Gamma Factory

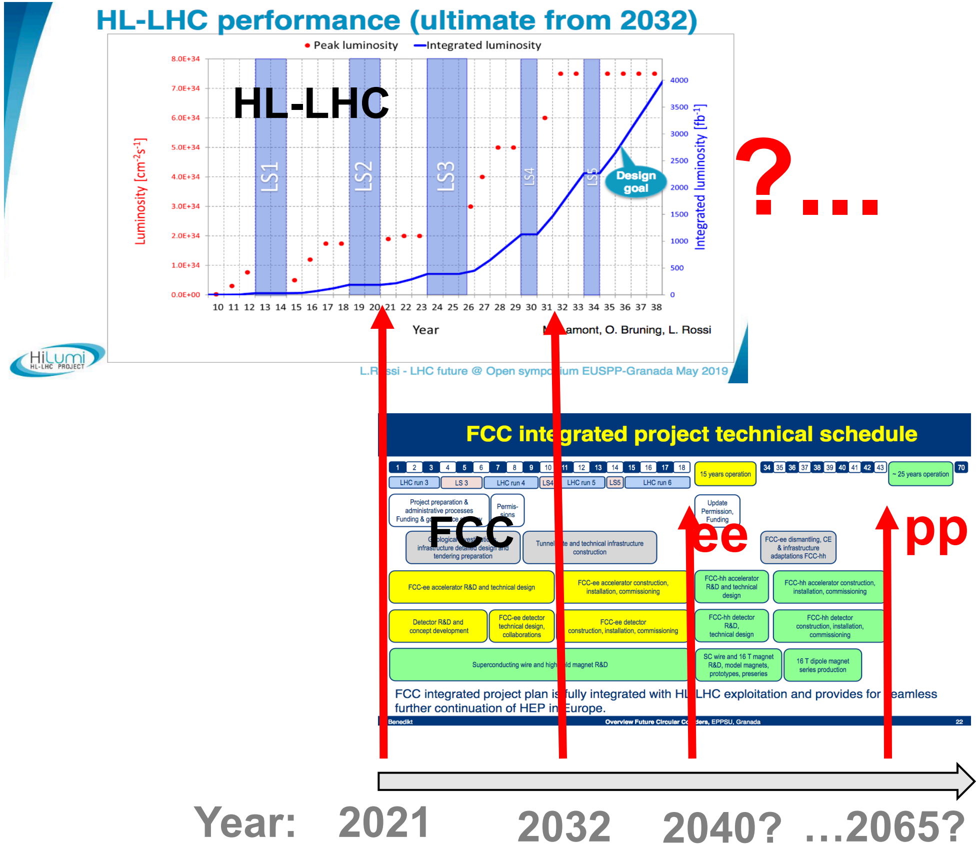
Physics context and opportunities for Particle Physics

ECFA Plenary Meeting, November 2020

Mieczyslaw Witold Krasny

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

Particle Physics: “état de grâce” for the next 70 years?



- Can we afford disregarding a substantial unpredictability of the future-research priorities in the “post-Covid”, global-warming world?

- Shouldn't we develop in parallel, already now, less costly, but equally attractive, research options for CERN?

… So far diversity has proven to be the most successful survival strategy of living ecosystems …

A potential place of Gamma Factory in the future CERN research programme

- *The **next** CERN **high-energy frontier** project may take **long time** to be approved, built and become operational, … unlikely before 2045 (FCC-ee) or 2050+ (μ-collider)*

- *The **present** LHC **research programme** will certainly reach **earlier** (~2032) its discovery **saturation** (little physics gain by a simple extending its pp/pA/AA running time)*

- *A strong **need** will certainly arise for a **novel** multidisciplinary programme which could **re-use** ("co-use") the **existing** CERN facilities (including LHC) in **ways** and at **levels** that were **not** necessarily **thought** of when the machines were **designed***

***The Gamma Factory** research programme (2032-????) could fulfil such a role. It can exploit **the existing world unique opportunities** offered by the CERN accelerator complex and CERN's scientific infrastructure **(not available elsewhere**) to conduct new, diverse, and vibrant research.*

Outline of the talk

- *What is* ***Gamma Factory***

- *Scientific context*

- *Project status*

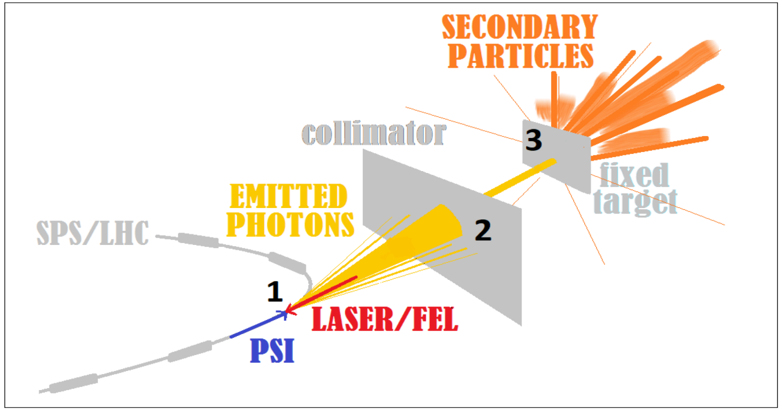
  (technical aspects in Yann Dutheil's talk)

- *Three examples of physics opportunities in Particle and Accelerator Physics*

  (opportunities in Nuclear, Atomic and Applied Physics in Dima Budker's talk)

- *Conclusions*

What is Gamma Factory?



The Gamma Factory proposal for CERN

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

e-Print: 1511.07794 [hep-ex]

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"*

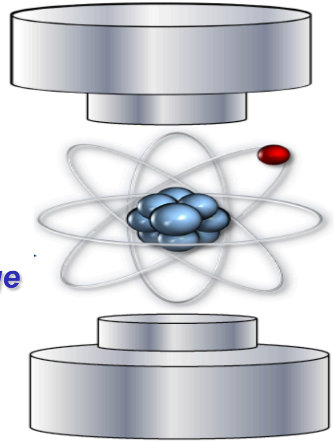
Gamma Factory: "Novel research tools made from light"

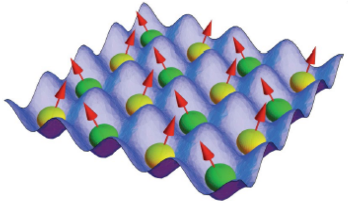
1. *Atomic traps of highly charged atoms*
2. *Electron beam for ep collisions in the LHC interaction points*
3. *High intensity photon(γ)-beams*
4. *Laser-light based cooling methods of high-energy hadronic beams*
5. *Sources of polarised electrons, polarised positrons, polarised muons, neutrinos, neutrons and radioactive ions*

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

Atomic rest-frame

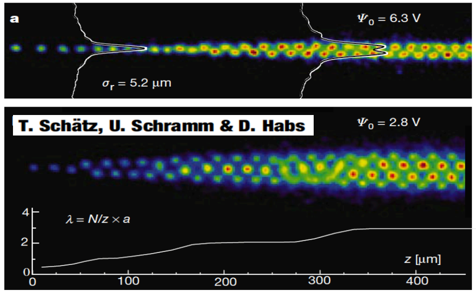
Trapped stationary atoms
Exposed to pulsed magnetic and electric fields of the storage ring





Crystalline beams?

letters to nature



Opening new research opportunities in atomic physics:

- *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*

adp annalen der physik

Feature Article | Open Access

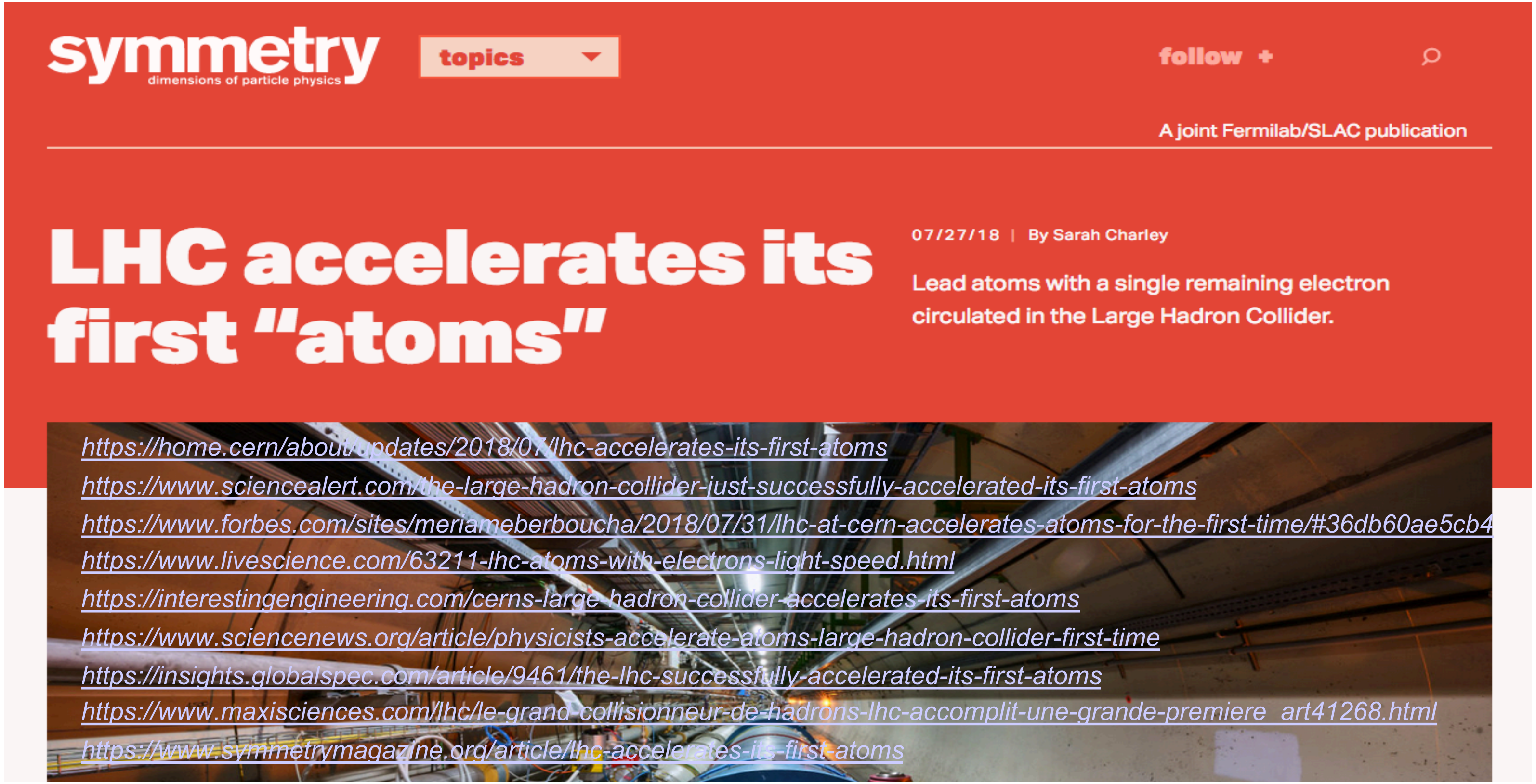
Atomic Physics Studies at the Gamma Factory at CERN

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

More in the talk by Dima Budker…

July 2018: Birth of Atomic Physics research at CERN



https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms

https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms

https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4

https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.html

https://interestingengineering.com/cerns-large-hadron-collider-accelerates-its-first-atoms

https://www.sciencenews.org/article/physicists-accelerate-atoms-large-hadron-collider-first-time

https://insights.globalspec.com/article/9461/the-lhc-successfully-accelerated-its-first-atoms

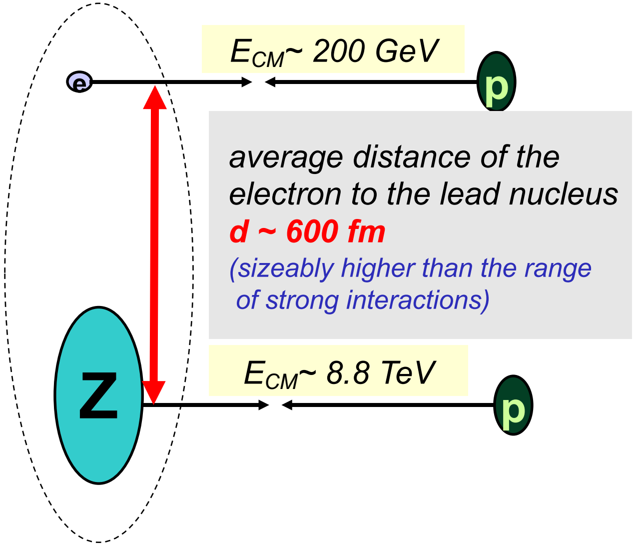
https://www.maxisciences.com/lhc/le-grand-collisionneur-de-hadrons-lhc-accomplit-une-grande-premiere_art41268.html

https://www.symmetrymagazine.org/article/lhc-accelerates-its-first-atoms

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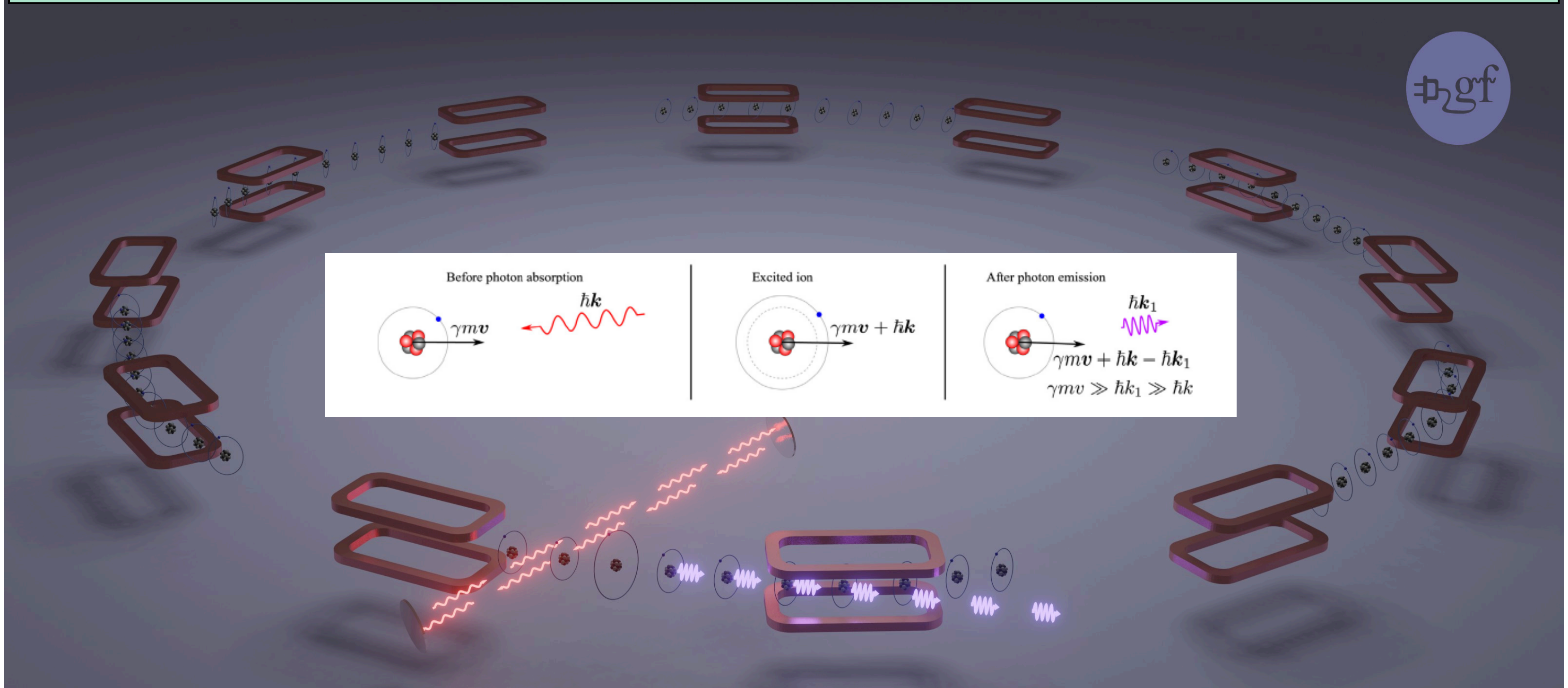
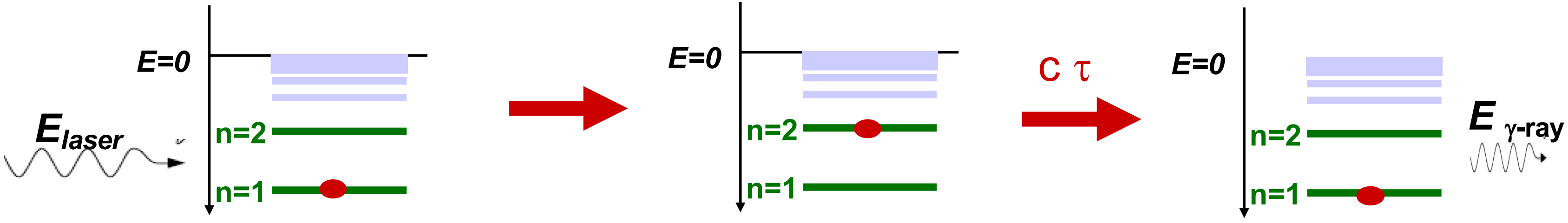
(Received 3 August 2020; accepted 5 October 2020; published 23 October 2020)

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, $\gamma_L = E/M$ is the Lorentz factor for the ion beam

3.Tuneable energy:

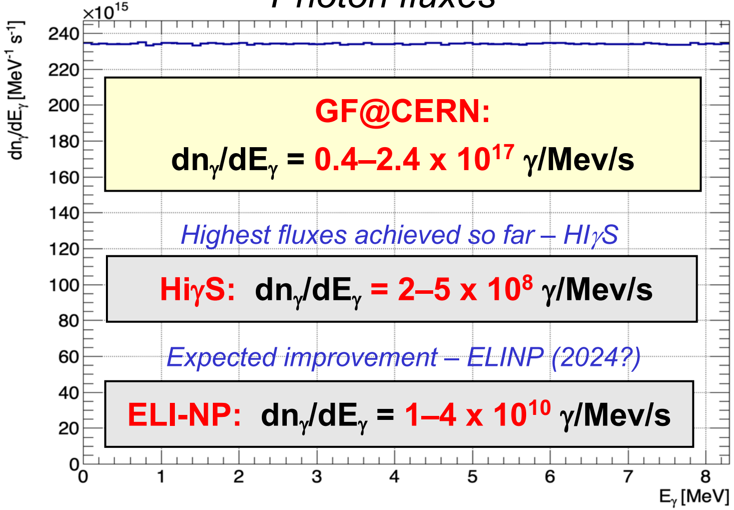
- *The tuning of the beam energy (SPS or LHC), the choice of the ion, the number of left electrons and of the laser type allow to tune the γ-ray energy at CERN in the energy range of 10 keV – 400 MeV (extending, by a factor of **~1000**, the energy range of the FEL X-ray sources)*

4. Plug power efficient:

- *Atoms 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

Photon fluxes

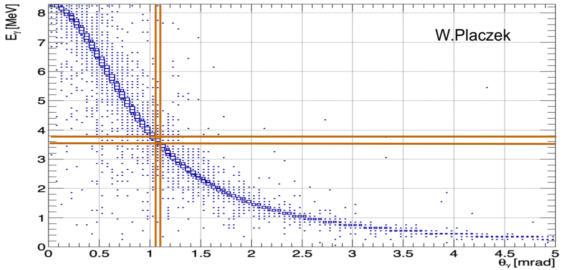


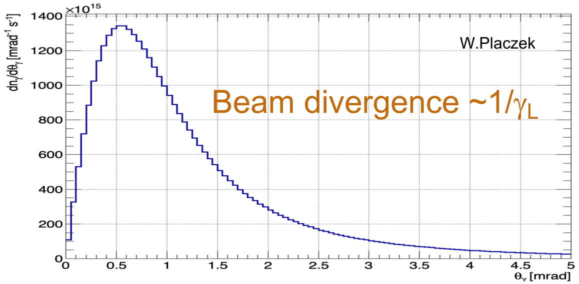
laser pulse parameters

- 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.

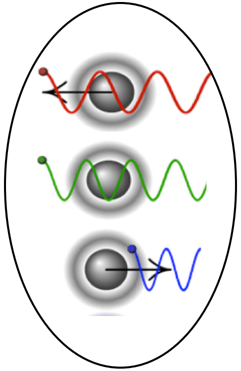
5. Highly-collimated monochromatic γ–beams:

- *the beam power is concentrated in a narrow angular region (facilitates beam extraction)*
- *the (E_γ,Θ_γ) correlation can be used (collimation) to "monochromatise" the beam*

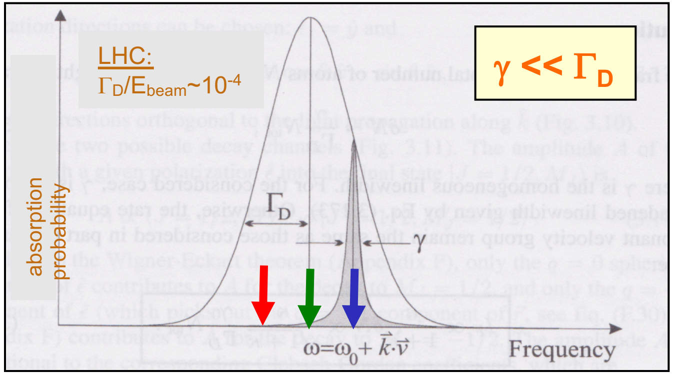


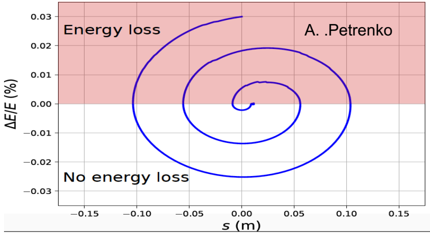


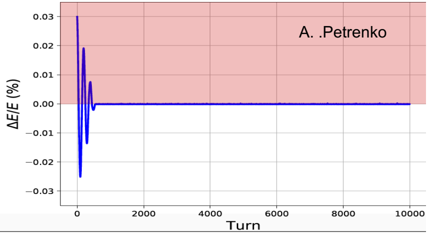
4.Doppler laser cooling methods of high energy beams



Bunch

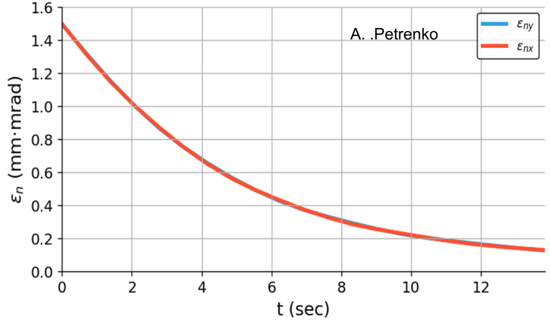






Beam cooling speed: *the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

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.

5.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 ($dN_\pi /dEdp_T dP$ [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 of 10^4 in intensity w.r.t. e.g. ALTO*

Scientific context




Revisiting three paths of progress in experimental science

1. ***Increasing*** *(incrementally)* ***precision*** *of the canonical measurements to* ***test*** *well-established* ***theories*** *and* ***models*** *(e.g. ~40 years of the SM building + ESPP recommendation to remain on this paths over the next 60 years)*

2. ***Verifying*** *predictions of* ***new*** *theoretical* ***models*** *(35 years of the SUSY searches ended up in disillusion – at present no guidance from the theory, neither for the energy scale of new physics, nor for couplings of new particles)*

3. ***Technological leaps****, creating* ***new research tools*** *… or* ***increasing*** *the* ***precision*** *of the existing ones by* ***several orders of magnitude****!*

- ***At this moment*** *of particular* ***importance*** *for our discipline, since we* ***neither*** *have any* ***hints*** *for a* ***new physics*** *which is accessible by the* ***present*** *technologies at a* ***reasonable*** *cost,* ***nor*** *a* ***certainty*** *that our discipline will* ***survive*** *next* ***60 years*** *of remaining solely on the* ***"incremental path"!***

Two Nobel Prizes for “predicted discoveries” at CERN (W/Z, Higgs)

… and 19 Nobel Prizes for X-ray based research

The development of X-ray tools was not motivated by the predicted discoveries
– the discoveries resulted form development of the tools!

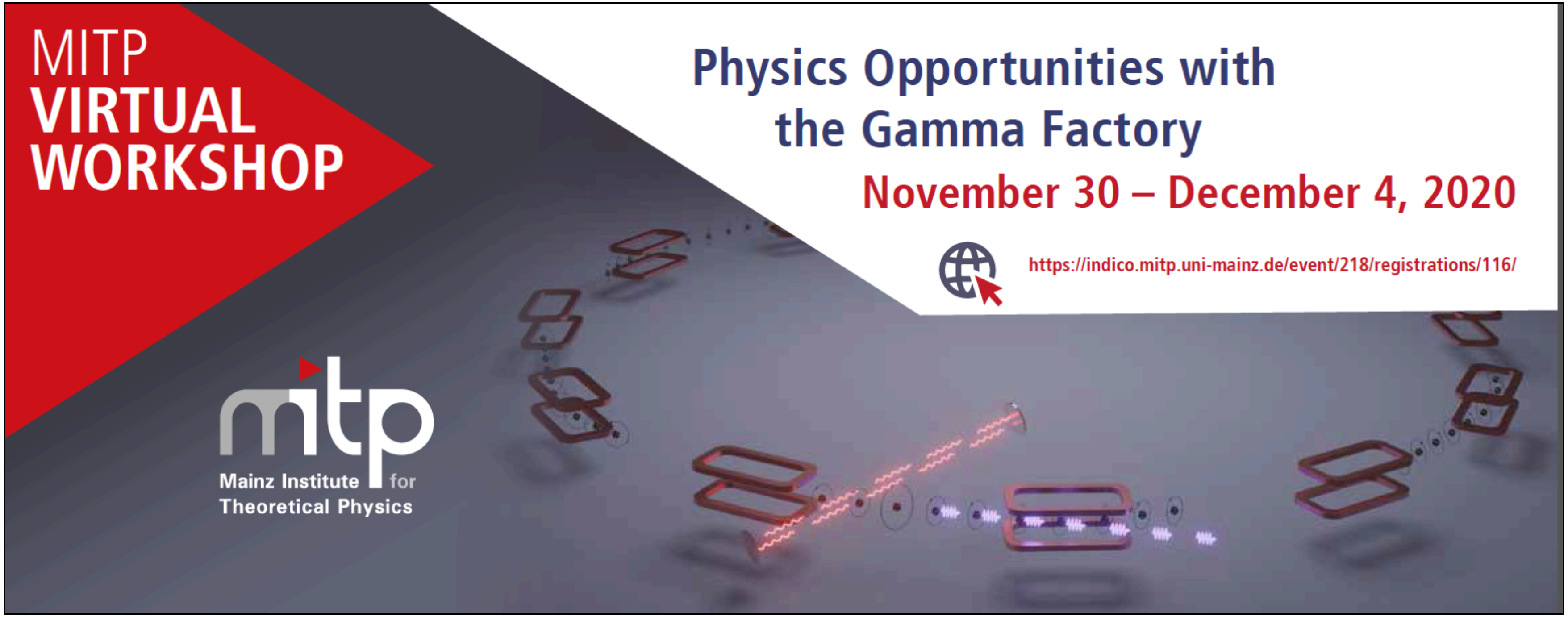
Application domains of the Gamma Factory research tools

- ***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).*

Examples in this talk

- ***nuclear physics*** *(confinement phenomena, nuclear spectroscopy, nuclear photo-physics, fission research, gamma polarimetry, physics of rare radioactive nuclides,…).*
- ***atomic physics*** *(electronic and muonic atoms, pionic and kaonic atoms).*
- ***applied physics*** *(accelerator driven energy sources, cold and warm fusion research, medical isotopes' and isomers' production, …).*

Examples in Dima's talk


MITP
VIRTUAL
WORKSHOP
Physics Opportunities with
the Gamma Factory
November 30 – December 4, 2020
https://indico.mitp.uni-mainz.de/event/218/registrations/116/
Mainz Institute for
Theoretical Physics

Three examples of the Gamma Factory contributions to particle and accelerator physics

The first example →

The Gamma Factory path to high-luminosity LHC

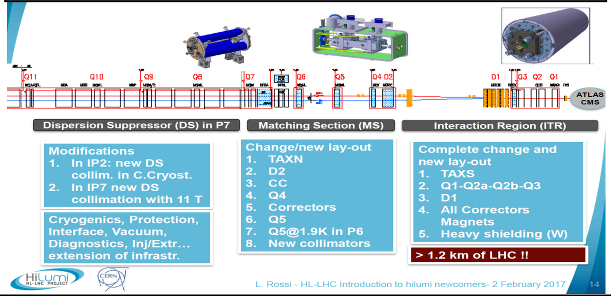
$$\mathscr{L} = f \frac{n_1 n_2}{4\pi \sqrt{\epsilon_x \, \beta_x^* \, \epsilon_y \, \beta_y^*}}$$

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

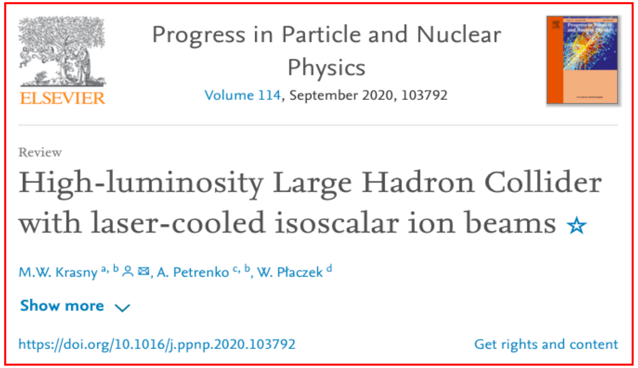
- ***increase** the focusing strength, $\beta *$ ↘*
- ***reduce** the beam emittance, ε ↘*
- ***both**.*

*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**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Progress in Particle and Nuclear Physics

Volume 114, September 2020, 103792

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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The GF scheme of reducing the transverse beam emittance

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

- ***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).*

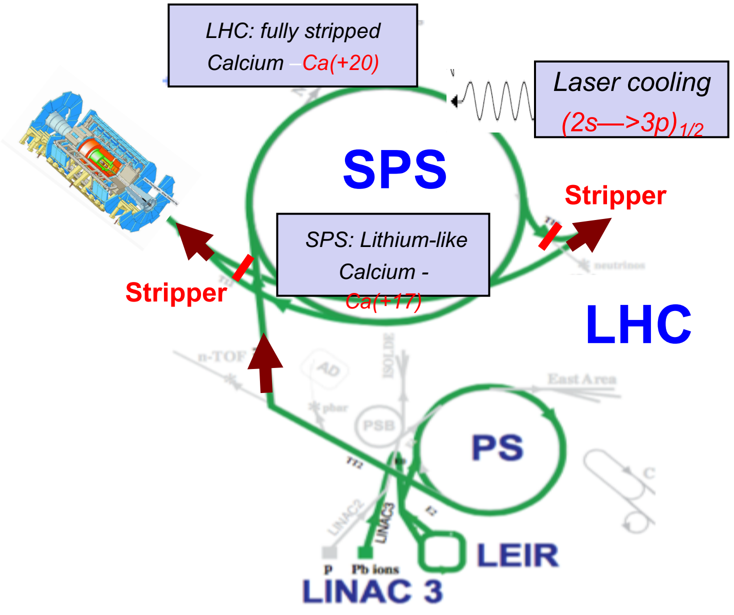
- ***Cool the atomic beam*** *with the specialised laser system at the top SPS energy to reduce its emittance (longitudinal and the transverse cooling).*

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

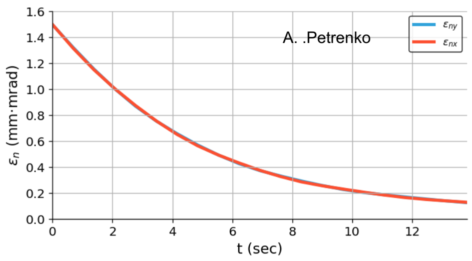
- *Accelerate and* ***collide fully stripped ion*** *beams in the LHC.*

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** – sufficiently short to avoid the CA(+17) beam losses in the SPS.*

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)

The merits of the cold isoscalar 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.*

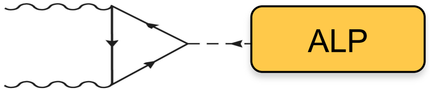
- ***New research opportunities*** *for the EW symmetry breaking sector.*

Three examples of the Gamma Factory contributions to particle and accelerator physics

The second example →

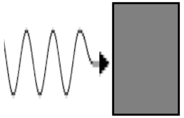
DM searches (and studies?): Axion-Like-Particles (ALP) example

Collision schemes for ALP production:

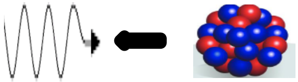


Search phase

γ_{GF} – B field
m_{ALP} < 1 keV



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



γ_{GF} – A collisions (LHC)
m_{ALP} ~ 10 MeV – 10 GeV

"Production" phase

γ_{GF} – γ_{Laser} collisions
m_{ALP} ~ 1–100 keV

γ_{GF} – γ_{GF} collisions (LHC)
m_{ALP} ~ 100 keV – 800 MeV

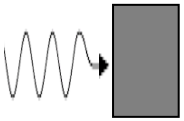
Concurrent, rich QED programme (e.g. $\gamma\gamma$ elastic scattering)

Three principal advantages of the Gamma Factory photon beams:

- ***Large fluxes***: *10^{24} 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**.*

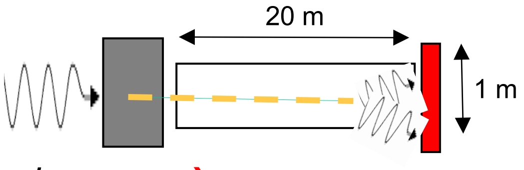
A concrete example: Gamma Factory APL-finding potential
(beam-dump search mode mode)

Search phase
Example: beam-dump mode

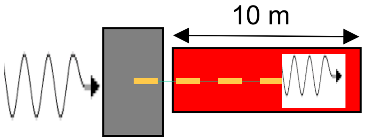


γ_{GF}–A collisions

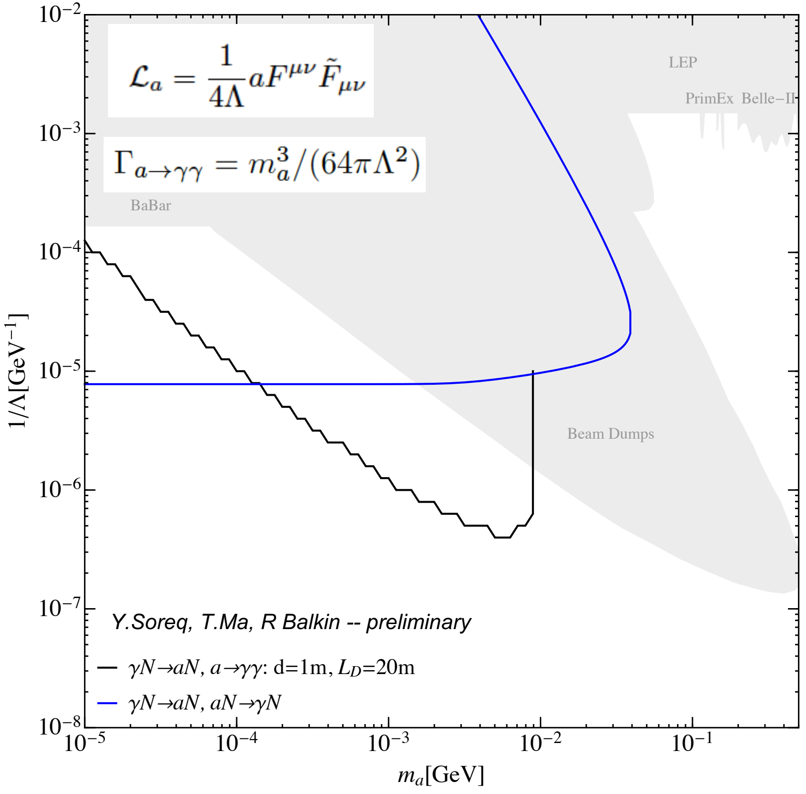
Two appearance modes:



- *decay: $a \rightarrow \gamma\gamma$*



- *reconversion: $aN \rightarrow \gamma N$*



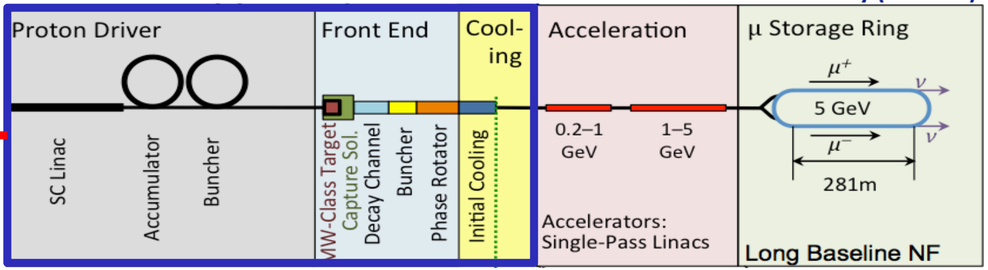
Three examples of the Gamma Factory contributions to particle and accelerator physics

The third example →

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

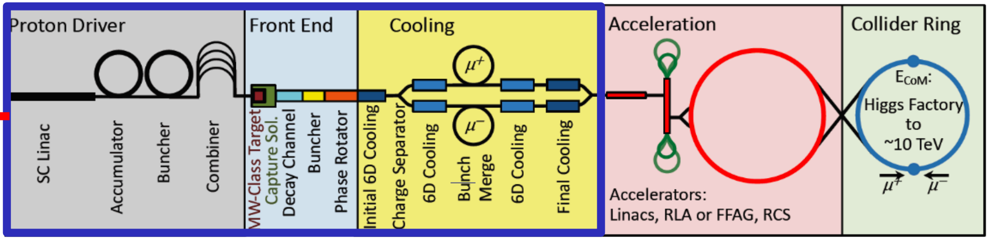
?

Neutrino Factory (NuMAX)



?

Proton-driven Muon Collider Concept (MAP)

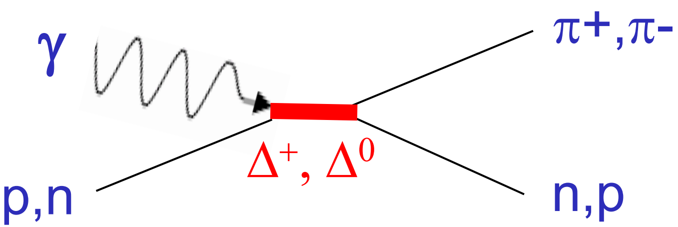


Shouldn't we try to avoid constructing a costly, high power Proton Driver, and to get rid of the necessity of building a ~1000 m long, sophisticated cooling section?

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 cost of digging the tunnel for the 100 km long, 350 GEV, e^+e^- collider (5.5 BCHF)?

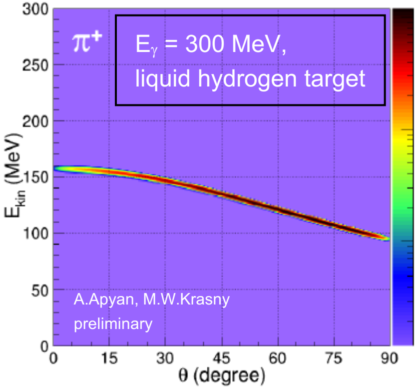
<u>**Novel paradigm:**</u> μ and ν sources based on exclusive pion production in photo-excitation of Δ resonances with the Gamma Factory photon beam

$$\gamma + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$
$$\gamma + n \rightarrow \Delta^{0} \rightarrow p + \pi^{-}$$

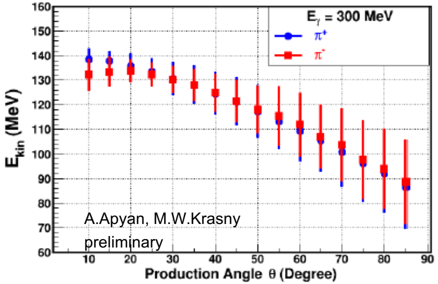


Exclusive process:

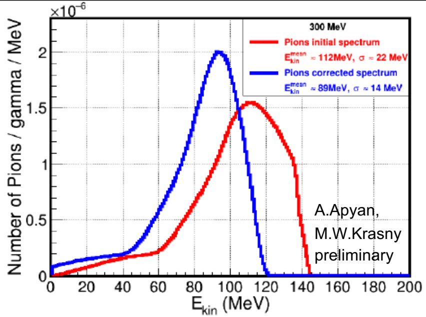
- *Pion energy and transverse momentum **no** longer random*
- ***Fully** specified by **one** parameter: the pion **emission angle**, θ*



Symmetry of π^+ and π^- production for **isoscalar target** (e.g. graphite) *(the cost: Fermi smearing - error bars)*



Further "Monochromatisation" of the pion kinetic energy by a suitable choice of the target radius

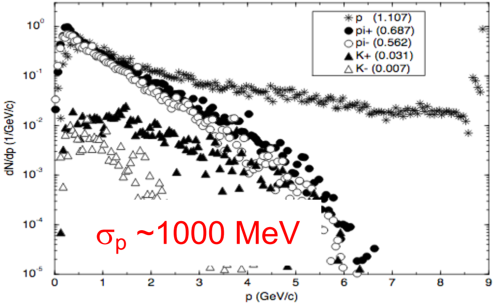


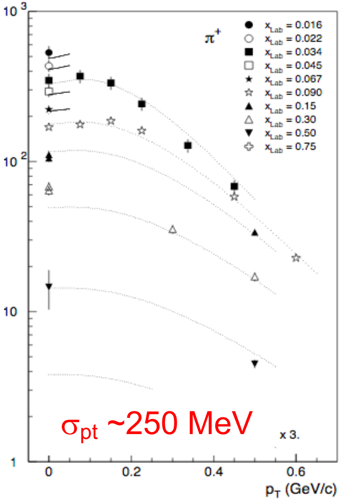
Pion production rate and spectra: proton versus GF γ–beams

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

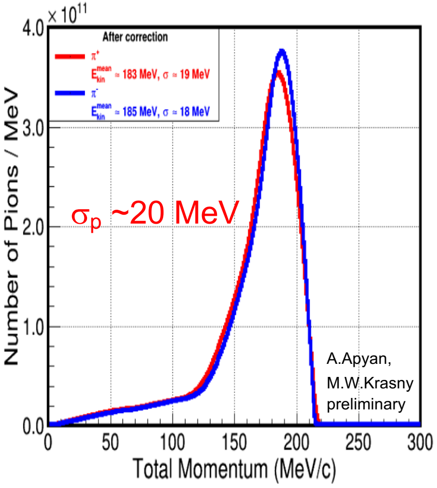
1 MW photon beam deposits ~ 6 times less energy in the λ_i = 2 graphite target! …in addition ~20% muons lost in the cooling channel

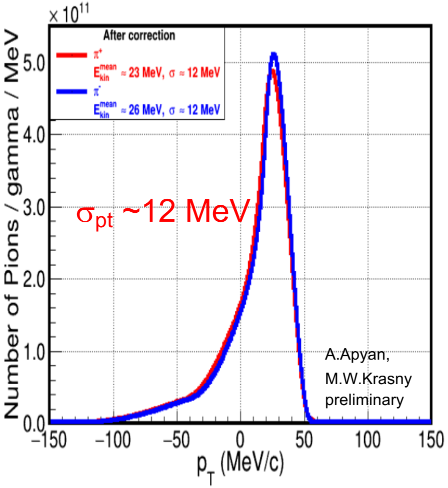




300 MeV GF γ-beam

For λ_i = 2 **graphite** target :
~ 2 x 10^{13} π^+ and π^- /s for 1 MW γ beam (2 x 10^{16} γ/s)





$\varepsilon_{T(x,y)}$ ~$(\sigma_T \sigma_{pt})/mc^2$
ε_L ~$(\sigma_z \sigma_p)/mc^2$

Expected **reduction** of the **transverse pion-beam emittance** (x,y) by a factor of > **10** and **longitudinal emittance** by a factor of > **20**. If preserved while forming μ-beam (under study), no cooling necessary!

Potential advantages of the Gamma Factory photon-beam-driven neutrino and muon sources

- *Replacing the high-power proton Linac beam by the **LHC-driven GF photon-beam** may turn out to be an exciting, cost-optimising option for the future **neutrino factory** and **muon collider.***
- ***Producing** and **handling** of **> 1 MW photon beams** may turn out be **easier** than > 1 MW proton beams (less power deposited in the target).*
- ***GF** source could produce **low-emittance muon beams** for which the **muon-cooling** phase may be **avoided** (CW beam!).*
- *High spectral density of the pion beams allows to generate a **Very-Narrow-Band Neutrino Beams** (VNBNB).*
- *The almost exact **symmetry** of the $\pi+/\pi-$ and $\mu+/\mu-$ is **assured** (contrary to the proton driven sources).*
- *The above two merits may **facilitate** the design of the **neutrino factory** and **muon collider** (for the latter, the bunch merging scheme at the top energy would need to be developed).*
- ***Muon polarisation** provides an unique path towards the **CP** and **flavour tagged neutrino beams**.*

This exciting option needs further studies …

Gamma Factory status

Gamma Factory (PBC) study group

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The Gamma Factory initiative (arXiv:1511.07794 [hep-ex]) was endorsed 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.* → *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 → waiting for CERN's approval (Yann's talk)*

future

1. *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).*
2. *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 (examples in this talk and in Dima Budker's talk)*

- *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 which must be finalised prior to the next European Strategy Update*

Conclusions

- *The initial enthusiasm and the corresponding exponential growth of the community contributing to the Gamma Factory studies cannot be maintained if there is no "formal" recognition and support for this initiative coming from CERN (potential host of the Gamma Factory) and, what follows, from the funding agencies in our countries*

- *Such a recognition is a "sine qua non' condition to apply for grants and include PhD students and postdocs in the group activities – creating a sustainable project development framework*

  - ***This is what we need the most at this stage of the project development!***

- *We hope, our three talks will contribute to divulge the highlights of the Gamma Factory research programme, provide help in an evaluation of the importance of our R&D effort, and (hopefully) result in recognition and support for the project*

Post Scriptum

"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

"Do not fear to be eccentric in opinion, for every opinion now accepted was once eccentric."

— **Bertrand Russell**

Post Scriptum

The existence of the Standard Model does not imply the existence of a standardized anticipation of the future. The only thing that deserves institutionalization is doubt. This problem of maintaining diversity of approach afflicts both experiment and theory, and if I have any concern about how the field is developing, it is about this point I worry the most.

James D. Bjorken (Bj)