Recent validation of the UFO dynamics model and ICBLM time profiles analysis

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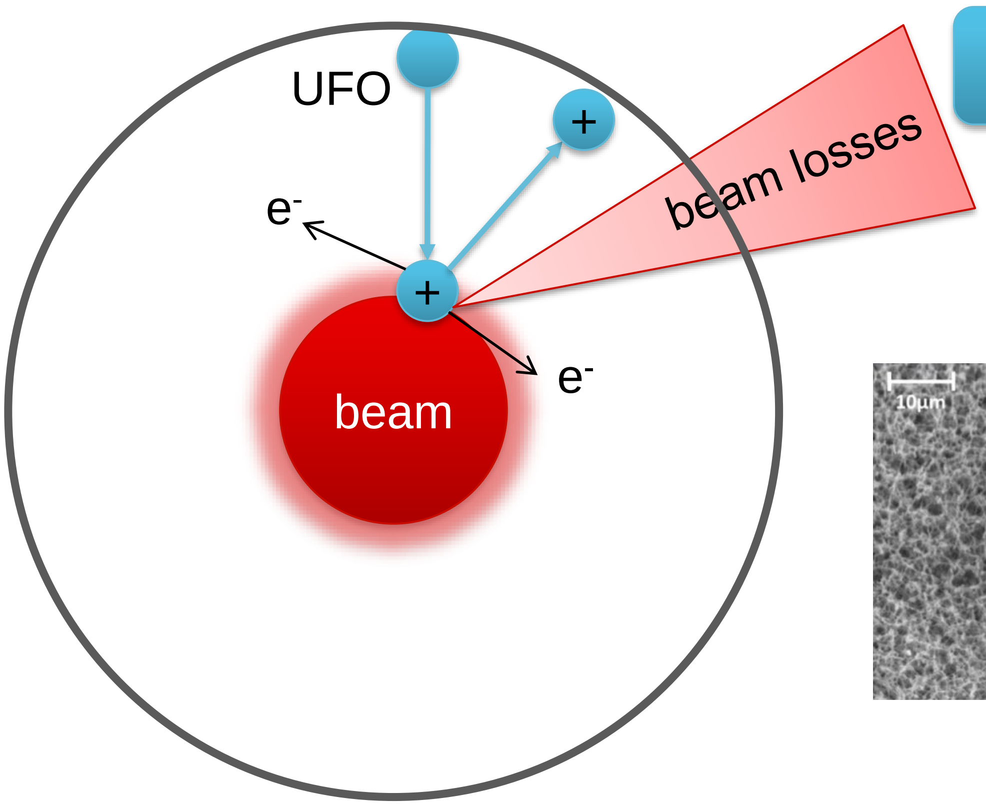
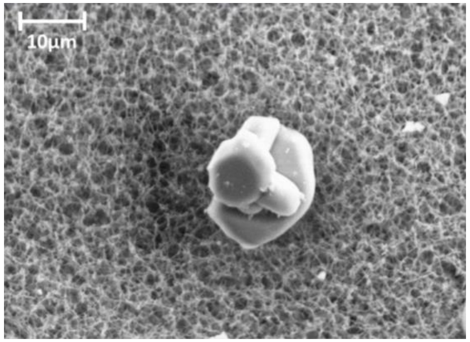
Unidentified Falling Objects (UFO)

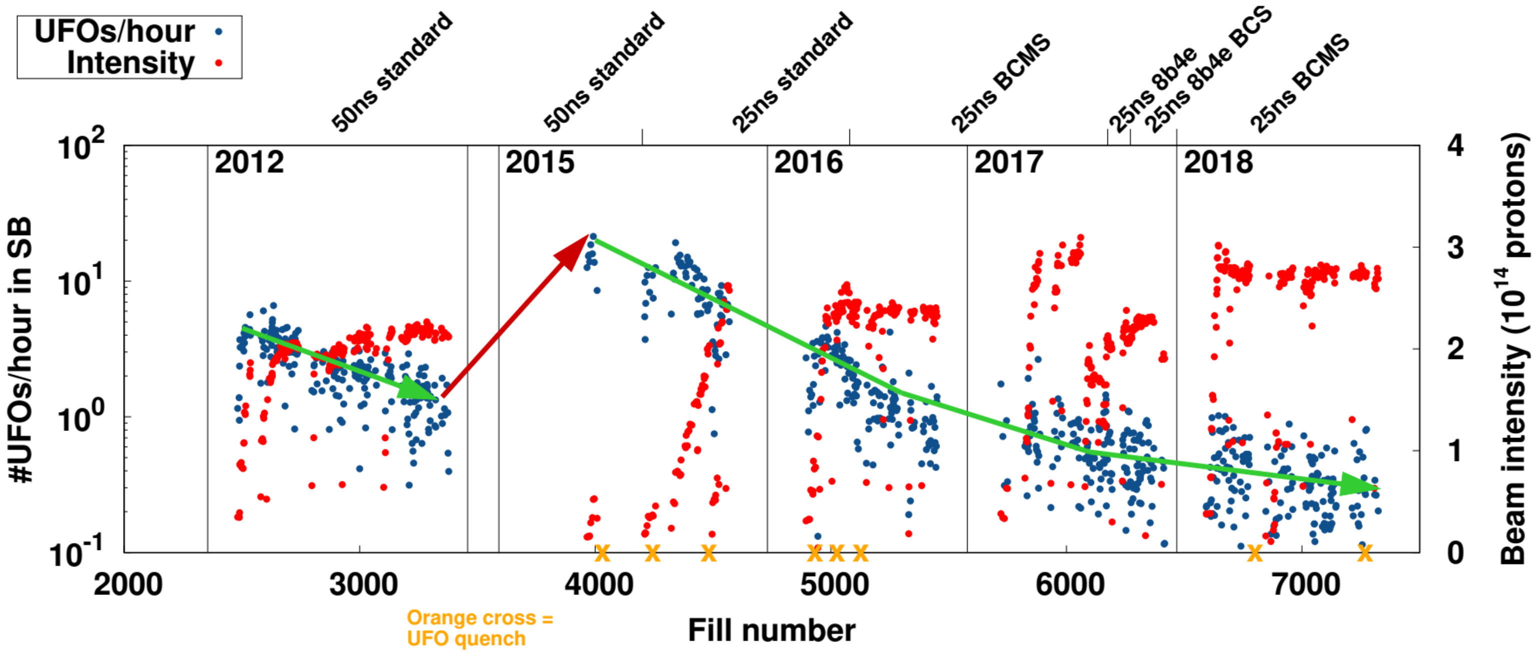
- Beam-macroparticle interactions
  - Intense beam losses, duration < 1 ms
  - Premature beam dumps and superconducting magnet quenches





Unidentified Falling Objects (UFO)

- From A. Lechner, 2018

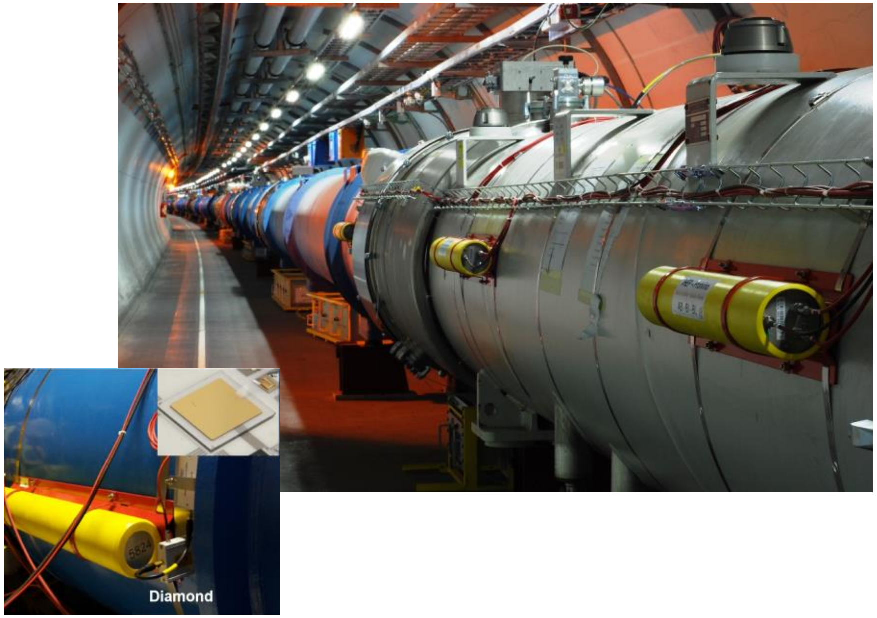


- Why do we care?
  - Beam dumps, 115 during Run II
  - Magnet quenches, 8 during Run II
  - Intensity drop? No, negligible during p-p physics

Detecting UFO events

Instruments :

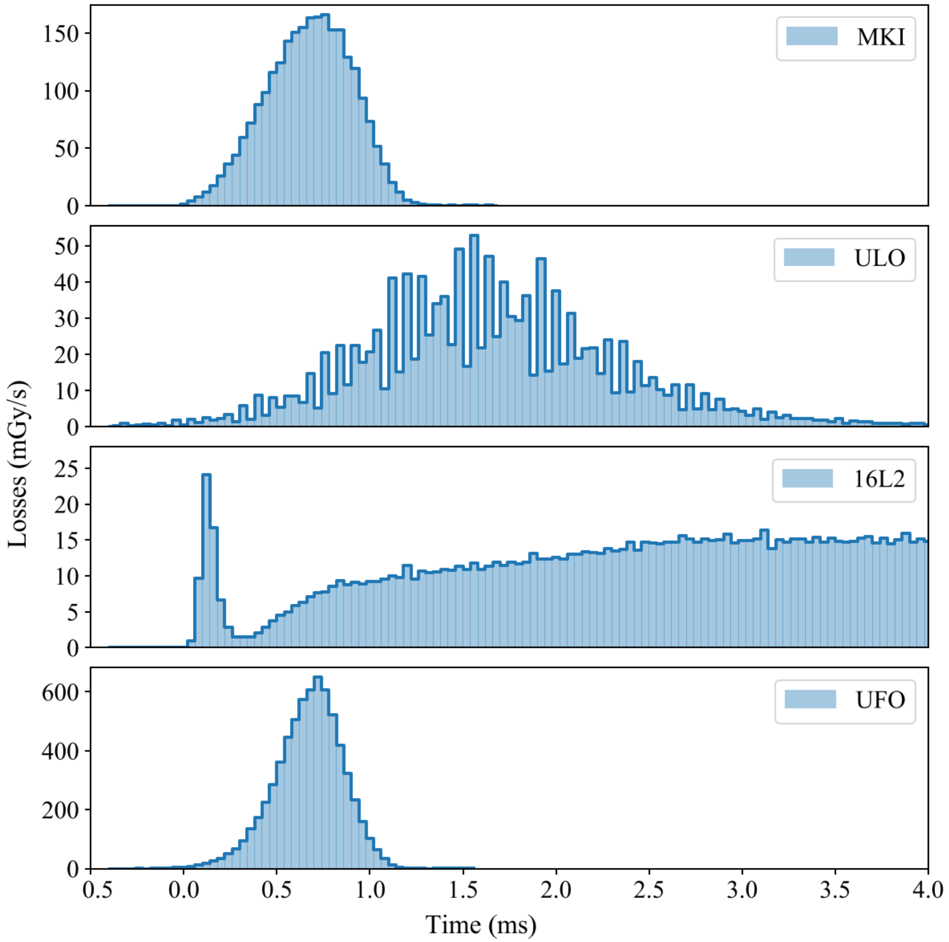
- Beam loss Monitors (BLMs)
- Diamond BLMs (dBLMs) in IP7



Databases :

- UFO Buster,
  - Beam parameters
  - Triggers Capture Buffer, 80 us resolution (RS2)
- Post-Mortem, 40 us resolution (RS1)
- dBLM, 1.6 ns resolution

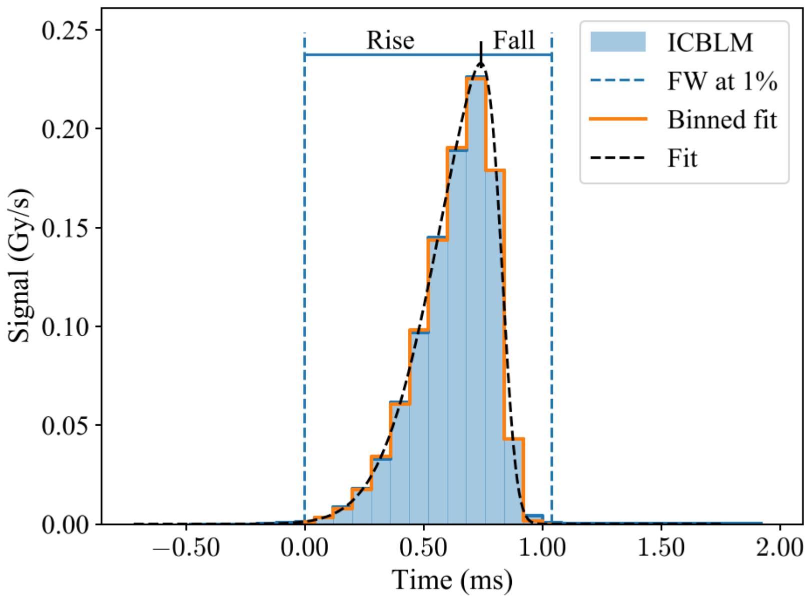
UFO types in the LHC

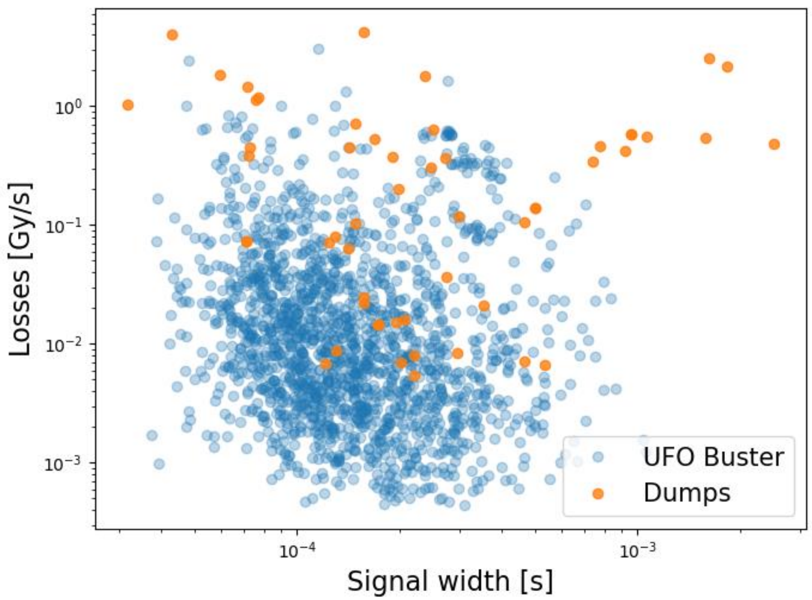


- MKI : Occurring 2 ms after injection, believed to be Al_2O_3 particulates from the ceramic tube, consistent with dust inspection
- ULO : Strip of plastic lying at the bottom of the beam screen. Signal oscillating with the LHC frequency, because most events were recorded with only few pilot bunches
- 16L2 : UFO-like spike (interaction with solid matter) followed by increasing losses (transverse beam instabilities). It is believed that solid nitrogen/oxygen/water were subject to phase transition to gas phase
- Typical UFO : observed all around the LHC, happening sporadically

Data collection : valid events

Source	Number of events
UFO Buster	337,217
Matching Capture Buffer	57,262
→ Filter 1 (SNR > threshold)	32,137
→ Filter 2 (min. 5 points signal)	3,035



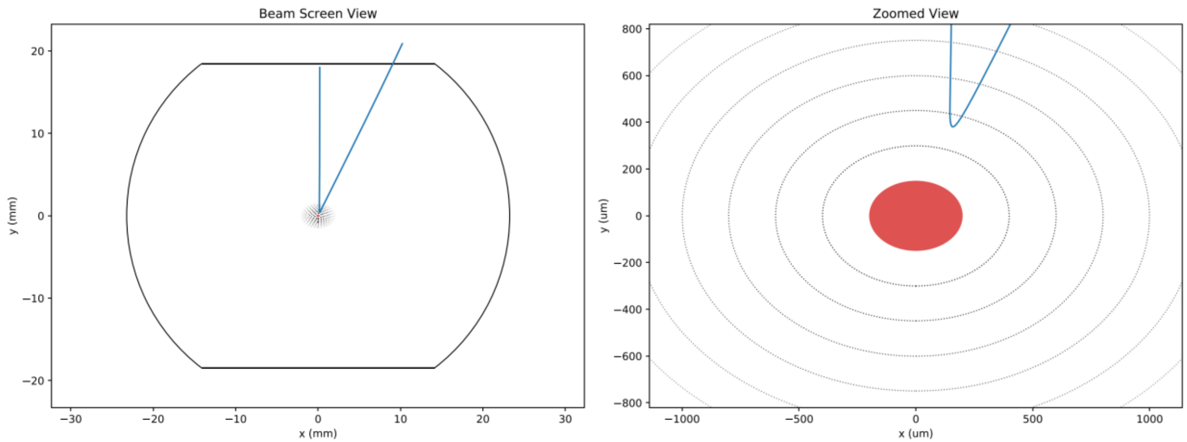


Dynamics Simulation Tool

Tool developed (starting in 2010, F. Zimmermann, B. Auchmann et al.) to simulate UFO dynamics:

1. UFO begins to fall and/or be attracted toward the proton beam
2. UFO is ionized by elastic collisions with the proton beam
3. The now positively charged UFO is repelled from the beam by its electric field

Was recently transcribed in Python and maintained on GitLab

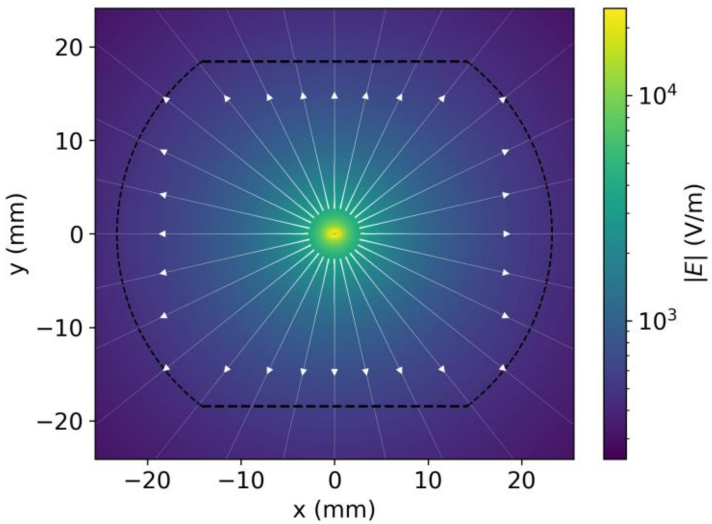


Model validation

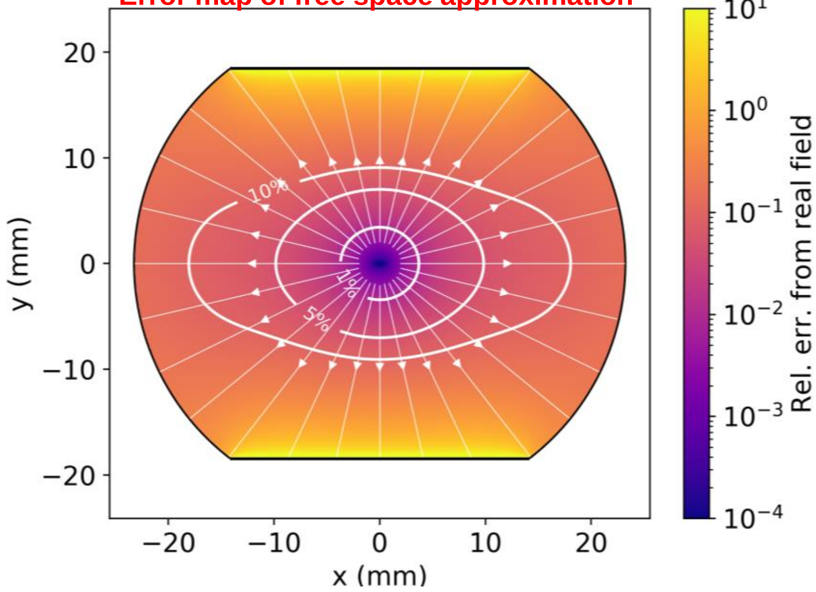
- Difficult to generate UFO on demand, with controlled parameter
- Bunch-by-bunch measurements (dBLMs) could be used to obtain more information, but difficult to measure bunch-by-bunch locally
- Two options to benchmark :
  1. Breaking down the model, separately validating the physics with other simulation tools (FLUKA, Geant4, COMSOL, etc.)
  2. Ensemble behaviour, comparing UFO Buster data (thousands of events) with Monte-Carlo simulations

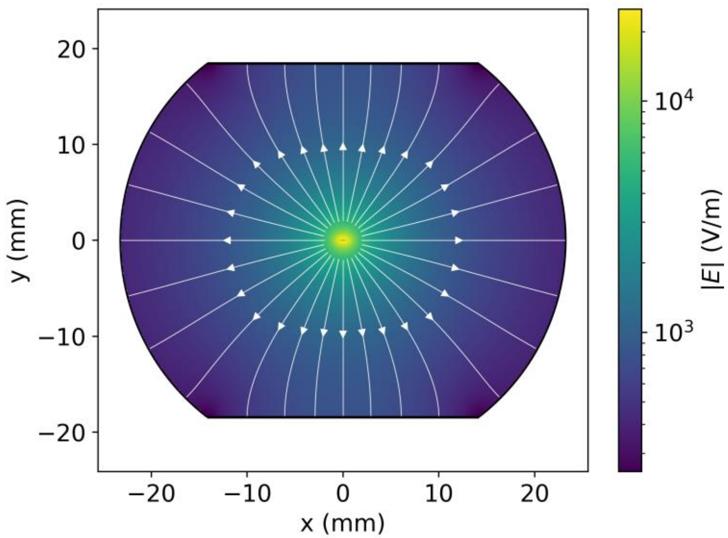
Beam’s Electric Field

- Previously using free space approximation
- Now considering beam screen using a numerical method based on the Method of Images
- Necessary update for dynamics of charged UFOs far away from the beam



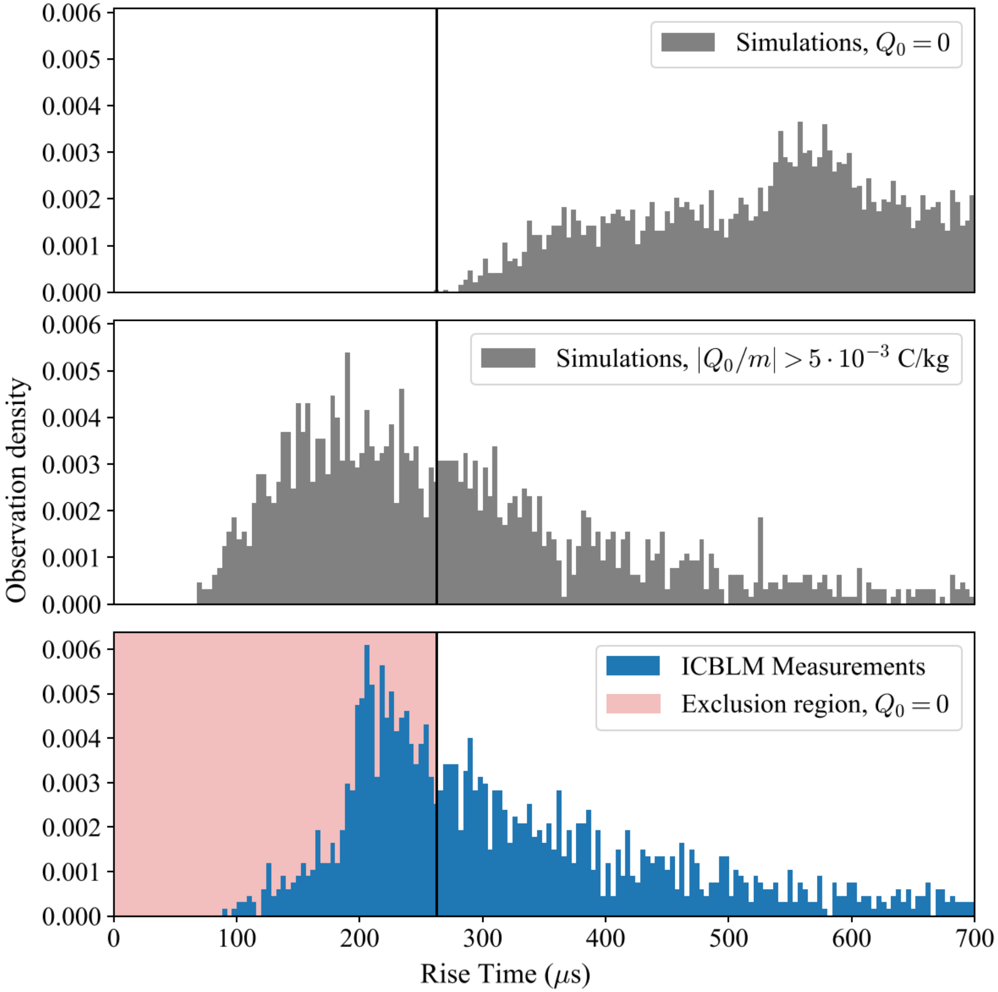
Error map of free space approximation





Signal Rise Time

- ICBLM measurements show very fast rise time, cannot be explained by neutral UFO falling with gravity
- Initially negatively charged UFOs give rise time distribution in agreement with measurements
- Plausible charging mechanism:
  - Induction through oxide layer due to beam's E-Field
  - Photoelectrons generation from synchrotron radiation

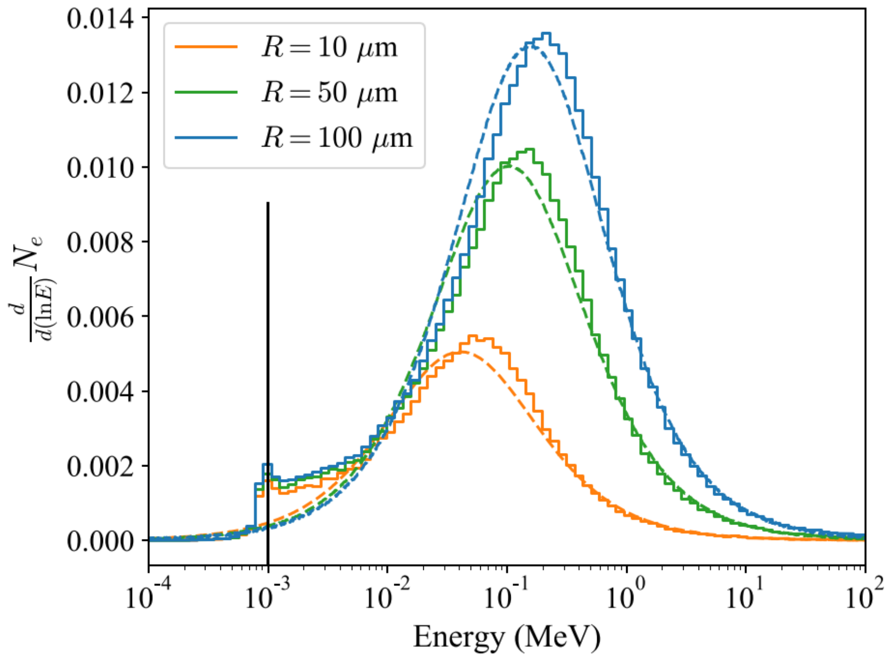


UFO charging rate: work function

- UFO work function is critical in the charging rate mechanism as it is the **minimal energy required** for an electron to escape the UFO

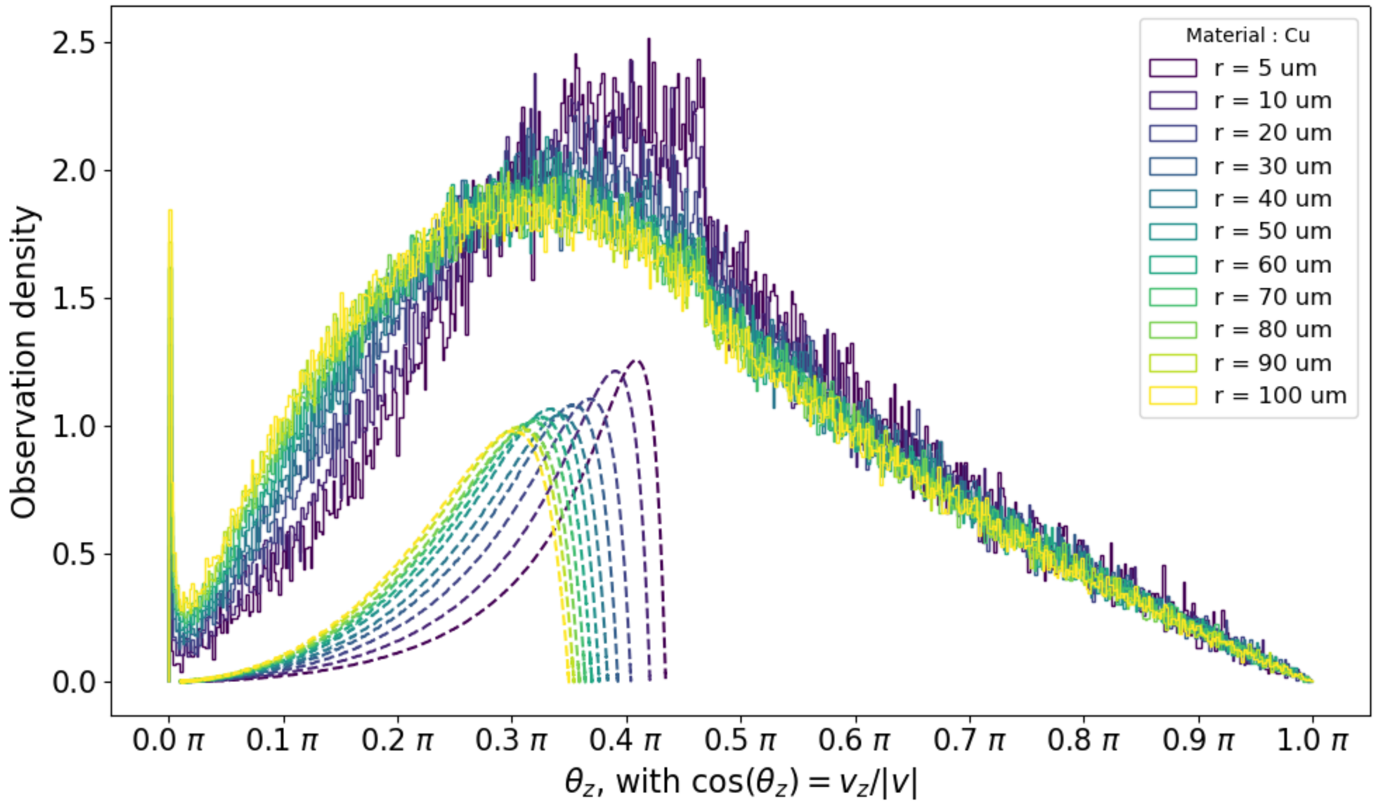
- Empirical relation of the practical range of electrons in matter (**adapted for the model**) gives good estimate of the work function (~ 50-150 keV)

- Allows to compute the **energy spectrum of knock-on electrons** as they escape a neutral UFO (dashed lines) and compare it with FLUKA (solid lines)



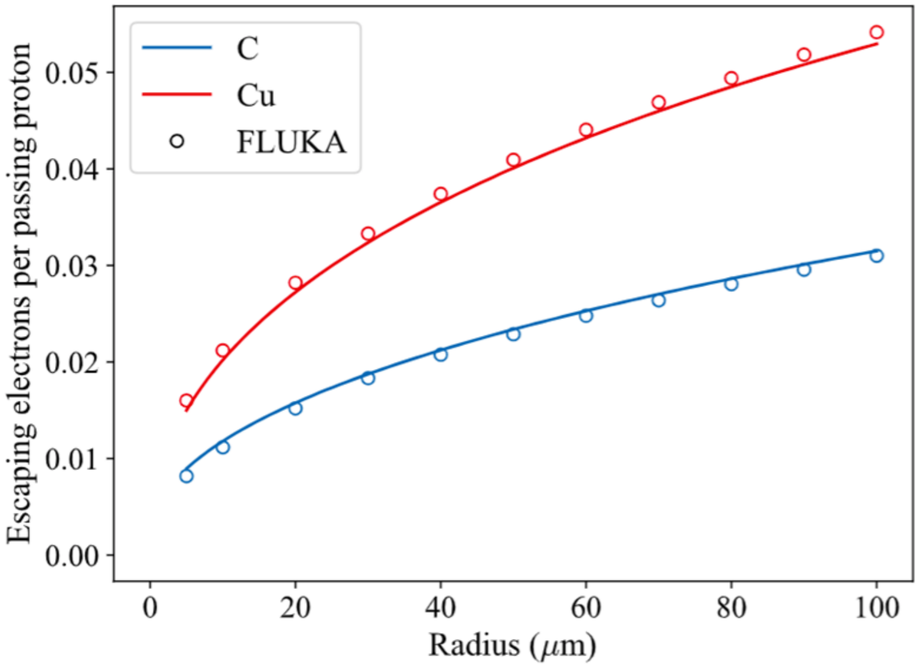
UFO charging rate: work function

- As an **additional validation**, one can also look at the angular distribution (relative to beam's axis) of the knock-on electrons
- Dashed lines are production angles from the model (normalized for visualization), solid lines are exiting angles from FLUKA, broaden by random coulomb scattering before exiting UFO



UFO charging rate: neutral UFO

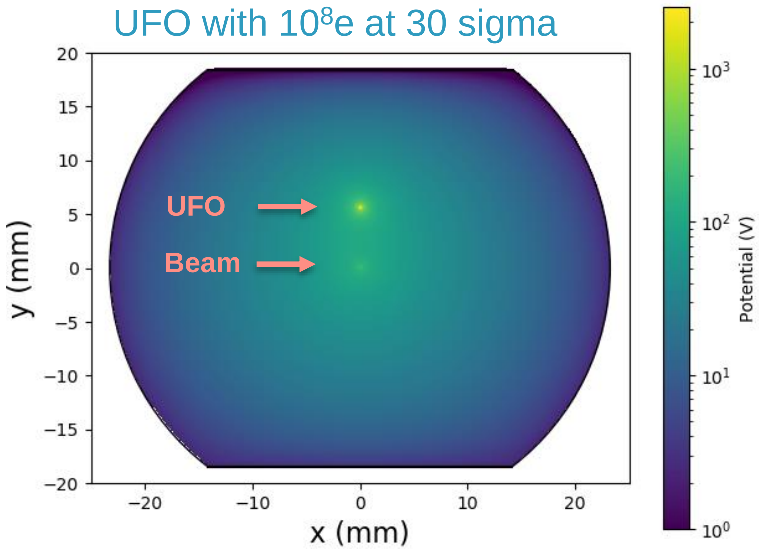
- Integrating the knock-on electrons with the required energy (slide 9) leads to the number of escaping electrons per passing protons
- Combined with the proton flux hitting the UFO, the charging rate is obtained
- **Previous simulations were off by a factor ~2**
- This is **for a neutral UFO**, what happens when it is already charged?

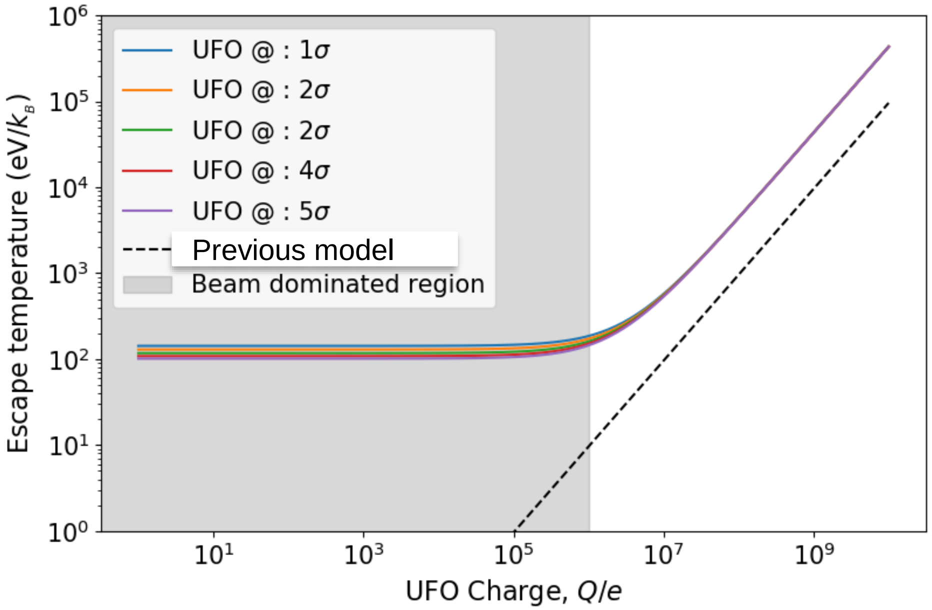


UFO charging rate: escaping charged UFO

- For a charged UFO close to the beam, electrons have to escape the coulomb potential.
  - For small UFO charge, the beam dominates
  - For high UFO charge, the UFO dominates and electrons need more and more energy to escape

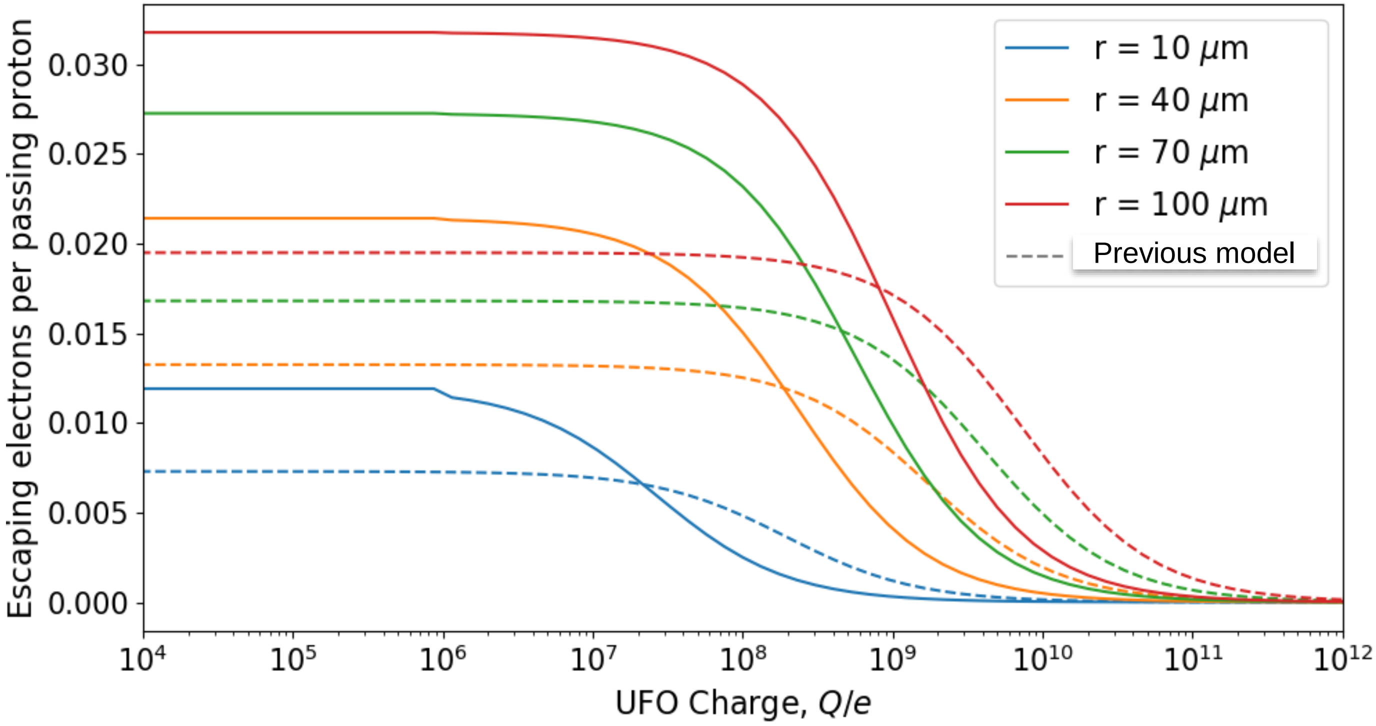
UFO with 10^8e at 30 sigma





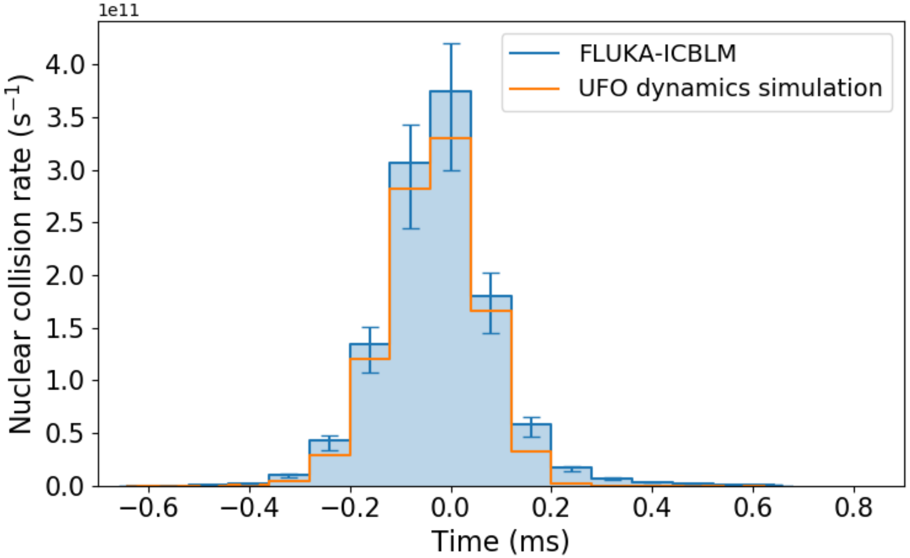
UFO charging rate: escaping charged UFO

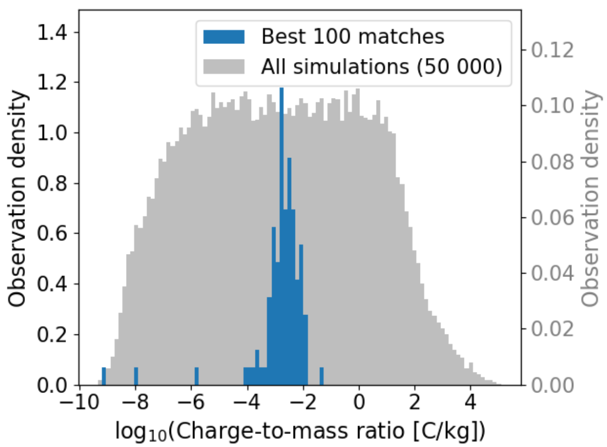
- Taking into account the change of minimal energy required to escape, the number of escaping electrons per passing proton ultimately goes to 0 for high UFO charge

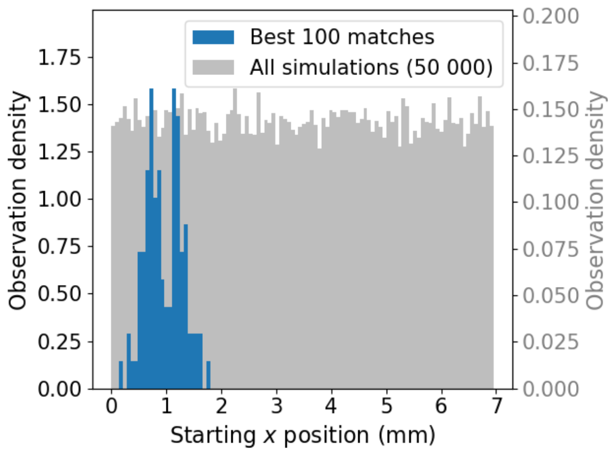


Monte-Carlo simulations convergence

- Time profile analysis (fit) allows to find **best UFO candidate** based on ICBLM measurement by comparing with Monte-Carlo simulations
- Here, Cu dust of 33 um radius with -2x10^{7}e initial charge
- The **important physical quantities** (in order to understand UFO release mechanism) **converge** well

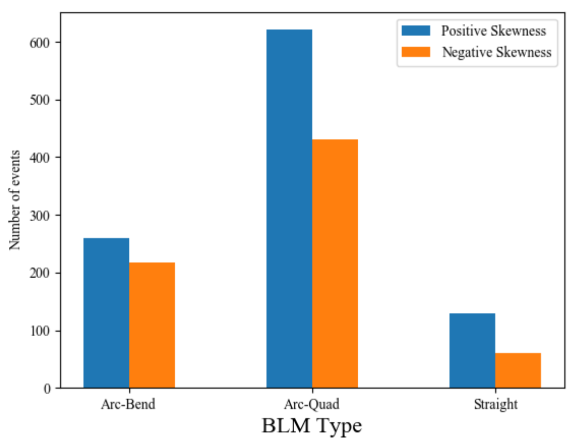


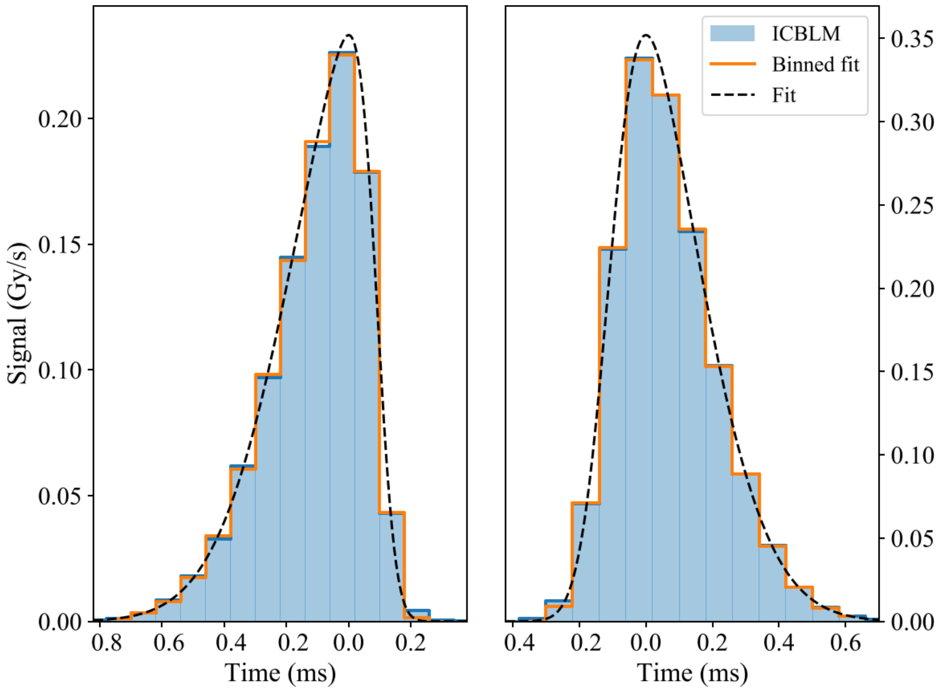




Positive skewness in time profiles

- Time asymmetry observed in measurement : both positive and negative skewness
- Negative **skewness expected from first principles and current simulations** (entry speed is lower than exiting speed due to ionization)
- The long tail doesn't seem to be:
  1. A systematic effect from the ICBLMs
  2. Correlated with location
  3. Correlated with event length



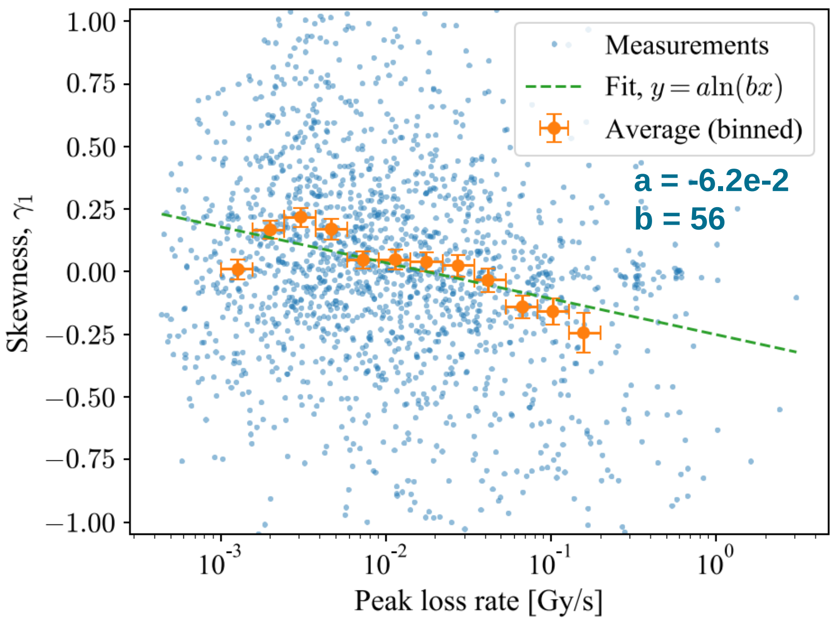


Negative skewness (compatible with simulations)

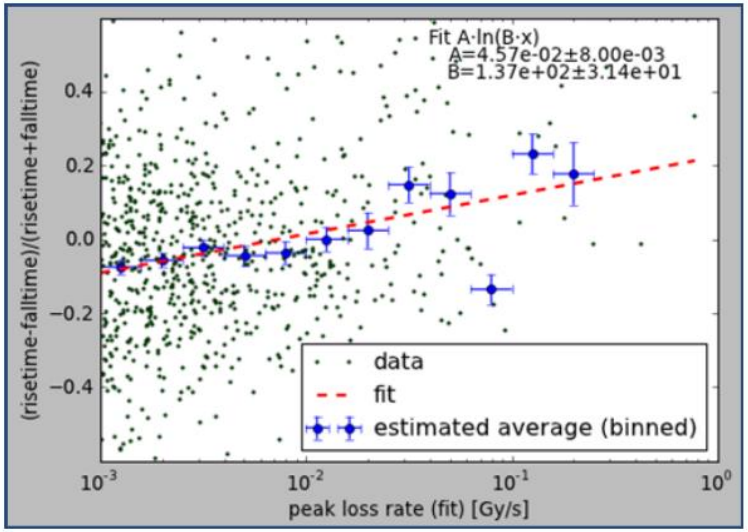
Positive skewness (Not compatible with simulations)

Positive skewness distribution

- Very similar distribution between Run I and Run II
- Small correlation with the signal amplitude



* T. Baer plot, shows –(gamma)



(b) Measured asymmetry.

Conclusion

- Updated UFO dynamics tools
  - Reviewed beam's E-Field approximations
  - Reviewed and benchmarked charging rate with FLUKA
- Can successfully obtain UFO profiles with compatible rise time by considering initially charged UFOs
- Can find UFO candidate to match negatively skewed events based on Monte-Carlo simulation
- Positive skewness in measurements still needs to be explained

Outlook

- Several hypothesis to explain positive skewness have been explored with no success so far. More have to be tested.
- Studying ionisation electrons using PyECLOUD could help improving the model furthermore
- Studying plausible release mechanism and energy required to leave the beam screen is required to understand UFOs origins

Questions?

Model validation from measurement

Success

- Temporal width of UFO losses in agreement with measurements (T. Baer et al., 2013)
- Using radii distribution from dust inspection measurements, accurate description of peak BLM signals during Run I (S. Rowan et al., 2015)
- ULO confirmation of solid matter interacting with the beam (2015)
- Very fast rise times of UFO signals can be explained by charged UFOs (2019)
- Finding UFO candidates in agreement with both ICBLM and dBLMs measurements (next presentation)

Challenges

- No triggering mechanism found so far
- Time profile asymmetry (skewness) inconsistent with simulations

Dynamic Simulation Skeleton

- Release Mechanism
  - **Dust particulates on conductive surface (litterature, to do, COMSOL?)**
  - Hypothesis to evaluate (falling UFO, orbiting UFOs, dust agglomeration in high EM fields)
- Dynamics of charged particles in E-M fields
  - Beam's electric field (litterature)
  - Beam screen effect (simple math)
  - **Electron clouds effects (PyECLOUD, to do)**
- Beam-UFO interaction
  - Inelastic collision rate (litterature)
  - **Charging rate (FLUKA, discussed here)**
  - **Thermal expansion?**
- UFO Detection
  - Bunch-by-bunch losses for dBLM detection
  - **ICBLM response to local losses (to do?)**
- Conditionning mechanism

Skewed Gaussian Fit

$$\Phi(t) = Ae^{-\frac{(t-\mu)^2}{2\sigma^2}}\left[1 + \mathrm{erf}\left(\frac{\alpha(t-\mu)}{\sqrt{2\sigma^2}}\right)\right] \quad (1)$$

The shape parameter α is linked to the skewness of the distribution (third standardized moment), γ_1 :

$$\gamma_1 = \frac{4-\pi}{2}\left(\frac{\delta}{\sqrt{\pi/2-\delta^2}}\right)^3 \quad \text{with} \quad \delta = \frac{\alpha}{\sqrt{1+\alpha^2}} \quad (2)$$