Accelerator Technology Challenges (Part 3) : Accelerator operation and **design** challenges (2/2)

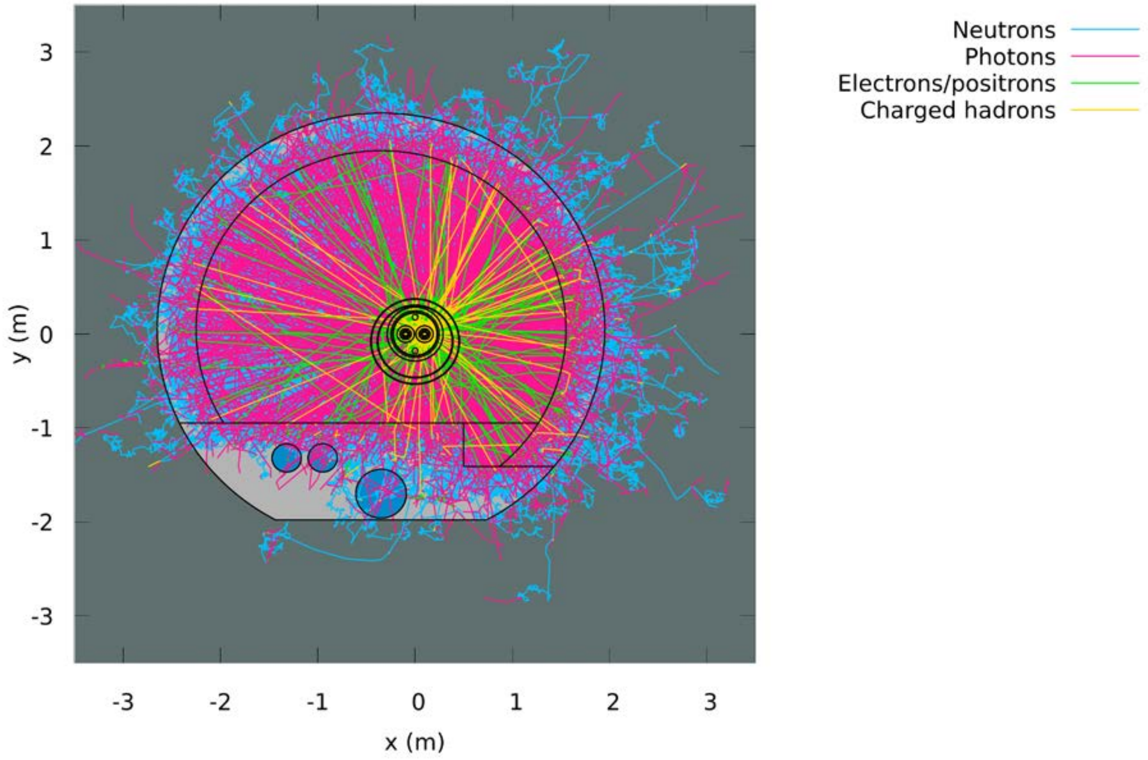
Francesc Salvat Pujol

With precious input from many CERN colleagues, especially A. Lechner, B. Humann, D. Calzolari

In the previous lecture

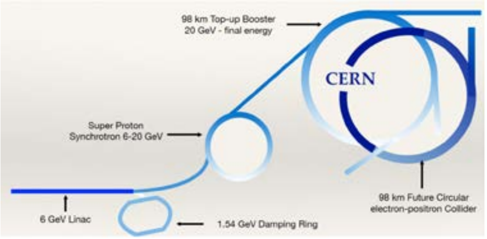
- Particle accelerator building blocks and operational cycle
- Beam losses
  - Causes and macroscopic effects (heating, displacement damage, activation, etc).
- Beam-matter interaction
- **Monte Carlo simulation tools**
- **Applications to accelerator design**
  - **HL-LHC**
  - **FCCee**
  - **Muon colliders**

Radiation shower set up by a single 450 GeV p loss



In this lecture

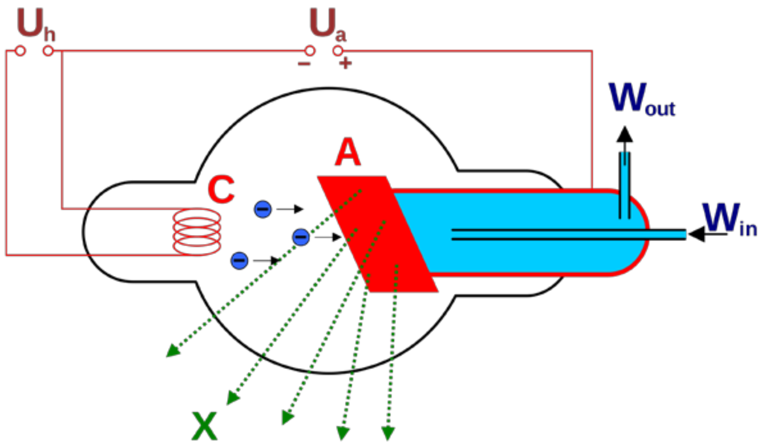
- An introduction to Monte Carlo simulations of particle transport for beam-matter interaction problems: FLUKA GEANT4 A SIMULATION TOOLKIT …
- **Application**: the present LHC and its upgrade HiLumi HL-LHC PROJECT
- Basic interaction mechanisms of e-, e+, and photons
- **Applications** in the design future lepton machines:
  - FCCee
  - Muon colliders



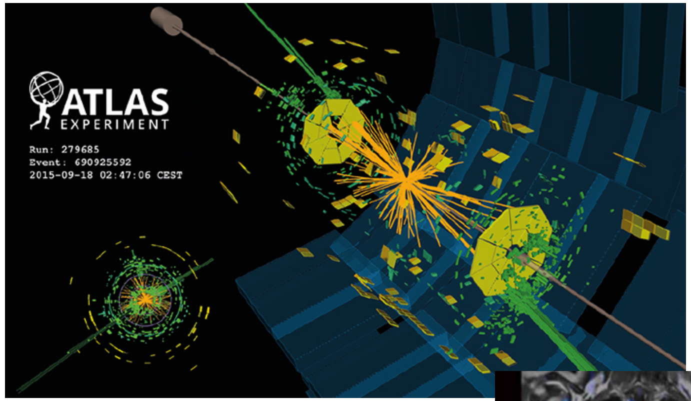
International
MUON Collider
Collaboration

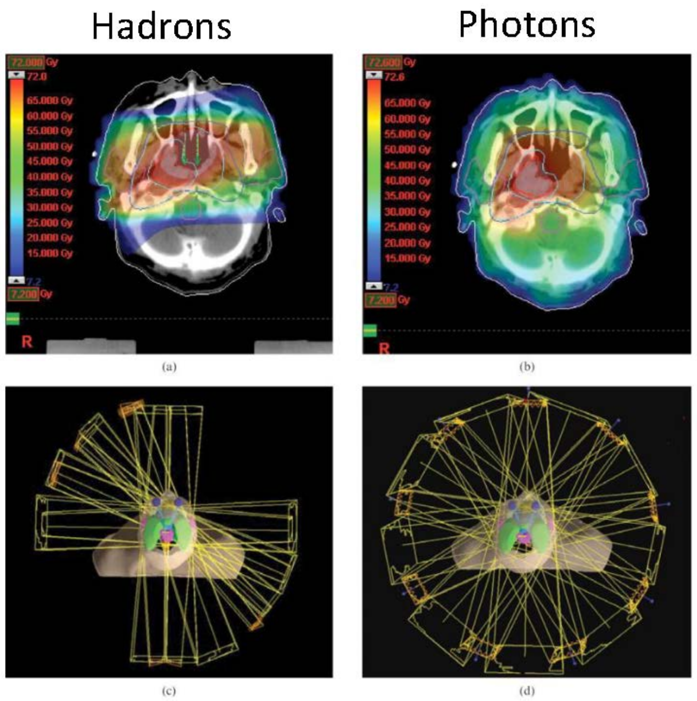
An introduction to the Monte Carlo method for the simulation of beam-matter interaction

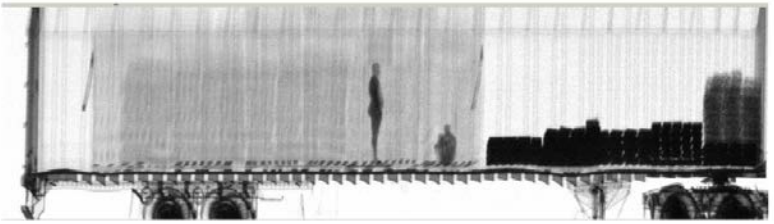
The radiation transport problem

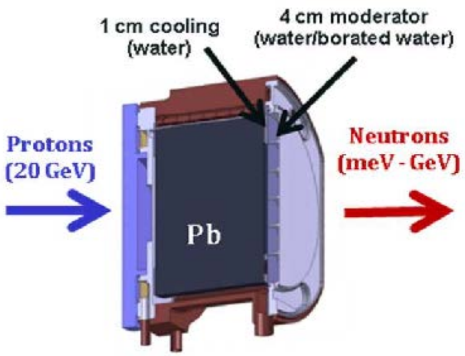


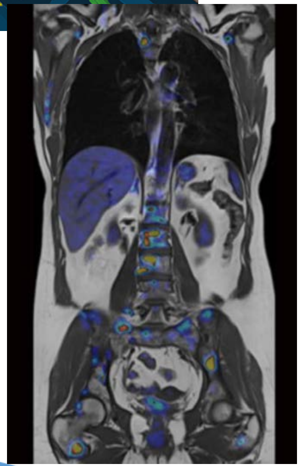
Source: Wikipedia







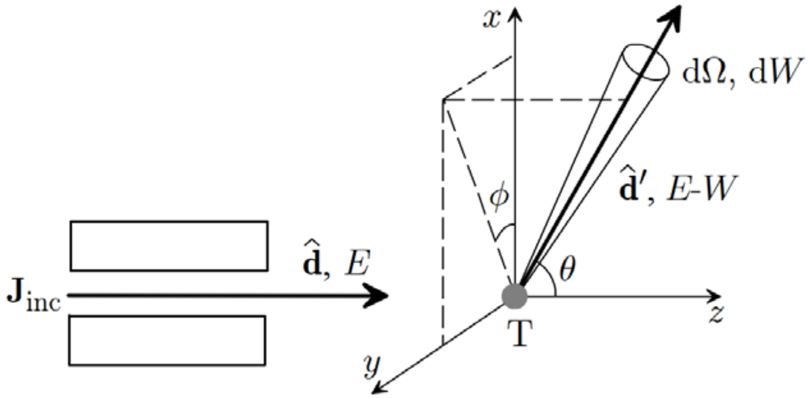




Radiation source → Propagation in matter → Detection

Cross section and mean free path

- **Cross section**: measure of the likelihood of an interaction



Differential cross section

$$\frac{d^2\sigma}{d\Omega\, dW} \equiv \frac{\dot{N}_{\text{count}}}{|\mathbf{J}_{\text{inc}}|\, d\Omega\, dW}$$

Dimensions of L^2/E/solid angle

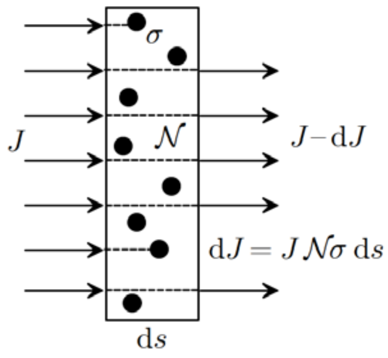
(Integrated) cross section

$$\sigma = \int_0^E dW \int \frac{d^2\sigma}{d\Omega\, dW}\, d\Omega$$

Dimensions of L^2

Typical unit: 1 barn = 10^{-24} cm^2

- **Mean free path (λ)**: average distance to the next interaction



$$p(s) = \mathcal{N}\sigma \exp\left[-s\left(\mathcal{N}\sigma\right)\right]$$

Path length

Number of atoms per unit volume

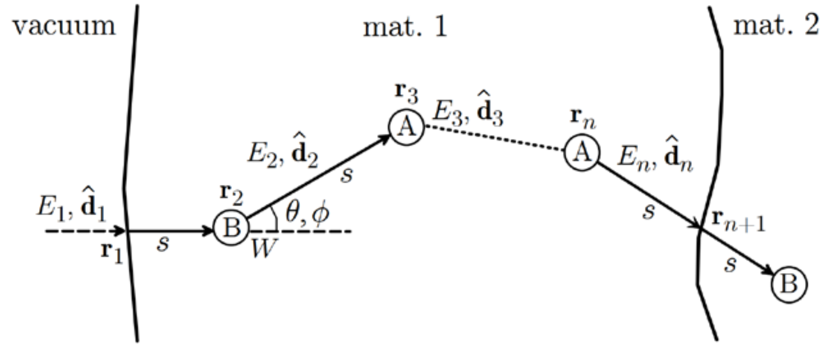
$$\lambda = \frac{1}{\mathcal{N}\sigma}$$

Dimensions of L

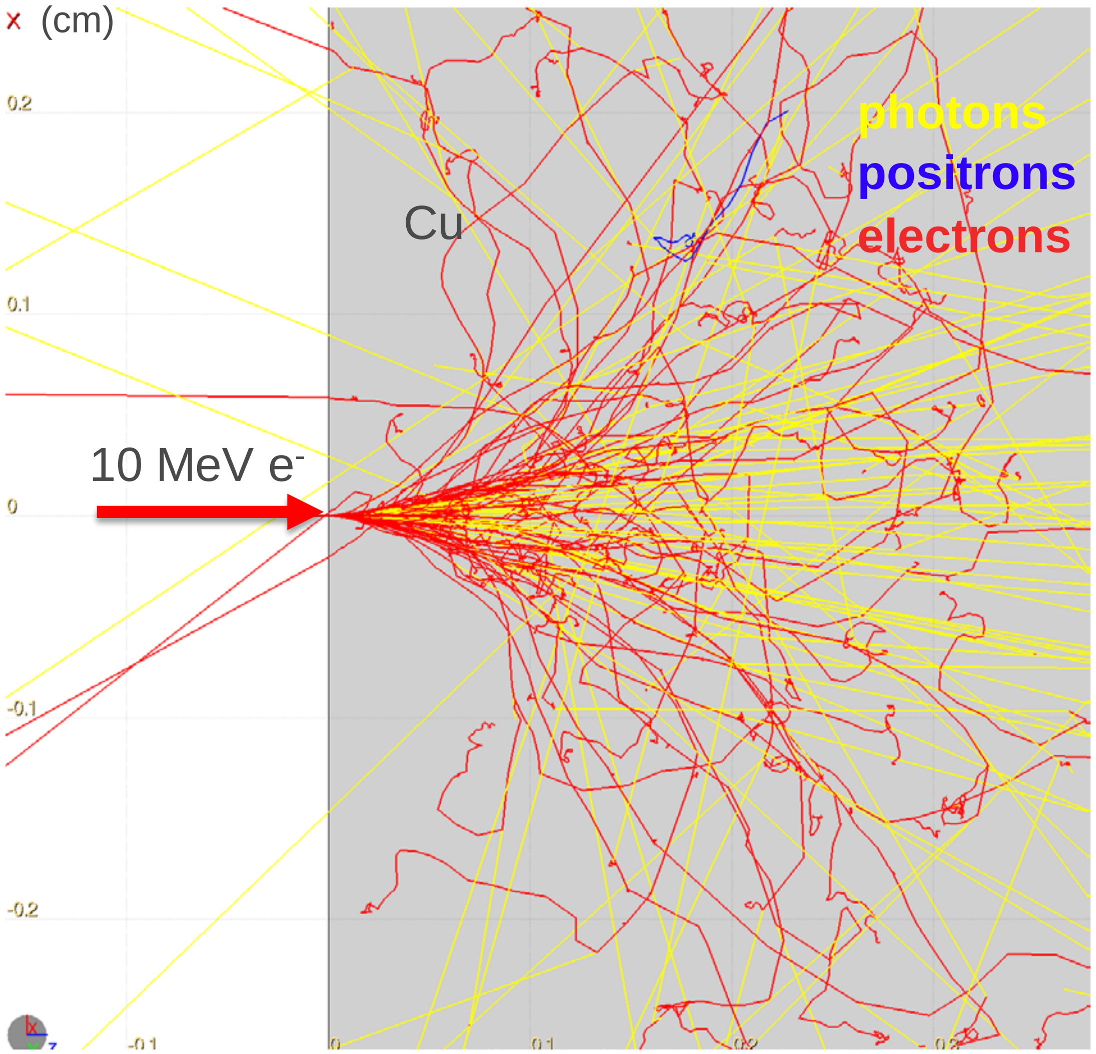
Derivation and figures: PENELOPE manual (NEA 2018)

The Monte Carlo method

MARS, PHITS, MCNP, PENELOPE, EGS, …



- List of particles: e-, e+, g, p, n, …
- List of interaction mechanisms (integrated and diff cross section for each)
- Define radiation source and material geometry
- Evaluate mean free path λ(E)
- Sample **random** step length to next interaction
- Decide kind of interaction: A, B, C, D,…
- Sample final state (possible secondaries)
- Contribute to statistical estimator of desired observables
- Sample an ensemble of particle trajectories



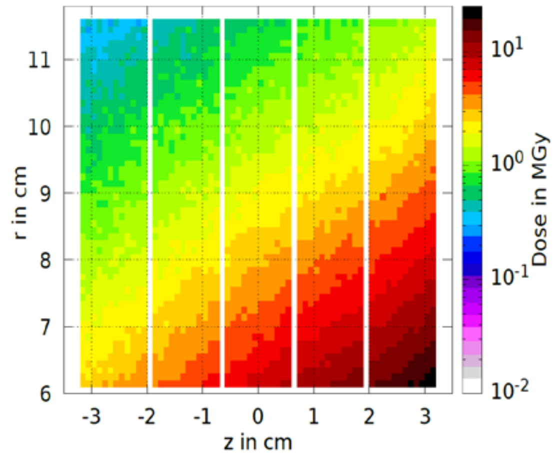
Relevant quantities to extract from MC for beam-loss effects

Short-term effects

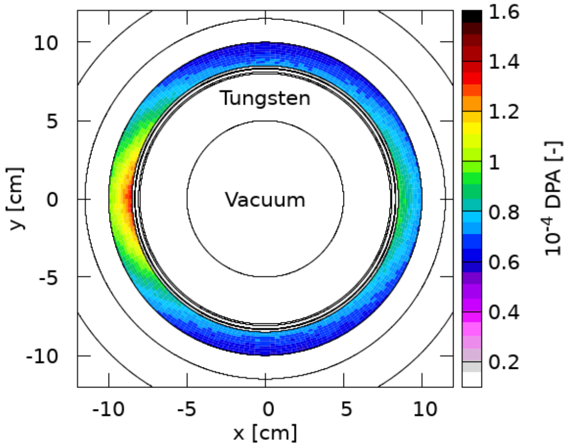
- Energy/Power deposition:
  - Superconducting magnet quench limit
  - Structural damage (melting, thermal shocks…)

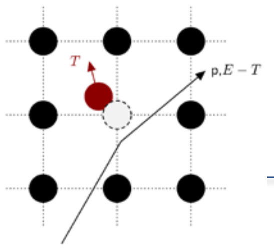
Long-term effects

- Dose during e.g. one operational year:
  - SC magnet insulator failure/oxidation



- Displacements per atom (DPA):
  - Microscopic structural defects

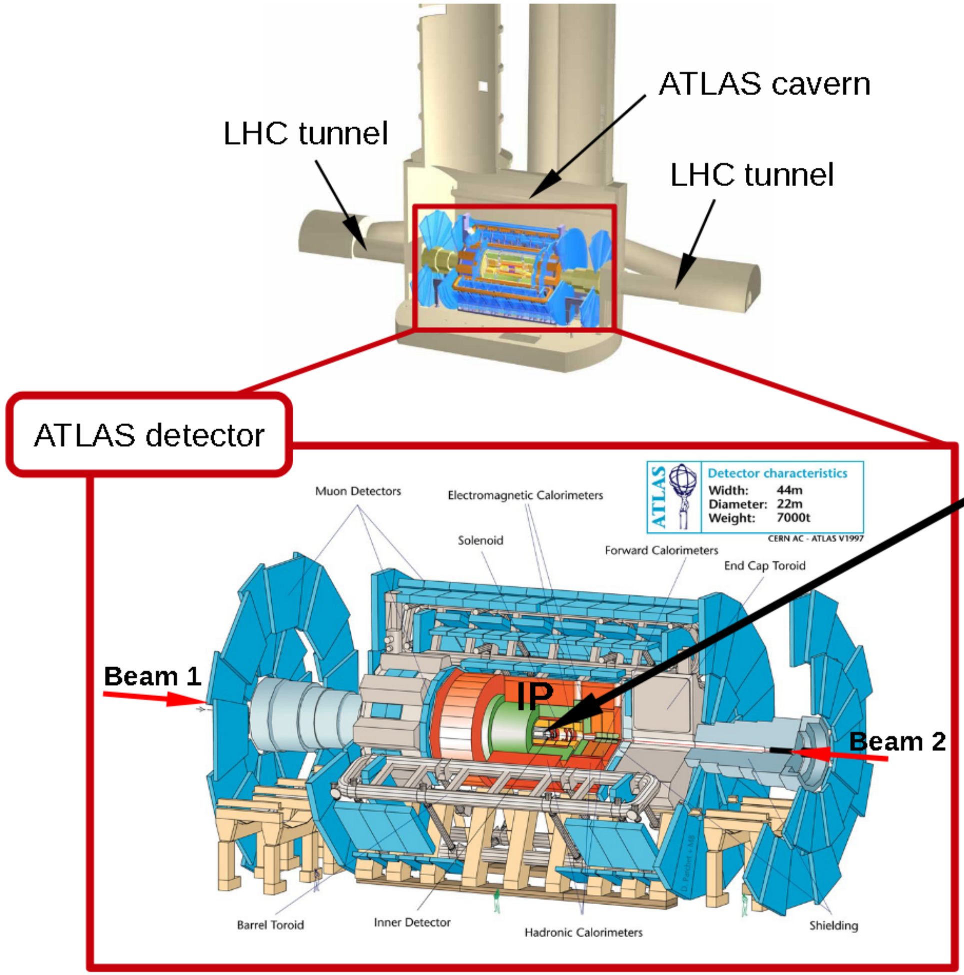


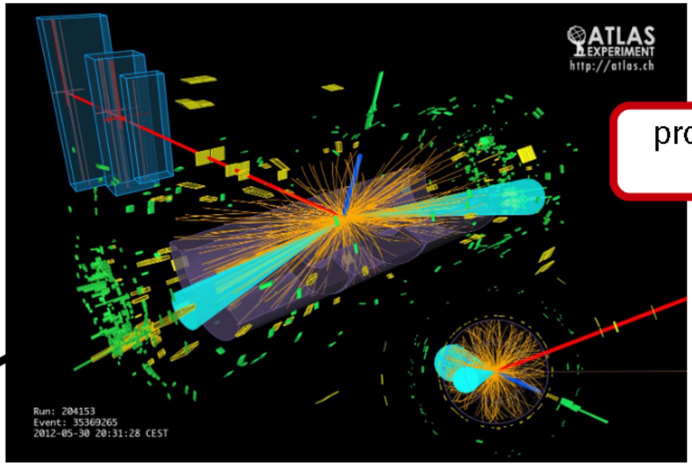


Beam loss / radiation source → MC simulation → Mitigation strategy

Example for HL-LHC

Power leakage to the LHC





*How much **power** is released in the collisions?*

Peak luminosity (2018): $\mathcal{L} \approx 2\times10^{34}\,\mathrm{cm^{-2}s^{-1}}$

Inelastic pp x-section: $\sigma_{inel} = 80\,\mathrm{mb}$ $(=80\times10^{-27}\,\mathrm{cm^2})$

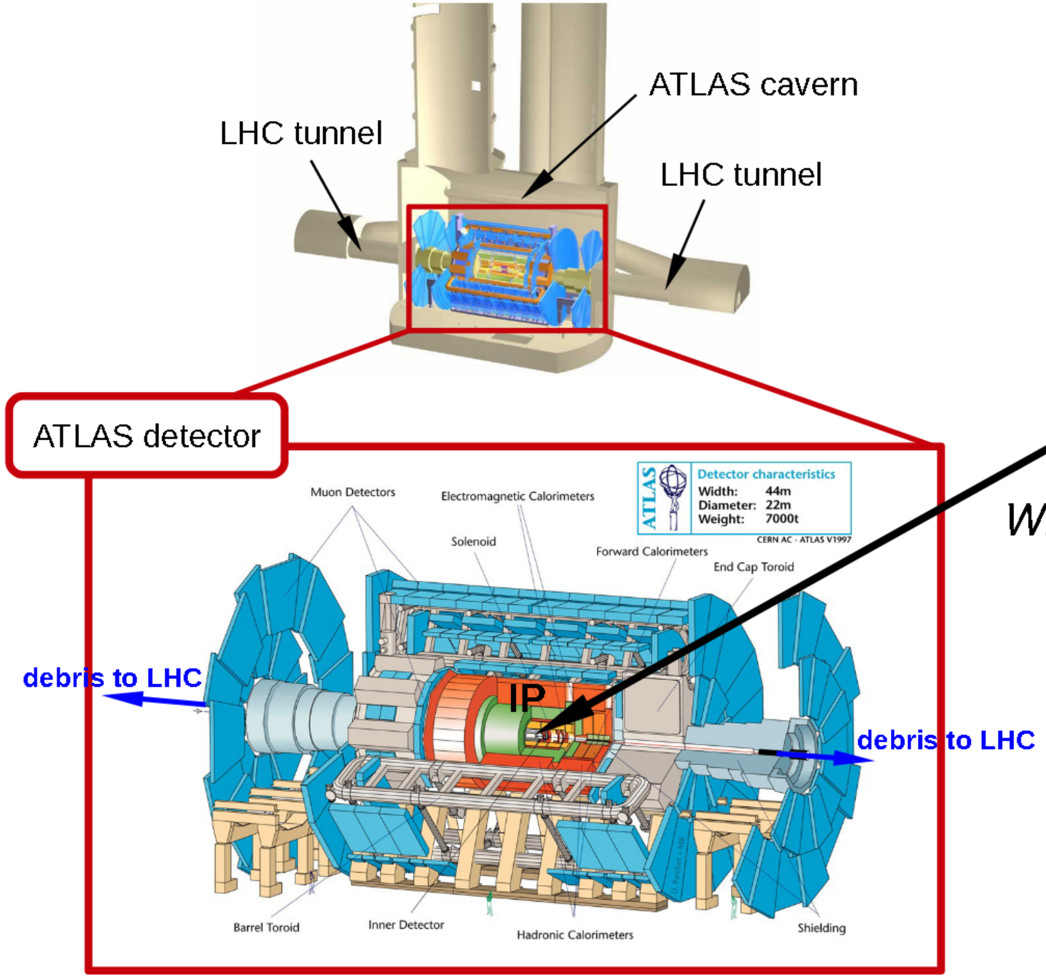
$\Rightarrow \mathcal{L}\cdot\sigma_{inel} = 1.6\times10^{9}$ collisions/s

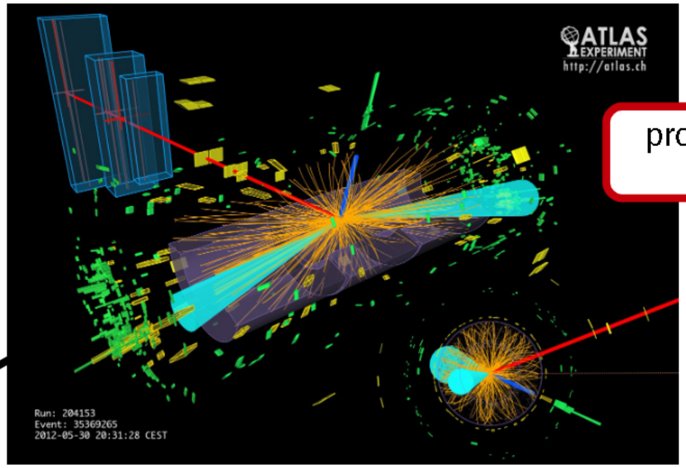
$\Rightarrow 2\cdot 6500\,\mathrm{GeV}\cdot 1.602\times10^{-10}\,\frac{\mathrm{J}}{\mathrm{GeV}}\cdot 1.6\times10^{9}\,\mathrm{coll/s}$

$= $ **3.3 kW (=kJ/s)**

(same for CMS, a factor of 50 less in LHCb)

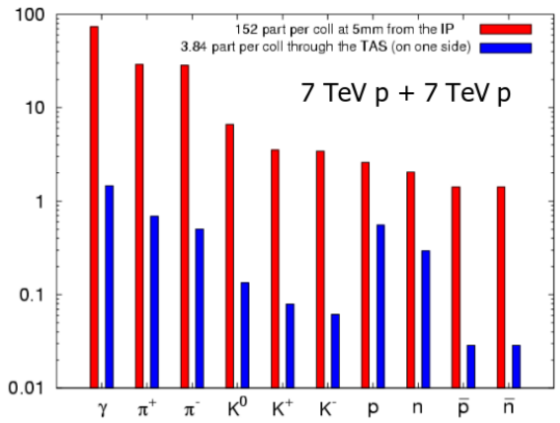
Power leakage to the LHC





proton-proton collision

Which particles are produced in the collisions?

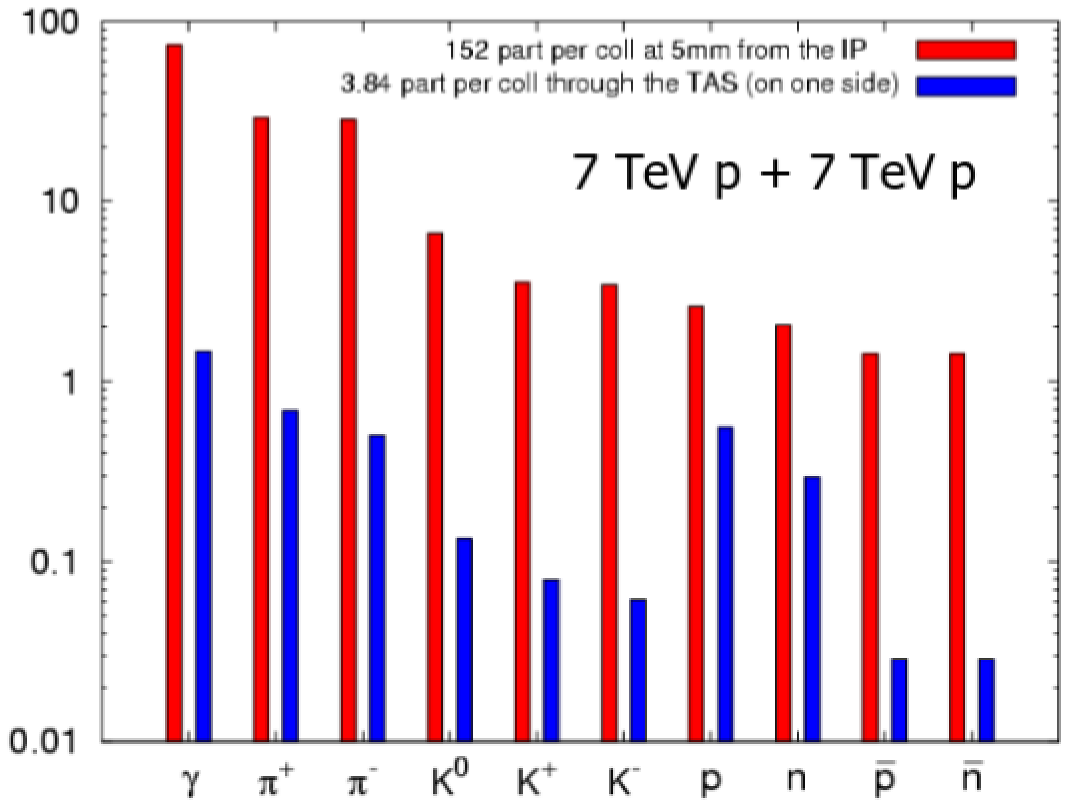


with 7.5 10^{-10} Higgs bosons

Red: secondary particles emerging from IP
→ on average 150 particles/pp coll

Blue: secondary particles leaving ATLAS cavern through vacuum chamber towards LHC
→ on average 8 particles/pp coll

Power leakage to the LHC



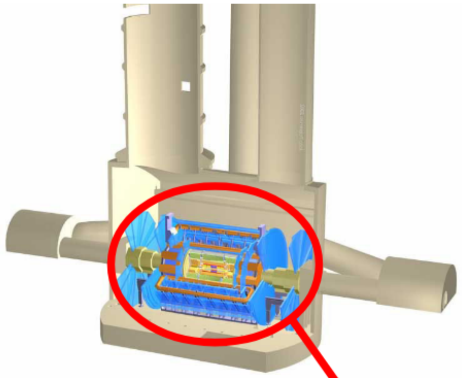
Roughly 5% of the secondary particles reach the LHC machine

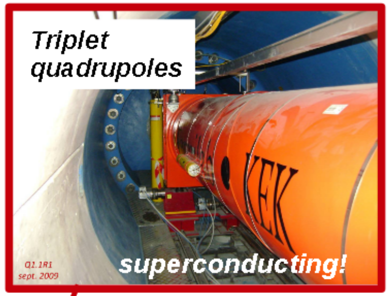
but:

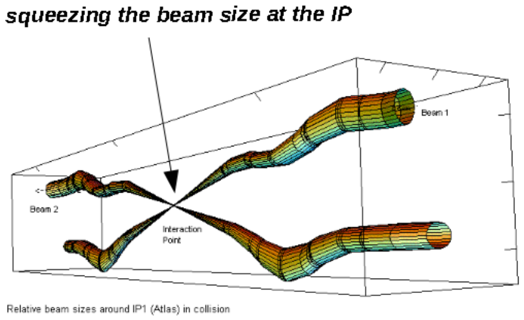
they carry about 70% of the power released in the collisions!!!

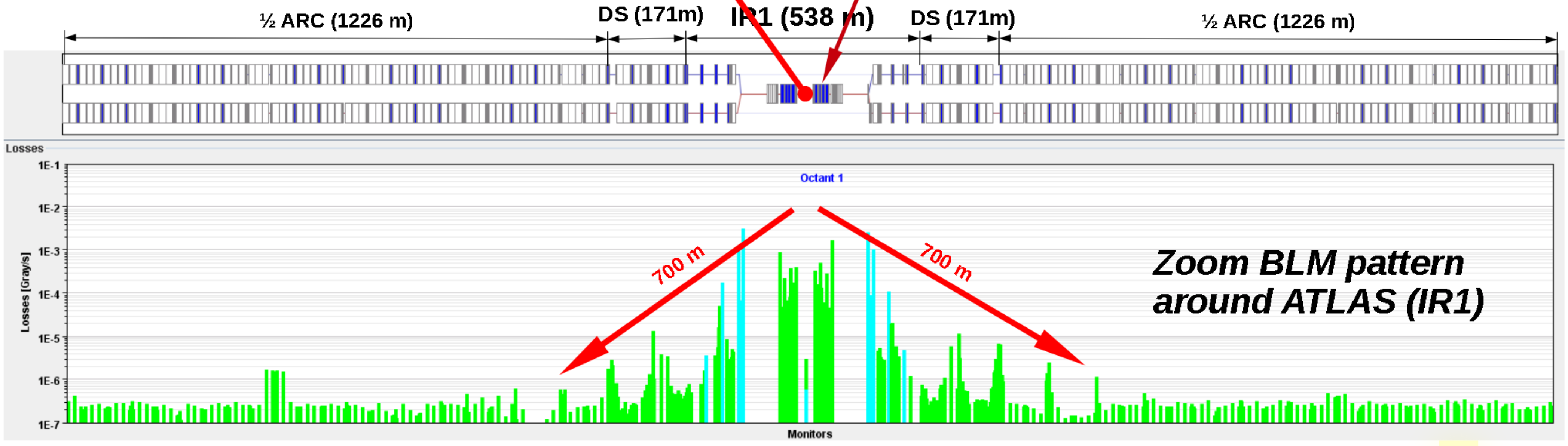
Where does the power go? Beam-loss monitor signal

Debris-induced showers visible over more than 1/2 km on each side of the experiment!

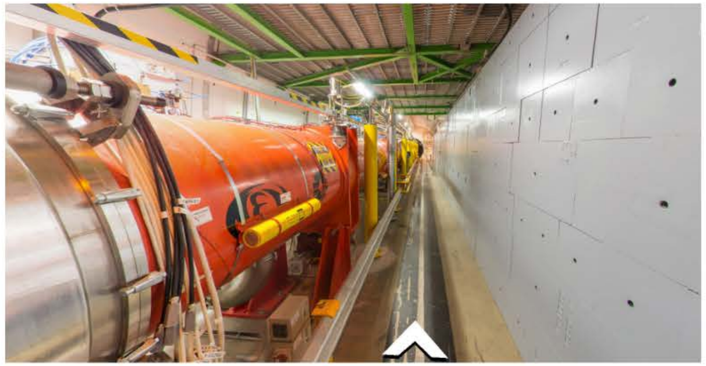


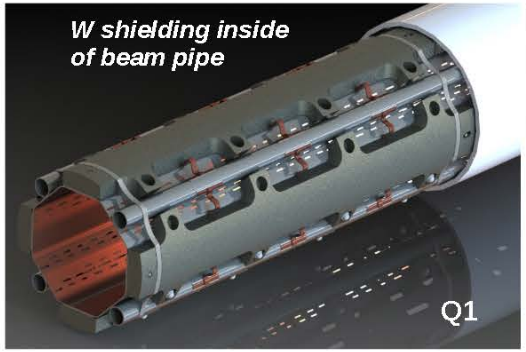




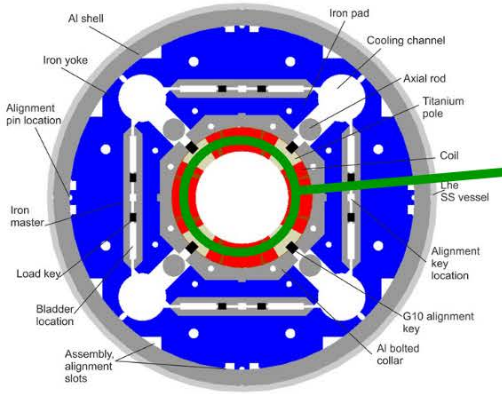


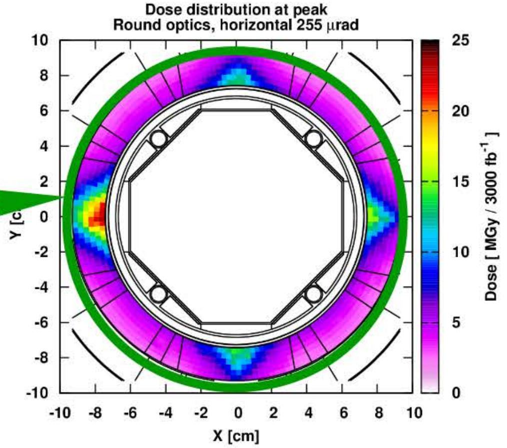
Inner triplet W shielding for HL-LHC





HL-LHC upgrade:





Charg
magn

Key element during design → shielding:
→ avoid quenches
→ avoid that magnet fails due to long-term radiation damage

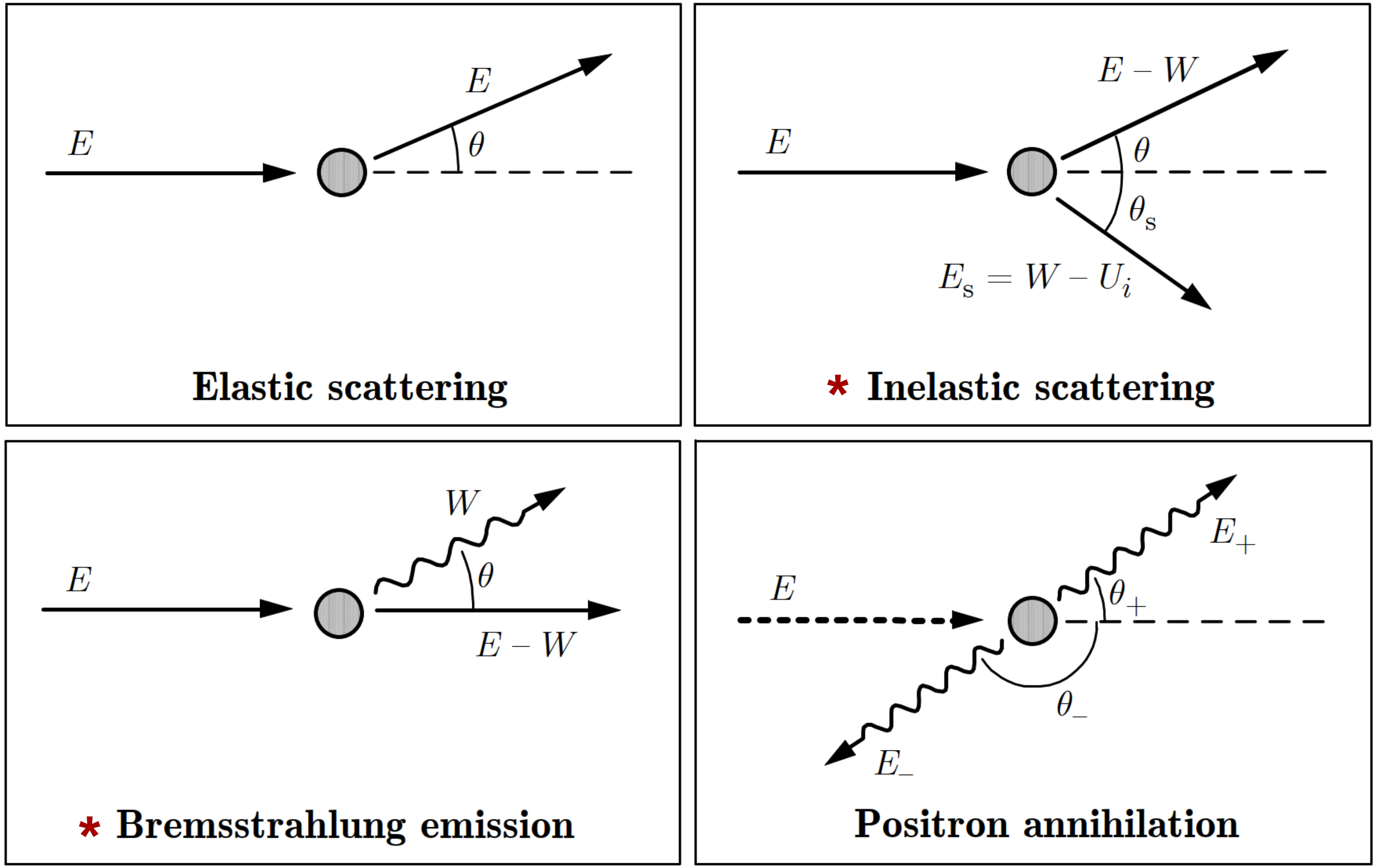
Dose < 30 MGy

A. Tsinganis, F. Cerutti

Beam loss / radiation source → MC simulation → Mitigation strategy

Interlude before turning to lepton machines

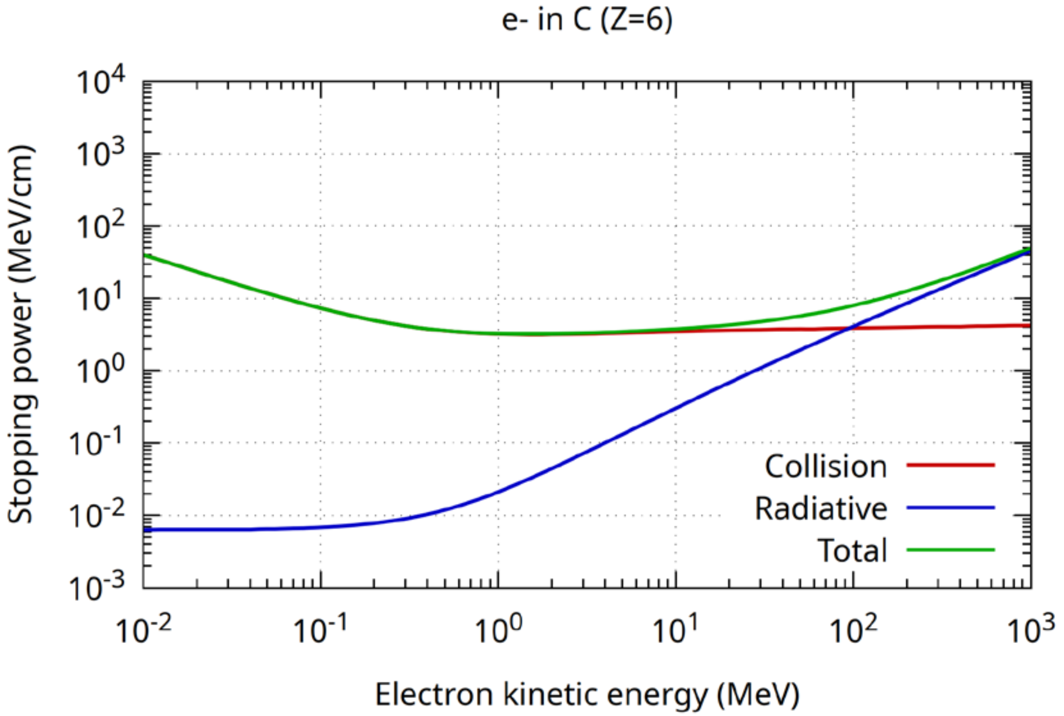
Short recap - Electron and positron interactions

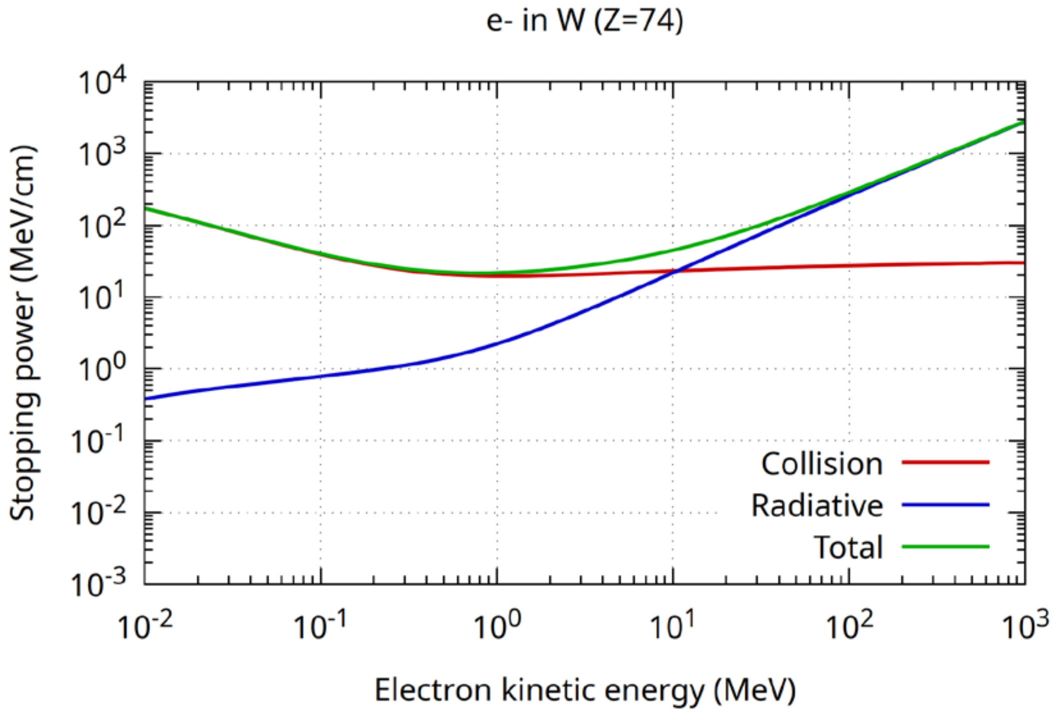


Figures: PENELOPE manual (NEA 2018)

Electron stopping powers

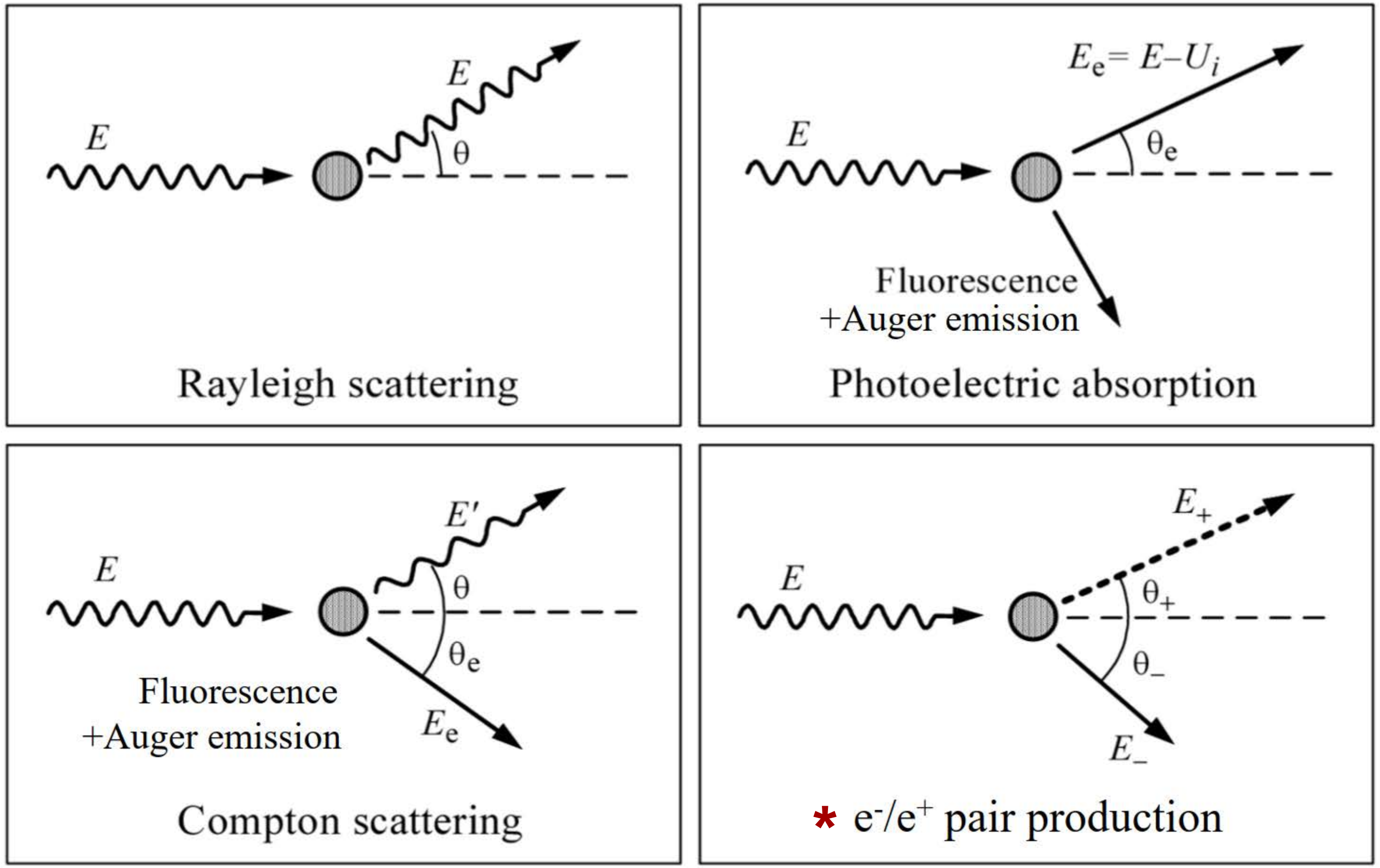
- Stopping power: average energy loss per unit path length
- At high energies: **Bremsstrahlung emission** dominates
- At low energies: Ionization losses dominate





https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

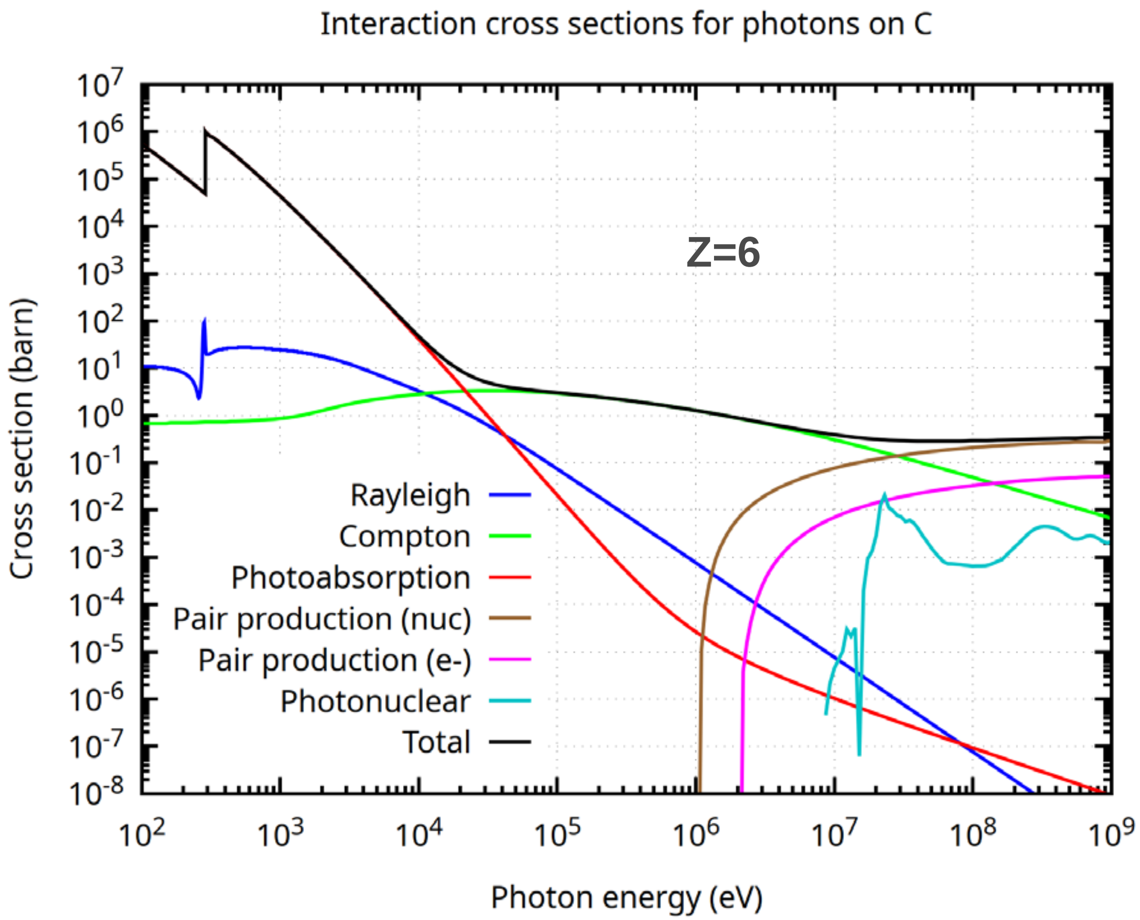
Most relevant interaction mechanisms of photons

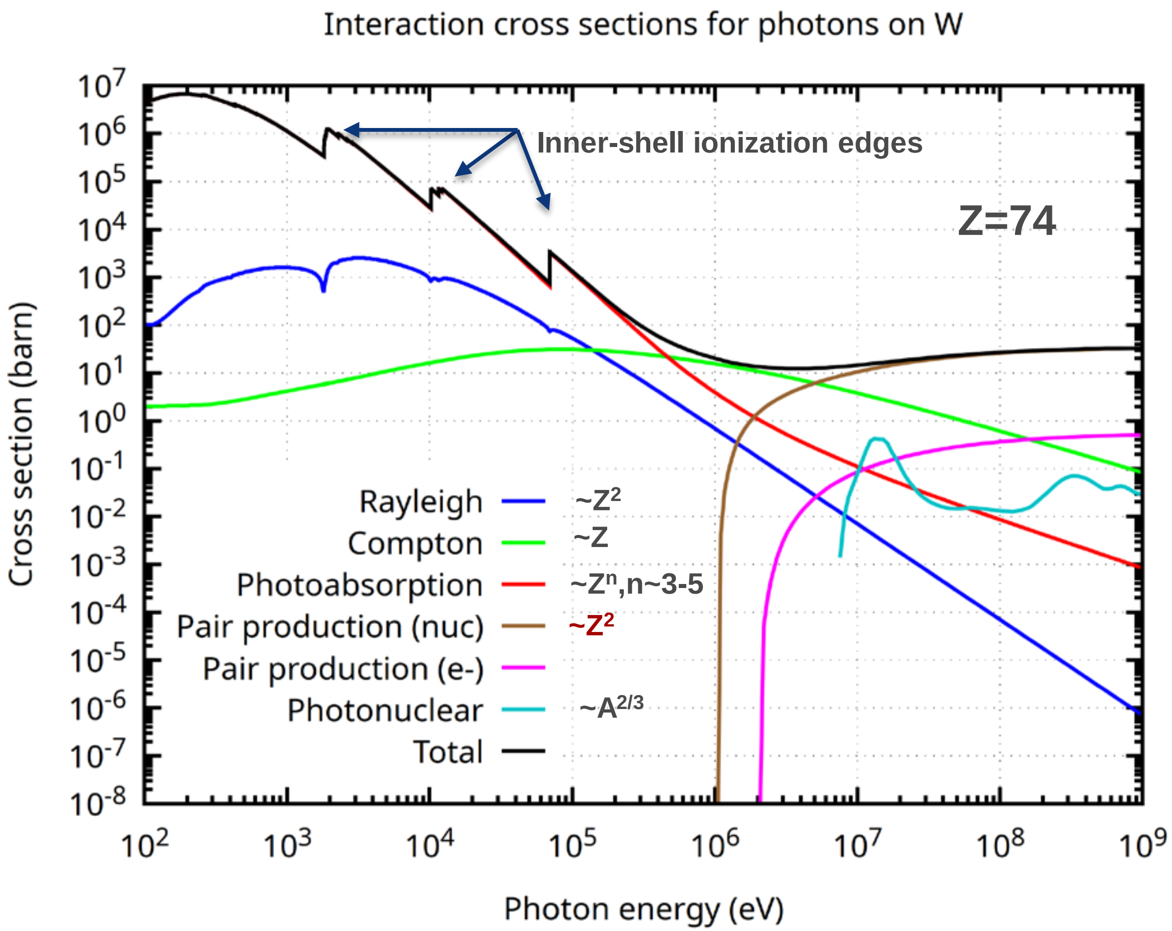


- Photonuclear reactions:
  - (γ,n), $(\gamma,2n)$,…
- $\mu^{\pm}$ pair production

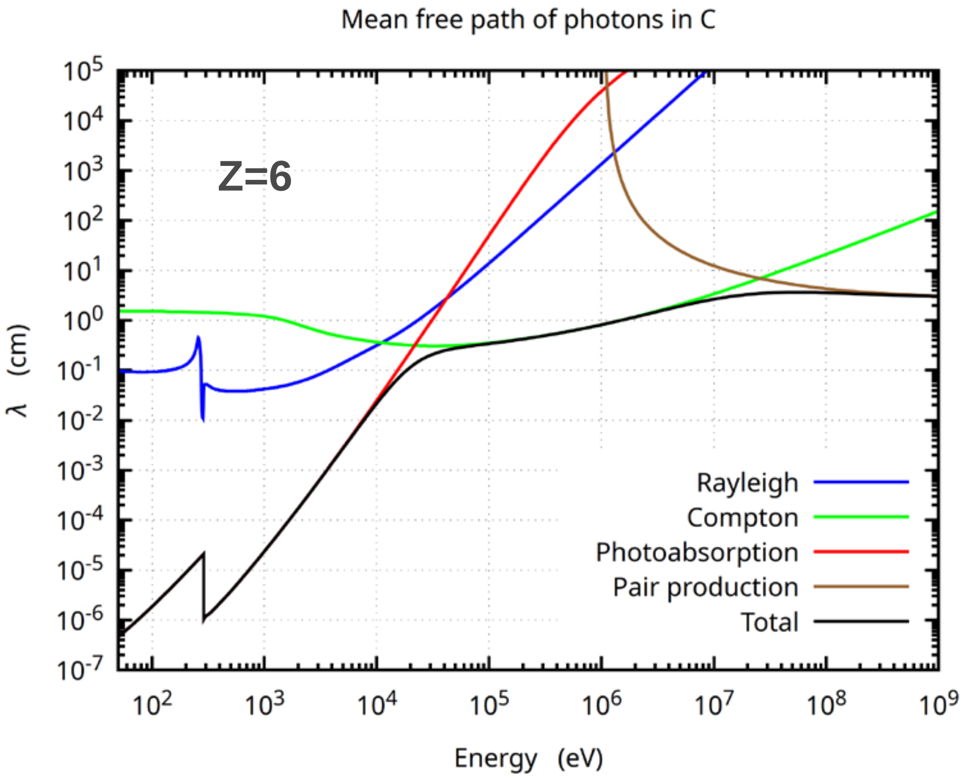
Figures: PENELOPE manual (NEA 2018)

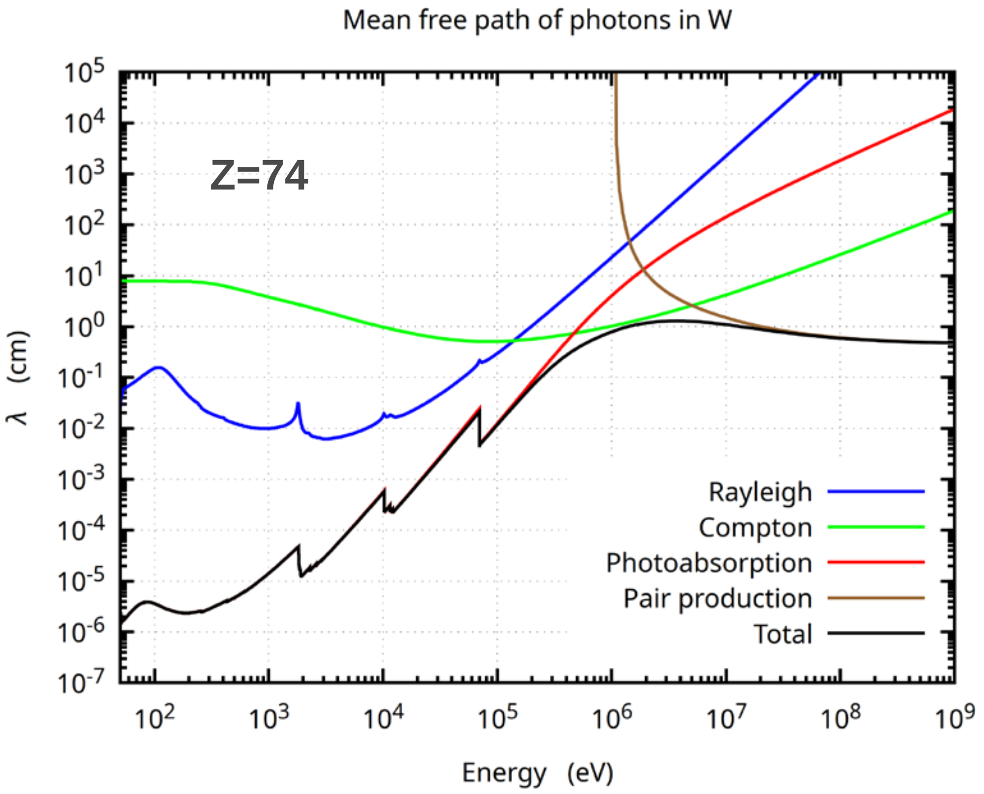
Photon interaction cross sections





Photon mean free paths





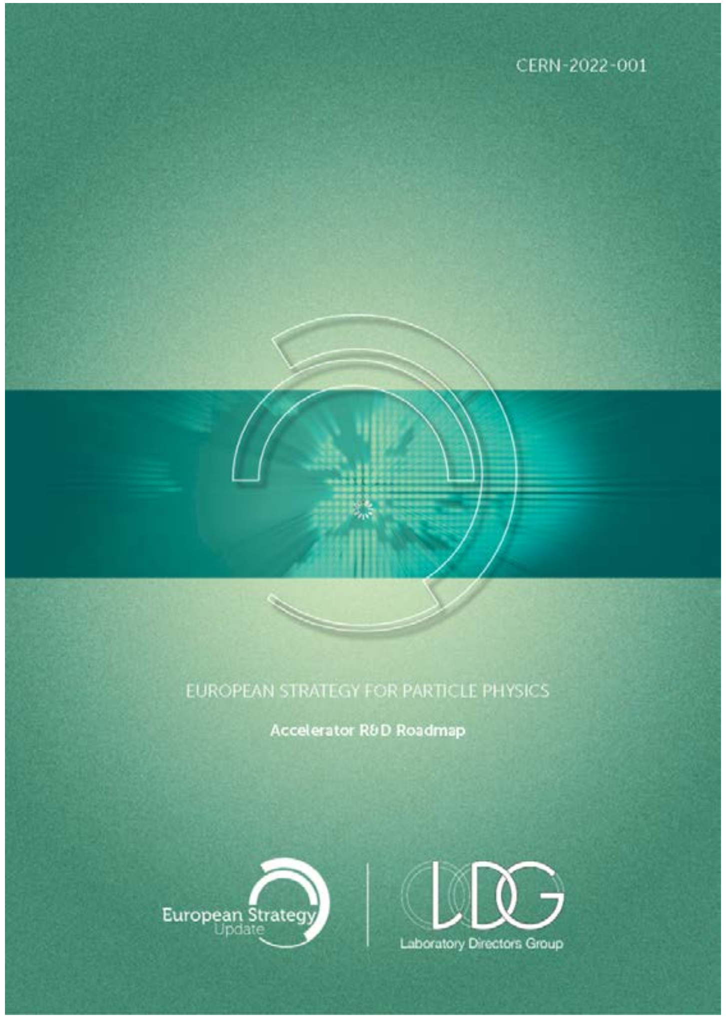
- MFP for e^-/e^+ pair production:
  - **C: O(1-10 cm)**
  - **W: O(1-10 mm)**

Beam loss / radiation source → MC simulation → Mitigation strategy

Application to the design of **future** particle accelerators (FCCee positron production target)

ESPPU

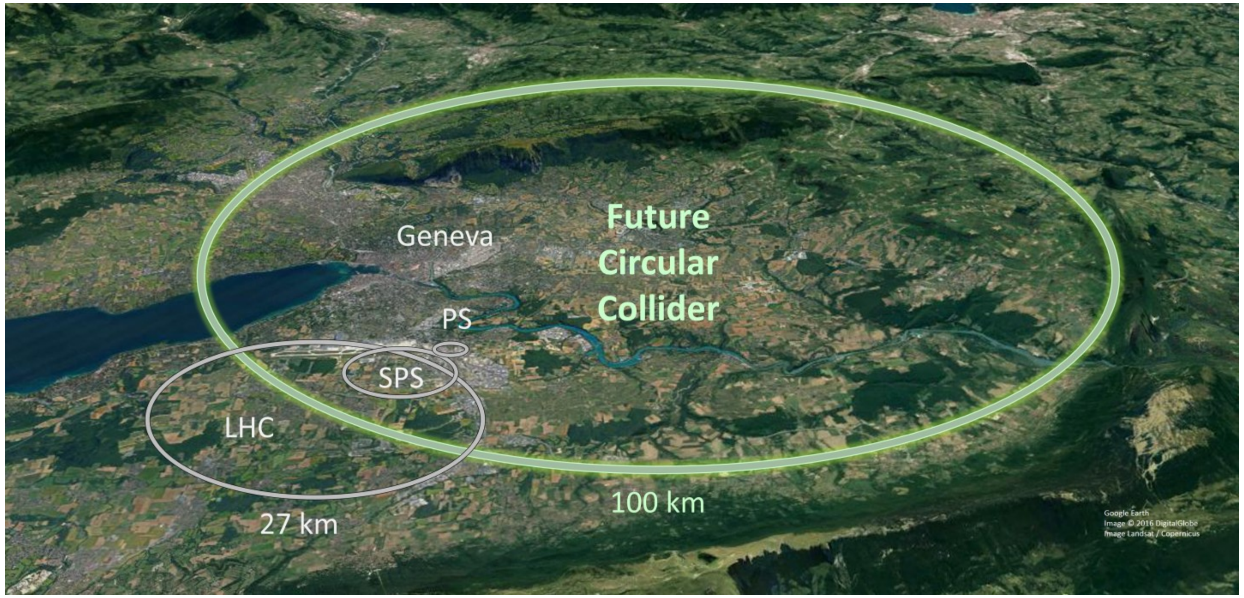
- European Strategy for Particle Physics Update
- "The ESPPU identified five key areas where an intensification of R&D is required to meet scientific goals:
  1. Further development of high-field superconducting magnet technology.
  2. Advanced technologies for superconducting and normal-conducting radio frequency (RF) accelerating structures.
  3. Development and exploitation of laser/plasma acceleration techniques.
  4. **Studies and development towards future bright muon beams and muon colliders.**
  5. Advancement and exploitation of energy-recovery linear accelerator technology

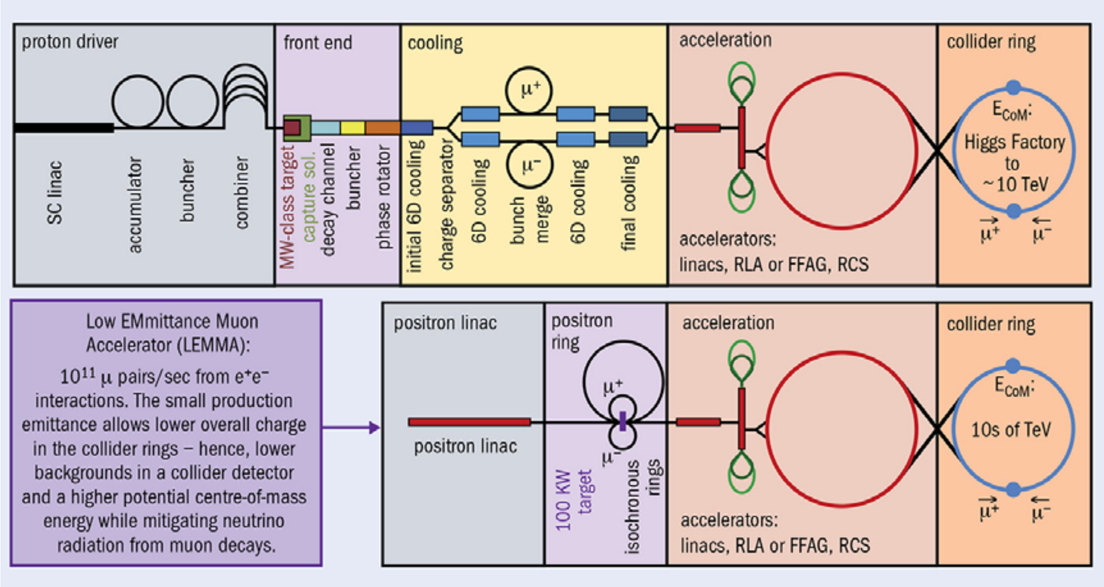


Ref: https://e-publishing.cern.ch/index.php/CYRM/issue/view/146

Future colliders

- See B. Dalena's lectures on Thu, Jul 28:
  "Future High-Energy Collider Projects (1 and 2)"

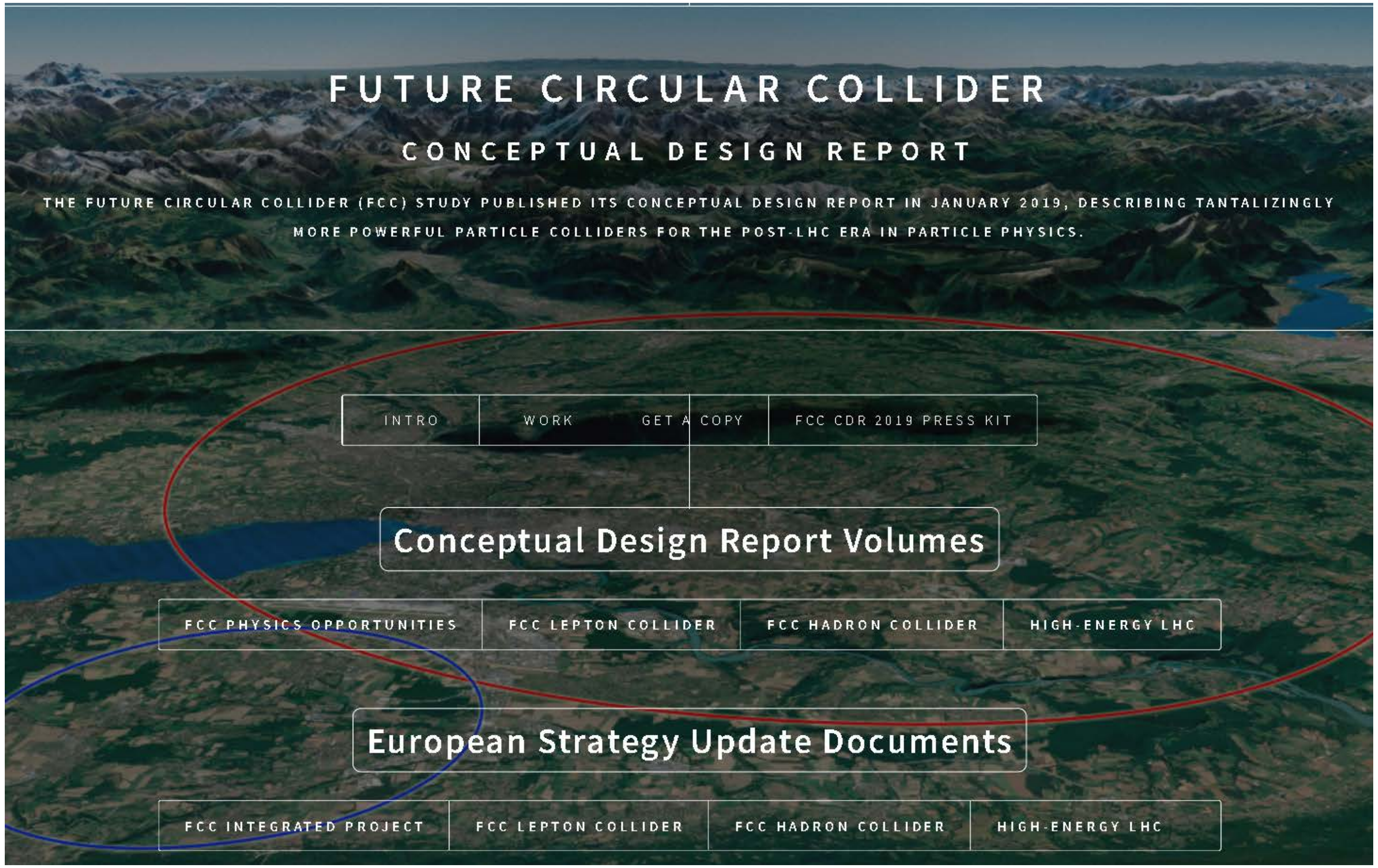




and more!!

Future Circular Collider (FCC)

- https://fcc-cdr.web.cern.ch/



FCCee

- https://link.springer.com/article/10.1140/epjst/e2019-900045-4

Eur. Phys. J. Special Topics **228**, 261–623 (2019)

https://doi.org/10.1140/epjst/e2019-900045-4

THE EUROPEAN PHYSICAL JOURNAL
SPECIAL TOPICS

Regular Article

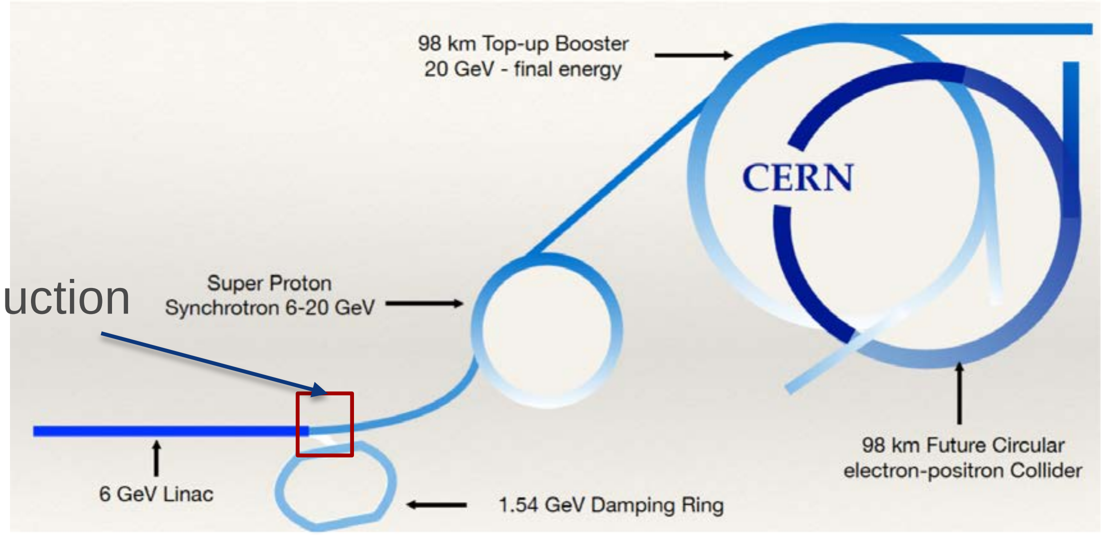
FCC-ee: The Lepton Collider

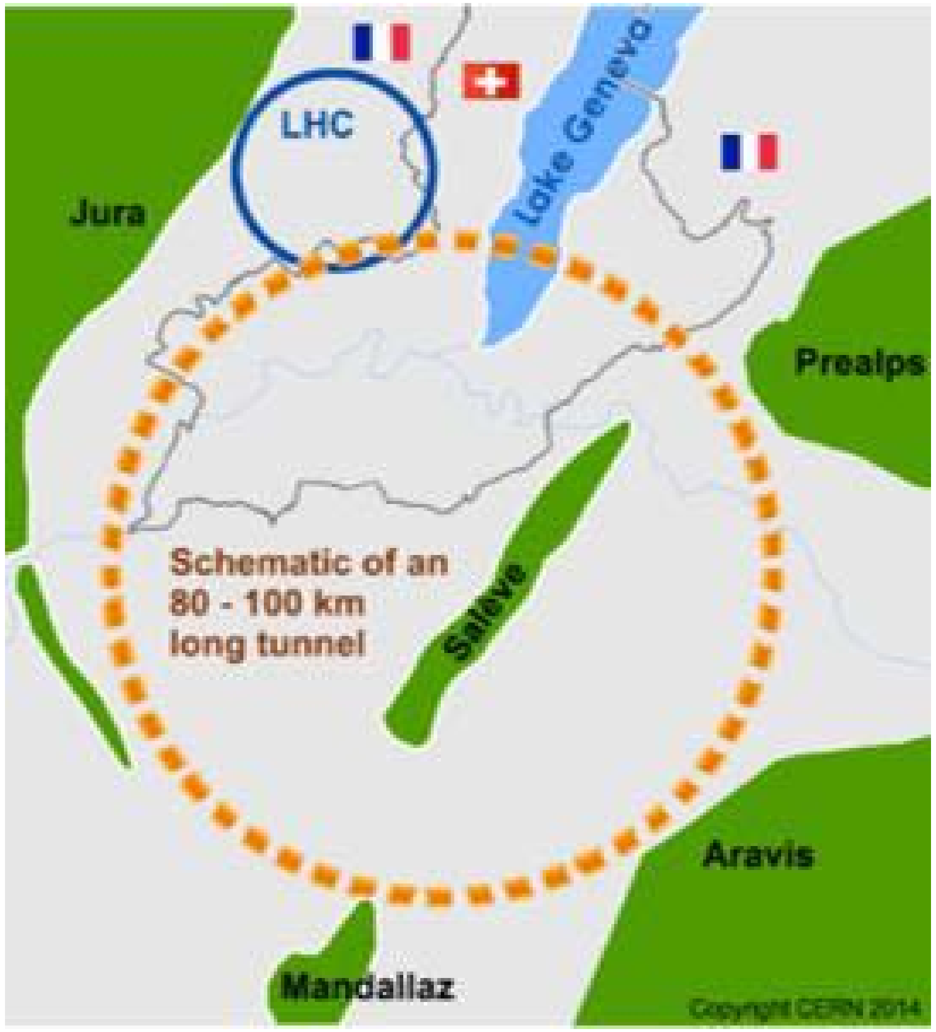
Future Circular Collider Conceptual Design Report Volume 2

FCC ee

- ~91 km tunnel
- Beam energy: 45 GeV – 182.5 GeV
- 6 GeV e^- on heavy target → e^+ production
- Initial acceleration to 20 GeV
- Injection to booster ring (20 GeV to final energy)
- Injection to collider ring

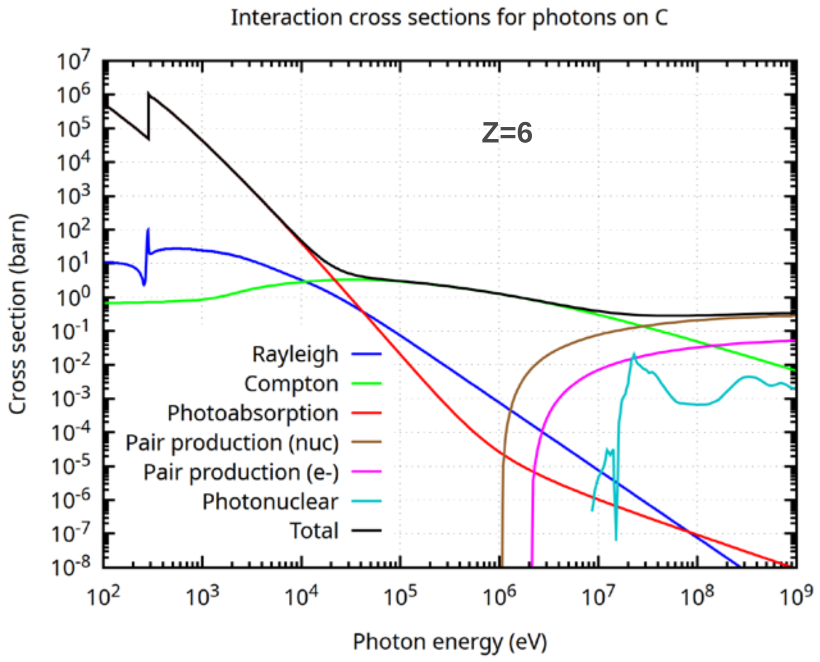
e^+ production target

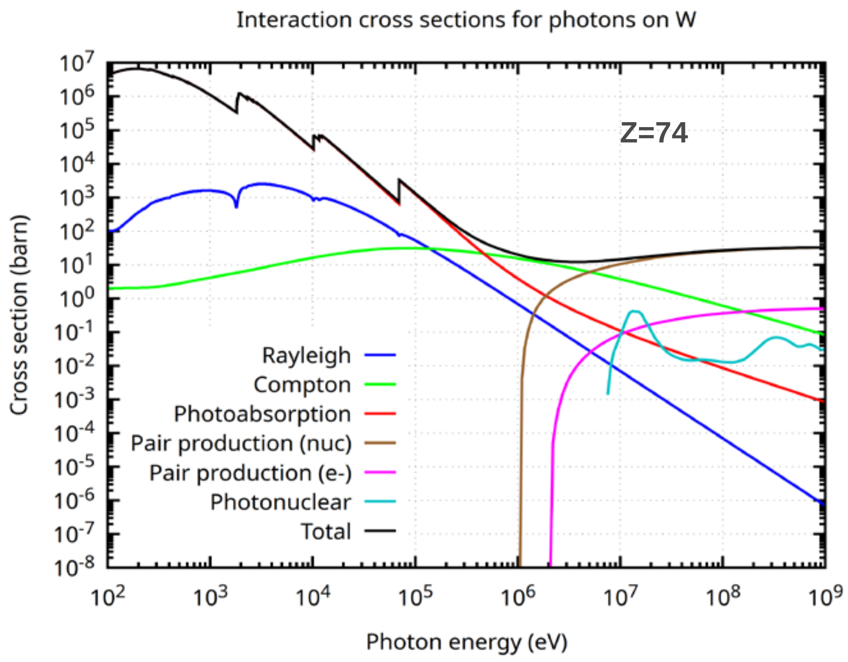


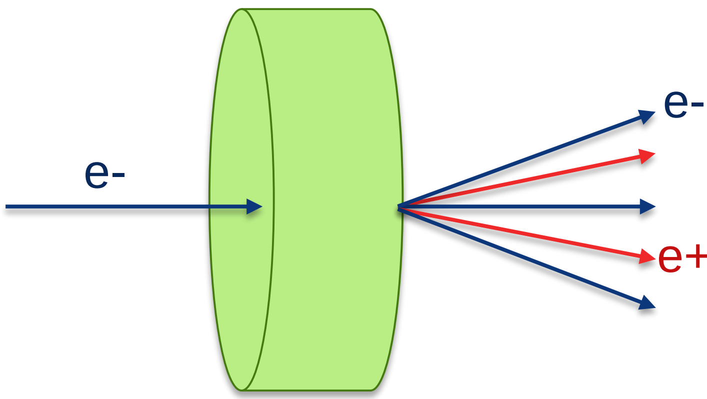


FCCee positron production target

- 6 GeV electrons on a target
- Basic idea: Bremsstrahlung → pair production



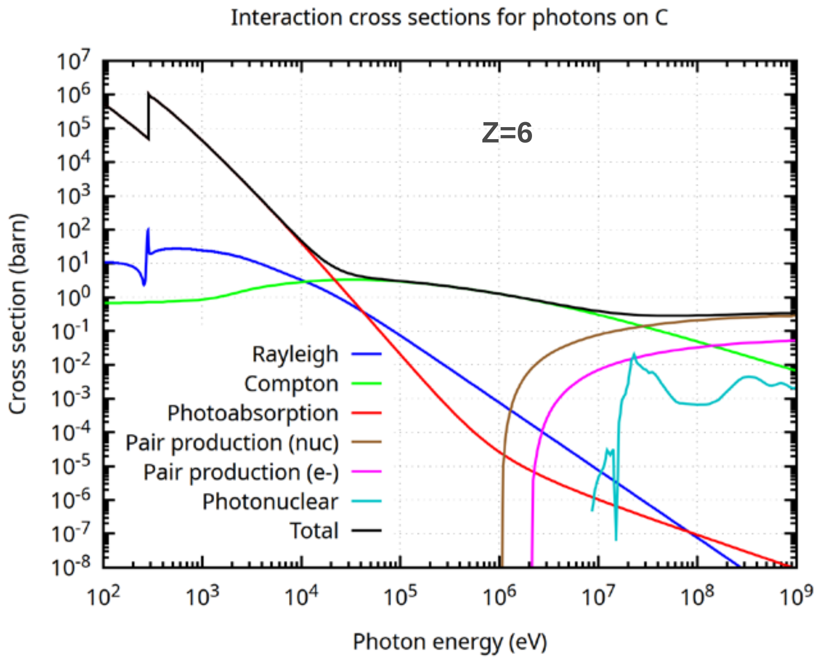


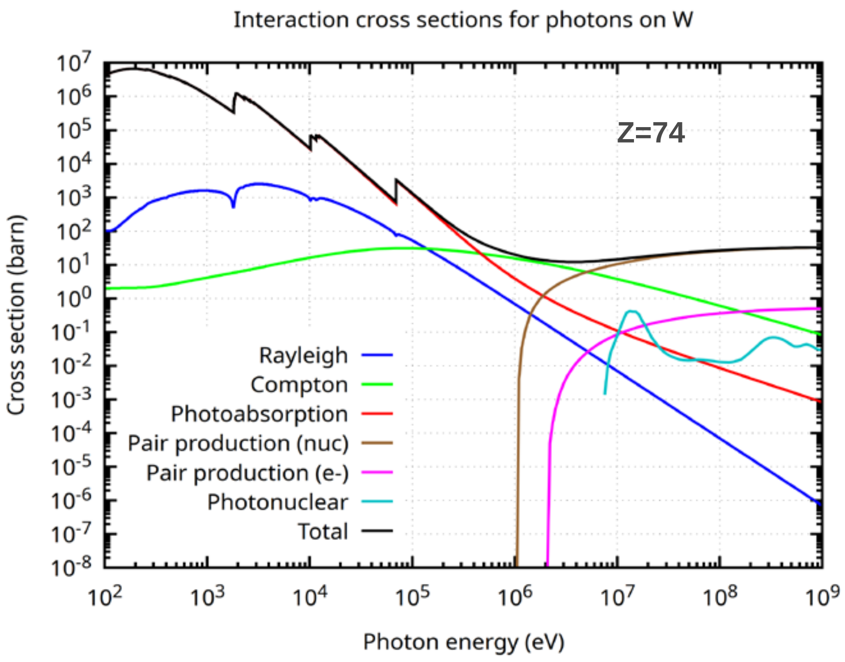


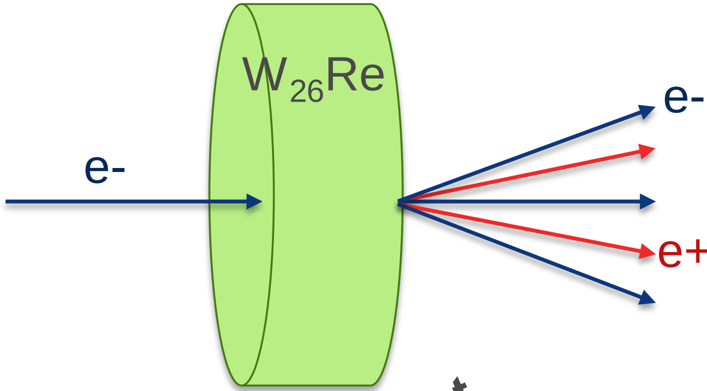
- **Given GeV photons, would you take C or W for the e+ production target?**

FCCee positron production target

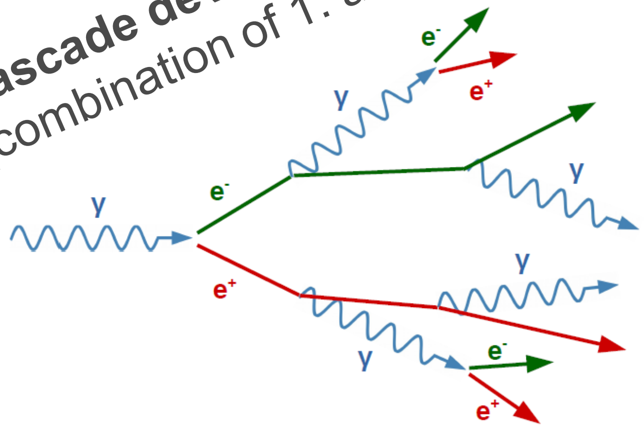
- 6 GeV electrons on a target
- Basic idea: Bremsstrahlung → pair production





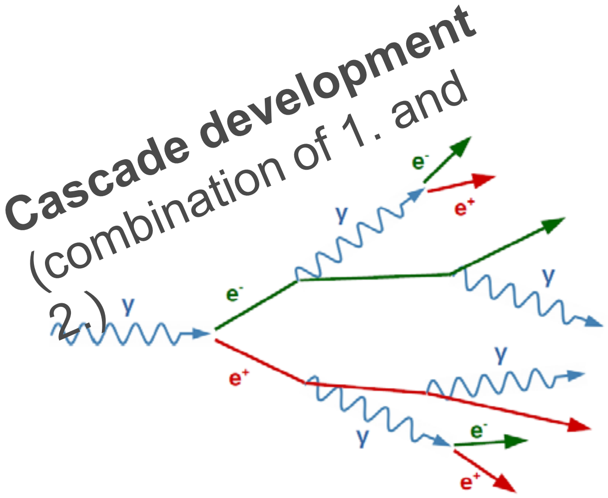


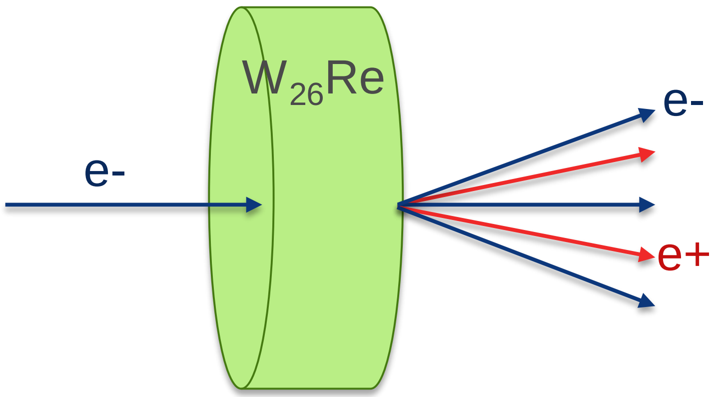
Cascade development
(combination of 1. and 2.)

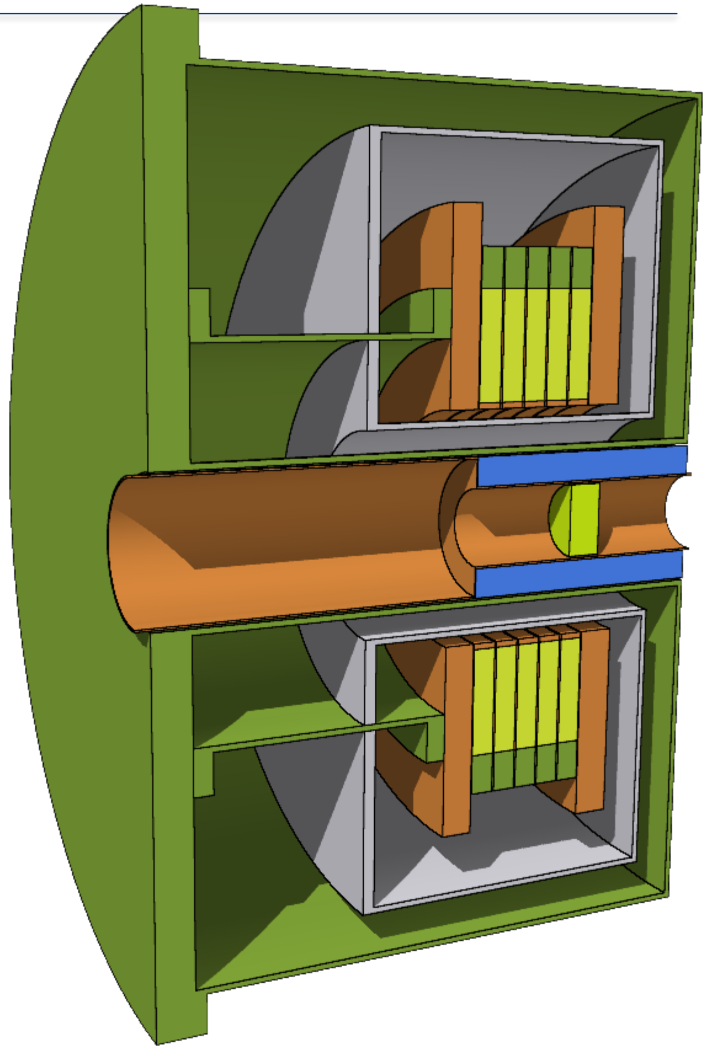


Positron production target

- 6 GeV electrons on a W-Re target
  (high Z + good thermo-mechanical properties)
- Bremsstrahlung → pair production
- High magnetic fields (high-T_c superconducting coils)
- Design questions:
  - What's the power density and dose HTS coils?
  - Are we within operational limits for short- and long-term effects?

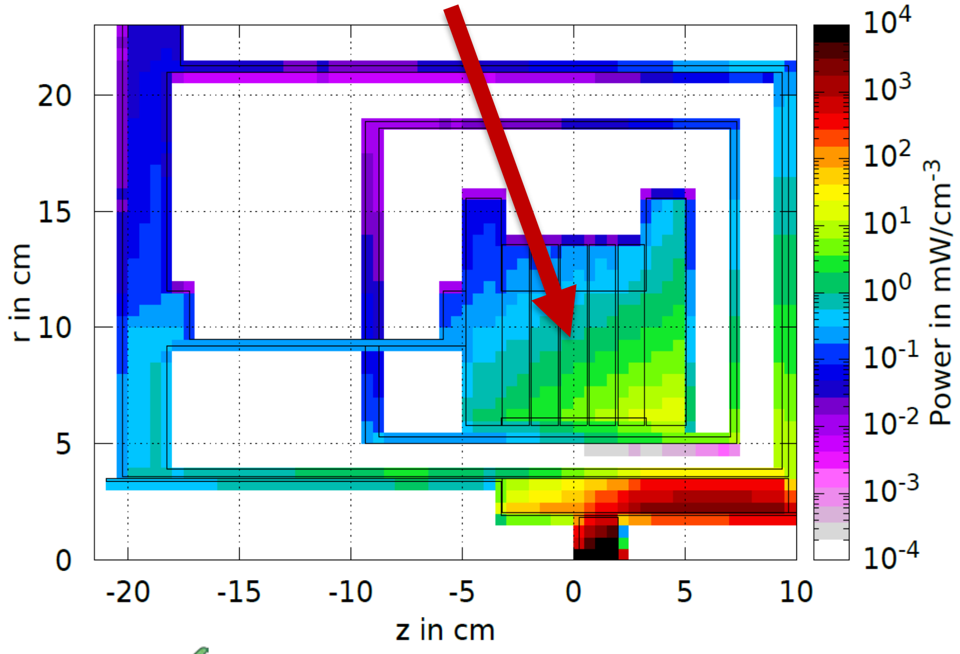






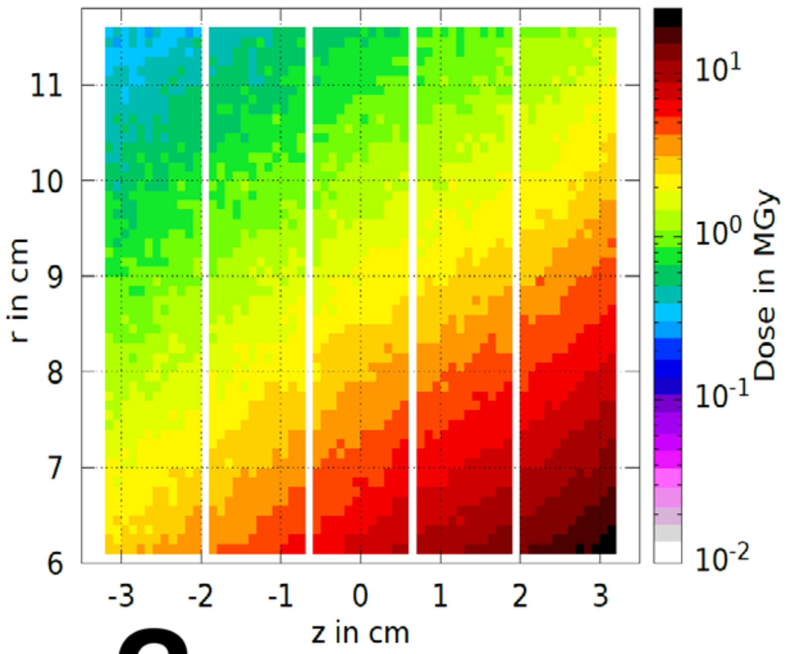
Short and long-term radiation effects

Power density on the HTS coils



Compared to the quench limit of ~15-20 mW/cm³ for bending dipoles of the LHC

Dose per year



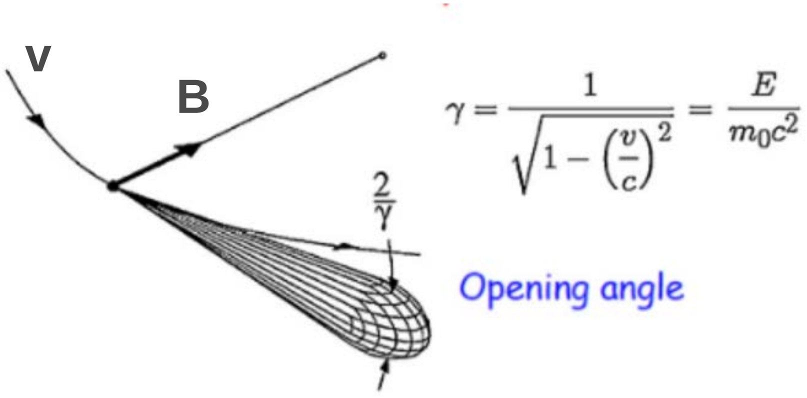
?

- x10 for FCCee duration: **220 MGy**
- Low-T_c superconductor insulators: limit is **30 MGy**
- For high-T_c superconductors: open question

Thanks to B. Humann for kindly making this material available!

FCCee – Synchrotron radiation in the arc

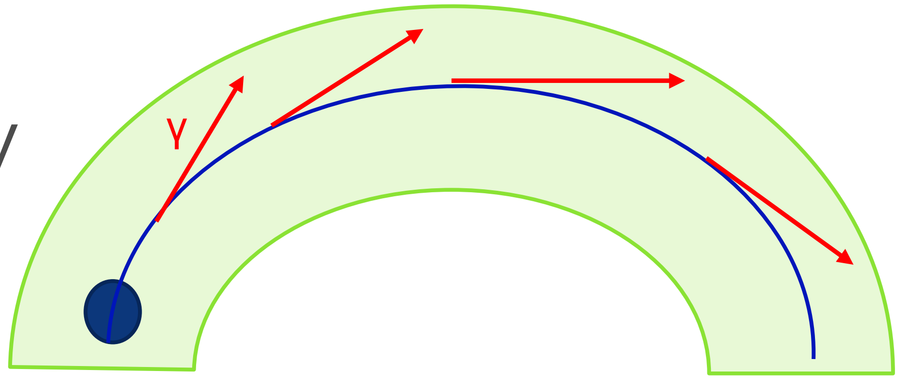
- Charged particles in a magnetic field emit synchrotron radiation (SR)



- Radiated power $$P = \frac{2}{3}\frac{e^2c}{4\pi\epsilon_0}\frac{\beta^4\gamma^4}{\rho^2}$$

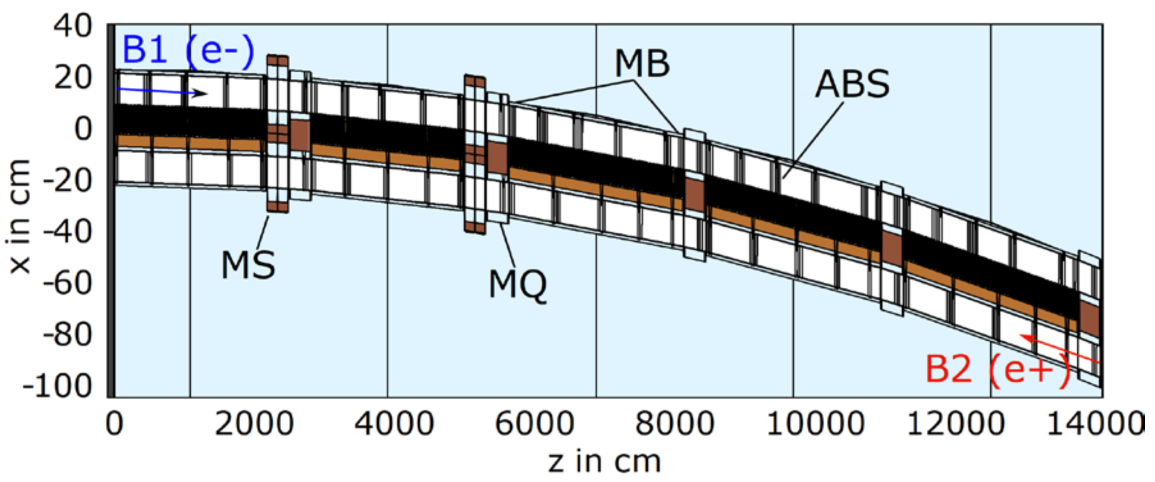
- FCCee:
  - Radius ρ=10.76 km, E=182.5 GeV
  - Energy radiated by e⁻ per turn in FCCee: 9.2 GeV

SR is a major source of radiation in lepton machines like FCC-ee

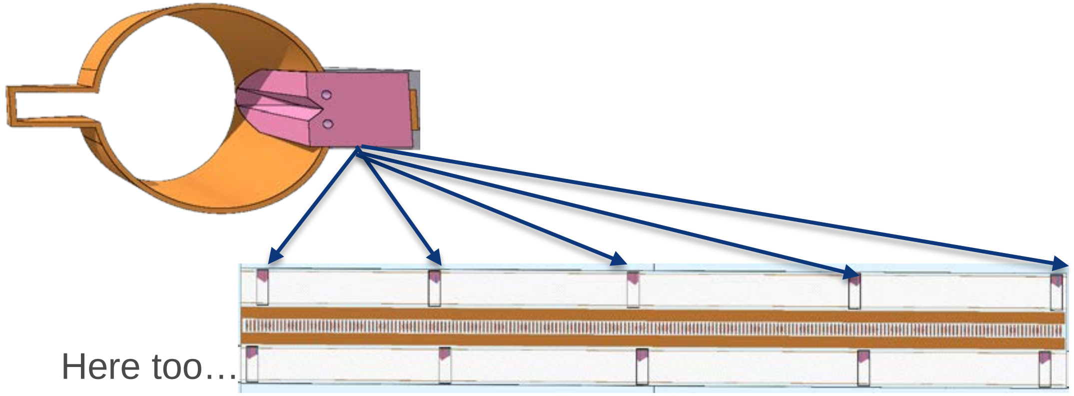


FCCee arc

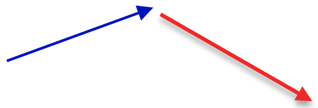
- Representative arc cell:
  - 140 m long
  - 5 dipoles, 5 quadrupoles, 4 sextupoles
- Copious SR emission
- Absorbers: shield the outside
- But what about the inner side?



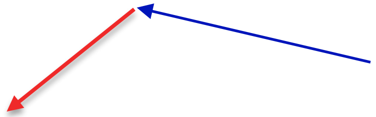
CuCrZr absorbers



External beam:
reflected particle → magnet yoke



Internal beam:
reflected particle → tunnel



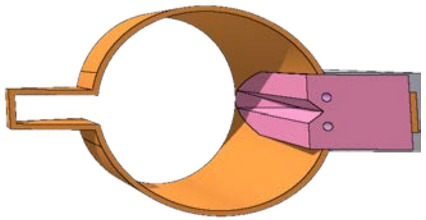
3

Power budget and dose

- 78% of the radiated power is effectively deposited in the absorbers
- Power loads elsewhere are acceptable (warm magnets!)

	Copper
ABS	131 kW
MB	23.4 kW
MQ	2.6 kW
MS	0.09 kW
Tunnel	9.5 kW
Total	**167 kW**

(Power radiated by SR by the 2 circulating beams in the 140-m long arc cell)



- Dose estimate at inner side of vacuum chamber: **1 Mgy**
- Dose estimate above the beam plane: **300 kGy**
- Such dose levels pose problems for electronics.
- Reference value* for HL-LHC arc: **1.4 Gy**
- Dedicated shielding necessary. Studies ongoing.

?

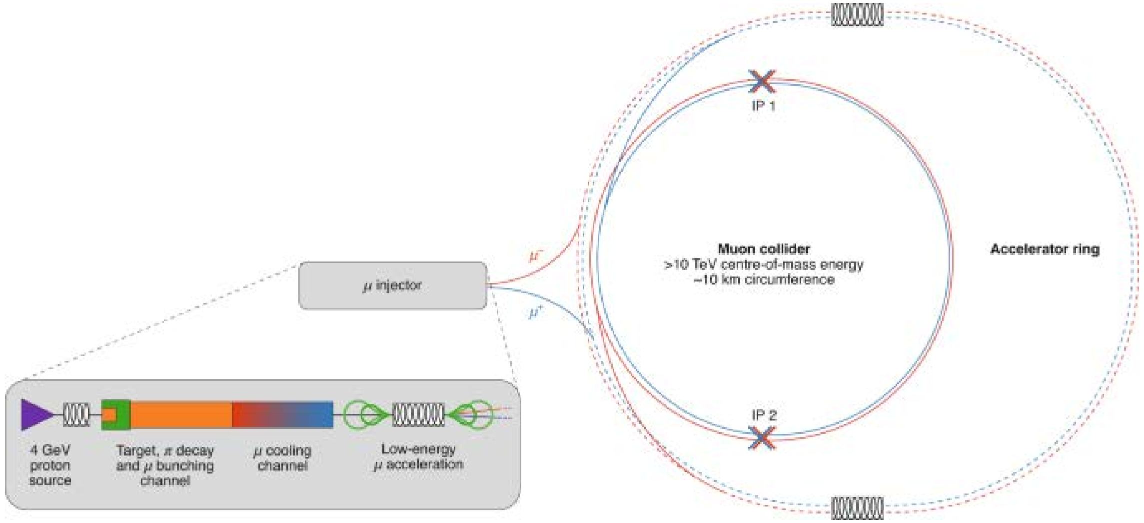
*https://edms.cern.ch/ui/file/2302154/1.0/HLLHC_Specification_Document_v1.0.pdf , page 16

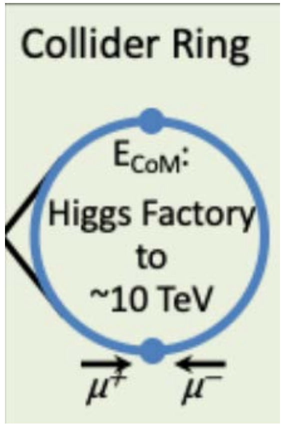
Application to the design of future particle accelerators (Muon Collider)

Thanks to D. Calzolari for kindly making this material available!

Muon collider

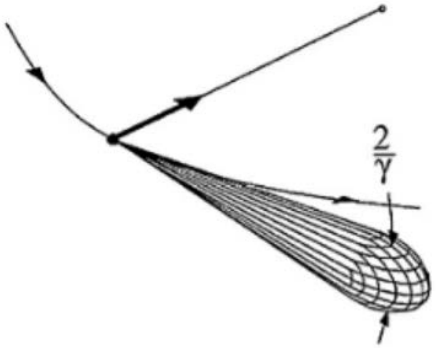
- Recommended to be explored by ESPPU
- Among proposed future colliders, highest collision energy prospects (>=10 TeV collision energy)
- https://muoncollider.web.cern.ch/node/25





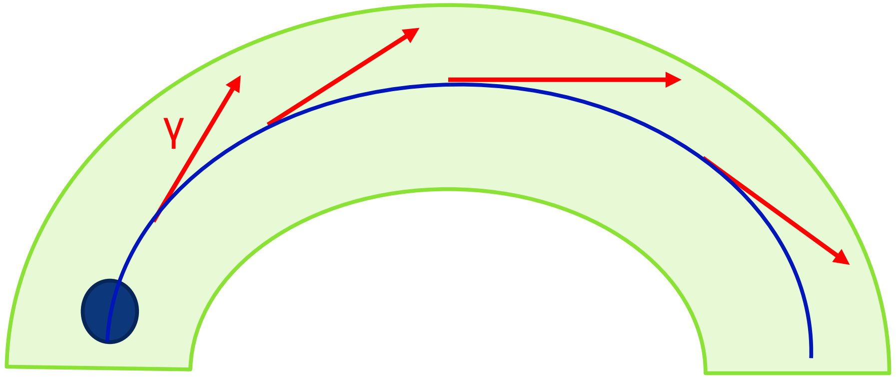
Synchrotron radiation

- Charged particles in a magnetic field emit synchrotron radiation (SR):



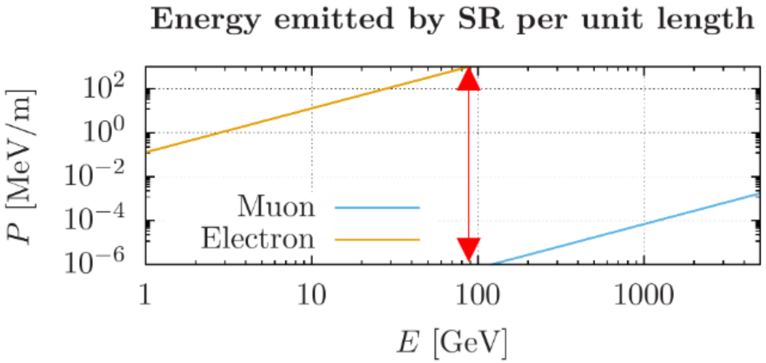
$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{E}{m_0 c^2}$$

Opening angle



- Muon decay: $\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- \, \bar{\nu}_e \, \nu_\mu$ (t~2.2 us)
- Radiated power:

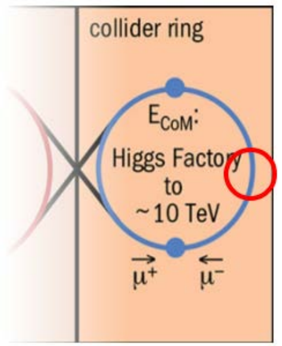
$$P = \frac{2}{3} \frac{e^2 c}{4\pi\epsilon_0} \frac{\beta^4 \gamma^4}{\rho^2}$$

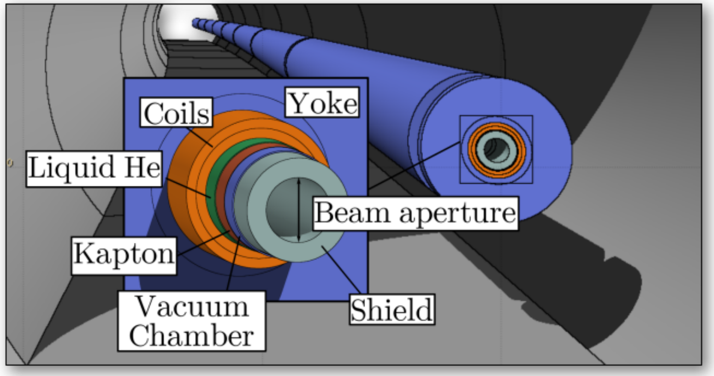


SR emission by decay e± poses radiation challenges

Radiation load on SC coils

- Simplified geometry:

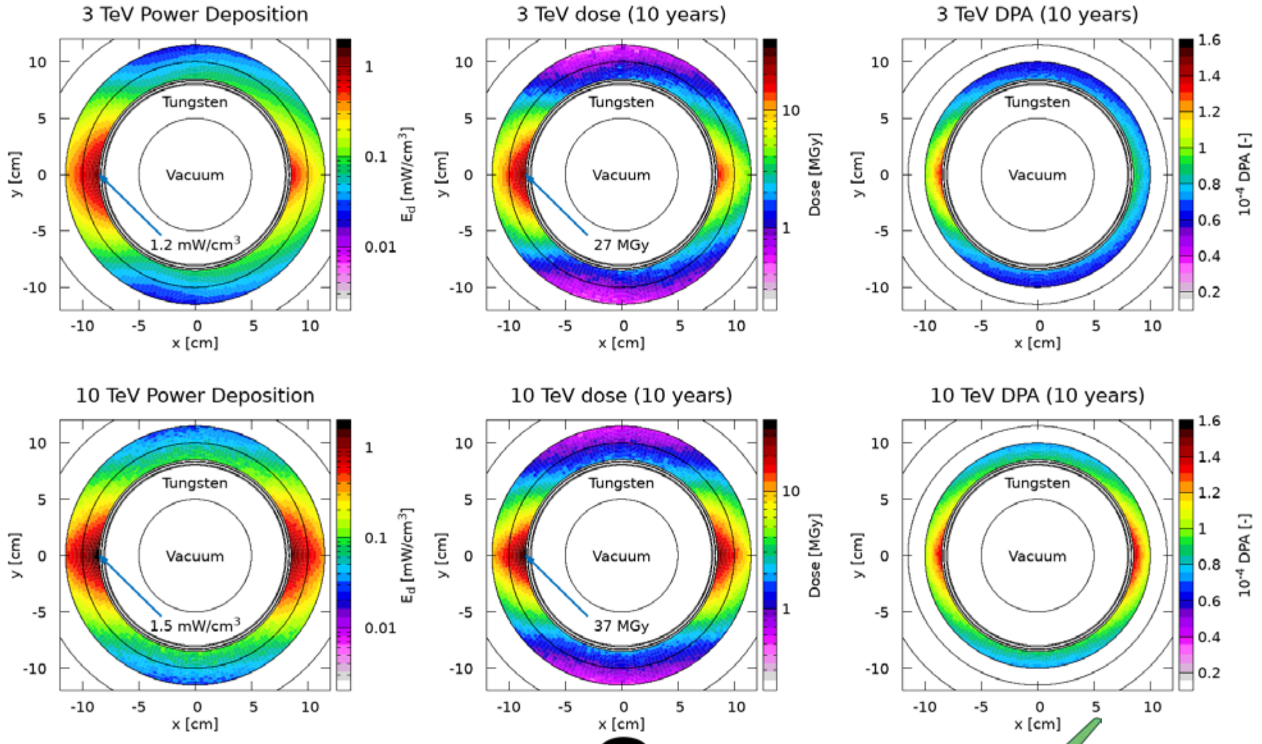




- Questions:
  - What's the power load on the superconducting coils?
  - Dose delivered to SC coil insulators after 10 years?
  - DPA after 10 years?

Power, dose, and DPA in superconducting coils

Short-term effects **Long-term effects**



?

$<<$15-20 mW/cm^3
Bending dipoles of the LHC

~30 MGy, exceeding customary limit
→ Shielding design

- Nb3Sn samples degrade above 10^{-3} DPA
- ~inner triplet magnets for the HL-LHC after 3000 fb^{-1}

Summary

Summary and key points

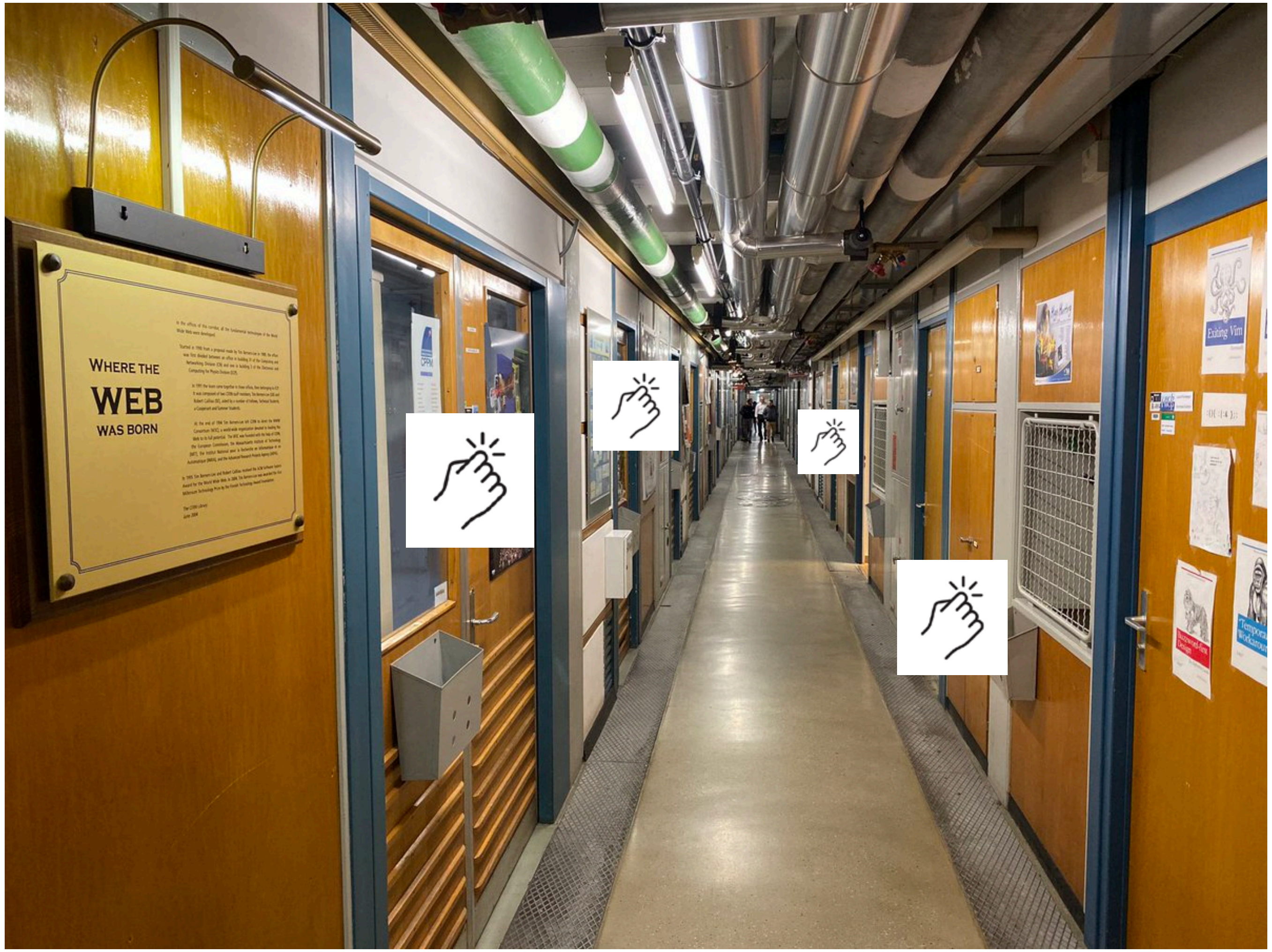
- **Beam losses:**
  - Microscopic causes, macroscopic effects, and implications for operation of a particle accelerator (Lecture 1)

- **Monte Carlo** method as powerful tool to assess the effect of beam losses and other sources of radiation in the design/operation of particle accelerators
  - Quantities relevant for short-term effects (power deposition)
  - Quantities relevant for long-term effects (dose and displacements per atom)

- Assessment of beam losses and general radiation challenges:
  - Inner triplet shielding in view **HL-LHC** upgrade (putting limits to duration of LHC Run3)
  - **FCCee**: positron production target (implications of radiation field on HTS coils)
  - **FCCee**: implications of synchrotron radiation emission in the arc
  - **Muon** collider: radiation challenges on SC dipole magnet due to emission of SR

Farewell note

- Use the Summer Student opportunity to **approach people** at CERN working on topics you are genuinely interest in!
- While being exquisitely mindful of people’s working time, shoot them an e-mail, say hi, and if conditions are favorable, you may get a valuable in-person chat and **precious information** on what’s going on in your field of interest!



Thanks for your attention!

Enjoy the rest of CERN's Summer Student Lecture Programme!