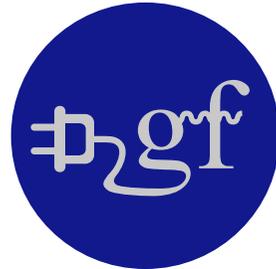


Gamma Factory

Status and Physics Highlights

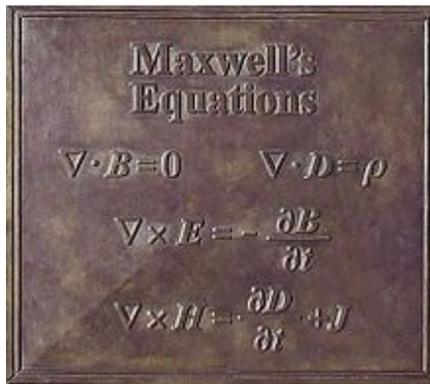


**Corfu Workshop on the Standard Model and
Beyond, Sept 2021**

Mieczyslaw Witold Krasny

LPNHE, CNRS and University Paris Sorbonne and CERN, BE-ABP

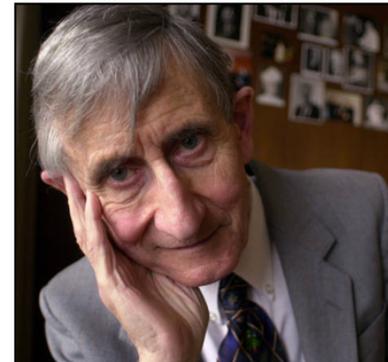
HEP future: concepts and tools



"New directions in science are launched by new tools much more often than by new concepts."

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained" - F. Dyson



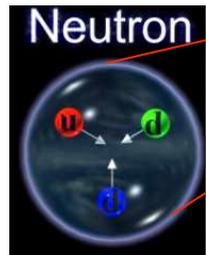
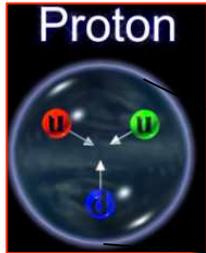
Outline of the talk

- *Gamma Factory research tools*
- *Examples of physics highlights*
- *Gamma Factory status*
- *Conclusions*

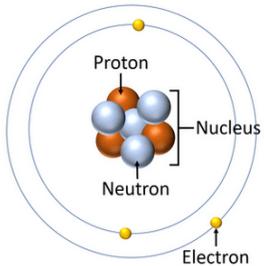
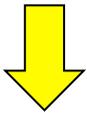
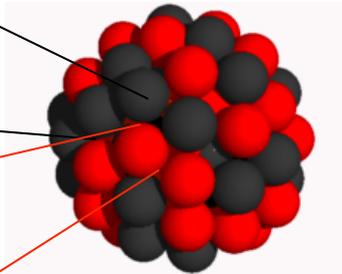
The Gamma Factory in a nutshell

- *The infrastructure and the operation mode of the CERN accelerators allowing to:*
 - *produce, accelerate, cool, and store **beams of highly ionised atoms***
 - *excite their atomic degrees of freedom by **laser photons** to form high intensity **secondary beams of gamma rays***
 - *produce plug-power-efficient diverse **tertiary beams***

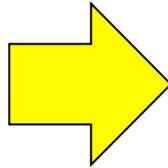
- *The research programme in a broad domain of science enabled by the “**Gamma Factory tools**”*



Present LHC beam particles:



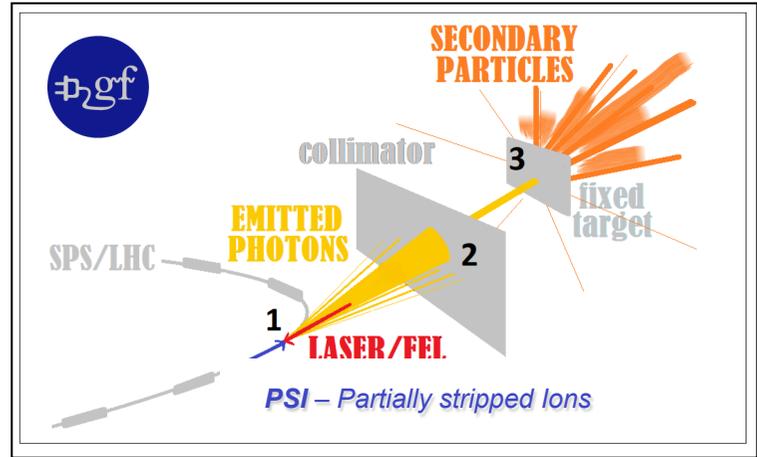
Future LHC beam particles:
Partially Stripped Ions (highly ionized atoms)



The Gamma Factory proposal for CERN

Mieczyslaw Witold Krasny (Paris U., VI-VII) (Nov 24, 2015)

e-Print: 1511.07794 [hep-ex]

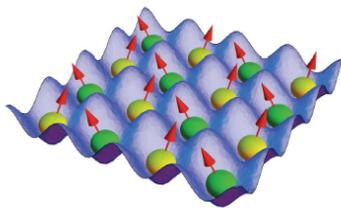
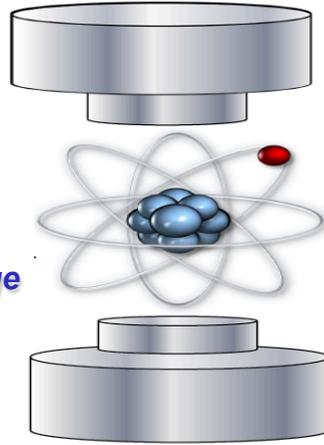


GF research tools made from light

1. Atomic traps of highly-charged, “small-size” atoms

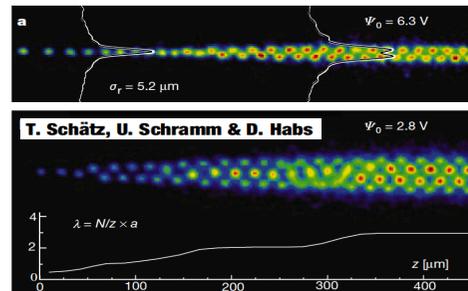
Atomic rest-frame

Trapped stationary atoms
Exposed to pulsed magnetic
and electric fields of the storage
ring



Crystalline beams?

letters to nature



Opening new research opportunities:

- Highly-charged atoms – very strong ($\sim 10^{16}$ V/cm) electric field (QED-vacuum effects)
- Small size atoms (electroweak effects)
- Hydrogen-like and Helium-like atomic structure (calculation precision and simplicity)
- Atomic degrees of freedom of trapped highly-charged atoms can be resonantly excited by lasers
- Circular, repetitive relativistic motion of the GF atomic traps \rightarrow Lorentz invariance tests and gravitational wave detection



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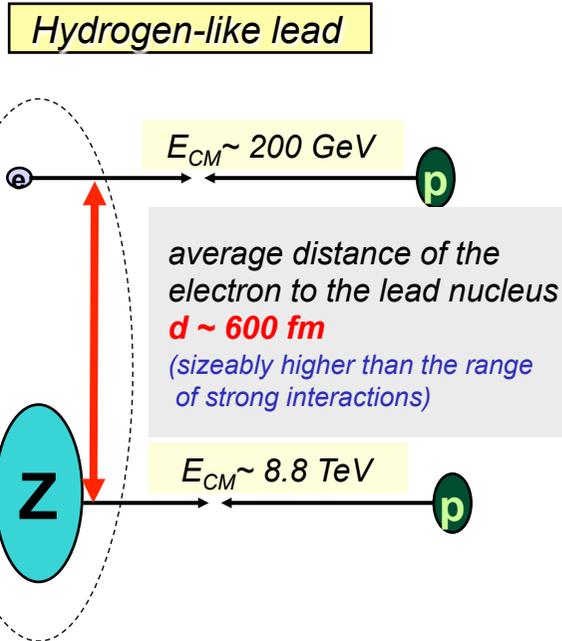
Atomic Physics Studies at the Gamma Factory at CERN

Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczysław Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotarev ... See fewer authors ^

First published: 09 July 2020 | <https://doi.org/10.1002/andp.202000204>

2. Electron beam for ep collisions at LHC

(in the ATLAS, CMS, ALICE and LHCb interaction points)



Atomic beams can be considered as **independent electron and nuclear beams** as long as the incoming proton scatters with the momentum transfer $q \gg 300 \text{ KeV}$!

Opens the possibility of collecting, by each of the LHC detectors, over one day of the **Pb+81-p** operation, the effective ep-collision luminosity comparable to the HERA integrated luminosity in the first year of its operation (1992) – **in-situ diagnostic of the emittance of partonic beams at the LHC!**



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Nuclear Instruments and Methods in Physics Research A 540 (2005) 222–234

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Electron beam for LHC

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Received 14 September 2004; received in revised form 19 November 2004; accepted 23 November 2004

Available online 22 December 2004

Initial studies:

Very recent important development:

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23**, 101002 (2020)

Editors' Suggestion

Collimation of partially stripped ions in the CERN Large Hadron Collider

A. Gorzawski^{1,2,*}, A. Abramov^{1,3,†}, R. Bruce¹, N. Fuster-Martinez¹, M. Krasny^{1,4},
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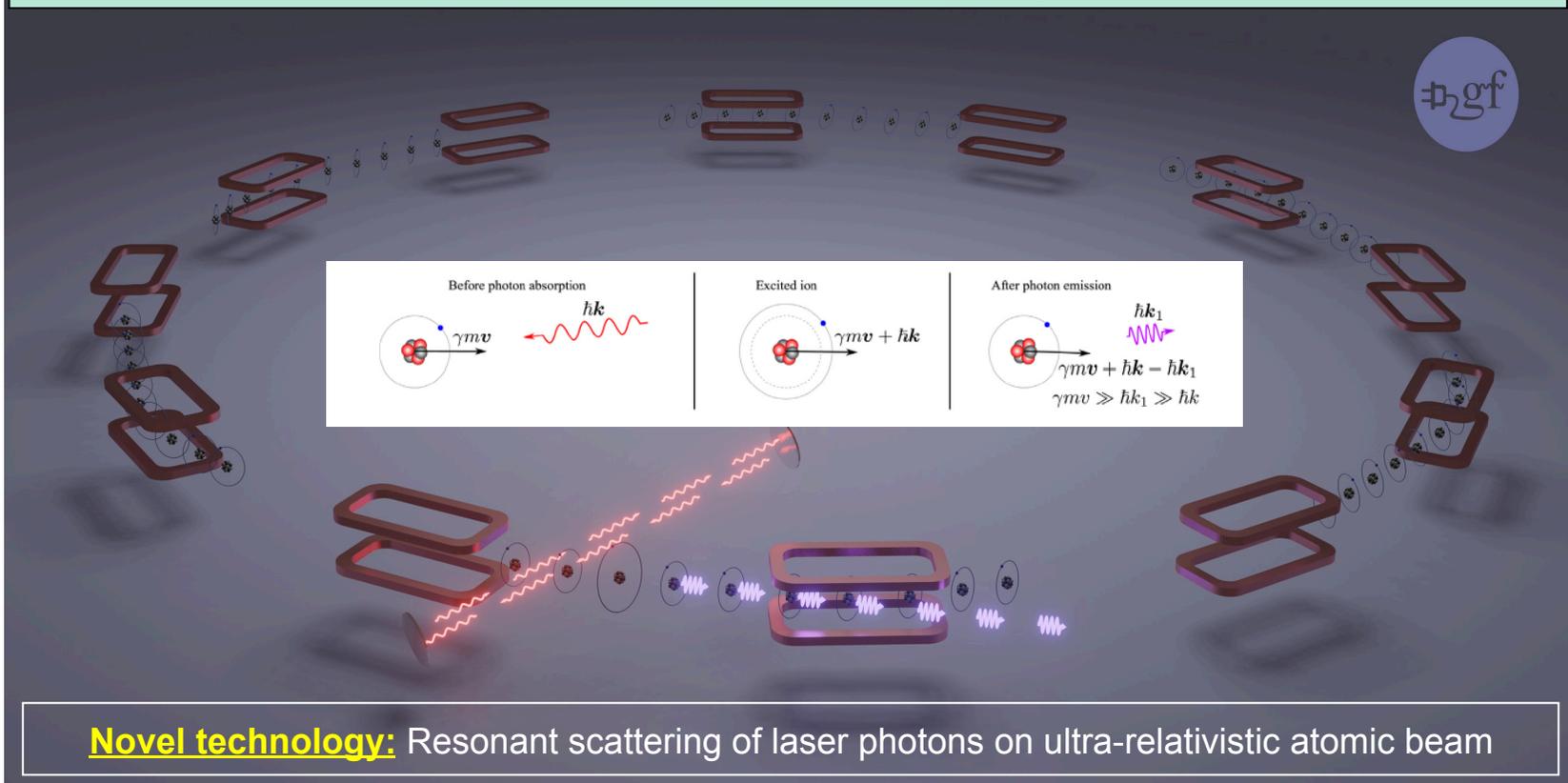
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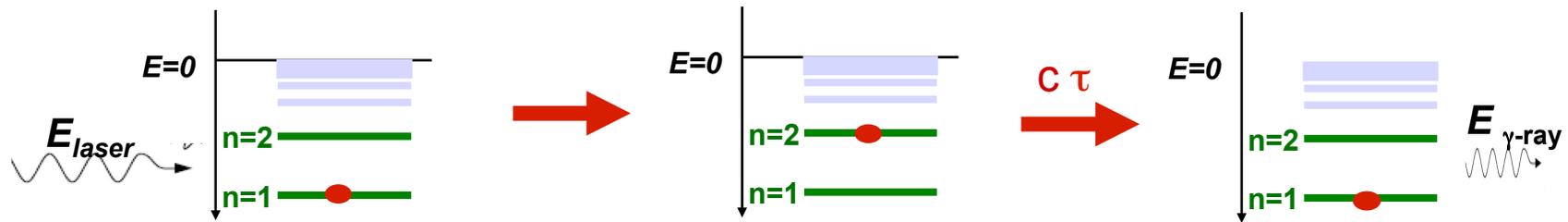
✉ (Received 3 August 2020; accepted 5 October 2020; published 23 October 2020)

3. Gamma Factory γ -source



Novel technology: Resonant scattering of laser photons on ultra-relativistic atomic beam

Source properties



1. Point-like:

- For high-Z, hydrogen- and helium-like atoms: **decay length ($c\tau\gamma_L$) $\ll 1$ cm**

2. High intensity:

- **Resonant process.** A leap in the intensity by **6–8 orders of magnitude** w.r.t. electron-beam-based Inverse Compton Sources (ICS) (at fixed γ_L and laser power)

Source properties

High energy atomic beams play the role of **high-stability light-frequency converters**:

$$\nu^{\max} \longrightarrow (4 \gamma_L^2) \nu_{\text{Laser}}$$

for photons emitted in the direction of incoming atoms, $\gamma_L = E/M$ is the Lorentz factor for the ion beam

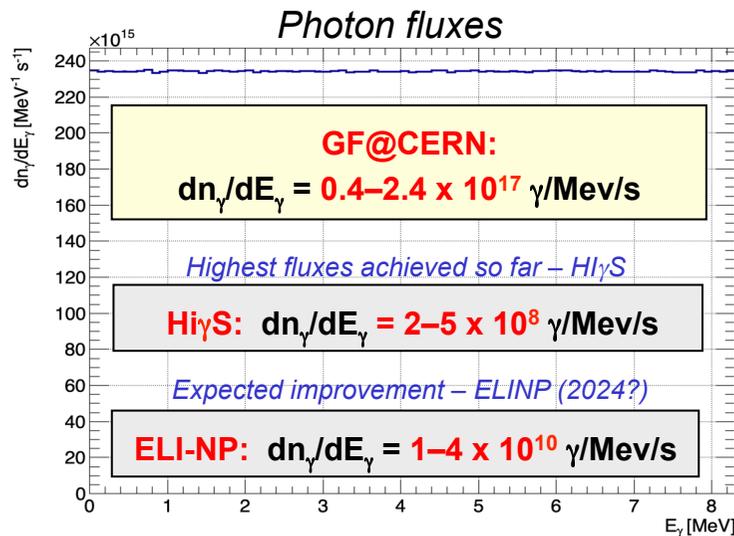
3. Tuneable energy:

- The tuning of the beam energy (SPS or LHC), the choice of the ion, the number of left electrons and of the laser type allow to tune the γ -ray energy at CERN in the energy range of 10 keV – 400 MeV (extending, by a factor of **~1000**, the energy range of the FEL X-ray sources)

4. Plug power efficient:

- Atoms lose a tiny fraction of their energy in the process of the photon emission. **Important:** No need to refill the driver beam. The RF power is **fully converted** to the power of the photon beam

A concrete example: Nuclear physics application: He-like, LHC
 Calcium beam, $(1s \rightarrow 2p)_{1/2}$ transition, TiSa laser

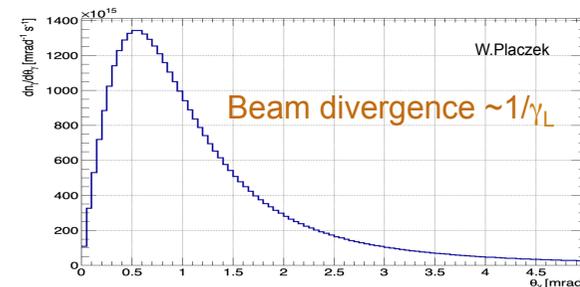
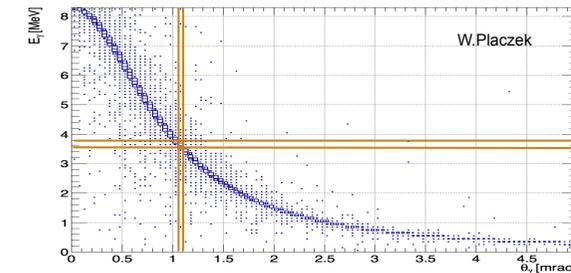


laser pulse parameters

- Gaussian spatial and time profiles,
- photon energy: $E_{\text{photon}} = 1.8338 \text{ eV}$
- photon pulse energy spread: $\sigma_{\omega}/\omega = 2 \times 10^{-4}$,
- photon wavelength: $\lambda = 676 \text{ nm}$,
- pulse energy: $W_{\text{f}} = 5 \text{ mJ}$,
- peak power density $1.12 \times 10^{13} \text{ W/m}^2$
- r.m.s. transverse beam size at focus: $\sigma_{\text{x}} = \sigma_{\text{y}} = 150 \text{ um}$ (micrometers),
- Rayleigh length: $R_{\text{L,x}} = R_{\text{L,y}} = 7.5 \text{ cm}$,
- r.m.s. pulse length: $l_{\text{f}} = 15 \text{ cm}$.

5. Highly-collimated monochromatic γ -beams:

- the beam power is concentrated in a narrow angular region (*facilitates beam extraction*)
- the $(E_\gamma, \Theta_\gamma)$ correlation can be used (collimation) to “*monochromatise*” the beam



4. Tertiary beams' sources – Intensity/quality targets

- **Polarised positrons** – potential gain of up to **a factor of 10^4** in intensity w.r.t. the KEK positron source, satisfying both the LEMMA and the LHeC requirements
- **Pions** – potential, gain by **a factor of 10^3** , gain in the spectral density ($dN_{\pi}/dEdp_{\tau}dP$ [$\text{MeV}^{-2} \times \text{MW}$] with respect to proton-beam-driven sources at KEK and FNAL (P is the driver beam power)
- **Muons** – potential gain by **a factor of 10^3** in intensity w.r.t. the PSI muon source, charge symmetry ($N_{\mu^+} \sim N_{\mu^-}$), polarisation control, no necessity of the muon beam cooling?
- **Neutrinos** – fluxes comparable to NuMAX but: (1) **Very Narrow Band Beam**, driven by the small spectral density pion beam and (2) unique possibility of creating **flavour- and CP-tuned beams** driven by the beams of polarised muons
- **Neutrons** – potential gain of up to **a factor of 10^4** in intensity of primary MeV-energy neutrons per 1 MW of the driver beam power
- **Radioactive ions** – potential gain of up to **a factor 10^4** in intensity w.r.t. e.g. ALTO

The SPS as a driver of secondary beams

1974-2021: 47 years of the experimental program with the SPS extracted beams

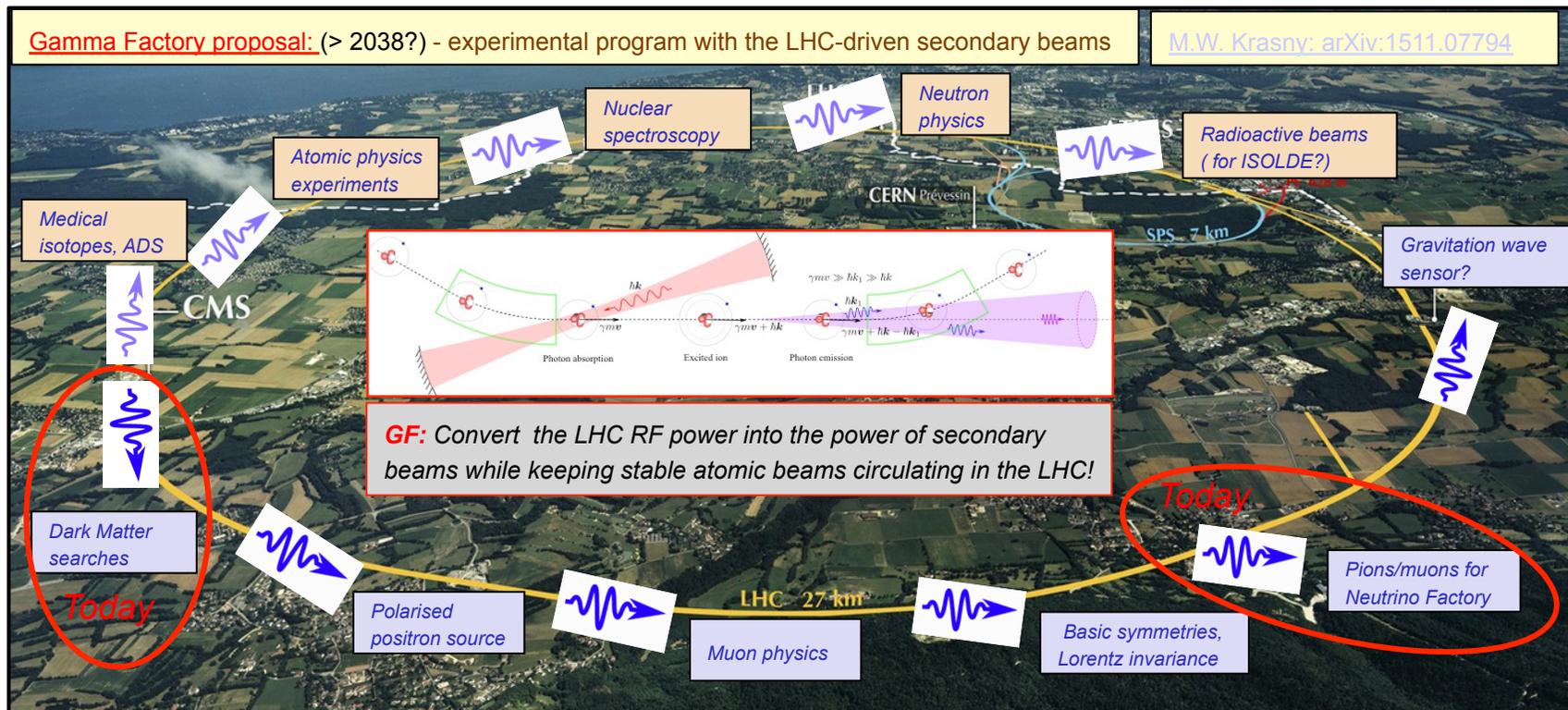
North Area



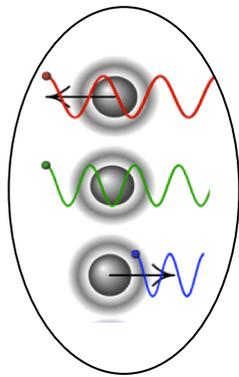
West Area



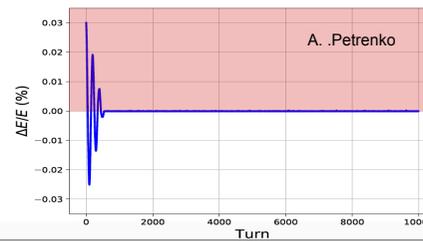
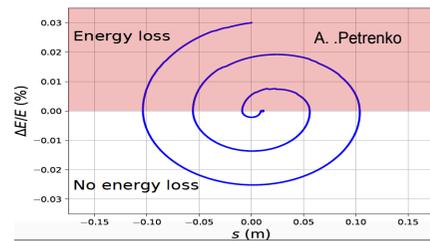
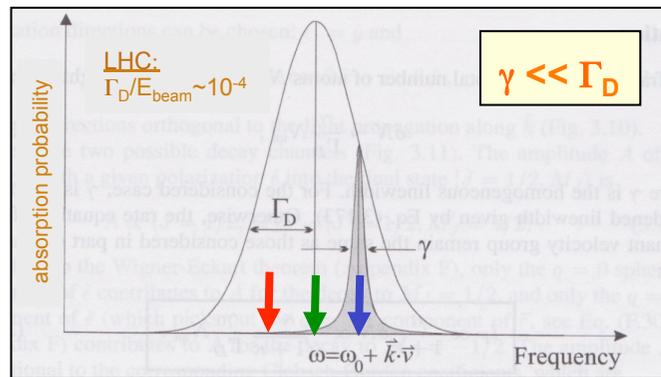
The LHC as a driver of secondary beams?



5. Doppler laser cooling methods of high energy beams

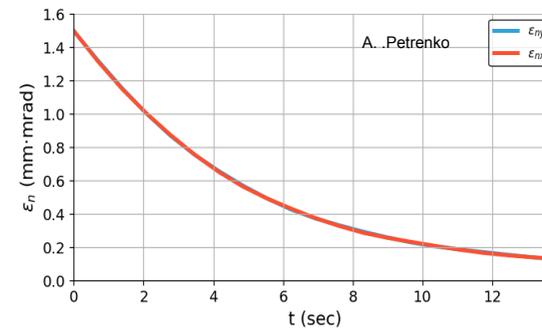


Bunch



Beam cooling speed: the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.

Opens a possibility of forming at CERN hadronic beams of the required longitudinal and transverse emittances within a seconds-long time scale



Simulation of laser cooling of the lithium-like Ca(+17) bunches in the SPS: [transverse emittance evolution](#).

Physics with the GF tools

- **particle physics** (studies of the basic symmetries of the universe, dark matter searches, precision QED and EW studies, vacuum birefringence studies, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, ...).
- **accelerator physics** (beam cooling techniques, low emittance hadronic beams, plasma wake field acceleration, high intensity polarized positron and muon sources, beams of radioactive ions and neutrons, very narrow band, and flavour-tagged neutrino beams).
- **particle physics** (studies of the basic symmetries of the universe, dark matter searches, precision QED and EW studies, vacuum birefringence studies, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, ...).
- **accelerator physics** (beam cooling techniques, low emittance hadronic beams, plasma wake field acceleration, high intensity polarized positron and muon sources, beams of radioactive ions and neutrons, very narrow band, and flavour-tagged neutrino beams).

Very recent Gamma Factory physics papers - particle physics



Review

High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams[†]

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ABSTRACT

The existing CERN accelerator infrastructure is world unique and its research capacity should be fully exploited. In the coming decade its principal modes *operandi* will be focused on producing intense proton beams, accelerating and colliding them at the Large Hadron Collider (LHC) with the highest achievable luminosity. This activity should, in our view, be complemented by new initiatives and their feasibility studies targeted on re-using the existing CERN accelerator complex in novel ways that were not conceived when the machines were designed. They should provide attractive, ready-to-implement research options for the forthcoming *paradigm-shift* phase of the CERN research. This paper presents one of the case studies of the Gamma Factory initiative (Krasny, 0000) – a proposal of a new operation scheme of ion beams in the CERN accelerator complex. Its goal is to extend the scope and precision of the LHC-based research by complementing the proton-proton collision programme with the high-luminosity nucleus-nucleus one. Its numerous physics highlights include studies of the exclusive Higgs-boson production in photon-photon collisions and precision measurements of the electroweak (EW) parameters. There are two principal ways to increase the LHC luminosity which do not require an upgrade of the CERN injectors: (1) modification of the beam-collision optics and (2) reduction of the transverse emittance of the colliding beams. The former scheme is employed by the ongoing high-luminosity (HL-LHC) project. The latter one, applicable only to ion beams, is proposed in this paper. It is based on laser cooling of bunches of partially stripped ions at the SPS flat-top energy. For isoscalar calcium beams, which fulfil the present beam-operation constraints and which are particularly attractive for the EW physics, the transverse beam emittance can be reduced by a factor of 5 within the 8 seconds long cooling phase. The predicted nucleon-nucleon luminosity of $L_{NN} = 4.2 \times 10^{34} \text{ s}^{-1} \text{ cm}^{-2}$ for collisions of the cooled calcium beams at the LHC top energy is comparable to the levelled luminosity for the HL-LHC proton-proton collisions, but with reduced pile-up background. The scheme proposed in this paper, if confirmed by the future Gamma Factory proof-of-principle experiment, could be implemented at CERN with minor infrastructure investments.

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arXiv:2105.10289v1 [hep-ph] 21 May 2021

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UCI-TR-2021-12

Gamma Factory Searches for Extremely Weakly-Interacting Particles

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Abstract

The Gamma Factory is a proposal to back-scatter laser photons off a beam of partially-stripped ions at the LHC, producing a beam of ~ 10 MeV to 1 GeV photons with intensities of 10^{16} to 10^{18} s^{-1} . This implies $\sim 10^{23}$ to 10^{25} photons on target per year, many orders of magnitude greater than existing accelerator light sources and also far greater than all current and planned electron and proton fixed target experiments. We determine the Gamma Factory's discovery potential through "dark Compton scattering," $\gamma e \rightarrow eX$, where X is a new, weakly-interacting particle. For dark photons and other new gauge bosons with masses in the 1 to 100 MeV range, the Gamma Factory has the potential to discover extremely weakly-interacting particles with just a few hours of data and will probe couplings as low as $\sim 10^{-9}$ with a year of running. The Gamma Factory therefore may probe couplings lower than all other terrestrial experiments and is highly complementary to astrophysical probes. We outline the requirements of an experiment to realize this potential and determine the sensitivity reach for various experimental configurations.

arXiv:2105.15072v1 [hep-ph] 31 May 2021

Probing ALPs at the CERN Gamma Factory

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June 1, 2021

Abstract

The aim of the proposed CERN Gamma Factory is to produce $\sim 10^{23}$ photons per second with energies up to 400 MeV. The photon beam intensity is expected to be a factor of $\mathcal{O}(10^3)$ larger than that of the presently available photon beams in the MeV energy range. In this work, we explore its potential to probe physics beyond the Standard Model. In particular, we discuss searches for axion like particles (ALPs) with dominant couplings to photons and consider various production scenarios – fixed target, photon-photon collision, and conversion by a magnetic field – and detection schemes – via decay to photons or back-conversion. We find that the Gamma Factory in a fixed target mode can probe ALPs with mass $m_a \lesssim \mathcal{O}(10)$ MeV and decay constants larger than 10^7 GeV, improving by an order of magnitude the discovery potential of previous beam dump experiments.

1 Introduction

Physics beyond the Standard Model (BSM) is well motivated both by experimental evidence and by theoretical arguments; see [1] for recent discussions. One of the target goals of the Gamma Factory initiative [2, 3] is to produce photon beams, in the energy range $\mathcal{O}(1 - 400)$ MeV, by colliding partially stripped ion beams stored in the LHC with laser pulses. If the HL-LHC project [4] is realized, this energy range can be extended in the future to 1 TeV. The Gamma Factory can provide a leap both in the photon beam intensity (by up to 7 orders of magnitude) and energy (by up to two orders of magnitude) with respect to the existing photon sources. The large photon flux in the Gamma Factory provides a unique opportunity to search for new particles with extremely weak couplings to the photon. Here we propose to use the Gamma Factory for probing weakly coupled, light pseudoscalars, which are collectively referred to as axions or axion-like-particles (ALPs). For a recent study of dark photons at the Gamma Factory see [5].

ALPs are found in many well-motivated BSM models. One notable type of ALP is the so-called QCD axion, which was predicted as part of the Peccei-Quinn solution for the strong CP problem [6, 7]. ALPs also appear in solutions to various hierarchy problems in the Standard Model [10–14]. In some cases, ALPs can be viable dark matter candidates [15–17] or act as portals to dark sectors [18–21]. For relevant reviews see [22–26], while for recent studies of ALPs with \sim MeV–GeV masses, see [27–45].

ALPs are commonly realized as pseudo Nambu-Goldstone bosons (pNGB). Thus, the mass of the ALP, m_a , is generated as a result of a small explicit breaking of a global symmetry, which is also spontaneously broken at some UV scale Λ , with $\Lambda \gg m_a$. An additional consequence of their pNGB nature is the fact that ALPs are often pseudoscalars (i.e. odd under CP). Hence, we consider an ALP a which couples predominantly to the photon,

$$\mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{\alpha}{4f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}. \quad (1)$$

In this minimal setup, the lifetime of the ALP is determined by its decay width to two photons, given by

$$\Gamma_{a \rightarrow \gamma\gamma} = \frac{m_a^4}{64\pi f_a^2}. \quad (2)$$

Very recent Gamma Factory physics papers – atomic and nuclear physics

FEATURE ARTICLE

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Atomic Physics Studies at the Gamma Factory at CERN

Dmitry Budker,^a José R. Crespo López-Urrutia,^b Andrei Derevianko,^c Victor V. Flambaum,^d Mieczysław Witold Krasny,^e Alexey Petrenko,^f Szymon Pustelny,^g Andrey Surzhykov,^h Vladimir A. Yerokhin,ⁱ and Max Zolotarev

The Gamma Factory initiative proposes to develop novel research tools at CERN by producing, accelerating, and storing highly relativistic, partially stripped ion beams in the SPS and LHC storage rings. By encoding the electronic degrees of freedom of the stored ions with lasers, high-energy narrow-band photon beams will be produced by properly collimating the secondary radiation that is peaked in the direction of ion propagation. Their intensities, up to 10^{17} photons per second, will be several orders of magnitude higher than those of the presently operating light sources in the particularly interesting γ -ray energy domain reaching up to 400 MeV. This article reviews opportunities that may be afforded by utilizing the primary beams for spectroscopy of partially stripped ions circulating in the storage ring, as well as the atomic-physics opportunities made possible by the use of the secondary high-energy photon beams. The Gamma Factory will enable ground-breaking experiments in spectroscopy and novel ways of testing fundamental symmetries of nature.

1. Introduction

The Gamma Factory (GF) is an ambitious proposal, currently endorsed within the CERN Physics Beyond Colliders program [1]. The proposal aims at developing a source of narrow-band photons with energies up to ~ 400 MeV, with photon fluxes up to $\sim 10^{17}$ photons per second, exceeding those of the currently available γ -ray sources (table 1) by many orders of magnitude. In this paper, we identify several types of the new opportunities that may be afforded by the GF in atomic physics and related fields. The GF is based on circulating partially stripped ions (PSI), that is, nuclei with a few bound electrons rather than bare nuclei, in a high-energy storage ring. The electrons intrinsic to the PSI open new experimental possibilities for

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Expanding Nuclear Physics Horizons with the Gamma Factory

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Radioactive ion beam production at the Gamma Factory

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Keywords: Gamma Factory, partially stripped ions, radioactive ion beams, ion stopping cell

A very intense γ beam of the Gamma Factory facility proposed at CERN can be used to generate radioactive ion beams (RIBs) with high production yields and exotic structure of exotic neutron-rich nuclei. The radioactive nuclei are generated via photo-fission in several actinide targets and thermalized in high-purity cryogenic beam, filling a gas cell which is enclosing the target. Electric fields are used to extract heavy ions and form RIBs which can be used to various scientific and measurement stations. Parameters for the production and extraction yields of exotic neutron-rich nuclei with such a setup are provided. A study of the impact of open-charge, build-up inside the gas cell on the extraction properties is presented and it is demonstrated that the beam needs to be disposed for achieving optimal extraction yields.

1. Introduction

The Gamma Factory (GF) facility at CERN [1, 2] can provide the next generation γ beams, based on resonant absorption and emission of laser photons on partially stripped ultra-relativistic heavy-ion (PSI) beams. The state-of-the-art γ -beam facilities, such as HRS at Duke University, USA [3] or the VEGA system at ELI-NP, which is in a final stage of construction at Magurele, Romania, are based on Compton back-scattering of laser photons off relativistic electrons (ECB). The γ -beam flux at the GF is expected to be several orders of magnitude higher compared to the present generation γ -beam facilities. This is mainly due to the interaction cross section which is higher by up to nine orders of magnitude for the absorption of laser photons by PSIs than that for ECB.

One of the potential applications of this unprecedented γ -beam intensity is the generation of high yield radioactive ion beams (RIBs) via photon induced fission. The fission process has been used successfully in the production of intermediate mass ($A \sim 70$ –150) nuclei in the neutron-rich region far away from the valley of β stability. The study of exotic nuclei in this region is the test-bench for theory in areas like the nuclear equation of state, nuclear structure models and nucleosynthesis via the rapid neutron capture process (r -process). Recent measurements of γ -radiation spectra emitted from neutron star mergers [4] have indicated that these cosmic events are one of the likely locations where r -process nucleosynthesis takes place. This has increased the interest in studying the neutron-rich nuclei along the r -process path, with special interest around the waiting points at neutron numbers $N = 50$, $N = 82$ and $N = 126$, the first two being accessible in fission, while the last is reached in fragmentation or multi-nucleon transfer reactions.

Several RIB facilities are currently active worldwide, such as CARIBU (ANL) [5], ISAC (Triumf) [6], ISOLDE (CERN) [7], FRS (GSI) [8], SPIRAL (GANIL) [9], JYFL (Jyväskylä) [10], and RIBF (RIKEN) [11]. For a recent review see Reference [12]. To a large degree, they complement each other by employing a variety of methods and technologies, such as beam types (from heavy ions to photons), target types (thick or thin), fragment separation (in-flight separators or in-cell catchers) and selection (with lasers, magnets, time-of-flight spectrometers), and experimental stations. Among the RIB facilities with γ -driver beams and thick actinide targets, like the one discussed here, the current ALTO (JFN Orsay) [13] and the future ARIEL (TRIUMF) [14] facilities employ bremsstrahlung sources, while the future ELISOL

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arXiv:2106.06584v1 [nucl-ex] 11 Jun 2021

Very recent Gamma Factory physics papers – fundamental physics

Local Lorentz invariance tests for photons and hadrons at the Gamma Factory

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High-precision tests of local Lorentz invariance, via monitoring of the sidereal time variation of the photon energies emitted by ultra-relativistic heavy-ion beams and of the beam momenta, are proposed. This paper includes descriptions of the physics ideas and the concept for the detector. The experiment results will allow high-precision tests of LLI via anisotropy of the maximum attainable speed of a photon and an ion. The projected accuracy for the anisotropies interpreted in the framework of the anisotropic relativistic mechanics corresponds to the limit on sidereal time variation of the one-way maximum attainable speed at the levels between 10^{-14} and 10^{-17} .

1. INTRODUCTION

Integrity of the speed of light, a key postulate of the special theory of relativity (STR), has been tested in many experiments over almost 150 years, the precision improving by many orders, see reviews [1–3]. These experiments belong to a larger group of investigations related to tests of local Lorentz invariance (LLI). Advanced theoretical models have been developed [4–6] for accurate interpretation of the experimental limits on LLI violation. Many experiments and observations have been analyzed in the framework of the Standard-Model extension (SME), see Ref. [2]. There are two classes of experiments on speed-of-light anisotropy. Experiments in the first class, starting from the famous work of Ref. [7], test the round trip (two-way) speed, c_2 . The second class of experiments addresses the one-way speed of light, c_1 . In STR, the speed of light is the maximum attainable speed for all types of matter. It was suggested about 20 years ago [8, 9] that particles could have different values of the maximum attainable speed, so many additional experiments would be useful.

In this paper, we present three schemes for testing LLI. Two tests are based on the correlations between the energies of two photon beams moving in the same or opposite directions and the third test is based on a correlation between the photon energy and the ion beam momentum.

II. SPECIAL RELATIVITY TESTS WITH BEAMS OF FAST PARTICLES

The relativistic Doppler effect (DE) was already considered by A. Einstein in his 1905 paper [10]. Doppler effect provided a way to observe a key feature of relativistic space-time: the time-dilation effect. The longitudinal DE, originating in time-dilation, results in a change in photon frequency due to Lorentz boost. The first such test was successfully realized by Ives and Stilwell [11] using a beam of fast atoms. With progress in photon and accelerator technology, a number of experiments have been performed, see reviews [1, 3].

Thanks to modern experimental methods, the most advanced experiment using ions in a storage ring was completed in 2014 [12], which directly tested the DE formula and achieved sensitivity to a speed-of-light variation at the level of 10^{-8} . The anisotropy of maximum attainable speed (MAS) via the sidereal time variation of DE could also be tested, but this requires a very stable energy of the ion beam. Hereafter, we referring to the average value of the energy of the ion beam because the ion beam energy spread is small enough for considerations presented below.

Photon scattering from a fast moving electron (inverse Compton scattering) has also been proposed to search for sidereal time variation of the photon MAS [13]. The large value of Lorentz factor of the electron beam (γ) made possible a high-precision test due to the enhanced sensitivity of the final photon energy (E) to the variation of the speed-of-light, $dE/E = -2\gamma^2 d c/c$. The result of the experiment [14], interpreted in the framework of SME, provided a limit on the anisotropy of the one-way MAS at the level of 10^{-10} .

High-energy particle beams in a storage ring can be used for precision tests of the Lorentz-force variation with sidereal time, especially with two beams moving in opposite directions at the same magnetic structure [15, 16]. In such an experiment the use of two counter-propagating beams provides a way to reduce the impact of the magnetic system instability and beam-energy variations. The sensitivity to a potential variation of the electron MAS is enhanced by an additional factor of 2. The result of that experiment interpreted in the framework of anisotropic relativistic mechanics (ARM) [17] as a limit on the anisotropy of the electron MAS (in this case, c_1) is $5 \cdot 10^{-11}$.

Vacuum birefringence at the Gamma Factory

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(Dated: June 14, 2021)

Abstract

We explore the perspectives of studying vacuum birefringence at the Gamma Factory. To this end, we assess in detail the parameter regime which can be reliably analyzed resorting to the leading contribution to the Heisenberg-Euler effective Lagrangian. We explicitly show that – contrarily to naive expectations – this approach allows for the accurate theoretical study of quantum vacuum signatures up to fairly large photon energies. The big advantage of this parameter regime is the possibility of studying the phenomenon in experimentally realistic, manifestly inhomogeneous pump and probe field configurations. Thereafter, we focus on two specific scenarios giving rise to a vacuum birefringence effect for traversing gamma probe photons. In the first scenario the birefringence phenomenon is induced by a quasi-constant static magnetic field. In the second case it is driven by a counter-propagating high-intensity laser field.

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Resonance photoproduction of pionic atoms at the proposed Gamma Factory

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We present a possibility of direct resonance production of pionic atoms (Coulomb bound states of a negative pion and a nucleus) with a rate of up to $\sim 10^{10}$ per second using the gamma-ray beams from the Gamma Factory.

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I. INTRODUCTION

The pionic atom [1] consists of a negative pion trapped in the Coulomb potential of an atomic nucleus. Such systems provide great opportunities to study the strong interaction and derive information on nuclear structure. Theoretical study of energy levels in pionic atoms started long ago [2, 3] and initiated extensive theoretical and experimental studies; see, for example, the recent experiment on laser spectroscopy of pionic ⁴He of Ref. [4], and references therein.

A conventional production mechanism of pionic atoms involves creation of free negative pions which are then captured by nuclei. Here, we explore a possibility of direct production of pion-nucleus bound states by a monochromatic gamma-ray beam with the energy tuned to that of the bound state. This monochromatic gamma-ray beam is expected at the proposed Gamma Factory (GF) [5, 6] currently studied within the CEBAF Physics Beyond Colliders program. It is noted that photoproduction of pionic atoms was once put forward by Tzara [7]. Here, we introduce different approaches to evaluating photoproduction cross sections, and, making use of experimental data for free-pion (both charged and neutral) photoproduction, we extend the analysis to a range of nuclei. Estimates presented below show that the pionic-atom production rate μ may, in principle, reach $\sim 10^{10}$ atoms per second, i.e., it may exceed the production rate at existing facilities ($\sim 10^6$ pionic atoms per second; see, for example, Ref. [4]) by many orders of magnitude. Specific experimental arrangements, the discussion of which is beyond the scope of the present paper, may reduce this gain in the production rate, but the problem

certainly deserves a preliminary investigation, which is the aim of the present note.

II. ESTIMATE OF THE PRODUCTION RATE

We assume an arrangement where the gamma rays impinge onto a fixed target. Photoproduction of pionic atoms is realized through the reaction $\gamma + n \rightarrow p + \pi^-$ within a nucleus, i.e.,

$$\gamma + \sum X \rightarrow (\sum X + \pi^-)_i, \quad (1)$$

where $\sum X$ and $\sum X'$ are the initial and final nuclei, respectively (both in their nuclear ground state), Z_i and $Z_f = Z_i + 1$ are the corresponding atomic numbers, A_i is the number of nucleons, which is the same for the initial nucleus and the final one, π_i is the pionic atom principal quantum number, and i is the angular momentum quantum number. We will focus mainly on n states since π^- in n states have larger probability densities inside the nucleus and thus larger cross sections for their production.

An example of the reaction is

$$\gamma + {}^3\text{H} \rightarrow ({}^3\text{He} + \pi^-)_n. \quad (2)$$

Similar reactions occur with heavier nuclei. Assuming that the initial atom is at rest, we obtain an equation for the resonant photon energy $E_\gamma = mc^2 + E_{\text{cm}} + D_{\text{cm}} + E_i + \Delta M_i c^2$, where $mc^2 = 139.57$ MeV is the rest energy of the negative

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Example 1:

*High-Luminosity LHC with low emittance,
Gamma Factory “cold” beams*

The Gamma Factory path to high-luminosity LHC

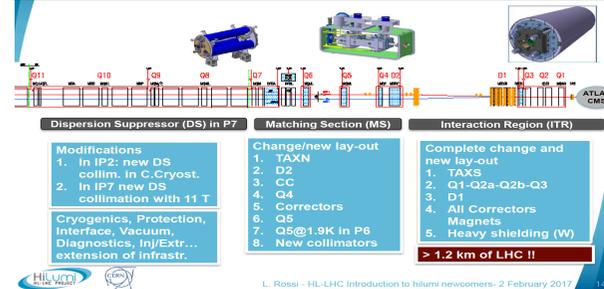
$$\mathcal{L} = f \frac{n_1 n_2}{4\pi \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

Two complementary ways to increase collider luminosity:

- **increase the focusing strength, β^*** ↘
- **reduce the beam emittance, ϵ** ↘
- **both.**

A **low-emittance** particle beam is the beam where particles are confined within small distances and have nearly the same momentum vectors – **cold beams**.

The on-going HL(pp)-LHC project



Levelled Luminosity: **2.5 (5) x 10³⁴ cm⁻²s⁻¹**, **cost ~ 1 billion euro**

Progress in Particle and Nuclear Physics
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Review
High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams ☆

M.W. Krasny ^{a, b, R, E}, A. Petrenko ^{c, b}, W. Placzek ^d

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The GF scheme of reducing the transverse beam emittance

Produce

- Produce highly charged ion bunches (partially stripped atoms) with the existing CERN ion source

Leave electrons

- Leave a couple of electrons attached to their parent nuclei for the SPS acceleration phase (in the canonical SPS heavy ion operation all electrons are already stripped off).

Cool

- Cool the atomic beam with the specialised laser system at the top SPS energy to reduce its emittance (longitudinal and the transverse cooling).

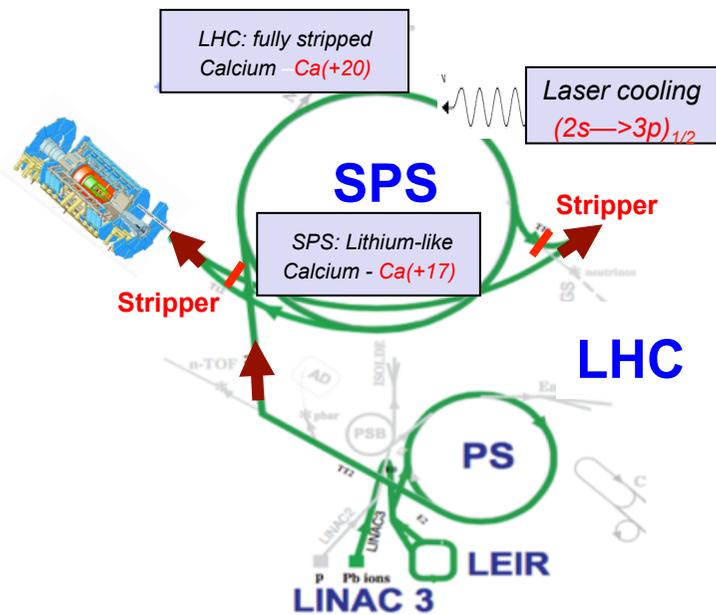
Strip

- Strip the electrons in the SPS-to-LHC transfer line.

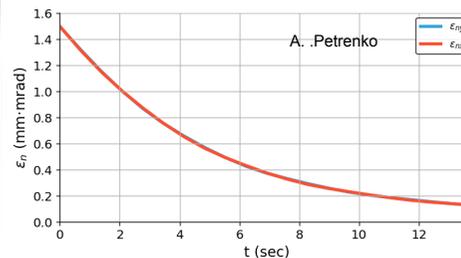
Accelerate and collide

- Accelerate and collide fully stripped ion beams in the LHC.

Gamma Factory path to HL(AA)-LHC: A concrete implementation scheme with **Ca** beams



Ion Source + Linac: charge state after stripping: $\text{Ca}(+17)$



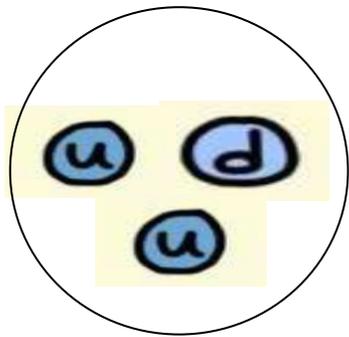
Reduction of the transverse x,y, emittances by a factor of 5 can be achieved in 9 seconds



Parameter	Value
$s^{1/2}$ [TeV]	7
$\sigma_{BFPP}(\text{Ca})/\sigma_{BFPP}(\text{Pb})$	5×10^{-5}
$\sigma_{had}(\text{Ca})/\sigma_{tot}(\text{Ca})$	0.6
N_b	3×10^9
$\epsilon_{(x,y)n}$ [μm] ⁽¹⁾	0.3
IBS [h]	1–2
β^* [m]	0.15
L_{NN} [$\text{cm}^{-2}\text{s}^{-1}$]	4.2×10^{34}
Nb of bunches	1404
Collisions/beam crossing	5.5

Optical stochastic cooling time for the Ca beam, if necessary, at the top energy – 1.5 hours (V. Lebedev)

Significantly higher precision can be achieved in measuring EW processes with isoscalar ion beams (e.g. Ca) rather than proton beams - WHY?



u and **d** quarks have different charges, weak isospin and vector and axial couplings.
For EW-physics: proton beams are equivalent to neutrino and electron beam mixed in not precisely known proportions.

In addition the relative distributions of the valence and sea u and d quarks determine the effective W/Z boson polarisation. Proton beams → polarisation cannot be precisely controlled.

Isoscalar (A=2Z) ion beams

Profit from the flavour symmetry of strong interactions to equalize the distributions of the u and d quarks:

$$u_{v,s}^{A=2Z,Z}(x, k_t, Q^2) = d_{v,s}^{A=2Z,Z}(x, k_t, Q^2)$$

M.W. Krasny, F. Dydak, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C69* (2010) 379-397.

F. Fayette, M.W. Krasny, W. Placzek, A. Siodmok, *Eur.Phys.J. C63* (2009) 33-56.

M.W. Krasny, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C51* (2007) 607-617.

M.W. Krasny, S. Jadach, W. Placzek, *Eur.Phys.J. C44* (2005) 333-350.

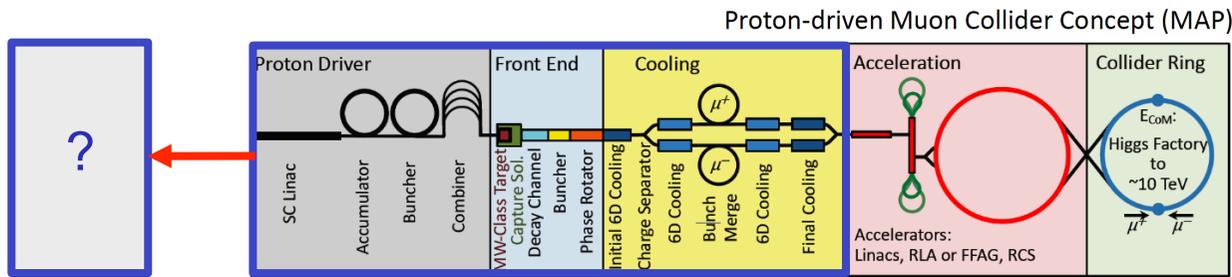
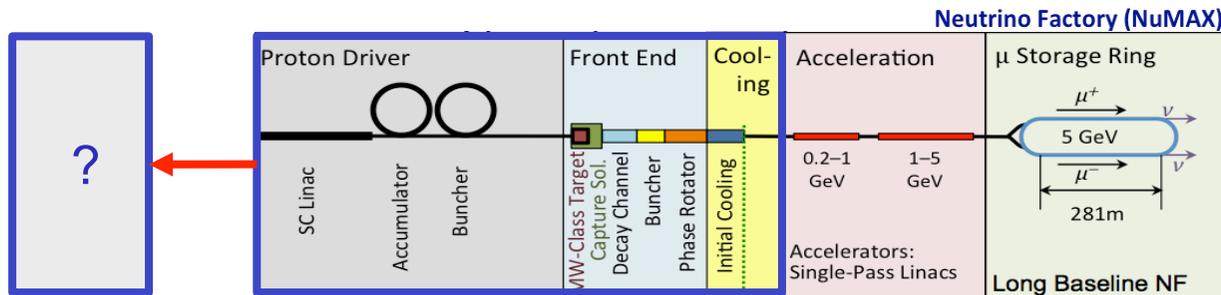
The merits of
the low-
emittance
isoscalar
($Z=A/2$)
beams

- Partonic **emittances** (longitudinal and transverse) can be **fully controlled by the LHC data alone** (no precision brick-walls coming from the LHC-external data, and PDFs, PS models).
- Significantly **higher systematic precision** in measuring the **EW processes** by using **isoscalar ion beams** rather than proton beams (as in the earlier fixed target experiments).
- A **Z^4 leap in photon fluxes** – access to **exclusive Higgs boson production in photon–photon collisions** – unreachable for the pp running mode.
- **Lower pileup background** at the equivalent (high) nucleon-nucleon luminosity.
- **New research opportunities** for the EW symmetry breaking sector.

Example 2:

*Gamma-Factory-driven, **neutrino source***
and
*polarised **muon source***

Towards the Gamma-Factory-driven, **neutrino source** and **polarised muon source**

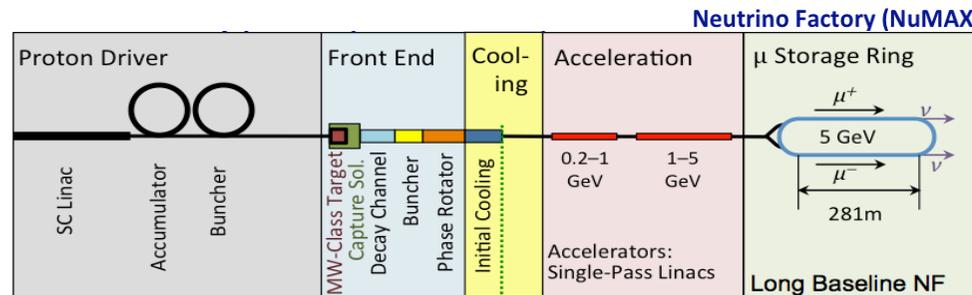


Shouldn't we try to avoid constructing a costly, high power Proton Driver, and to get rid of the necessity of building a ~1000 m long, sophisticated cooling section?

*Who would not be excited by the perspective of constructing a **3 TeV muon-collider** in the existing, 7 km long, SPS tunnel, for the **(5.5 BCHF)** cost of digging the tunnel for the **100 km long, 350 GEV, e⁺e⁻ collider**?*

Muon-beam driven neutrino beams

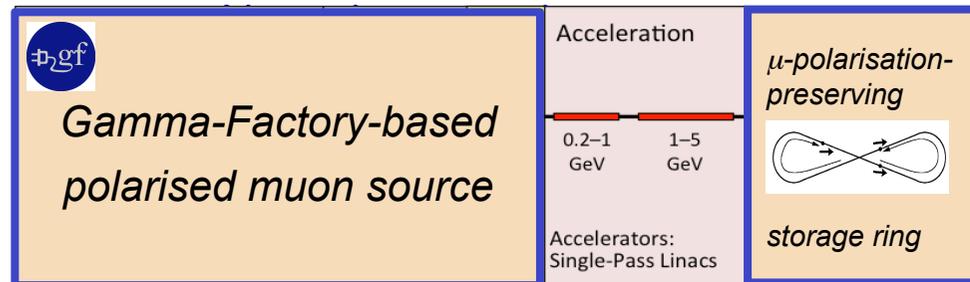
Detailed studies over the last 20 years...



Neutrino Factory parameters

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ^+ or μ^- /year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}

Gamma Factory
ongoing studies



1. **Can we deliver 10^{13} - 10^{14} muons/second of each sign?**
2. **Can we produce polarised muon beam?**
3. **Can we avoid the μ -cooling phase?**

The importance of muon (longitudinal) polarisation

Precise control of CP and flavour composition of the μ -beam driven neutrino source

$$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

- The GF source for isoscalar targets is “charge-symmetric”!
- Selection of $\nu_e\bar{\nu}_\mu$ or $\bar{\nu}_e\nu_\mu$ beam by changing the sign of collected pions
- Control of the relative $\bar{\nu}_e/\nu_\mu$ ($\nu_e/\bar{\nu}_\mu$) fluxes by changing muon polarisation 

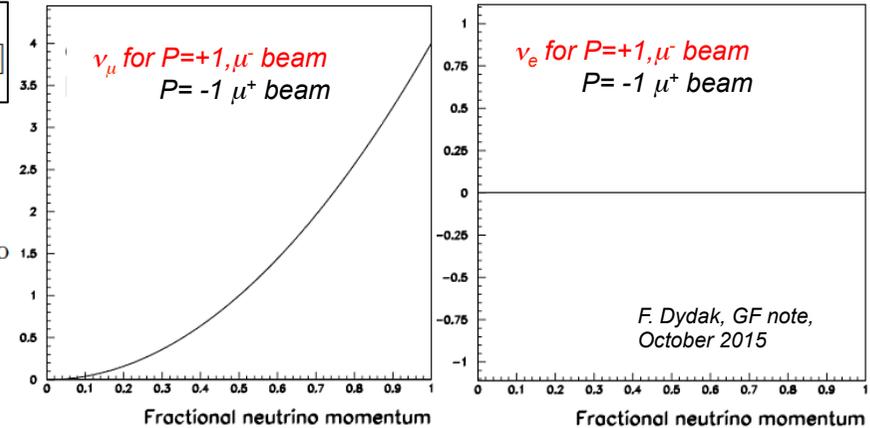
$$\frac{d^2N}{dx d\Omega} = \frac{1}{4\pi} [f_0(x) \mp \mathcal{P}_\mu f_1(x) \cos \theta]$$

$$x = 2E_\nu/m_\mu$$

\mathcal{P}_μ is the muon polarization

θ is the angle between the neutrino momentum vector and the muon spin direction

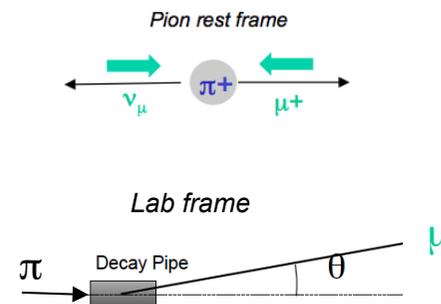
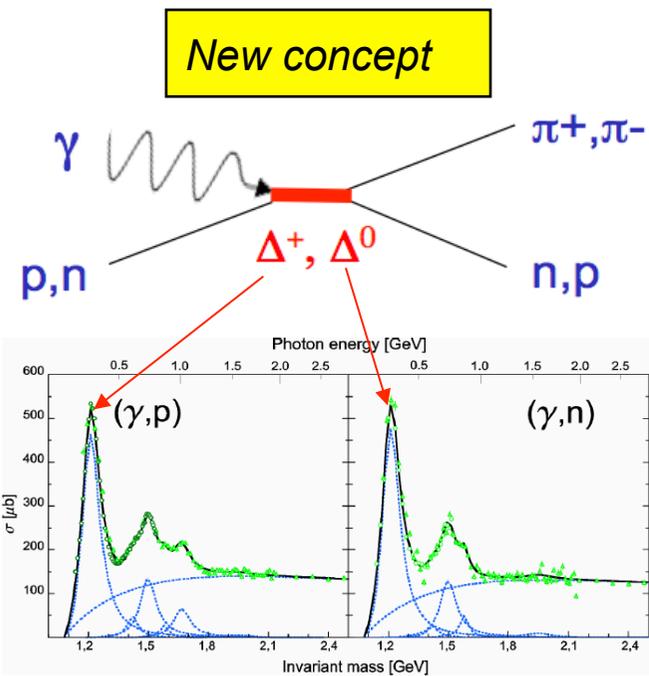
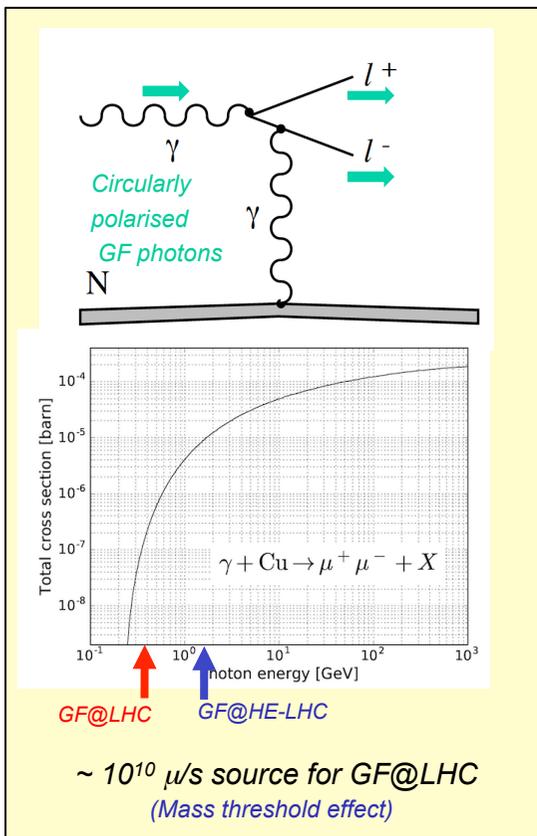
	$f_0(x)$	$f_1(x)$
$\nu_{\mu, e}$	$2x^2(3 - 2x)$	$2x^2(1 - 2x)$
ν_e	$12x^2(1 - x)$	$12x^2(1 - x)$



Conceptually optimal experiment to search for CP violation in the neutrino sector:

The experiment would compare the oscillation probabilities of $\nu_\mu \rightarrow \nu_e$, with the ν_μ flux obtained from the decay under zero forward angle from fully polarized μ^- , and of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with the $\bar{\nu}_\mu$ flux obtained from the decay under zero forward angle from fully polarized μ^+ .

Gamma Factory - producing polarised muons by photons



Polarisation = $P(\theta)$

Requires quasi-monochromatic pion beam ...and θ -dependent packing of muons into successive RF buckets to minimise the polarisation smearing!

High intensity source: 2×10^{13} (10^{14}) μ^+ and μ^- per second for the 2X0 graphite (deuterium) target and 1 MW, 300 MeV photon beam!

Quasi-monochromatic pion source:

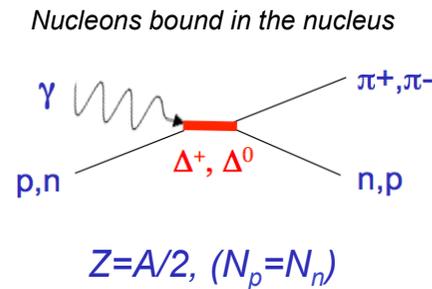
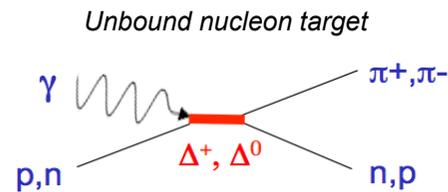
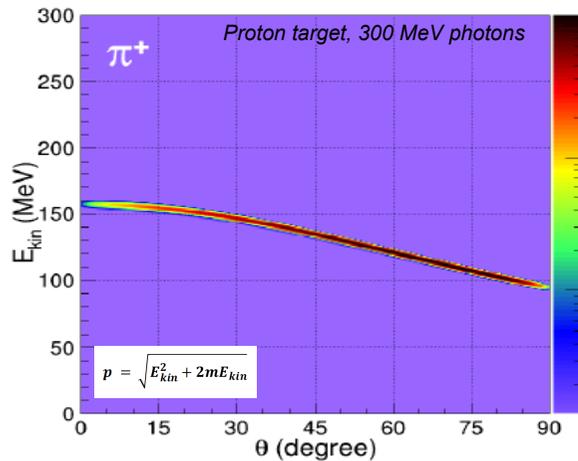
De-randomising pion spectra and restoring their charge symmetry

CM frame:

Monochromatic pions

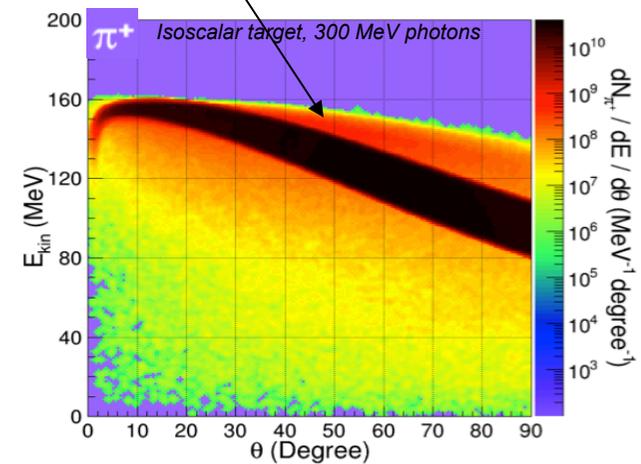
Laboratory frame:

➤ Pion energy and transverse momentum fully specified by one parameter: *the pion emission angle, θ*



Isoscalar target choice:

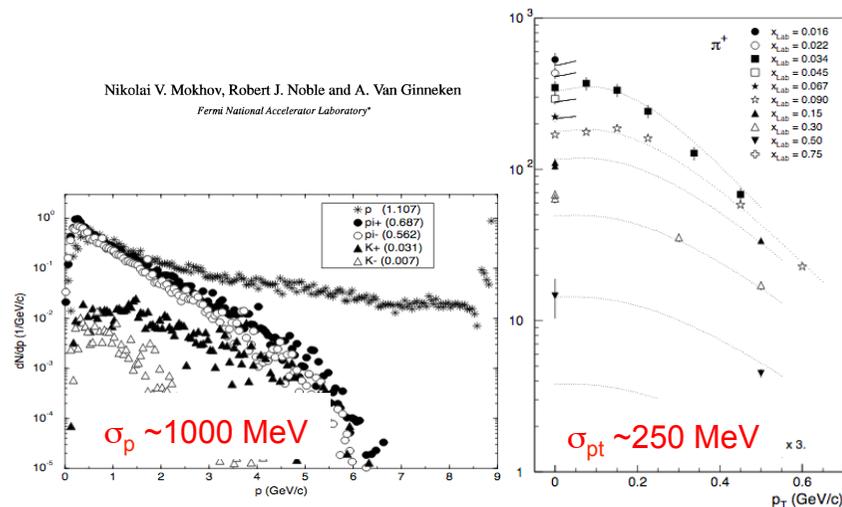
assures almost exact charge symmetry of π^+ and π^- production (below 2π production threshold) (note the effect of the nucleon Fermi motion smearing – relative to hydrogen target)



Can we avoid μ -cooling stage? – pion spectral density

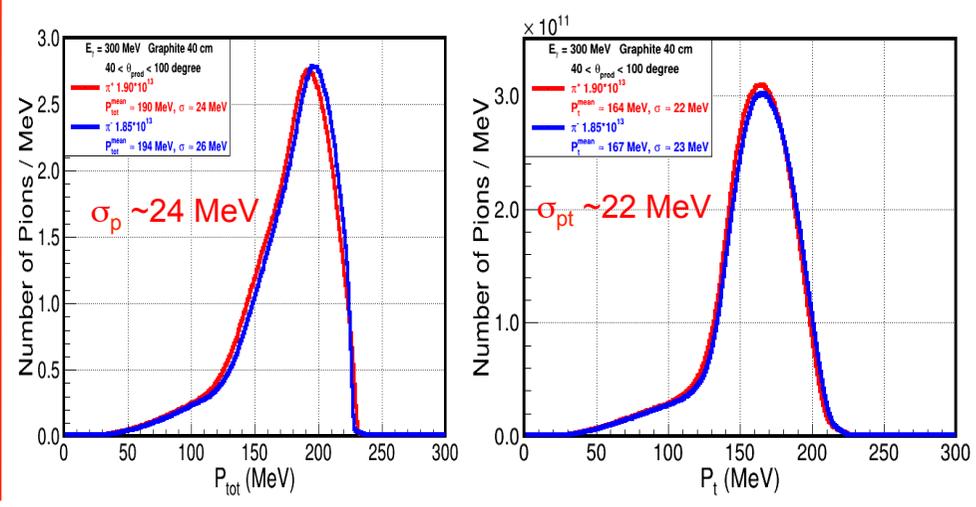
8 GeV proton beam

For $\lambda_1 = 2$ graphite target:
 $\sim 4.1 \times 10^{14} \pi^+$ /s and $\sim 2.6 \times 10^{14} \pi^-$ /s for 1 MW p beam



300 MeV GF γ -beam

For $\lambda_1 = 2$ graphite target :
 $\sim 3 \times 10^{13} \pi^+$ and π^- /s for 1 MW γ beam ($2 \times 10^{16} \gamma$ /s)



A factor of 10 less pions produced by 1 MW photon beam w.r.t. 1 MW proton beam, ...but significantly higher, by a factor ~ 500 , spectral density [1/MeV³] of produced “beam-like” pions!

Mark Palmer for the Muon Accelerator Program (MAP)

Proposed scheme:

Expected pion source beam emittance:

$$\epsilon_T \sim \sigma_T \sigma_p / mc \sim 0.8 \text{ mm}$$

$$\epsilon_L \sim \sigma_{||} \sigma_p / mc \sim 20 \text{ mm}$$

1 MW gamma beam, 20 cm long graphite target, $N_\pi = 1.3 \times 10^{13}$ of each sign

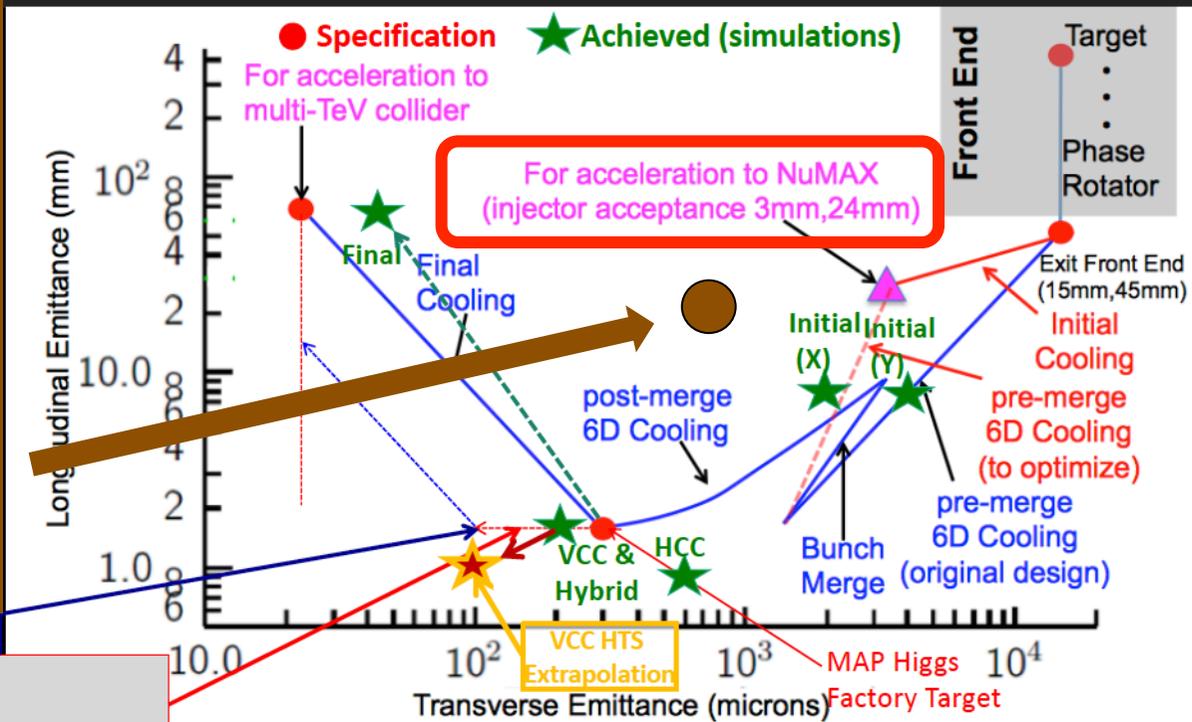
Remaining challenge: design a pion/muon collection scheme in which the emittance is preserved (...or worsen by not more than a factor of ~4) (under study)

Rubbia's Proposal

Advanced techniques \Rightarrow
Improved HF Luminosity
Simplified Final Cooling requirements

December 1, 2020

Cooling



PITT PACC Workshop: Muon Collider Physics

11

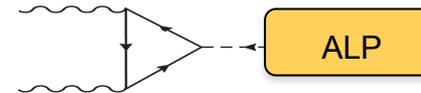
BROOKHAVEN
NATIONAL LABORATORY

Example 3:

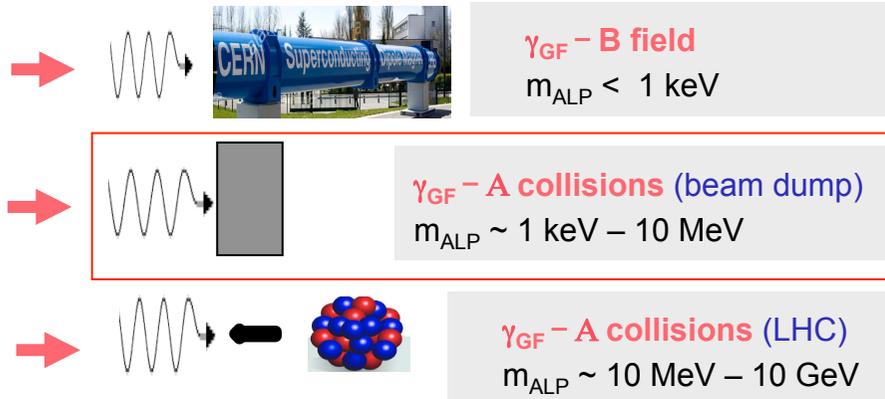
Dark Matter searches in Gamma-Factory
ALPs and Dark Photons

DM searches (and studies): Axion-Like-Particles (ALP) example

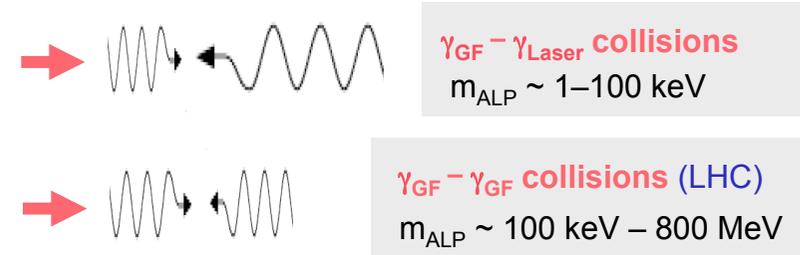
Collision schemes for ALP production:



Search phase



“Production” phase



Concurrent, rich QED programme (e.g. vacuum birefringence studies)

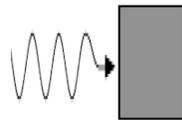
Three principal advantages of the Gamma Factory photon beams:

- **Large fluxes:** $\sim 10^{25}$ photons on target over year (SHIP – 10^{20} protons on target).
- **Multiple ALP production schemes** covering a vast region of ALP masses (**sub eV – GeV**)
- **Once ALP candidate seen** \rightarrow a unique possibility to **tune the GF beam energy to the resonance.**

Gamma Factory APL-finding potential (beam-dump search mode)

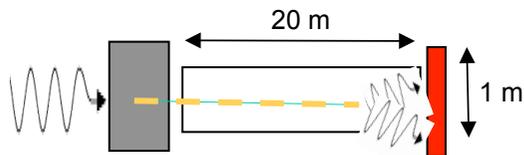
Search phase

Example: beam-dump search mode

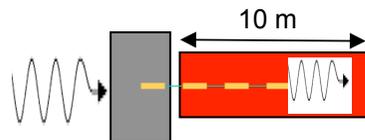


$\gamma_{GF} - A$ collisions
1.6, 0.2, 0.02 GeV
beams (A, B, C)

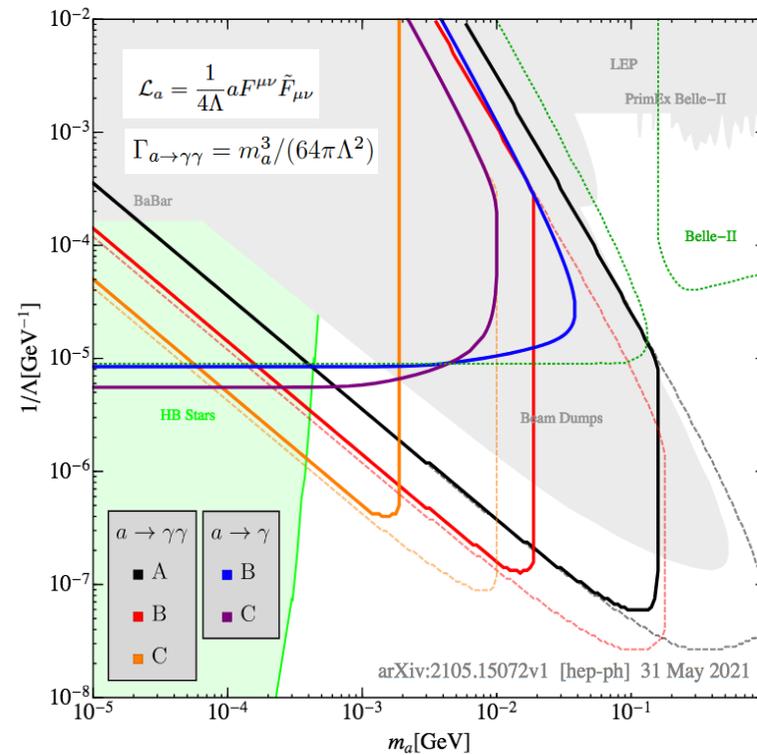
Two appearance modes:



➤ decay: $a \rightarrow \gamma\gamma$ (A, B, C)



➤ reversion: $aN \rightarrow \gamma N$ (B, C)



Gamma Factory dark photon discovery potential (beam-dump search mode)

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \varepsilon e \sum_f q_f \bar{f} A' f$$

$$\gamma e \rightarrow e X$$

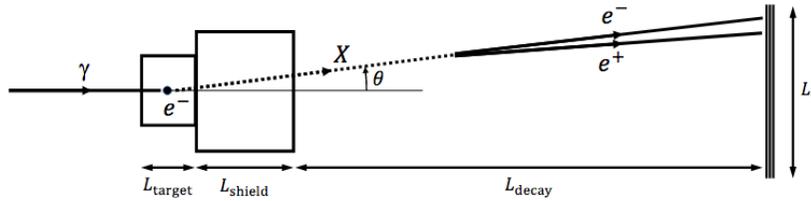


FIG. 1. **Experiment layout.** The experiment consists of a (graphite) target with thickn $L_{\text{target}} = 1$ m, followed by a (lead) shield with thickness $L_{\text{shield}} = 2$ m, an open air decay reg with length L_{decay} , and a tracking detector, centered on the beam axis, which we take to be a circular disk with diameter L_{det} . The GF photon beam enters from the left and produces an particle through dark Compton scattering $\gamma e \rightarrow e X$. The X particle is produced with an angl relative to the GF beamline and decays to an e^+e^- pair, which is detected in the tracking detect

Gamma Factory Searches for
Extremely Weakly-Interacting Particles

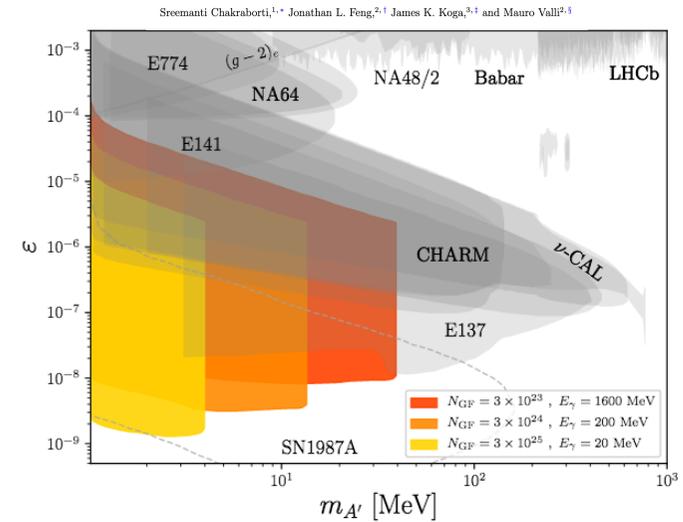


FIG. 3. **Dark photon sensitivity.** The sensitivity reach for the three sets of GF parameters $(E_\gamma, N_{\text{GF}})$ indicated, each corresponding to a year of running, and detector parameters $L_{\text{decay}} = 12$ m and $L_{\text{det}} = 3$ m. The contours are for 3 e^+e^- signal events and assume no background. The gray shaded regions are existing bounds from the terrestrial experiments indicated [32–42] (for further details, see also [43, 44]), from $(g-2)_e$ [45], and the dashed gray line encloses the region probed by supernova cooling, as determined in Ref. [46].

Gamma Factory status



Gamma Factory group

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The Gamma Factory initiative ([arXiv:1511.07794](https://arxiv.org/abs/1511.07794) [hep-ex]) was supported by the CERN management by creating (February 2017) the **Gamma Factory study group**, embedded within the *Physics Beyond Colliders* studies framework.

~90 physicists from 35 institutions have contributed so far to the development of the project. The GF group is open for everyone who wants to contribute.

We acknowledge the crucial role of the **CERN PBC framework** in bringing our accelerator tests, the PoP experiment design, software development and physics studies to its present stage!

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Gamma Factory milestones – where we are?

1. *Successful demonstration of efficient production, acceleration and storage of “atomic beams” in the CERN accelerator complex.*
2. *Development “ab nihilo” the requisite Gamma Factory software tools.*
3. *Building up the physics cases for the LHC-based GF research programme and attracting wide scientific communities to evaluate and use (in the future) the GF tools in their respective research.*
4. ***Successful execution of the GF Proof-of-Principle (PoP) experiment in the SPS tunnel.***



Done...



Done...



Work ongoing...



Lol submitted to the SPSC on the 25th of September 2019, public presentation on the 13th of October 2020 → GF PoP collaboraion being formed...

future

-
5. *Extrapolation of the PoP experiment results to the LHC case and precise assessment of the performance figures of the GF programme (prior to the next European Strategy Update).*
 6. *Elaboration of the TDR for the LHC-based GF research programme.*

Conclusions

- ❑ *Gamma Factory can create, at CERN, a variety of novel research tools, which could open novel research opportunities in a very broad domain of basic and applied science*
- ❑ *The Gamma Factory research programme can be largely based on the existing CERN accelerator infrastructure – it requires “relatively” minor infrastructure investments*
- ❑ *Its “quest for diversity of research subjects and communities” is of particular importance in the present phase of accelerator-based research, as we neither have any solid theoretical guidance for a new physics “just around the corner”, accessible by FCC or CLIC, nor an established “reasonable cost” technology for a leap into very high energy “terra incognita”*
- ❑ *Gamma Factory requires extensive R&D studies (including its proof-of-principle experiment), which must be finalised prior to the next European Strategy Update*