Emergency Information

Incident Notification

Life Threat

Smoke, Fire, Explosion

Large Hazardous Material Release

Call 911

Call ext. 5555

Supervisor

If in doubt, call 911 or ext. 5555

Incident Notification

Non-Life Threatening

Notify Immediately

Injury

"Off Normal" Events

(e.g., equipment damage, near misses, etc.)

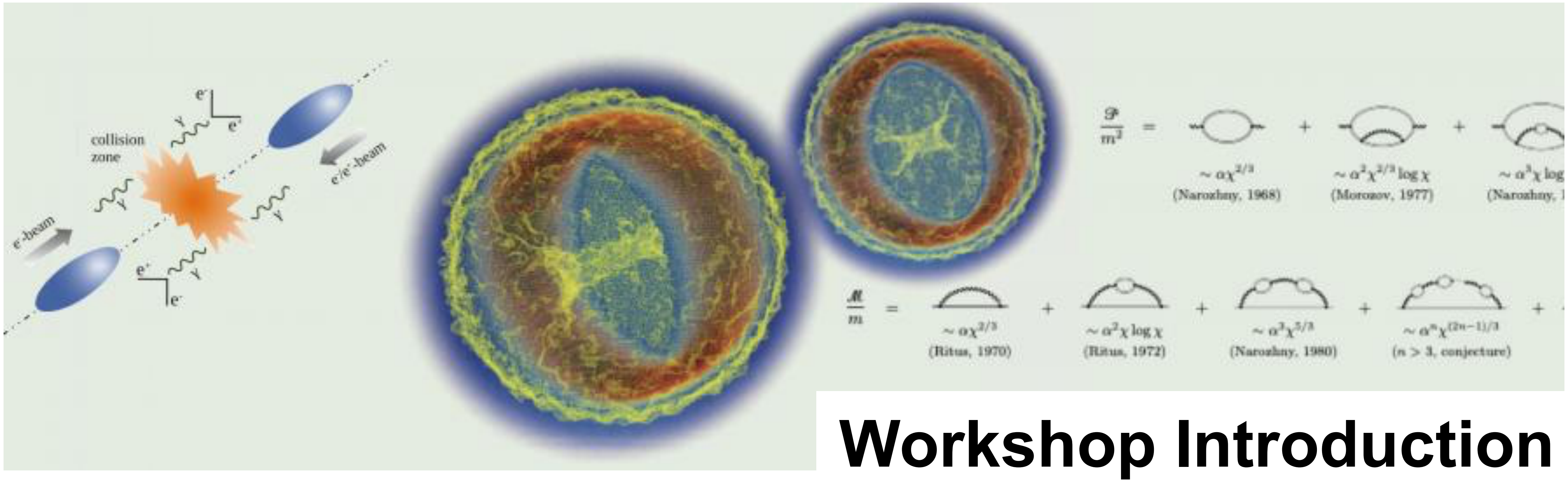
If in doubt, call 911 or ext. 5555

Fire

- Evacuate. Be aware of building exits.
- Follow building residents to the assembly area.
- Do not leave until you are accounted for, and have been instructed to.

Earthquake

- Remain in building: duck, cover, and hold position.
- When shaking stops: evacuate building via a safe route to the assembly area.
- Do not leave until you are accounted for, and have been instructed to do so.



Workshop Introduction and Concept for a Fully Non-perturbative QED Collider

Workshop on Physics Opportunities at a Lepton Collider in the Fully Non-perturbative QED Regime

Vitaly Yakimenko
August 7, 2019

Strong Field QED in Laboratory Experiments

More details in talk by
G. Dunne, A. Di Piazza,
S. Meuren

- Critical Field $E_{cr} \approx 10^{16}\ V/cm$ Critical Intensity $I_{cr} \approx 2.3 \text{ x } 10^{29}\ W/cm^2$
- Decisive Measure: electric field in the particle rest frame (E^*):

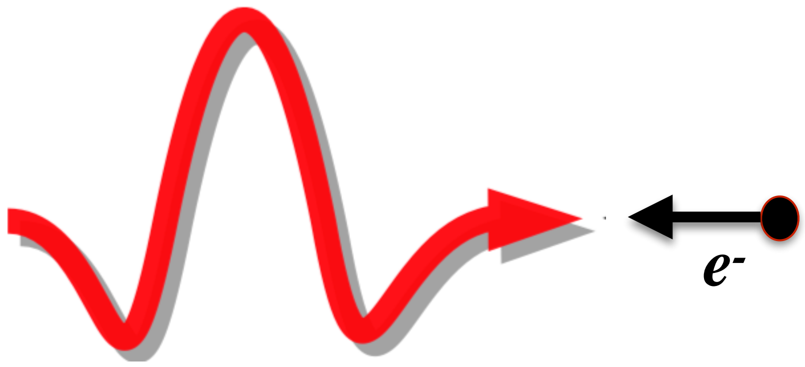
$$\chi = \frac{\sqrt{pF^2p}}{E_{cr}mc^2} = \frac{\varepsilon}{mc^2}\frac{E}{E_{cr}} = \frac{E^*}{E_{cr}}$$

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

V. N. Baier 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



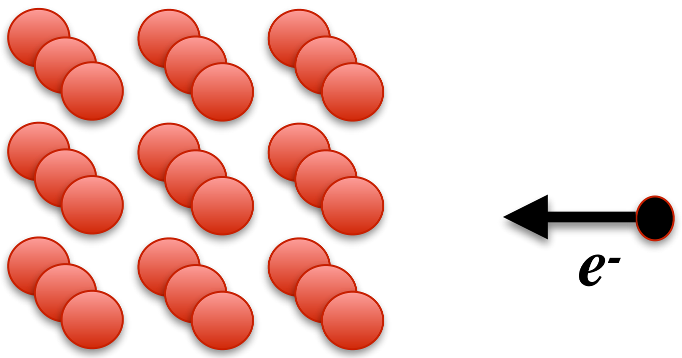
Quantum parameter

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

ε: electron energy,

I: Laser intensity

Particle-crystals interaction



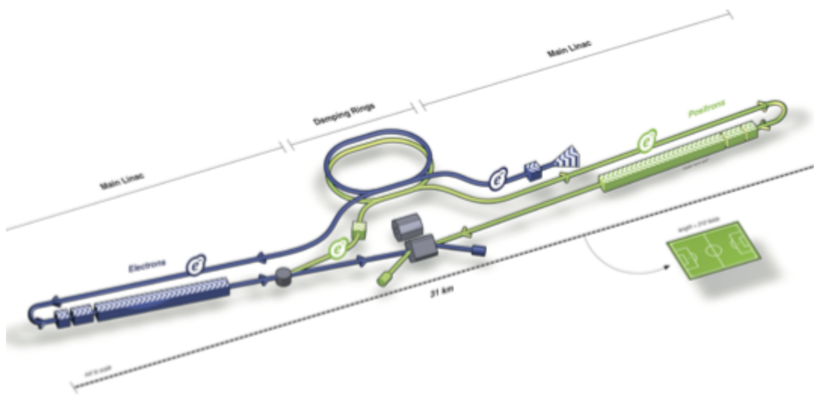
Quantum effects threshold

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

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

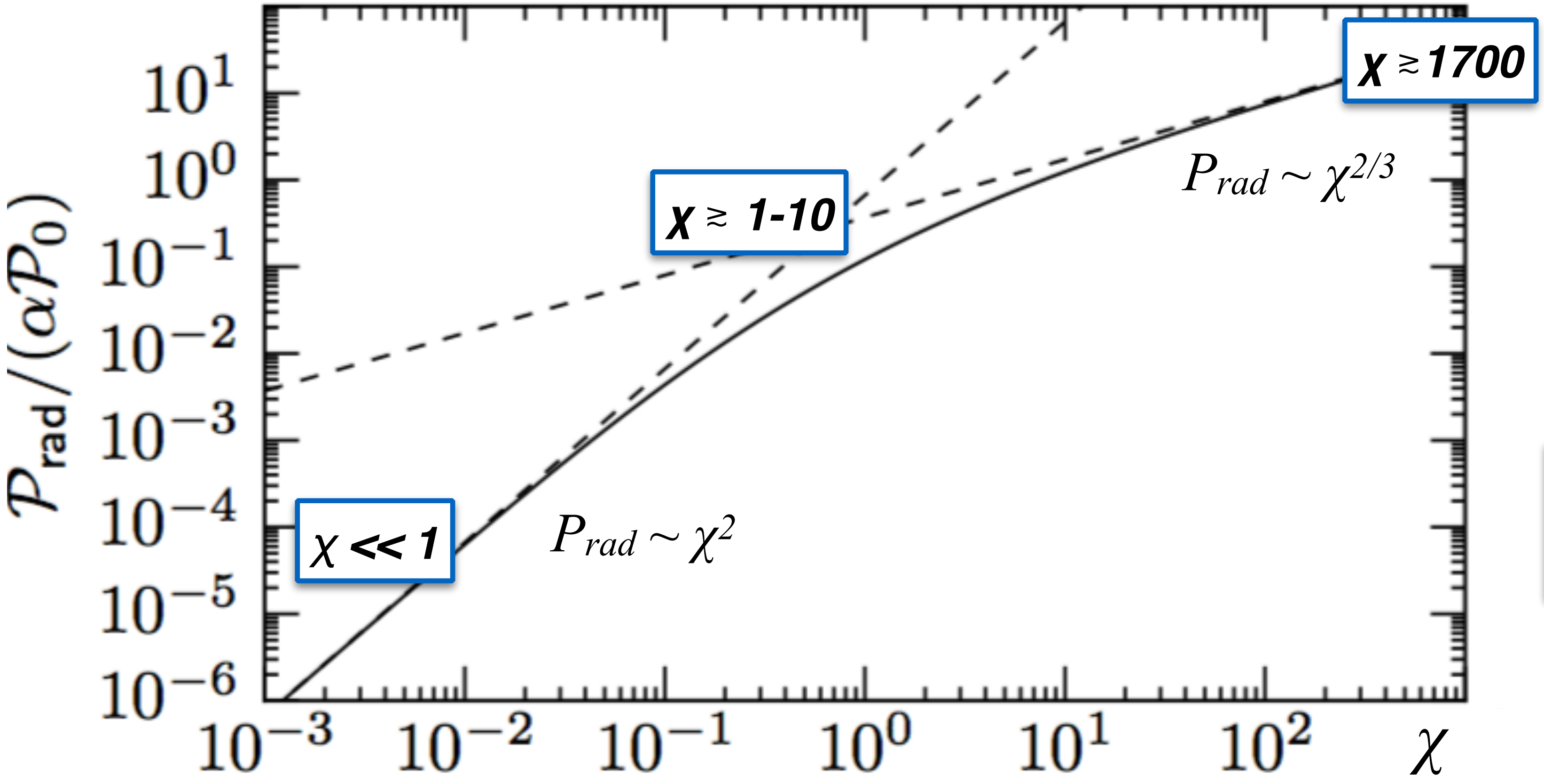
Different Scales of Strong-Field QED

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

$\chi \gtrsim 0.1, \chi \lesssim 10$: *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

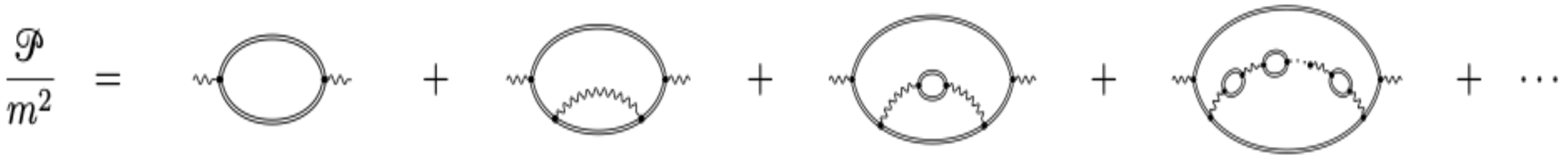


More details in talk by S. Meuren

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

<ins>**Scaling of diagrams considered so far**</ins>



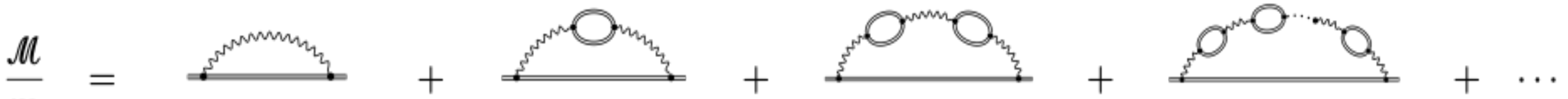
$\sim \alpha\chi^{2/3}$ (Narozhny, 1968)

$\sim \alpha^2\chi^{2/3}\log\chi$ (Morozov, 1977)

$\sim \alpha^3\chi\log^2\chi$ (Narozhny, 1980)

$\sim \alpha^n\chi^{(2n-3)/3}$ ($n > 3$, conjecture)

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);



$\sim \alpha\chi^{2/3}$ (Ritus, 1970)

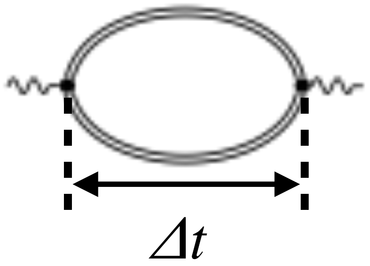
$\sim \alpha^2\chi\log\chi$ (Ritus, 1972)

$\sim \alpha^3\chi^{5/3}$ (Narozhny, 1980)

$\sim \alpha^n\chi^{(2n-1)/3}$ ($n > 3$, conjecture)

More details in talk by A. Fedotov and A. Mironov

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** m (note, $\chi \sim m^{-1/3}$),
$m_\gamma(\chi) = \alpha\chi^{2/3} m$: **breakdown of perturbation theory when** $\alpha\chi^{2/3} \gtrsim 1$ **or** $m_\gamma(\chi) > m$

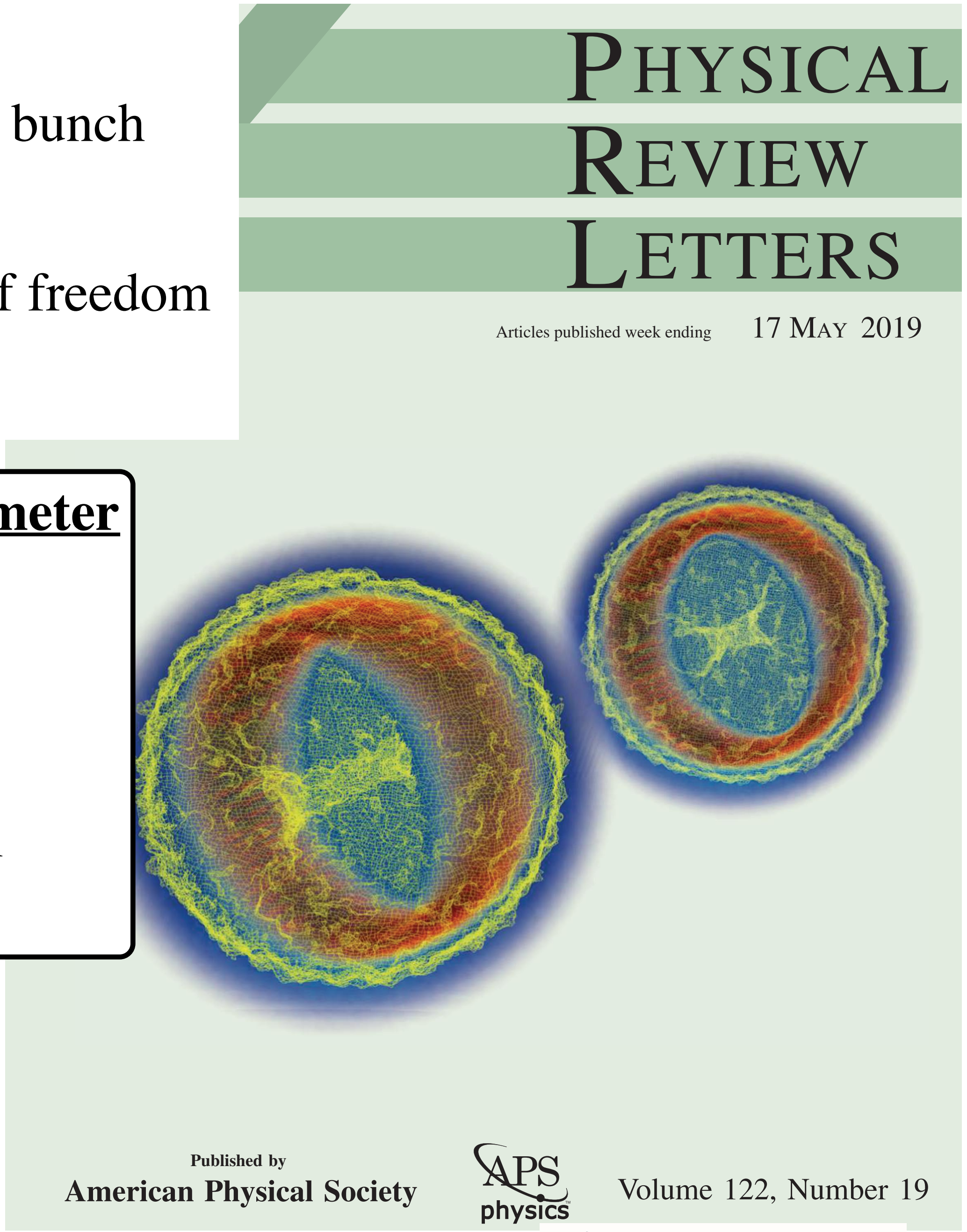
Non-Perturbative Strong Field QED Collider Parameters

SLAC

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 → three degrees of freedom
- we can simultaneously fulfill three constraints:

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



PHYSICAL REVIEW LETTERS

Articles published week ending 17 MAY 2019

Published by American Physical Society

APS physics

Volume 122, Number 19

Quantum Parameter

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

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

reaching fully non-perturbative regime

Radiation Probability

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

$$\boldsymbol{W < 1}$$

acceptable radiation loss

Disruption Parameter

$$D \approx \frac{2N\alpha\bar{\lambda}_c\sigma_z^*}{\sigma_r^2}$$

$$\boldsymbol{D < 0.01}$$

small disruption

NpQED Collider scale

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

SLAC

PRINCETON UNIVERSITY

TÉCNICO LISBOA

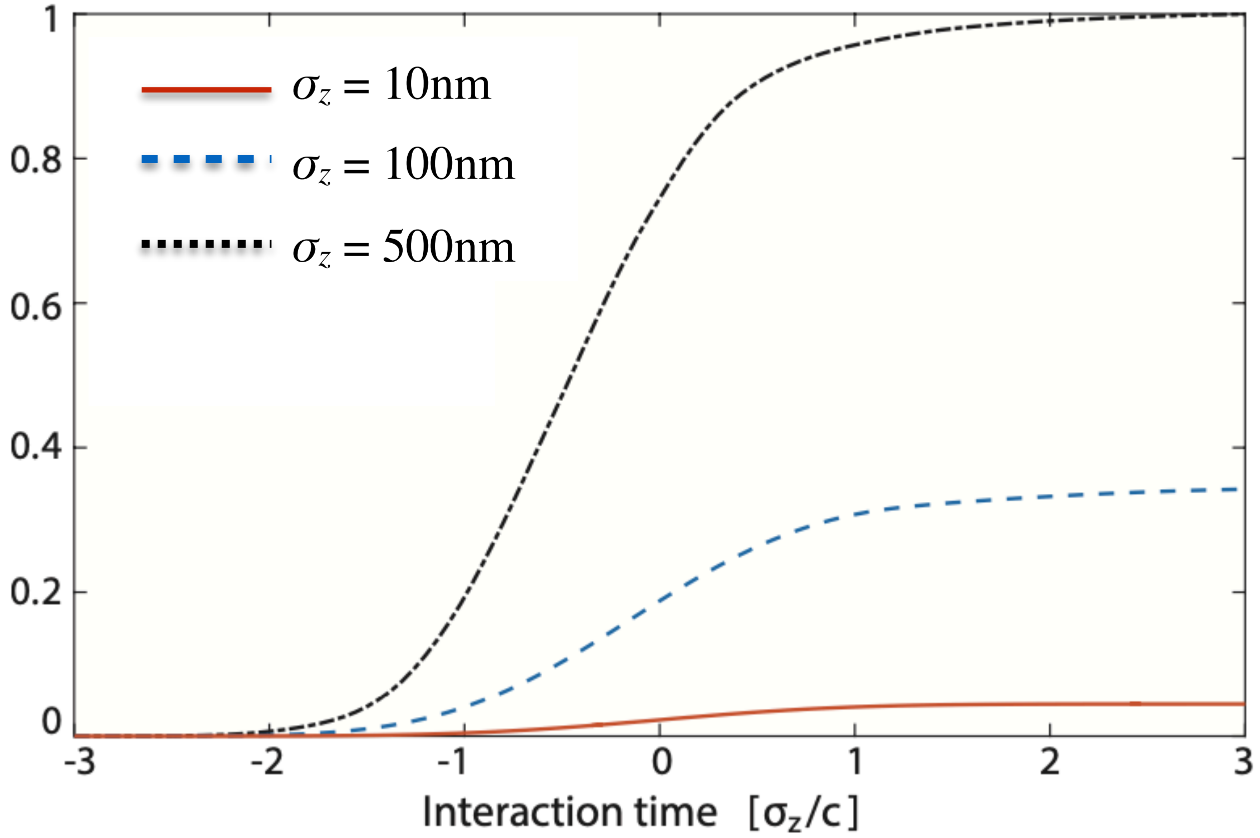
MEPhI

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

Hierarchy of Numbers that Enables NpQED Collider

- Radiative lifetime (125GeV, $\chi \sim 1700$): $L_E \sim \gamma \bar{\lambda}_c / (\alpha \chi^{2/3}) \sim 100\ nm$
  (length to emit hard photon with probability ~1)
- Field switching (bunch) length: $\sigma_z \sim 10\ nm$
- Formation length for hard photon: $L_f \sim \alpha L_E \sim 1\ nm$

Simulations of relative energy loss:



This hierarchy ensures:

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

More details in talk by G. Dunne and A. Ilderton

Linear Collider Luminosity Optimization

Beam Power

Number of particles per bunch

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

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

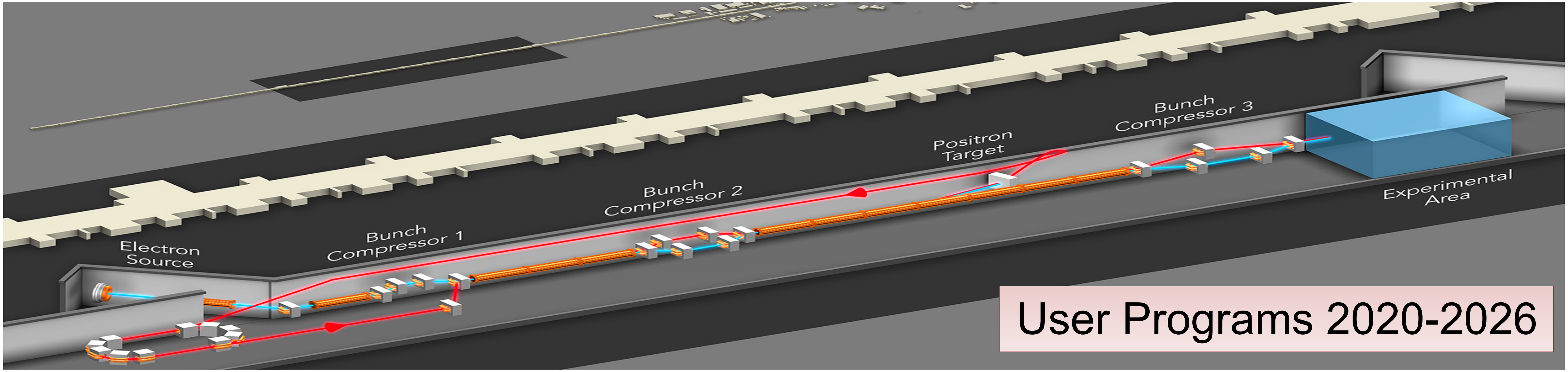
Normalized vertical emittance

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**	

Present Linear Colliders designs use increased transverse beam size (flat bunches) to manage beamstrahlung

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

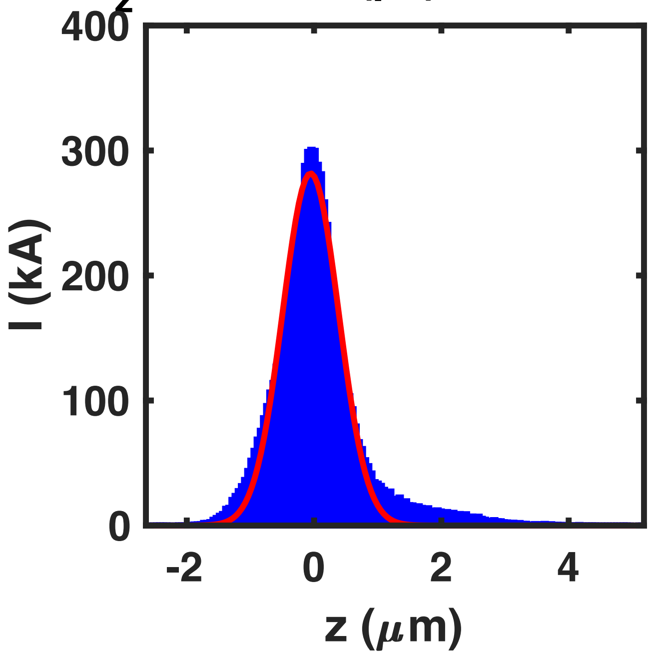


User Programs 2020-2026

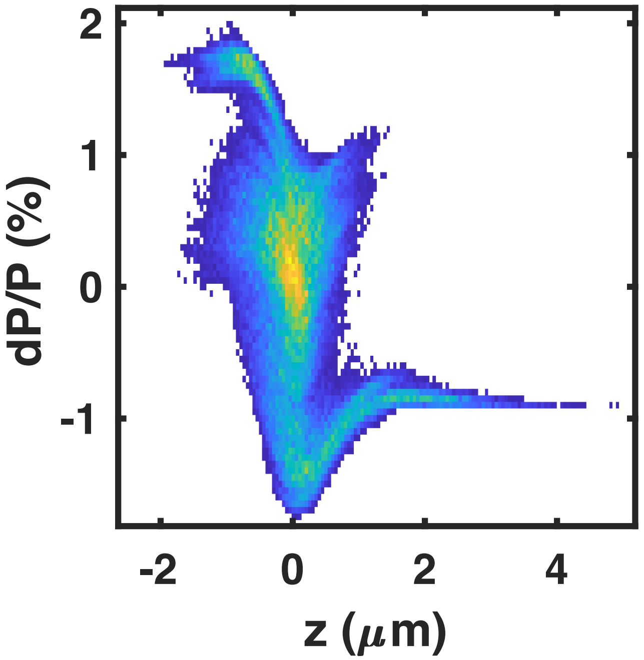
Low-emittance (state of the art photoinjector) and ultra-short (improved compression) beam will generate:

- >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

σ_z = 0.4 um I(pk) = 300.65 kA

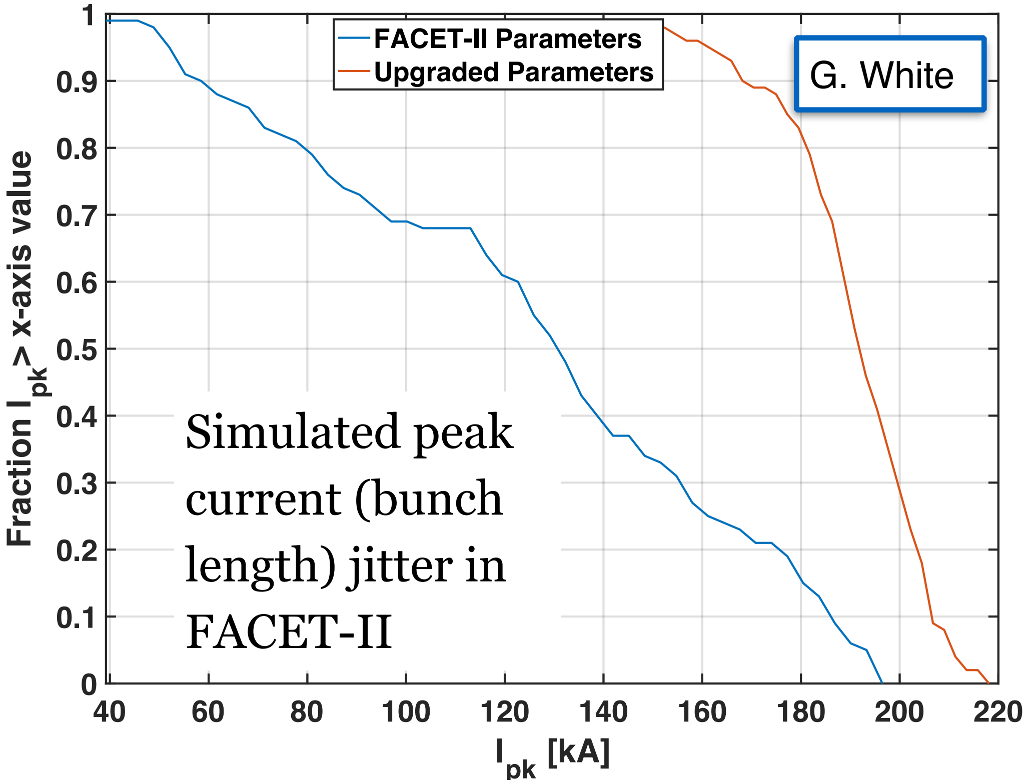


Mean Energy = 9.998 GeV



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

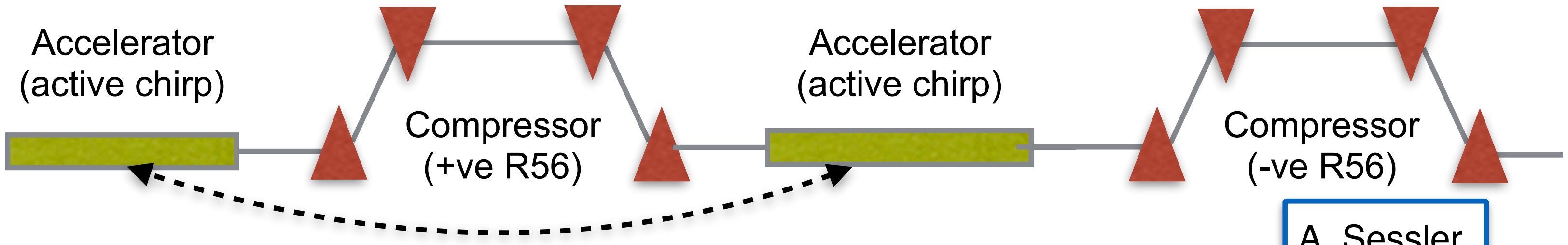
Working Group to Study Challenges Associated with “Extreme” Compression: Stability of the Compression



Simulated peak current (bunch length) jitter in FACET-II

G. White

Compensation of phase jitter impact on bunch length:

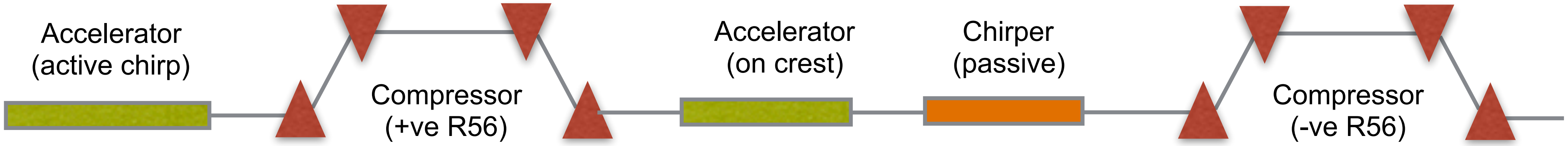


A. Sessler
C. Emma

$$\frac{\Delta\sigma_z}{\sigma_z} = \left[C_1^2E_1/E_2 - 1/C_2\right]\frac{\Delta\phi_1}{\phi_1} + \left[C_1C_2E_1/E_2 - 1/C_1\right]\frac{\Delta\phi_2}{\phi_2} \quad => \quad C_2 = \frac{E_2}{C_1^2E_1}$$

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)

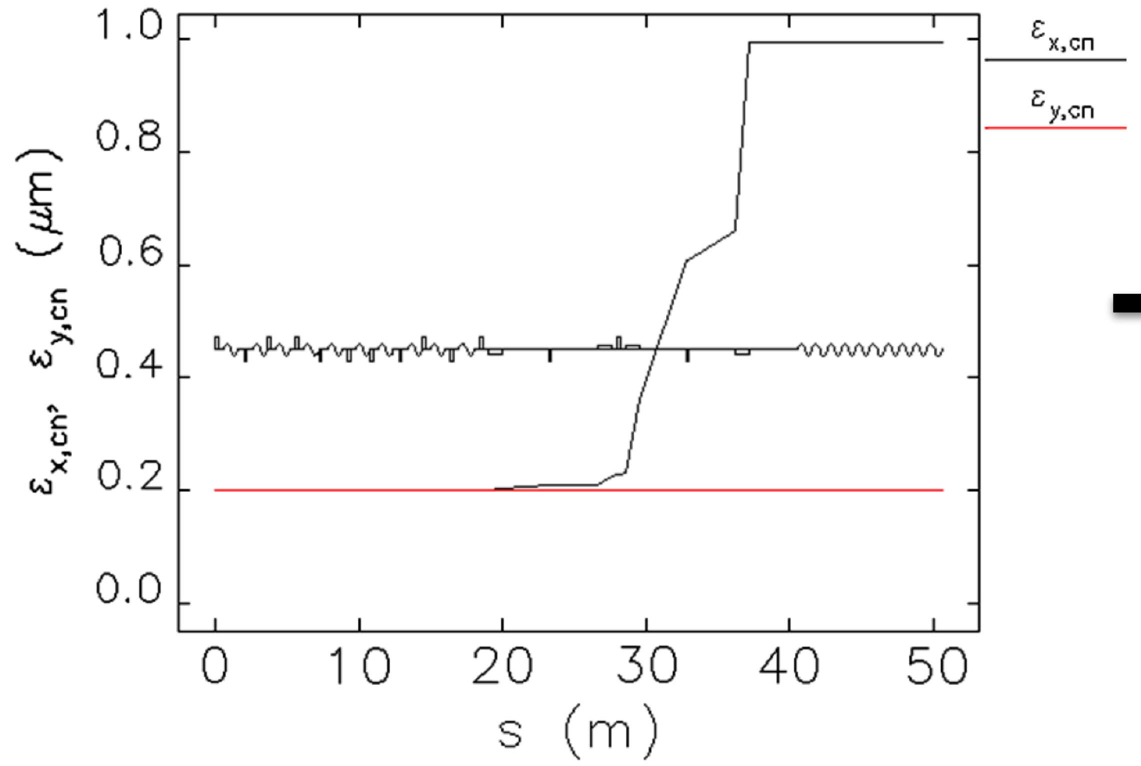
Compensating Effect of the Coherent Synchrotron Radiation (CSR) in Bunch Compressors

- 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

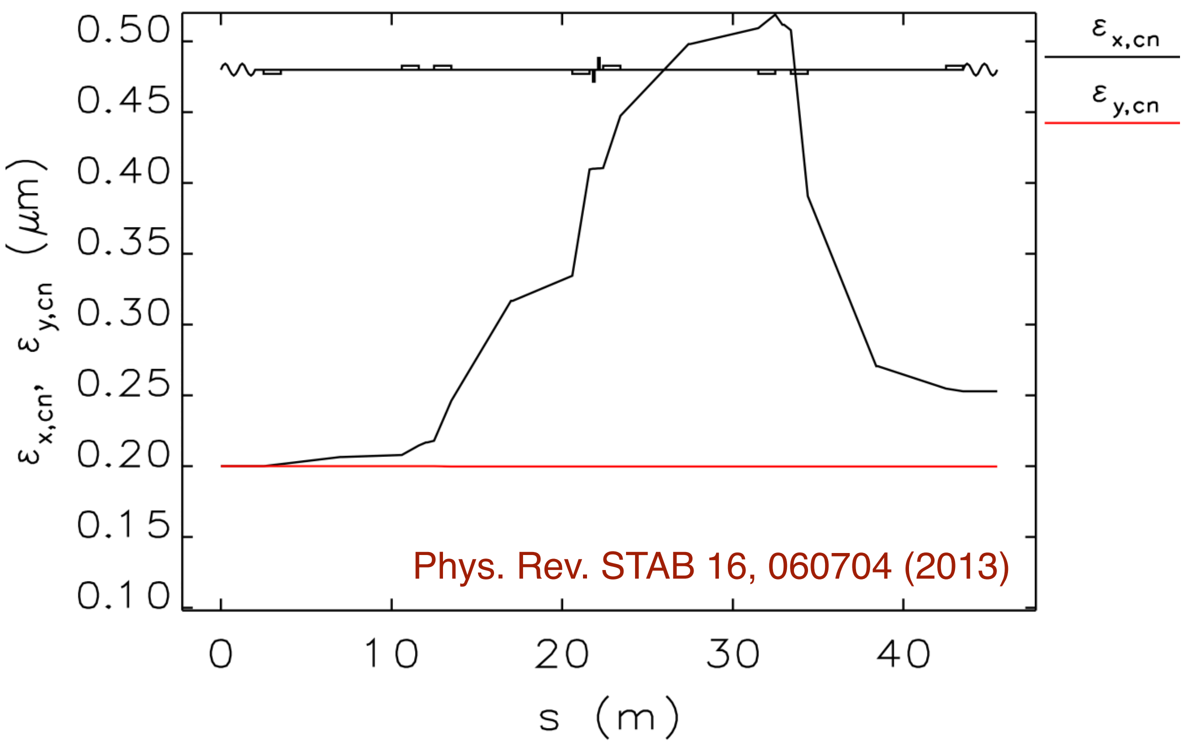
D. Douglas, JLAB-TN-98-012, 1998

- 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



Phys. Rev. STAB 16, 060704 (2013)

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

Merging high-energy, high transverse quality beams of linear collider designs with high peak-compression

Source: NpQED physics is mostly equivalent for either e^-e^- or e^-e^+ collisions

- first option mitigates the challenge of generating e^+ with longitudinal brightness.
- next-generation cryo-photoinjectors promise factor >4 improvement in emittance: ~35μm at 100pC => focusing requirements same as the CLIC design (in the vertical plane)

Accelerators:

- Cryogenically cooled high gradient technology is attractive due to low average beam power requirement and will address tight phase stability requirement with High Q designs

Compression: The required bunch compression extends the current state-of-the-art as expressed by the FACET-II design by a factor of ~10.

- Stability and beam quality preservation are the key challenges

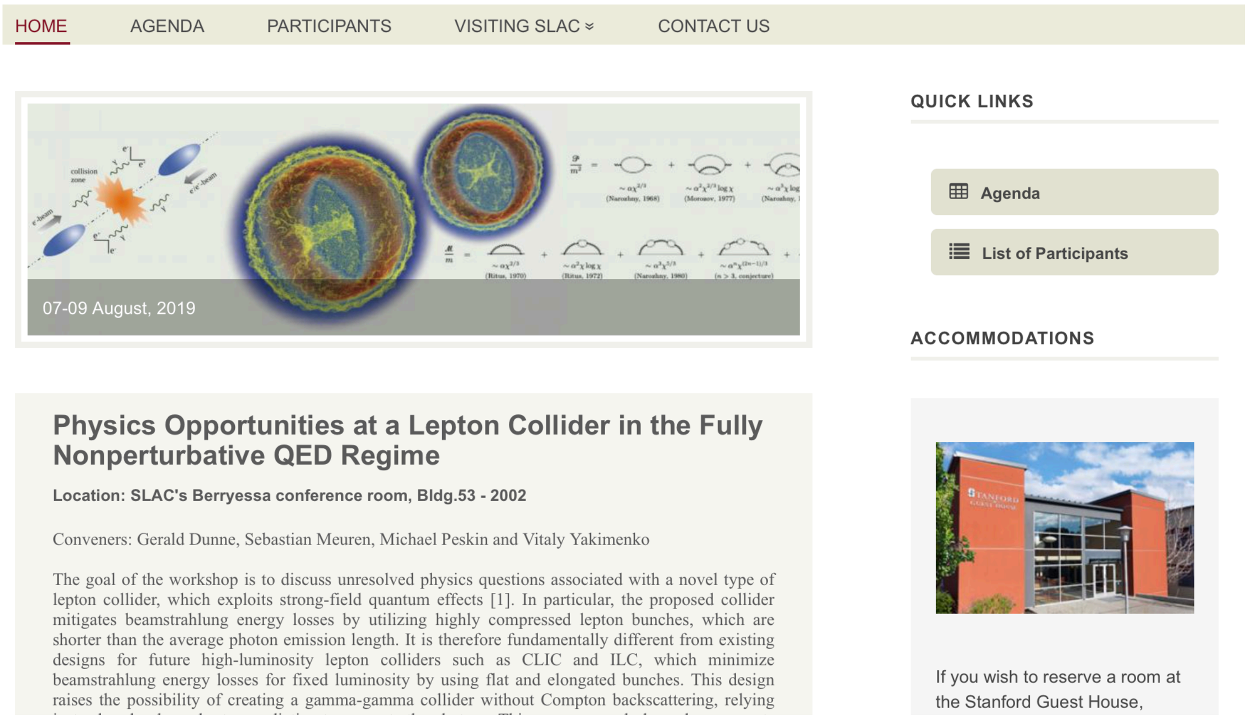
Final Focus and Beam Delivery System: The final focus system can be based on the CLIC design, with similar focusing requirements.

- Combining round-beam focusing together with the required chromaticity compensation presents a unique challenge

There are number of ideas on how to deal with accelerator design challenges.
Strong physics case is needed to justify accelerator R&D efforts

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

https://conf.slac.stanford.edu/npqed-2019/



07-09 August, 2019

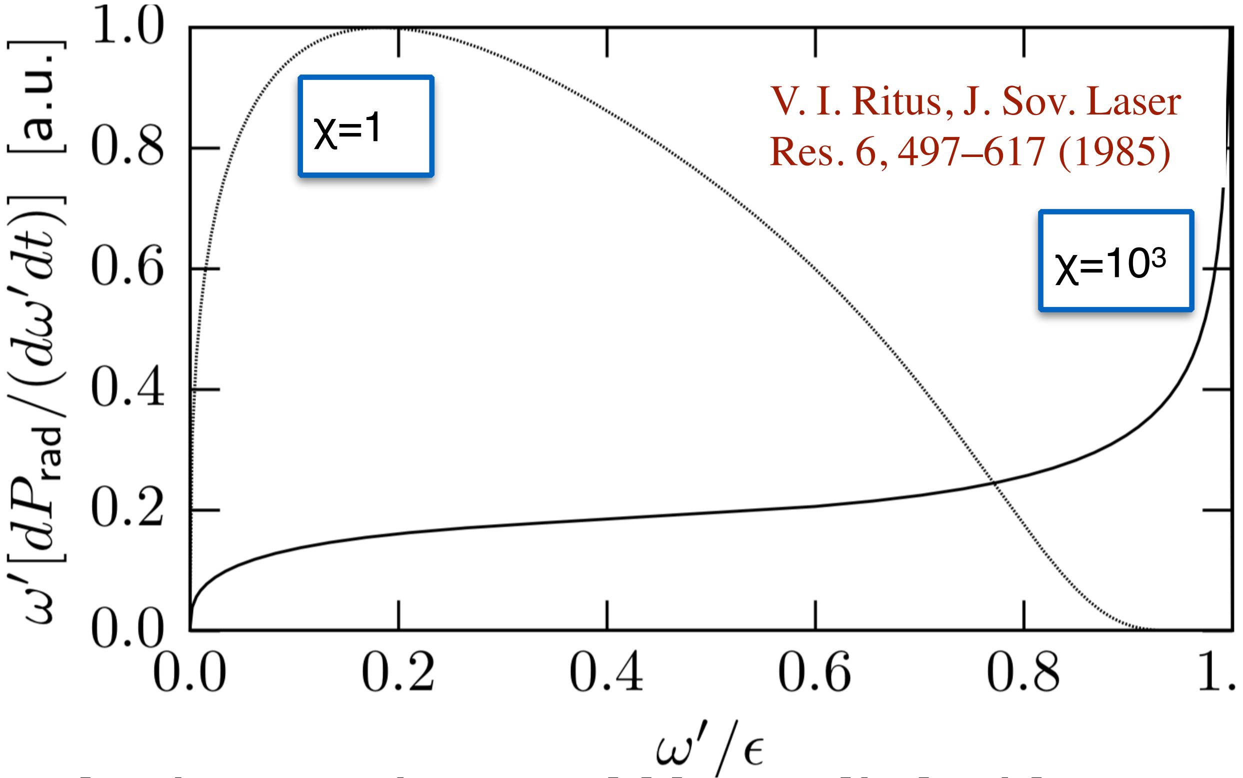
Physics Opportunities at a Lepton Collider in the Fully Nonperturbative QED Regime

Location: SLAC's Berryessa conference room, Bldg.53 - 2002

Conveners: Gerald Dunne, Sebastian Meuren, Michael Peskin and Vitaly Yakimenko

The goal of the workshop is to discuss unresolved physics questions associated with a novel type of lepton collider, which exploits strong-field quantum effects [1]. In particular, the proposed collider mitigates beamstrahlung energy losses by utilizing highly compressed lepton bunches, which are shorter than the average photon emission length. It is therefore fundamentally different from existing designs for future high-luminosity lepton colliders such as CLIC and ILC, which minimize beamstrahlung energy losses for fixed luminosity by using flat and elongated bunches. This design raises the possibility of creating a gamma-gamma collider without Compton backscattering, relying

If you wish to reserve a room at the Stanford Guest House,



V. I. Ritus, J. Sov. Laser Res. 6, 497–617 (1985)

- **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.)

  More details in talk by M. Tamburini

- **Fully non-perturbative QED physics:** developing framework for $\alpha\chi^{2/3} \gtrsim 1$ and what its potentially observable features

  More details in talk by A. Fedotov and A. Mironov

- **Particle physics opportunities beyond standard model:** (axions like particles, dark photons, milli-charged particles, etc.)

  More details in talk by S. Ellis

- **Physics of e^-e^+ pair plasma** that is created in these extreme background fields and its effects on the colliding beams

  More details in talk by L. O’Silva, D. Reis

Agenda (Wednesday, August 7):

Start Time	Title	Presenter	Affiliation
08:00 am	Workshop introduction, concept for a fully nonperturbative QED collider	Vitaly Yakimenko	SLAC
Session on Introductory Quantum Field Theory			
08:30 am	Formalism for beamstrahlung in quantum regime	Michael Peskin	SLAC/Stanford University
09:15 am	Non-perturbative methods for strong-field physics	Gerald Dunne	University of Connecticut
10:00 am	**Coffee**		
10:15 am	Perturbation theory in strong field QED	Antonino Di Piazza	MPIK Heidelberg
Session on Fully Nonperturbative QED			
11:00 am	The Ritus-Narozhny conjecture: history and re-summation of QED radiative corrections in a strong constant crossed field	Alexander Fedotov and Arseny Mironov	MEPhI
11:45 am	Photon emission probability beyond tree level: possible approaches and review of the literature	Sebastian Meuren	Princeton University
12:30 pm	**Lunch**		
01:30 pm	Nonperturbative calculations and open problems of QED in	Anton Ilderton	University of Plymouth
02:15 pm	Trident pair production and double Compton scattering in SF	Greger Torgrimsson	Helmholtz Institute Jena
03:00 pm	**Coffee**		
03:15 pm	Euler-Heisenberg effective action beyond leading order	Felix Karbstein	Helmholtz Institute Jena
Session on Techniques and Applications in Other Fields			
04:00 pm	Dimensional reduction and catalysis of dynamical symmetry breaking by a magnetic field	Igor Shovkovy	Arizona State University
05:30 pm	**Reception**		

Agenda (Thursday, August 8):

Start Time	Title	Presenter	Affiliation
08:00 am	Potentially relevant techniques from QCD/Lattice	Lance Dixon	SLAC/Stanford University
08:45 am	Real-time evolution of lattice gauge theories in the classical-statistical regime	Valentin Kasper	Harvard University
09:30 am	Strong field effects in heavy ions collisions (critical magnetic	Kirill Tuchin	Iowa State University
10:15 am	**Coffee**		
10:30 am	Connection of strong field and fully nonperturbative QED physics to astrophysics and cosmology	Peter Meszaros	Penn State University
11:15 am	Non-Perturbative QED to go Beyond the Standard Model	Sebastian Ellis	SLAC/Stanford University
12:00 PM	**Lunch**		
Session on Experimental Tests			
1:00 PM	Plans for strong field QED experiments around the world with high intensity laser	Alexander Thomas	University of Michigan
01:45 pm	Plans for strong field QED experiments at FACET-II	David Reis	SLAC/Stanford University
02:30 pm	Strong-field QED physics enabled by FELs	Claudio Pellegrini	SLAC
03:15 pm	**Coffee**		
Session on Simulations			
03:30 pm	History and theory of beam-beam interactions in linear	Pisin Chen	National Taiwan University
04:15 pm	QED implementation and simulations with PIC codes	Luis O. Silva	Instituto Superior Tecnico
05:00 pm	Strong-field QED simulations beyond the local constant field approximation	Matteo Tamburini	MPIK Heidelberg

Agenda (Friday, August 9):

Start Time	Panel discussion	Panel members
08:30 am	Questions towards theory and plasma physics: Which are the open questions about e+e- plasmas, SFQED calculations, especially related to non-perturbative effects, how well are simulations connect to the calculations, next questions to be answered?	Gereld Dunne Anton Ilderton Sebastian Meuren Luis O. Silva
10:00 am	**Coffee**	
10:15 am	Questions towards high-energy physics applications: What do we need to know to propose a gamma-gamma collider for a Higgs factory, how do we justify the strong-field physics that makes that possible, to what extend will scheduled experiments test that this physics is correct, is there a gap and what further experiments are needed to bridge it?	Claudio Pellegrini Michael Peskin Alexander Thomas Vitaly Yakimenko

The central goal is to identify steps towards complete quantitative understanding of radiation in extremely strong background fields and its application that will be adequate for a proposal for the dedicated facility

Workshop presentations and discussions will be summarized by the conveners
Summary and submitted presentations will be available on the Website

Summary:

New capability	What is enabled
Tightly focussed and compressed high charge bunches	Extreme field in the laboratory frame
	Strong Field sector of QED: field of the bunch is probed by laser or x-rays beams
	Beyond standard model physics: search for dark sectors, i.e. dark photons and "millicharged particles”
	Plasma physics enabled by extreme densities of the charge particle beam
Beamstrahlung suppression with short bunches	Linear collider with round bunches, reduced beam power requirement, path to very high energies particle physics
	Ability to probe extreme fields while preserving initial energy
High energy electrons experience extreme field of opposite bunch	Fully Non-perturbative QED physics
	e^+e^- cascades, collective plasma-beam effects, astrophysics
	Beamstrahlung spectrum is peaked at full energy, path to γ/γ collider without laser backscattering, path to very high energies
	Beyond standard model physics (axion-like particles, dark sectors, etc.)