LUXE: a new experiment to study non-perturbative QED and search for new particles in electron-laser and photon-laser collisions

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Particle Physics seminar
Université de Genève
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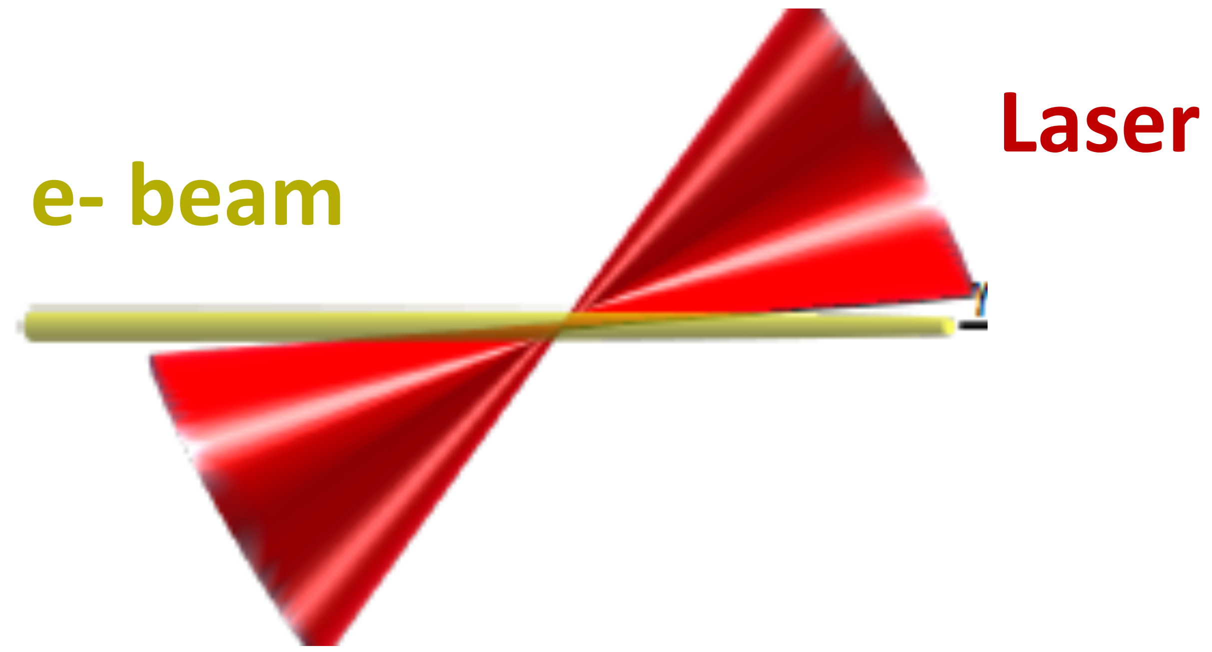
Many thanks to all LUXEies who contributed material, especially to Louis & Ruth!

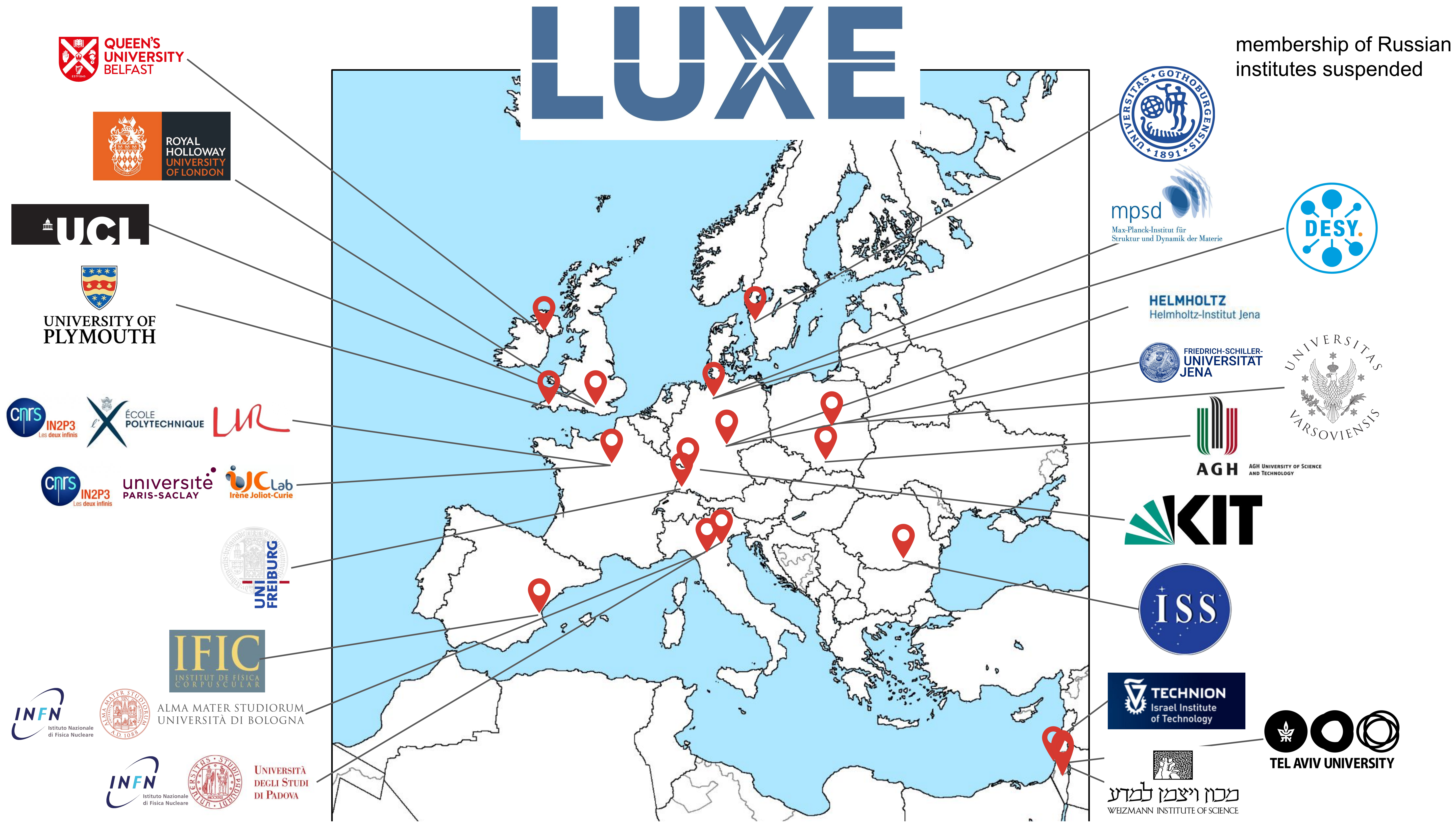
What is LUXE?

And what are we going to discuss today?

- **L**aser **U**nd **XFEL** **E**xperiment
  - New experiment planned in Hamburg using
    - European XFEL electrons accelerator
    - High-intensity laser
  - Synergy between accelerator, particle physics and laser physics



- Documents:
  - LOI (2019): arXiv:1909.00860
  - CDR (2021): EPJST: arXiv:2102.02032
  - TDR (2023): arXiv:2308.00515
- Collaboration size:
  - ~150 authors 22 institutes
  - Theory and Experiment
- Menu for today:
  - What is strong-field QED and why is it interesting?
  - What does LUXE add compared to previous SF-QED experiments?
  - What are the key technologies to obtain LUXE's measurement goals?



Strong-field QED: Theory & Experiments

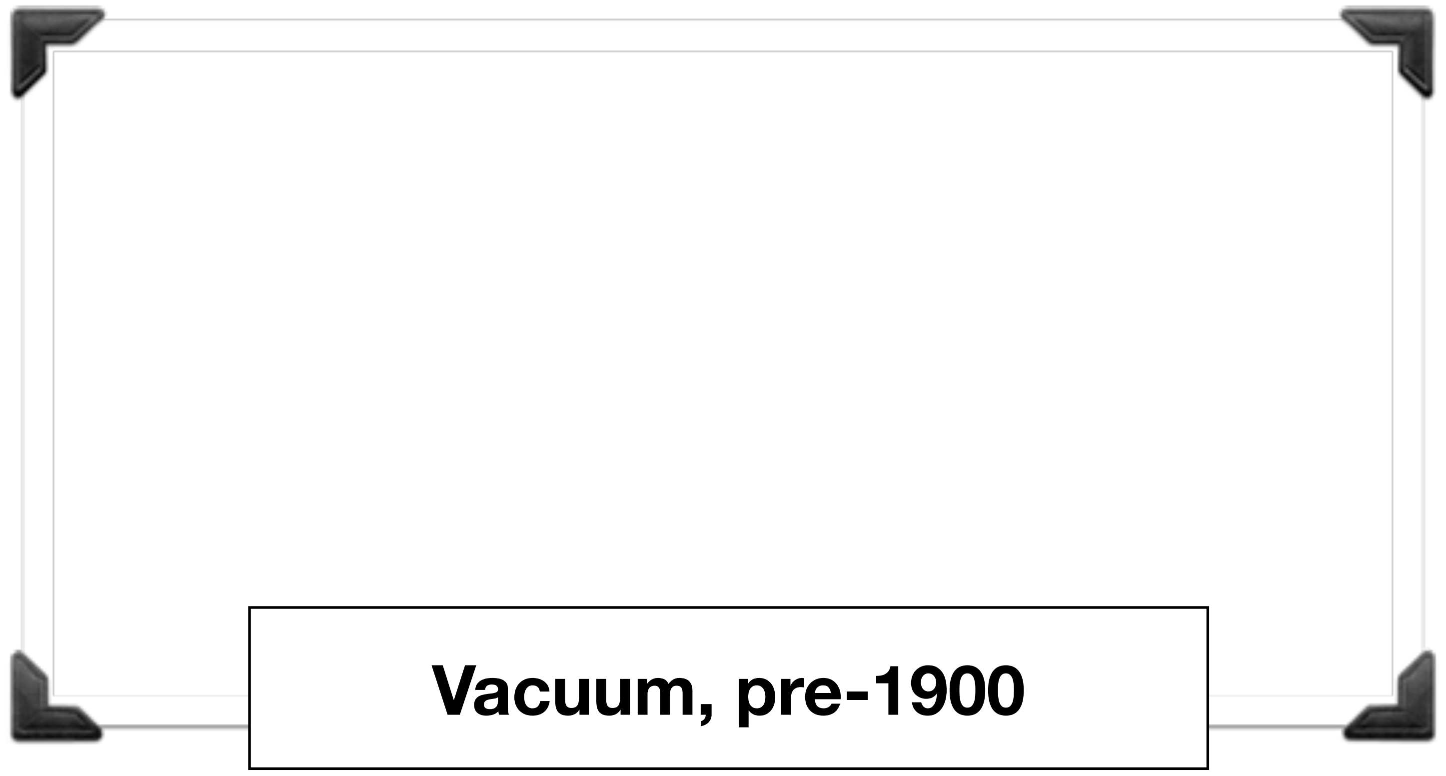
QED and Vacuum

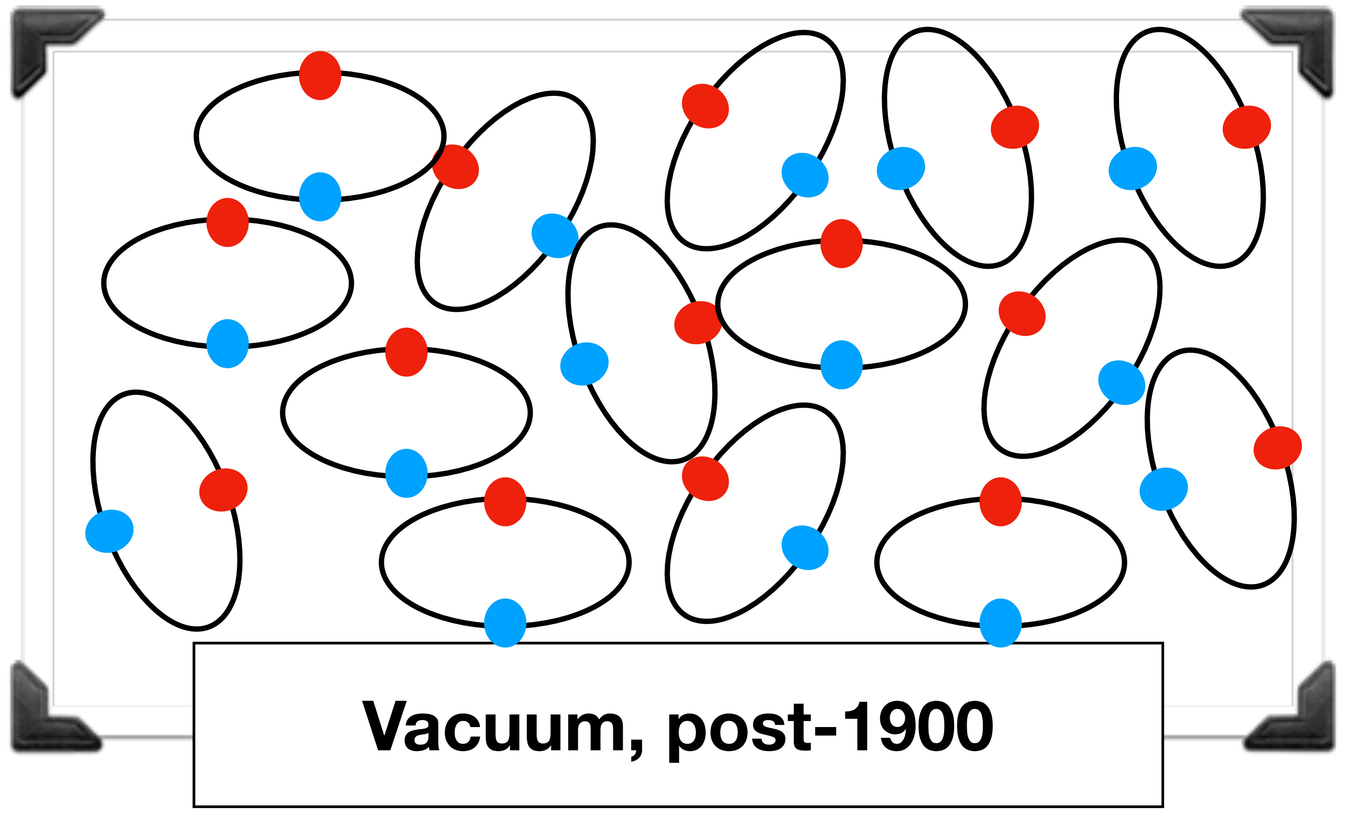
No or weak fields

Nobel prize 1965

- QuantumElectroDynamics: One of the most well-tested physics theory
  - Calculation in QED based on perturbative theory of α_{EM}.
  - Anomalous moment of electron (g-2) as a precision better than 1 part in a trillion and data in agreement with theory.

- The vacuum:
  - State with the lowest energy.
  - Vacuum consists of virtual particles that can be charged and couple to fields.
  - Quantum fields: average is zero (apart from the Higgs ;)), but variance is not!
  - Coupling to virtual particles affects physical particle processes

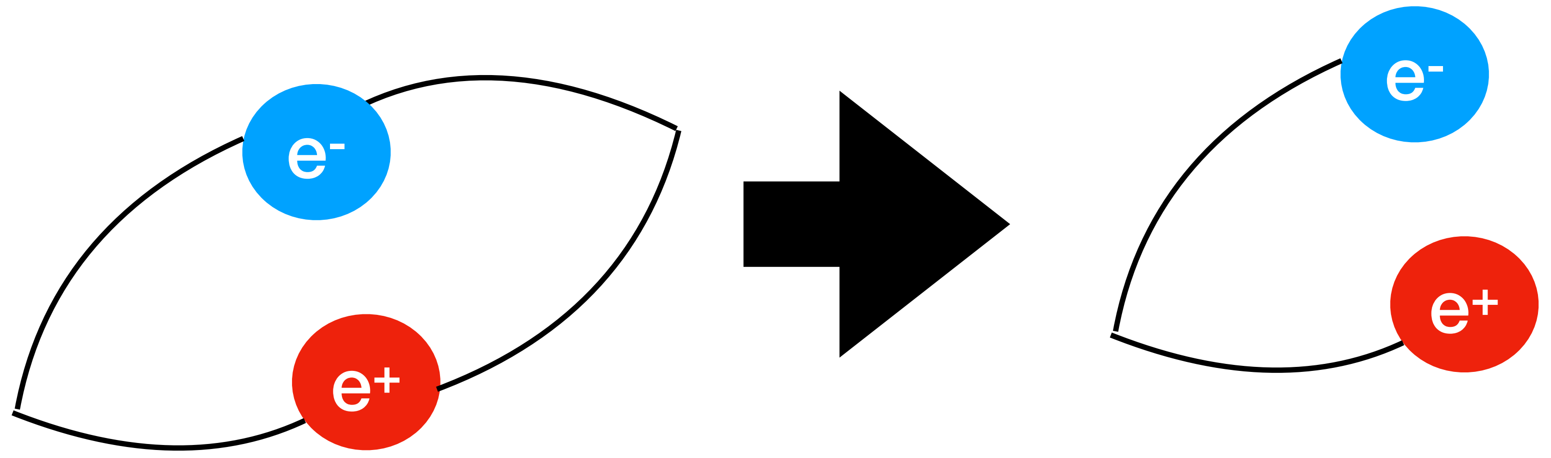




Strong-Field QED

When things get special

- If one apply a strong electromagnetic field on a vacuum:
  - $W_{field} < 2\ m_e$ $\qquad$ $W_{field} > 2m_e$



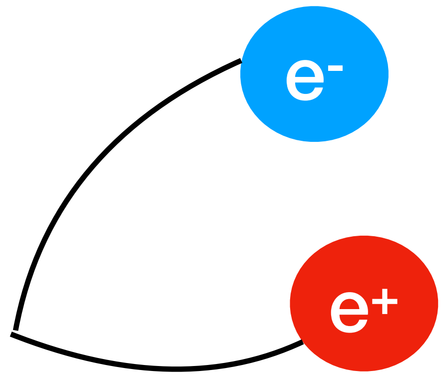
$$W_{field} = \frac{\varepsilon e}{m_e}$$

Euler and Heisenberg
Z.Phys. 98 (1936) no.11-12, 714-732 (translation at arXiv:physics/0605038

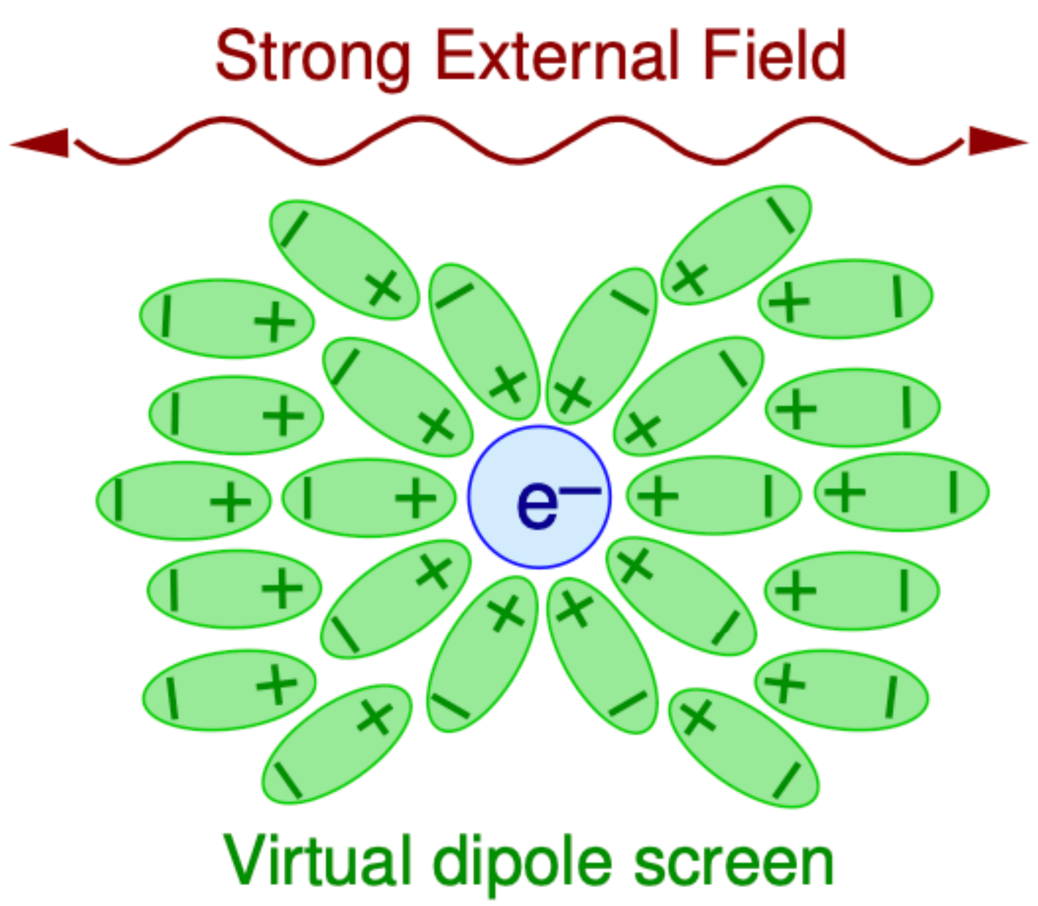
Schwinger
Phys. Rev. 82 (1951), 664

- Vacuum boils if field large enough to create real pairs:
  - "critical field" → Schwinger-Limit: $\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \mathrm{V/m}$
  - QED becomes non perturbative above Schwinger-limit → Strong field QED (SFQED)!

- Experimental consequences:
  - **Field-induced ("Breit-Wheeler") Pair Creation:**



  - **Modified Compton Spectrum:**
    - Effect on Compton edge position.
    - Electrons obtains (significantly) larger effective rest mass.

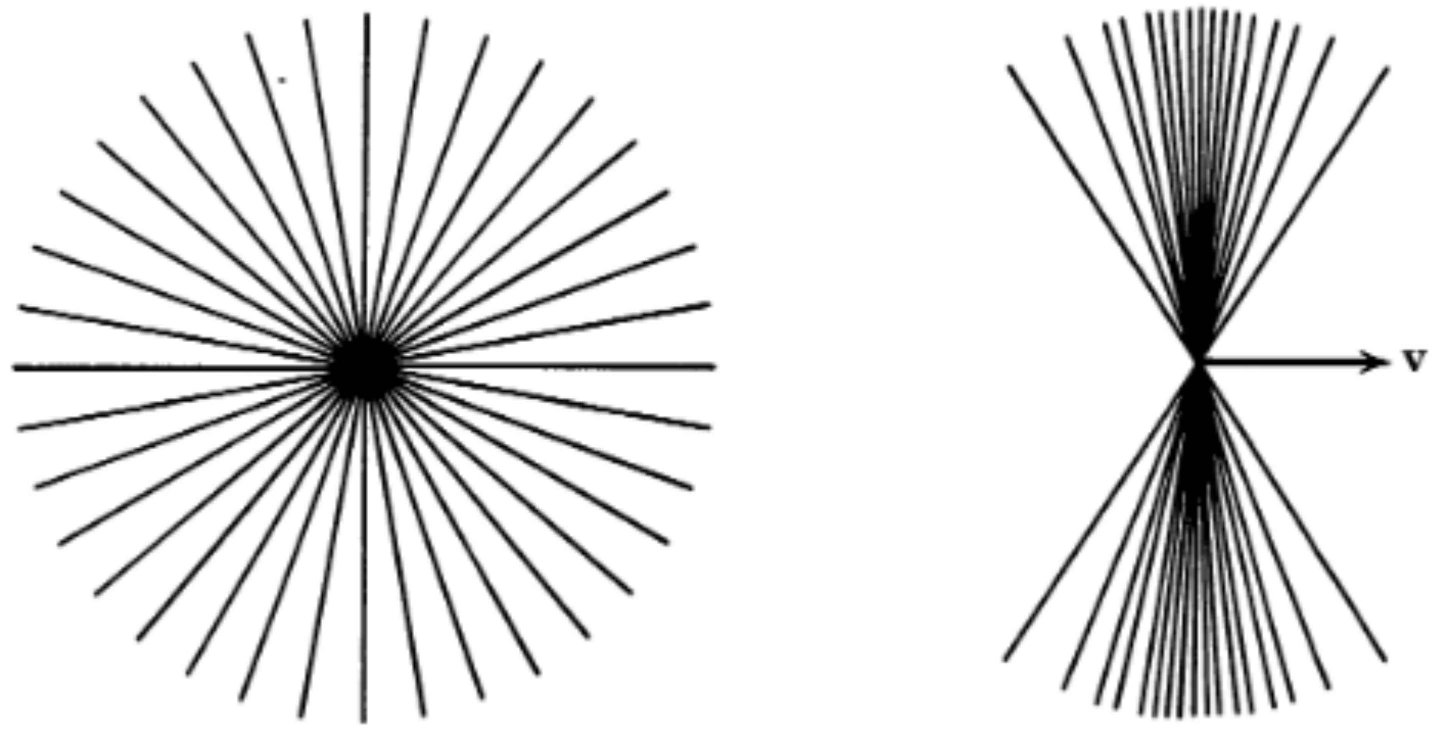


- Non-perturbative and strong field QED can be probed in laboratory at LUXE!

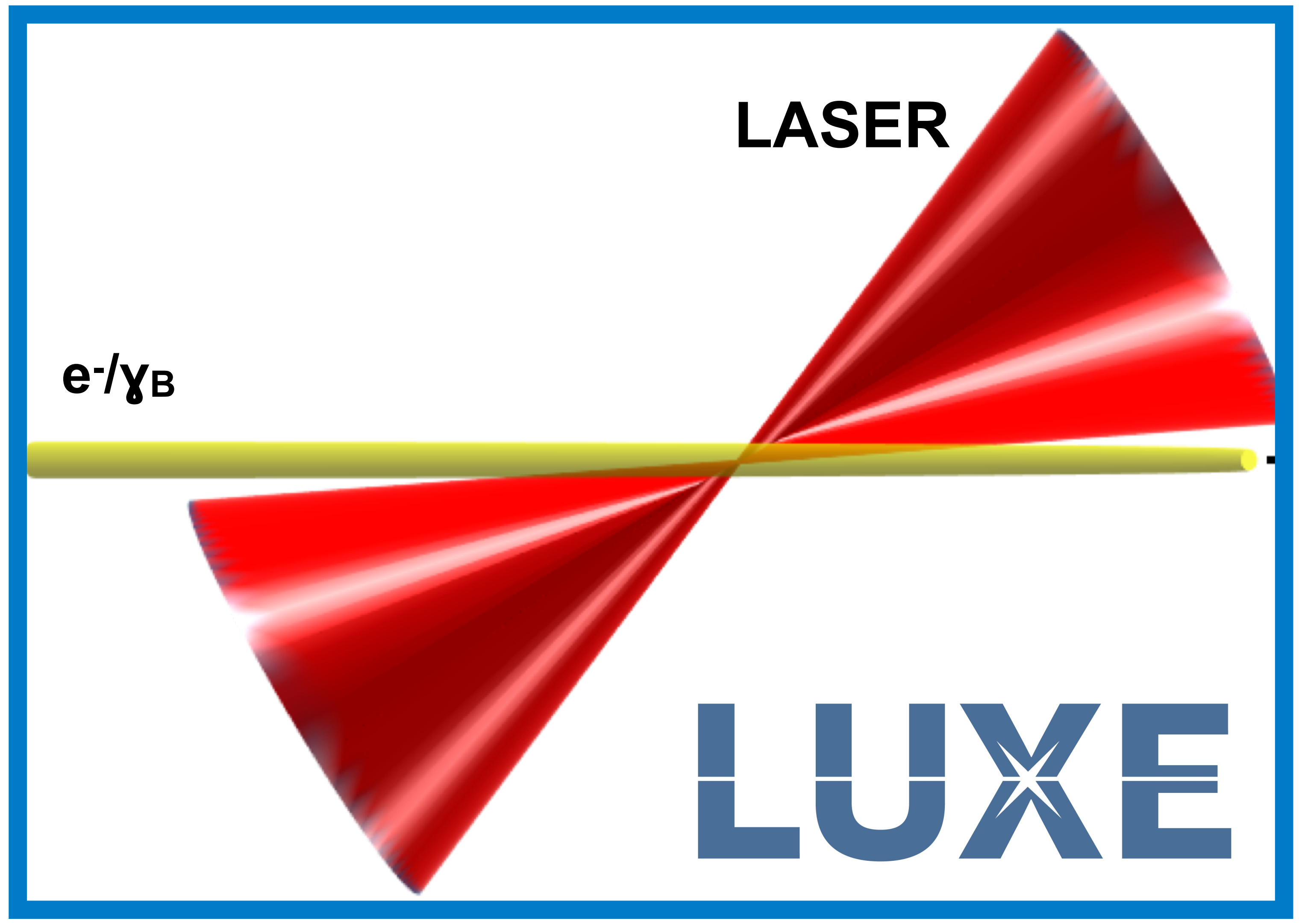
SFQED with relativistic probes

Advantage of a high-energy electron beam

- In the lab: reach fields at Schwinger limit in the rest frame of highly relativistic probe particles
  → LUXE: 16.5 GeV electrons + multi-TW optical LASER



J. D. Jackson, *Classical Electrodynamics* 3rd. Edition

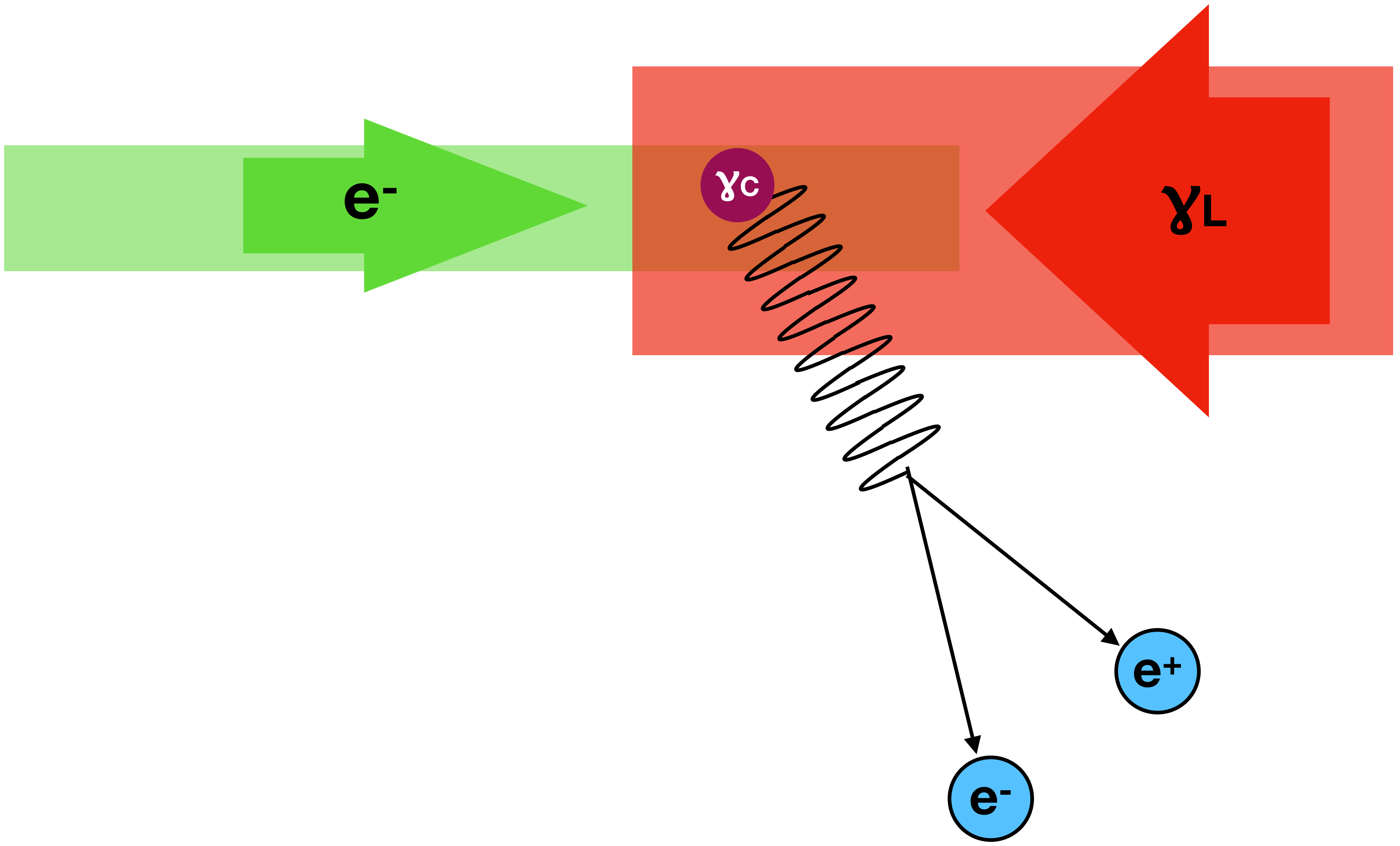


$$\mathscr{E}_{rest\ fr.} = \gamma \mathscr{E}_{lab\ fr.}$$

- Important consequence of having a relativistic probe:
  → any field background can be approximated as a plane wave

Electron-Laser Collisions

The LUXE operation modes



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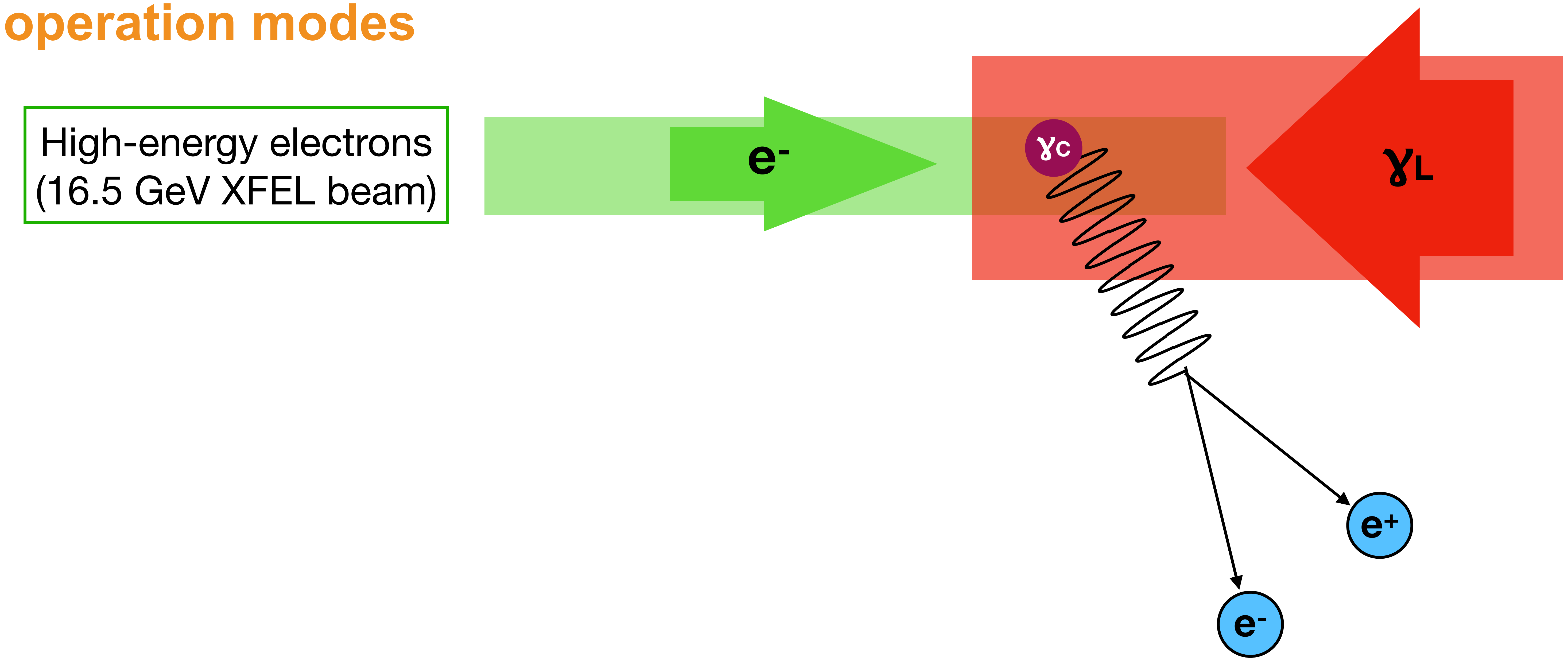

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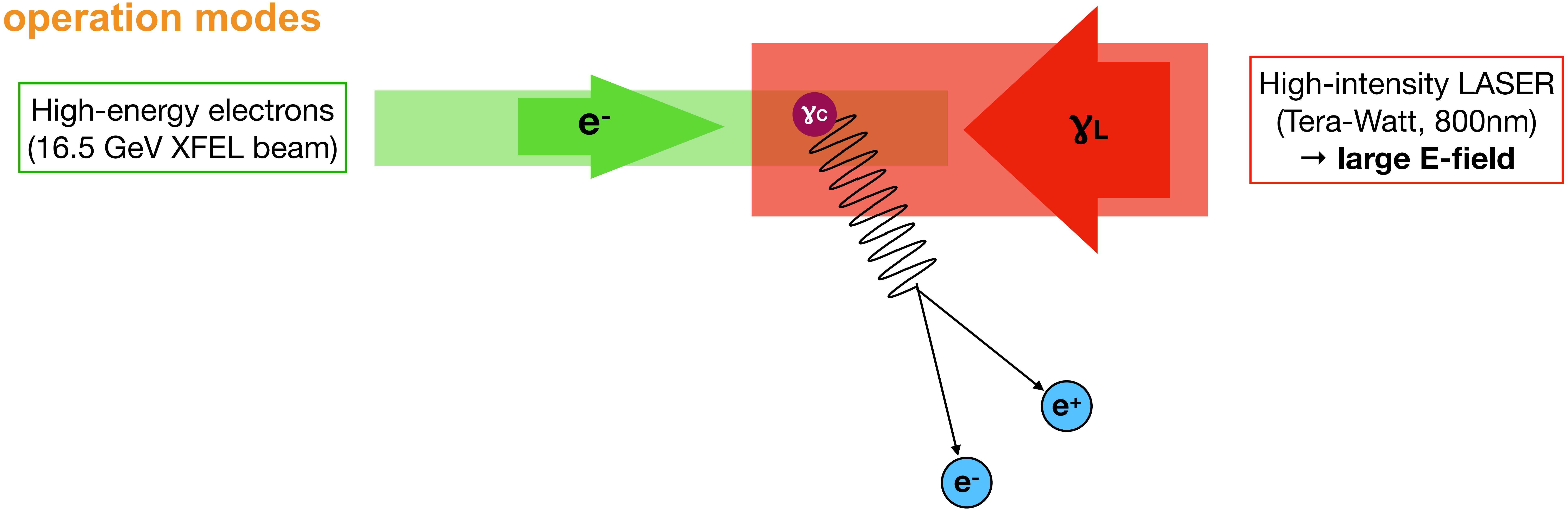

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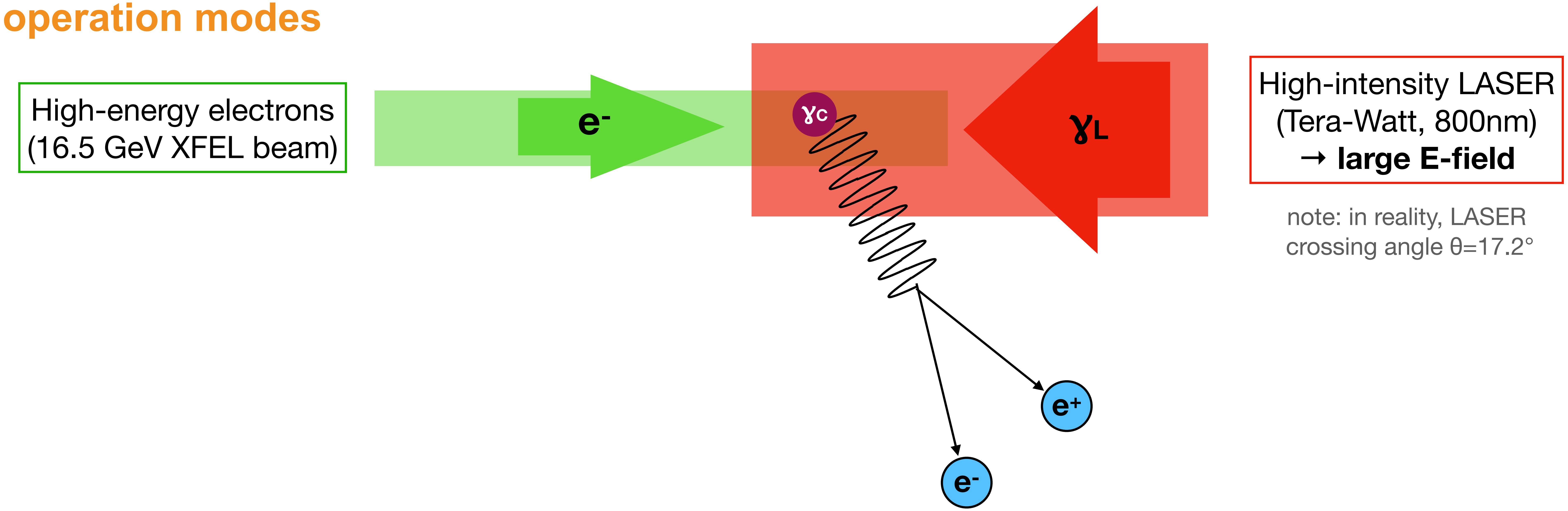
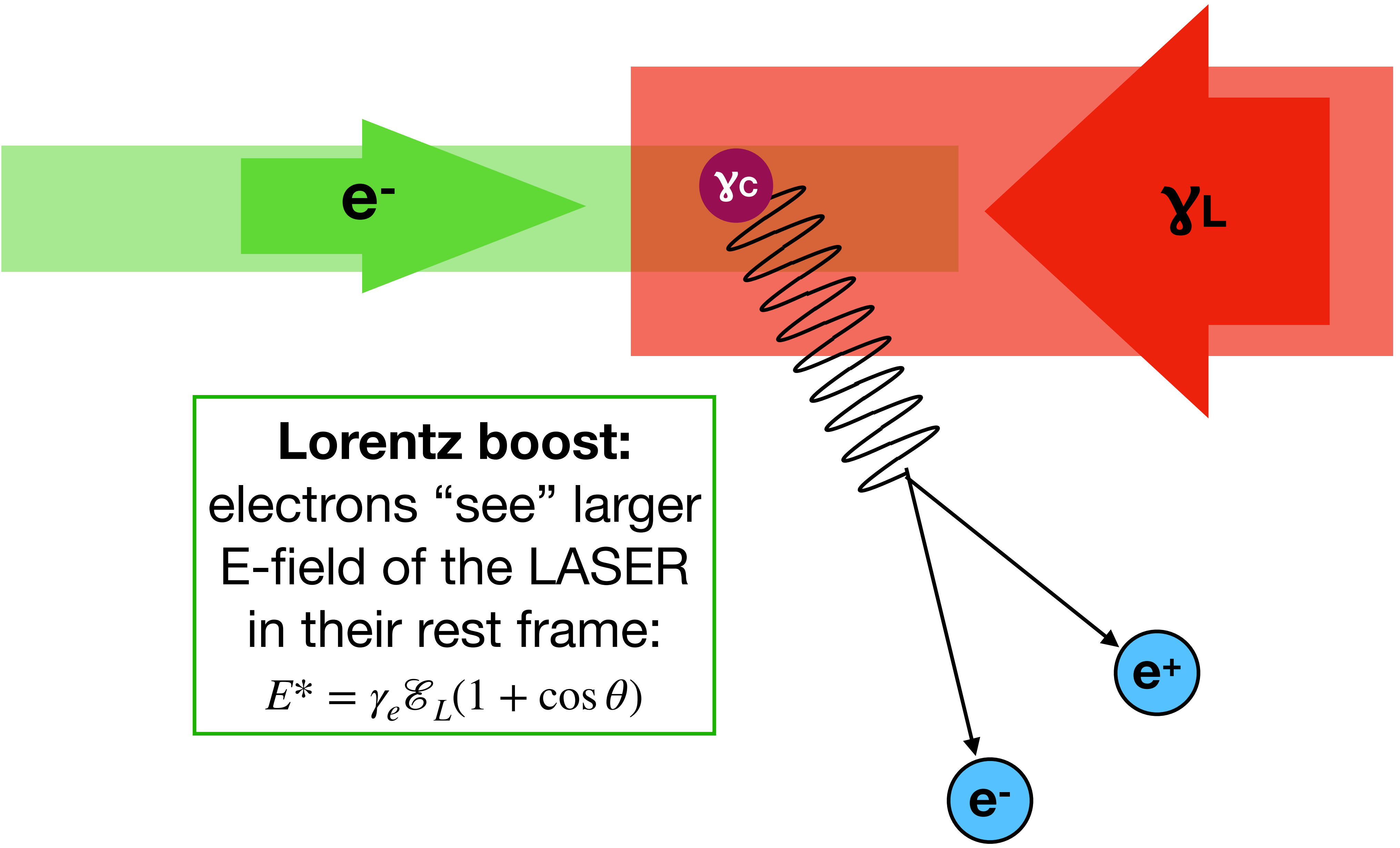


Electron-Laser Collisions

The LUXE operation modes

High-energy electrons
(16.5 GeV XFEL beam)



High-intensity LASER
(Tera-Watt, 800nm)
→ **large E-field**

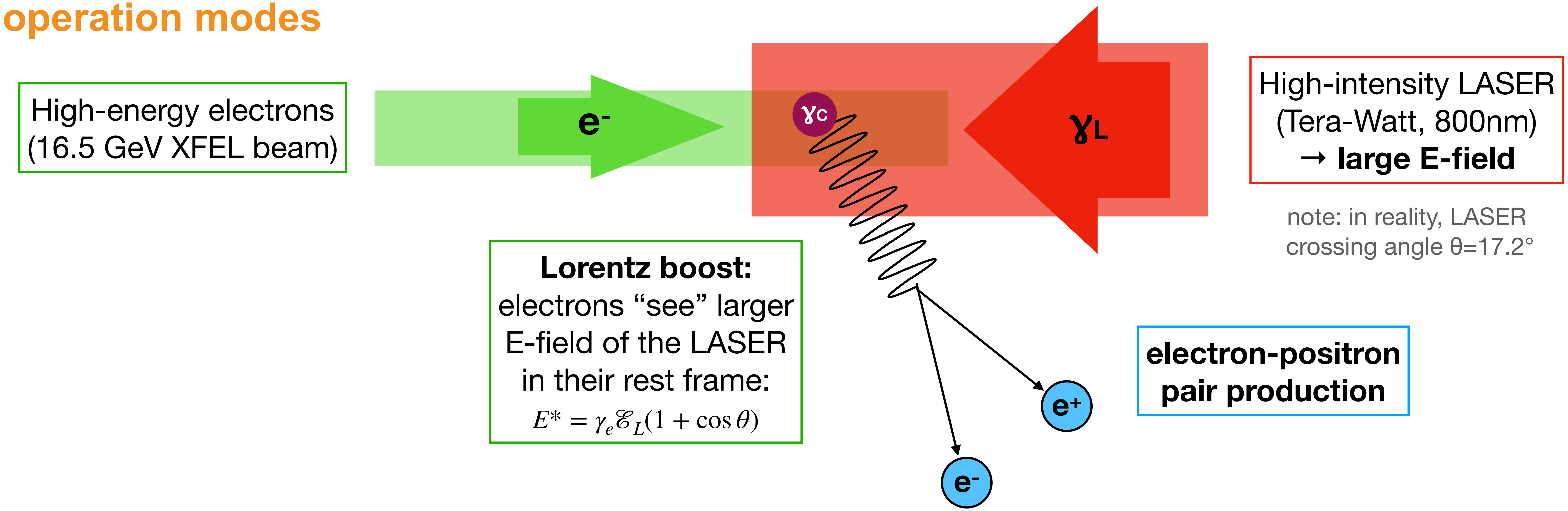
note: in reality, LASER crossing angle θ=17.2°

Lorentz boost:
electrons "see" larger E-field of the LASER in their rest frame:

$E^* = \gamma_e \mathcal{E}_L (1 + \cos\theta)$

Electron-Laser Collisions

The LUXE operation modes



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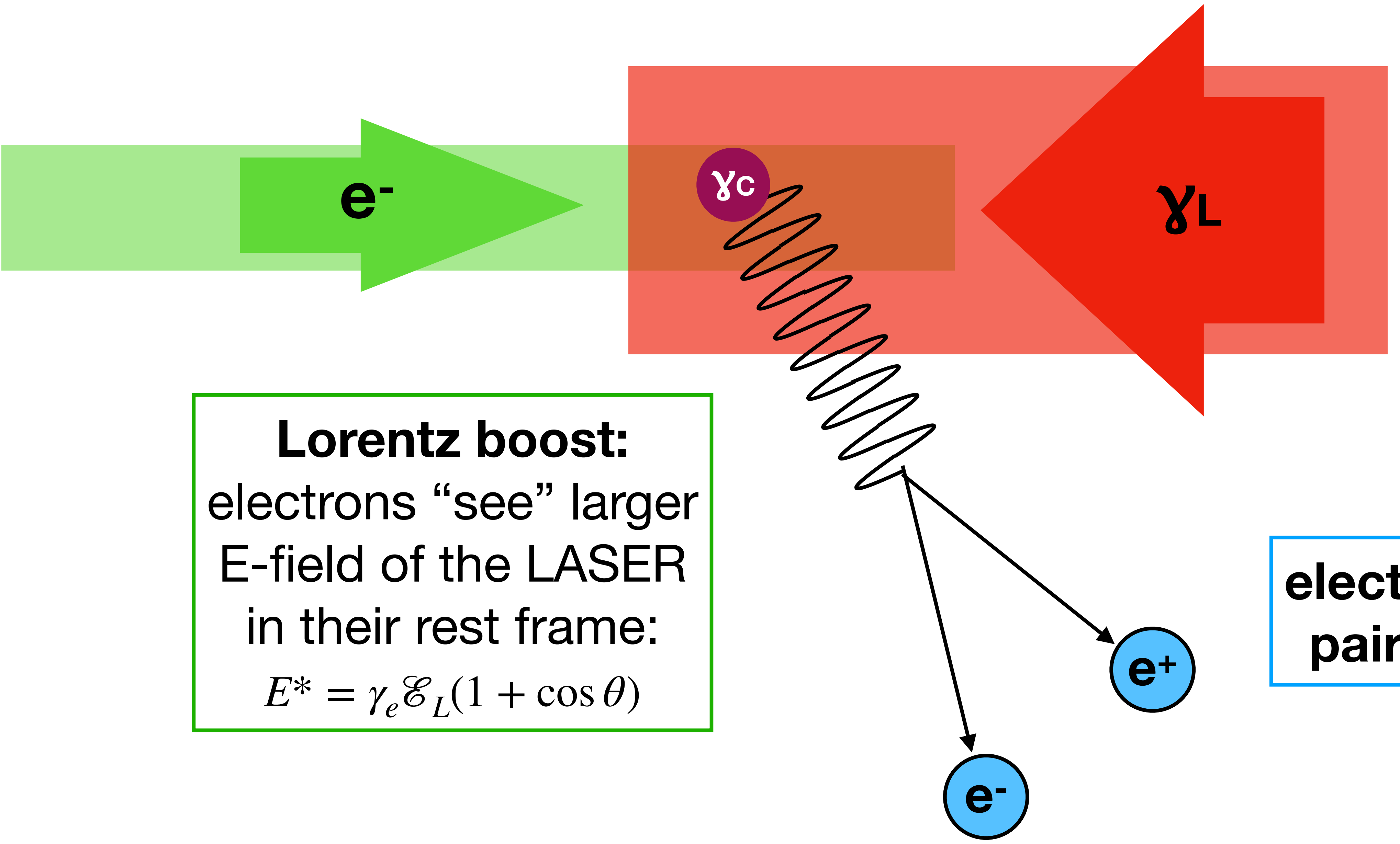

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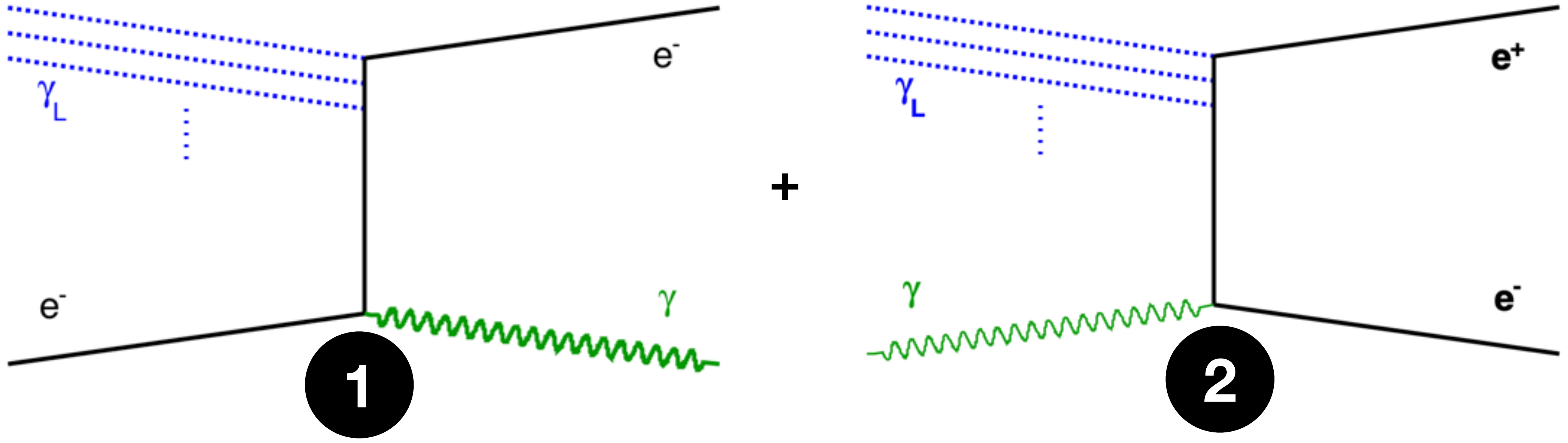
electron-positron pair production



Physics processes:

1 **Non-linear Compton Scattering:** $e^- + n\gamma_L \rightarrow e^- + \gamma_C$

2 **Non-linear Breit-Wheeler pair production :** $\gamma_C + n\gamma_L \rightarrow e^+ + e^-$

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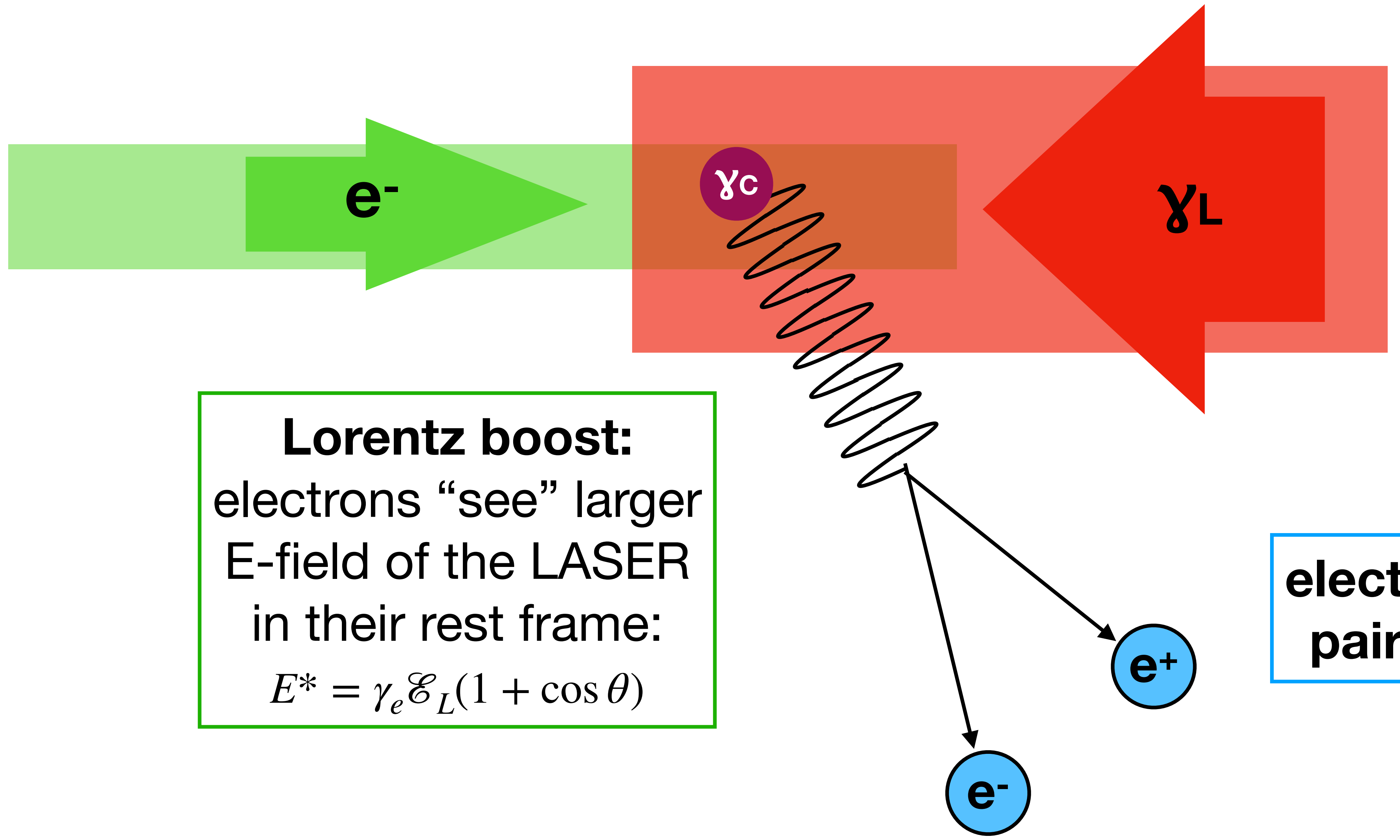

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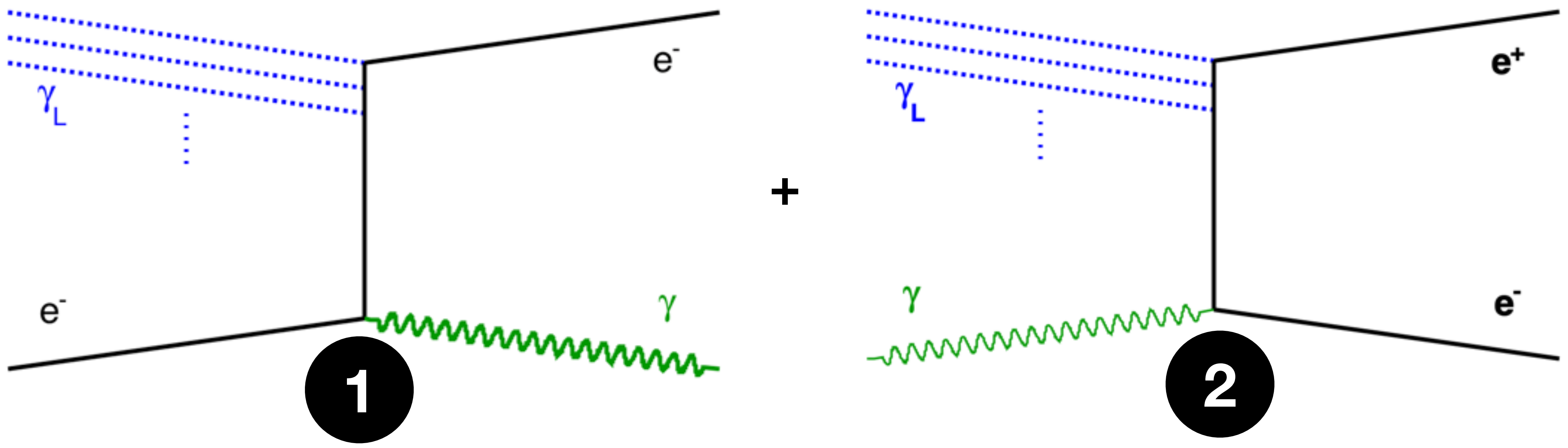

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Measure positron rate as function of LASER intensity

Electron-Laser Collisions

The LUXE operation modes

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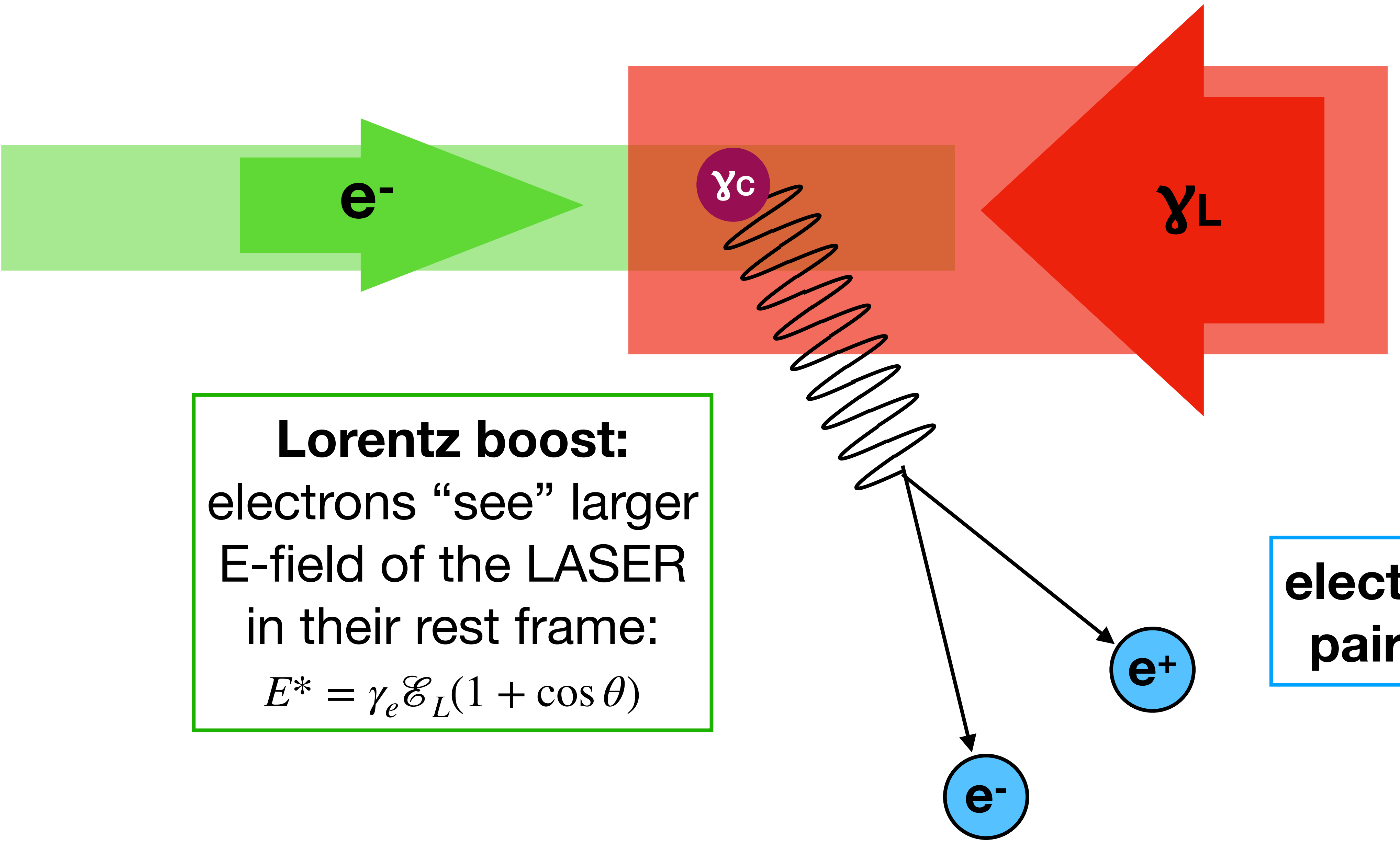

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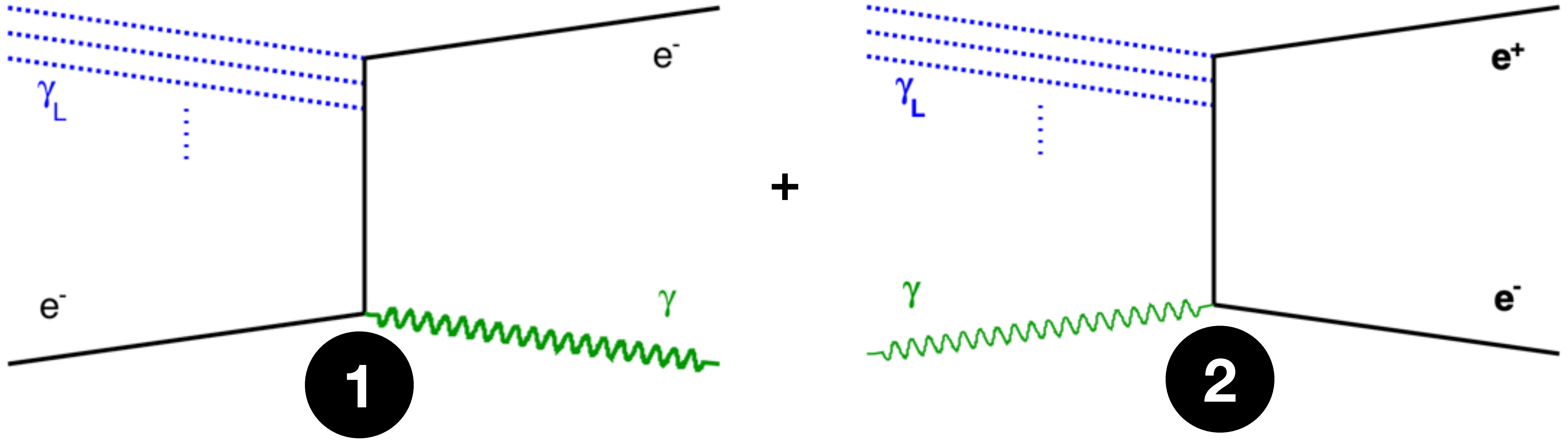

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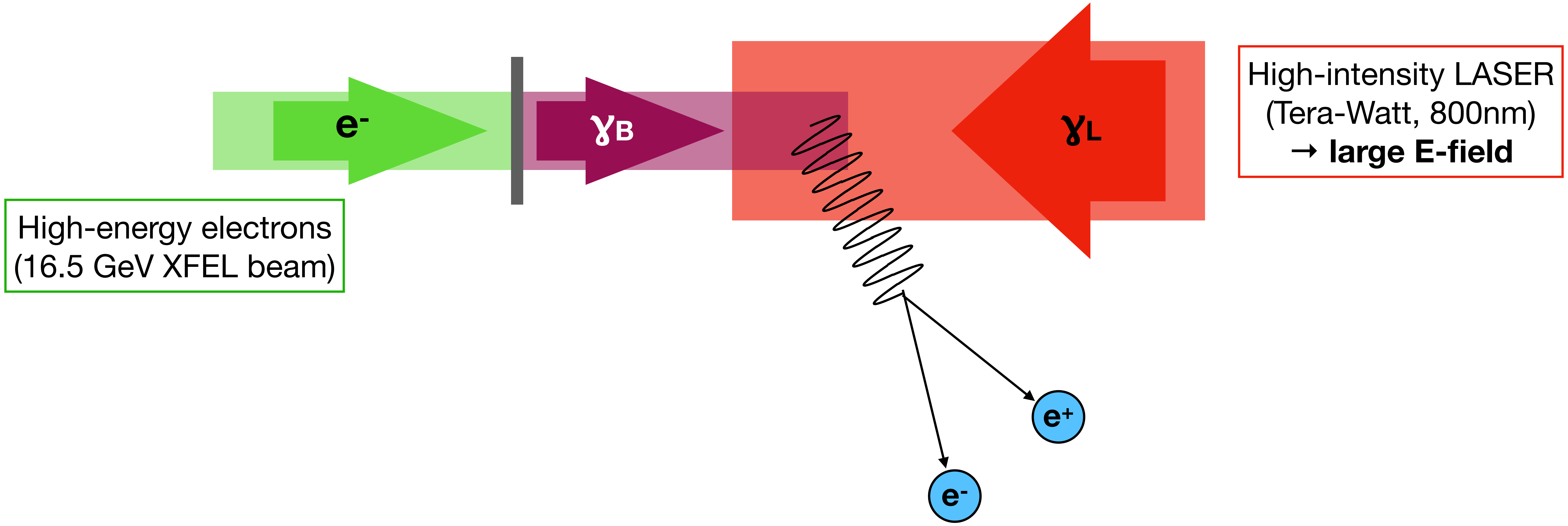
Measure Compton edge position as function of LASER intensity

Measure positron rate as function of LASER intensity

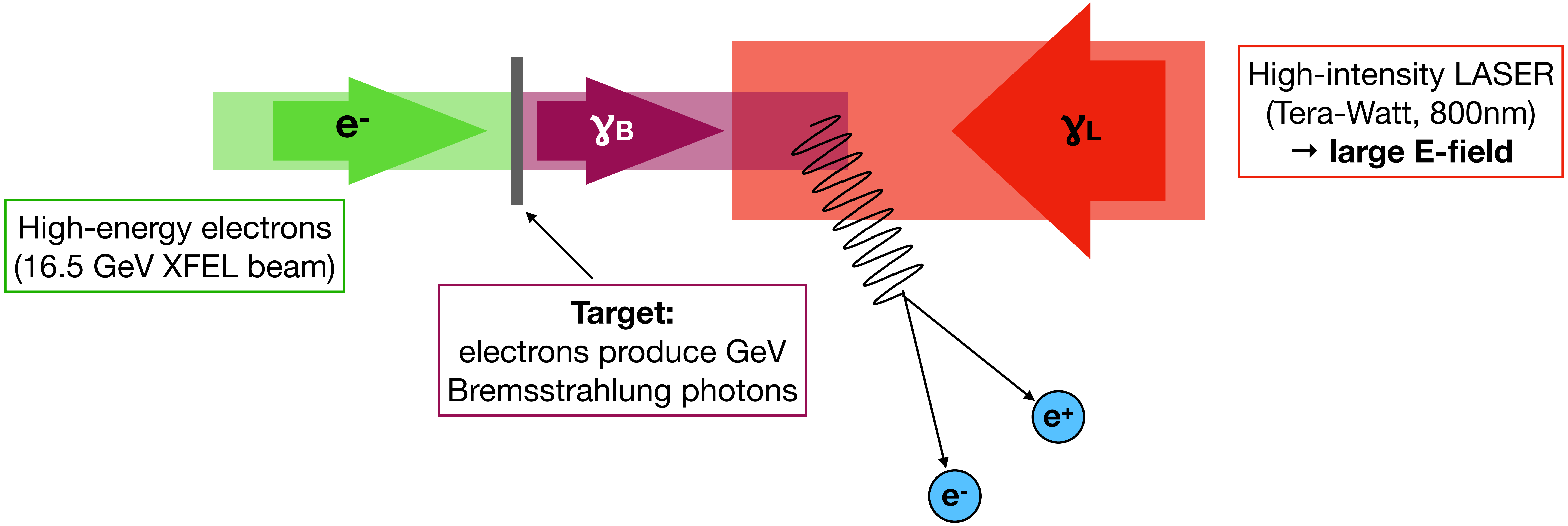
Gamma-Laser Collisions

The LUXE operation modes



Gamma-Laser Collisions

The LUXE operation modes



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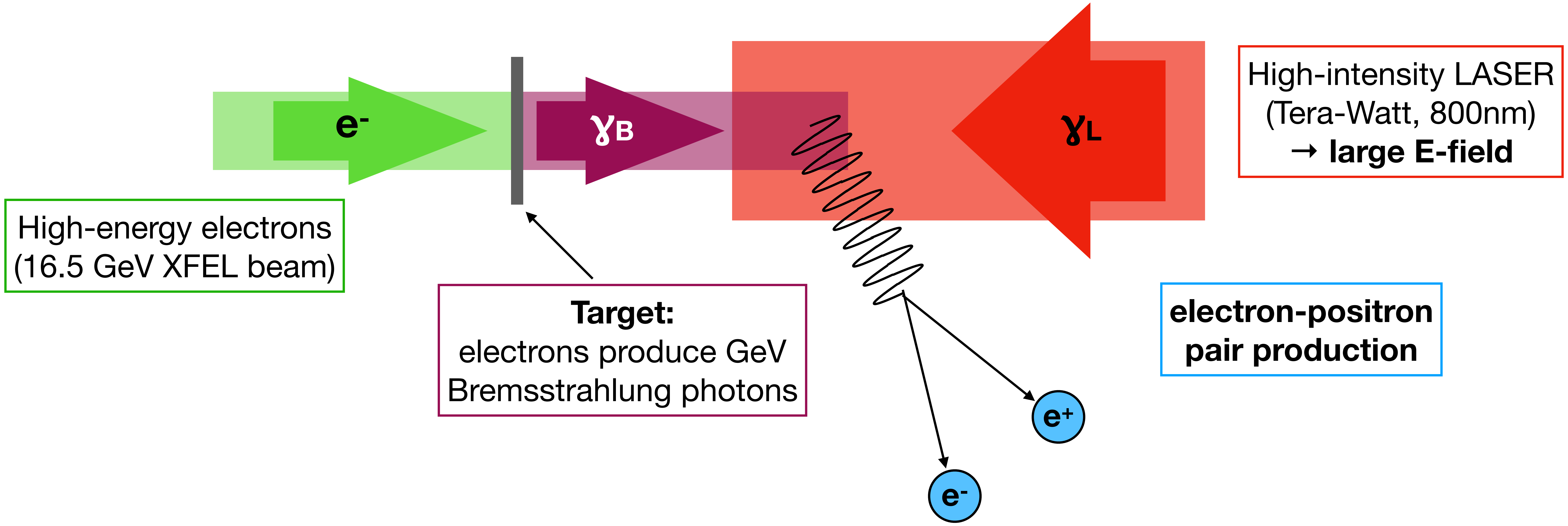
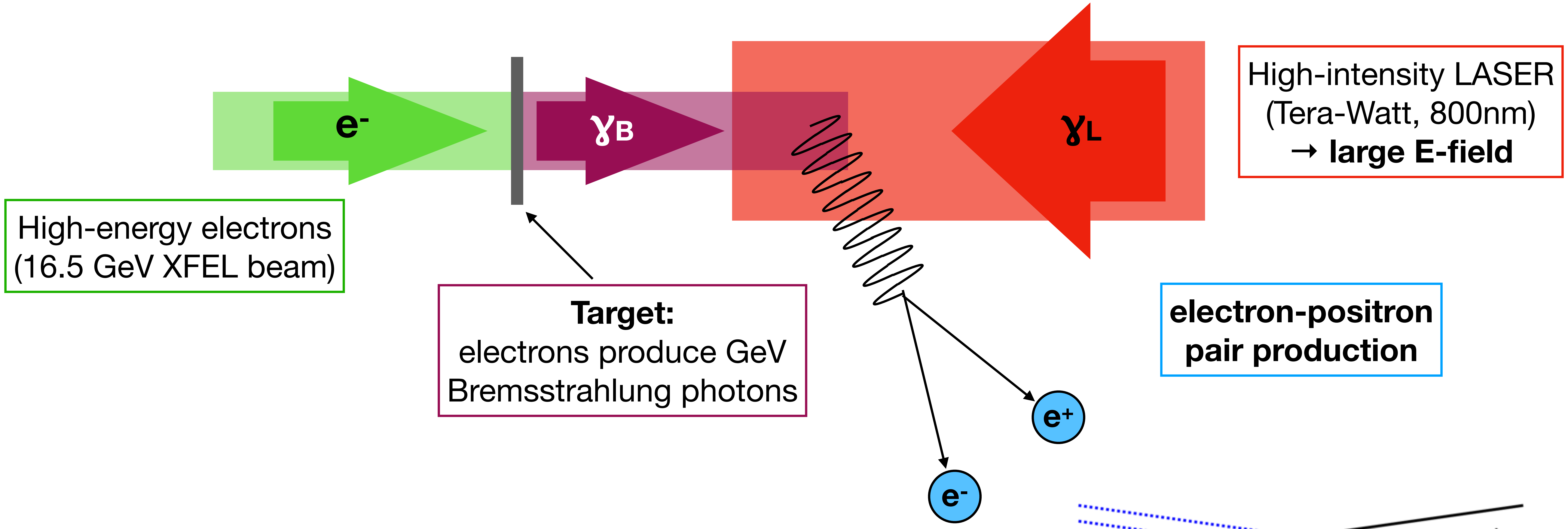
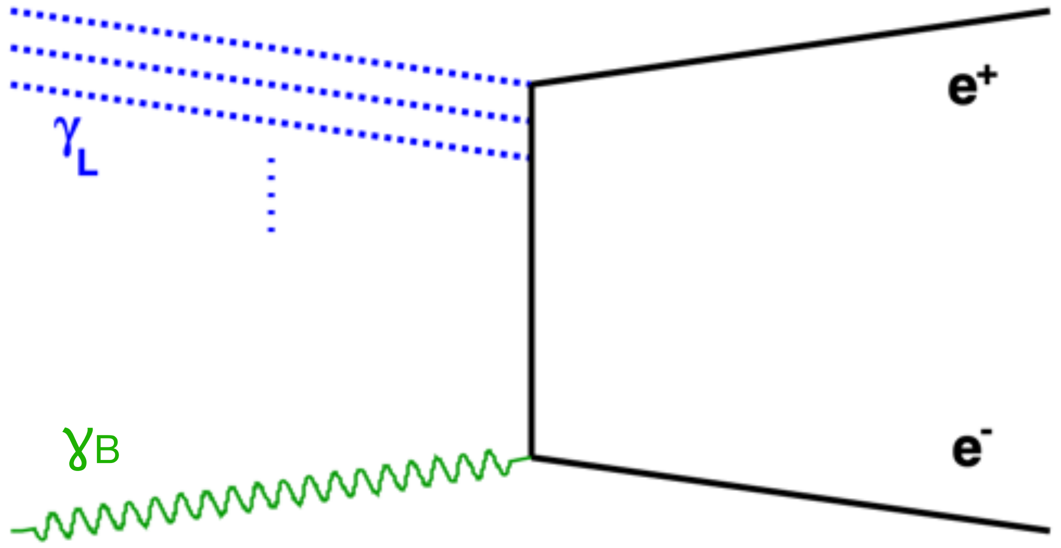


Unique
in LUXE!

Gamma-Laser Collisions

The LUXE operation modes





Physics process:

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Non-linear Breit-Wheeler pair production : $\gamma_B + n\gamma_L \rightarrow e^+ + e^-$

Gamma-Laser Collisions

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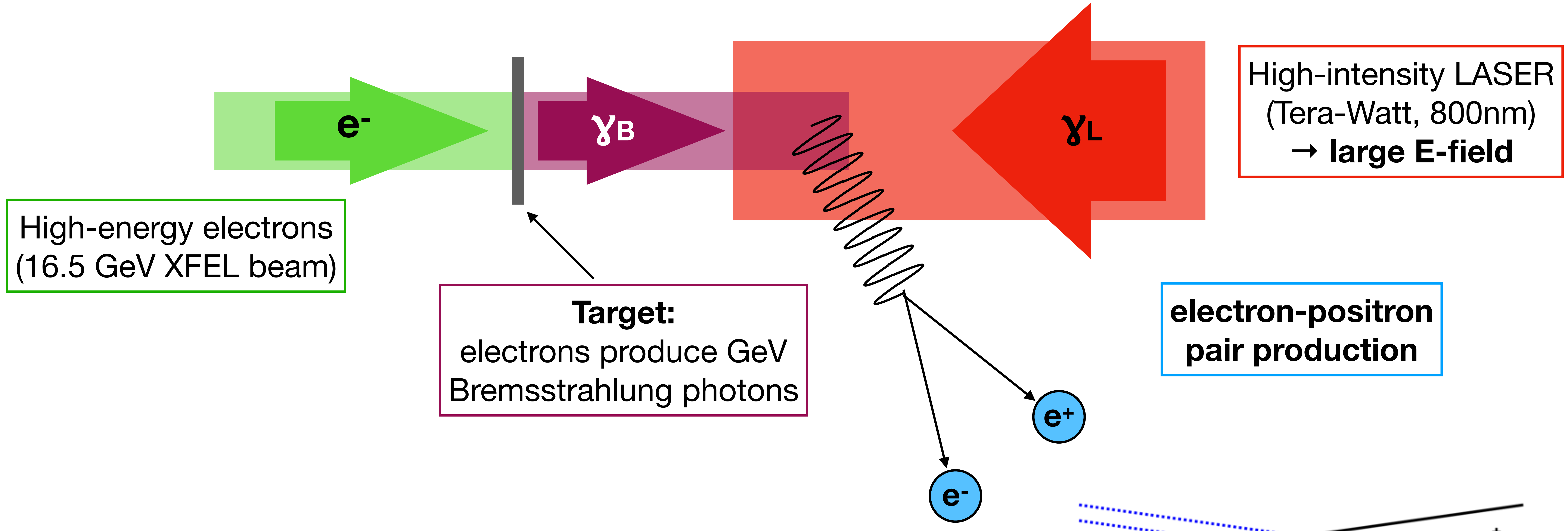
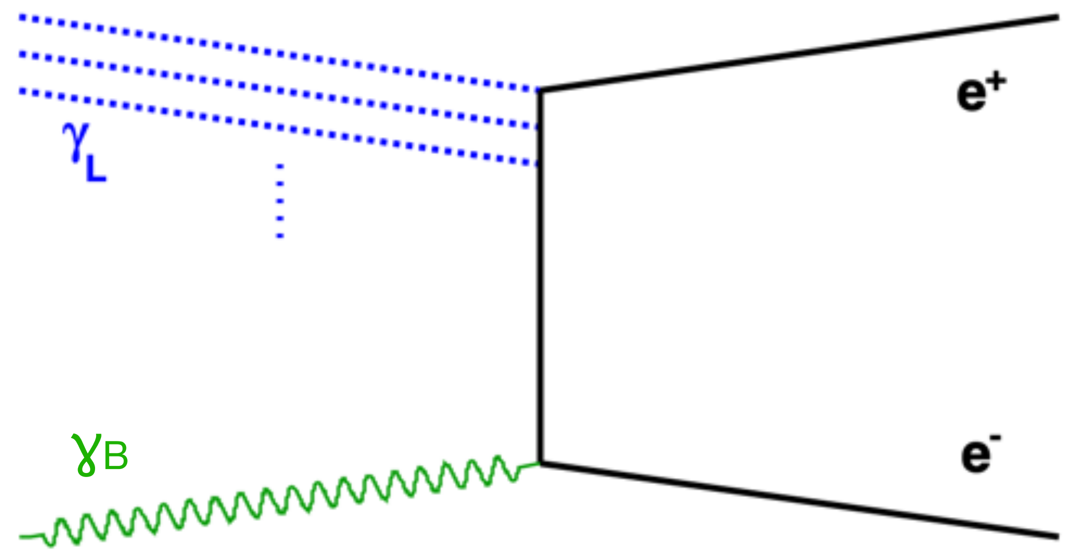




Physics process:

Non-linear Breit-Wheeler pair production : $\gamma_B + n\gamma_L \rightarrow e^+ + e^-$

LUXE: first SF-QED experiment to probe directly photon-photon interaction

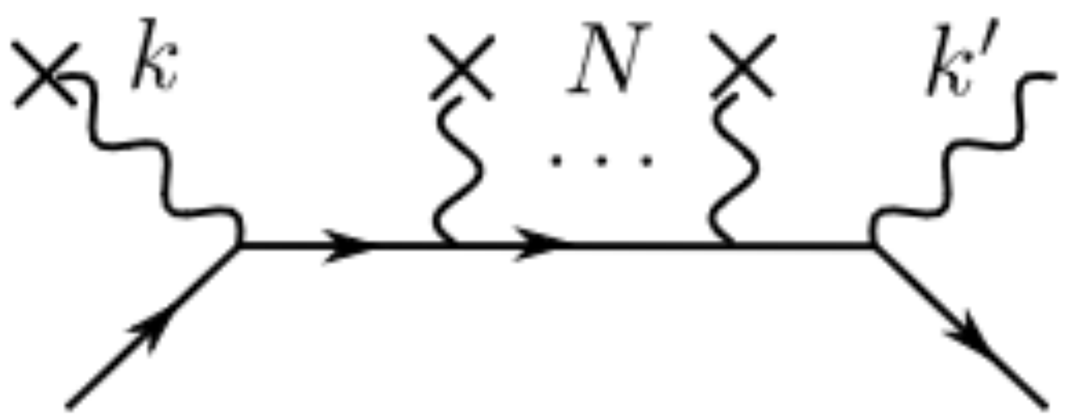
Unique in LUXE!

[Link](#) to QU lecture by Ben King
Review paper: A. Fedotov et al, 2203.00019 [arXiv:hep-ph]

Compton scattering in strong fields

Multi-photon interactions

- Consider Compton scattering in plane-wave background field: $A(x) = A_0 \sin(k \bullet x)$



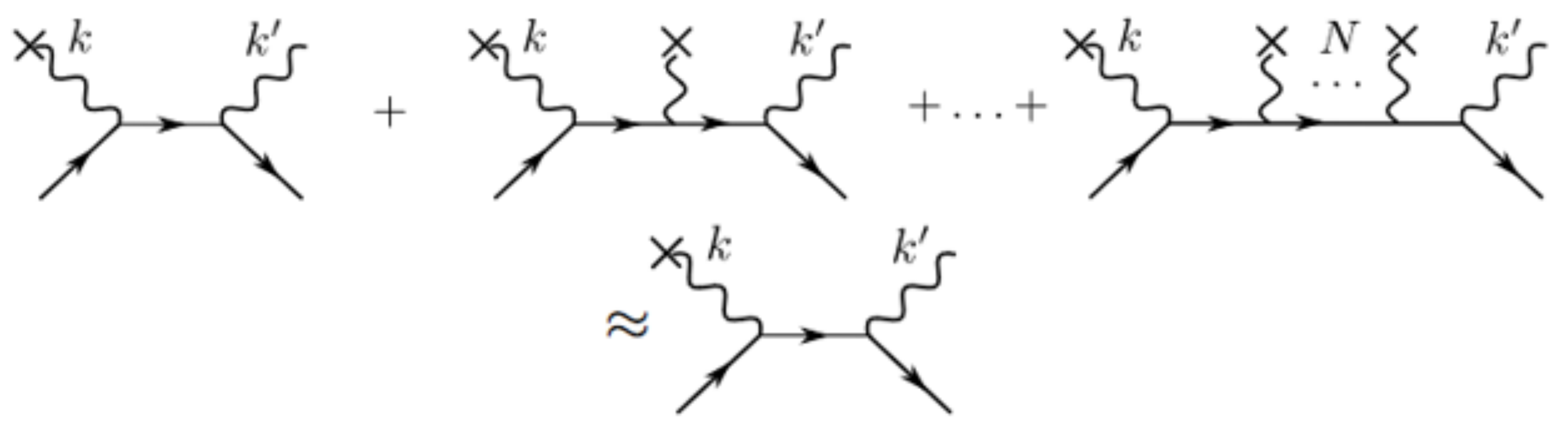
$+$ exchange diagram

fine structure constant

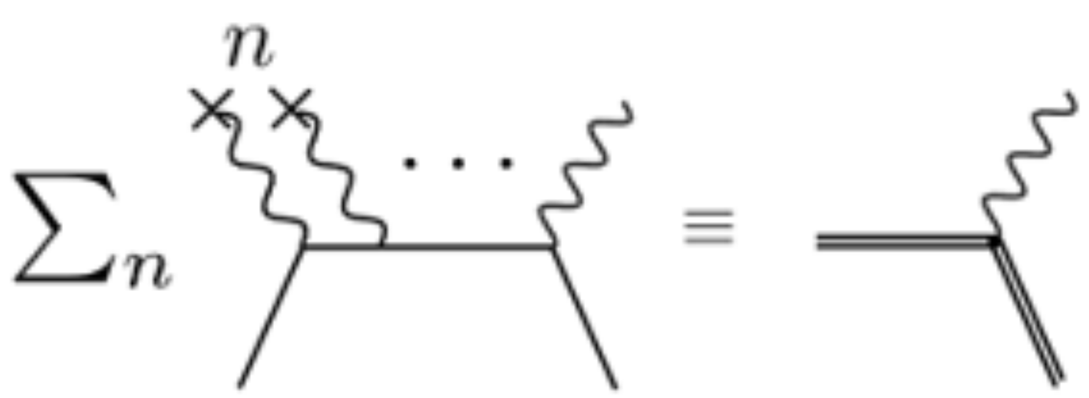
Probability $\mathrm{P} \sim \alpha \left(\frac{eA_0}{m}\right)^{2N} = \alpha \xi^{2N}$

$$\boxed{\xi = \frac{eA_0}{m}}$$

'Classical nonlinearity / intensity parameter', ξ.



"weak" field $\xi < 1$



'Nonlinear' Compton scattering

strong field: $\xi \geq 1$

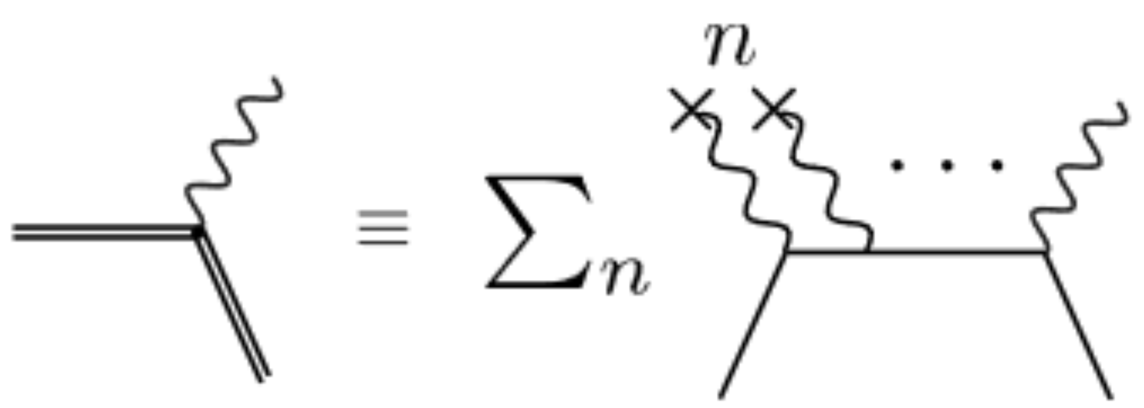
Strong field ($\xi \geq 1$): Need to take into account all order diagrams!

The Furry picture

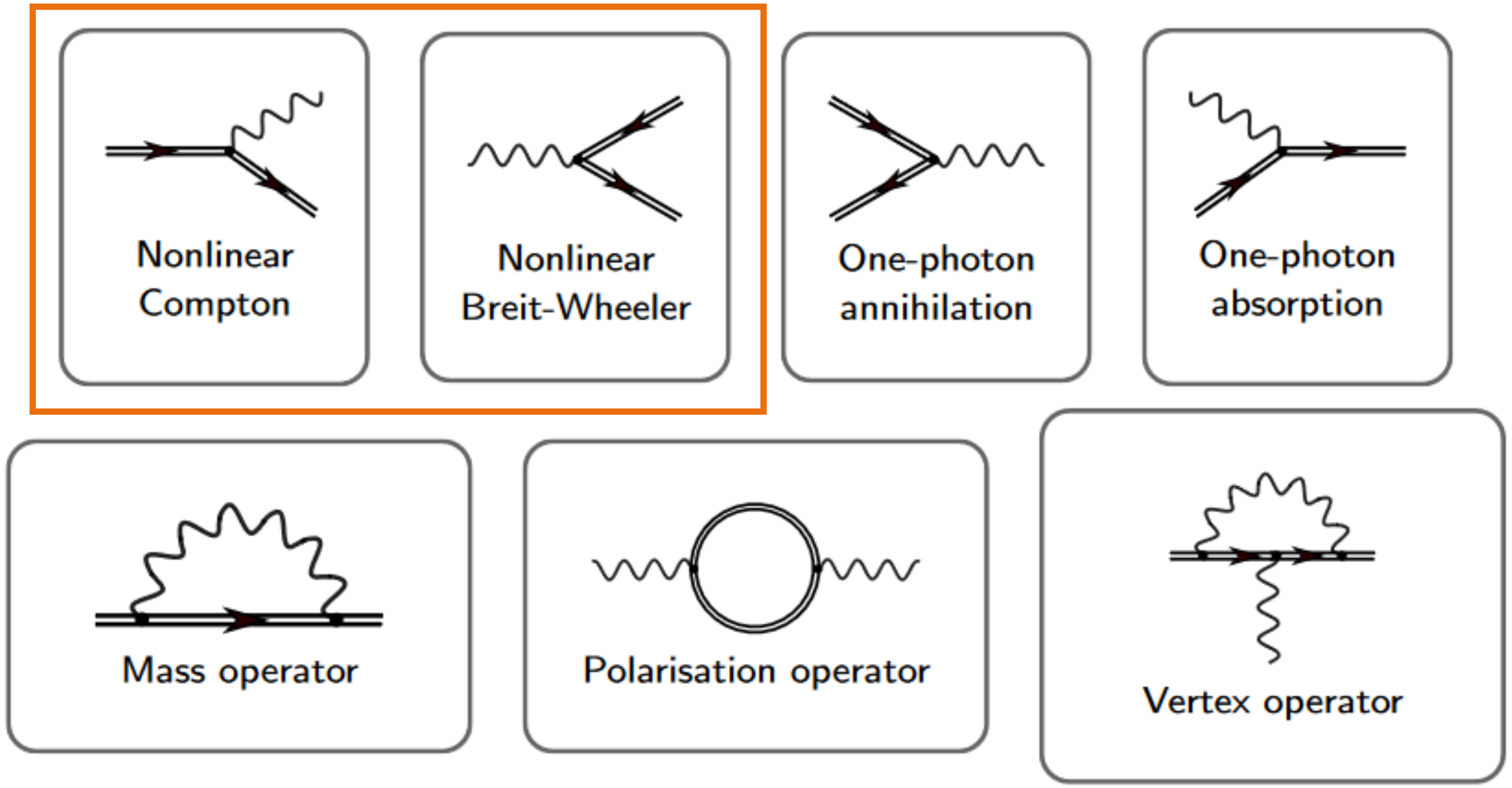
How to do calculations?

- Solve equations of motion (Dirac equation) in field background
  → analytical solutions exist in plane wave background („Volkov wave functions“)
- derive Feynman rules for „dressed“ states („Furry expansion“)
  → treat background exactly, particle scattering perturbatively ($\alpha \ll 1$)

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\left(i\not{D} - m\right)\psi}_{\text{'unperturbed'}} \quad \underbrace{-e\bar{\psi}\not{A}\psi}_{\text{interaction}},$$



„dressed“ state



SFQED parameters

some definitions

Intensity parameter:

$$\xi = \sqrt{4\pi\alpha}\left(\frac{\mathcal{E}_L}{\omega_L m_e}\right) = \frac{m_e \mathcal{E}_L}{\omega_L \mathcal{E}_{cr}}$$

- work done by background field over a Compton wavelength of the electron in units of the background field's photon energy
- measure of coupling between probe and background (laser) field
(also: square root of laser intensity)
- $\xi \geq 1$: non-perturbative regime

Note:

$\mathcal{E}_L$: Laser field
$\mathcal{E}_{cr}$: Schwinger critical field

θ: Laser - probe crossing angle

ω_L: Laser frequency

$E_{e/\gamma}$: probe electron (photon) energy

Quantum parameters:

$$\chi_e = (1+\cos\theta)\frac{E_e}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

$$\chi_\gamma = (1+\cos\theta)\frac{E_\gamma}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

- ratio of background laser field and Schwinger critical field
- $\chi \geq 1$: non-linear quantum effects become probable
(e.g. pair production)

e+e- colliders:
$\chi_e = \Upsilon$ "beamstrahlung parameter"

$$\Upsilon = \frac{2}{3}\frac{\langle E_c\rangle}{E_{\mathrm{beam}}} = \frac{5 r_e^2 \gamma N_e}{6\alpha_e \sigma_z(\sigma_x^* + \sigma_y^*)}$$

Energy Parameter

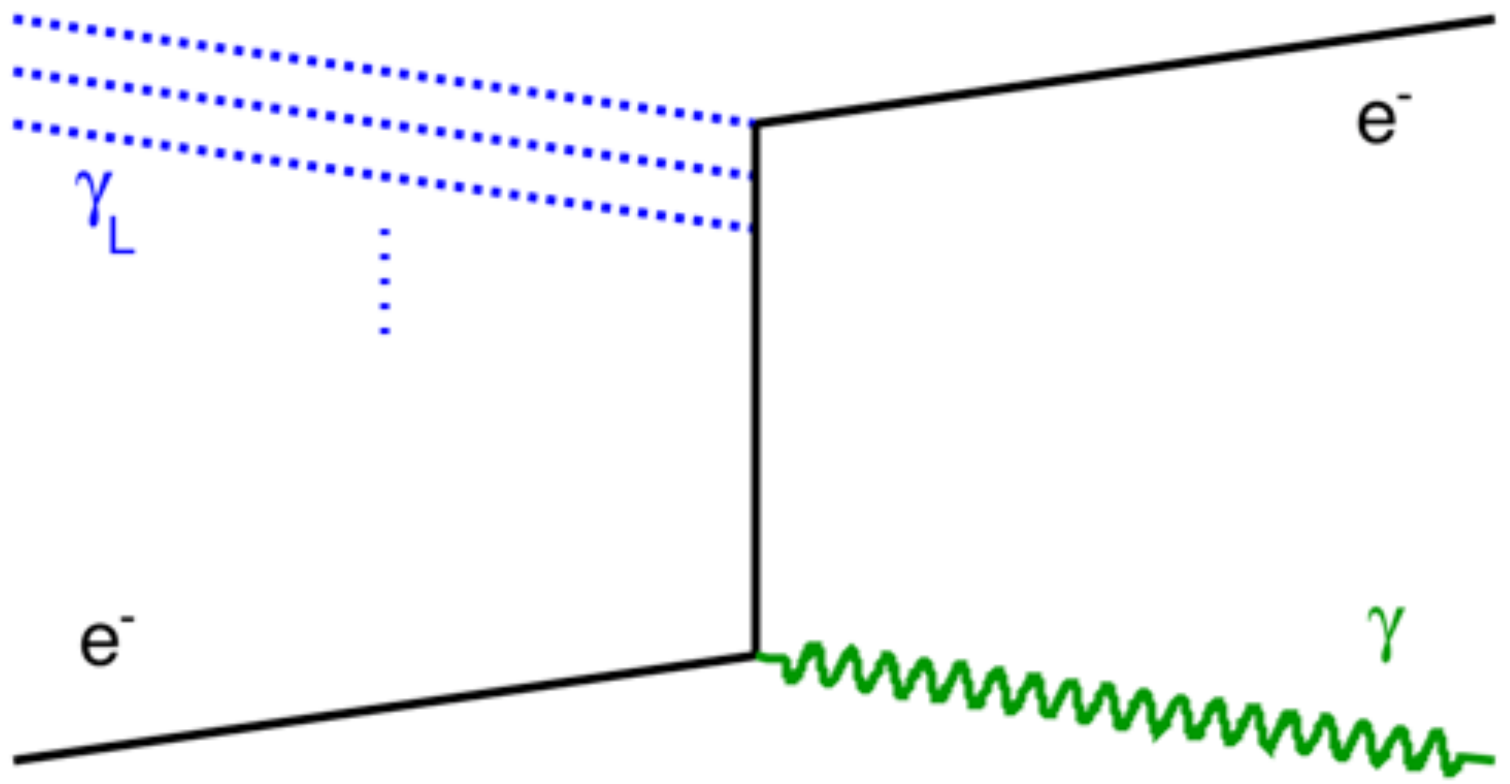
$$\eta = \frac{\chi}{\xi} = (1+\cos\theta)\frac{\omega_L E_{e/\gamma}}{m_e{}^2}$$

- (dimensionless) energy of collision between probe particle and background

Different combinations of ξ and χ result in different types of non-linear behavior!

Non-linear Compton scattering

Electrons gaining mass



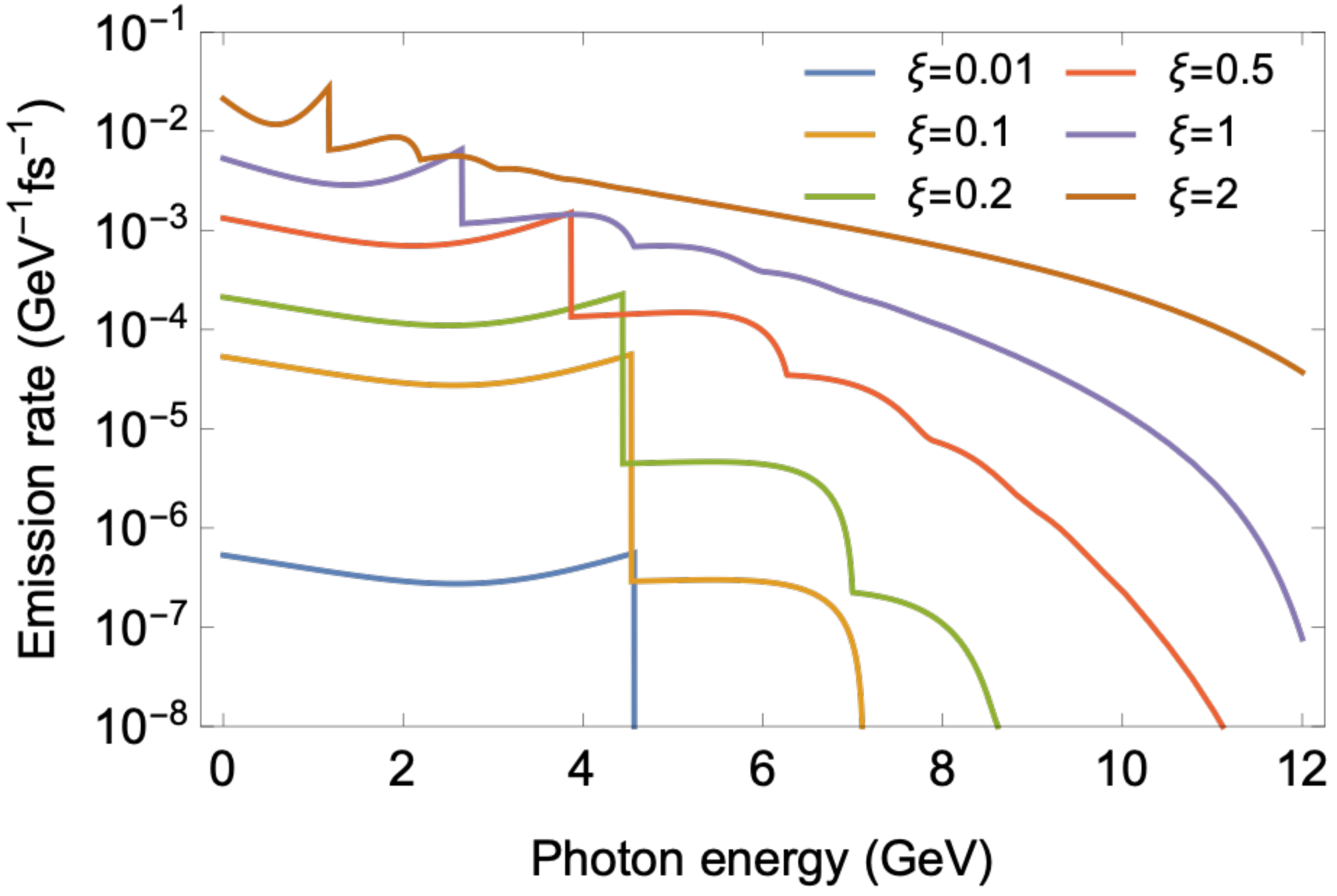
Non-linear Compton Scattering

$$e^- + n\gamma_L \rightarrow e^- + \gamma_C$$

- in strong fields, electron obtains larger effective mass
  $m_* = m_e\sqrt{1+\xi^2}$
  → Compton edge shifts as function of ξ
  → higher harmonics appear (interaction with n laser photons)

- theoretical prediction for QED: $E_{edge}(\xi) = E_e \dfrac{2n\eta}{2n\eta + 1 + \xi^2}$
  (with $\eta_{LUXE} = 0.192$)

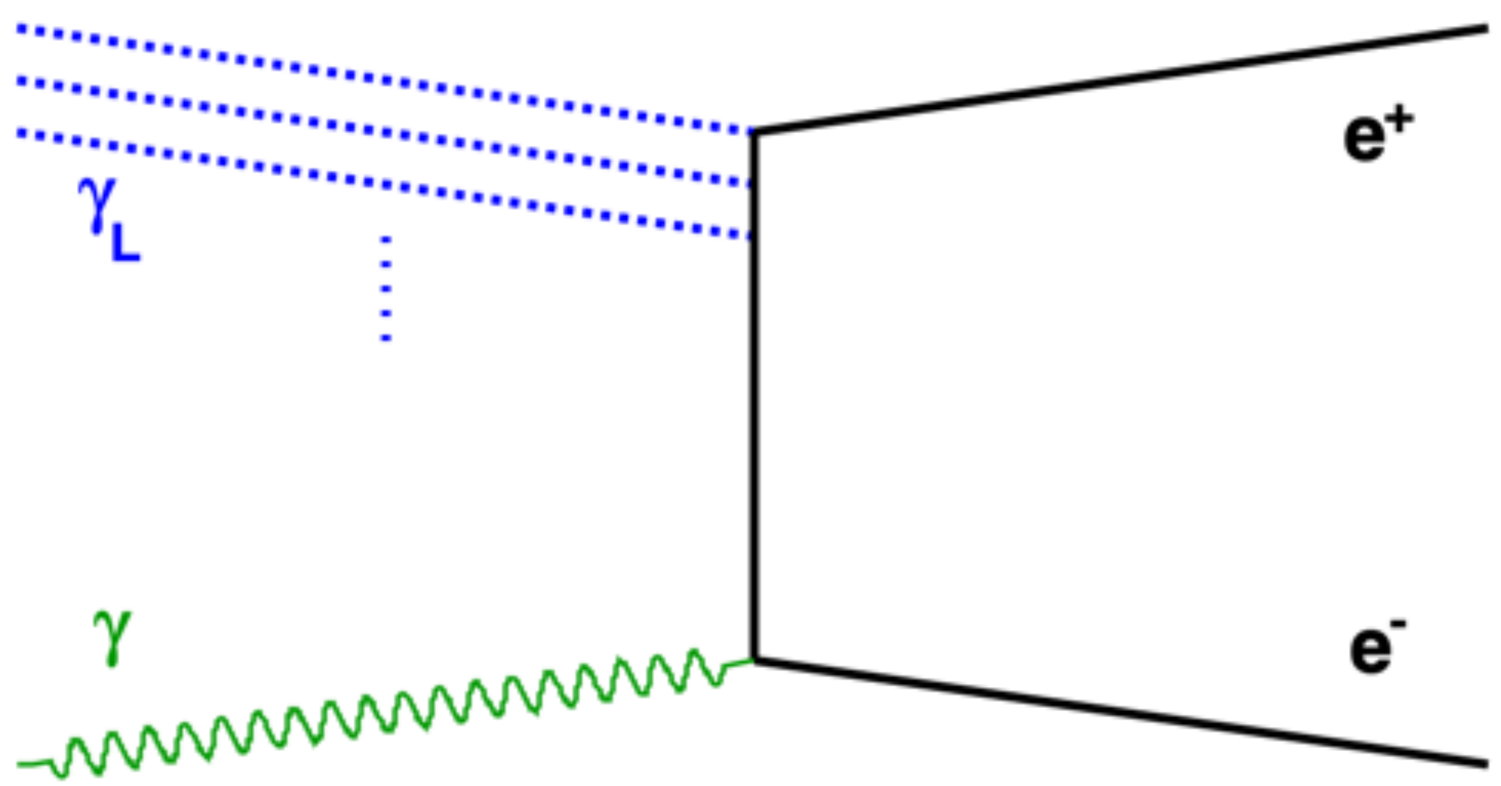
16.5 GeV electron, 800 nm laser, 17.2° crossing angle



- Note: Non-linear Compton scattering has a classical limit:
  $$E_{edge}(\xi) = E_e \frac{2n\eta}{1+\xi^2}$$
  → QED deviation from classical determined by quantum parameter χ!

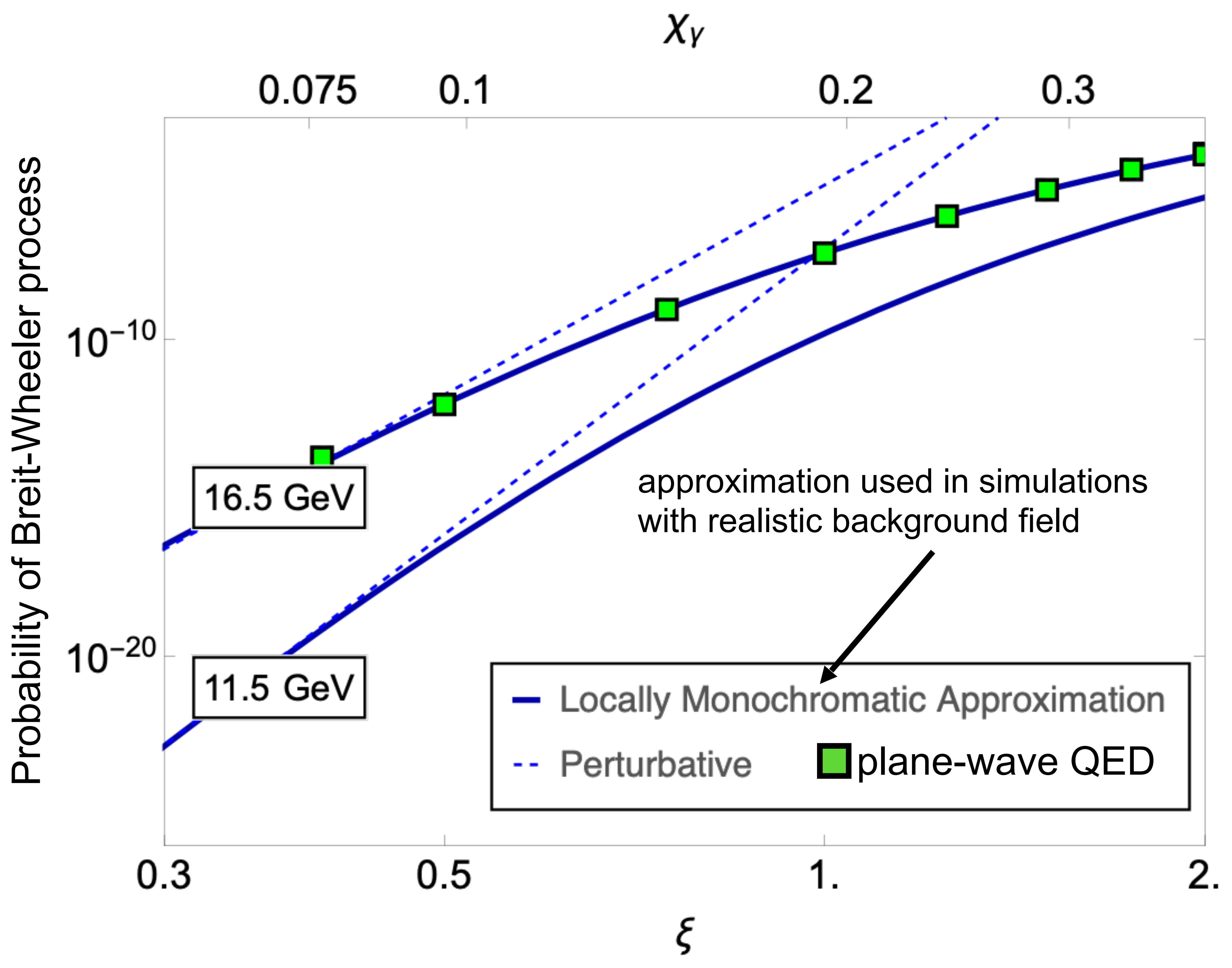
Breit-Wheeler pair production

Boiling the vacuum



(non-linear) Breit-Wheeler pair production

$$\gamma_C + n\gamma_L \rightarrow e^+ + e^-$$



- initial photon from Compton scattering or secondary beam
- Note: This process has no classical limit (energy threshold)!
  → purely quantum, requires $\chi \sim \mathcal{O}(1)$!

$\boxed{\xi \ll 1:}$ $R_{e^+} \propto \xi^{2n} \propto I^n$ Perturbative regime → power law

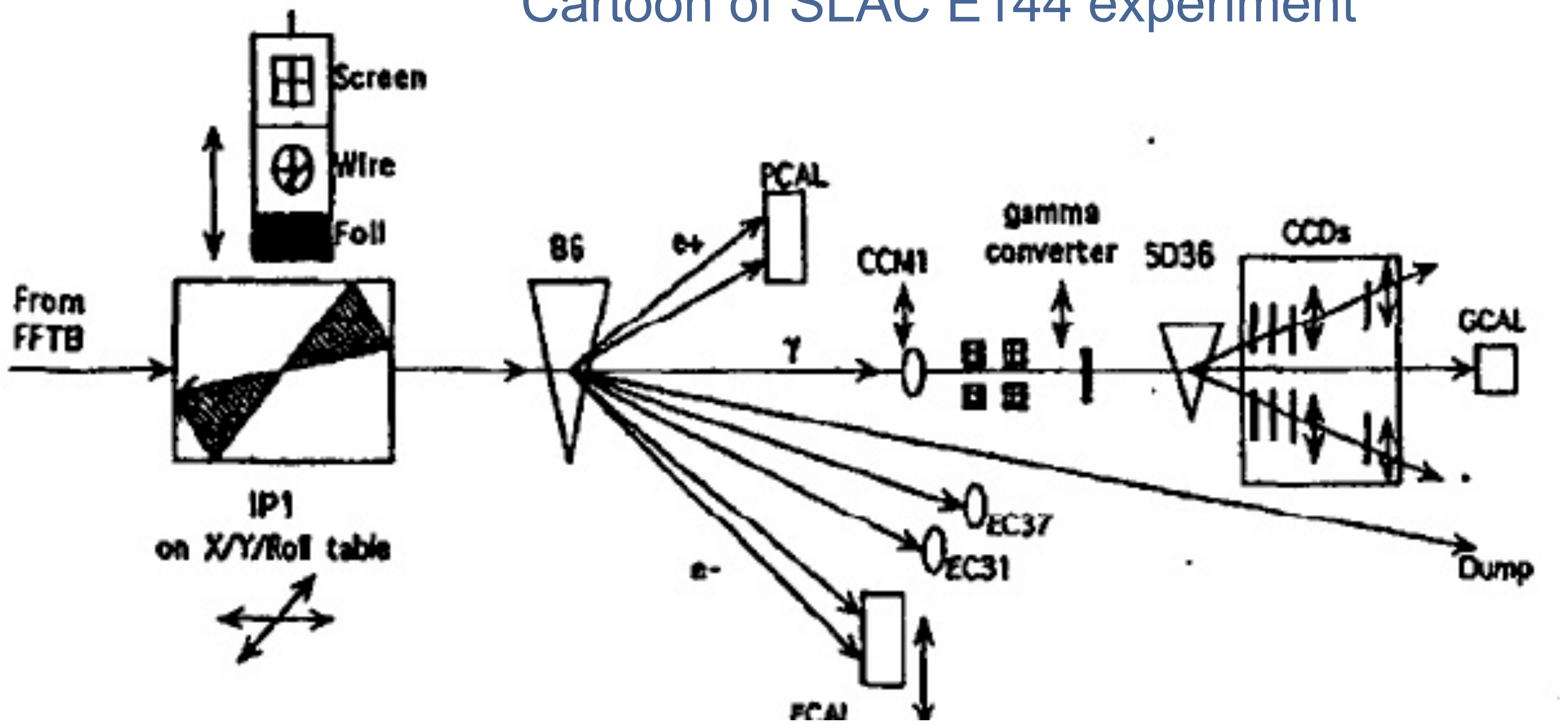
$\boxed{\xi \gg 1:}$ $R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$ Non-perturbative regime → departure from power law

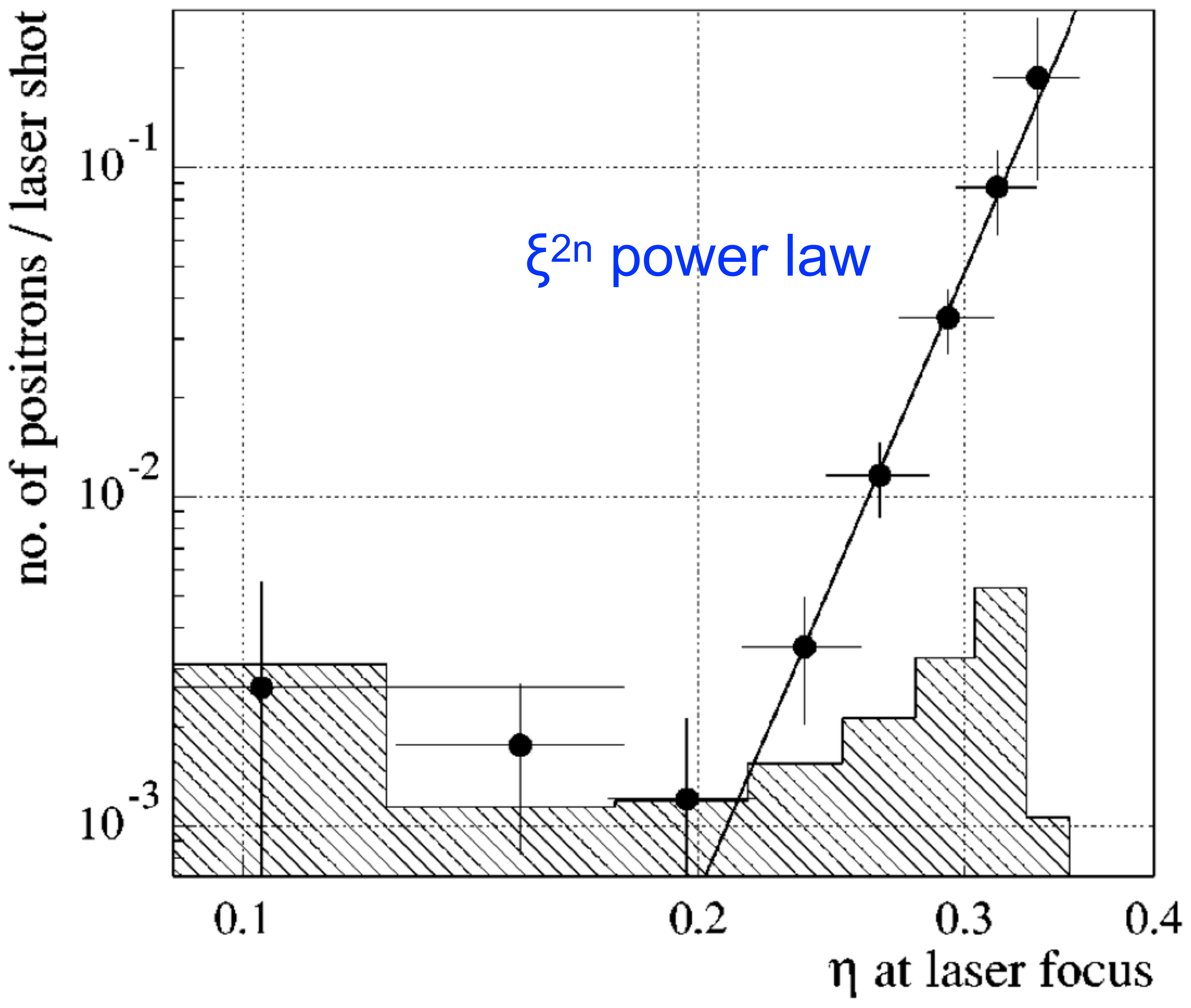
LUXE: first experiment to measure Breit-Wheeler pair production with real photons!

E144 experiment at SLAC

Reminder of the 1990ies….

Cartoon of SLAC E144 experiment





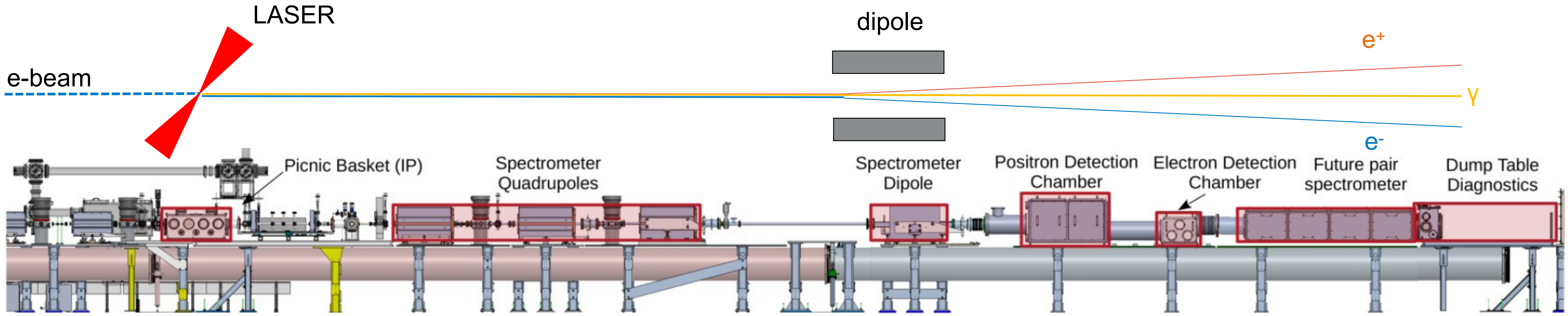
- E144: SLAC experiment in 1990’s using 46.6 GeV electron beam (e+LASER only!)
- reached $\chi \leq 0.25$, $\xi<0.4$
- observed process $e^- + n\gamma_L \rightarrow e^- e^+ e^-$
- observed start of the ξ^{2n} power law, but not departure

LUXE : Three orders of magnitude more powerful laser than E144, will enter non-perturbative regime

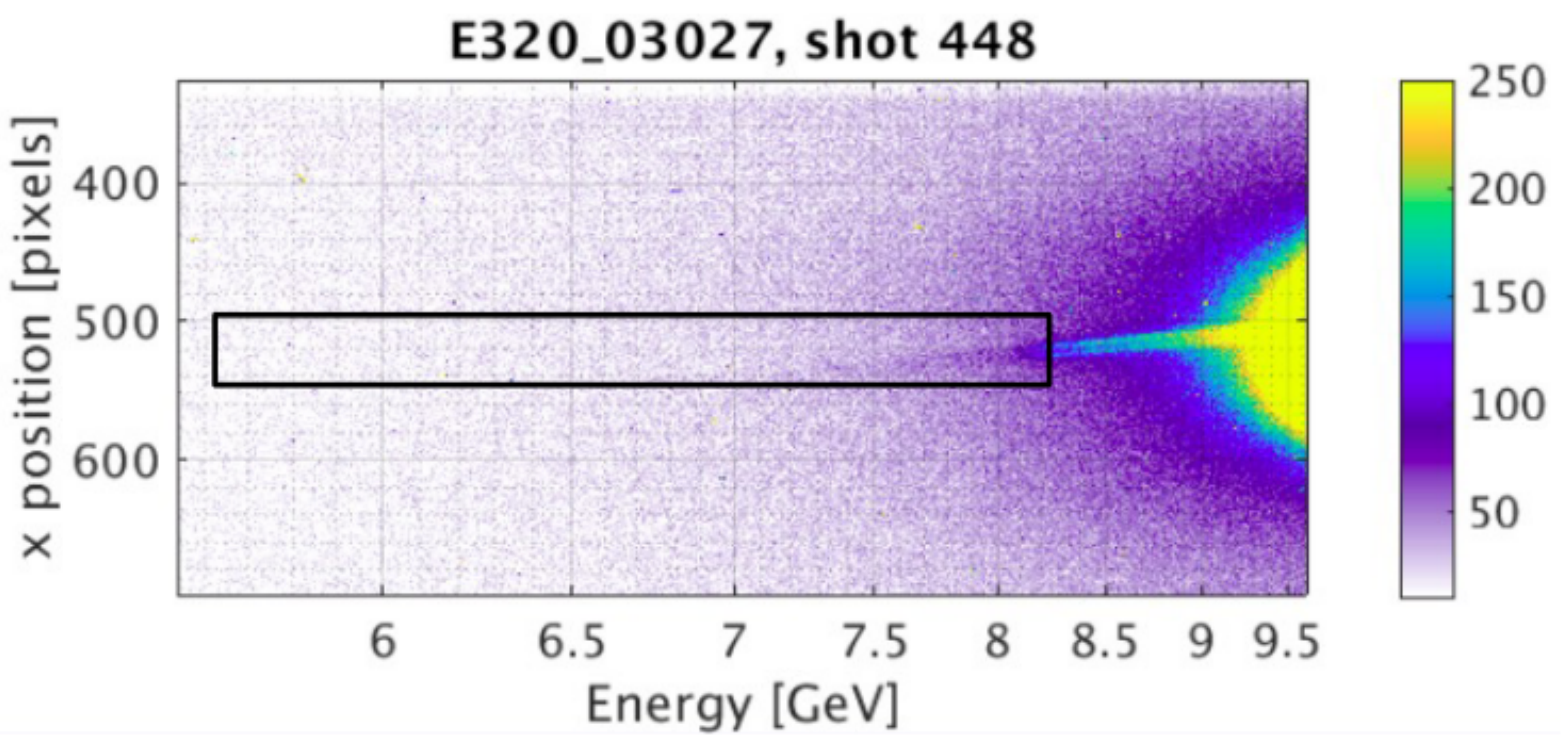
E-320 experiment at SLAC

Link to E320 overview by S. Meuren

…and back to the future



- E320: ongoing SF-QED experiment at SLAC using 13 GeV electron beam (FACET-II) and 16 TW optical Laser
- first electron-laser collisions in 2022
- By design: similar parameter reach as LUXE (after laser and detector upgrades)
- Main differences to LUXE:
  - electron-laser collision mode only
  - E-320 data-taking time limited due to other users of FACET-II



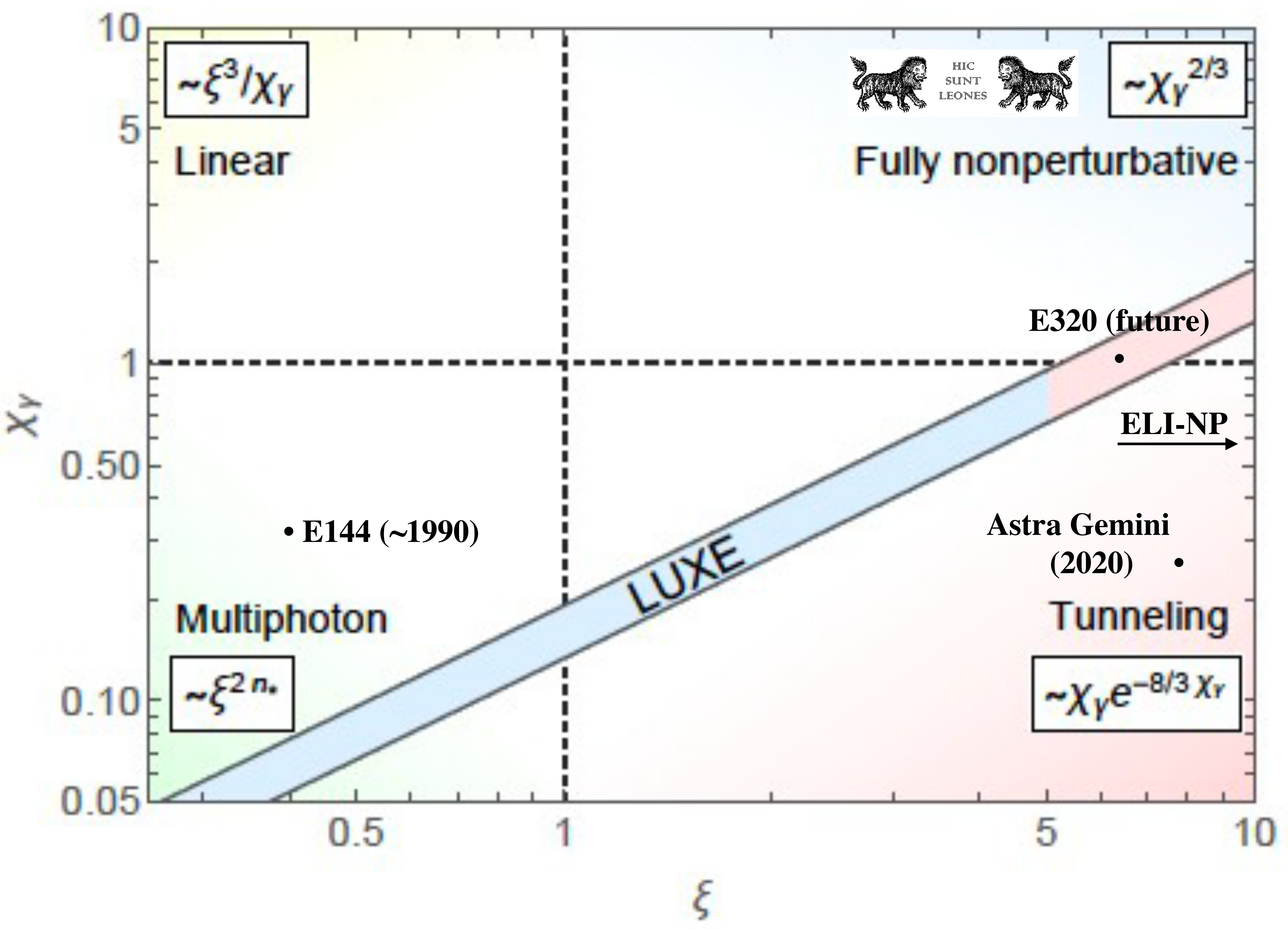
Laser-Plasma Experiments

and comparison with LUXE

- Nowadays multiple experiments proposed worldwide:
  - Astra Gemini (UK), ELI-NP (RO), LUXE (DE)
  - Summary of parameters needed to reach non-perturbative regime

e- Beam	I_{Laser} [W/cm²]	
1 eV	10^{29}	(Not currently achievable)
1 GeV	10^{22}	(corresponds to 10 PW laser)
10 GeV	10^{20}	(corresponds to 100 TW laser)

- LUXE: precision measurents over large part of ξ vs X phase space.
  - Might be the first one to report observation of non perturbative regime.
  - Only experiment proposed to directly explore photon-laser interactions.



SF-QED and e+e- Colliders

Beamstrahlung and Depolarisation in Collision

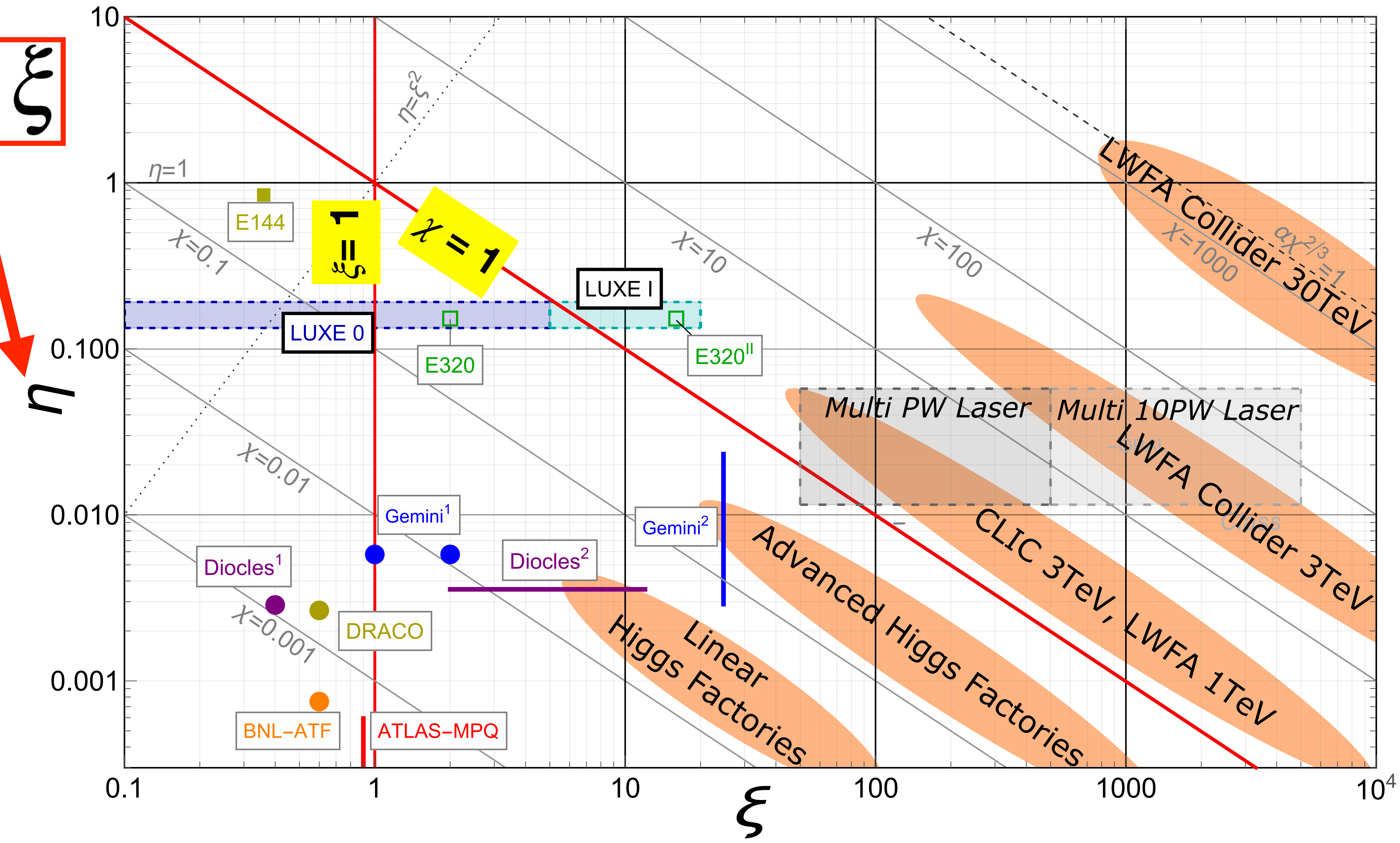
$$\boxed{\chi = \eta\xi}$$

ξ (a0) "obvious" in laser context - less clear how that translates to beam-beam collisions?

estimated for **round** beams [arxiv:1807.06968]

(I don't know a corresponding formula for flat beams - if you do, let me know!)

$$\boxed{a_0 = \sqrt{\frac{2}{\pi^3}\frac{r_e}{\sigma_0}N}}$$



SF-QED and e+e- Colliders

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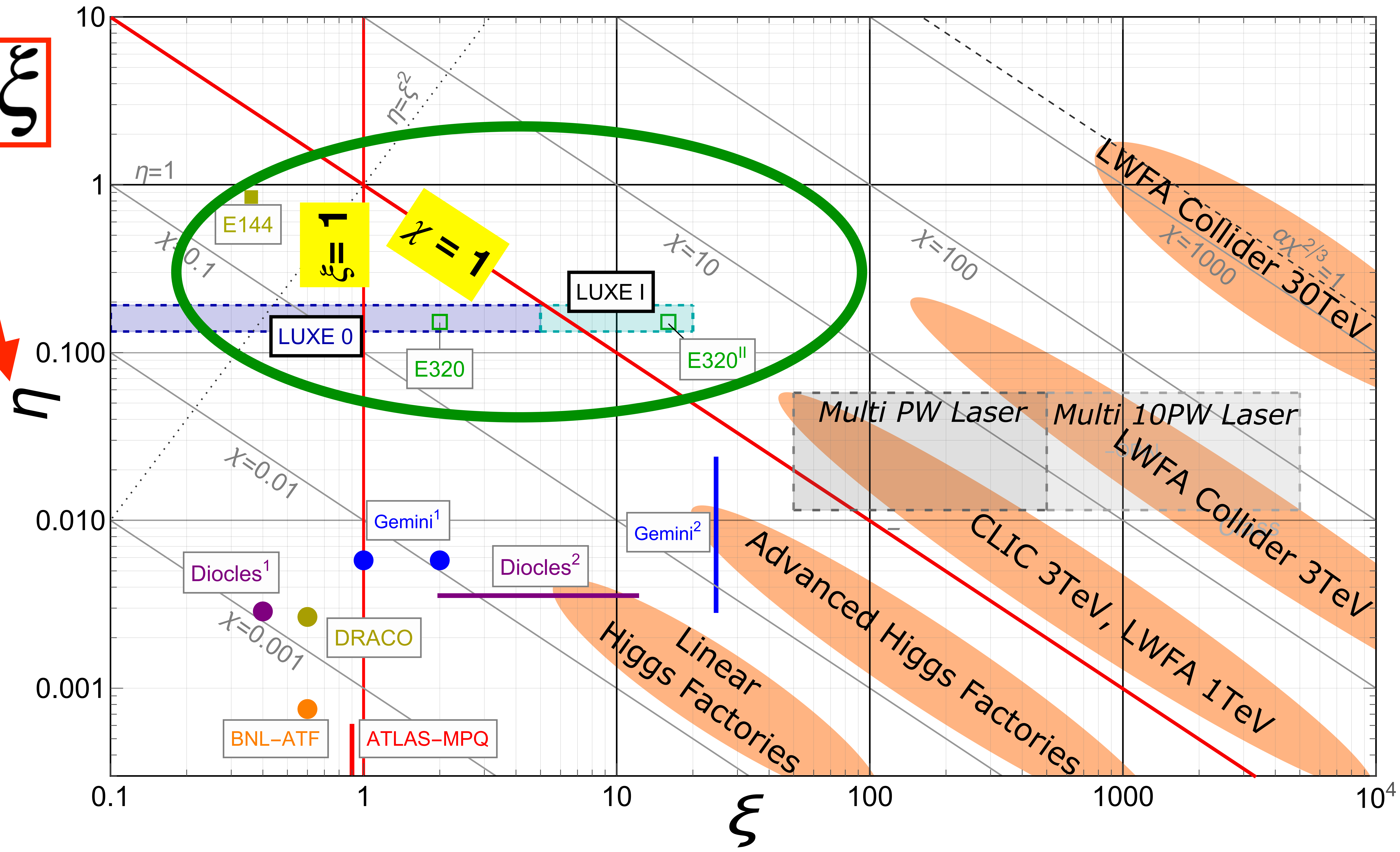

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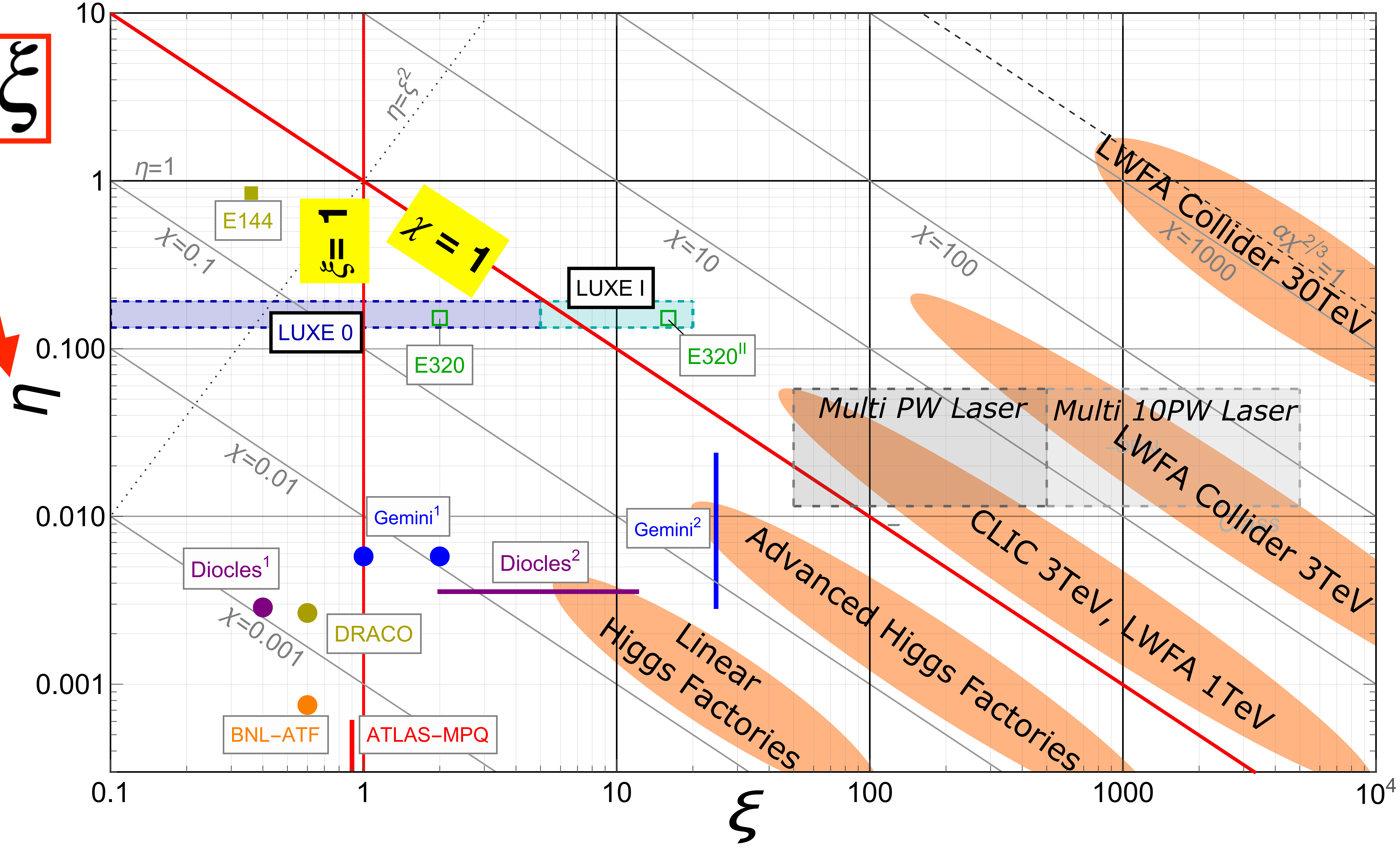

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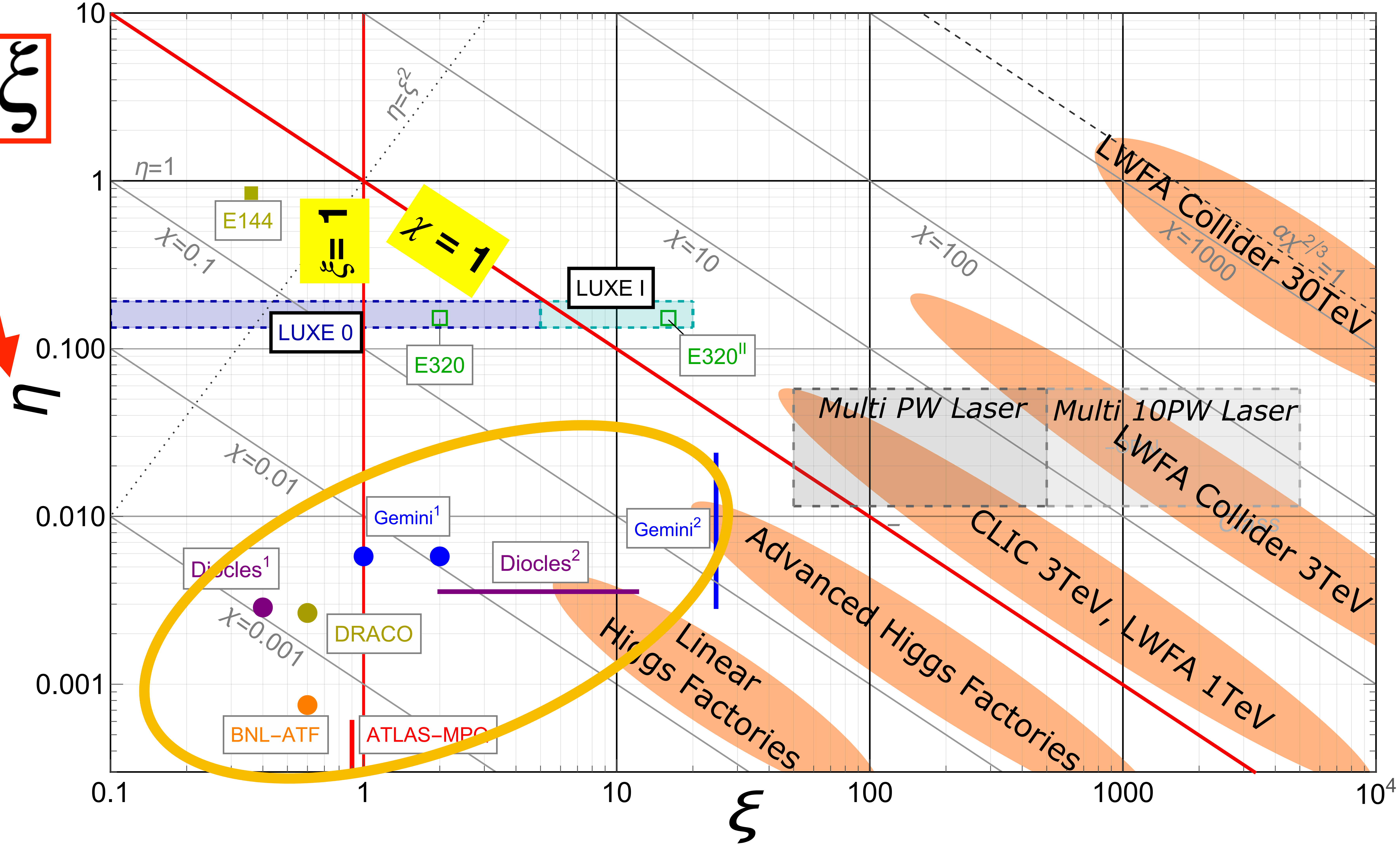

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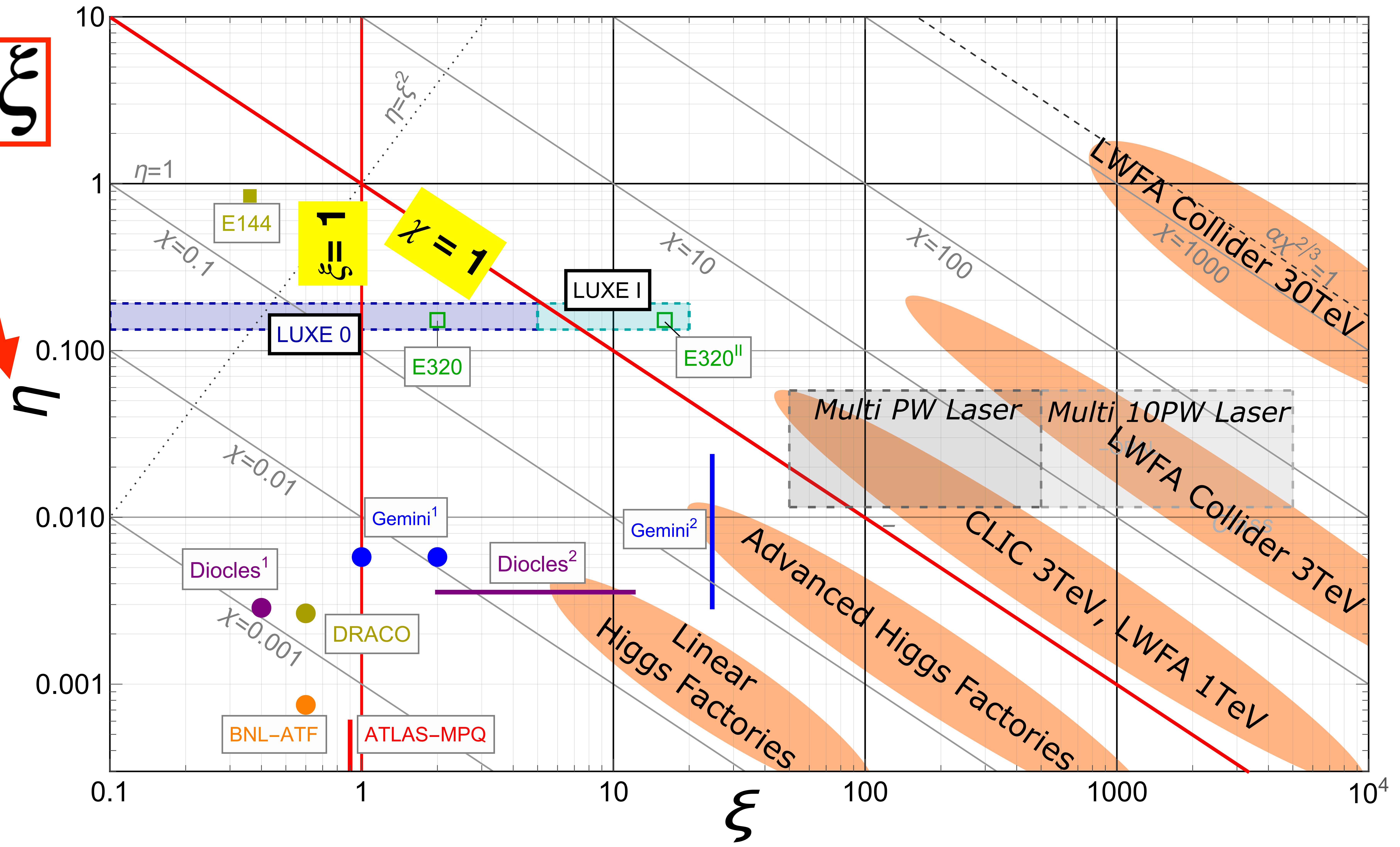

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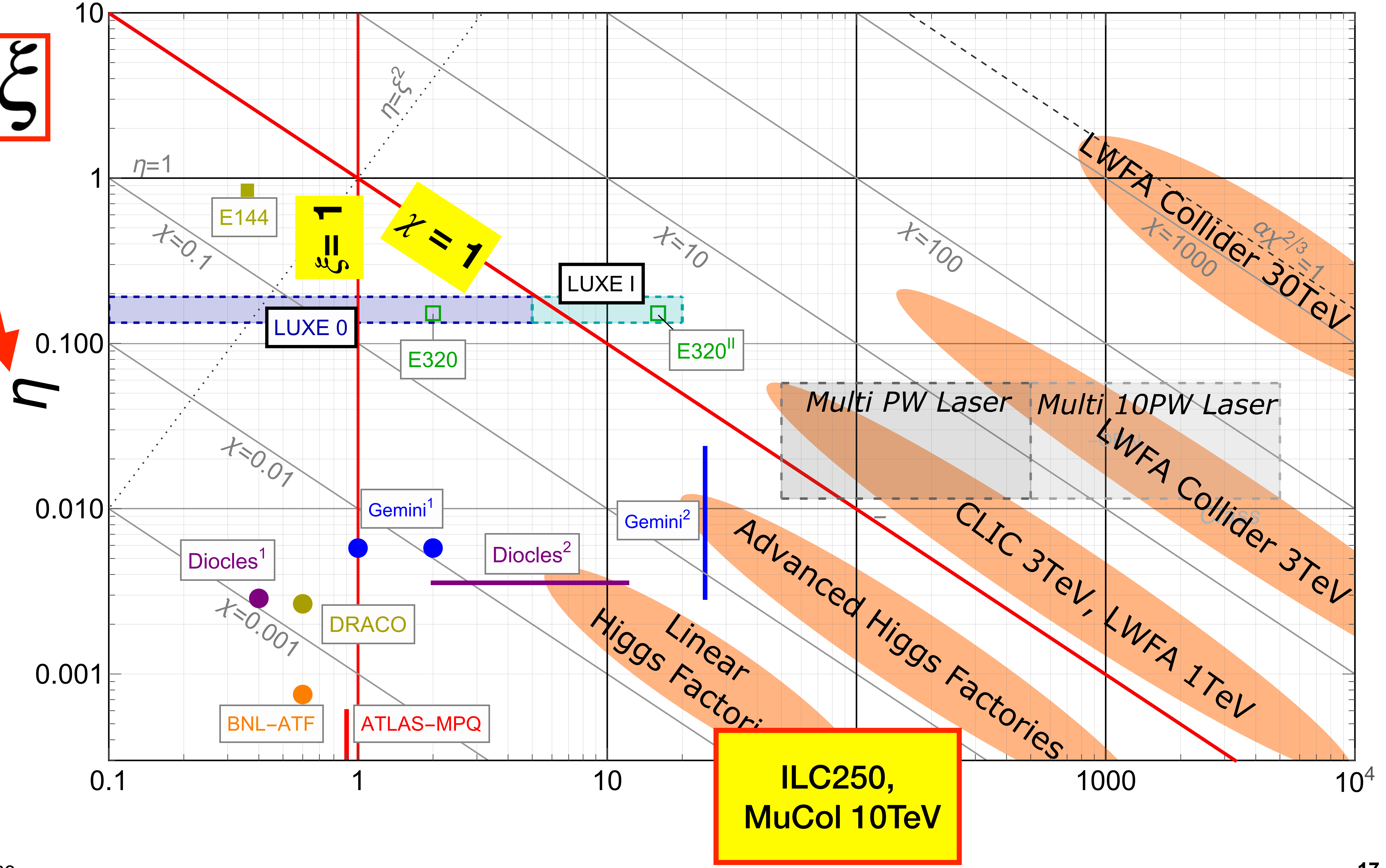

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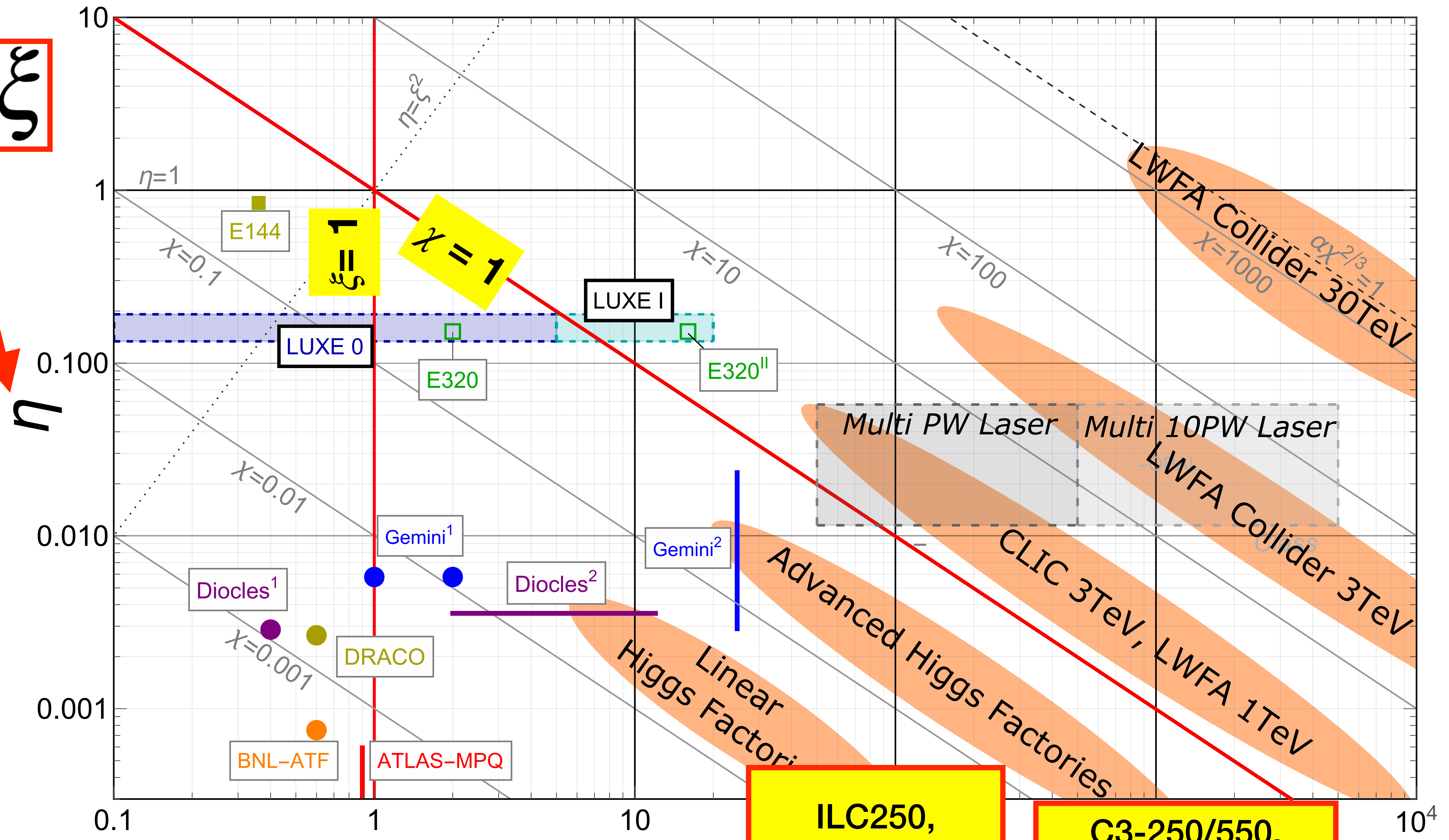

ILC250, MuCol 10TeV

C3-250/550, ILC1000 CLIC380 HALHF, ALIC250

SF-QED and e+e- Colliders

Beamstrahlung and Depolarisation in Collision

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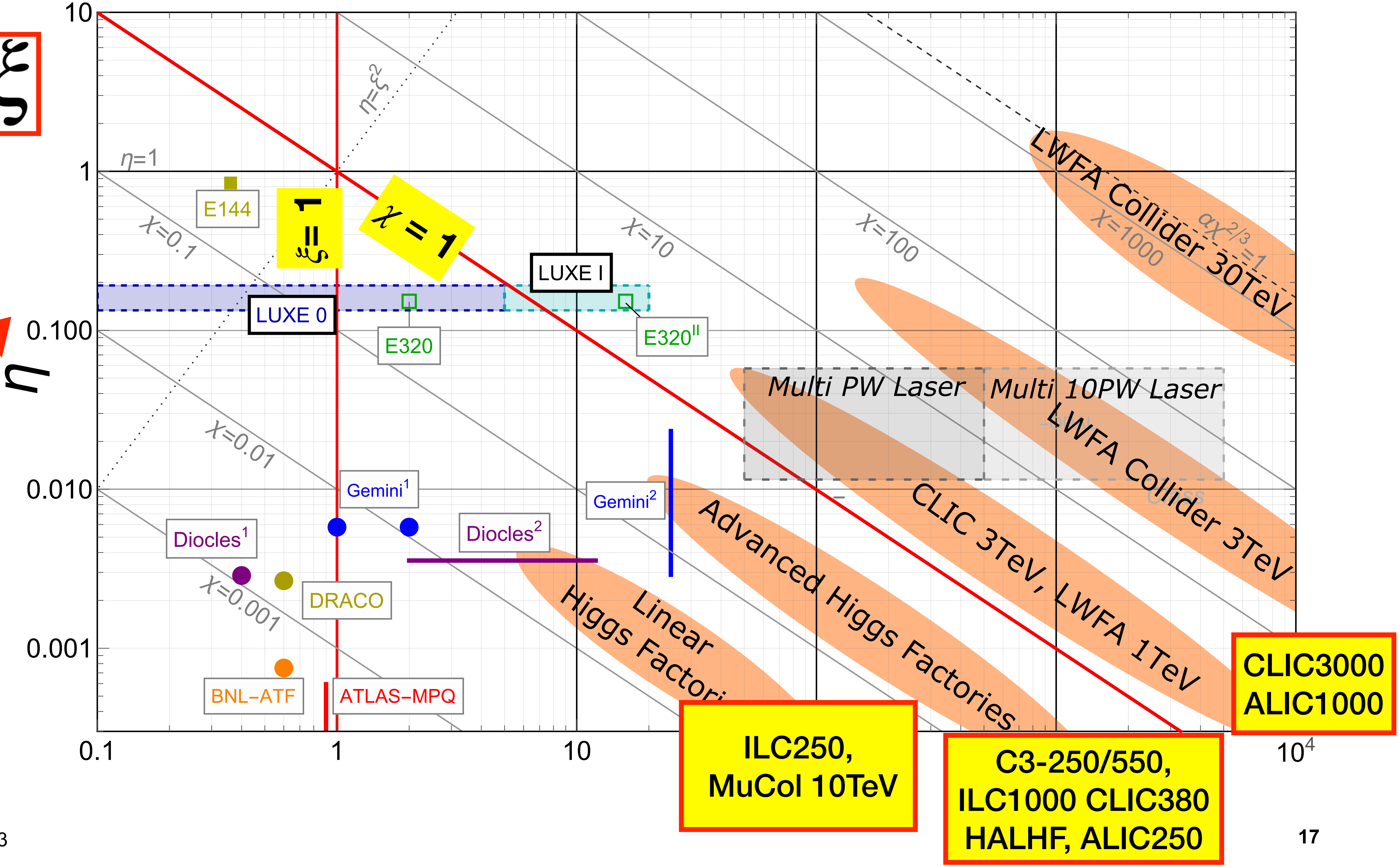

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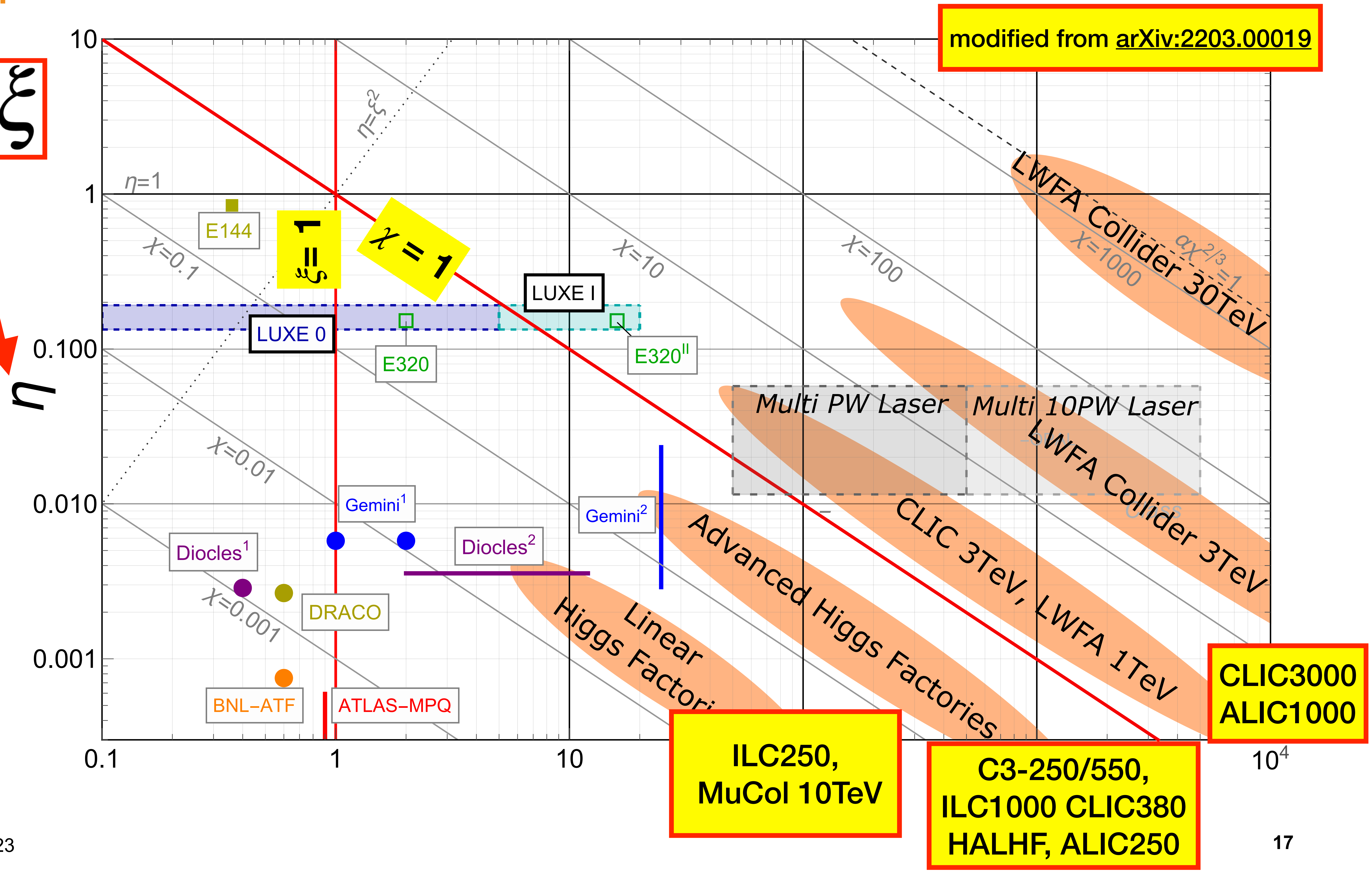


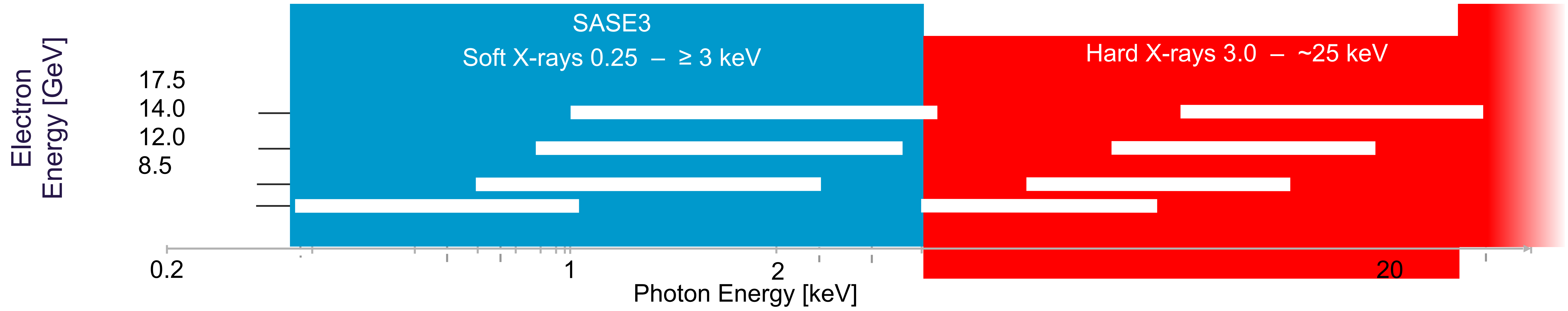
LUXE
Experimental Setup
& Challenges

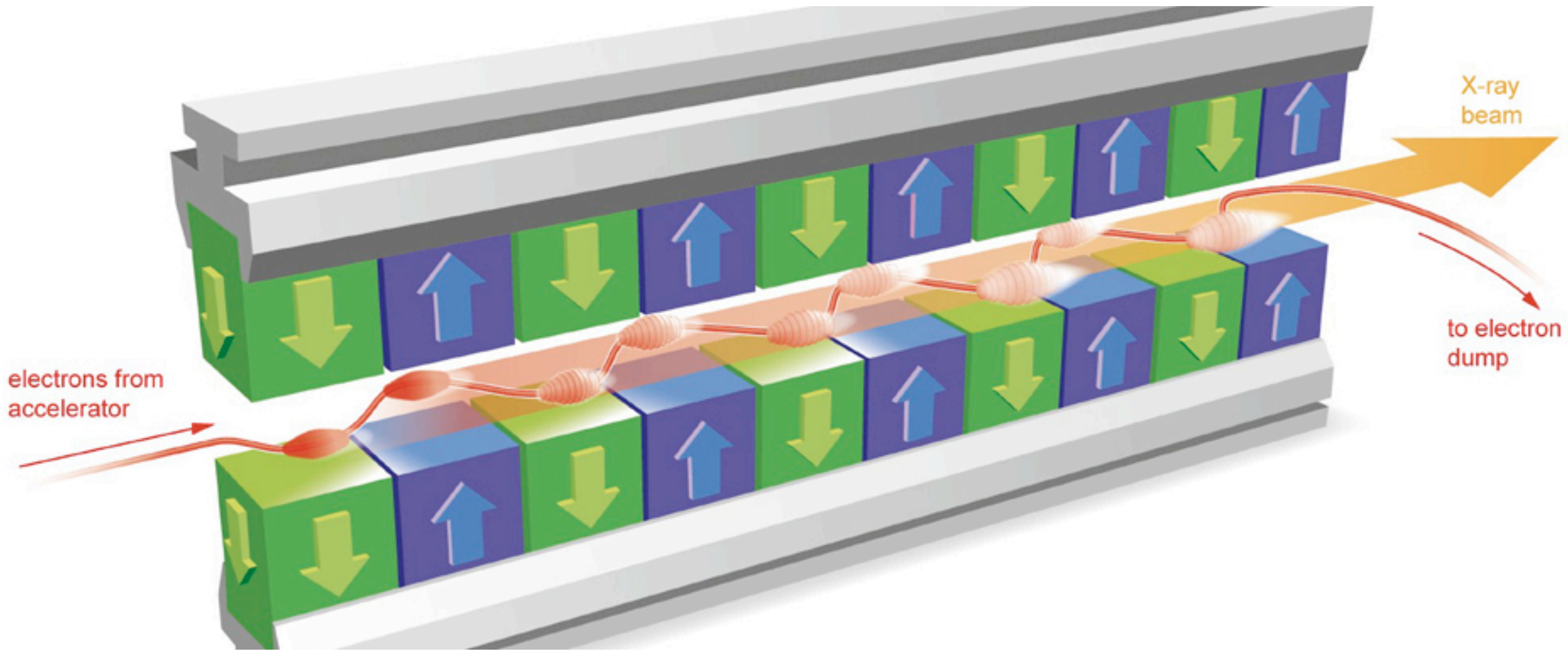
The European XFEL

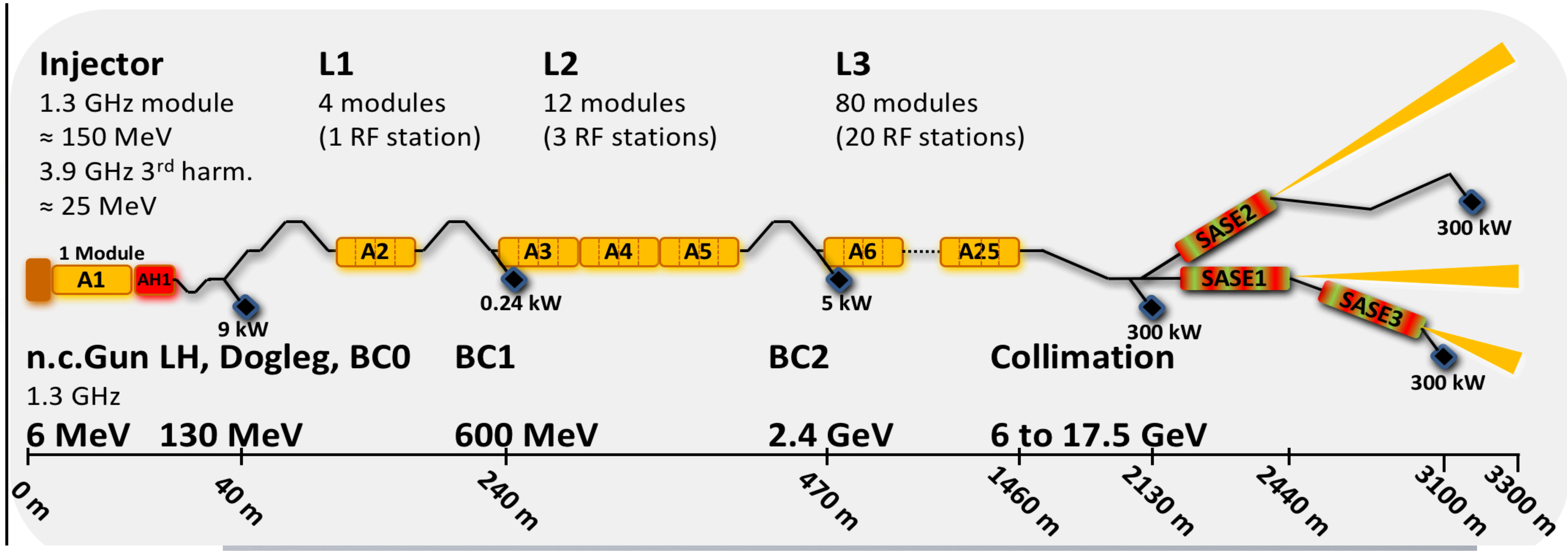
Running since 2017

European XFEL

- Linear electron accelerator.
  - 1.9 km long.
  - Up to 17.5 GeV.
  - 2700 electron bunches at 10 Hz.
- Provide X-ray photons to 6 experiments.
  - Electron through undulator:
    - SASE (self-amplified spontaneous emission)
  - 0.25 keV to 25 keV.



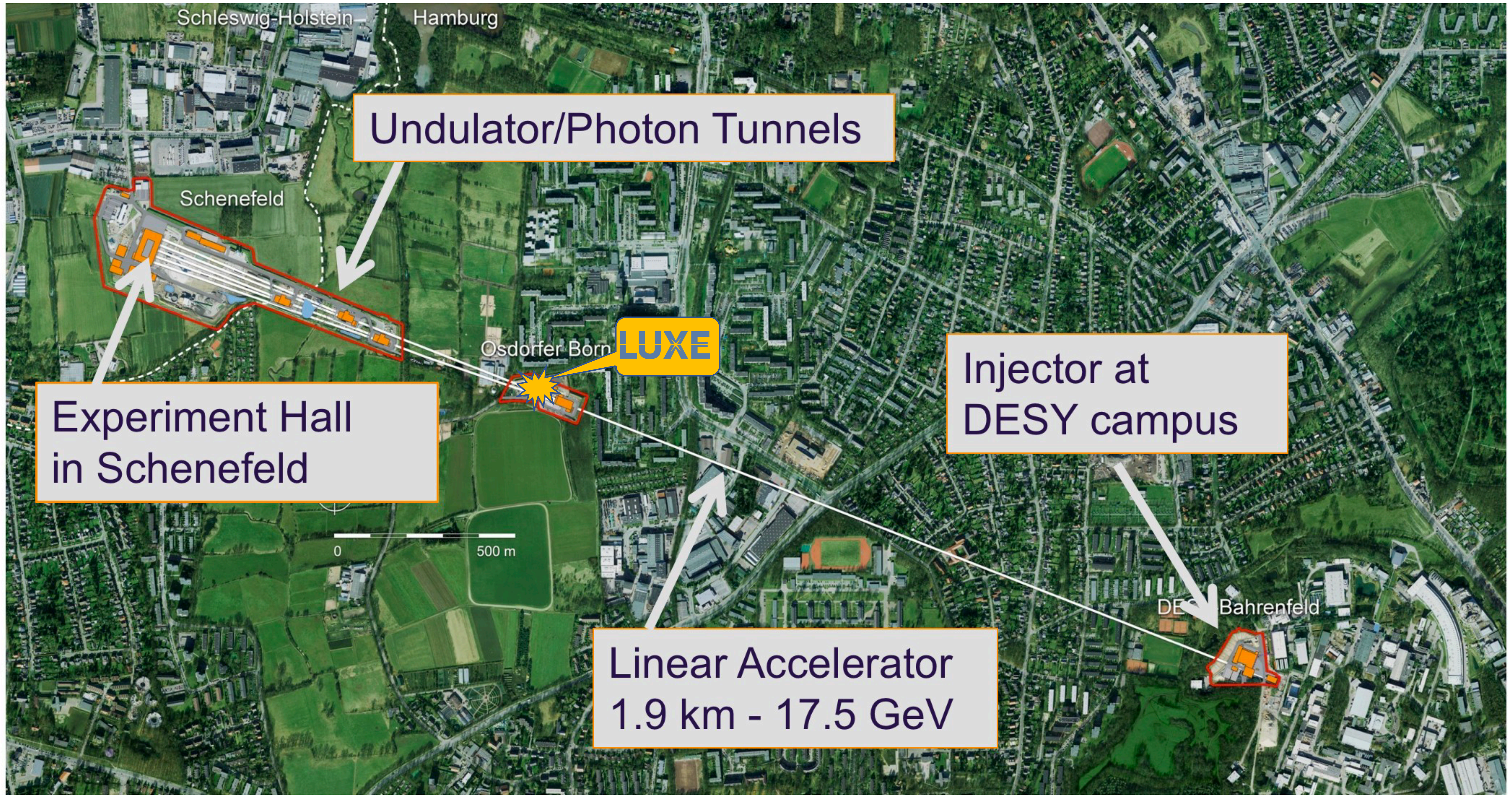


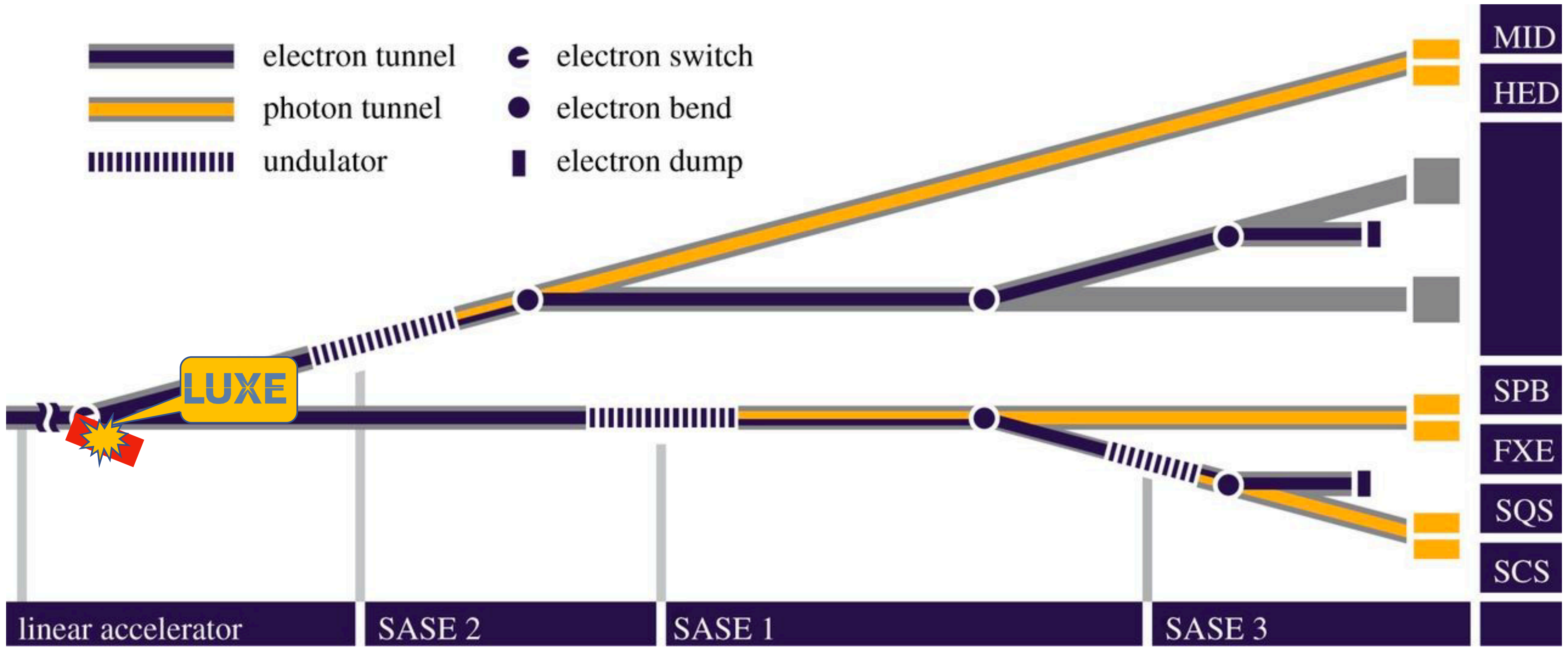


LUXE@Eu.XFEL

Located in Osdorfer Born

- in annex of XS1 shaft building.
  - Built for XFEL extension (after 2030).
- Experiment will have no impact on photon science:
  - Only use 1 of the 2700 bunches.
- Beam parameters:
  - 1 bunch at 10 Hz
  - 1.5 10^9 electrons/bunch (0.25nC).
  - E = 16.5 GeV
  - Width $\sigma_x, \sigma_y = 5...10\mu m$.
  - Length 130 fs



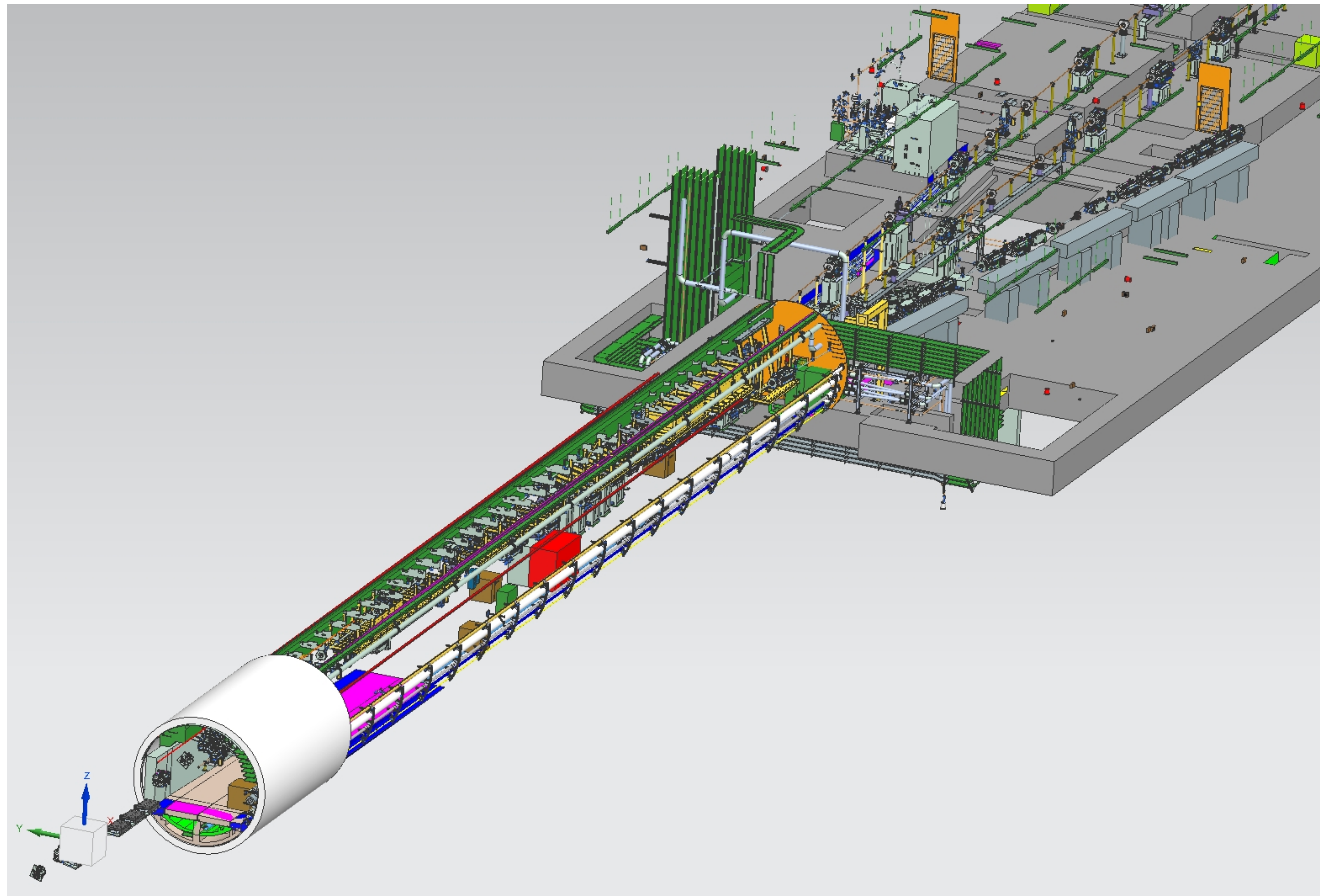


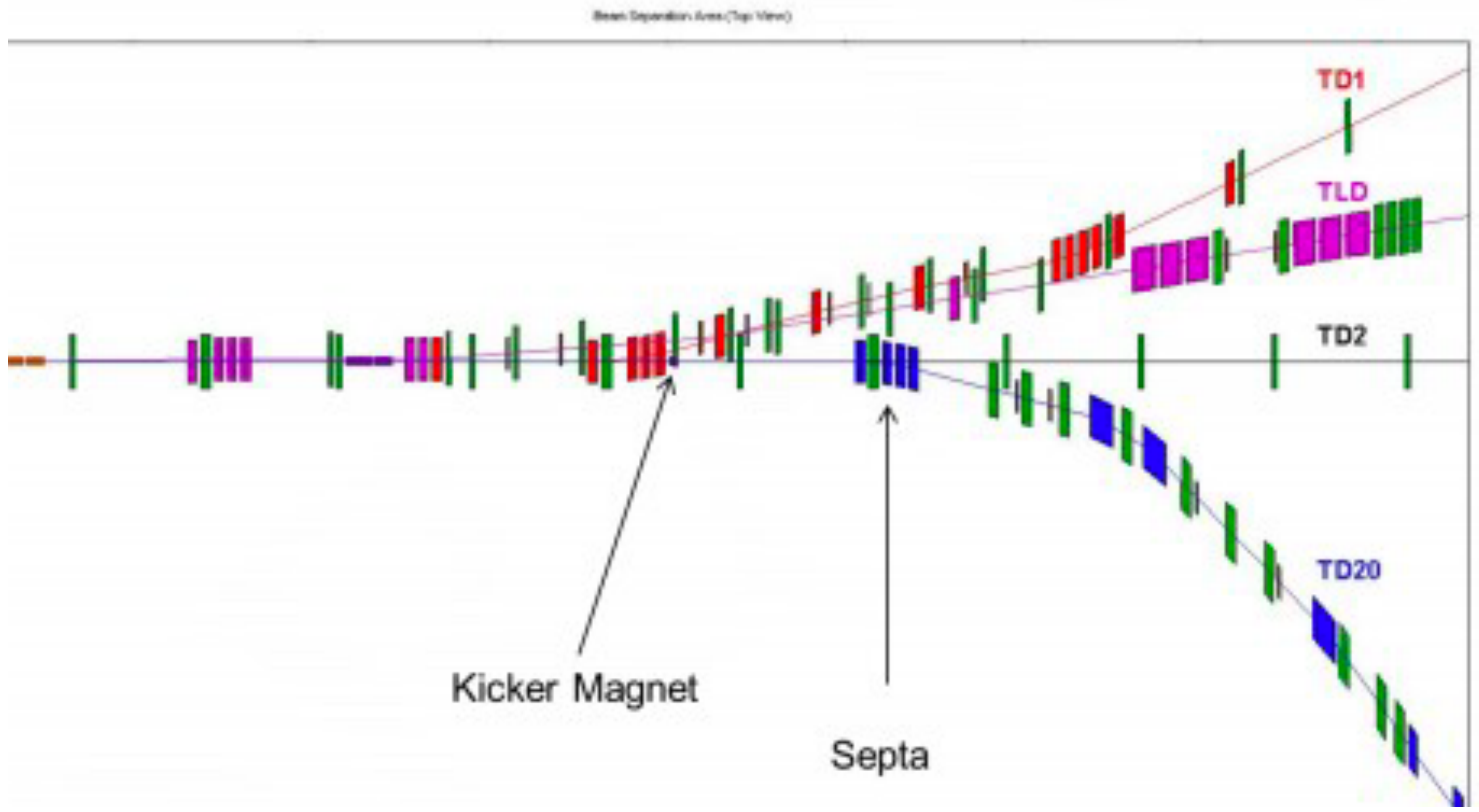
From the Accelerator to the Experiment

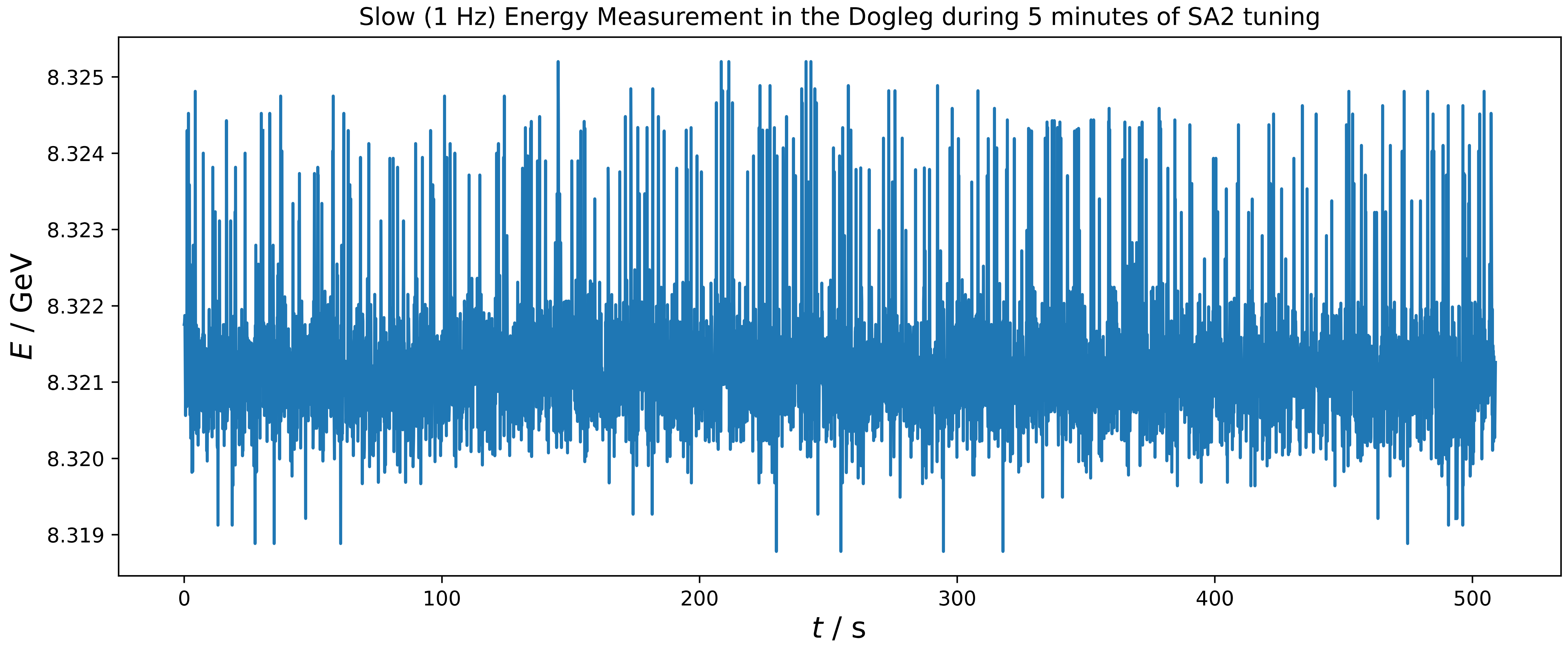
New extraction line

- Construct dedicated new extraction line at the end of the LINAC.
  - Reusing magnet design from XFEL for septum and dipoles.
  - New fast kicker magnets (2 µs: kicks bunch at end of bunch train).
  - Reuse quads from HERA.
    - retrofit to reduce aperture size and power consumption.
- Design of the beam line mostly ready.

- Beam jitter parameters measured at the machine recently:
    - Shot to shot position: ~1μm.
    - Energy variation <0.1%.
    - Time of arrival variation: ~20 fs.

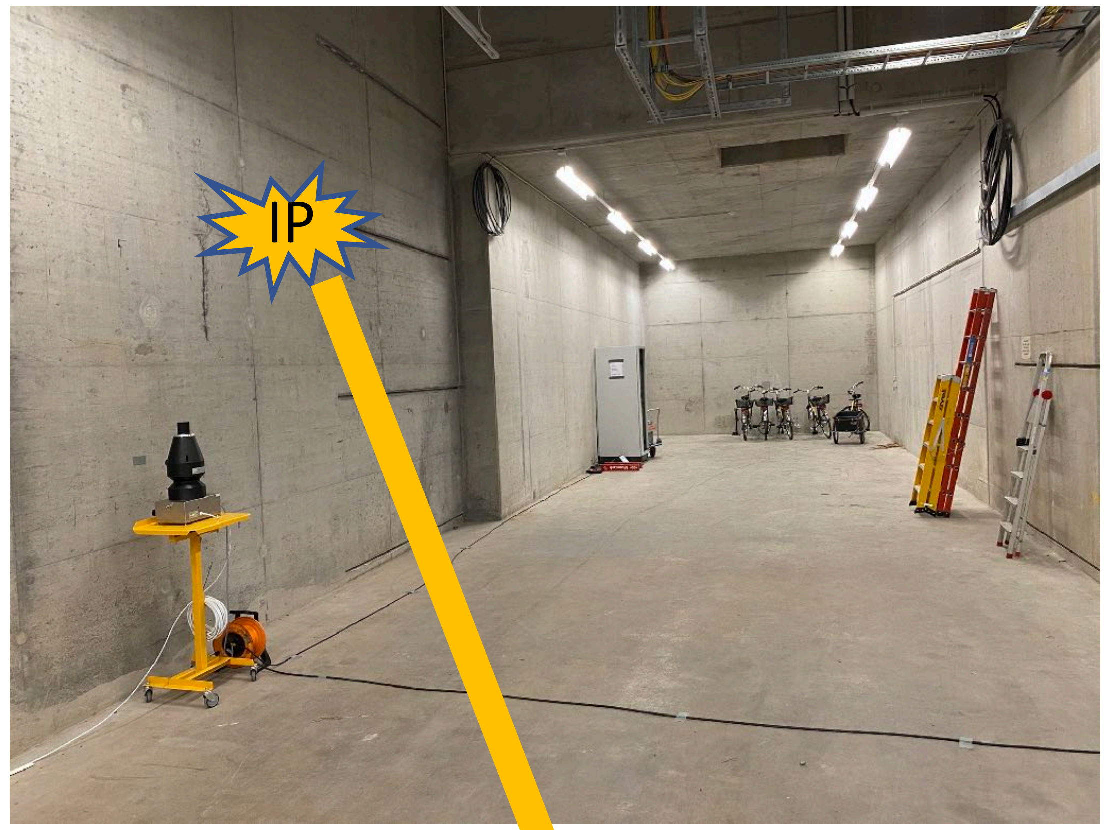




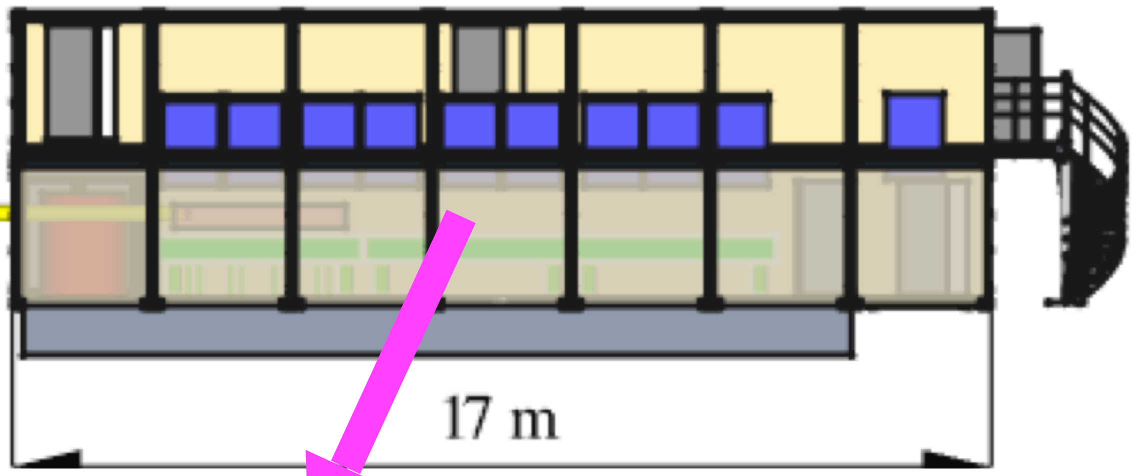


Implementing LUXE

Zoom into XS1 locations



Laser



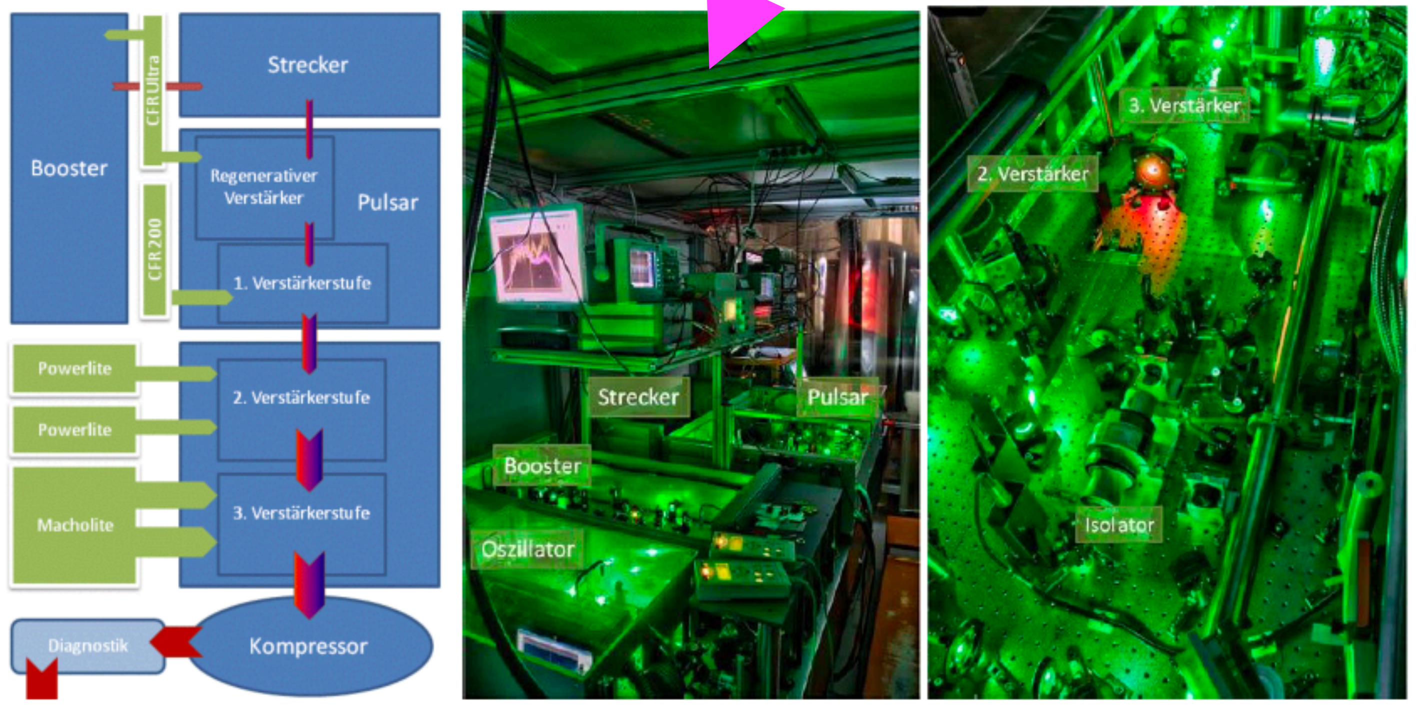
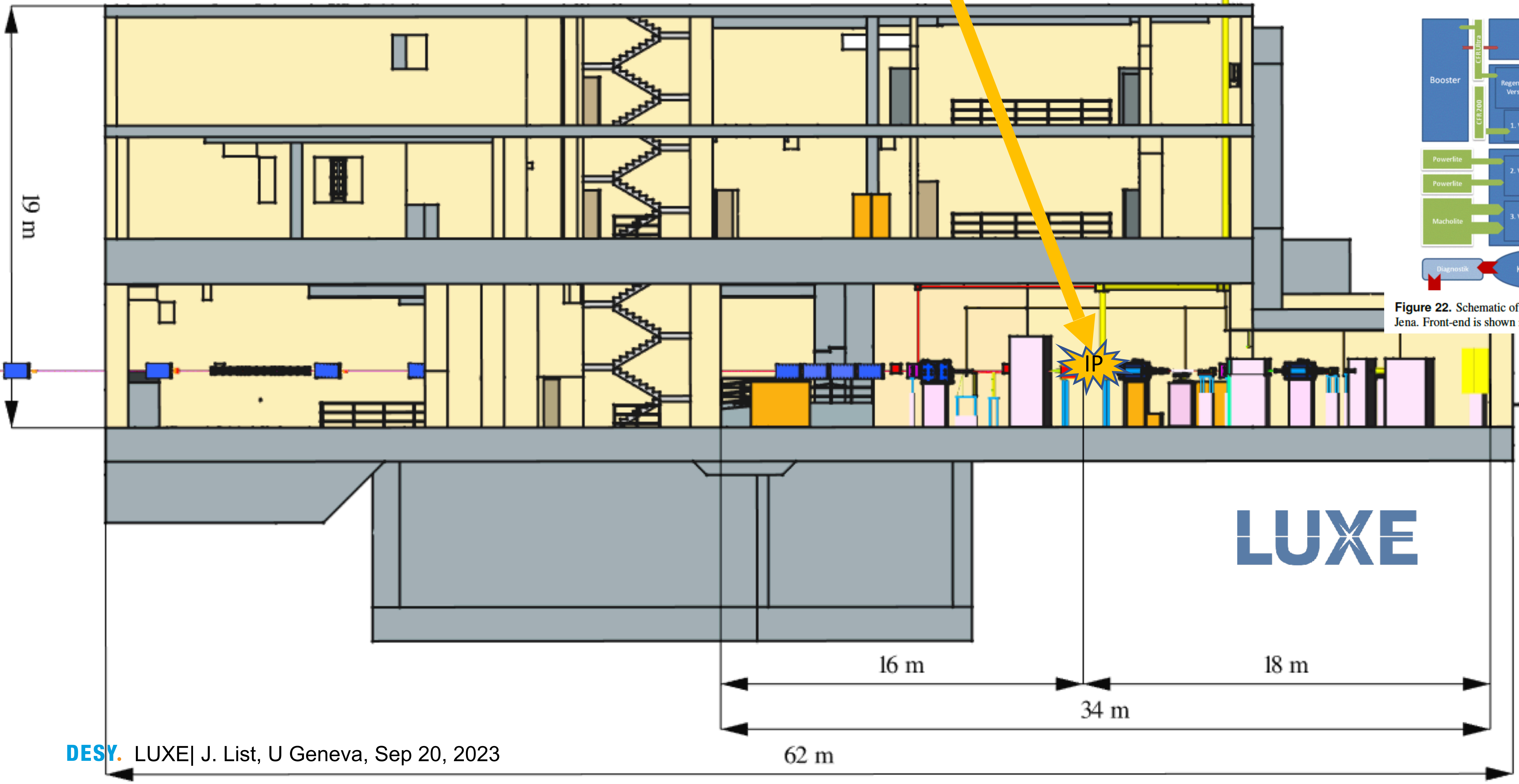


Figure 22. Schematic of the JETI system highlighting major assemblies. Current Installation of JETI-40 at the University of Jena. Front-end is shown in centre and power amplifiers right.



The LUXE laser

JETI40 & Co

LUXE basic Laser parameters	
active medium	Ti:Sa
wavelength (energy)	800nm (1.55eV)
crossing angle	17.2°
pulse length	30fs
spot size	≥3μm
power	40TW / 350TW
peak intensity [10^{19} W/cm^2]	13.3 / 120
repetition rate	1 Hz

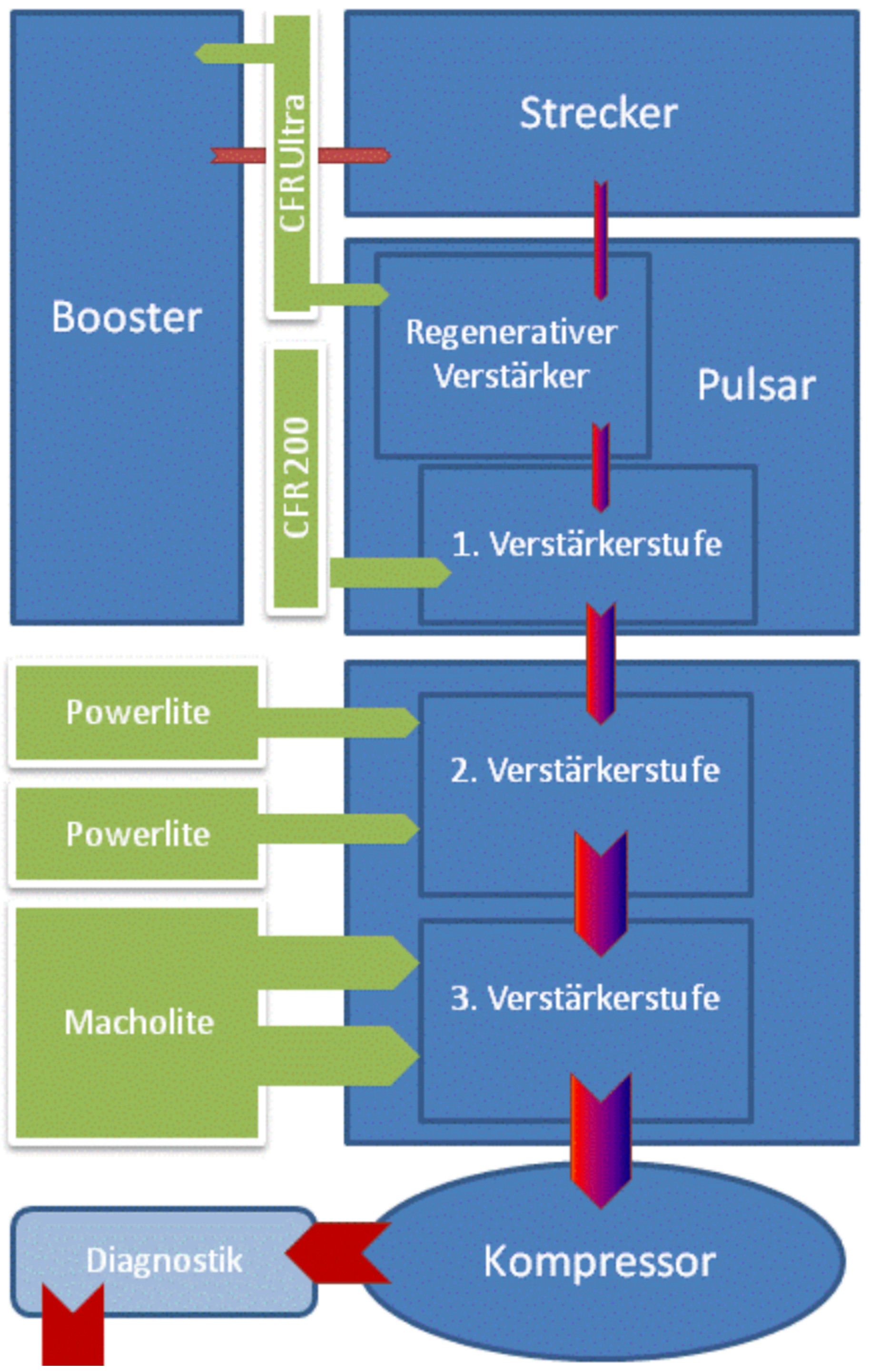
Laser intensity:

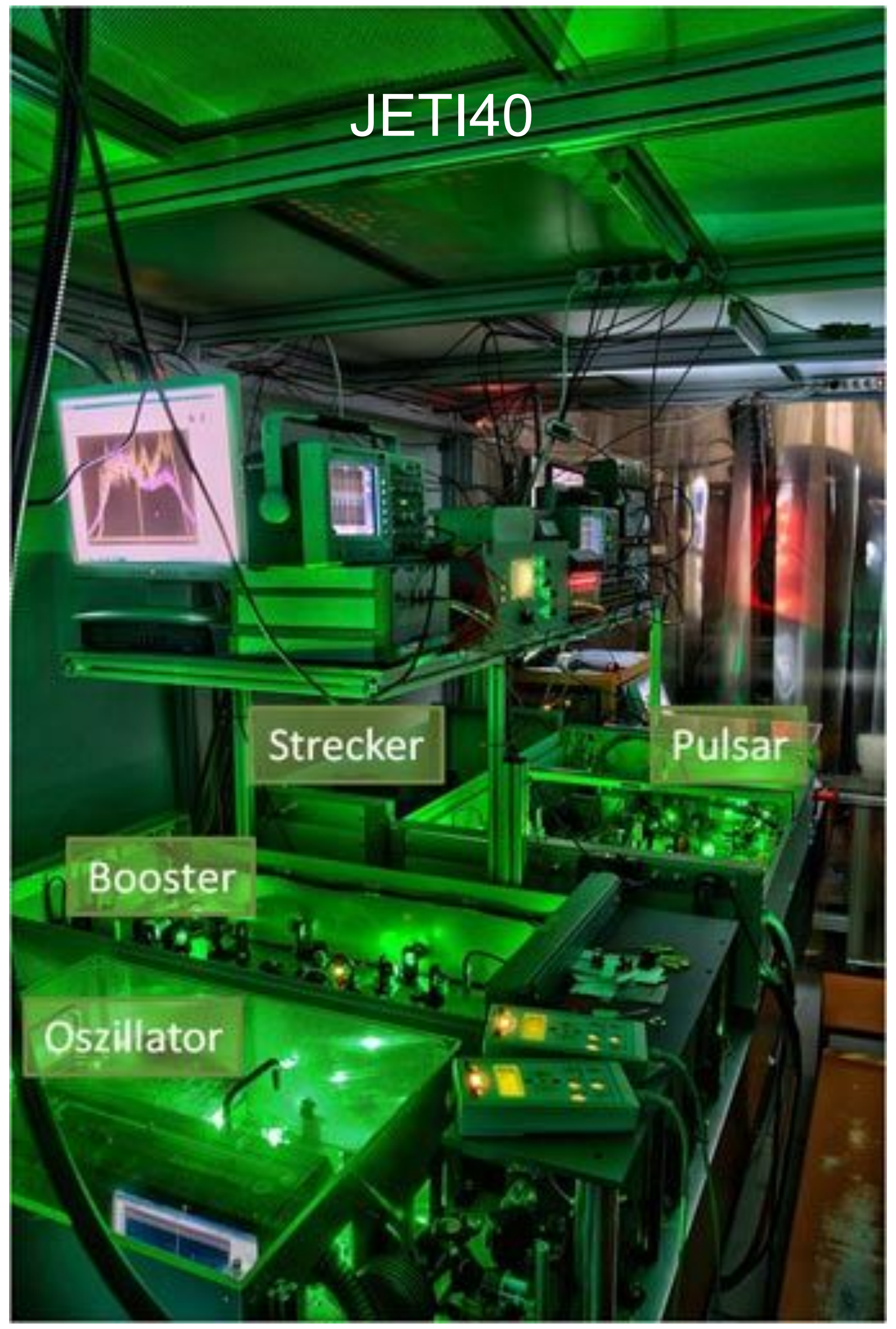
$$I = \frac{E_L}{\Delta t \pi d^2}$$

E_L: laser energy (J)

Δt: pulse length (s)

πd^2 : focus area (m^2)





- for LUXE Phase-0: existing 40TW JETI40 (Jena) laser will be used (alternatively: custom LASER)
- LUXE Phase-1: upgrade to 350TW laser system
- thanks to electron boost, don't need to push limits of current state-of-the-art of laser intensity
- electrons 10Hz, laser 1 Hz → 9 bunches for background measurements, calibration shots etc
- BUT: need exceptional shot-to-shot stability! → precision LASER diagnostics

Laser Stability

Energy, positron, focus

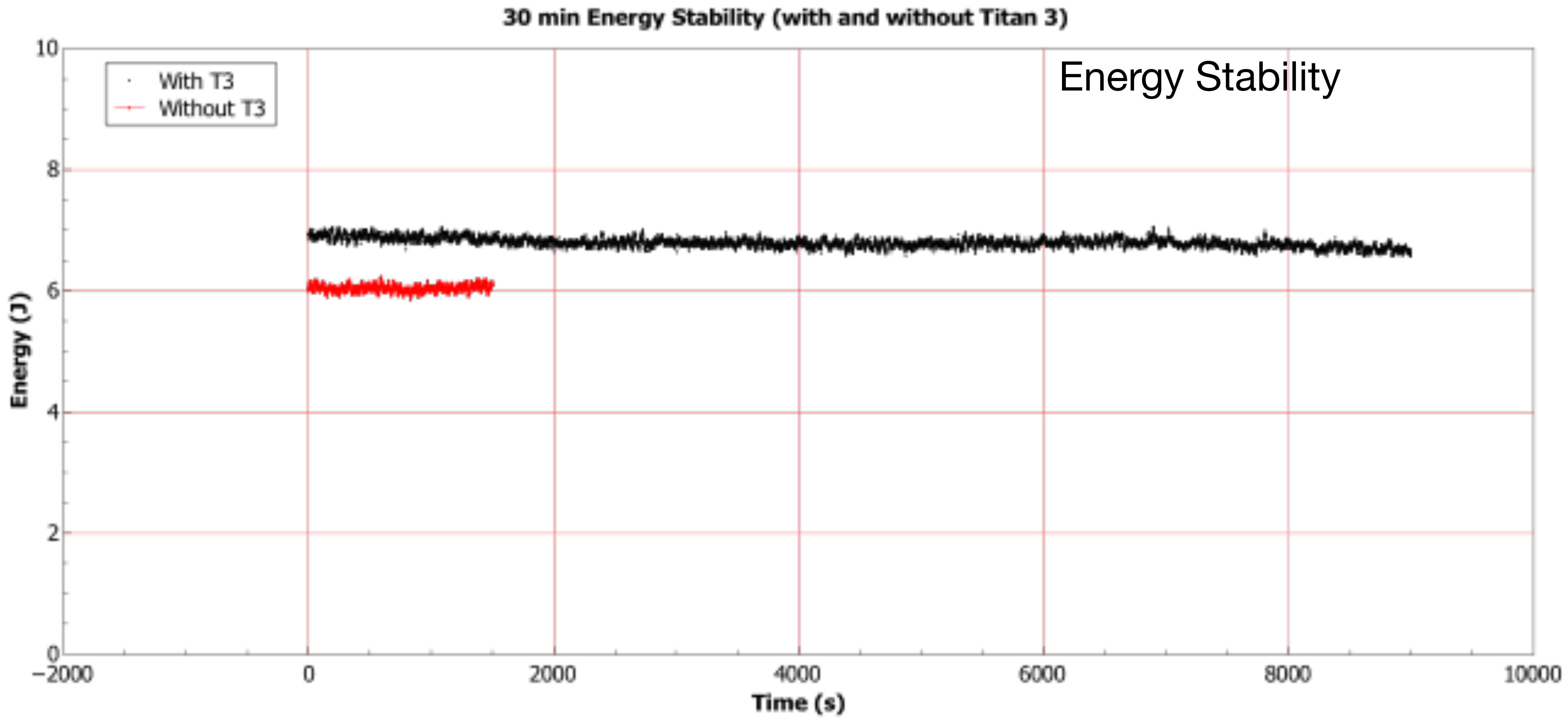
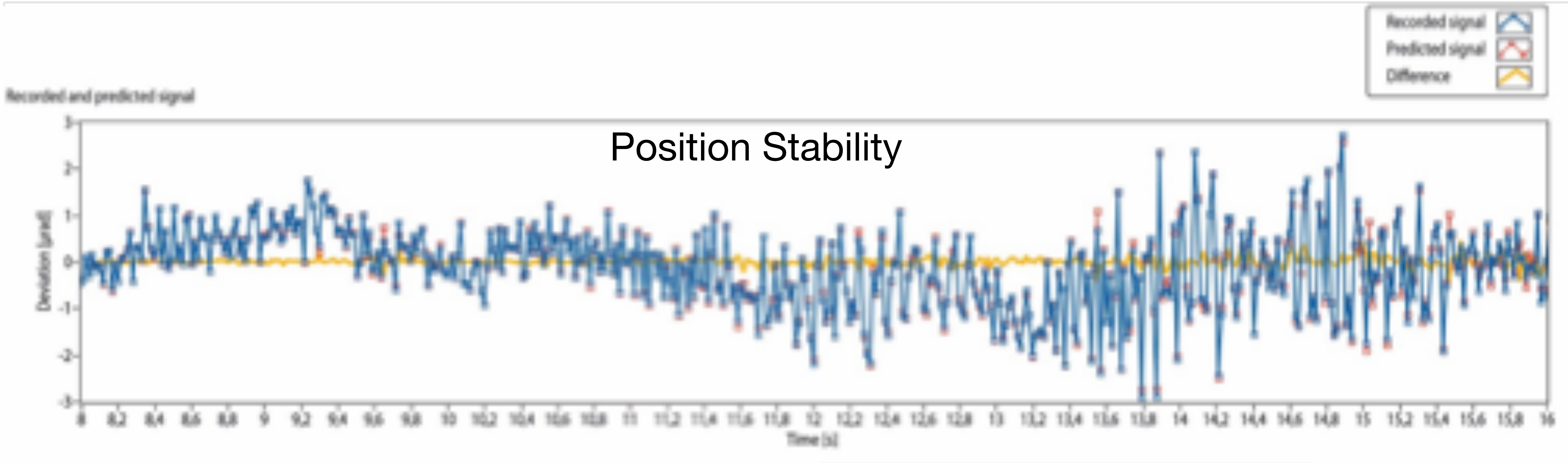
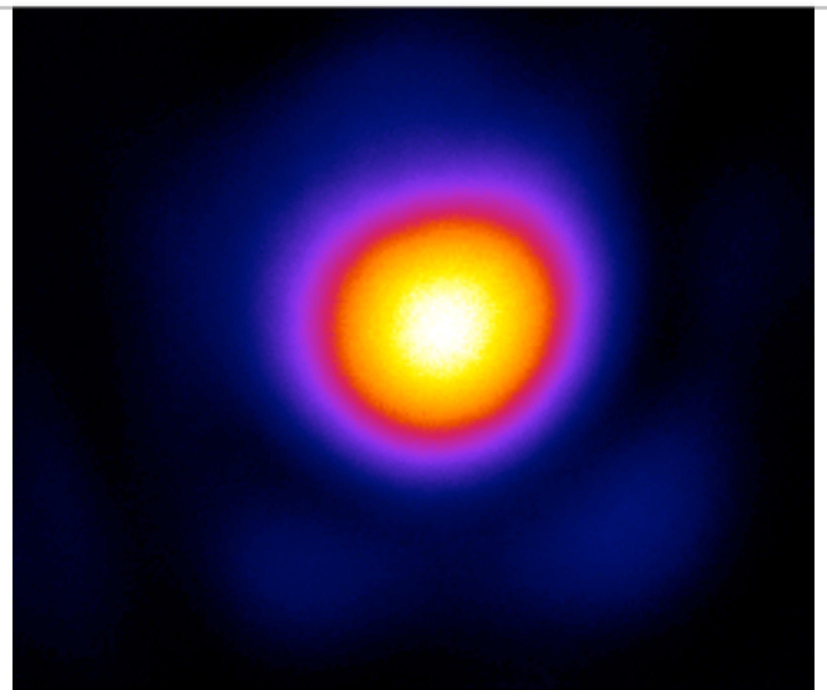
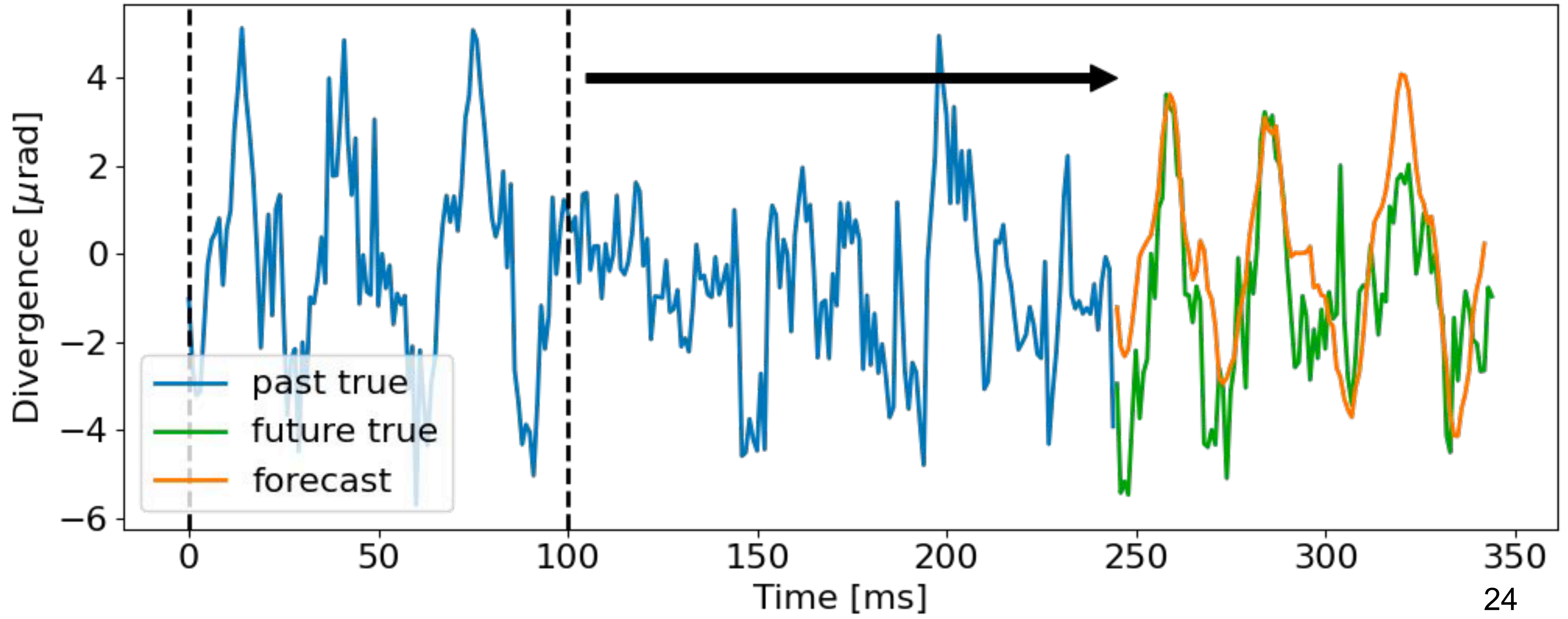


Figure 2: 30 mn energy stability



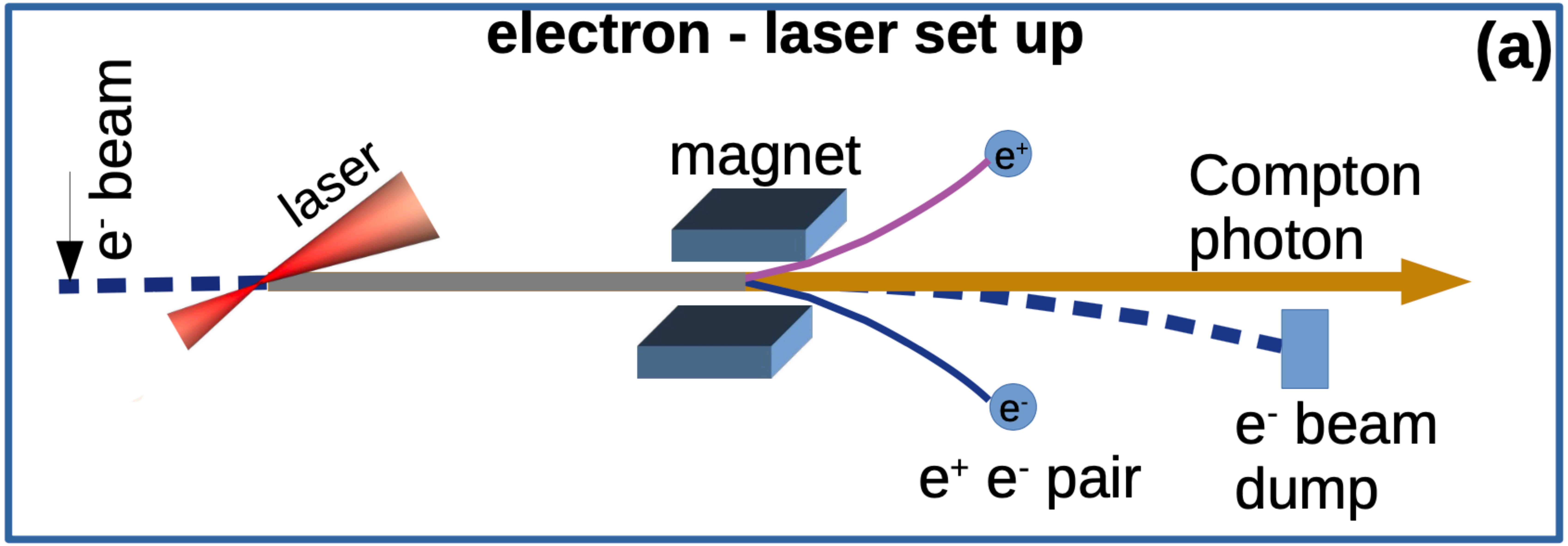


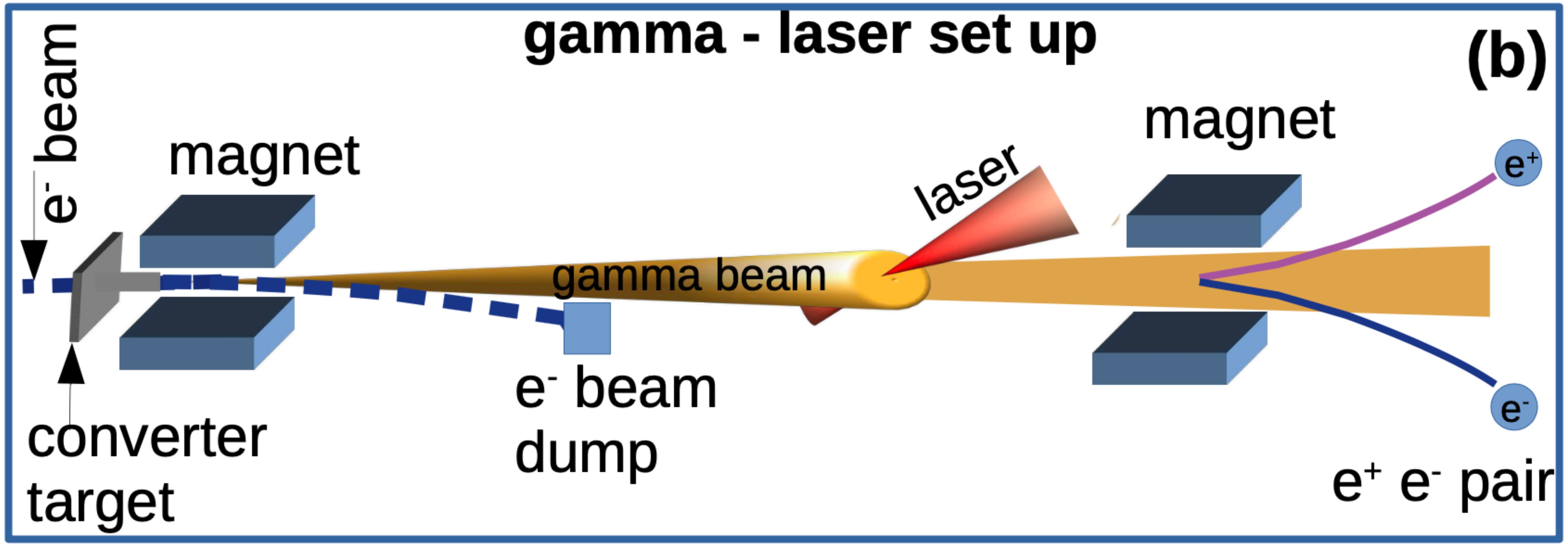
- System tested in Jena at JETI40 and JETI200 lasers.
  - Energy stability measure <1.13%
  - Focal intensity distribution
    - Measured at 10% RMS
  - Position stability is extremely important as it is challenging to overlap
    3 μm laser with <10 μm e-beam focus.
    - Jitter due to vibrations
    - Can be corrected with recurrent neural net approach.



Data Taking Modes

Two setups

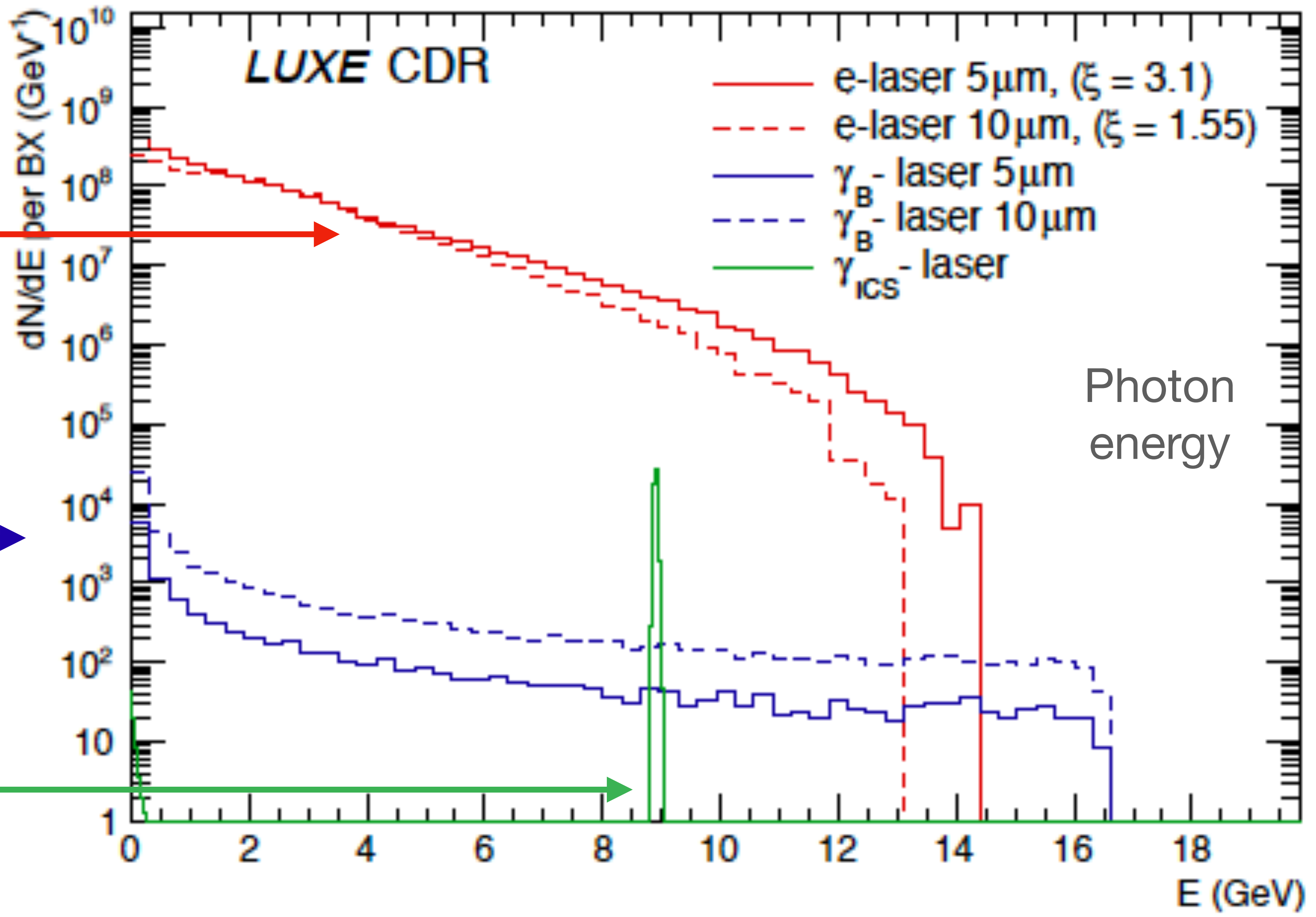


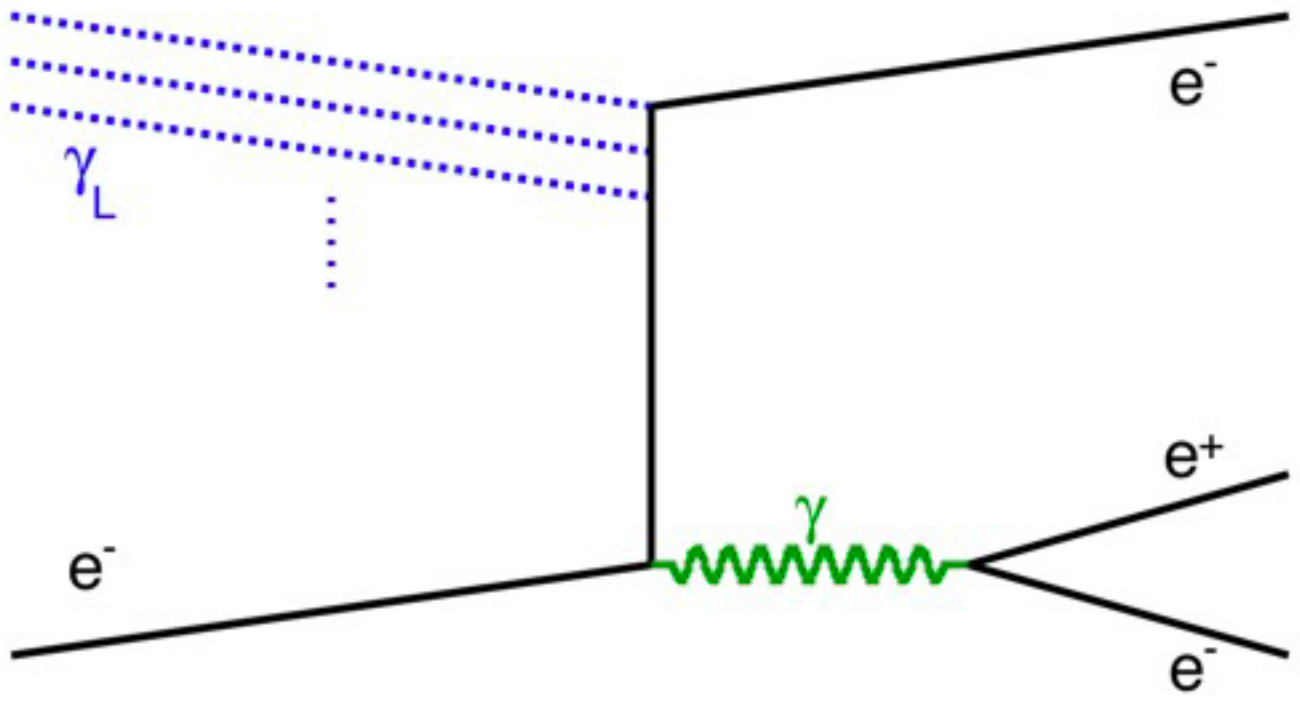


e+e- Pair Production Modes

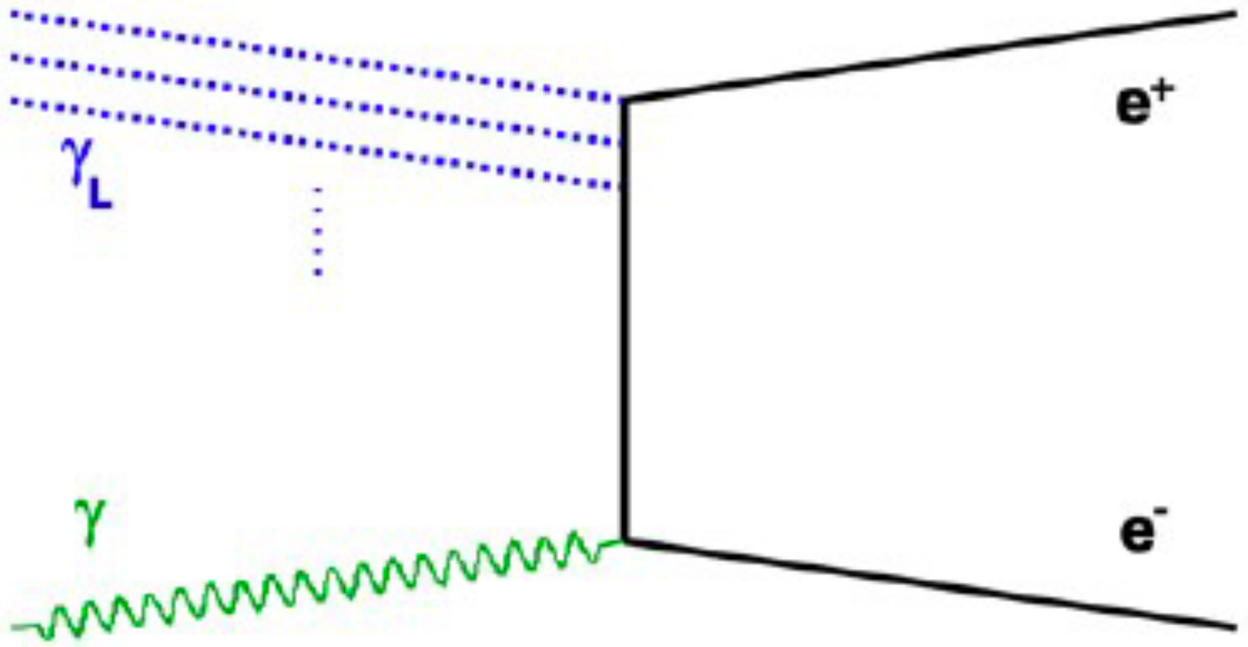
Three methods with different energy ranges

- Compton scattering with interaction between Compton photon and laser.
  - Largest rate via trident production
  - e-laser mode
- Bremsstrahlung photons produced upstream (with target).
  - Highest energy available.
  - gamma-laser mode.
- Compton photon produced upstream.
  - Monochromatic photon source: E=9 GeV.
  - gamma-laser mode via Inverse Compton Scattering

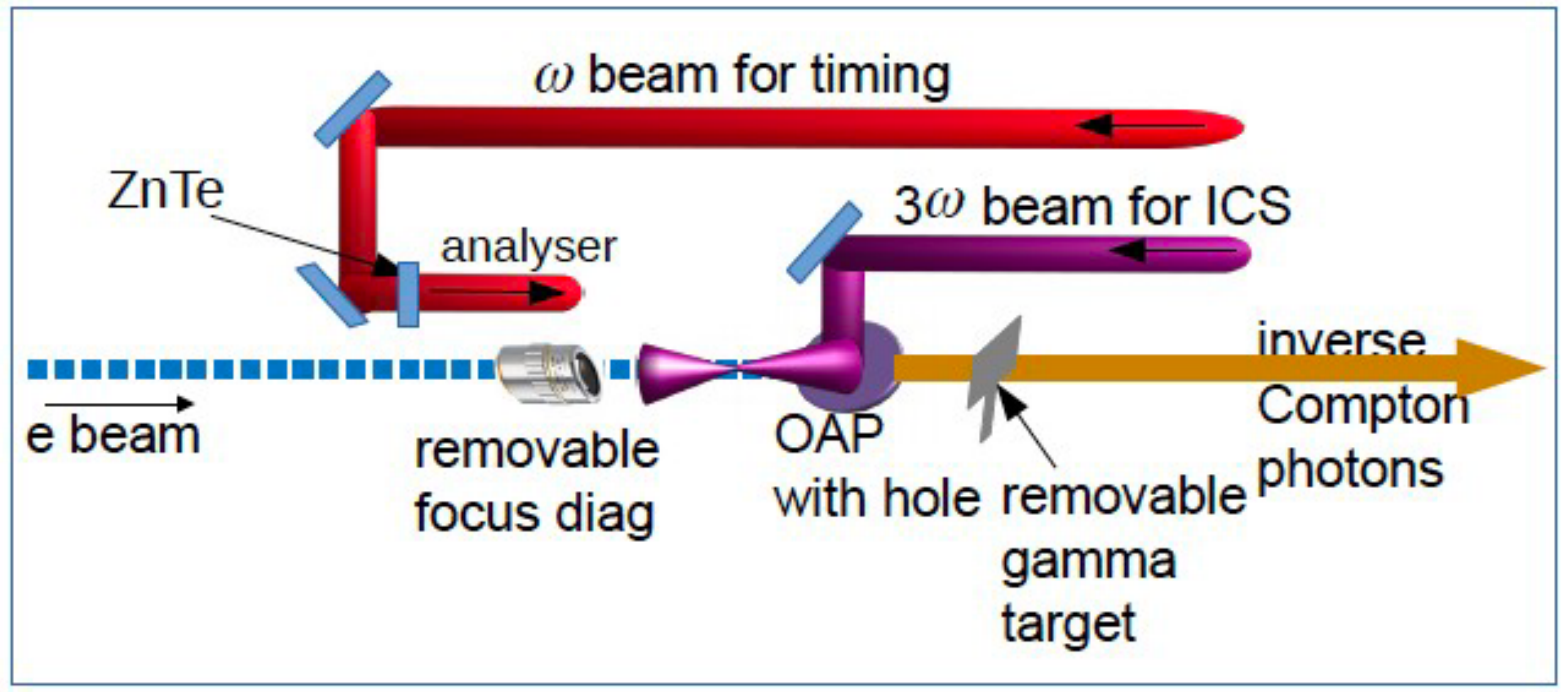




Trident



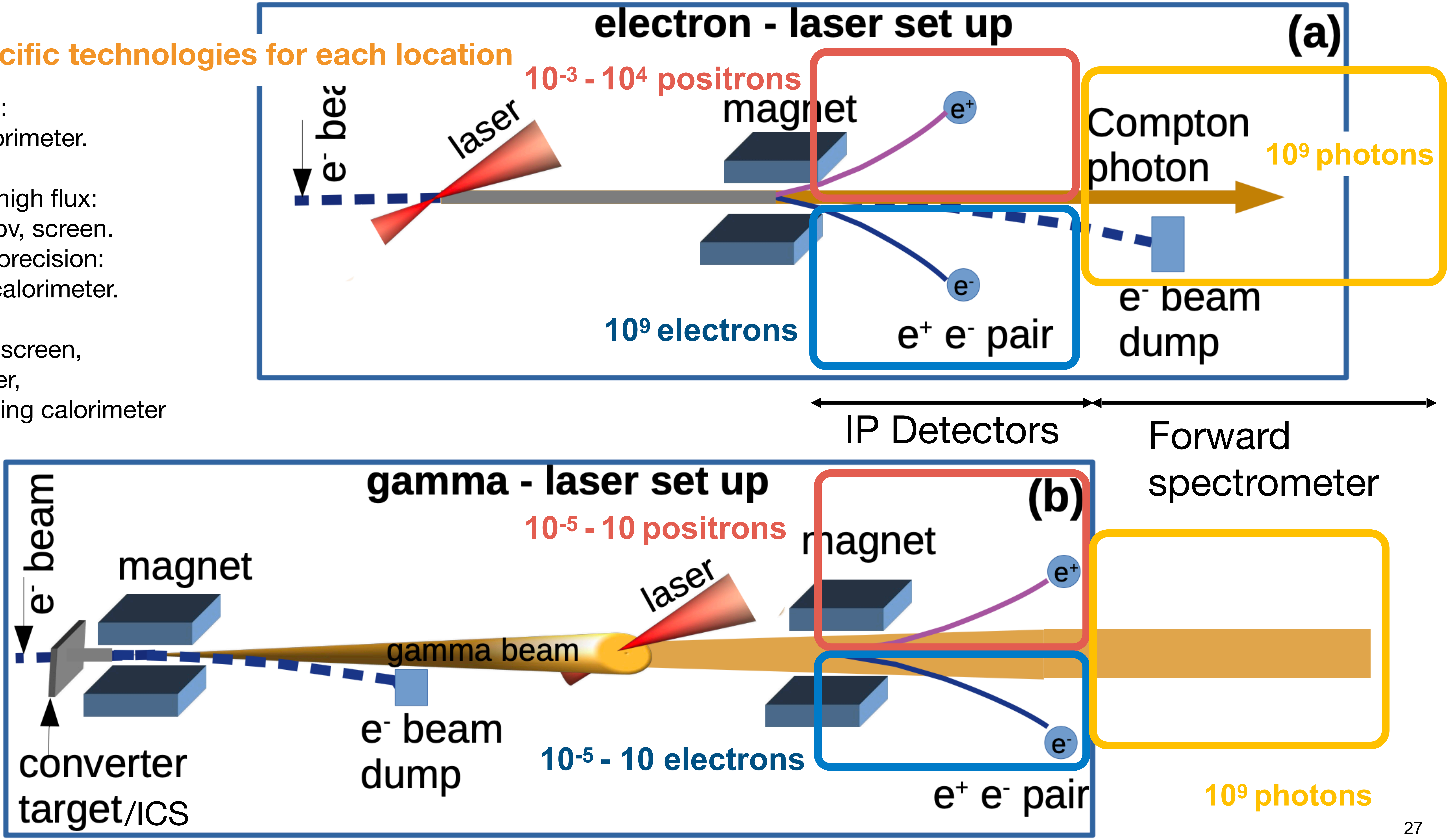
Breit-Wheeler



Rates

Need specific technologies for each location

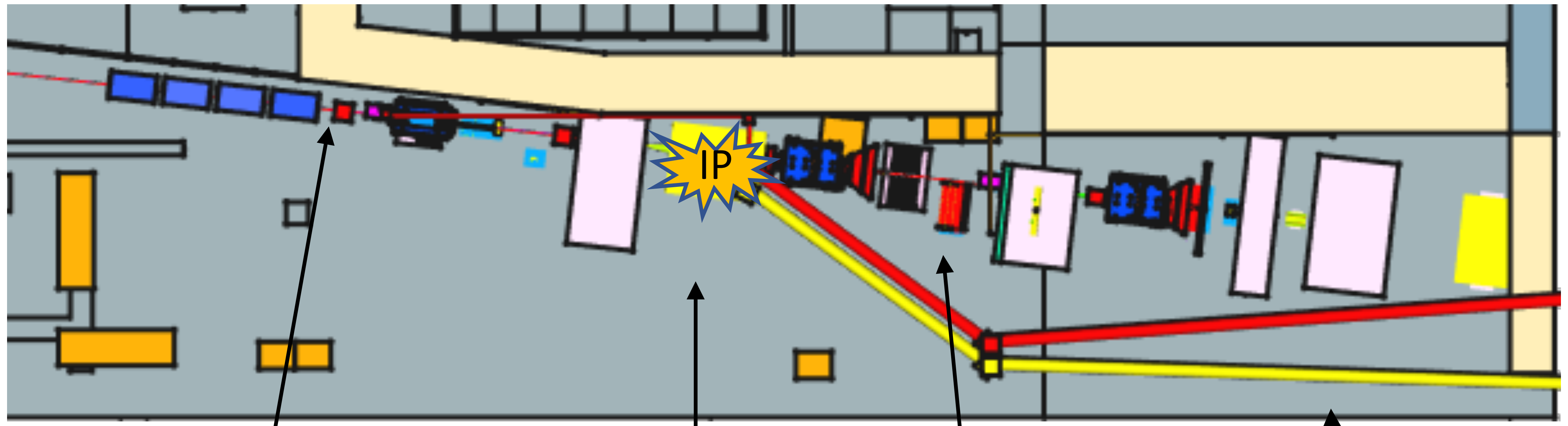
- e+ precision: tracker, calorimeter.
- e-
  - (e-laser) high flux: Cherenkov, screen.
  - (ɣ-laser) precision: tracker, calorimeter.
- ɣ high flux: scintillating screen, beam profiler, backscattering calorimeter



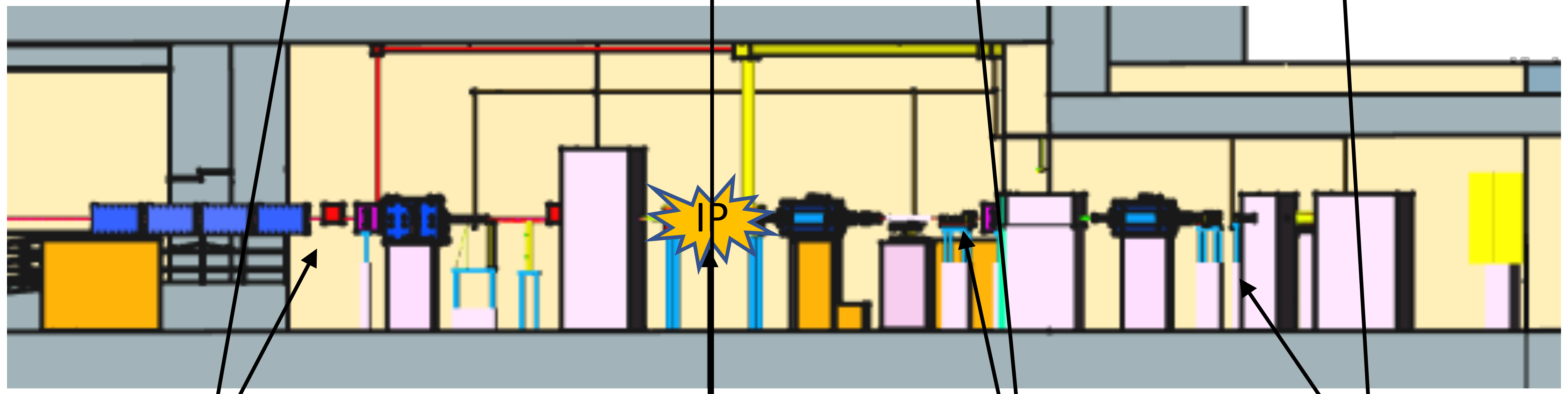
What will it look like?

CAD & Geant4

CAD:



top view of experimental area



side views of experimental area

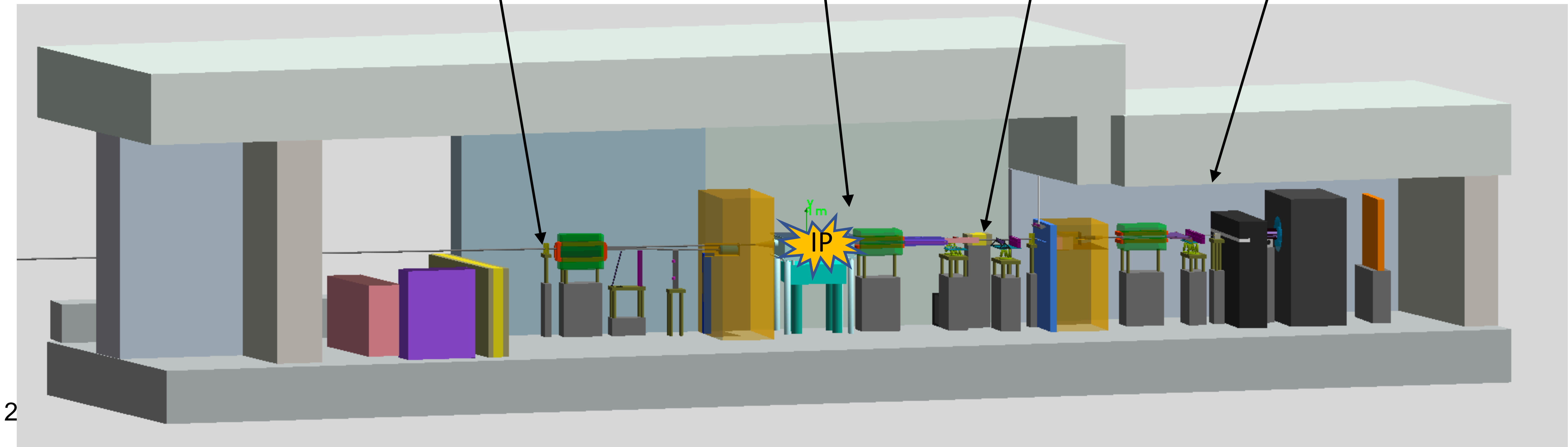
Bremsstrahlung Target

Interaction Point

IP detectors

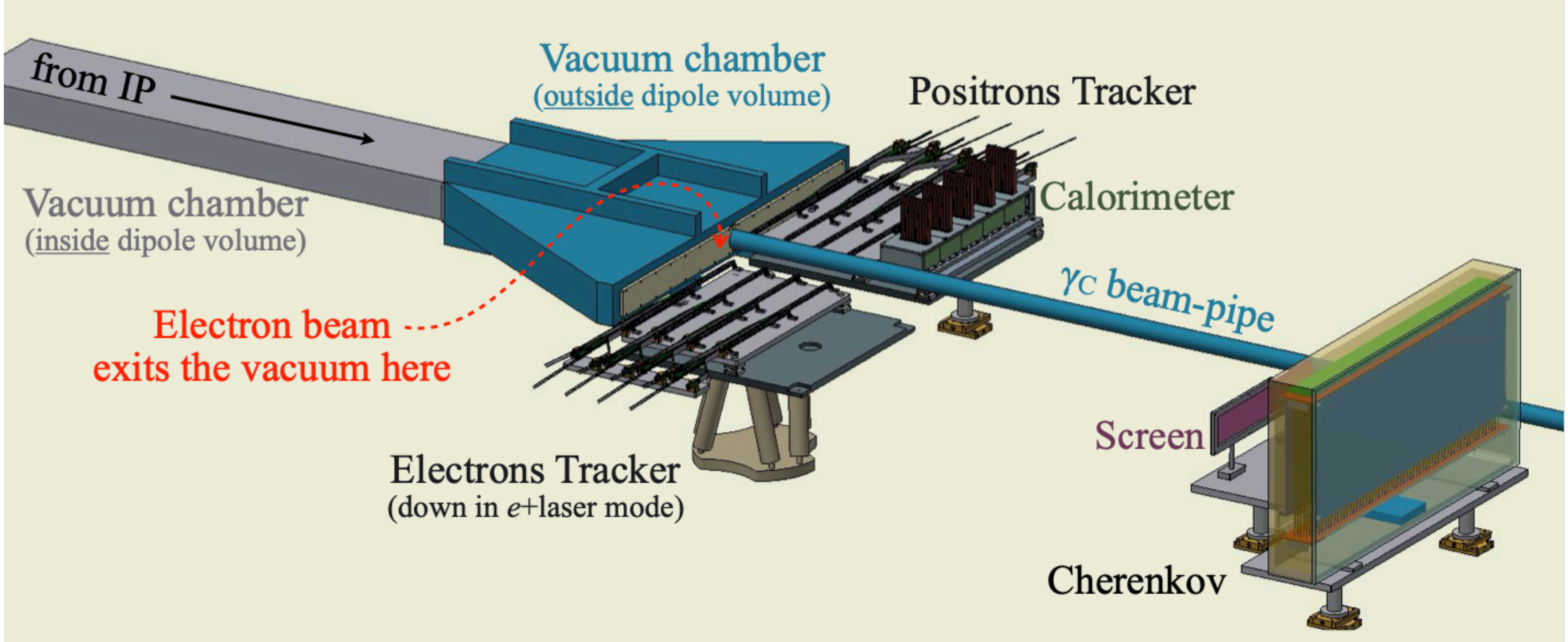
Gamma forward spectrometer

Full Geant4 simulation:



The Electron & Positron Systems

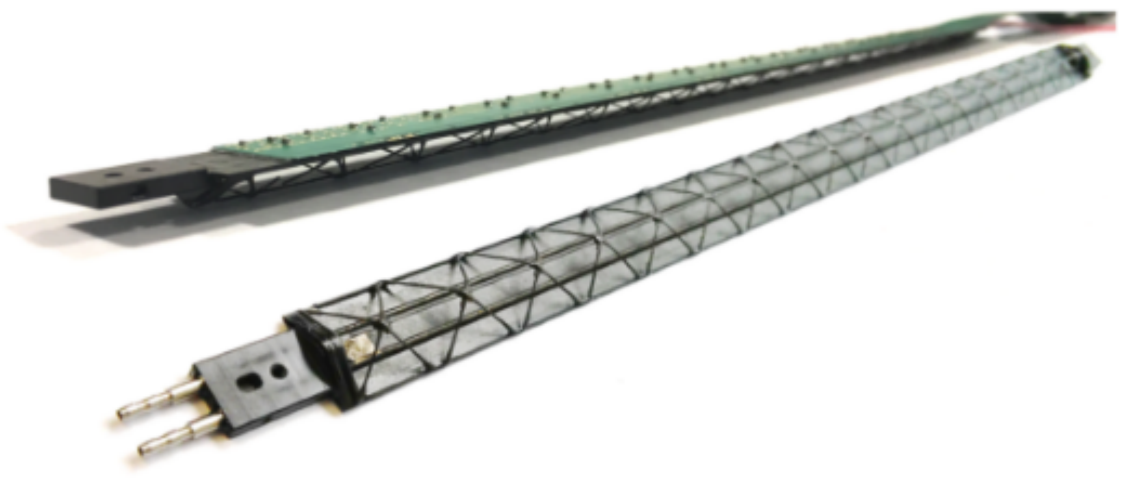
Overview



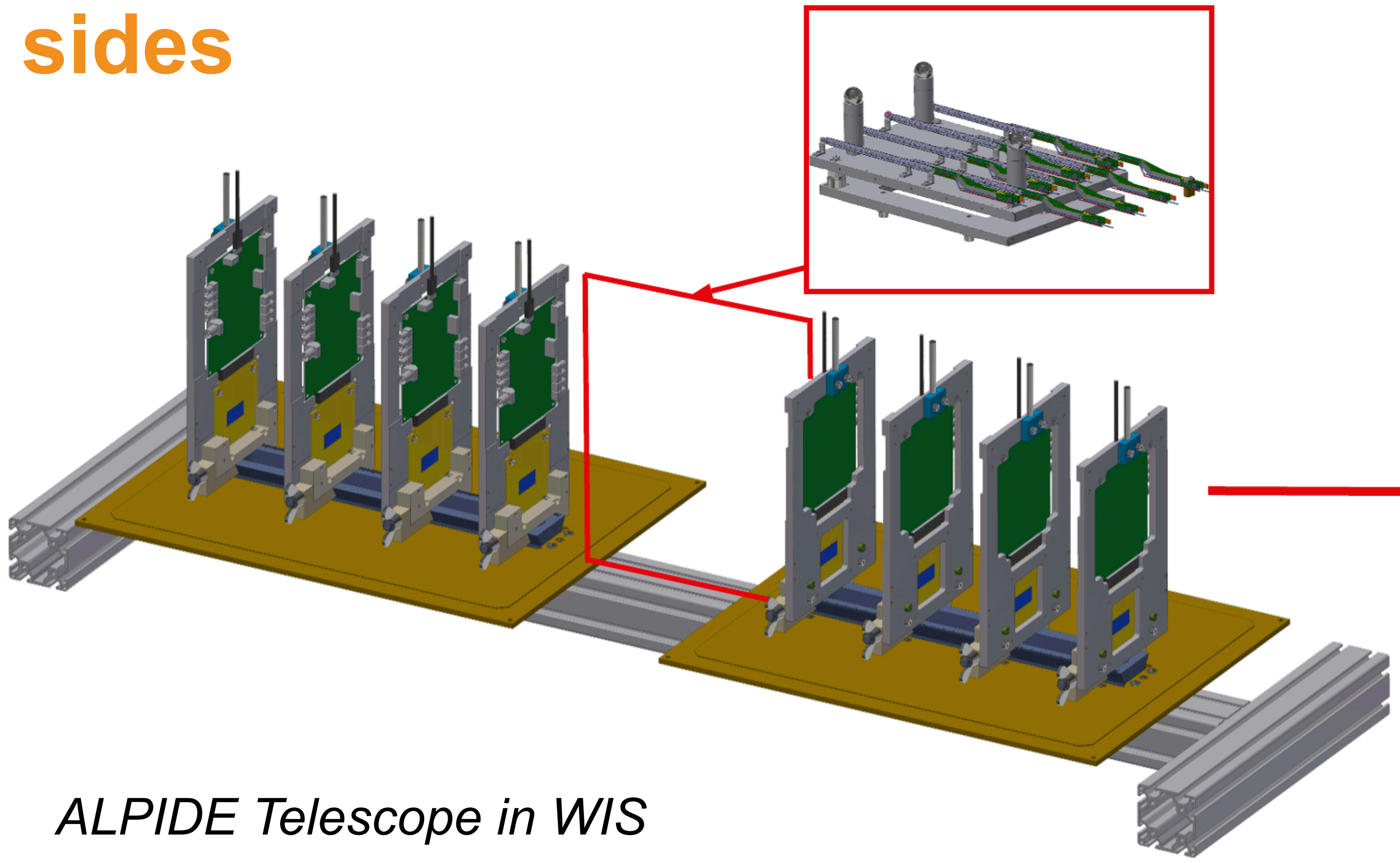
- Two complementary detector technologies per measurement:
- Cross-calibration, reduction of systematic uncertainties.

The Pixel Tracker

e-laser: positron side, γ-laser: both sides

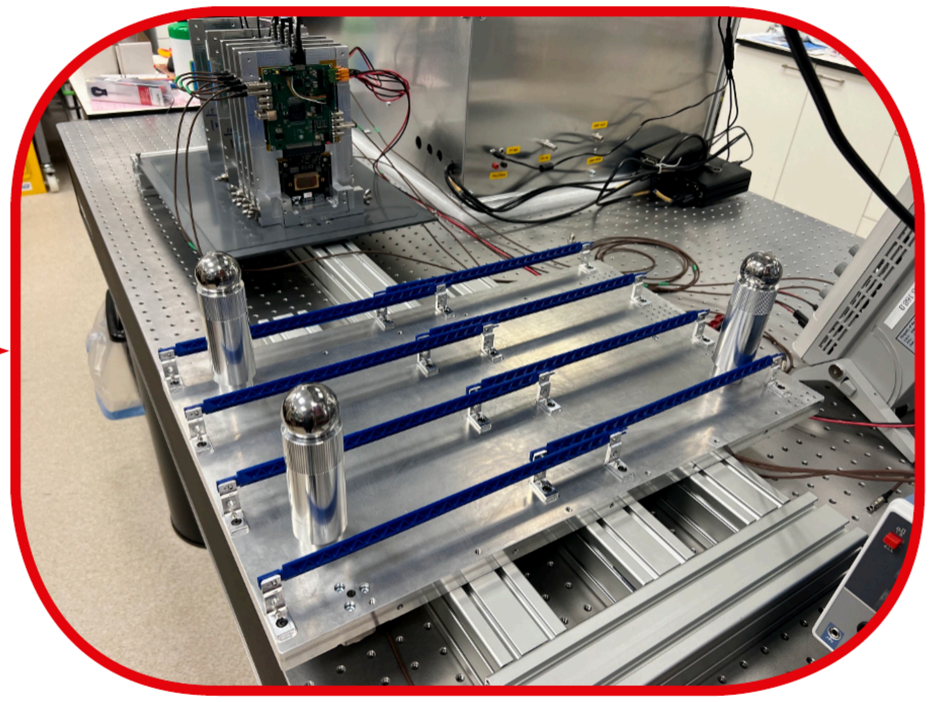


ALPIDE tracking detector stave



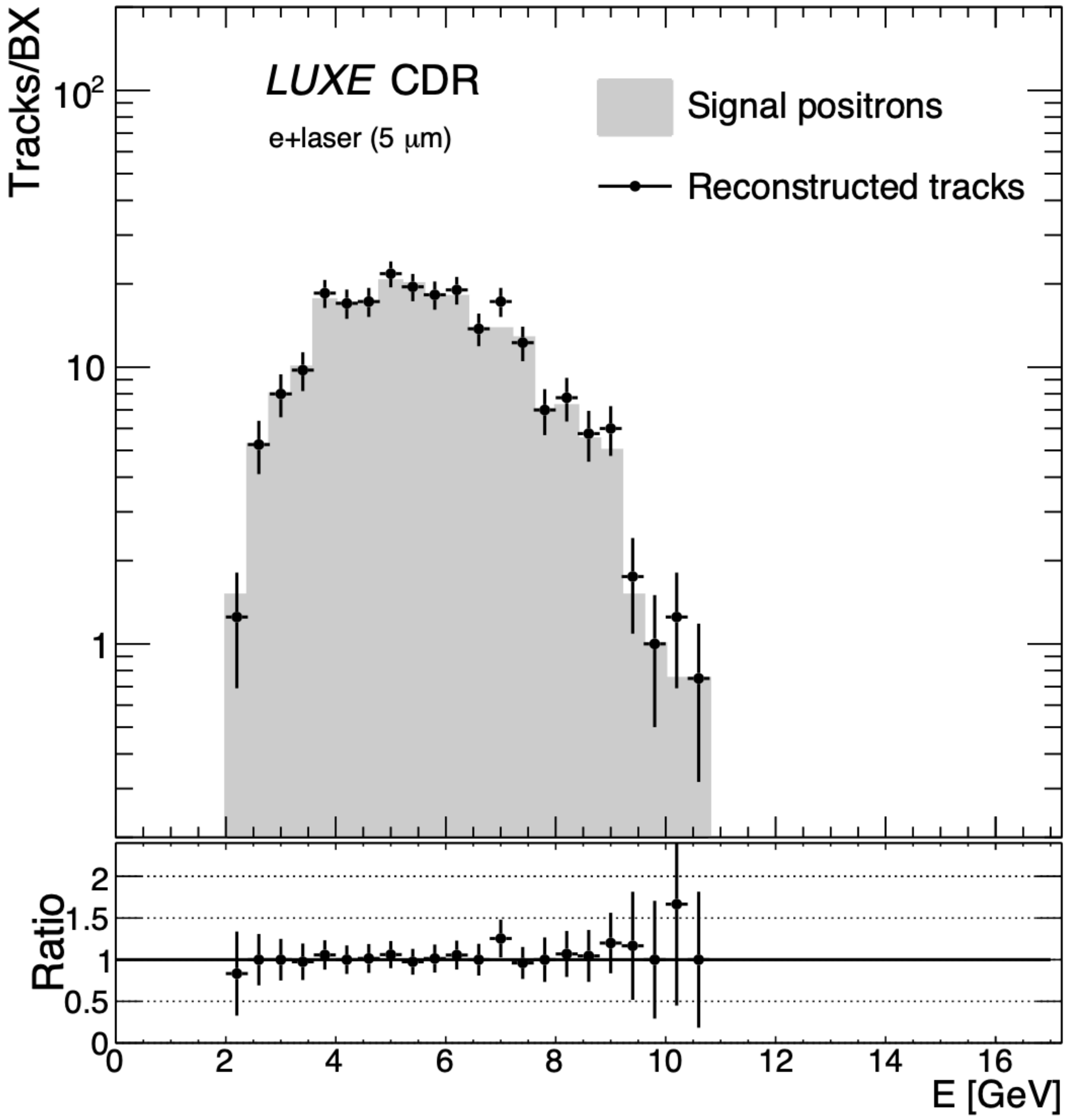
ALPIDE Telescope in WIS

Mockup of electron tracker



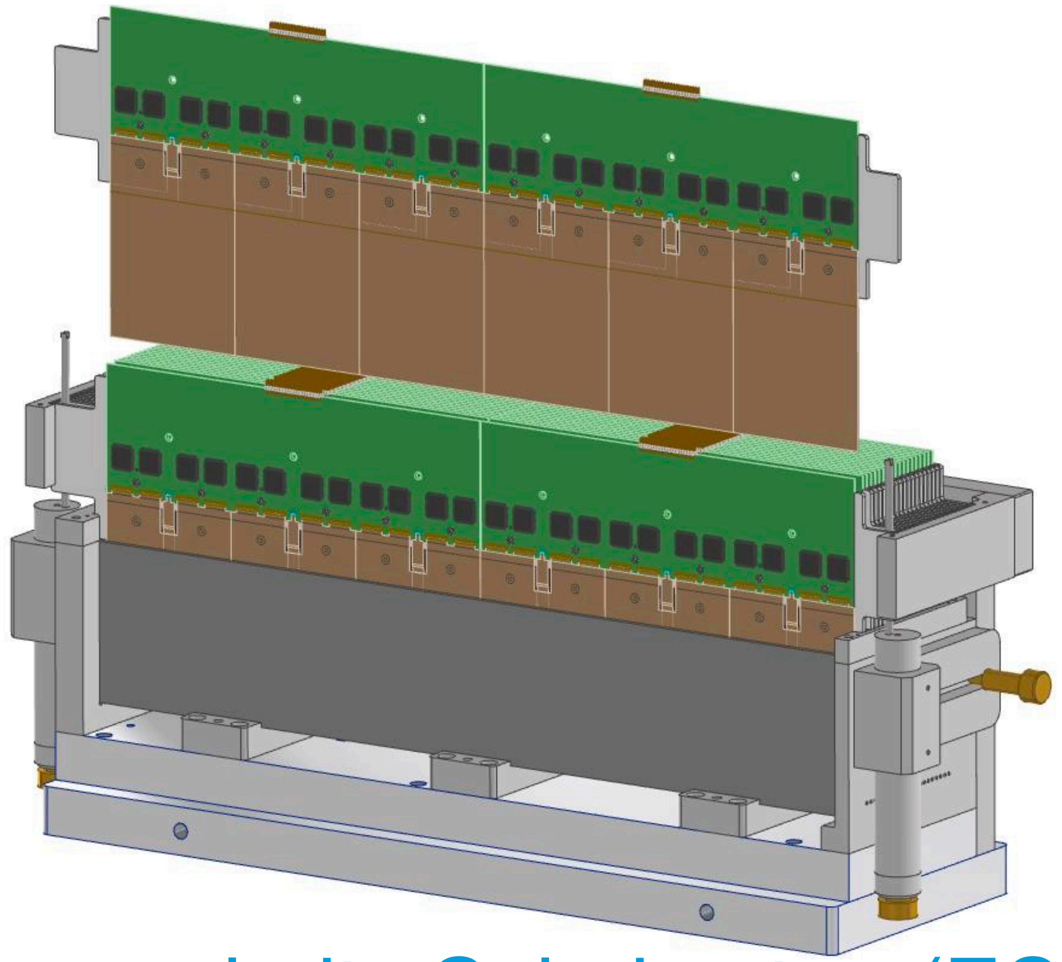
- four layers of ALPIDE silicon pixel sensors
  → developed for ALICE pixel tracker upgrade
- pitch size (27 x 29 µm), 5 µm resolution
- Radiation hard (99.5 to 98% efficiency after 1MRad).
- tracking performance: $\varepsilon > 98\%, \quad \frac{\delta p}{p} \approx 0.3\%$
- very small background (<0.1 event / bunch crossing)
- Telescope built in WIS.
- Plan to get full system in fall 2023.
- Test beam will follow until installation.

High signal efficiency, high resolution!

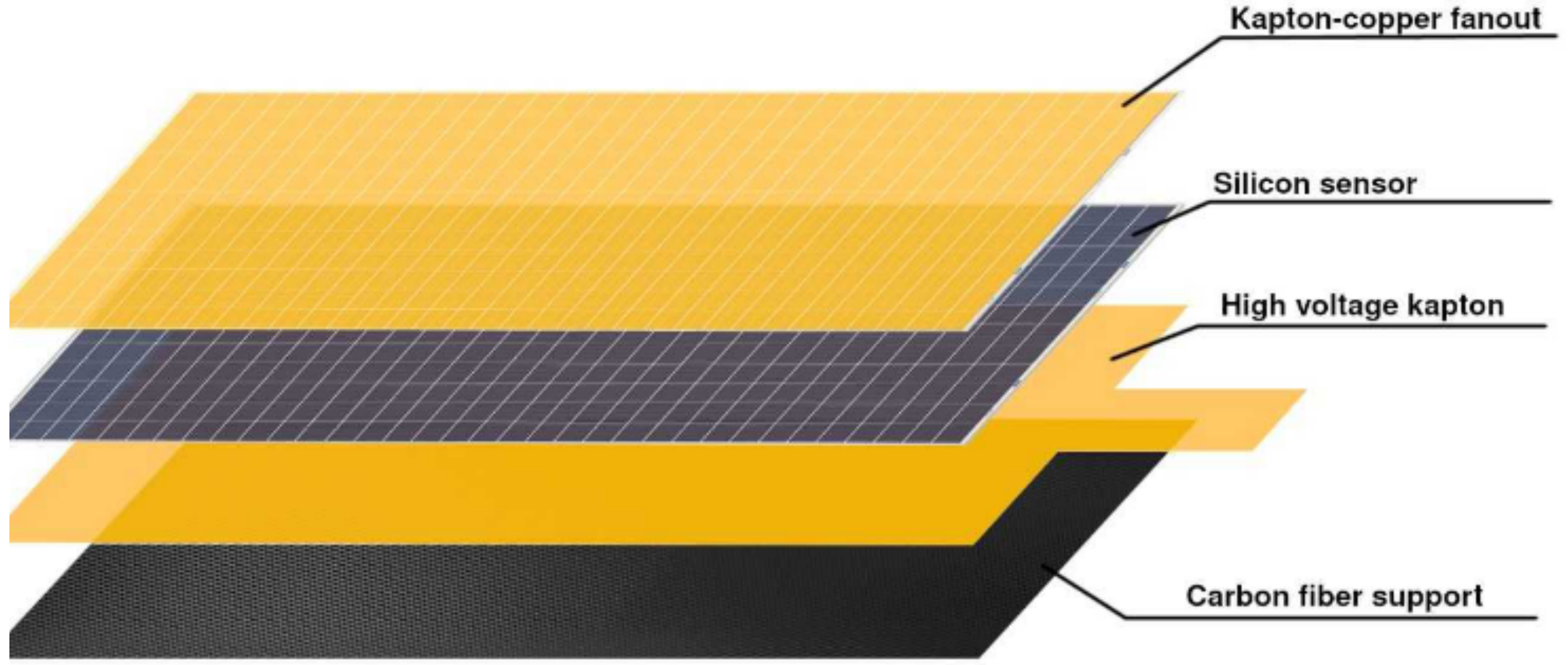


Electromagnetic Calorimeter

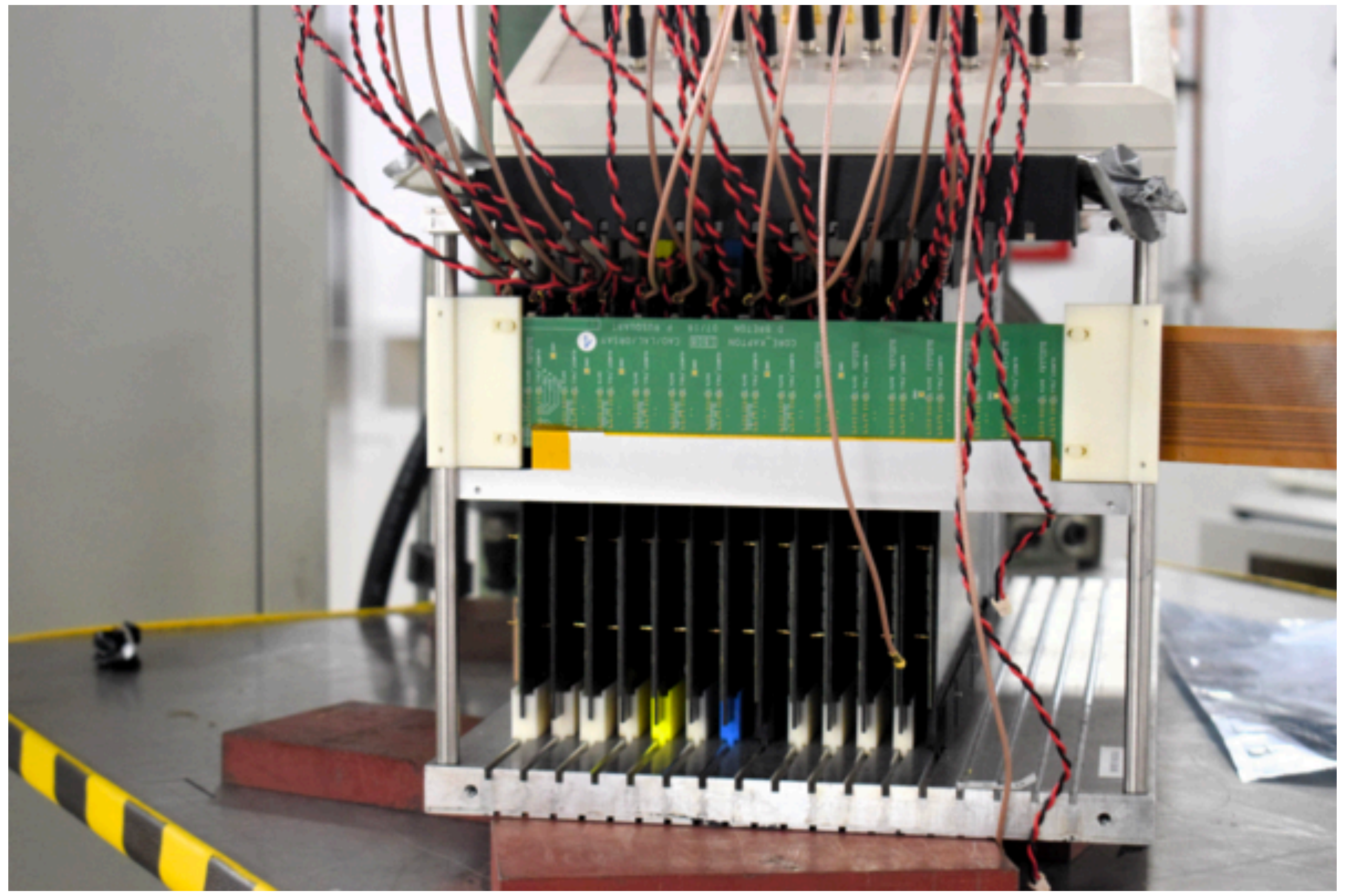
e-laser: positron side, γ-laser: both sides



Ecal-P model



High-granularity ECAL layer

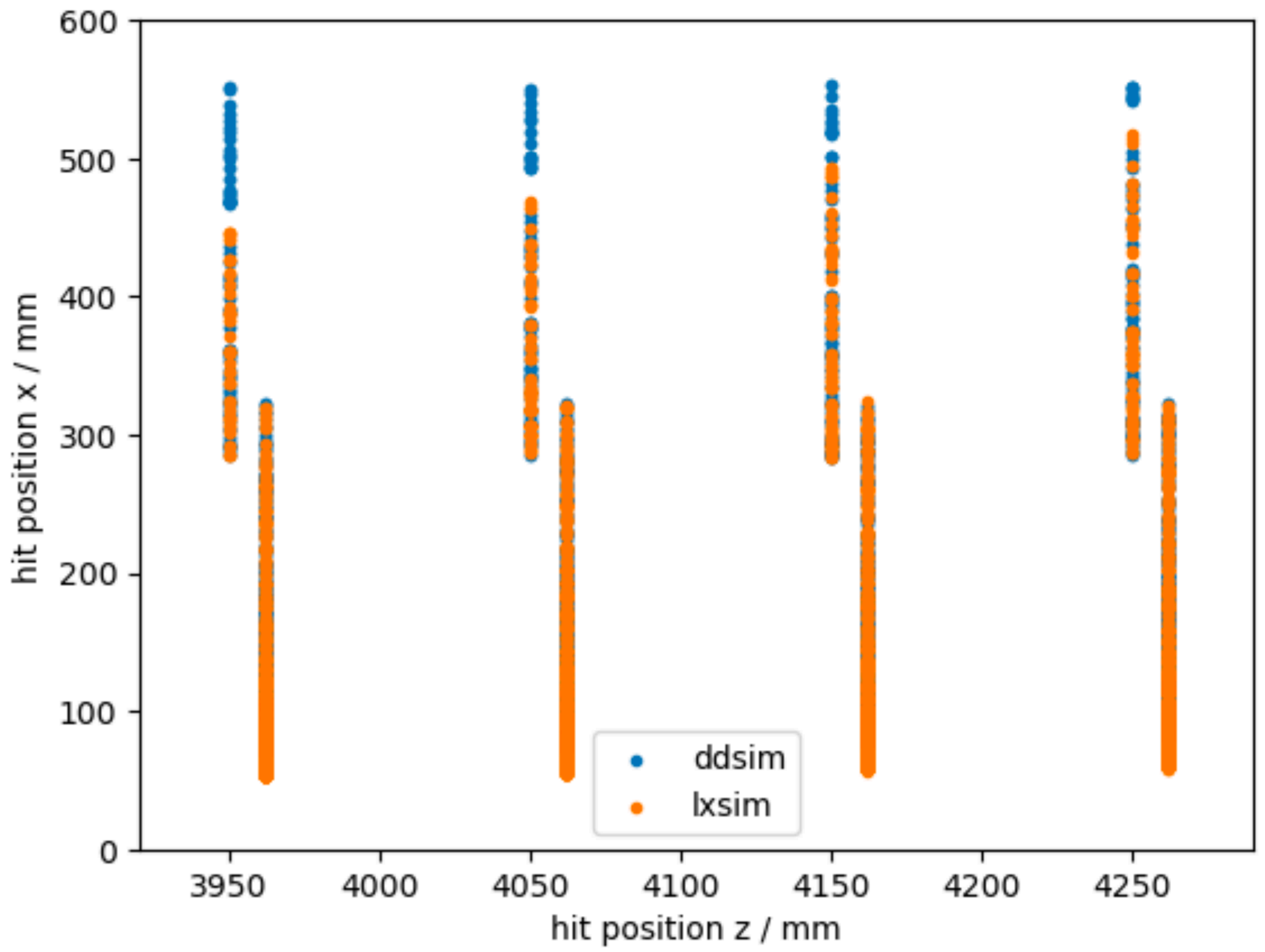


ECAL-E prototype

- Si High-granularity Calorimeter: (ECAL-P - e-laser)
  - Based on Forward Calorimeter for ILC (FCAL). Read out by FLAME ASIC.
  - 20-layer sampling calorimeter (15 active layer) – high granularity: independent energy measurement through shower and positio
  - Energy $\frac{\sigma_E}{E} = \frac{19.3\%}{\sqrt{E/GeV}}$, position: $\sigma_x = 0.78\ mm$
  - shower medium: 3.5mm Tungsten plates ($1X_0$), active medium: Silicon sensors ($9x9cm^2$, 320µm thick).
  - Procurement of sensors started.
- Si High-granularity Calorimeter: (ECAL-E - γ-laser)
  - Based on ILC ECal. Read out by SKIROC2A ASICs.
  - 15-layer sampling calorimeter – high granularity: independent energy measurement through shower and position
  - shower medium: Tungsten plates ($21X_0$), active medium: Silicon sensors ($5x5cm^2$, 500µm thick)
  - Prototype of detector exist, assembly of 15 layers for LUXE scheduled for 2024.

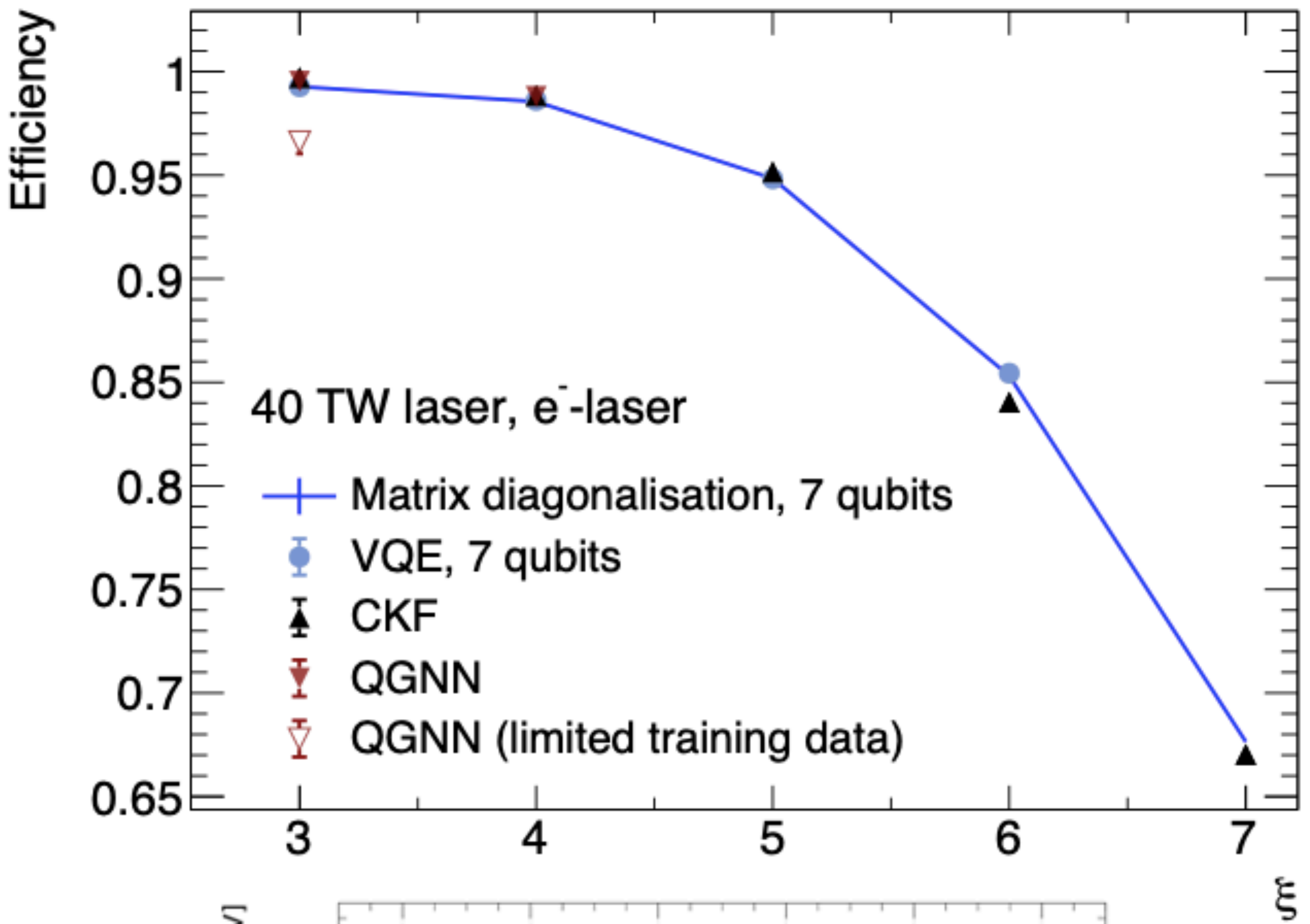
Reconstruction performance

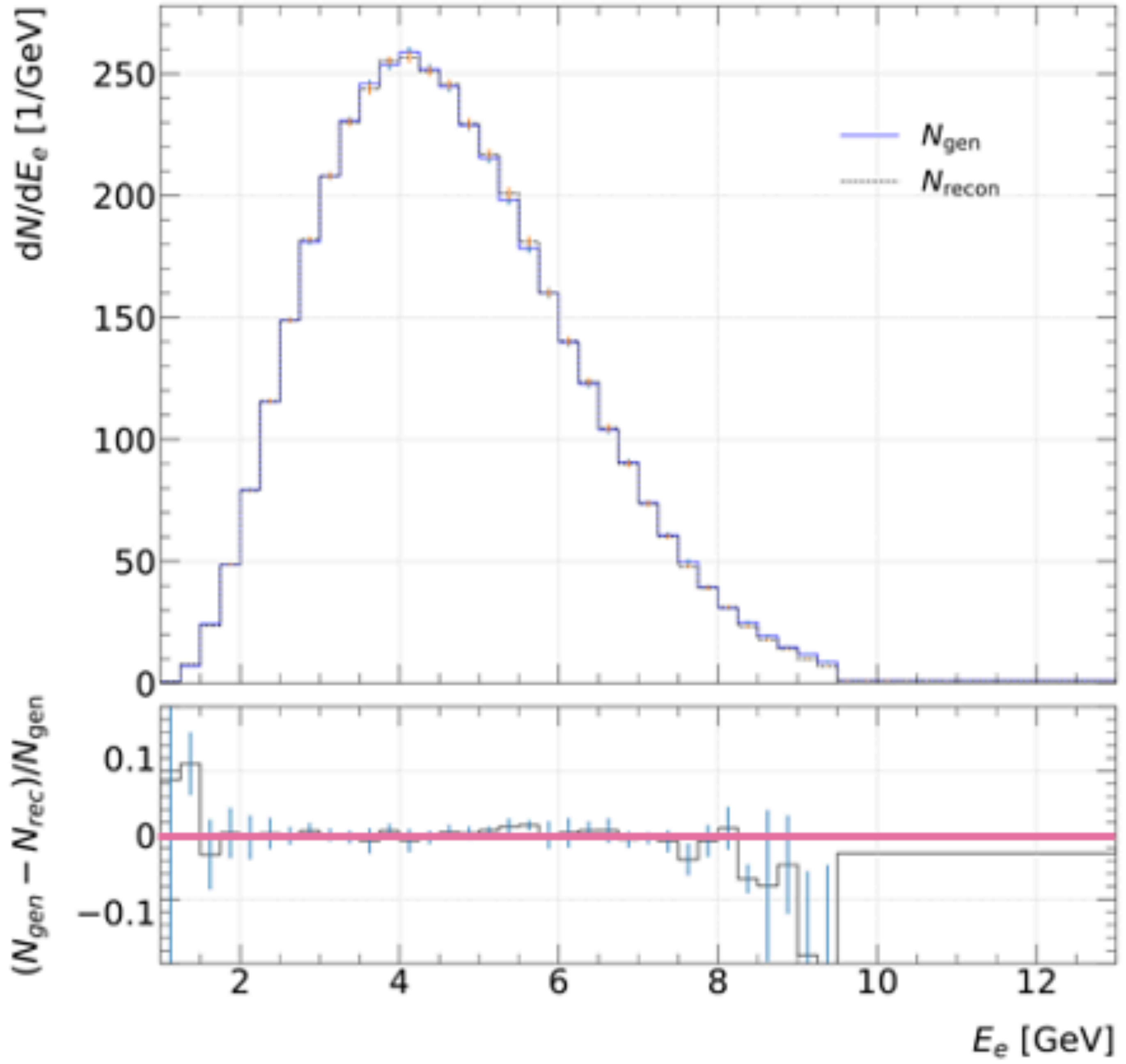
Tracking Efficiency and ECal Energy Reconstruction



Key4hep

acts





- First implementation of the detector geometry in Key4HEP:
  - Tracker geometry in DD4HEP used as guinea pig.
  - Allows out of the box usage of tracking with ACTS.
  - Next: implementation of the calorimeter.

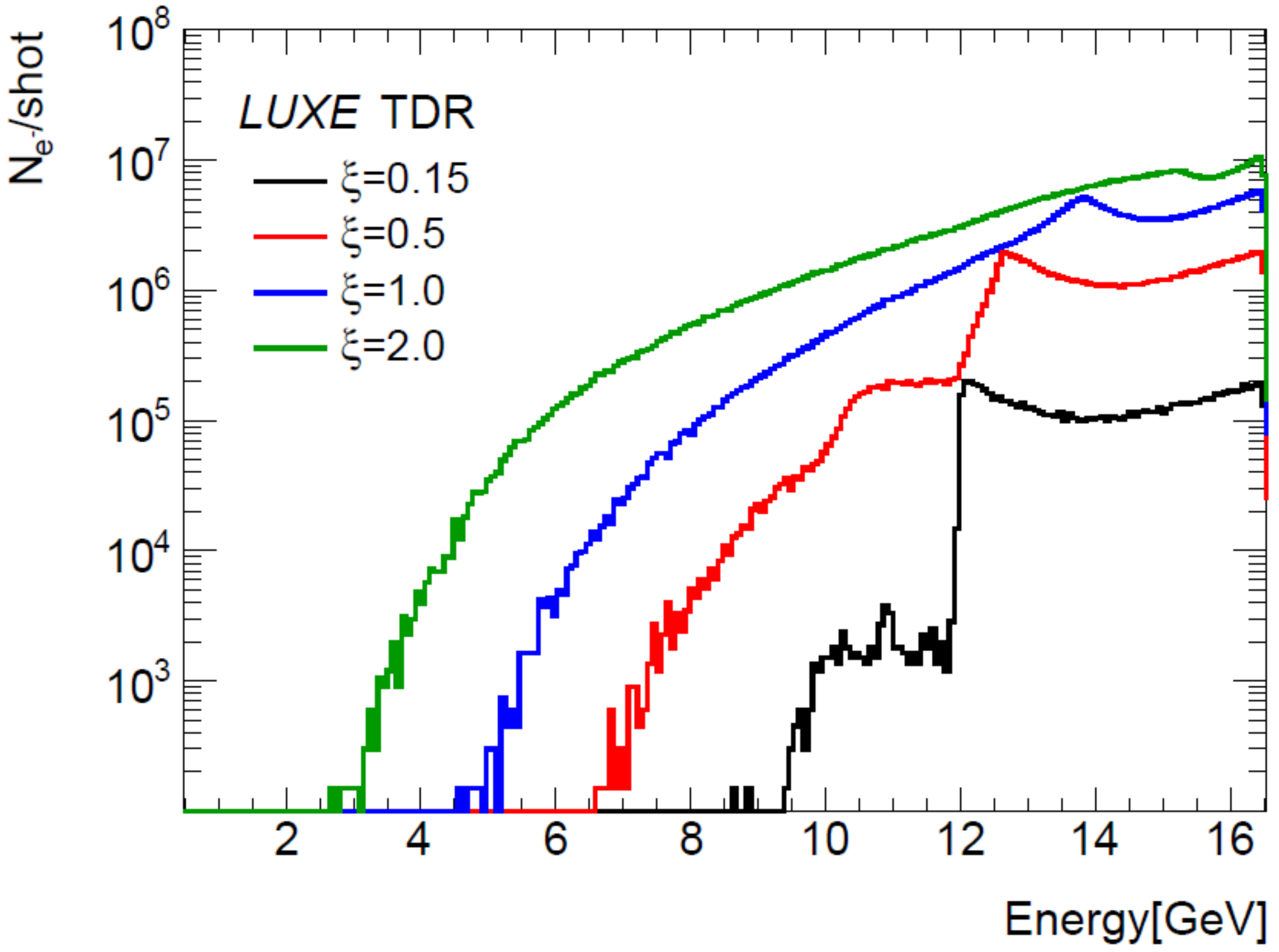
  => full ParticleFlow roconstruction!

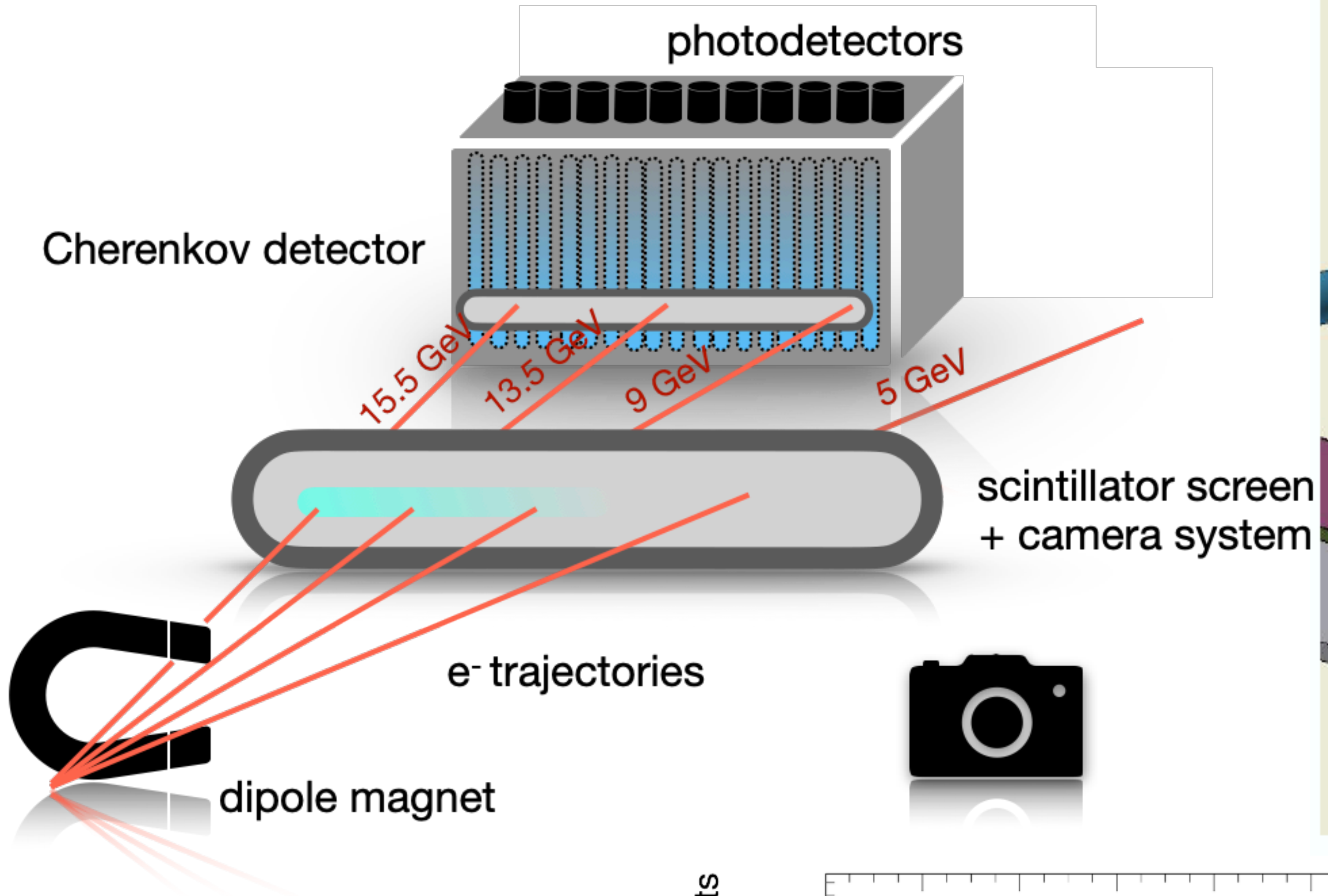
- Given high occupancy expected in detectors need to develop modern reco algo.
  - Tracking with quantum computing.
  - Calorimeter energy reconstruction with ML.

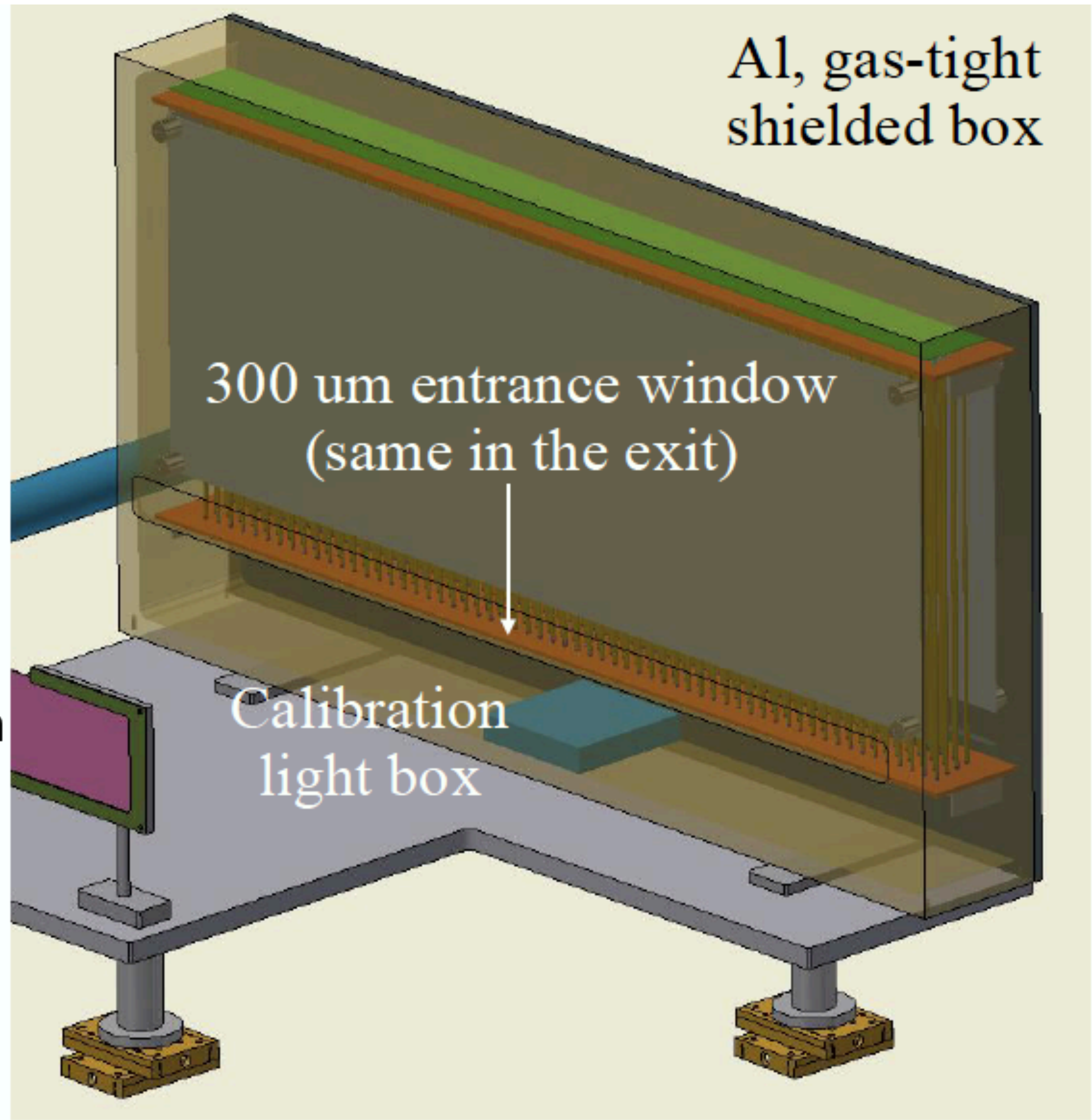
  => Results in agreement with standard algorithms.

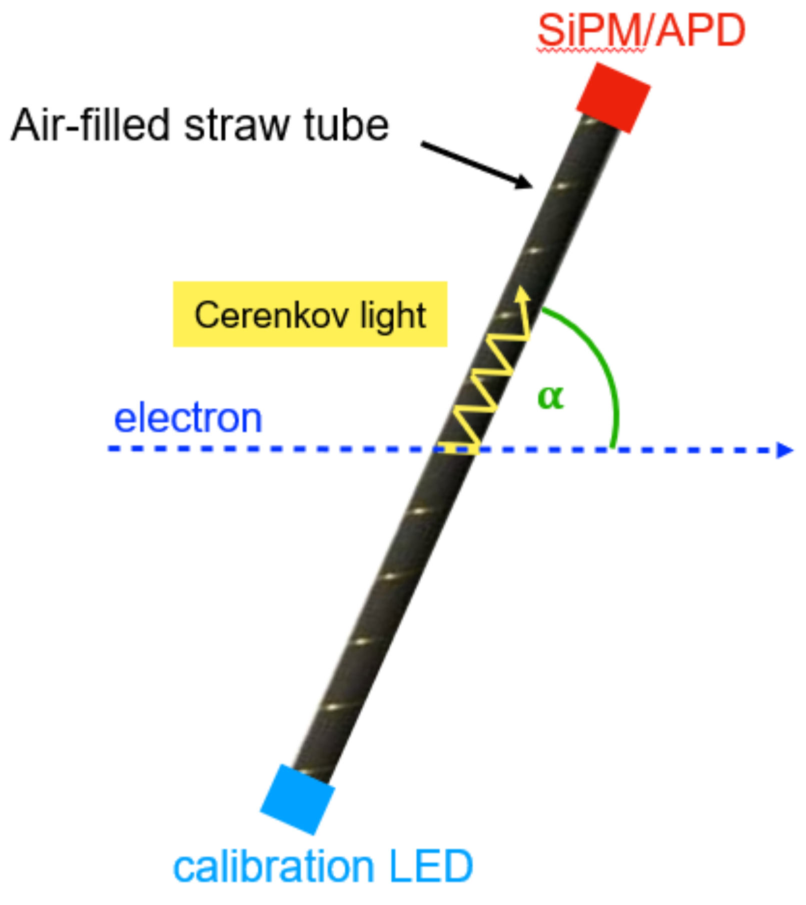
High-Rate Electron Detection System

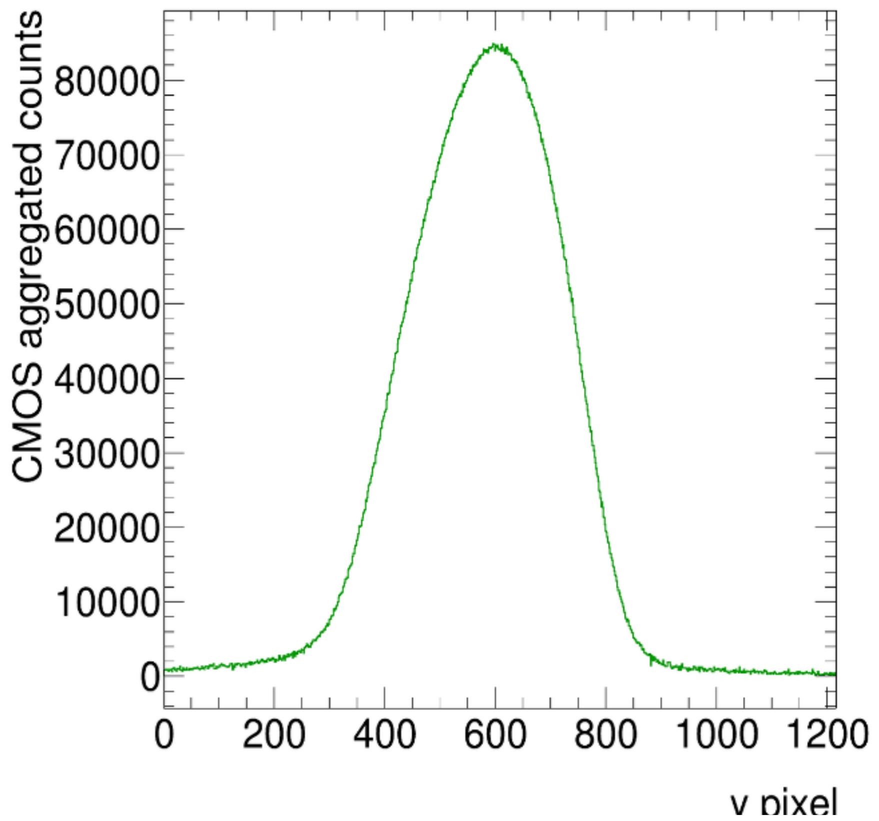
e-laser: IP electron side, γ-laser: brems target instrumentation

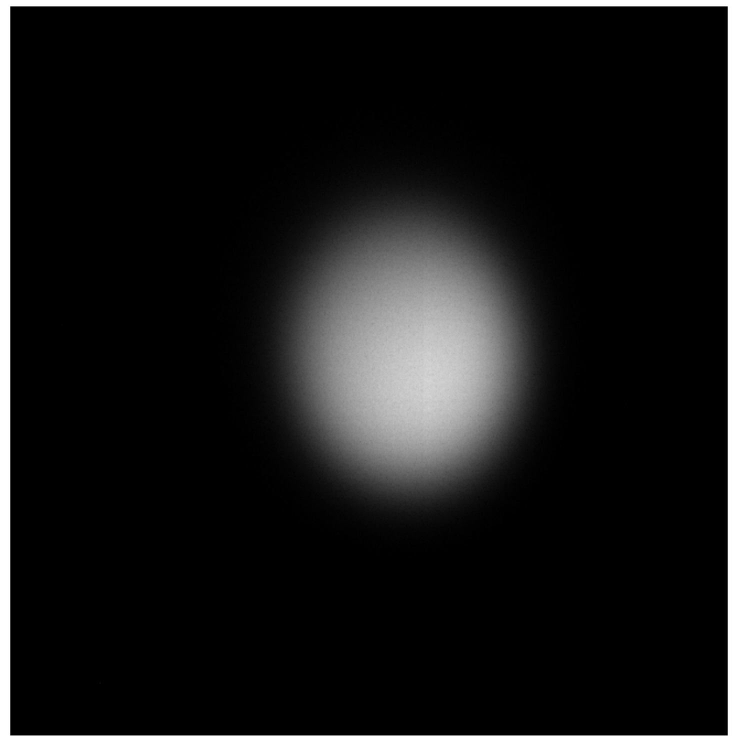












Beam spot imaged on Scint. Screen

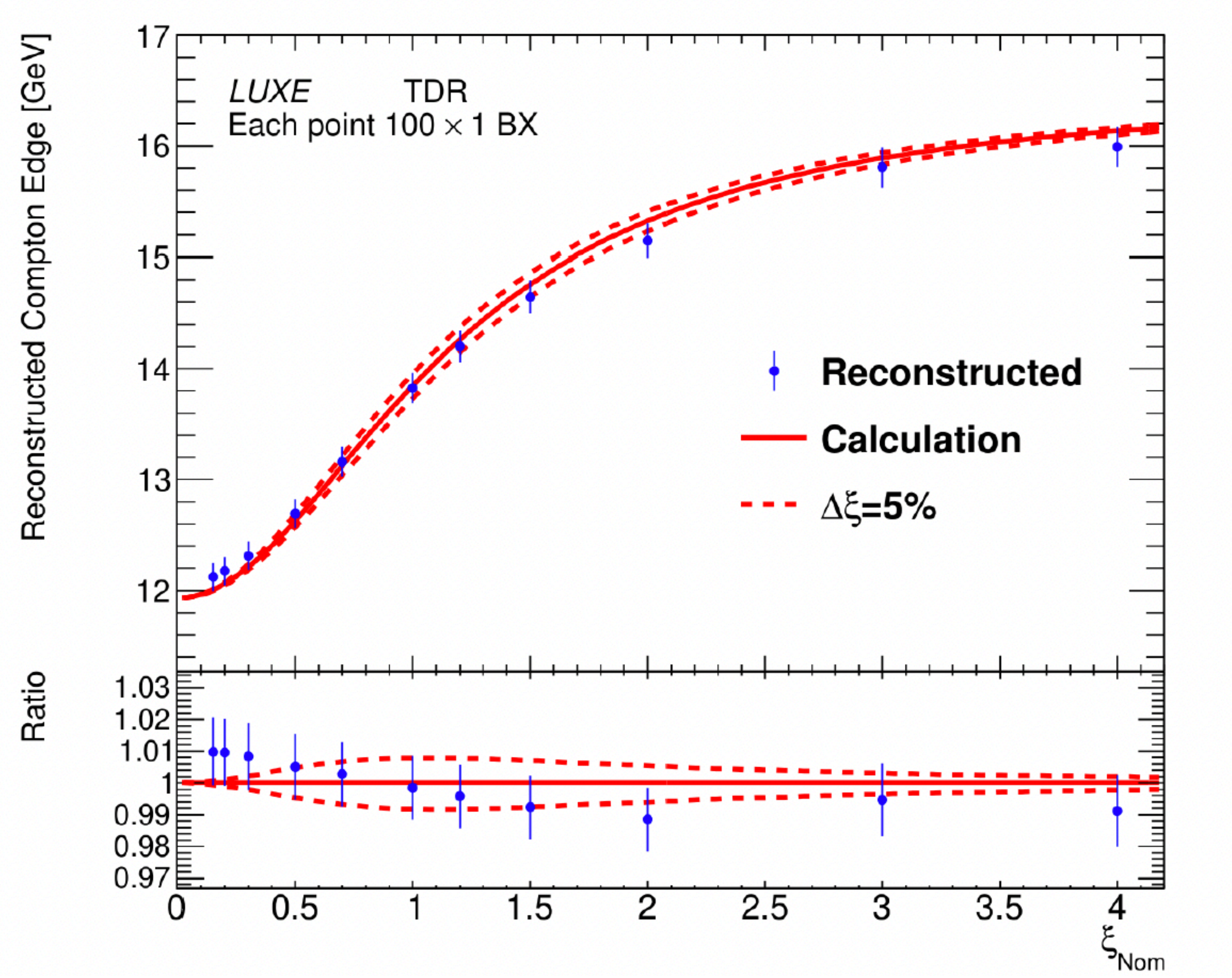
Straw prototype

- Scintillator screen (LANEX) with camera:
  - Camera takes pictures of scintillation light.
  - resolution of full system ~500µm
- Cherenkov detector:
  - Finely segmented ($\varnothing = 4mm$) Air-filled channel (reflective tubes as light guides) → charged particles create Cherenkov light
  - Active medium Air: low refractive index - reduce light yield, suppress backgrounds (Cherenkov threshold 20 MeV)

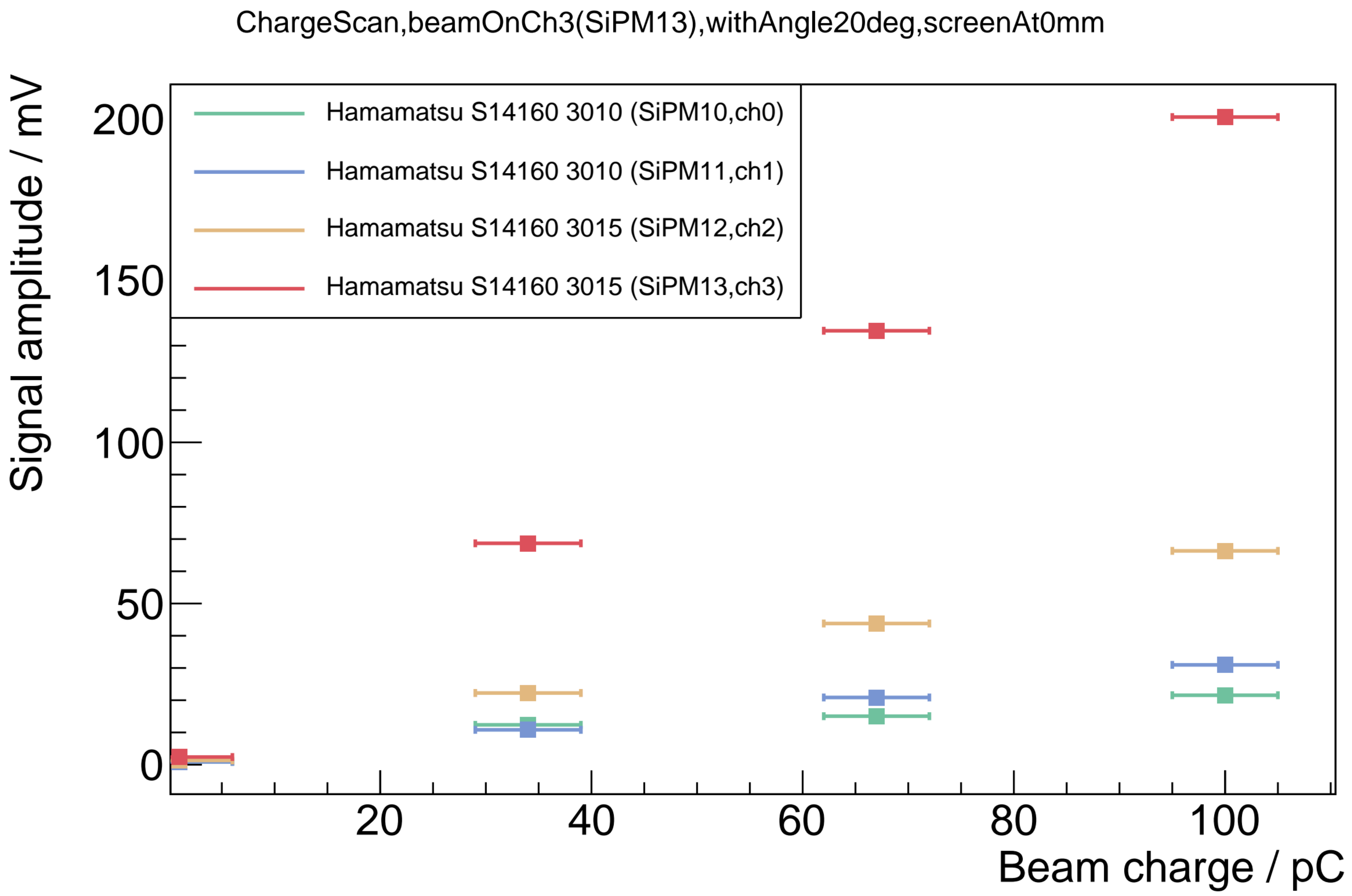
Electron detectors: High rate tolerance, large dynamic range!

Electron Detection - Performance

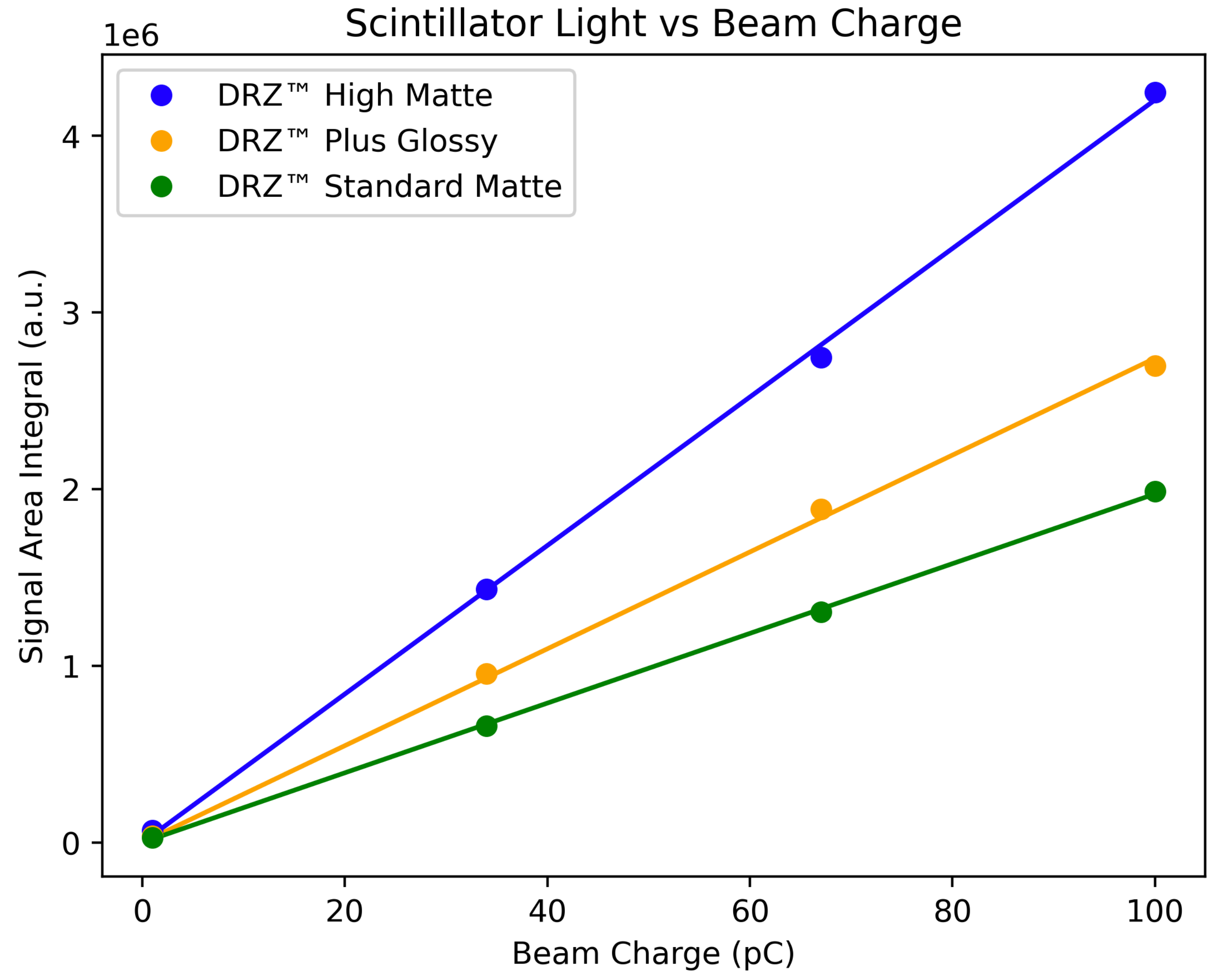
e-laser: IP electron side, γ-laser: brems target instrumentation



Edge reconstruction with FIR on screen output



Light yield measured in different straw of the Cherenkov detector at the ARES testbeam.



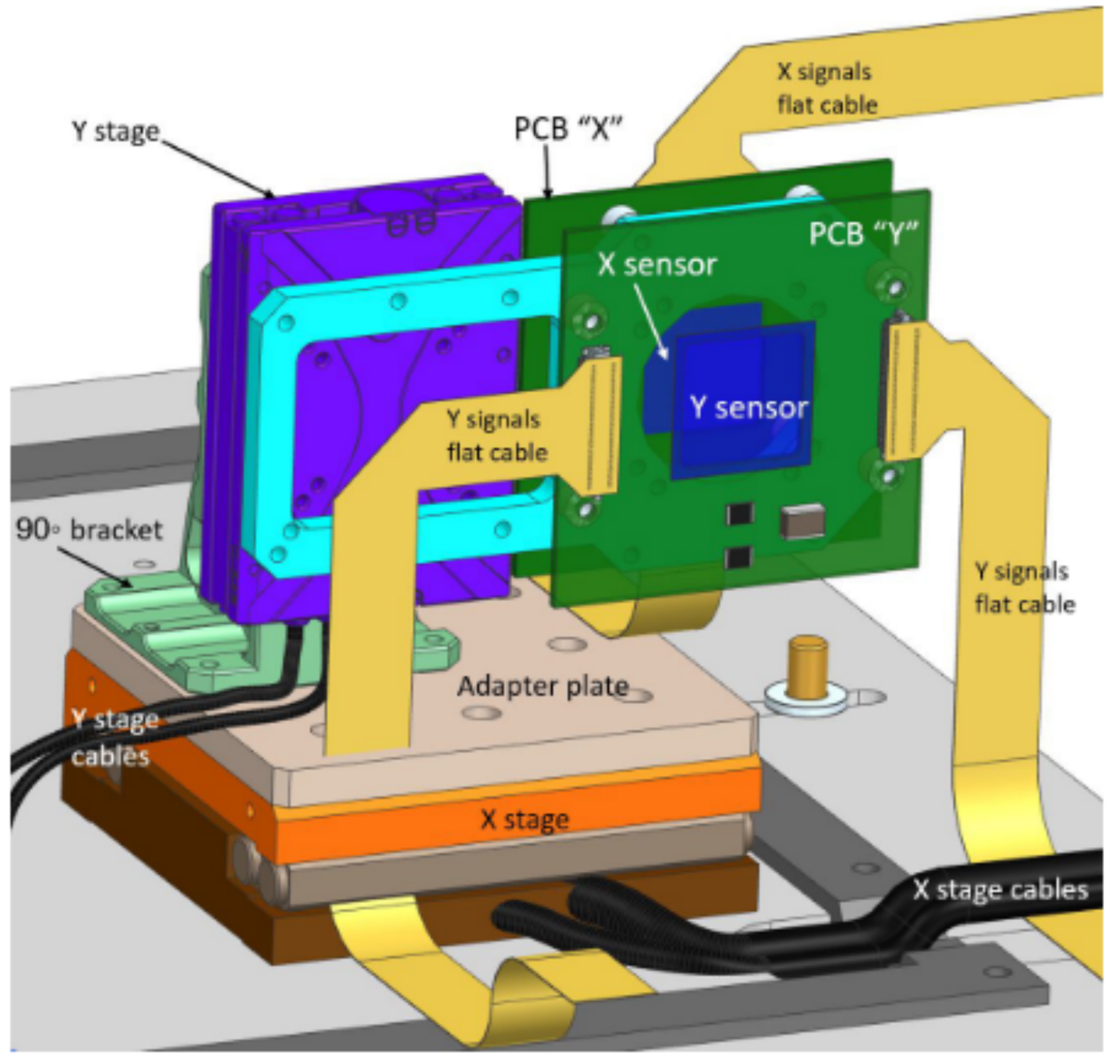
Light yield measured in the scintillating screen detector at the ARES testbeam.

- Reconstruction of Compton edges position using Finite Impulse Response filters.
  - Allow model independent reconstruction of kinematic edges in a smooth spectrum.
  - Tested successfully on both scintillating screen and Cherenkov detectors output.

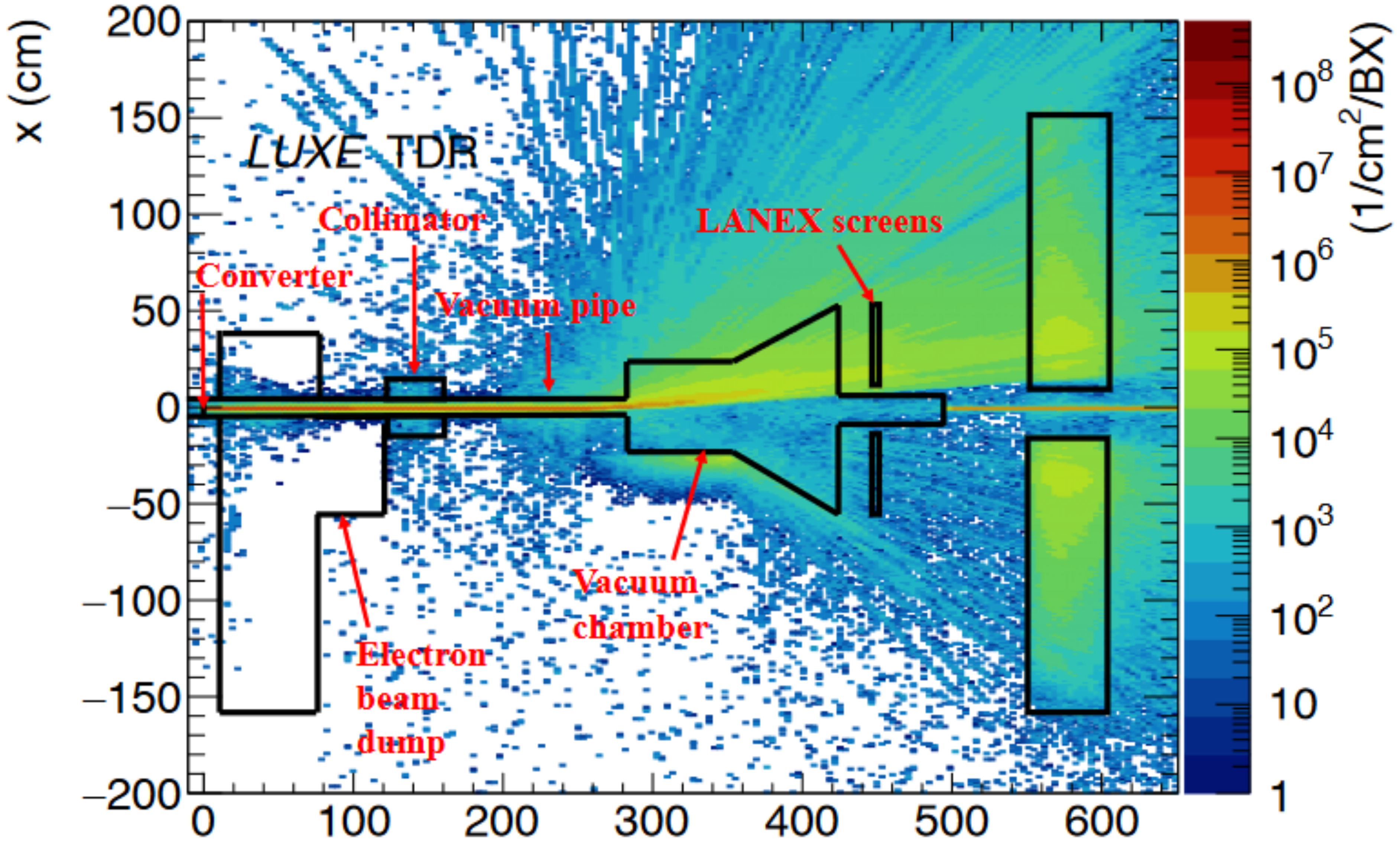
- Test beams results
  - Both systems tested together in various facilities (DESY2, Laser wakefield facility in DESY), ARES.
  - Accessed different level of beam parameters (bunch charge, electron energy, stability, etc..).
  - ARES deliver very stable electrons @150 MeV with bunch charge 1-100 pC.

Photon Detection System

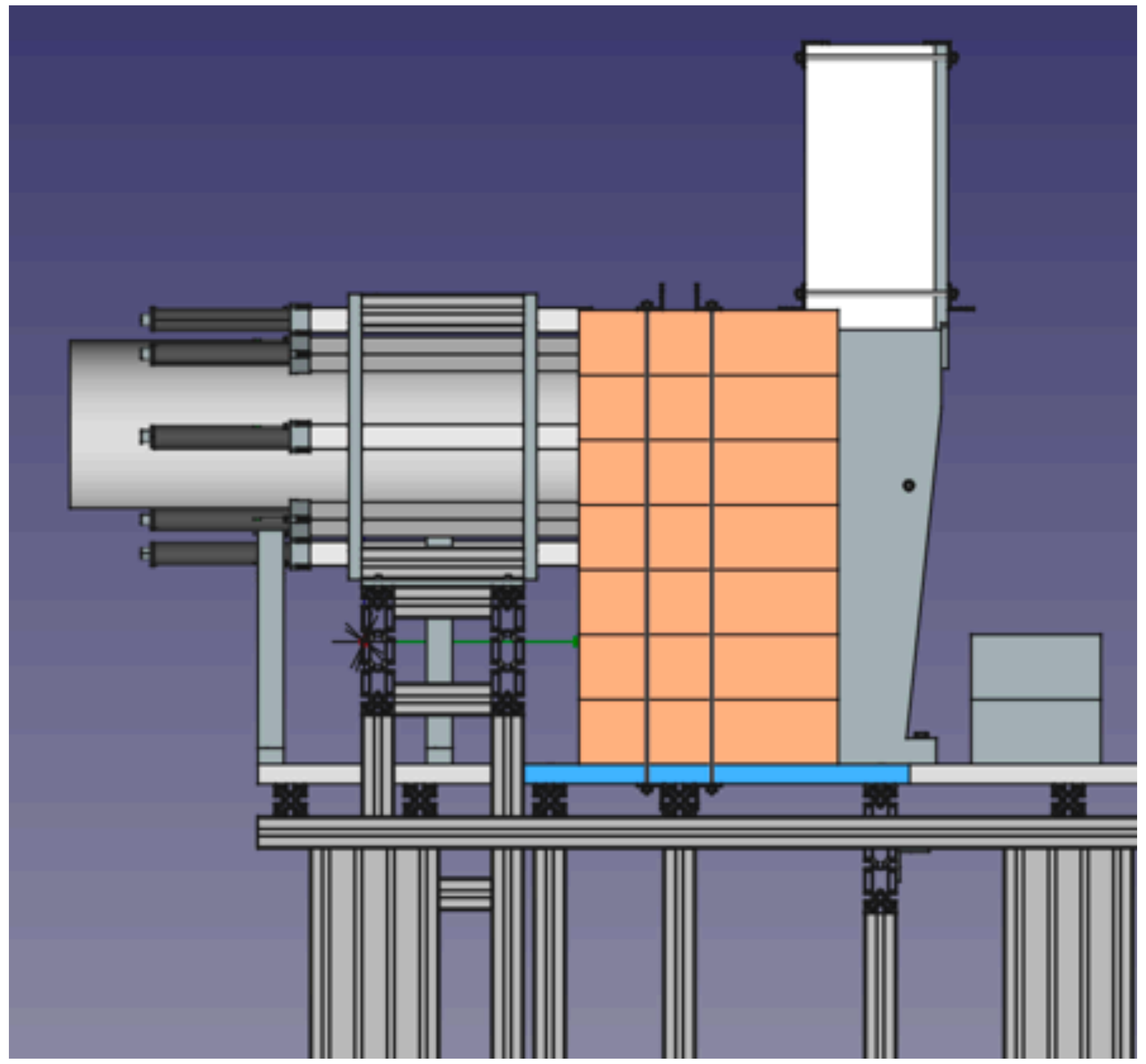
Technology choices



Gamma Beam Profiler



Electrons simulated in Gamma Spectrometer



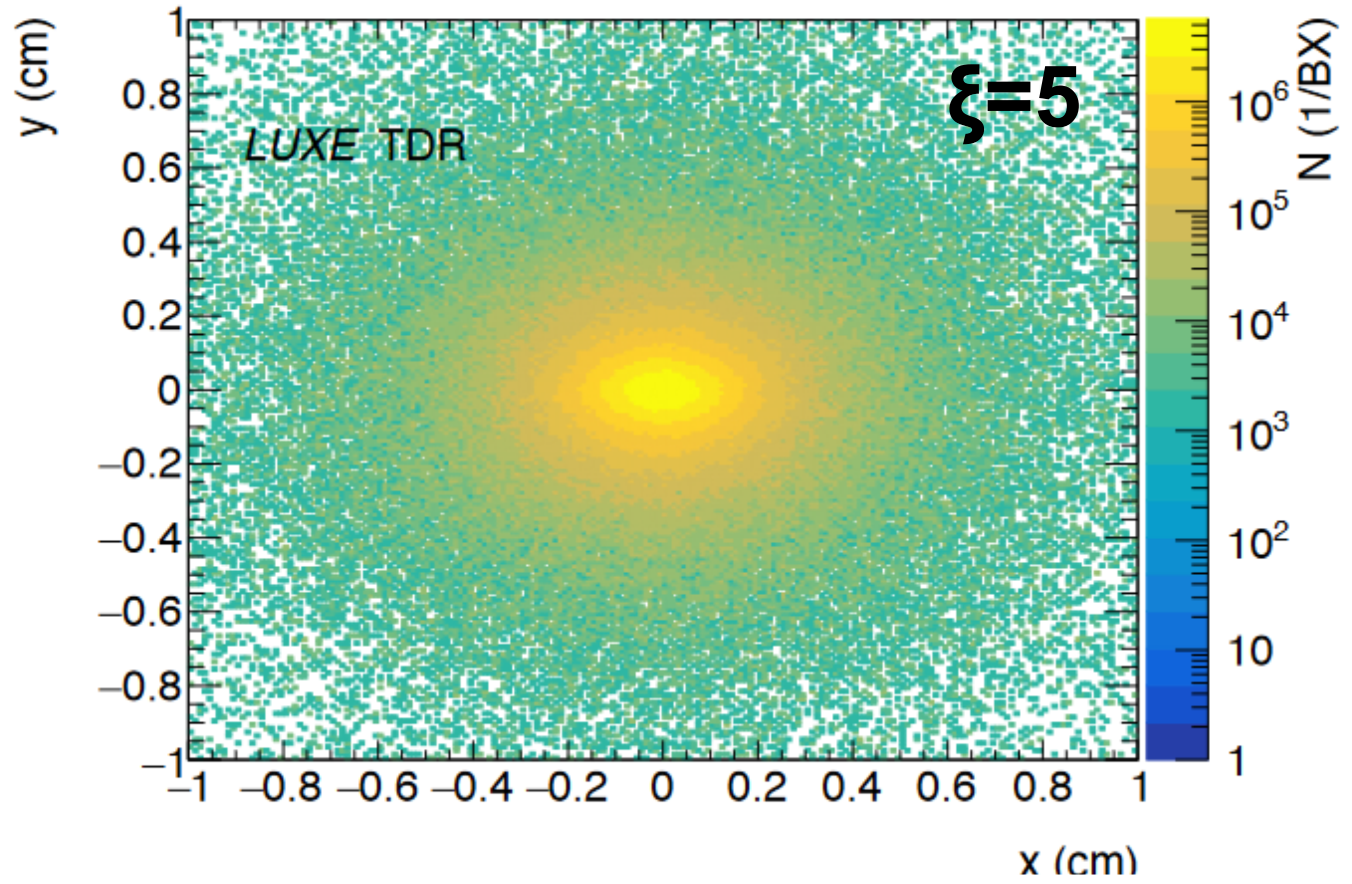
Gamma flux prototype

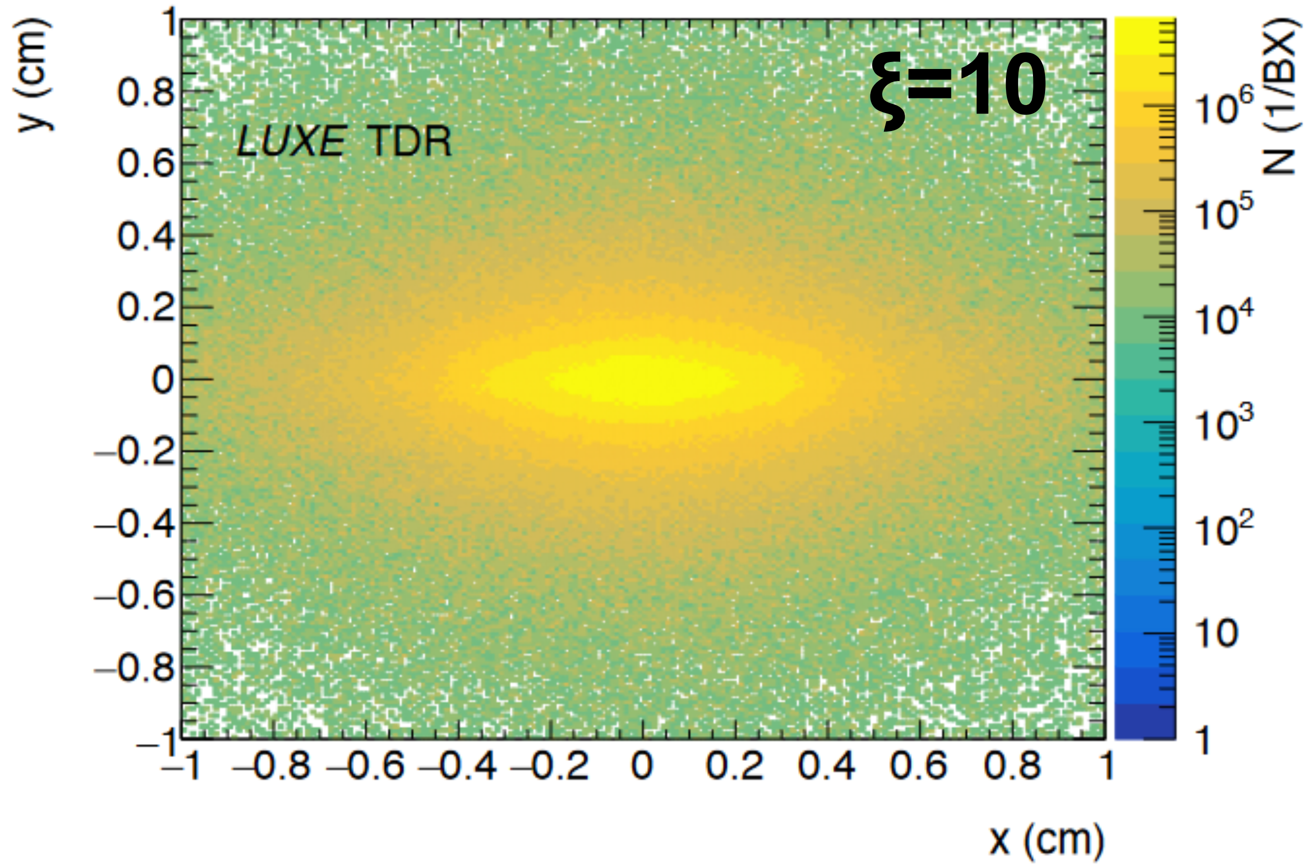
- Gamma profiler (sapphire strips)
  - Measure profile of ɣ beam using sapphire strips.
  - Prototype tested successfully in various high-rate facility.
- Gamma spectrometer with scintillator screens behind converter
  - Measure ɣ energy spectrum thanks to converter target and spectrometer magnet.
- Gamma flux monitor
  - Measure photon flux using crystal placed around final beam dump.
  - Plan to do measurement to test concept at FlashForward.

Photon detectors: precision measurement of ξ, complementary to laser diagnostics

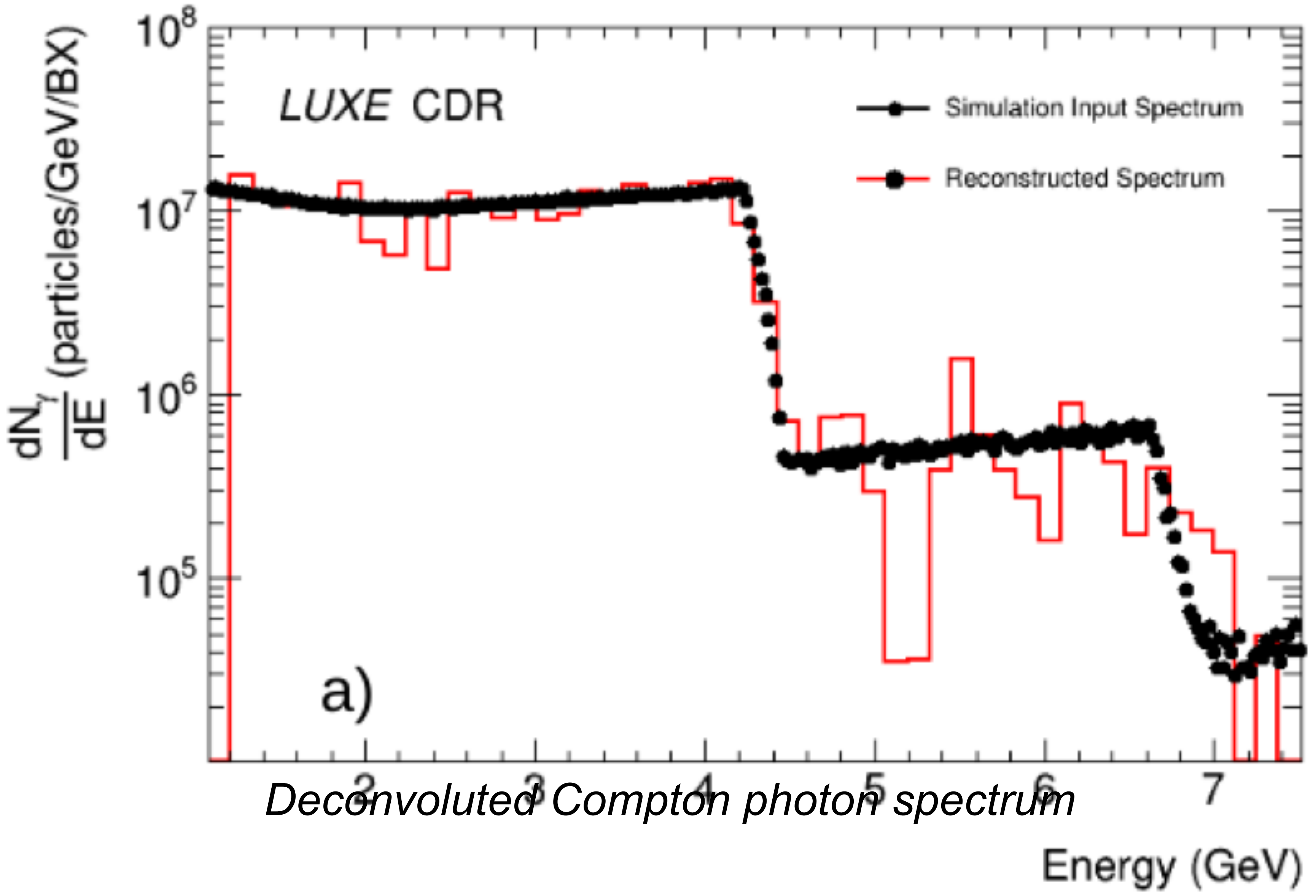
Photon Detection System

Performances





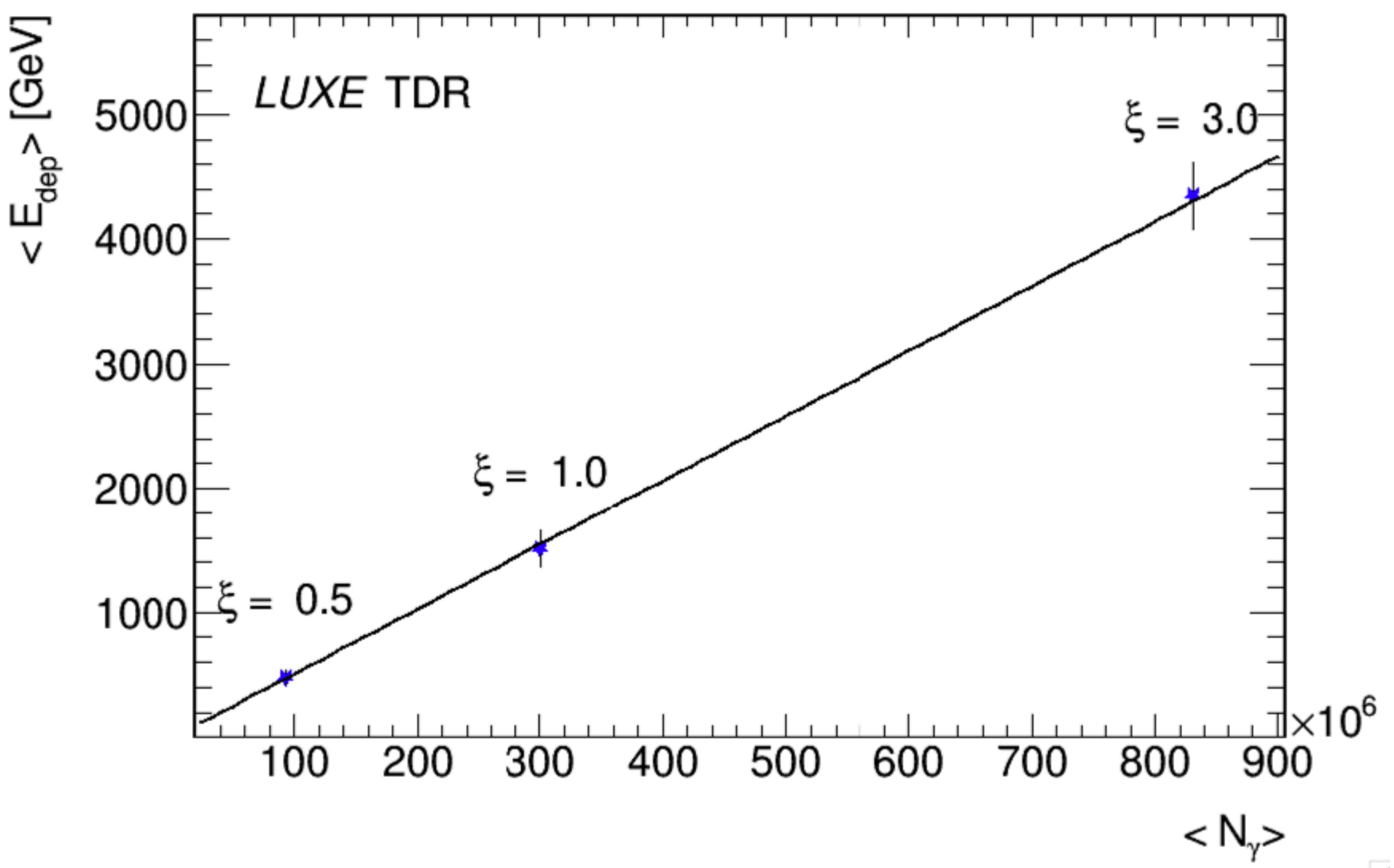
- Gamma profiler (sapphire strips)
  - ɣ beam location and shape
  - precision measurement of Laser intensity



Deconvoluted Compton photon spectrum

- Gamma spectrometer with scintillator screens behind converter
  - Energy spectrum ($\frac{\delta E}{E} < 2\%$)
  - Measurement method successfully tested at Apollon.

Number of photons reconstructed from energy deposited in gamma flux monitor

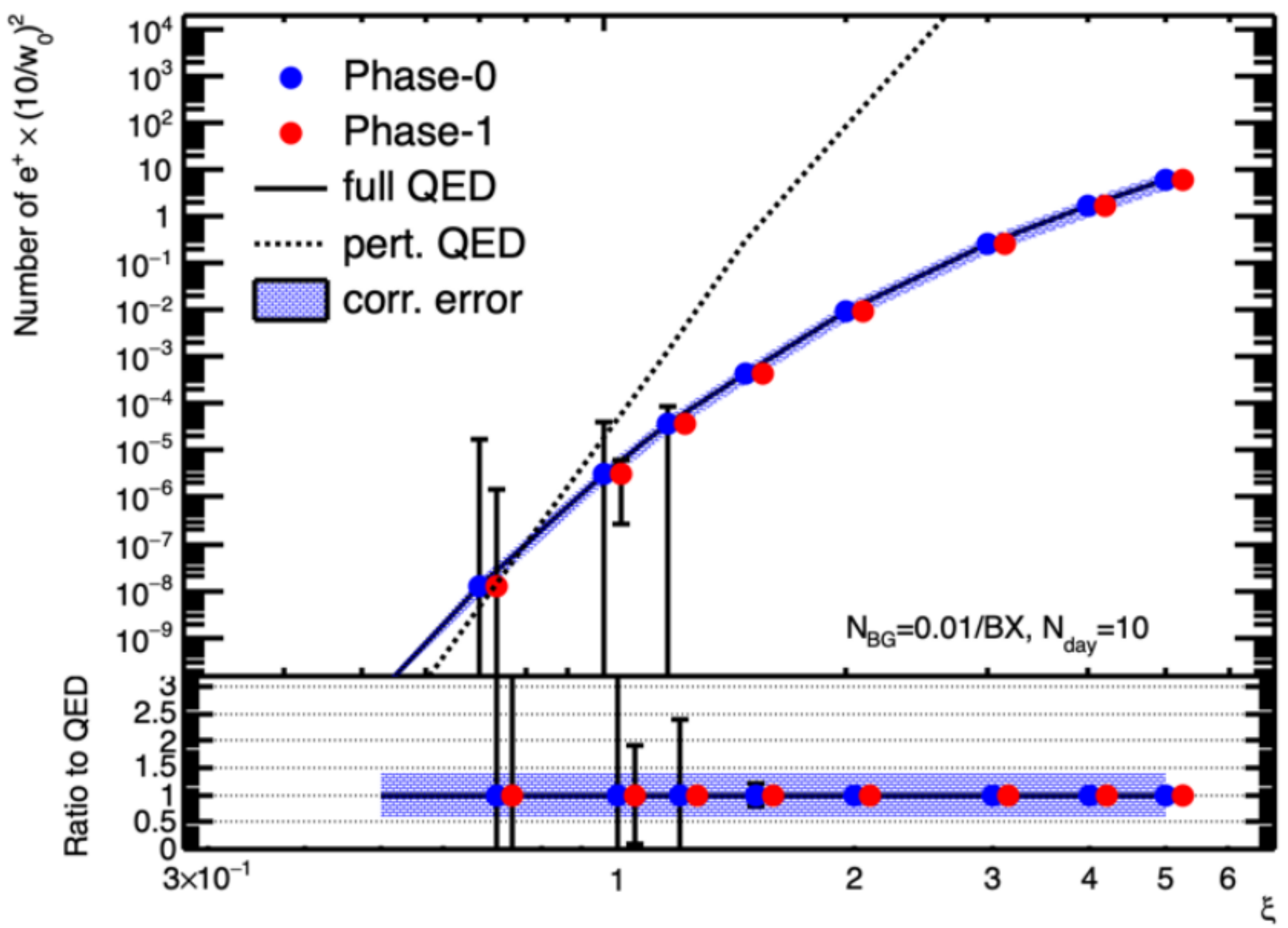


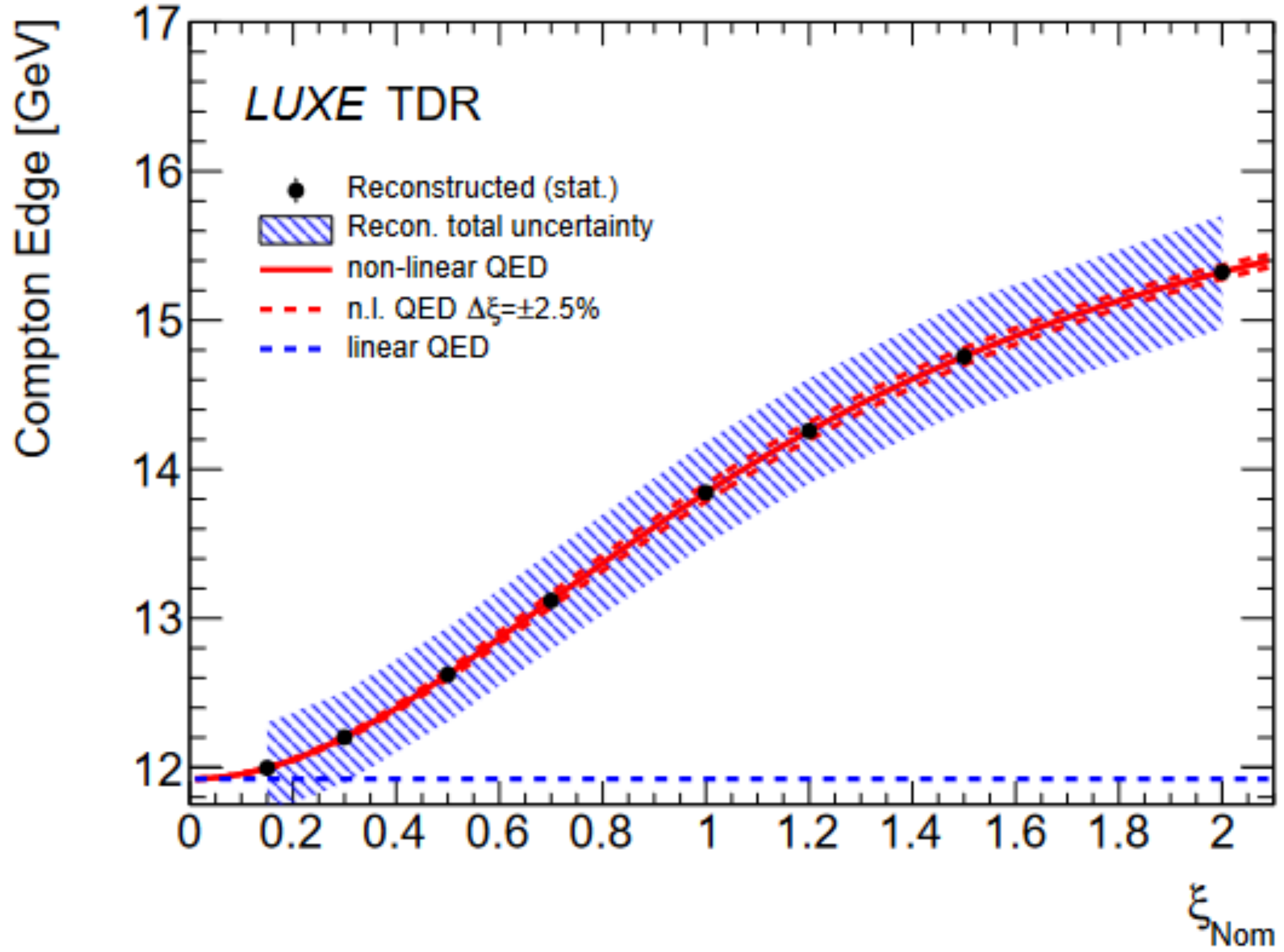
- Gamma flux monitor
  - Precision 3-10% depending on the point studied

LUXE
Expected Results,
Bonus Option & Timeline

Projected Results

Combining several systems

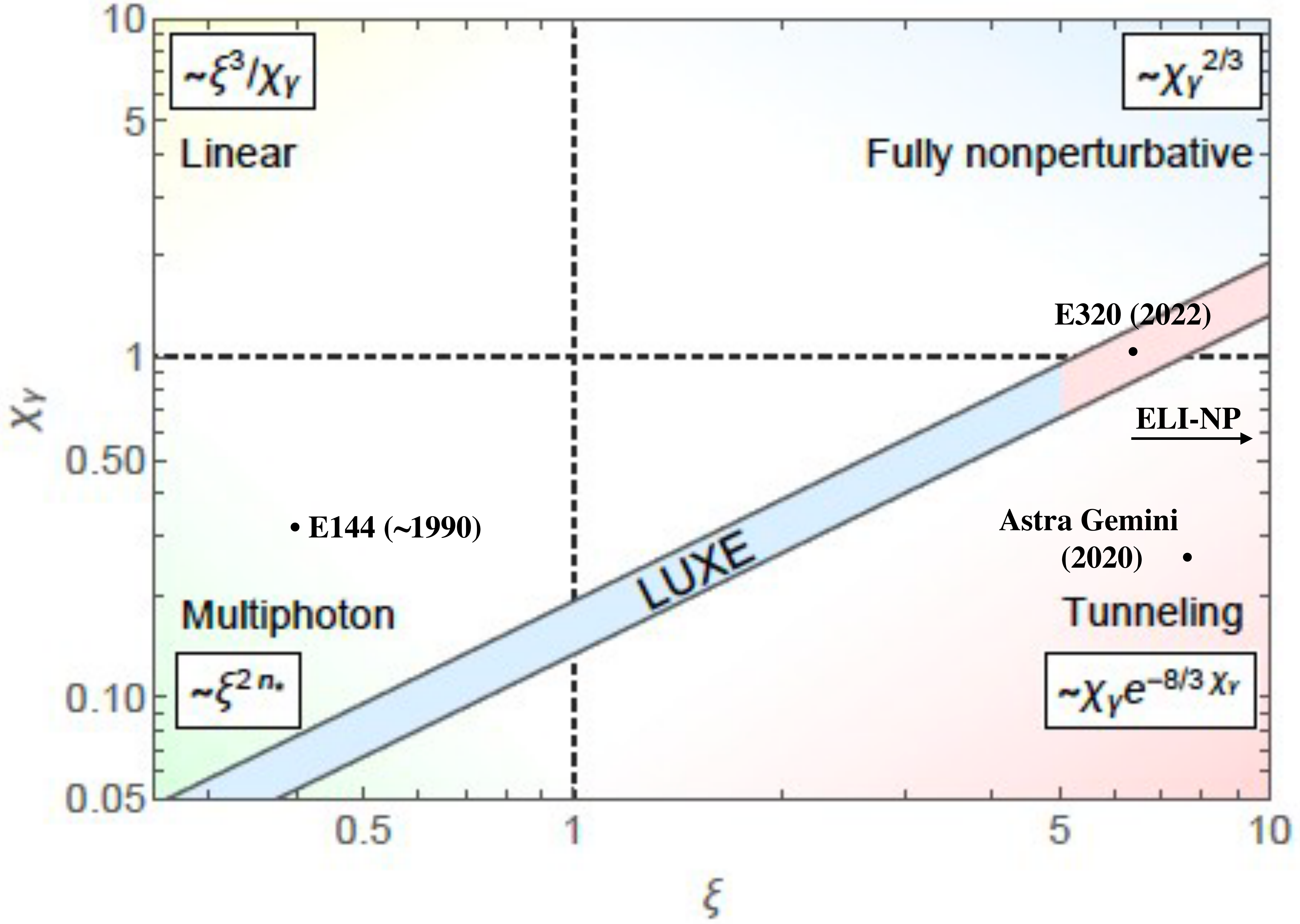




- Positrons rates
  - Number of Breit-Wheeler pairs produced in γ-laser collisions
  - HEre: 10 days data-taking, 0.01 background events/BX
  - 40% correlated uncertainty to illustrate effect
- Compton Edge Position
  - simulated measurement as function of ξ in e-laser mode.
  - Here: 1h data-taking, no background.
  - 2% energy scale uncertainty to illustrate impact
    => can easily be calibrated to perturbative Comtpon edge at low ξ

Looking back at the ξ-χ phase space

LUXE will provide precision measurements over large range

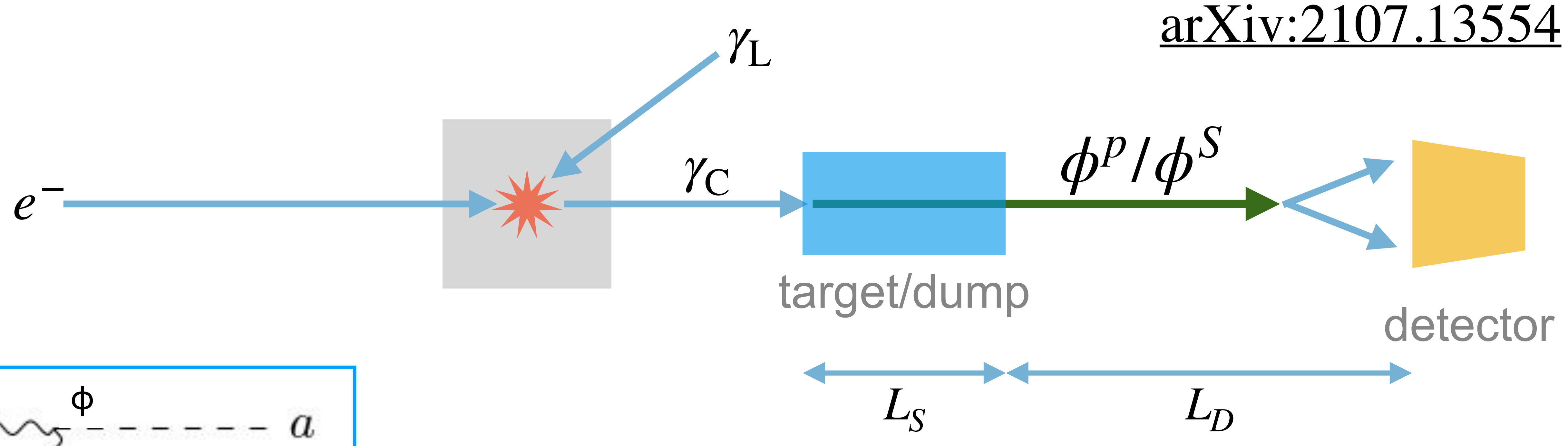


- Plan to provide high precision data that can be compared to state of the art theoretical predictions.
- Complementary and unique measurements with respect to other existing experiments.

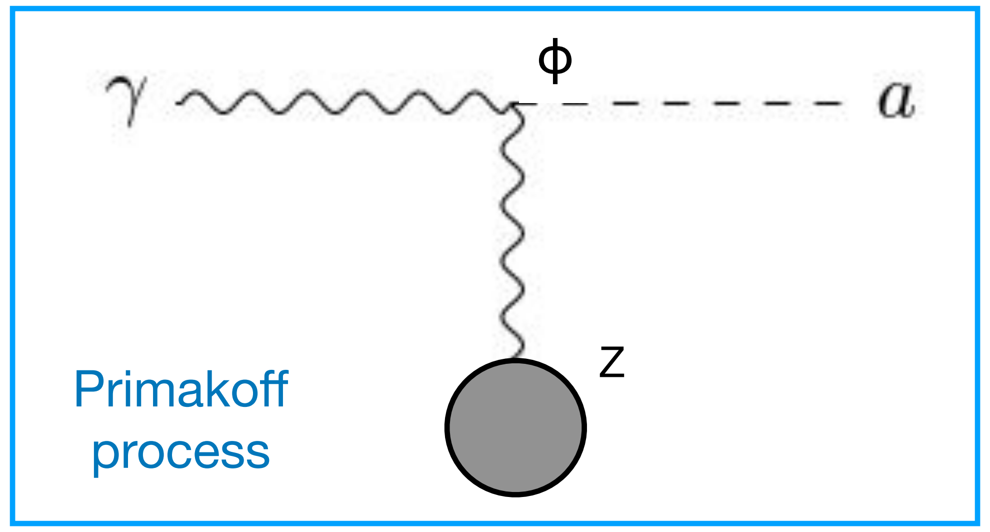
Light Exotic Particle Production?

In Beam Dump - Place Detector Behind

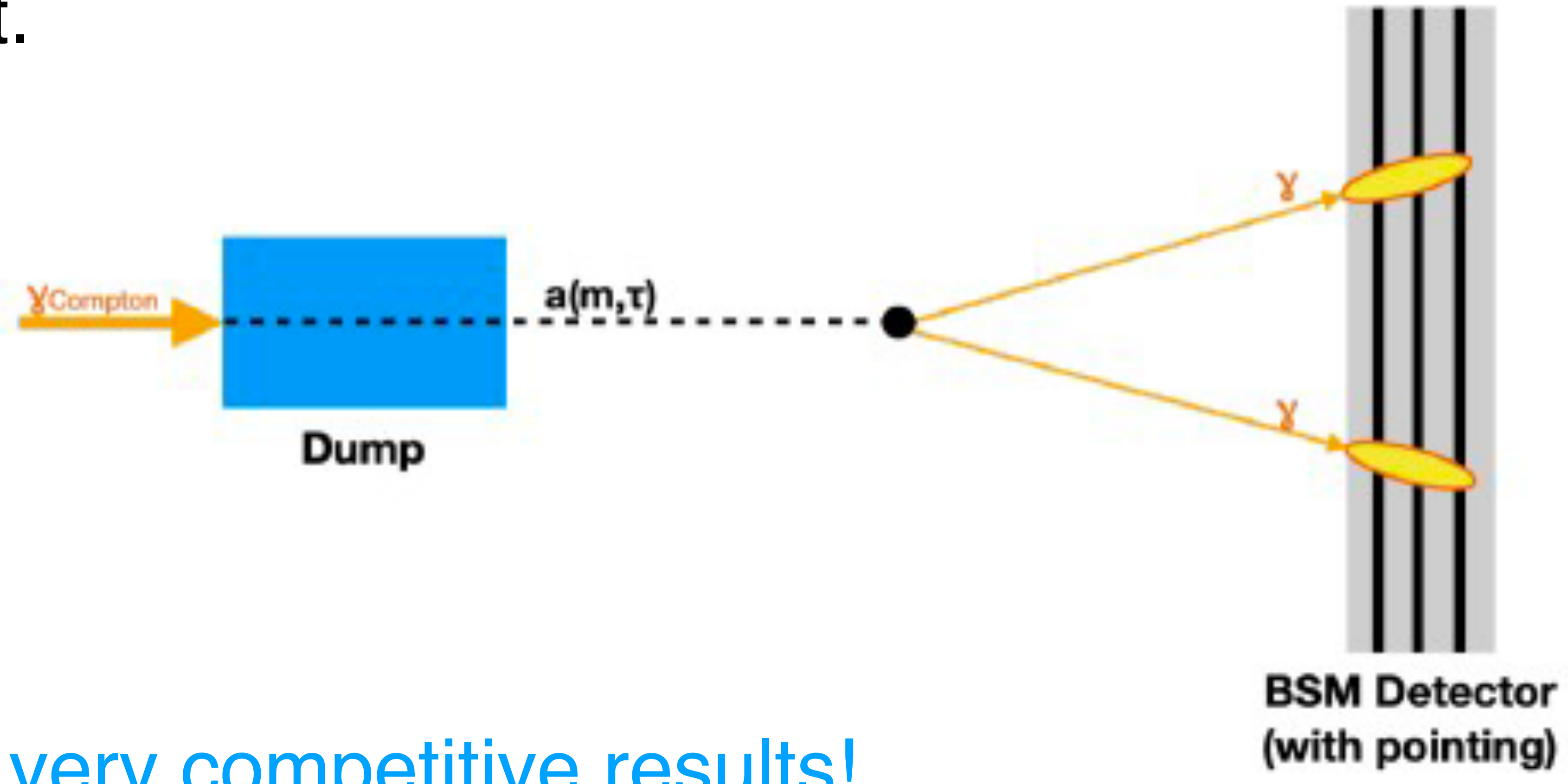
arXiv:2107.13554

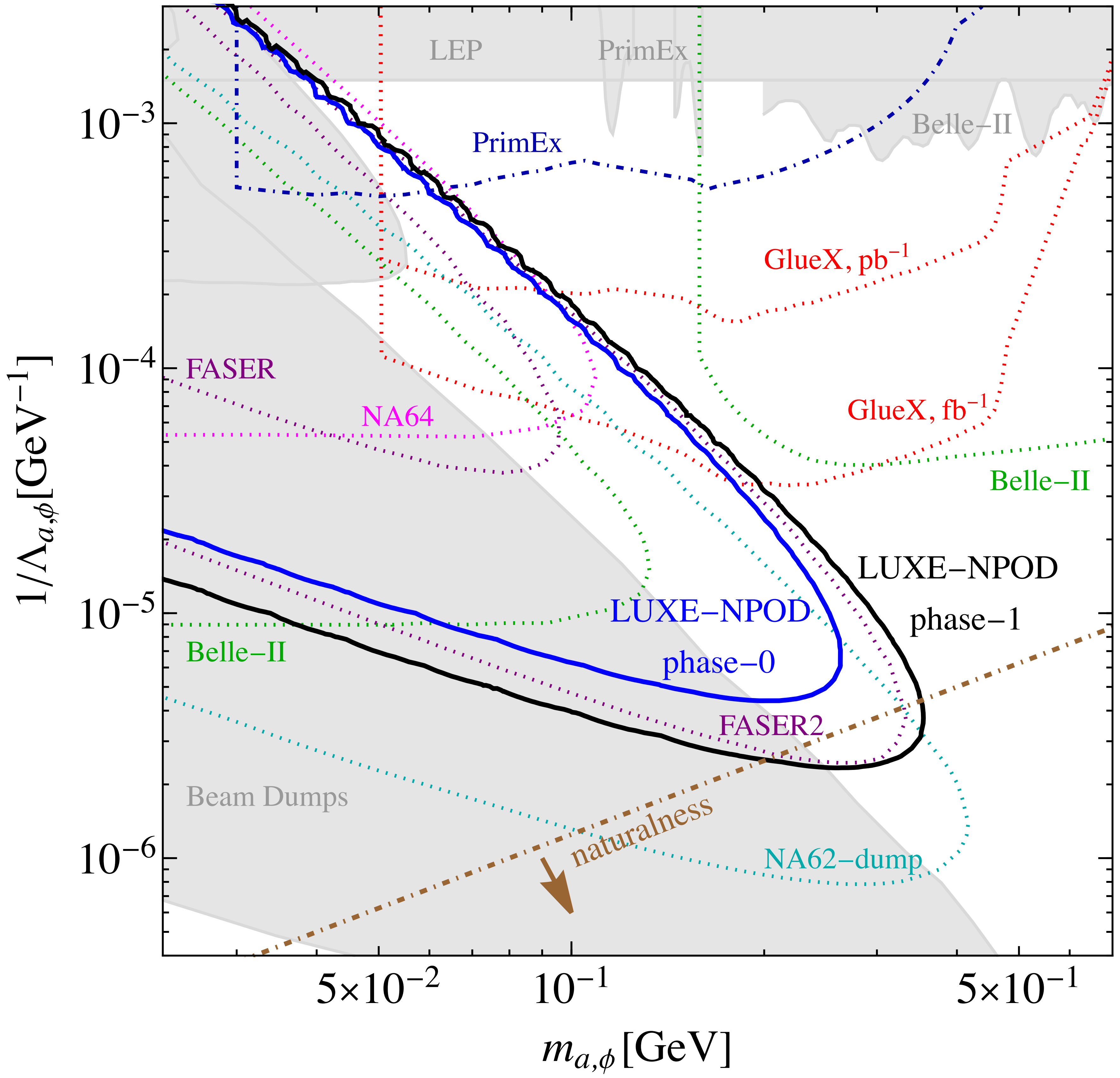


- Explore sensibility to BSM theories.
  - Axion-like particles (ALPs) produced in dump.
  - New neutral particles produced at IP.
  - Milli-charged particles.



- For ALPs:
  - sensitive to masses m(a)~100 MeV.
  - decay to photons after some lifetime τ.
  - Place detector behind dump.
  - Could use calorimeter with good pointing resolution to constrain decay point.





- First sensitivity show very competitive results!
  - After just 1 year of data.

Timeline of LUXE

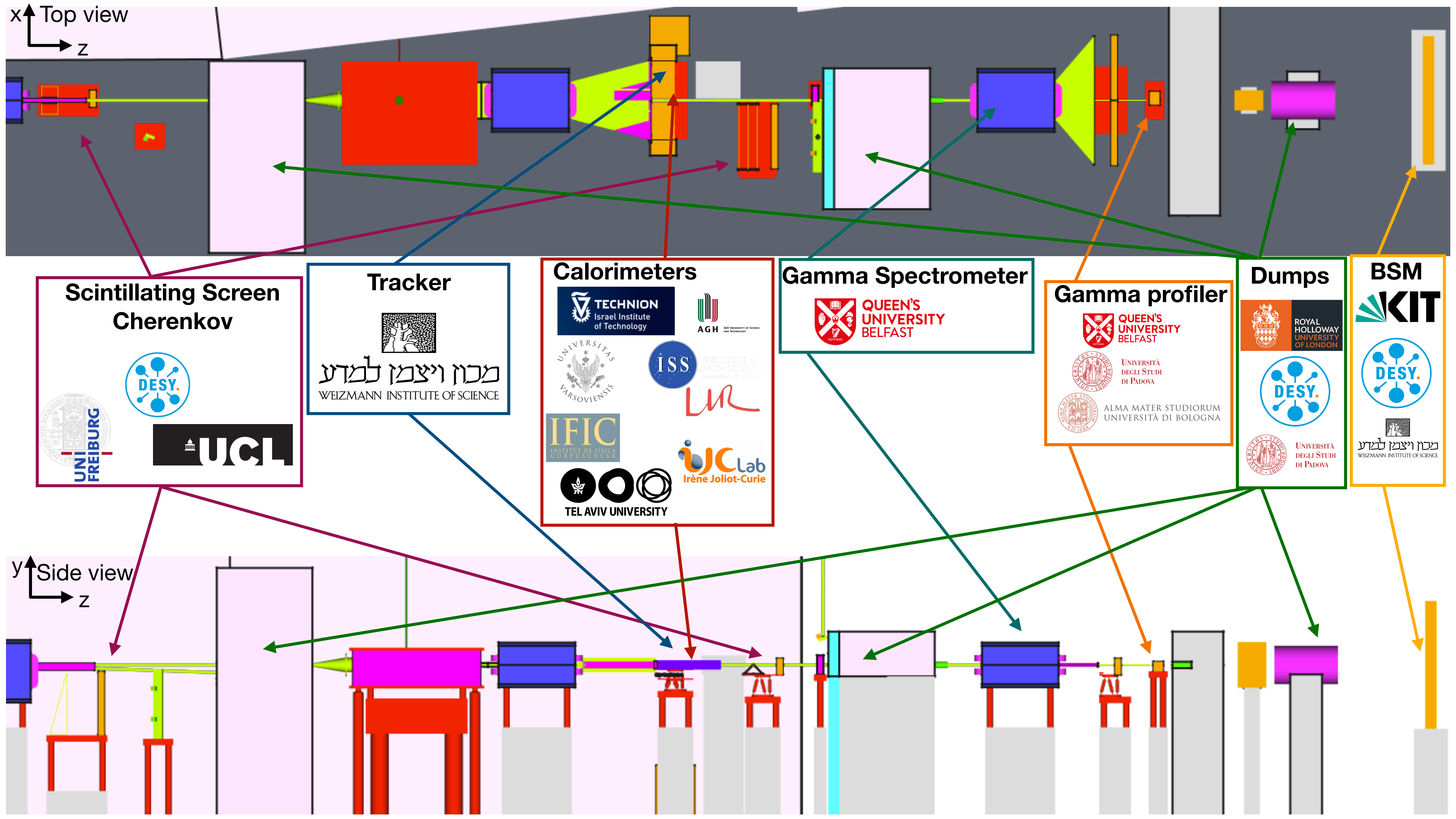
Past, presence and future

- initiated in 2017 (A. Ringwald, B. Heinemann)

- 2022: international collaboration with ~20 institutional members, significant contributions to the experiment by external partners envisioned.
- **Nov 2022: officially recognized as a DESY experiment**
- August 2023: TDR published arXiv:2308.00515

- Currently securing funding - in parallel detector prototyping
- Need ~3 years for full construction & installation
  - Data-taking could start as early as 2027.
  - Use long shutdown of EUXFEL in 2025 as much as possible.

- Extensive material on detailed design and planning available



Conclusions

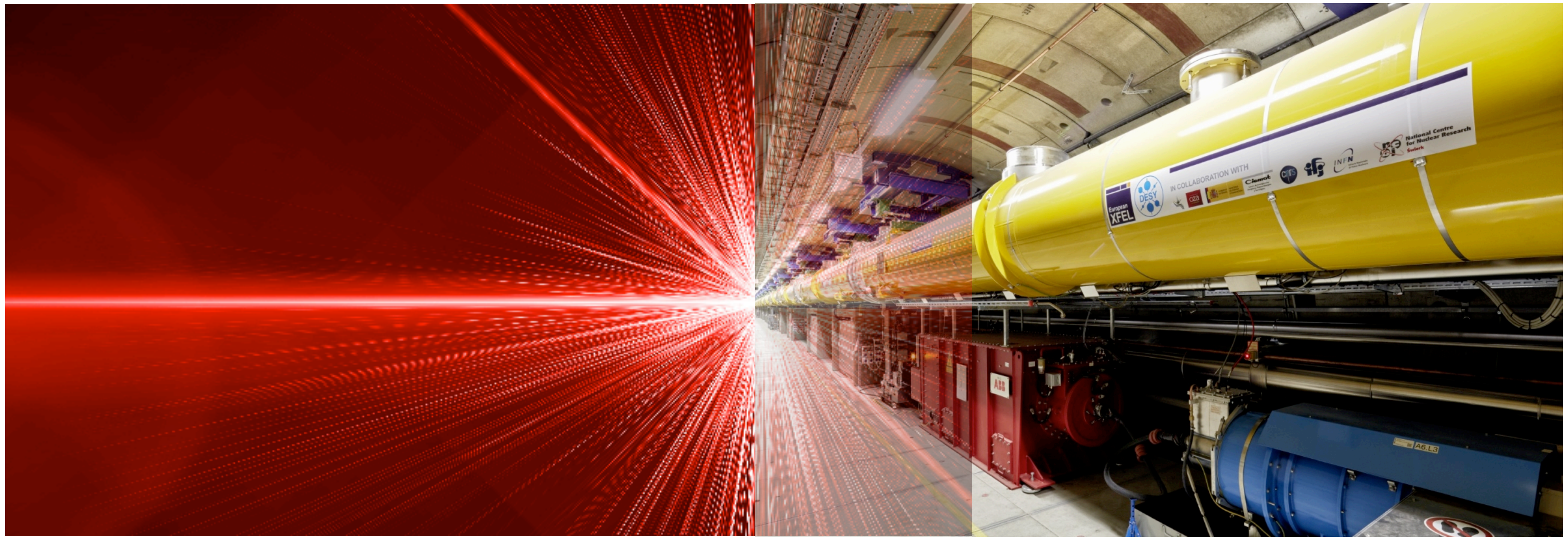
and Outlook

- LUXE will explore QED in uncharted regime
  - Observe transition from perturbative to non-perturbative QED
  - Directly observe pair production from real photons
  - Complementary approach to other ongoing SFQED experiments
  - Search for BSM physics with photon beam dump

LUXE: exciting window of opportunity for a near-term new particle physics experiment

Open to new collaborators!

- Goal: installation in 2025 during extended shutdown planned for European XFEL
  - Very diverse detector technologies, optimized for LUXE physics goals
  - Ideal testbed for new technologies for future colliders



BACKUP

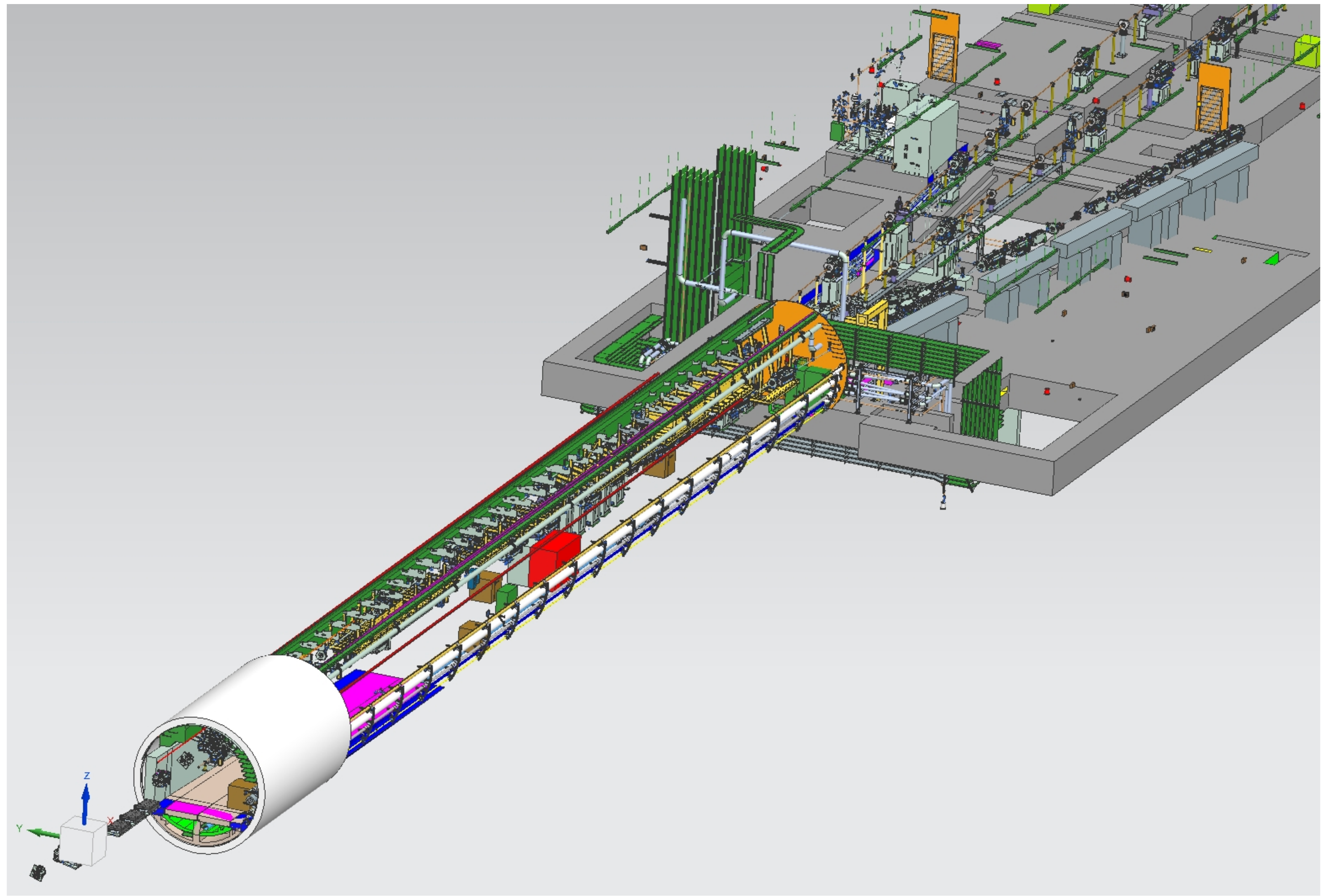
more…

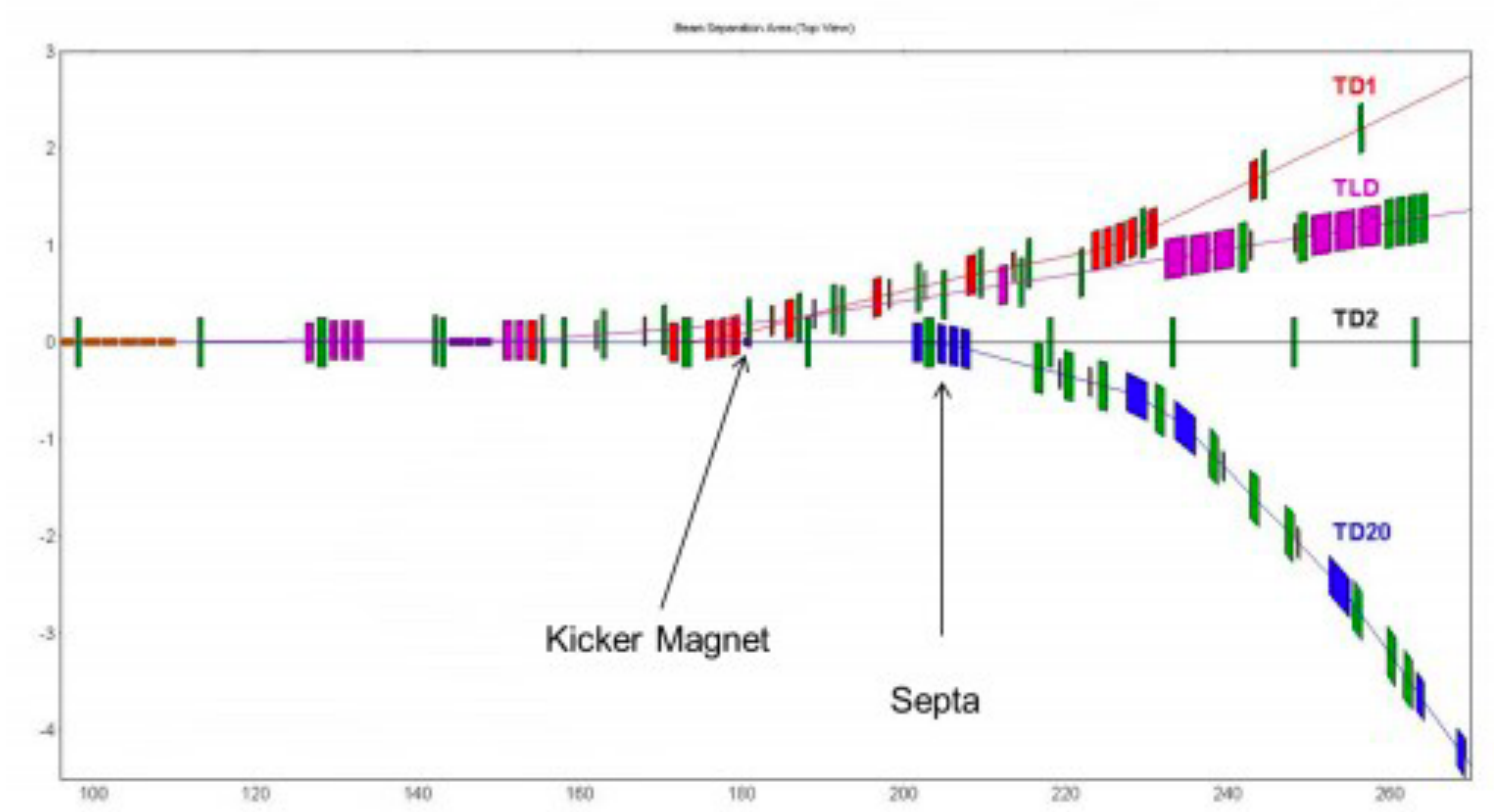
From the Accelerator to the Experiment

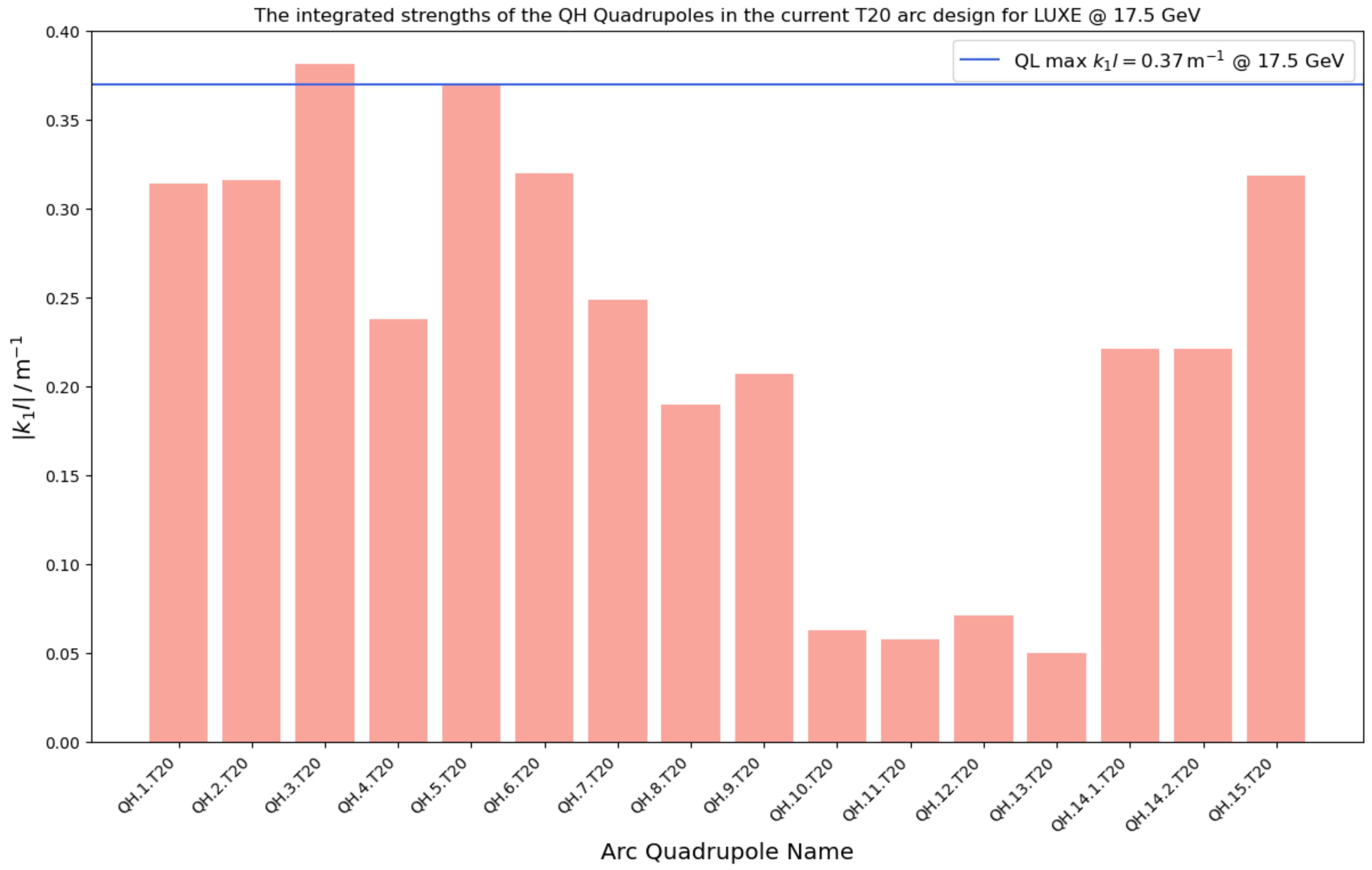
New extraction line

- Construct dedicated new extraction line at the end of the LINAC.
  - Reusing magnet design from XFEL for septum and dipoles.
  - New fast kicker magnets (2 µs: kicks bunch at end of bunch train).
  - Reuse quads from HERA.
    - retrofit to reduce aperture size and power consumption.

- Design of the beam line mostly ready.
  - MVS, support structure concept done, need to finish production design.
  - Magnet tender being prepared.
  - MCS, BI, power supply, etc are standard.



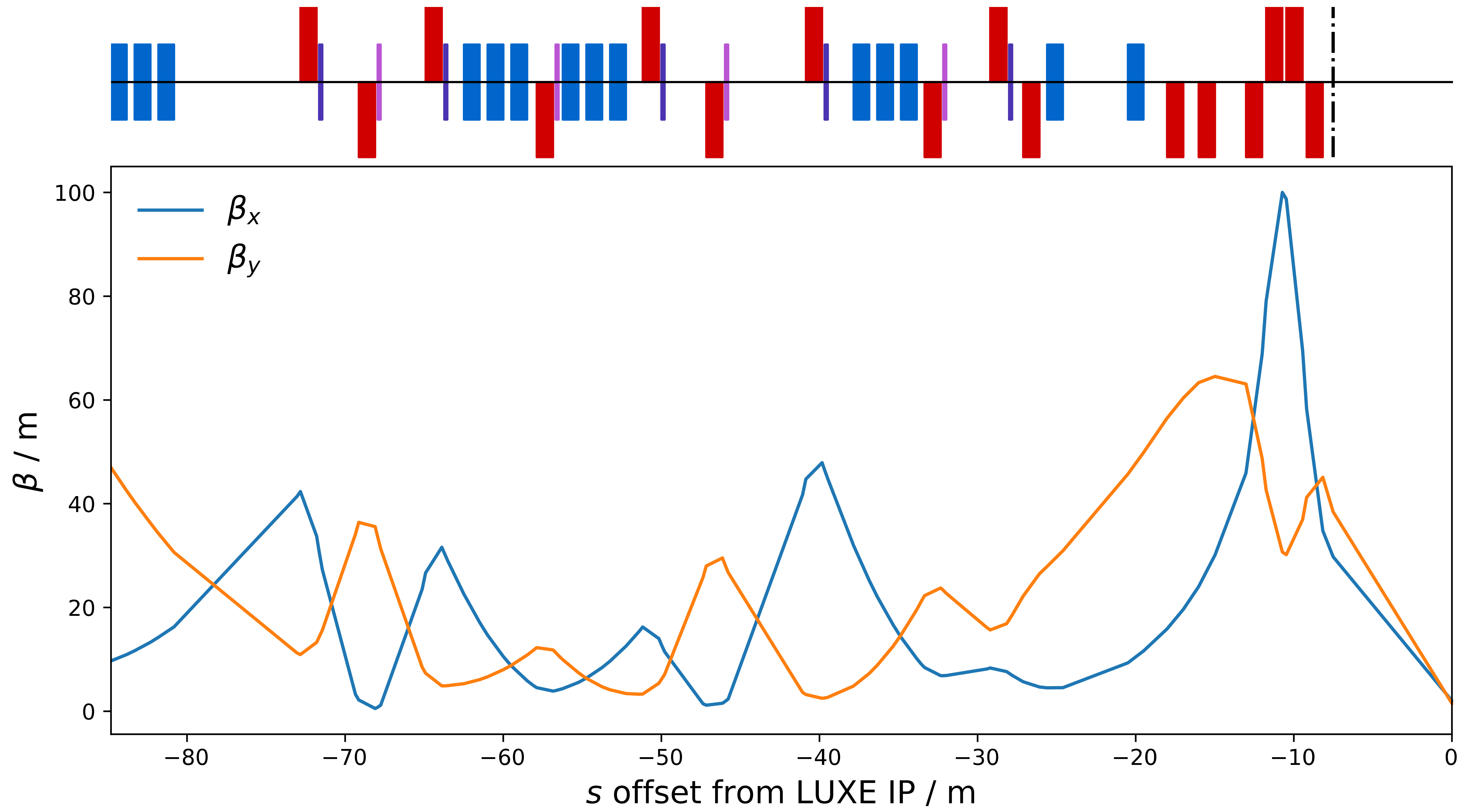


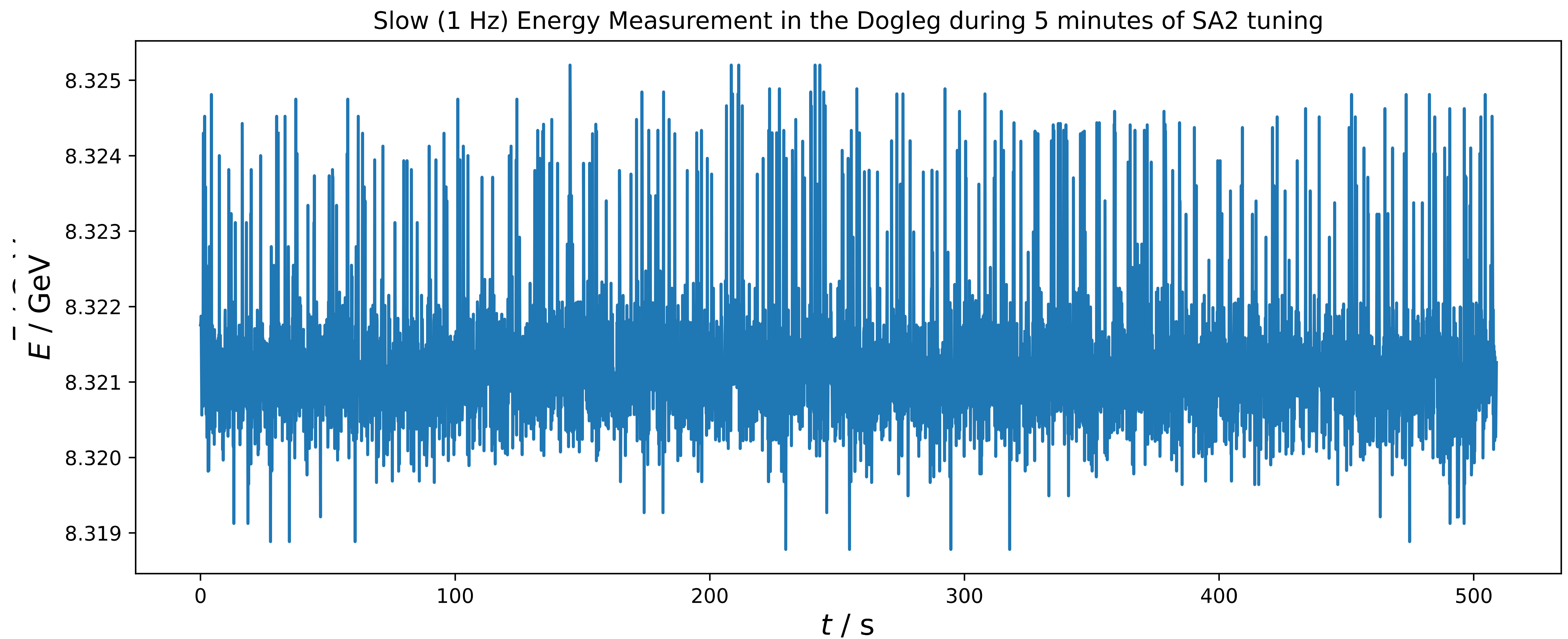


ACCELERATOR PERFORMANCES

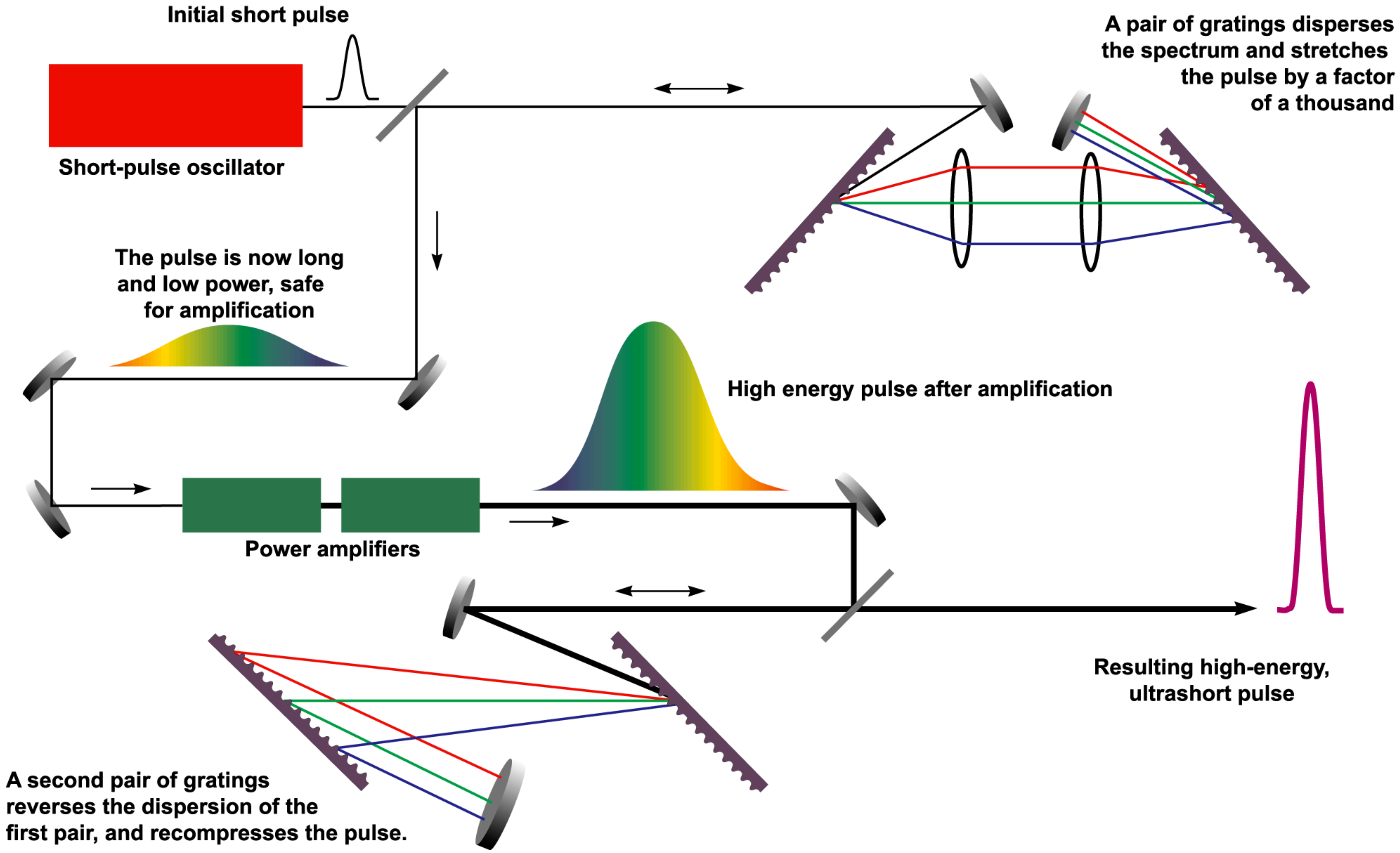
- Design of the lattice
  - Mostly comes from machine CDR (2019).
  - Tweaked to match building constraints.
  - Final focus added recently.

- Performances:
  - CDR simulations:
    - $\sigma_x, \sigma_y = 5\mu m$.
  - Achievable:
    - $\sigma_x = 9.3\mu m, \sigma_y = 8.1\mu m$.
    - Studied the effect on signal production, impact should be limited.
    - Can still be further optimized
  - Pulse length: 130 fs.
  - Beam jitter parameters studied at the machine recently.
    - Shot to shot position: ~1μm.
    - Energy variation <0.1%.
    - Time of arrival: ~20 fs.

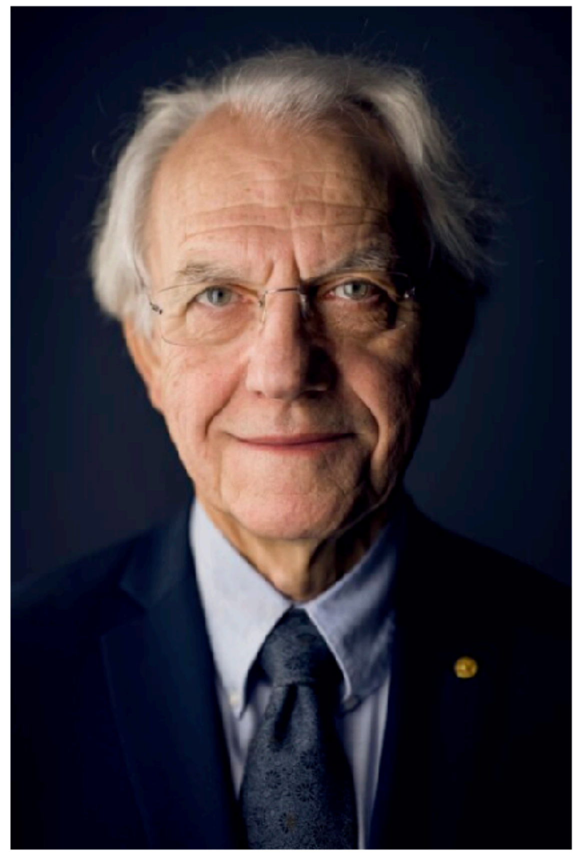




ULTRA INTENSE LASER - CPA TECHNIQUE



- Use Chirped Pulse Amplification (CPA) technique
  - Half of the NP 2018 shared by Gerard Mourou and Donna Strickland
    - *"for their method of generating high-intensity, ultra-short optical pulses."*
  - Technological leap to reach very-high intensity with laser!



Gérard Mourou

Prize share: 1/4

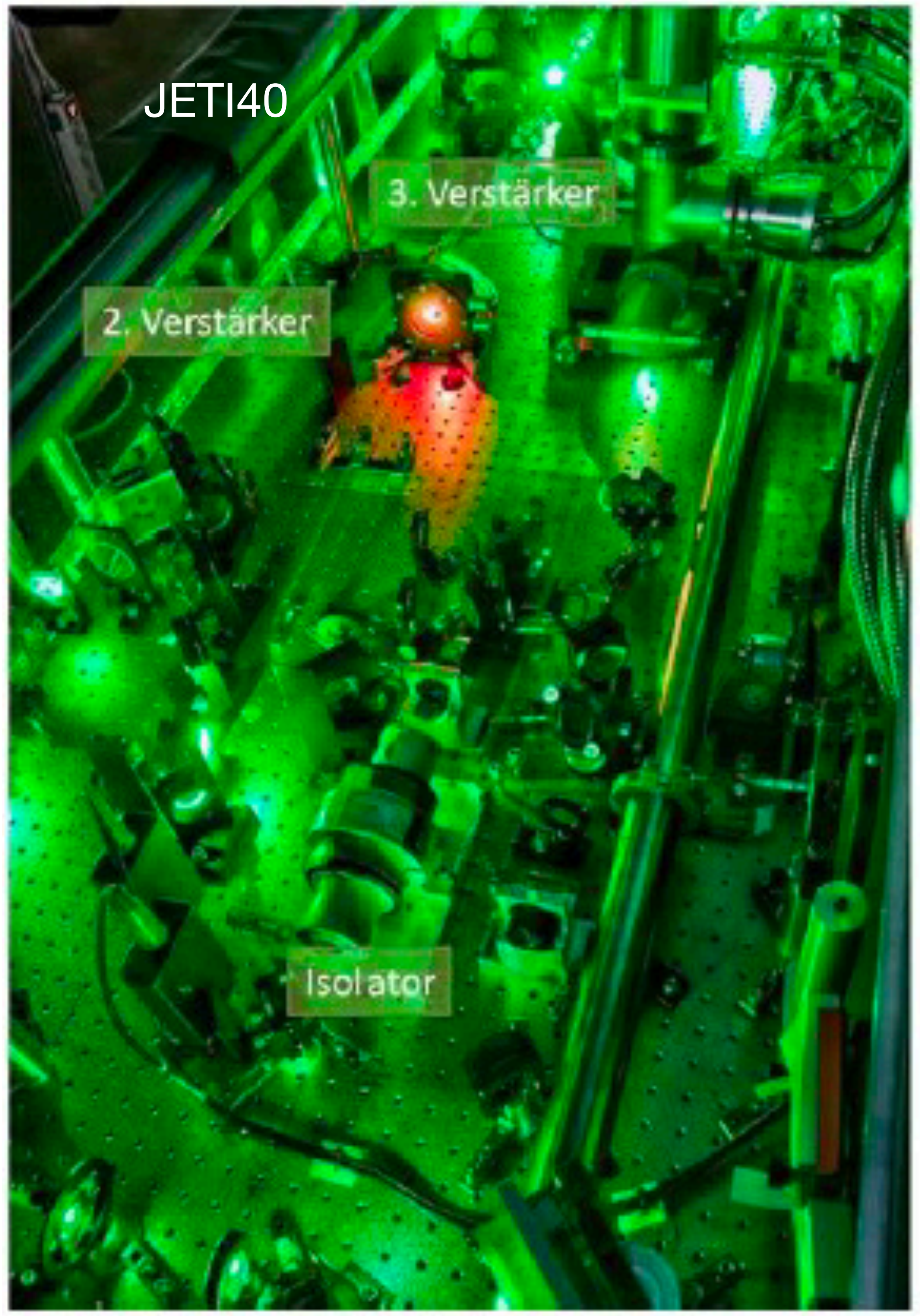
Donna Strickland

Prize share: 1/4

LASER IN LUXE

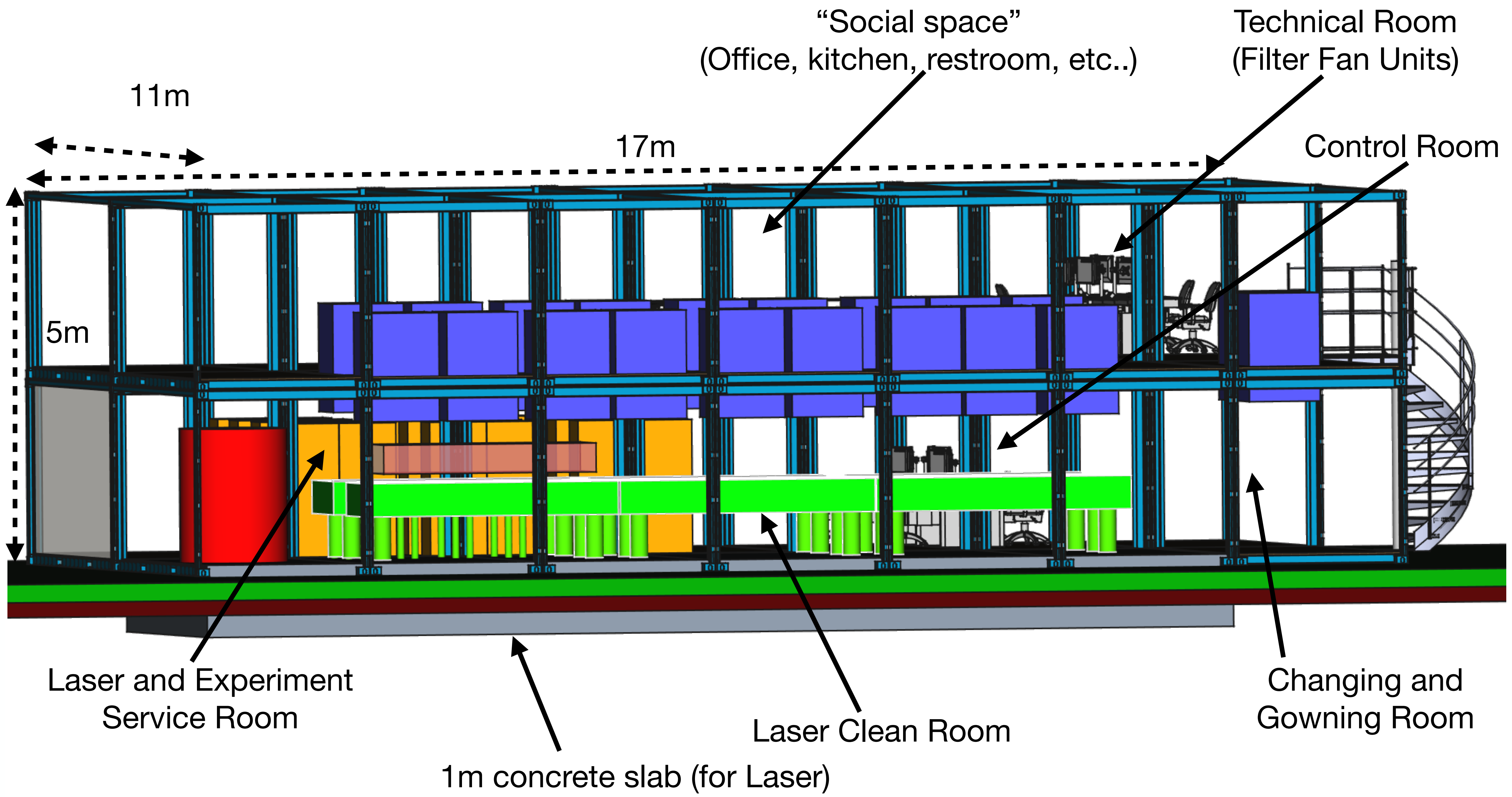
- Use Ti:Sa laser with 800 nm wavelength (E=1.55 eV).
- Energy focused strongly in both time and space to obtain high intensity.
- Two phases:
  - In phase 0 reuse JETI40 (Jena custom 40 TW laser), or new system.
  - In phase I will use commercial 350 TW laser.
- Laser parameters:
  - Repetition rate: 1Hz.
  - Pulse length 30 fs

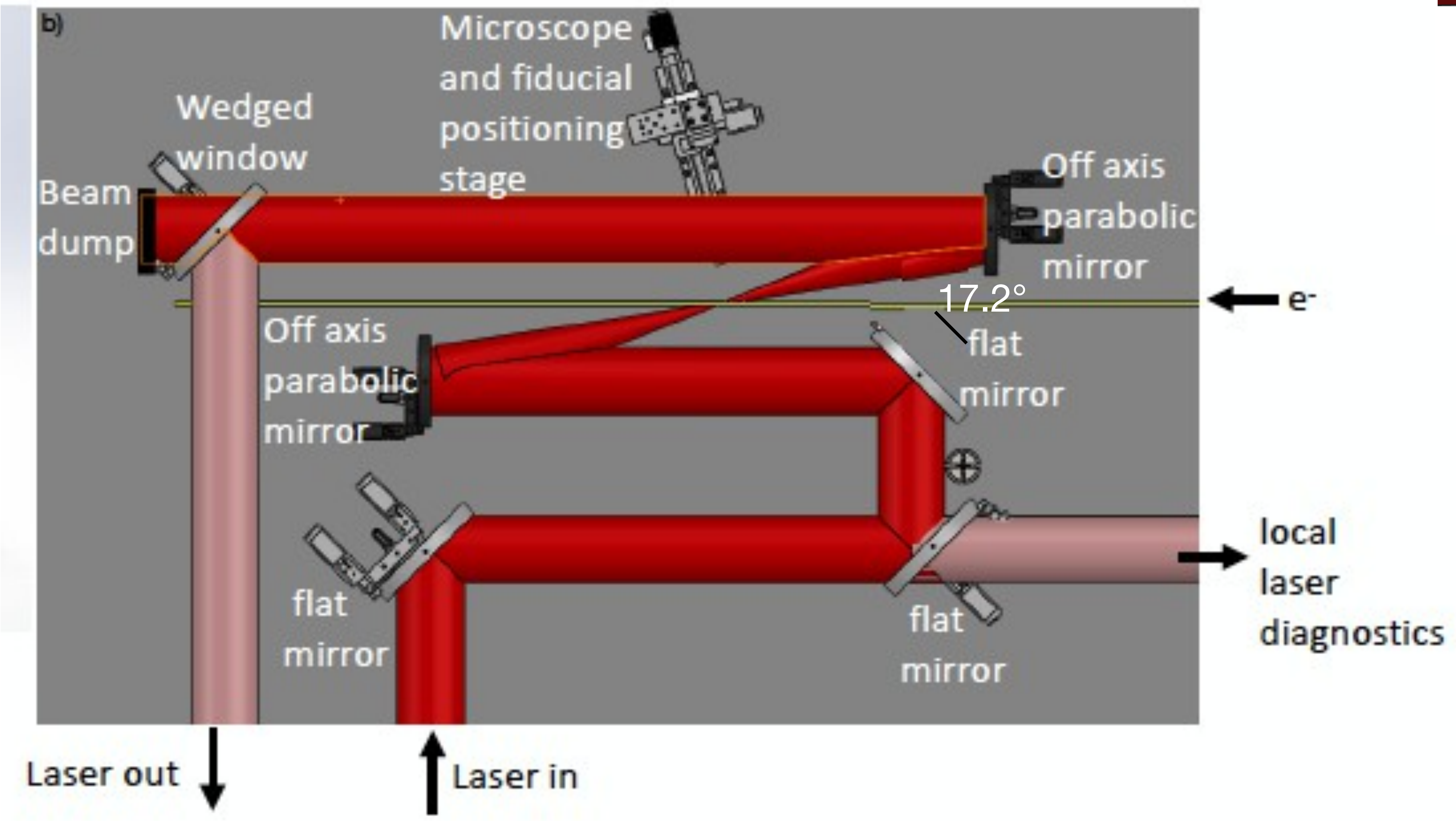
Parameter	Phase 0	Phase 0	Phase I
Laser power	40 TW		350 TW
Laser energy after compression [J]	1.2		10
Percentage of laser in focus [%]	50		
Laser focal spot size w_0 [µm]	>8	>3	>3
Peak intensity [10^{19} W/cm2]	1.9	13.3	120
Peak intensity parameter ξ	3.0	7.9	23.6
Peak quantum parameter X E_{beam}=16.5 GeV	0.56	1.5	4.5

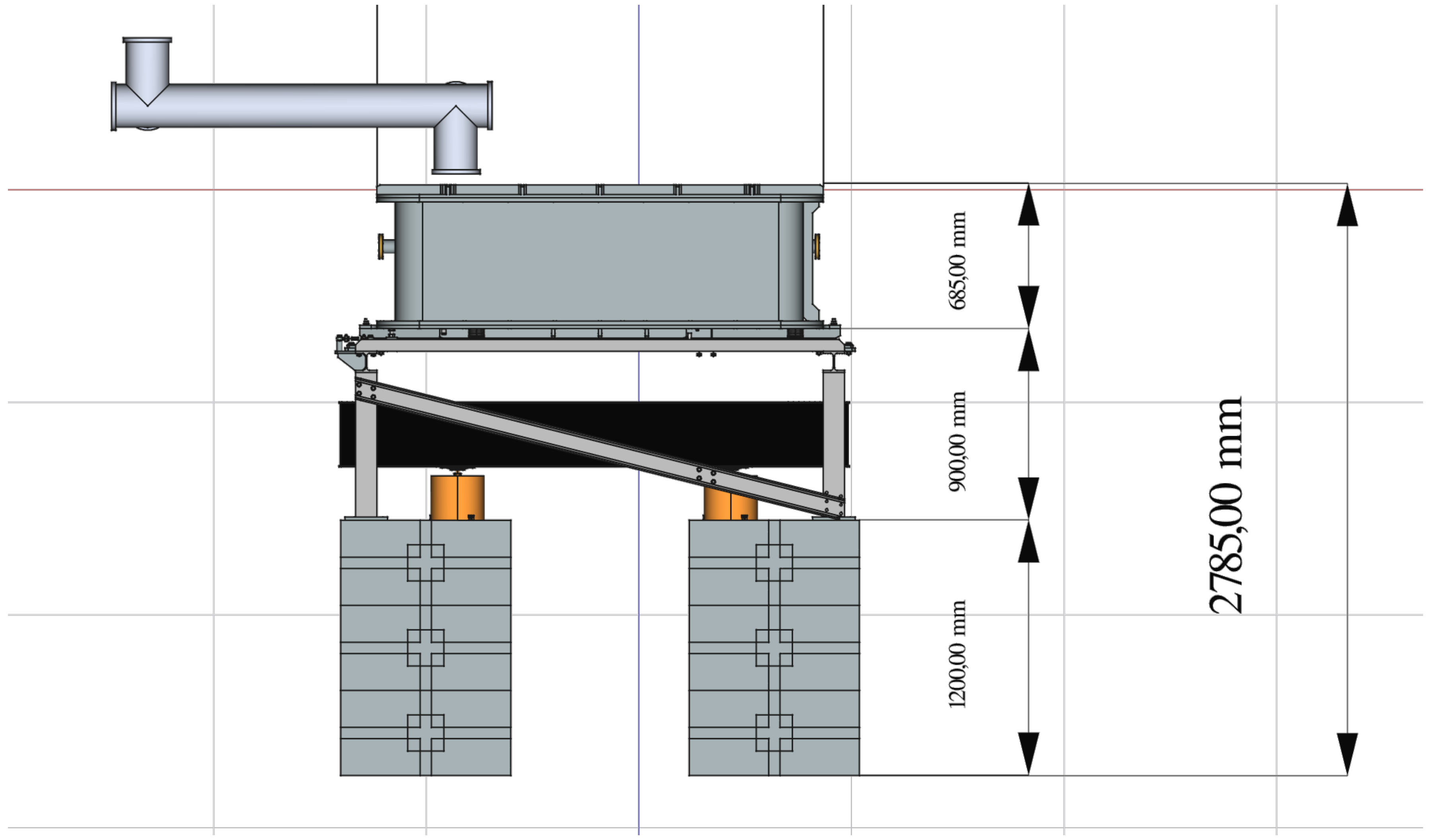


LASER BEAMLINE AND IP CHAMBER

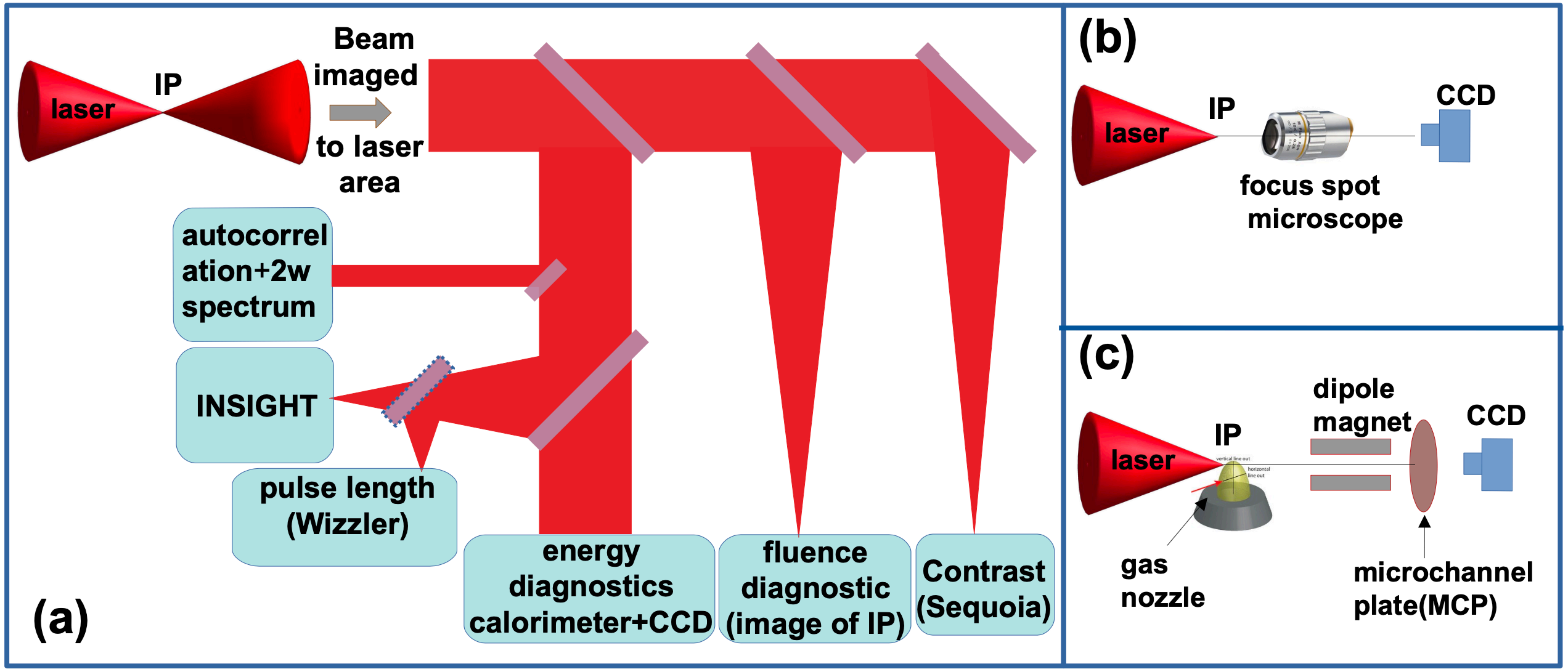
- Laser installed in new surface building.
- Guided from iso-6 clean room down to IP via ~50m beam line.
- Thick concrete slab in laser lab to allows laser stability.
- Final focusing done just before IP in dedicated chamber.
- IP chamber vacuum vessel reusing ALPS2 design.







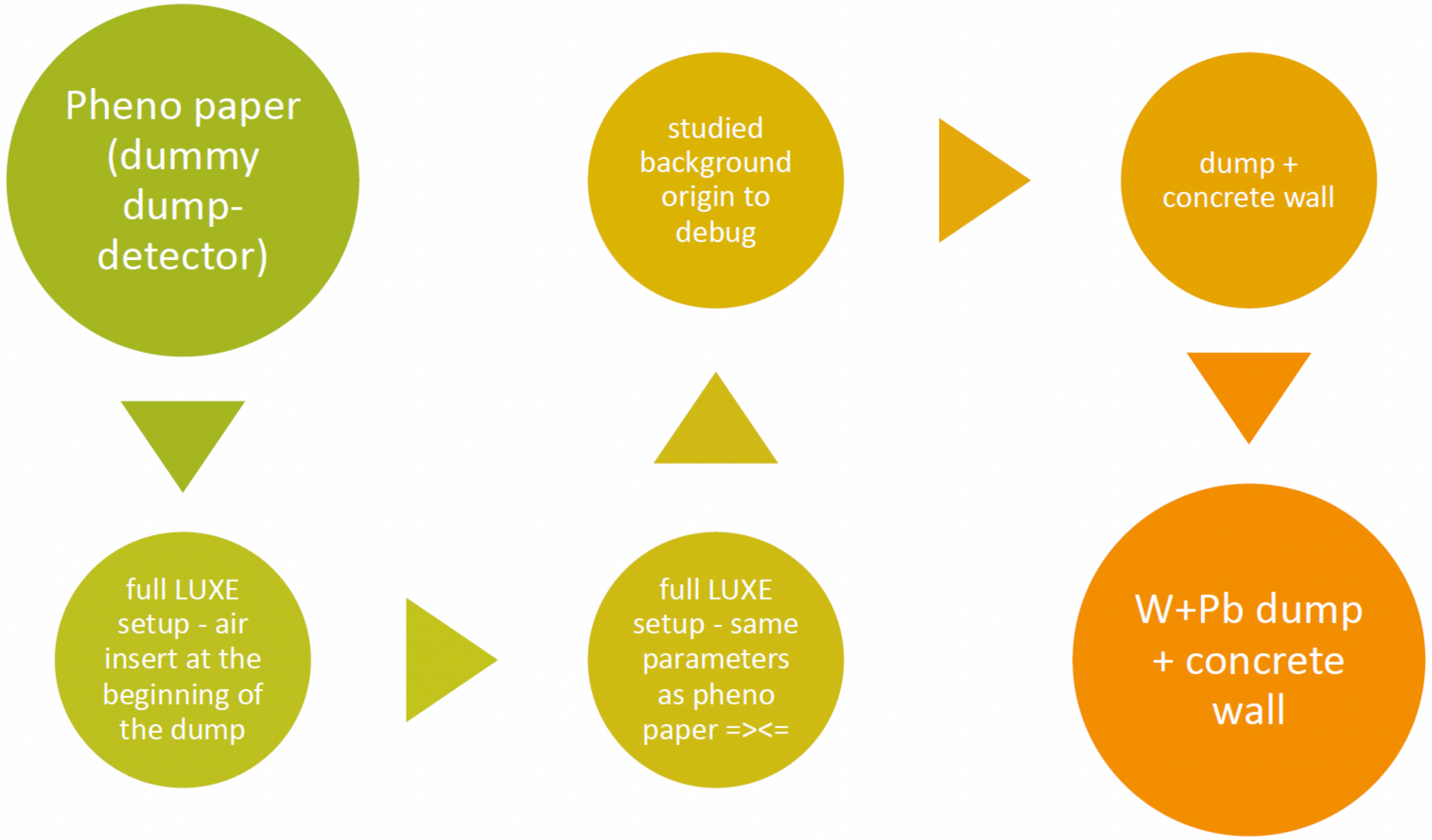
LASER DIAGNOSTICS



- Laser characterisation quantities: energy, pulse length, spot size
- many (partially redundant) measurements planned
  - Laser is not perturbed by e^- beam allow multiple diagnostics
    - In IP chamber and back in laser clean room.
- Laser intensity uncertainty has a large impact on sensitivity
- goal: ≤ 5% uncertainty on Laser intensity, 1% shot-to-shot uncertainty

BSM PHYSICS? RECENT STUDIES.

- Optimised photon dump geometry to minimise background and maximise signal
  - Computing challenge.
    - Need to compare tens of geometries and simulate billions of electrons with G4.
- Determined optimal detector characteristics for signal detection and background rejection
- Investigation of options that have been developed which could match these requirements
  - Alice FoCal.
  - H1 SPACAL.
  - Calice SiPM on Tiles.
  - etc.
- Understand if prototypes are available or impact on resources.

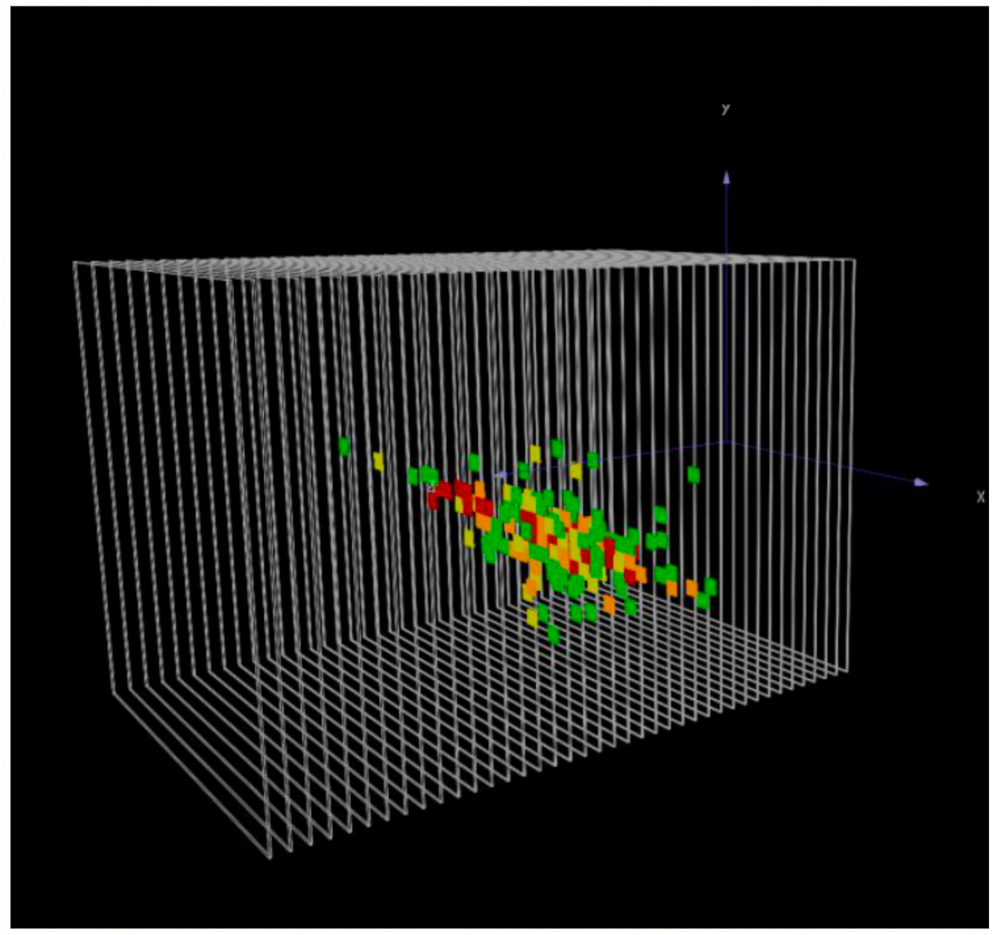


Detector physics goals:

- Signal efficiency
  - Photons shower separation (~ 2 cm)
- Suppression of residual backgrounds
  - Shower shape determination (neutrons)
  - Good time resolution (< 1ns) (neutrons)
- Precise reconstruction of ALP invariant mass
  - Good resolution of photons direction and energy (in the range of the few GeV)
  - Non-resonant photons rejections

A small detector (r ≤ 50 cm) will also ensure a high signal acceptance

→ Ideal candidate: tracking calorimeter



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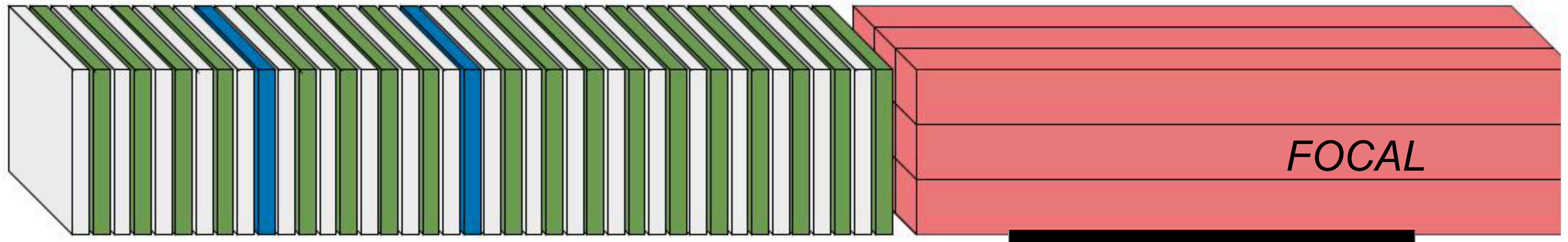

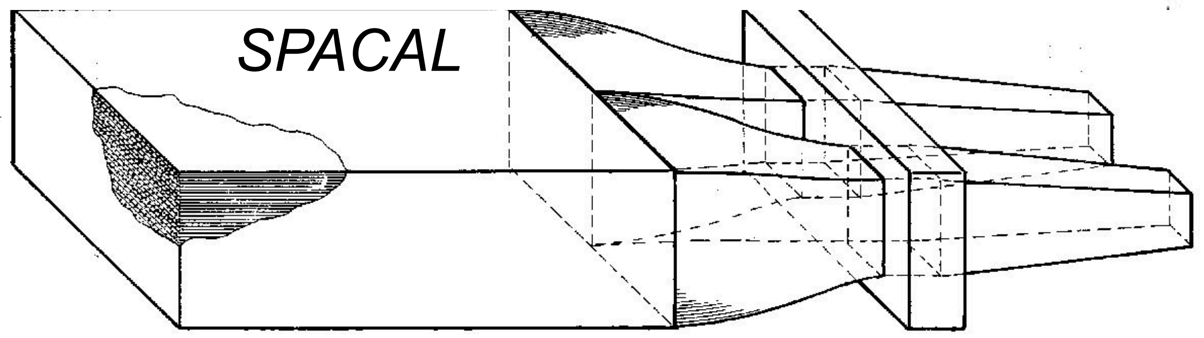

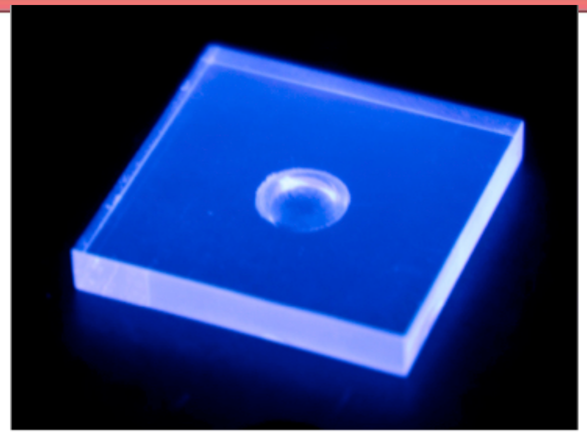

Calice Tile