Mauro Valli
University of California, Irvine, USA	Kansai Photon Science Institute, National Institutes for Quantum and Radiological Science and Technology, Japan	YITP, Stony Brook University, USA

Features

Some obvious questions

- *How light are the particles ?* $\Longrightarrow \sim$ 1-100 MeV
- *How weak is the interaction strength ?* $\Longrightarrow \sim 10^{-9}$
- *Why probe at Gamma Factory ?* $\Longrightarrow$ coming later, stay tuned !

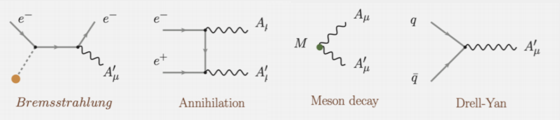
Some obvious questions

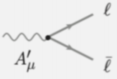
- *How light are the particles ?* $\Longrightarrow \sim$ 1-100 MeV
- *How weak is the interaction strength ?* $\Longrightarrow \sim 10^{-9}$
- *Why probe at Gamma Factory ?* $\Longrightarrow$ coming later, stay tuned !

A possible candidate particle would be dark photons

Dark Photon

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \varepsilon\, e \sum_f q_f \bar{f} \not{A}' f$$



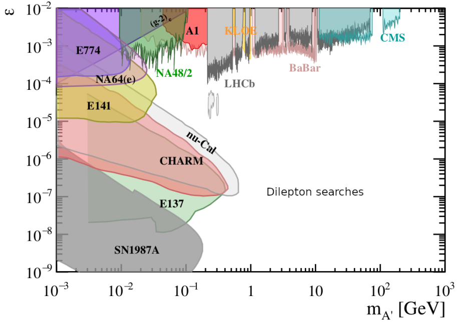


relevant production & decay channels

1) B. Holdom, Phys. Lett. B **166**, 196 (1986);

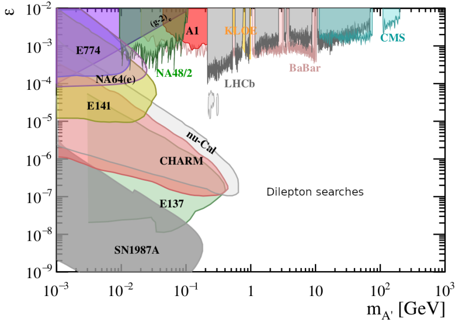
2) M. Fabbrichesi, E. Gabrielli and G. Lanfranchi, SpringerBriefs in Physics (2020), [arXiv:2005.01515].

Existing probes for light dark photon



M. Fabbrichesi, E. Gabrielli and G. Lanfranchi, SpringerBriefs in Physics (2020), [arXiv:2005.01515]

Existing probes for light dark photon



M. Fabbrichesi, E. Gabrielli and G. Lanfranchi, SpringerBriefs in Physics (2020), [arXiv:2005.01515]

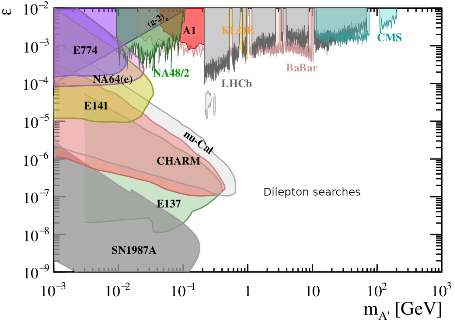
- Around low mass, only astrophysical probes from supernova cooling exists for $\varepsilon \lesssim 10^{-8}$.

PHYSICAL REVIEW D **101,** 123025 (2020)

Is there a supernova bound on axions?

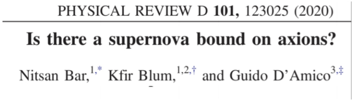
Nitsan Bar,[1,*] Kfir Blum,[1,2,†] and Guido D'Amico[3,‡]

Existing probes for light dark photon



M. Fabbrichesi, E. Gabrielli and G. Lanfranchi, SpringerBriefs in Physics (2020), [arXiv:2005.01515]

- Around low mass, only astrophysical probes from supernova cooling exists for $\varepsilon \lesssim 10^{-8}$.



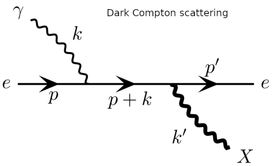
PHYSICAL REVIEW D **101,** 123025 (2020)

Is there a supernova bound on axions?

Nitsan Bar,[1,*] Kfir Blum,[1,2,†] and Guido D'Amico[3,‡]

- Is a robust complementary probe possible ?

$\Downarrow$



How about photoproduction ?

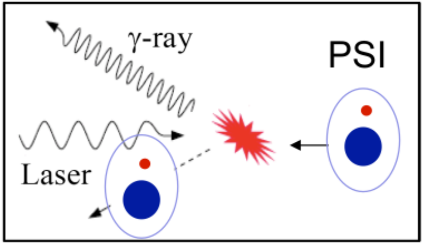
Difficulties

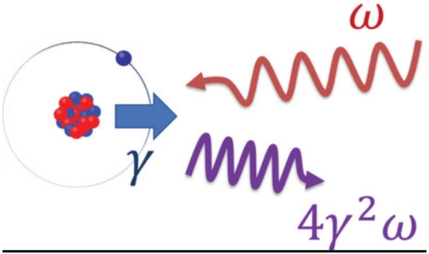
- Dark photon production is very suppressed for low ϵ, being proportional to ε^4
- Dark photon decay is too long with a very small probability to decay within the detector
- Existing light sources cannot provide the required number of photons to probe such low coupling

Parameter of the γ-ray sources around the world

Project name	LADON[a]	LEGS	ROKK-1M[b]	GRAAL	LEPS	HIγS[c]
Location	Frascati Italy	Brookhaven US	Novosibirsk Russia	Grenoble France	Harima Japan	Durham US
Storage ring	Adone	NSLS	VEPP-4M	ESRF	SPring-8	Duke-SR
Electron energy (GeV)	1.5	2.5–2.8	1.4–6.0	6	8	0.24–1.2
Laser energy (eV)	2.45	2.41–4.68	1.17–4.68	2.41–3.53	2.41–4.68	1.17–6.53
γ-beam energy (MeV)	5–80	110–450	100–1600	550–1500	1500–2400	1–100 (158)[d]
Energy selection	Internal tagging	External tagging	(Int or Ext?) tagging	Internal tagging	Internal tagging	Collimation
γ-energy resolution (FWHM)						
ΔE (MeV)	2–4	5	10–20	16	30	0.008–8.5
$\frac{\Delta E}{E}$ (%)	5	1.1	1–3	1.1	1.25	0.8–10
E-beam current (A)	0.1	0.2	0.1	0.2	0.1–0.2	0.01–0.1
Max on-target flux (γ/s)	5×10^5	5×10^6	10^6	3×10^6	5×10^6	10^4–5×10^8
Max total flux (γ/s)						10^6–3×10^9[e]
Years of operation	1978–1993	1987–2006	1993–	1995–	1998–	1996–

M. W Krasny, Photon-2017

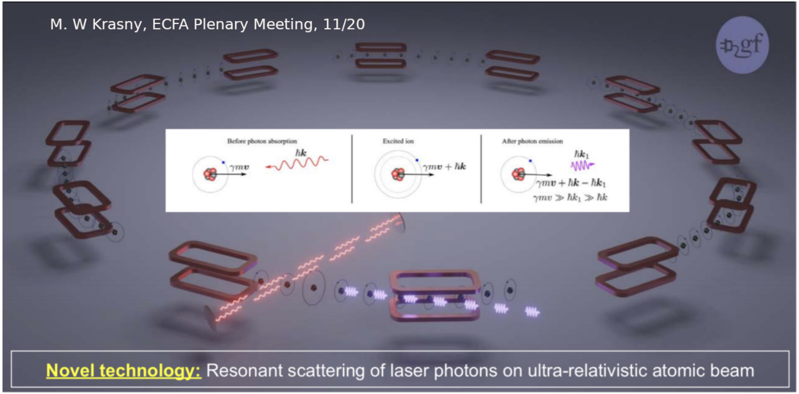




Example (maximal energy):
LHC, Pb^{80+} *ion*, γ_L = 2887, n=1→2, λ_{laser} = 104.4 nm, E_γ (max) = 396 MeV

M. W Krasny, Photon-2017

- GF is based on circulating partially stripped ions (PSI), i.e., nuclei with a few bound electrons rather than bare nuclei, in a high-energy storage ring. The bound electrons make electronic transitions possible.
- Light from a laser beam is sent head-on to a PSI beam with a high γ. In the ion frame, the energy of the incident photons is boosted by a factor of 2γ. PSI excited with the primary beam emit secondary photons, which, upon transformation to the lab frame, are emitted in the direction of propagation of the PSI. Their energy in the lab frame is boosted by another factor of 2γ



Gamma Factory at CERN - a New Intensity Frontier

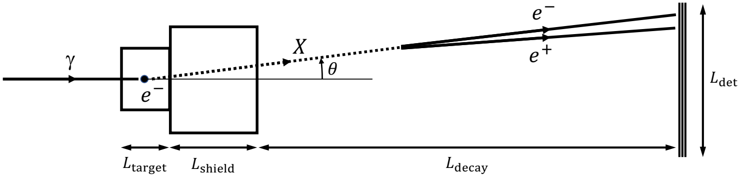
- $E_{\rm GF} = E_{\rm laser}\left(\sqrt{\frac{1+v/c}{1-v/c}}\right)^2 \approx 4\gamma^2 E_{\rm laser} \sim 10$ MeV-1 GeV
- Big jump in intensity (by 6 - 8 orders of magnitude) compared to existing photon sources

$$E_\gamma = 20\ \text{MeV},\quad \Phi_{\rm GF} = 10^{18}\ \text{s}^{-1},\quad N_{\rm GF} = 3\times 10^{25}$$
$$E_\gamma = 200\ \text{MeV},\quad \Phi_{\rm GF} = 10^{17}\ \text{s}^{-1},\quad N_{\rm GF} = 3\times 10^{24}$$
$$E_\gamma = 1.6\ \text{GeV},\quad \Phi_{\rm GF} = 10^{16}\ \text{s}^{-1},\quad N_{\rm GF} = 3\times 10^{23}$$

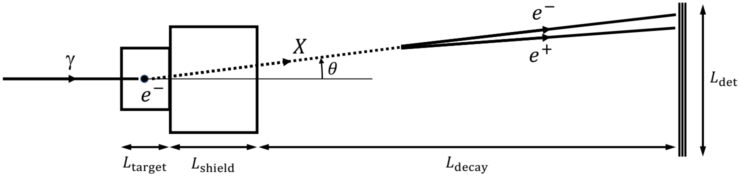
D. Budker *et. al.*, Annalen Phys. **532**, no.8, 2000204 (2020)

- Huge potential for rare BSM searches ☺

A minimal fixed-target setup

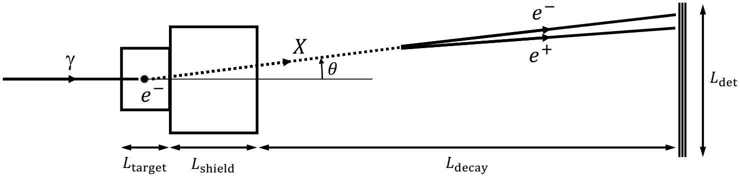


A minimal fixed-target setup



- Target is chosen to be a low-Z material to enhance new physics event rate

A minimal fixed-target setup

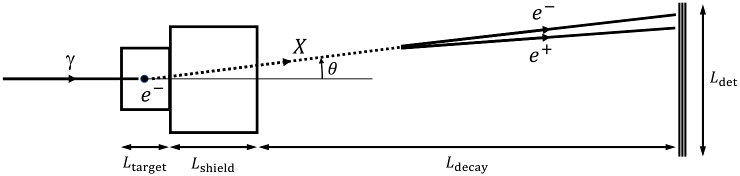


- Target is chosen to be a low-Z material to enhance new physics event rate

A few feasible choices $\Longrightarrow$

$$\sigma^{\rm H}_{\rm SM}/Z = 36,\ 19,\ 20 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}$$
$$\sigma^{\rm Be}_{\rm SM}/Z = 46,\ 38,\ 42 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}$$
$$\sigma^{\rm C}_{\rm SM}/Z = 52,\ 51,\ 58 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}.$$

A minimal fixed-target setup



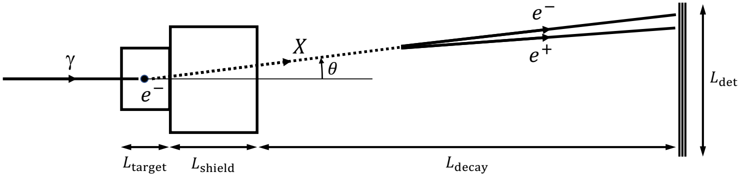
- Target is chosen to be a low-Z material to enhance new physics event rate

A few feasible choices $\Longrightarrow$

$$\sigma^{\rm H}_{\rm SM}/Z = 36,\ 19,\ 20 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}$$
$$\sigma^{\rm Be}_{\rm SM}/Z = 46,\ 38,\ 42 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}$$
$$\sigma^{\rm C}_{\rm SM}/Z = 52,\ 51,\ 58 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}.$$

- Shield is a high-Z material such as Pb to eliminate GF photons & SM background

A minimal fixed-target setup



- Target is chosen to be a low-Z material to enhance new physics event rate

A few feasible choices $\Longrightarrow$

$$\sigma^{\rm H}_{\rm SM}/Z = 36,\ 19,\ 20 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}$$
$$\sigma^{\rm Be}_{\rm SM}/Z = 46,\ 38,\ 42 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}$$
$$\sigma^{\rm C}_{\rm SM}/Z = 52,\ 51,\ 58 \text{ mb for } E_\gamma = 20,\ 200,\ 1600 \text{ MeV}.$$

- Shield is a high-Z material such as Pb to eliminate GF photons & SM background

A reasonable experimental setup : L_{target} (Graphite) $= 1$ m, L_{shield} (Pb) $= 2$ m
$L_{decay} = 12$ m, $L_{det} = 3$ m

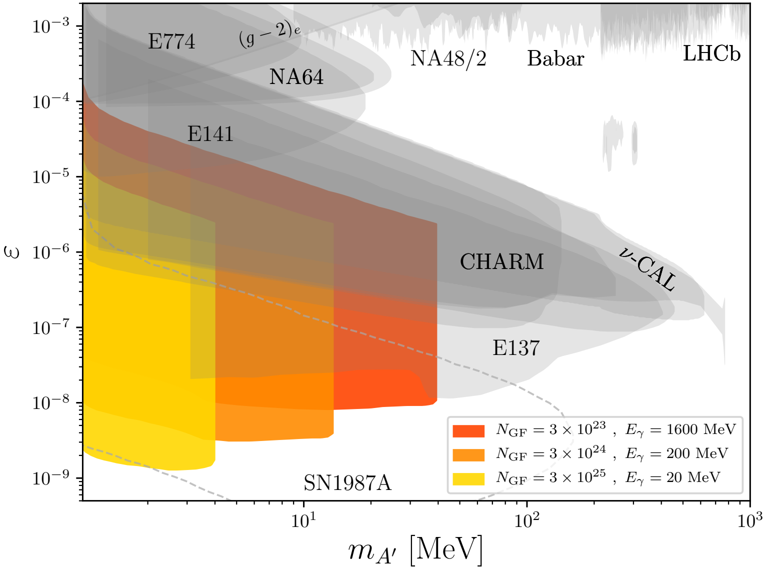
A rough estimate

$$
\begin{aligned}
N_S &= N_{\mathrm{GF}} P_{\mathrm{prod}} P_{\mathrm{decay}} P_{\mathrm{det}} \sim N_{\mathrm{GF}} \frac{Z\sigma_X}{\sigma_{\mathrm{SM}}} \frac{L_{\mathrm{decay}}}{d_{A'}} \\
&\sim N_{\mathrm{GF}} \frac{6\ \varepsilon^2\ 1\ \mathrm{mb}}{50\ \mathrm{mb}} \left[\frac{10\ \mathrm{MeV}}{m_{A'}}\right]^2 \frac{12\ \mathrm{m}}{6.5\times 10^5\ \mathrm{m}} \left[\frac{\varepsilon}{10^{-8}}\right]^2 \left[\frac{m_{A'}}{10\ \mathrm{MeV}}\right]^2 \\
&= 3\ \frac{N_{\mathrm{GF}}}{3\times 10^{24}} \left[\frac{\varepsilon}{2.6\times 10^{-9}}\right]^4
\end{aligned}
$$

Number of signal events are

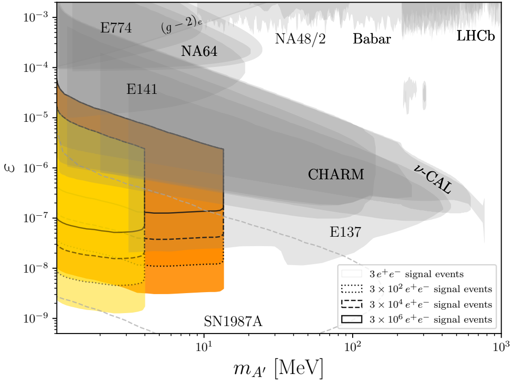
- Highly sensitive to ε
- Largely insensitive to dark photon mass
- Proportional to number of GF photons on target

Results

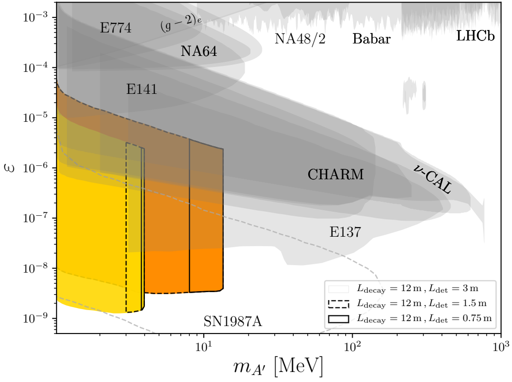

E774
$(g-2)_e$
NA64
NA48/2
Babar
LHCb
E141
CHARM
ν-CAL
E137
SN1987A
$N_{\rm GF} = 3 \times 10^{23}$, $E_\gamma = 1600$ MeV
$N_{\rm GF} = 3 \times 10^{24}$, $E_\gamma = 200$ MeV
$N_{\rm GF} = 3 \times 10^{25}$, $E_\gamma = 20$ MeV
ε
$m_{A'}$ [MeV]

Results

Sensitivity vs. number of events



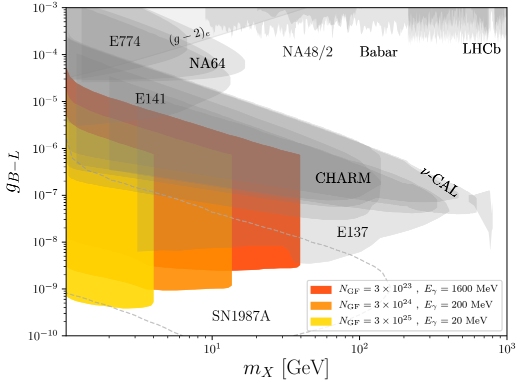
Sensitivity vs. length of detector



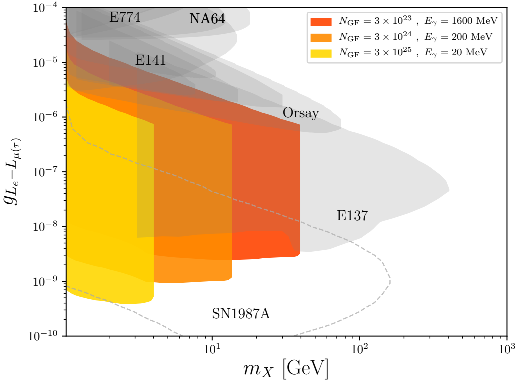
- Only a few hours of observation can probe new parameter space
- $L_{det}/L_{decay} \approx 1/3$, $L_{decay} \sim \mathcal{O}$ (10 m) for full sensitivity reach within a year

Anomaly free gauge bosons

$B - L$ gauge boson sensitivity



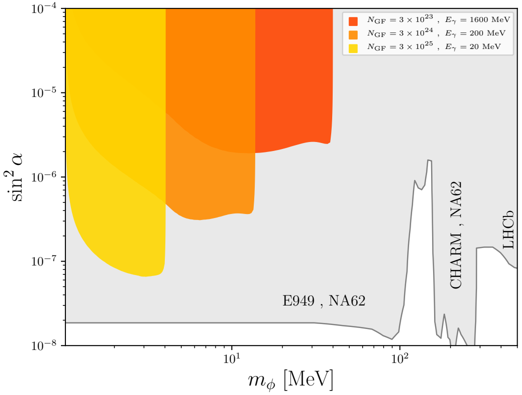
$L_e - L_{\mu(\tau)}$ gauge boson sensitivity



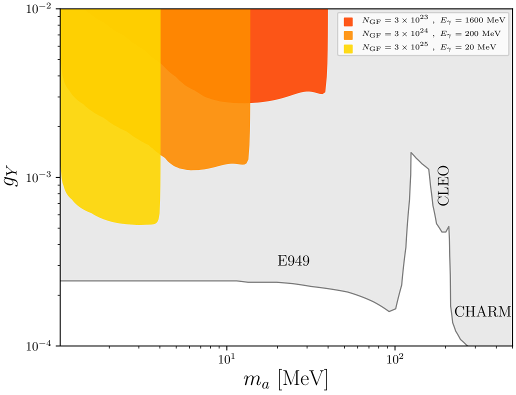
- Promising probe for anomaly free Gauge bosons
- $L_\mu - L_\tau$ gauge boson remains difficult to probe in this setup

Other light species

Dark Higgs sensitivity



Dark pseudo scalar sensitivity



- Signal rate is compromised due to Yukawa suppressed dark mediator decay into electrons
- Even after one year of running, this setup does not probe new parameter region

Highlights

- Gamma Factory is a multi-physics proposal currently under scrutiny @ CERN

Highlights

- Gamma Factory is a multi-physics proposal currently under scrutiny @ CERN

- Due to its huge intensity and energy reach, GF can provide a promising probe for light dark sector

Highlights

- Gamma Factory is a multi-physics proposal currently under scrutiny @ CERN

- Due to its huge intensity and energy reach, GF can provide a promising probe for light dark sector

- We study the complementary sensitivity probe for light, weakly coupled dark photons in parameter region so far exclusive to only astrophysical probes

Highlights

- Gamma Factory is a multi-physics proposal currently under scrutiny @ CERN
- Due to its huge intensity and energy reach, GF can provide a promising probe for light dark sector
- We study the complementary sensitivity probe for light, weakly coupled dark photons in parameter region so far exclusive to only astrophysical probes
- We found promising reach also for the anomaly-free Gauge bosons

Highlights

- Gamma Factory is a multi-physics proposal currently under scrutiny @ CERN
- Due to its huge intensity and energy reach, GF can provide a promising probe for light dark sector
- We study the complementary sensitivity probe for light, weakly coupled dark photons in parameter region so far exclusive to only astrophysical probes
- We found promising reach also for the anomaly-free Gauge bosons
- The full potential of this facility for new physics still needs to be explored

see R. Balkin *et. al.*, arXiv:2105.15072 for ALP probe at GF

Thank you!

Timeline

The initial accelerator feasibility tests in 2017 and 2018

1. *Test runs with the $^{129}_{54}Xe(+39)$ (P-like) ions in the SPS (2017)*

2. *Preparation of the optimal stripping scenario to run the $^{208}_{82}Pb(+80)$ (He-like) ions in the SPS and in the LHC for the year 2018) (2017)*

3. *Test runs with the $^{208}_{82}Pb(+54)$ (Ni-like) and $^{208}_{82}Pb(+80)$ (He-like) ions in the SPS (2018)*

4. *Test runs and a short physics run with $^{208}_{82}Pb(+80)$ (He-like) ions in the LHC (2018)*