Gamma Factory and precision physics at LHC

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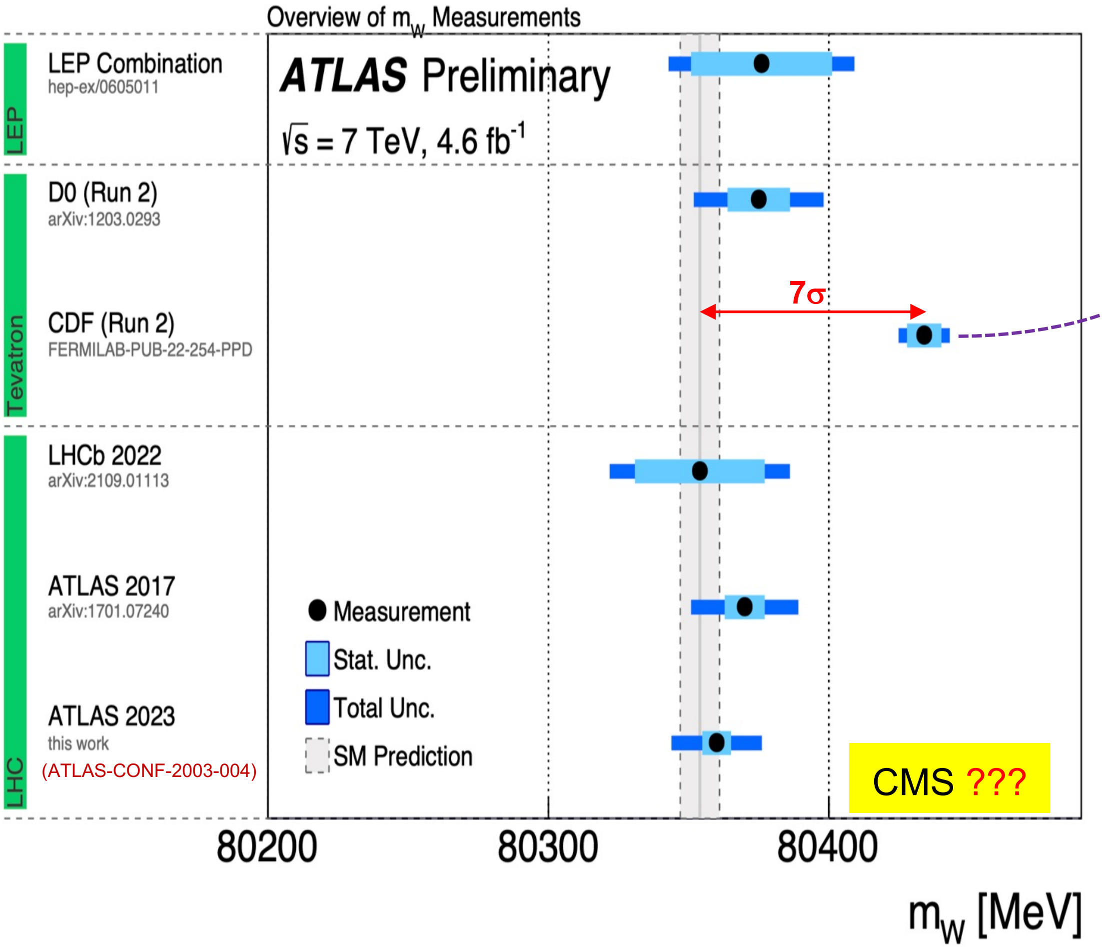
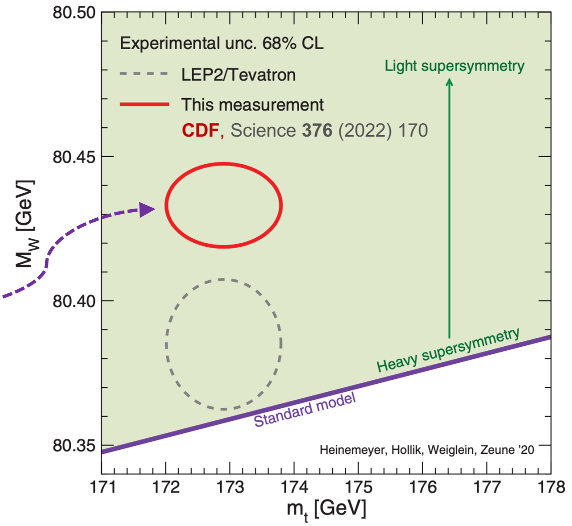
dedicated to the memory of Staszek Jadach

PRECISION MEASUREMENT OF STANDARD MODEL PARAMETERS AT LHC

W-boson mass measurement





CDF 2022:

4M events, **δM_W = 9 MeV**

ATLAS 2023:

14M events, δM_W = 16 MeV

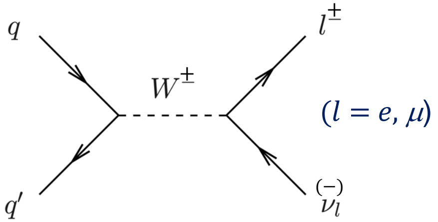
- ATLAS 2023: improvement by ~15% of ATLAS 2017 **M_W** measurement with the **same data**, i.e. **2011** run at centre-of-mass energy of **7 TeV**.

W-boson mass measurement

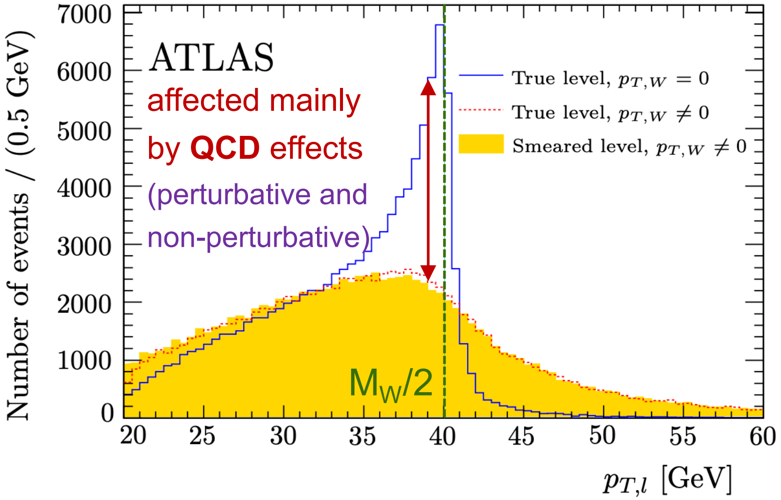
- **ATLAS** precision target: **$\delta M_W = 5$ MeV** → **$\delta M_W / M_W < 0.01\%$**

  (e.g. M. Boonecamp, Conference „Physics at LHC", Krakow, 3–8 July 2006)

- Recent measurements:
  - **CDF**: $M_W = 80433.5 \pm 6.4$ (stat.) ± 6.9 (syst.) MeV
  - **ATLAS**: $M_W = 80360 \pm 5$ (stat.) ± 15 (syst.) MeV
- Main observables (final-state neutrino not detected):
  - charged-lepton transverse momentum $p_{T,l}$
  - leptons transverse mass m_T



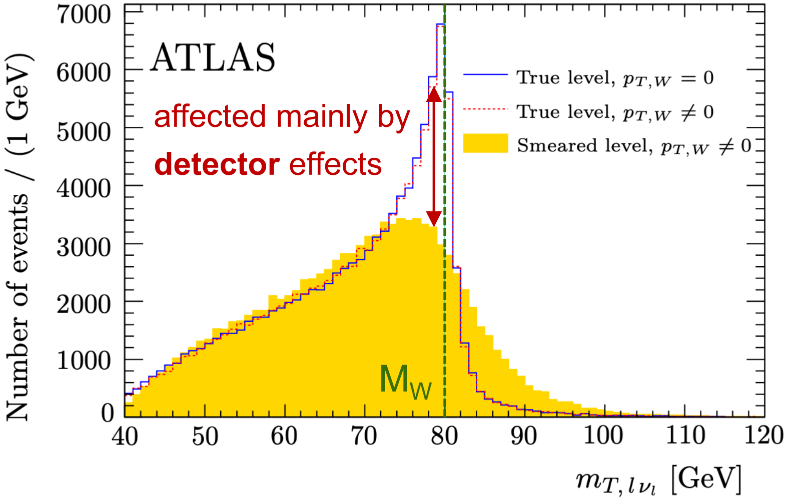
(a) - Charged lepton transverse momentum



affected mainly by **QCD** effects (perturbative and non-perturbative)

→ theory uncertainties dominant!

(b) - Leptons transverse mass



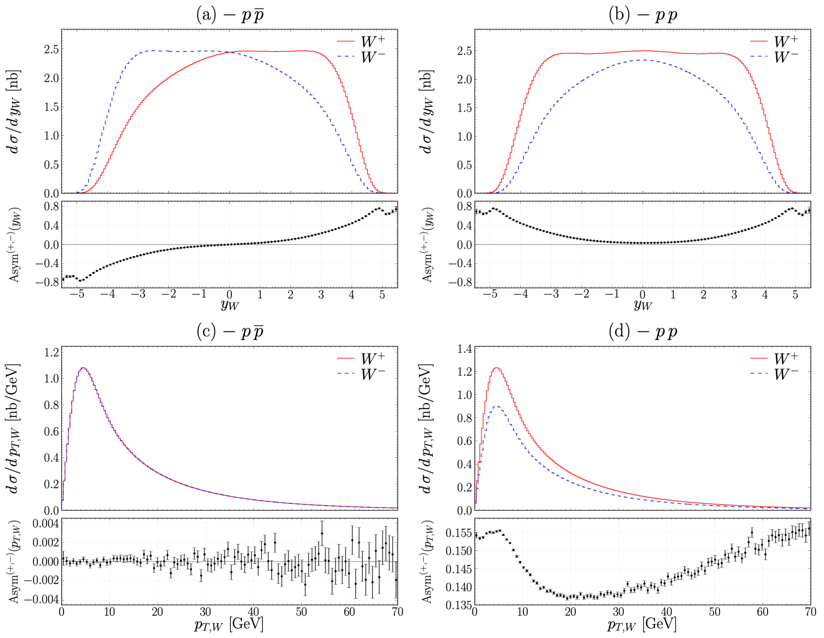
affected mainly by **detector** effects

→ experimental uncertainties dominant!

Differences between Tevatron and LHC

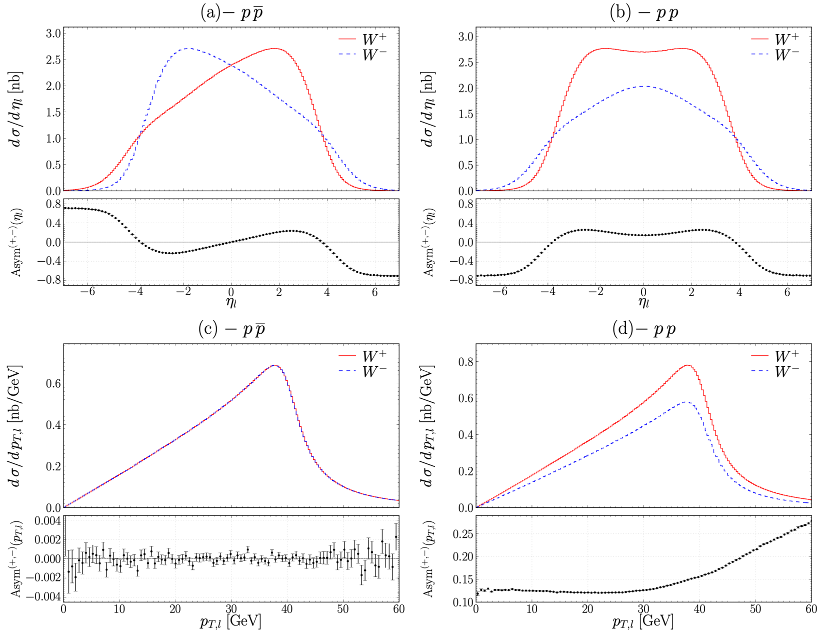
W boson

Tevatron **LHC**



charged lepton

Tevatron **LHC**



	W^+					W^-				
Subprocesses	$u\bar{d}$	$u\bar{s}$	$c\bar{d}$	$c\bar{s}$	$c\bar{b}$	$d\bar{u}$	$s\bar{u}$	$d\bar{c}$	$s\bar{c}$	$b\bar{c}$
Tevatron II	90	2	1	7	0	90	2	1	7	0
LHC	74	4	1	21	0	67	2	3	28	0

	Z				
Subprocesses	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$
Tevatron II	57	35	5	2	1
LHC	36	34	15	9	6

Flavour decomposition W and Z bosons in pp and pp̄ collisions [%]

❑ **Tevatron** → distributions:

- $y_{W+} + y_{W-} \sim y_Z$ (V ↔ A couplings)
- $p_{T,W+} + p_{T,W-} \sim p_{T,Z}$ (quark flavours)

➢ Most of QCD/PDF uncertainties **cancel** in **ratios** of ($W^+ + W^-$) to Z distributions!

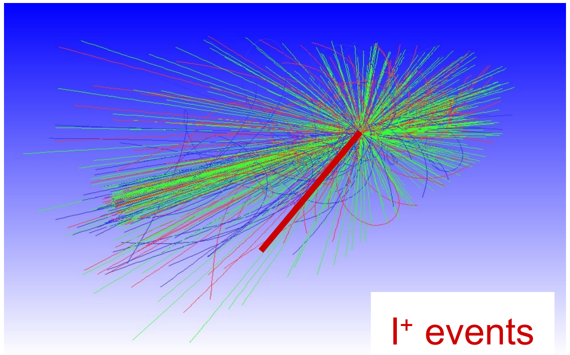
❑ **LHC – the above not true!**

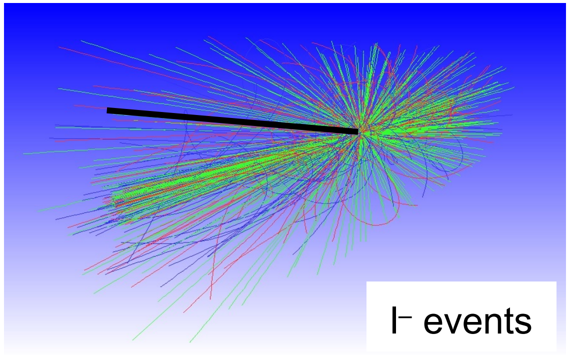
➢ **High precision theory** predictions needed, particularly for $\boldsymbol{p_{T,W}}$!

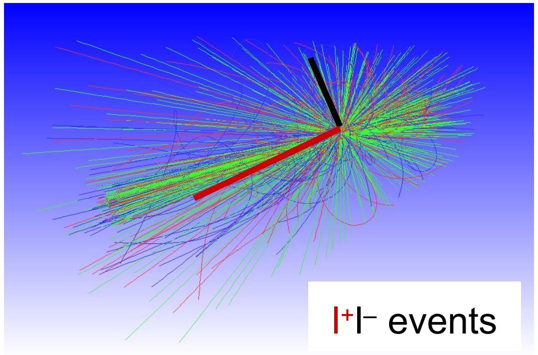
Possible ways to reduce **systematic** uncertainties at **LHC**

- **Observables** for **simultaneous** unfolding of **partonic emittances** and **Standard Model parameters** (W^+, W^- and Z boson production):

M.W. Krasny, S. Jadach, WP, *Eur. Phys. J. C 44 (2005) 333.*
M.W. Krasny, F. Fayette, WP, A. Siódmok, *Eur. Phys. J. C 51 (2007) 607.*
F. Fayette, M.W. Krasny, WP, A. Siódmok, *Eur. Phys. J. C 63 (2009) 33.*
M.W. Krasny, F. Dydak, F. Fayette, WP, A. Siódmok, *Eur. Phys. J. C 69 (2010) 379.*







- $O_{W^+}(p_{T,l},\eta_l) = \frac{d^2\sigma}{dp_{T,l^+}d\eta_{l^+}}(\text{“}l^+\text{ events”})$,
- $O_{W^-}(p_{T,l},\eta_l) = \frac{d^2\sigma}{dp_{T,l^-}d\eta_{l^-}}(\text{“}l^-\text{ events”})$,

functions of $u, d, s, c, \bar{u}, \bar{d}, \bar{s}, \bar{c}, M_W, \Gamma_W$

- $O_{Z/\gamma}(M_{ll},p_{T,ll},y_{ll}) = \frac{d^3\sigma}{dM_{ll}dp_{T,ll}dy_{ll}}(\text{“}l^+l^-\text{ events”})$,
- $O_{(Z/\gamma)^+}(M_{ll},p_{T,ll},y_{ll},p_{T,l},\eta_l) = \frac{d^5\sigma}{dM_{ll}dp_{T,ll}dy_{ll}dp_{T,l^+}d\eta_{l^+}}(\text{“}l^+l^-\text{ events”})$,
- $O_{(Z/\gamma)^-}(M_{ll},p_{T,ll},y_{ll},p_{T,l},\eta_l) = \frac{d^5\sigma}{dM_{ll}dp_{T,ll}dy_{ll}dp_{T,l^-}d\eta_{l^-}}(\text{“}l^+l^-\text{ events”})$.

functions of $u, d, s, c, b, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}, M_Z, \Gamma_Z, \sin^2\theta_W, \alpha$

- Partonic distributions: $q(x, M_{W,Z}, k_T)$

☐ MC simulations with **WINHAC**, WP and S. Jadach *EPJC 29 (2003) 305.*

Precision observables

“almost” **insensitive** to **strong-interaction** effects

1. $$\mathrm{Asym}_W^{(+,-)}(p_{T,l},\eta_l) = \frac{O_{W^+}(p_{T,l},\eta_l) - O_{W^-}(p_{T,l},\eta_l)}{O_{W^+}(p_{T,l},\eta_l) + O_{W^-}(p_{T,l},\eta_l)},$$

→ sensitive to $M_{W+} - M_{W-}$ and $\Gamma_{W+} - \Gamma_{W-}$

2. $$\mathrm{Asym}_Z^{(+,-)}(y_{ll},p_{T,ll},p_{T,l},\eta_l) = \frac{O_{Z^+}(y_{ll},p_{T,ll},p_{T,l},\eta_l) - O_{Z^-}(y_{ll},p_{T,ll},p_{T,l},\eta_l)}{O_{Z^+}(y_{ll},p_{T,ll},p_{T,l},\eta_l) + O_{Z^-}(y_{ll},p_{T,ll},p_{T,l},\eta_l)},$$

→ sensitive to $\sin^2\theta_W$

3. $$\boxed{\mathrm{R}_{WZ}(p_{T,l},\eta_l) = \frac{O_{W^+}(p_{T,l},\eta_l) + O_{W^-}(p_{T,l},\eta_l)}{O_{Z^+}(p_{T,l},\eta_l) + O_{Z^-}(p_{T,l},\eta_l)},}$$

→ sensitive to α_s, $M_{W+} + M_{W-}$, and $\Gamma_{W+} + \Gamma_{W-}$

4. $$\mathrm{R}_Z^{norm}(p_{T,ll},y_{ll}) = \frac{O_Z(p_{T,ll},y_{ll})}{O_{l^+l^-}^{norm}},$$

$$O_Z(p_{T,ll},y_{ll}) = \int_{M_Z-3\Gamma_Z}^{M_Z+3\Gamma_Z} O_{(Z/\gamma)}(M_{ll},p_{T,ll},y_{ll})\,dM_{ll},$$

$$O_{Z^{+(-)}}(y_{ll},p_{T,ll},p_{T,l},\eta_l) \;=\; \int_{M_Z-3\Gamma_Z}^{M_Z+3\Gamma_Z} \left[O_{(Z/\gamma)^{+(-)}}(M_{ll},y_{ll},p_{T,ll},p_{T,l},\eta_l)\right] dM_{ll}\,,$$

} only Z-peak region

$$O_{l^+l^-}^{norm} = \int\int\int O_{Z/\gamma}(M_{ll},y_{ll},p_{T,ll})\,dM_{ll}\,dy_{ll}\,dp_{T,ll}.$$

→ coplanar pairs – dedicated method of absolute normalization,
M.W. Krasny et al., NIMA 584 (2008) 42

- Measurements of **SM parameters** are based on **observables** with **reduced** sensitivity to **experimental** systematic errors (e.g. calibration of lepton momenta) and to **theoretical** uncertainties of **perturbative** and **non-perturbative QCD**.

Unconstrained PDF degrees of freedom for pp collisions at LHC

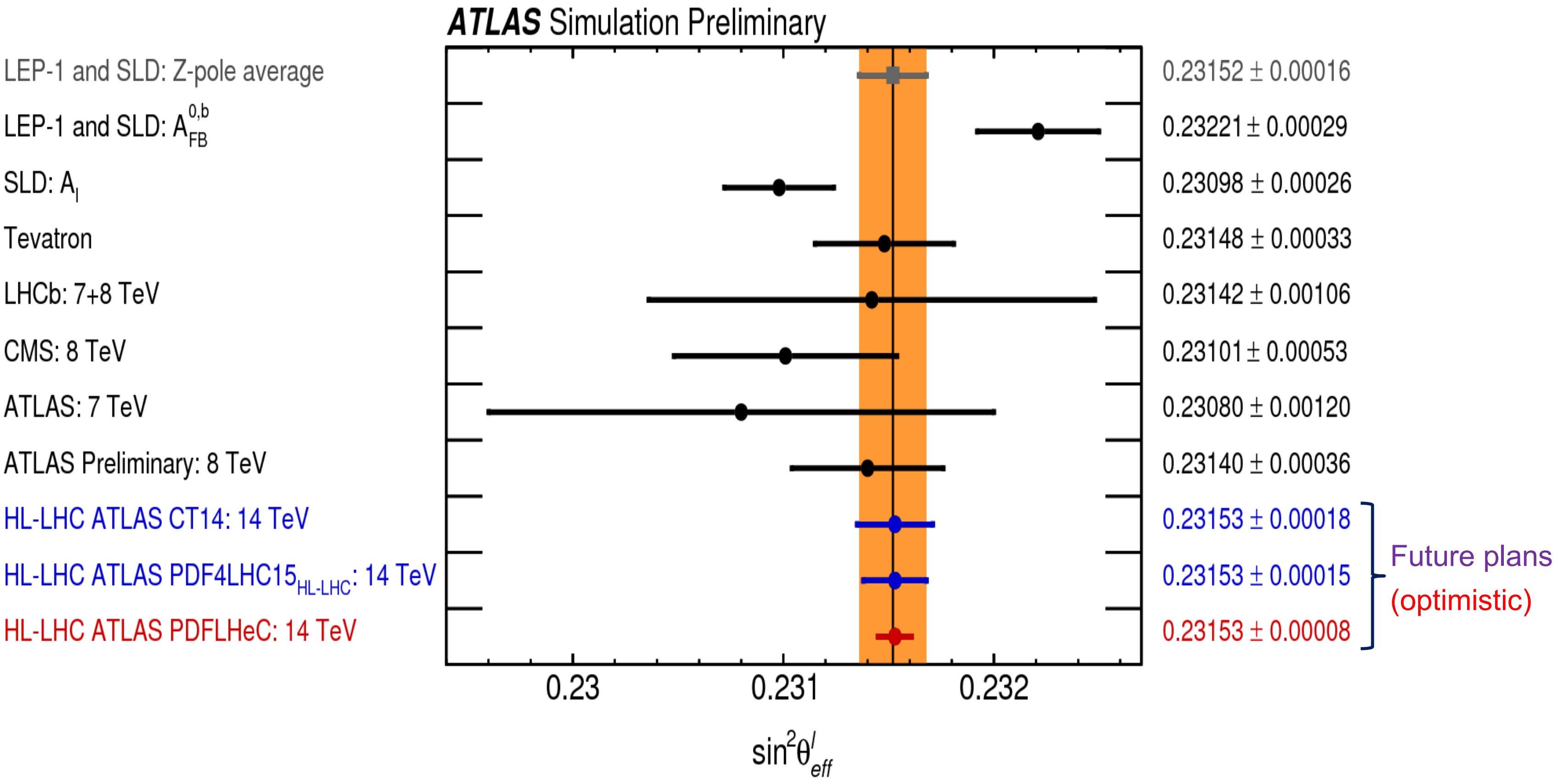
- Assuming $s(x) = \bar{s}(x)$, $c(x) = \bar{c}(x)$, $b(x) = \bar{b}(x)$:
  - ☐ **5** sea-quark flavours (u,d,s,c,b) + **2** valence-quark flavours (u_v,d_v) = **7 unknown** PDFs
  - ✓ **4 constraints** coming from measurement of precision observables
  - ➢ **7 – 4 = 3** degrees of freedom in flavour-dependent PDFs remain **unconstrained** at **LHC:** $u_v(x) - d_v(x)$, $c(x) - s(x)$, $b(x)$.

- ➢ **Precision** of **δM_W < 12 MeV cannot** be achieved at LHC in **pp** runs (even in **HL-LHC** phase)
  - ✓ **Missing external input**: Tevatron data + dedicated muon-nucleon DIS experiment, e.g. at COMPASS (CERN)

- ➢ **Similar** conclusions for **$\sin^2\theta_W$** and Γ_W
  - ☐ Note: in order to match **δM_W ~ 5 MeV**, one needs **$\delta(\sin^2\theta_W)$ ~ 10^{-4}**

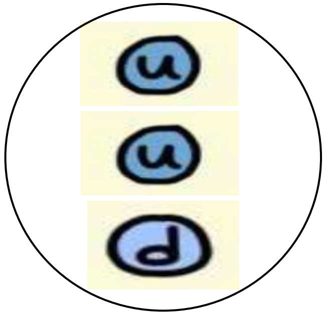
    (indirect determination of **M_W** → **consistency** test of **SM**).

Measurement of $\sin^2\theta_W$



- **Most precise** measurement from **electron-positron** colliders LEP/SLD: $\delta(\sin^2\theta_W) = 1.6 \times 10^{-4}$
- Precision at **hadron** colliders by factor **more** than **2 worse** (the best from Tevatron).
- Main **limiting** factor at **LHC**: **PDF uncertainty** of $u_v - d_v$.

Isoscalar ion beams



Proton

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

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

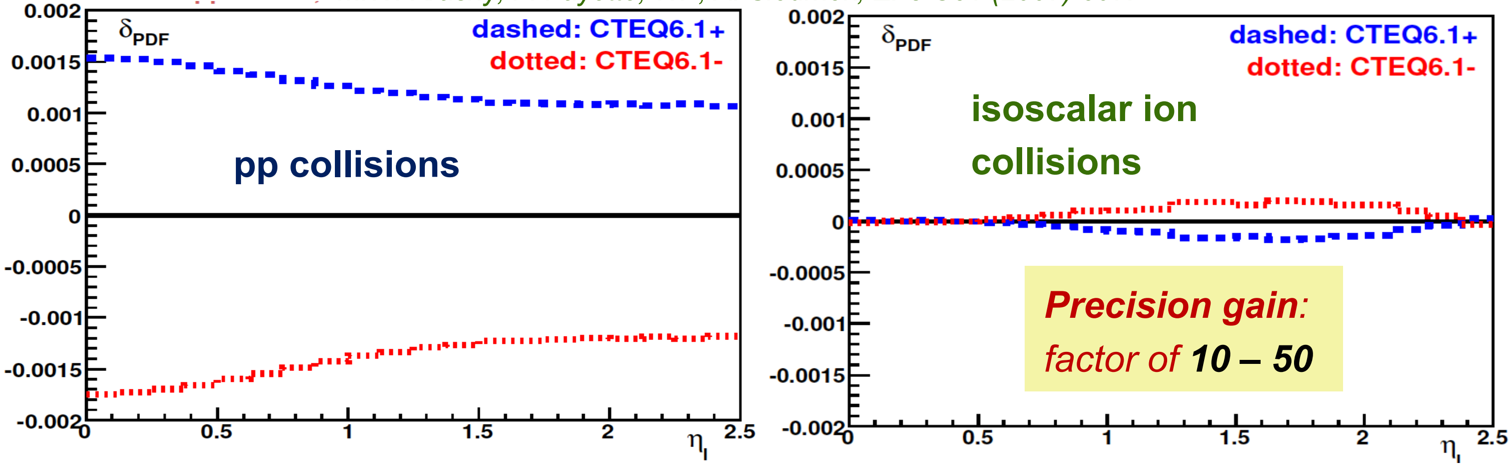
❑ **Isoscalar ion beams** (# of protons = # of neutrons: A = 2Z) profit from **flavour symmetry** of strong interactions to **equalize** distributions of **u** and **d** quarks:

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

Significantly **higher precision** in measuring **EW processes** by using **isoscalar-ion** rather than proton beams at LHC

- **Uncertainty** reflecting the limited knowledge of the **partonic** composition of **protons** and **isoscalar ions** in measurement of $\mathbf{R_{WZ}(p_{T,l},\eta_l)}$ observable (**precision-optimised** method).

M.W. Krasny, F. Fayette, WP, A. Siodmok, EPJ C51 (2007) 607.



Isoscalar beams provide a unique way for improving the present precision of SM parameters, such as M_W, $\sin^2\theta_W$, … at the LHC!

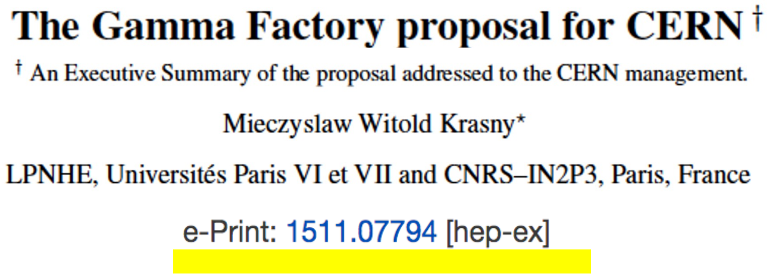
- **High-statistics** (> 100 fb^{-1}) data from isoscalar-beam collisions needed!

How to get such a luminosity at LHC?

- ☐ M.W. Krasny, A. Petrenko and WP, *Prog. Part. Nucl. Phys.* 114 (2020) 103792.
- **For nucleon-nucleon luminosity of 1000 fb^{-1}: $\delta M_W <$ 5 MeV, $\delta(\sin^2\theta_W) < 10^{-4}$**

GAMMA FACTORY

Gamma Factory studies



The Gamma Factory proposal for CERN †

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

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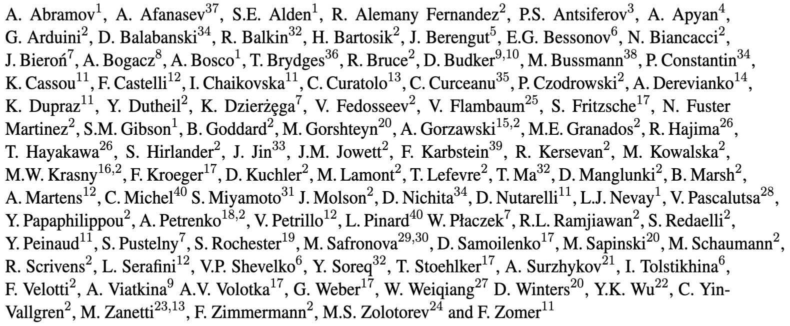
LPNHE, Universités Paris VI et VII and CNRS–IN2P3, Paris, France

e-Print: 1511.07794 [hep-ex]

~100 physicists from ~40 institutions have contributed so far to the Gamma Factory studies



A. Abramov[1], A. Afanasev[37], S.E. Alden[1], R. Alemany Fernandez[2], P.S. Antsiferov[3], A. Apyan[4], G. Arduini[2], D. Balabanski[34], R. Balkin[32], H. Bartosik[2], J. Berengut[5], E.G. Bessonov[6], N. Biancacci[2], J. Bieroń[7], A. Bogacz[8], A. Bosco[1], T. Brydges[36], R. Bruce[2], D. Budker[9,10], M. Bussmann[38], P. Constantin[34], K. Cassou[11], F. Castelli[12], I. Chaikovska[11], C. Curatolo[13], C. Curceanu[35], P. Czodrowski[2], A. Derevianko[14], K. Dupraz[11], Y. Dutheil[2], K. Dzierżęga[7], V. Fedosseev[2], V. Flambaum[25], S. Fritzsche[17], N. Fuster Martinez[2], S.M. Gibson[1], B. Goddard[2], M. Gorshteyn[20], A. Gorzawski[15,2], M.E. Granados[2], R. Hajima[26], T. Hayakawa[26], S. Hirlander[2], J. Jin[33], J.M. Jowett[2], F. Karbstein[39], R. Kersevan[2], M. Kowalska[2], M.W. Krasny[16,2], F. Kroeger[17], D. Kuchler[2], M. Lamont[2], T. Lefevre[2], T. Ma[32], D. Manglunki[2], B. Marsh[2], A. Martens[12], C. Michel[40] S. Miyamoto[31] J. Molson[2], D. Nichita[34], D. Nutarelli[11], L.J. Nevay[1], V. Pascalutsa[28], Y. Papaphilippou[2], A. Petrenko[18,2], V. Petrillo[12], L. Pinard[40] W. Płaczek[7], R.L. Ramjiawan[2], S. Redaelli[2], Y. Peinaud[11], S. Pustelny[7], S. Rochester[19], M. Safronova[29,30], D. Samoilenko[17], M. Sapinski[20], M. Schaumann[2], R. Scrivens[2], L. Serafini[12], V.P. Shevelko[6], Y. Soreq[32], T. Stoehlker[17], A. Surzhykov[21], I. Tolstikhina[6], F. Velotti[2], A. Viatkina[9] A.V. Volotka[17], G. Weber[17], W. Weiqiang[27] D. Winters[20], Y.K. Wu[22], C. Yin-Vallgren[2], M. Zanetti[23,13], F. Zimmermann[2], M.S. Zolotorev[24] and F. Zomer[11]

Volume 534, Issue 3

Special Issue: Physics Opportunities with the Gamma Factory

March 2022

Issue Edited by: **Dmitry Budker, Mikhail Gorchtein, Mieczyslaw Witold Krasny, Adriana Pálffy, Andrey Surzhykov**

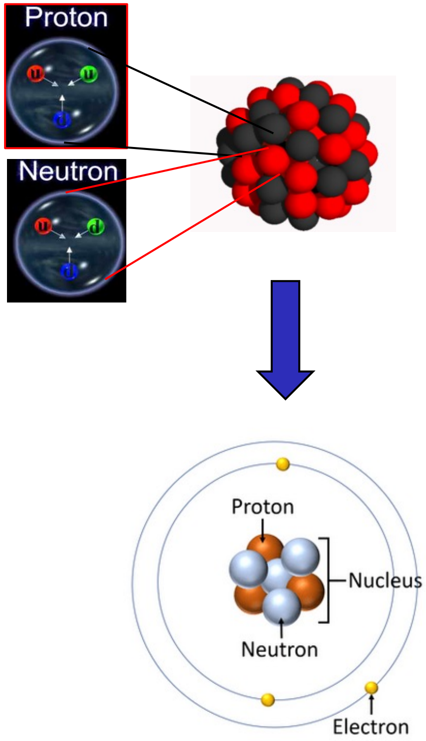
Gamma Factory studies are **anchored and supported** by the CERN **Physics Beyond Colliders (PBC)** framework.

More info on all the GF group activities:
https://indico.cern.ch/category/10874

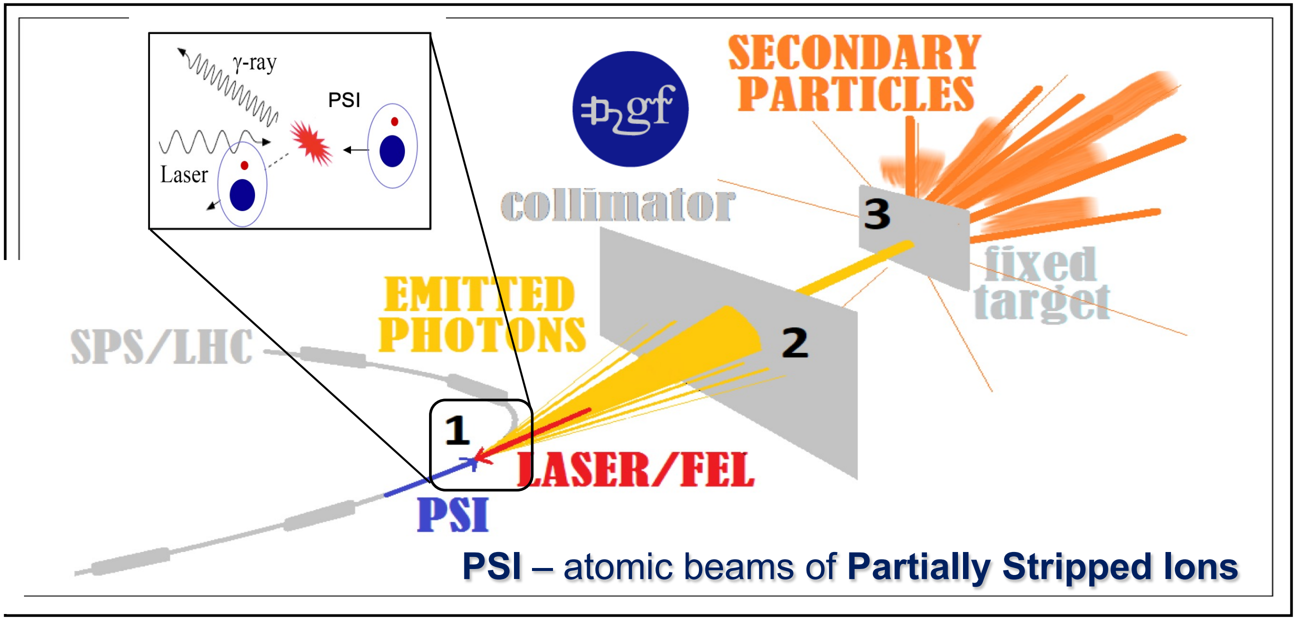
*We acknowledge the crucial role of the CERN **PBC** framework in bringing our accelerator tests, GF-PoP experiment design, software development and physics studies to their present stage!*

Gamma Factory beams

LHC beams



- Include **atomic beams of partially stripped ions** in the LHC menu.
- Collide them with laser pulses (circulating in Fabry-Pérot resonators) to **produce beams of polarised photons** and secondary beams of polarised electrons/positrons/muons, neutrons and radioactive ions.



PSI – atomic beams of **Partially Stripped Ions**

Extraordinary properties GF photon source

1. Point-like, small divergence:

- $\Delta z \sim l_{PSI\text{-}bunch} < 7$ cm; Δx, $\Delta y \sim \sigma^{PSI}_{x}$, $\sigma^{PSI}_{y} < 50\ \mu$m; $\Delta(\theta_x)$, $\Delta(\theta_y) \sim 1/\gamma_L < 1$ mrad

2. Huge jump in intensity:

- ***More than 7 orders of magnitude*** *w.r.t. existing (being constructed) γ-sources: up to* ***10^{18} γ/s***

3. Very wide range of tuneable energy photon beam:

- ***10 keV – 400 MeV –*** *extending by a factor of* ***~1000*** *the energy range of FEL photon sources*

4. Tuneable polarisation:

- ***Polarisation transmission*** *from laser photons to γ-beams of* ***up to 99%***

5. Unprecedented plug power efficiency (energy footprint):

- ***LHC RF power can be converted to the photon beam power.*** *Wall-plug power efficiency of the* ***GF photon source is*** *by a factor of* ***~300 better*** *than that of* ***DESY-XFEL***
  (assuming power consumption: 200 MW at CERN and 19 MW at DESY)

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 (for muon collider) and the LHeC requirements;
→ A. Apyan, M.W. Krasny and WP, *Phys. Rev. Accel. Beams* ***26****, 083401 (2023).*

- **Pions** – potential, gain by a factor of 10^3, gain in the spectral density ($d^2N/dpdp_T$) with respect to proton-beam-driven sources at KEK and FNAL → *PRAB* ***26****, 083401 (2023).*

- **Muons** – potential gain by a factor of 10^3 in intensity w.r.t. the PSI (Villigen, Switzerland) muon source, charge symmetry ($N\mu^+ \sim N\mu^-$), polarisation control → *PRAB* ***26****, 083401 (2023).*

- **Neutrinos** – fluxes comparable to the proposed NuMAX (FNAL) 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.

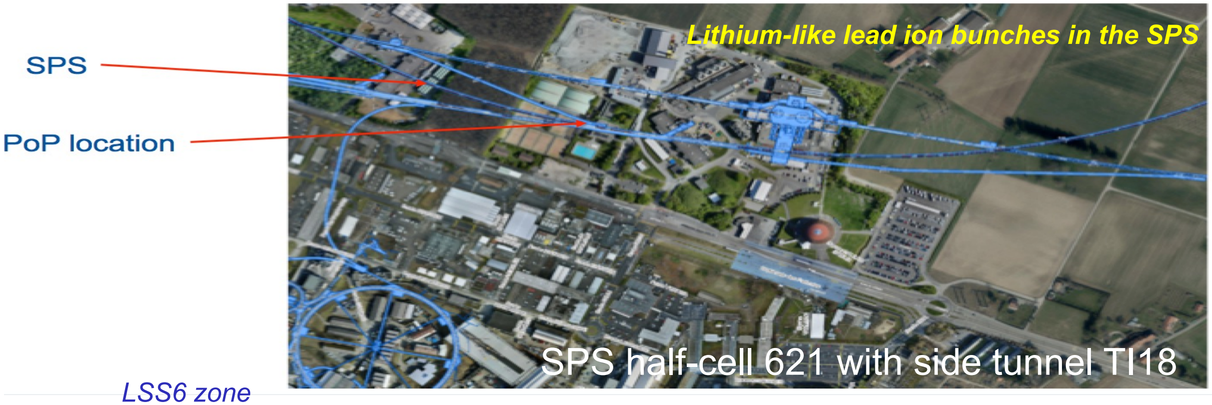
- **Neutrons** – potential gain of up to a factor of 10^4 in intensity of primary MeV-energy neutrons per 1 MW of the driver beam power.

- **Radioactive ions** – potential gain of up to a factor of 10^4 in intensity w.r.t. e.g. ALTO (Orsay).

Examples of potential applications domains of **Gamma Factory** research tools

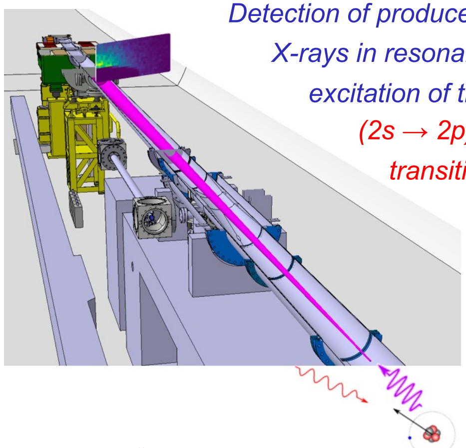
- **Particle physics:** **precision** QED and **EW studies**, vacuum birefringence, **Higgs physics in $\gamma\gamma$ collision mode with laser-cooled ion beams**, rare muon decays, precision neutrino physics, QCD-confinement studies, …
- **Nuclear physics:** nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear photo-physics, photo-fission research, gamma polarimetry, physics of rare radioactive nuclides,…
- **Atomic physics:** highly charged atoms, electronic, muonic, pionic and kaonic atoms, …
- **Astrophysics:** dark matter searches, gravitational waves detection, gravitational effects of cold particle beams, $^{16}O(\gamma,\alpha)^{12}C$ reaction and S-factors …
- **Fundamental physics:** studies of the basic symmetries of the universe, atomic interferometry, …
- **Accelerator physics:** beam cooling techniques, low-emittance hadronic beams, plasma wake field acceleration, high-intensity polarised positron and muon sources, beams of radioactive ions and neutrons, very narrow band and flavour-tagged neutrino beams, neutron sources, …
- **Applied physics:** accelerator driven energy sources, nuclear fusion research, medical isotope and isomer production, …

Gamma Factory Proof-of-Principle (PoP) experiment at SPS



Lithium-like lead ion bunches in the SPS

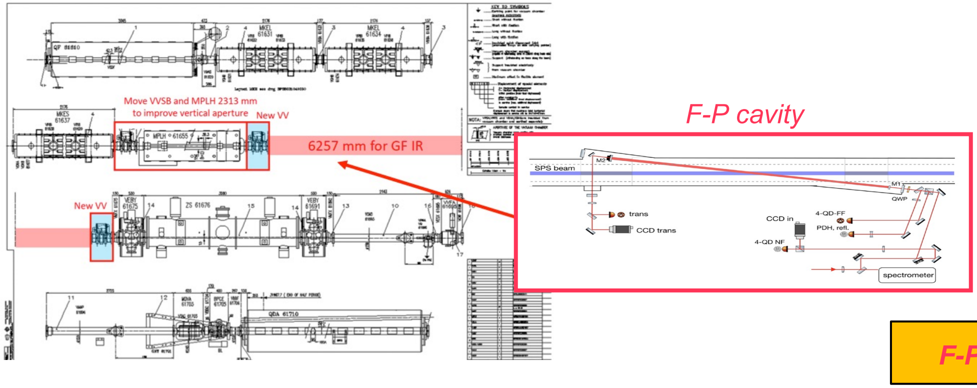
SPS half-cell 621 with side tunnel TI18



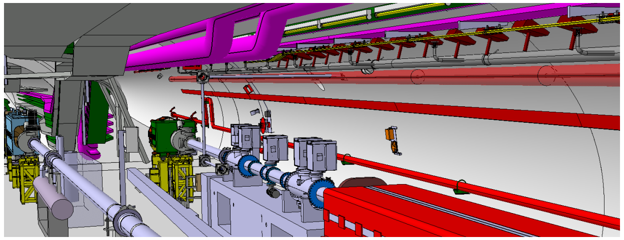
Detection of produced X-rays in resonant excitation of the $(2s \rightarrow 2p)_{1/2}$ transition

LSS6 zone

F-P cavity



F-P cavity – “in beam” position



F-P cavity length: 3.75 m *– vertically tilted by 2.6 deg*

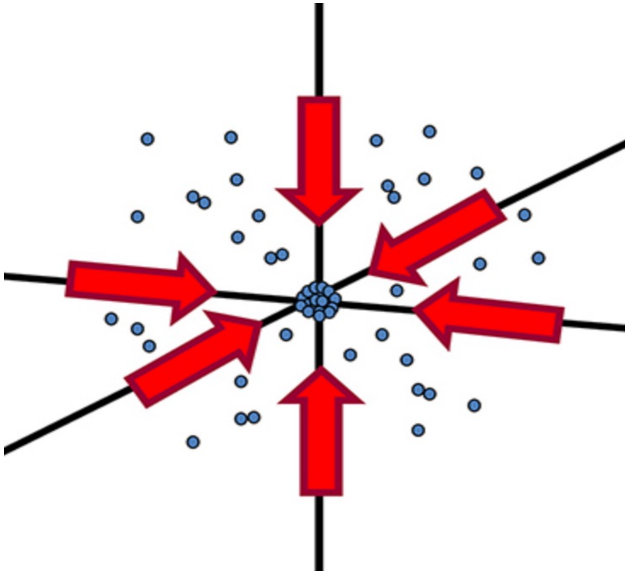
Purpose of GF SPS PoP experiment

1. Demonstrate that an adequate laser system (5 mJ @ 40 MHz) can be (remotely) operated in the high-radiation field of the SPS.
2. Demonstrate that very high rates of photons are produced: almost all ions are excited in a single collision of a PSI bunch with a laser pulse.
3. Demonstrate stable and repeatable operation.
4. Confront data and simulations.
5. Demonstrate **laser ion-beam cooling**: longitudinal and transverse.
6. New atomic physics measurements.

- *Target installation time:* ***LS3*** *(2026–2027).*
- *Estimated cost: 2.5 MCHF*

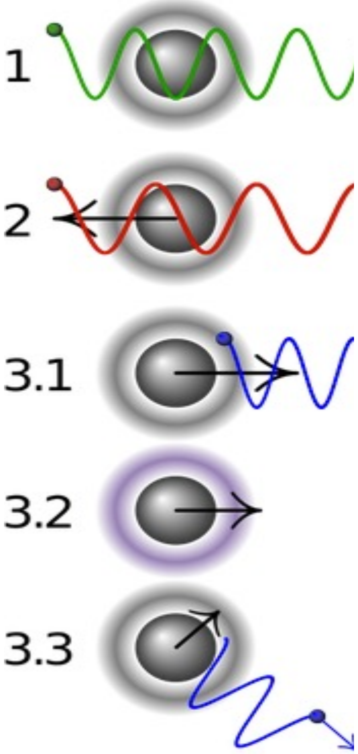
LASER COOLING OF HIGH-ENERGY ION BEAMS

Doppler laser-cooling of stationary atoms



Six “red-detuned” laser beams

(optical molasses)



A stationary atom sees the laser neither red- nor blue-shifted and does not absorb the photon.

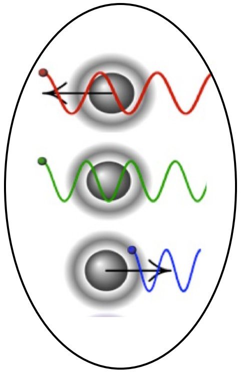
An atom moving away from the laser sees it red-shifted and does not absorb the photon.

An atom moving towards the laser sees it blue-shifted and absorbs the photon, slowing the atom.

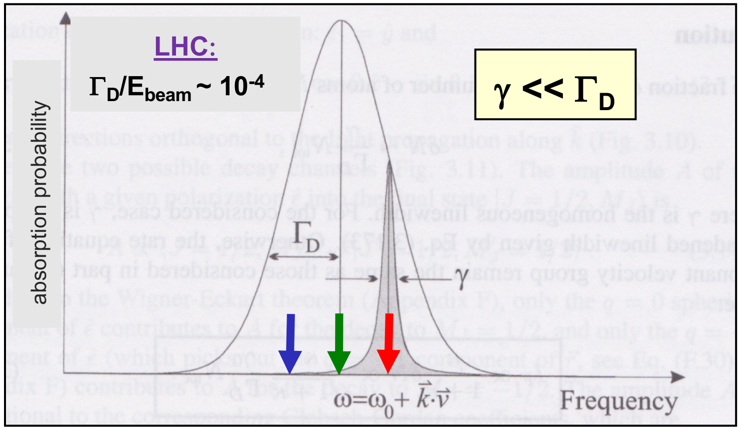
The photon excites the atom, moving an electron to a highe quantum state.

The atom re-emits a photon. As its direction is random, there is no net change in momentum over many absorption-emission cycles.

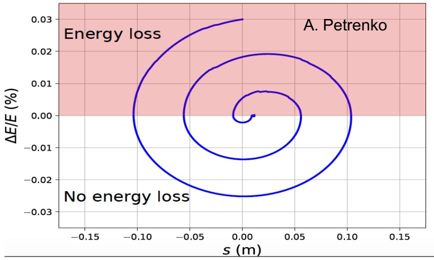
Doppler laser-cooling methods of high-energy beams

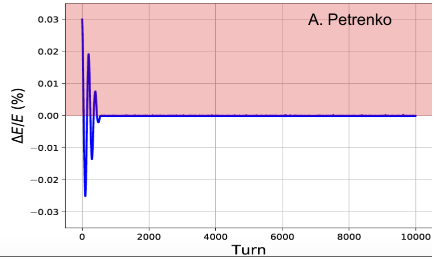


Bunch



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

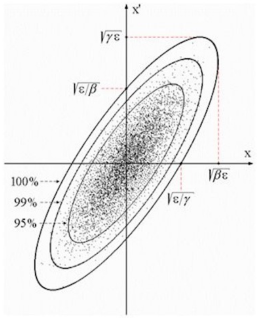




Beam cooling speed: the laser **wavelength** band is chosen such that only the **ions** moving in the **laser-pulse direction** (in the bunch rest frame) can resonantly **absorb** photons.

Beam emittance: is the volume in the phase space occupied by the particle beam. The space is 6-dimensional (x,x',y,y',W,ϕ) but are important the projections in the 3 dimensions: transverse emittance in x and y (ε_x, ε_y) and longitudinal emittance (ΔW, ϕ).

Liouville theorem: under the action of linear forces, the beam emittance is constant. (BUT: in presence of non-linear forces, it increases). Consequence: in an accelerator, where non-linear forces are often present, the emittance will progressively increase.



Gamma Factory path to high-luminosity LHC

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

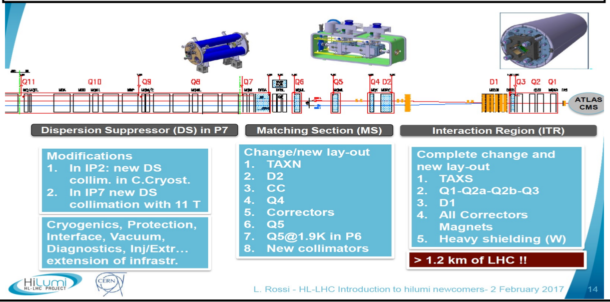
Two complementary ways to **increase** collider **luminosity**:

1. **Increase** the **focusing** strength: β* ↘
2. **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



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

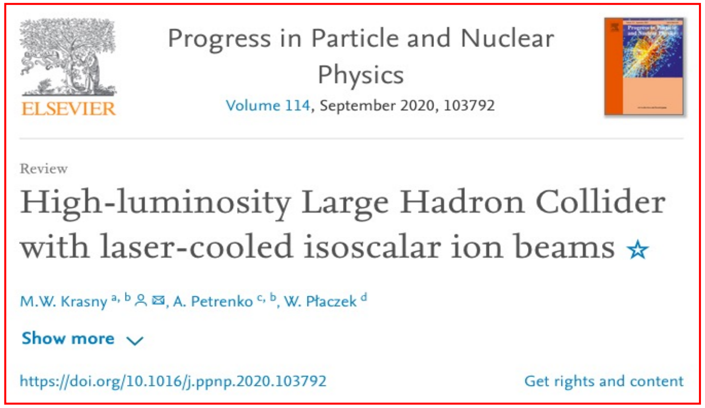
Interaction Region (ITR)

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 !!

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

Levelled luminosity: **2.5 (5) × 10^{34} cm^{-2}s^{-1}**, **cost ~ 1 billion euro**



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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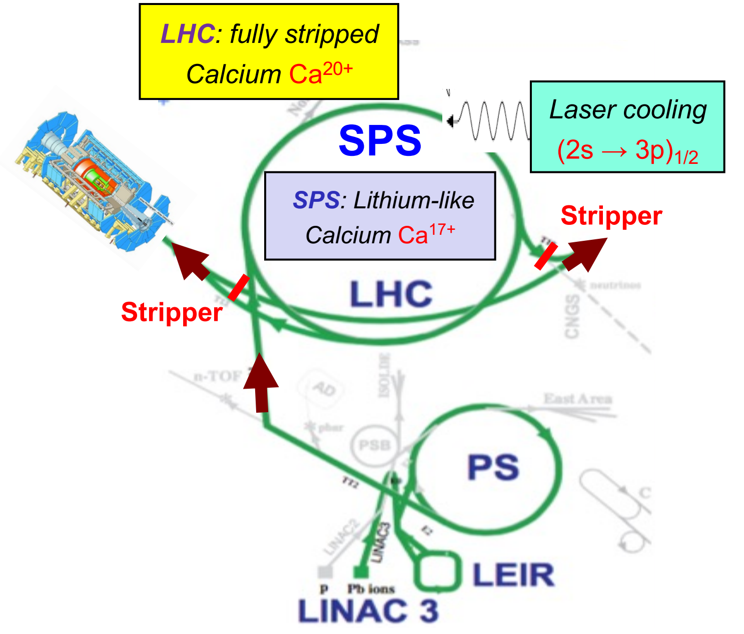
GF scheme of reducing transverse beam emittance

1. **Produce highly-charged-ion** bunches (partially stripped ions) with existing CERN ion source.
2. **Leave a few electrons** attached to their parent nuclei for **SPS** acceleration phase (in the canonical SPS heavy-ion operation all electrons are already stripped off).
3. **Cool atomic beams** with specialised **laser system** at the top SPS energy to reduce its emittance (longitudinal and transverse cooling).
4. **Strip electrons** in **SPS-to-LHC** transfer line.
5. **Accelerate** and **collide fully stripped ion** beams in **LHC**.

Gamma Factory path to HL(AA)-LHC:

A concrete implementation scheme with Ca beams

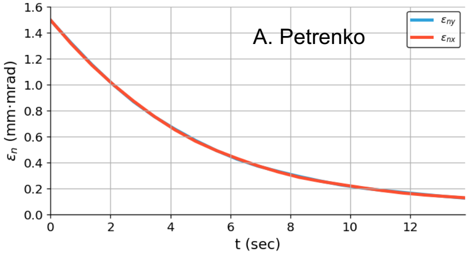


***LHC**: fully stripped Calcium Ca^{20+}*

Laser cooling (2s → 3p)$_{1/2}$

***SPS**: Lithium-like Calcium Ca^{17+}*

Ion Source + LINAC 3: charge state after stripping: Ca^{17+}



Reduction of **transverse** (x, y) **emittances** by a factor of **5** can be achieved in **8 seconds** – sufficiently short to avoid **Ca^{17+}** beam losses in SPS.

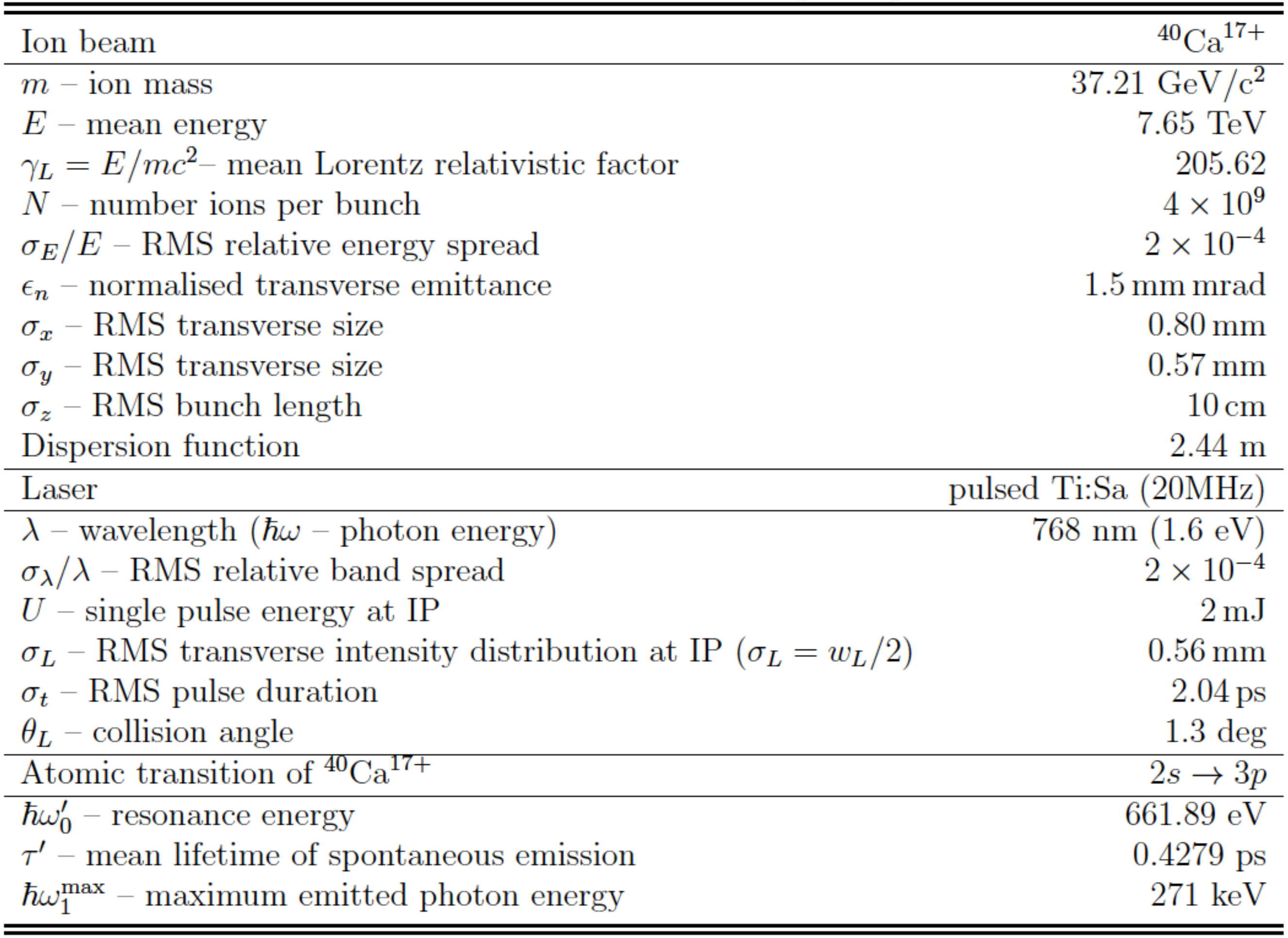
Optical stochastic cooling time for Ca beam, if necessary, at the top energy ~ 1.5 hours (V. Lebedev).

Parameter	Value
$s^{1/2}$ [TeV]	7
$\sigma_{BFPP}(Ca)/\sigma_{BFPP}(Pb)$	5 x 10^{-5}
$\sigma_{had}(Ca)/\sigma_{tot}(Ca)$	0.6
N_b	3 x 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 x 10^{34}**
No of bunches	1404
Collisions/beam crossing	**5.5**

~700 for **pp** for the same luminosity L_{NN}

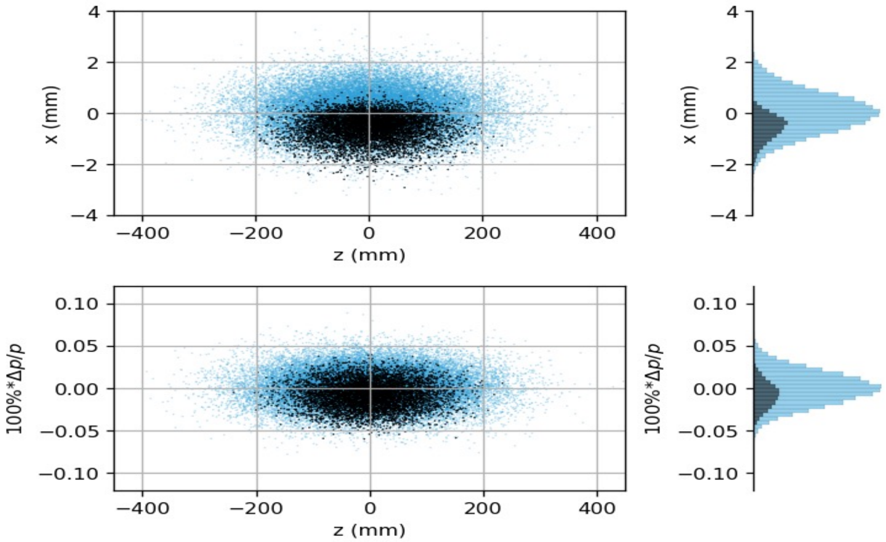
Simulation of laser cooling of lithium-like Ca^{17+} bunches in SPS – input parameters

Table 1: Parameters of the calcium-beam cooling configuration in the SPS.

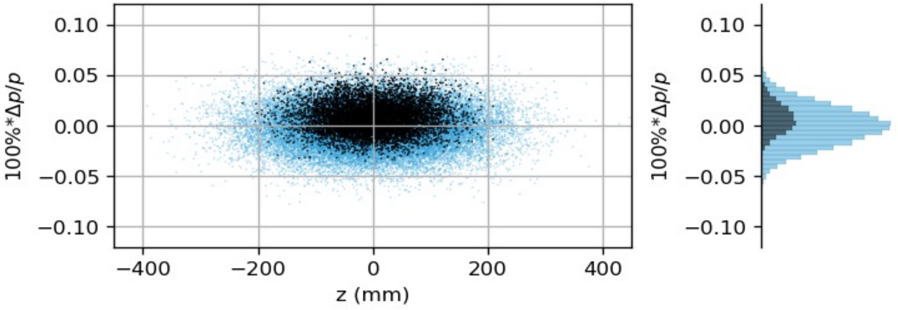


Ion beam	$^{40}Ca^{17+}$
m – ion mass	37.21 GeV/c^2
E – mean energy	7.65 TeV
$\gamma_L = E/mc^2$– mean Lorentz relativistic factor	205.62
N – number ions per bunch	4×10^9
σ_E/E – RMS relative energy spread	2×10^{-4}
ϵ_n – normalised transverse emittance	1.5 mm mrad
σ_x – RMS transverse size	0.80 mm
σ_y – RMS transverse size	0.57 mm
σ_z – RMS bunch length	10 cm
Dispersion function	2.44 m
Laser	pulsed Ti:Sa (20MHz)
λ – wavelength ($\hbar\omega$ – photon energy)	768 nm (1.6 eV)
σ_λ/λ – RMS relative band spread	2×10^{-4}
U – single pulse energy at IP	2 mJ
σ_L – RMS transverse intensity distribution at IP ($\sigma_L = w_L/2$)	0.56 mm
σ_t – RMS pulse duration	2.04 ps
θ_L – collision angle	1.3 deg
Atomic transition of $^{40}Ca^{17+}$	$2s \rightarrow 3p$
$\hbar\omega'_0$ – resonance energy	661.89 eV
τ' – mean lifetime of spontaneous emission	0.4279 ps
$\hbar\omega_1^{\max}$ – maximum emitted photon energy	271 keV

Simulation of laser cooling of lithium-like Ca^{17+} bunches in SPS: laser pulse tuning



Horizontal positions and **momenta** of ions interacting with pulse of **first laser** in momentum-dispersive region (**black dots – excited** ions, **blue dots – non-excited** ions). **Shift** of laser pulse by **1.4 mm** provides **optimal coupling** of horizontal **betatron** oscillations to **synchrotron** oscillations (**dispersive coupling**, I. Lauer *et al.*, Phys. Rev. Lett. 81 (1998) 2052). **17% of all ions are excited in each bunch crossing!**



Momentum and **longitudinal** positions of the ions interacting with the photon-pulse of the **second laser**. The laser pulse focal point is aligned with the ion beam centre, but its **frequency** band is **shifted** to excite the **higher-momentum** ions.

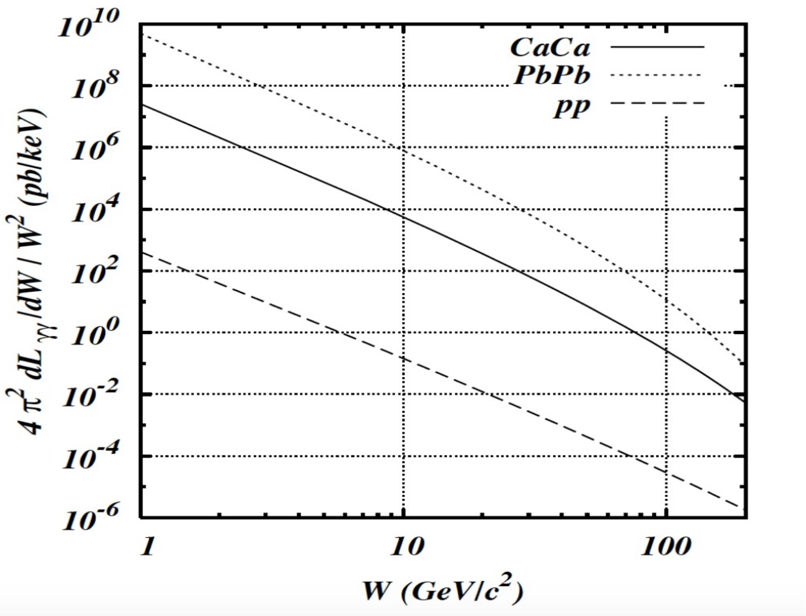
Merits of cold isoscalar beams

1. **Impact of modelling uncertainties of partonic emittances** (longitudinal and transverse) on achievable **measurement precision** can be drastically **reduced** and controlled by LHC data alone (no precision brick-walls coming from LHC-external data, PDFs, and PS models).
    - Significantly **higher systematic precision** in measuring **SM parameters** (M_W, $\sin^2\theta_W$, …) than for **proton** beams.
2. **Z^4 leap in photon fluxes** – access to **exclusive Higgs boson production in photon–photon collisions** – **unreachable** for the **pp** running mode.
3. **Lower pile-up background** at the equivalent (high) nucleon-nucleon luminosity.
4. **New research opportunities** for the EW-symmetry breaking sector.

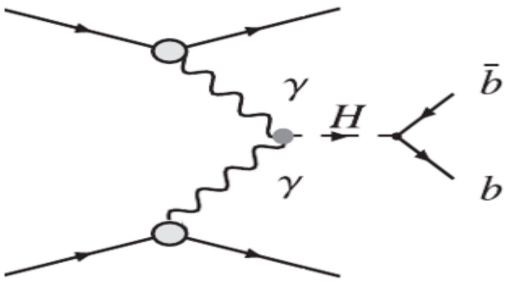
Leap in photon fluxes – access to **exclusive Higgs-boson** production in **photon–photon** collisions – beyond reach of pp running mode

Factor of $\mathbf{Z^4}$ gain in

photon-photon luminosity



[50] G. Baur, K. Hencken, D. Trautmann, S. Sadovsky and Y. Kharlov, Phys. Rept. **364** (2002) 359, doi:10.1016/S0370-1573(01)00101-6 [hep-ph/0112211].



For collected **nucleon-nucleon luminosity** of **1000 fb^{-1}**, expected **number** of exclusively produced **Higgs** bosons in **photon-photon** collisions is **~420 per experiment**

→ **unique possibility** for studies of

$$\gamma\gamma \to \mathbf{H} \to \mathbf{b\bar{b}}$$

in **clean** environment.

Higgs boson production in photon-photon interactions with proton, light-ion, and heavy-ion beams at current and future colliders

David d'Enterria (CERN), Daniel E. Martins (UFRJ, Rio de Janeiro), Patricia Rebello Teles (Rio de Janeiro State U.) (Apr 26, 2019)

Published in: *Phys.Rev.D* 101 (2020) 3, 033009 • e-Print: 1904.11936 [hep-ph]

CONCLUSIONS

Gamma Factory in general

- ☐ **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**.

- ☐ 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 ILC/CLIC, **nor** an established **"reasonable-cost" technology** for a leap into very high-energy "terra incognita".

- ☐ The **Gamma Factory research programme** can be **largely based on the existing CERN accelerator infrastructure** – it requires "relatively" minor infrastructure investments.

Gamma Factory for HL-LHC

- **HL(AA)-LHC with laser-cooled isoscalar ion beams** appears to be attractive option to **significantly enlarge research potential of LHC.**

- Achievable nucleon-nucleon **luminosities** in **HL-LHC** modes:

  L_{NN} in **pp** mode **2.5 – 5 × 10^{34} cm^{-2}s^{-1}**

  L_{NN} in **AA** mode **~ 4 × 10^{34} cm^{-2}s^{-1}**

  ➤ *Optimal **running-time sharing**: **2/3** in **pp** mode, **1/3** in **AA** mode.*

- Of particular **importance**, if **no new phenomena** are discovered over **initial** phase of **HL(pp)-LHC** operation.

- It provides also **a new way to maximise partonic luminosities** at **future** high-energy frontier **hadron colliders**, such as **FCC-hh**.

BACKUP SLIDES

Sources of uncertainties in M_W measurements

ATLAS 2023

Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

CDF 2022

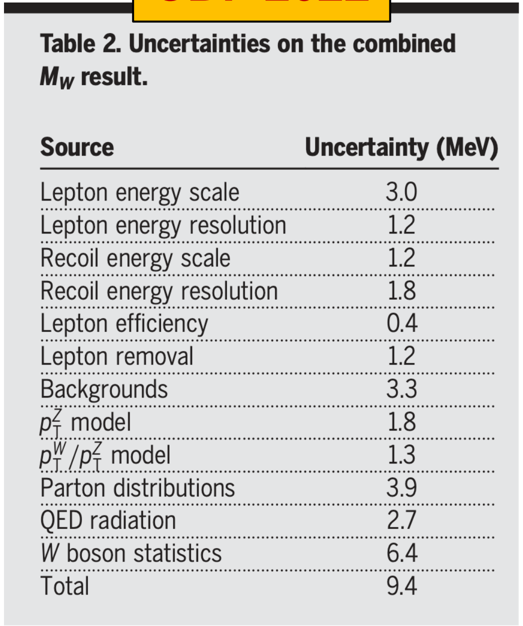


Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Collisions of **deuteron** (isoscalar) beams at **LHC**

➢ **Main uncertainties:**

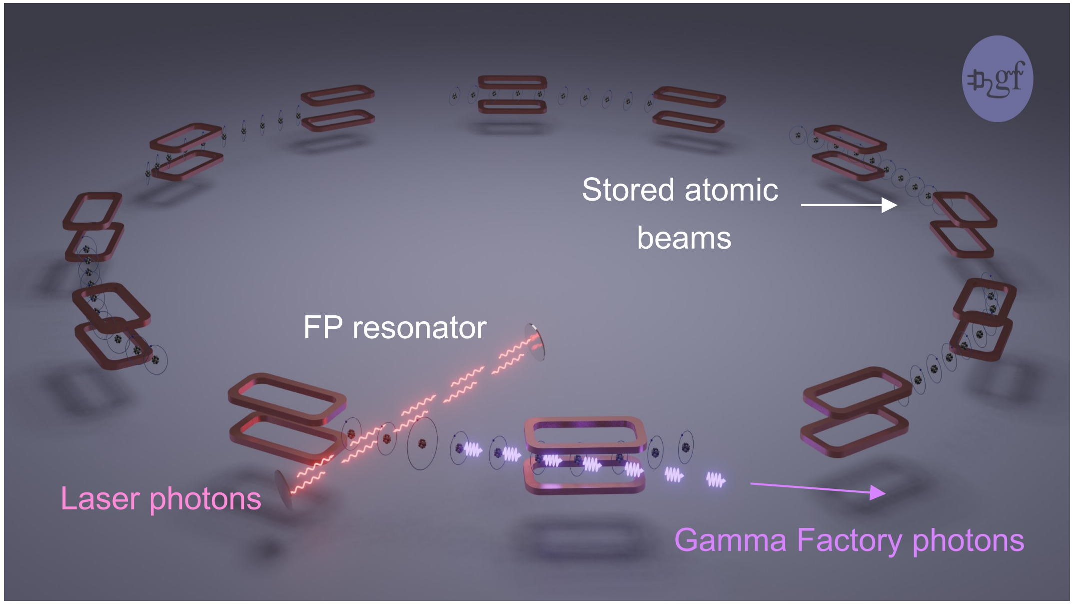
Systematic ξ	Expected precision [%]	ΔM [MeV]
"$u^{(v)} - d^{(v)}$"	0.2	< 5
"$s - c$" $\mathcal{L}_{int} = 2.5 fb^{-1}$	2	25
"$s - c$" $\mathcal{L}_{int} = 25 fb^{-1}$	0.7	8
"b" $L_{int} = 50\ fb^{-1}$	40	< 10

(L_{int} – *dd* luminosity, $L_{NN} = 4L_{int}$)

A. Siódmok, PhD thesis, 2010.

Gamma Factory photon source: intensity leap

Requirements: Accelerated bunches of ~10^8–10^9 partially stripped atoms, delivered with ~20 MHz frequency, ~5 mJ laser photon pulses stacked in 20 MHz Fabry-Perot resonator

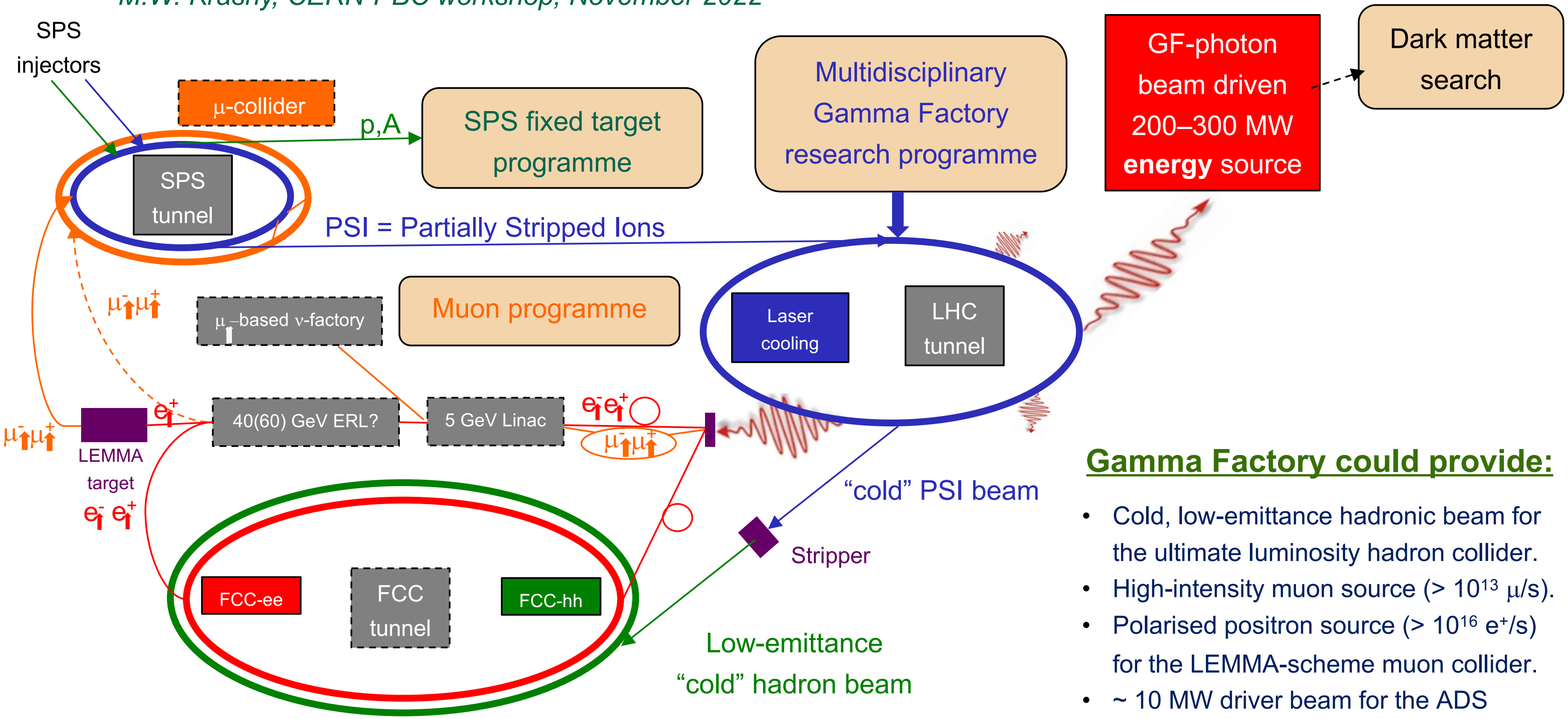


Novel technology:

Resonant scattering of laser photons on ultra-relativistic atomic beam

Potential **Gamma Factory** role in the incremental, sustainable and multi-disciplinary development of the research infrastructure at **CERN**

M.W. Krasny, CERN-PBC workshop, November 2022



SPS injectors

μ-collider

p,A

SPS fixed target programme

Multidisciplinary Gamma Factory research programme

GF-photon beam driven 200–300 MW **energy** source

Dark matter search

SPS tunnel

PSI = Partially Stripped Ions

$\mu^-_{\uparrow}\mu^+_{\uparrow}$

$\mu_{\uparrow}$-based ν-factory

Muon programme

Laser cooling

LHC tunnel

$e^+_{\uparrow}$

40(60) GeV ERL?

5 GeV Linac

$e^-_{\uparrow}e^+_{\uparrow}$

$\mu^-_{\uparrow}\mu^+_{\uparrow}$

$\mu^-_{\uparrow}\mu^+_{\uparrow}$

LEMMA target

$e^-_{\uparrow}\ e^+_{\uparrow}$

"cold" PSI beam

Stripper

FCC-ee

FCC tunnel

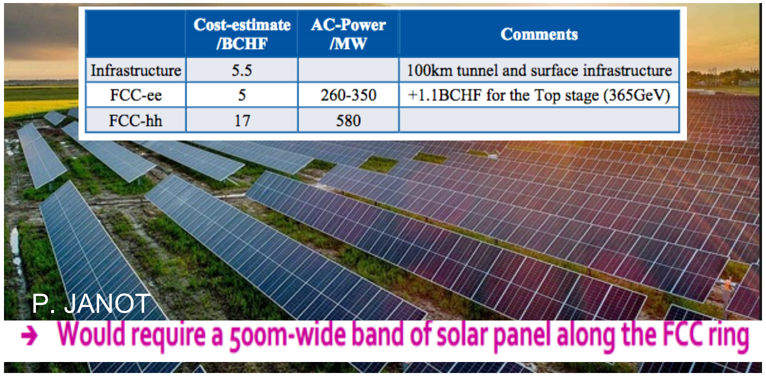
FCC-hh

Low-emittance "cold" hadron beam

Gamma Factory could provide:

- Cold, low-emittance hadronic beam for the ultimate luminosity hadron collider.
- High-intensity muon source (> 10^{13} μ/s).
- Polarised positron source (> 10^{16} e^+/s) for the LEMMA-scheme muon collider.
- ~ 10 MW driver beam for the ADS energy source (under study).

High-intensity (MW) photon beams



	Cost-estimate /BCHF	AC-Power /MW	Comments
Infrastructure	5.5		100km tunnel and surface infrastructure
FCC-ee	5	260-350	+1.1BCHF for the Top stage (365GeV)
FCC-hh	17	580	

P. JANOT

→ Would require a 500m-wide band of solar panel along the FCC ring

P. JANOT

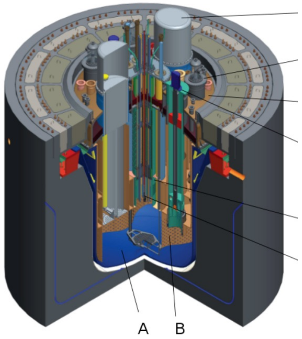
→ Would require 500 such turbines (one every 200m) along the FCC ring

Best use of the CERN expertise to produce rather than buy the plug-power:

GF photon-beam-driven energy source (ADS)

Satisfying three conditions;

- requisite power for the present and future CERN scientific programme
- operation safety **(a subcritical reactor)**
- efficient transmutation of the nuclear waste (**very important societal impact if demonstrated at CERN – given its reputation)**



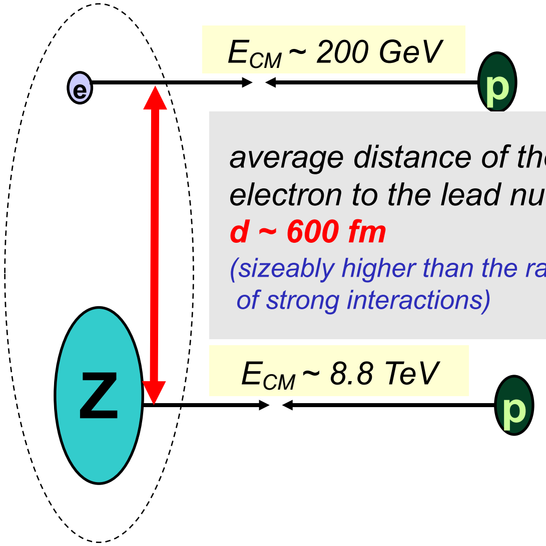
APS April Meeting 2023
Minneapolis, Minnesota (Apr 15-18)

M06 Invited Accelerate Solving Energy Crisis: From Fission to Fusion
Room: MG Salon F - 3rd Floor **Sponsor**: DPB FIP **Chair**: Christine Darve, European Spallation Source
Invited Speakers: Hamid Ait Abderrahmane, Mieczyslaw Witold Krasny, Ahmed Diallo, Alireza Haghighat

Electron beam for ep collisions at LHC

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

Hydrogen-like lead

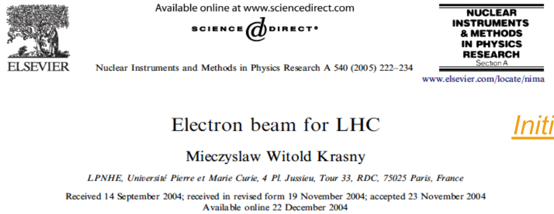


average distance of the electron to the lead nucleus
d ~ 600 fm
(sizeably higher than the range of strong interactions)

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: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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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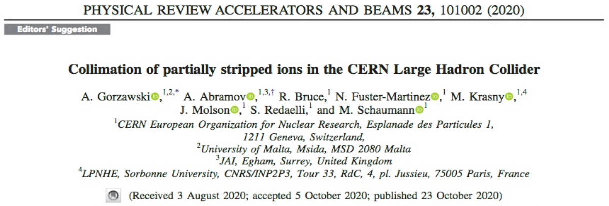
Received 14 September 2004; received in revised form 19 November 2004; accepted 23 November 2004
Available online 22 December 2004

Recent development:


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

Editors' Suggestion

Collimation of partially stripped ions in the CERN Large Hadron Collider

A. Gorzawski,[1,2,*] A. Abramov,[1,3,†] R. Bruce,[1] N. Fuster-Martinez,[1] M. Krasny,[1,4]
J. Molson,[1] S. Redaelli,[1] and M. Schaumann[1]
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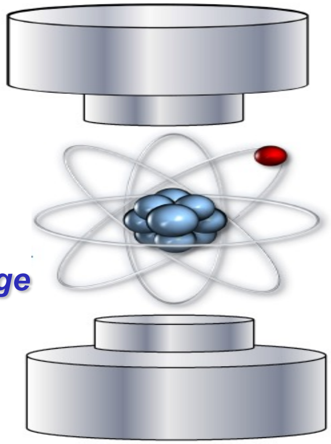
(Received 3 August 2020; accepted 5 October 2020; published 23 October 2020)

Atomic traps of highly-charged “small-size” atoms

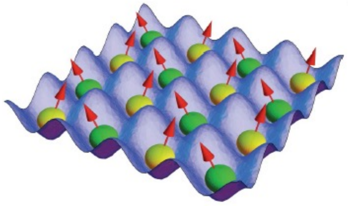
Atomic rest-frame

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

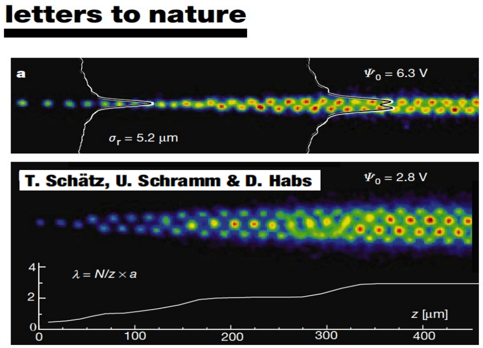


Opening new research opportunities in atomic physics**:**

- 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 ions can be resonantly excited by lasers



Crystalline beams?



letters to nature

T. Schätz, U. Schramm & D. Habs

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 ^

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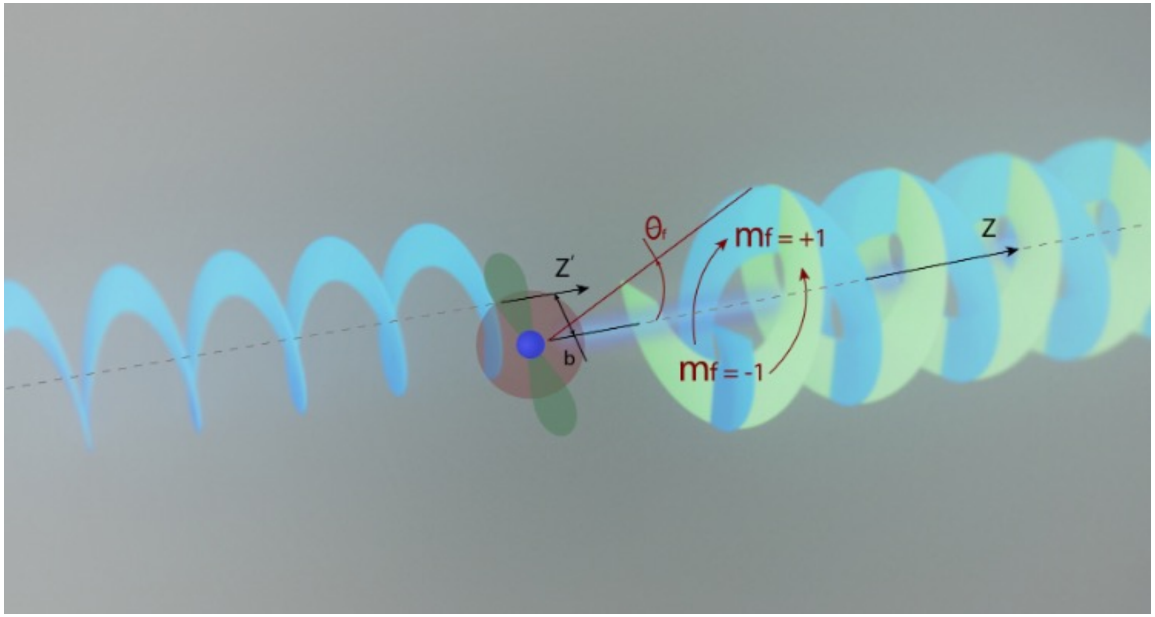
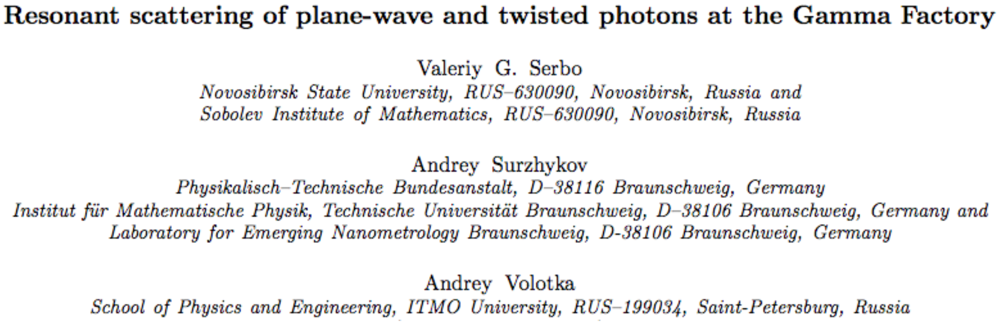
Gamma Factory twisted photons




Resonant scattering of plane-wave and twisted photons at the Gamma Factory

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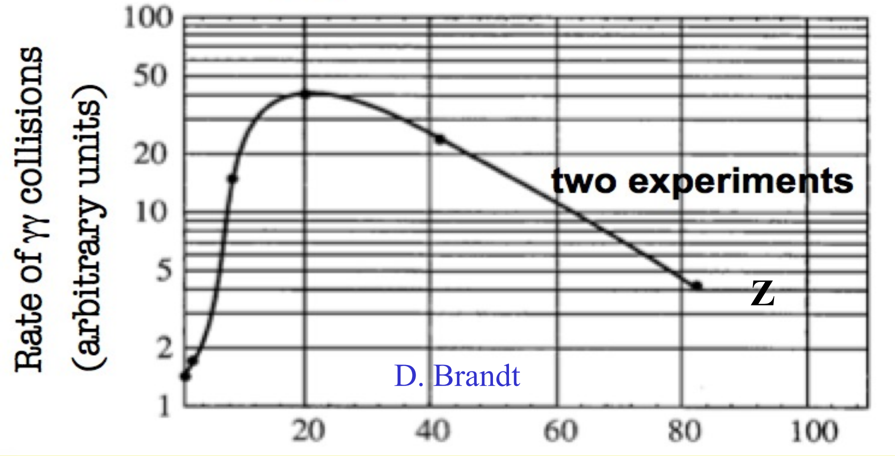
Gamma Factory path is restricted to a narrow range of nuclei

1. Ion source.
2. Space-charge tune shift
   $\sim Z^2 N_{ion} / A \gamma_L^3$.
3. Electron stripping pattern.
4. Laser constraints.
5. Lifetime of atomic beams in SPS.
6. Intra beam scattering (IBS):
   $\alpha_{IBS}^A = Z^3/A^2 \; \alpha_{IBS}^p$
7. Beam collimation: $\xi_{x,y} = \frac{r_0 N \beta^*_{x,y}}{2\pi\gamma\sigma^*_{x,y}(\sigma^*_x + \sigma^*_y)}$
8. Beam-beam parameter.
9. Parasitic beam burning:
   e^+e^- production $\sim Z^7$ and
   nucleus dissociation $\sim[(A - Z)Z^3/A^{2/3}]$.

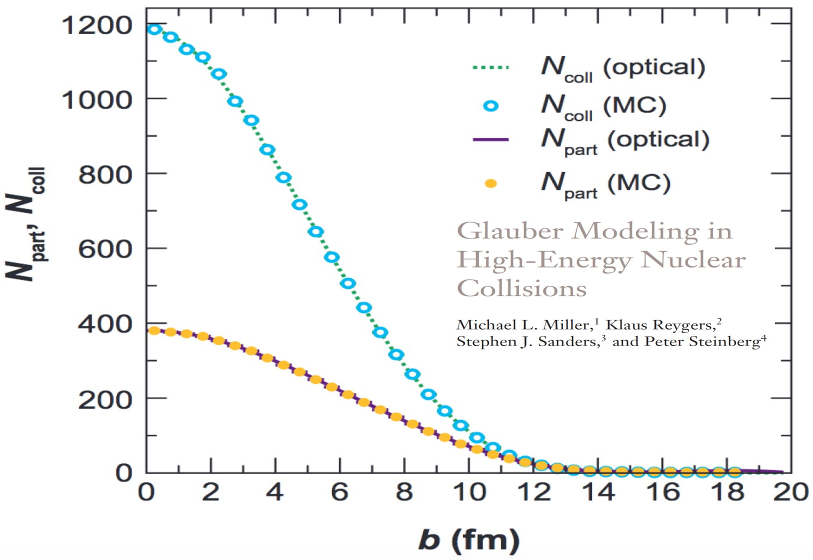
Ca^{20+} beam turns out to be **the best candidate for HL(AA)-LHC "parton carrier"** – it has a stable **isoscalar isotope** and **maximises photon-photon luminosity** in **AA** collisions.



Lower pile-up background at equivalent (high) partonic luminosity

$$\nu_{AA} = \nu_{pp} \times \frac{\sigma_{AA}}{\sigma_{pp}} \times A^{-2}$$

Example: Au-Au collisions



Reduction of the average number of **beam-particle collisions** per bunch-crossing at the same partonic luminosity by a factor of 40, **136**, 650 and 1260 for O-O, **Ca-Ca**, Xe-Xe and Pb-Pb collisions – opens a possibility of studying **exclusive processes**.

Reduction of the multiplicity of soft, **pile-up** particles – opens a possibility to run the LHC detectors (trackers) at **higher partonic luminosity** w.r.t. HL(pp)-LHC.

$N_{pile-up}$* (*pp*)** ~ ***N_{coll}*, *$N_{pile-up}$* (*AA*)** ~ ***$N_{part}/2$
(stripping-off of soft partons and nucleus surface)