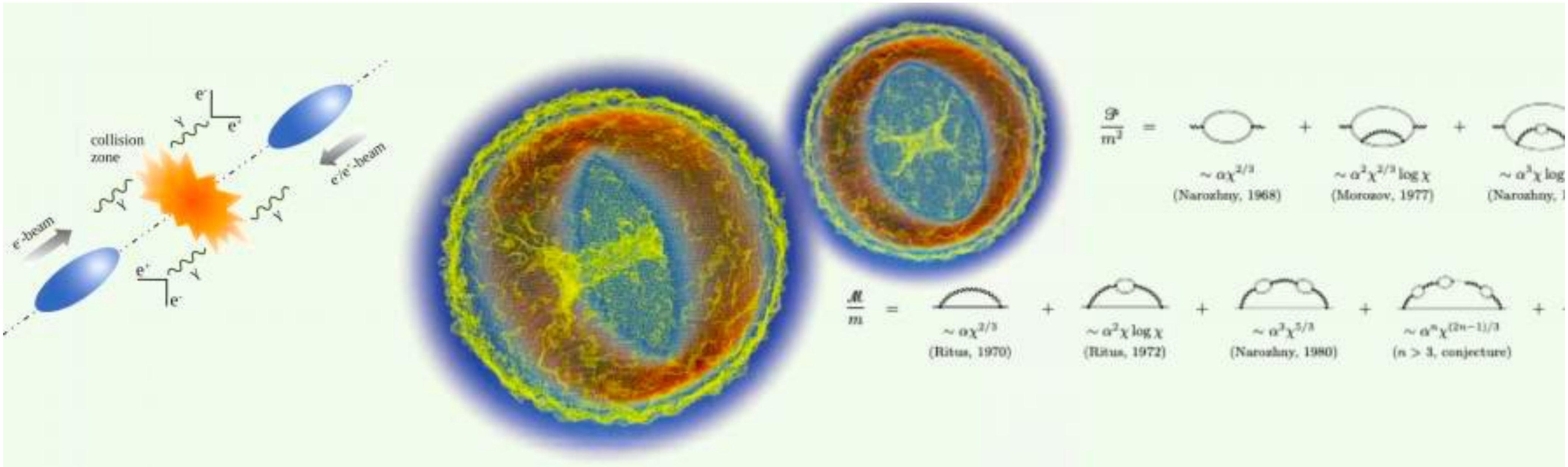


Concept for a Fully Non-perturbative QED Collider

4th European Advanced Accelerator Concepts Workshop

Vitaly Yakimenko

September 18, 2019

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

SUNDAY REVIEW The New York Times

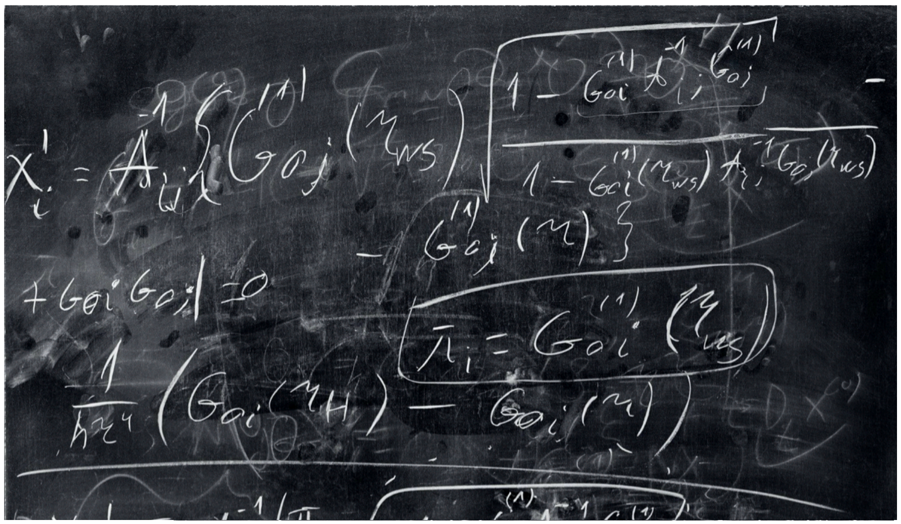
Opinion

Even Physicists Don't Understand Quantum Mechanics

Worse, they don't seem to want to understand it.

By Sean Carroll
Dr. Carroll is a physicist.

Sept. 7, 2019



"Scientists can *use* quantum mechanics with perfect confidence. But it's a black box."

"…quantum mechanics, … , seems to require separate rules for how quantum objects behave when we're not looking at them, and how they behave when they are being observed…"

"…what is the wave function? Is it a complete and comprehensive representation of the world? Or does the wave function have no direct connection with reality at all…"

"Until physicists definitively answer these questions, they can't really be said to understand quantum mechanics — thus Feynman's lament."

"Our best attempts to understand fundamental physics have reached something of an impasse, stymied by a paucity of surprising new experimental results. It's hard to make progress when the data just keep confirming the theories we have, rather than pointing toward new ones"

Strong Field QED in Laboratory Experiments

- Critical Field $E_{cr} \approx 10^{16}\ V/cm$ Critical Intensity $I_{cr} \approx 4.6 \times 10^{29}\ W/cm^2$
- Decisive Measure: electric field in the particle rest frame (E^*):

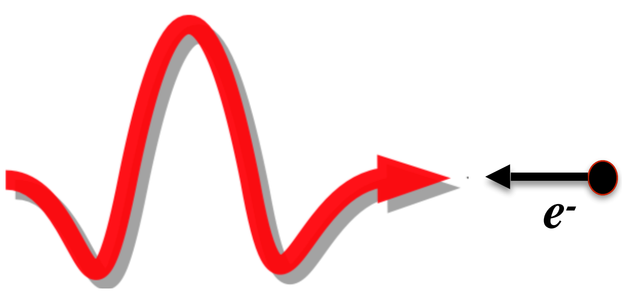
$$\chi = \frac{\sqrt{pF^2p}}{E_{cr}mc^2} = \frac{\varepsilon}{mc^2}\frac{E}{E_{cr}} = \frac{E^*}{E_{cr}}$$

A. Di Piazza, et. al Extremely high-intensity laser interactions with fundamental quantum systems. Rev. Mod. Phys. 84, 1177 (2012)

V. N. Biaer et al, Interaction of high-energy electrons and photons with crystals. Sov. Phys. Usp. 32 972 (1989)

K. Yokoya and P. Chen, Frontiers of Particle Beams, 415–445 (1992)

Electron-laser interaction

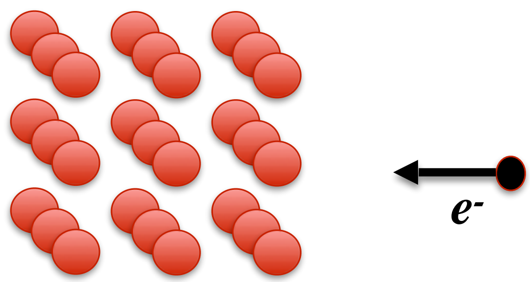


Quantum parameter

$$\chi \approx 0.57\frac{\varepsilon}{10GeV}\sqrt{\frac{2I}{10^{20}W/cm^2}}$$

ε: electron energy, I: Laser intensity

Particle-crystals interaction

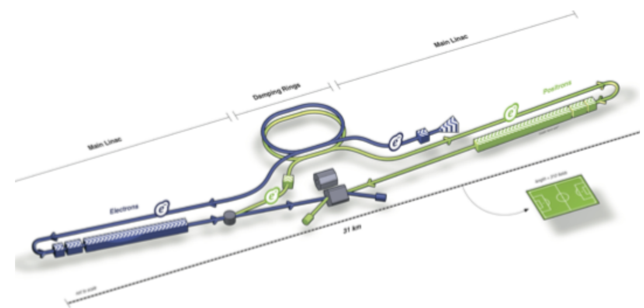


Quantum effects threshold

$$\chi \approx \frac{\varepsilon}{mc^2}\frac{U_0}{mc^2}\frac{r_e}{\alpha a_s}$$

U_0: transverse potential, a_s: screening distance

Beam-beam interaction



Beamstrahlung parameter

$$\chi \approx 0.57\frac{\varepsilon}{mc^2}\frac{2Nr_e^2}{\alpha\sigma_z(\sigma_x+\sigma_y)}$$

N: Number of particles, $\sigma_{x,y,z}$: dimensions of the bunch

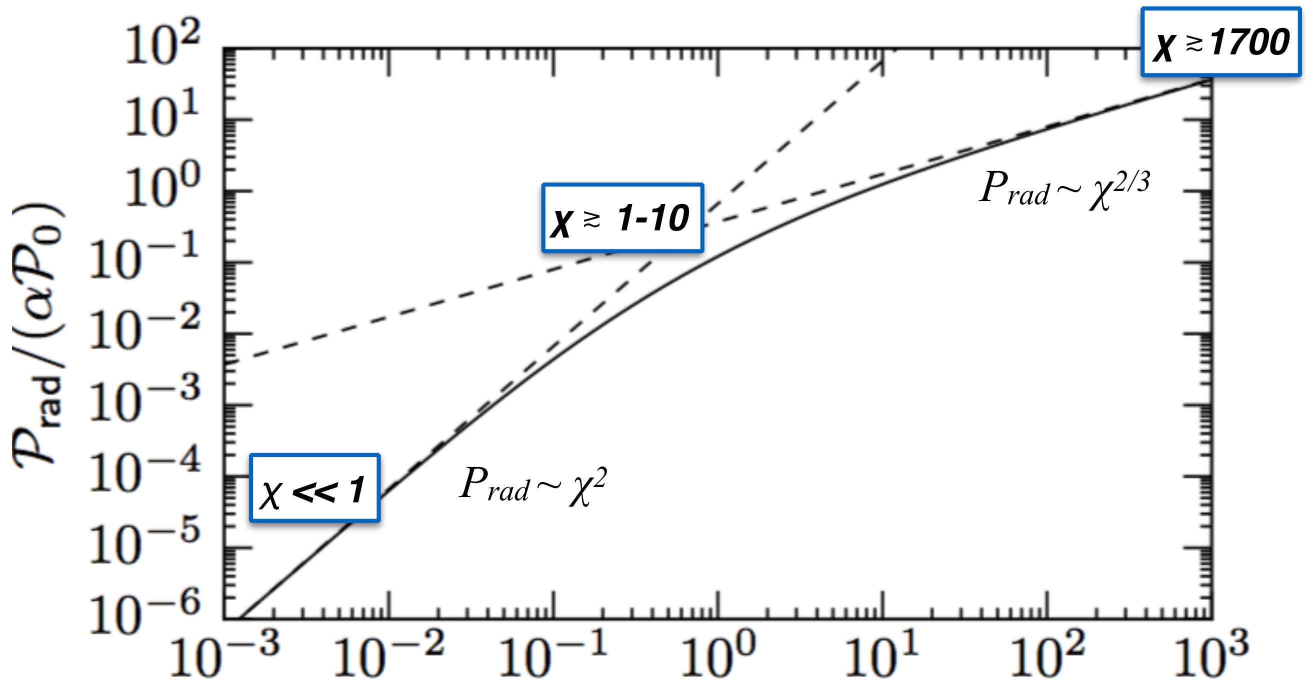
Different Scales of Strong-Field QED

$\chi << 1$: **classical regime:** Quantum effects are small, pair production is exponentially suppressed

$\chi \gtrsim 0.1, \chi <\sim 10$: ***transition to*** **quantum regime:** Recoil and pair production are important

$\chi \gtrsim 10, \alpha\chi^{2/3} < 1$: **quantum regime:** Importance of pair production cascades, the radiation field is a perturbation

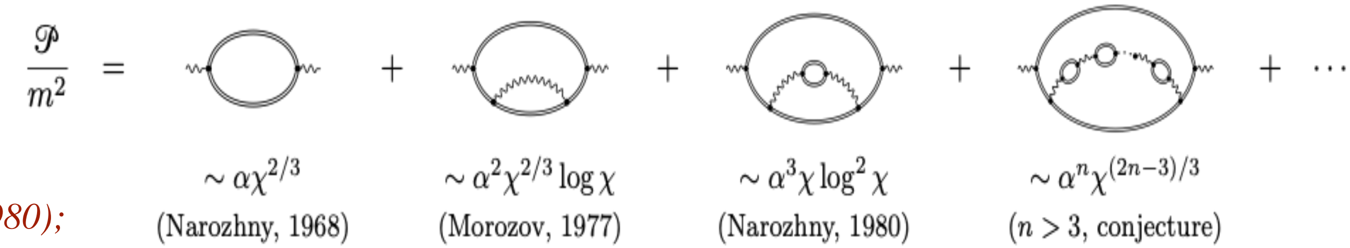
$\alpha\chi^{2/3} \gtrsim 1$ ($\chi \gtrsim 1700$): **fully non-perturbative regime:** Perturbative treatment of the radiation field breaks down



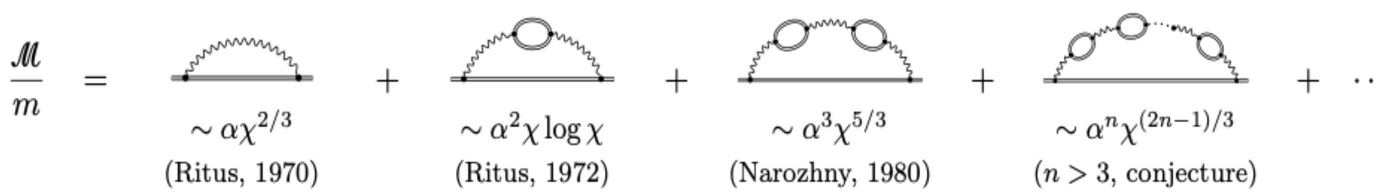
Developing framework for non-perturbative regime was generally considered to be of minor academic interest for quantum electrodynamics because of the inaccessibly large field scale at which the breakdown occurs

Fully Non-Perturbative QED: Intuitive Picture

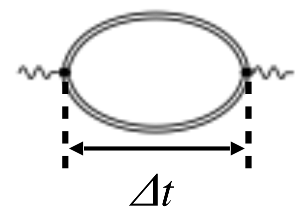
Scaling of diagrams considered so far



V. I. Ritus, Ann. Phys. 69, 555–582 (1972)
N. B. Narozhny, Phys. Rev. D 21, 1176–1183 (1980);
A. M. Fedotov, J. Phys.: Conf. Ser. 826, 012027 (2017);



An electric field E introduces a new mass scale $m_\gamma^2(\chi) \sim \alpha M^2$, $M \sim eE\Delta t / c$,
where *Δt is characteristic time scale of quantum fluctuations*
The lifetime Heisenberg uncertainty principle: $\Delta t \Delta\varepsilon \sim \hbar$; $\Delta\varepsilon \sim (eE\Delta t/c)^2 / (\hbar\omega_\gamma)^2$



is obtained by comparing $\varepsilon = pc$ (photons) and $\varepsilon = [(pc)^2 + m^2c^4 + (eE\Delta t/c)^2]^{1/2} \sim pc + (eE\Delta t/c)^2/(2pc)$ *(pair particles)*

The resulting field-induced mass scale $M \sim m\chi^{1/3}$ **independent of** $\boldsymbol{m}$ (note, $\chi \sim m^{-1/3}$),
$m_\gamma(\chi) = \alpha\chi^{2/3} m$: **breakdown of perturbation theory when** $\boldsymbol{\alpha\chi^{2/3} \gtrsim 1}$ **or** $\boldsymbol{m_\gamma(\chi) > m}$

Non-Perturbative Strong Field QED Collider Parameters

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Key challenge: radiative energy loss in field transition (if $\chi \gtrsim 1$) prevents reaching $\chi \gg 1$

- Four (main) beam parameters: transverse σ_r and longitudinal σ_z bunch sizes; number of particles per bunch N; Lorentz factor γ
- Lorentz invariance: only $\sigma_z^* = \sigma_z/\gamma$ relevant $\rightarrow$ three degrees of freedom
- we can simultaneously fulfill three constraints:

Quantum Parameter

$$\chi_{av} \approx \frac{5}{12}\frac{N\alpha ƛ_c^2}{\sigma_r \sigma_z^*}$$

$$\alpha\chi^{2/3} \gtrsim 1$$

reaching fully non-perturbative regime

Radiation Probability

$$W \approx \alpha\chi_{av}^{2/3}\frac{\sigma_z^*}{ƛ_c}$$

$$W < 1$$

acceptable radiation loss

Disruption Parameter

$$D \approx \frac{2N\alpha ƛ_c \sigma_z^*}{\sigma_r^2}$$

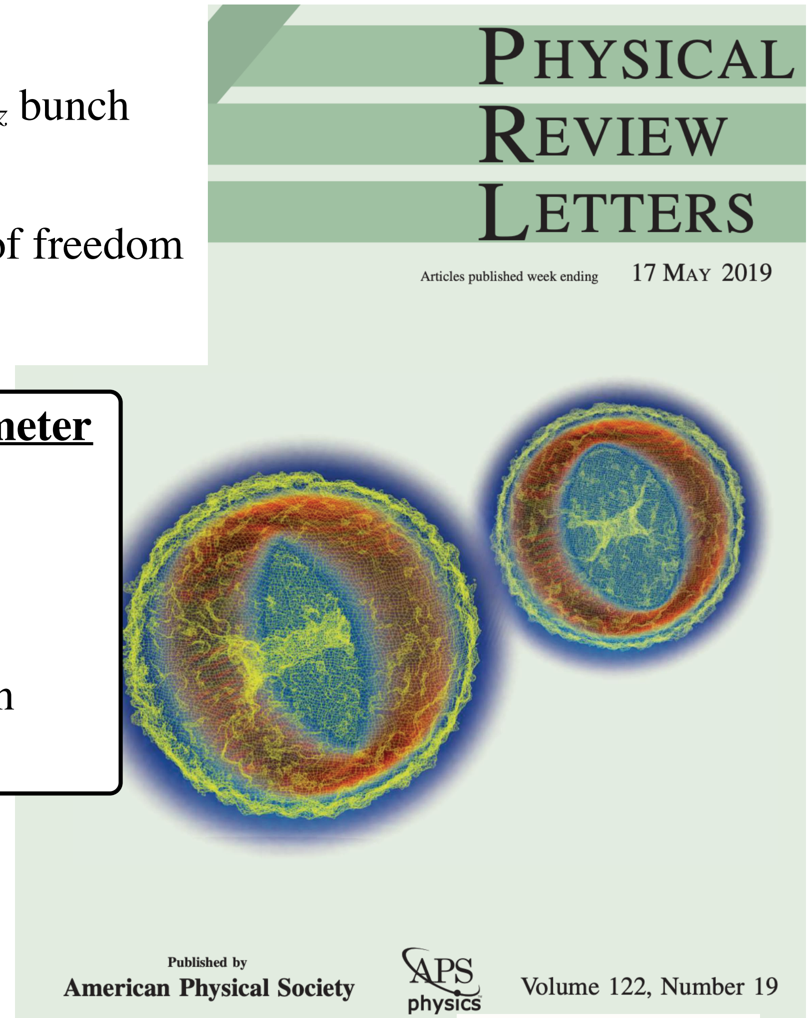
$$D < 0.01$$

small disruption

NpQED Collider scale

- $\sigma_z^* \le ƛ_c$ — $\sigma_z \lesssim 100nm$ @ $100GeV$
- $N \ge \frac{1}{\alpha^4} \sim 10^9$ — I.e., $\gtrsim$ 100 pC per bunch
- $\sigma_r \sim 10\sqrt{N\alpha}ƛ \approx 10nm$

Phys. Rev. Lett. 122, 190404 (2019)



Hierarchy of Numbers that Enables NpQED Collider

- Formation Length for hard photon (for 100GeV e- in $\chi >> 1$ field): $L_f \sim 1nm$
- Field switching length: $\sigma_z \sim 10\ nm$
- Length to emit a hard photon with probability ~1 : $L_f / \alpha \sim 100nm$

This hierarchy ensures:

- Majority of electrons go through the collision without emitting hard photons and preserving initial energy as a result ($\sigma_z << L_f / \alpha$)
- Local Constant Field Approximations is valid ($L_f << \sigma_z$)

For 100 GeV:

$$\chi_{max} = \frac{\gamma E_r}{E_{cr}} \sim \overbrace{\gamma \alpha}^{\sim 1400} \overbrace{\frac{N_e \lambda\!\!\!^{-}{}_c^2}{\sigma_z \sigma_r}}^{\sim 1}$$

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With increased beam energy to ~3TeV ($\sigma_r \sim \sigma_z \sim$ 1nm) beam generated field E_r can exceed E_{cr} in the lab frame (without Lorentz boost)

Linear Collider Luminosity Optimization

Luminosity: $$L = \frac{P_b}{E_b} \frac{N_b}{4\pi\sigma_x\sigma_y}$$

Beam Power

Number of particles per bunch

Beam Energy

Area of the beam

$$L \propto \frac{P_b}{E_b}\sqrt{\frac{\delta_{BS}}{\varepsilon_{ny}}}$$

Loss of energy associated with beamstrahlung

Normalized vertical emittance

Parameter	Symbol [Unit]	ILC (TDR)	NpQED Collider
Center mass Energy	E_{CM} [GeV]	250 GeV	
Beam Energy	E [GeV]	125	
Bunch Charge	Q [nC]	**3.2**	**1.4**
Peak Current	I_{pk} [kA]	0.4	1700
rms Bunch Length	σ_z [μm]	**300**	**0.1**
rms Bunch Size	$\sigma^*_{x,y}$ [μm]	**0.73, 0.008**	**0.01, 0.01**
Pulse rate x # Bunches/pulse	f_{rep} [Hz] x N_{bunch}	5 x 1312	700
Beamstrahlung Parameter	χ_{av}, χ_{max}	0.06, 0.15	969, 1721
Beam Power	P [MW]	**2.6**	**0.12**
Luminosity	L [$cm^{-2}s^{-1}$]	**3E+33**	

Linear colliders can be designed to manage beamstrahlung with short bunches and not increased transverse size compensated by demand for beam intensity

HEP LC with round bunches: ~10 times reduction of required beam power and corresponding reduction in cost by ~3 times

FACET-II User Facility will Provide Access to Electron Bunches with Extreme Intensity

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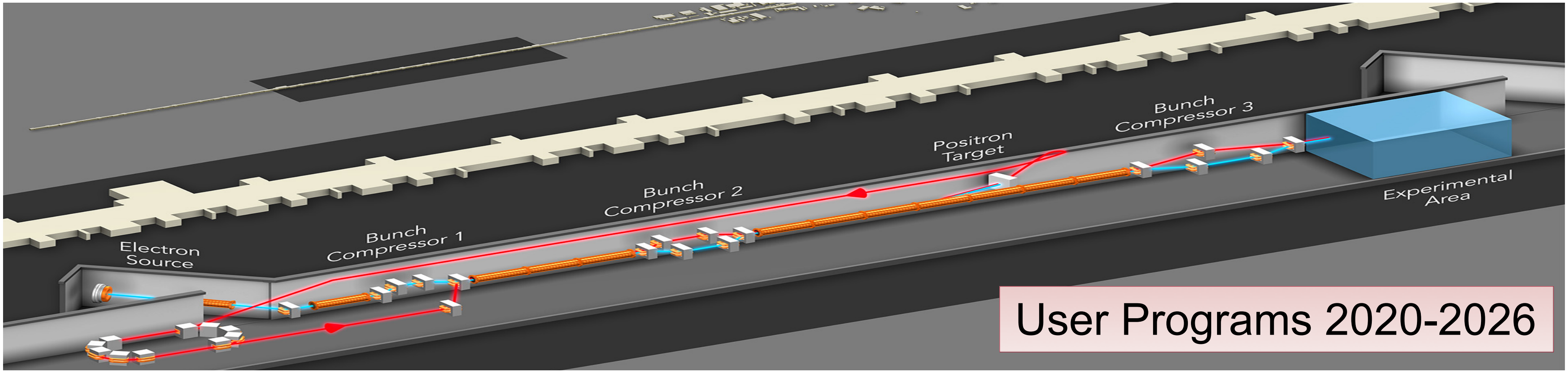
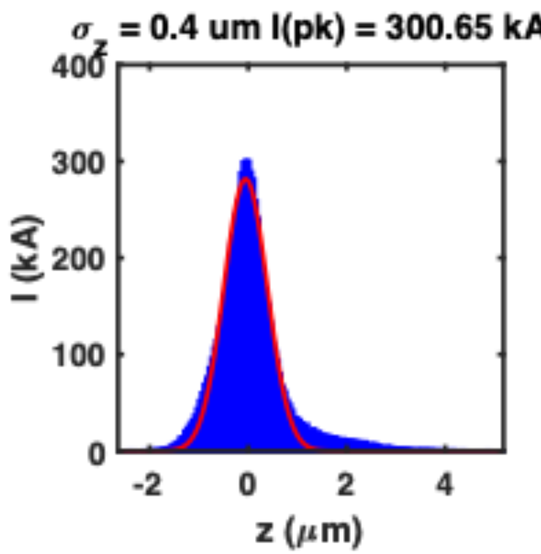
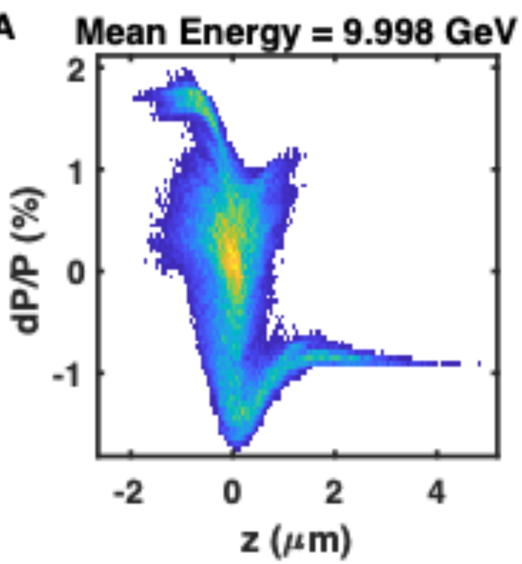


Low-emittance (state of the art photoinjector) and ultra-short (improved compression) beam will generate:

- >300 kA peak current (~0.4 μm long)
- ~100 nm focus by plasma ion column
- **~10^{12} V/cm** radial electric field (Es=1.3x10^{16} V/cm)
- **~10^{24} cm^{-3}** beam density





Proposals to further compress bunches to $I_{peak} > 1.5$ MA using wakefileds

Working Group to Study Challenges Associated with "Extreme" Compression: Stability of the Compression

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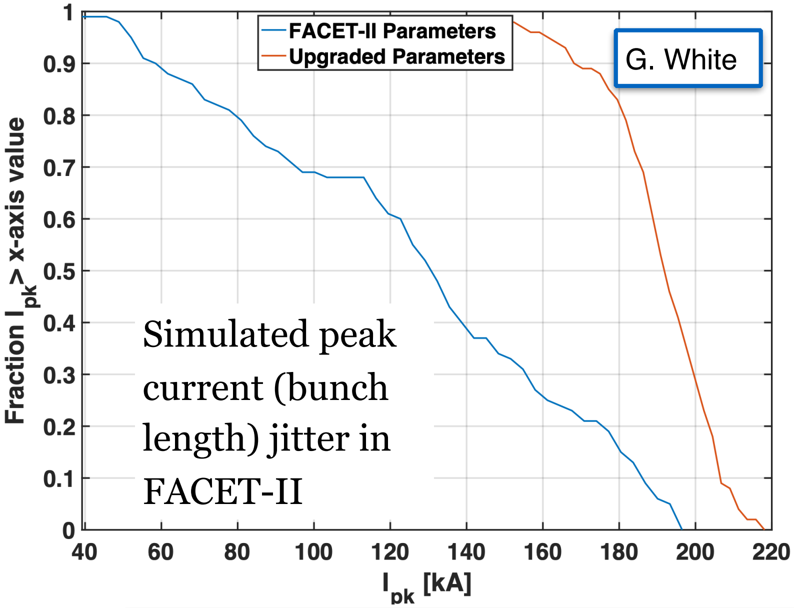
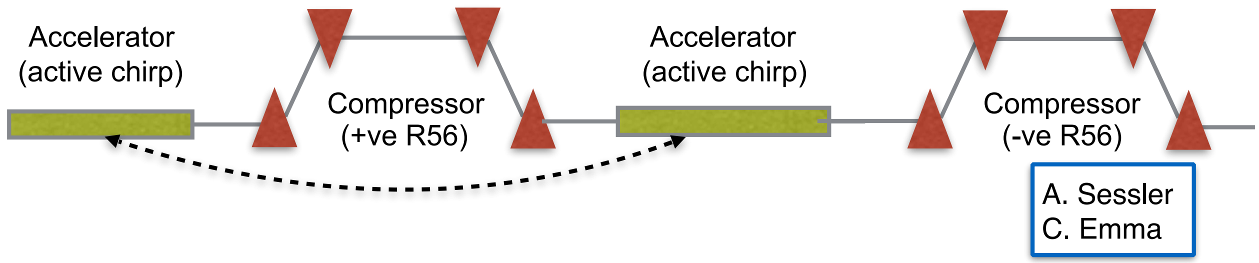


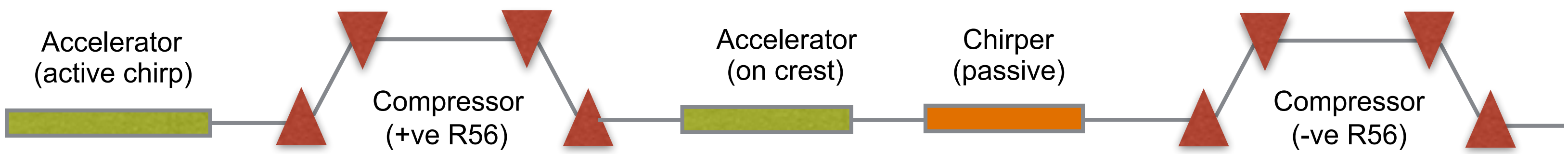
Compensation of phase jitter impact on bunch length:



$$\frac{\Delta\sigma_z}{\sigma_z} = \left[C_1^2 E_1/E_2 - 1/C_2\right]\frac{\Delta\phi_1}{\phi_1} + \left[C_1 C_2 E_1/E_2 - 1/C_1\right]\frac{\Delta\phi_2}{\phi_2} => C_2 = \frac{E_2}{C_1^2 E_1}$$

Two stage jitter compensation ex.: C1~3, C2~3, E1~300MeV, E2~10GeV

Numbers are not practical for XFEL-linacs; likely useful for 100GeV scale machine. Nonlinear terms will be important



Approaches to improved stability:

- Alternating sign and multi-stage compensation (equivalent to FODO focusing concept)
- High-Q RF (SRF) and resonant enhancement laser cavities for improved phase stability
- Passive chirpers: self induced wakes (longer bunch => smaller induced chirp)

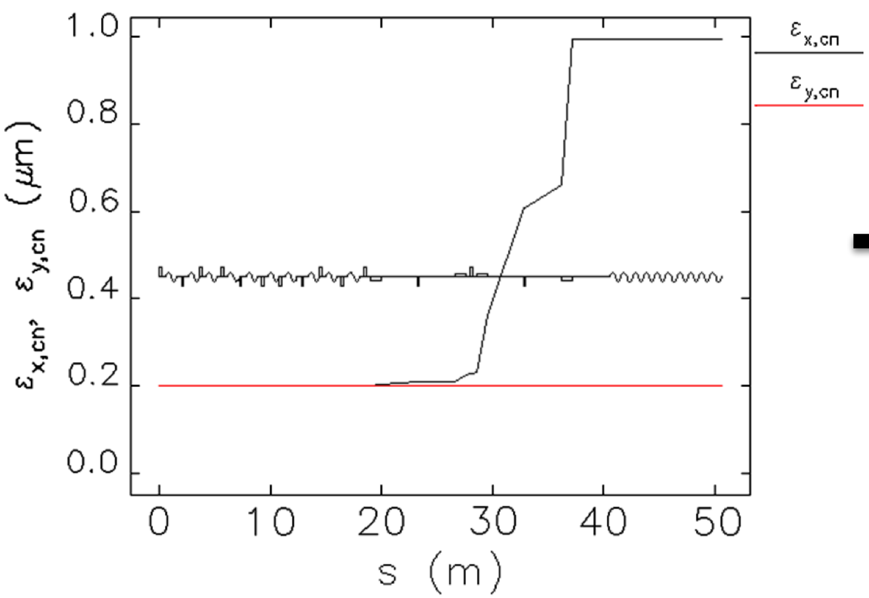
Compensating Effect of the Coherent Synchrotron Radiation (CSR) in Bunch Compressors

- CSR is a key contributor in emittance degradation for short intense bunches
  - longitudinal energy variation induced by CSR wake is coupled to the transverse plane through nonzero local dispersions in the chicane

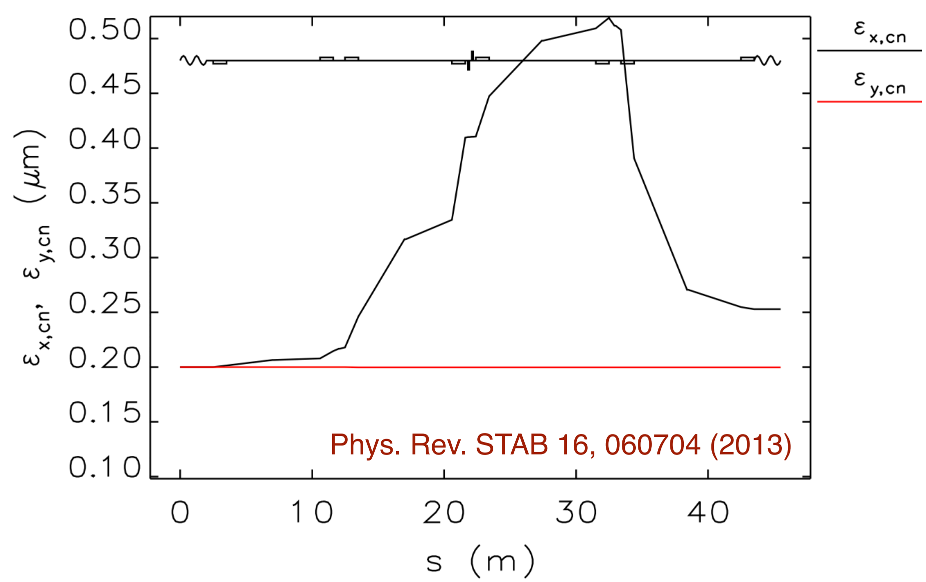
D. Douglas, JLAB-TN-98-012, 1998

- Longitudinal and transverse degrees of freedom can be decoupled and detrimental effects of CSR can be mostly suppressed by using opposite sign dispersion with reversing bending directions

Emittance blowup due to CSR with single chicane



Emittance growth compensated with two chicanes



Cancelation of CSR kicks with optics balance were simulated and tested for 10kA beams. 3D CSR theory and experiments are needed for NpQED class beams

Various Physics Opportunities Enabled by this Novel Regime of Colliding Lepton Beams in the Presence of Extreme Fields

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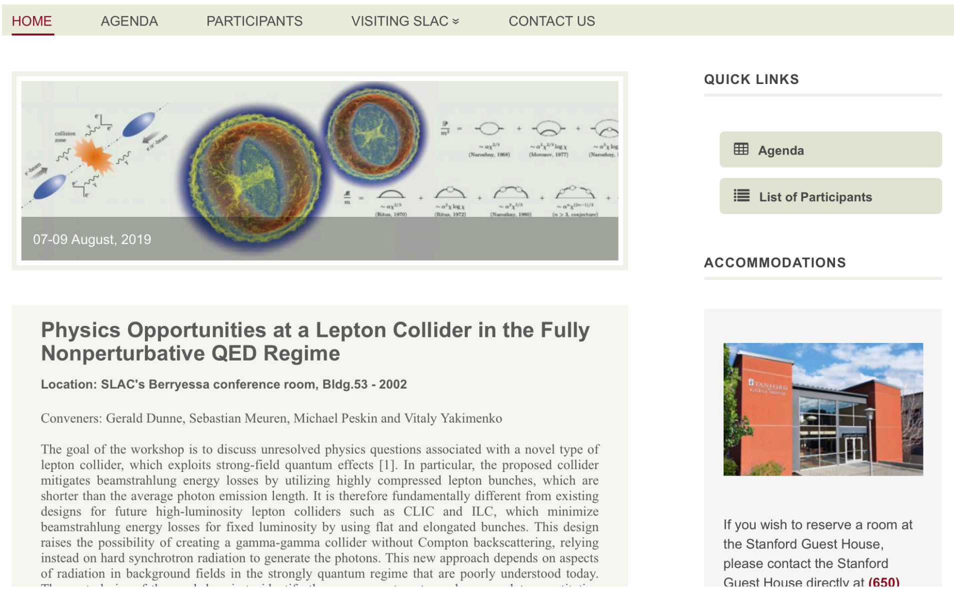

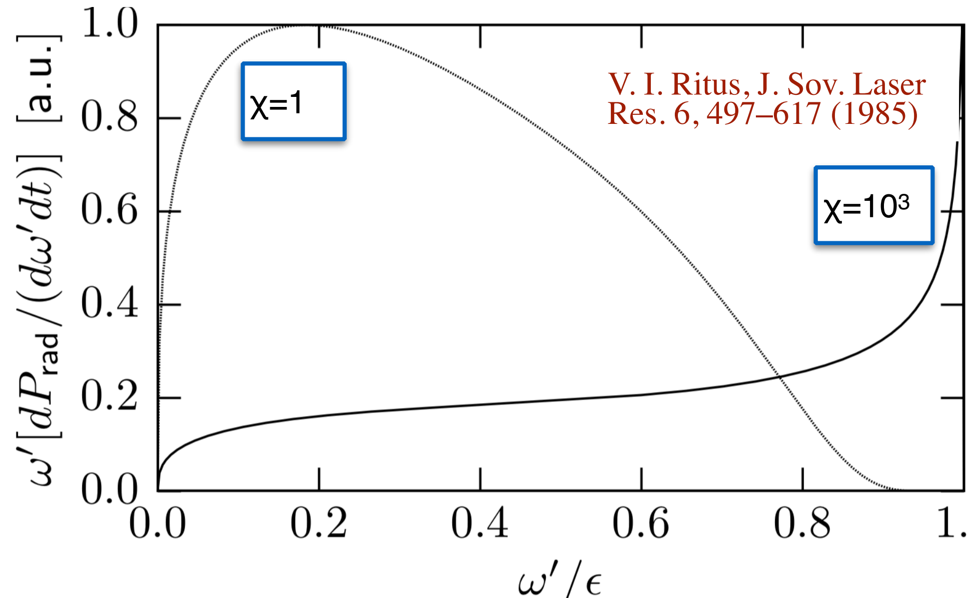

- **Laser-less γ-γ collider:** Determine which particle physics questions could be studied with such collider and at which energy scale. (ex. probe s-channel Higgs resonances, approach for future multiple-TeV scale collider etc.)
- **Fully non-perturbative QED physics:** developing framework for $\alpha\chi^{2/3} \gtrsim 1$ *and what its potentially observable features*
- **Particle physics opportunities beyond standard model:** (axions like particles, dark photons, milli-charged particles, etc.)
- **Physics of e^-e^+ pair plasma** that is created in these extreme background fields and its effects on the colliding beams

References:

NY Times: Even Physicists Don't Understand Quantum Mechanics
By Sean Carroll, Sept. 7, 2019

Prospect of Studying Nonperturbative QED with Beam-Beam Collisions,
Phys. Rev. Lett. 122, 190404 (2019)

Workshop on Physics Opportunities at a Lepton Collider in the Fully Nonperturbative QED Regime, SLAC, August 7-9, 2019