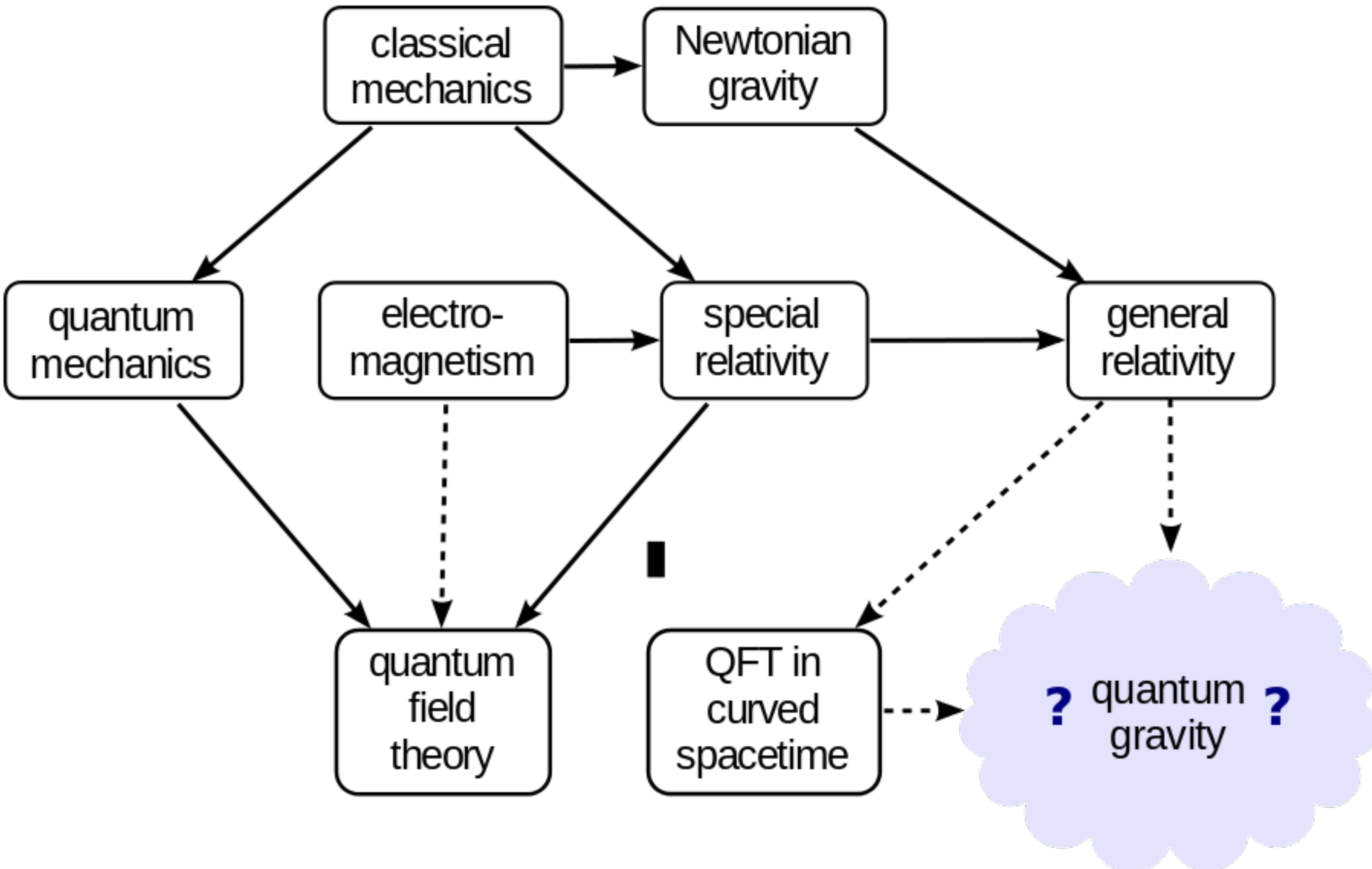
Using a positron beam to measure the speed of light anisotropy

Bogdan Wojtsekhowski, Jefferson Lab

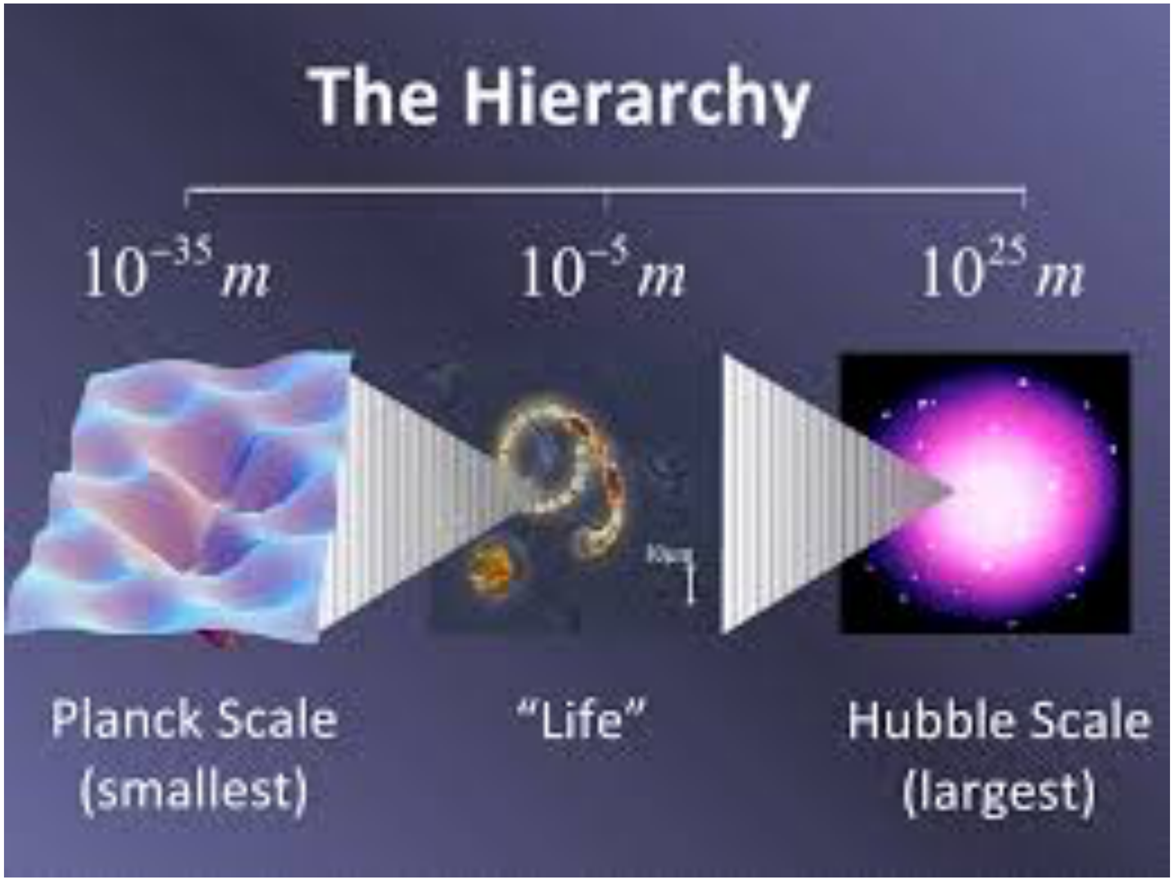
- Physics landscape
- Search for new beyond-the-Standard-Model physics
- Positron & electron test of the theory of special relativity

Physics


classical mechanics
Newtonian gravity
quantum mechanics
electro-magnetism
special relativity
general relativity
quantum field theory
QFT in curved spacetime
? quantum gravity ?

Quantum Gravity

- Black hole radius — no escape (Schwarzschild) radius: $r_s = \frac{2Gm}{c^2}$
- Quantum scale — Compton wave length: $\lambda = \frac{h}{mc}$
- Quantum gravity scale



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  $L_{Pl} = 10^{-19}$ fm

The proton size is one fermi: 10^{-13} cm

Quantum EM scale is an atom size : 10^{-8} cm

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Physics beyond the Standard Model

- Neutrino masses
- Dark matter
- Searches in PVDIS, Moller, QWeak

The proposed experiment has sensitivity to reach the onset of Quantum Gravity

Einstein's postulates of physics

The laws by which the states of physical systems undergo change are not affected, whether these changes of state be referred to the one or the other of two systems of coordinates in uniform translatory motion.

Any ray of light moves in the "stationary" system of coordinates with determined velocity ***c***, whether the ray be emitted by a stationary or by a moving body.

*Einstein, Ann. d. Physik **17** (1905)*

The speed of light measurement

The speed of light is said to be *isotropic* if it has the same value when measured in any/every direction.
The constancy of the one-way speed in any given inertial frame is the basis of the special theory of relativity.

How do we measure the speed?

one-way: $v_1 = d_{AB}/t_{AB}$

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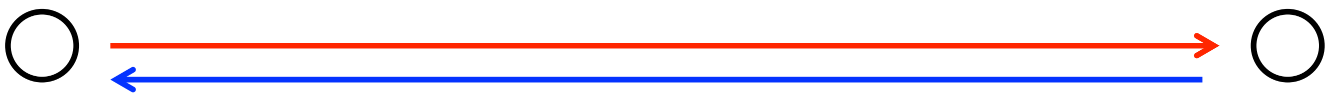

A

round-trip (two-way):
$v_2 = (d_{AB}+d_{BA})/(t_{AB}+t_{AB})$

B

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One-way speed and two-way speed: What is the difference?

What is experimentally investigated most often is the **round-trip speed** (or **"two-way" speed of light**) from the source to the detector and back.

Michelson-Morley experiment

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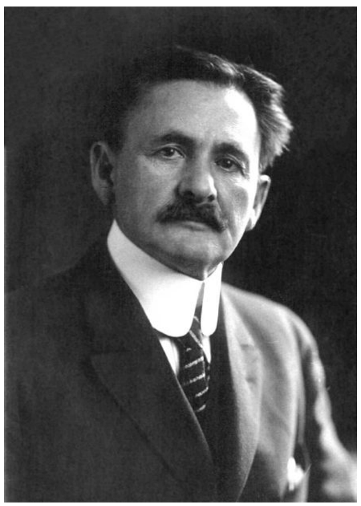
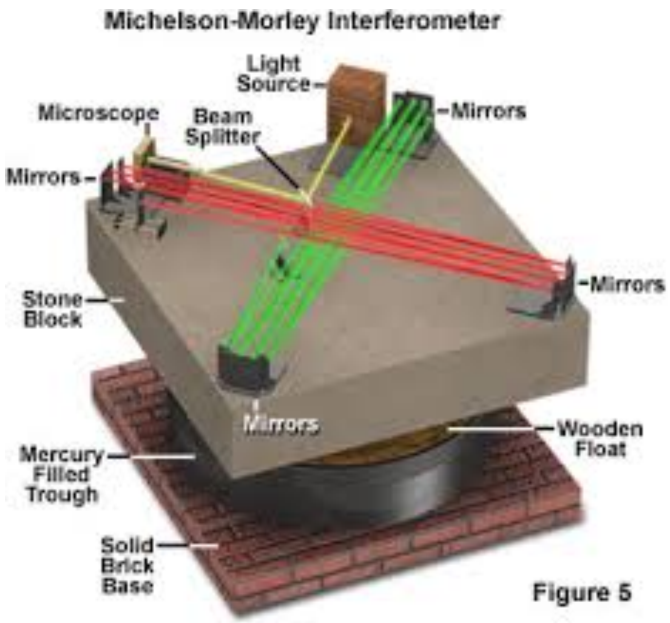
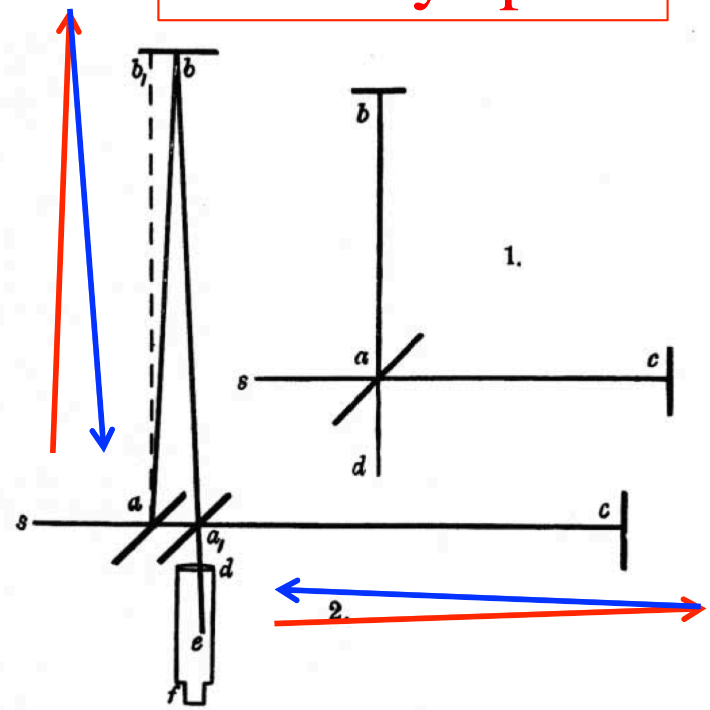




two-way speed



accuracy scale: 1μm / 10m ~ 10^{-7}

The most recent experiment

ARTICLE Communications/Nature

Received 17 Jan 2015 | Accepted 25 Jul 2015 | Published 1 Sep 2015 DOI: 10.1038/ncomms9174 OPEN

Direct terrestrial test of Lorentz symmetry in electrodynamics to 10^{-18}

Moritz Nagel[1,*], Stephen R. Parker[2,*], Evgeny V. Kovalchuk[1], Paul L. Stanwix[2], John G. Hartnett[2,3], Eugene N. Ivanov[2], Achim Peters[1] & Michael E. Tobar[2]

Lorentz symmetry is a foundational property of modern physics, underlying the standard model of particles and general relativity. It is anticipated that these two theories are low-energy approximations of a single theory that is unified and consistent at the Planck scale. Many unifying proposals allow Lorentz symmetry to be broken, with observable effects appearing at Planck-suppressed levels; thus, precision tests of Lorentz invariance are needed to assess and guide theoretical efforts. Here we use ultrastable oscillator frequency sources to perform a modern Michelson-Morley experiment and make the most precise direct terrestrial test to date of Lorentz symmetry for the photon, constraining Lorentz violating

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A Two clocks and stable distance A-to-B B

Tests of Lorentz Invariance

- Two-way speed via rotating cavities: $\Delta c_2/c < 10^{-18}$

- One-way speed via asymmetric optical ring: $\Delta c_1/c < 10^{-14}$

At what level could we expect a Lorentz Invariance violation?

$$E^2 = m^2 + p^2 + \boxed{E_{\rm Pl} f_i^{(1)} p^i} + f_{ij}^{(2)} p^i p^j + \frac{f_{ijk}^{(3)}}{E_{\rm Pl}} p^i p^j p^k + \ldots,$$

dispersion equation in some LI violation models
see, Mattingly, Living Rev.Rel. 8 (2005) 5

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The extra term leads to a directional variation of the speed of light.

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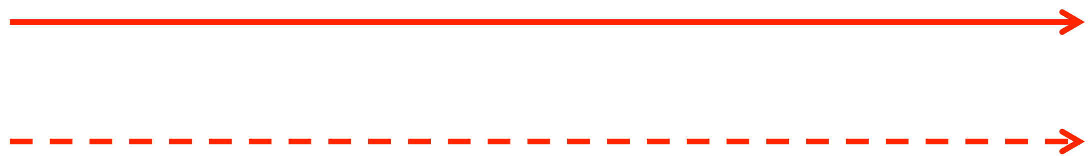
At what level could we expect a LI violation?

$$M_z/M_{Pl} \sim 10^{-17}$$

Measurement of the speed

Relative speed would be enough: light vs. beam

Stable beam of electrons



photons

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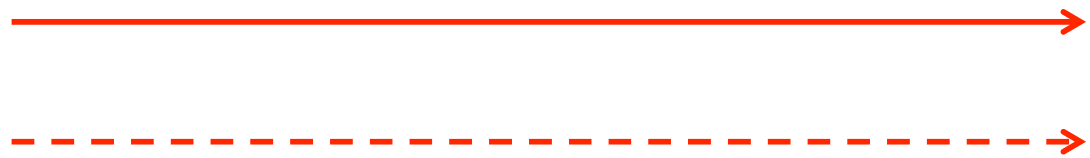
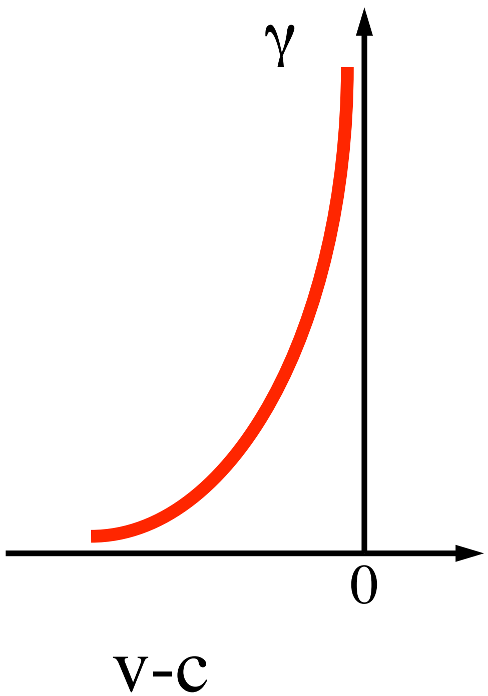


photons

The difference (c-v) defines the Lorentz factor.

Speed of light variation and Lorentz factor

$$\gamma = \frac{c}{\sqrt{(c-v)\cdot(c+v)}}$$



When the value of the speed $\boldsymbol{v}$ is fixed, a tiny variation of **c** in the direction of motion leads to a large variation of **γ**, which provides a powerful enhancement of sensitivity to a possible variation of **c**.

$$\frac{\Delta\gamma}{\gamma} = \gamma^2 \cdot \frac{\Delta c}{c}$$

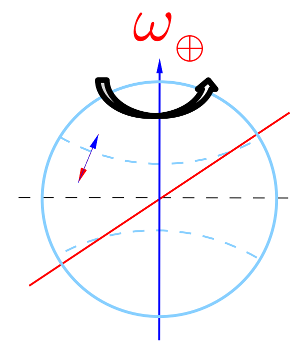
A concept of a new Lorentz Invariance test

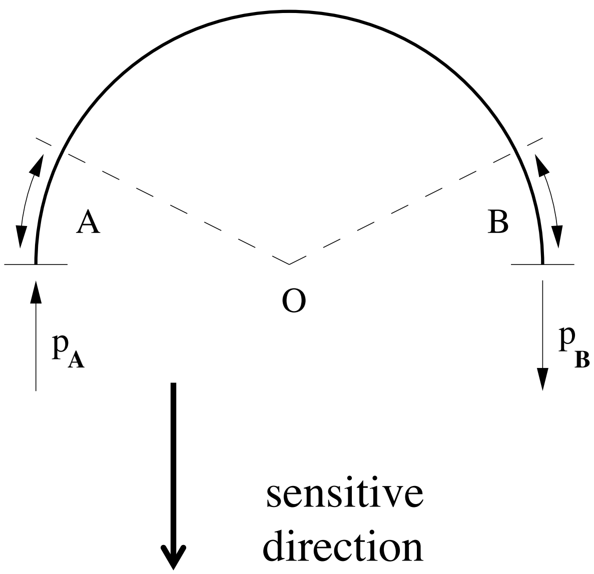
- ➢ Explore the difference of (v-c) in opposite directions of v
- ➢ Use a very small value of (v-c)/c ~ 10^{-9}, ultra relativistic electrons

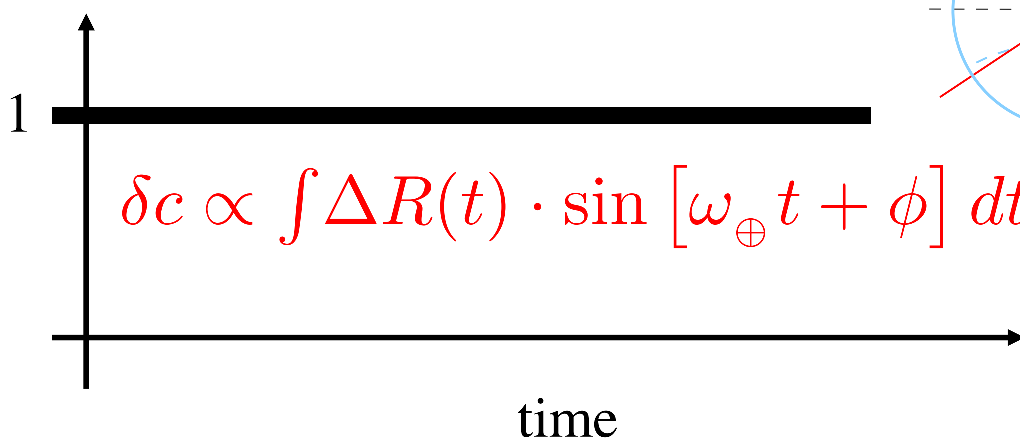
The method (BW in EPL, 108 (2014) 31001; arXiv:150902754)

- Momentum measurements at the opposite ends of the arc:

$$R = \frac{P_A}{P_B}$$, ratio of momenta in segments A and B







Beam in an accelerator

$$x(s) = x_\beta(s) + \eta(s) \times \frac{\Delta p}{p}$$

Hor. displacement = Dispersion times Momentum deviation

as a first-order estimate using the dispersion along the orbit:

$$\eta_{large} \sim 1.5m \; , \; \sigma_x \sim 50\mu m$$

$$\sigma\left[\frac{p_A - p_B}{p_{aver}}\right] = \sigma\left[\frac{x_A}{\eta_A}\right] \oplus \sigma\left[\frac{x_B}{\eta_B}\right] \sim 0.5 \cdot 10^{-4}$$

A large number of Beam Position Monitors could be used for higher accuracy.

Beam in an accelerator

$$x(s) = x_\beta(s) + \eta(s) \times \frac{\Delta p}{p}$$

$$\frac{\sigma_{\Delta p}}{p} = \sigma\left[\Delta \frac{x}{\eta}\right] \oplus \frac{x}{\eta} \cdot \frac{\sigma_\eta^{time}}{\eta}$$

consider the first term statistics over 100 seconds:

$$\frac{\sigma_{\Delta p}}{p} = 0.5 \cdot 10^{-4} \times \sqrt{\frac{2.5 \cdot 10^{-6}}{100}} \sim 10^{-8}$$

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Hor. displacement = Dispersion times Momentum deviation

Back to statistical estimations:

$$\frac{\sigma_{\Delta p}}{p} = 10^{-8}$$ a short time ~100 s

A measurement over 24 hours => $\frac{\sigma_{\Delta\gamma}}{\gamma} = 3 \cdot 10^{-10}$

a few days' experiment: $\delta c/c \sim 10^{-18}$

It would be 10,000 times better than the current limit for the one-way $\delta c/c$

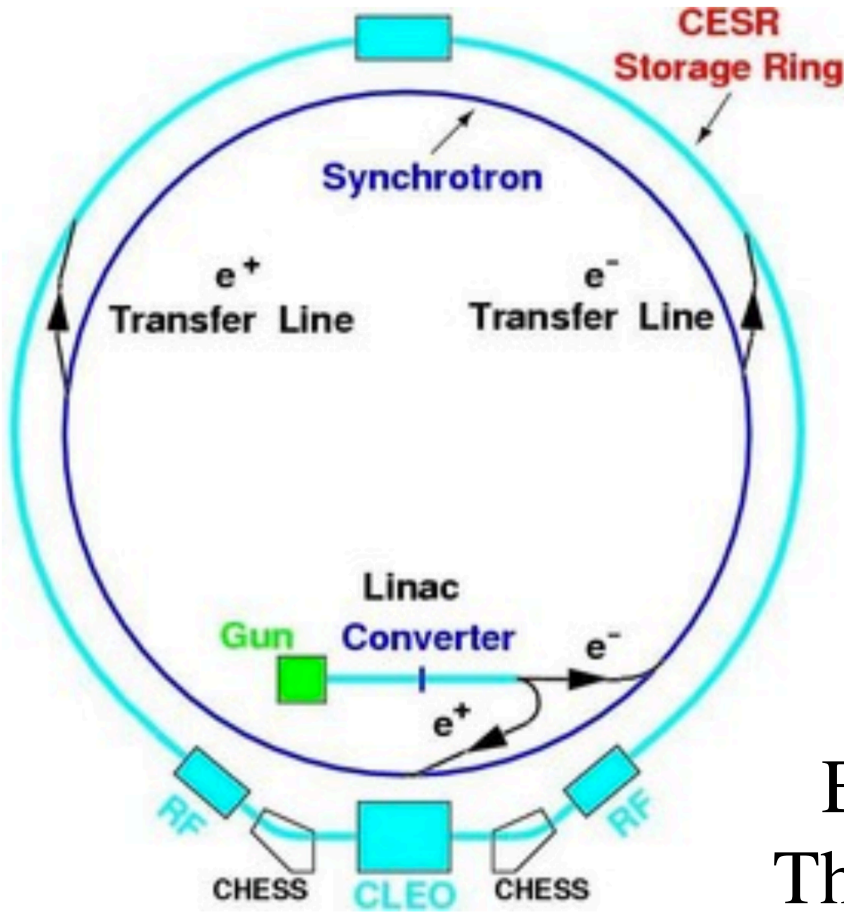
Accelerator stability

It would be great to have a 10^{-10} level of magnet and geometry stability (over 24 hours).

However, typical stability is of 10^{-6}!
Analysis of the frequency will help, but ..

The solution is two beam operation:
positrons and electrons,
moving in opposite directions.

Cornell electron/positron storage ring

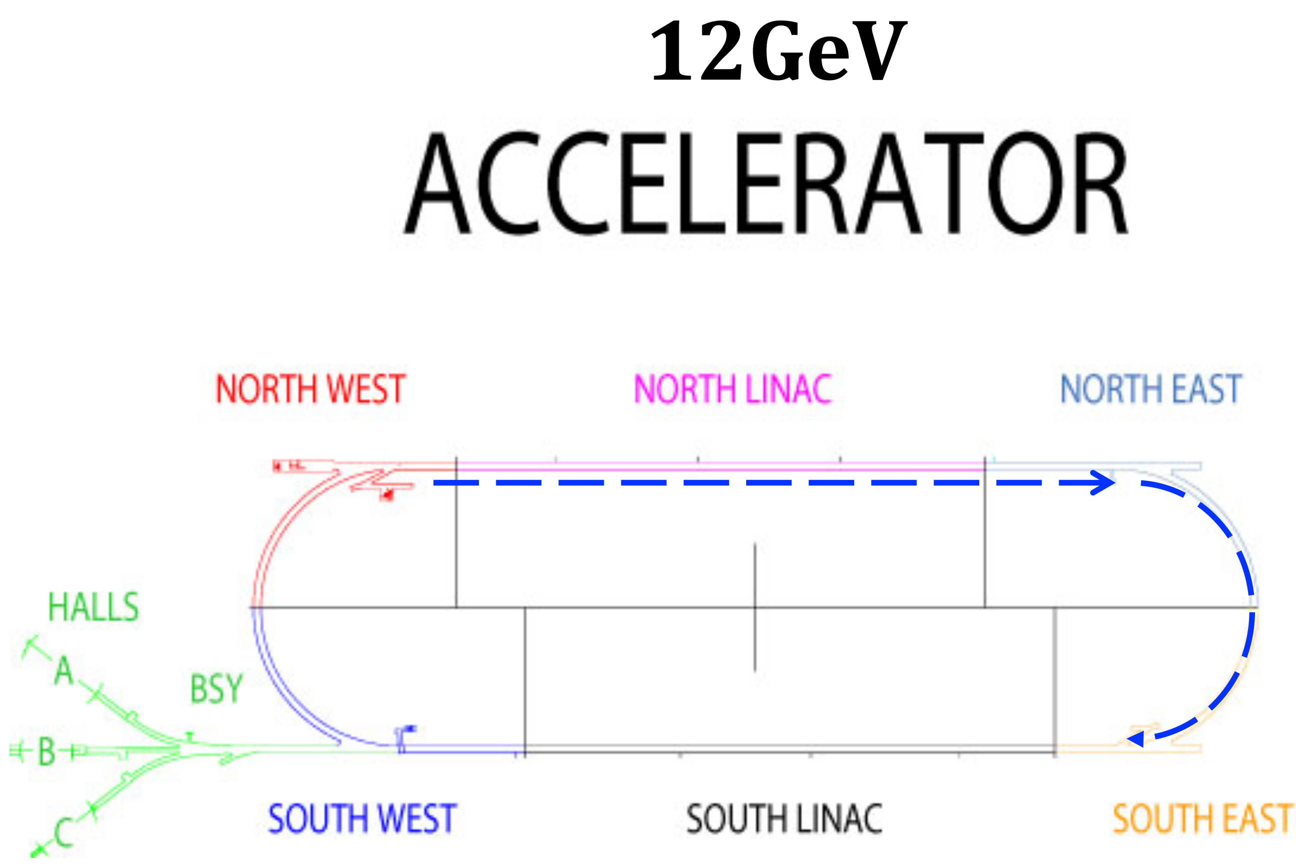


99 BPMs, two single-bunch beams

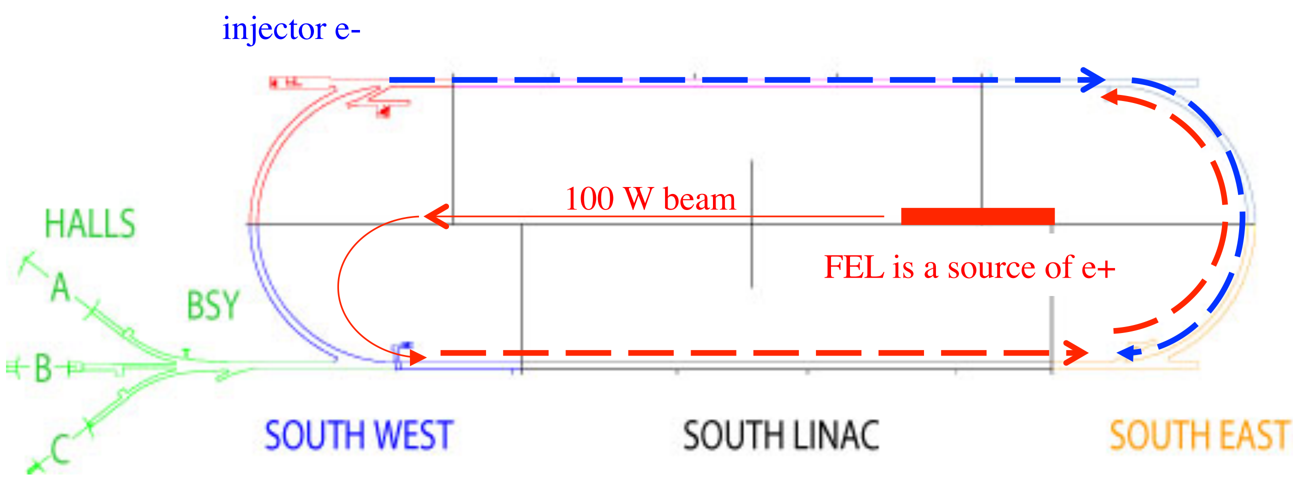
Four 5-8 hour data runs were taken.

Experiment analysis is in progress.
The first result will be posted in 2017.

Experiment at CEBAF



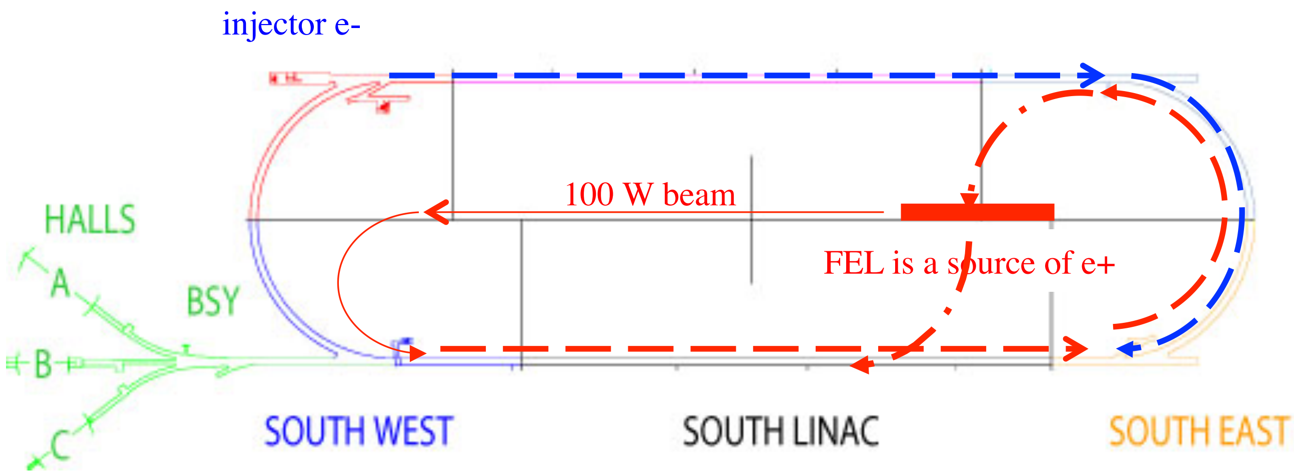
Positron beam for CEBAF



Always both beams – electron and positron!

Minimum new construction.

Positron beam for CEBAF



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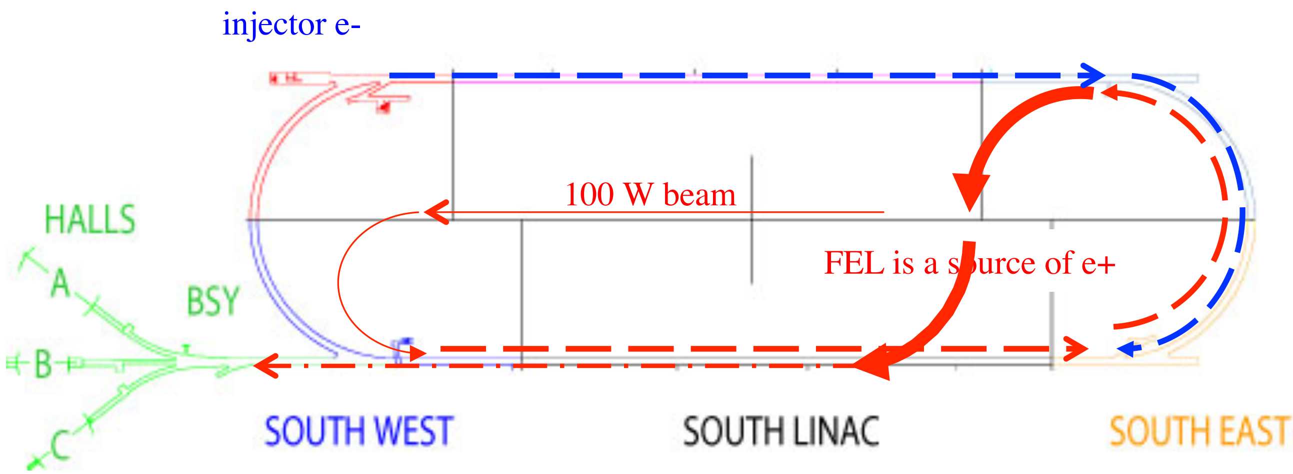

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Summary

- The search for a Quantum Gravity effect in the dispersion formula is well motivated. The onset of QG is within current capability.

- A search for possible anisotropy of the maximum attainable speed is proposed using the high energy electron and positron beams via beam deflections in the magnetic arcs at CEBAF.

Backup slides

Synchrotron Radiation

$$\frac{C_\gamma E^4}{\rho} = 26.5\ (E[\mathrm{GeV}])^3\ B[\mathrm{T}]\ [\mathrm{keV}].$$

agnetic ring is $\langle P_\gamma \rangle = \frac{U_0}{T_0} = \frac{c C_\gamma E^4}{2\pi R \rho},$

$$u_c\ [\mathrm{keV}] = \hbar\omega_c = 0.665\ E^2[\mathrm{GeV}]\ B[\mathrm{T}],$$

Photon energy ~ 30 keV

$$N_\gamma = \mathcal{N} 2\pi \frac{\rho}{c} = \frac{5\pi}{\sqrt{3}} \alpha\gamma.$$

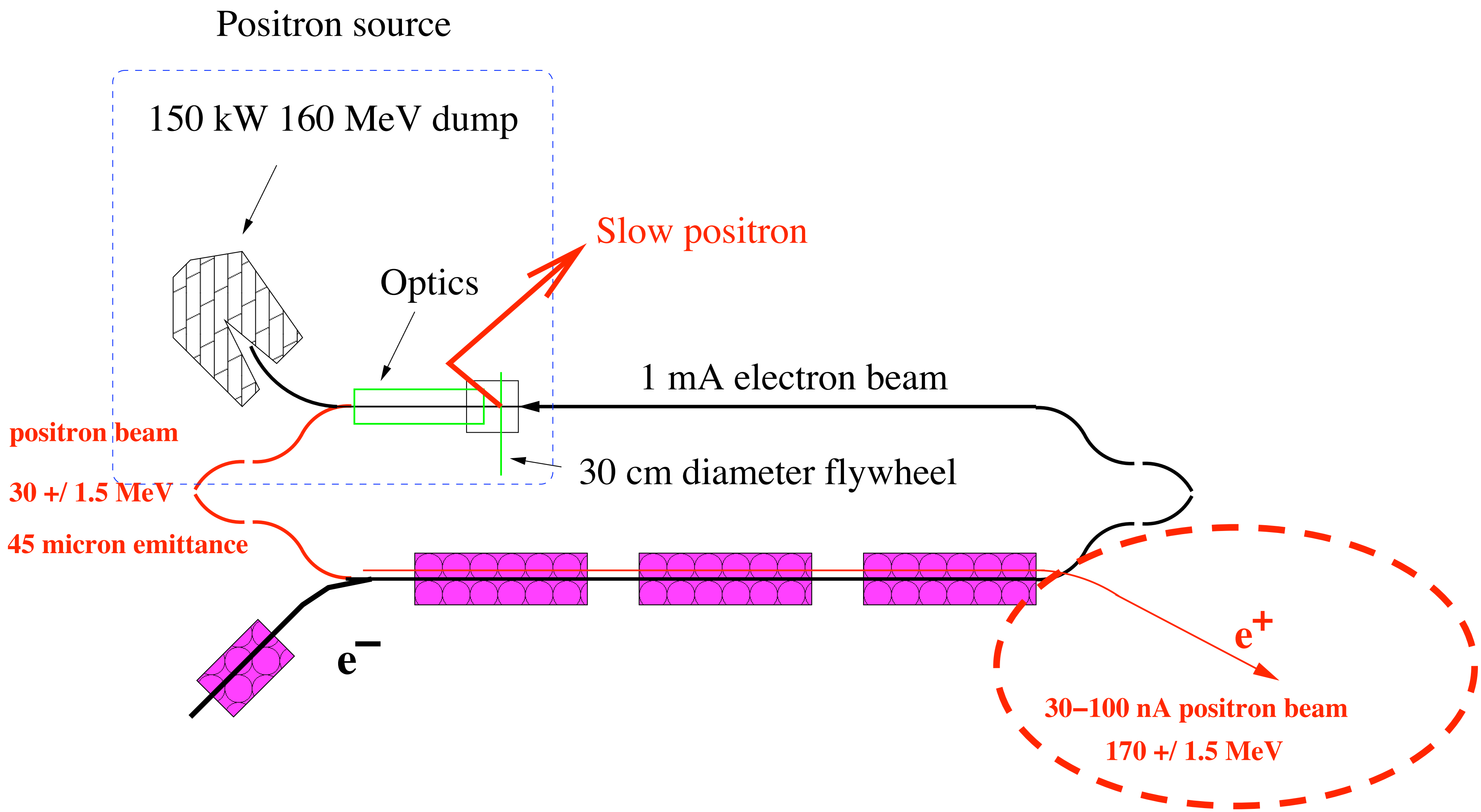
Number of emitted photons per revolution = γ/15 ~ 1000

Jitter of beam energy centroid (in one second)

< 1 MeV/10^6 => 10^{-10} relative effect

U-boson search, concept 2006

B. Wojtsekhowski, P. Degtiarenko, A. Freyberger, L. Merminga



JPos09: JLab positron beam considerations

$$\epsilon^n = \gamma \frac{\sigma_x^2}{\beta_{SRF}}$$

$$\sigma_x \sim 2 \text{ mm}, \ \beta_{SRF} \sim 5 \text{ m}$$

$$\epsilon^n = 60 \frac{4[mm]^2}{5000[mm]} = 50 \ \mu m \times rad$$

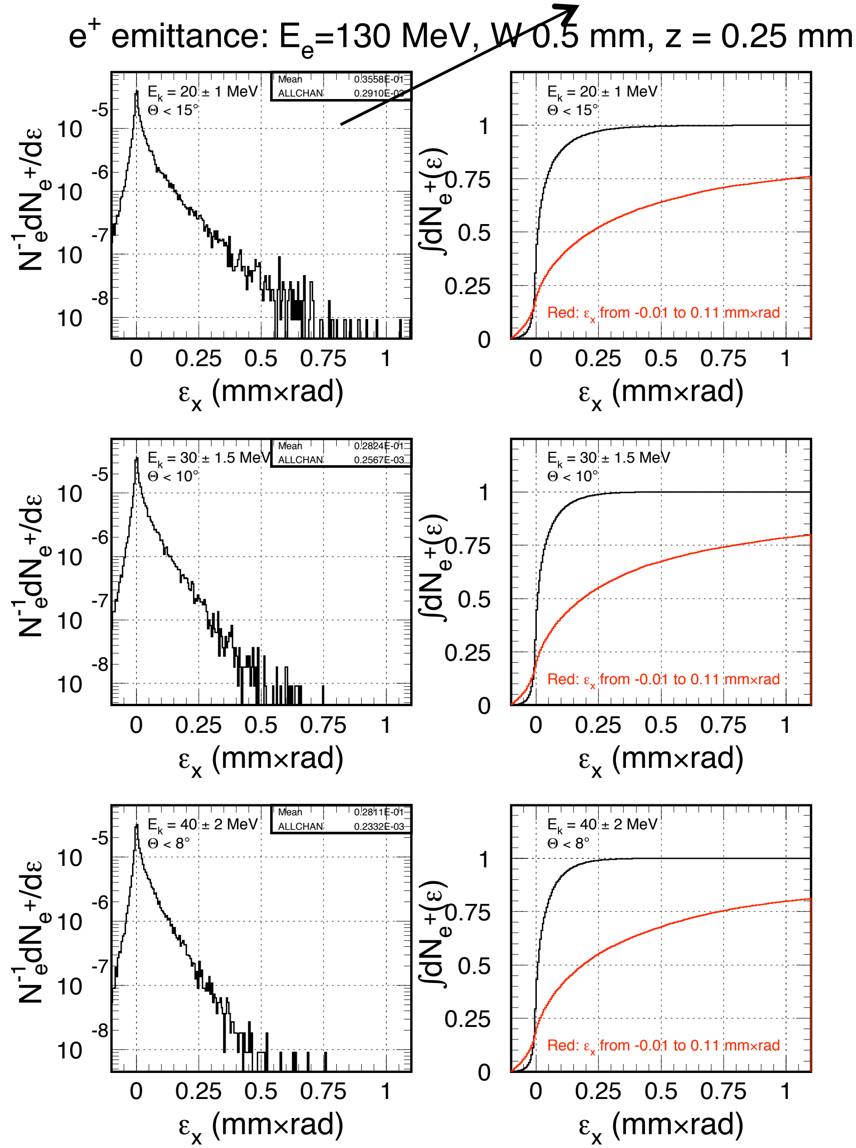
$$E_e = 130 \text{ MeV}, \ E_+ = 20 \pm 1 \text{ MeV}, \ \theta_+ < 15^\circ$$

$$\epsilon_x = \gamma \, x \, \theta_x$$

$$J_+ = J_- \times (\epsilon_x^{max})^2 \times N_+/N_-$$

Production: ~10^{-4} positrons per each 160 MeV electron into acceptance SRF

$$N_+/N_- \sim 3 \times 10^{-4}$$



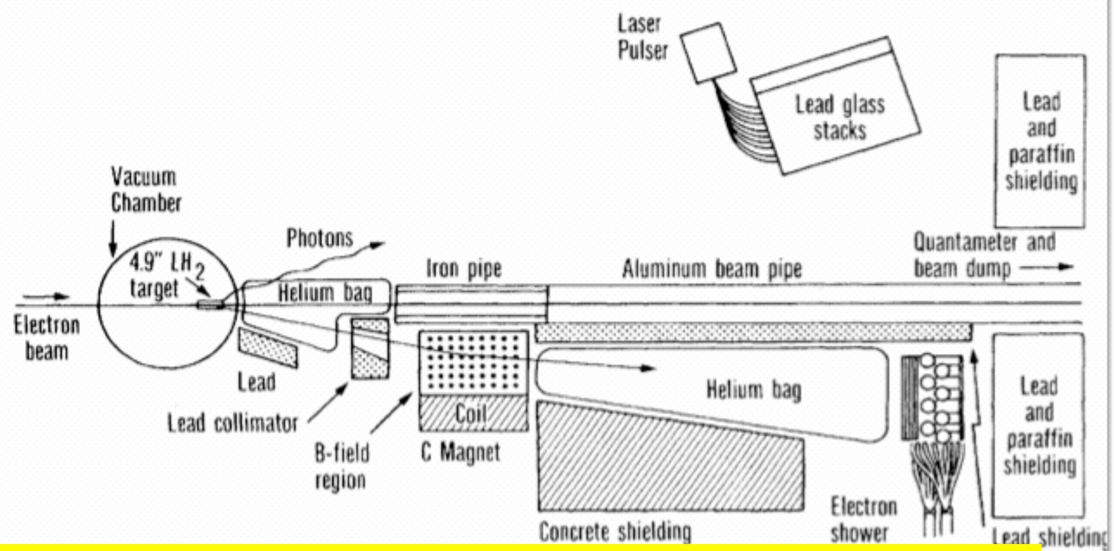
SLAC 1977 -Measurement of e^+-e^- Asymmetry in Deep-Inelastic Bremsstrahlung, D.L. Fancher et al.

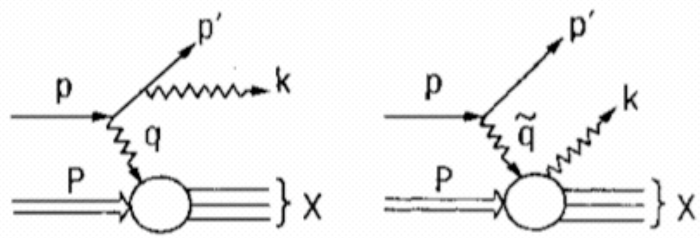
p(e,eγ')X, γ^* max energy of 9.5 GeV, $-t$ up to 2 GeV^2, 2 nA * 200 hours run

Brodsky, Gunion, Jaffe (1972)

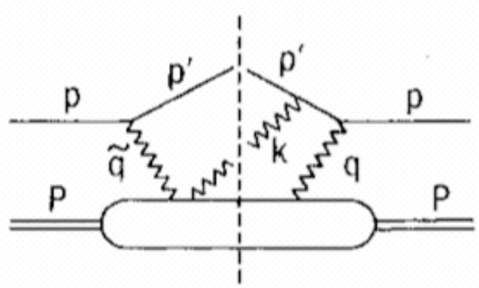
$$\frac{d\sigma(e^+p\to e^+\gamma X)}{dp_0'd\Omega_e'dk_0d\Omega_k}-\frac{d\sigma(e^-p\to e^-\gamma X)}{dp_0'd\Omega_e'dk_0d\Omega_k}=\frac{\alpha^3p_0'k_0|T_{\rm int}|^2V(x')}{2\pi^2M_pp_0(-q^2)}, \qquad (1)$$

where M_p, p_0, p_0', and k_0 are the energy components of the four-vectors shown in Fig. 1, Ω_e,





(a) Bethe-Heitler (b) Compton



(c) Compton-Bethe-Heitler Interference

FIG. 1. Diagrams for the reaction $e^\pm + p \to e^\pm + \gamma$ + anything.

A probe of the u/d ratio at high x

$$V(x)=\sum_i e_i^3 u_i(x)$$

only valence quarks

$$\int_0^1 V(x)dx=\langle\sum_i e_i^3\rangle$$

$$\frac{N(e^+p\to e^+\gamma X)}{N(e^-p\to e^-\gamma X)}=1.08\pm0.03$$