LUXE

Proposal for a new experiment using a Laser and XFEL to test QED in strong field regime

Beate Heinemann (DESY and University of Freiburg) on behalf of
put all names of LUXE collaborators

March 2019

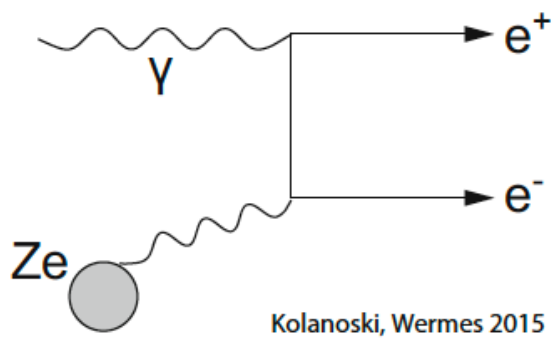
PRODUCING MATTER FROM LIGHT

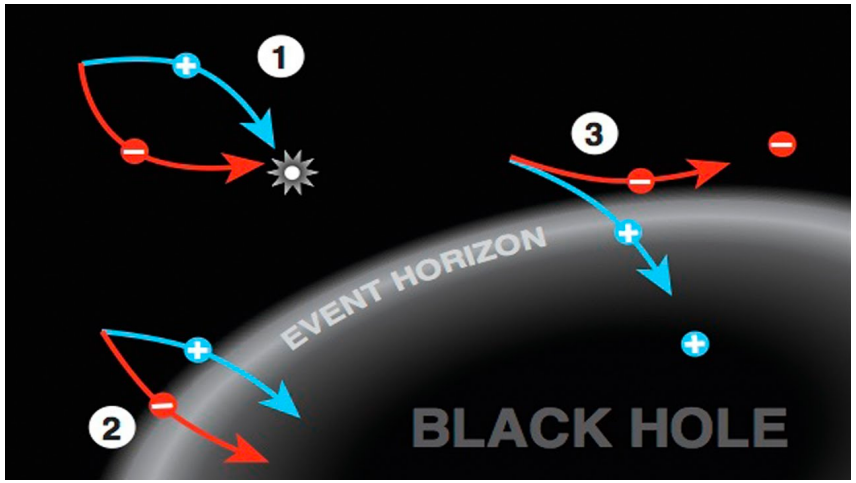
Process of interest: $\gamma \rightarrow e^+e^-$

- In vacuum normally possible as cannot satisfy both energy and momentum conservation
- Occurs frequently near nucleus of atoms

Proposal: create extremely strong field so that pair production becomes possible in vacuum

- Only possible due to uncertainty principle
- E.g. required for Hawking radiation
  - Black-body radiation released by black holes at event horizon due to quantum fluctuations
  - Quantum fluctuations of photons into electron-positron pairs
  - Pair can be separated if the gravitational field large enough
- Such strong fields relevant for several astrophysical phenomena
  - Neutron stars, Early Universe, Black holes, …





HAWKING RADIATION IN A NUTSHELL

Energy needed to create on-shell e^+e^- pair: $\Delta E = 2mc^2$

Minimal time (using Heisenberg's uncertainty principle):

- $\Delta t \geq \frac{\hbar}{\Delta E}$ => $t_{min} = \frac{\hbar}{2mc^2}$

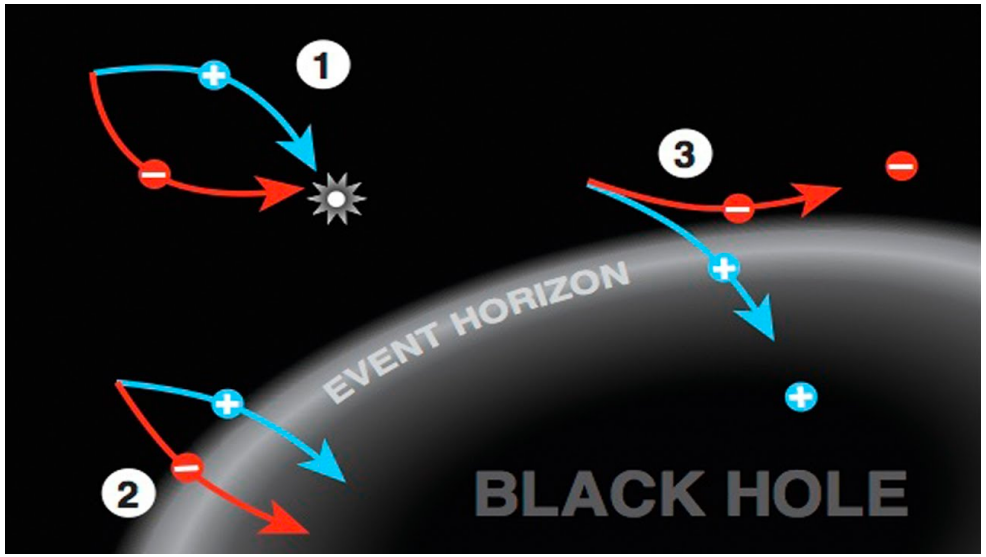
Minimum distance between pair: $d_{min} = 2c\Delta t_{min} = \frac{\hbar}{mc}$

- since they both fly with c away from each other

Grav. Field near the event horizon: $F = \frac{G_N M m}{r_s^2}$

Schwarzschild radius $r_s = \frac{2G_N M}{c^2}$**. =>** $F = \frac{mc^4}{4G_N M}$

Energy to separate pair: $E = F d_{min} = \frac{mc^4}{4G_N M} \times \frac{\hbar}{mc} = \frac{\hbar c^3}{4G_N M}$

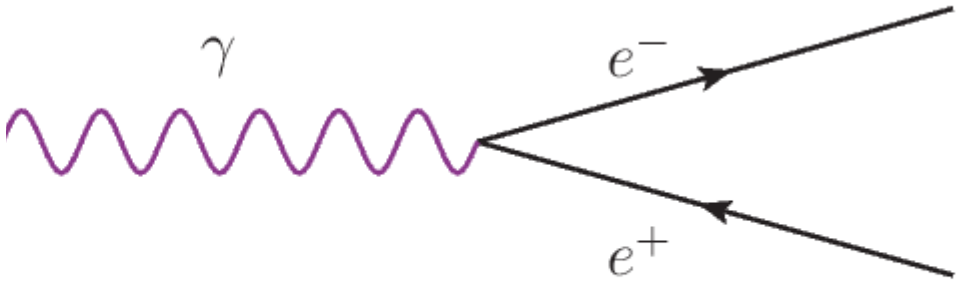


Hawking radiation possible if virtual pair becomes real, i.e. $\frac{\hbar c^3}{4G_N M} > 2mc^2$

LUXE: USE E-FIELD INSTEAD OF G-FIELD

Analogous to gravitational force

- The EM force is $F = e\varepsilon$
- Energy to separate pair: $E = Fd_{min} = \frac{\hbar e\varepsilon}{mc}$
- Virtual pair becomes real if $E = Fd_{min} = \frac{\hbar e\varepsilon}{mc} > 2mc^2$



$\Rightarrow$ **Possible if** $\varepsilon > \frac{2m^2c^3}{\hbar e} = 2\varepsilon_{Schwinger}$

$$\varepsilon_{Schwinger} = \frac{m_e^2 c^3}{e\hbar} \approx 1.3{\times}10^{18}\ V/m$$

J. Schwinger calculated in 1950s that at this field strength quantum electrodynamics (QED) becomes non-perturbative

This field strength (”Schwinger limit”) has never been reached experimentally

NON-LINEAR QED PROCESSES

Use Laser to generate electric field

- Relevant quantities: $\xi = eE_L/(m_e\omega_L c)$ and $\chi=2(\omega_L\gamma/m_e)E_L/E_{crit}$

Predictions for rate

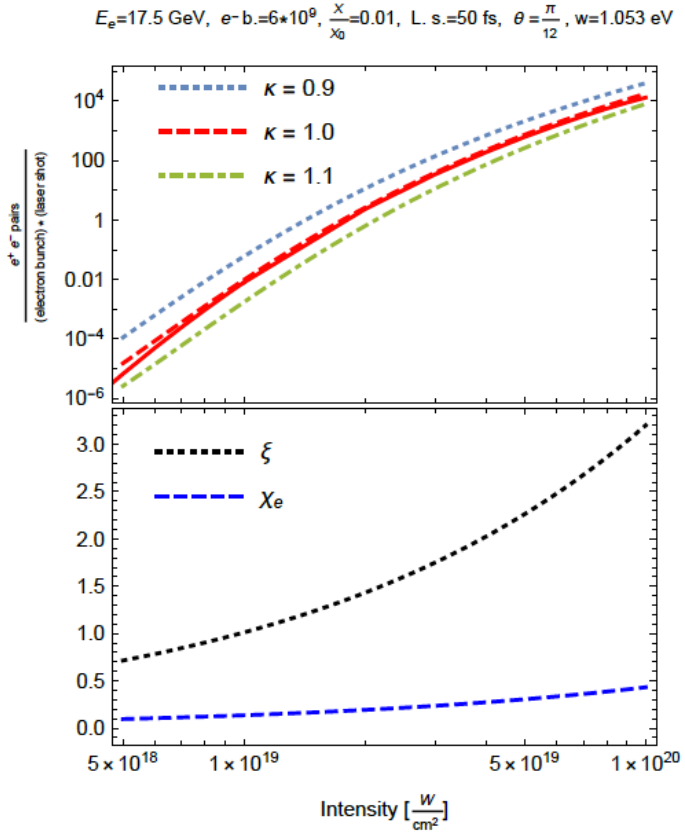
- Pair production positron rate: depends on adiabacity

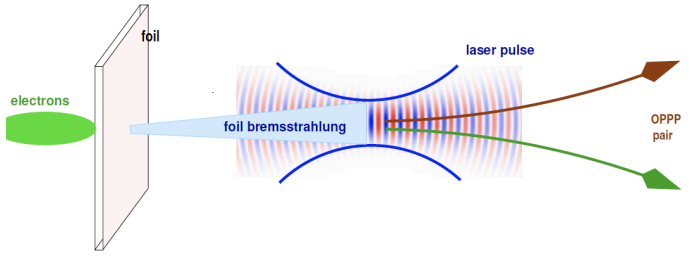
$\xi \ll 1$ Stimulated process: $R_{e+} \propto \eta^{2n} \propto I^n$

$\xi \gg 1$ Non-pert. process $R_{e+} \propto \exp(-8/(3\kappa))$

European XFEL:

- Use high energy electron beam to create high-energy photons
- Electric field seen by photon within its rest frame enhanced by relativistic factor $\gamma = E_\gamma/m_e$





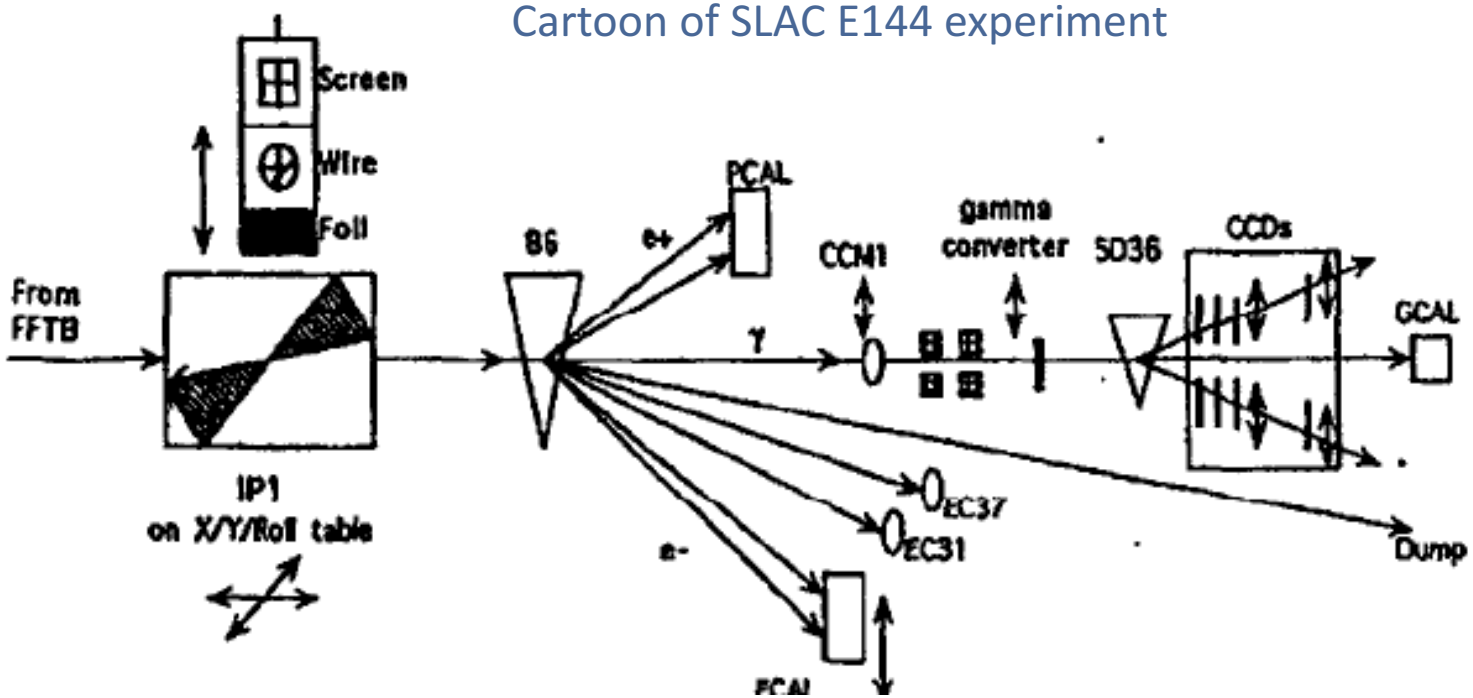
EXPERIMENT E144 AT SLAC

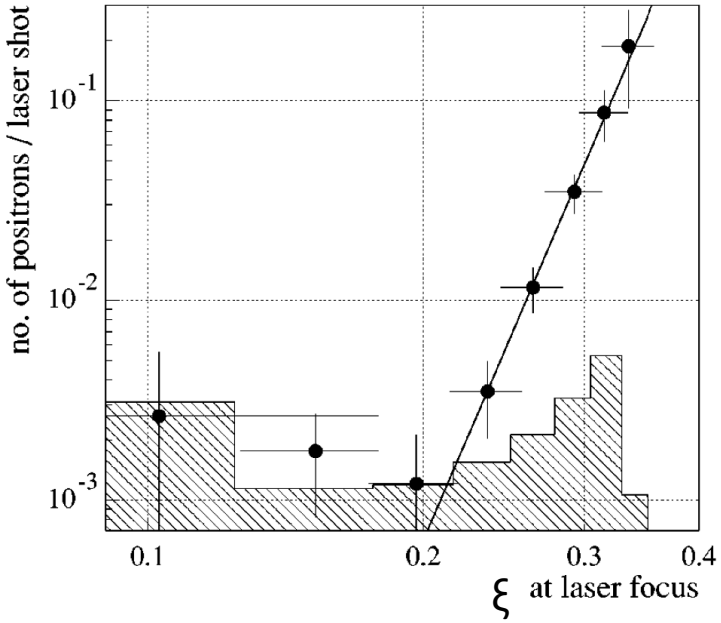
Experiment at SLAC in 1990s

Achieved $\xi<0.4$ and $\chi<0.25$

- Did observe the strong rise $\propto \xi^{2n}$ but not the asymptotic limit
- Did not reach the Schwinger field

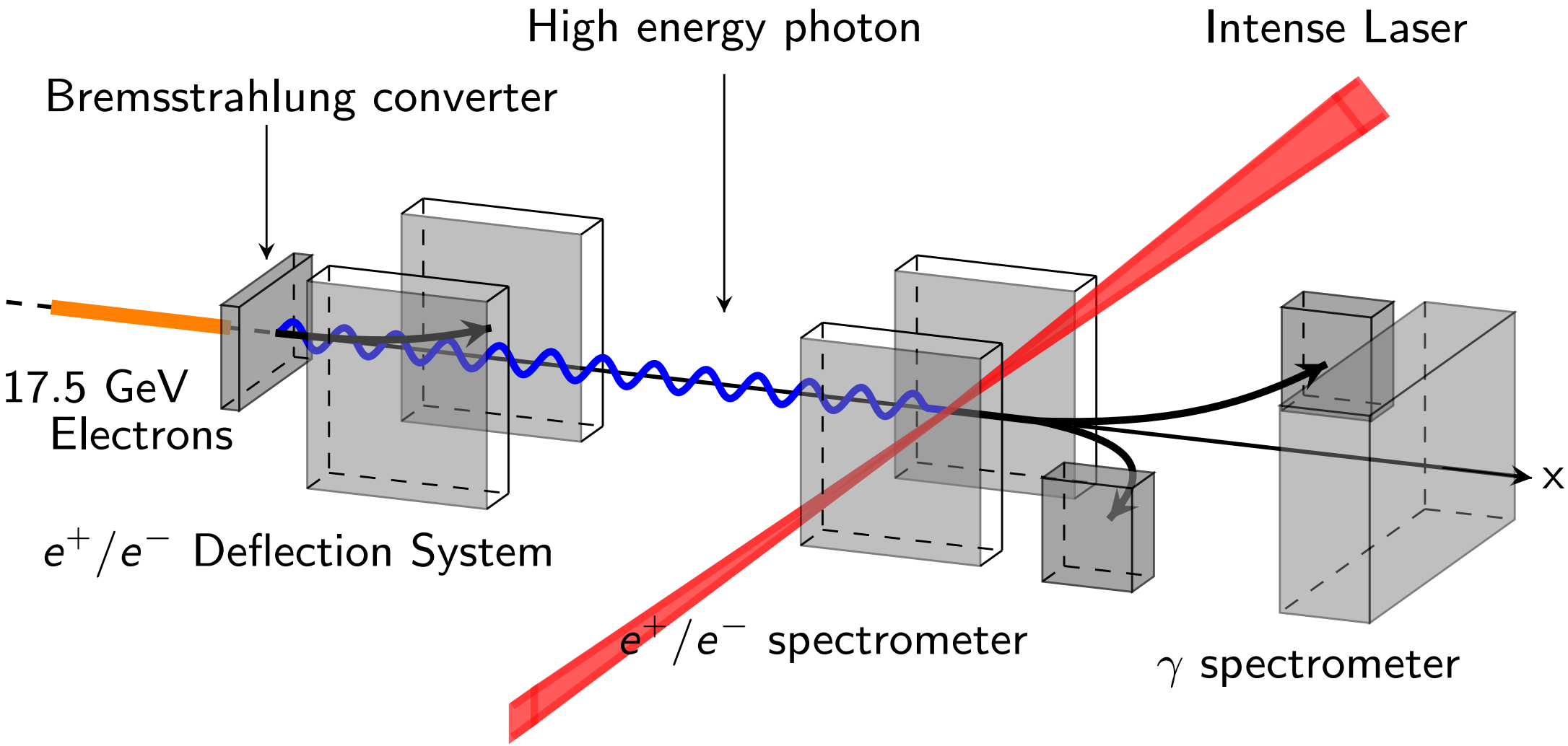
Cartoon of SLAC E144 experiment





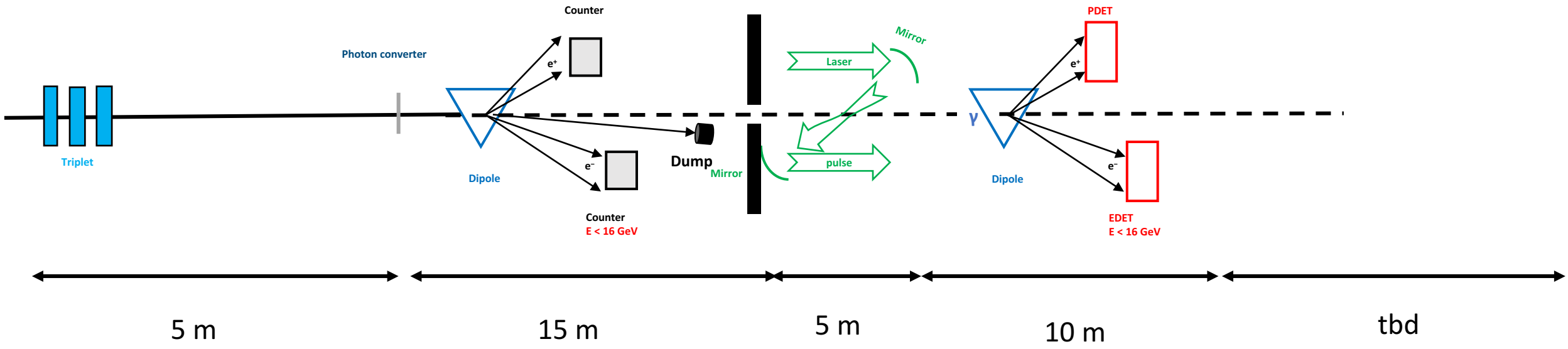
[Bamber et al. (SLAC 144) '99]

BEAMLINE AND DETECTOR SETUP



PHOTON LASER COLLISIONS

$\gamma + n\omega$



LUXE LASER PARAMETERS

	STAGE 0	STAGE 1
Energy [J]	0.35	7.0
Power [TW]	10	200
Intensity [W/cm^2]	10^{19}	$2x10^{20}$
η Parameter	1.5	0.3
χ Parameter	6.8	1.4

Ti:Sapphire technology
Pulse length: 35 fs
Focal length: 1m
Focus area: 100 μm^2

- Initial Stage (stage 0):
  - proof of principle, less costly, smaller laser
  - similar to E144 but higher precision
- Design Stage (stage 1):
  - Reach critical field strength => pioneering new territory of quantum theory
  - Requires room of about 100 m^2

EVENT RATE

Measure event rate vs laser intensity

Stage-0:

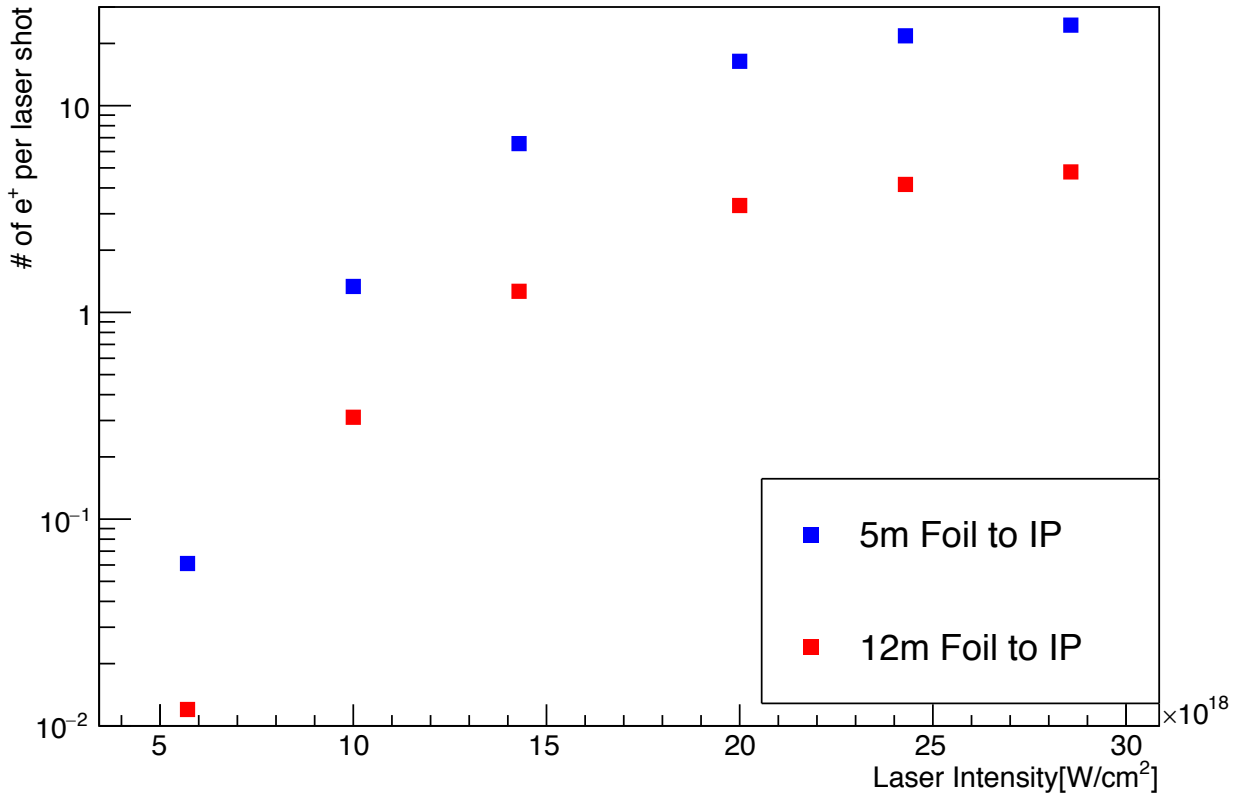
- Reach laser intensity of 10^{19} W/cm^2
- Observe steep rise

Stage-1

- Reach laser intensities up to 2x10^{20} W/cm^2
- Well into ”asymptotic regime”

Real time required:

- Determined by laser: shot rate up to 10 Hz
- 1M laser shots ≈ 24 hours



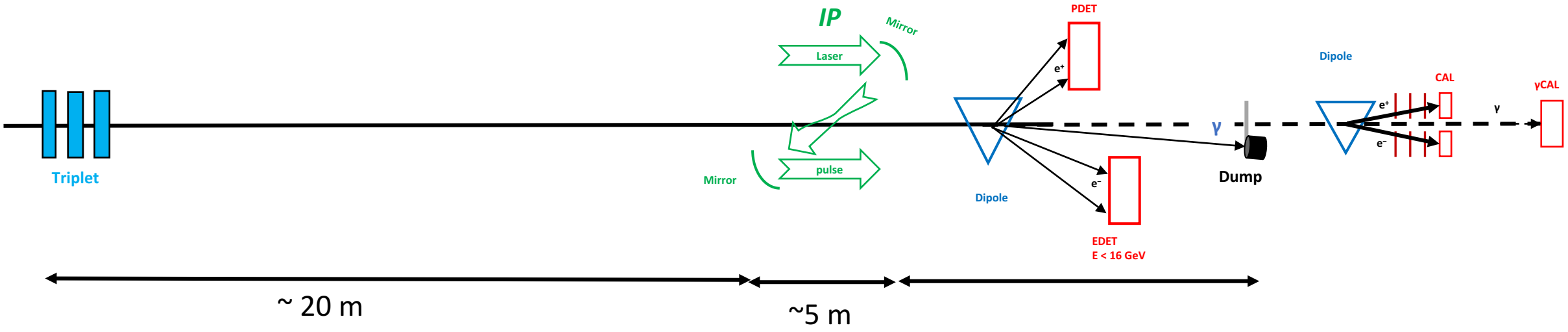
(assumes 6x10^9 electrons/bunch, E_e=17.5 GeV)

ELECTRON LASER COLLISIONS

Plan to also study electron directly in laser field (ω is a laser photon):

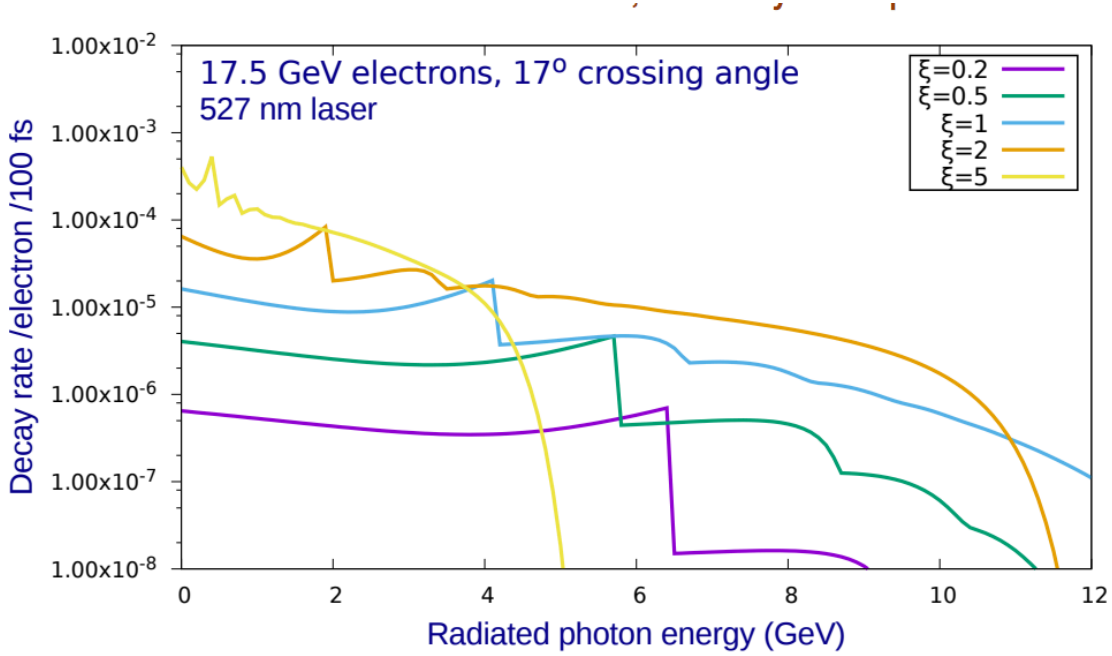
- **Study Compton process:** $e^- + n\omega \rightarrow e^- + \gamma$
- **Study "trident" process:** $e^- + n\omega \rightarrow e^- e^+ e^-$

$e^- + n\omega$

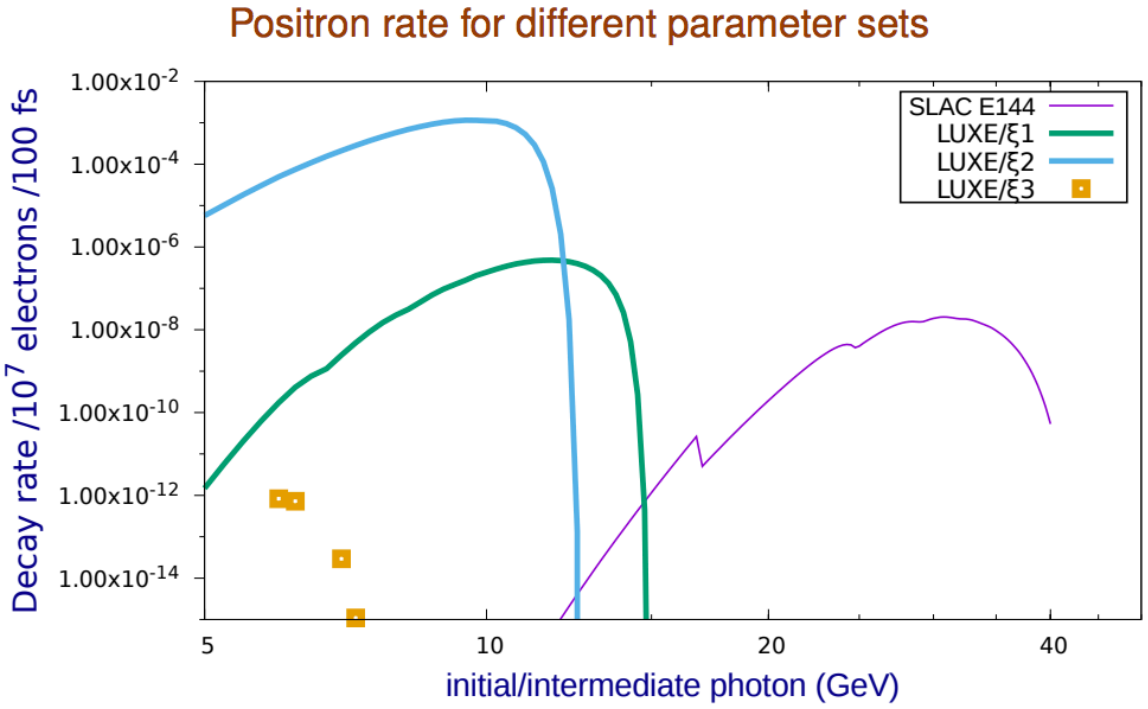


SLIDE ON MASS SHIFT AND TRIDENTS?

$$e^- + n\omega \rightarrow e^- + \gamma$$



$$e^- + n\omega \rightarrow e^- e^+ e^-$$

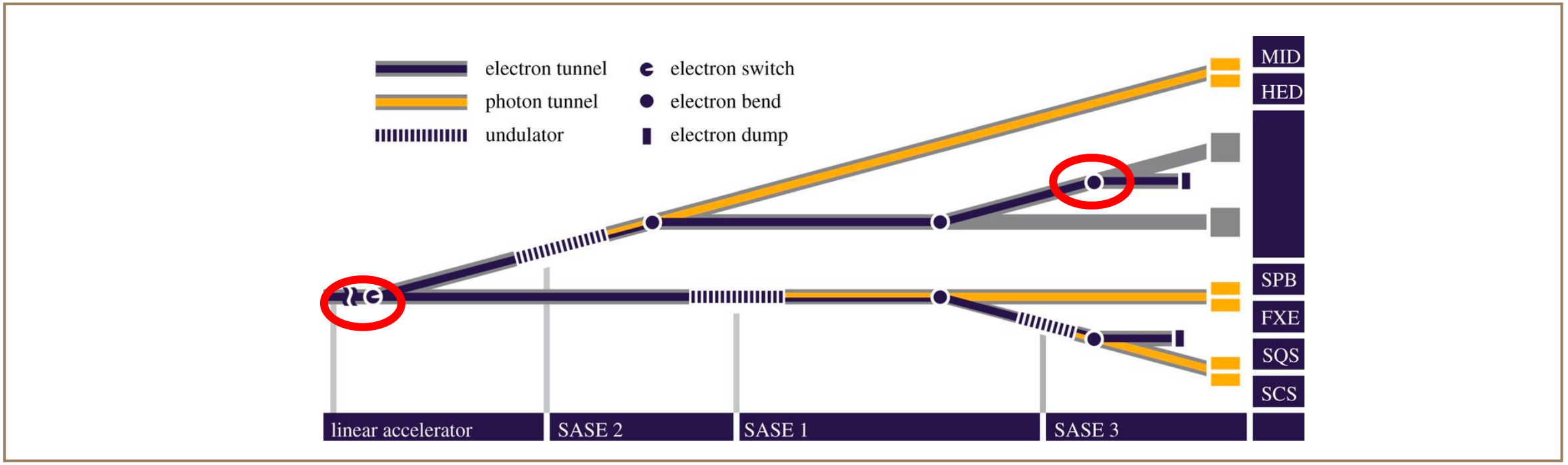


Plots by A.Hartin

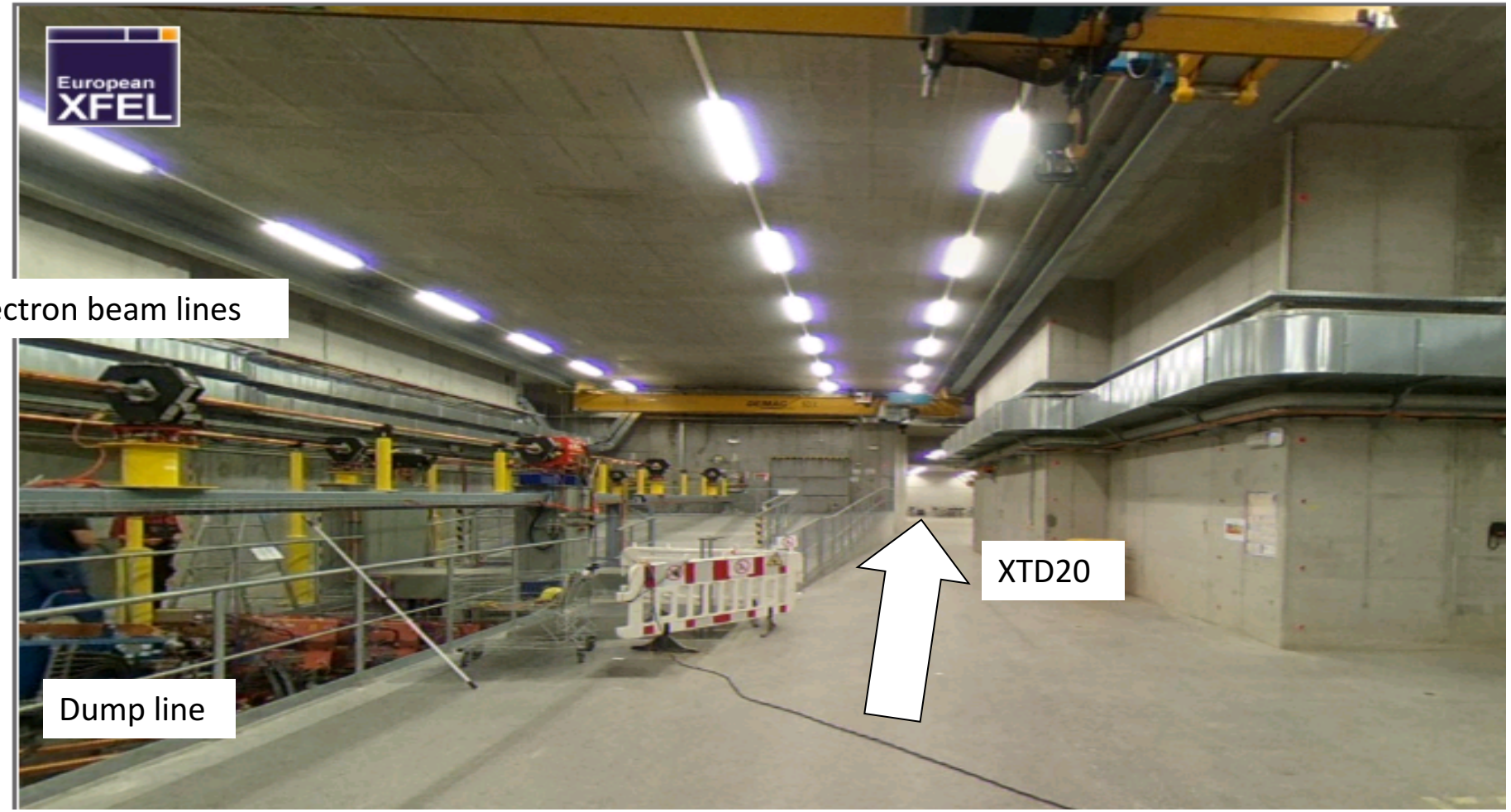
POSSIBLE LOCATIONS IN XFEL TUNNEL

Location in XFEL either right before the beam dump (XSDU1) or at the end of LINAC (XTD20)

- Design aims to have no impact on photon science programme
- 100m space in longitudinal direction should be sufficient
- Use only 1 of the 2700 bunches in bunch train (kicked out by kicker)



PICTURE OF XS1



PICTURE OF XSDU1

DISCUSSIONS OF TWO LOCATIONS

XSDU1 (near beam dump)

- Modification of beam line
  - downtime to be evaluated.
- Potential delay due to legal situation
  - additional extraction/beam dump, beam line) → plan-approval procedure.
- Maybe radiation towards XTD7
  - additional shiedling required.
- New building at the surface
  - funded by DESY
- Background from beam dump for experiment?
  - Being evaluated

XTD20 (end of LINAC)

- Uses existing building and beam line design.
- Modification of extraction beam line
  - downtime to be evaluated.
  - Extraction and beam line already included in plan-approval.
- Laser beam line transport via XS1 shaft.
- Early implementation of the beam extraction for future XFEL upgrade (2nd XFEL fan) and/or test beam area.
- Additional demonstration of the flexibility of the facility.

TIME SCALE

- **By Summer 2019:**
  - Determine feasibility, work plan and possible time scales for the two locations in XFEL tunnel
- **November 2019**
  - Application for ERC synergy grant (synergies of laser, particle physics and accelerator physics)
  - Obtain letter of support by management and council of EU.XFEL
- **Dec 2020/Jan 2021**
  - Start of installation (?): May extend over two shutdowns (should know in summer2019)
- **2021-2022 or 2022-2023**
  - Phase-0 experiment data taking: about 2-3 weeks per year
- **2023/2024:**
  - install more powerful laser
  - Publish results of phase-0 experiment
- **2025-2027:**
  - Data taking with high-power laser: a few weeks per year

COLLABORATION, FUNDING AND MISCELLANEOUS

Collaborating institutes (so far): about 15 collaborators total

- Germany: DESY, University of Hamburg, University of Freiburg, Helmholtz-Institut Jena, Helmholtz-Zentrum Dresden Rossendorf
- United Kingdom: University College London,
- Israel: Tel Aviv University, Weizmann Institute

Funding sources:

- DESY strategy fund for design of overall experiment (about 200k)
- Helmholtz Innovation Pool for design of laser (about 500k)
- ERC synergy grant (planned)

International landscape:

- Similar experiment planned at FACET at SLAC

CONCLUSIONS

Presented Proposal for new experiment at EU.XFEL: LUXE

Goal: study quantum field theory in novel regime

- Relevant for several astrophysical phenomena
- Relevant for future high energy accelerators

Experimental setup

- Design aims to be completely parasitic for XFEL,
  - i.e. not compromise any photon science but to add this aspect
- Aim to start installation in 1.5 years
  - Subject to identifying funding and receiving approval by relevant bodies

BACKUP SLIDES

BEAMLINE AND DETECTOR SETUP