The Gamma Factory project and $\gamma \rightarrow \mu\mu$ conversions

SFT Simulation meeting, CERN, the 2nd of October 2018

Mieczyslaw Witold Krasny, CERN BE-ABP division,
LPNHE, CNRS-IN2P3 and University Paris Sorbonne

Gamma Factory CERN-based framework

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:

Mandate of the "Physics Beyond Colliders" Study Group

CERN Management wishes to launch an exploratory study aimed at exploiting the full scientific potential of its accelerator complex and other scientific infrastructure through projects complementary to the LHC and HL-LHC and to possible future colliders (HE-LHC, CLIC, FCC). These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments.

The Gamma Factory group members

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The group is open to everyone willing to join the adventure of creating new research opportunities at CERN

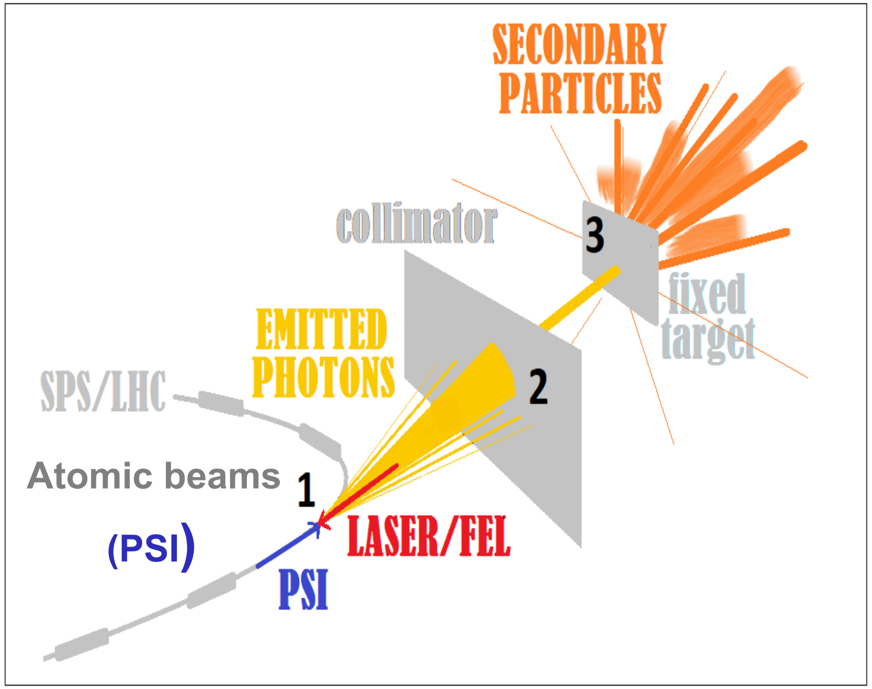
The Gamma Factory in a nutshell

1. *Produce, accelerate and store high energy atomic beams of* ***Partially Stripped Ions (PSI)*** *and excite their atomic degrees of freedom, by laser photons to form high intensity primary beams of gamma rays and, in turn, secondary beams of polarised leptons, neutrinos, vector mesons, neutrons and radioactive ions.*

2. *Provide a new, efficient scheme of transforming the accelerator RF power (selectively) to the above primary and secondary beams trying to achieve a* ***leap, by 4-7 orders of magnitude****, in their intensity and/or brightness, with respect to all the existing facilities.*

3. *Use the primary and the secondary beams as principal tools of the Gamma Factory research programme.*

Gamma Factory



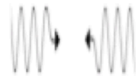
primary beams:

- 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

$\gamma-\gamma_L$ collisions,
E_{CM} = 1 – 100 keV

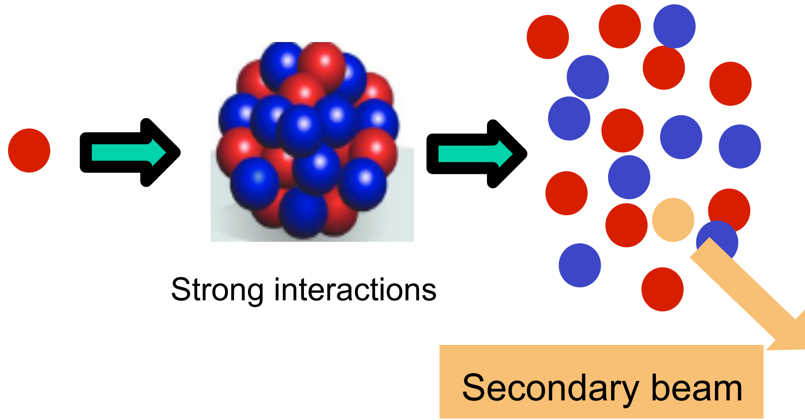
γ–p(A), ep(A) collisions,
E_{CM} = 4 – 200 GeV

A leap in production efficiency, intensity and purity

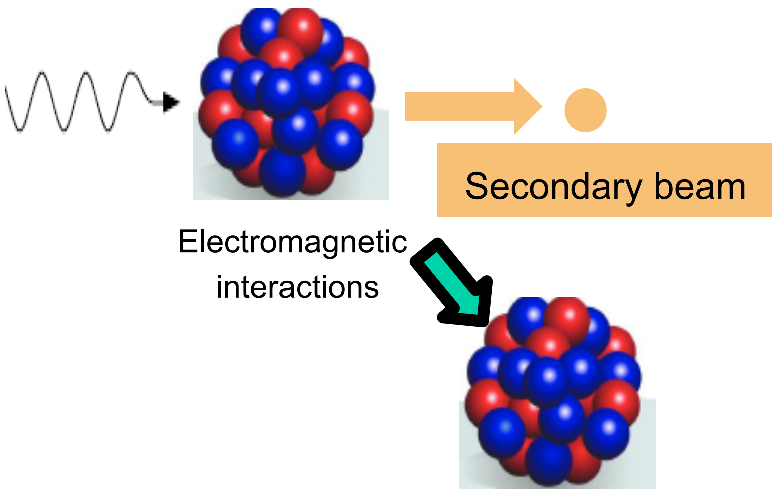
Gamma Factory secondary beams

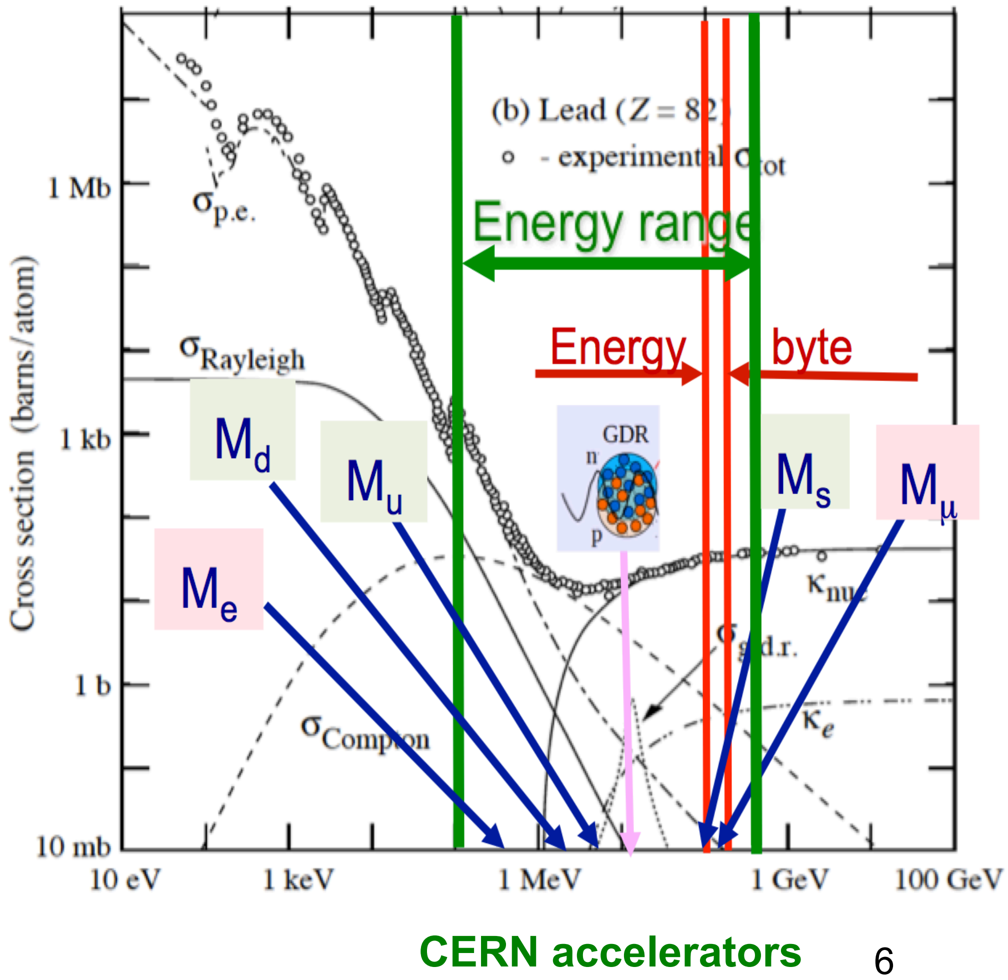
(from "mining" paradigm to "production-by-demand" paradigm)

"mining" paradigm:



"production" paradigm:





The Gamma Factory beam intensity targets

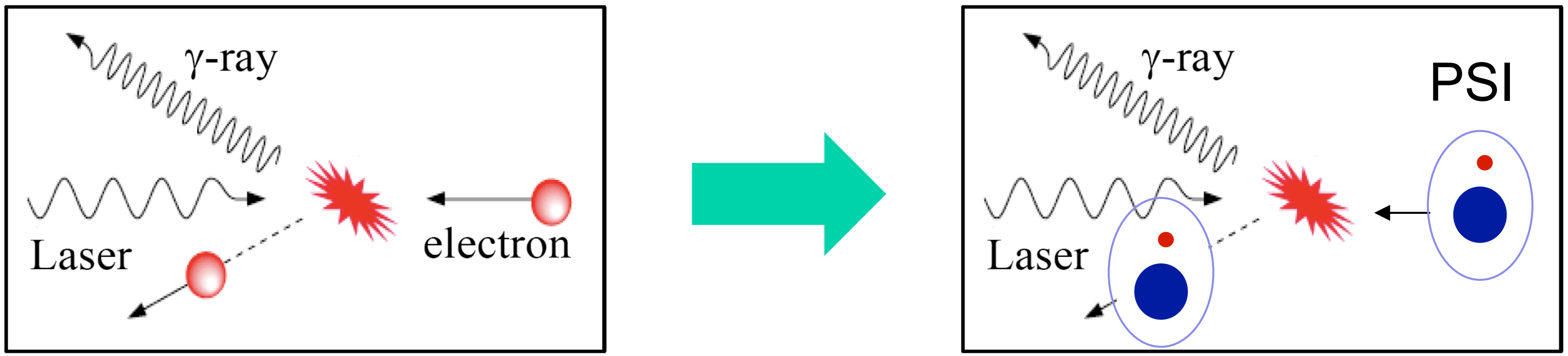
- ***Highly ionised atoms*** *– new at relativistic energies*
- ***Photons*** *– up to a factor of 10^7 gain in intensity w.r.t the present gamma sources*
- ***Polarised positrons*** *– up to a factor of 10^4 gain in intensity w.r.t KEK positron source*
- ***Polarised muons*** *- up to a factor 10^3 gain in intensity w.r.t to PSI muon source – (low emittance beams → muon collider, high purity neutrino beams)*
- ***Neutrons*** *– up to a factor of 10^4 in flux of neutrons per 1 kW of the driver beam power*
- ***Radioactive ions*** *– up p to a factor 10^4 gain in intensity w.r.t to e.g. ALTO*

GF research highlights

- ***particle physics*** *(studies of the basic symmetries of the universe, dark matter searches, precision QED studies, rare muon decays, neutrino-factory physics, precision-support measurements for the LHC - DIS physics, muon collider physics)*
- ***nuclear physics*** *(confinement phenomena, link between the quark-gluon and nucleonic degrees of freedom, photo-fission research program)*
- ***accelerator physics*** *(beam cooling techniques, low emittance hadronic beams, plasma wake field acceleration, high intensity polarized positron and muon sources, secondary beams of radioactive ions and neutrons, neutrino-factory)*
- ***atomic physics*** *(electronic and muonic atoms),*
- ***applied physics*** *(accelerator driven energy sources , cold and warm fusion research, isotope production: e.g alpha-emitters for medical applications, …).*

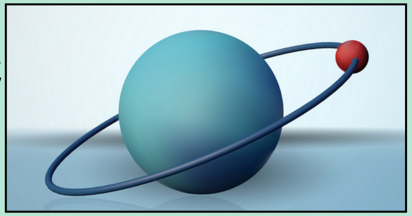
The gamma ray source for Gamma Factory

The idea: replace an electron beam by a beam of highly ionised atoms:
Partially Stripped Ions ***(PSI)*** ***(giga-barn instead of barn cross sections!)***

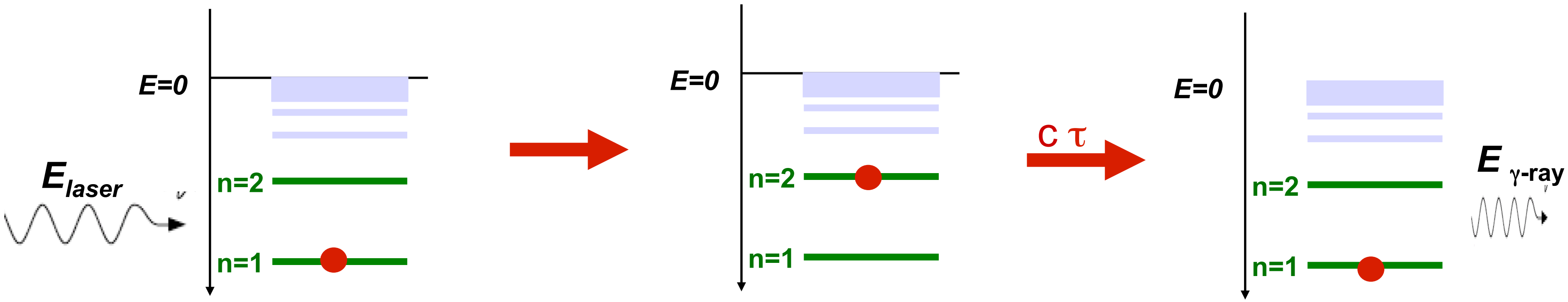


K.A. ISPIRIAN, A.T. MARGARIAN, N.G. BASOV,
A.N. ORAEVSKI, B.N. CHICHKOV. A. BOGACZ
E.G. BESSONOV, K-J. KIIM, M.W. KRASNY…

Scattering of photons on ultra-relativistic hydrogen-like, Rydberg atoms



$-E_n = 1Ry\ \ Z^2/n^2$



$E_{laser}=1Ry\ (Z^2 - Z^2/n^2)/2\gamma_L$

$E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L^{\ 2}/(1+(\gamma_L\theta)^2)$

The Gamma Factory project milestones

1. Production, acceleration and storage of “atomic beams” (PSI) at CERN

2. Development “ex nihilo” Gamma Factory software tools.

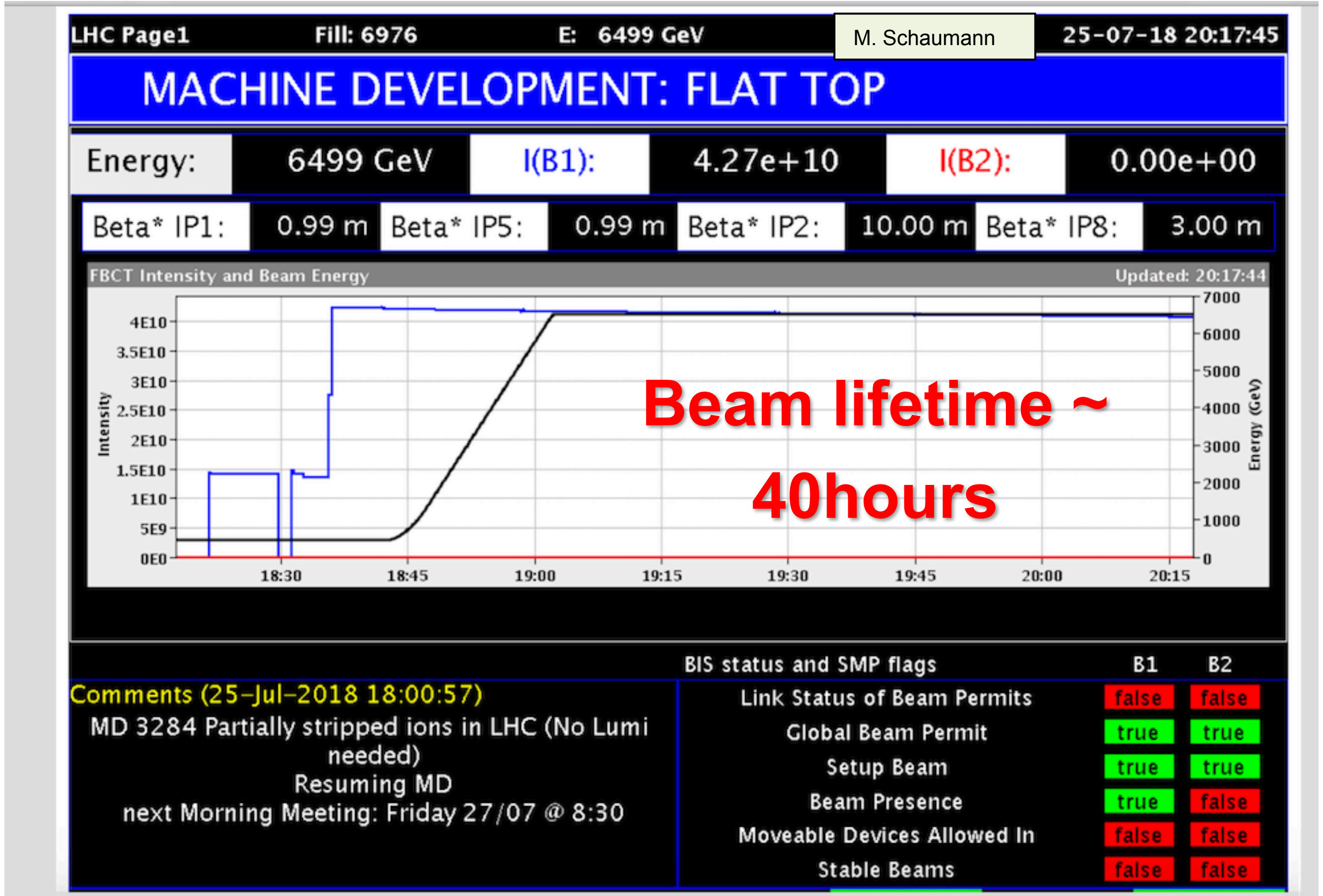
3. Proof-of-Principle experiment in the SPS tunnel.

4. Realistic assessment of the Gamma Factory performance figures.

5. Physics highlights of the Gamma Factory based research program.

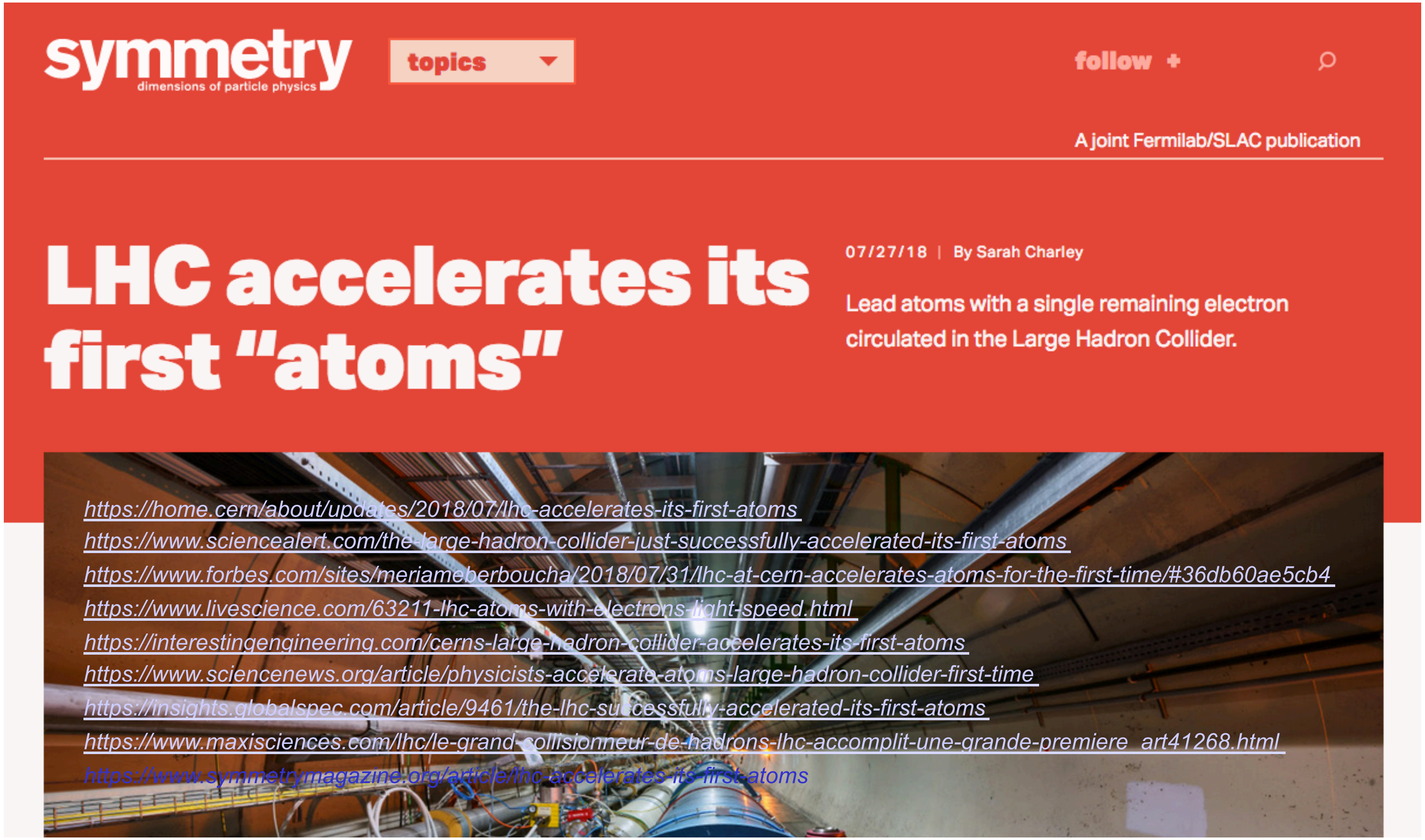
6. Gamma Factory TDR

July 2018 – Successful production, injection, ramp and storage of the **Hydrogen-like Lead beam in the LHC!**



intensity/bunch (~7 x 10^9), 6 bunches circulating

The 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

First steps in the development of the GF simulation tools

1. *PSI-beam simulation (beam cooling, IBS, IBS, Space Charge, Instabilities,….)*

2. *Electron stripping in metallic foils (to design an efficient electron stripping scheme).*

3. *Collisions of atomic beams with the residual gas in the accelerator rings.*

4. *Collisions of PSI bunches with photons (laser +F-P cavity or FEL)*

5. *Production of secondary beams in collisions of photons with matter:* ***positrons, polarised muons, neutrons, neutrinos, mesons, radioactive nuclei***

today

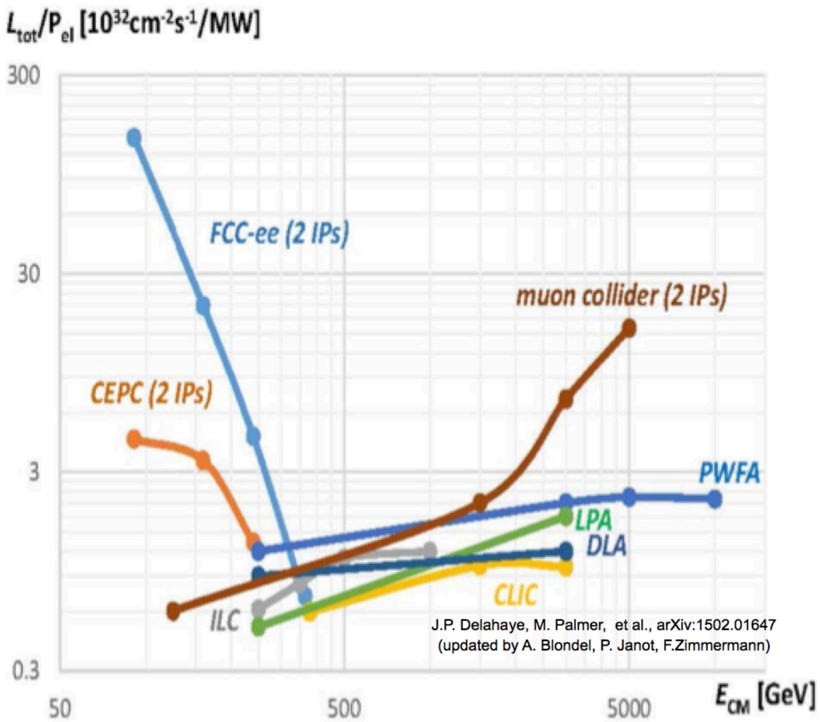
GF beam of polarised muons

Muon Collider Workshop 2018

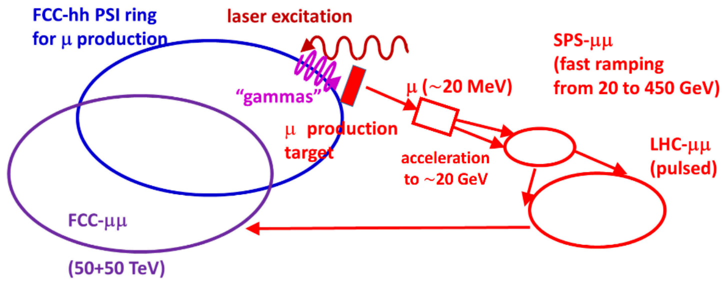
1-3 July 2018
Università di Padova - Orto Botanico
Europe/Zurich timezone

Search...

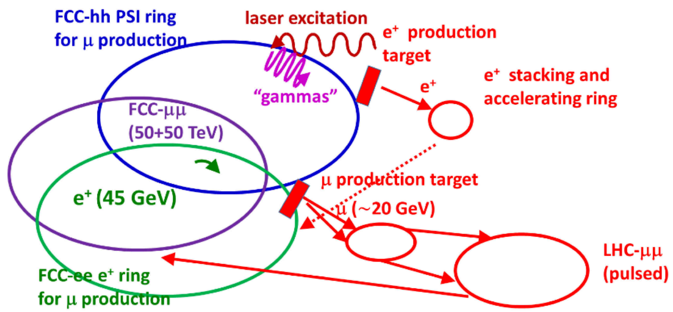
Variants of a multi-TeV scale muon colliders **based on the Gamma Factory concept**



For the CM-energies above 2 TeV (10 fold increase w.r.t LEP) a muon collider appears to be the only way to achieve a requisite luminosity with reasonable wall power consumption



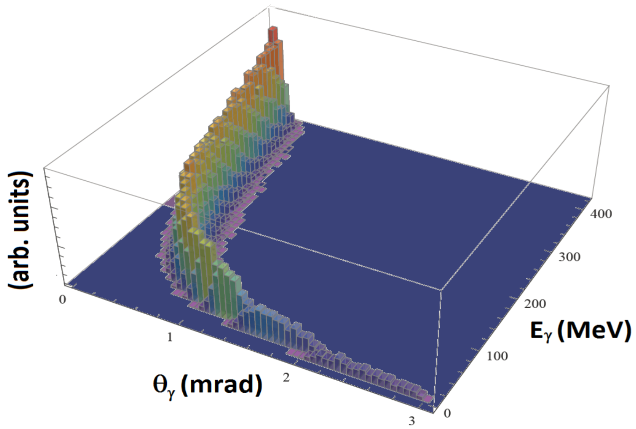
100 TeV μ collider FCC-μμ with FCC-hh PSI e^+ & FCC-ee $\mu^\pm$ production

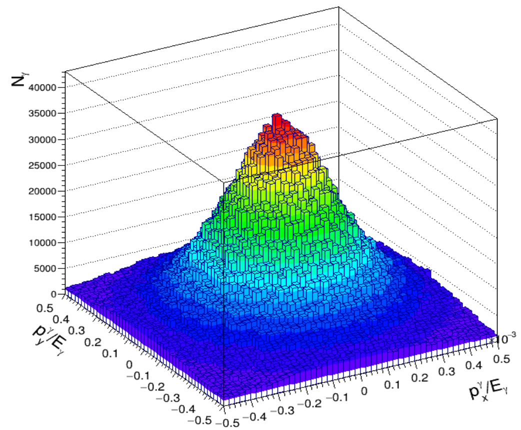


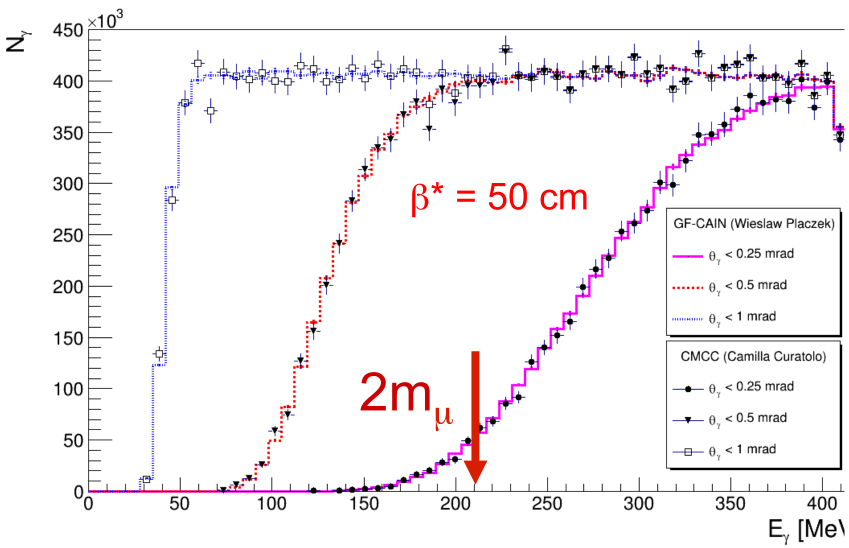
LHC/FCC-BASED MUON COLLIDERS*

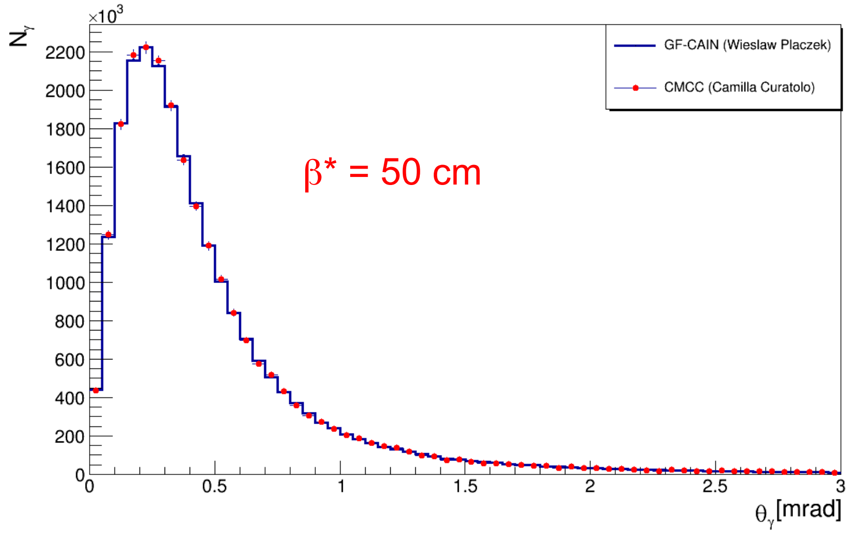
F. Zimmermann†, CERN, Geneva, Switzerland

Gamma ray production spectra for +81 Pb beam collisions with photon bunches at the top LHC energy (two generators being developed)

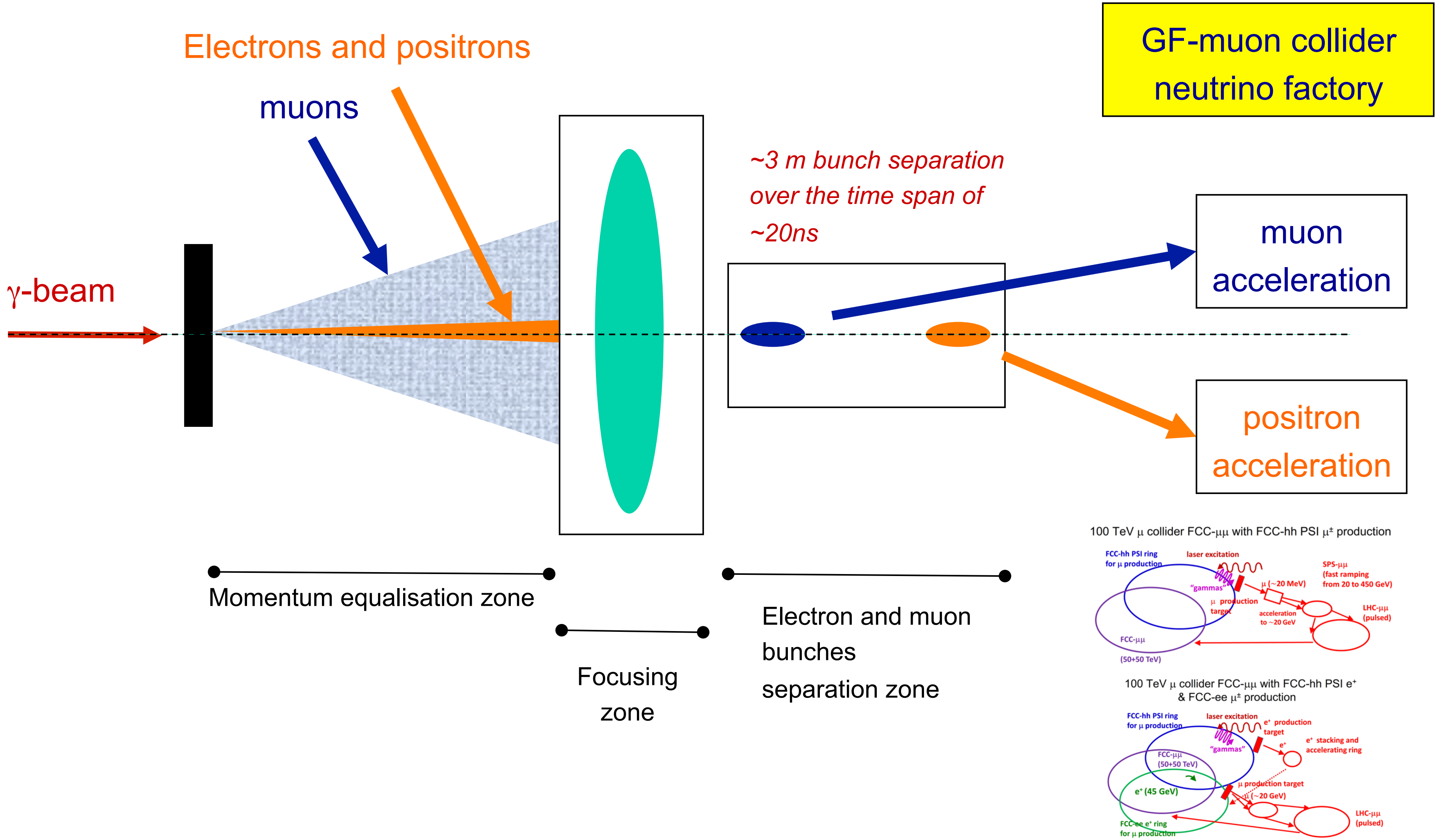








Initial conceptual ideas for the polarised muon source



The way forward

- *Development of the specialized generator for photon conversion into muon pairs close to the production threshold*
- *Design of the gamma production IP, gamma beam extraction, and the gamma conversion target*
- *Design of the muon/electron beam separator and the beam transport including “muon beam emittance corrector”*

Monte Carlo Generator for Muon Pair Production

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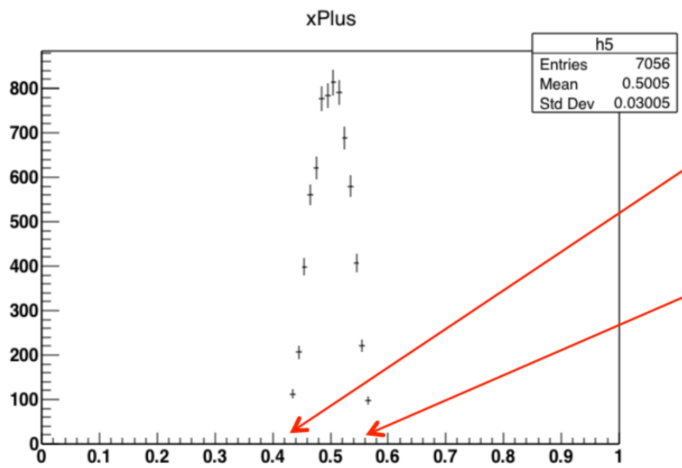
Abstract

A Monte Carlo Generator for the electromagnetic pair production of muon pairs by high energy photons in matter is described. The computer code is designed as a standard electromagnetic process for GEANT4. The relevant formulas and algorithms are described and illustrated in detail.

Muon production for 430 MeV gamma energy beam

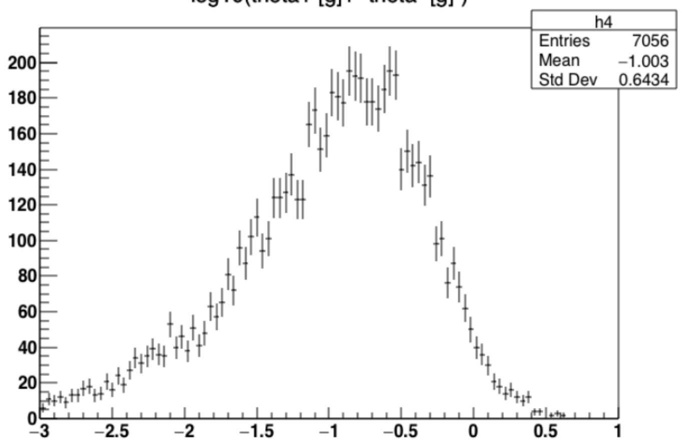


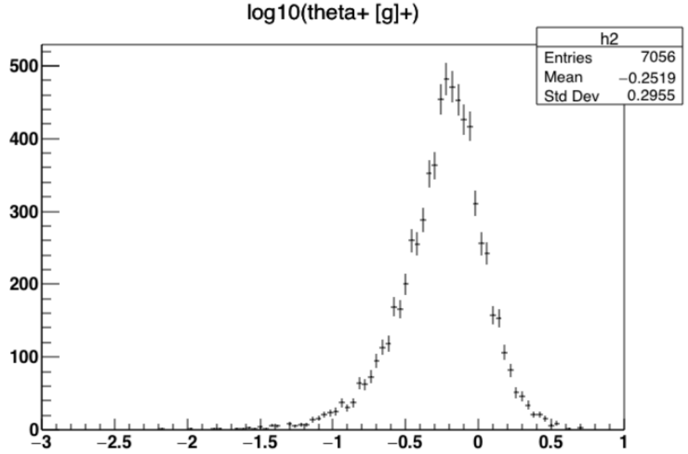
$$x_{min} = \frac{1}{2} - \sqrt{(\frac{1}{4} - \frac{m_\mu}{E_\gamma})}$$

xmin=0.42

$$x_{max} = \frac{1}{2} + \sqrt{(\frac{1}{4} - \frac{m_\mu}{E_\gamma})}$$

xmax=0.57





Pair production and bremsstrahlung of charged leptons*

Yung-Su Tsai

Stanford Linear Accelerator Centers, Stanford University, Stanford California 94305

Photo pair productions of electrons, muons, and heavy leptons and bremsstrahlung of electrons and muons are reviewed. Atomic and nuclear form factors necessary for these calculations are discussed. Straggling of electrons in matter and other effects due to finite target thickness are considered. Tables of radiation lengths of all materials and the energy dependence of photon absorption coefficients of many materials are presented. Problems associated with production of particles by photon and electron beams are also discussed.

Erratum: Pair production and bremsstrahlung of charged leptons* [Rev. Mod. Phys. 46, 815 (1974)]

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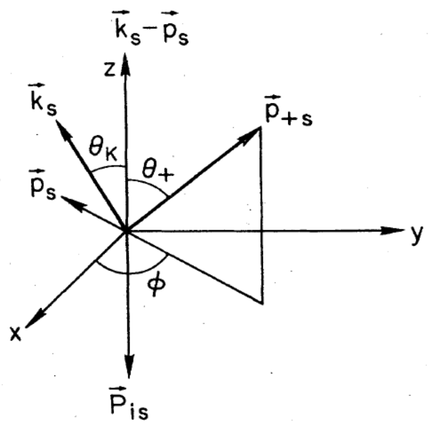


FIG. 2. The coordinate system used in the integration of the unobserved particle p_+. The subscript s refers to the rest frame of $U = p_+ + p_f$.

$$d\sigma = e^6 \frac{m_i}{4(k\cdot p_i)} \frac{d^3p}{E} \frac{d^3p_+}{E_+} \frac{1}{(2\pi)^5} \frac{1}{q^4} (L^{\mu\gamma} W_{\mu\nu}),$$

$$-L^{\mu\nu}W_{\mu\nu} = W_2(q^2, m_f^2)\left[\frac{H}{(p_+\cdot k)^2} + \frac{B}{(p_+\cdot k)} + C + D(p_+\cdot k)\right] + W_1(q^2, m_f^2)\left[\frac{H'}{(p_+\cdot k)^2} + \frac{B'}{(p_+\cdot k)} + C' + D'(p_+\cdot k)\right], \quad (2.3)$$

where

$$H = -m^2\{\tfrac{1}{2}q^2(1 - 2E/m_i) + 2E^2 + 2E\Delta\},$$

$$B = -(2/k\cdot p)\{(m^2 - q^2/2)[2E(E-k) + \tfrac{1}{2}q^2((k-2E)/m_i + 1) + (2E-k)\Delta] - \tfrac{1}{2}q^2k^2\} + (q^2/m_i)(m_i + E - k - \tfrac{1}{2}q^2/m_i) - 2\Delta(\Delta - k + E - q^2/m_i) + k\cdot p,$$

$$C = -[m^2/(k\cdot p)^2]\{2(k - E - \Delta + q^2/2m_i)(k-E) + q^2/2\} + (k\cdot p)^{-1}\{q^2(1 - E/m_i) + 2E\Delta\},$$

$$D = 1/(k\cdot p),$$

$$H' = m^2(2m^2 + q^2),$$

$$B' = -[(q^4 - 4m^4)/k\cdot p + 2q^2 + 2k\cdot p + 4m^2],$$

$$C' = m^2(2m^2 + q^2)/(k\cdot p)^2 - 2(2m^2 + q^2)/(k\cdot p),$$

$$D' = -2/(k\cdot p),$$

$$\Delta = (m_f^2 - m_i^2)/(2m_i) \quad \text{and} \quad q^2 = (k - p - p_+)^2.$$

Conclusions

Gamma Factory project requires a substantial effort to create, to develop, and/or to modify the existing simulation tools, both to asses its expected physics reach and to design its experimental facilities.

Your help in developing such tools will be crucial for the success of this project.

The development of the event-generator code for the close-to-the-production-threshold photo-production of muon pairs (including polarisation) is particularly important for the European Strategy update (2019-2020) to evaluate the feasibility and merits of various options for the new energy frontier machine at CERN (including an option of a muon collider)

Could you help us by developing such a generator?

Extra transparencies

The expected magnitude of the γ-source intensity leap

Electrons:

$$\sigma_e = 8\pi/3 \times r_e^2$$

r_e - classical electron radius

Partially Stripped Ions:

$$\sigma_{res} = \lambda_{res}^2 / 2\pi$$

λ_{res} - photon wavelength in the ion rest frame

Electrons:

$$\sigma_e = 6.6 \times 10^{-25}\ cm^2$$

Partially Stripped Ions:

$$\sigma_{res} = 5.9 \times 10^{-16}\ cm^2$$

Numerical example: λ_{laser} = 1540 nm

~ 9 orders of magnitude difference in the cross-section

~ 7 orders of magnitude increase of gamma fluxes

Partially Stripped Ion beam as a light frequency converter

$$\nu^{max} \longrightarrow (4\,\gamma_L^2)\,\nu_i$$

γ_L =E/M - Lorentz factor for the ion beam

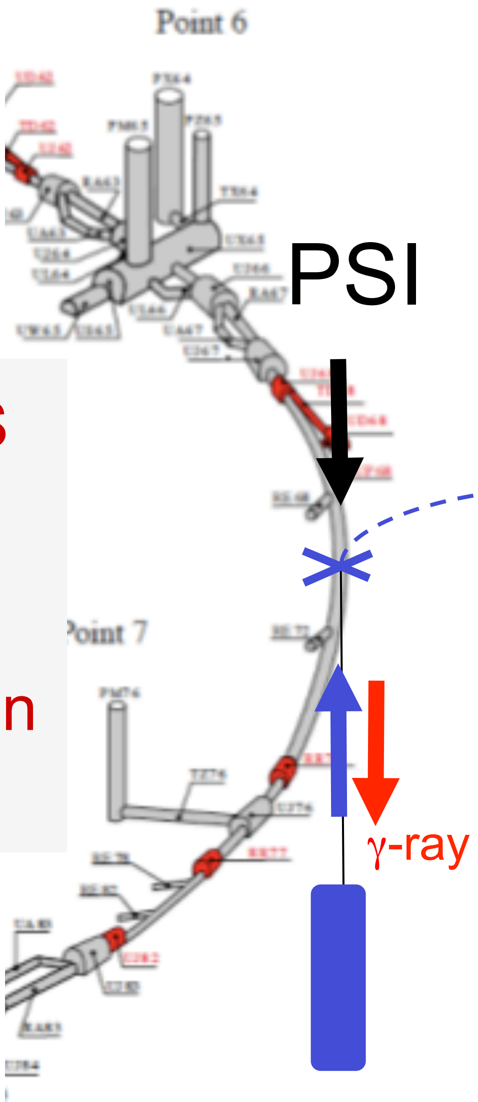
The tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the γ-ray energy, at CERN, in the energy domain of 40 keV – 400 MeV.

Example (maximal energy):

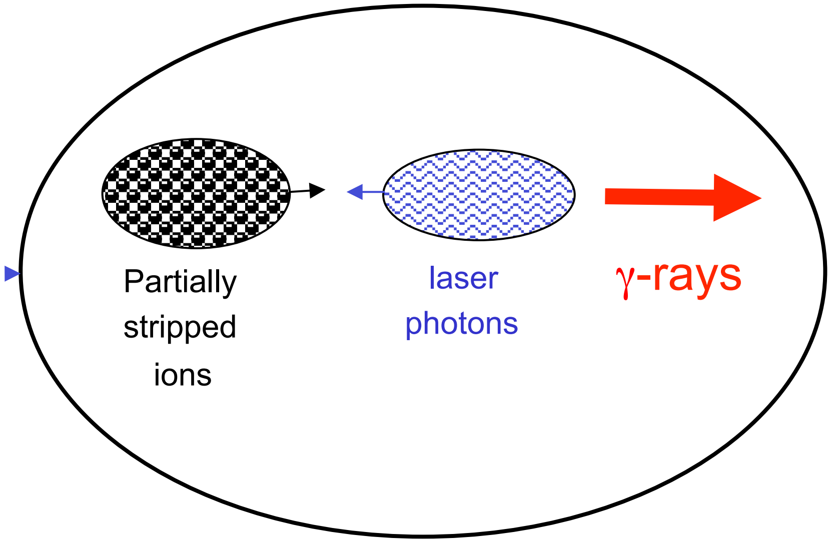
LHC, Pb^{80+} *ion,* γ_L = 2887, n=1→2, λ = 104.4 nm, E_γ (max) = 396 MeV

The γ-ray source scheme for CERN

LHC/SPS filled with partially stripped ion bunches



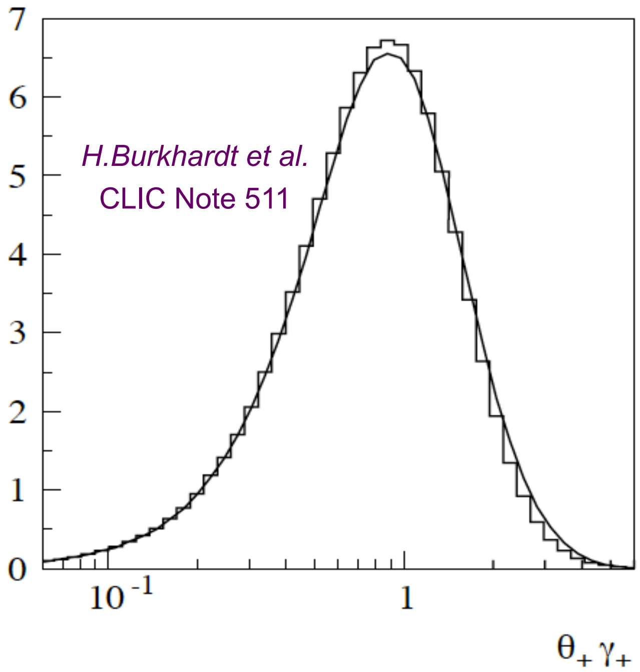
Laser photon



Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$ *~ 0.04 mm for* $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

Hint1

The conversions, especially on high Z material, lead to a simple relation between the outgoing muon energy and angle:



Hint2

Electrons are relativistic, muons are not:

$\beta_e = 1, <\beta_\mu> \sim 0.5$

20 ns following the collision of the photon bunch with the conversion target, electron and muon bunches are separated by (on average) 200 cm allowing for their efficient separation