Gamma Factory

Physics Beyond Colliders Working Group Meeting

November 2019

Mieczyslaw Witold Krasny

LPNHE, CNRS-IN2P3 and University Paris Sorbonne

The Gamma Factory proposal for CERN [†]

Abstract

This year, 2015, marks the centenary of the publication of Einsteins Theory of General Relativity and it has been named the International Year of Light and light-based technologies by the UN General Assembly It is thus timely to discuss the possibility of broadening the present CERN research program by including a new component based on a novel concept of the light source which could pave a way towards a multipurpose Gamma Factory. The proposed light source could be realized at CERN by using the infrastructure of the existing accelerators. It could push the intensity limits of the presently operating light-sources by at least 7 orders of magnitude, reaching the flux of the order of 10^{17} photons/s, in the particularly interesting γ-ray energy domain of $1 \leq E_{photon} \leq 400$ MeV. This domain is out of reach for the FEL-based light sources. The energy-tuned, quasi-monochromatic gamma beams, together with the gamma-beams-driven secondary beams of polarized positrons, polarized muons, neutrons and radioactive ions would constitute the basic research tools of the proposed Gamma Factory. The Gamma Factory could open new research opportunities at CERN in a vast domain of uncharted fundamental physics and industrial application territories. It could strengthen the leading role of CERN in the high energy frontier research territory by providing the unprecedented-brilliance secondary beams of polarized muons for the TeV-energy-scale muon collider and for the polarized-muon-beam based neutrino factory.

Mieczyslaw Witold Krasny*

LPNHE, Universités Paris VI et VII and CNRS–IN2P3, Paris, France

2017:

Creation of the Gamma Factory PBC study group

† An Executive Summary of the proposal addressed to the CERN management.

*e-mail: krasny@lpnhe.in2p3.fr

Gamma Factory PBC study group

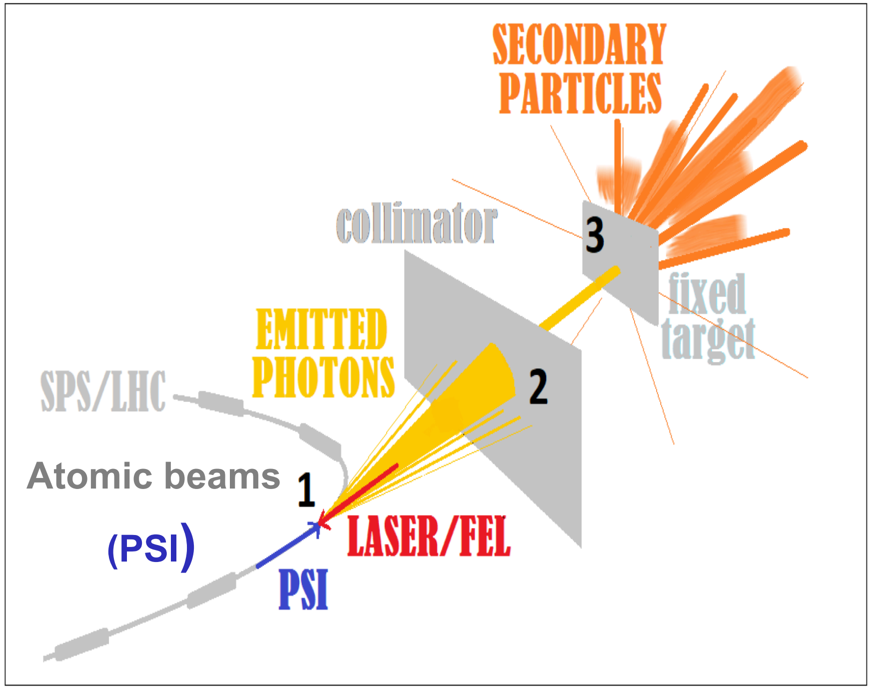
A. Abramov[1], S.E. Alden[1], R. Alemany Fernandez[2], P.S. Antsiferov[3], A. Apyan[4], H. Bartosik[2], E.G. Bessonov[5], N. Biancacci[2], J. Bieroń[6], A. Bogacz[7], A. Bosco[1], R. Bruce[2], D. Budker[8], K. Cassou[9], F. Castelli[10], I. Chaikovska[9], C. Curatolo[11], P. Czodrowski[2], A. Derevianko[12], K. Dupraz[9], Y. Dutheil[2], K. Dzierżęga[6], V. Fedosseev[2], N. Fuster Martinez[2], S. M. Gibson[1], B. Goddard[2], A. Gorzawski[13,2], S. Hirlander[2], J.M. Jowett[2], R. Kersevan[2], M. Kowalska[2], M.W. Krasny[14,2], F. Kroeger[15], D. Kuchler[2], M. Lamont[2], T. Lefevre[2], D. Manglunki[2], B. Marsh[2], A. Martens[9], J. Molson[2], D. Nutarelli[9], L. J. Nevay[1], A. Petrenko[2], V. Petrillo[10], W. Płaczek[6], S. Redaelli[2], S. Pustelny[6], S. Rochester[8], M. Sapinski[16], M. Schaumann[2], M. Scrivens[2], L. Serafini[10], V.P. Shevelko[5], T. Stoehlker[15], A. Surzhikov[17] I. Tolstikhina[5], F. Velotti[2], G. Weber[15], Y.K. Wu[18], C. Yin-Vallgren[2], M. Zanetti[19,11], F. Zimmermann[2], M.S. Zolotorev[20] and F. Zomer[9]

[1] *Royal Holloway University of London Egham, Surrey, TW20 0EX, United Kingdom*
[2] *CERN, Geneva, Switzerland*
[3] *Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region, Russia*
[4] *A.I. Alikhanyan National Science Laboratory, Yerevan, Armenia*
[5] *P.N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia*
[6] *Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland*
[7] *Center for Advanced Studies of Accelerators, Jefferson Lab, USA*
[8] *Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany*
[9] *LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
[10] *Department of Physics, INFN–Milan and University of Milan, Milan, Italy*
[11] *INFN–Padua, Padua, Italy*
[12] *University of Nevada, Reno, Nevada 89557, USA*
[13] *University of Malta, Malta*
[14] *LPNHE, University Paris Sorbonne, CNRS–IN2P3, Paris, France*
[15] *HI Jena, IOQ FSU Jena and GSI Darmstadt, Germany*
[16] *GSI, Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[17] *Braunschweig University of Technology and Physikalisch-Technische Bundesanstalt, Germany*
[18] *FEL Laboratory, Duke University, Durham, USA*
[19] *University of Padua, Padua, Italy*
[20] *Center for Beam Physics, LBNL, Berkeley, USA*

Today:
66 scientists
20 institutes
9 countries

GF group is open to everyone willing to contribute to this initiative!

Gamma Factory research tools:
primary and secondary beams



primary beams:

- partially stripped ions
- electron beam (for LHC)
- gamma rays

secondary beam sources:

- polarised electrons,
- polarised positrons
- polarised muons
- neutrinos
- neutrons
- vector mesons
- radioactive nuclei

collider schemes:

γ–γ collisions,
E_{CM} = 0.1 – 800 MeV

γ–γ_L collisions,
E_{CM} = 1 – 100 keV

γ–p(A), ep(A) collisions,
E_{CM} = 4 – 200 GeV

A leap in production efficiency, intensity and purity

Gamma Factory research potential

Physics

Particle	*basic symmetries, dark mater, EW precision measurements with PSI, n, μ and ν beams…*
Nuclear	*nuclear charge and spin structure, neutron skin, confinement studies, photo-fission…*
Accelerator	*beam cooling, plasma wake field acc., high-int. polarized e+ & μ sources, ν-sources…*
Atomic	*physics of highly charged electronic and muonic atoms: strong EM fields, EW effects…*
Applied	*accelerator driven energy sources , cold & warm fusion, medical isotope production…*

Opening new research domains and a leap in the measurement precision in existing research domains – a paradise for creative physicists…

Gamma Factory milestones – where we are?

1. *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. ***Successful execution of the GF Proof-of-Principle (PoP) experiment in the SPS tunnel.***
4. *Building up the physics cases for the LHC-based GF research programme and attracting wide scientific communities to use the GF tools in their respective research.*
5. *Extrapolation of the PoP experiment results to the LHC case and realistic assessment of the performance figures of the GF programme.*
6. *Elaboration of the TDR for the LHC-based GF research programme.*

→ *Documented in Vol.1 of the the Gamma Factory Yellow Report.*

→ *LoI submitted to the SPSC on the 25th of September 2019.*

→ *Documents summarising highlights of the GF research potential in the domains of Atomic and Nuclear physics in preparation.*

September 25, 2019

Gamma Factory

Proof-of-Principle Experiment

LETTER OF INTENT

CERN-SPSC-2019-031 / SPSC-I-253
25/09/2019

Gamma Factory Study Group

Contact persons:

M. W. Krasny, krasny@lpnhe.in2p3.fr, krasny@mail.cern.ch – **Gamma Factory team leader**

A. Martens, martens@lal.in2p3.fr – **Gamma Factory PoP experiment spokesperson**

Y. Dutheil, yann.dutheil@cern.ch – **Gamma Factory PoP study – CERN coordinator**

…motivation

The experimental studies of elementary particle collisions at the high energy frontier of the accelerator technologies have established, over the last century, the basic laws that govern our Universe at small distances. Each new generation of particle accelerators and particle colliders have delivered important discoveries. It is thus natural to continue the high-energy frontier path as the leading one in the High Energy Physics (HEP) research at CERN. The basic question which triggered the GF initiative is not whether this research path needs to be pursued – it certainly does – but if it is the most optimal one *in the present phase of the HEP research* in which:

- a large number of theoretical model scenarios for Beyond the Standard Model (BSM) phenomena exist without pointing to the optimal energy and beam particles for the future particle collider to observe these phenomena,
- the quantum field theory framework providing the link between the results of precise measurements of the quantum loop virtual phenomena and their (future) direct observation no longer provides any solid landmarks for *predicted discoveries* that are accessible for the present accelerator technologies or their incremental upgrades,
- we do not have a mature, affordable technology to make a significant leap into high energy "terra incognita".

The Gamma Factory (GF) initiative and its associated Proof-of-Principle (PoP) experiment, presented in this Letter of Intent (LoI), target a new and complementary research path which can be pursued concurrently with the ongoing CERN research programme and in parallel to preparing a novel technology for a cost-efficient return to the high-energy frontier research. Its primary goal is to extend the research scope of the existing world-unique CERN accelerator infrastructure. It is proposed at a crucial moment for CERN. The approval, financing and construction of CERN's next high-energy frontier project will very likely be a lengthy process. It is also possible that the on-going LHC-based research program will reach earlier its discovery potential saturation. This generates an opportunity for novel research programmes in basic and applied science which could re-use CERN's existing facilities in ways and at levels that were not conceived when the machines were designed.

PoP experiment in the SPS tunnel

Placement of the FP cavity in the SPS tunnel

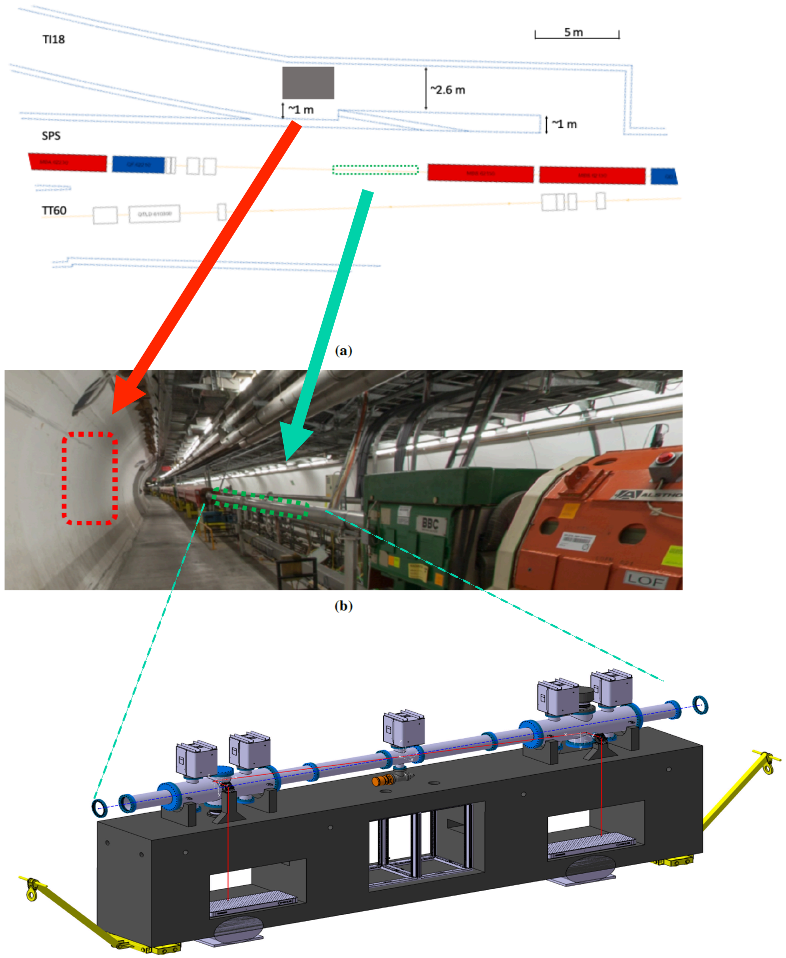
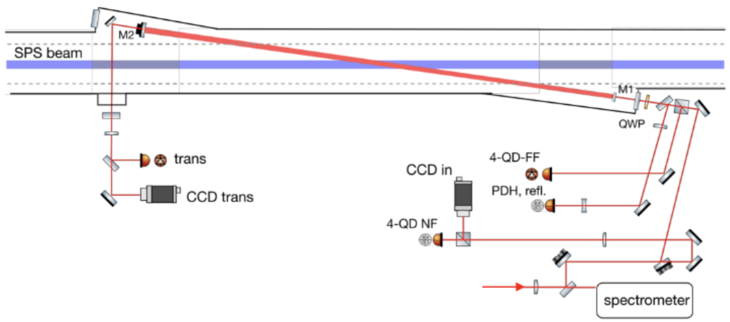


Table 3: SPS PoP experiment parameters.

PSI beam	$^{208}\mathrm{Pb}^{79+}$
m – ion mass	193.687 GeV/c^2
E – mean energy	18.652 TeV
$\gamma = E/mc^2$ – mean Lorentz relativistic factor	96.3
N – number ions per bunch	0.9×10^8
σ_E/E – RMS relative energy spread	2×10^{-4}
ϵ_n – normalised transverse emittance	1.5 mm mrad
σ_x – RMS transverse size	1.047 mm
σ_y – RMS transverse size	0.83 mm
σ_z – RMS bunch length	6.3 cm
Laser	Infrared
λ – wavelength ($\hbar\omega$ – photon energy)	1034 nm (1.2 eV)
σ_λ/λ – RMS relative band spread	2×10^{-4}
U – single pulse energy at IP	5 mJ
σ_L – RMS transverse intensity distribution at IP ($\sigma_L = w_L/2$)	0.65 mm
σ_t – RMS pulse duration	2.8 ps
θ_L – collision angle	2.6 deg
Atomic transition of $^{208}\mathrm{Pb}^{79+}$	$2s \rightarrow 2p_{1/2}$
$\hbar\omega_0'$ – resonance energy	230.81 eV
τ' – mean lifetime of spontaneous emission	76.6 ps
$\hbar\omega_1^{max}$ – maximum emitted photon energy	44.473 keV



What we want to learn/demonstrate with the GF Proof-of-Principle (PoP) experiment at the SPS?

1. *Demonstrate integration and operation of laser and a Fabry-Perot cavity in a high energy hadron storage ring.*
2. *Benchmark simulations of atomic excitation rates.*
3. *Develop a collision scheme and implement the operational tools, match the laser photon spectrum to the atomic excitation width to maximise excitation rate.*
4. *Demonstrate laser and atomic bunches synchronisation.*
5. *Measure and characterise the photon flux.*
6. *Develop atomic and photon beams diagnostic methods.*

Today…

7. ***Evaluate the performance of laser cooling techniques of the atomic beams***

8. *Perform atomic physics measurements in the ultra-relativistic regime.*

Two complementary paths to HL-LHC

$$\mathscr{L} = f_{\text{coll}} \frac{n_1 n_2}{4\pi \sigma_x^* \sigma_y^*}$$

The beam width σ can be expressed in terms of the β* parameter describing beam focussing strength in the interaction point and a beam emittance ε.

$$\varepsilon_x \equiv \frac{\sigma_x^2}{\beta_x}\,, \quad \longrightarrow \quad \mathscr{L} = f \frac{n_1 n_2}{4\pi\sqrt{\epsilon_x\,\beta_x^*\,\epsilon_y\,\beta_y^*}}$$

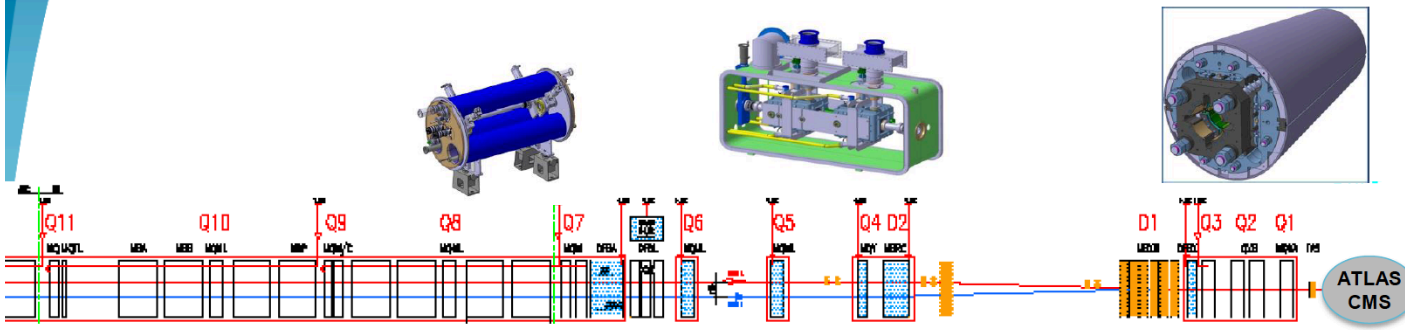
Two ways to increase the machine luminosity:

1. ***Increase beam focusing at the IPs of the experiments.***
2. ***Decrease transverse beam emittance of colliding beams.***

… and, perhaps the best option, a mixing of the previous two

On-going HL(pp) -LHC project

The largest HEP accelerator in construction



Dispersion Suppressor (DS) in P7

Modifications
1. In IP2: new DS collim. in C.Cryost.
2. In IP7 new DS collimation with 11 T

Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr… extension of infrastr.

Matching Section (MS)

Change/new lay-out
1. TAXN
2. D2
3. CC
4. Q4
5. Correctors
6. Q5
7. Q5@1.9K in P6
8. New collimators

Interaction Region (ITR)

Complete change and new lay-out
1. TAXS
2. Q1-Q2a-Q2b-Q3
3. D1
4. All Correctors Magnets
5. Heavy shielding (W)

> 1.2 km of LHC !!

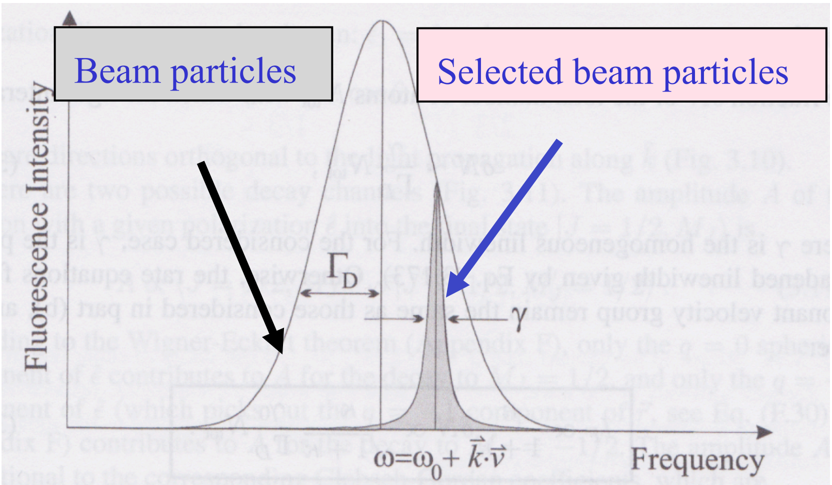
HiLumi HL-LHC PROJECT CERN

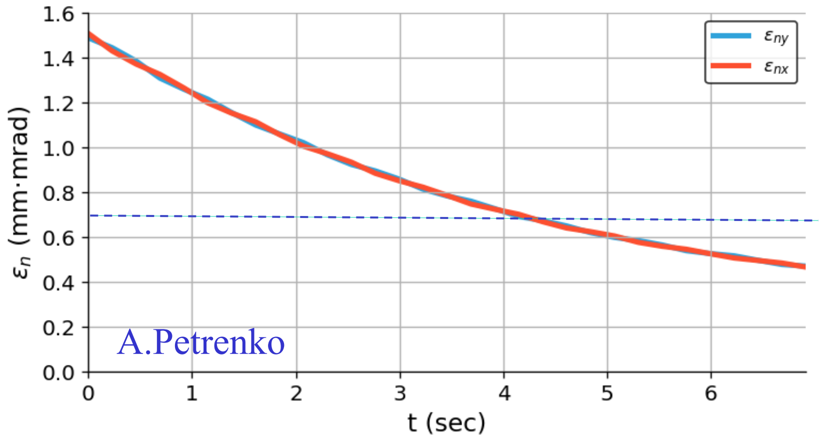
L. Rossi - HL-LHC Introduction to hilumi newcomers- 2 February 2017 14

Levelled Luminosity: 2.5 (5) x 10^{34} $cm^{-2}s^{-1}$

estimated cost ~ 1 billion euro

Beam cooling of atomic beams at the SPS:





<u>Merit of atomic beams</u>: highly efficient, selective, manipulation of the beam particles confined in the particle bunches by the laser photons – opening a path to a very fast beam cooling.

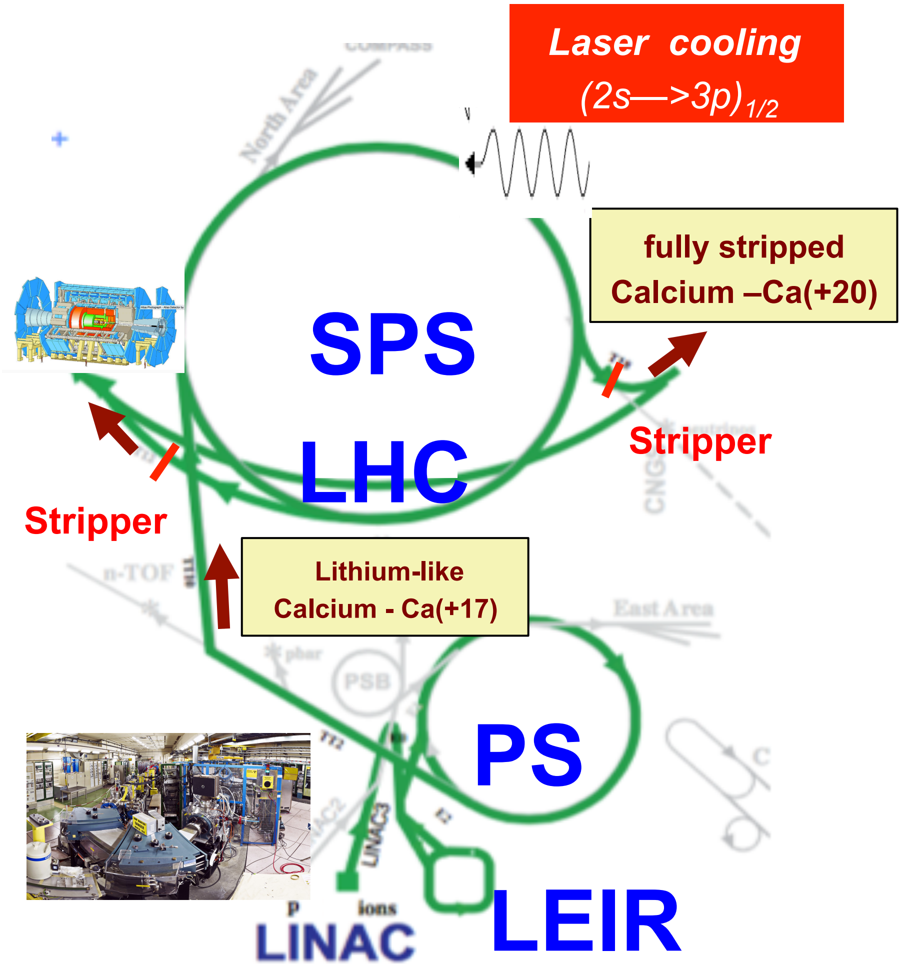
<u>Transverse beam cooling at the SPS -- Li-like Calcium ions:</u>

- *$(2s \text{—>} 3p)_{1/2}$ transition*
- *Laser light wavelength: 768 nm (t.c.). 768.3 nm(l.c.)*
- *Laser pulse energy: 2 mJ (t.c.), 0.25 mJ (l.c.)*
- *Laser pulse length: 2 ps*
- *Laser transverse pulse size: 1.1 mm*
- *Crossing angle: 1.3 deg*
- *Expected cooling time ~ 7 s*

<u>… to be experimentally confirmed by the GF PoP experiment…</u>

Gamma Factory proposal for HL(NN)-LHC:

An implementation scheme with Ca beams



Source+Linac: Charge state after stripping: Ca^{17+}, 80 K cooler than Pb!

Initial estimates

Parameter	Cooling only	Cooling/ focusing
$s^{1/2}$ [TeV]	7.	7.
$\sigma_{BFPP}(Ca)/\sigma_{BFPP}(Pb)$	5×10^{-5}	5×10^{-5}
$\sigma_{had}(Ca)/\sigma_{tot}(Ca)$	0.6	0.6
Nb	6×10^{9}	3×10^{9}
$\varepsilon_{(x,y)n}$ [μm] (1)	0.7	0.7
IBS horizontal [h]	1.2	2.3
β^*	0.5	0.15
L_{NN} [cm-2s-1]	5.1×10^{34}	4.3×10^{34}
Nb of bunches	1404	1404
Collisions/beam crossing	3.9	3.3

(1) Beam emittanace must be preserved through the LHC acceleration cycle

Gamma Factory PoP experiment at the SPS (2.4 MCHF) may open a complementary path to HL-LHC (with equivalent, …or higher partonic luminosities), by storing quark and gluons in "cold"-nucleus rather than in "hot"-proton bunches…

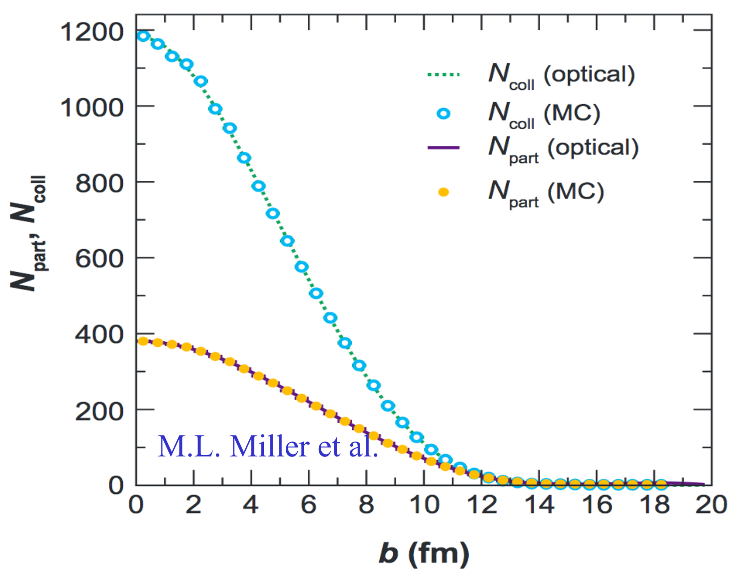
… the most likely achievable luminosity limit od this scheme is IBS – a stochastic optical cooling at the beam collision energies, and blow up of the longitudinal emittance over the LHC acceleration cycle, may be required to preserve the beam emittance of the SPS-cooled beam…

Three merits of HL(NN)-LHC w.r.t. HL(pp)-LHC (at equivalent partonic luminosities)

1. Better signal to noise for point-like partonic processes:

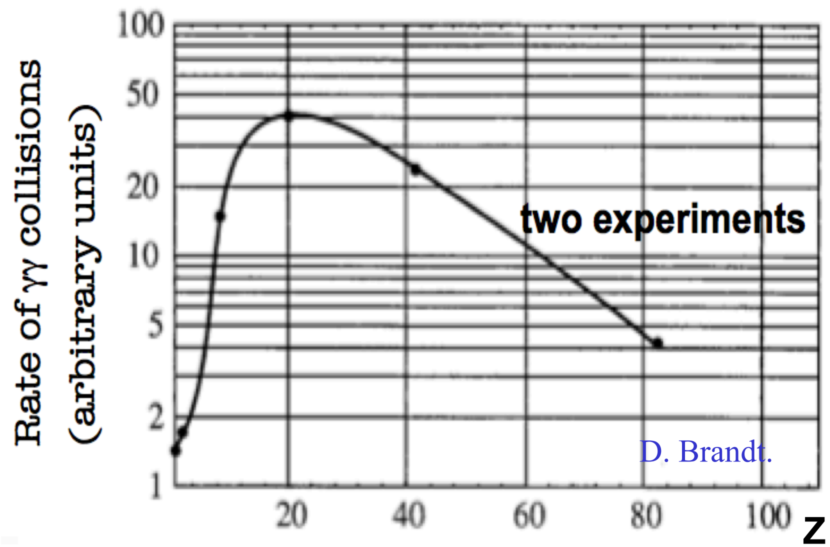
- lower number of collisions/b.c.
- lower average multiplicity of soft hadrons

$n_{soft}(AA) \sim Npart < Ncoll$

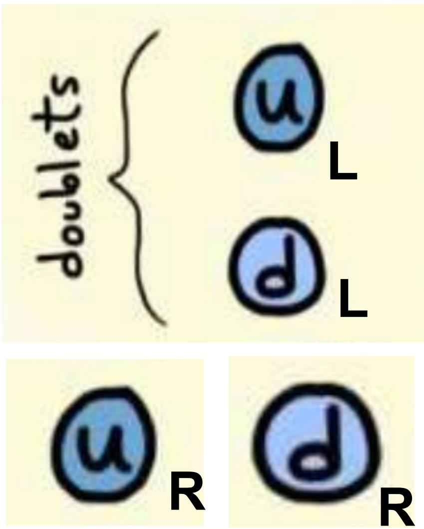


2. Maximizing the luminosity of photon-photon collisions:

- avoid excessive beam burning at high Z
- profit from the Z^4 (coherence) enhancement



The canonical LHC pp collision mode (including HL-LHC) is not optimal for the precision EW programme [1], why?



u and d quarks have different charges, weak isospin and vector and axial couplings:

$$g_V^i \equiv t_{3L}(i) - 2Q_i \sin^2\theta_W,$$
$$g_A^i \equiv t_{3L}(i),$$

*Need to know -- to a very high precision – the composition of partonic beam: in particular the relative momentum distributions of **u** and **d** quarks in the proton!*

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[1] *For the quantification of these statements see e.g..:*

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.*

Three merits of HL(NN)-LHC w.r.t. HL(pp)-LHC (at equivalent partonic luminosities)

3.Why choosing the Ca ions? → **Isoscalar (Z=A/2) ion beam**

Profit from the flavour symmetry of strong interactions to control the partonic beam composition and their longitudinal and transverse emittances:

$$u_{neutron}(x,pt,Q2) = d_{proton}(x,pt,Q2) \quad \text{and} \quad d_{neutron}(x,pt,Q2) = u_{proton}(x,pt,Q2)$$

…allowing to equalize(1) the distributions of the u and quarks:

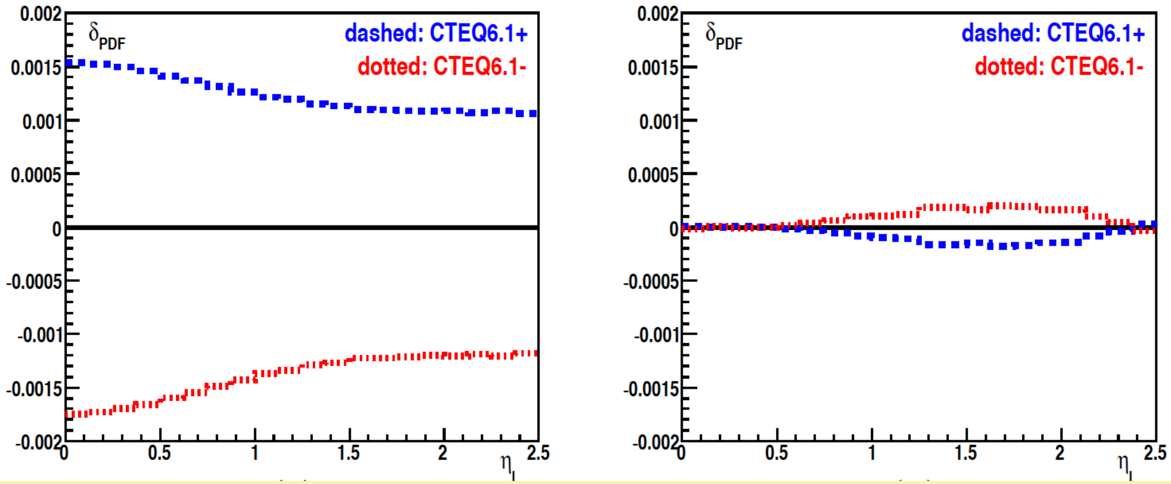
$$d_{Ca}(x,pt,Q2) = u_{Ca}(x,pt,Q2)$$

(1) Up to a tiny EM corrections

An illustration of the gain in the measurement precision by using isoscalar ion instead of proton beams

Measurement of the ratio of the pseudo-rapidity distributions of the charged lepton for W and Z production at the LHC. ***Gain in precision a factor of ~8.***

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



Isoscalar LHC beams provide the unique way to improve our present knowledge of the SM basic parameters such as M_W, $\sin^2\theta_W$,…

Conclusions

- Over the last **2 years** the **Gamma Factory** initial ideas developed into a **well-defined project** involving a group of **~70 scientists** from 19 institutes in 9 countries.

- Progress has been impressive. The next steps are clear.

- GF had already passed its first and **most important milestone**: the **proof** that one can **produce**, **accelerate** and **store atomic beams** in the **CERN accelerator complex**.

- It is now entering its **second and decisive phase** with a proposition of a GF **Proof-of-Principle** experiment at the CERN **SPS**.

Conclusions

- The ultimate target of the GF initiative is to develop a variety of novel research tools and research concepts which could open new exciting opportunities in a broad domain of basic and applied science.

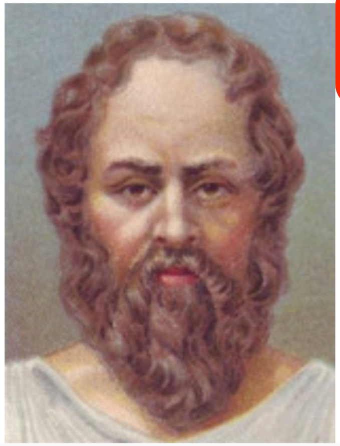
- A specific example of the HL(NN)-LHC concept and its physics potential was presented in this talk as an illustration of a possible impact of the Gamma Factory ideas and tools on the ongoing and the future CERN research programme.

- We hope that the SPS PoP experiment will be approved and the requisite resources (2.4 MCHF) allocated by CERN and by the national Funding Agencies (ERC funds) allowing to pass the next and decisive Gamma Factory R&D phase.

Postscriptum

- PBC has provided an ideal cradle for the development of the GF project in its initial stage (we are grateful for this "early childhood" care).

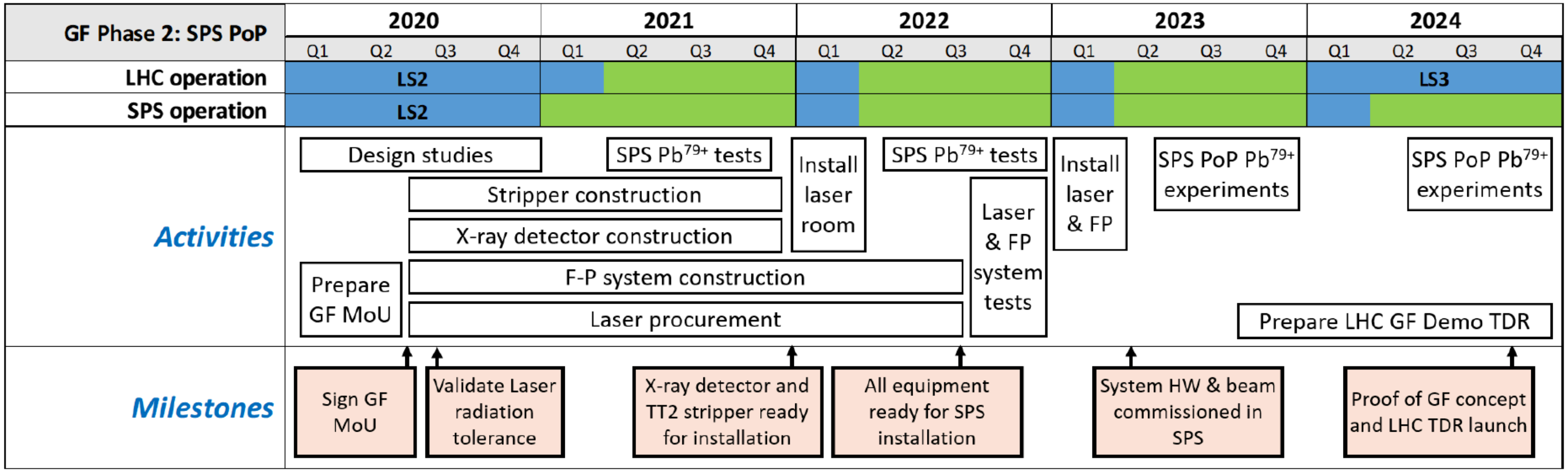
- For the success of the subsequent GF R&D stages a recognition of the enormous GF research potential is crucial (ESPP process)



"Strong minds discuss ideas, average minds discuss events, weak minds discuss people."

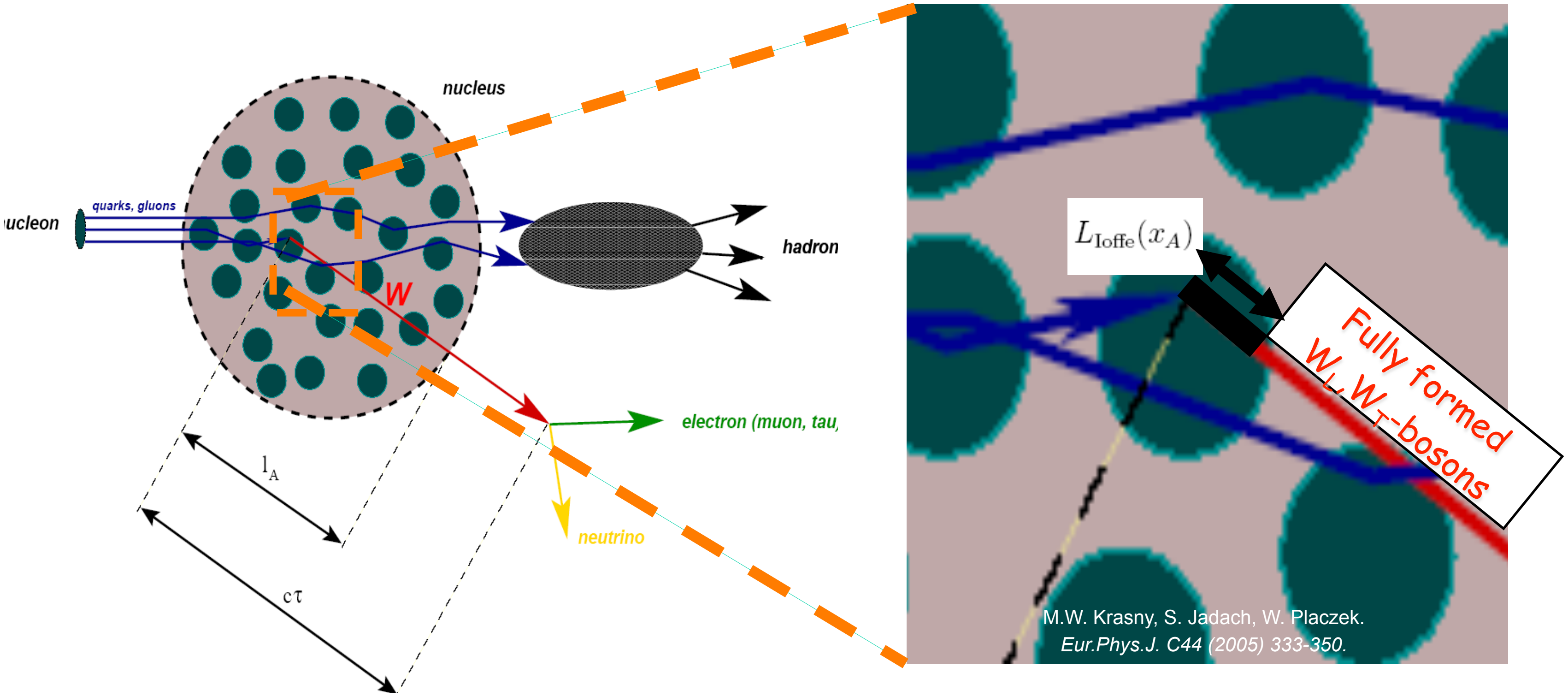
— Socrates

The GF timeline (2020-2024)



An additional merit of HL(AA)-LHC w.r.t. HL(pp)-LHC

Tagged beams of transversely and longitudinally polarized W and Z bosons



Quantum uncertainty of the Longitudinal position of W-production

$$L_{\rm Ioffe}(x_A) = \frac{1}{2M_A x_A}$$

Quantum formation lengths of W-boson

$$\delta z = \gamma_W / M_W$$