Gamma Factory

Status and Physics Highlights

Corfu Workshop on the Standard Model and Beyond, Sept 2021

Mieczyslaw Witold Krasny

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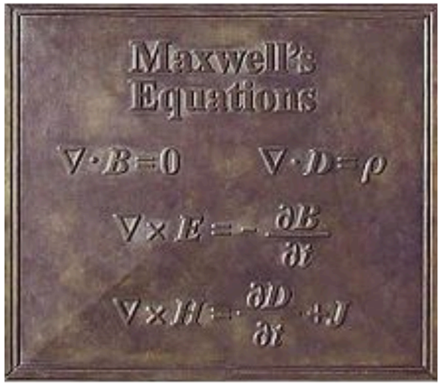
HEP future: concepts and tools



"*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.

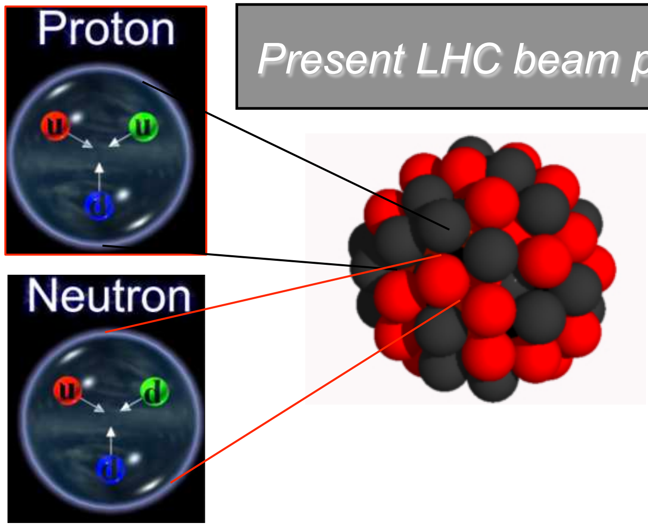
The effect of a tool-driven revolution is to discover new things that have to be explained" - F. Dyson

Outline of the talk

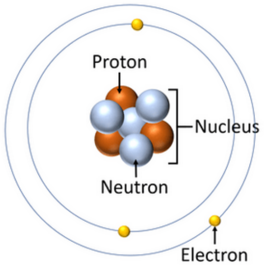
- *Gamma Factory research tools*
- *Examples of physics highlights*
- *Gamma Factory status*
- *Conclusions*

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:



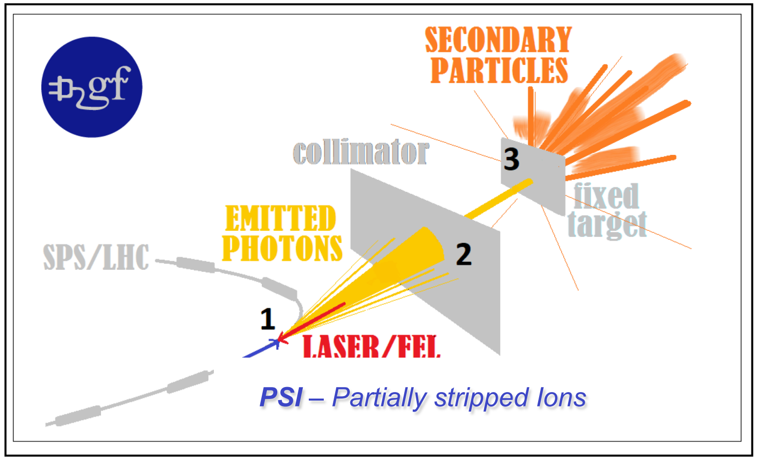
Future LHC beam particles:

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]

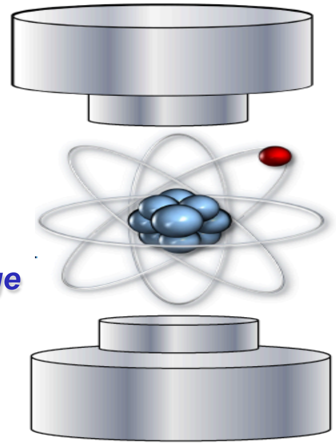


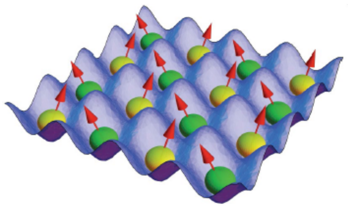
GF research tools made from light

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

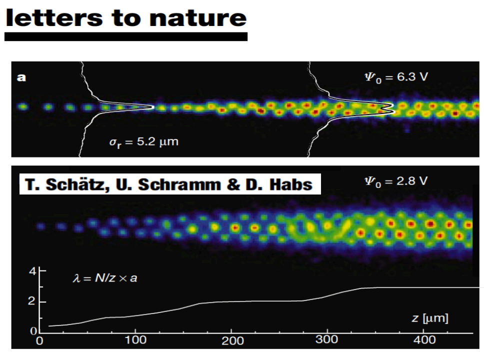
Atomic rest-frame

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





Crystalline beams?



Opening new research opportunities:

- *Highly-charged atoms – very strong (~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 → Lorentz invariance tests and gravitational wave detection*


adp annalen der physik

Feature Article | Open Access

Atomic Physics Studies at the Gamma Factory at CERN

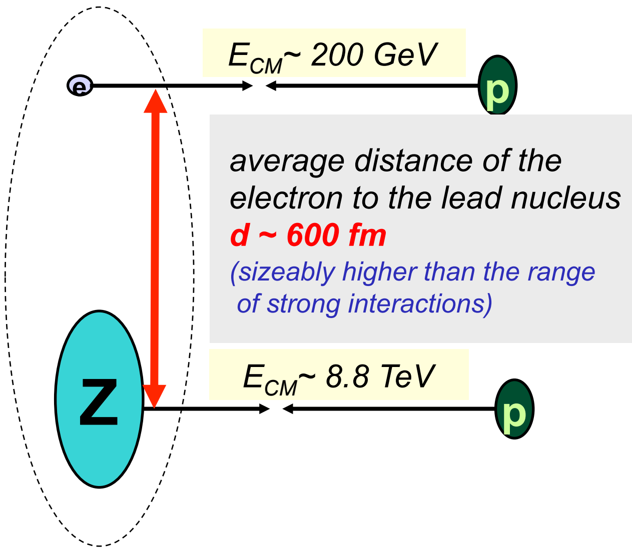
Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotorev ... See fewer authors

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)

Hydrogen-like lead



Atomic beams can be considered as ***independent electron and nuclear beams*** *as long as the incoming proton scatters with the momentum transfer q >> 300 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!*

Initial studies:

Available online at www.sciencedirect.com

SCIENCE DIRECT

ELSEVIER

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

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

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

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

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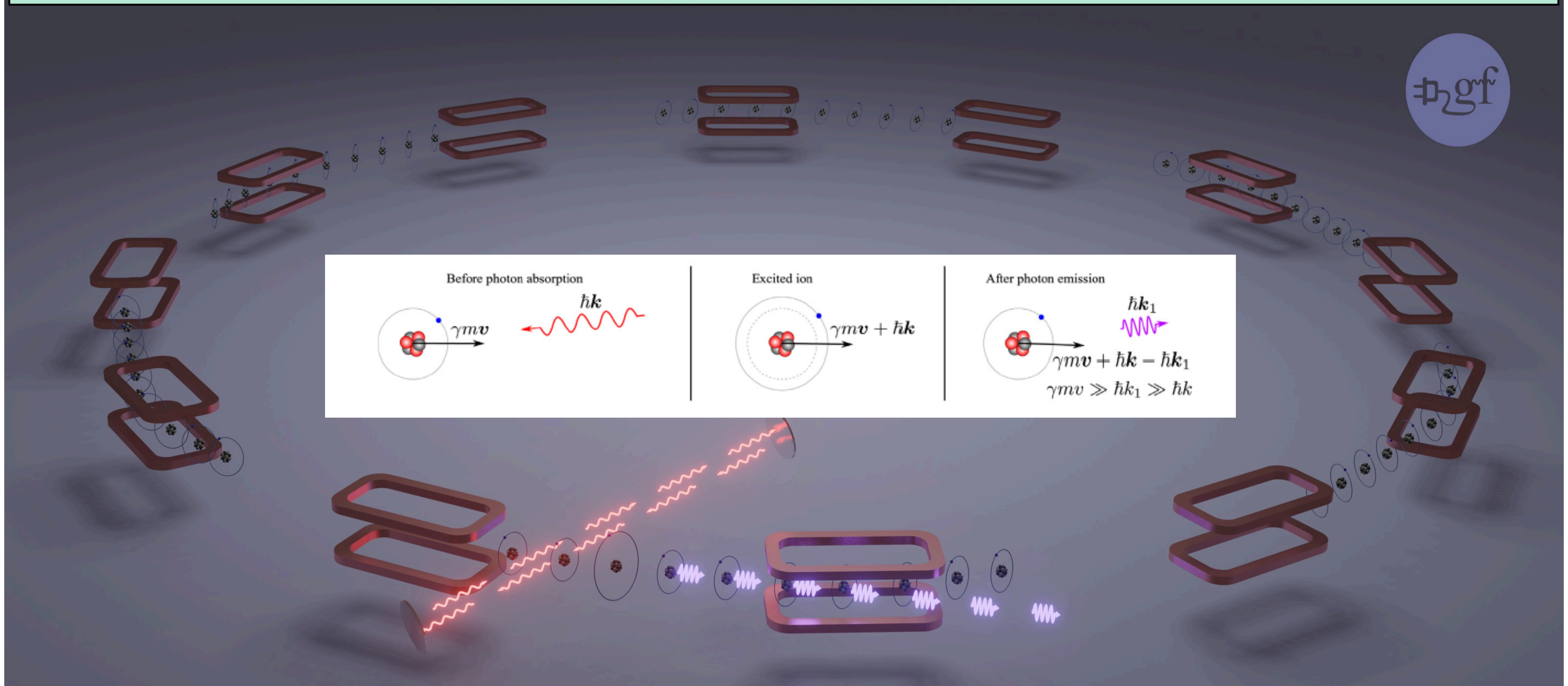
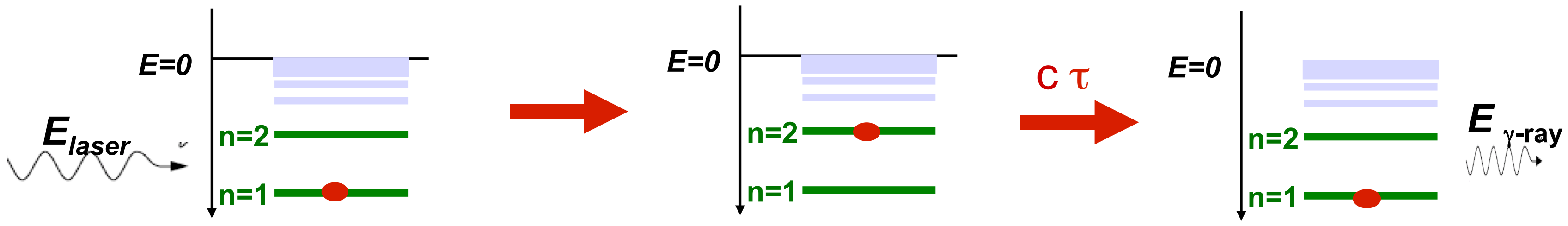
(Received 3 August 2020; accepted 5 October 2020; published 23 October 2020)

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 ($c\tau\gamma_L$) << 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**:

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

for photons emitted in the direction if incoming atoms, γ_L = E/M is the Lorentz factor for the ion beam

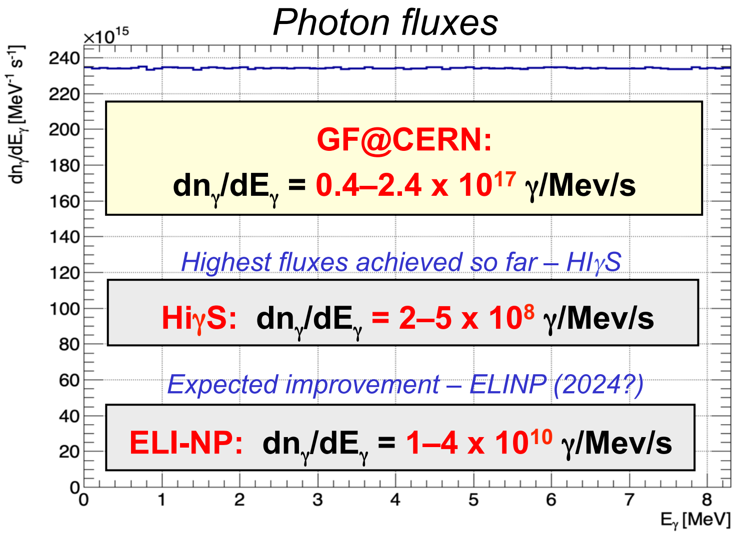
3.Tuneable energy:

- *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 loose 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

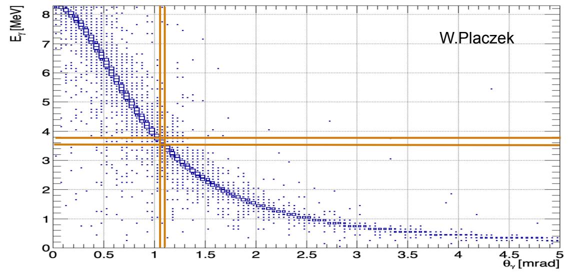


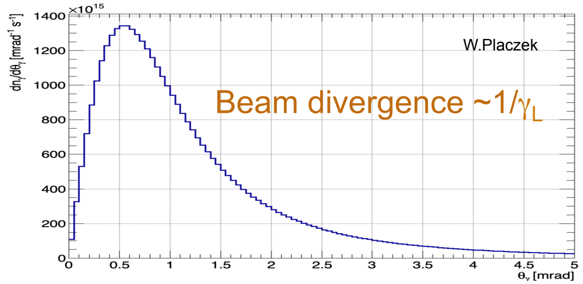
laser pulse parameters

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

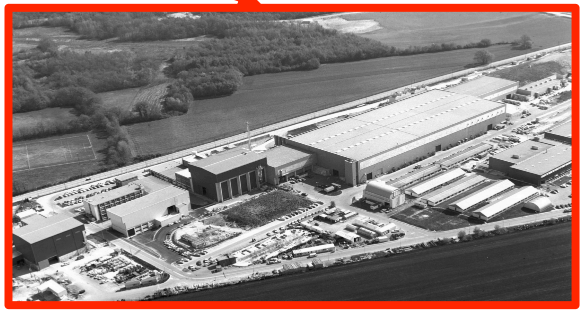
- ***Polarised positrons*** – potential gain of up to *a factor of 10^4* in intensity w.r.t. the KEK positron source, satisfying both the LEMMA and the LHeC requirements
- ***Pions*** – potential, gain by *a factor of 10^3, gain* in the spectral density ($dN_\pi/dEdp_TdP$ [MeV^{-2} x MW] with respect 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

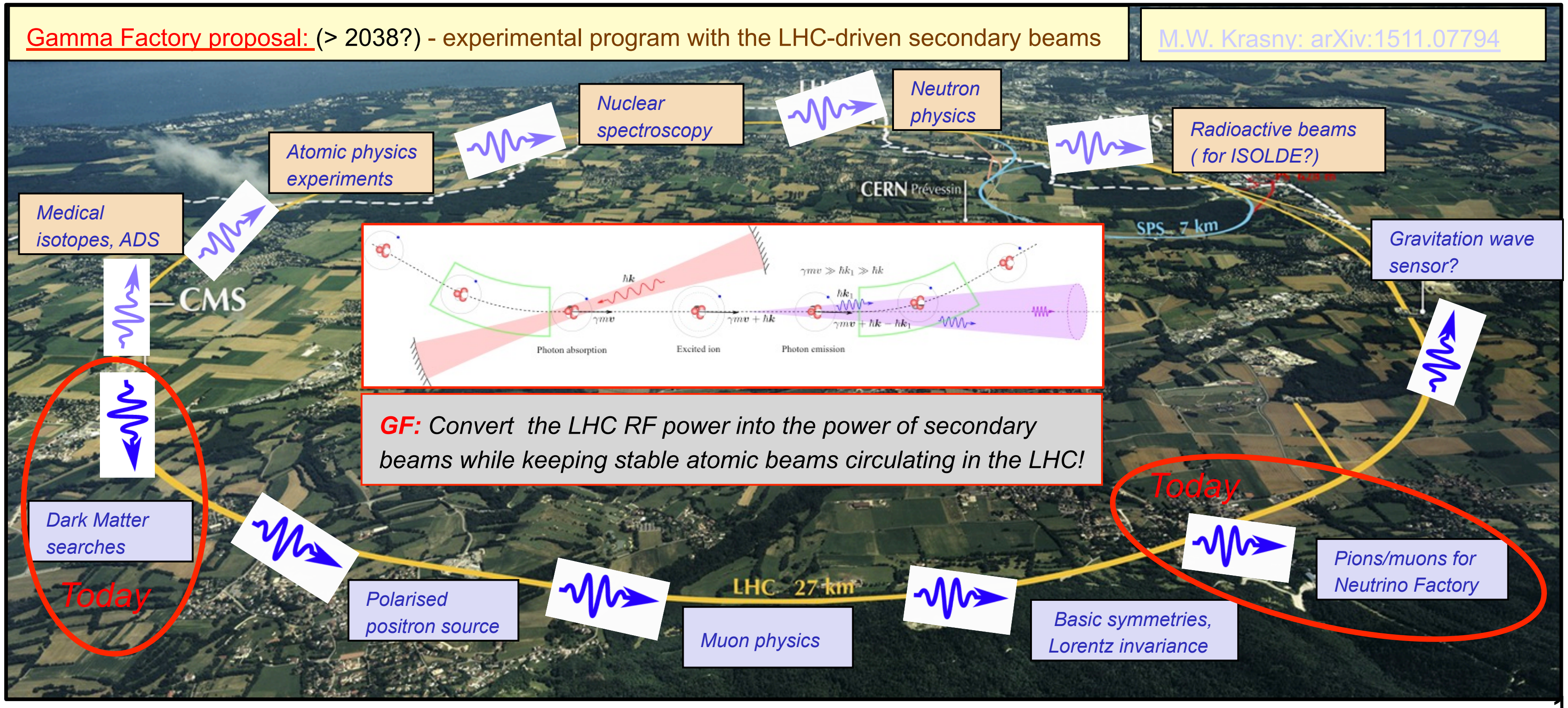
1974-2021: 47 years of the experimental program with the SPS extracted beams

North Area

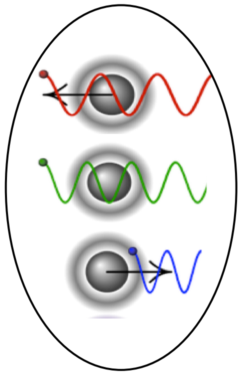
West Area



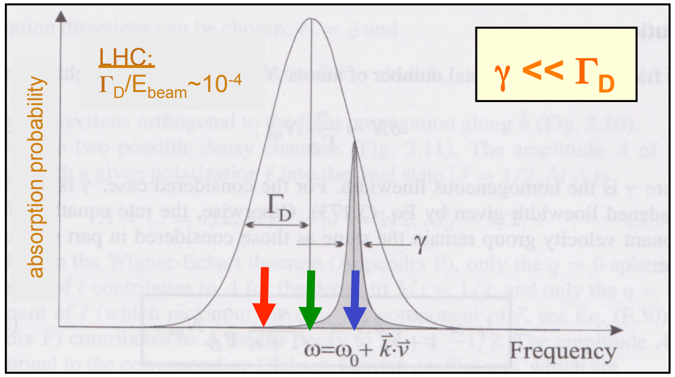
The LHC as a driver of secondary beams?

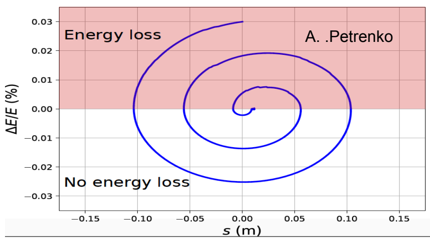


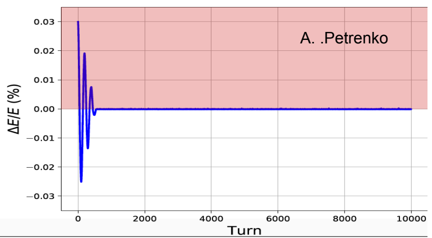
5.Doppler laser cooling methods of high energy beams



Bunch

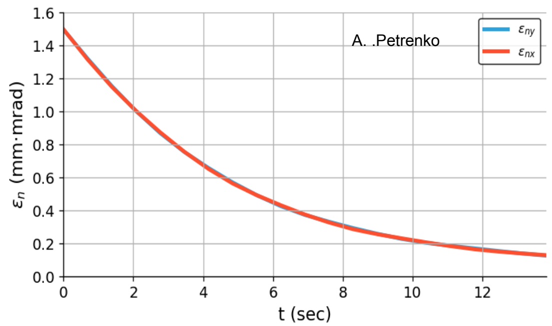






***Beam cooling speed**: the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

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).*

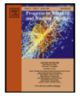
- ***particle physics*** *(studies of the basic symmetries of the universe, dark matter searches, precision QED and EW studies, vacuum birefringence studies, Higgs physics in* $\gamma\gamma$ *collision mode, rare muon decays, precision neutrino physics, …).*
- ***accelerator physics*** *(beam cooling 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

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp



Review

High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams☆

M.W. Krasny [a,b,*], A. Petrenko [c,b], W. Płaczek [d]

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ARTICLE INFO

Article history:
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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 *modus 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 constrains 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 $L_{NN} = 4.2 \times 10^{34}\,s^{-1}cm^{-2}$ 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.

Contents

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

UCI-TR-2021-12

Gamma Factory Searches for Extremely Weakly-Interacting Particles

Sreemanti Chakraborti,[1,*] Jonathan L. Feng,[2,†] James K. Koga,[3,‡] and Mauro Valli[2,§]

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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 $\sim$ 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.

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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 $\sim 10^{17}$ photons per second with energies up to 400 MeV. The photon beam intensity is expected to be a factor of $\mathcal{O}(10^7)$ 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 $m_a \lesssim \mathcal{O}(100\,\text{MeV})$ 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 HE-LHC project [4] is realized, this energy range can be extended in the future to 1.6 GeV. 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 [6–9]. 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 ~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). Here, we consider an ALP a which couples predominantly to the photon,

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

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

$$\Gamma_{a\rightarrow\gamma\gamma} = \frac{m_a^3}{64\pi\Lambda^2} . \quad (2)$$

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, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, and Max Zolotorev*

1. Introduction

DOI: 10.1002/andp.202000204


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

Expanding Nuclear Physics Horizons with the Gamma Factory

Dmitry Budker

Julian C. Berengut

Victor V. Flambaum

Mikhail Gorchtein

Junlan Jin

Felix Karbstein

Mieczyslaw Witold Krasny

Yuri A. Litvinov

Adriana Pálffy

Vladimir Pascalutsa and Marc Vanderhaeghen

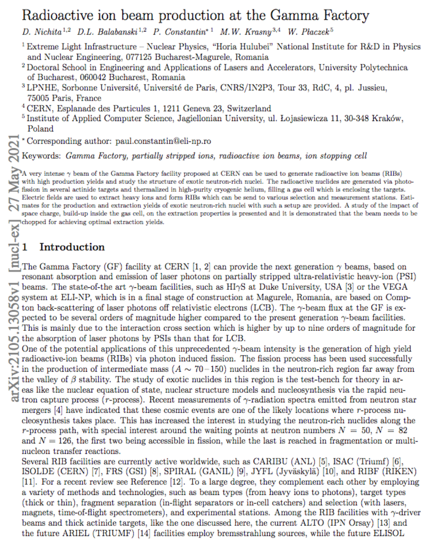
Alexey Petrenko

Andrey Surzhykov

Peter G. Thirolf

Hans A. Weidenmüller

Vladimir Zelevinsky


arXiv:2105.13058v1 [nucl-ex] 27 May 2021

Radioactive ion beam production at the Gamma Factory

D. Nichita, D.L. Balabanski, P. Constantin, M.W. Krasny, W. Płaczek

1 Introduction

Very recent Gamma Factory physics papers – fundamental physics

arXiv:2104.03784v1 [hep-ex] 8 Apr 2021

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 ultrarelativistic heavy-ion beams and of the beam momentum, 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 asymmetries 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}.

I. INTRODUCTION

Isotropy 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 …

II. SPECIAL RELATIVITY TESTS WITH BEAMS OF FAST PARTICLES

…

arXiv:2106.06359v1 [hep-ph] 11 Jun 2021

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.

PHYSICAL REVIEW C **103**, 054603 (2021)

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 $\approx 10^{10}$ per second using the gamma-ray beams from the Gamma Factory.

DOI: 10.1103/PhysRevC.103.054603

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. …

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

II. ESTIMATE OF THE PRODUCTION RATE

…

Example 1:

High-Luminosity LHC with low emittance,

Gamma Factory "cold" beams

The Gamma Factory path to high-luminosity LHC

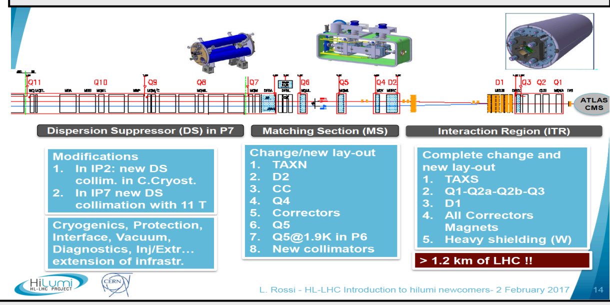
$$\mathscr{L} = f \frac{n_1 n_2}{4\pi \sqrt{\epsilon_x \, \beta_x^* \, \epsilon_y \, \beta_y^*}}$$

***Two complementary** ways to*
***increase** collider **luminosity**:*

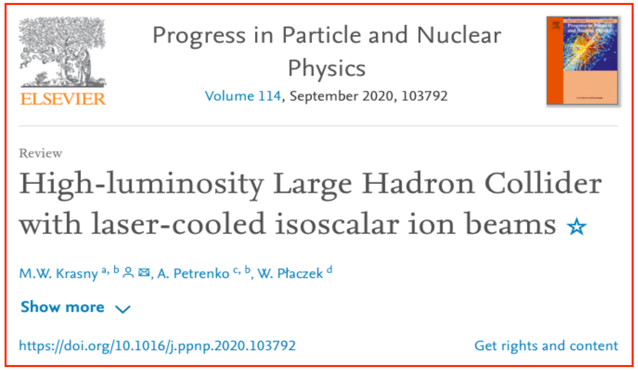
- ***increase** the focusing strength, $\beta*$ ↘*
- ***reduce** the beam emittance, ε ↘*
- ***both**.*

*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 10^{34} $cm^{-2}s^{-1}$** , **cost ~ 1 billion euro**



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

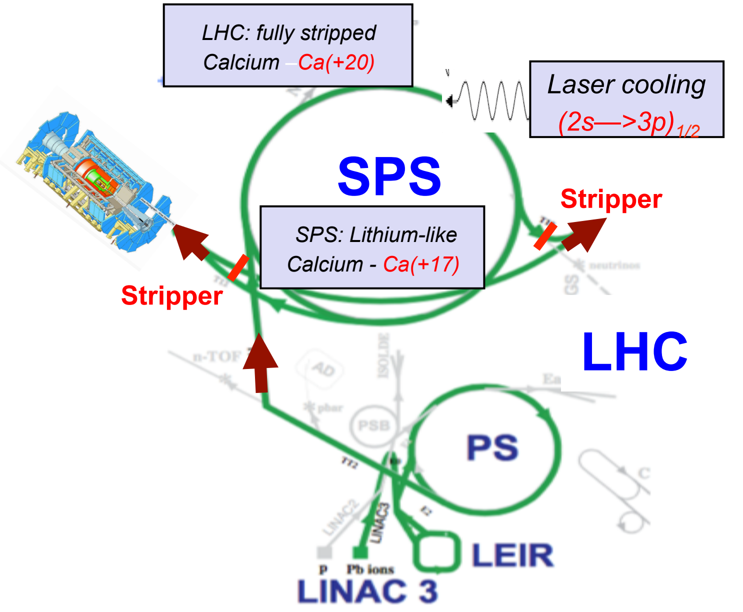
- Strip the electrons in the SPS-to-LHC transfer line.

Accelerate and collide

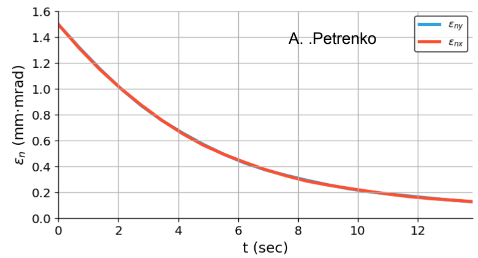
- Accelerate and collide fully stripped ion beams in the LHC.

Gamma Factory path to HL(AA)-LHC:

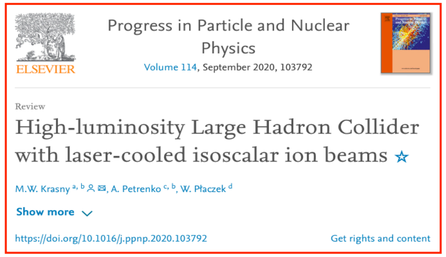
A concrete implementation scheme with **Ca** beams



Ion Source + Linac: *charge state after stripping:* Ca(+17)



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


Progress in Particle and Nuclear Physics
Volume 114, September 2020, 103792
ELSEVIER

Review

High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams ☆

M.W. Krasny a, b, A. Petrenko c, b, W. Płaczek d

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https://doi.org/10.1016/j.ppnp.2020.103792

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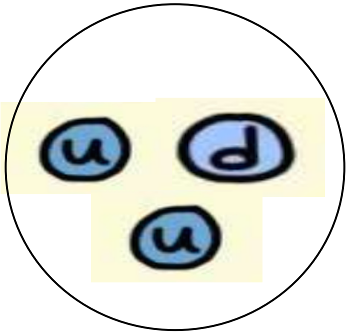
Parameter	Value
$s^{1/2}$ [TeV]	7
$\sigma_{BFPP}(Ca)/\sigma_{BFPP}(Pb)$	5×10^{-5}
$\sigma_{had}(Ca)/\sigma_{tot}(Ca)$	0.6
N_b	3×10^{9}
$\varepsilon_{(x,y)n}$ [μm] (1)	**0.3**
IBS [h]	1–2
β^* [m]	0.15
L_{NN} [$cm^{-2}s^{-1}$]	**4.2×10^{34}**
Nb of bunches	1404
Collisions/beam crossing	**5.5**

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 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:

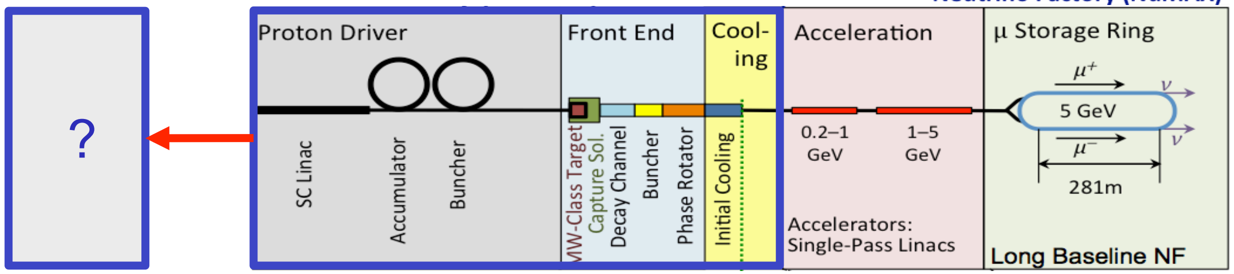
*Gamma-Factory-driven, **neutrino source***

and

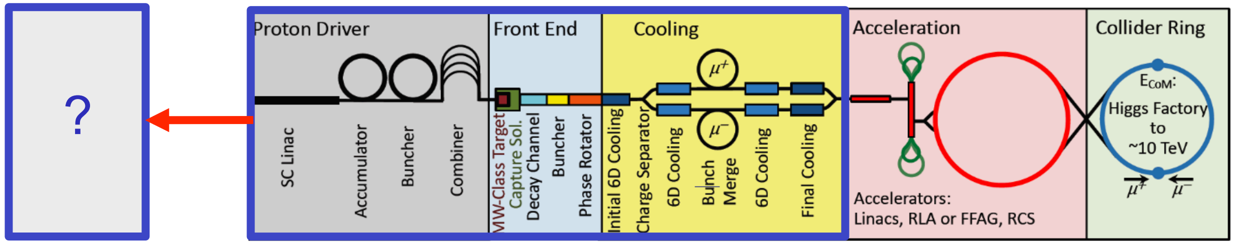
*polarised **muon source***

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

Neutrino Factory (NuMAX)



Proton-driven Muon Collider Concept (MAP)

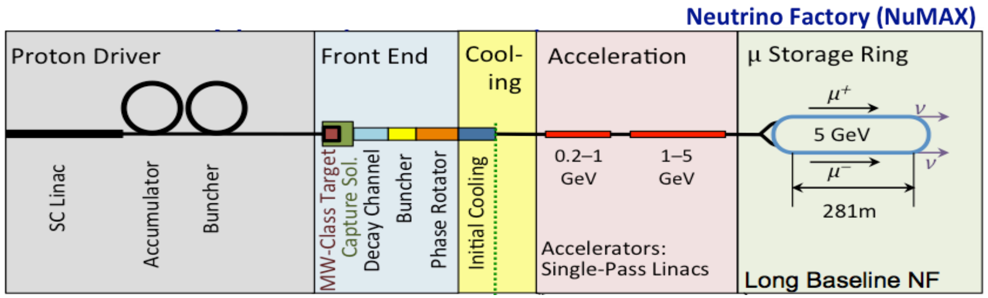


Shouldn't we try to avoid constructing a costly, high power Proton Driver, and to get rid of the necessity of building a ~1000 m long, sophisticated cooling section?

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

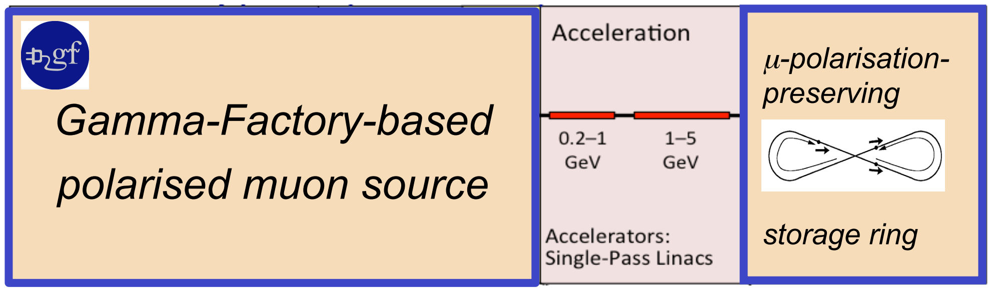
Detailed studies over the last 20 years…



Neutrino Factory parameters

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Perfor-mance	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*

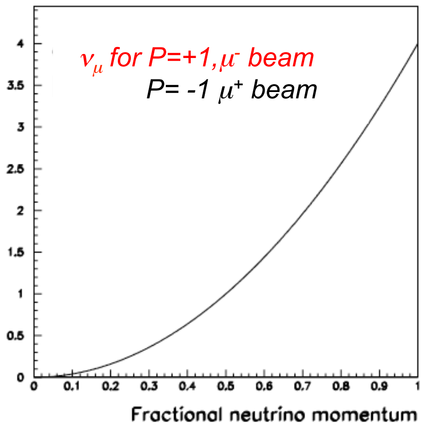
$$\frac{d^2N}{dx d\Omega} = \frac{1}{4\pi}[f_0(x) \mp \mathcal{P}_\mu f_1(x) \cos\theta]$$

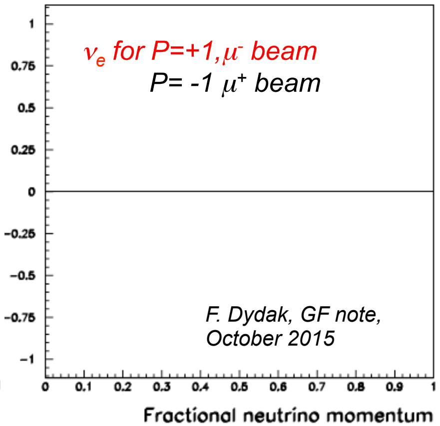
$x = 2E_\nu/m_\mu$

$\mathcal{P}_\mu$ is the muon polarization

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

	$f_0(x)$	$f_1(x)$
ν_μ, e	$2x^2(3-2x)$	$2x^2(1-2x)$
ν_e	$12x^2(1-x)$	$12x^2(1-x)$

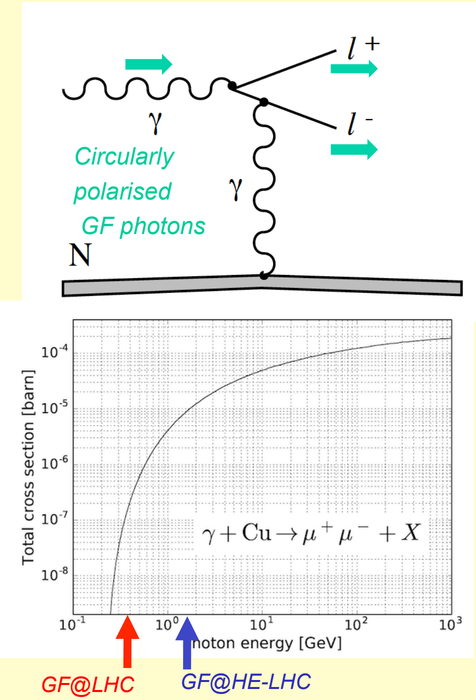




Conceptually optimal experiment to search for CP violation in the neutrino sector:

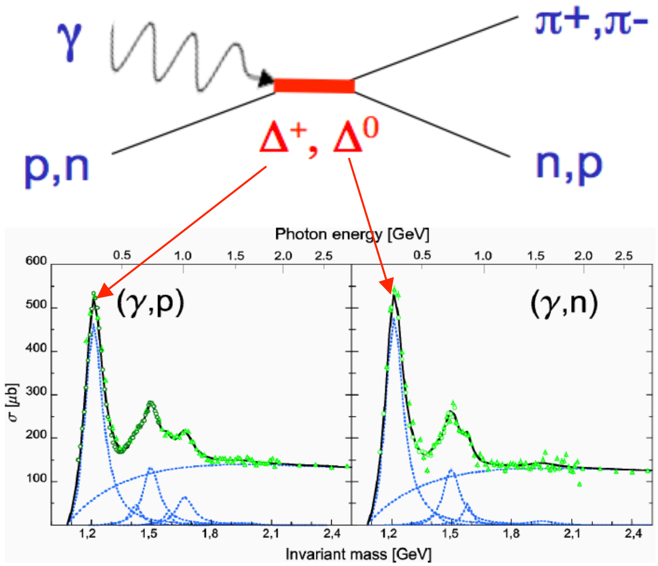
The experiment would compare the oscillation probabilities of $\nu_\mu \rightarrow \nu_e$, with the ν_μ flux obtained from the decay under zero forward angle from fully polarized μ^-, and of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with the $\bar{\nu}_\mu$ flux obtained from the decay under zero forward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

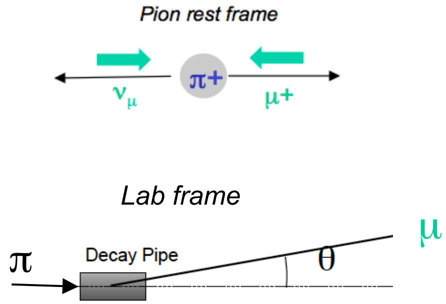
Gamma Factory - producing polarised muons by photons



~ 10^{10} μ/s source for GF@LHC
(Mass threshold effect)

New concept





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:

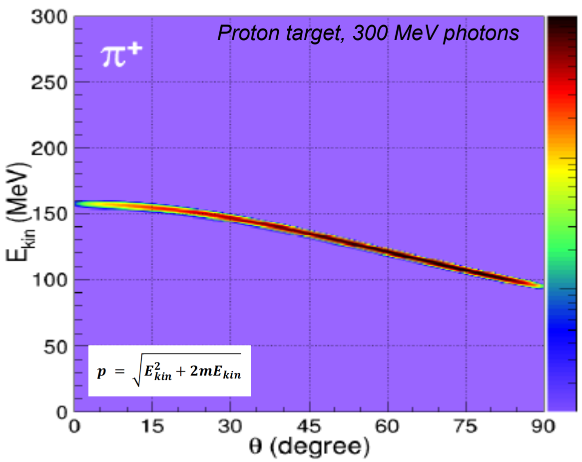
De-randomising pion spectra and restoring their charge symmetry

CM frame:

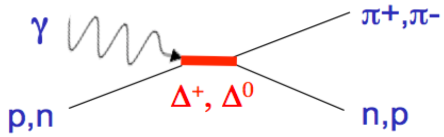
Monochromatic pions

Laboratory frame:

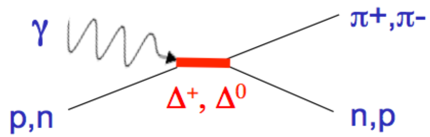
- *Pion energy and transverse momentum fully specified by one parameter: the pion emission angle, θ*



Unbound nucleon target



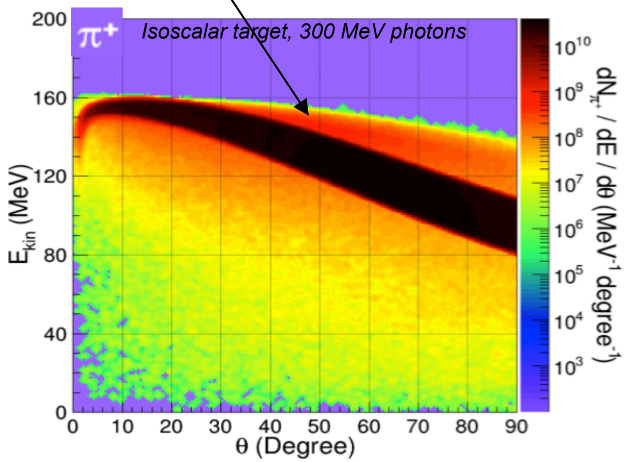
Nucleons bound in the nucleus



Z=A/2, (N_p=N_n)

Isoscalar target choice:
assures almost exact charge symmetry of π^+ and π^- production (below 2π production threshold)

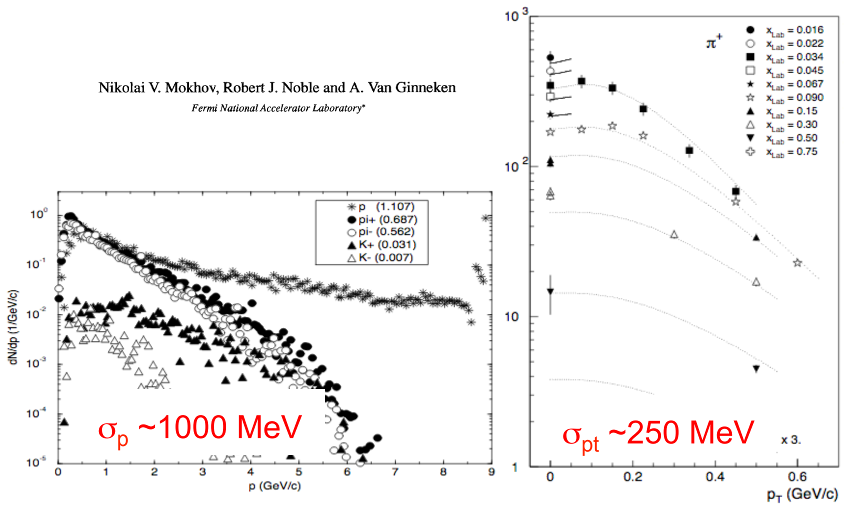
(note the effect of the nucleon Fermi motion smearing – relative to hydrogen target)



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

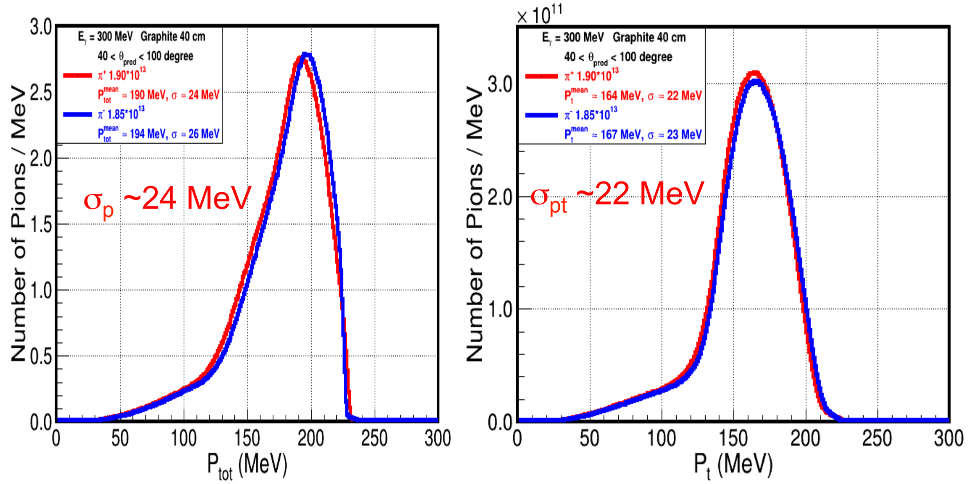
8 GeV proton beam

For λ_i = 2 **graphite** target:
~ 4.1 x 10^{14} π^+/s and ~ 2.6 x 10^{14} π^-/s for 1 MW p beam



300 MeV GF γ-beam

For λ_i = 2 **graphite** target :
~ 3 x 10^{13} π^+ and π^- /s for 1 MW γ beam (2 x 10^{16} γ/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 of factor ~ 500, spectral density [1/MeV^3] of produced "beam-like" pions!

Mark Palmer *for the Muon Accelerator Program (MAP)*

Cooling

Proposed scheme:

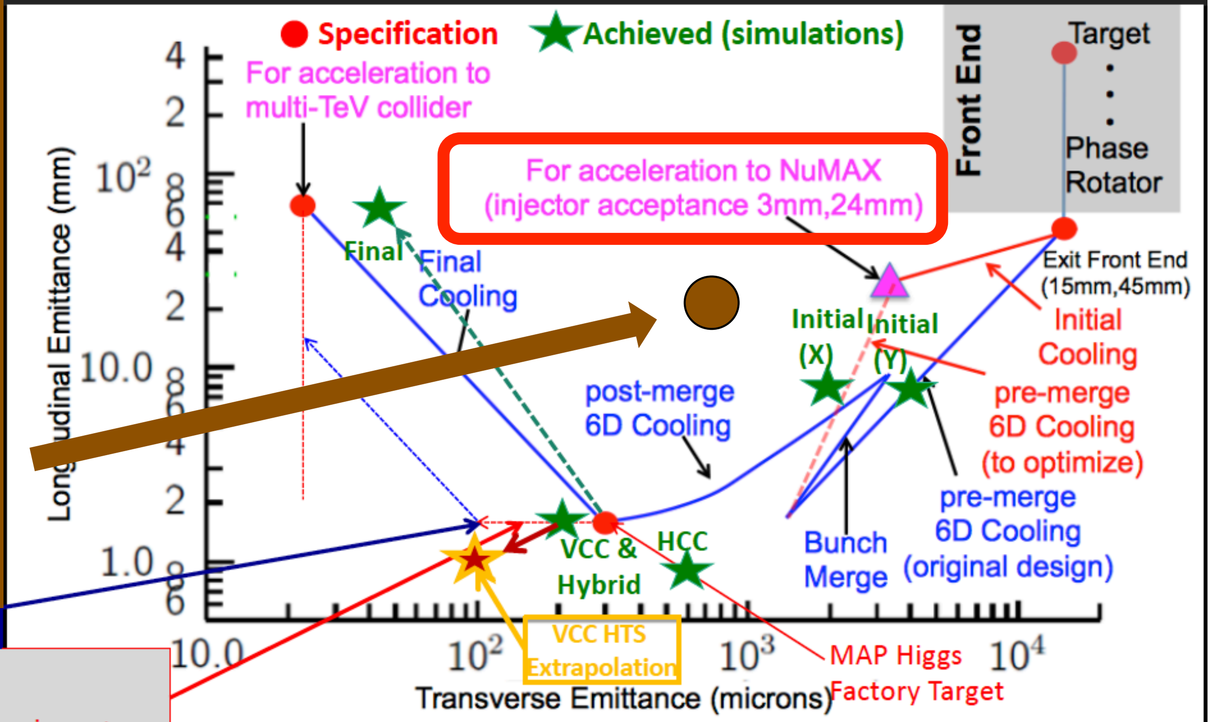
Expected ***pion source*** *beam emittance:*

$\varepsilon_T \sim \sigma_T \sigma_{pT}/mc \sim 0.8$ ***mm***

$\varepsilon_L \sim \sigma_{||} \sigma_p/mc \sim 20$ ***mm***

1 MW gamma beam, 20 cm long graphite target, Nπ= 1.3x10^13 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

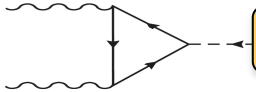
Advanced techniques ⇨
Improved HF Luminosity
Simplified Final Cooling requirements

Example 3:

Dark Matter searches in Gamma-Factory

ALPs and Dark Photons

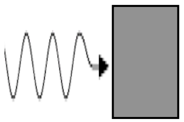
DM searches (and studies): Axion-Like-Particles (ALP) example

Collision schemes for ALP production: 

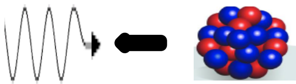
ALP

Search phase

γ_{GF} – B field
$m_{ALP} <$ 1 keV



γ_{GF} – A collisions (beam dump)
$m_{ALP} \sim$ 1 keV – 10 MeV



γ_{GF} – A collisions (LHC)
$m_{ALP} \sim$ 10 MeV – 10 GeV

"Production" phase

γ_{GF} – γ_{Laser} collisions
$m_{ALP} \sim$ 1–100 keV

γ_{GF} – γ_{GF} collisions (LHC)
$m_{ALP} \sim$ 100 keV – 800 MeV

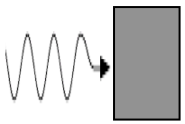
Concurrent, rich QED programme (e.g. vacuum birefringence studies)

Three principal advantages of the Gamma Factory photon beams:

- ***Large fluxes***: *~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*** *→ a unique possibility to* ***tune*** *the GF beam* ***energy*** *to the* ***resonance****.*

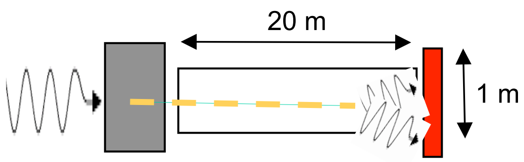
Gamma Factory APL-finding potential
(beam-dump search mode)

Search phase
Example: beam-dump mode

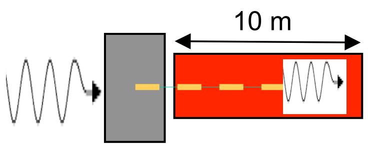


γ_{GF}–A collisions
1.6, 0.2, 0.02 GeV
beams (A,B,C)

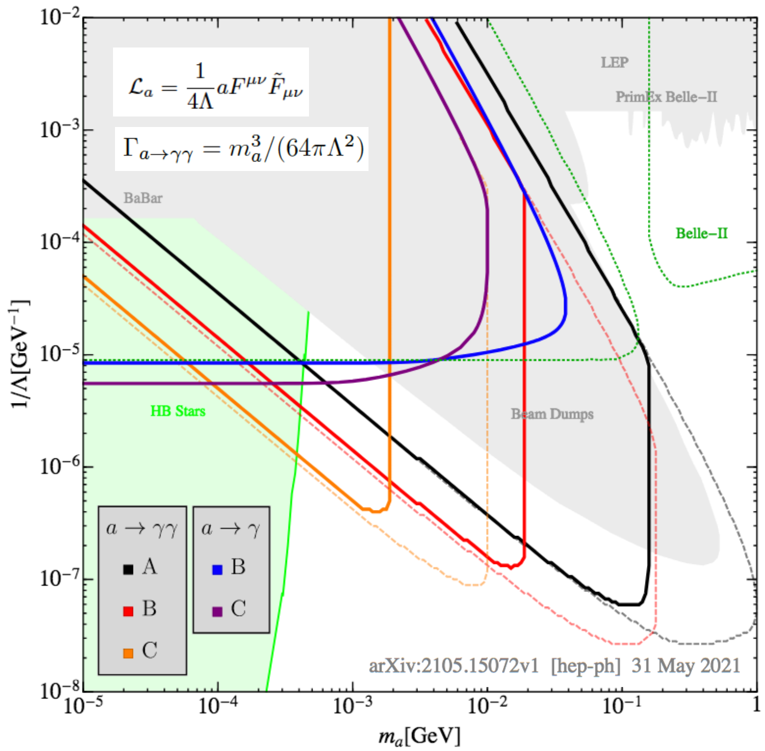
Two appearance modes:



- *decay: a →γγ (A,B,C)*



- *reconversion: aN →γN (B,C)*



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

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

$$\gamma e \rightarrow eX$$

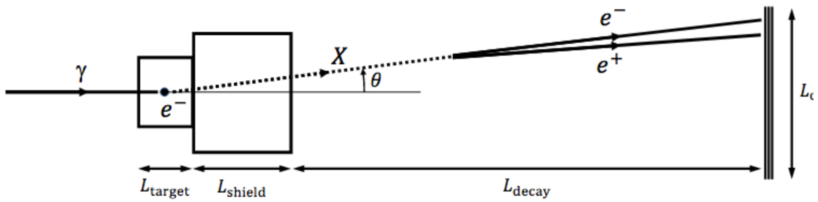


FIG. 1. **Experiment layout.** The experiment consists of a (graphite) target with thickn $L_{\rm target} = 1$ m, followed by a (lead) shield with thickness $L_{\rm shield} = 2$ m, an open air decay regi with length $L_{\rm decay}$, and a tracking detector, centered on the beam axis, which we take to be circular disk with diameter $L_{\rm det}$. The GF photon beam enters from the left and produces an particle through dark Compton scattering $\gamma e \rightarrow eX$. 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

Sreemanti Chakraborti,[1,*] Jonathan L. Feng,[2,†] James K. Koga,[3,‡] and Mauro Valli[2,§]

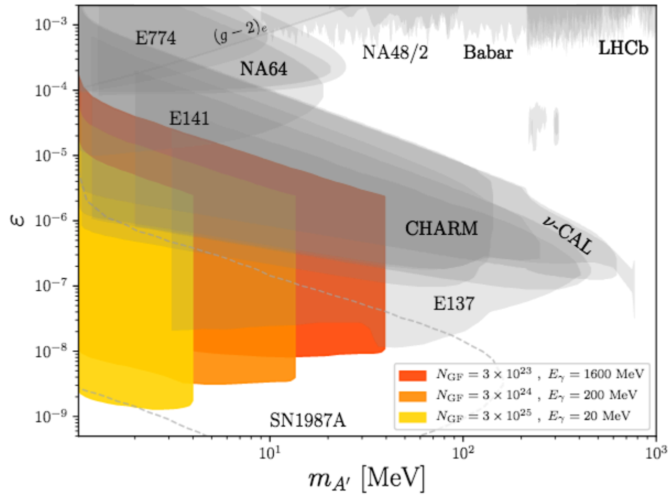


FIG. 3. **Dark photon sensitivity.** The sensitivity reach for the three sets of GF parameters $(E_\gamma, N_{\rm GF})$ indicated, each corresponding to a year of running, and detector parameters $L_{\rm decay} = 12$ m and $L_{\rm det} = 3$ m. The contours are for 3 e^+e^- signal events and assume no 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 [hep-ex]) was suported 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!*

Gamma Factory milestones – where we are?

1. *Successful demonstration of efficient production, acceleration and storage of "atomic beams" in the CERN accelerator complex.* → *Done…*
2. *Development "ab nihilo" the requisite Gamma Factory software tools.* → *Done…*
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.* → *Work ongoing…*
4. ***Successful execution of the GF Proof-of-Principle (PoP) experiment in the SPS tunnel.*** → *LoI 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*