# The LUXE experiment
# and
# Squeezing High-Mass Dilepton Data in ATLAS

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ATLAS EXPERIMENT

LUXE

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

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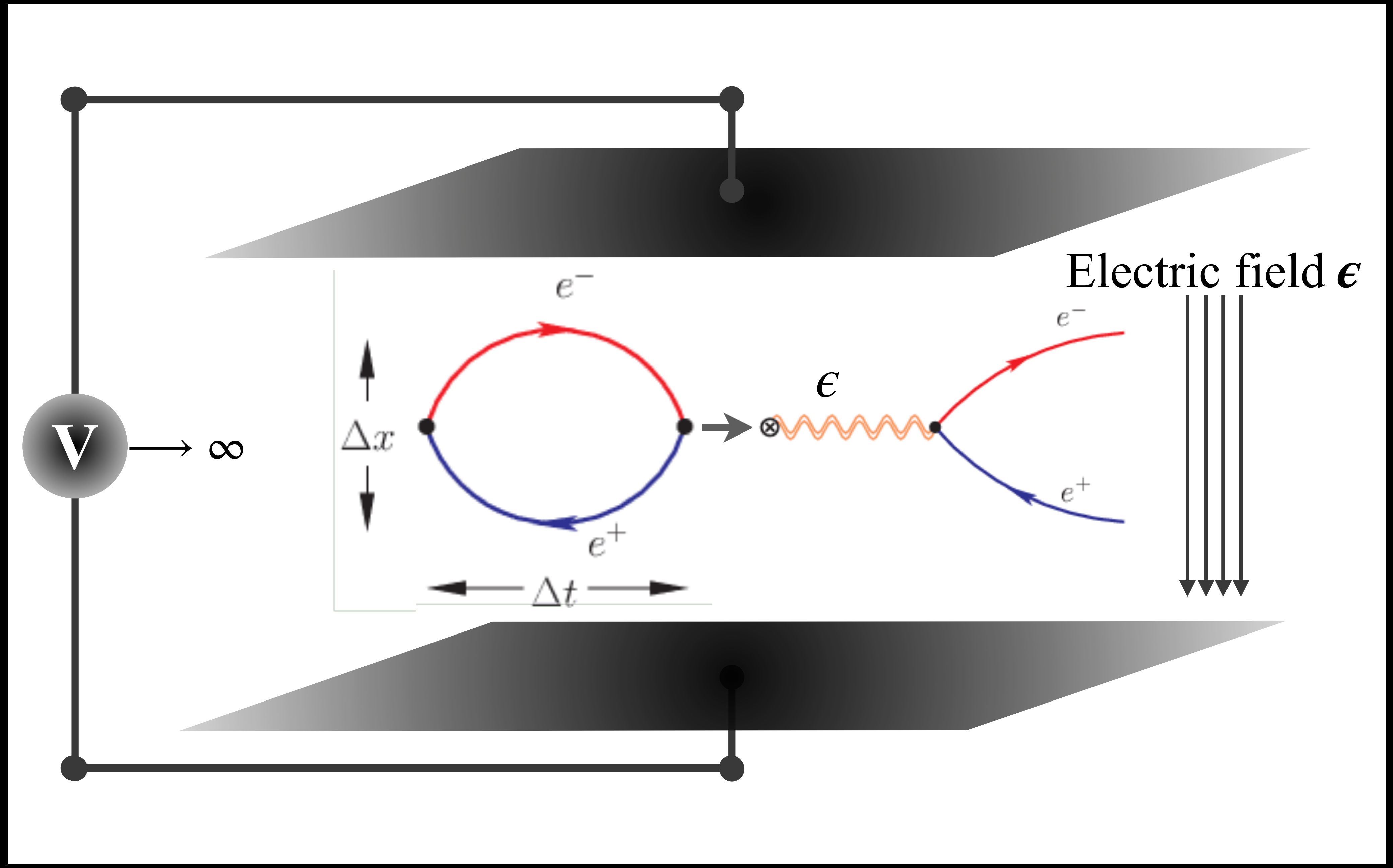
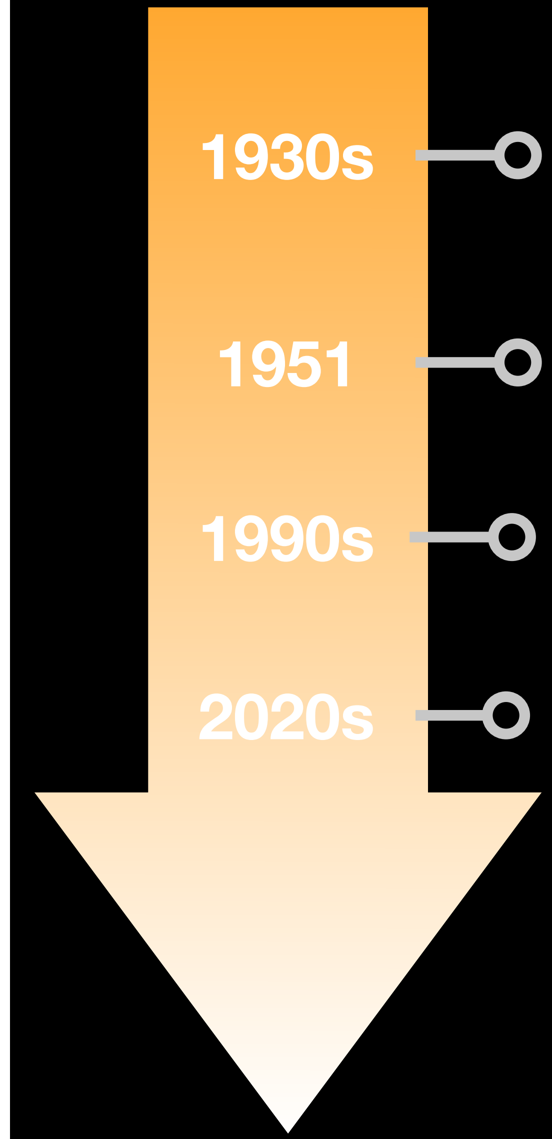
# The LUXE Experiment

# Strong electric fields

- ✦ Spontaneous $e^+e^-$ pair production in a strong static electric field in Vacuum: prediction of QED.
- ✦ Schwinger gave the critical field: $\boldsymbol{\epsilon_S = m_e^2c^3/e\hbar \simeq 1.32 \cdot 10^{18}}$ **V/m**.
- ✦ The probability to materialise one virtual $e^+e^-$ pair from the vacuum: $P \sim exp\left(-a\epsilon_s/\epsilon\right)$

$a$ numeric constant





- **1930s — First discussions by Sauter, Heisenberg & Euler**
- **1951 — First calculations by Schwinger: $\boldsymbol{\epsilon_S}$**
- **1990s — E144 at SLAC first to approach $\boldsymbol{\epsilon_S}$ (reached $\epsilon \to \epsilon_S/4$)**
- **2020s — LUXE: reach $\boldsymbol{\epsilon_S}$ and beyond**

✦ **Goal of LUXE experiment:**

- ✦ Effort to reach $\epsilon_s$ and beyond
- ✦ Test basic predictions of novel Quantum Mechanics regime
- ✦ Search for Beyond Standard Model Physics

# A Brief Idea about the LUXE physics

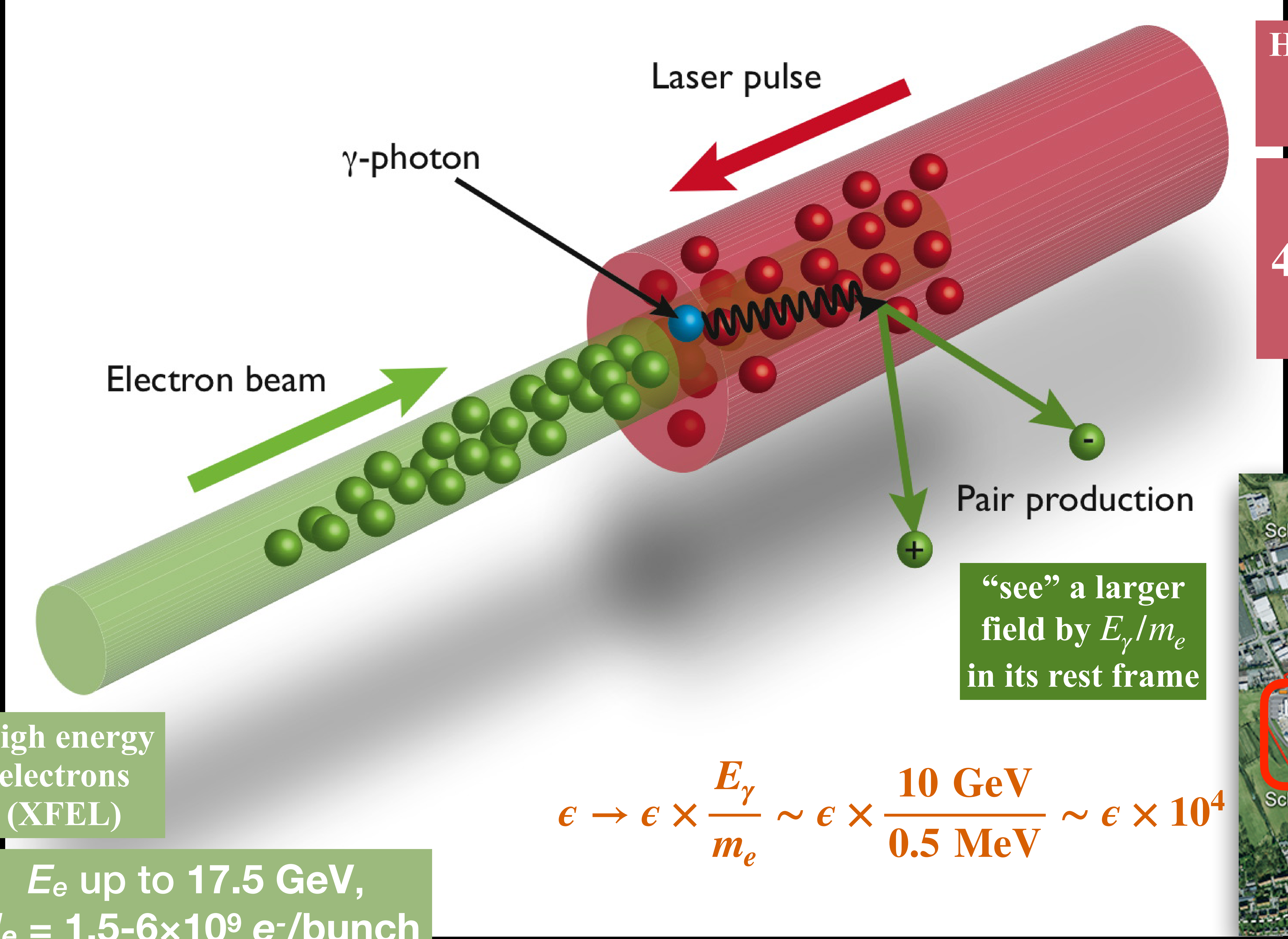
The Letter of Intent

Laser Und XFEL Experiment

The rate of laser assisted one photon pair production asymptotically resembles to that of the spontaneous pair production in vacuum.

Hartin et.al. Phys. Rev. D 99, 036008 (2019)

- ✦ **Nonlinear** Compton scattering: $e + n\gamma_L \rightarrow e' + \gamma_C$
- ✦ **Nonlinear** pair production: $\gamma_C + n\gamma_L \rightarrow e^+e^-$



**High-power laser generates large $E$-field**

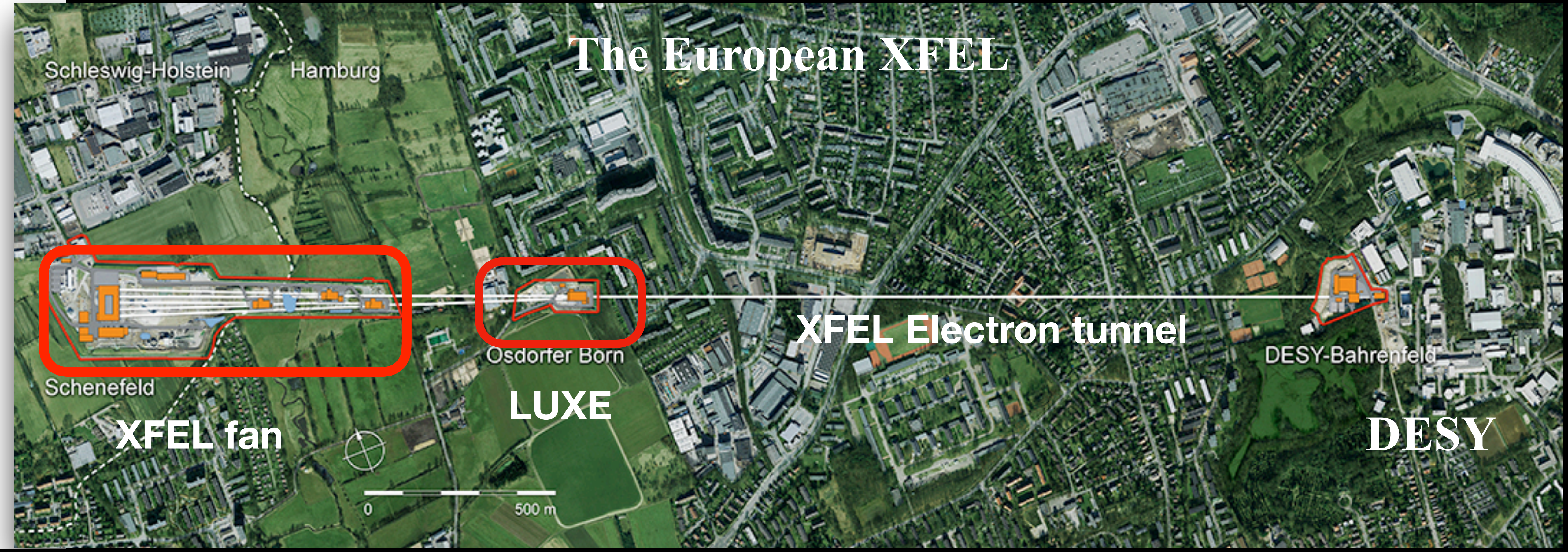
Ti-Sapphire, $\lambda_L$=800 nm,
**40 TW**(⟶350 TW), **~1 J**(⟶10 J),
25-200 fs pulse

"see" a larger field by $E_\gamma/m_e$ in its rest frame

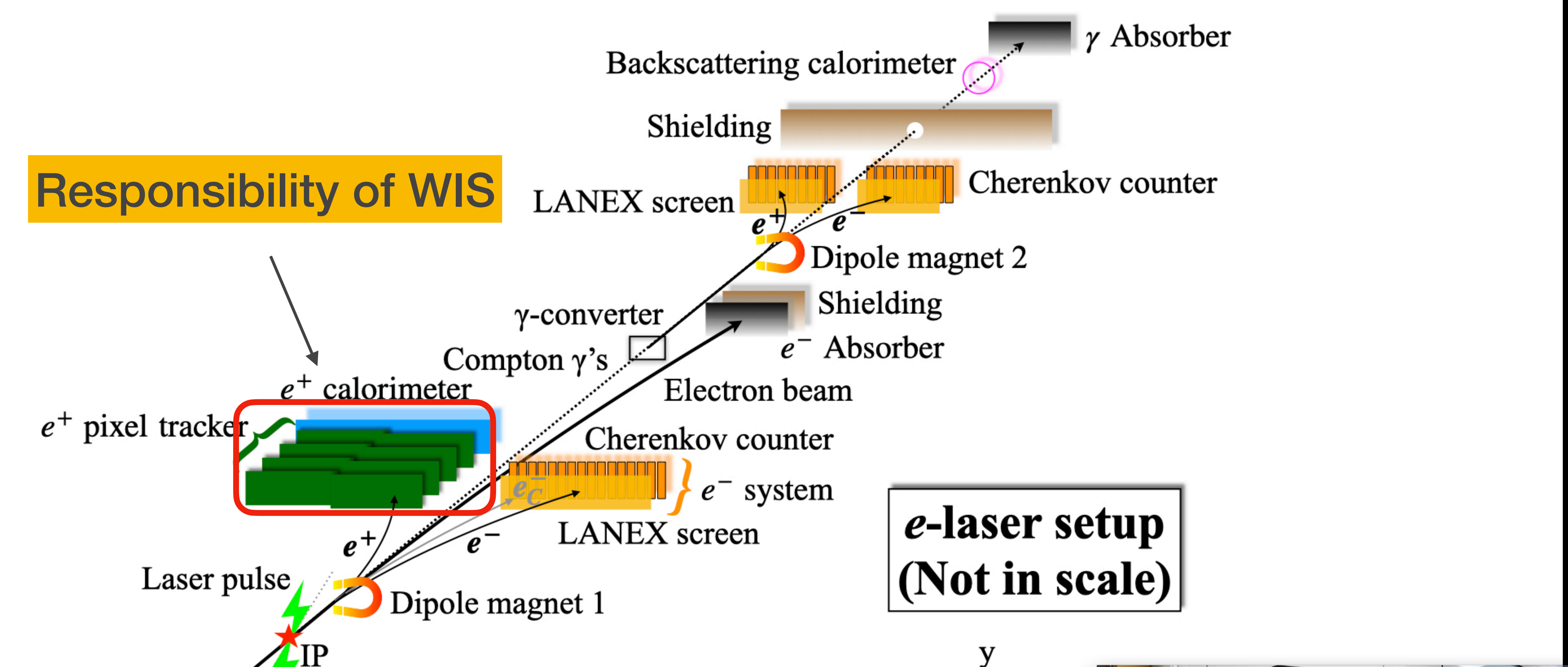
$$\epsilon \rightarrow \epsilon \times \frac{E_\gamma}{m_e} \sim \epsilon \times \frac{10\ \text{GeV}}{0.5\ \text{MeV}} \sim \epsilon \times 10^4$$

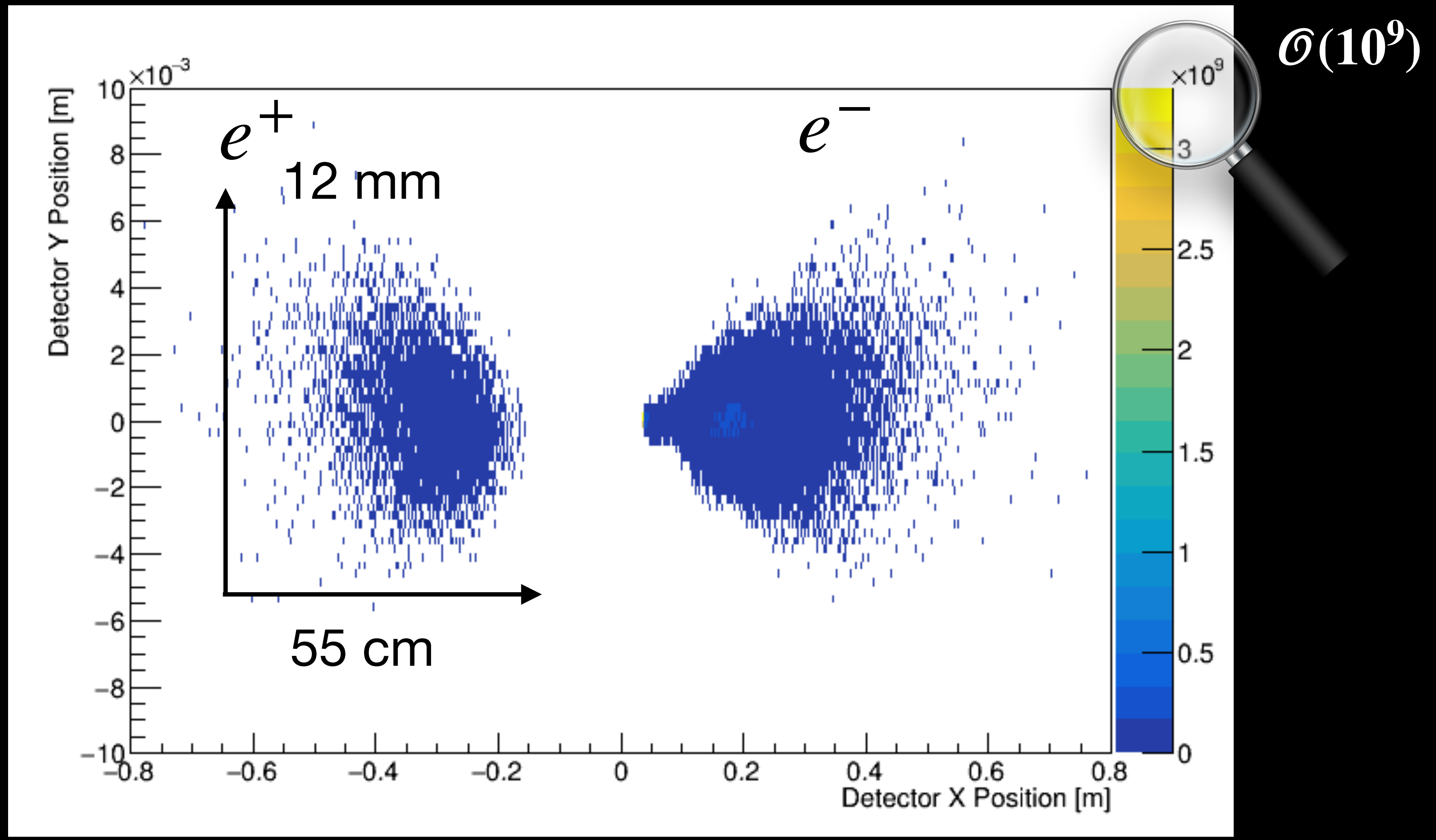
High energy electrons (XFEL)

$E_e$ up to 17.5 GeV,
$N_e$ = 1.5-6×$10^9$ $e^-$/bunch

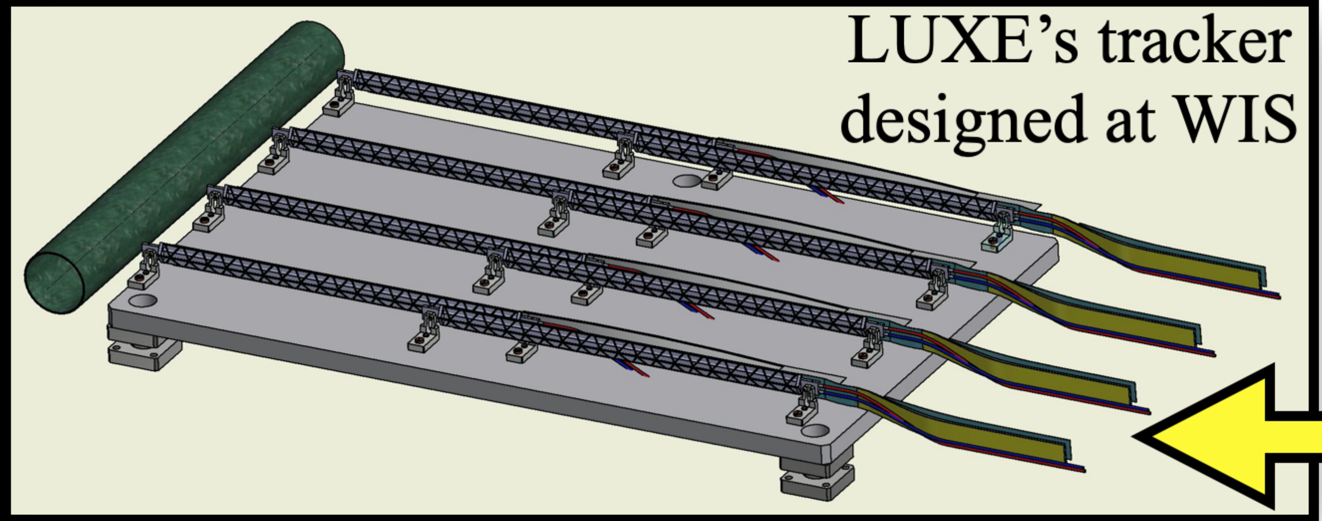


# Experimental setup

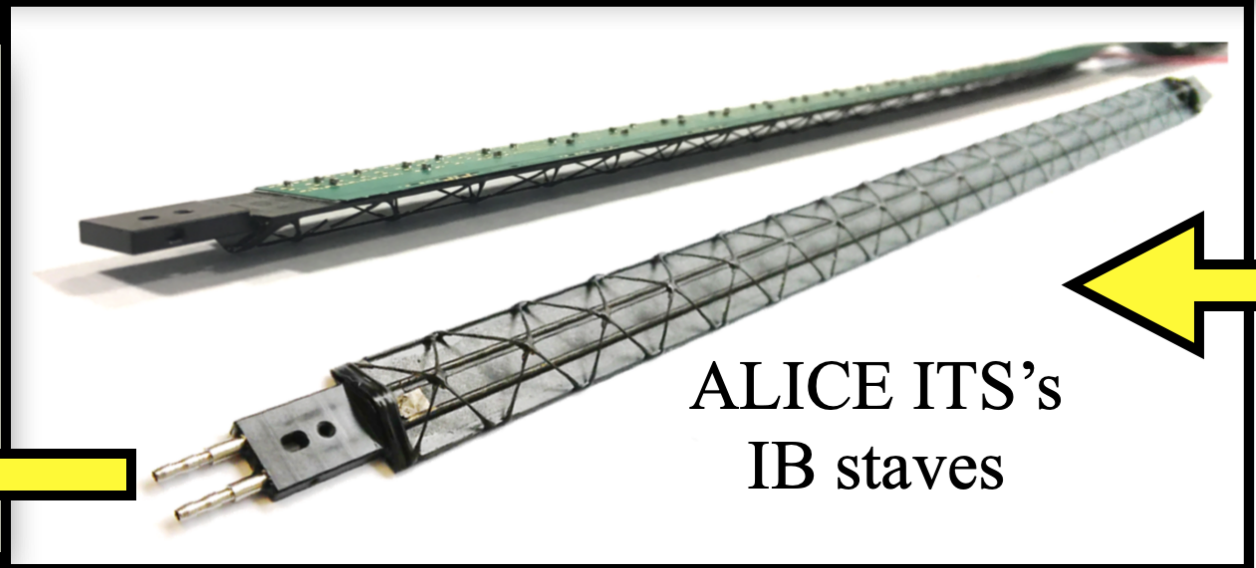




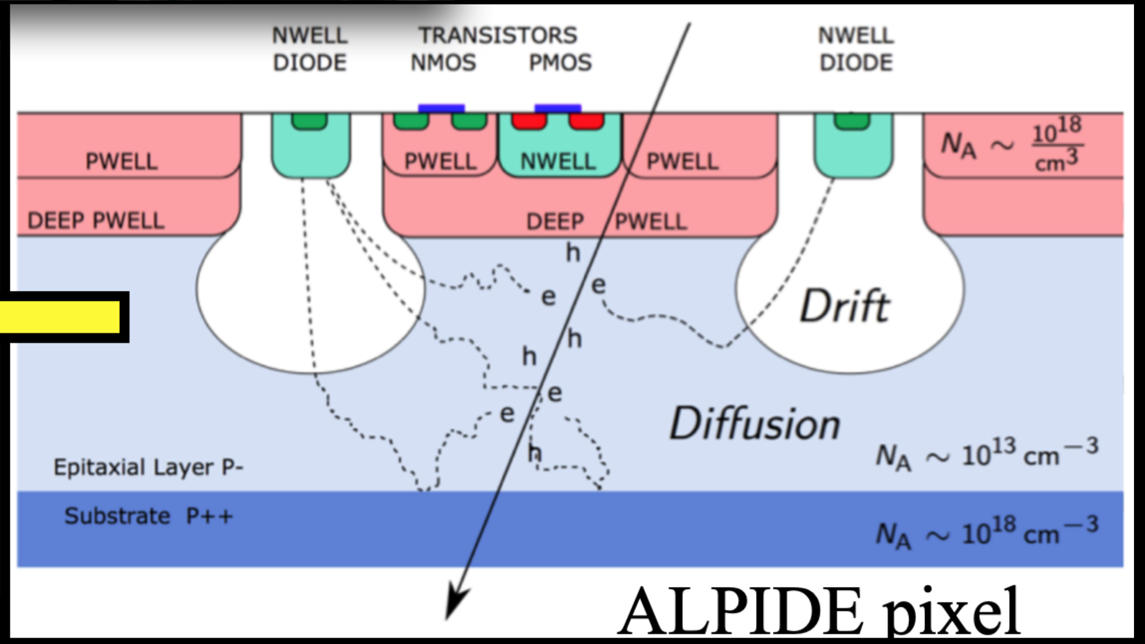
- ✦ Physics arriving at the first set of the sub-detector.



LUXE's tracker designed at WIS



ALICE ITS's IB staves



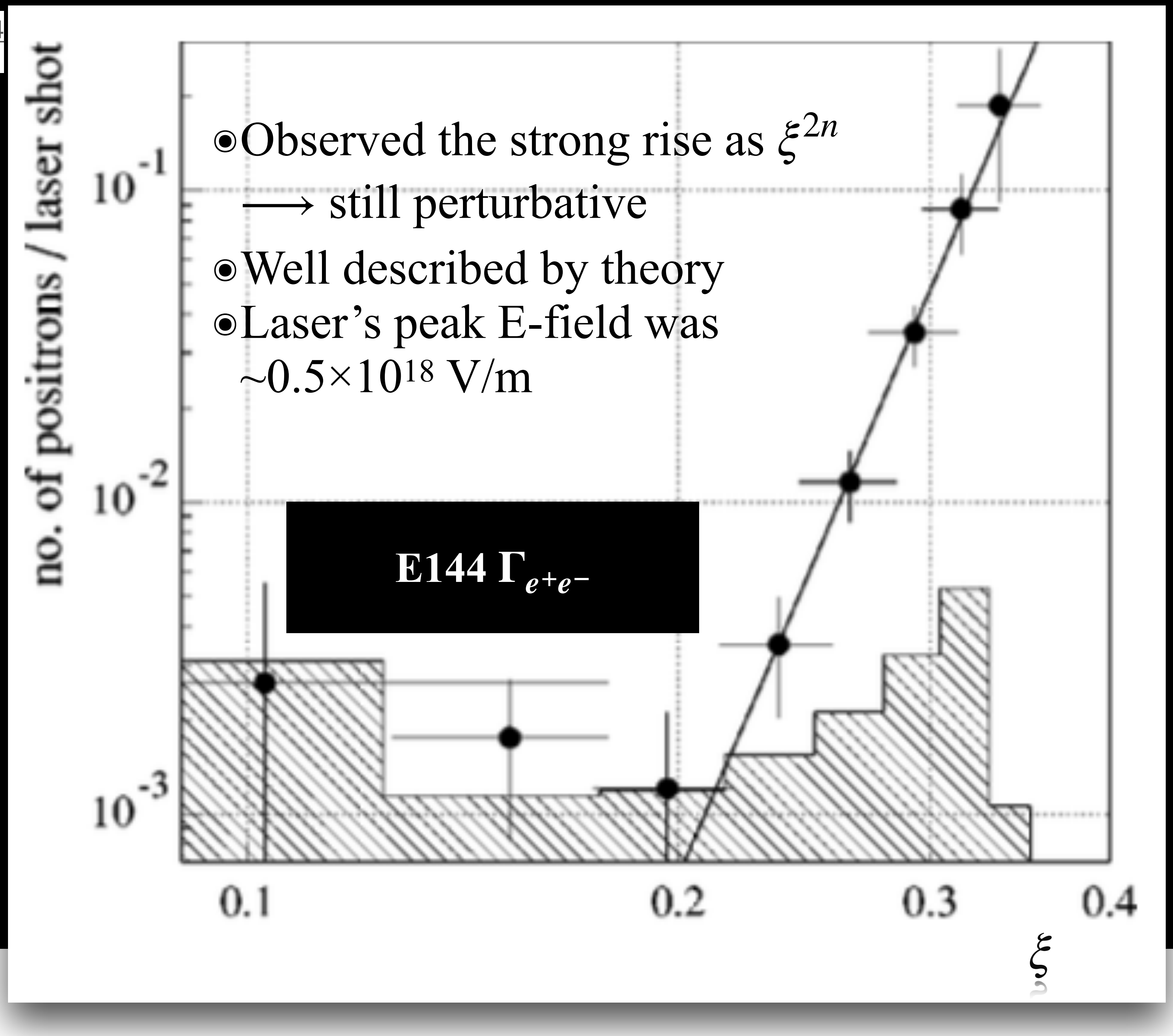
ALPIDE pixel

# The $\epsilon_s$ in the $e^+e^-$ rest frame

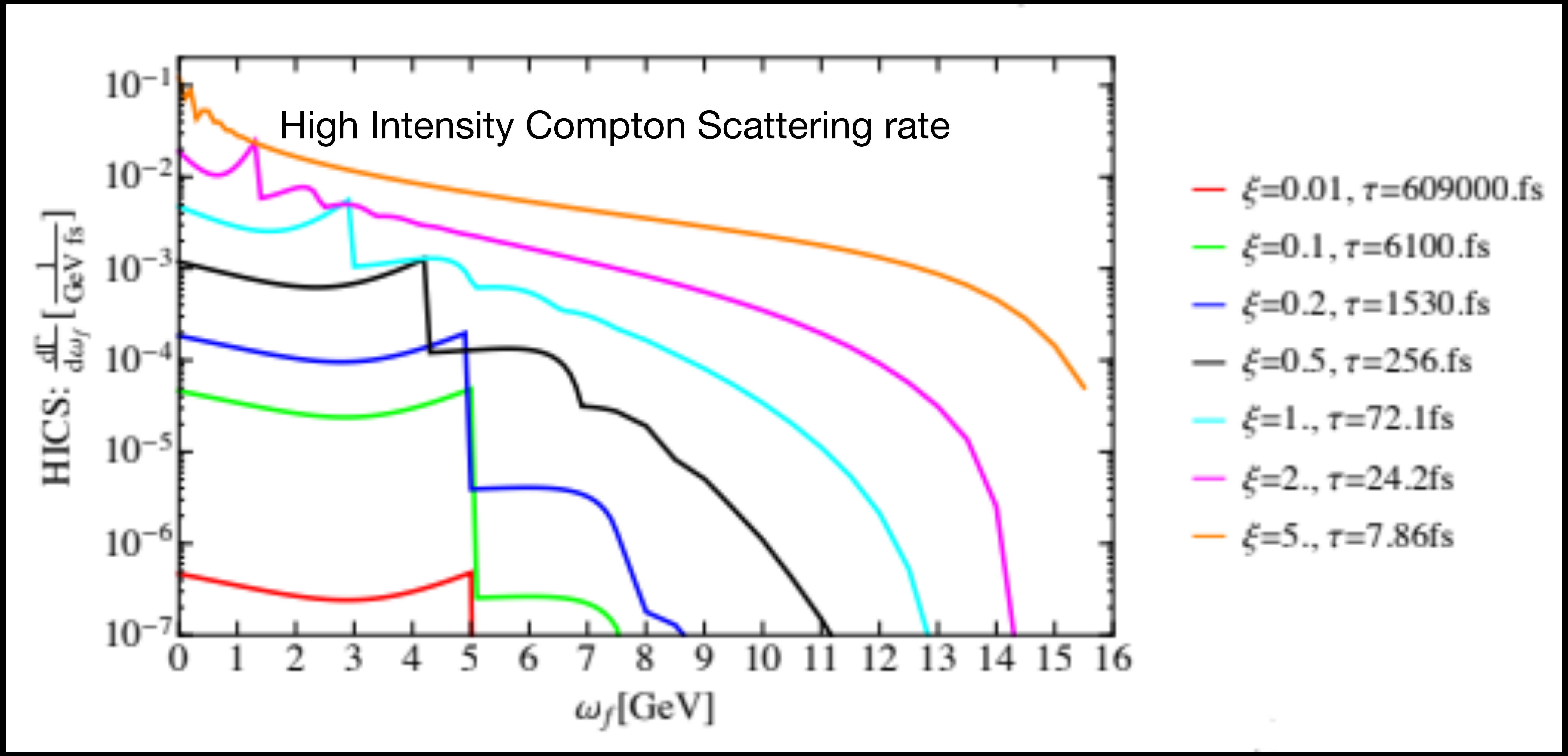
- ✦ Plan to measure the rate $\Gamma_{\gamma_C}$ and $\Gamma_{e^+e^-}$
- ✦ Use of dimensionless parameters
  - ✦ Laser intensity parameter: $\xi \propto \epsilon/\epsilon_s$
  - ✦ Quantum parameter: $\chi_{e,\gamma} \propto (E_{e,\gamma}/m_e)(\epsilon/\epsilon_s)$

E144 has achieved $\epsilon < \epsilon_s/4$

Phys. Rev. D 60, 092004

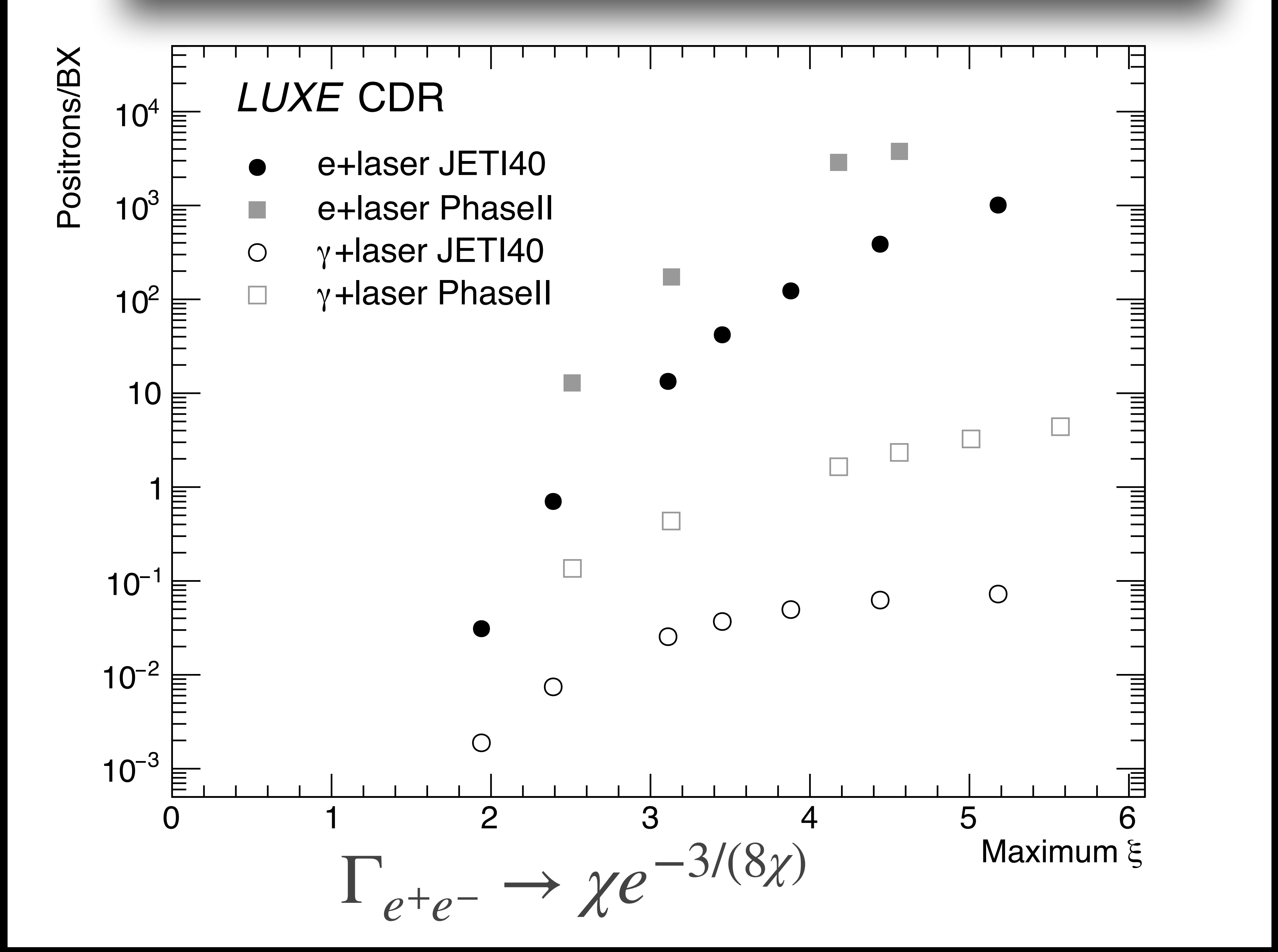


- ◉Observed the strong rise as $\xi^{2n}$ ⟶ still perturbative
- ◉Well described by theory
- ◉Laser's peak E-field was ~$0.5\times10^{18}$ V/m



$$e^- + \gamma_L : \Gamma_{\gamma C}$$

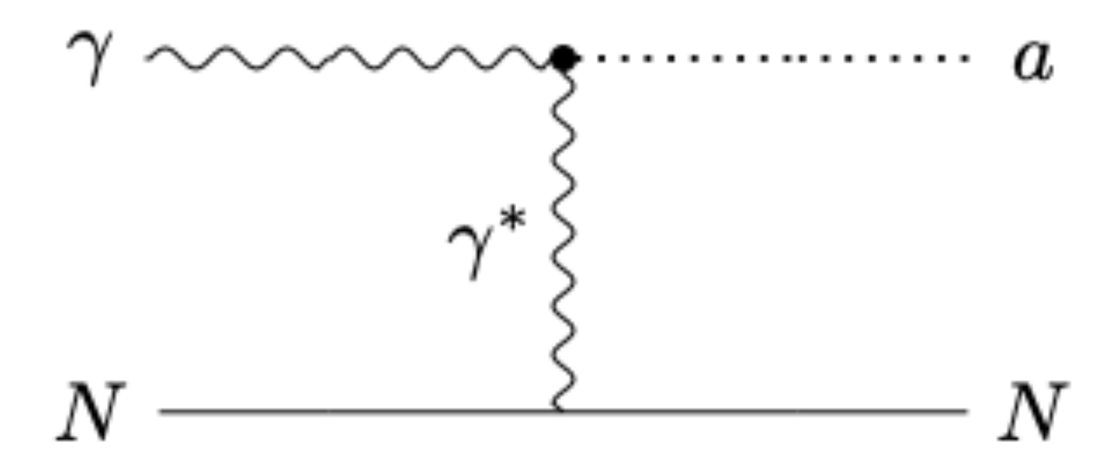
The "kinematic edges" of the scattered electron depend on the number of absorbed laser photons

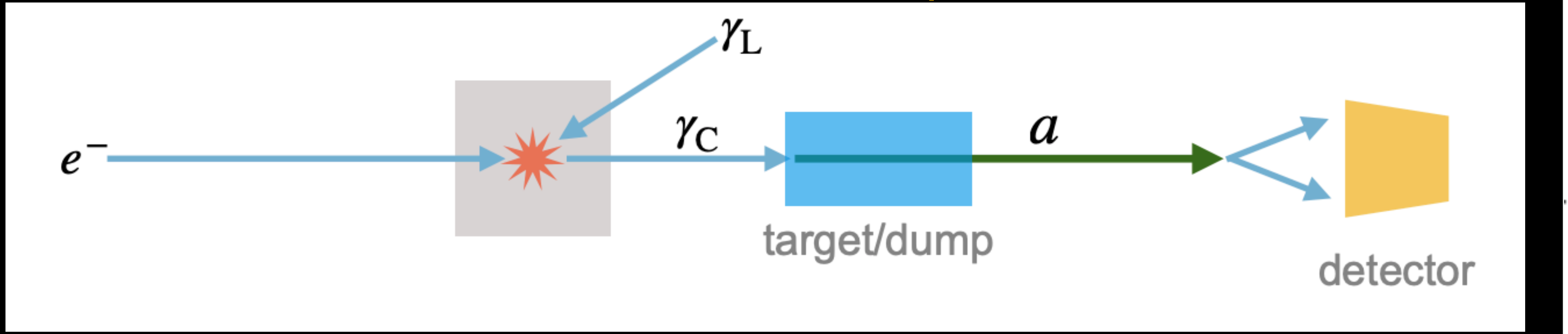


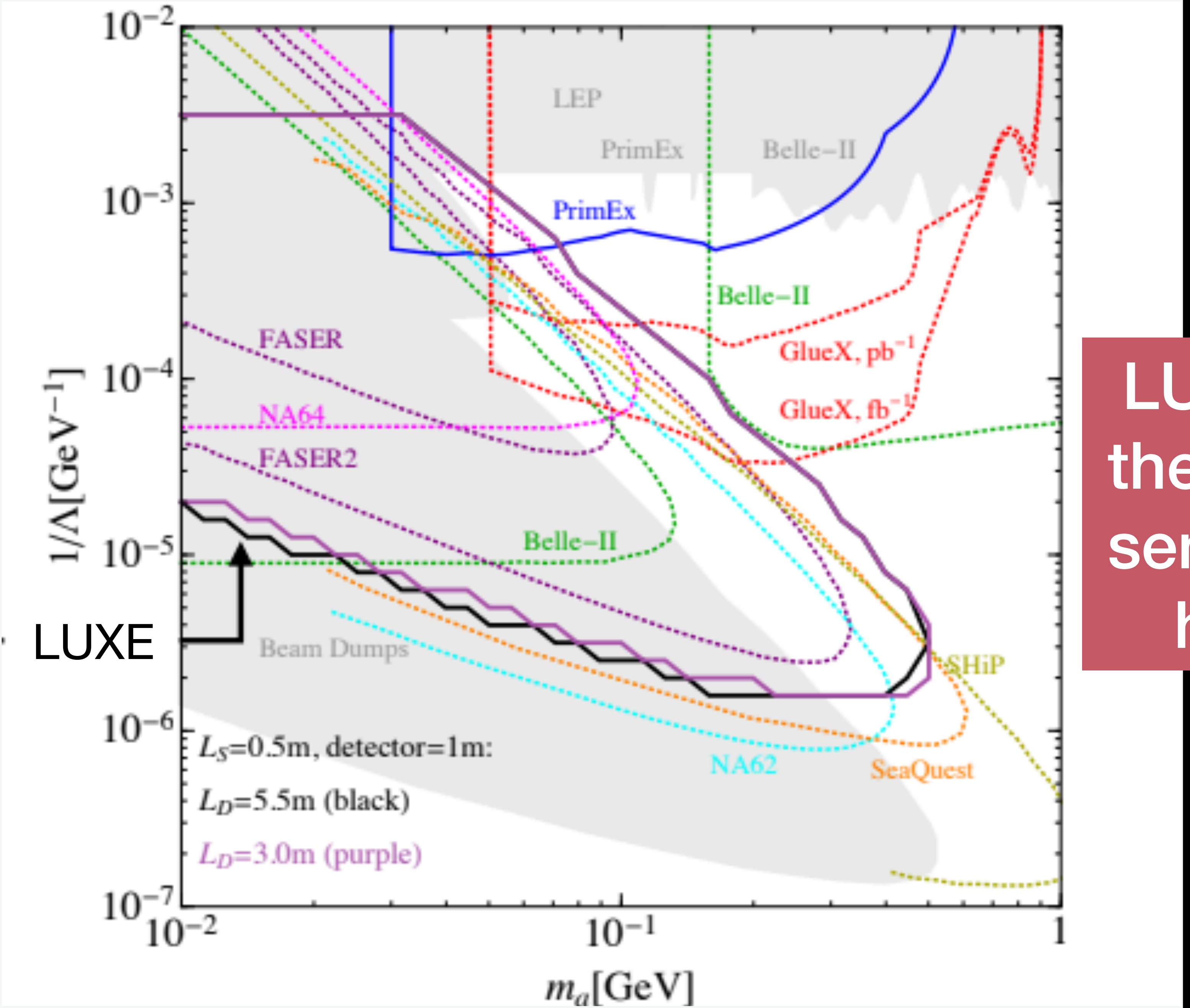
$$\Gamma_{e^+e^-} \to \chi e^{-3/(8\chi)}$$

# Beyond Standard Model search with LUXE

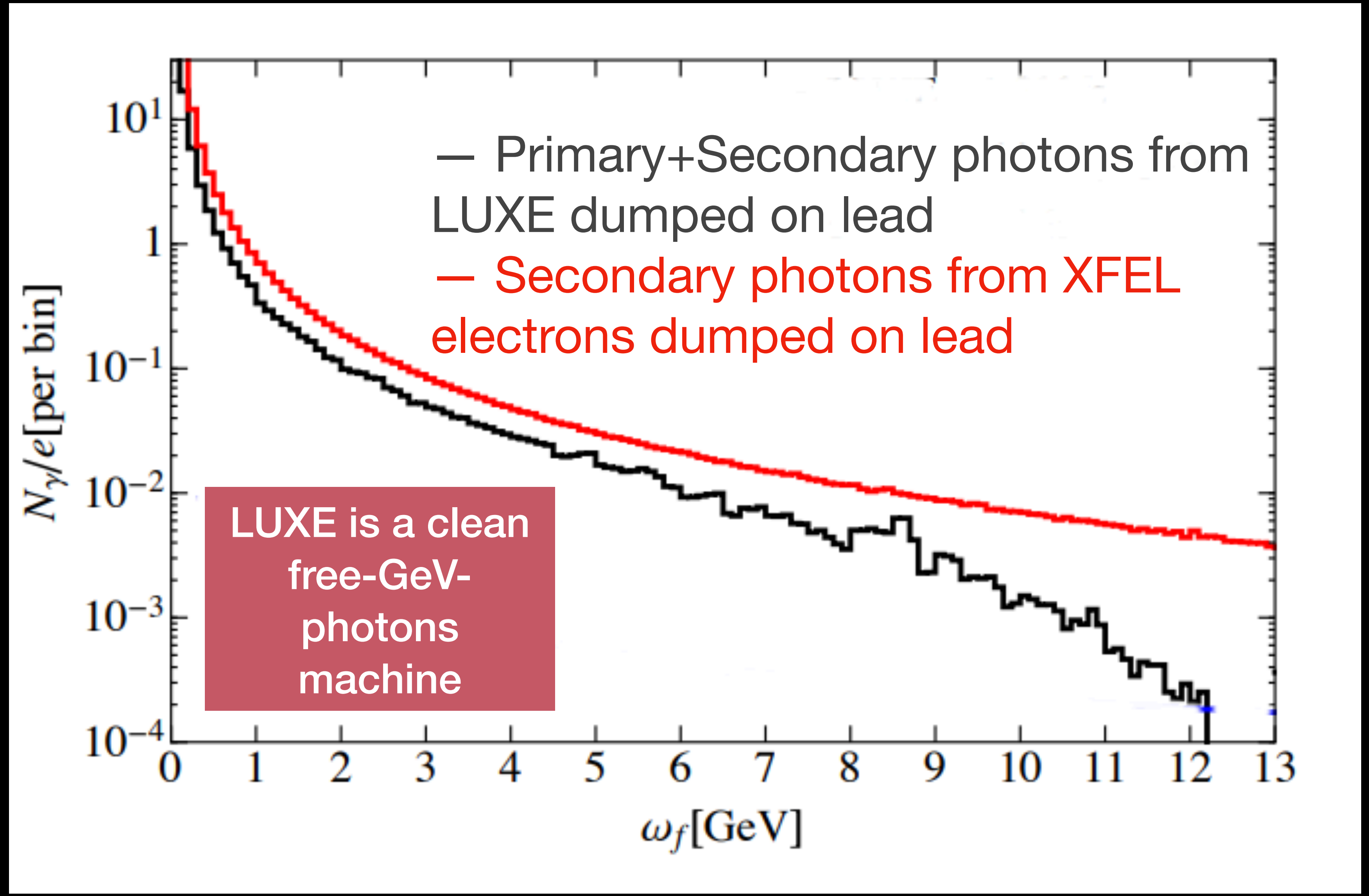
- ✦ Axion like particles (ALP): $\mathscr{L}_{\text{int}} = \frac{1}{4\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu} + g_{ae} a \bar{e} \gamma^5 a$
- ✦ Mass $m_a$ and photon coupling: $1/\Lambda$
- ✦ Electron coupling: $g_{ae}$
- ✦ Primakoff production







LUXE is the most sensitive here



LUXE is a clean free-GeV-photons machine

- ✦ The ALPs can also be produced at the IP
- ✦ Similar for scalars: $a \to \phi$, $\tilde{F} \to F$ and $\gamma^5 \to 1$
- ✦ Looking also at milli-charged particles production in strong field.

Plot done with:

$E_e = 17.5$ GeV

$N_e = 6 \times 10^9$

$t_L = 200$ fs

$\xi = 2.43$

$t_{op} = 10^7$ s

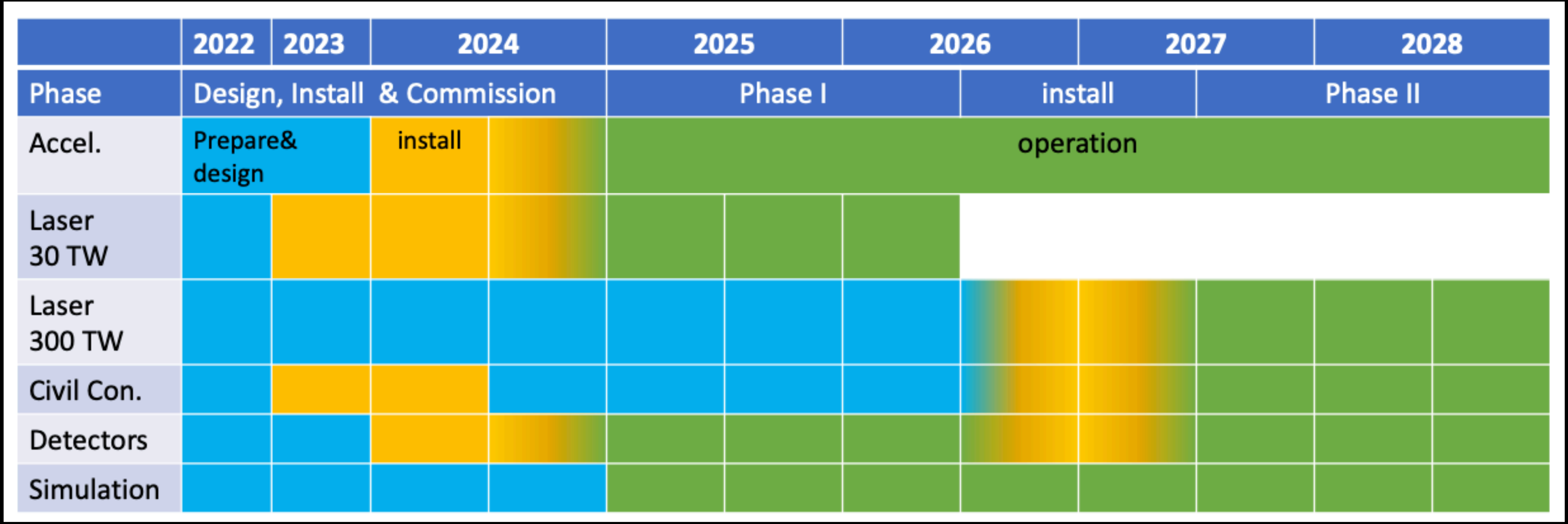
$R_L = 1$ Hz

$L_S = 1$ m

$L_{max} \sim 5.5$ m

# The LUXE experiment: in a Nutshell

- ✦ The critical field $\epsilon_s$ will be reached in the centre of mass of the $e^+e^-$ pair in a clean environment for the first time.
- ✦ The Strong-field may uncover new physics effects.
- ✦ The collaboration is small (~50 people).
  - ✦ The timeline is very streamlined (conclude within this decade).



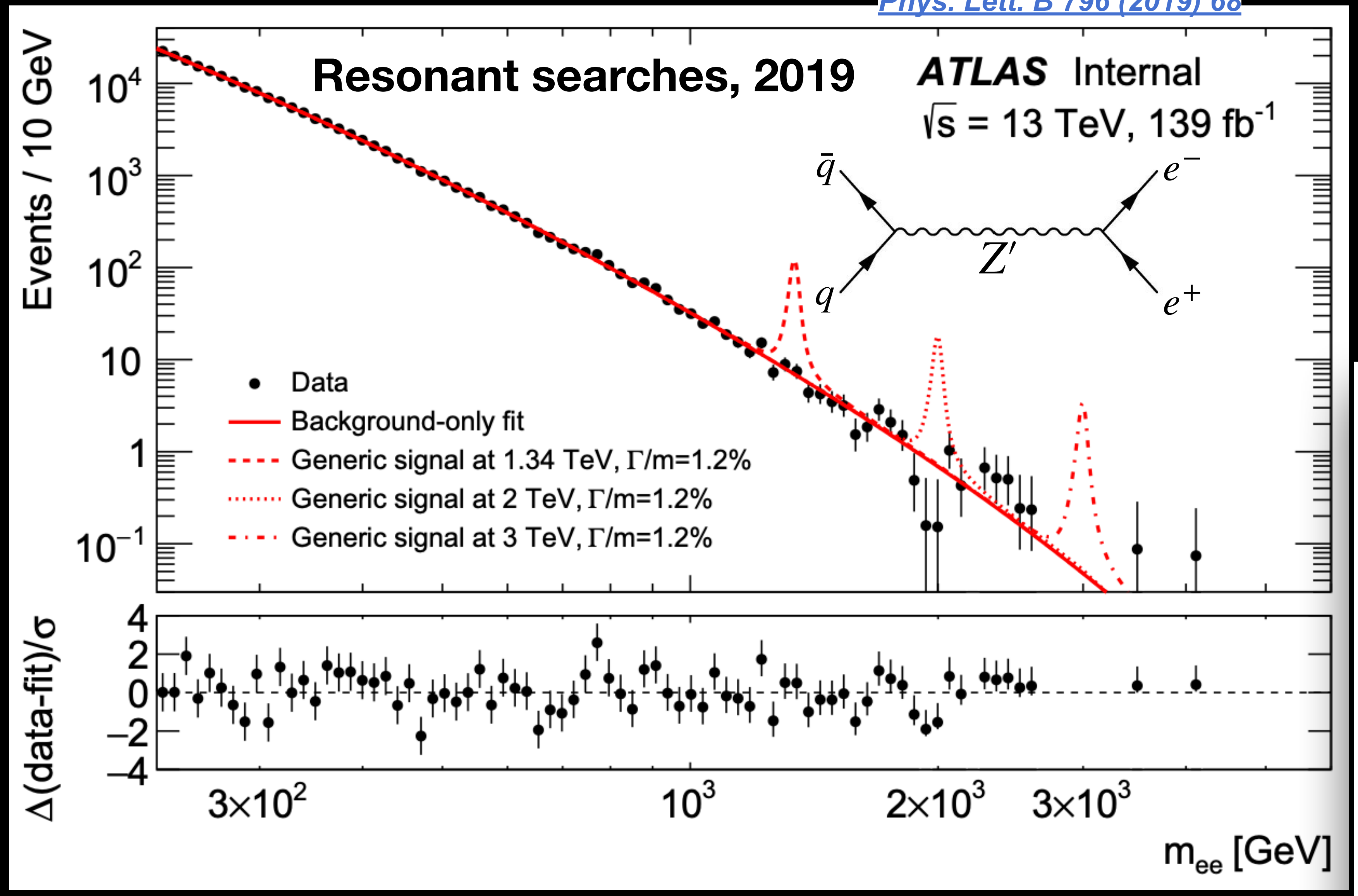
| | 2022 | 2023 | 2024 | | 2025 | | 2026 | | 2027 | | 2028 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase | Design, Install & Commission | | | | Phase I | | | install | | Phase II | | |
| Accel. | 🟦 Prepare&<br>design | 🟦 | 🟨 install | 🟨🟩 | 🟩 operation | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Laser<br>30 TW | 🟦 | 🟨 | 🟨 | 🟨🟩 | 🟩 | 🟩 | 🟩 | | | | | |
| Laser<br>300 TW | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦🟨 | 🟨🟩 | 🟩 | 🟩 | 🟩 |
| Civil Con. | 🟦 | 🟨 | 🟨 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦🟨 | 🟨🟩 | 🟩 | 🟩 | 🟩 |
| Detectors | 🟦 | 🟦 | 🟨 | 🟨🟩 | 🟩 | 🟩 | 🟩 | 🟩🟨 | 🟨🟩 | 🟩 | 🟩 | 🟩 |
| Simulation | 🟦 | 🟦 | 🟦 | 🟦 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

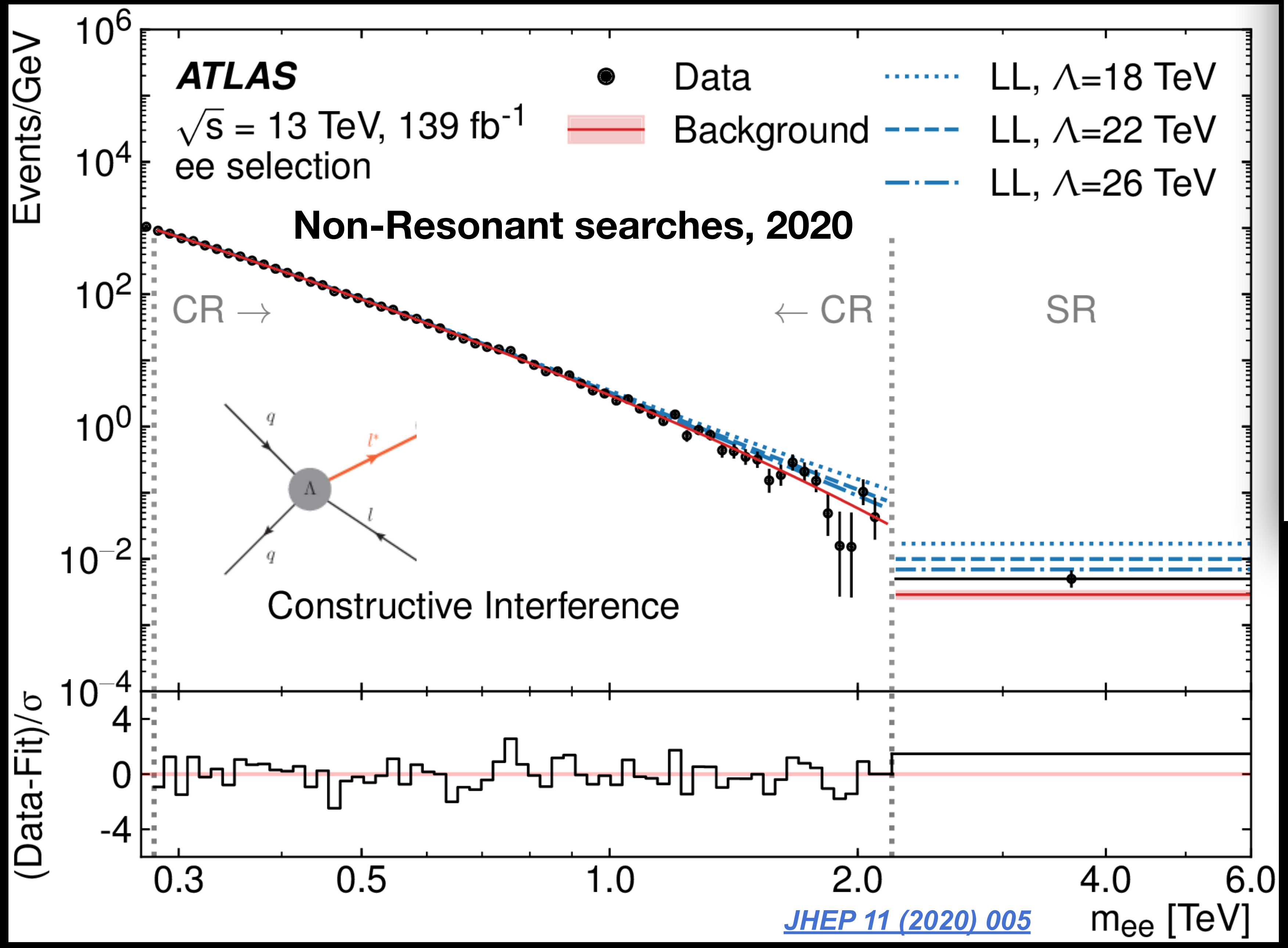
**LUXE Timeline**

# DiLepton ClockWork search @ ATLAS

# A very brief overview

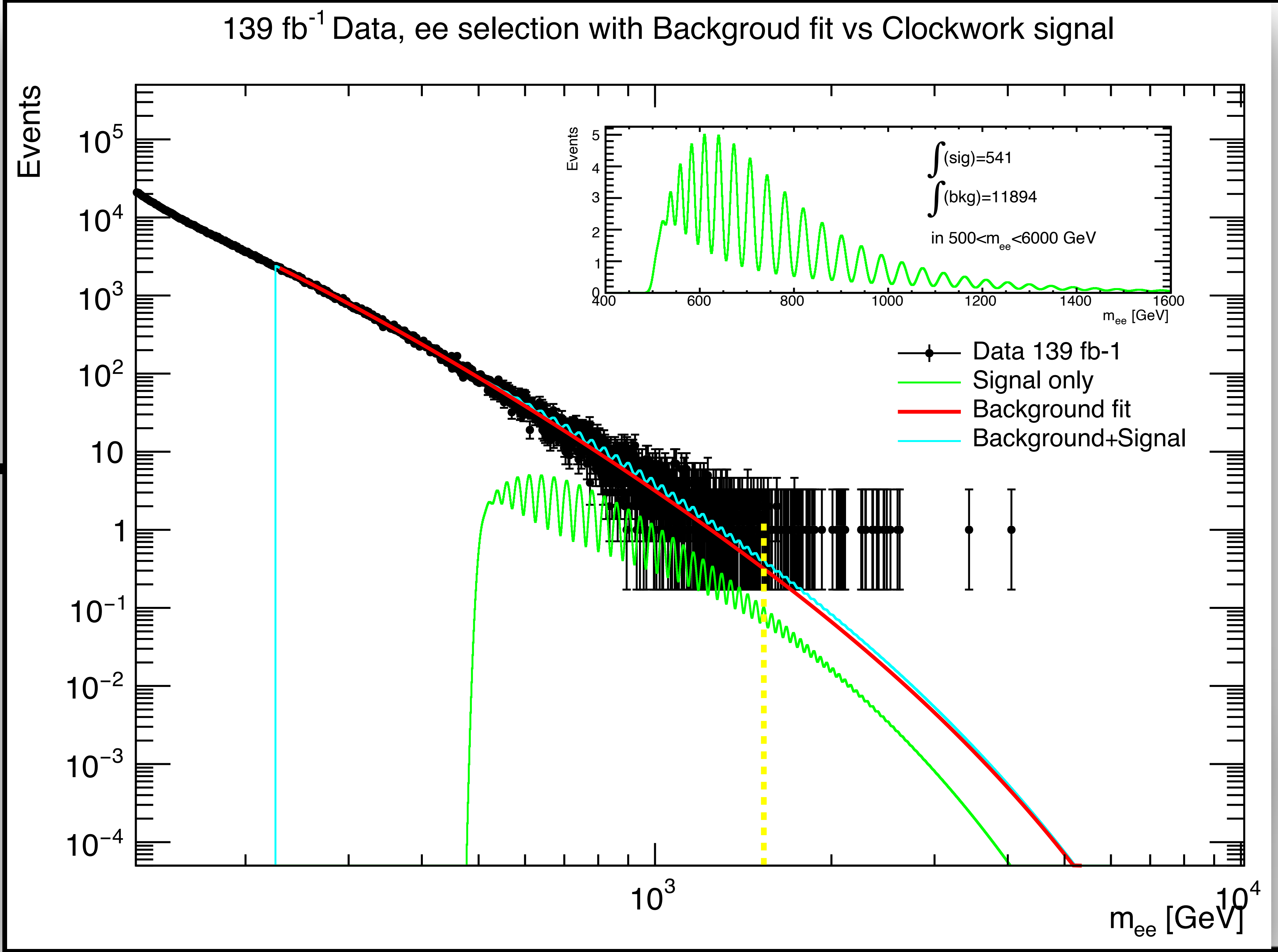
[Phys. Lett. B 796 (2019) 68]

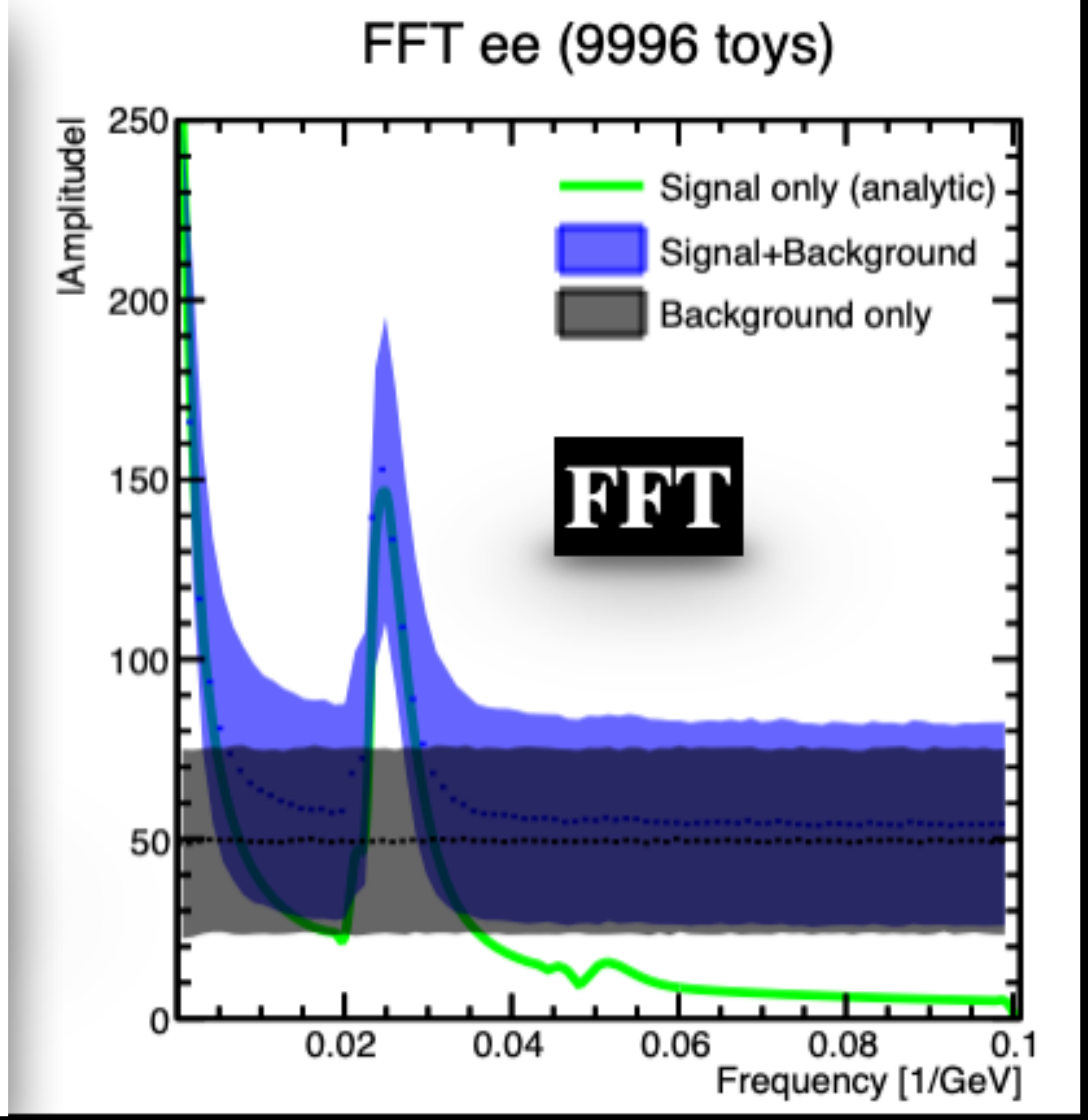




[JHEP 11 (2020) 005]

- ✦ The new particles/interactions search is in general a bump/tail hunting.
- ✦ Very challenging to spot other kind of signals.
  - ✦ Signals with very low event rate
  - ✦ Signals with periodic structure

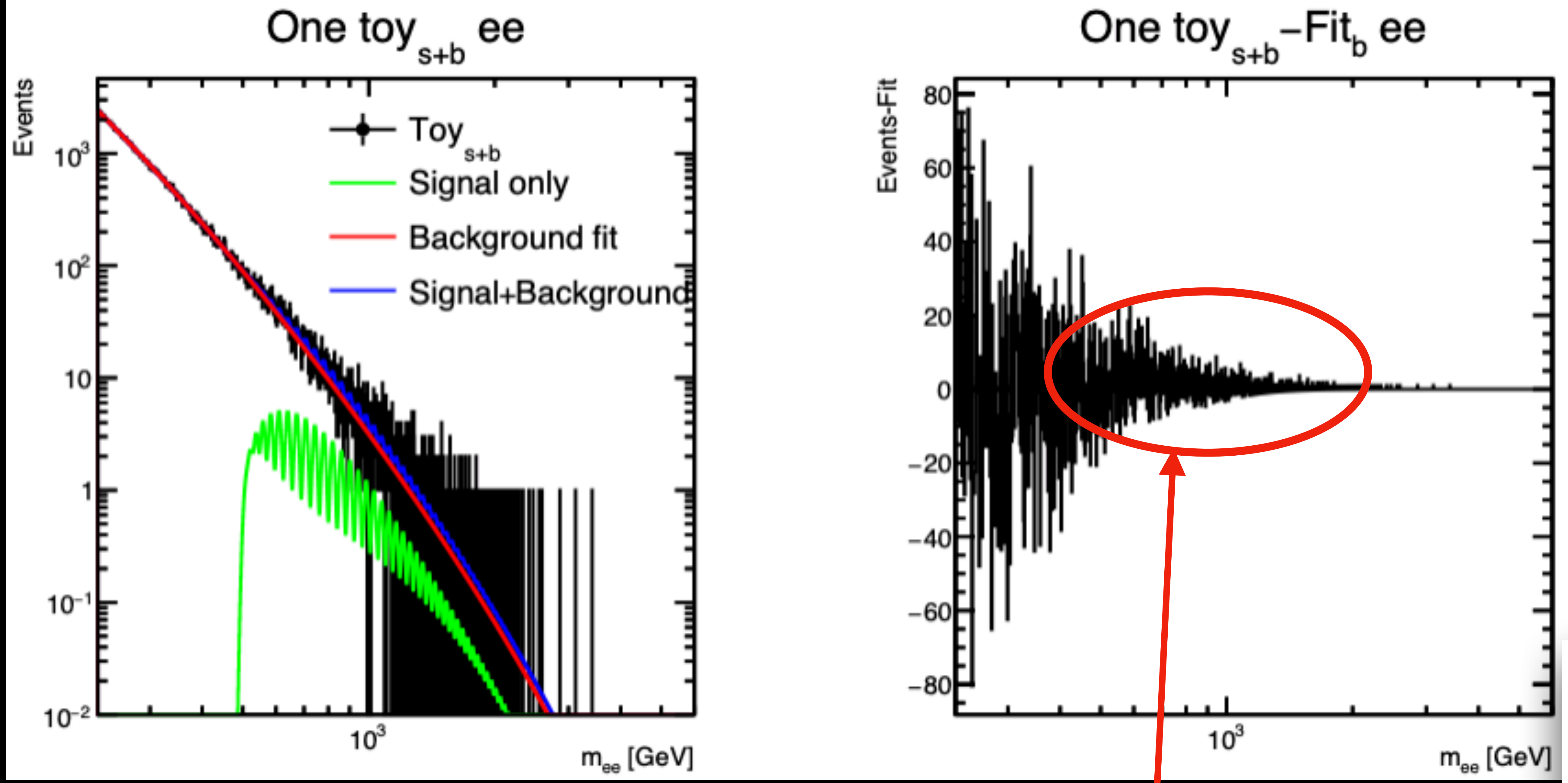




**This signal is invisible to our usual searches**

✦ The Fast Fourier Transformation, being one-dimensional, not helpful to point the position of the signal.

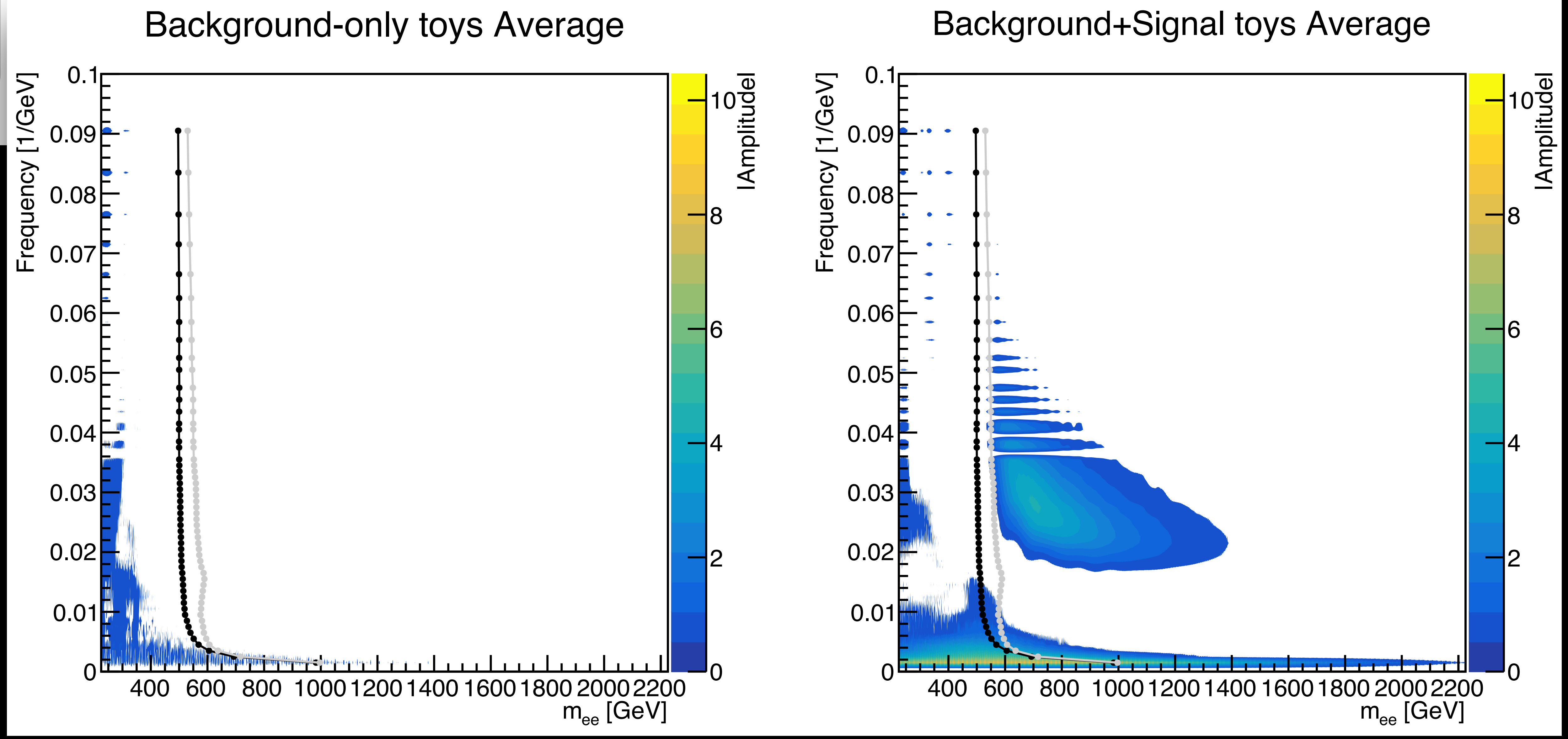
# Transformation from Mass space to Frequency space



Not possible to find signal here

- ✦Continuous wavelet transformation:
  - ✦Preserves the mass window of the signal.
  - ✦ Classify the signal and background using cutting edge Neural Networks, e.g. Autoencoders.

**Continuous Wavelets Transform⟶**




Thank You
For Your Attention

# Backup

# Details of the LUXE system

| | |
|---|---|
| **Electrons** | $E_e$ up to **17.5 GeV**, with $N_e$ **= 1.5-6×$10^9$ $e^-$/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), 25-200 fs pulse, 1-10 Hz rate |
| | 8×8⟶3×3 µm$^2$ FWHM spot with up to ***I*~ 3.5×$10^{19}$ W/cm$^2$**(⟶1.5×$10^{21}$), 60% loss |

# Lasers strong field “how-to”

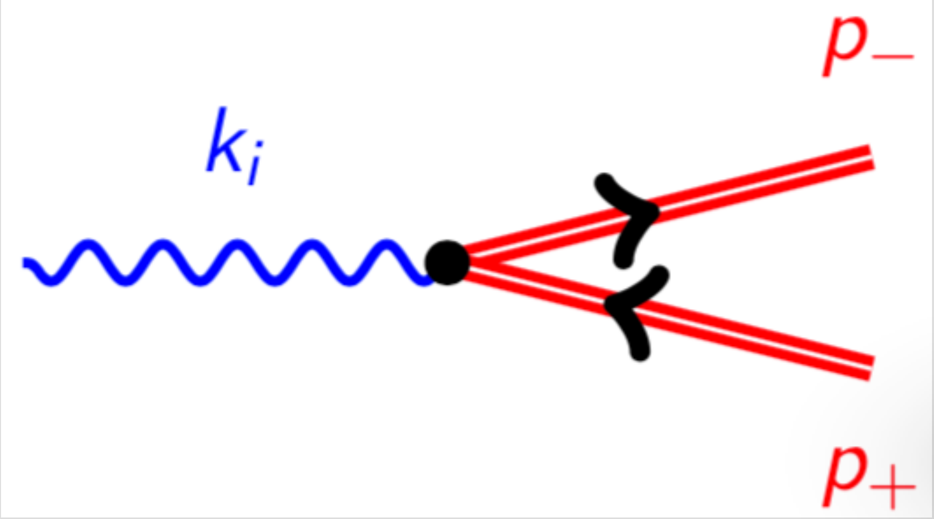
- Laser-assisted one photon pair production, OPPP (SPP ⟶OPPP)
  - the laser’s E-field frequency is $\omega$, with momentum $k = (\omega, \mathbf{k})$
  - the laser’s E-field strength is $|\epsilon|$, with $I \sim |\epsilon|^2$
  - The $e^+e^-$ pair picks up momentum from the laser photons

- OPPP rate is a function of the laser intensity $\xi$ and the photon recoil $\chi$:

Dimensionless and Lorentz-invariant

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

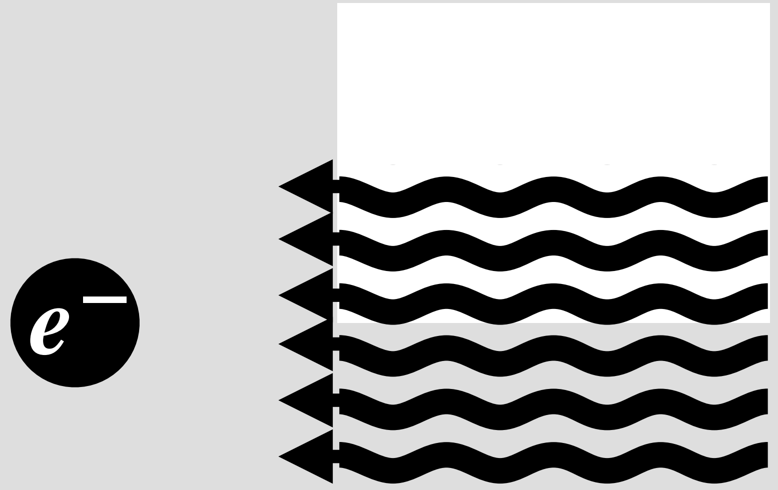
Initial photon : $k_i = (\omega_i, \mathbf{k}_i)$



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

# Understanding $\xi$

Electron “at rest”



Infinite E-field plane wave with frequency $\omega$

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

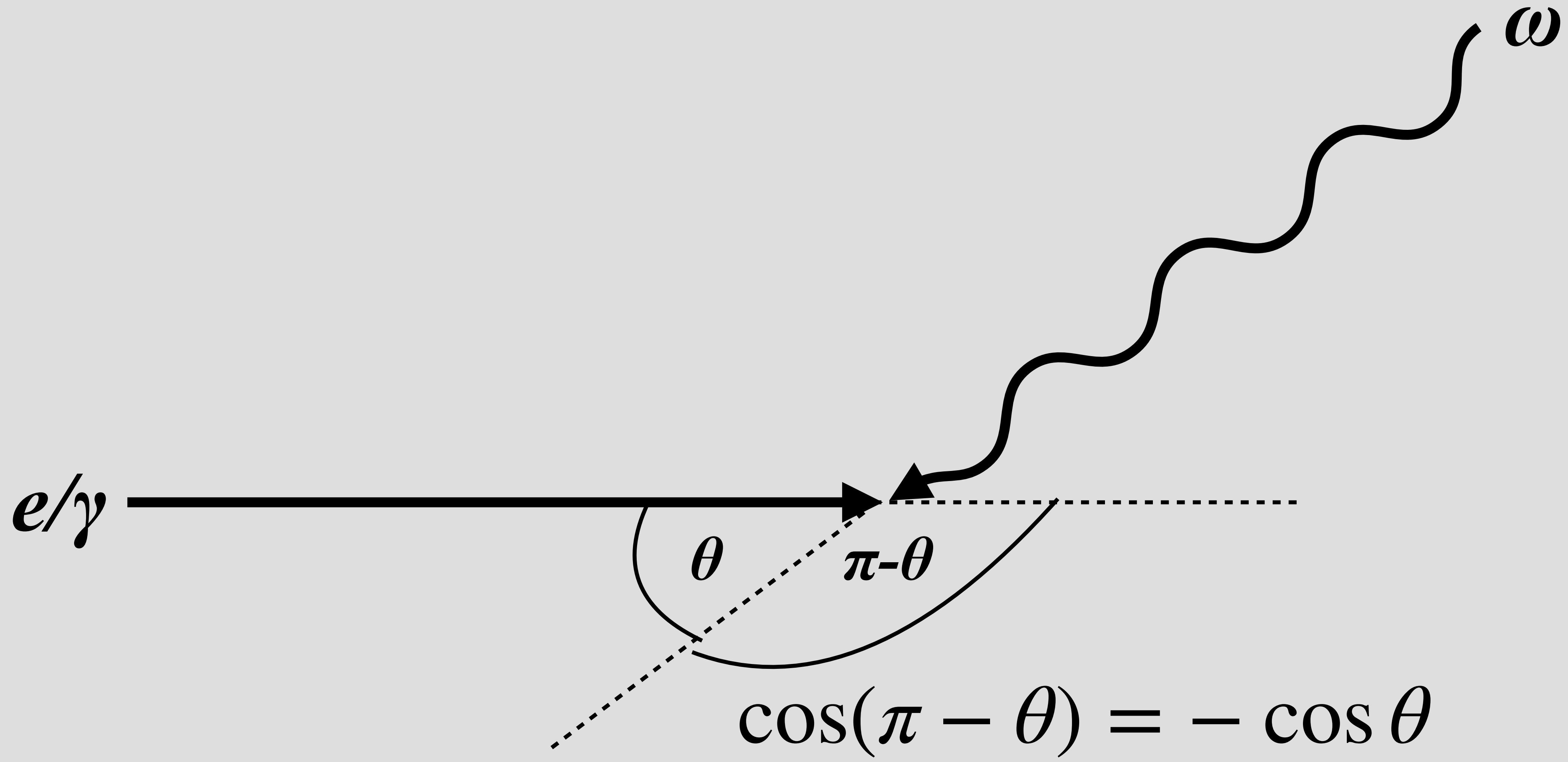
The electron’s maximum velocity is: $v_{\max} = a \cdot \Delta t = \frac{eE}{m_e} \cdot \frac{1}{\omega}$

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

$\xi$ reaches unity for e.g. a $\lambda = 800$ nm laser at an intensity of $I \sim 10^{18}$ W/cm$^2$

# Understanding $\chi$

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

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

$$\frac{\mathbf{1}}{\epsilon_\mathrm{S}} = \frac{e}{m_e^2}$$

$\hbar = c = 1$

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

Sum on number of absorbed laser $\gamma$'s

$J_n$ are Bessel functions

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

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

threshold number of absorbed $\gamma$'s

As the laser intensity $\xi$ 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 <u>circularly polarised</u> infinite plane wave

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

# Mass shift

- Electron motion in a circularly polarised field, $\epsilon_L$, with frequency $\omega_L$:
  - 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: $k_\mu$
  - outside the field, the (free) charged particle 4-momentum is: $p_\mu$
  - inside the field, the effective 4-momentum ($q_\mu$) and mass are:

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

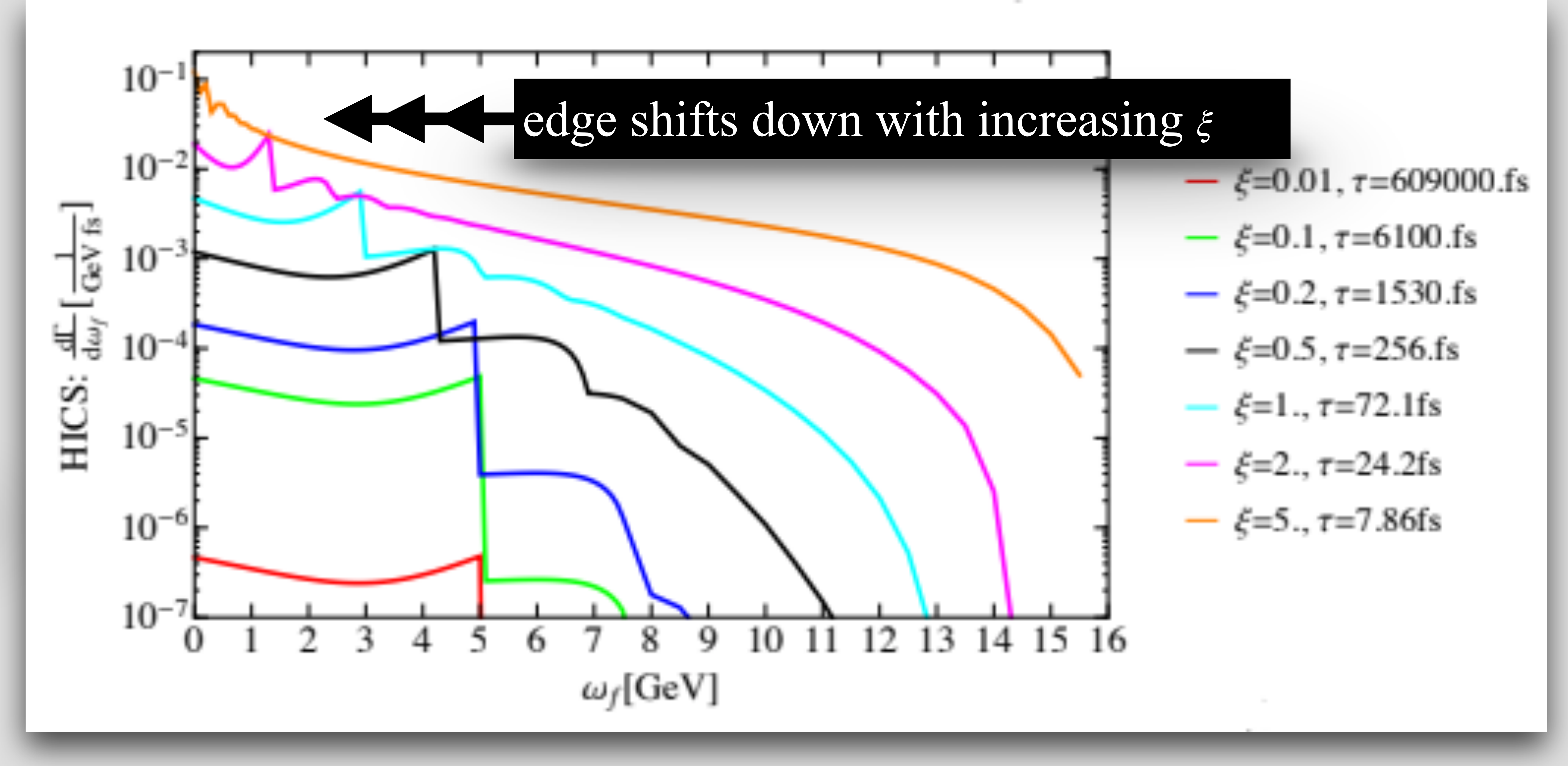
# Mass shift ⟶ kinematic edge

- 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, $\omega'$, 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 $\xi$ and recoils less
  - the min energy of the scattered electron (kinematic edge) is higher

# Compton edges

- With increasing laser intensity $\xi$:
  - higher order (n) contributions become more prominent
  - edge shifts to lower energies due to electron’s higher effective mass

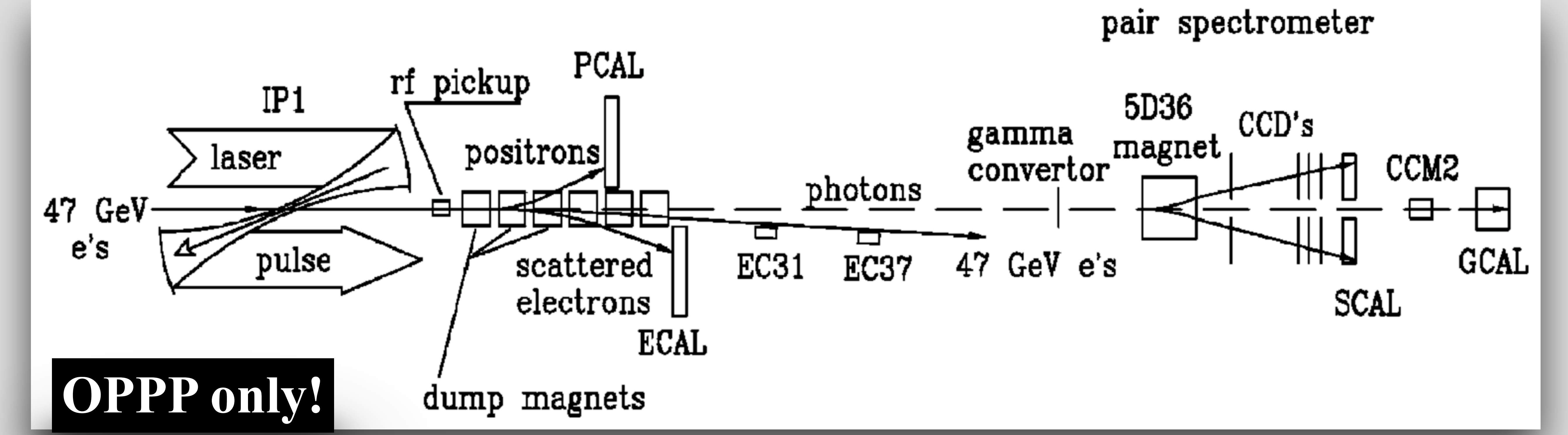
**The rate is a series of Compton edges for n=1,2,3,… absorbed photons**


edge shifts down with increasing $\xi$

# History: E144 @ SLAC

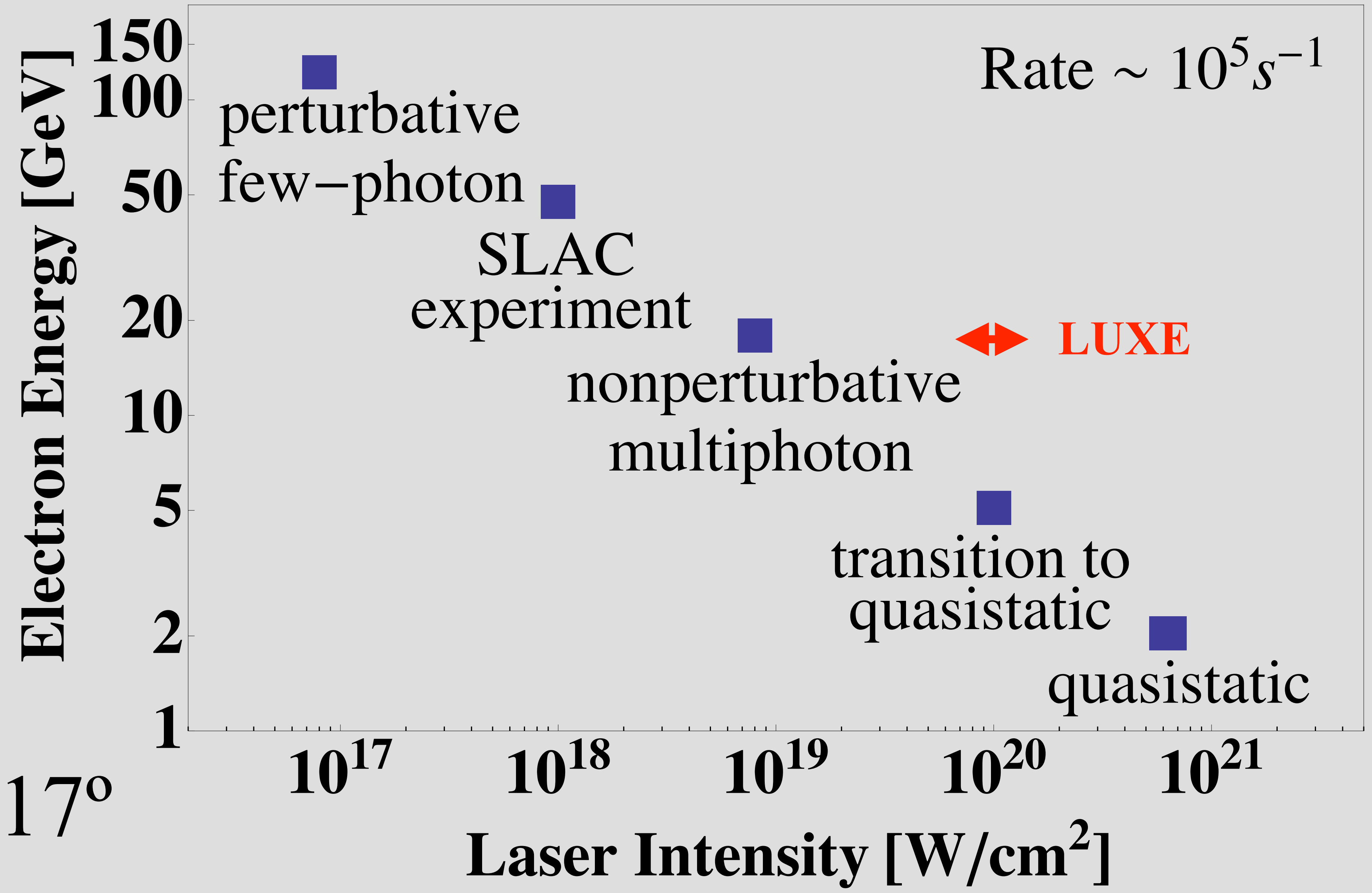
E144 at SLAC
during the 90s

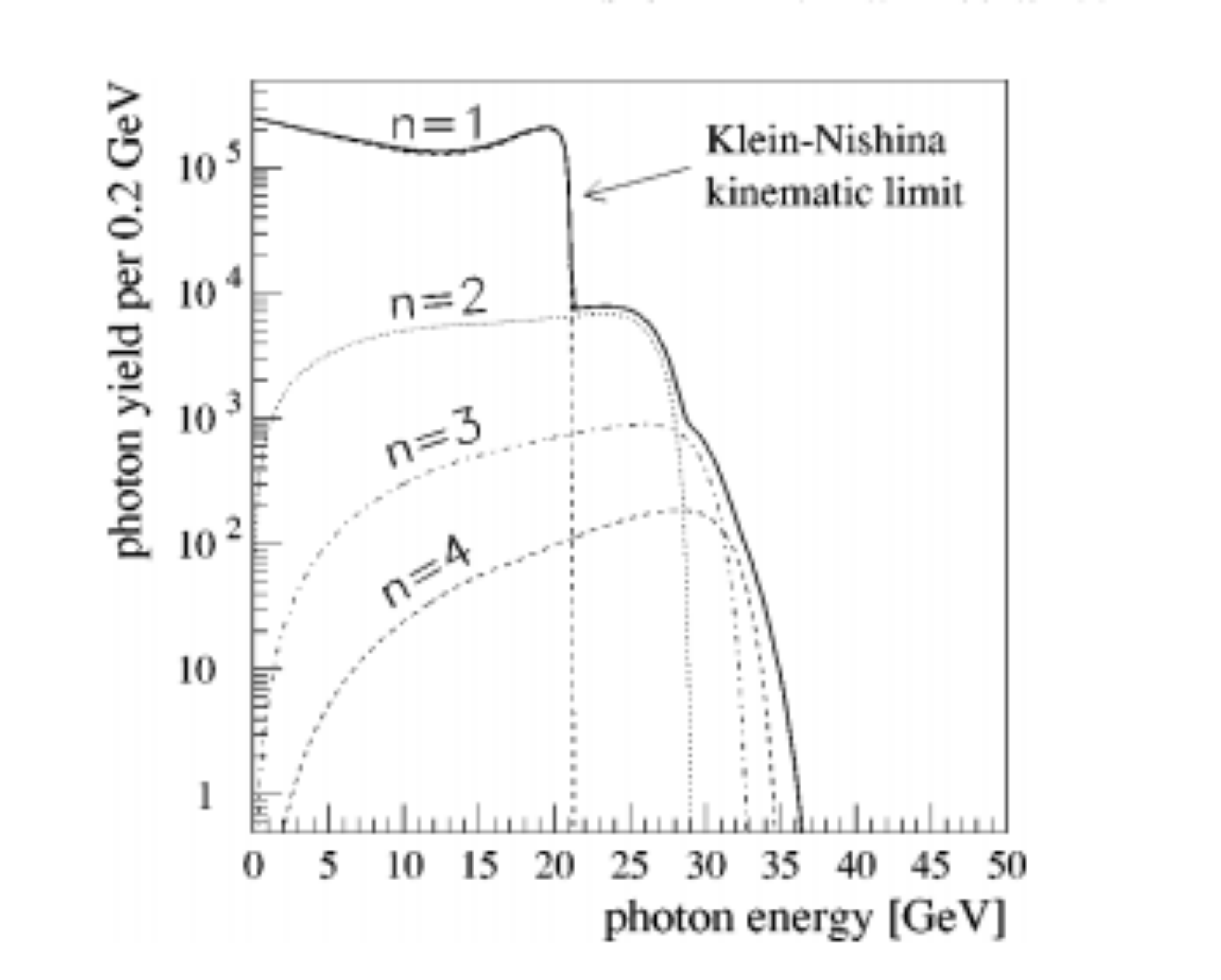
Phys.Rev. D60 (1999) 092004



**OPPP only!**

- 46.6 GeV electron beam
- $5\times10^9$ electrons per bunch
- Bunch rates up to 30 Hz
- Terawatt laser pulses
- Intensity of ~$0.5\times10^{18}$ W/cm$^2$
- Frequency of 0.5 Hz for wavelengths 1053 nm, 527 nm
- electrons-laser crossing angle: 17°





# History: E144 @ SLAC

**OPPP only!**

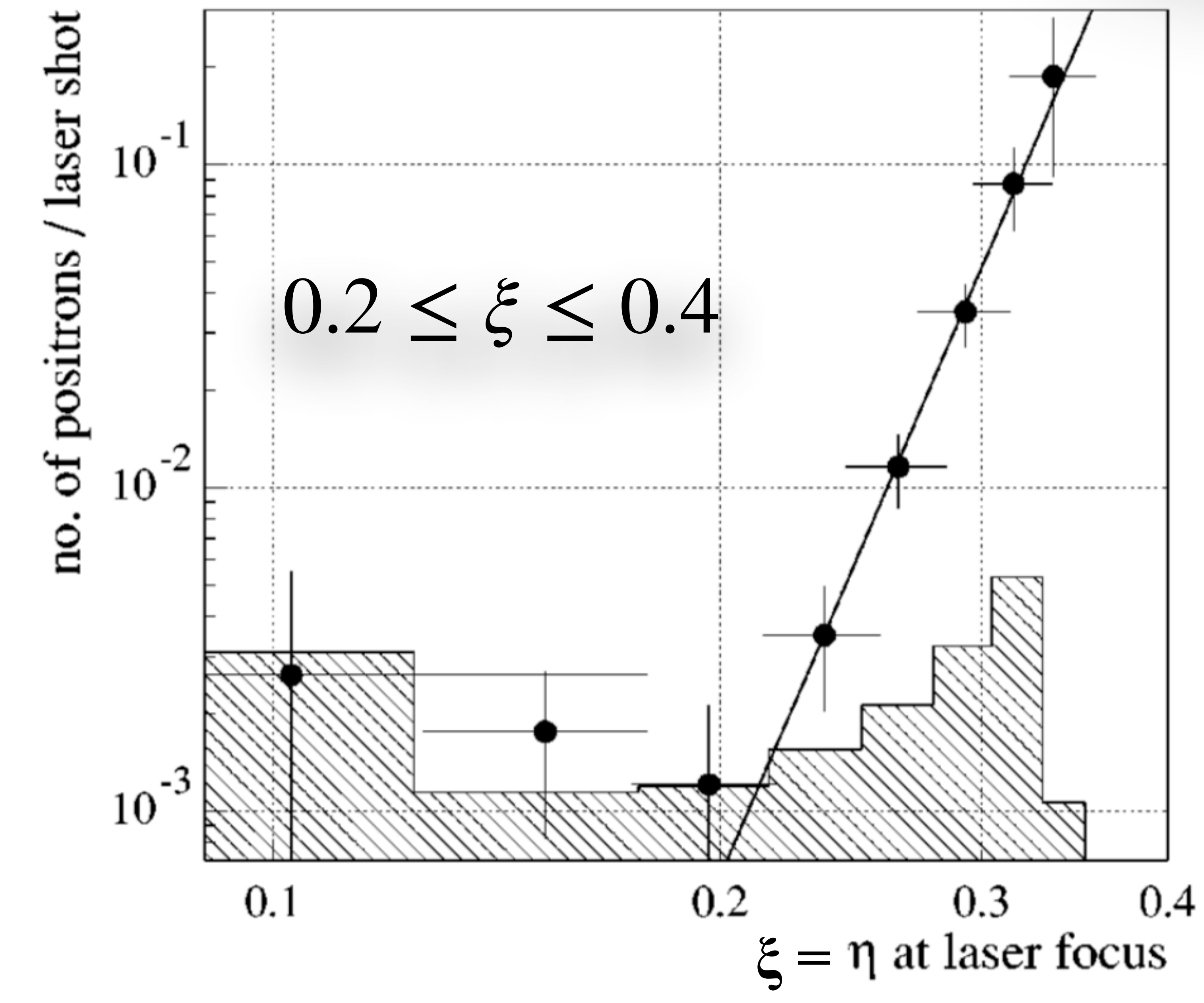


FIG. 44. The dependence of the positron rate per laser shot on the laser field-strength parameter $\eta$. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron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

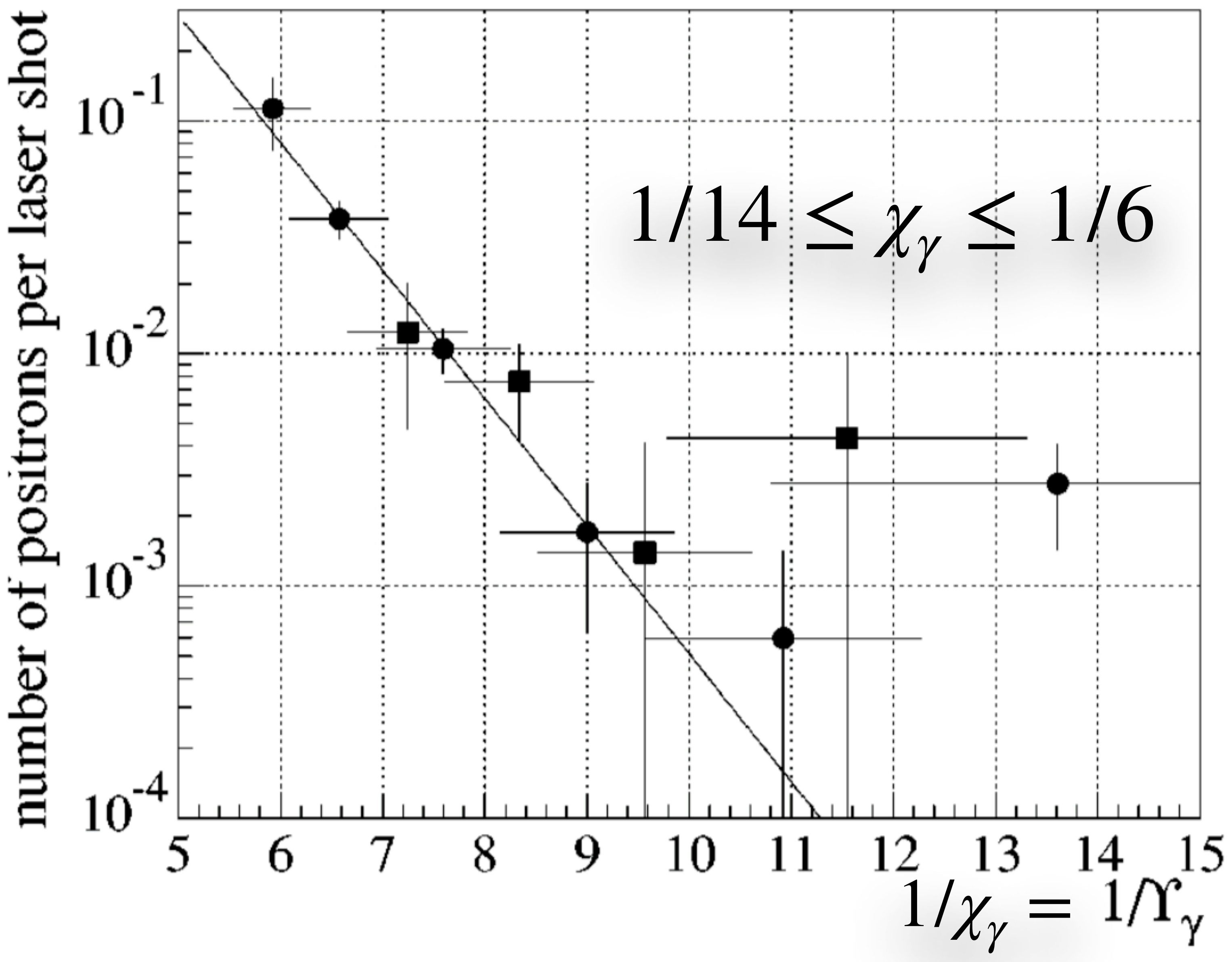
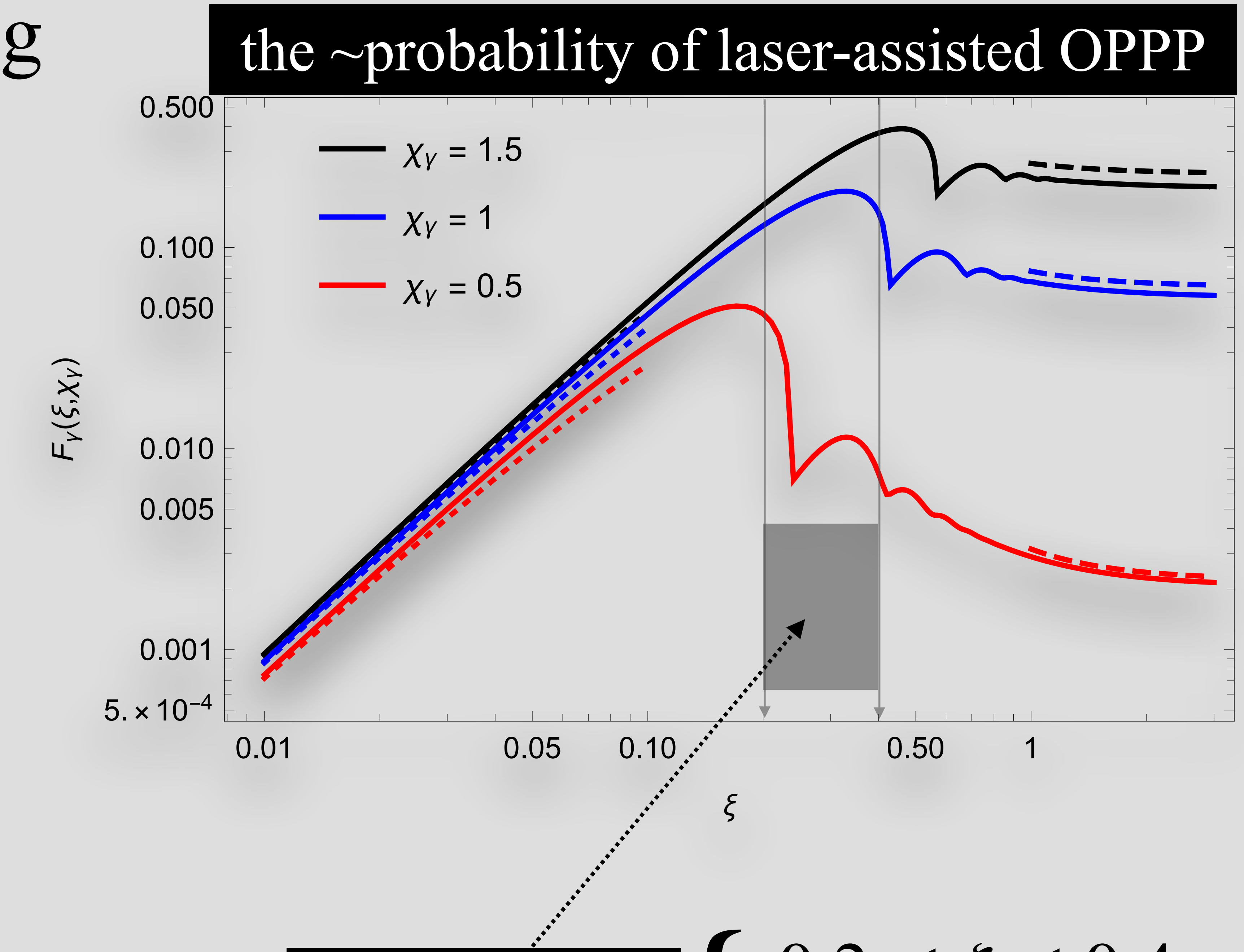


FIG. 49. Number of positrons per laser shot as a function of $1/\Upsilon_\gamma$. The circles are the 46.6 GeV data whereas the squares are the 49.1 GeV data. The solid line is a fit to the data.

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 peak E-field of the laser: $0.5\times10^{18}$ V/m


the ~probability of laser-assisted OPPP

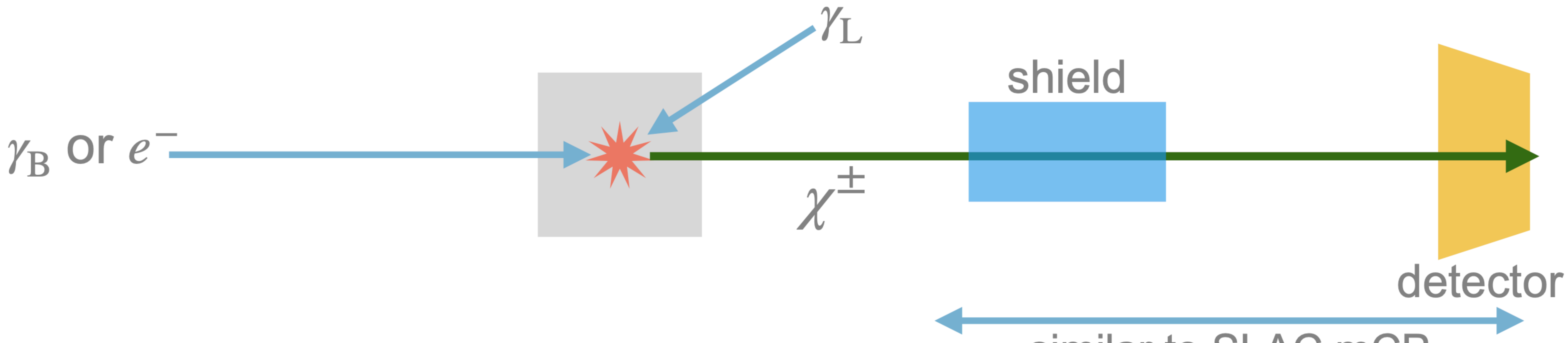
**E144 should be somewhere here**

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

# Details Of milli-Charged Particle Search at the LUXE

$$\mathscr{L}_{\text{int}} = eq\bar{\chi}\gamma^{\mu}\chi A_{\mu}$$

mass - $m_\chi$, fractional charge - $q$



similar to SLAC mCP

PRL, 1998

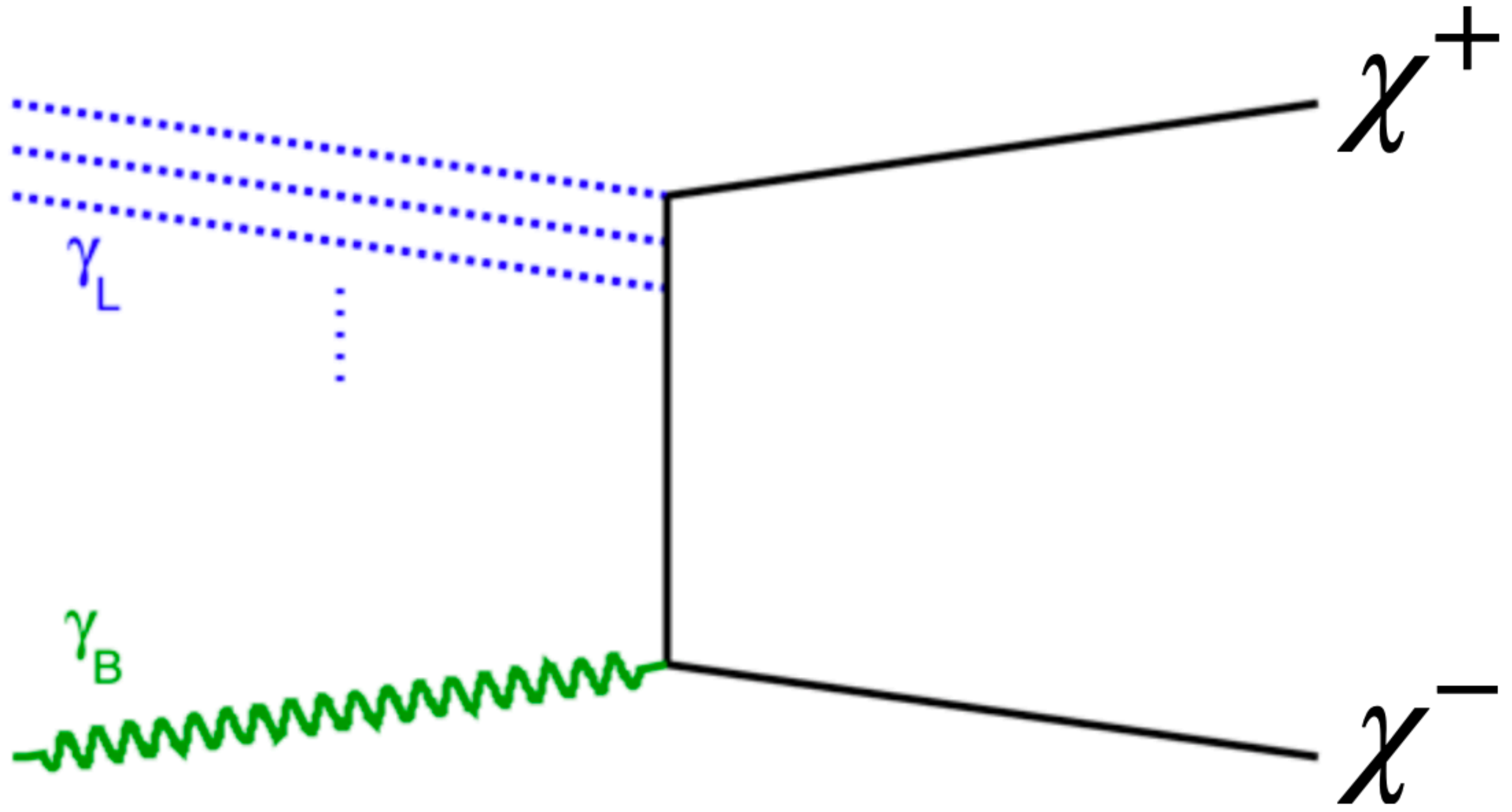
similar production as $e^+e^-$

$$m_e \to m_\chi\ ,\ e \to qe$$

Schwinger critical field

$$\frac{\mathscr{E}_{\text{cr}}^{\chi}}{\mathscr{E}_{\text{cr}}^{e}} = \frac{10^{-6}}{q}\left(\frac{m_\chi}{0.5\,\text{keV}}\right)^2$$

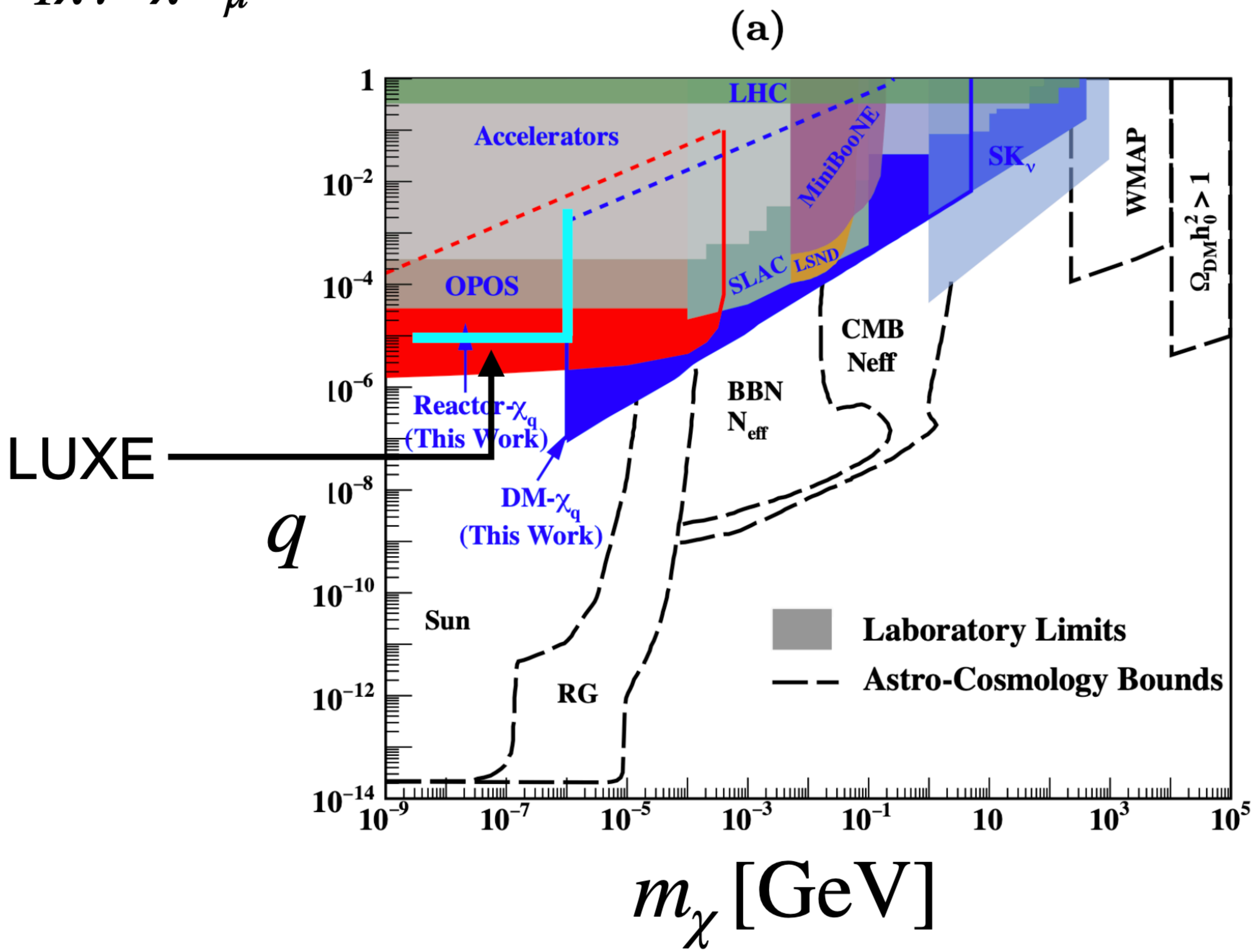
$$\mathscr{E}_{\text{cr}}^{e/\chi} = m_{e/\chi}^2/eq$$



From Yotam Soreq

# Details Of milli-Charged Particle Search at the LUXE

$$\mathscr{L}_{\text{int}} = eq\bar{\chi}\gamma^{\mu}\chi A_{\mu}$$



From Yotam Soreq

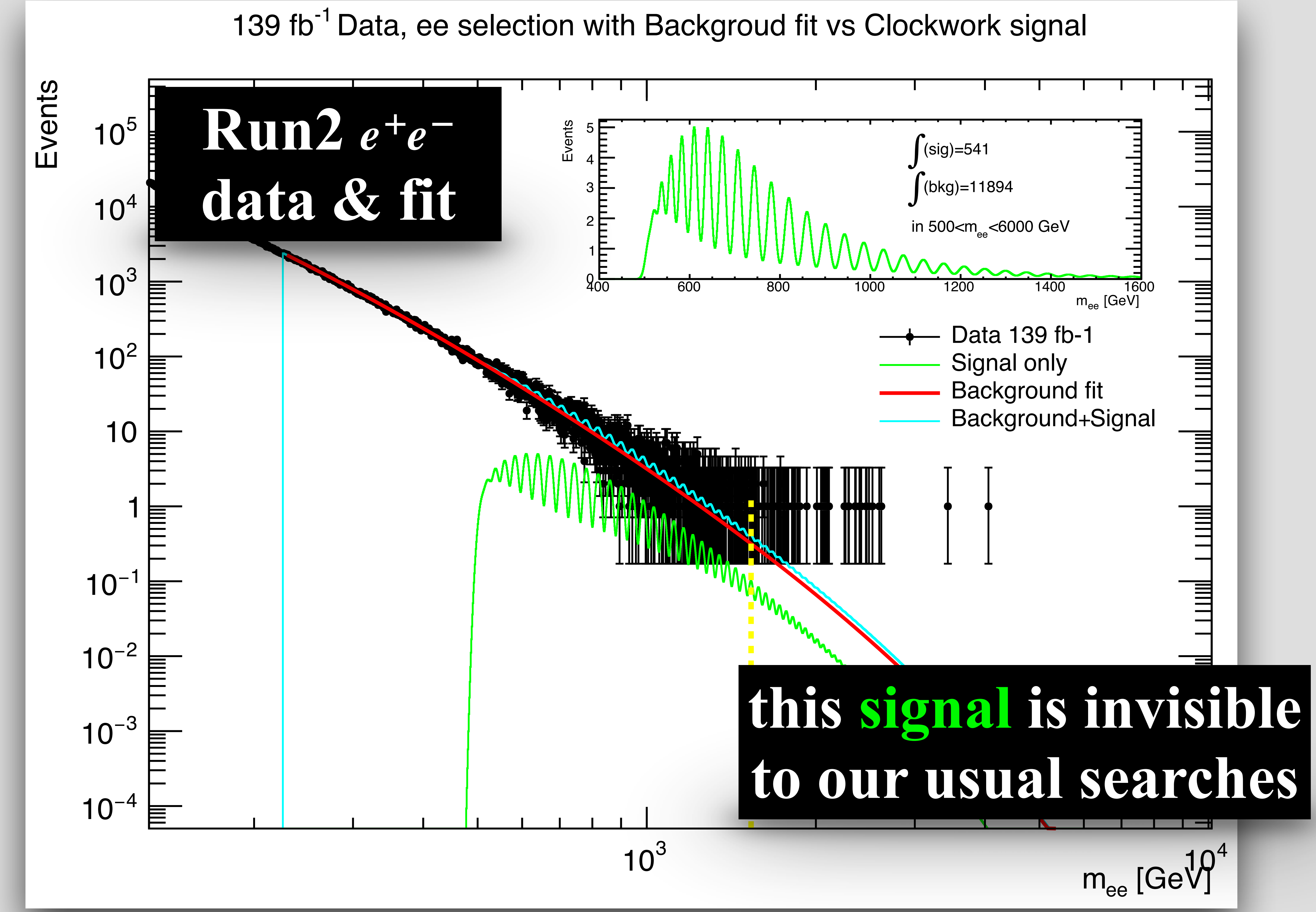
# Clockwork theory in a nutshell

- Mechanism for generating light particles with exponentially suppressed interactions in theories with no small parameters at the fundamental level. Can be implemented as a discrete set of new fields or through an extra spatial dimension in its continuum version. Exhibits novel phenomenology with a distinctive spectrum of closely spaced resonances.
- The most exciting application is the clockwork graviton, offering a novel solution to the naturalness problem of the electroweak scale and providing a dynamical explanation for the weakness of gravity
  - In one implementation, the theory describes a tower of massive spin-two particles, which can be interpreted either as the Kaluza-Klein excitations of the 5D graviton or as the continuum version of the clockwork gears
  - This theory has only two parameters: the fundamental gravity scale $M_5$ and the mass $k$
  - Here, $R$ does not measure the proper size of the extra dimension, which is much larger than its natural value $1/M_5$. As a result, the hierarchy $M_P/M_5$ is explained by a combination of volume (as in LED) and warping (as in RS): $M_\mathrm{P}^2 = \left(M_5^3/k\right)\left(e^{2\pi kR} - 1\right)$, while to account for the hierarchy one needs $kR \simeq 10$
  - The KK gravitons masses are $m_0 = 0,\ m_n^2 = k^2 + (n/R)^2$ with $n = 1,2,3,...$ and they couple to the SM stress-energy tensor as: $\mathscr{L} \sim -(1/\Lambda_G^{(n)})\tilde{h}_{\mu\nu}^{(n)}T^{\mu\nu}$ where $\Lambda_G^{(0)} = M_\mathrm{P}$ and $\Lambda_G^{(n)2} = M_5^3\pi R\left(1 + (kR/n)^2\right)$
  - The zeroth mode is the massless graviton, while the rest of the KK modes appear after a mass gap of order $k$ and their couplings to the SM are not suppressed by $M_P$.
  - The KK modes form a narrowly-spaced and approximately periodic spectrum above the mass gap with splittings greater than or comparable to the experimental resolution in the range of interest
  - The near-periodicity of mass distributions is with characteristic separations in the 1-5% range

# In dileptons

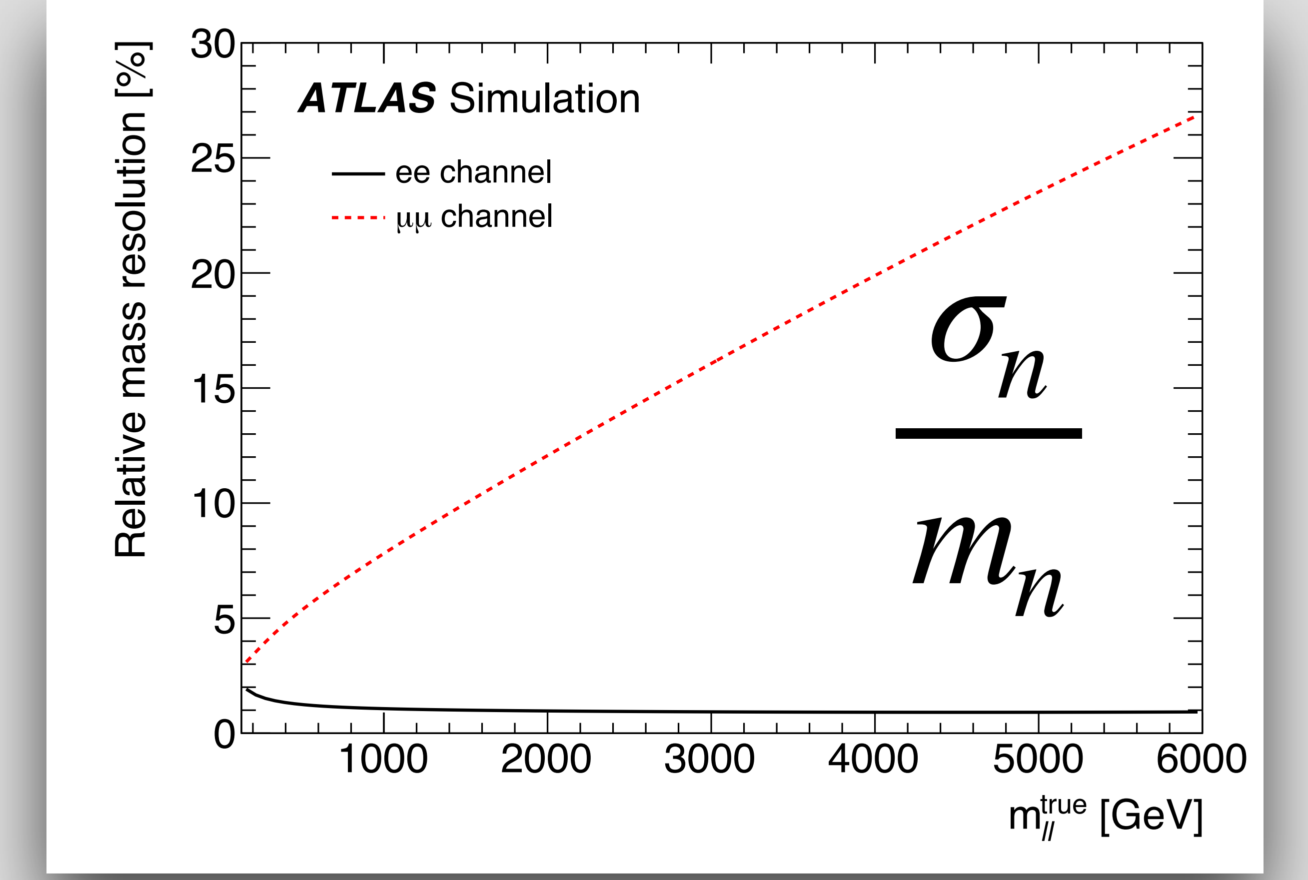
**Emulated signal⟶**

$$C \times \underbrace{\left(1-\frac{k^2}{m_n^2}\right)}_{\sim\text{Turn−on}} \times \underbrace{\text{Landau}(m_{\ell\ell},\mu,\sigma)}_{\sim\text{PDF}(gg)} \times \underbrace{\exp\left[-\frac{m_{\ell\ell}}{k}\right]}_{\text{Tail damp}} \times \underbrace{\sum_{n=1}^{\infty} G(m_{\ell\ell},m_n,\sigma_n)}_{\text{Resonances (resolutions)}} \times \mathscr{A}\epsilon$$

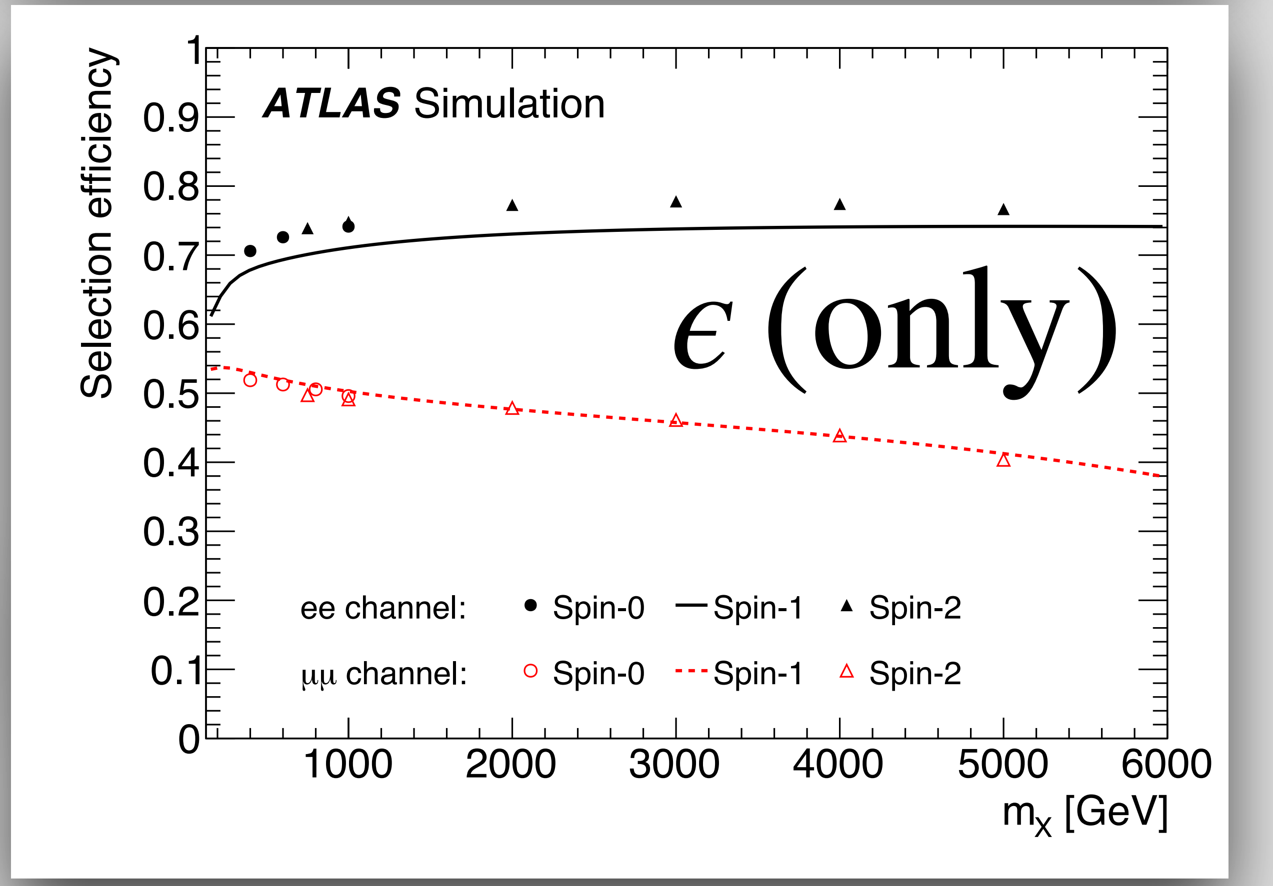


**Run2 $e^+e^-$ data & fit**

**this signal is invisible to our usual searches**



$$\frac{\sigma_n}{m_n}$$



$\epsilon$ (only)

# Continuous Wavelet Transformation

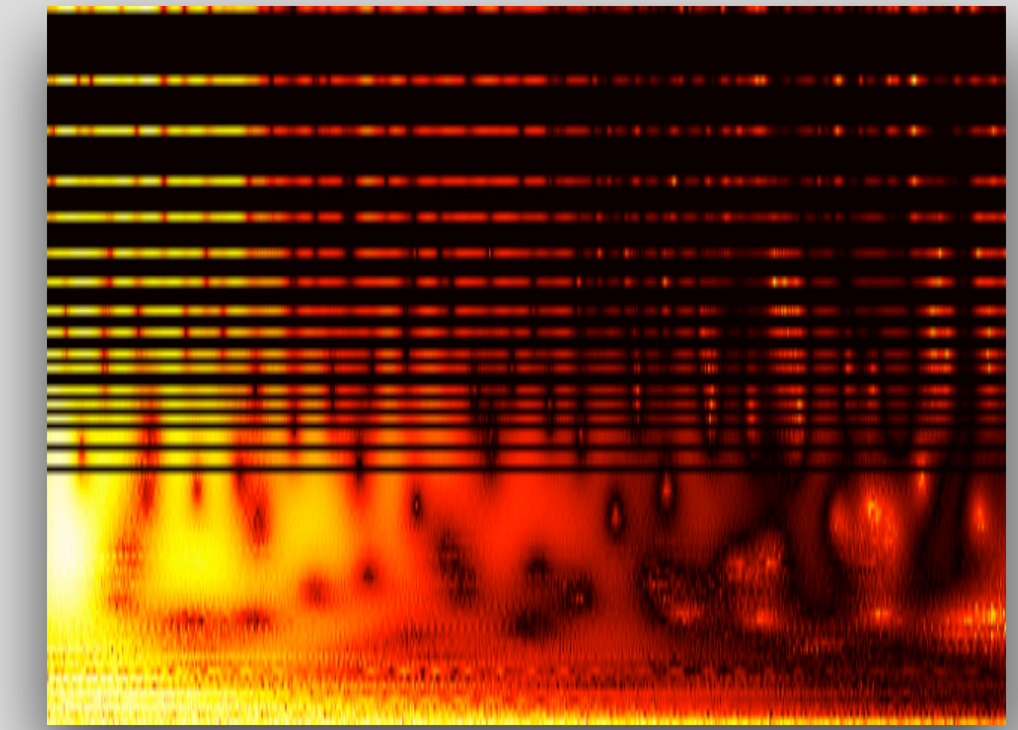
Eur. Phys. J. C 80, 192 (2020)

- ✦ Assume $\psi(t)$ is a basis function localized in both time and frequency space.
- ✦ The Continuous Wavelet Transformation of a signal $f(t)$ at a scale $a > 0$ and translational parameter $b \in \mathscr{R}$ is given by a projection over rescaled and shifted version of $\psi(t)$:

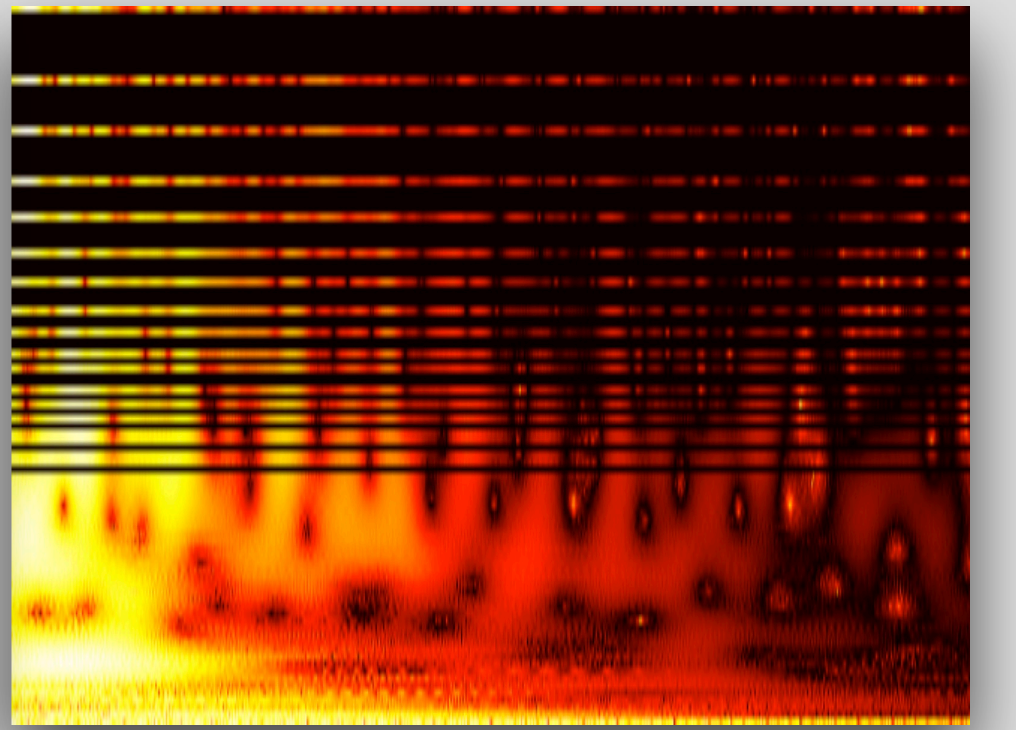
$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t)\ \psi^* \left(\frac{t-b}{a}\right) dt$$

- ✦ In practice, it is a measure of how much a certain frequency is present in the signal at a given time.
- ✦ Mother wavelet $\psi(t)$ is required to have: $\int_{-\infty}^{+\infty} |\psi(t)|^2 dt < \infty$ and $c_\psi \equiv 2\pi \int_{-\infty}^{+\infty} \frac{|\psi(\omega)|^2}{|\omega|} d\omega < \infty$
- ✦ Morlet wavelet as $\psi$: $\psi(t) \equiv \frac{1}{\sqrt{B\pi}} e^{-t^2/B} \left(e^{i2\pi Ct} - e^{-\pi^2 BC^2}\right)$.

# Working in Frequency domain



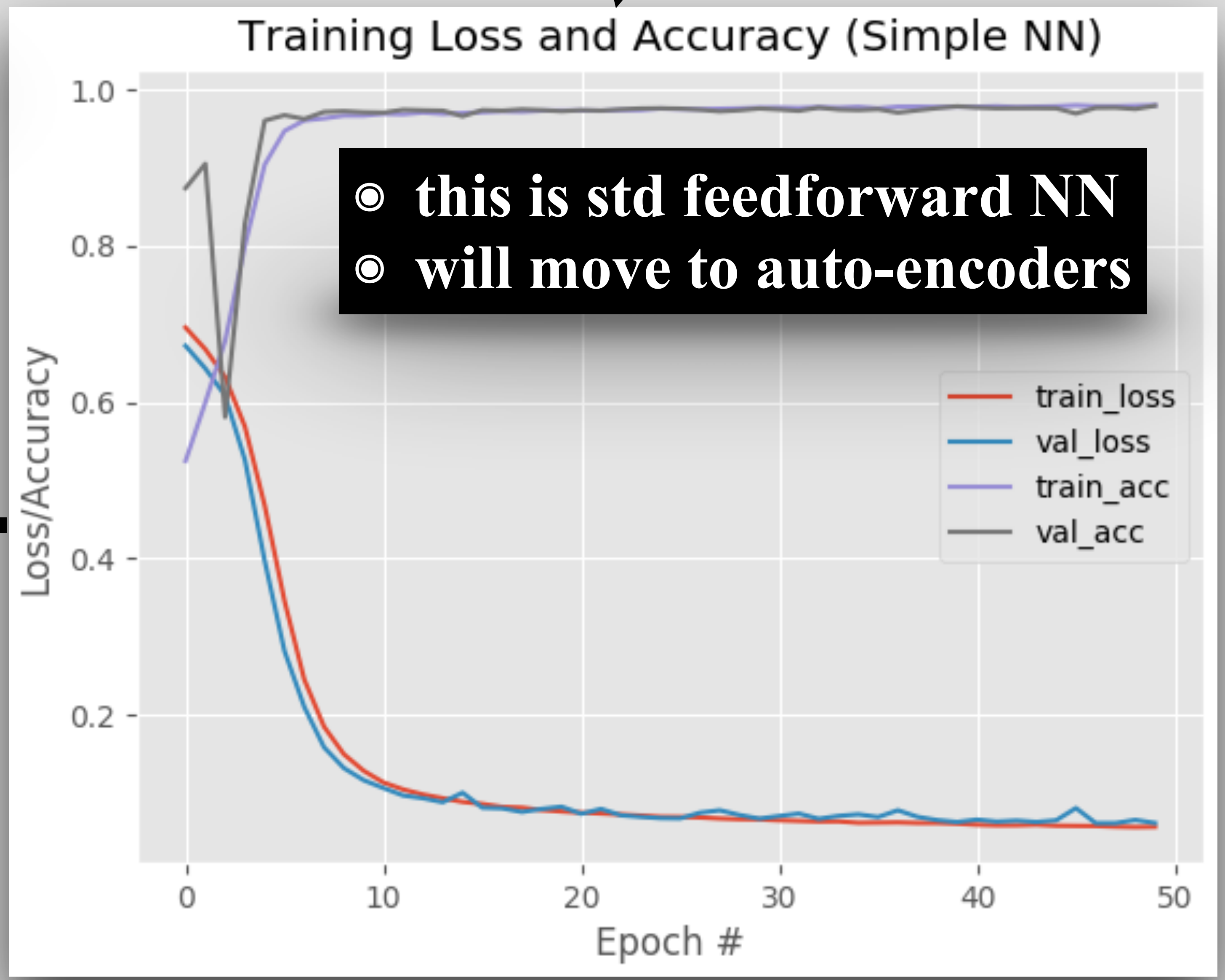
**Background toy**



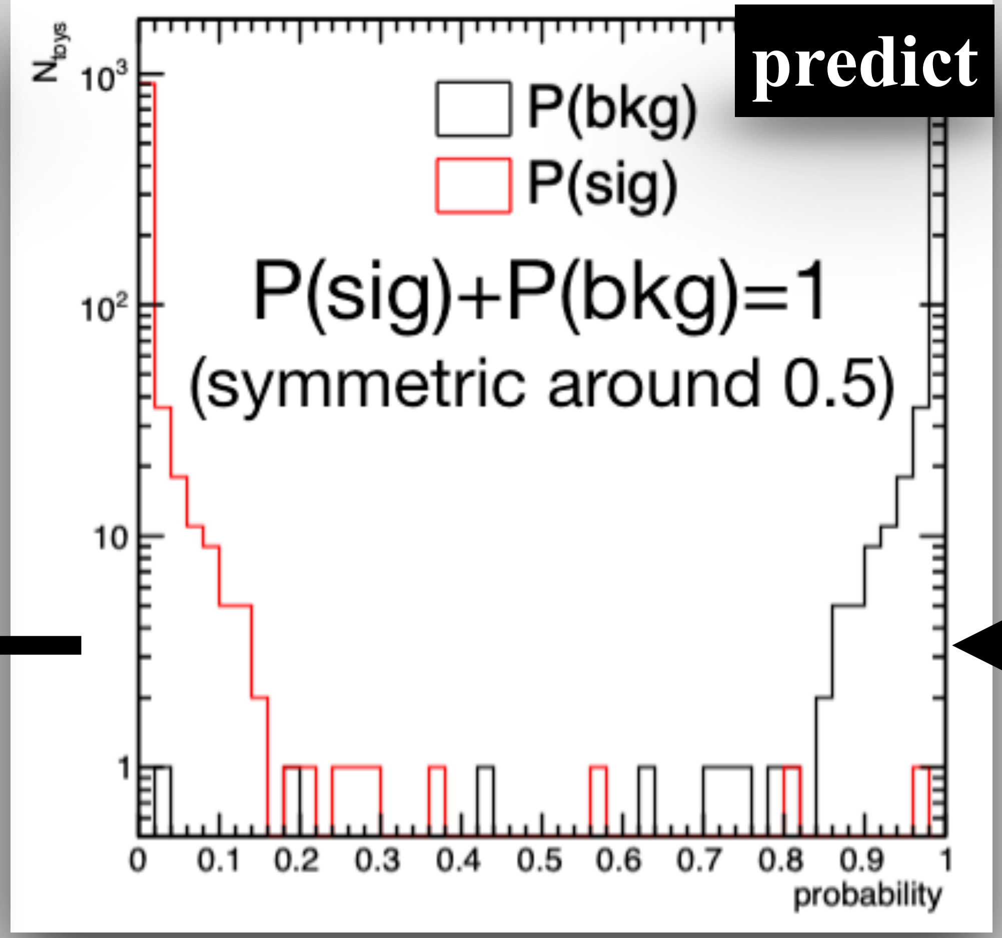
**Signal toy**

**Thousands of these…**

**Neural Net**

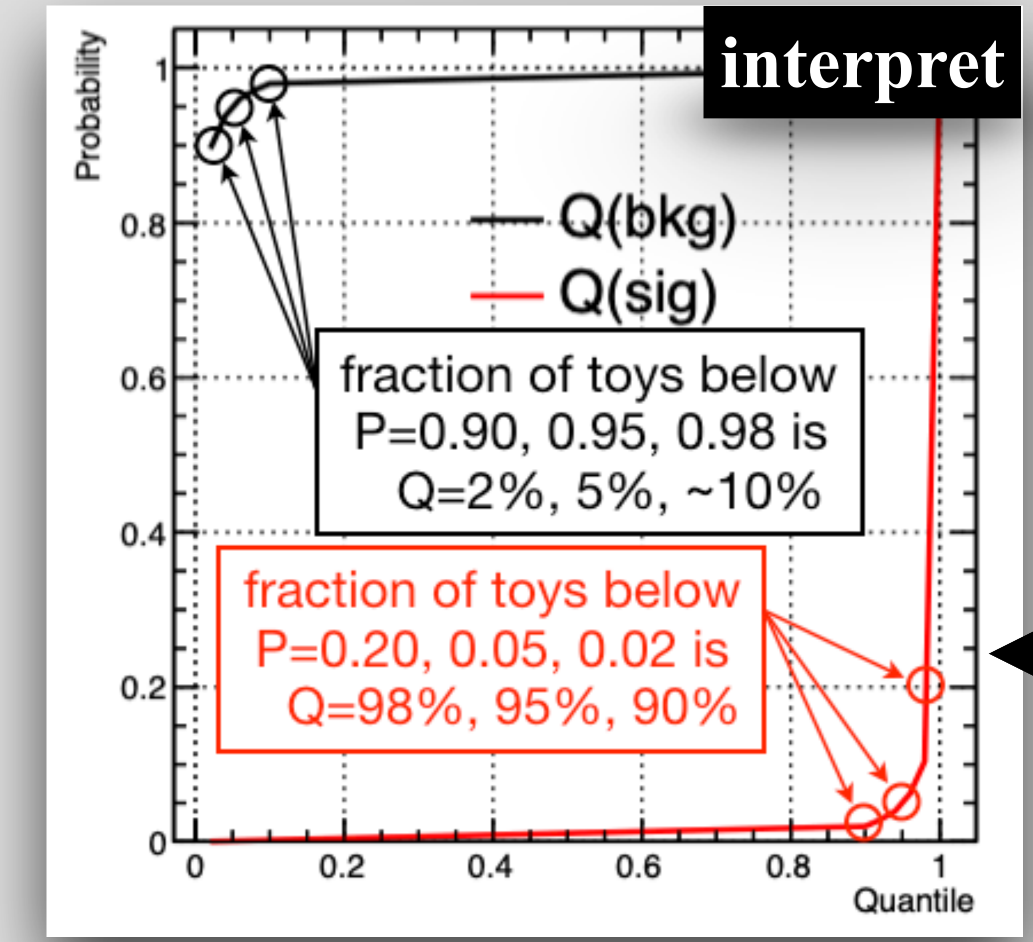


- this is std feedforward NN
- will move to auto-encoders



**predict**

P(sig)+P(bkg)=1
(symmetric around 0.5)



**interpret**

fraction of toys below
P=0.90, 0.95, 0.98 is
Q=2%, 5%, ~10%

fraction of toys below
P=0.20, 0.05, 0.02 is
Q=98%, 95%, 90%

**NN output used as test statistic**