Synchrotron Radiation (SR) Background

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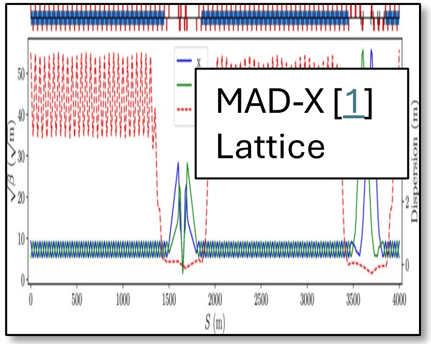
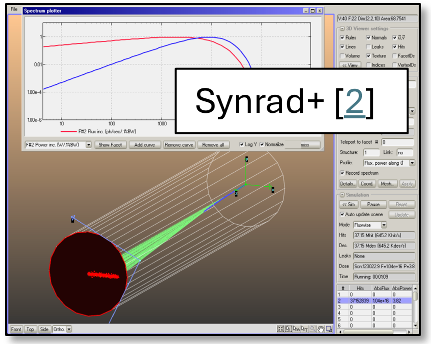
Previous SR Simulation Approach

ESR lattice design



SR production & tracking



Data sampling

Event generator CSV → HepMC

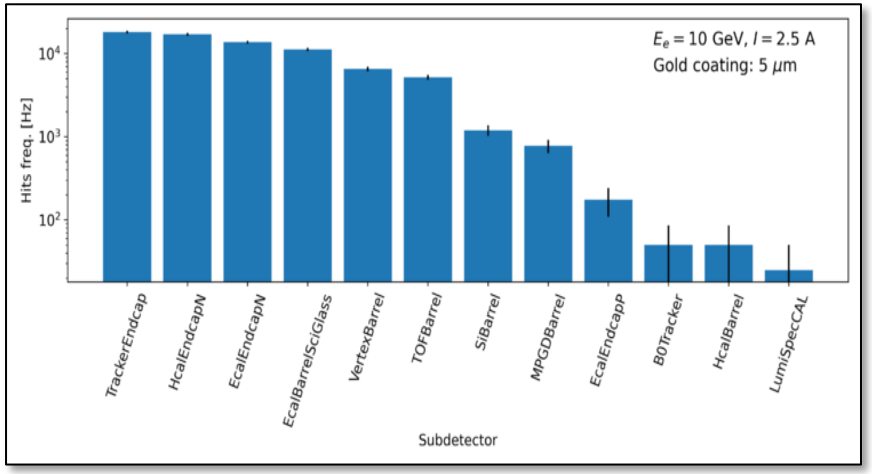
Detector simulation

EIC-Shell [3]: DD4Hep SOFTWARE

Data analysis

EIC-Shell: EIC-Recon SOFTWARE

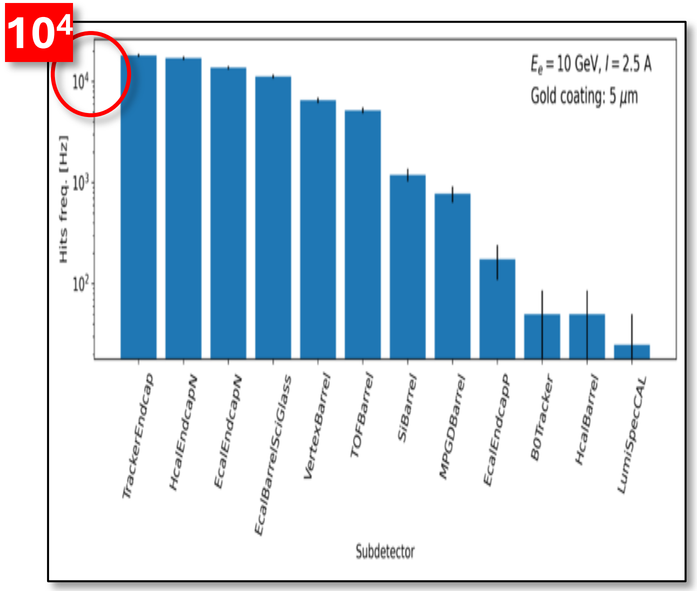
1. Time-consuming procedure:
   - Synrad+ stores photon coordinates on one facet at a time.
   - The IR beam pipe consists of ~30k facets.
2. Detailed SR masking design is limited:
   - Synrad+ describes SR as virtual photons with intrinsic weights, representing sampled flux and power generated by the given SR source.

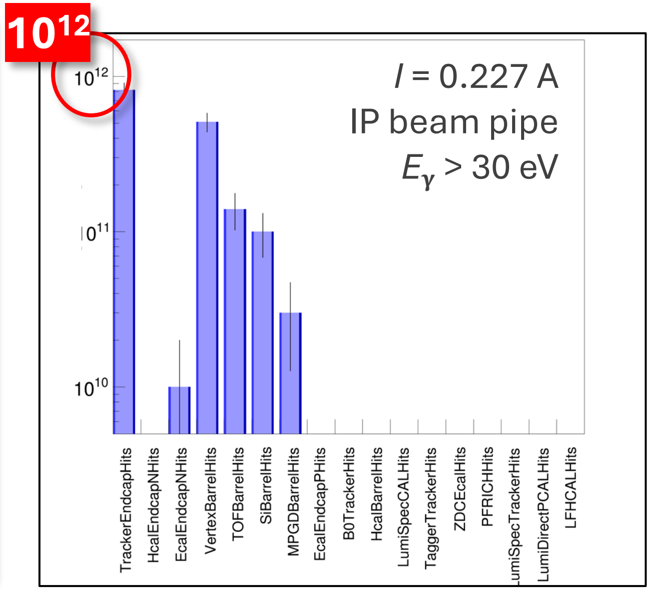


SR background rates in ePIC sub-detectors
https://wiki.bnl.gov/EPIC/index.php?title=Synchrotron_Radiation

Incorrect SR Sampling

- The **original Python script** published on the ePIC Wiki page that was used for SR sampling in the past **does not provide the correct hit rate estimation**.
  - It shoots SR photons one by one underestimating the total number of photons that should be simulated.
    - The photons should be simulated in a group following the expected photon rate.
- Therefore, the Wiki **Python script needs improvements** to provide correct hit rate estimation based on Synrad+ results; see below.





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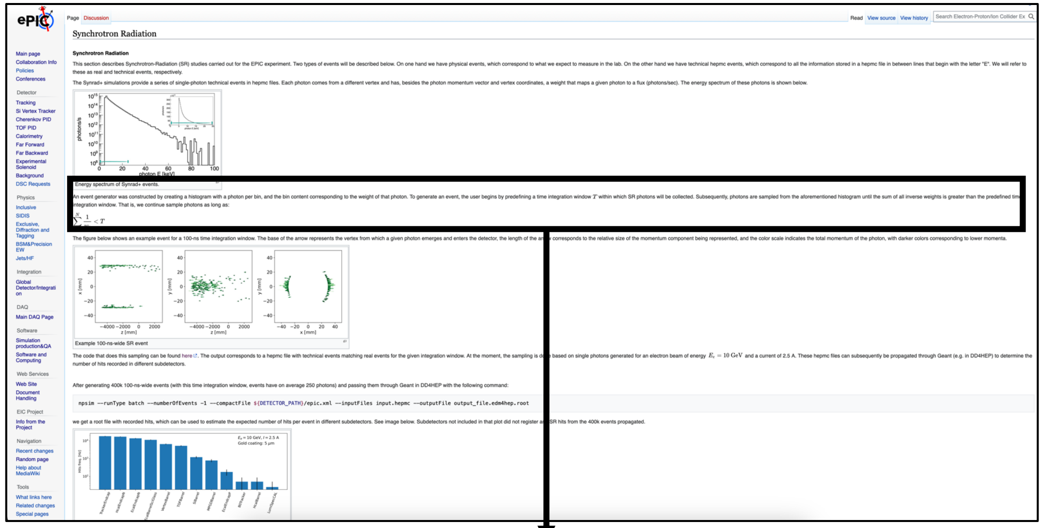
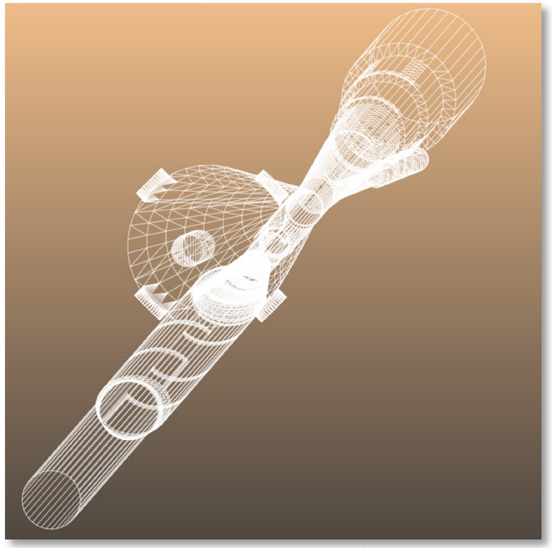


"... photons are sampled from the aforementioned histogram until the sum of all inverse weights is greater than the predefined time integration window ..."

Simulation Improvements

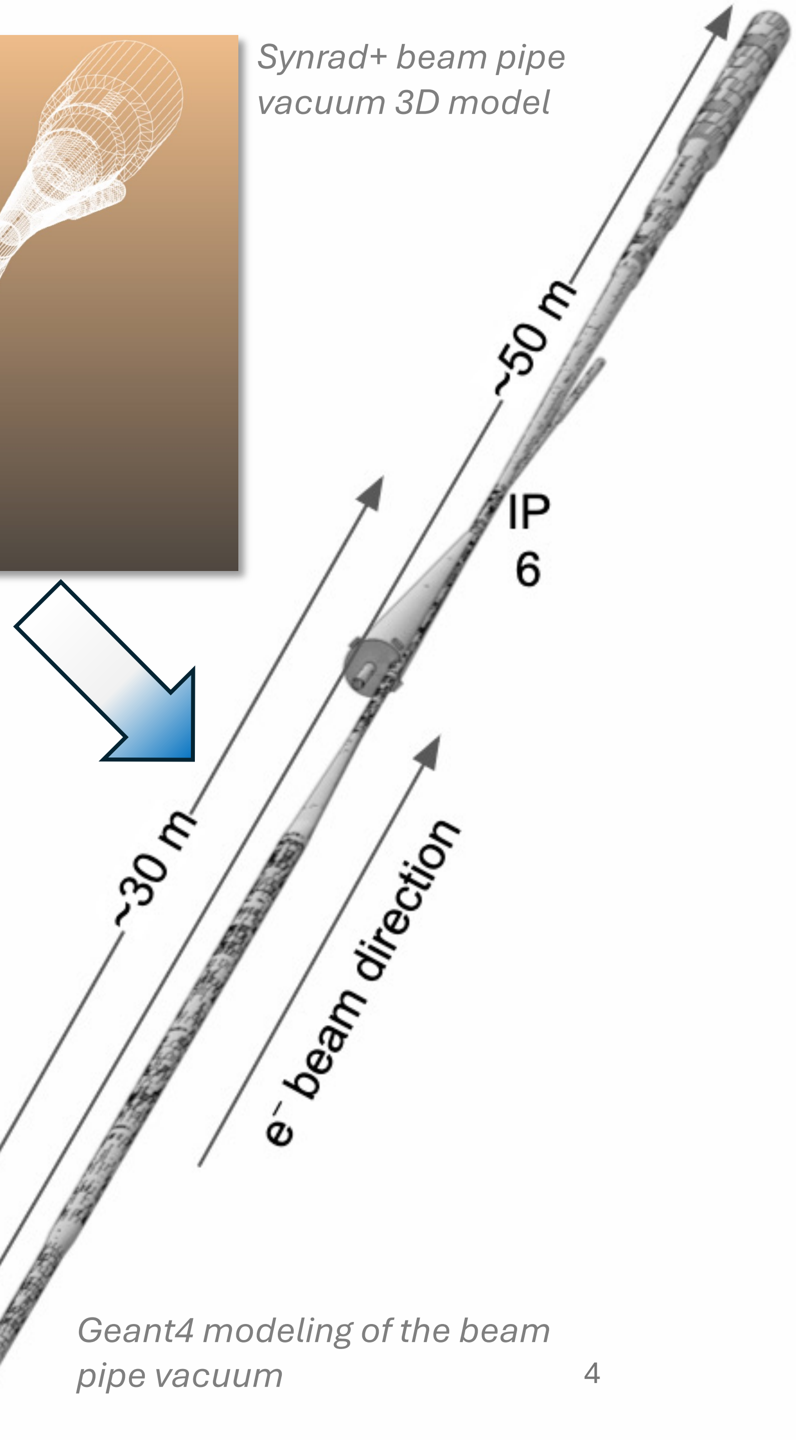


Synrad+ beam pipe vacuum 3D model

Synrad+ constraints/issues:
- Limited SR background studies
- Inadequate simulation results

Solution:
- Geant4-based model for SR simulation
  + photon reflection physics

Benefits:
- No weighting
  - Realistic SR photon tracking in the vacuum
  - Accurate SR mask development
  - Full information about SR photon trajectories
- Effective photon coordinate logging
- Ease and accurate implementation of any geometry changes



Geant4 modeling of the beam pipe vacuum

X-ray Reflection Physics in Geant4

Availability:

- X-ray reflection was missing in Geant4
  - Recent (Dec. 2023 [1]) implementation ← so-called *geant4-release*
    - Specular (mirror-like) reflection + attenuation factor for roughness

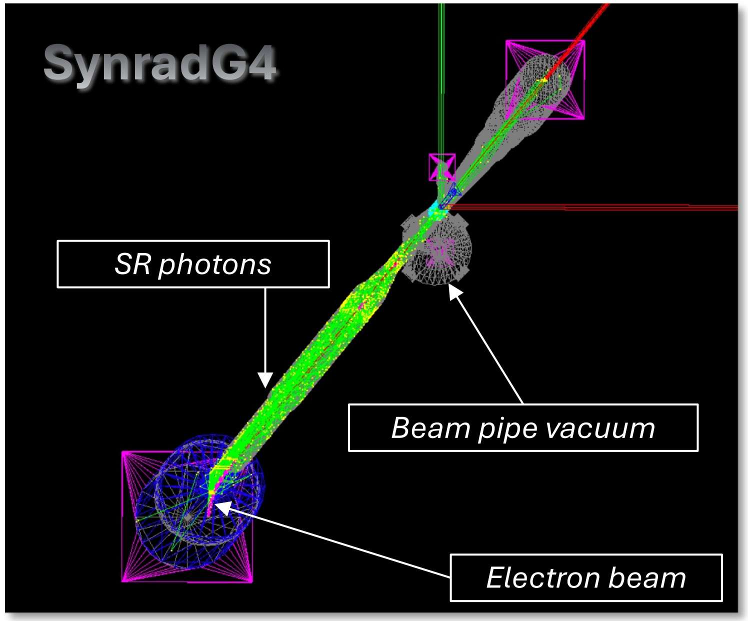
Solution:

- Develop a ***custom-built*** model for specular and diffuse X-ray reflection in Geant4 (same as in Synrad+) so-called **SynradG4**.

Benchmark (same material reflect. data prepared by B.L. Henke et al. (1993) [2]):

1. **Synrad+** (with bugfixes [3]) – diffuse reflection
   a) Old reflection model based on Synrad (1993) [4]
   b) New reflection model based on Synrad3D (2013) [5]
2. **Geant4-release** – specular reflection
3. **SynradG4**
   a) Same as geant4-release – specular reflection
   b) Same as the old model in Synrad+ – diffuse reflection
   c) Same as the new model in Synrad+ – diffuse reflection

Preprint and **open-source** code:
A. Natochii (2024)
https://arxiv.org/abs/2408.11709

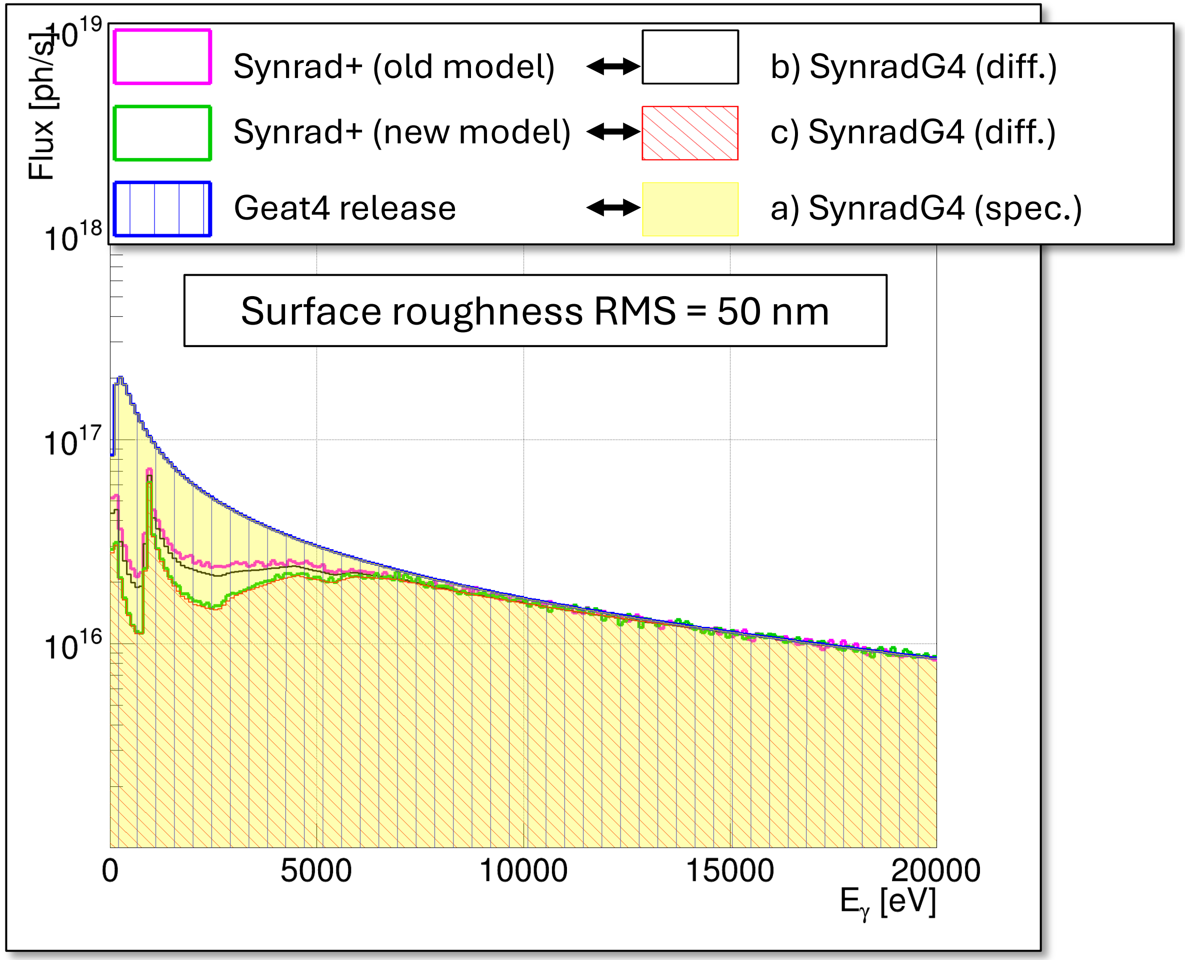


Geant4 geometry

Benchmark

- There is a **good agreement** between SynradG4 and Synrad+/G4-release
  - It **confirms the correct implementation** of X-ray reflection into the new custom-built code.
- The absorbed **SR photons can be transferred to DD4Hep.**
- Recently **more benchmarks** (including the Synrad3D framework [1]) were conducted and reported in Ref.[2].

The tool is ready for the SR background simulation !



Absorbed SR photon spectrum on the arbitrary beam pipe vacuum facet

SR Rates in the IR

Although one 18 GeV electron generates more SR photons, the highest SR is expected for the 10 GeV electron beam at 2.5 A.

Critical photon energy:

$$\varepsilon_c \sim \frac{\gamma^3}{\rho}$$

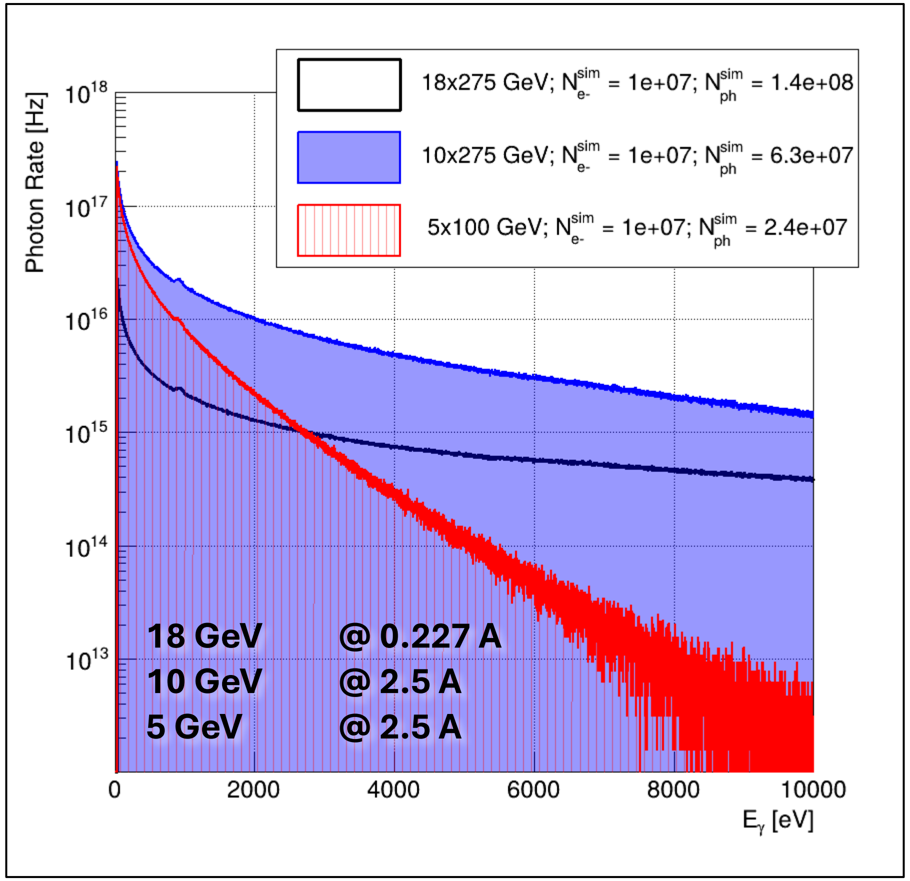
SR power:

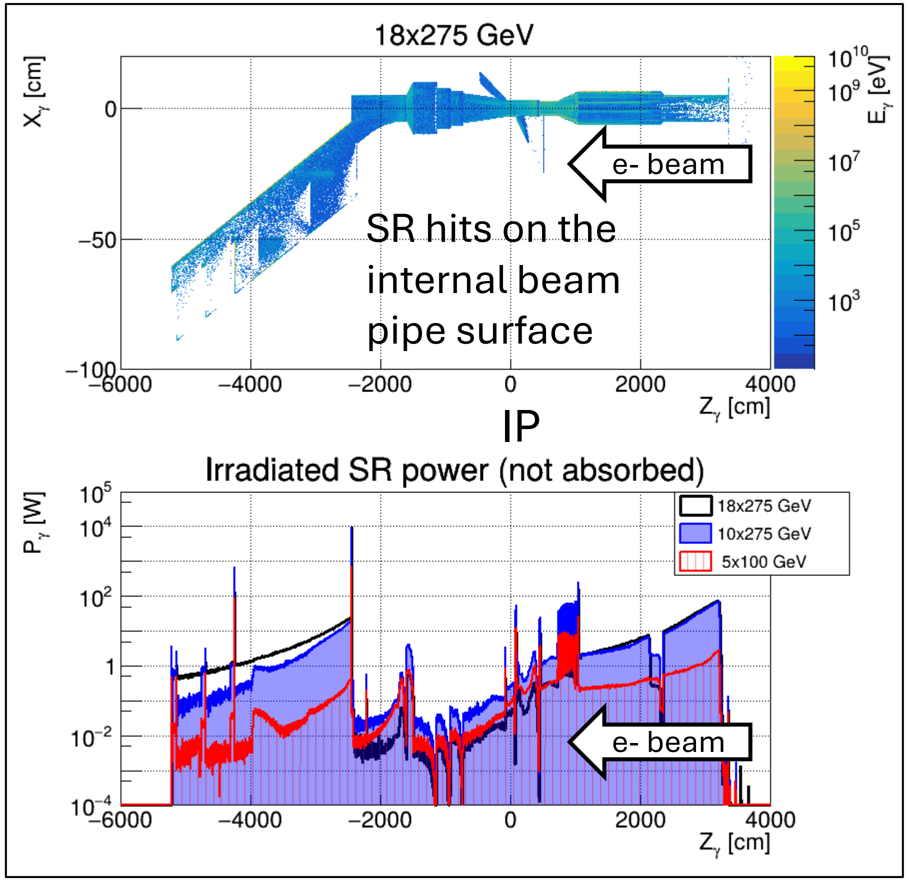
$$P_\gamma \sim \frac{\gamma^4}{\rho^2}$$

SR photon rate:

$$\dot{N}_{ph} \sim \frac{P_\gamma}{\varepsilon_c}$$

where γ and ρ are the Lorentz factor and curvature radius.

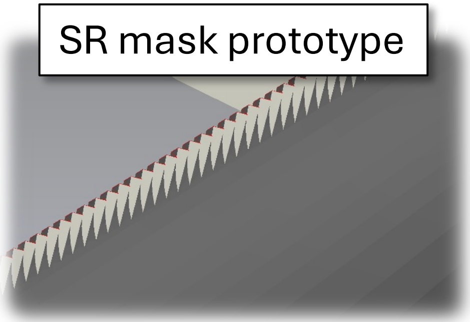




SR Masking

- **Without SR masks:**
  - The estimated SR background rate in the innermost vertex detector is **~1 THz**.

- **With SR masks:**
  - The SR background rate dropped below **~1 GHz**.



0.227 A at 18 GeV, Ref. [1]

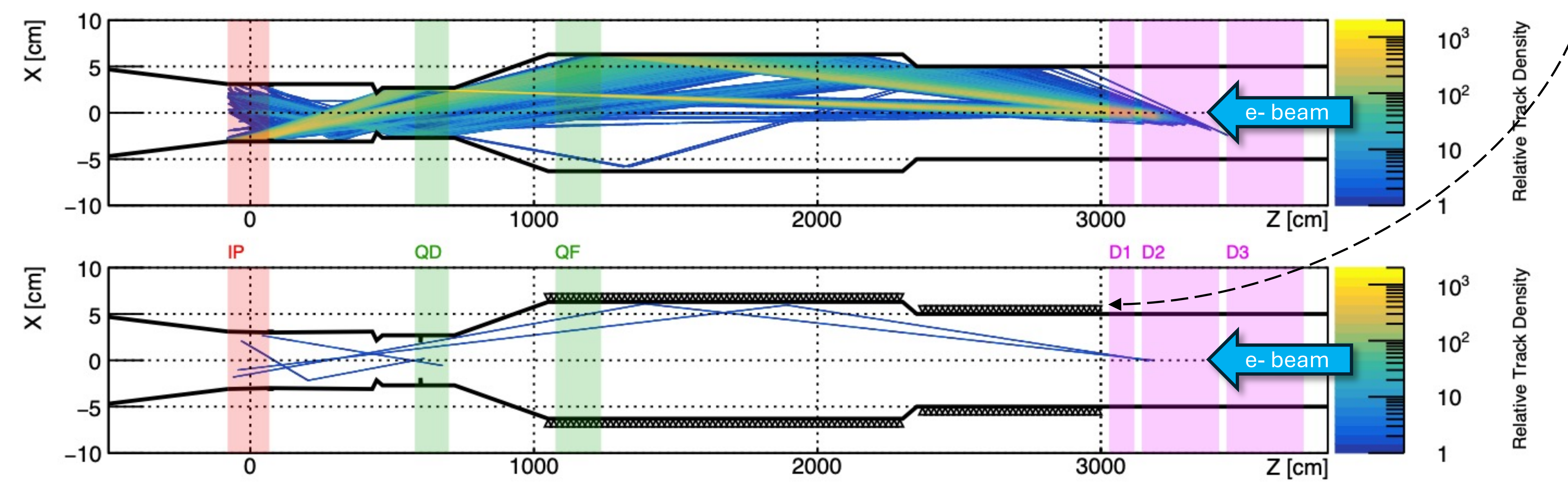
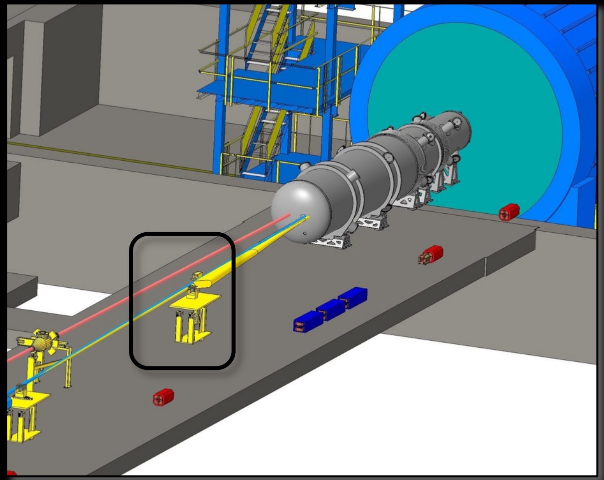
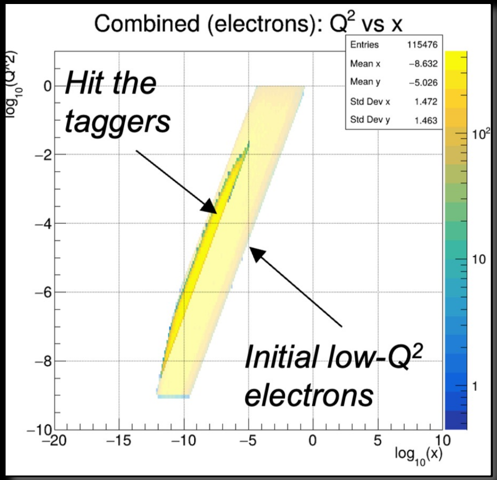


Figure 9: IP beam pipe absorbed SR tracks with $E_\gamma > 10\,\mathrm{keV}$. Top: without SR masks. Bottom: with SR masks shown with black, open triangles. Red, green, and magenta vertical bends show the IP beam pipe, quadrupole magnet (QD – defocusing, QF – focusing in the horizontal plane), and dipole magnet (D1-3) regions, respectively. Black, solid lines stands for the beam pipe aperture. The electron beam goes from positive toward negative Z coordinates.

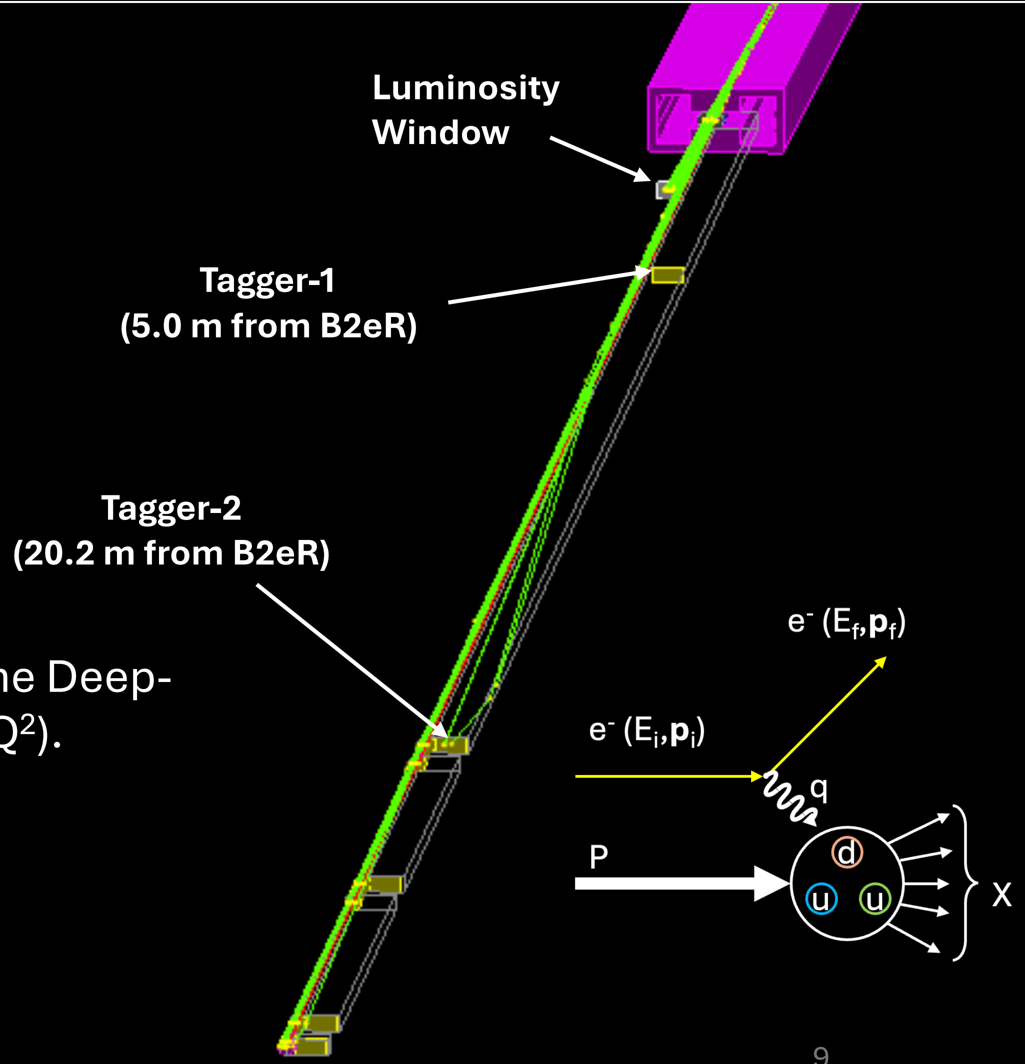
Low-Q^2 Taggers



Far-backward setup



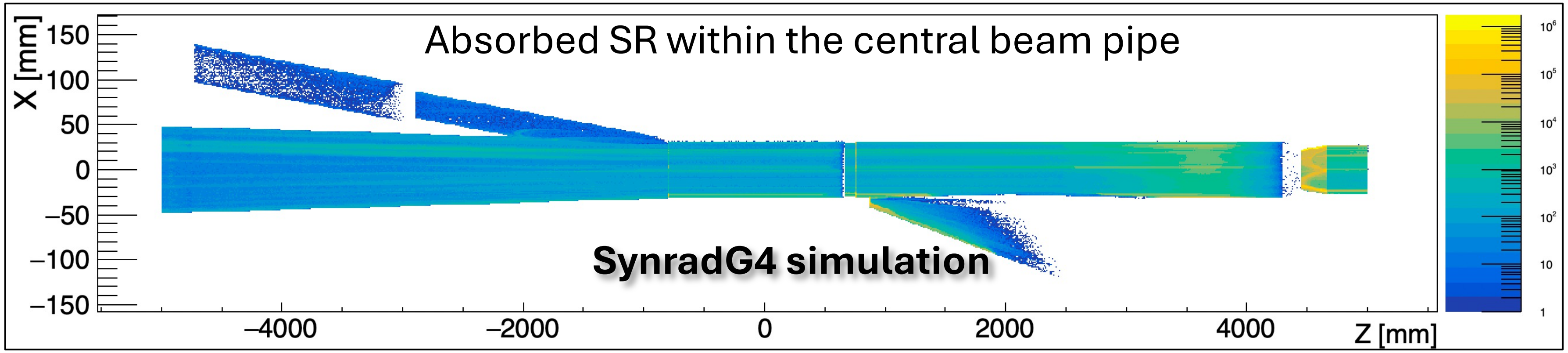
Momentum transfer (Q^2) vs Bjorken variable (x)

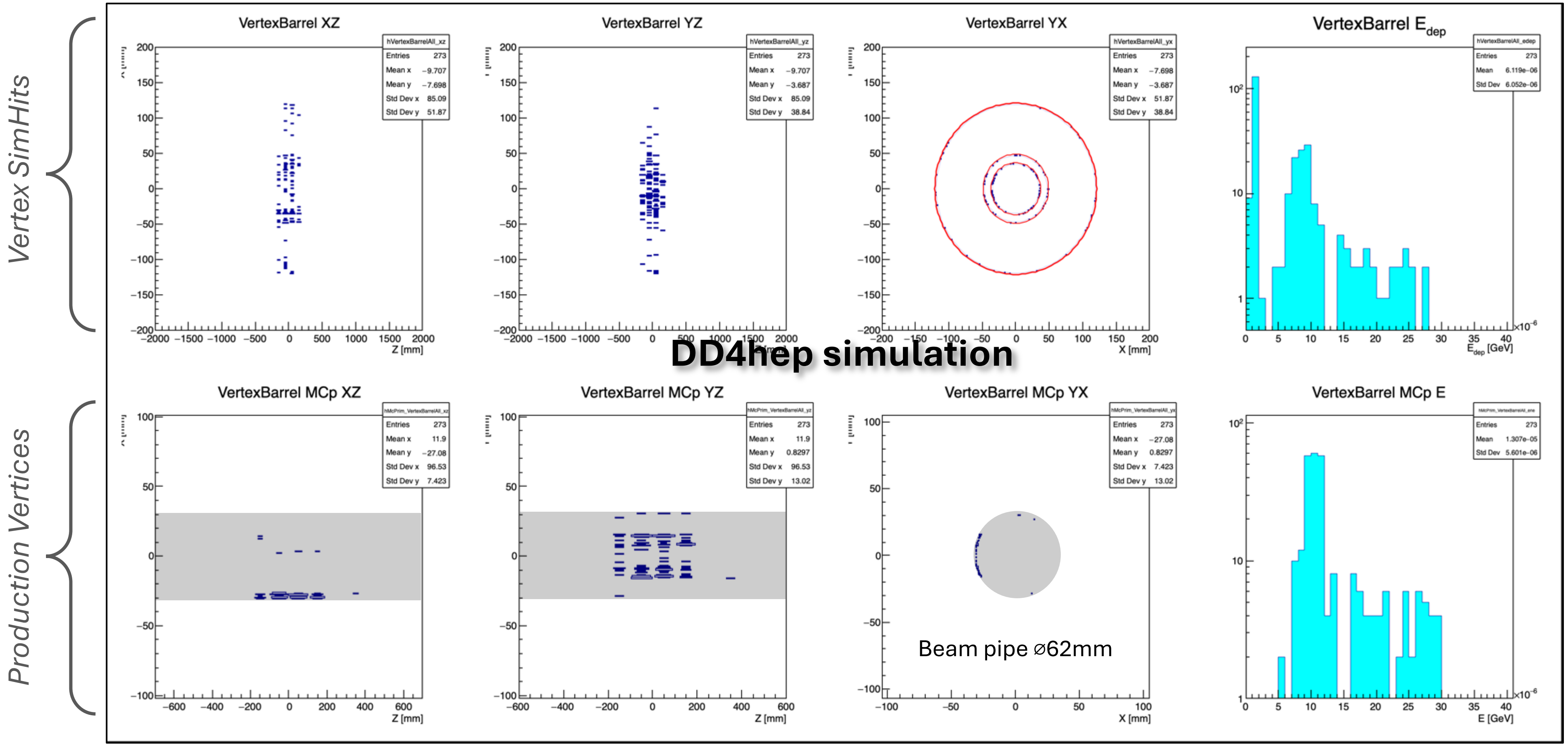


- SynradG4, helps us optimize the far-backward experimental setup for the Deep-Inelastic Scattering (DIS) measurements at a low momentum transfer (Q^2).
- Currently, only **12%** low-Q^2 electrons are detected by the taggers.
  - A big part of the electrons (~65%) goes through the quads.
- Further tunings of optics and tagger's configuration are ongoing.

Detector Hits

- Most of the SR will be absorbed by thick cryostat beam pipe walls.
- The tracking system sees SR photons primarily from the IP beam pipe.
- Only the SR photons with $E_\gamma > 5$ keV produce hits in the detector.



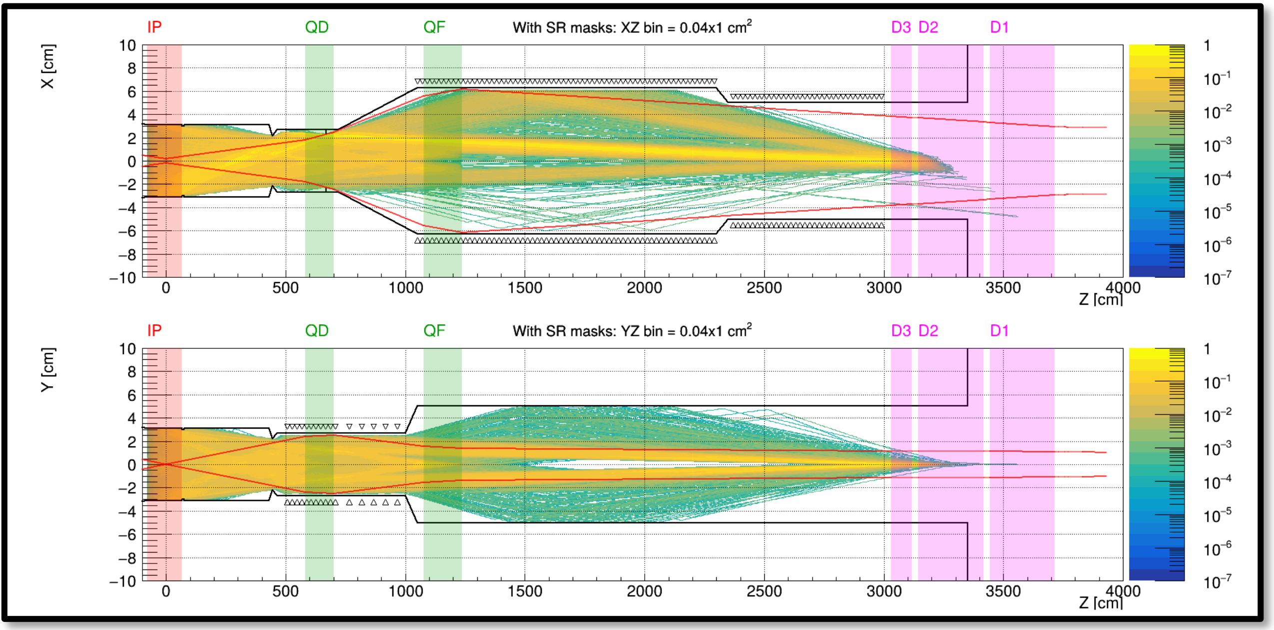


ESR SR Sample in HepMC3.ROOT for 18 GeV v6.3.1

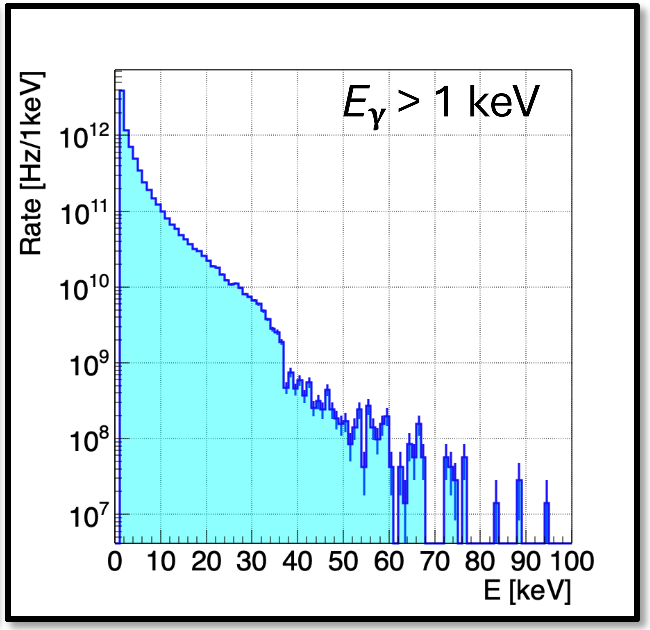
Statistics: 10^{11} electrons simulated at 18 GeV for the ESR lattice v6.3.1

Setup: IR6 vacuum from Charles Hetzel with SR masks

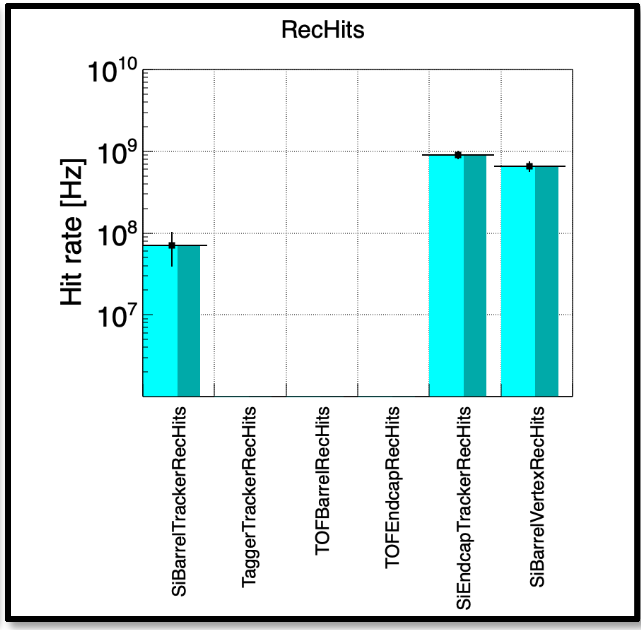
MC Sample: SR photons absorbed on the inner surface of the IP6 beam pipe (-80;+67)cm above 1 keV



SR photon tracks that hit the IP6 beam pipe (E_γ > 10 keV)



Spectrum of SR photons hitting the inner surface of the IP6 beam pipe



ePIC detector RecHit rate

HepMC3.ROOT: /gpfs/mnt/gpfs02/eic/anatochii/SynradG4_HepMC_Files_SR_on_IP6/ on SDCC

SR Rate/Weight: At 18 GeV, the ESR beam current is 0.227 A, which means N_e = 0.227/(elem_charge) = 1.4×10^{18} electrons/sec and W = $N_e/10^{11}$ = **14 [MHz] - the weight of one file**.

Code Repository: https://github.com/eic/EIC_SR_Geant4

Summary

- The intense SR generated by the high-energy electron beam passing the IR can negatively affect machine and detector operations
  - Leading to damage to sensitive equipment, temperature increases in SC magnets, and degraded performance.
- To address these challenges, an accurate and dedicated framework for studying SR in the ESR is essential.
  - Unfortunately, existing well-known frameworks have limitations that restrict their applicability to the EIC.
- A new Geant4-based framework, SynradG4, has been developed to meet the specific needs of the EIC.
- Previous studies using Synrad+ resulted in incorrect estimates of SR background rates in the ePIC detector.
  - Consequently, a new high-statistics MC sample has been prepared, incorporating the latest SR masking and updated beam pipe geometry.
- Further studies on SR mitigation are planned.