The LUXE Experiment

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on behalf of the LUXE collaboration

ICHEP 2020
July 30

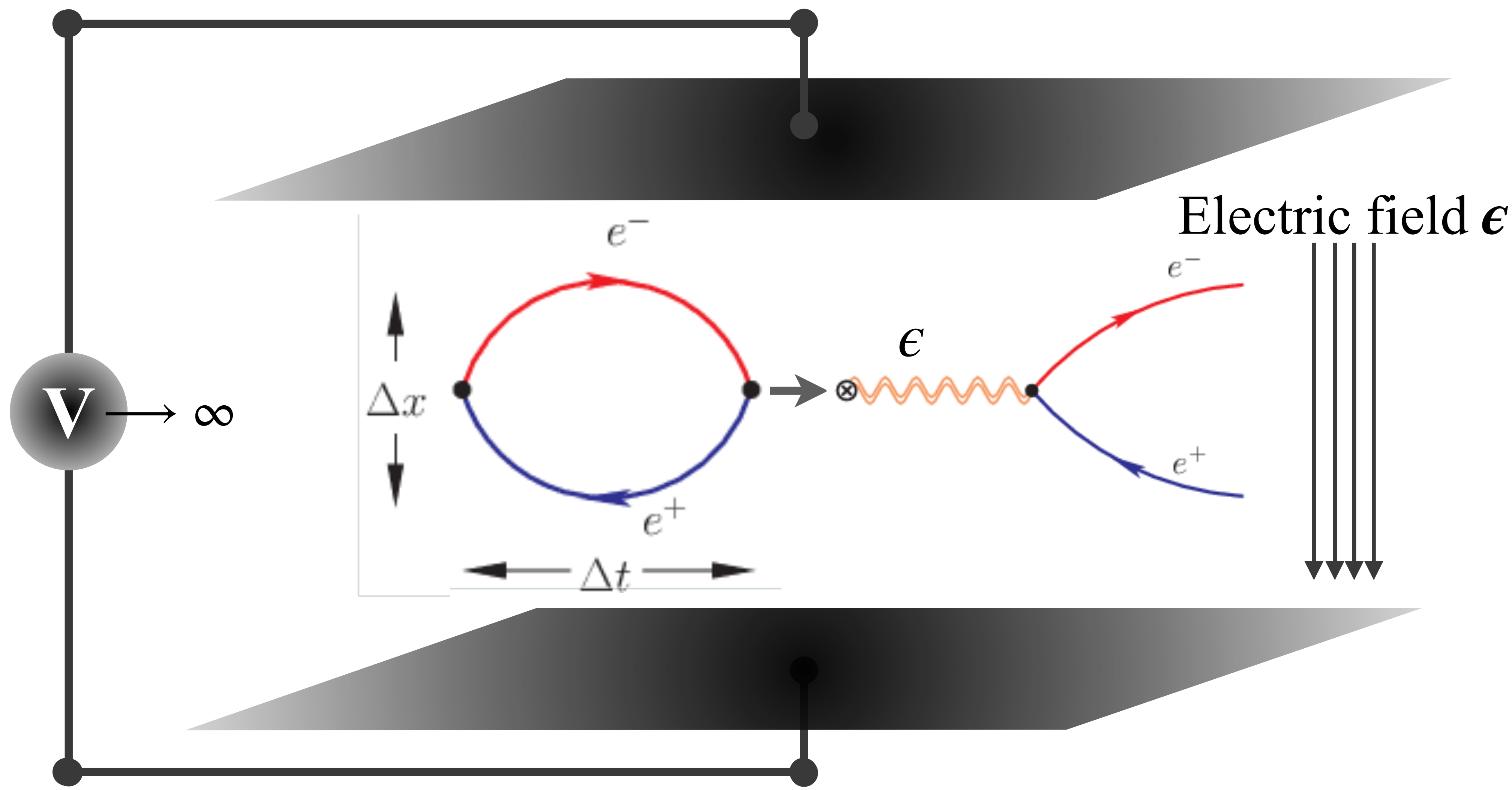
WEIZMANN INSTITUTE OF SCIENCE

LUXE

Outline

- Introduction
- Layout & Predictions
- New physics opportunities
- Experimental design
- Summary

What happens in strong fields?



The Schwinger critical field (1951)

$$\epsilon_S = \frac{m_e^2 c^3}{e\hbar} \simeq 1.32 \cdot 10^{18}\ \frac{\text{V}}{\text{m}}$$

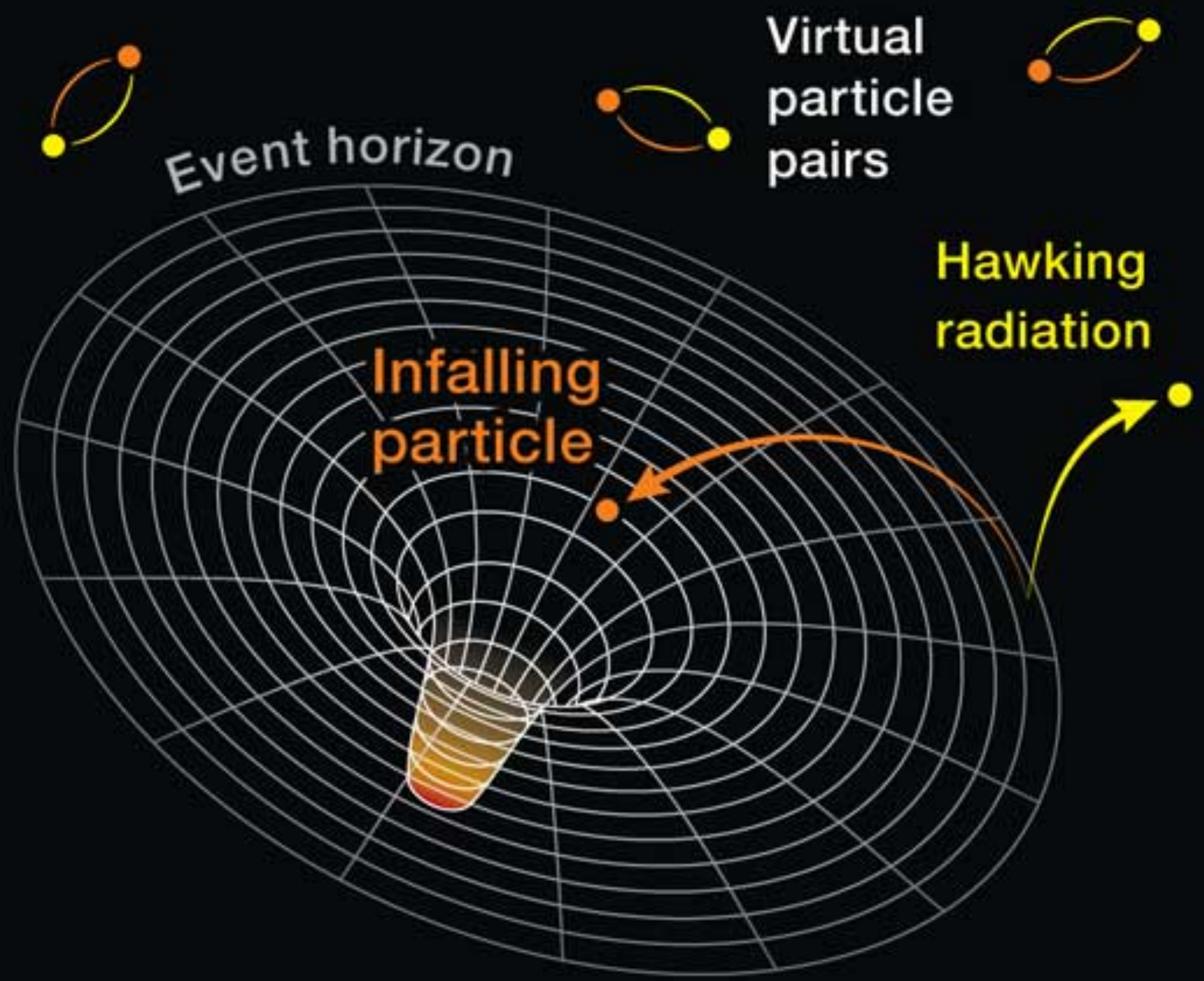
The probability to materialise one virtual e^+e^- pair from the vacuum

$$P \sim \exp\left(-a\frac{\epsilon_S}{\epsilon}\right)$$

a = numeric const.

non-perturbative with $\epsilon \longrightarrow \epsilon_S$

The Hawking equivalent



- Outside observer: the BH has radiated a particle so the energy must come from it
- Looking at the system: the BH energy has decreased so its mass must decrease

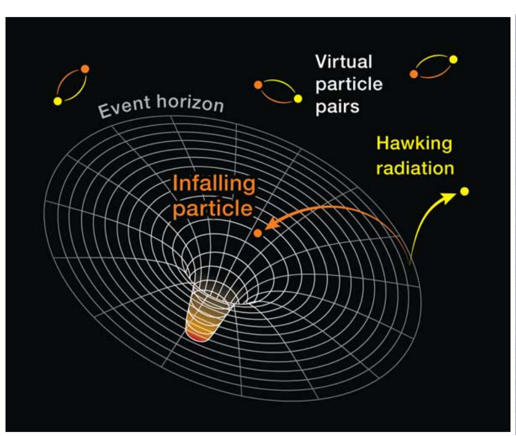
History & Impact

- **1930s** — First discussions by Sauter, Heisenberg & Euler
- **1951** — First calculations by Schwinger: ϵ_S
- **1990s** — E144 at SLAC first to approach ϵ_S*
- **2020s** — LUXE: reach ϵ_S and beyond*

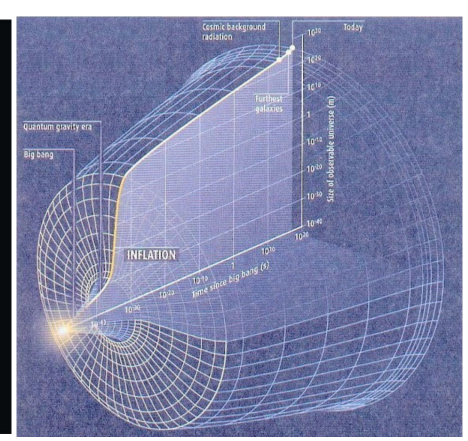
* The Schwinger's field may be approached/reached only within a highly-boosted system, e.g. the one produced at LUXE. See next slides

- never been reached in a clean environment*
- test basic predictions in a novel QM regime
- potential for seeing effects of new physics
- relevant to many areas in physics

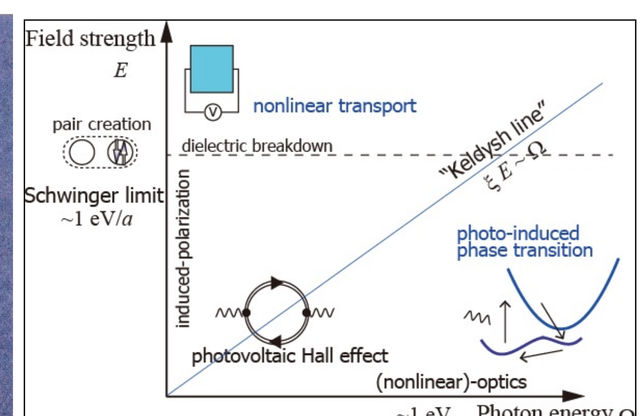
Neutron stars



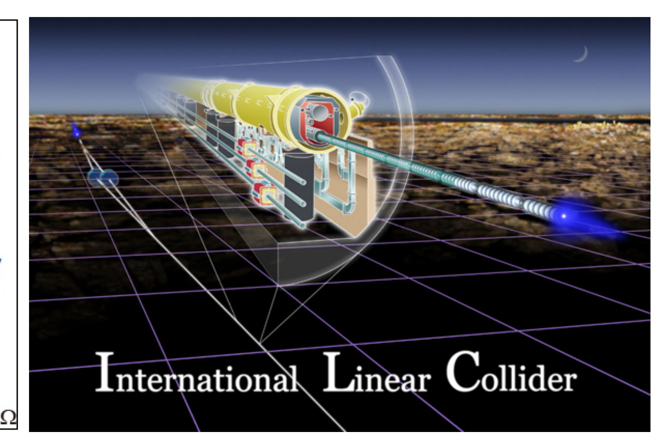
Hawking radiation



Inflation



Electrical breakdown

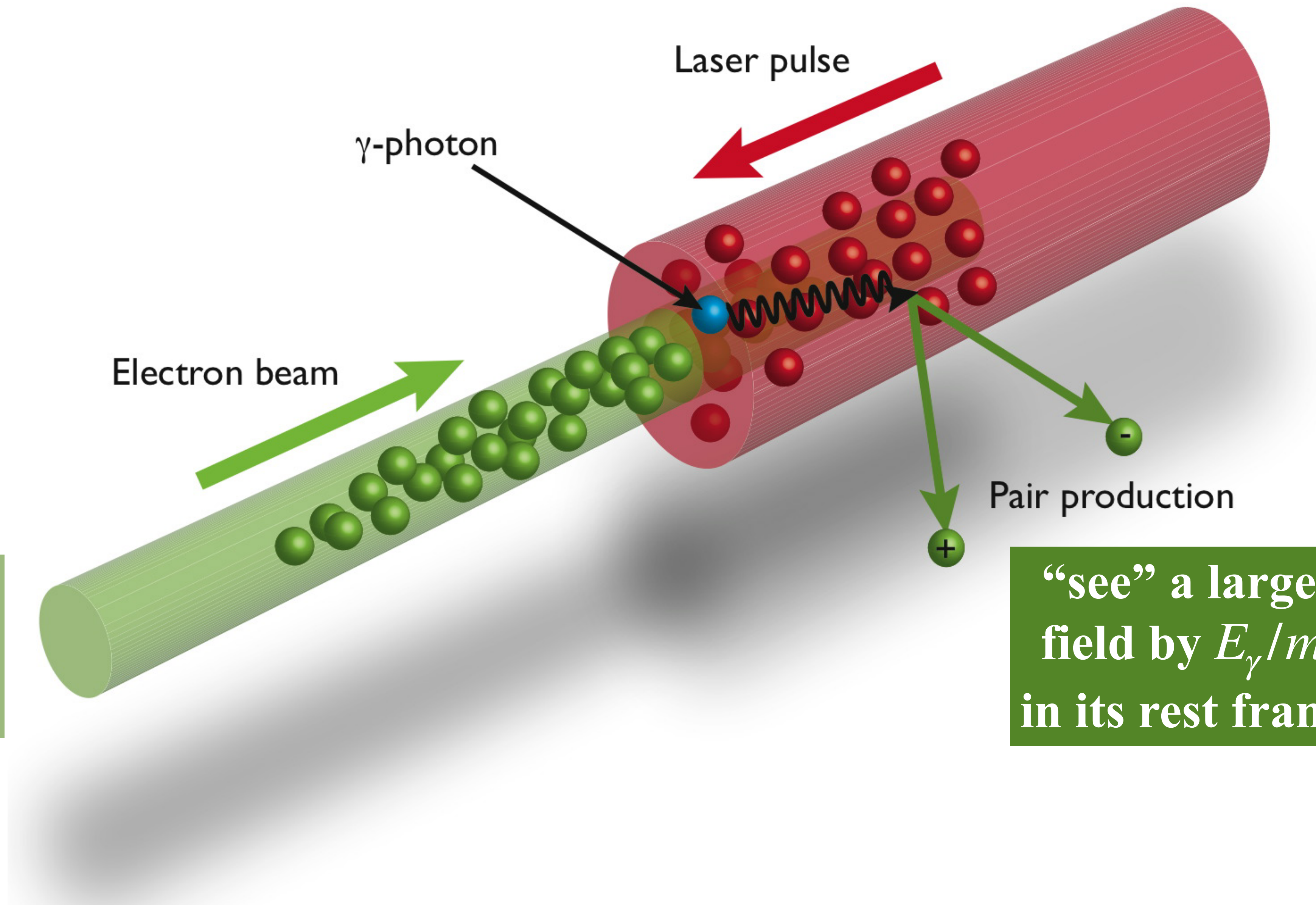


Colliders

LUXE physics in a nutshell

Laser Und XFEL Experiment

High-power laser generates large *E*-field



High energy electrons (XFEL)

"see" a larger field by E_γ / m_e in its rest frame

1 **<u>Nonlinear</u> Compton scattering**

$$e + n\gamma_{\mathrm{L}} \rightarrow e' + \gamma_{\mathrm{C}}$$

<u>Nonlinear</u> Breit-Wheeler pair production

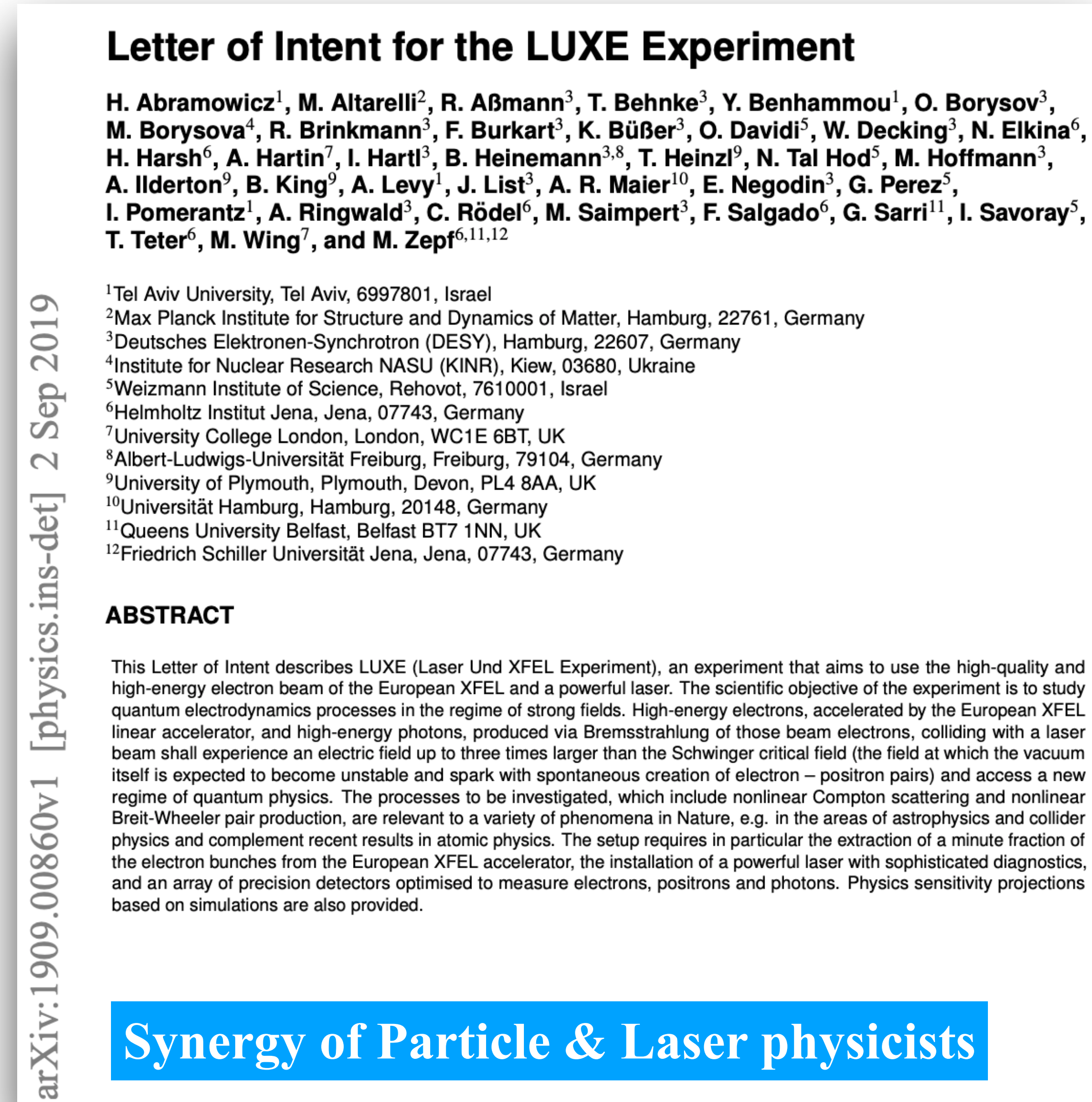
$$\gamma_{\mathrm{C}} + n\gamma_{\mathrm{L}} \rightarrow e^{+}e^{-}$$

2 **Bremss'-driven, <u>Nonlinear</u> Breit-Wheeler pair production**

$$\gamma_{\mathrm{B}} + n\gamma_{\mathrm{L}} \rightarrow e^{+}e^{-}$$

For more details on the theory see:
IJMP A, Vol. 33, No. 13 (2018) 1830011
Phys. Rev. D 99, 036008 (2019)

LUXE @ the Eur.XFEL



Letter of Intent for the LUXE Experiment

H. Abramowicz[1], M. Altarelli[2], R. Aßmann[3], T. Behnke[3], Y. Benhammou[1], O. Borysov[3], M. Borysova[4], R. Brinkmann[3], F. Burkart[3], K. Büßer[3], O. Davidi[5], W. Decking[3], N. Elkina[6], H. Harsh[6], A. Hartin[7], I. Hartl[3], B. Heinemann[3,8], T. Heinzl[9], N. Tal Hod[5], M. Hoffmann[3], A. Ilderton[9], B. King[9], A. Levy[1], J. List[3], A. R. Maier[10], E. Negodin[3], G. Perez[5], I. Pomerantz[1], A. Ringwald[3], C. Rödel[6], M. Saimpert[3], F. Salgado[6], G. Sarri[11], I. Savoray[5], T. Teter[6], M. Wing[7], and M. Zepf[6,11,12]

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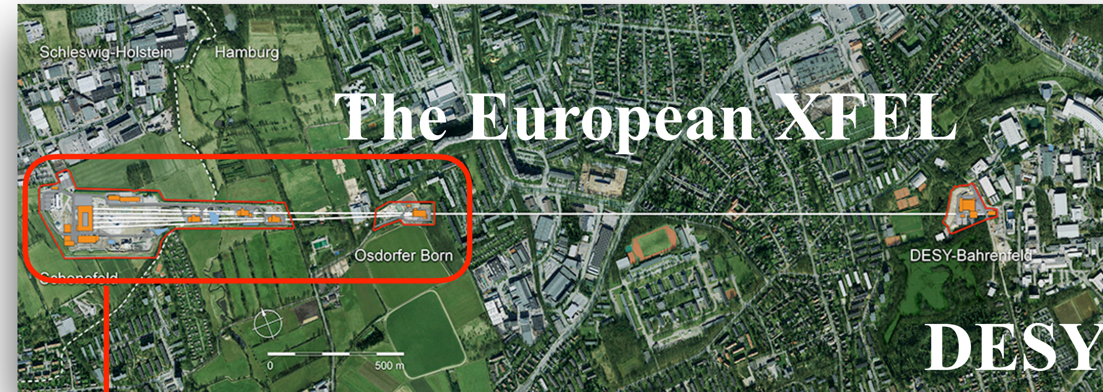
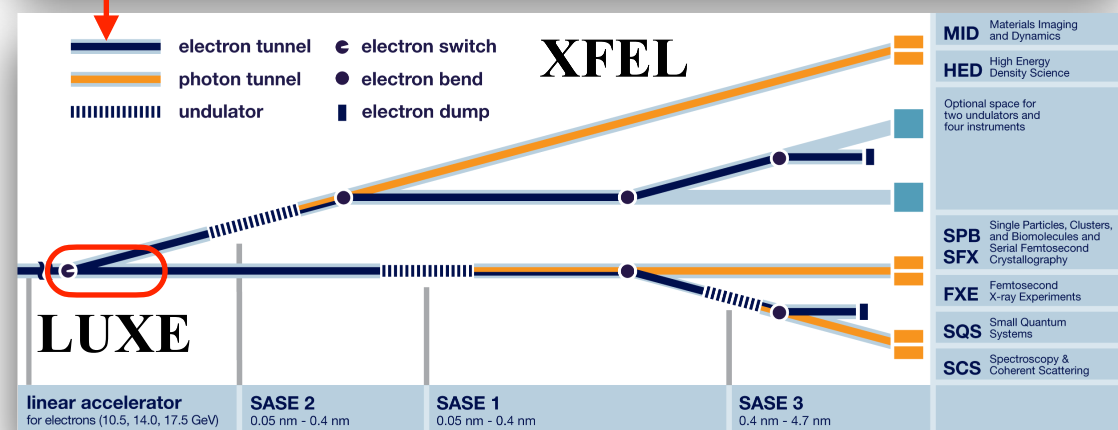
ABSTRACT

This Letter of Intent describes LUXE (Laser Und XFEL Experiment), an experiment that aims to use the high-quality and high-energy electron beam of the European XFEL and a powerful laser. The scientific objective of the experiment is to study quantum electrodynamics processes in the regime of strong fields. High-energy electrons, accelerated by the European XFEL linear accelerator, and high-energy photons, produced via Bremsstrahlung of those beam electrons, colliding with a laser beam shall experience an electric field up to three times larger than the Schwinger critical field (the field at which the vacuum itself is expected to become unstable and spark with spontaneous creation of electron – positron pairs) and access a new regime of quantum physics. The processes to be investigated, which include nonlinear Compton scattering and nonlinear Breit-Wheeler pair production, are relevant to a variety of phenomena in Nature, e.g. in the areas of astrophysics and collider physics and complement recent results in atomic physics. The setup requires in particular the extraction of a minute fraction of the electron bunches from the European XFEL accelerator, the installation of a powerful laser with sophisticated diagnostics, and an array of precision detectors optimised to measure electrons, positrons and photons. Physics sensitivity projections based on simulations are also provided.

arXiv:1909.00860v1 [physics.ins-det] 2 Sep 2019

Synergy of Particle & Laser physicists

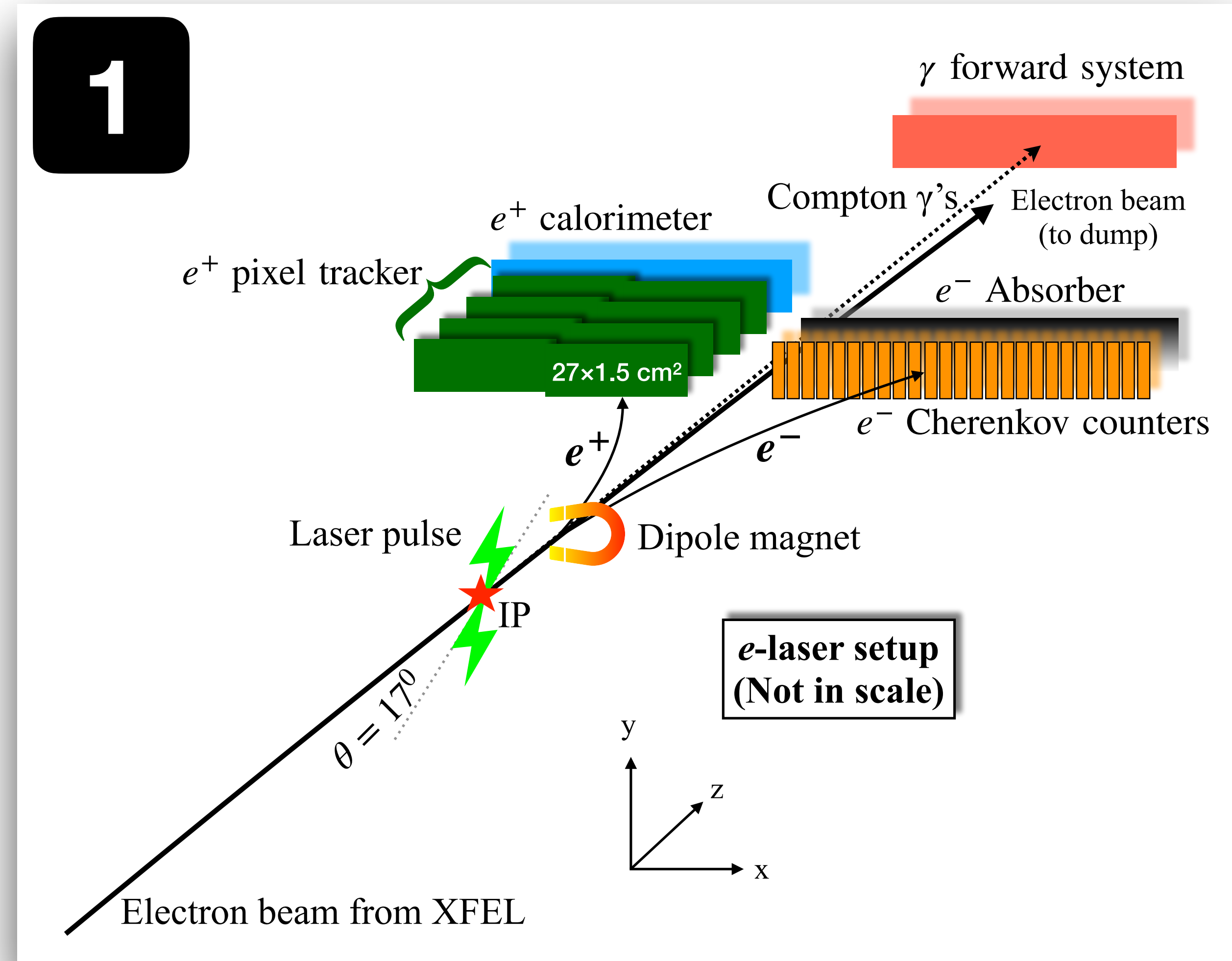


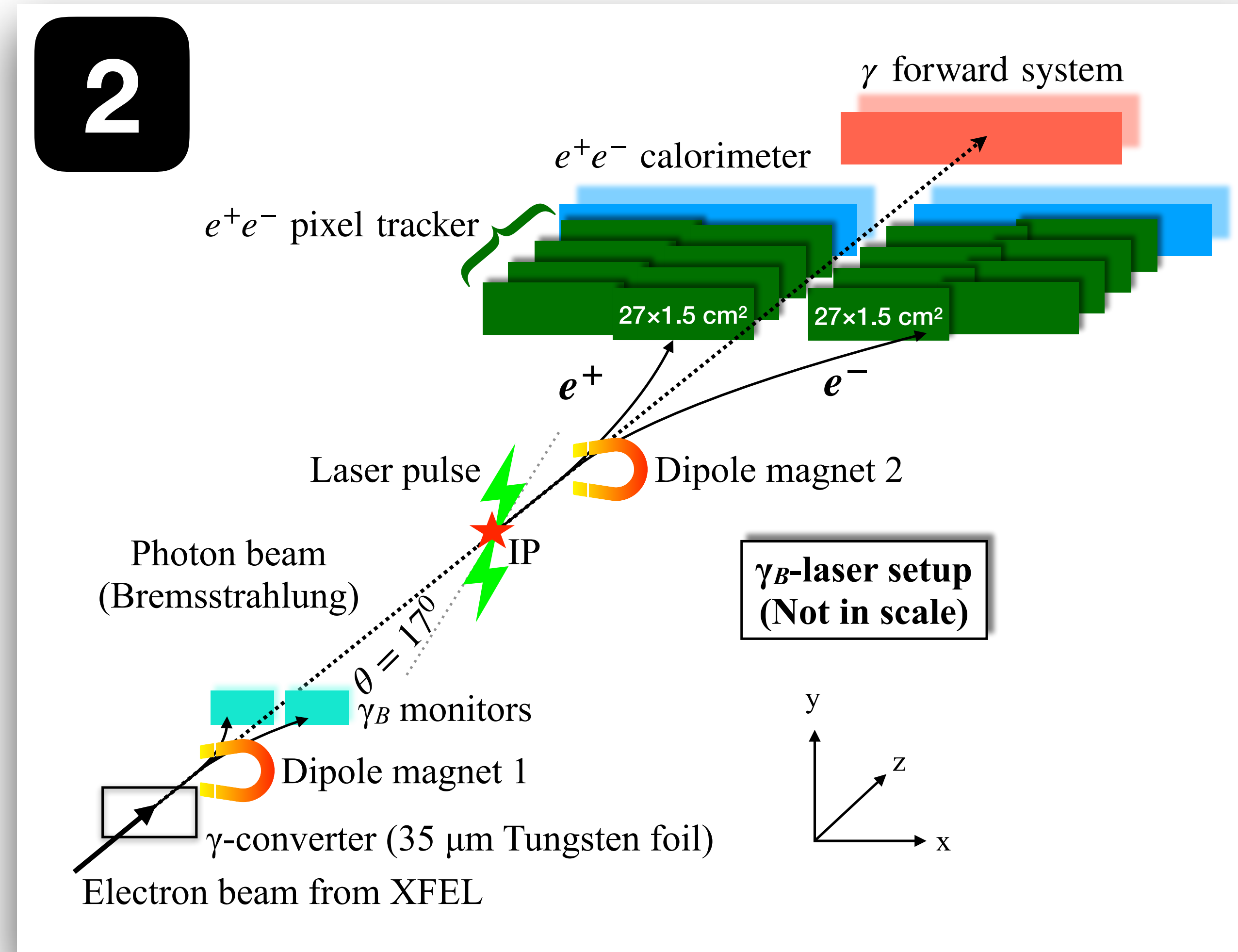


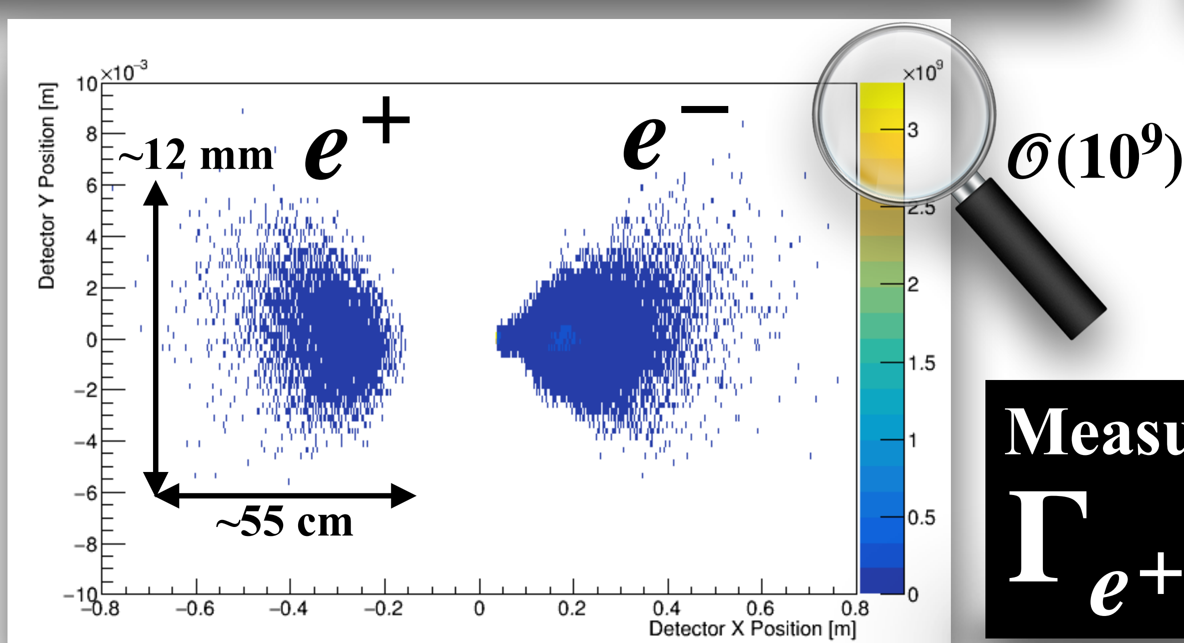
$$\epsilon \to \epsilon \times \frac{E_\gamma}{m_e} \sim \epsilon \times \frac{\mathbf{10\ GeV}}{\mathbf{0.5\ MeV}} \sim \epsilon \times 10^4$$

Electrons	E_e up to **17.5 GeV**, with N_e = **1.5-6×10⁹ e^-/bunch** and a bunch charge up to 1.0 nC,
	~1/2700 bunches/train, 1+9 Hz (collisions + background), spot r_{xy}=5 µm, l_z=24 µm
Laser	Ti-Sapphire, 800 nm, **40 TW**(⟶350), **~1 J**(⟶10), 25-30 fs pulse, 1-10 Hz rate
	8×8⟶3×3 µm² FWHM spot with up to ***I*~ 3.5×10¹⁹ W/cm²**(⟶1.5×10²¹), 60% loss

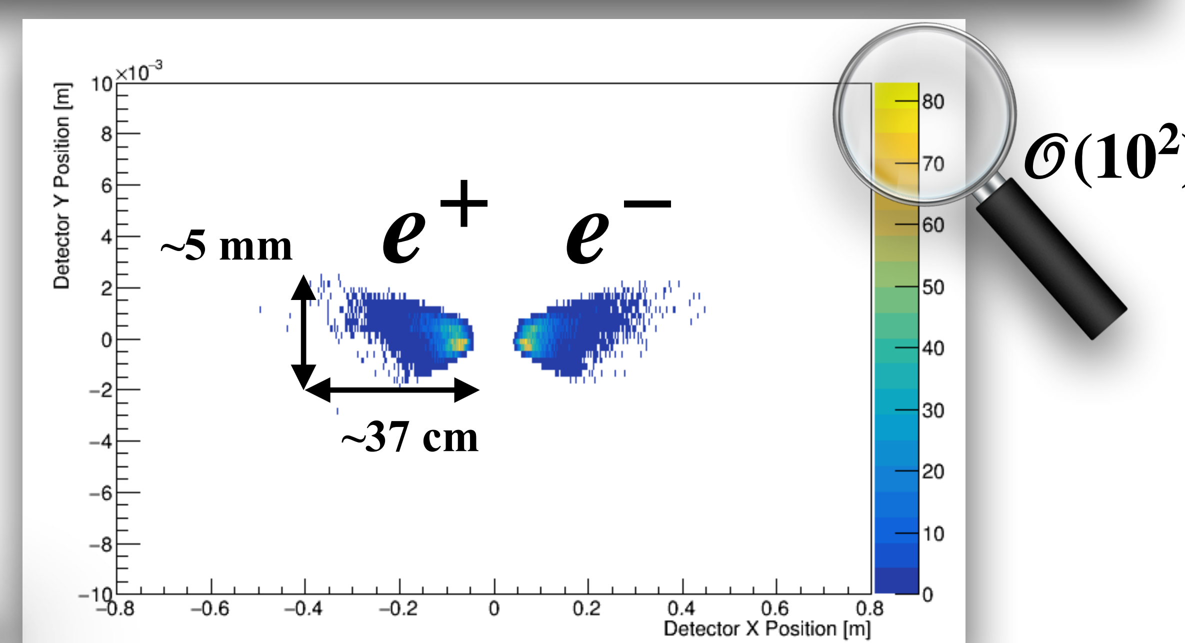
Experimental setup



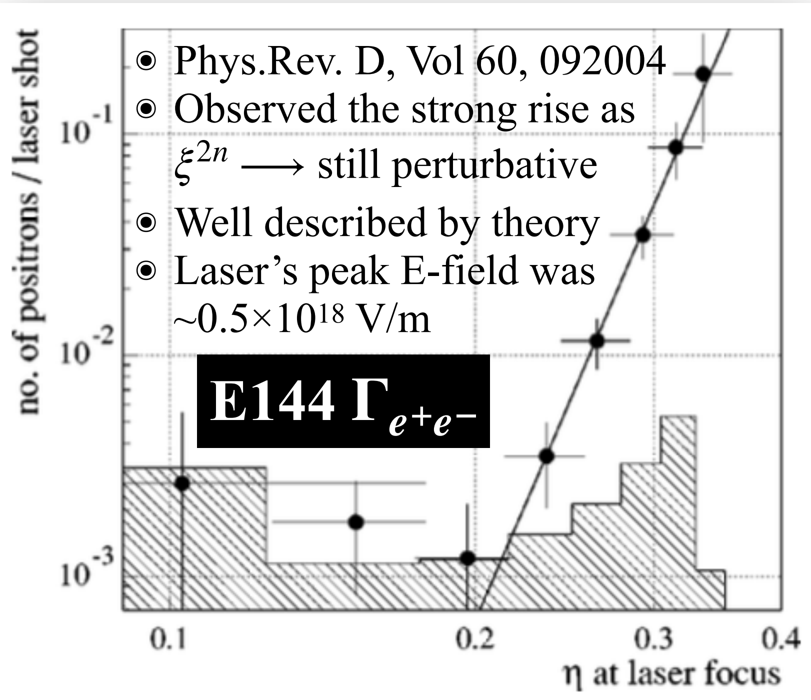




Measure:
$\Gamma_{e^+e^-}$

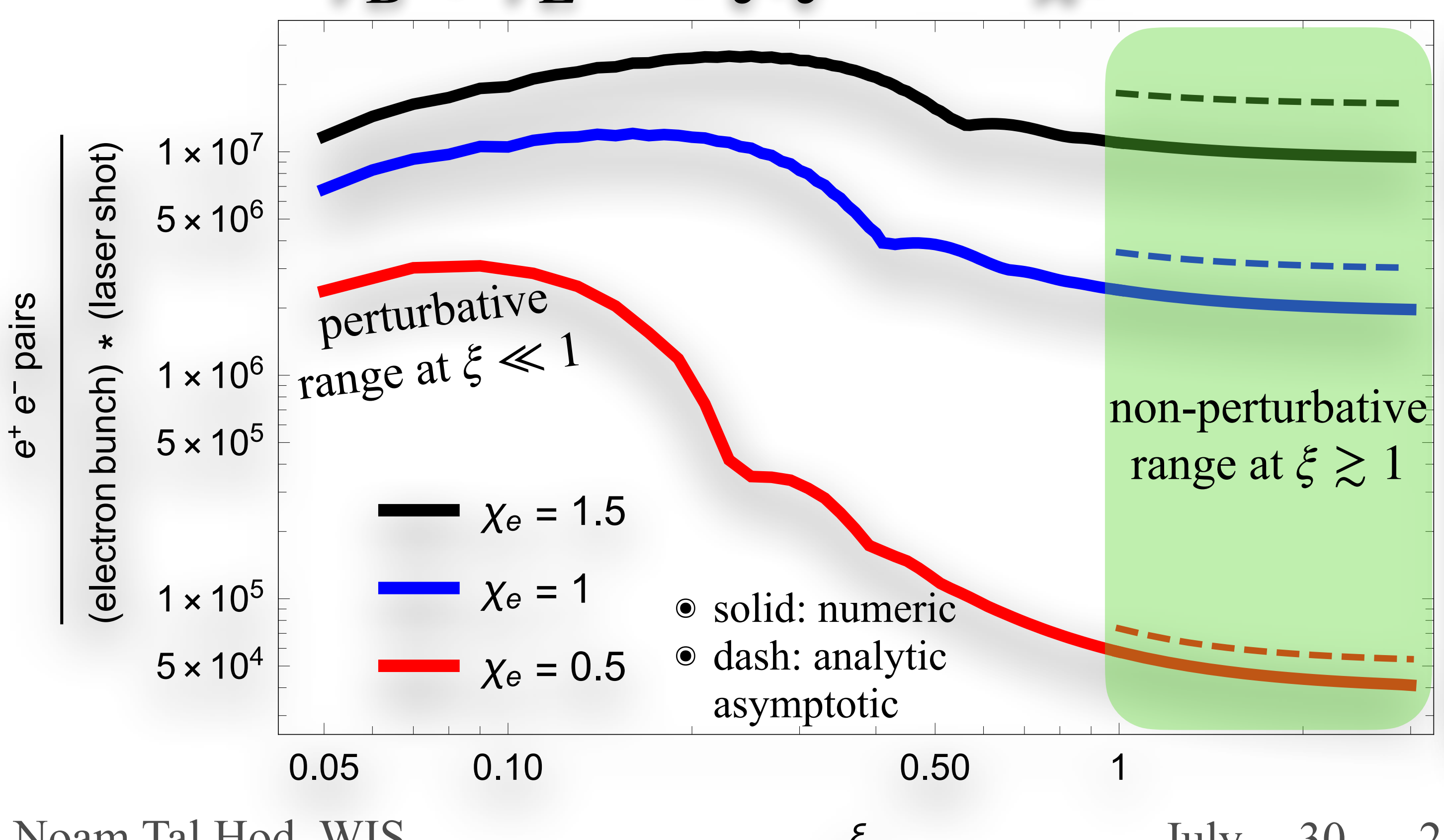


Reaching ϵ_S in the e^+e^- rest frame

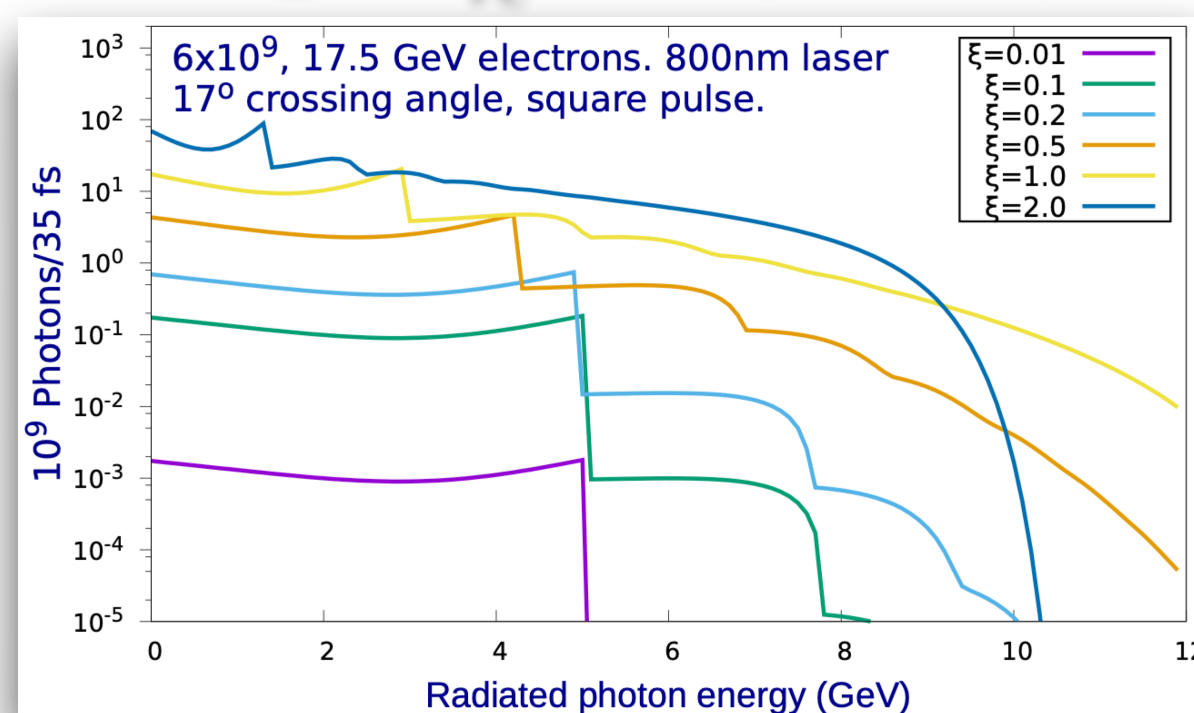


- We will measure the rates, $\Gamma_{e^+e^-}$ and Γ_{γ_C}
- Characterised by 2 dimensionless parameters:
  - Laser intensity parameter: $\xi \propto \epsilon/\epsilon_S$
  - Quantum parameter: $\chi_{e,\gamma} \propto (E_{e,\gamma}/m_e)(\epsilon/\epsilon_S)$
- E144 ($e^- + \gamma_L$ only) has achieved $\epsilon < \epsilon_S/4$

$\gamma_B + \gamma_L$: $\Gamma_{e^+e^-} \longrightarrow \chi e^{-3/(8\chi)}$



$e^- + \gamma_L$: Γ_{γ_C} (Compton edges)

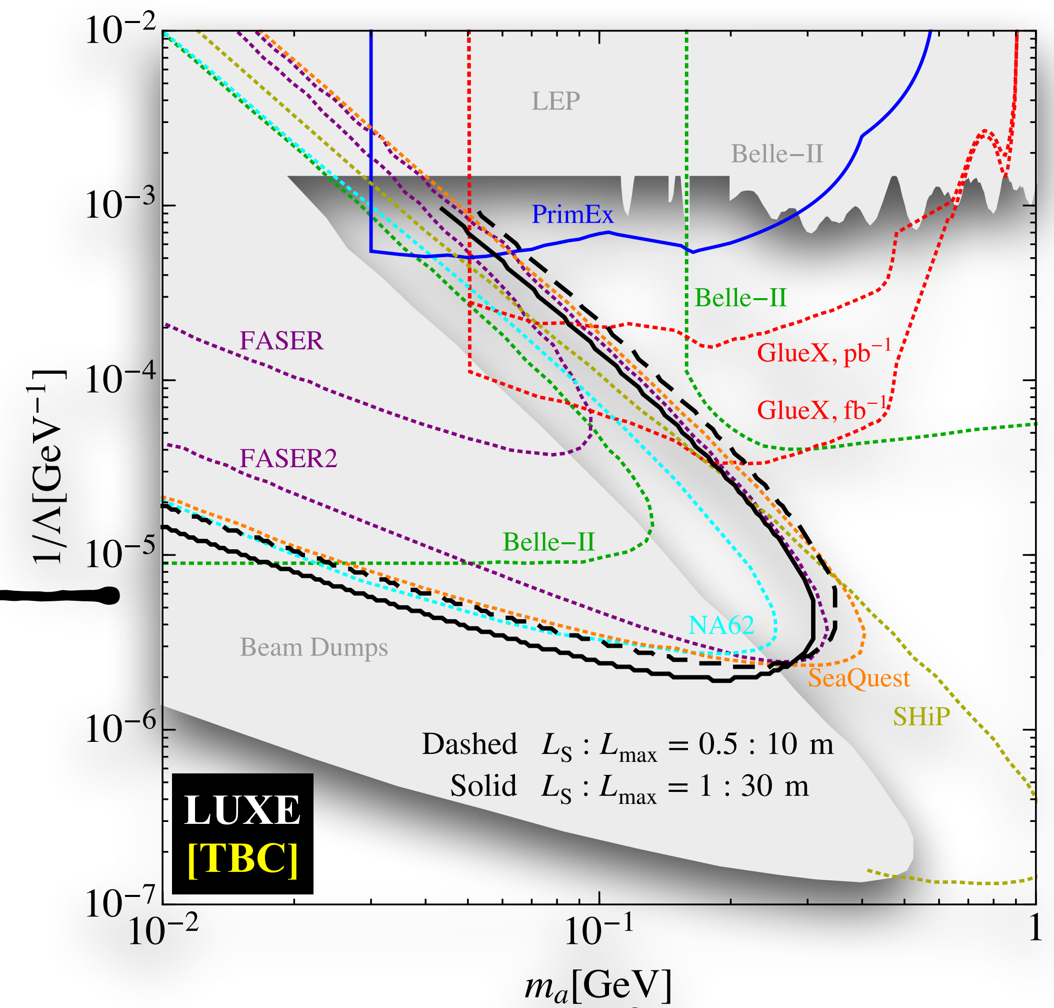


The "kinematic edges" of the scattered electron depend on the number of absorbed laser photons

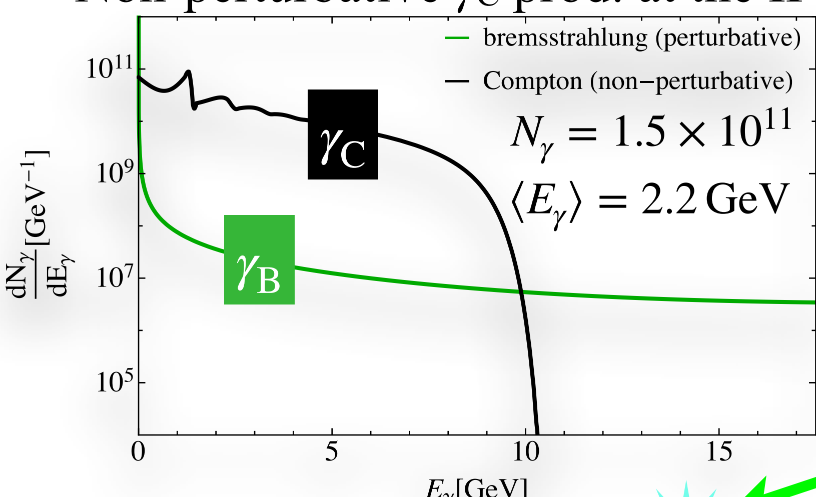
New-Physics with LUXE

ALPs: $\mathscr{L}_{\text{int}} = \frac{1}{4\Lambda} a F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{ae} a \bar{e}\gamma^5 a$

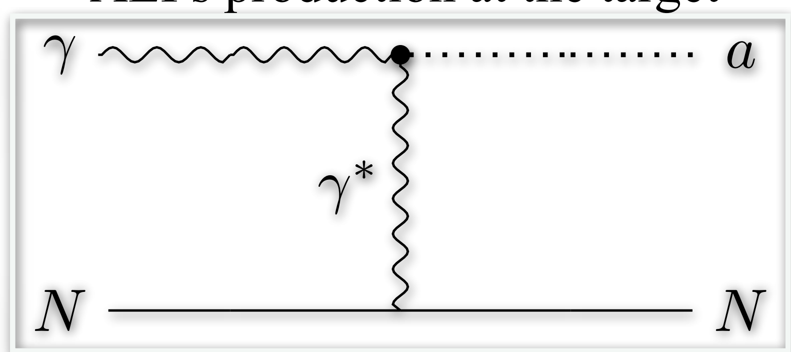
- mass: m_a
- Photon coupling: $1/\Lambda$
- Electron coupling: g_{ae}

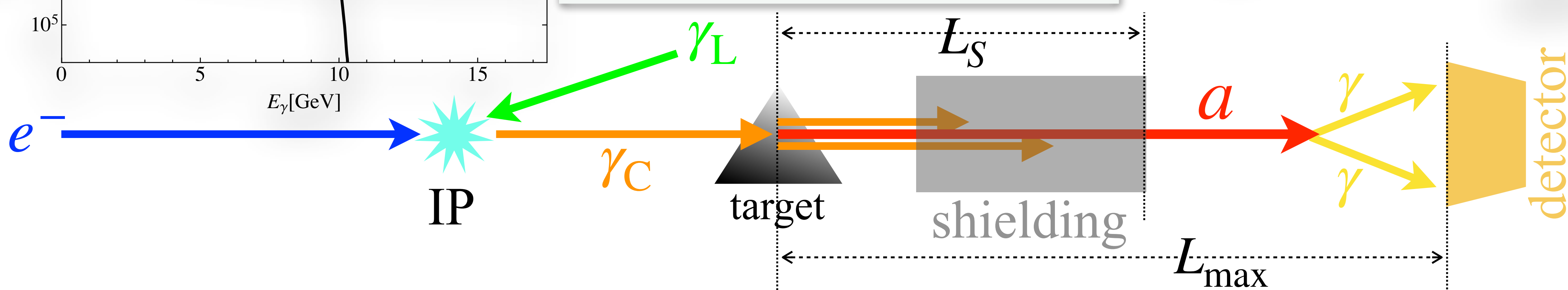


Non-perturbative γ_C prod. at the IP



ALPs production at the target



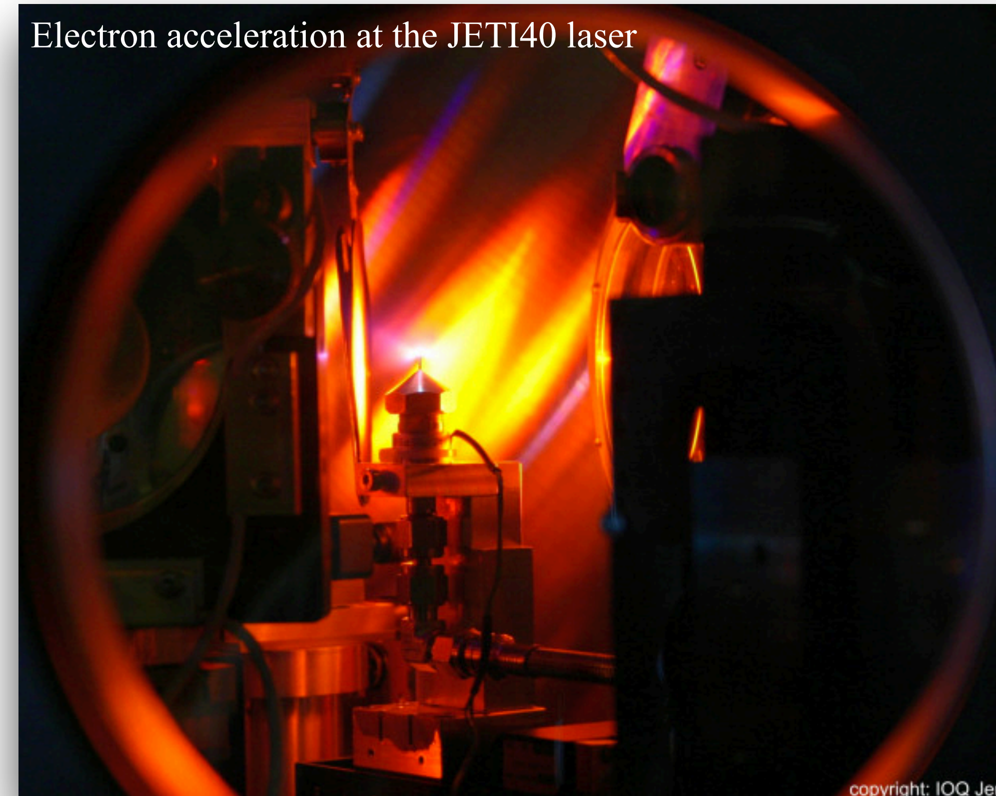


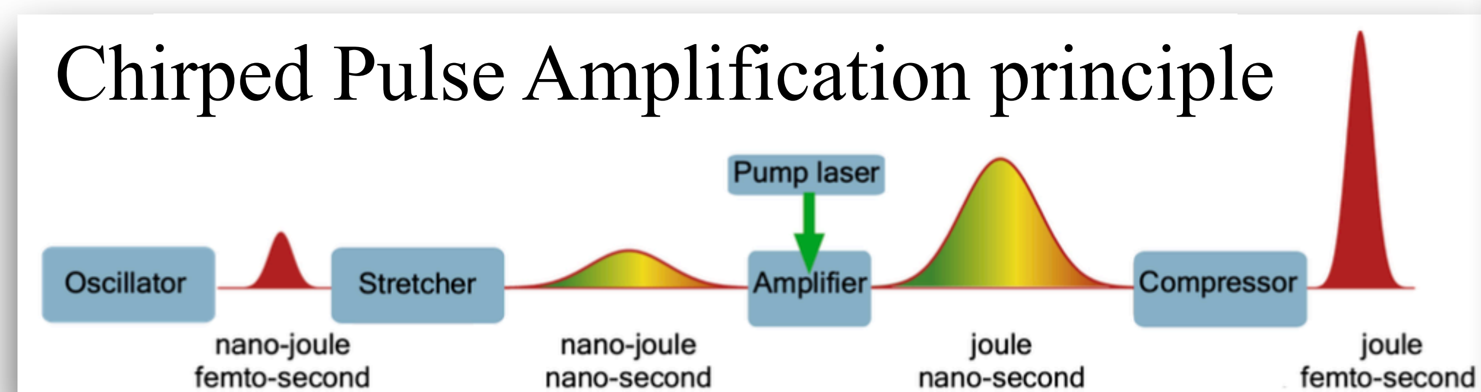
Plot done with:
$E_e = 17.5$ GeV
$N_e = 6 \times 10^9$
$t_L = 35$ fs
$\xi = 2.0$
$t_{op} = 10^7$ s
$R_L = 1$ Hz
$L_S = 1$ m
$L_{max} \sim 10$ m
Tungsten target: X/X_0=1% (35μm)

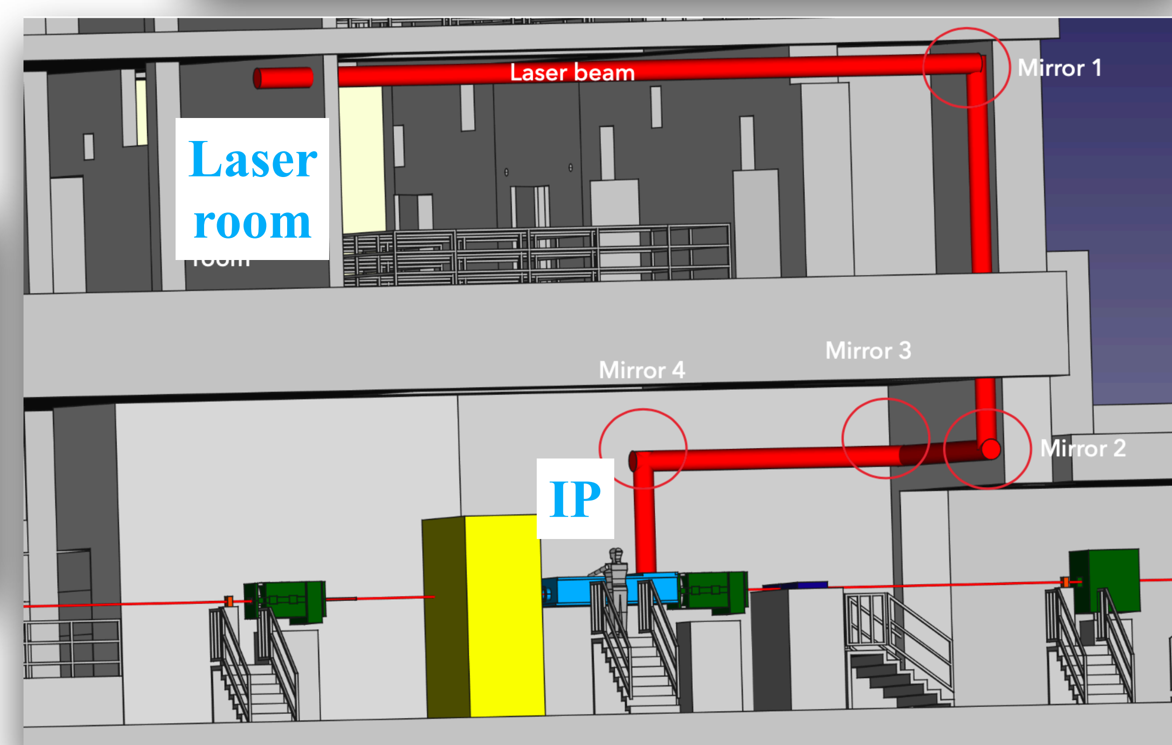
- The ALPs can also be produced at the IP
- Similar for scalars: $a \to \phi$, $\tilde{F} \to F$ and $\gamma^5 \to 1$

Laser

- Phase-I: the JETi40 40 TW laser already loaned to LUXE by Helmholtz Institute Jena
- Phase-II: looking up towards a 350 TW laser with as small as 3×3 μm^2 spot size
- **Challenge**: exact knowledge of the intensity at the IP
  - with the laser being ~10s of meters away from it
  - and with a remote diagnostics system







Laser diagnostics

- Measure laser parameters to infer the intensity, I
  - can be indirect and direct, relative and absolute

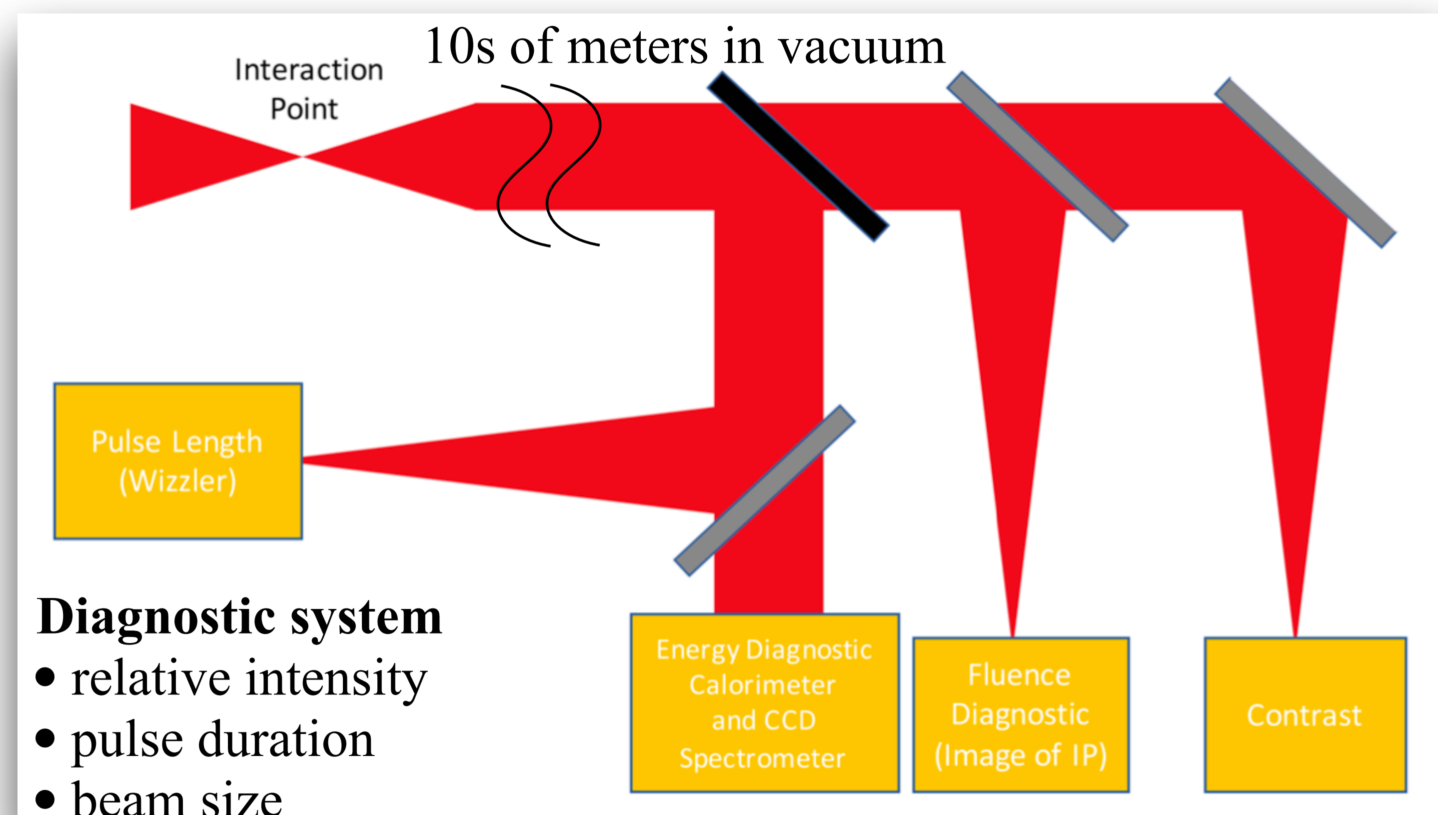
$$I = \frac{E}{A\tau}$$

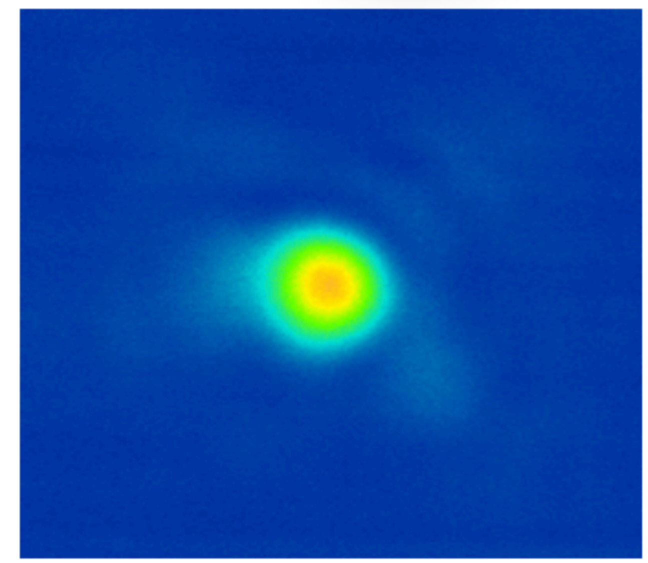
pulse energy (E)

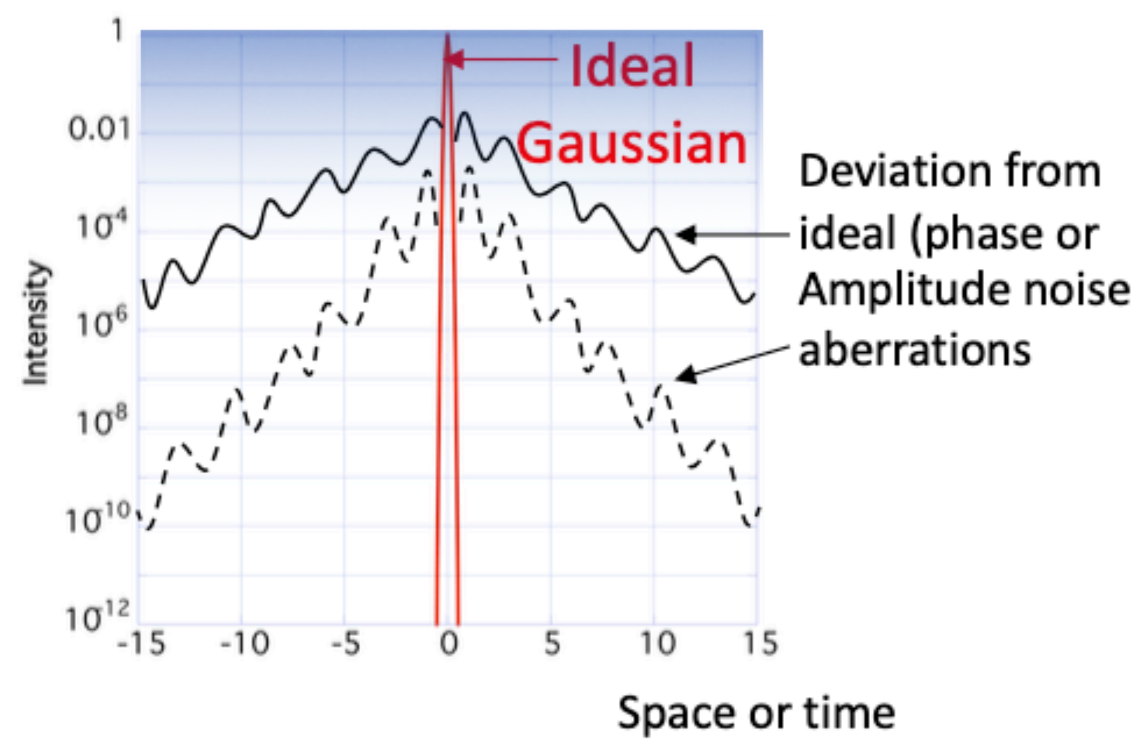
pulse spot size × pulse duration ($A\tau$)

- Small fluctuations in I lead to large rate fluctuations
  - air movement, vibrations, temp-drift, pump discharge variations, etc.

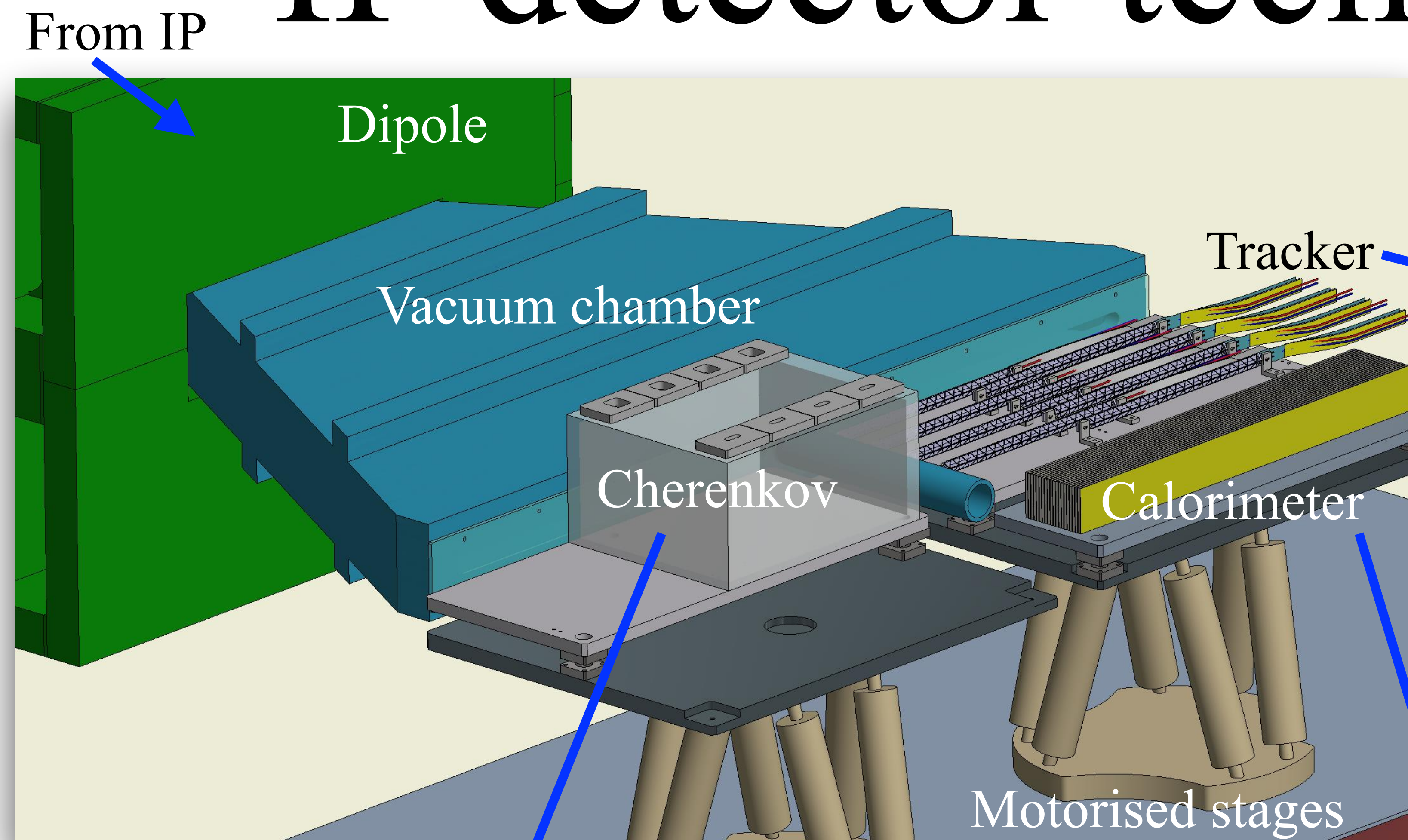
- Either increase the stability by a better design or come up with precision diagnostics per shot



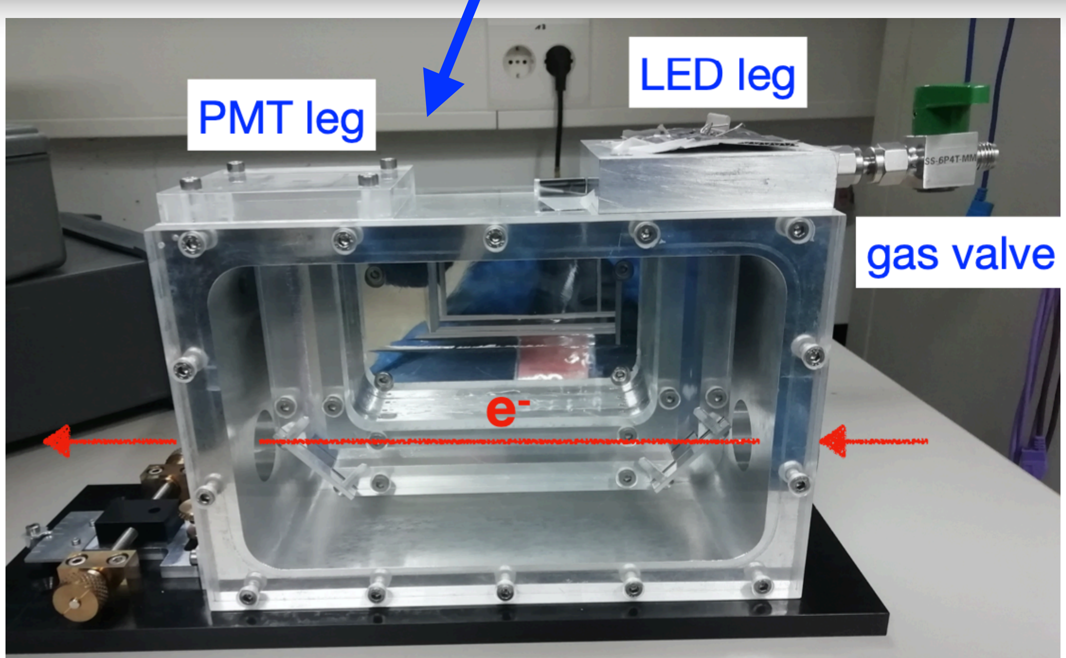




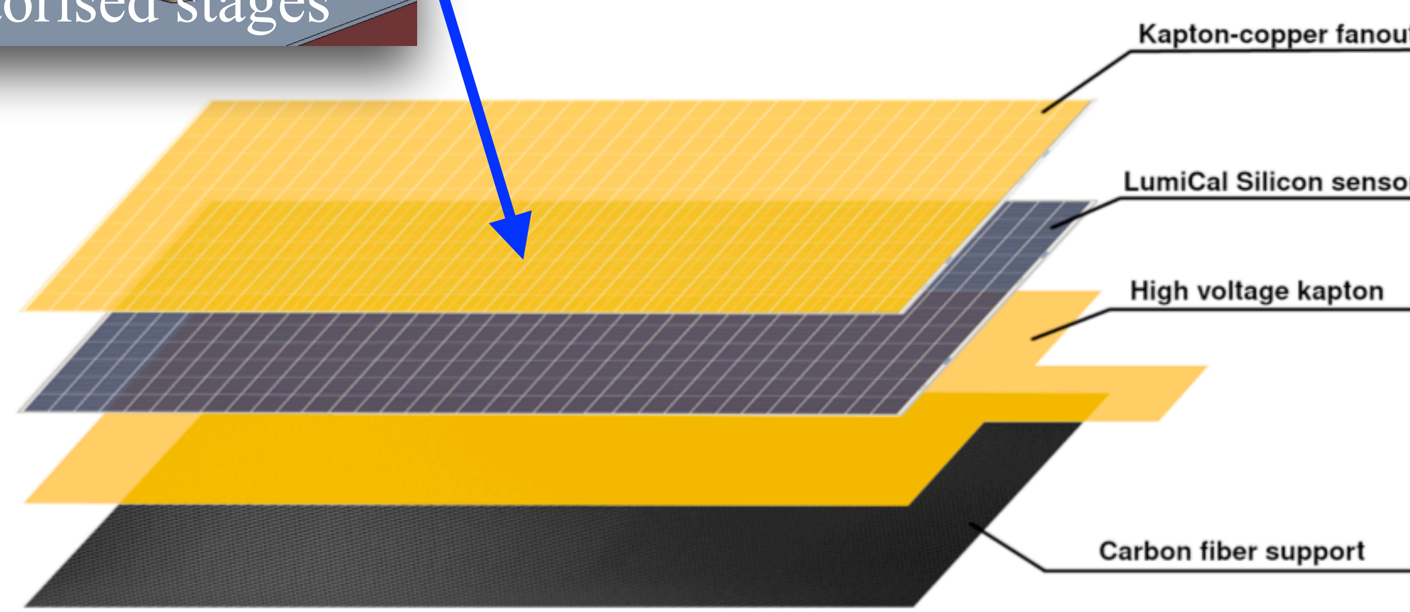
IP detector technologies



Tracker: based on ALICE ITS's ALPIDE staves

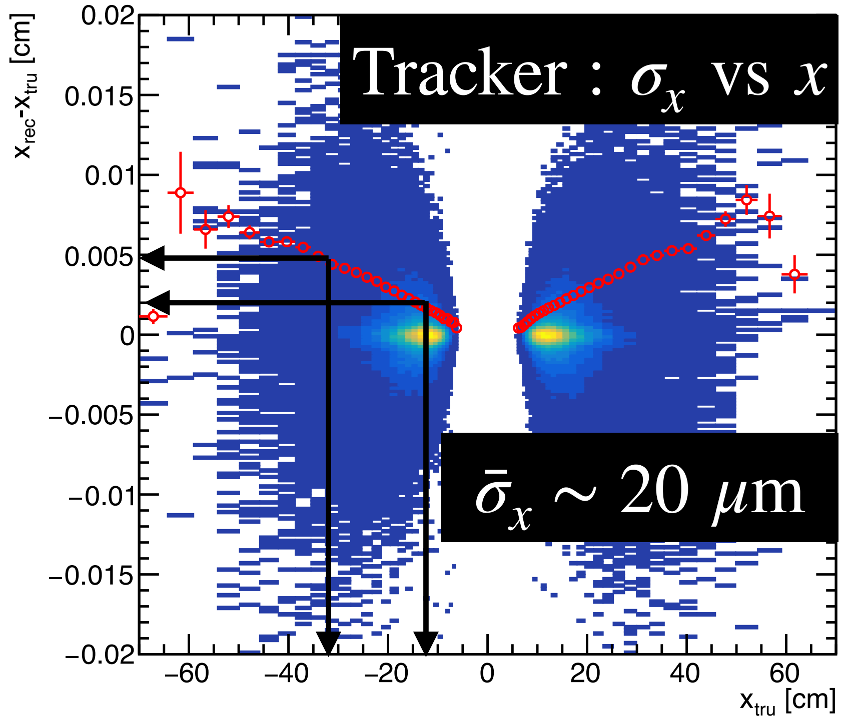


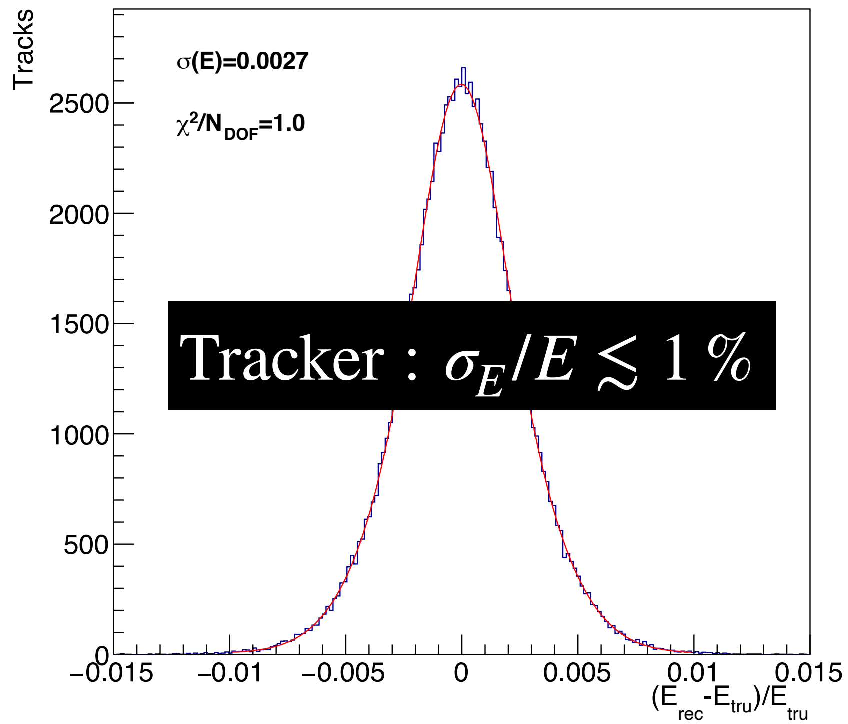
Cherenkov: prototype from ILC polarimetry

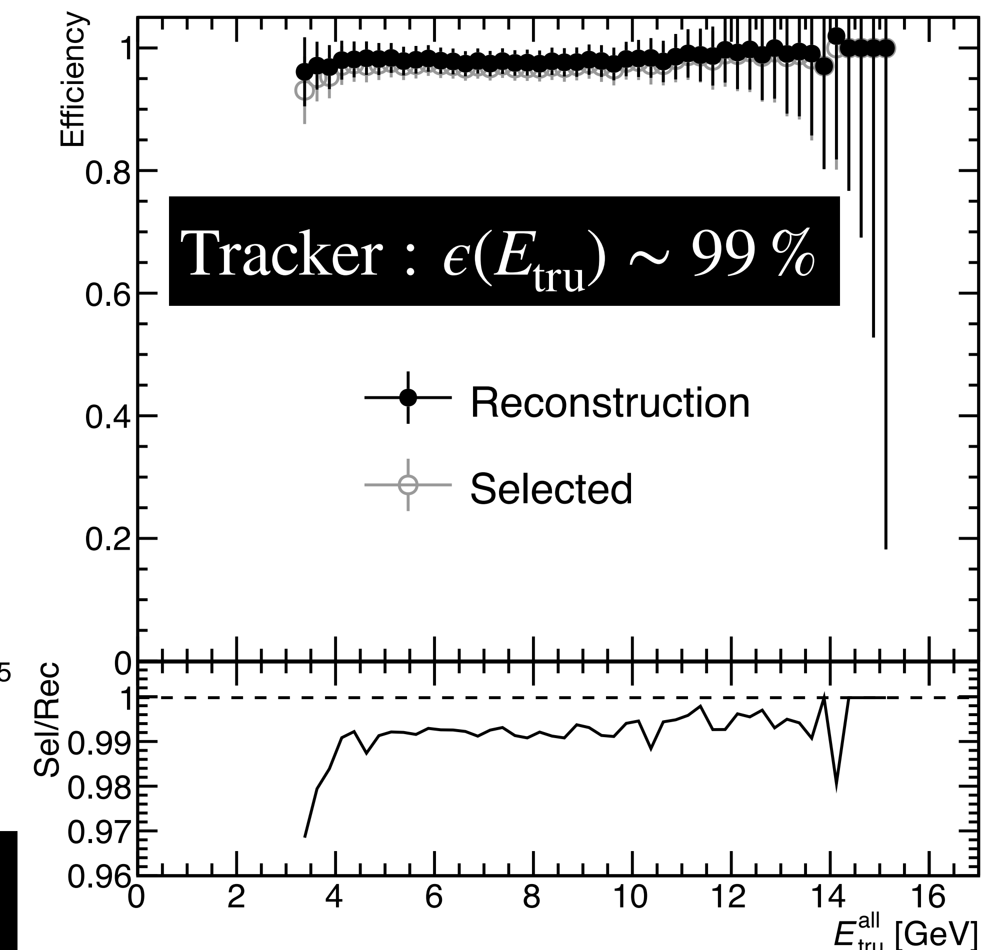


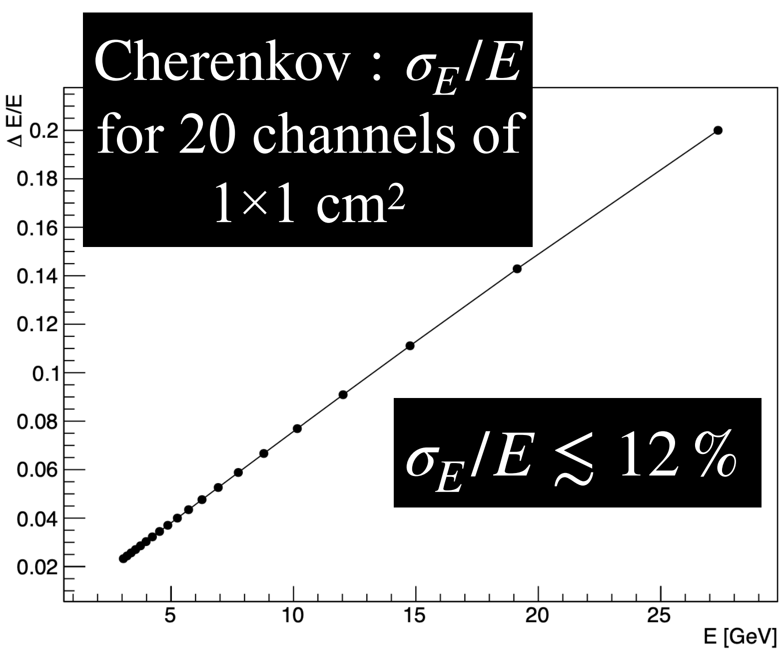
Calorimeter: ~20 Layers of W-Si,
inspired by the ILC's LumiCal (FCAL).
Investigating also CALICE and CMS HGCAL

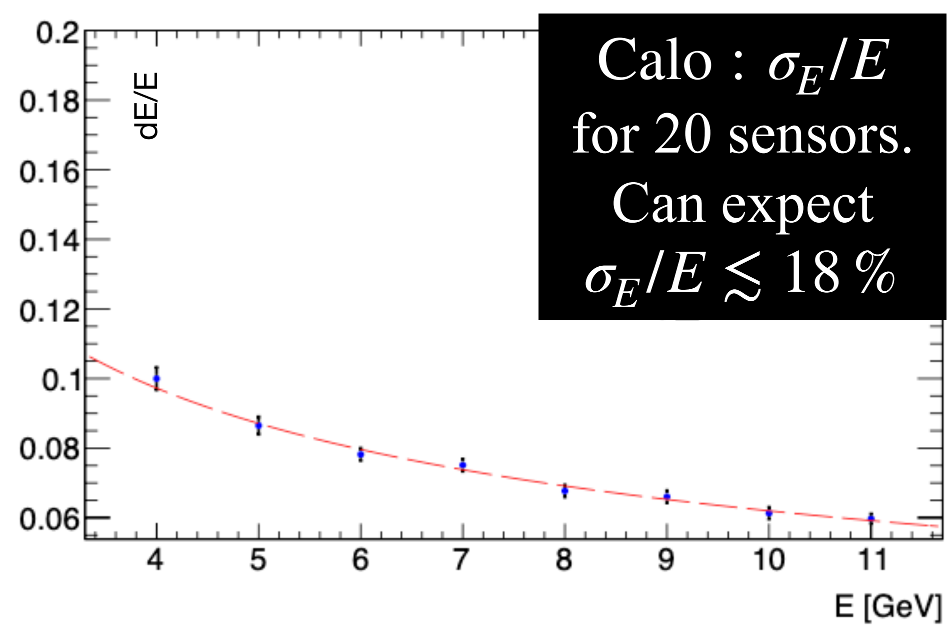
IP detectors performance (prelim.)

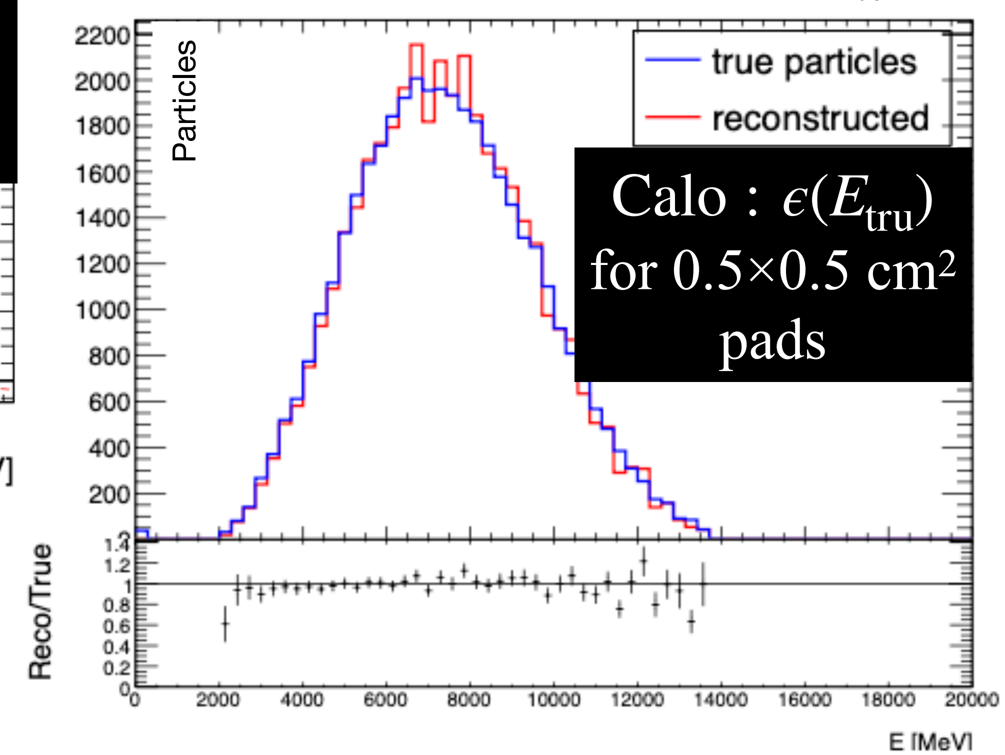










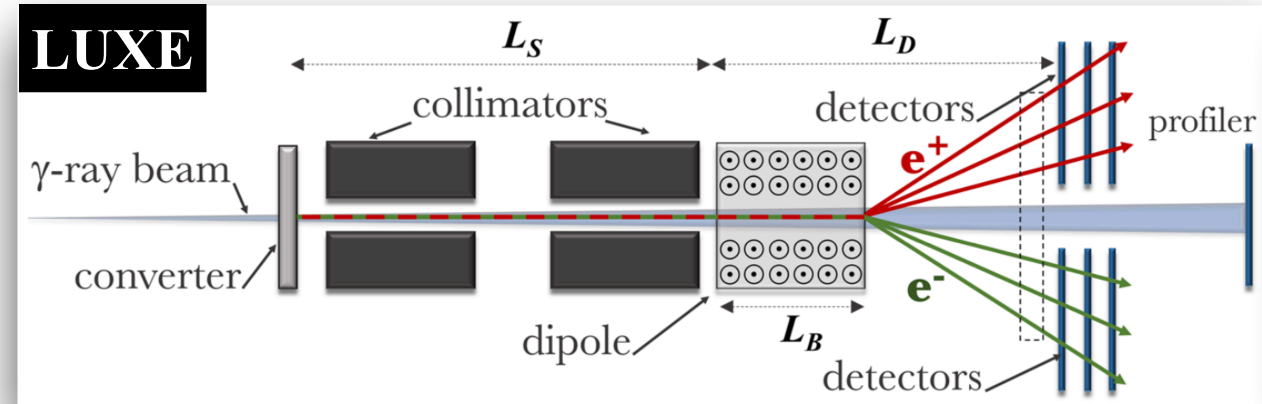


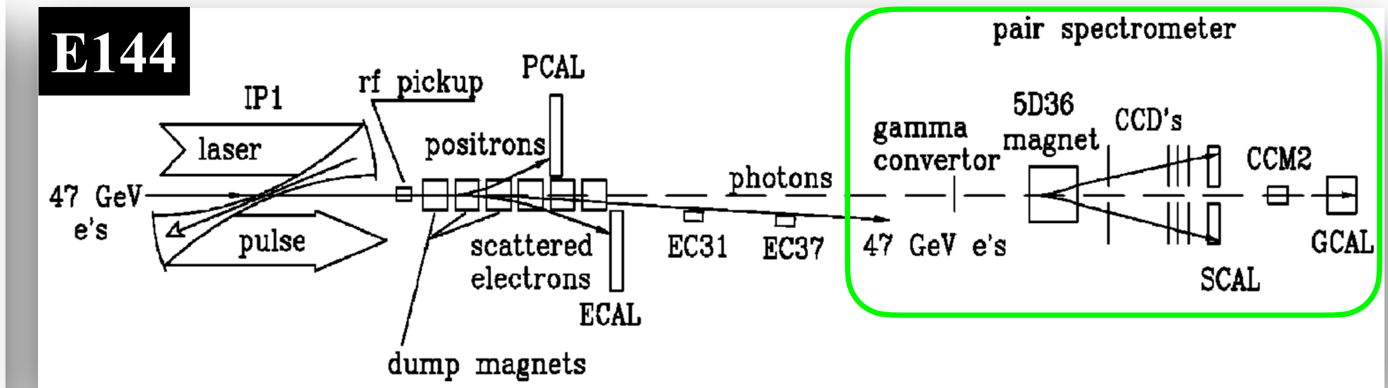
- Count number of e^+,e^- and reconstruct the energy spectra
- Combined operation of the tracker+calo: better redundancy

Fwd photons system (γ_B & γ_C)

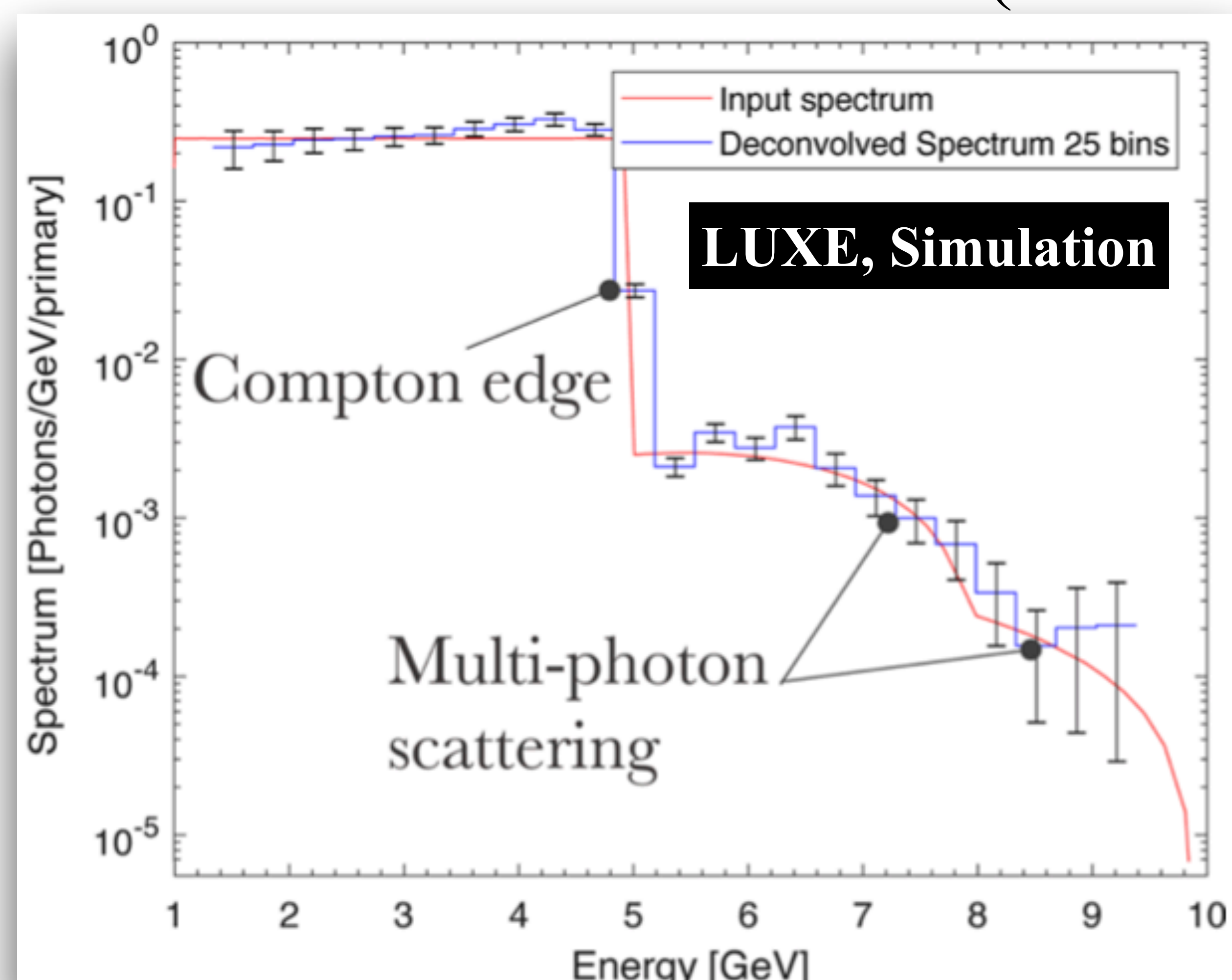
https://www.nature.com/articles/s41598-020-66832-x

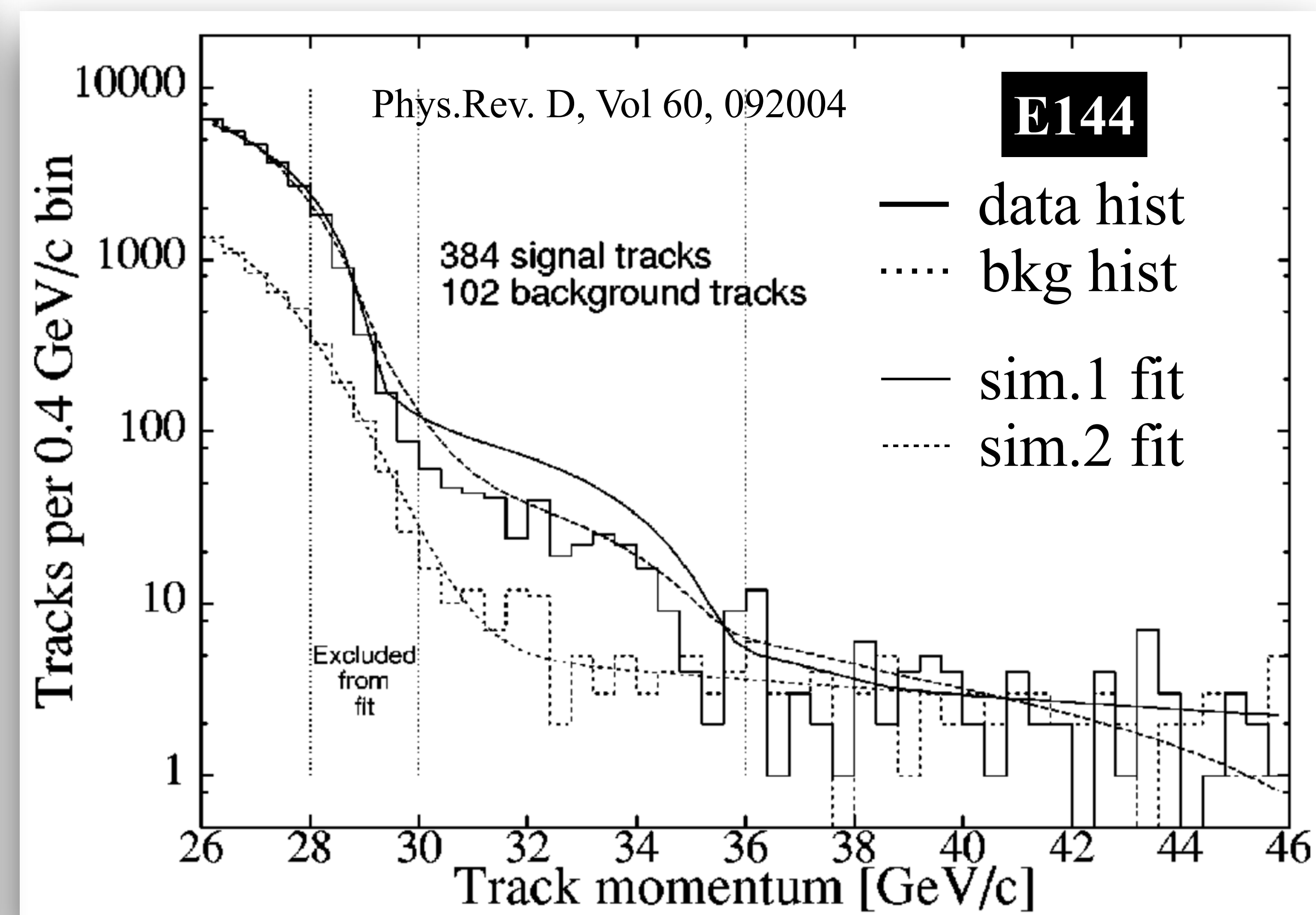
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.60.092004





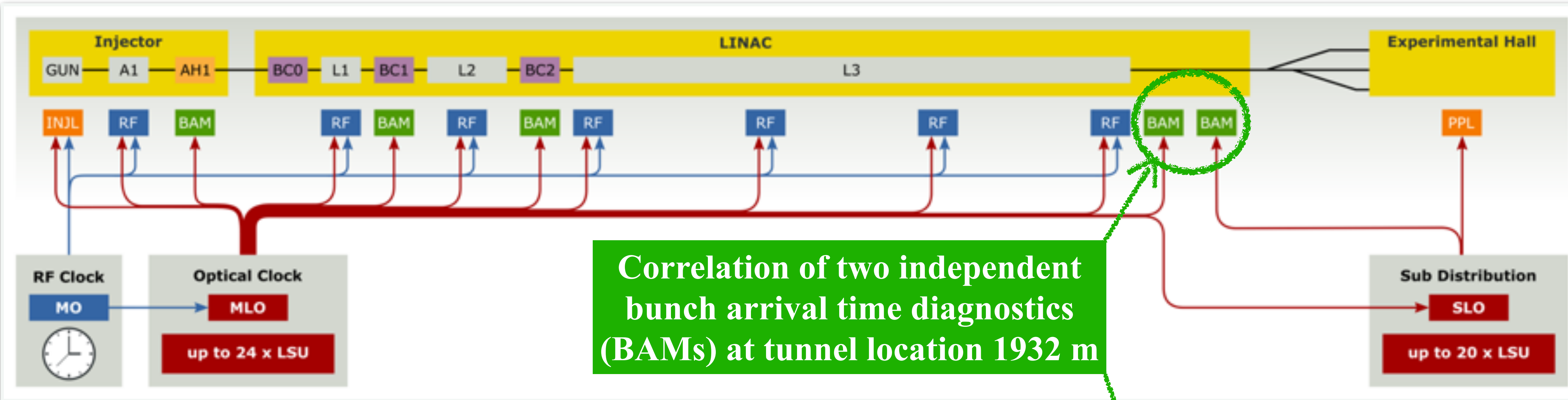
Nonlinear (converted) Compton photons





Synchronisation & Trigger

world's largest femtosecond-precision synchronisation system



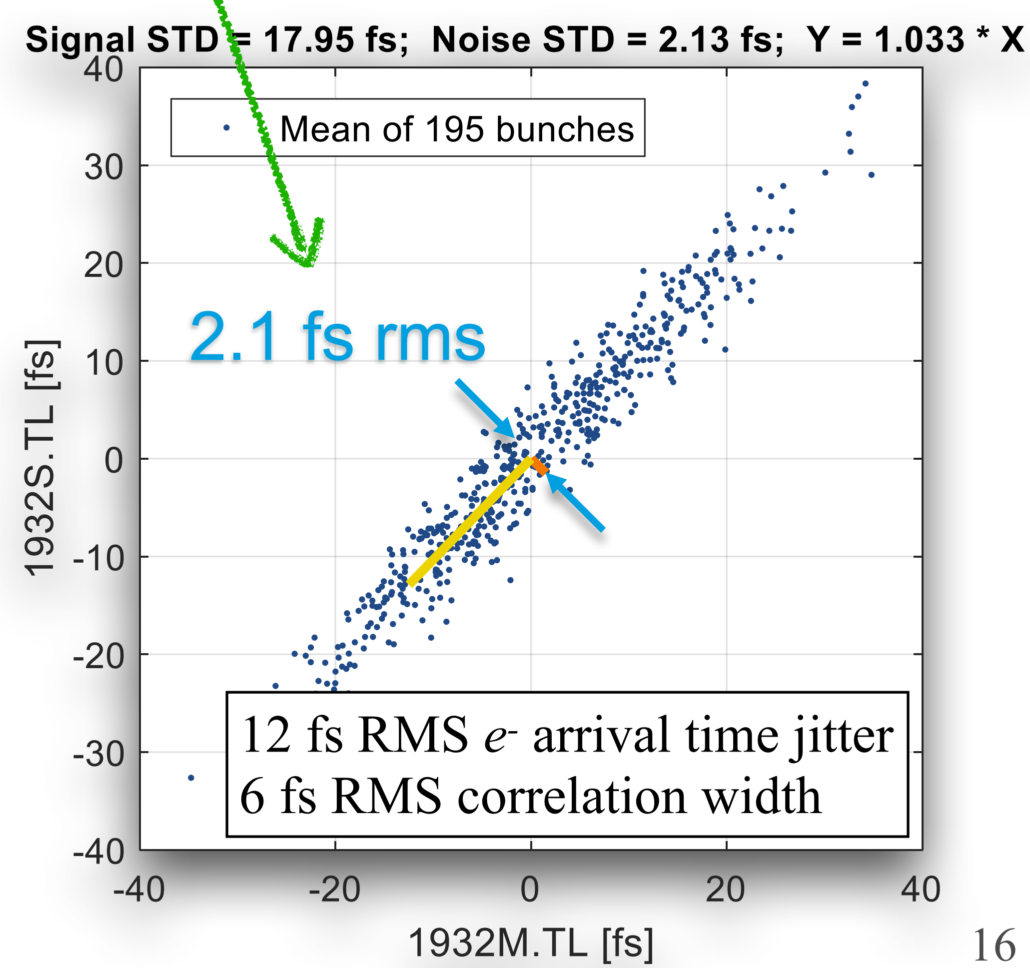
Synchronisation of the XFEL:

- Optical clock (master laser oscillator, MLO) provides stable pulsed optical reference
  - Phase-locked to radio frequency (RF) oscillator (MO)

- Optical reference distributed via length-stabilised optical fibre links for laser locking and RF re-sync

LUXE's laser oscillator:

- connected to the optical sync system, which will in turn trigger the detectors

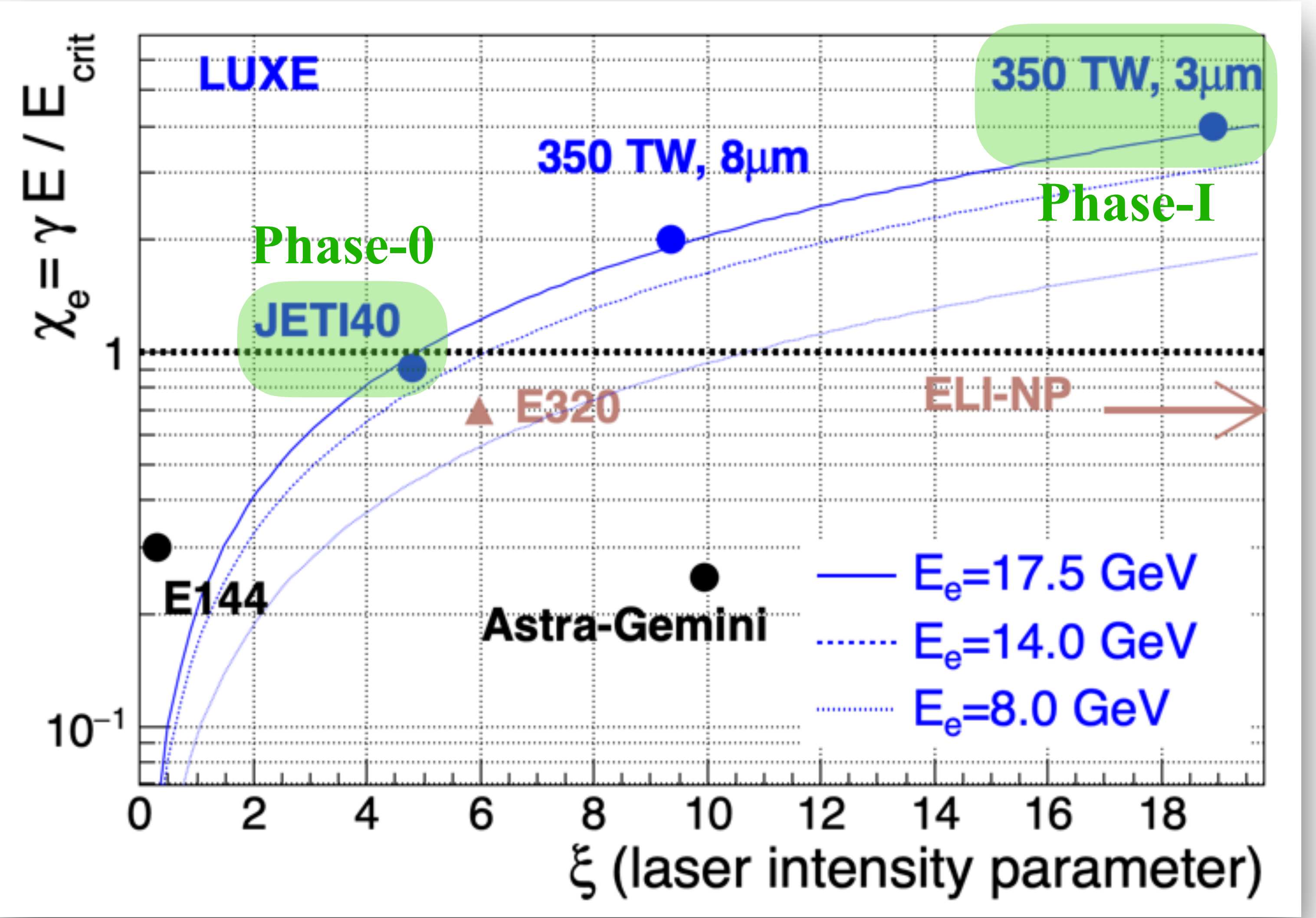


Summary

- Approach & pass ϵ_S (particle's rest frame) in a clean env for the first time
- Strong-field effects may enhance the potential to uncover new physics
- Collaboration is open for contributions
- Exciting times!

Timeline

- End of 2020: CDR
- 2021-2023: Phase-0 installation
- 2023-2024: Phase-0 $e^- + \gamma_L$ run
- 2025: Phase-0 $\gamma_B + \gamma_L$ run
- 2026: Install 350 TW laser
- 2027-2029: Phase-I experiment



Previous LUXE talks:
https://luxe.desy.de/documents/talks/index_eng.html

Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

Skoltech

Skolkovo Institute of Science and Technology

université PARIS-SACLAY

UNIVERSITAS GOTHOBURGENSIS 1891

AGH

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

KINR

KIEV INSTITUTE FOR NUCLEAR RESEARCH

MAX-PLANCK-GESELLSCHAFT

QUEEN'S UNIVERSITY BELFAST

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA · SEIT 1558

LUXE

DESY

JAI John Adams Institute for Accelerator Science

UNI FREIBURG

UNIVERSITY OF PLYMOUTH

UCL

MEPhI

NATIONAL RESEARCH NUCLEAR UNIVERSITY • MOSCOW ENGINEERING PHYSICS INSTITUTE • MEPhI

HELMHOLTZ

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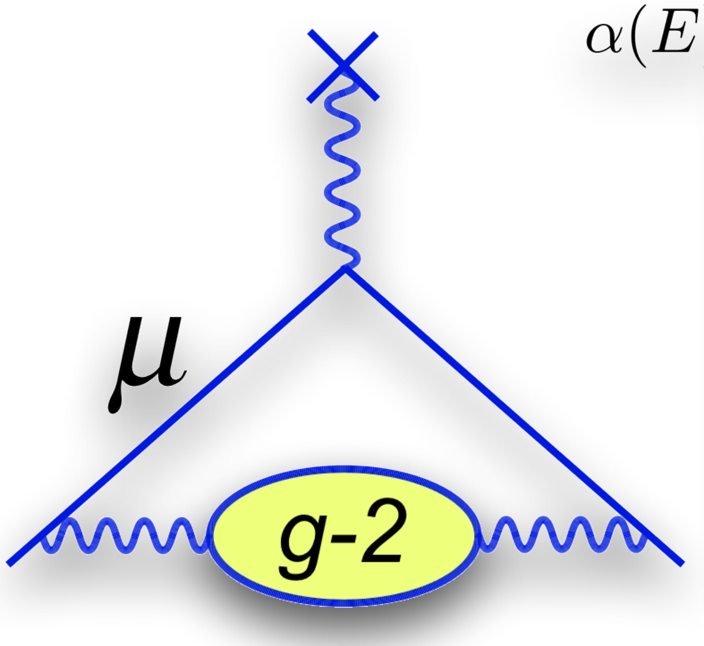
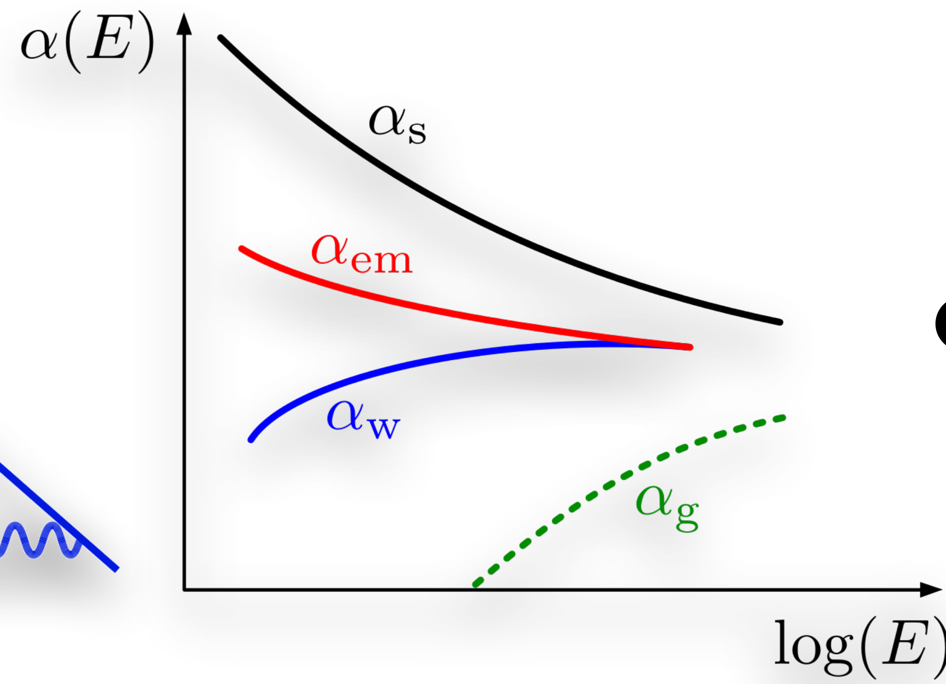
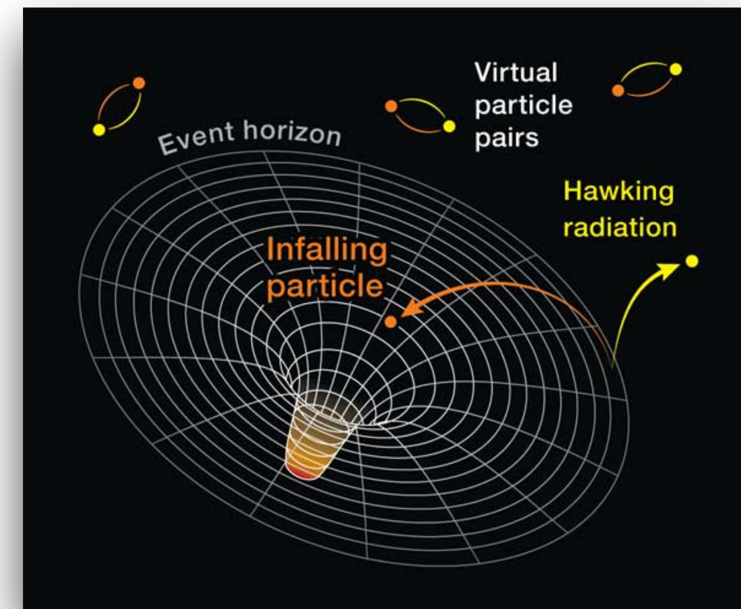
THANK YOU

BACKUP

Why strong field physics?

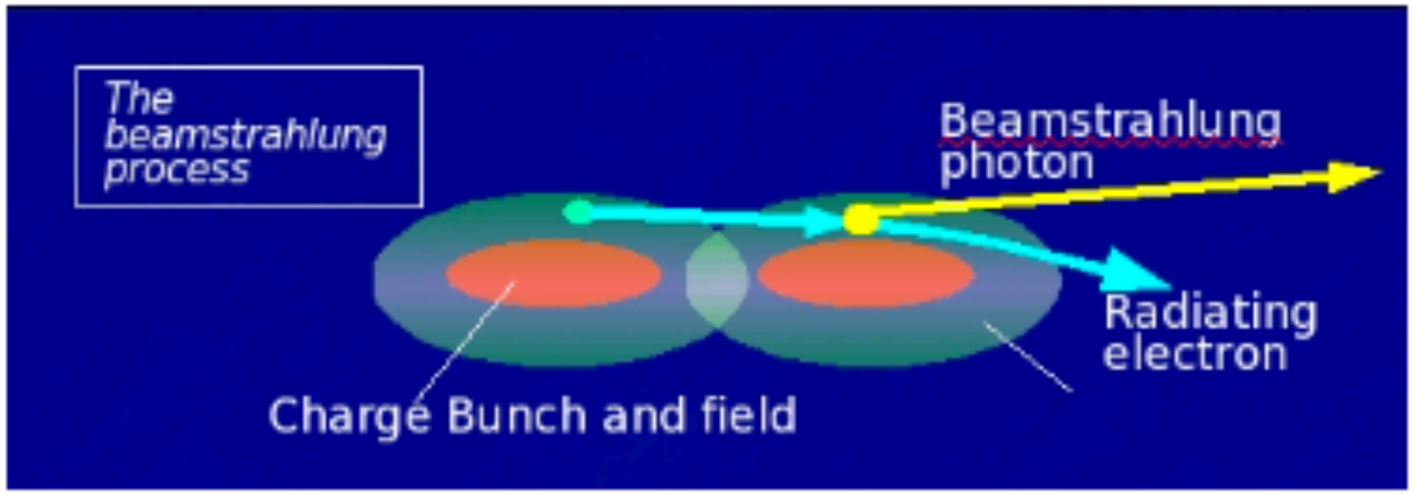






- Reaching ϵ_S is equivalent e.g. to the measurement of the anomalous magnetic moment or the coupling constant (deviations could be a hint for new physics)
- Non-perturbative QFT is still being actively developed
- Can provide insight into the vacuum state / Higgs mechanism
- Schwinger effect proposed as mechanism for reheating in the early universe
- New physics opportunities with strong field? (ALPs, mCPs,…)

Strong fields at the collider Interaction Point



$\Upsilon \approx 1$ **sets the strong field scale.**

$$\Upsilon = \frac{e|\vec{a}|}{mE_{\text{cr}}}(k \cdot p) \quad \text{c.f. } \chi$$

- The quantum theory of multiphoton beamstrahlung.
  Energy loss, Depolarisation, Backgrounds in the detectors
- Future linear colliders will have "strong" IP fields
  $\Upsilon/\Upsilon_{\text{av}}$ depends on collider bunch parameters and the pinch effect
- **All** collider processes are potentially "strong field processes"
  especially precision processes. A SQFT programme for colliders

Machine	LEP2	SLC	ILC	CLIC
E (GeV)	94.5	46.6	500	1500
$N(\times 10^{10})$	334	4	2	0.37
σ_x, σ_y (μm)	190, 3	2.1, 0.9	0.49, 0.002	0.045, 0.001
σ_z (mm)	20	1.1	0.15	0.044
Υ_{av}	0.00015	0.001	0.24	4.9

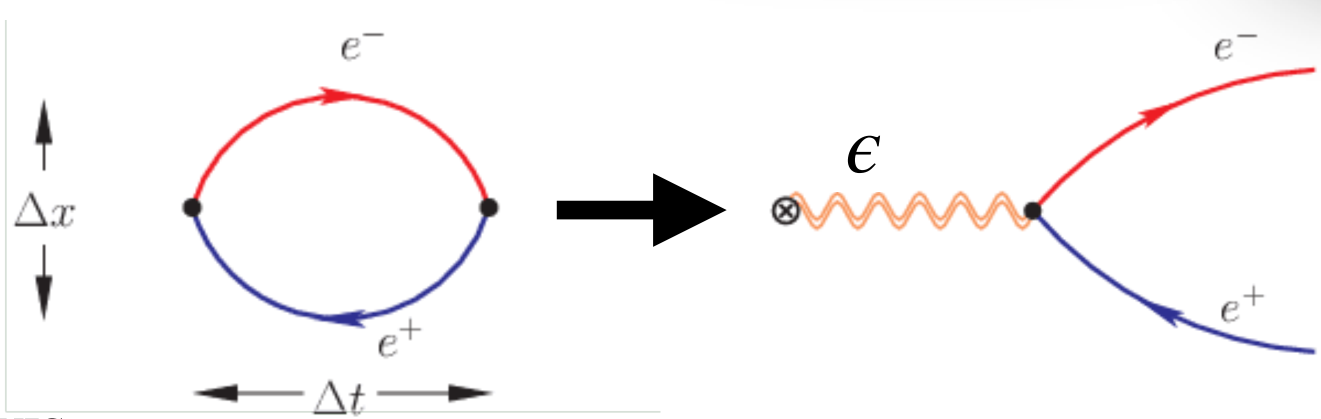
The Schwinger effect

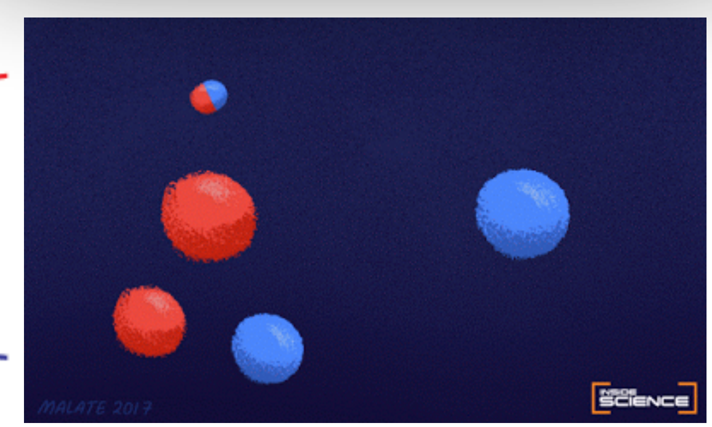
- Force of external static electric field is: $F = e\epsilon$
- Energy to separate the virtual pair in a distance d: $E = F \cdot d = e\epsilon \cdot d$
- Energy required to materialise as a real pair: $E = 2m_e c^2$
- Condition to materialise as a real pair in distance d: $e\epsilon d = 2m_e c^2$
- Compton wavelength (typical scale): $\lambda_C = \hbar/(m_e c)$
- Probability for d:

$$P \propto \exp\left(-\frac{d}{\lambda_C}\right) = \exp\left(-2\frac{m_e^2 c^3}{\hbar e \epsilon}\right) = \exp\left(-2\frac{\epsilon_S}{\epsilon}\right)$$

non-perturbative in *e*

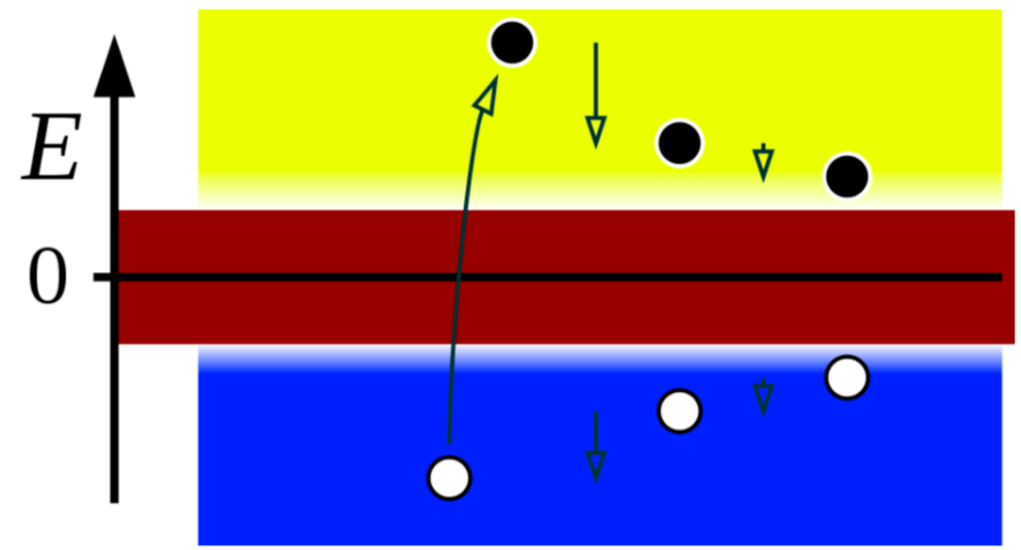
$$\epsilon_S = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \frac{\mathrm{V}}{\mathrm{m}}$$





The Furry Picture vacuum

The 2nd quantisation of the Dirac field relies on a gap between the positive and negative energy solutions



- The external field “closes” this energy gap
- Electrons are lifted from the sea to leave the vacuum charged
- The VEV of the EM current must no longer vanish
- Separation into creation and destruction operators is problematic
- This point is the limit of the validity of the Furry picture

The Furry Pictures

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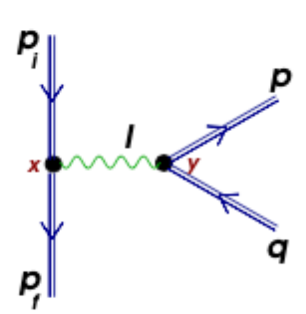
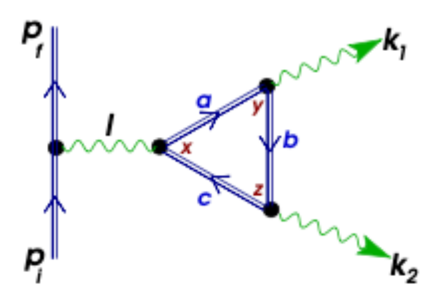
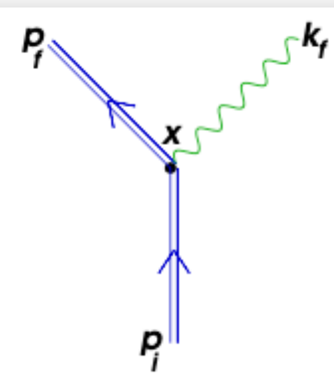
- If the external field is sufficiently strong: quantum interactions with it leave it essentially unchanged and it can be considered to be a classical background field
- Separate the gauge field to external and quantum parts:
  $\mathscr{L}_{\text{Int}} = \bar{\psi}(i\not{\partial} - m)\psi - \frac{1}{4}F^2_{\mu\nu} - e\bar{\psi}(\not{A}_{\text{ext}} + \not{A})\psi$ and shift $\not{A}_{\text{ext}}$ to the Dirac component:
  $\mathscr{L}_{\text{FP}} = \bar{\psi}^{\text{FP}}(i\not{\partial} - e\not{A}_{\text{ext}} - m)\psi^{\text{FP}} - \frac{1}{4}F^2_{\mu\nu} - e\bar{\psi}^{\text{FP}}\not{A}\psi^{\text{FP}}$
- The FP Lagrangian satisfies the Euler-Lagrange equation.
  - New equation of motion for the non-perturbative (bound) Dirac field (wrt $\not{A}_{\text{ext}}$) and new solutions ψ^{FP}: $(i\not{\partial} - e\not{A}_{\text{ext}} - m)\psi^{\text{FP}} = 0$
- Exact solutions exist for a certain classes of external fields (plane waves, Coloumb fields and combinations) [Volkov Z Physik 94 250 (1935), Bagrov & Gitman 1990]:
  $\psi^{\text{FP}} = \mathbf{E}_p e^{-ipx} u_p$ with $\mathbf{E}_p = \text{Exp}\left[-\frac{1}{2k\cdot p}\left(e\not{A}_{\text{ext}}\not{k} + i2e(A_{\text{ext}}\cdot p) - ie^2A^2_{\text{ext}}\right)\right]$



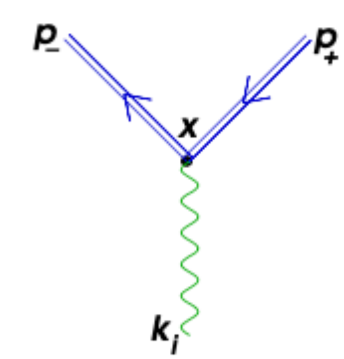
Trident process (vacuum resonance)



Photon splitting (vacuum birefringence)



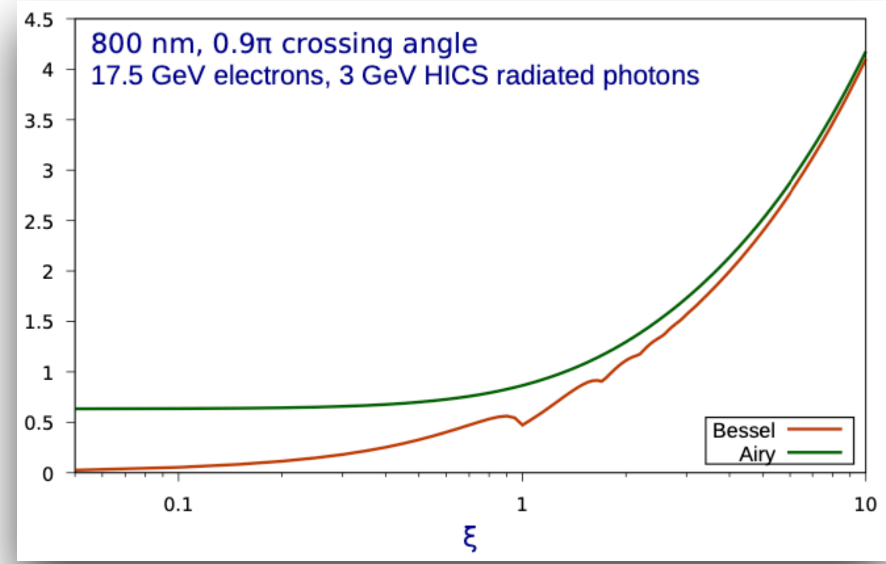
High intensity Compton scatter (HICS)



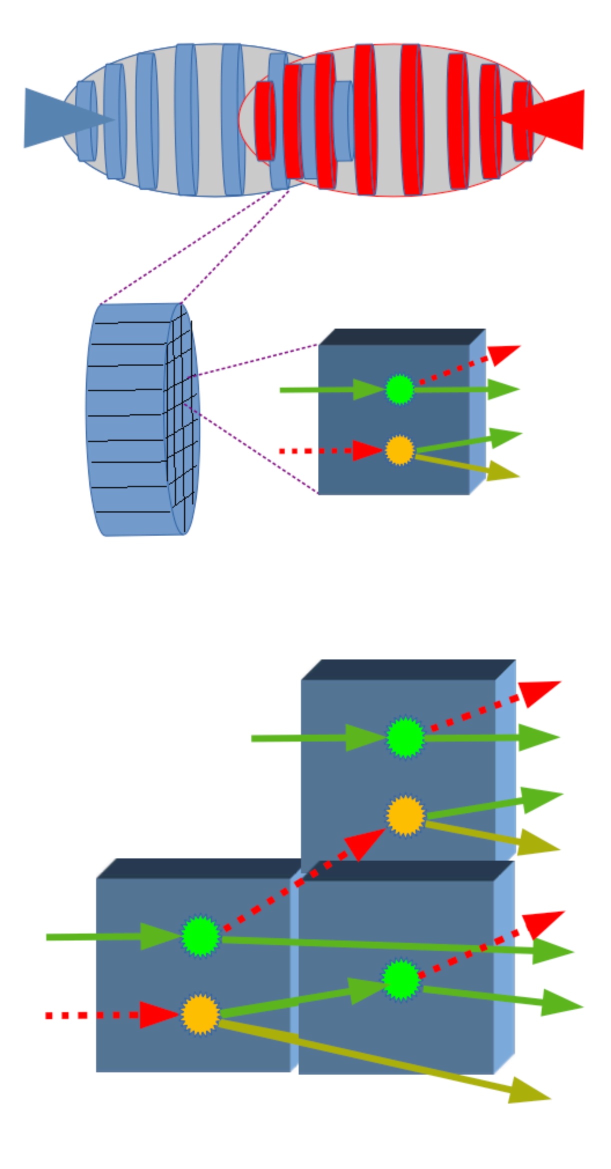
One photon pair production (OPPP)

Charge bunch/laser interaction simulation

- Take circular/linear/elliptical polarised plane wave
  - can expand in Bessel functions
  - use the Locally Constant Field Approximation (LCFA)
    - can approximate with Airy functions
    - since field strength varies across pulse, choose correct polarisation, sample pulse in small voxels, take local amplitude of the pulse in each voxel



- Discretise the interaction
  - transform to head-on collision
  - divide into overlapping slices
  - divide slices into mc voxels
  - calculate ξ and χ in each voxel
  - MC for each SQED process (rarest first)



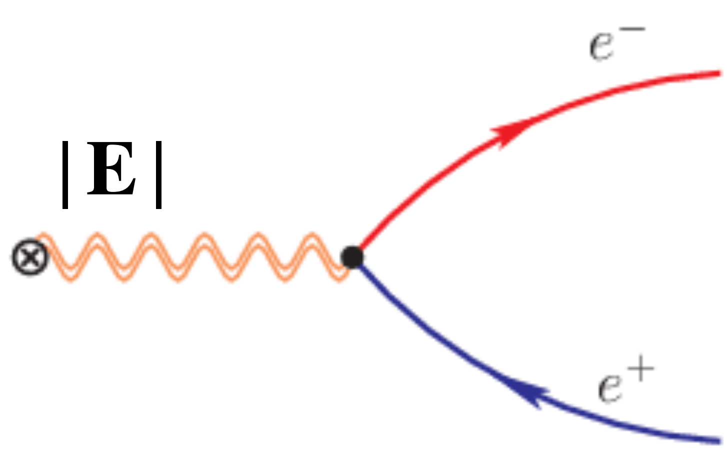
- Macro vs Micro
  - real particles enter/leave voxel
  - higher order processes tested in each voxel
  - distinguish between analytic rate within one voxel, and the effective global rate from sampling across whole bunch/pulse
  - final particle ensemble built up over successive voxel MC + time step through the whole collision (typically 5σ separation)

Boiling point of QED

- **Weak fields**: many accurate predictions of observables through ordinary perturbative expansion in the EM coupling (α_{EM})
- **Strong fields**: observables become inaccessible through ordinary perturbative expansion and there's no experimental verification
- **For example**: the spontaneous e^+e^- pair production (SPP) rate per unit volume in strong static E-field is:

$$\frac{\Gamma_{\mathrm{SPP}}}{V} = \frac{m_e^4}{(2\pi)^3}\left(\frac{|\mathbf{E}|}{\mathrm{E_c}}\right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n\pi\frac{\mathrm{E_c}}{|\mathbf{E}|}} \sim e^{-\frac{\pi m_e^2}{e|\mathbf{E}|}}$$

non-perturbative in α



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But how to produce static E-field of the order of ~1.3×10^18 V/m ???

Lasers strong field "how-to"

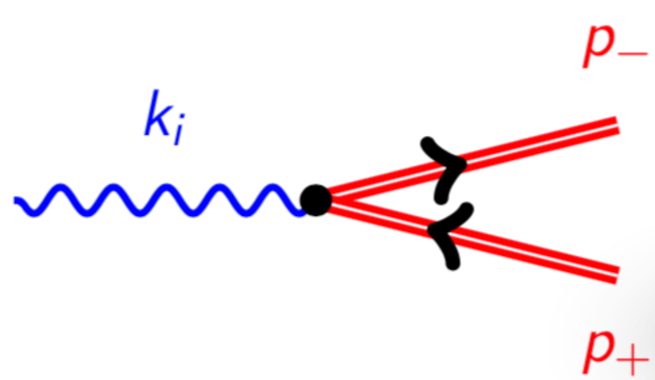
- Laser-assisted one photon pair production, OPPP (SPP $\longrightarrow$OPPP)
  - the laser's E-field frequency is ω, with momentum $k = (\omega, \mathbf{k})$
  - the laser's E-field strength is $|\epsilon|$, with $I \sim |\epsilon|^2$
  - The e^+e^- pair picks up momentum from the laser photons

- OPPP rate is a function of the <u>laser intensity ξ</u> and the <u>photon recoil χ</u>:

Dimensionless and Lorentz-invariant

$$\begin{cases} \text{Laser intensity}: \; \xi = \dfrac{e|\epsilon|}{\omega m_e} = \dfrac{m_e}{\omega}\dfrac{|\epsilon|}{\epsilon_S} \\[2ex] \text{Photon recoil}: \; \chi_\gamma = \dfrac{k \cdot k_i}{m_e^2}\xi = (1+\cos\theta)\dfrac{\omega_i}{m_e}\dfrac{|\epsilon|}{\epsilon_S} \end{cases}$$

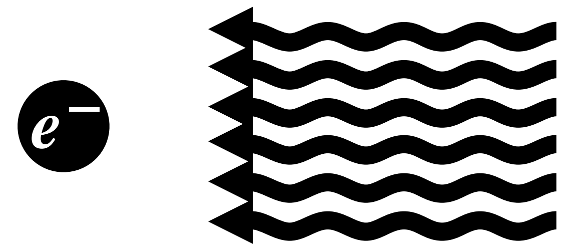
Initial photon : $k_i = (\omega_i, \mathbf{k}_i)$



$$\Gamma_{\text{OPPP}} = \frac{\alpha m_e^2}{4\omega_i} F(\xi, \chi_\gamma)$$

Understanding ξ

Electron "at rest"



Infinite E-field plane wave with frequency ω

The electron will oscillate with frequency ω and radiate in turn: $eE = m_e a$

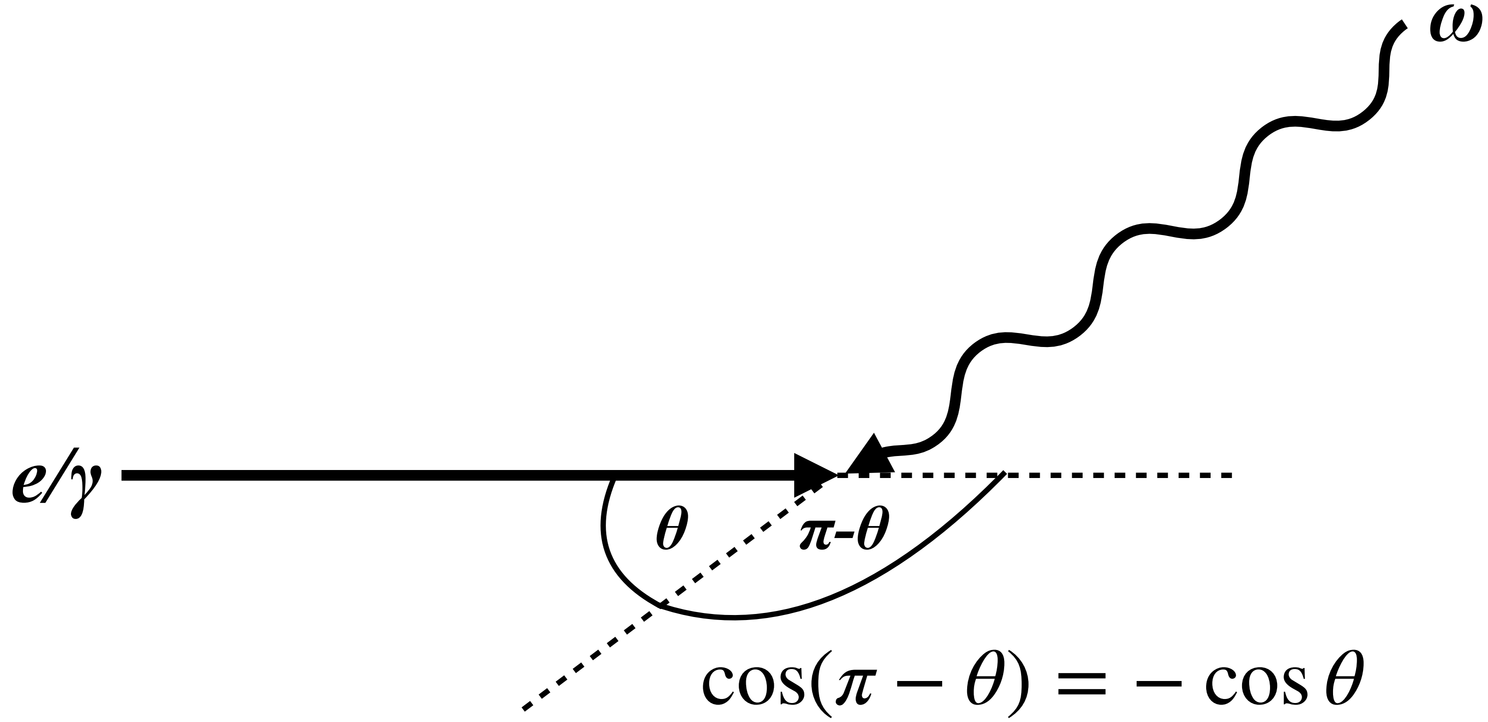
The electron's maximum velocity is: $v_{\max} = a \cdot \Delta t = \dfrac{eE}{m_e} \cdot \dfrac{1}{\omega}$

Normalise to c: $\xi \equiv \dfrac{v_{\max}}{c} = \dfrac{eE}{\omega m_e c}$ (dimensionless & Lorentz-invariant)

ξ reaches unity for e.g. a $\lambda = 800$ nm laser at an intensity of $I \sim 10^{18}$ W/cm²

Understanding χ

Recoil parameter: $\chi = \frac{k \cdot k_i}{m_e^2}\xi = (1+\cos\theta)\frac{\omega_i}{m_e}\frac{|\mathbf{E}|}{E_c}$



$$\cos(\pi-\theta) = -\cos\theta$$

Scattering geometry: $k \cdot k_i = \omega\omega_i - |\mathbf{k}||\mathbf{k}_i|\cos(\pi-\theta) = \omega\omega_i(1+\cos\theta)$

$$\chi = \frac{k \cdot k_i}{m_e^2}\xi = \frac{\omega\omega_i(1+\cos\theta)}{m_e^2}\frac{e\epsilon}{\omega m_e c} = (1+\cos\theta)\frac{\omega_i}{m_e}\frac{\epsilon}{\epsilon_S}$$

$\frac{1}{\epsilon_S} = \frac{e}{m_e^2}$

$\hbar = c = 1$

OPPP rate: $\Gamma_{\mathrm{OPPP}} \propto F(\xi, \chi_\gamma)$

Sum on number of absorbed laser γ's

J_n are Bessel functions

$$F_\gamma(\xi,\chi_\gamma) = \sum_{n>n_0}^{\infty} \int_1^{v_n} \frac{\mathrm{d}v}{v\sqrt{v(v-1)}} \left[2\,J_n^2(z_v) + \xi^2(2v-1)\left(J_{n+1}^2(z_v) + J_{n\text{-}1}^2(z_v) - 2J_n^2(z_v)\right)\right]$$

$$n_0 \equiv \frac{2\xi\left(1+\xi^2\right)}{\chi_\gamma}, \qquad z_v \equiv \frac{4\xi^2\sqrt{1+\xi^2}}{\chi_\gamma}\left[v\left(v_n - v\right)\right]^{1/2}, \qquad v_n \equiv \frac{\chi_\gamma\, n}{2\xi(1+\xi^2)}$$

threshold number of absorbed γ's

As the laser intensity ξ increases

- the threshold number of absorbed photons increases
- more terms in the summation drop out of the probability

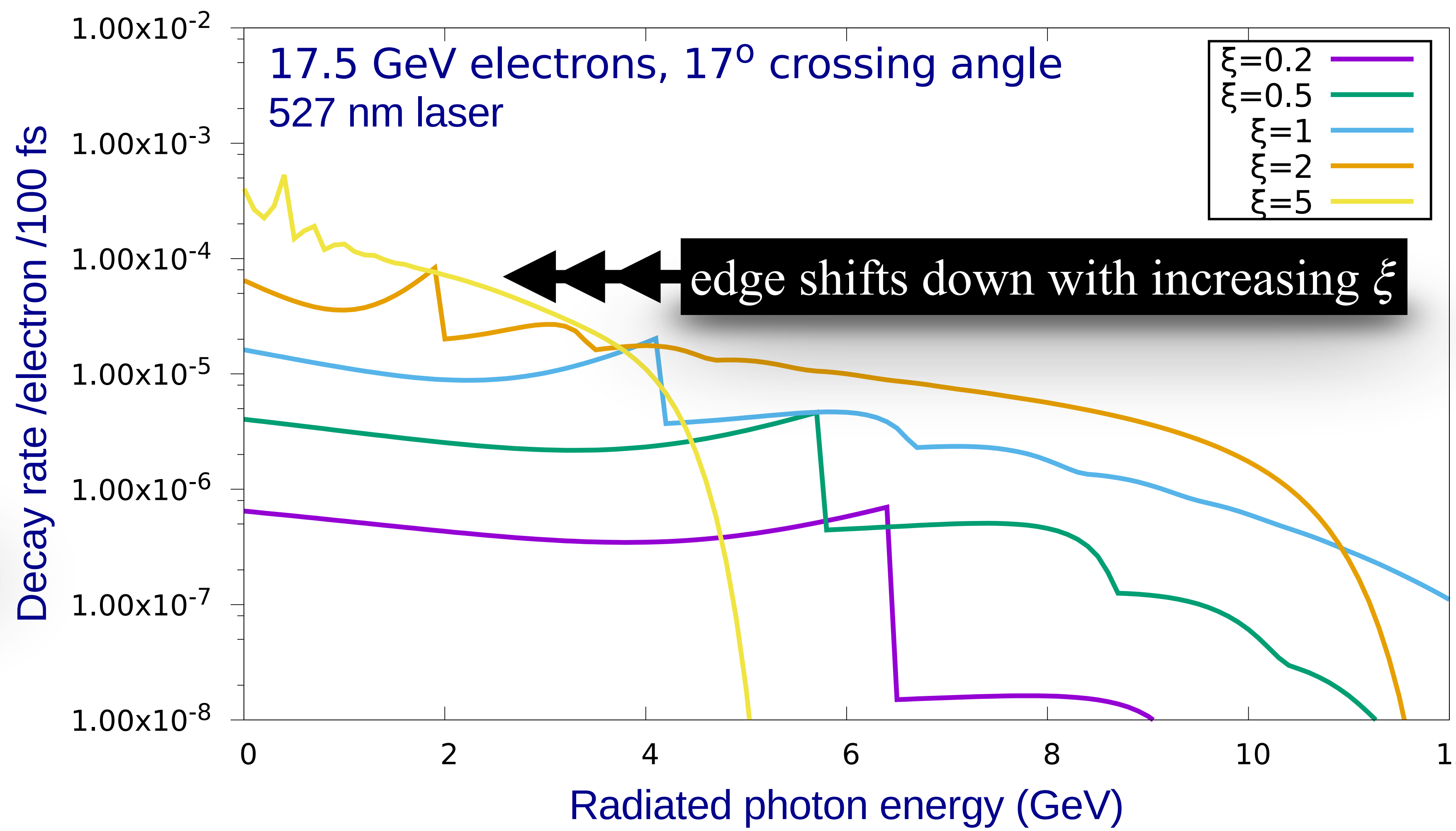
Assumption1: the laser E-field is a circularly polarised infinite plane wave

Assumption2: we can produce a mono-energetic photon beam with ~O(10 GeV)

Compton edges

- With increasing laser intensity ξ:
  - higher order (n) contributions become more prominent
  - edge shifts to lower energies due to electron's higher effective mass
- Cannot go much beyond $\xi \sim 1$ to produce high energy photons

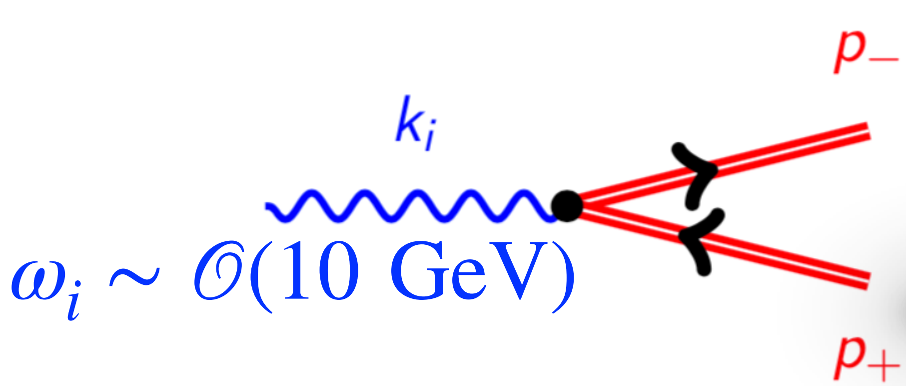
The rate is a series of Compton edges for n=1,2,3,… absorbed photons



Γ_{OPPP} asymptotically

Can measure ϵ_{S} from Γ_{OPPP}

$$\Gamma_{\mathrm{OPPP}} \longrightarrow \frac{3}{16}\sqrt{\frac{3}{2}}\alpha m_e (1+\cos\theta)\frac{|\epsilon|}{\epsilon_{\mathrm{S}}}\exp\left(-\frac{8}{3}\frac{1}{1+\cos\theta}\frac{m_e}{\omega_i}\frac{\epsilon_{\mathrm{S}}}{|\epsilon|}\right)$$

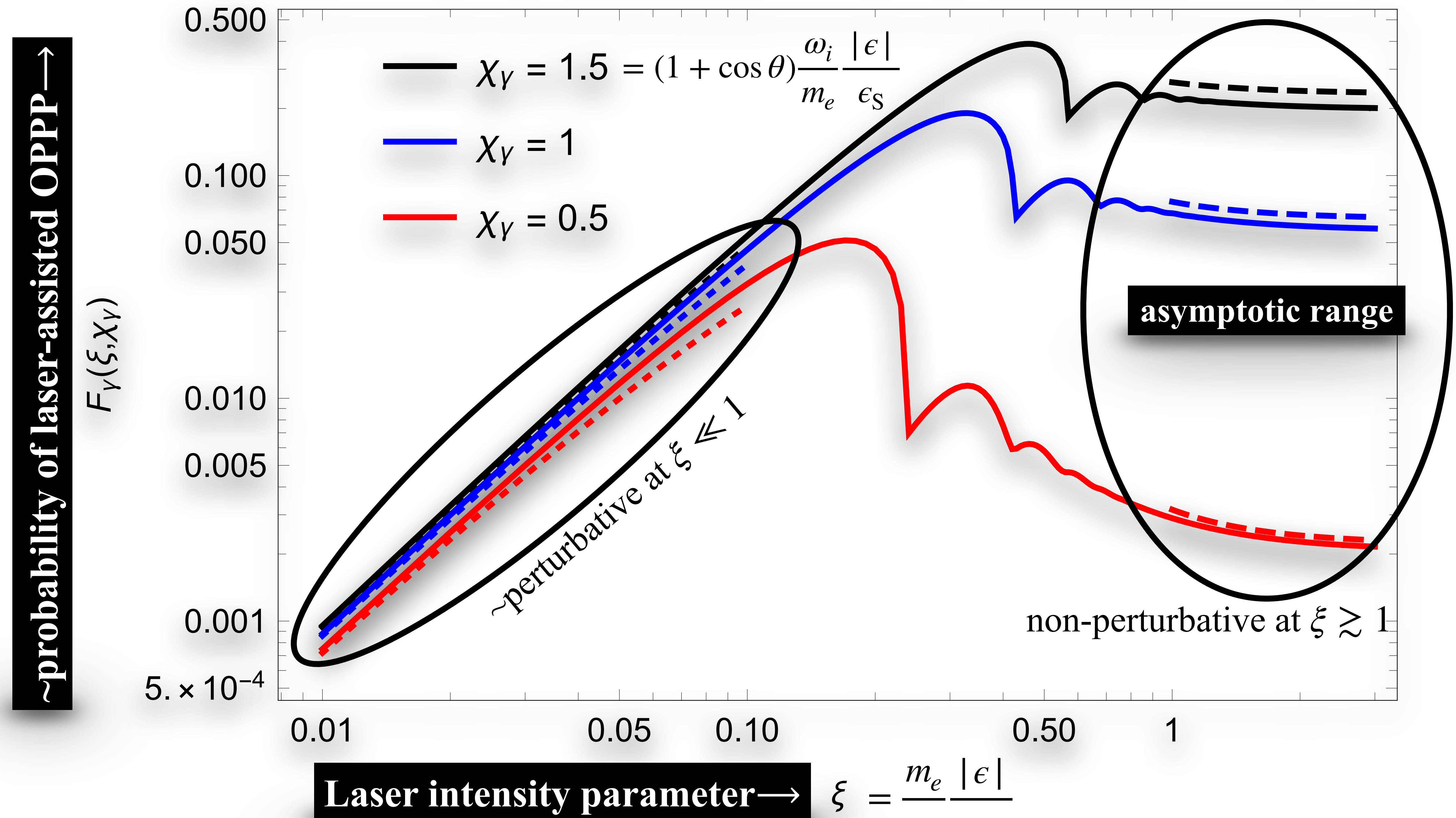


e^+e^- pair is boosted and the E-field is enhanced

- Unlike SPP, the e^+e^- pair (in its rest frame) experiences an E-field enhanced by the relativistic boost factor: $|\epsilon| \rightarrow |\epsilon| \times \omega_i/m_e$
- However, mono-energetic photon beams with energies in the $\omega_i \sim \mathcal{O}(10\ \mathrm{GeV})$ range are not available…

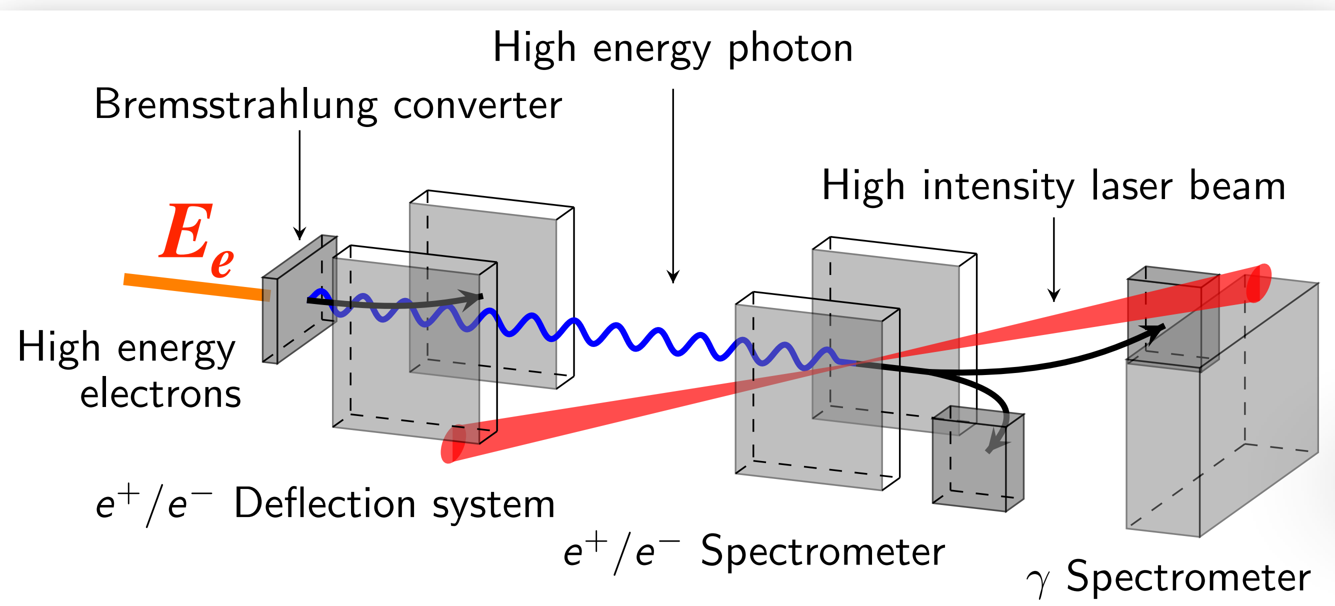
OPPP rate: $\Gamma_{\text{OPPP}} \propto F(\xi,\chi_\gamma)$

- solid lines: numerical solutions
- dashed lines: analytical asymptotic solutions



High-energy photons?

- An $\sim \mathcal{O}(10\text{ GeV})$ electron beam can be sent onto a high-Z target
- Converted into a collimated high-energy γ-beam (Bremsstrahlung)
- These photons are crossed with the high-intensity laser beam
- Laser-assisted **bremsstrahlung photon pair production (BPPP)**



E_e is the energy of the incident electrons

$$\text{Recall : } \Gamma_{\text{OPPP}} = \frac{\alpha m_e^2}{4\omega_i} F(\xi, \chi_\gamma(\omega_i))$$

$$\Gamma_{\text{BPPP}} = \frac{\alpha m_e^2}{4} \int_0^{E_e} \underbrace{\frac{d\omega_i}{\omega_i} \frac{dN_\gamma}{d\omega_i}}_{\text{Bremsstrahlung “PDF”}} F_\gamma(\xi, \chi_\gamma(\omega_i))$$

Asymptotically

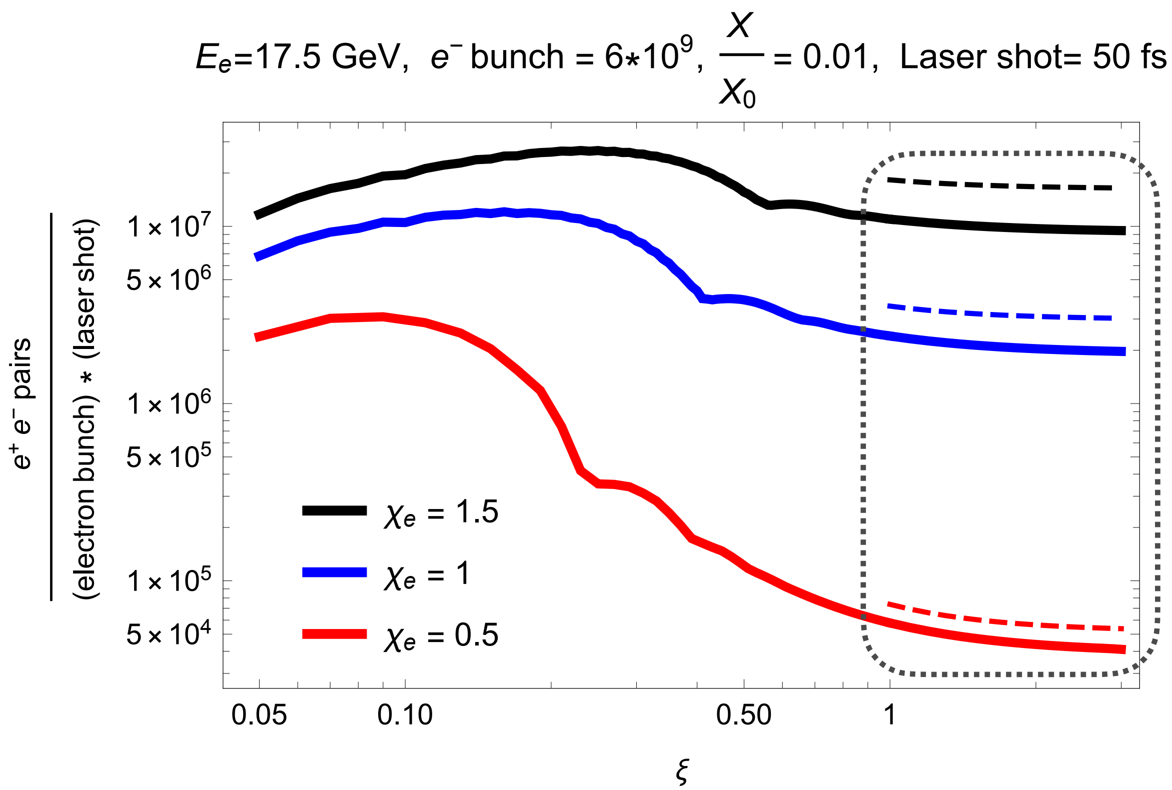
- For a target of thickness $X \ll X_0$, where X_0 is the radiation length:

$$\omega_i \frac{dN_\gamma}{d\omega_i} \approx \left[\frac{4}{3} - \frac{4}{3}\left(\frac{\omega_i}{E_e}\right) + \left(\frac{\omega_i}{E_e}\right)^2\right]\frac{X}{X_0}$$

- Similarly to OPPP, replacing χ_γ with χ_e, the BPPP rate is:

$$\Gamma_{\mathrm{BPPP}} \longrightarrow \frac{\alpha m_e^2}{E_e}\frac{9}{128}\sqrt{\frac{3}{2}}\frac{X}{X_0}\chi_e^2 e^{-\frac{8}{3\chi_e}\left(1-\frac{1}{15\xi^2}\right)}$$

Γ_{BPPP} per bunch per shot vs ξ:

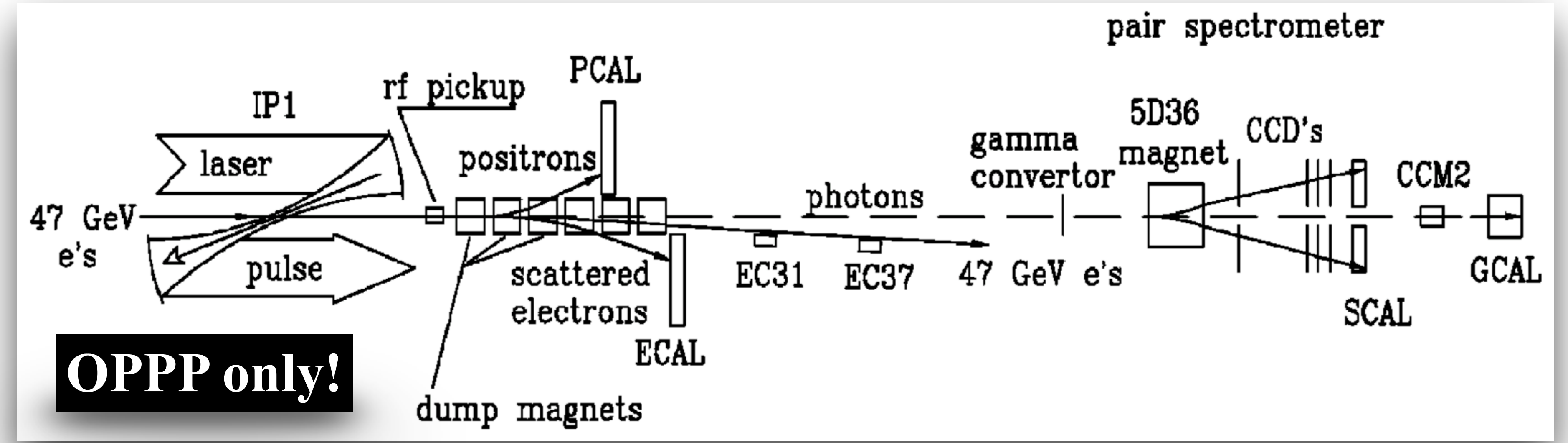


- Hence, the Schwinger critical field can be determined from Γ_{BPPP}

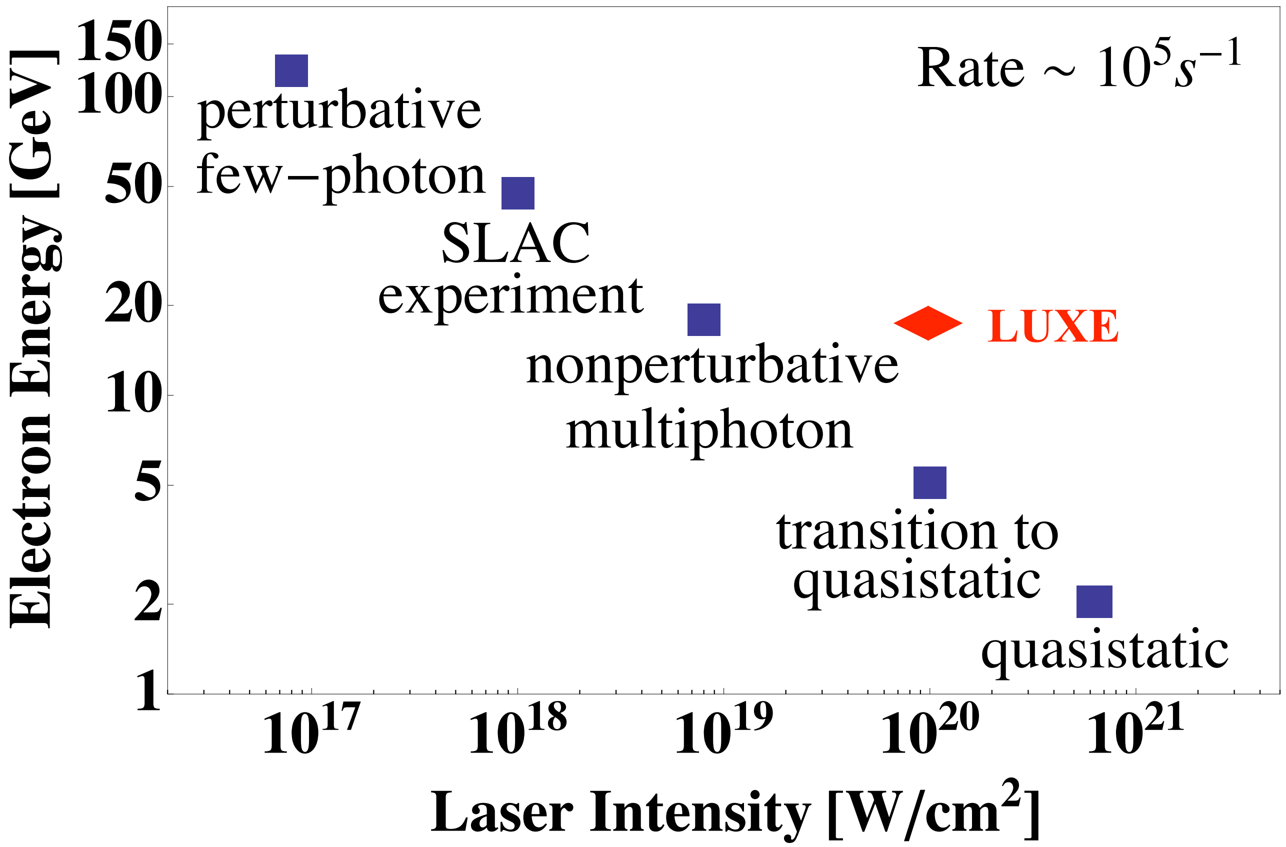
History: E144 @ SLAC

E144 at SLAC during the 90s

Phys.Rev. D60 (1999) 092004



- 46.6 GeV electron beam
- 5×10^9 electrons per bunch
- Bunch rates up to 30 Hz
- Terawatt laser pulses
- Intensity of ~0.5×10^{18} W/cm^2
- Frequency of 0.5 Hz for wavelengths 1053 nm, 527 nm
- electrons-laser crossing angle: 17°



History: E144 @ SLAC

OPPP only!

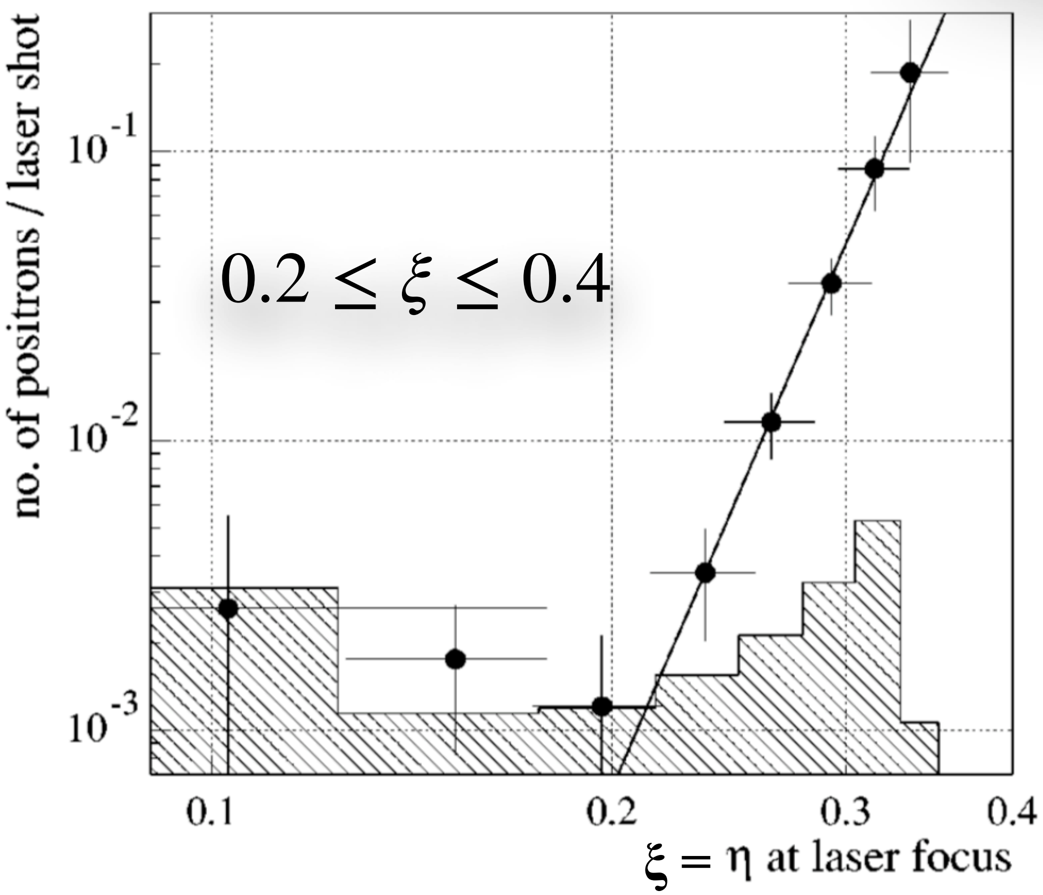


FIG. 44. The dependence of the positron rate per laser shot on the laser field-strength parameter η. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron rate.

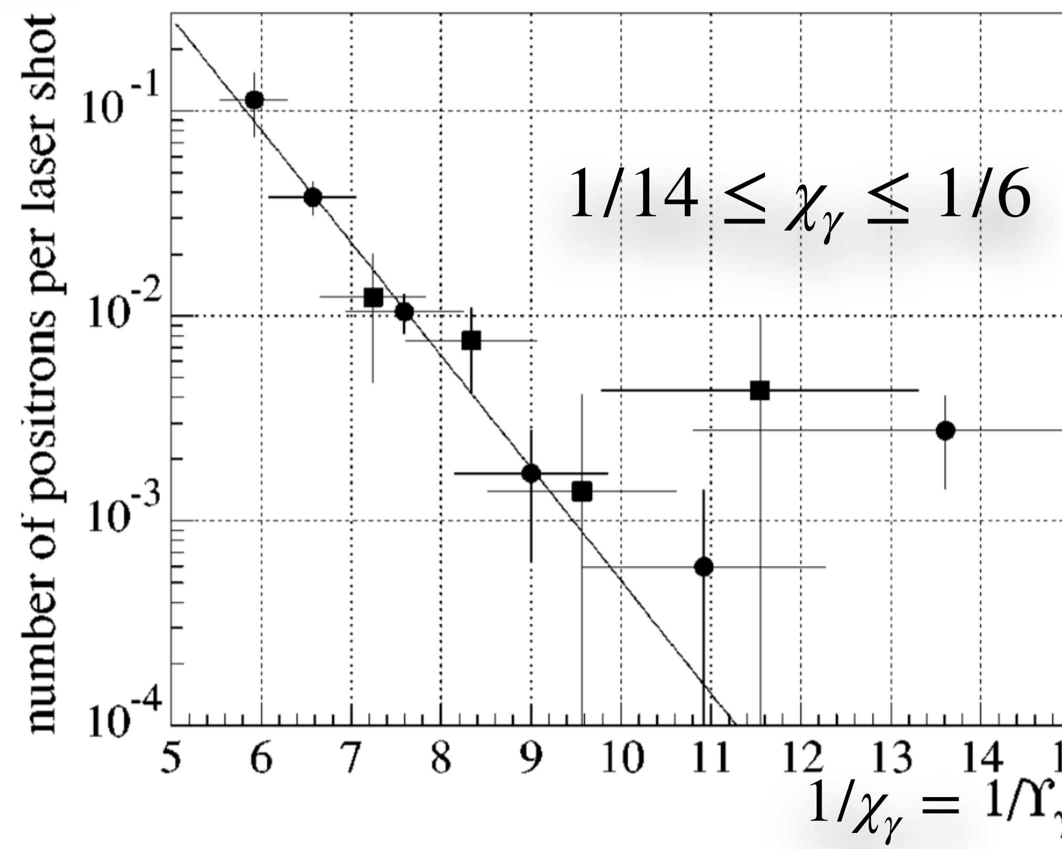


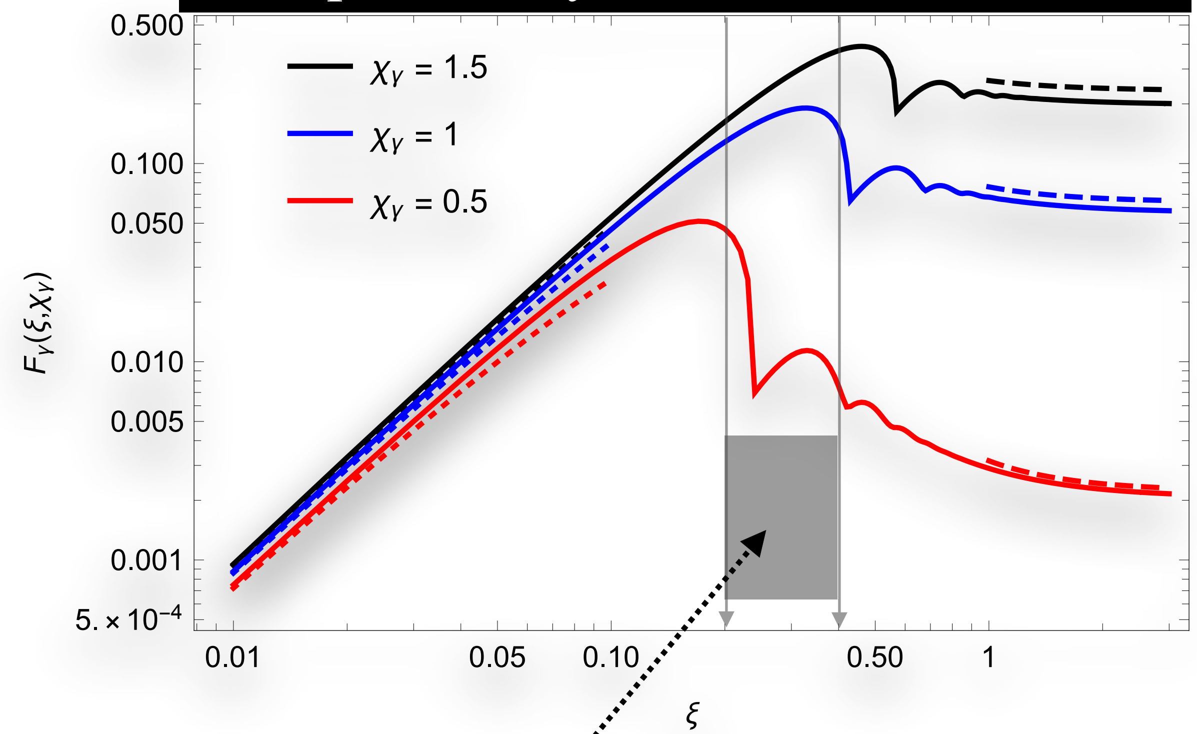
FIG. 49. Number of positrons per laser shot as a function of $1/\Upsilon_\gamma$. The circles are the 46.6 GeV data whereas the squares are the 49.1 GeV data. The solid line is a fit to the data.

Phys.Rev. D60 (1999) 092004

History: E144 @ SLAC

- Measured non-linear Compton scattering with $n = 4$ photons absorbed and pair production (with $n = 5$)
- Observed the strong rise $\sim \xi^{2n}$ but not asymptotic limit (still perturbative)
- Measurement well described by theory
- Large uncertainty on the laser intensity
- Did not achieve the critical field - the <u>peak</u> E-field of the laser: 0.5×10^{18} V/m

the ~probability of laser-assisted OPPP



E144 should be somewhere here

$$\begin{cases} 0.2 \le \xi \le 0.4 \\ 1/14 \le \chi_\gamma \le 1/6 \end{cases}$$

Mass shift

- Electron motion in a circularly polarised field, ϵ_L, with frequency ω_L:
  - Force: $F_\perp = e\epsilon_L = m_e a = m_e v^2/R \implies R = m_e v^2/e\epsilon_L$
  - Velocity: $v = \omega_L R = \omega_L m_e v^2/e\epsilon_L \implies v = e\epsilon_L/\omega_L m_e = \xi$
  - Momentum: $p_\perp = m_e v = m_e \xi$
  - Energy: $E = m_e^2 + \overrightarrow{p}^2 = m_e^2 + p_\perp^2 + p_\parallel^2 = m_e^2\left(1+\xi^2\right) + p_\parallel^2 = \bar{m}_e^2 + p_\parallel^2$
  - Mass shift:

$$m_e \longrightarrow \bar{m}_e = m_e\sqrt{1+\xi^2}$$

- The 4-momentum of the electron inside an EM wave is altered due to continuous absorption and emission of photons
  - the laser photon 4-momentum is: k_μ
  - outside the field, the (free) charged particle 4-momentum is: p_μ
  - inside the field, the effective 4-momentum (q_μ) and mass are:

$$q_\mu = p_\mu + \frac{\xi^2 m_e^2}{2(k\cdot p)}k_\mu \quad \Rightarrow \quad \bar{m}_e = \sqrt{q_\mu q^\mu} = m_e\sqrt{1+\xi^2}$$

Mass shift $\longrightarrow$ kinematic edge

- if n is the number of absorbed laser photons in the nonlinear Compton process, the energy-momentum conservation: $q_\mu + nk_\mu = q'_\mu + k'_\mu$

- The maximum value for the scattered photon energy, ω', corresponds to the minimum energy, or, "kinematic edge" of the scattered electron. it depends on the number of absorbed laser photons:
$\omega'_{\text{min}} = \dfrac{\omega}{1 + 2n(k \cdot p)/\bar{m}_e^2}$, where $\bar{m}_e = m_e\sqrt{1+\xi^2}$

- This energy decreases with increasing number of photons absorbed

- The electron is effectively getting more massive with ξ and recoils less
  - the min energy of the scattered electron (kinematic edge) is higher

Electric field vs Intensity

$$I = (1 - f_{\text{Losses}}) \times \frac{E_{\text{pulse}}}{T_{\text{pulse}} \times S_{\text{pulse}}} \rightarrow \frac{(1 - 60\%) \times 9 \ [\text{J}]}{30 \ [\text{fs}] \times (3 \times 3 \ [\mu\text{m}^2])}$$

$$I = 0.4/30 \ [\text{J/fs}/\mu\text{m}^2] \sim 1.33 \times 10^{-2} \times 10^{15} \times 10^{8} \ [\text{J/s/cm}^2]$$

$$I = 1.33 \times 10^{21} \ [\text{J/s/cm}^2] = 1.33 \times 10^{21} \ [\text{W/cm}^2]$$

$$E = \sqrt{\frac{I}{cn\epsilon_0}} \underbrace{\longrightarrow}_{n=1} \sim \sqrt{\frac{1.33 \times 10^{21}}{(2.99 \times 10^{8}) \times (8.85 \times 10^{-12})}} \quad \left[\sqrt{\frac{(\text{N} \cdot \text{m/s})/\text{cm}^2}{(\text{m/s}) \times (\text{N/V}^2)}}\right]$$

$$\boxed{\begin{aligned} c &= 2.99 \times 10^{8}[\text{m/s}] \\ \epsilon_0 &= 8.85 \times 10^{-12}[\text{N/V}^2] \\ [I] &= [\text{W}] = [\text{N} \cdot \text{m/s}] \end{aligned}}$$

$$E \sim 0.71 \times 10^{12} \ [\text{V/cm}]$$

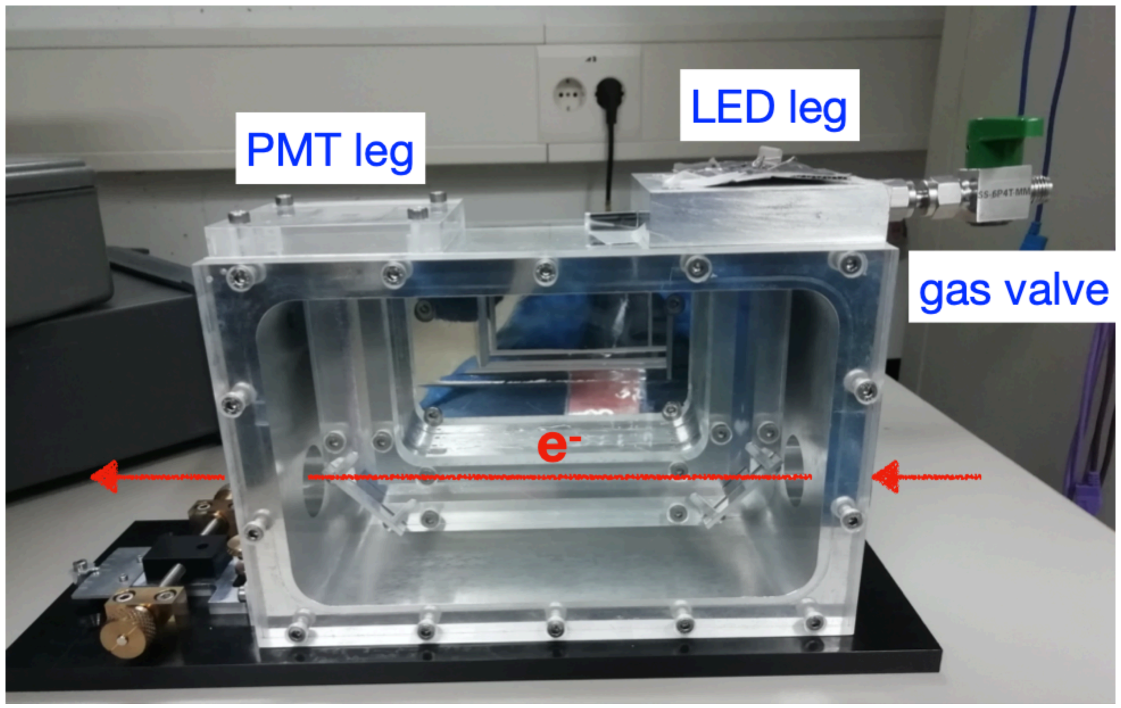
$$\text{Boost}: \quad E \longrightarrow E \times (3.4 \times 10^{4})$$

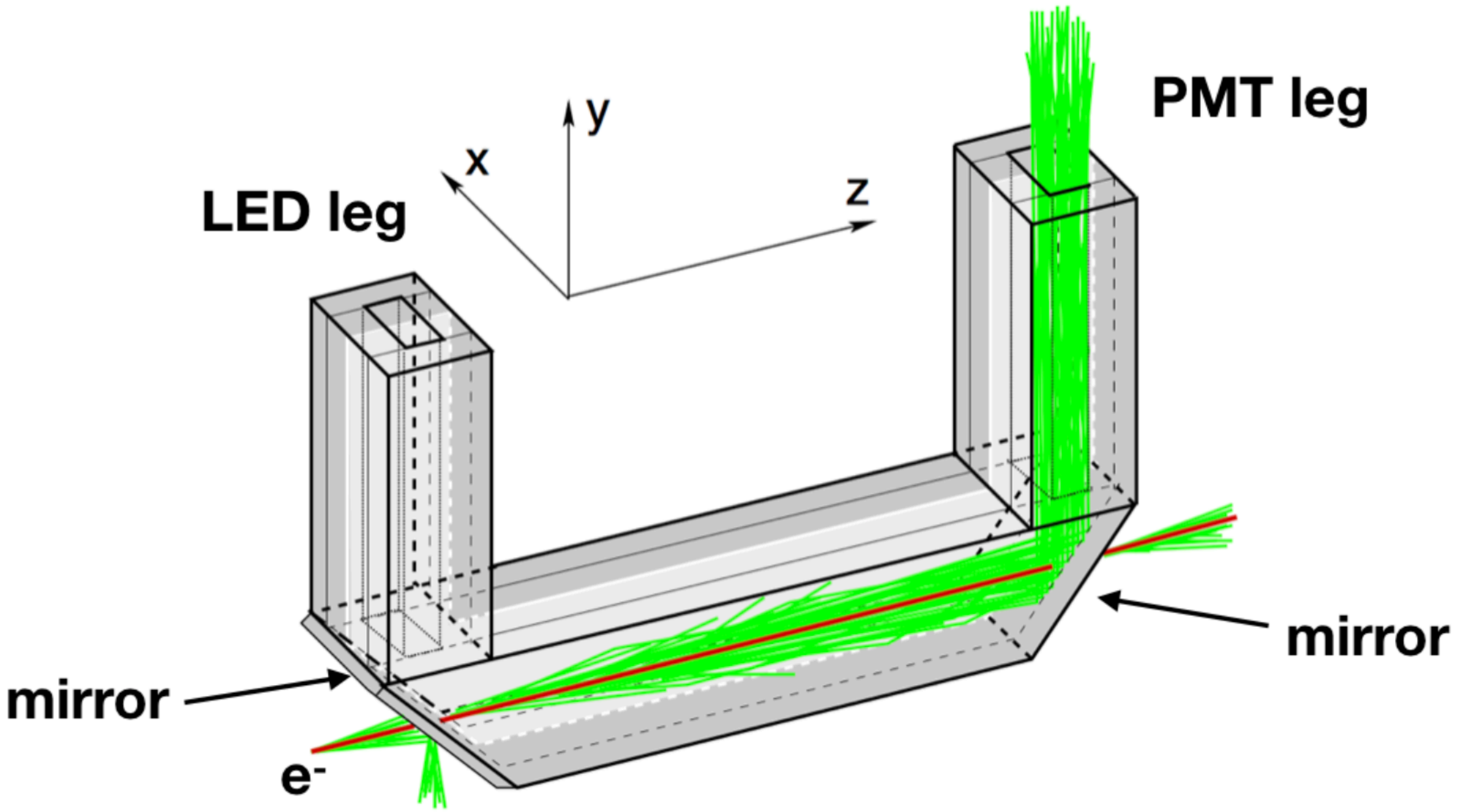
$$E_{\text{LUXE}} \sim 2.4 \times 10^{16} \ [\text{V/cm}]$$

$$E_{\text{Schwinger}} \sim 1.3 \times 10^{16} \ [\text{V/cm}]$$

Cherenkov Prototype

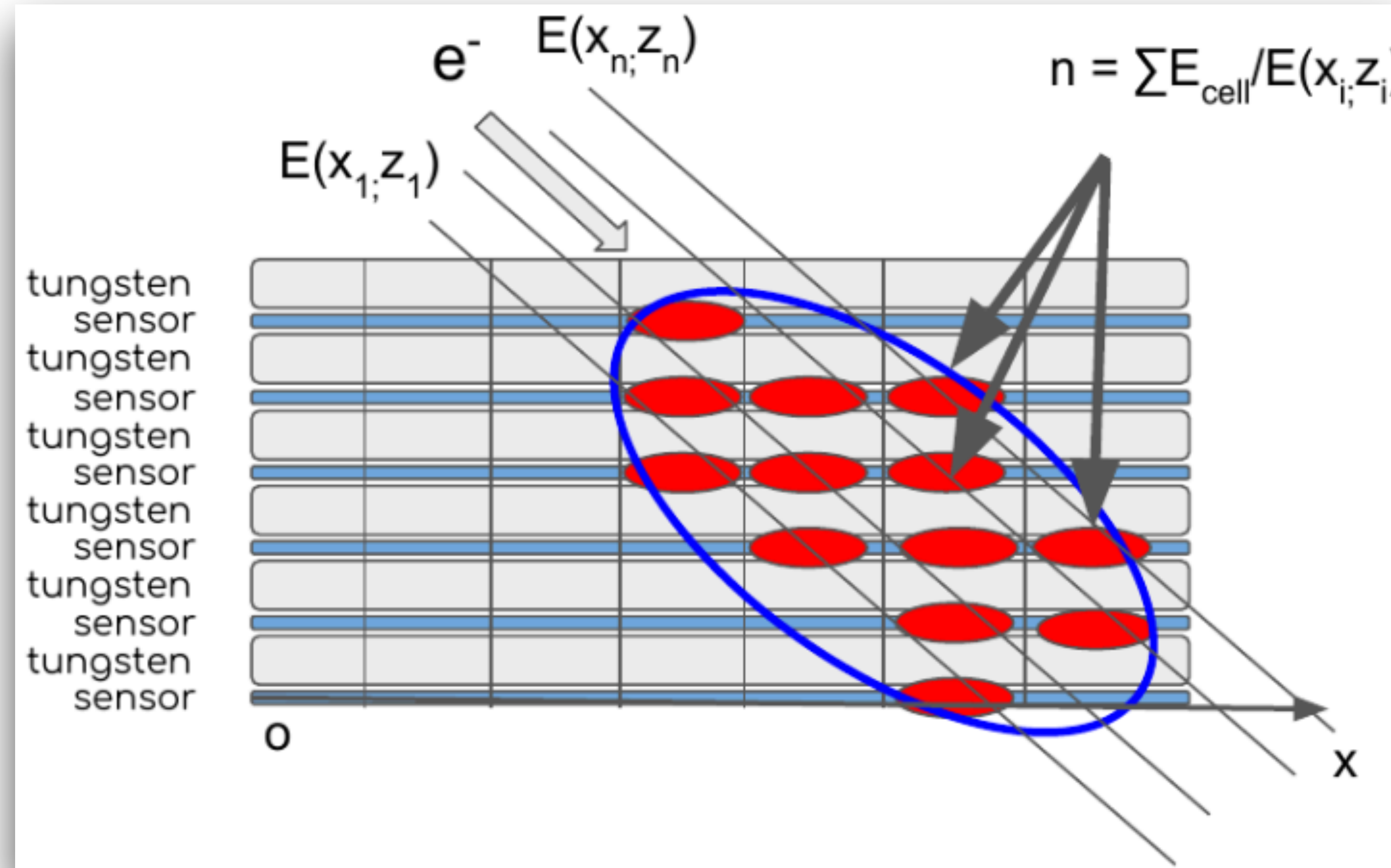
- U-shaped aluminium channels, filled with gas, mirrors to guide light
- Several channels (prototype has 2), separated by thin wall
- LED on one leg for calibration, PMT on other leg for light detection





Calorimeter prototype

- Sensors parameters:
  - Layer gap: 0.2mm
  - Silicon: 0.32mm
  - Carbon: 0.1mm
  - Aluminium: 0.02mm
  - Tungsten: 3.5mm
  - Density: 19.3g/cm3
  - Fanout: 0.15mm (with epoxy)
- Region covered
  - x: 100 mm to 650 mm
  - y: -27.5 mm to 27.5 mm



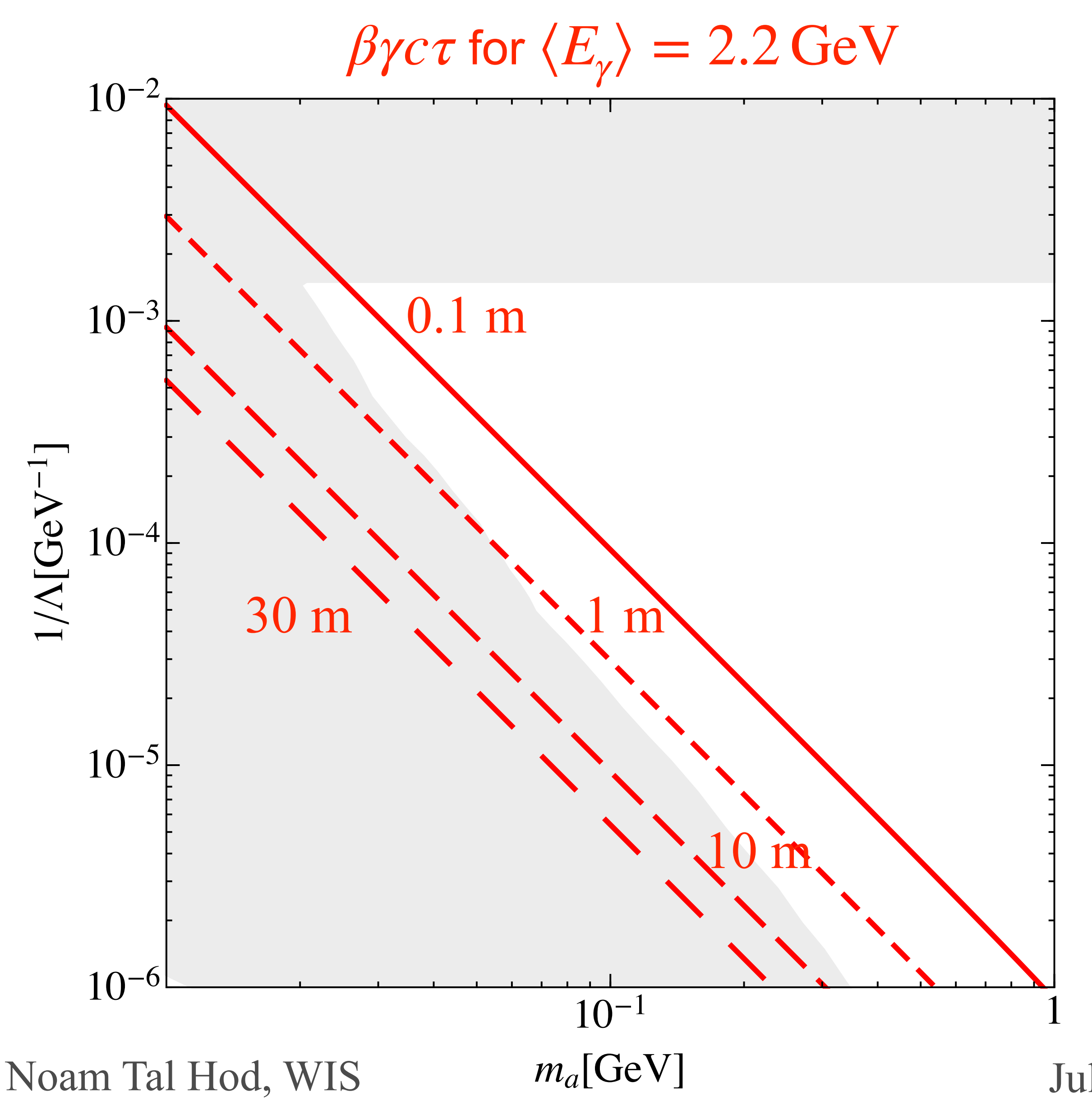
- We expect high multiplicity of tracks in the low-x range
- Highly overlapping showers can not be separated easily
  - Can use analytical solution to calculate what energy do we expect in (x,y,z)
  - "Particle density" in the cell is $N_{\text{cell}} = E_{\text{cell}}/E_{\text{expected}}$
  - Number of total particles is $N_{\text{tot}} = \Sigma N_{\text{cell}}$ where the sum goes over all cells

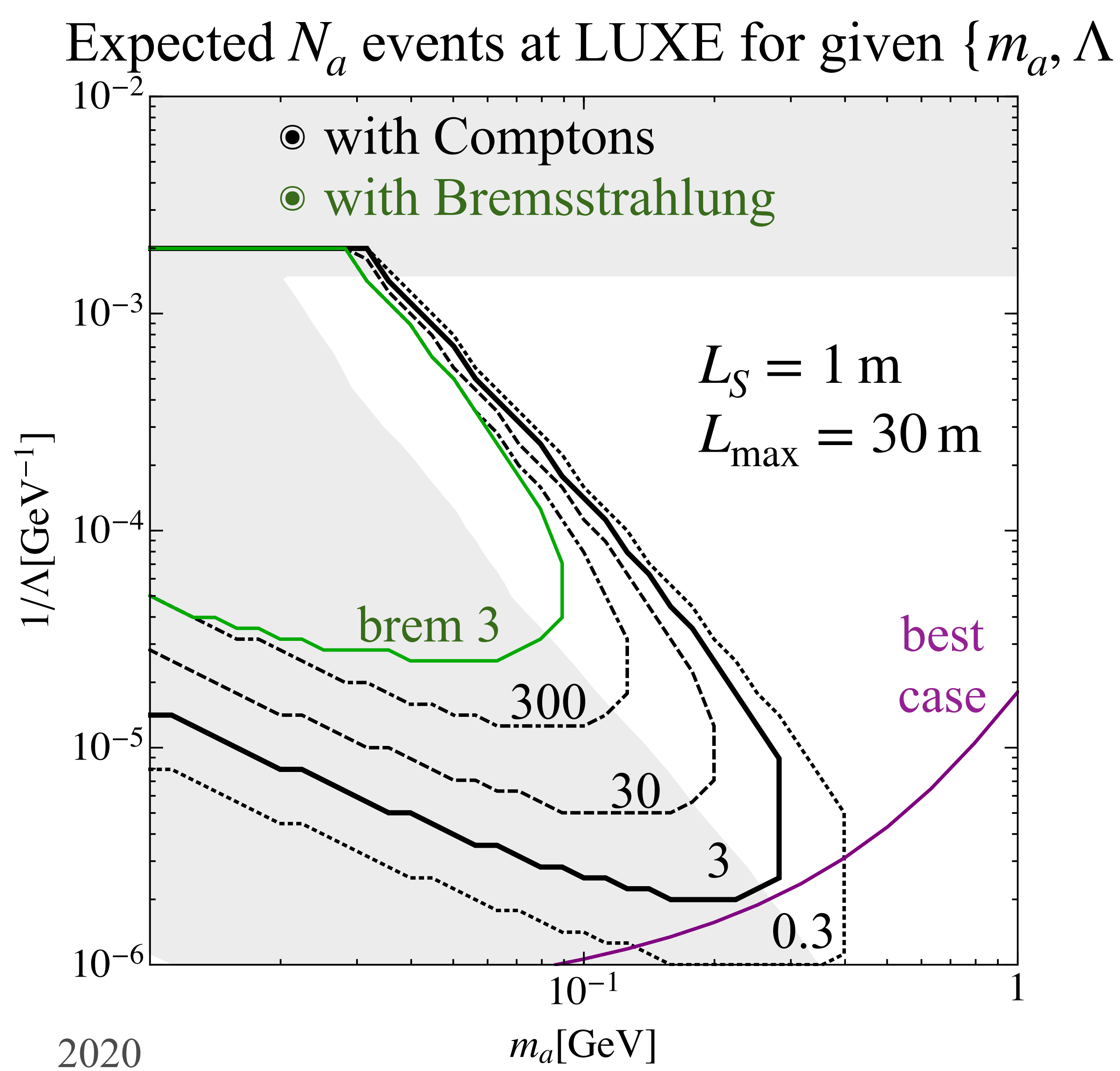
Number of ALPs

$$E_a \approx E_\gamma$$

$$N_a = \frac{\rho_T \Delta x}{A_T m_0} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \int dp_a \frac{d\sigma_a}{dp_a} \left(e^{-\frac{\Gamma_a L_S}{p_a/m_a}} - e^{-\frac{\Gamma_a L_{\max}}{p_a/m_a}} \right) \approx \frac{\rho_T \Delta x}{A_T m_0} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a \left(e^{-\frac{\Gamma_a L_S}{p_a/m_a}} - e^{-\frac{\Gamma_a L_{\max}}{p_a/m_a}} \right)$$

$E_e = 17.5\,\mathrm{GeV}$ $N_e = 6 \times 10^9$ $t_\mathrm{L} = 35\,\mathrm{fs}$ $\xi = 2.0$ $t_\mathrm{op} = 10^7\,\mathrm{s}$ $R_\mathrm{L} = 1\,\mathrm{Hz}$





Experimental area