SLAC NATIONAL ACCELERATOR LABORATORY

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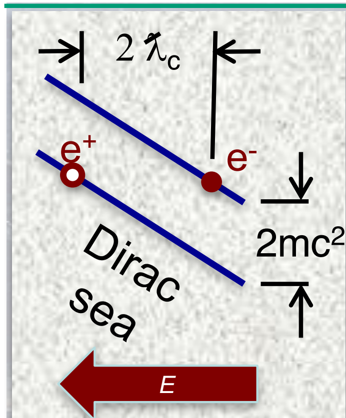

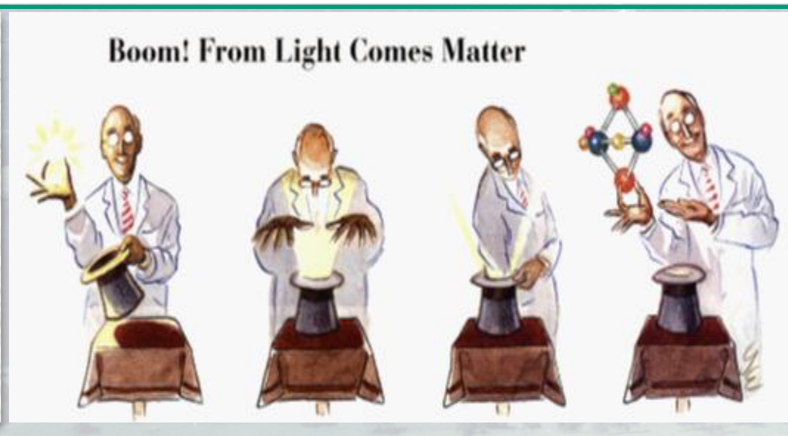

Strong-field QED opportunities on FACET-II

David A. Reis
Stanford PULSE Institute
Departments of Applied Physics and Photon Science

Strong-field QED@SLAC Working group

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- AMO: Bucksbaum and Reis
- Astrophysics and Cosmology: Abel and Blandford
- HEDS: Fiuza and Glenzer
- Accelerator: Hogan and Yakimenko
- FEL: Huang and Pellegrini
- Laser: Fry
- HEP: Brodsky

- Strong-field QED theory: Meuren (Princeton)

Quantum Electrodynamics (QED)

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- **Relativistic quantum field theory describing light-matter interaction including quantum vacuum**
- **Most precisely tested theory in weak field regime, perturbative in $\alpha \sim 1/137$**
  - Lamb Shift
  - Anomalous magnetic moment
- **Few tests in multiphoton regime (pair production, birefringence of vacuum…)**
- **strong-field, non-perturbative sector untested and theoretically challenging.**

QED Critical Field ("Schwinger Field")

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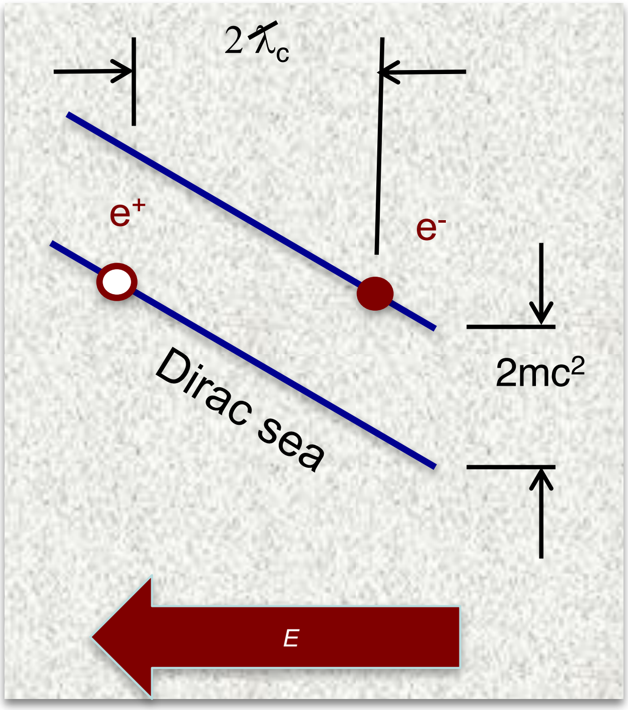
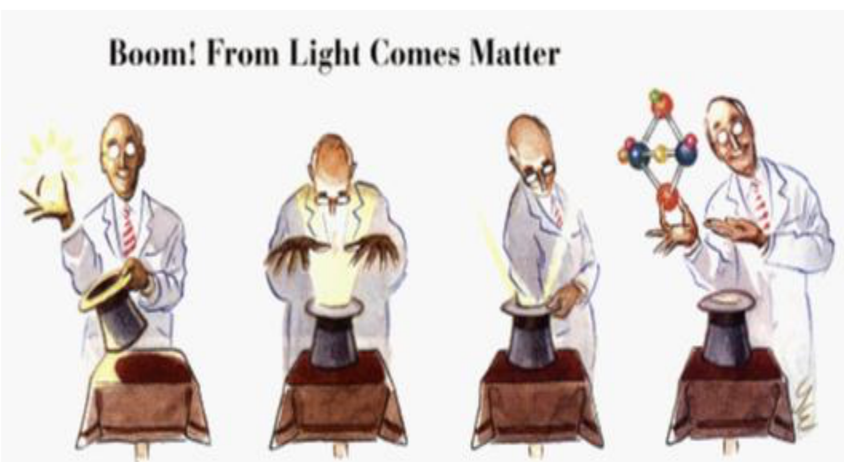




Photonics Spectra, Nov. 1997

- Materialize pairs when work done in (reduced) Compton wavelength equal rest mass $eE_{cr}\lambdabar_c = mc^2$

$$E_{cr} = \frac{m^2c^4}{e\hbar c} = 1.3 \times 10^{16}\mathrm{V/cm}$$

(four orders higher for $\mu^+\mu^-$)

- Exponentially suppressed $E < E_{cr}$
- Critical intensity for EM-field (peak):

$$I_{cr} = 4.6 \times 10^{29}\mathrm{W/cm}^2$$

- Need to also conserve momentum (not possible in single plane-wave)

Sauter (1931), Euler, Heisenberg, Schwinger

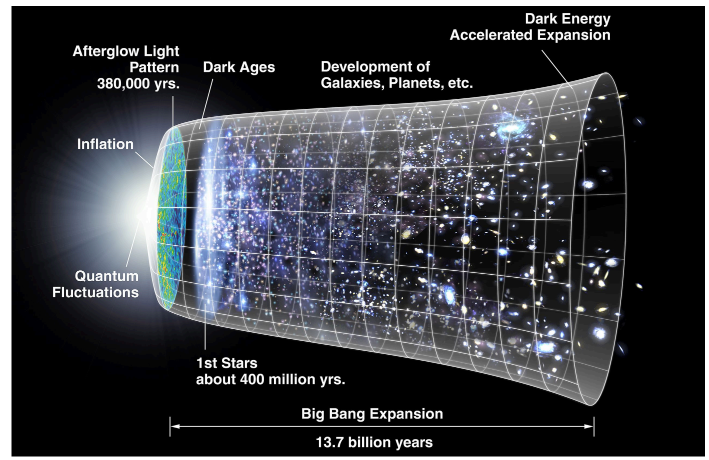
Why care about strong-field QED

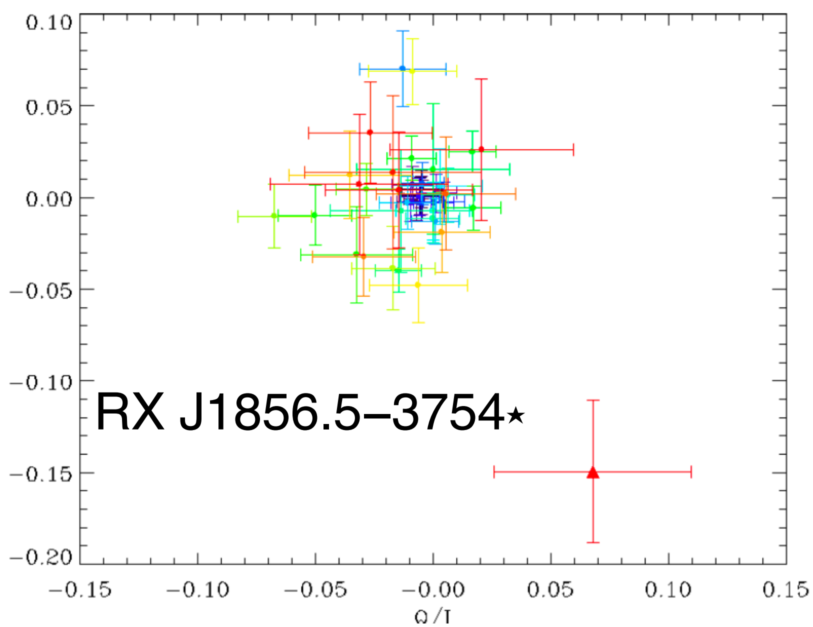
- **Astrophysical phenomena** (highest energy cosmic rays, gamma-ray bursts, neutron stars, …)
- **Unruh radiation, radiation reaction, electron-positron plasmas, relativistic positronium, axions, …?**
- **New phenomena in *much* stronger-fields than can achieve in Atomic and Molecular Physics.**
- **Can get there with existing technology but cannot calculate what we will see…**

Cosmology and astrophysics

- emission of coherent radio waves in pulsars/ x rays in magnetars, g amma ray bursts…

- electron-photon decoupling primordial nucleosynthesis





- Hints of vacuum birefringence in optical polarimetry of neutron stars

R. P. Mignani et al. *MNRAS*, 465, 2017.

Analogy: regimes of atomic ionization

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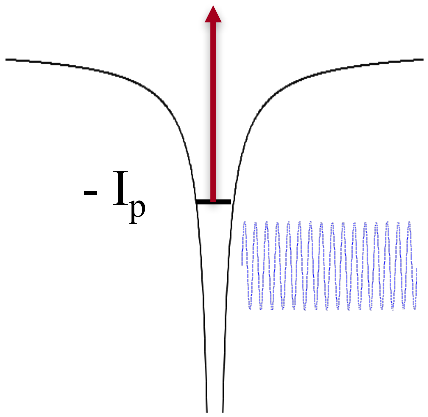
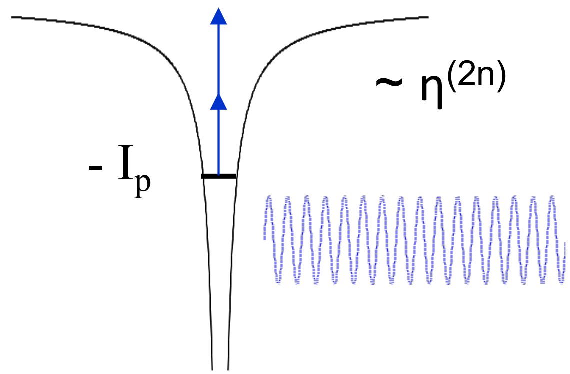
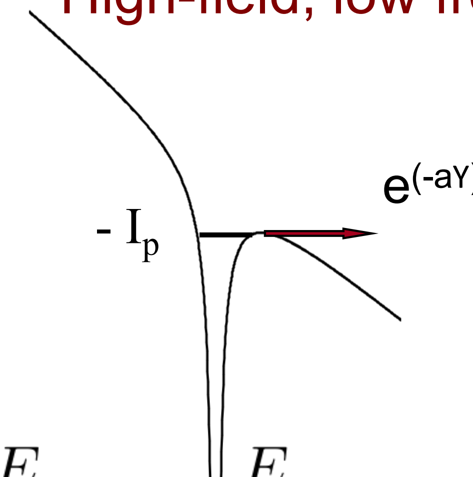
Photoionization/
linear Breit-Wheeler
Above threshold



Multi-photon Ionization
Nonlinear Breit-Wheeler
High field, below threshold



Tunneling
Schwinger breakdown
High-field, low frequency



$$\eta = \frac{eE}{m\omega c}, \Upsilon = \frac{E}{E_c}$$

Transition depends on both field and frequency

atomic:

$$\omega > 13.6eV(\mathrm{H})$$

$$\sigma_{\max} \sim a_0^2 \approx 25 \text{ Mb (H)}$$

pairs:

$$\sqrt{\omega_1\omega_2(1-\cos\theta)} > 2mc^2 = 1 \text{ MeV}$$

$$\sigma_{\max} \sim r_e^2 \approx 80 \text{ mb}$$

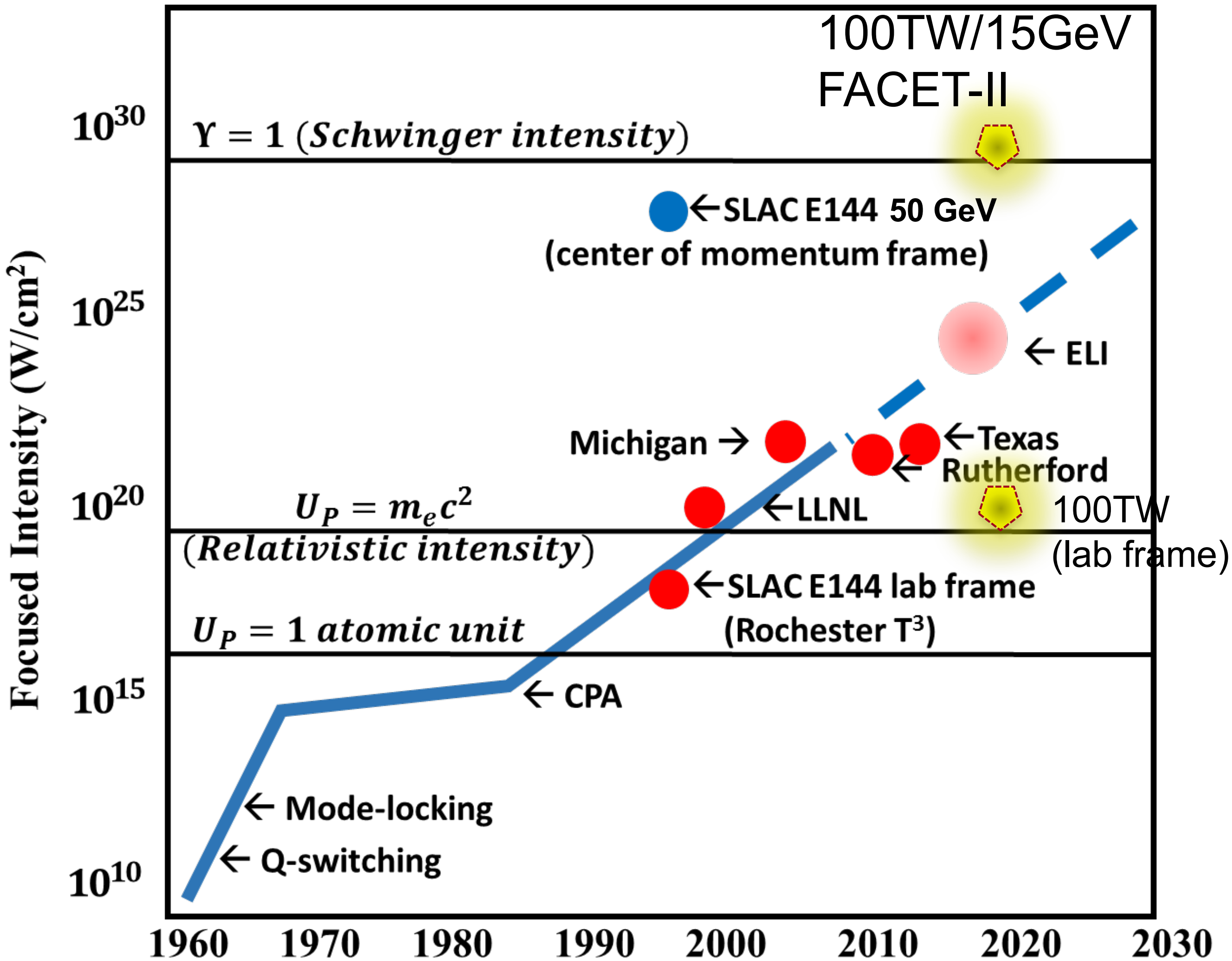
atomic

$$E_c = \alpha^4 mc^2/r_e = 2I_P/a_0 = 5\times 10^9 \mathrm{V/cm}$$

vacuum

$$E_c = \alpha mc^2/r_e = I_P/\lambda_c = 1.3\times 10^{16} \mathrm{V/cm}$$

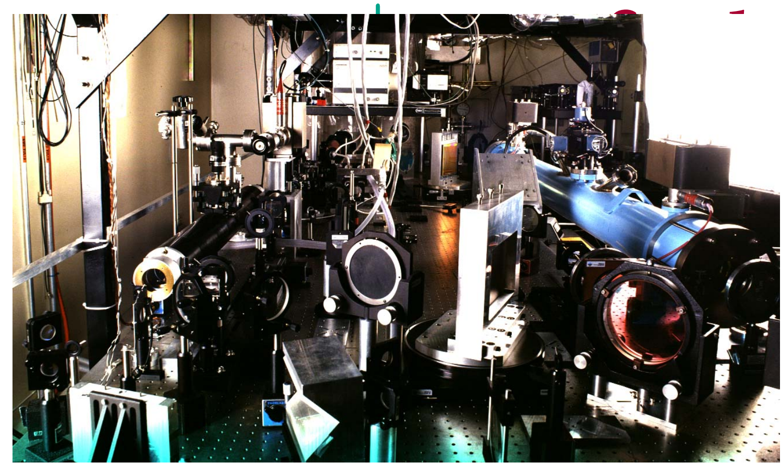
Focused Intensity Frontier

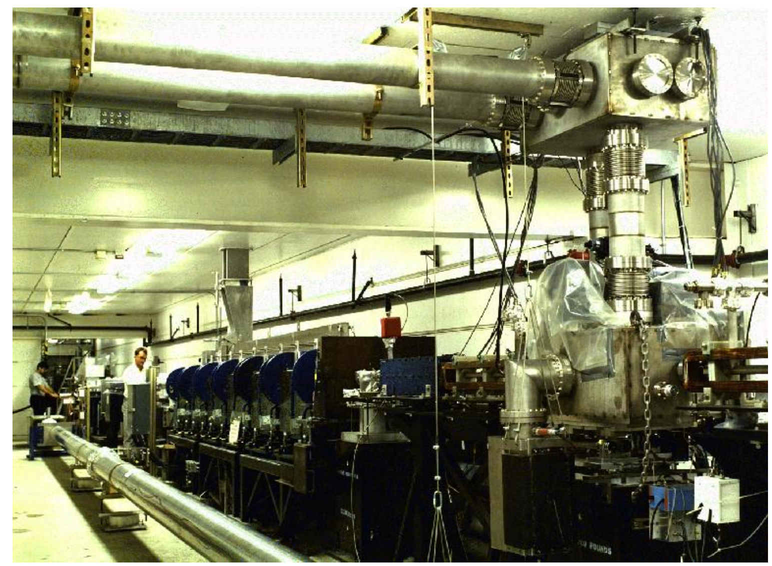


- Strong-field and collective phenomena accessible above QED critical intensity/field
- Current (future) light sources far from this limit in laboratory frame.
- Only possible by combining high energy particles with laser (relativistic boost)
  - $4\gamma^2$ intensity
  - 2γ field

Nonlinear Compton/pair production (SLAC E144, ca. 1997)

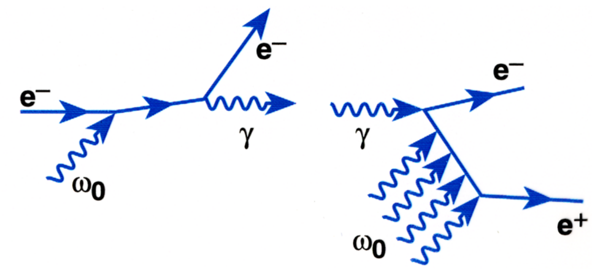
Front row: G. Horton-Smith, Th. Kotseroglou, W. Ragg, S. Boege
Middle row: D. Meyerhofer, W. Bugg, A. Weidemann,
D. Walz, J.Spencer, K.McDonald, A. Melissinos
Last row: K. Shmakov, C. Bamber, U. Haug, D.Burke, C.Bula
Absent: S. Berridge, C. Field, Th. Koffas, E. Prebys, D.Reis





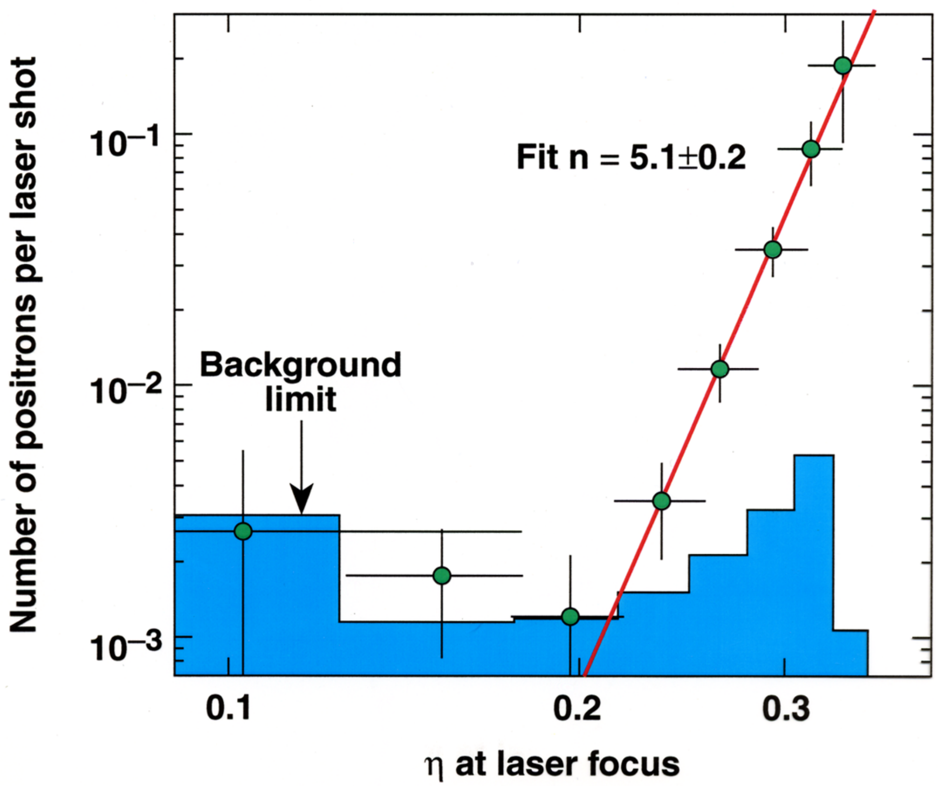
D.L.Burke et al, PRL79 1626(1997)
C.Bamber et al, Phys.Rev. D60 090024(1999)

E144 Measured in transition regime



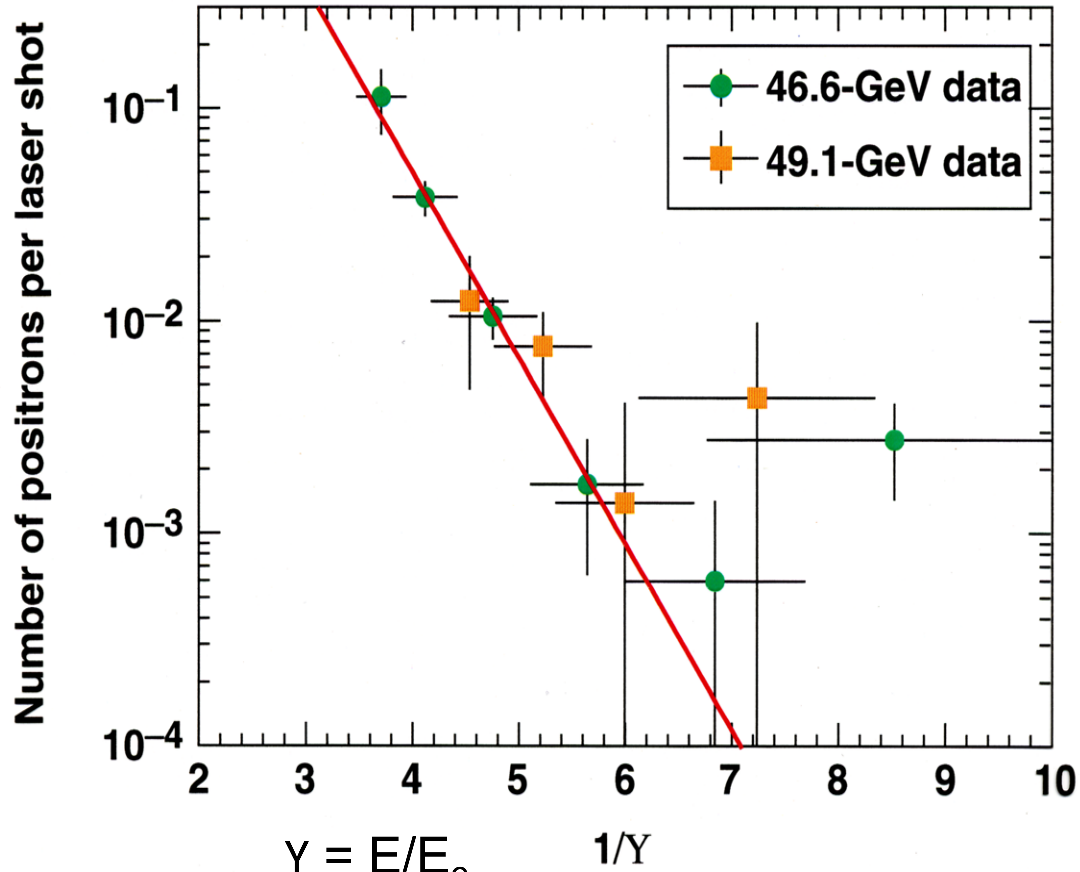
Process involving *n* laser photons has probability

$$P \sim \eta^{2n} \quad \text{where} \quad \eta^2 = \left[\frac{eE}{\omega mc}\right]^2 = \left[\frac{e}{\omega mc}\right]^2 Z_0 I$$



Multi-photon picture

Tunneling Picture (Schwinger)



$Y = E/E_c$

Fit to $e^{-\alpha/Y} \rightarrow \alpha = 2.02 \pm 0.12$

Light-by-light scattering in heavy ion collisions (ATLAS) ("quasi-real")

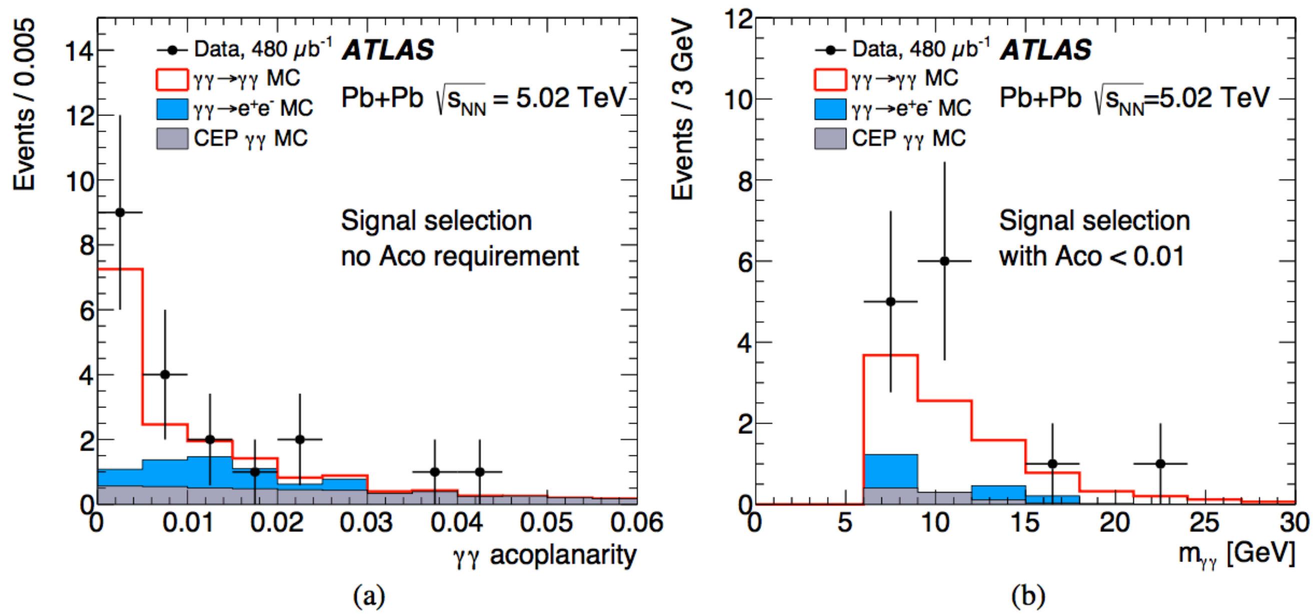
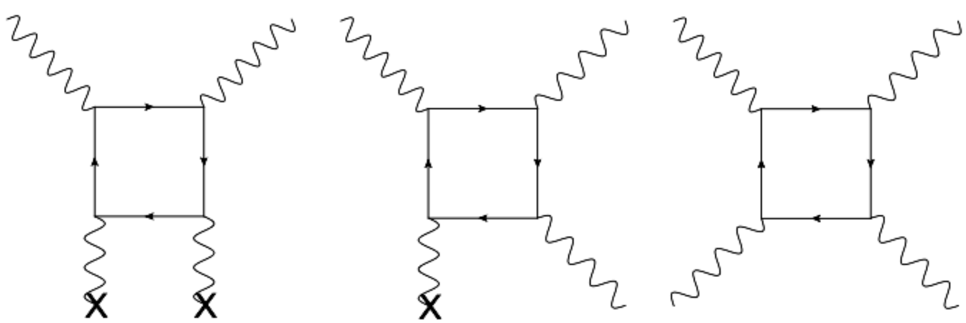
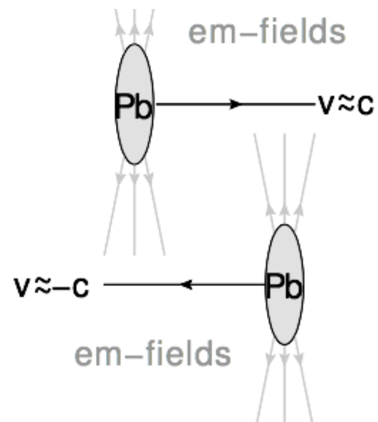


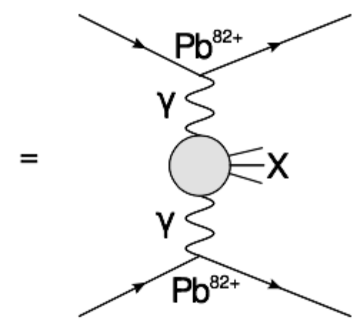
Figure 3: Kinematic distributions for $\gamma\gamma \to \gamma\gamma$ event candidates. (a) Diphoton acoplanarity before applying Aco < 0.01 requirement. (b) Diphoton invariant mass after applying Aco < 0.01 requirement. Data (points) are compared to MC predictions (histograms). The statistical uncertainties on the data are shown as vertical bars.

13 candidate events
in agreement with SM

ATLAS Collab. Nat. Phys. 13 , 852–858 (2017)





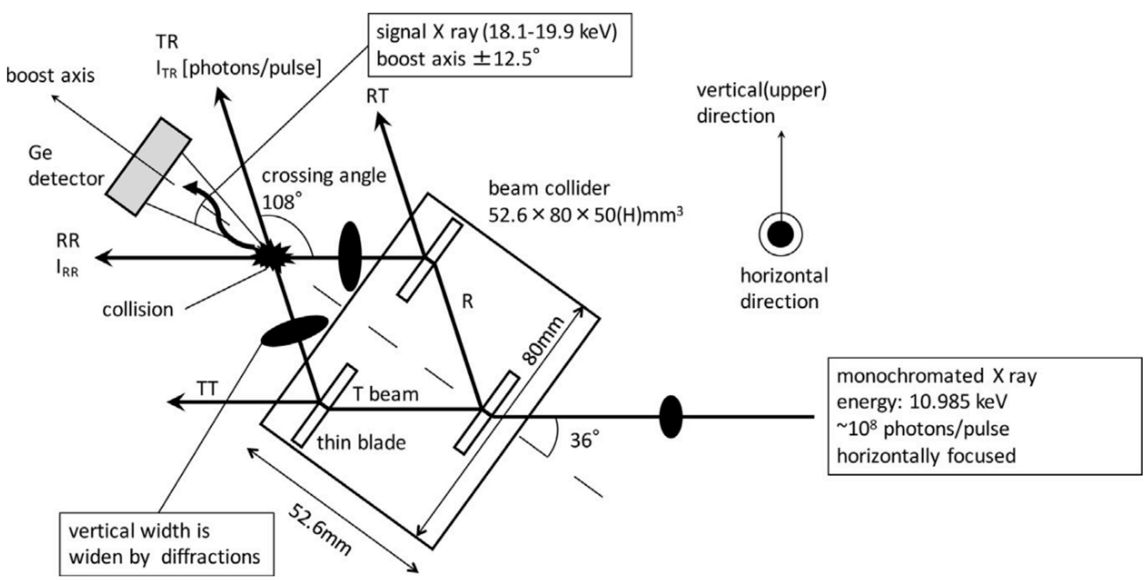


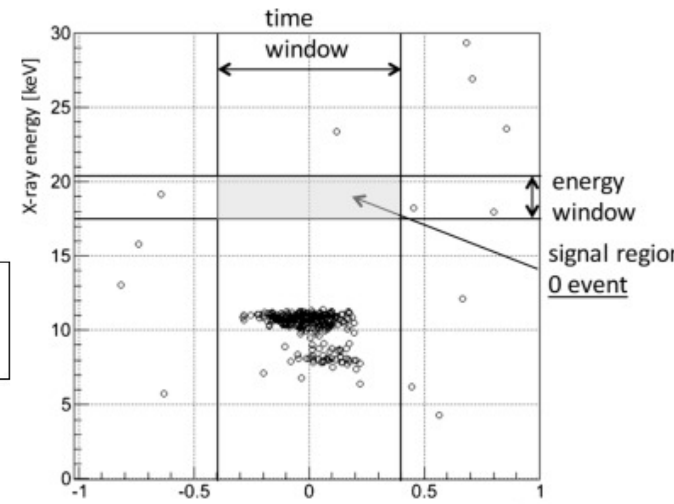
Light-by-light scattering search with x rays

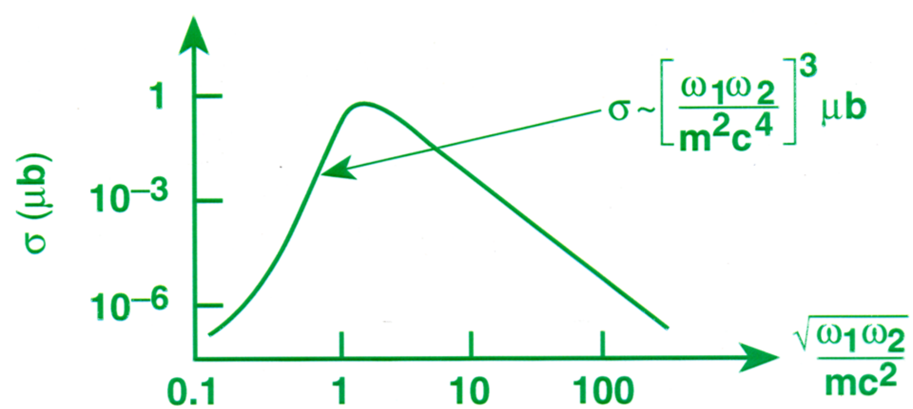
$\sigma_{\gamma\gamma\to\gamma\gamma} < 1.9 \times 10^{-27}\ \mathrm{m}^2$

Limit is 20 orders of magnitude above SM

T. Yamaji et al. / Physics Letters B 763 (2016) 454–457







Optical studies of vacuum polarization

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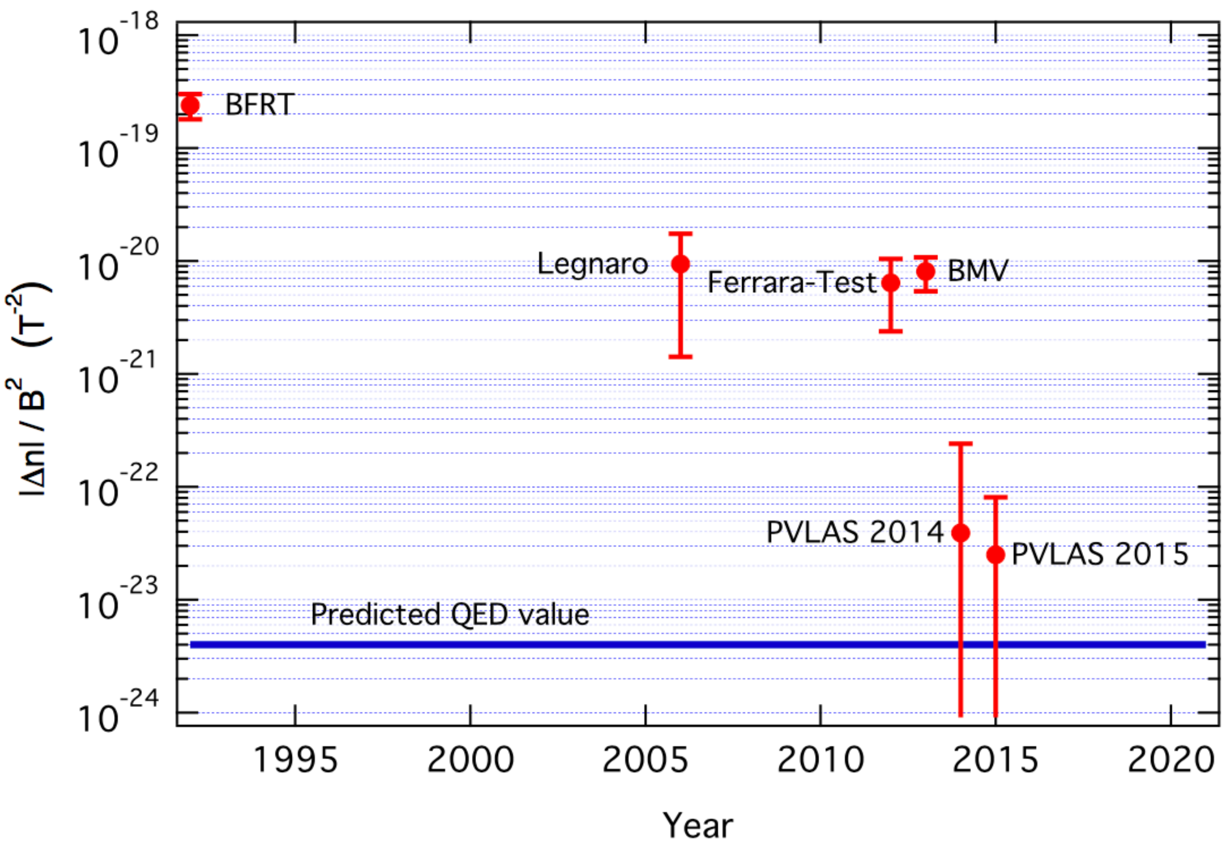
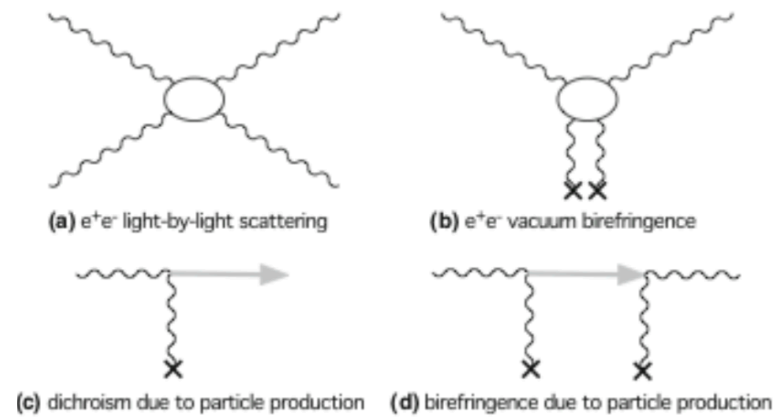




PVLAS collab. (low field, optical Fabry-Perot polarimeter).

Della Valle, F., Ejlli, A., Gastaldi, U. et al. Eur. Phys. J. C (2016) 76: 24.

Why SLAC

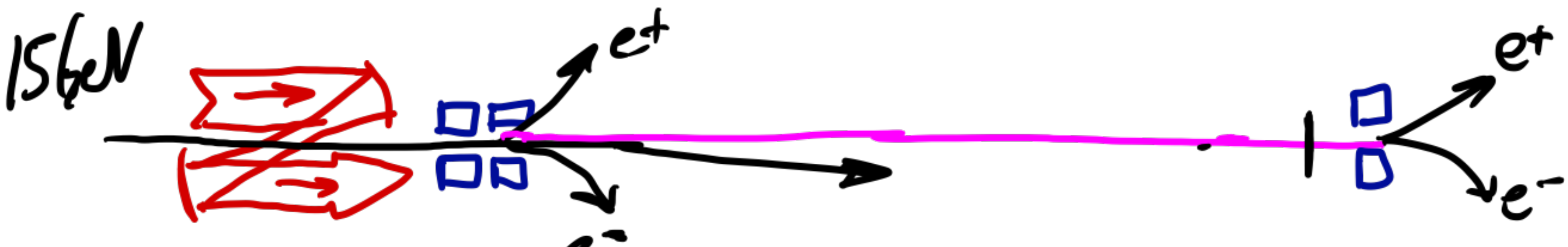
- Unique Facilities:
  - 15 GeV LINAC, upgradable to 30 GeV, or 60 GeV with plasma afterburner.
  - e + field, γ + field interactions much cleaner than proposed all-plasma based alternatives.
  - Ultra-intense x-ray + electron/gamma beam
- Local Expertise:
  - Core capabilities in Lasers, Accelerators, and Detectors
  - Broad scientific interest from AMO, Astrophysics, Cosmology, x-ray, HED, HEP communities
  - Institutional knowledge (E144)
- Parasitic operations possible

SFQED@FACET-II

Precision measurement using 100 TW, focused to 4μm

ω =1.55 eV, η = 17, Υ= 3

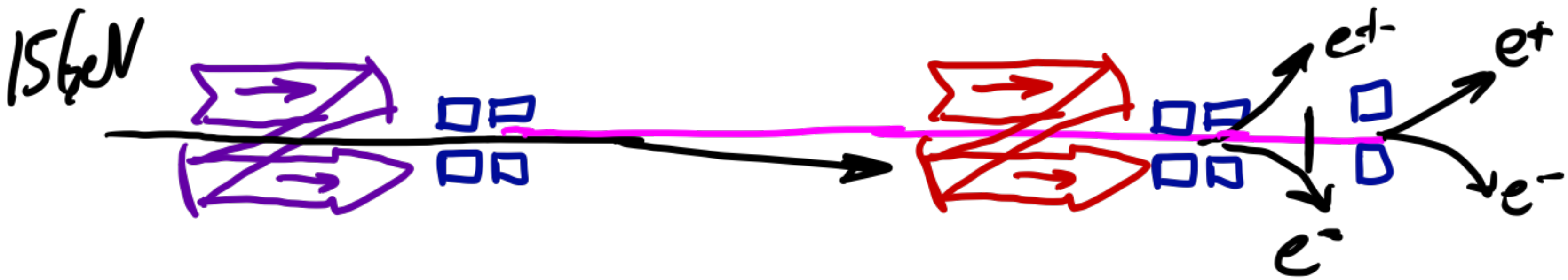
strong-field Compton, quantum rad. reaction



strong-field Pair production

ω =4.8 eV, η <<1, Ψ = 0

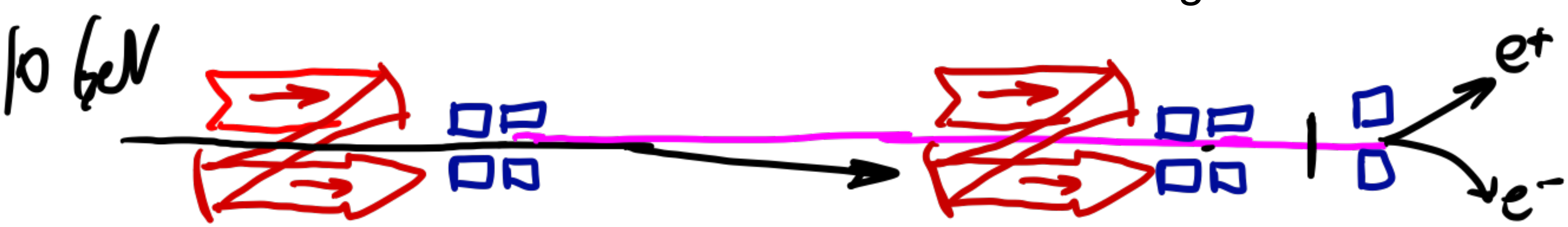
ω =1.55 eV, η = 17, Υ= 1.6



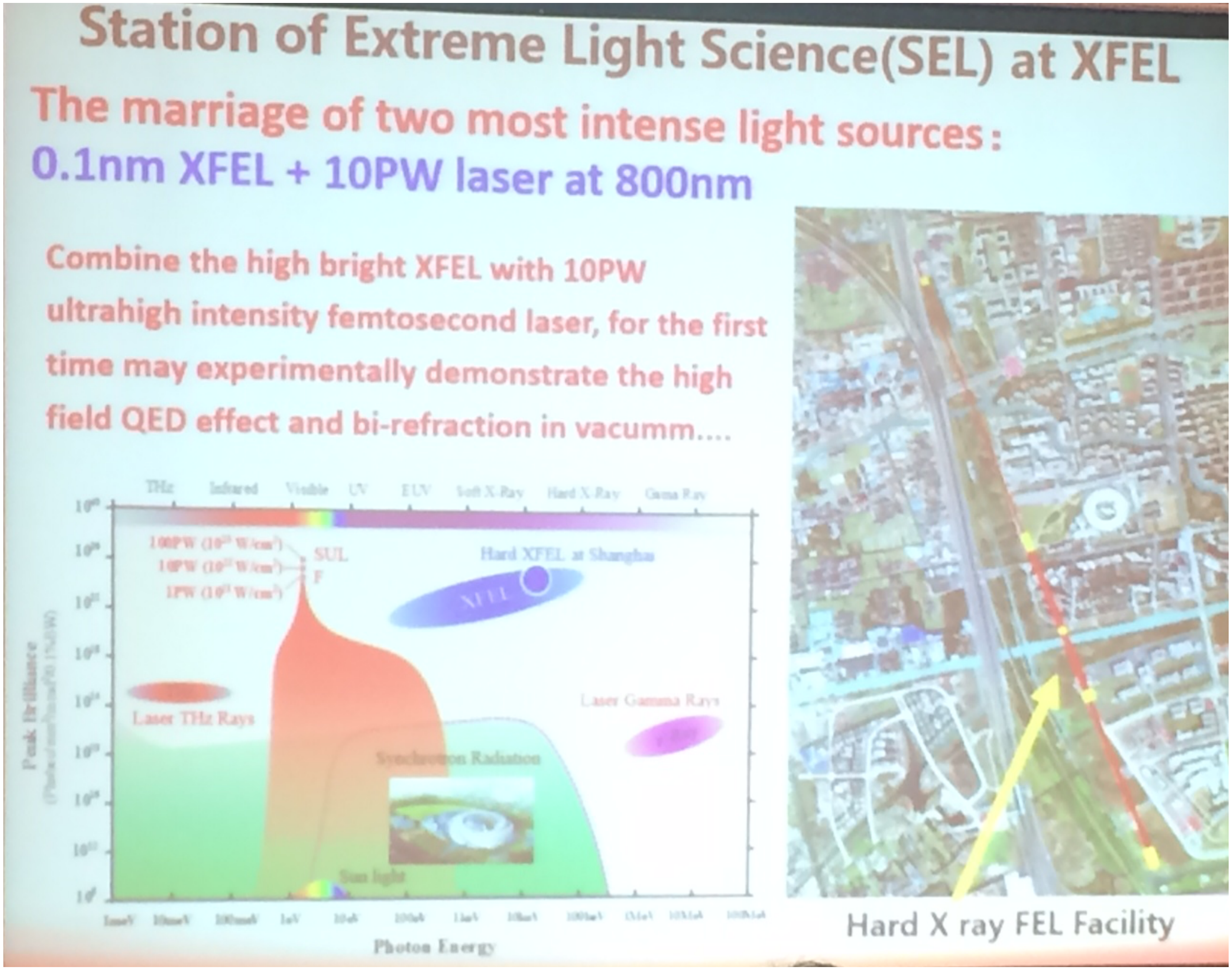
ω =1.55 eV, η <<1, Υ = 0, circ pol.

ω =1.55 eV, η < 17, Υ< 0.4

Vacuum birefringence



Competition…



Shanghai Ultraintense Laser Facility (green light for 100PW)+ XFEL

Υ >>1 physics, (see also Meuren talk)

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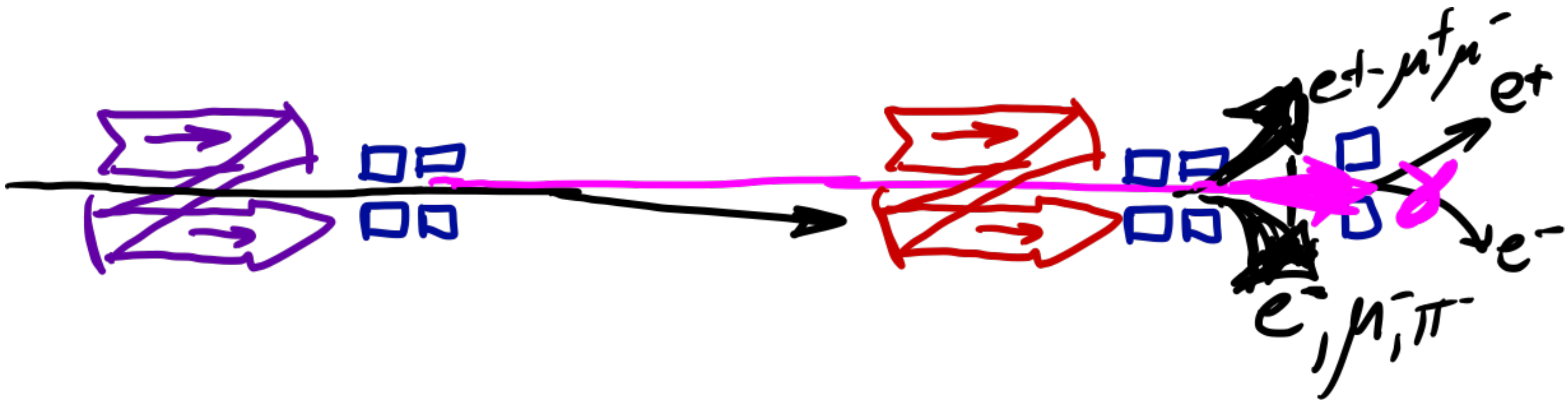
E>50 GeV, multi-PW laser, η>>1, Υ>>1



- e^+e^- cascades
- many-photon emission dominates radiation reaction
- fully non-perturbative QED including "loops" (no theory)
- collective effects (below-threshold muon, pion production)

Measuring Vacuum Birefringence

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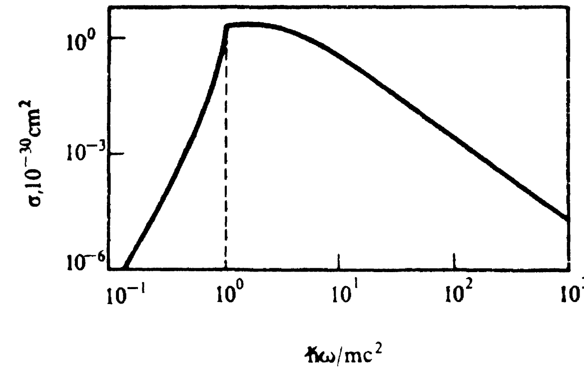
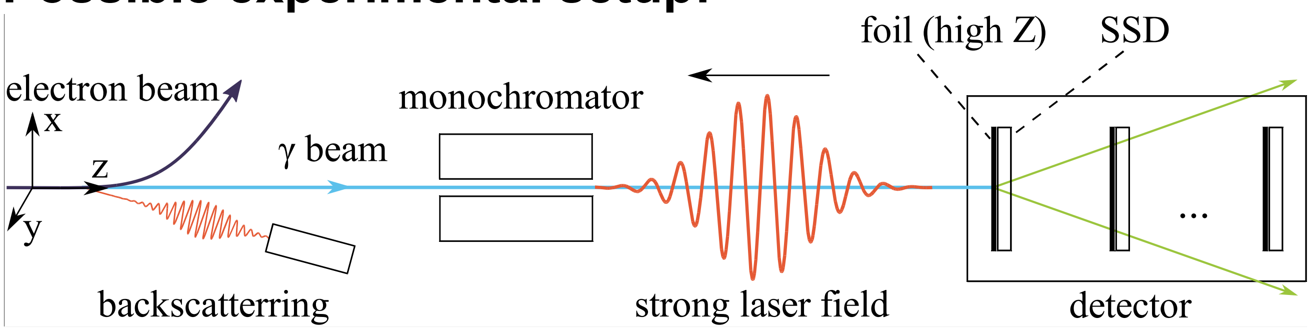


Probing VB close to the $e^- e^+$ production threshold:

- Advantage: largest possible effect
- Downside: GeV-scale polarization measurement

Possible experimental setup:



Stokes parameters:

S_0: normalized total flux
S_1,S_2: linear polarization
S_3: circular polarization

1st step: Compton backscattering:
5×10^4 photons/bunch, 2 GeV, $S_2>0.999$

FACET-II 10 GeV beam, 10^9 electrons/bunch, 10 Hz repetition rate, 4μm spot radius + optical laser (800nm, circ. pol.) 4×10^{16} W/cm^2, max scatt. angle: 6×10^{-6} rad

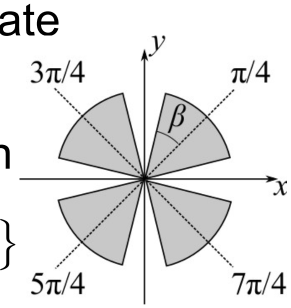
2nd step: Vacuum birefringence:
Induced linear polarization: $S_1=4\times10^{-3}$

Strong laser: 4J, 35fs (100 TW), 2×10^{20} W/cm^2 (4μm spot radius), η=7, Υ=0.2, 10 Hz repetition rate

3rd step: Measuring the polarization:
Asymmetry in the count rate: 2×10^{-4}
Required gamma photons: 5×10^{11}
Measurement time@10Hz: 12 days

Pair production in a foil: linear polarization induces asymmetric momentum distribution

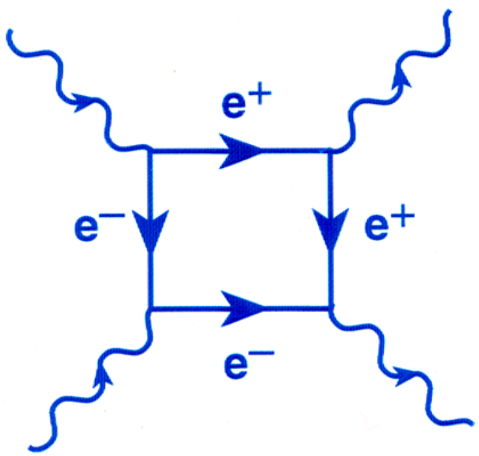
$$d\sigma_{pp} = \frac{d\varphi}{2\pi}\{S_0\sigma_0 + [S_1 \sin(2\varphi) + S_3 \cos(2\varphi)]\sigma_1\}$$

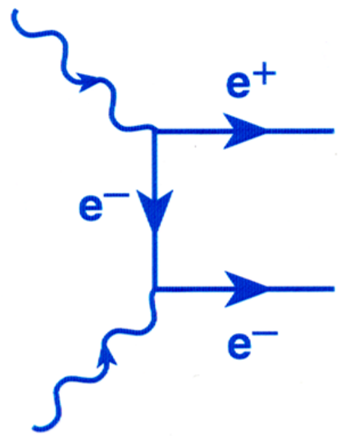


Bragin et al. arXiv:1704.05234

see also: King et al. PRA 2016, Ilderton et al. JoPP 2016, Nakamiya et al. arXiv:1512.00636

Connection between Light-by-light scattering and Pair production





$$4\omega_1\omega_2 > (2mc)^2$$

Competition (I). Accelerator-based facilities

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RIKEN SPring8

- two, 500 TW lasers on SACLA (not on e- beam–yet)
- tens nm focus x-ray
- Experiments in elastic light-by-light on SACLA, axion-like-particles on SPring8

DESY/EXFEL

- 18 GeV and lots of space.
- Proximity to leading theory groups
- Indication of interest

Competition (II) Extreme Light Infrastructure (first user operation 2018)

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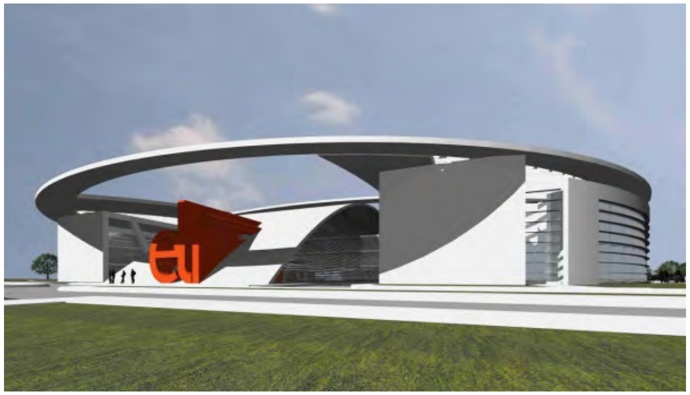


Attosecond Light Pulse Source (Szeged, Hungary)

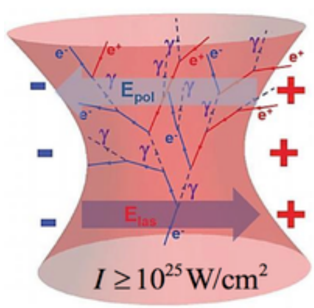
-Ultrafast light sources, and coherent x-ray sources
-PW drive laser
-Several beam lines, from 10KHz 100 mJ to 0.1 Hz 300J

High Energy Beam-Line Facilitiy (Prague, Czech Republic)

Beam lines from -200mJ to 1.3kJ lasers, including 2 10PW lasers;
Six experimental areas, including exotic physics, acceleration, x-rays, materials science.

Nuclear Physics Facility (Magurele, Romania)

2 multi-petawatt, 200J, 0.1Hz, <30fs lasers
Compton backscatter gamma ray source
Experiments aimed at nuclear physics.



10^{23-24} W/cm^2 @Beamlines and NP

eXtreme light infrastructure