UFO dynamics and pre-charged dust: Simulations and experimental observations in the LHC

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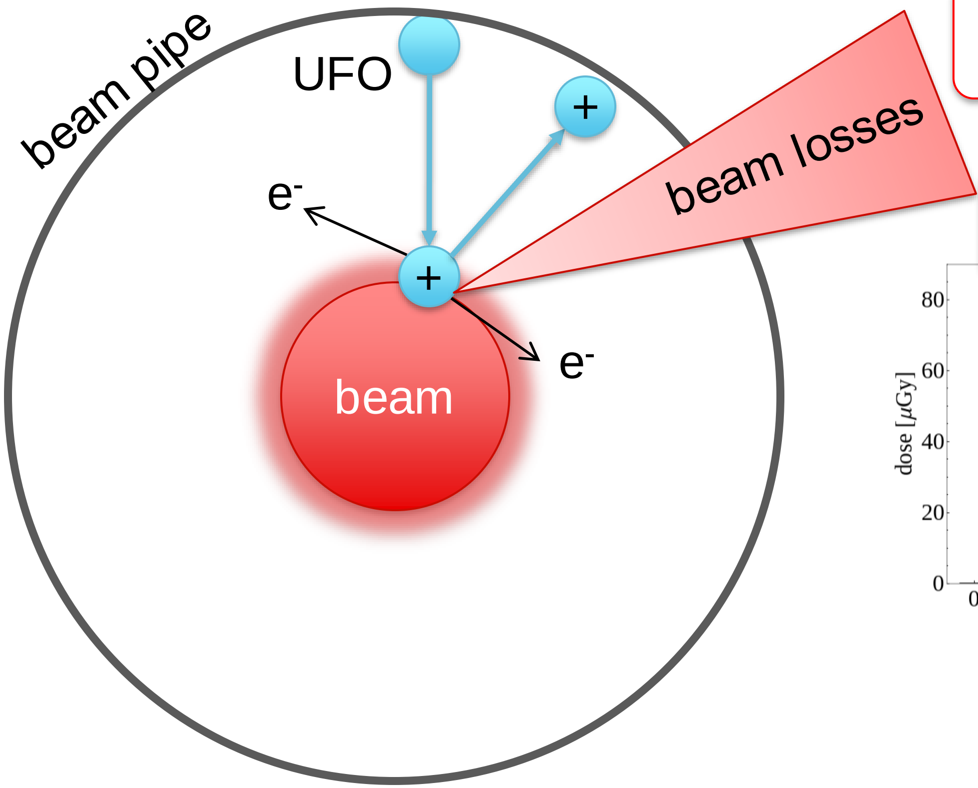
CERN

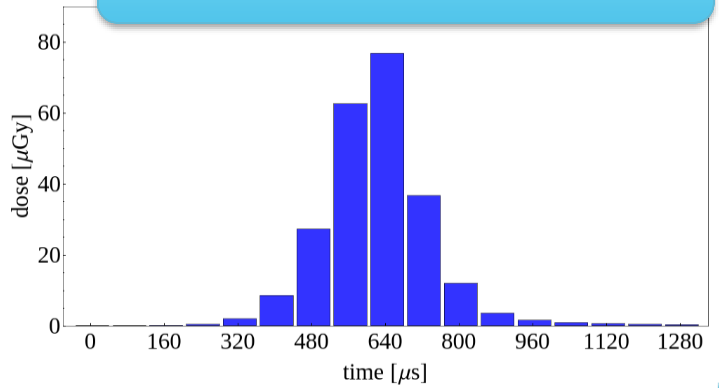
14th June 2023 – Workshop on Dust Charging and Beam-Dust Interaction in Particle Accelerators

Dust particle interaction with beam (UFO)?



premature beam dumps
magnet quenches

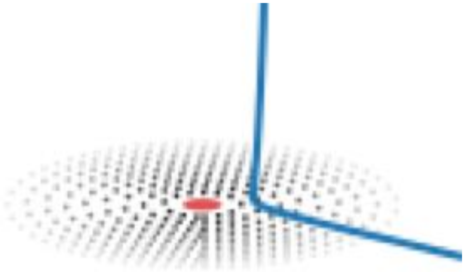
beam loss monitor (BLM)



- Many unknowns: origin? release mechanism? mitigation? future behavior (increased beam intensity/energy)?

BLMs and simulations are means of studying the UFO events in the LHC

Dynamics simulation tool



Python tool – dust dynamics and beam loss creation, ongoing development since 2010*

- Input Parameters:
  - UFO properties: Size, Mass, Material
  - Initial conditions: Charge, Position, Velocity
  - Beam properties: Energy, Intensity, Transverse dimensions

*B. Auchmann et al, "PROTON-BEAM MACRO-PARTICLE INTERACTION: BEAM DUMPS AND QUENCHES", https://cds.cern.ch/record/2727938

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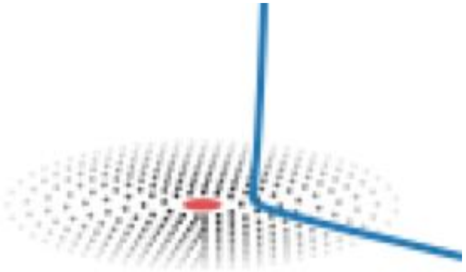

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  - **E** from beam and mirror charges on beam screen
  - **B** negligible due to low speed

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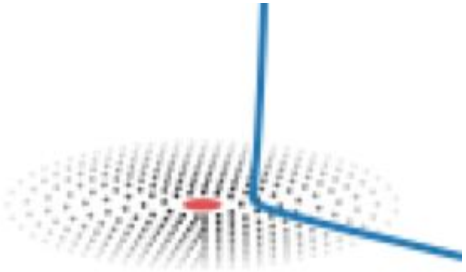

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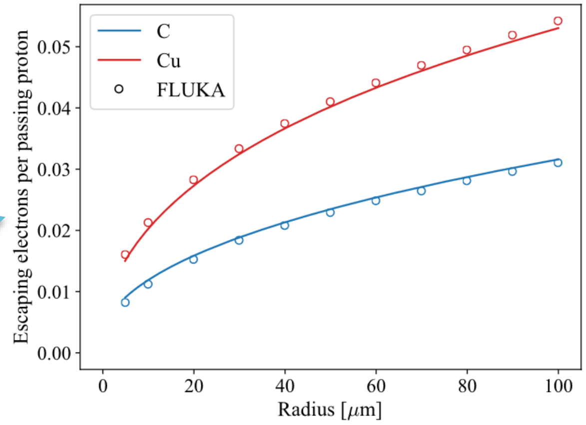
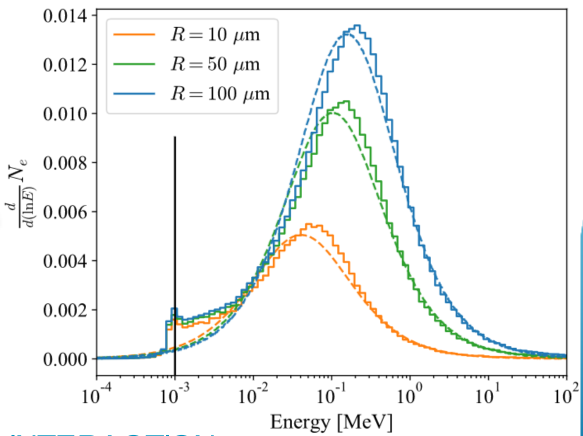
- Knock-on electrons (dust charging):
  - Empirically fitted to FLUKA simulations





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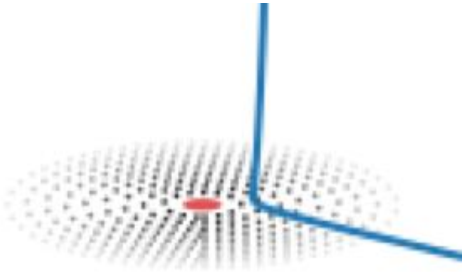

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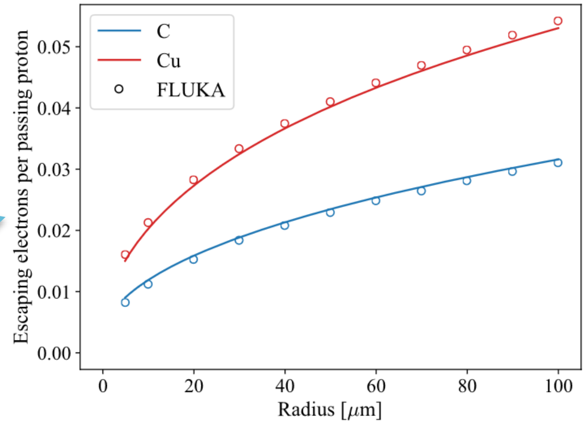
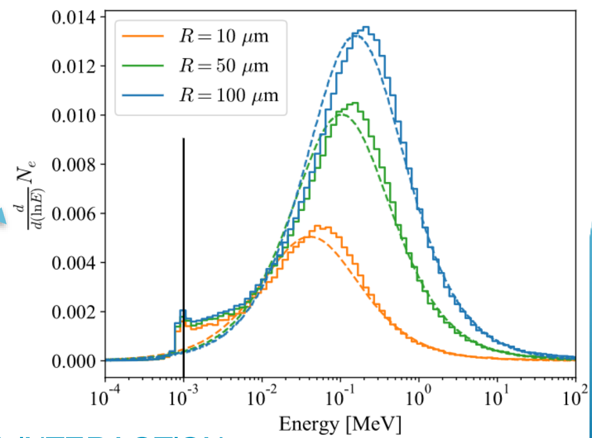


- Inelastic collisions (local beam losses):
  - Elastic collisions (→protons lost in collimators) proportional to inelastic collisions

$$\dot{N}_\mathrm{p} = -\frac{2N_\mathrm{p} f \sigma_\mathrm{iel} R^3 N_\mathrm{A} \rho}{3\sigma_x \sigma_y A M_\mathrm{u}} \mathrm{e}^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}}$$



- Dust heating: covered by A. Lechner (previous talk)

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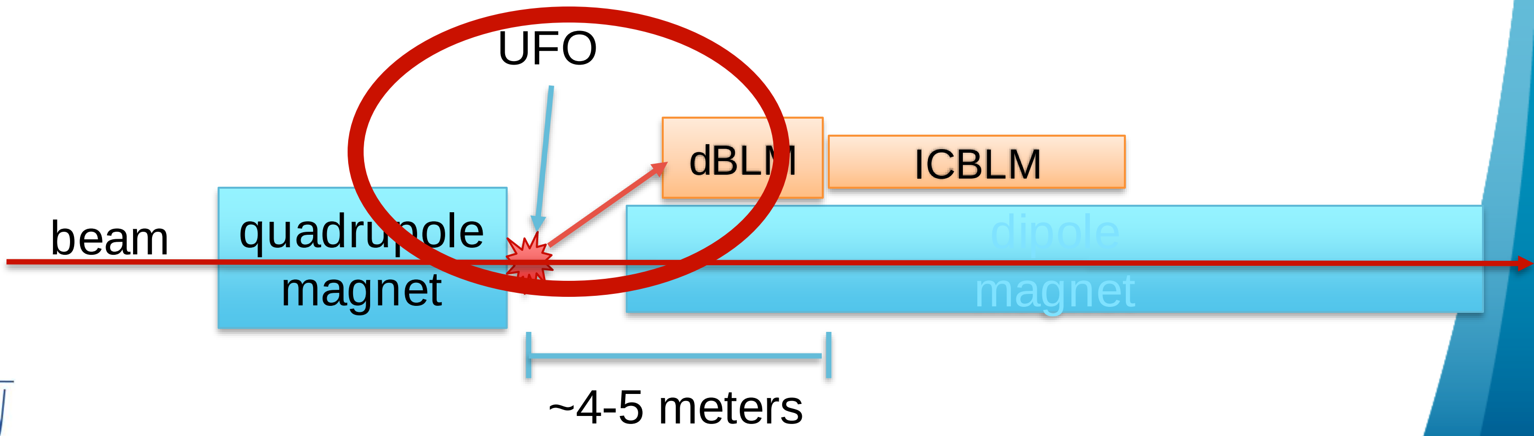
Beam Loss Monitors

ICBLM:

- Main beam loss monitoring system of LHC
- 4000, covers all 27 km
- Dumps beams when anomalous beam losses detected
- Large volume -> good signal to noise
- 40 μs time resolution (~half LHC turn)

dBLM:

- Small size -> signal fluctuations
- ns resolution (bunch-by-bunch, 25 ns)
- Installed at a few locations (e.g. IR7 collimators)



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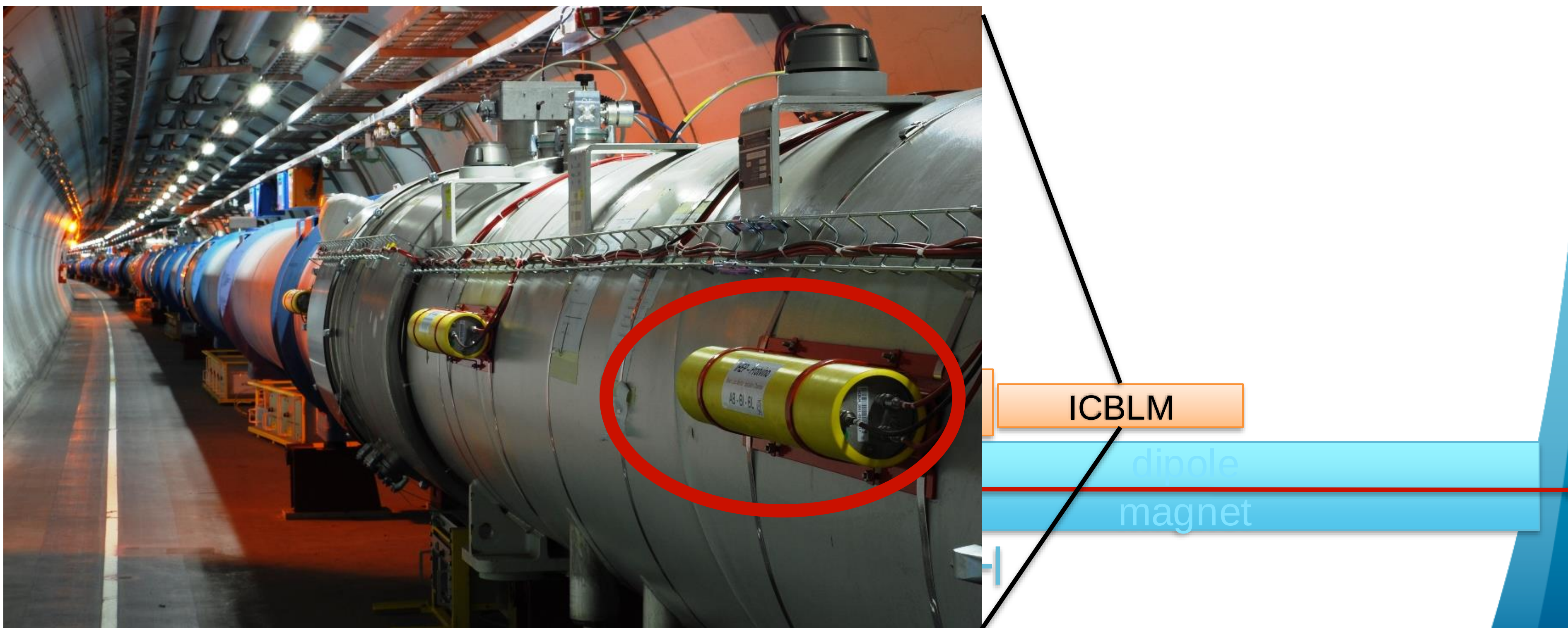

UFO type 2 ex

ICBLM:
- Main bean … of LHC
- 3600, cove…
- Dumps be… am loss
- Large volu… se
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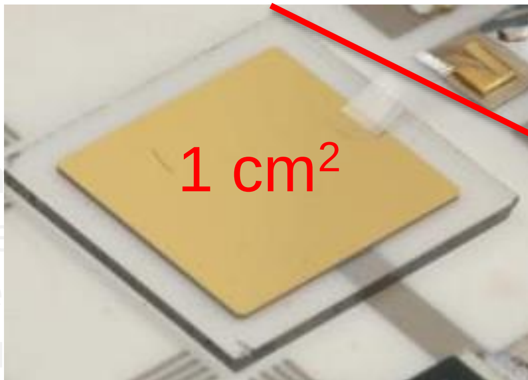

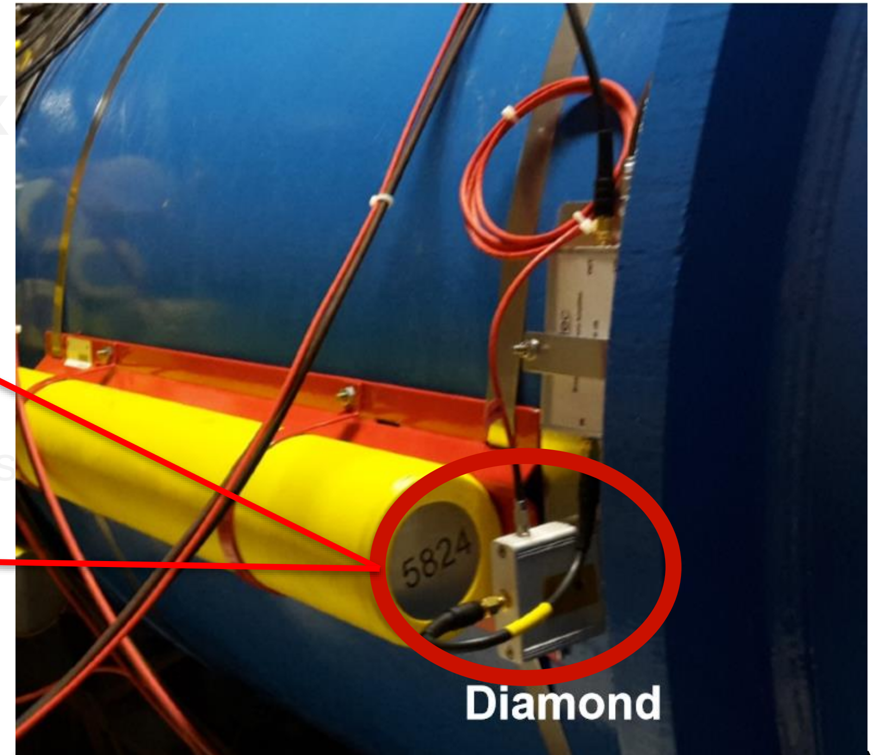

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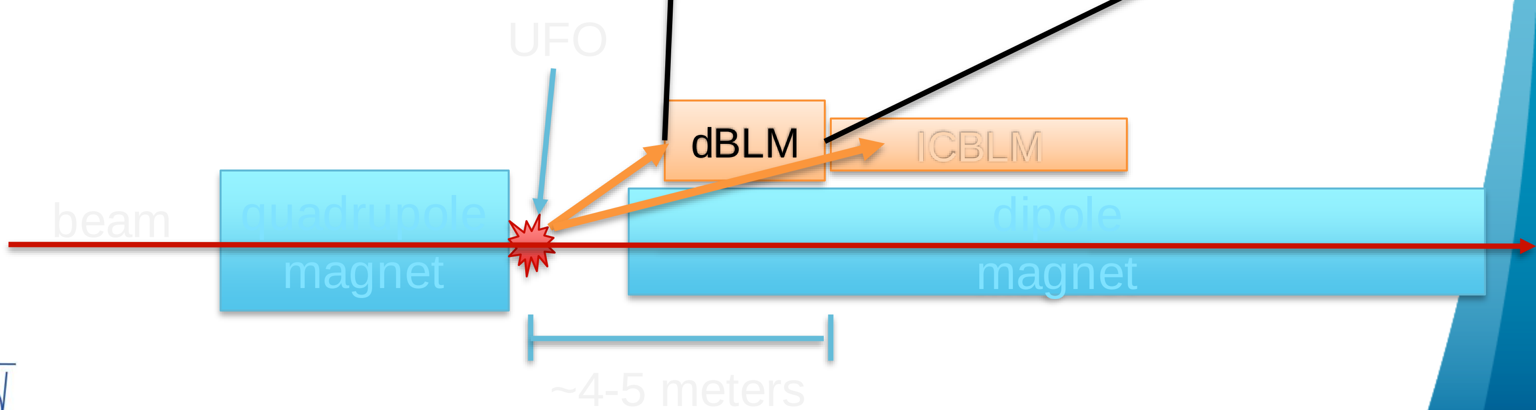
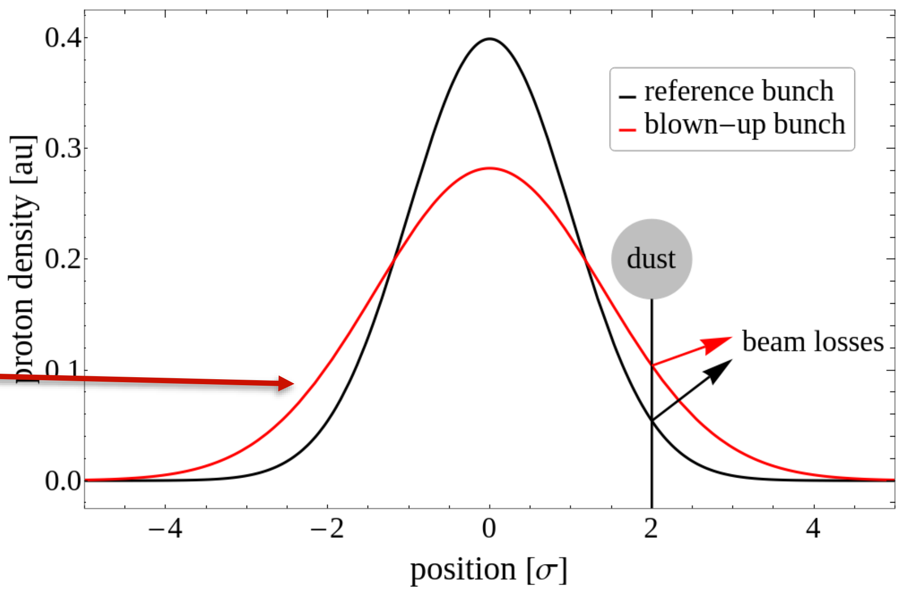
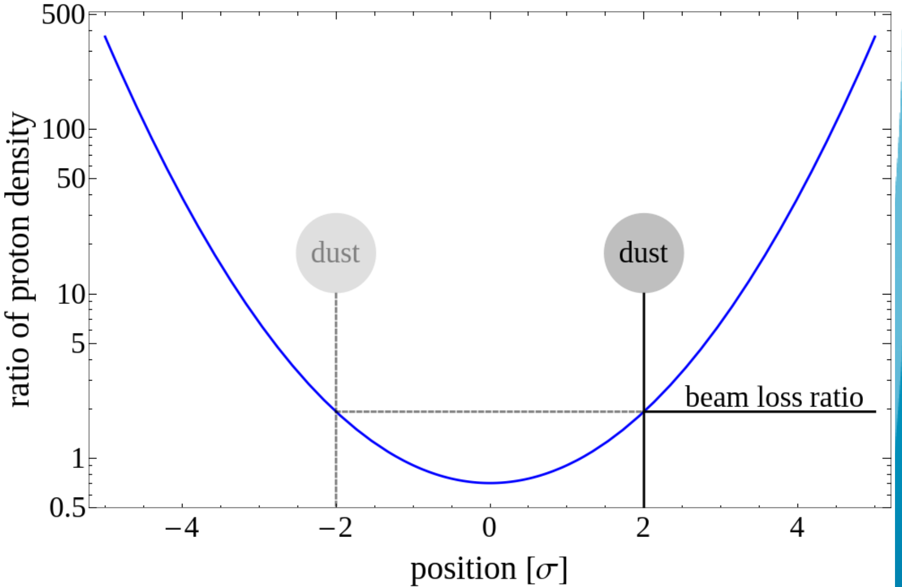


UFO movement measurements

- Bunch profiles gaussian
- Need blown-up bunches with a larger size

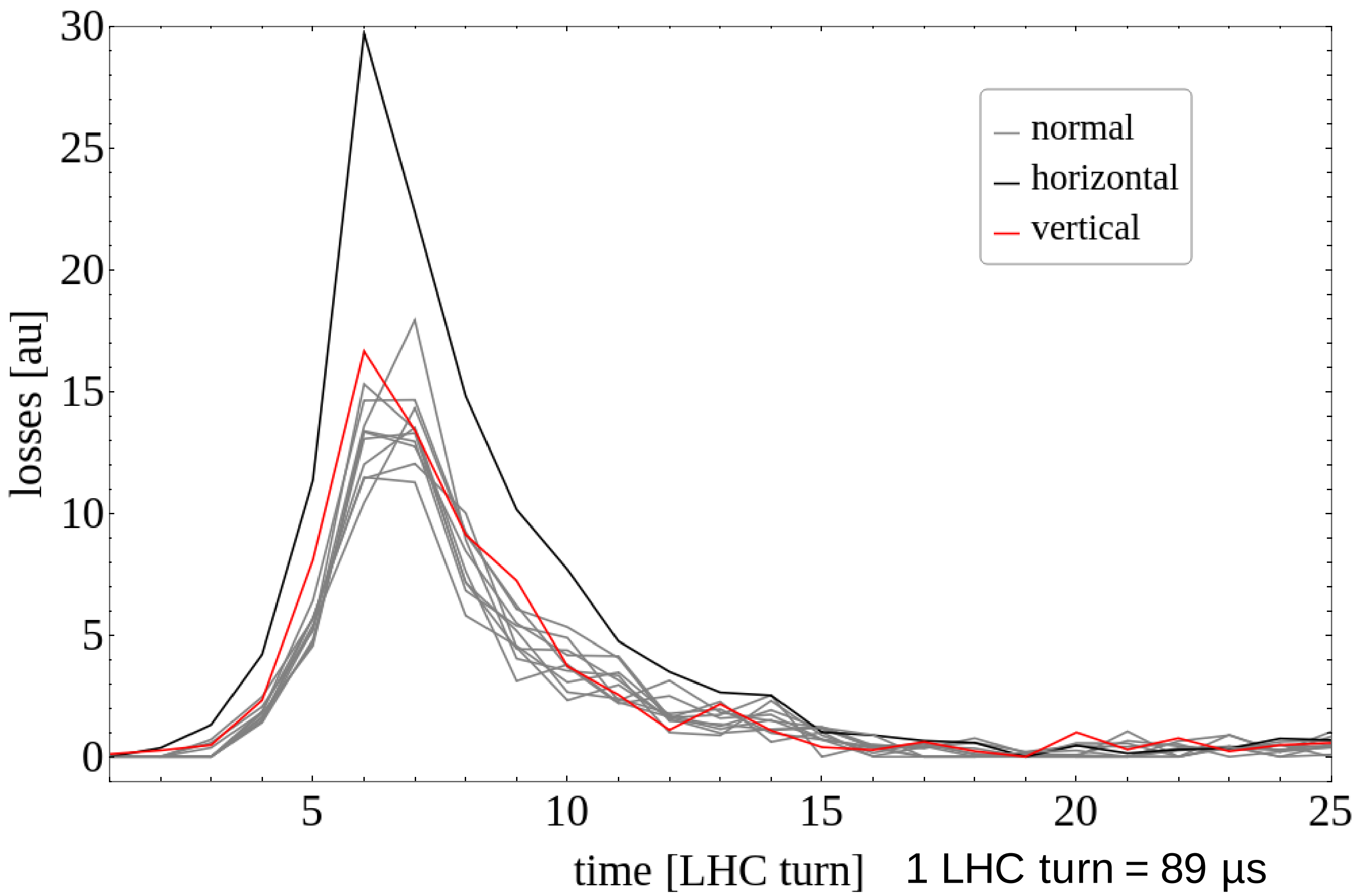


- Losses proportional to particle density
- Ratio of bunch profiles = ratio of losses
- In 2D, hyperbola/ellipses
  - 3 bunches required
  - 4 possible solutions



$$2\ln\left[\frac{m_i}{m_j}\frac{\sigma_{xi}\sigma_{yi}}{\sigma_{xj}\sigma_{yj}}\right] = x^2(s_{xj}^2 - s_{xi}^2) + y^2(s_{yj}^2 - s_{yi}^2)$$

Example: Bunch-by-bunch losses

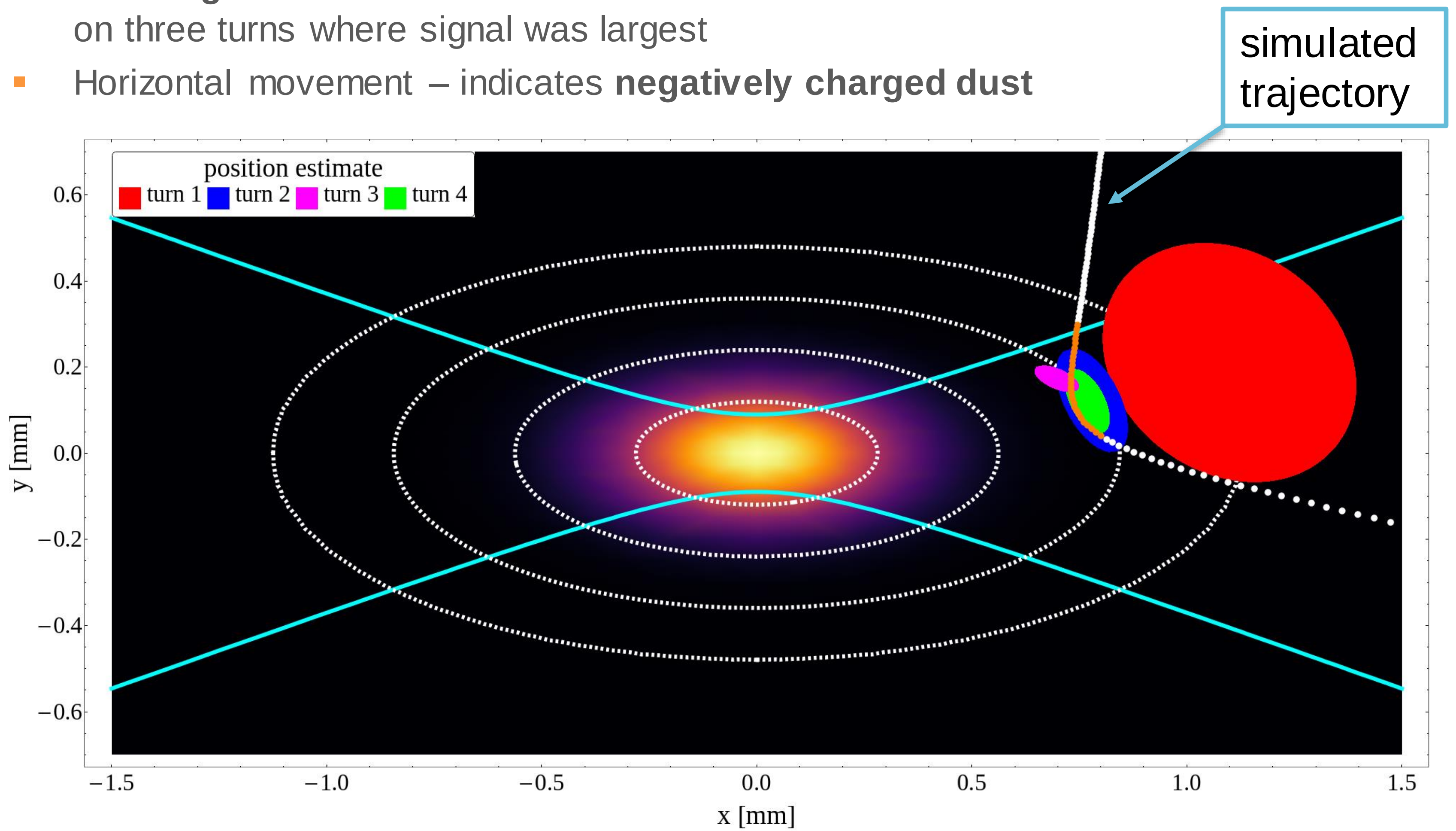


1 LHC turn = 89 µs

Increased losses from horizontally blown-up bunch
Implies that dust particle was offset horizontally

Bunch distribution with measured UFO position

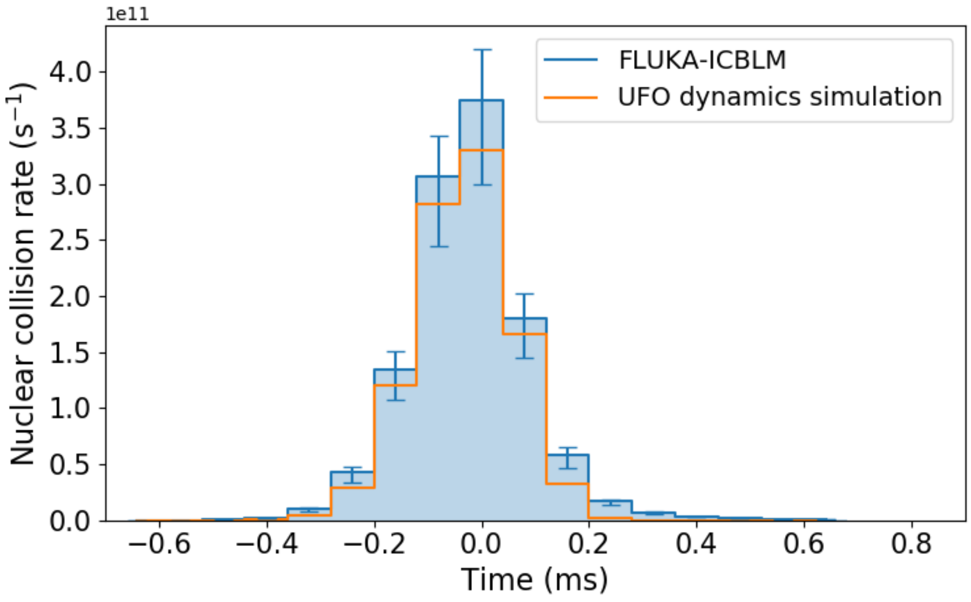
- Estimated **dust position** shown, with uncertainty, by ellipses
- **Good agreement** simulations/measurements
  on three turns where signal was largest
- Horizontal movement – indicates **negatively charged dust**

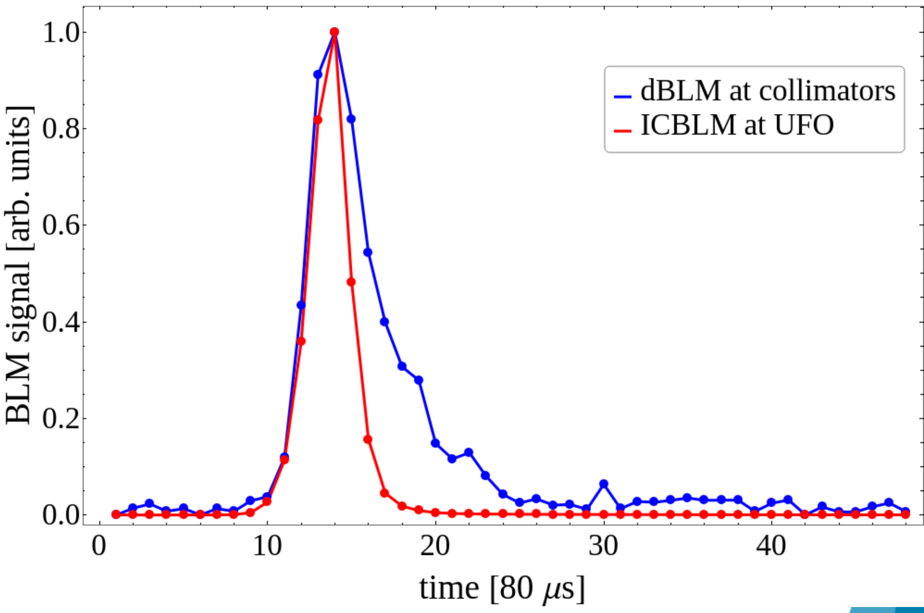


First direct validation of simulation model
Indication of negative charge

Finding UFO Candidate – for above event

- Monte-Carlo simulations with varying **parameters**:
  - Material, size, charge, initial position on beam screen and position in arc cell (beta function/dispersion)
- **Comparison** of simulations to local ICBLM measurements
  → identify the **best fitting candidate**



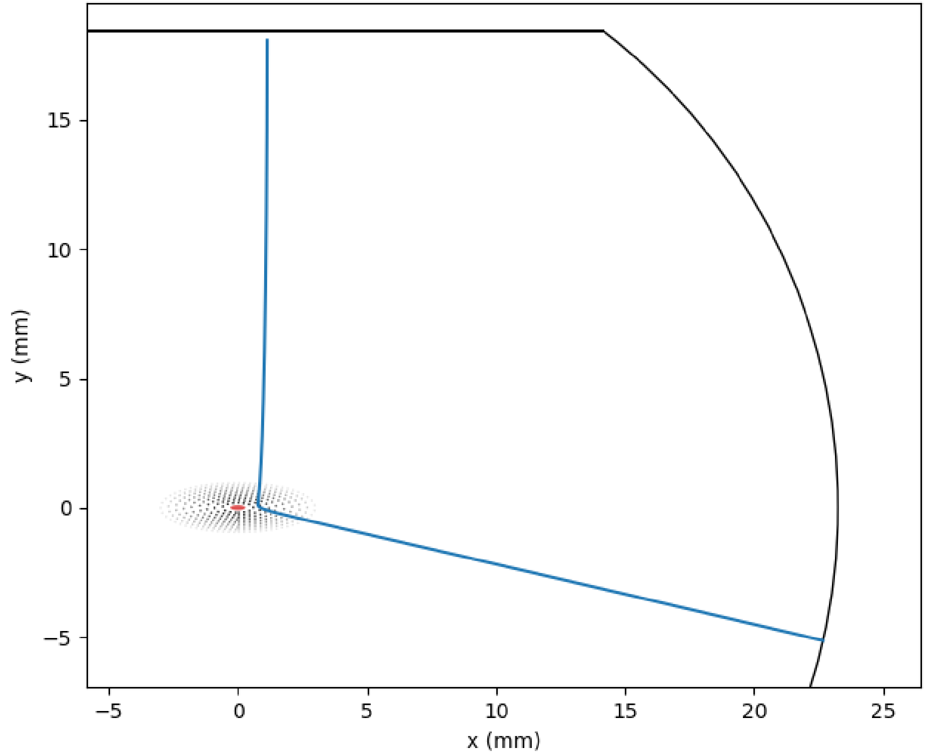


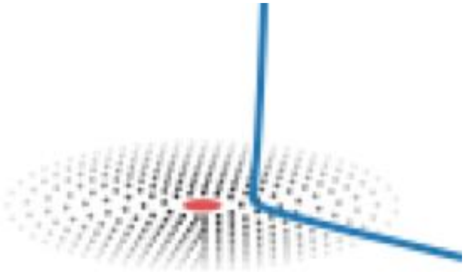
Event on Sep 30, 22:47, (Q15L1), B2, 6.5 TeV

Best agreement event

- Material: Cu
- Radius: 33 um
- **Initial Charge**: -2×10^7 e
- **Initial position** on beam screen: 1.1 mm off-center
- Estimated position in the arc cell (106.9 m total length): s ~ 57.9 m
- Consistent with FLUKA simulations (A. Lechner): C or Cu UFO, s ~ 59.5 m

Simulated trajectory



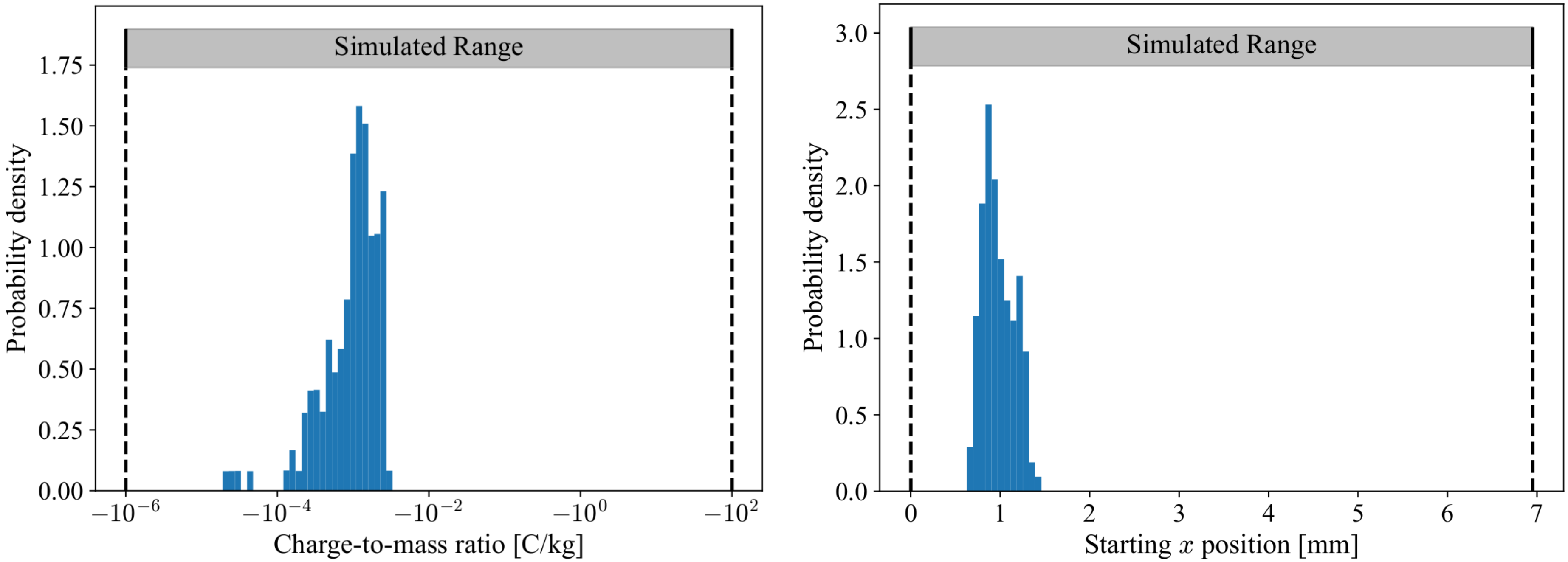


Event on 2018, Sep 30, 22:47, (Q15L1), B2, 6.5 TeV

"Best matches" between simulations and the event presented on previous slides

Simulations convergence

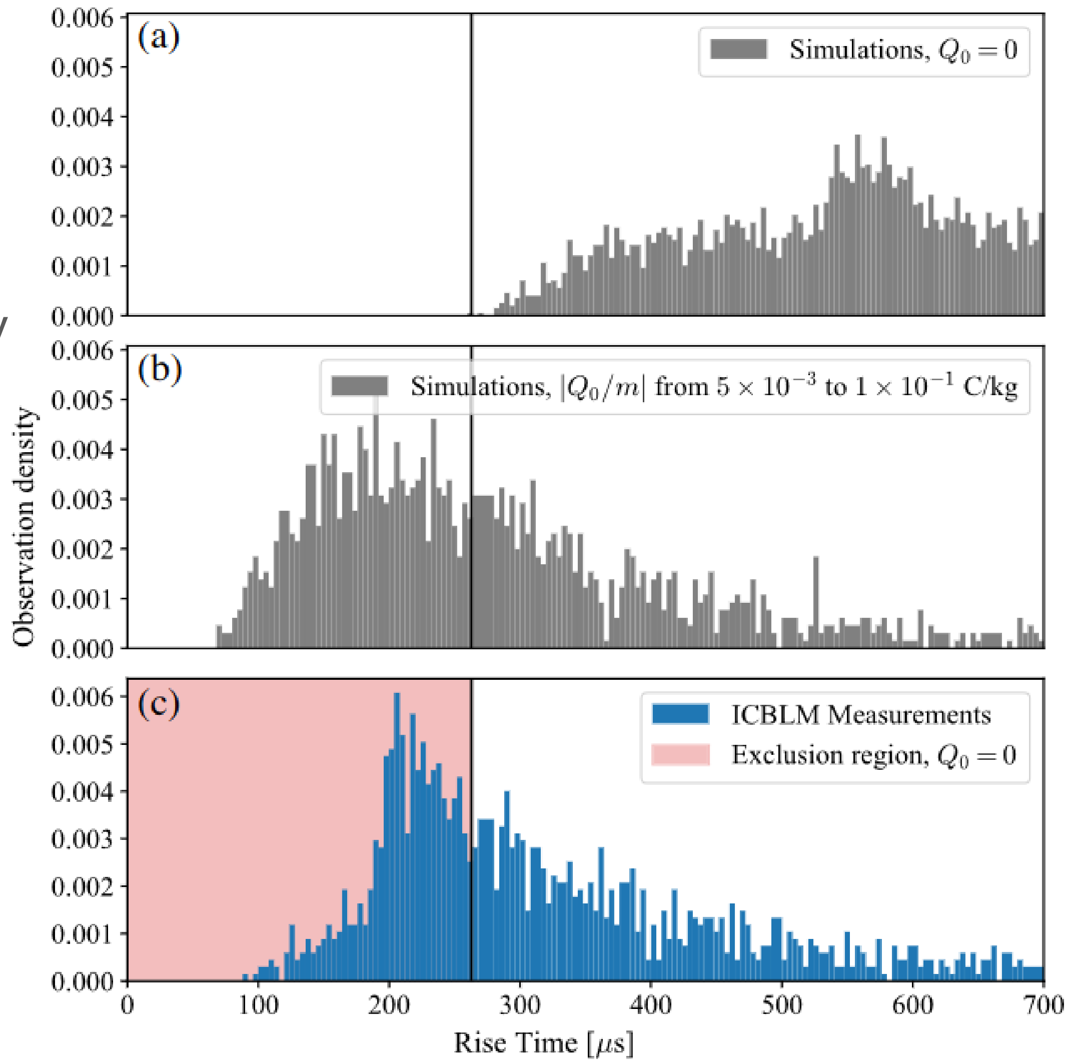
- Different UFO candidates could explain the measurements (ICBLM, dBLM)
  - **7 input** parameters → **1 output** signal
  - Different scenarios can lead to the same simulated output (ICBLM, dBLM)
- Nevertheless, the **important physical quantities** (in order to understand UFOs release mechanism) **converge** quite well



"Best matches" between simulations and the event presented on previous slides

Extending the simulations to all events

- BLM rise time for simulations with/without charge and ICBLM measurements (n=2964)
- Rise times are too fast in measurements to be explained by neutral dust
- Measurements can only be explained if **negative pre-charge** is included



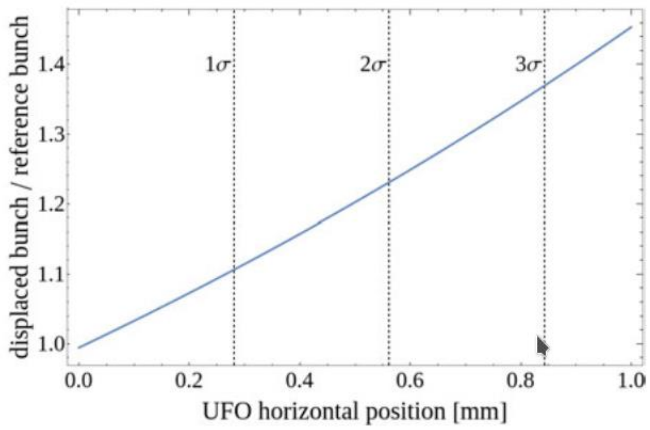
Dust in LHC is Negatively charged
– important for dynamics and release mechanism

Future measurements

- Method using blown-up bunches cannot distinguish the quadrant in x-y plane
- Displacing selected bunches up/down/left/right would remove symmetry
  - Two horizontal bunches displaced by Δx:

    signal ratio: $$\frac{m_i}{m_j} = e^{\frac{s_x^2 \Delta x^2}{2}} e^{s_x^2 \Delta x x_i}$$

- 30 µm displacement possible in LHC at 6.5 TeV using the transverse damper
  - →expected 37 % more signal from displaced bunch, when UFO at 3σ
  - PACMAN* bunches have orbit offsets up to similar values
  - Downside: Orbit offset will vary with phase advance



*bunches with different beam-beam encounters around the collision points

Conclusions

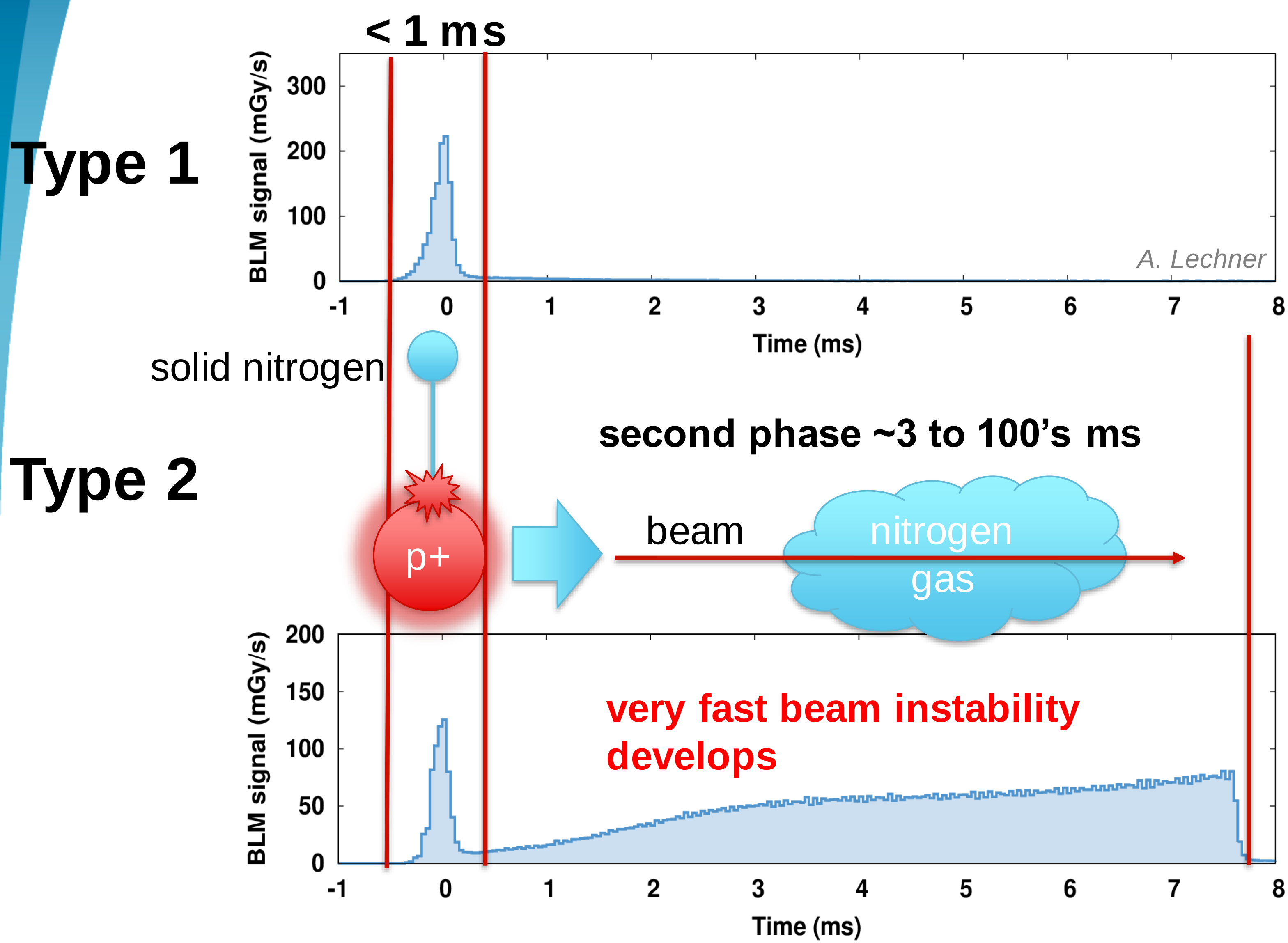
- Simulation model can accurately recreate the behavior:
  - Dynamics of dust particles
  - Charging of dust, due to interaction with beam protons
  - Beam losses
  - Verified by measurements of dust positions during interaction and beam loss signals (shape, length, amplitude)

- Dust particles are mostly negatively charged
  - Based on rise time of beam losses, measurements vs simulations
  - Charging mechanisms are discussed tomorrow (P. Bélanger)

- Release mechanism is yet to be understood
- Origin of dust (up/down) unknown
  - Future measurements could conclude on this

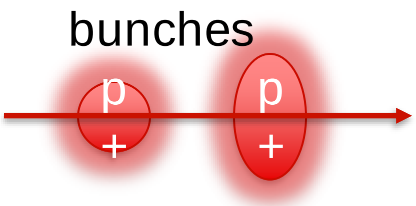
UFOs

UFO types



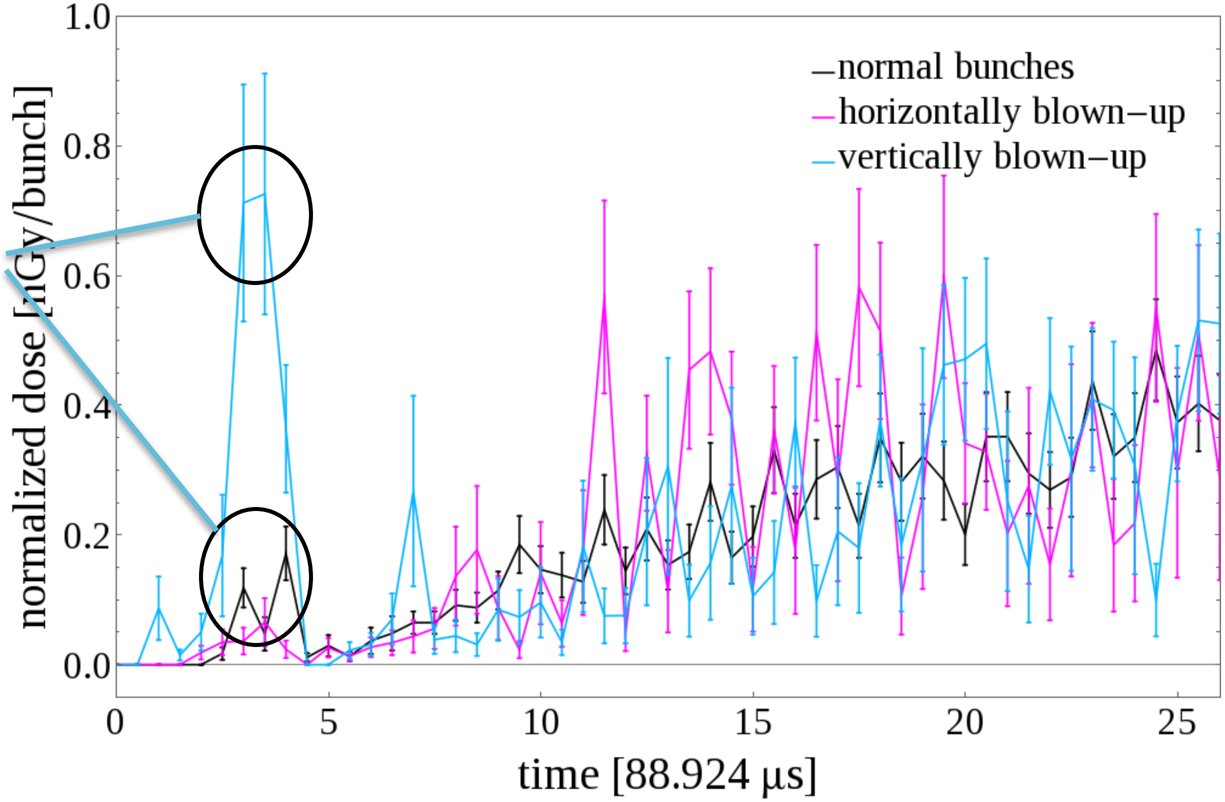
Type 1
Type 2
< 1 ms
BLM signal (mGy/s)
300
200
100
0
-1
0
1
2
3
4
5
6
7
8
Time (ms)
A. Lechner
solid nitrogen
second phase ~3 to 100's ms
p+
beam
nitrogen gas
BLM signal (mGy/s)
200
150
100
50
0
Time (ms)
very fast beam instability develops

UFO type 2 dynamics



- Splitting integration into the three different bunch groups:
  - Vertically blown-up detected ~1.5 turns earlier
  - Significantly more signal from vertically blown-up throughout whole spike

ratio of signals estimates position to 2.9-3.4 sigma

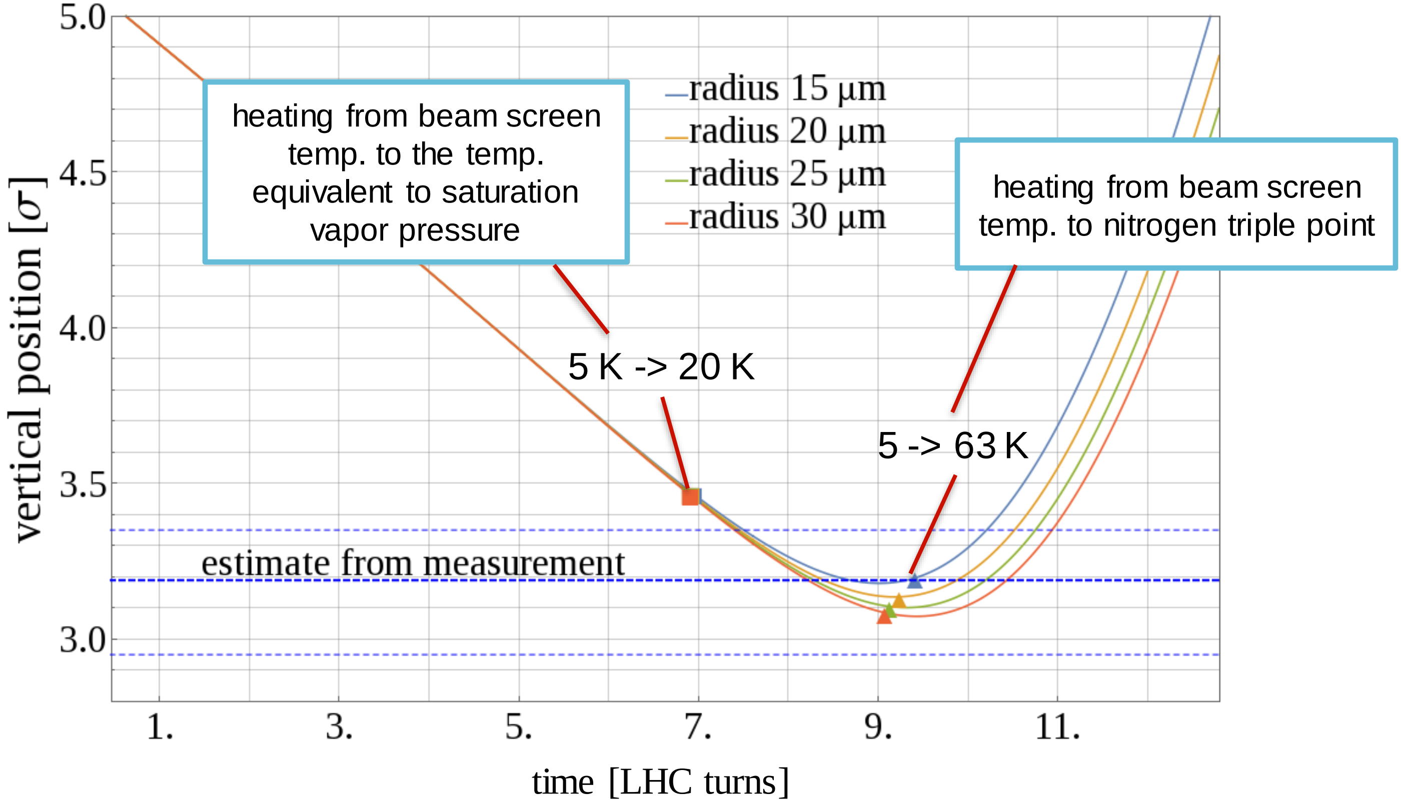


UFO intercepts beam in vertical plane and remains in the halo (2.9-3.4 sigma)

Simulation Results

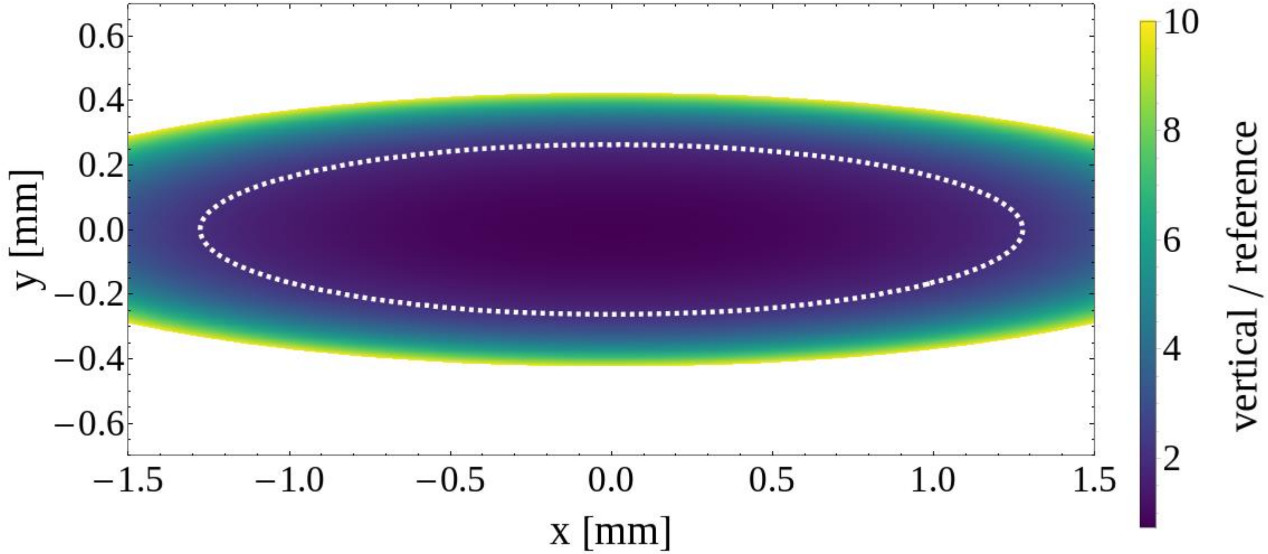
- Nitrogen particles assumed negatively charged (possibly from electron clouds), and **attracted from bottom**
- Phase change suspected, temperature increase simulated

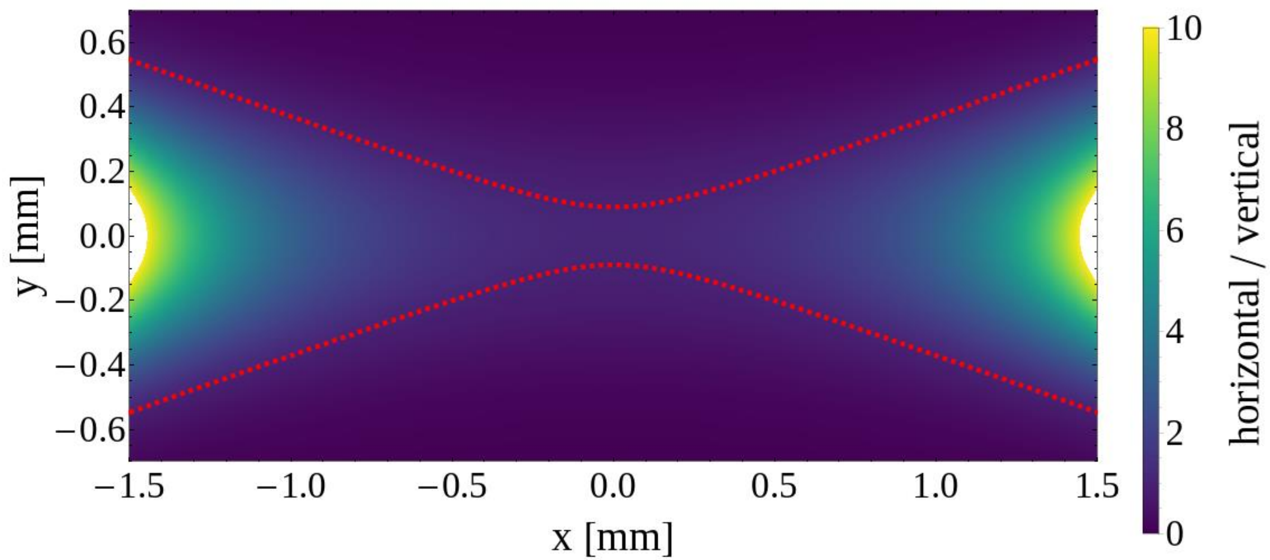
$1\ \sigma = 0.3\ mm$



Good agreement with measurements

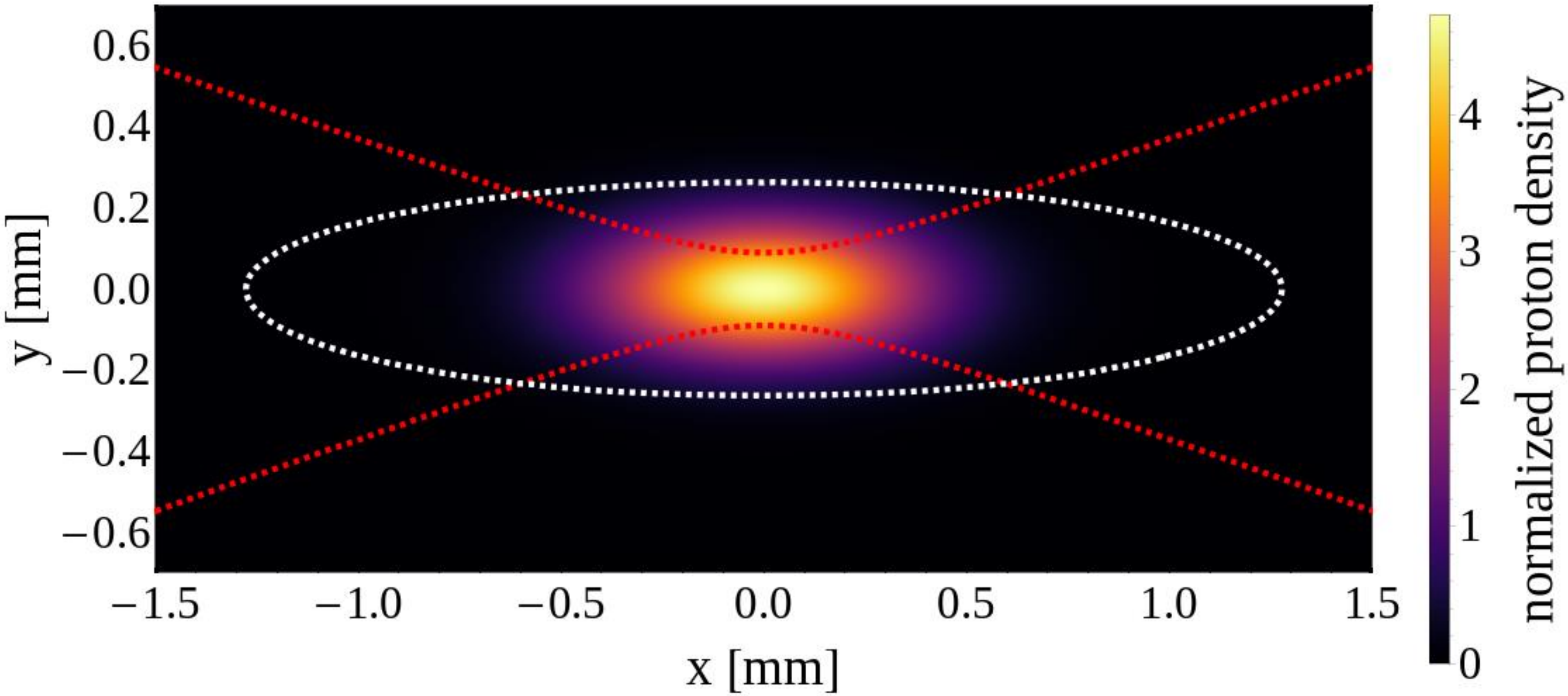
Ratio of bunches – Example

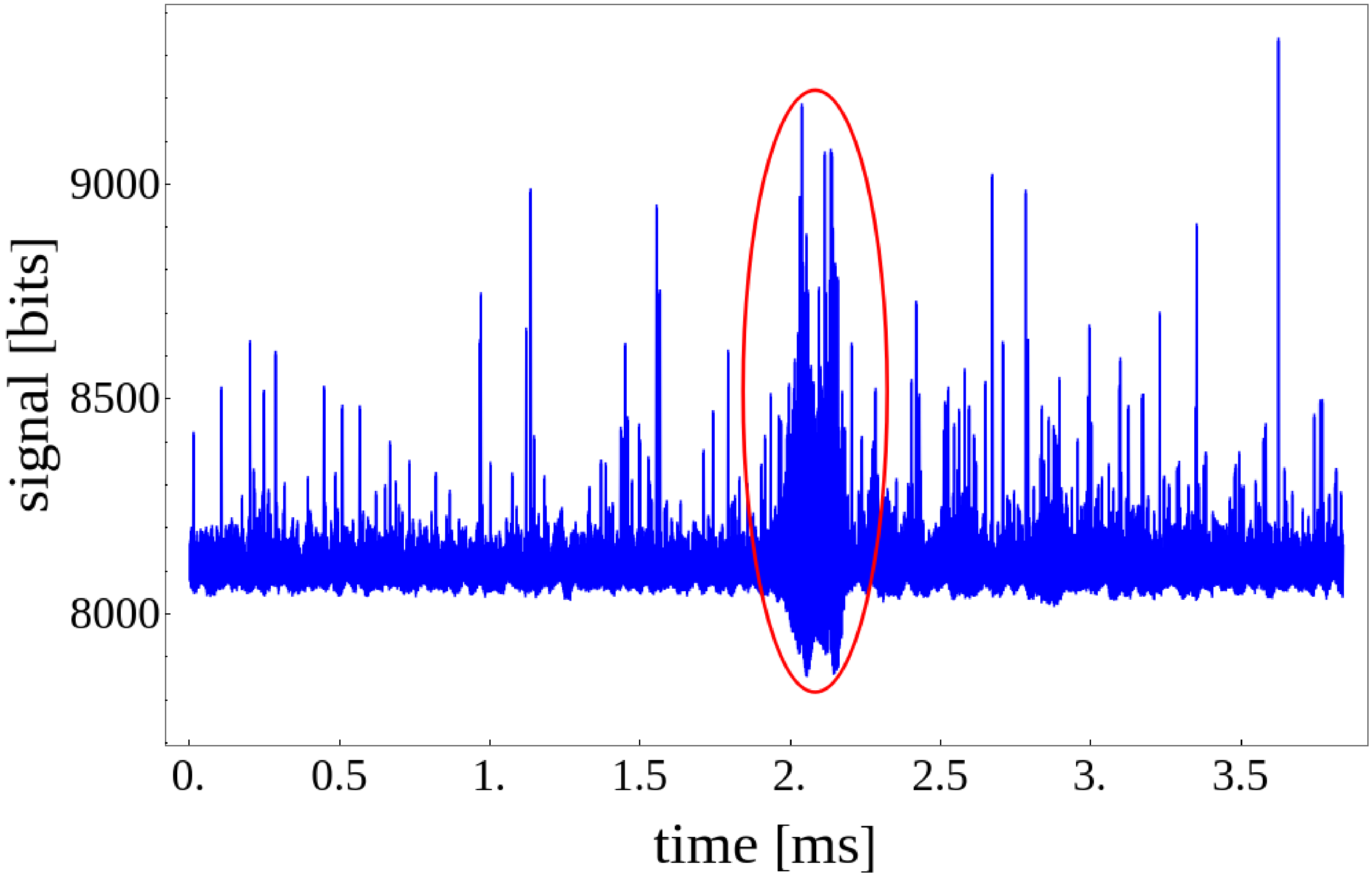


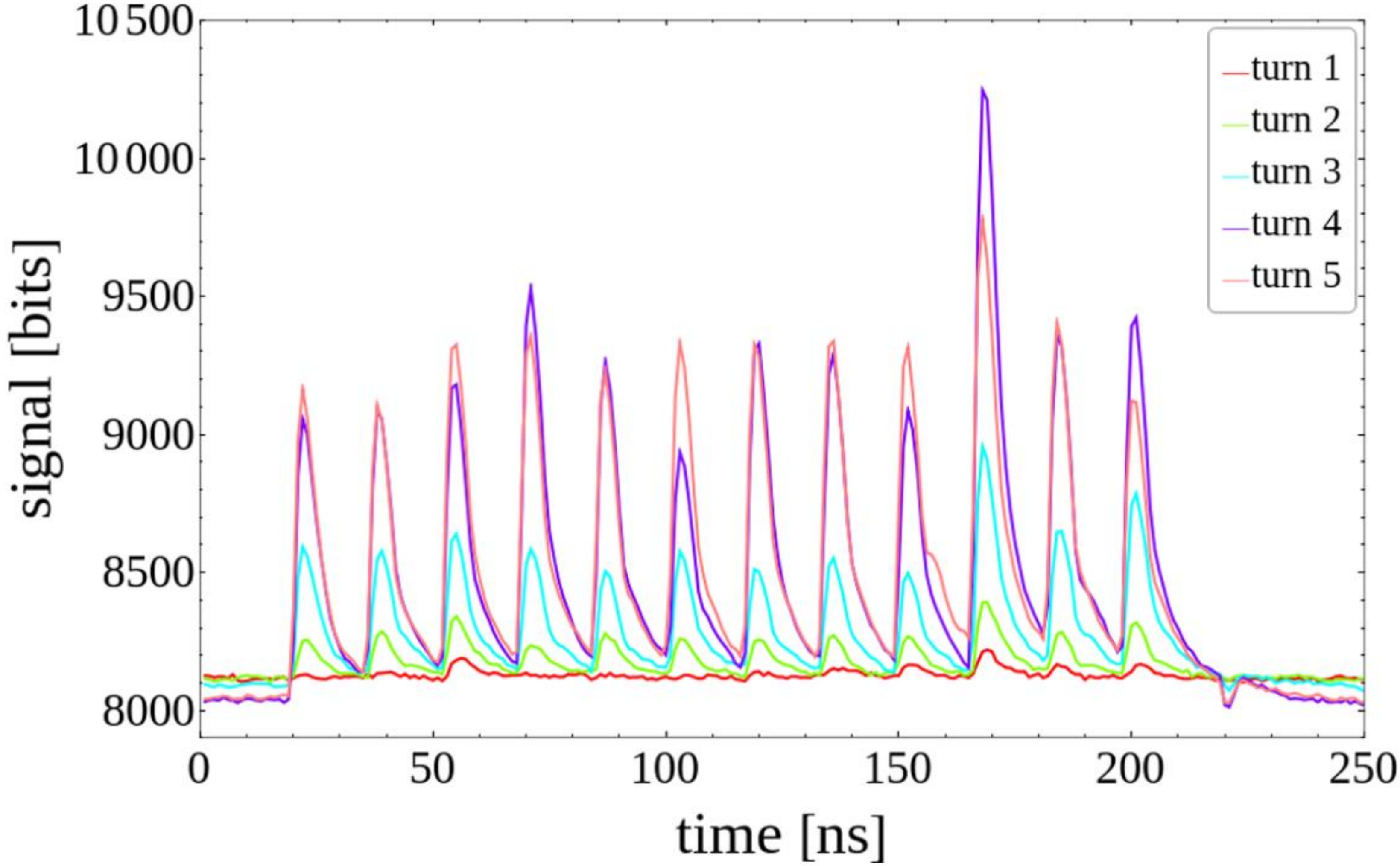


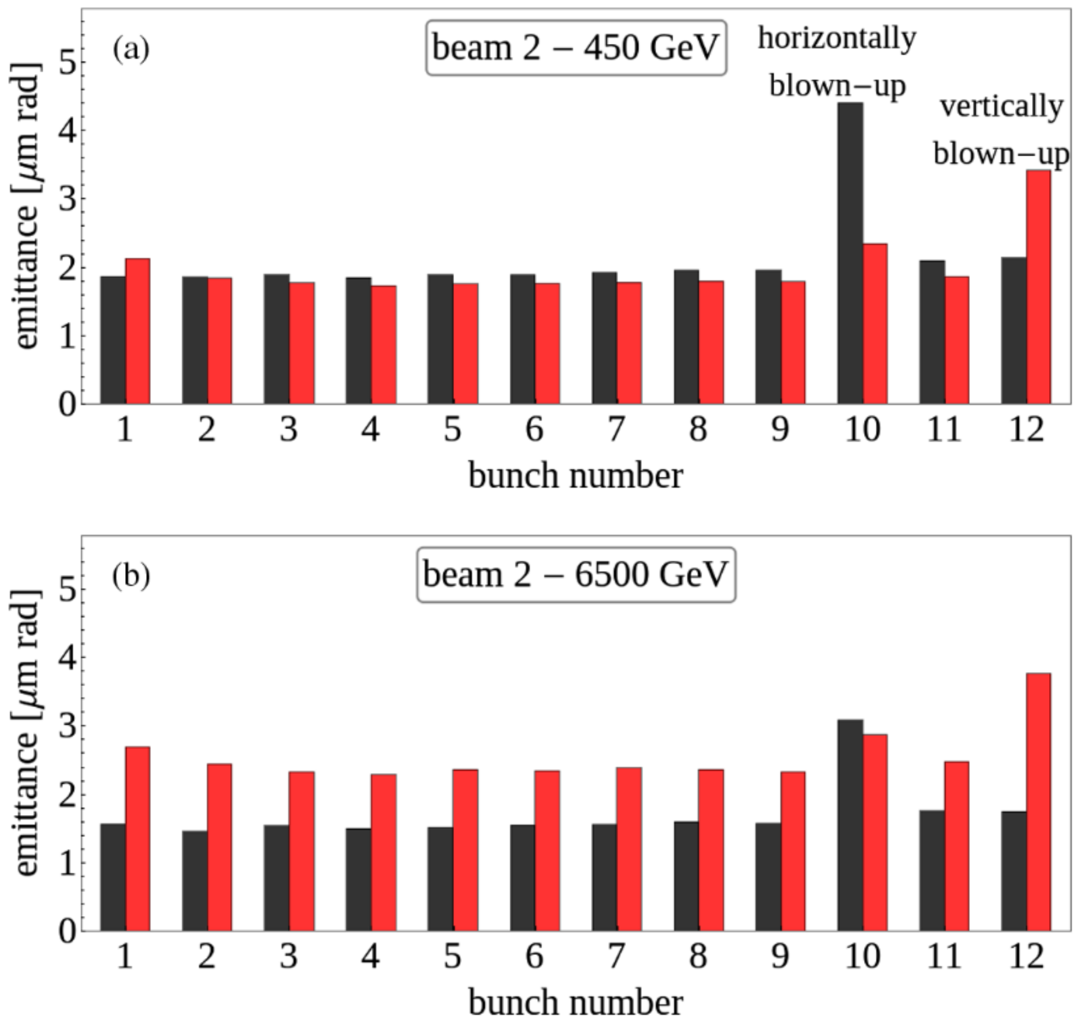
Dust particle position

- Combine contour lines for two sets of bunch ratios
  → Estimate of UFO position at intersection points




9000
8500
8000
signal [bits]
0.
0.5
1.
1.5
2.
2.5
3.
3.5
time [ms]


10 500
10 000
9500
9000
8500
8000
signal [bits]
0
50
100
150
200
250
time [ns]
turn 1
turn 2
turn 3
turn 4
turn 5



(a)
beam 2 – 450 GeV
horizontally blown–up
vertically blown–up
emittance [μm rad]
0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
12
bunch number
(b)
beam 2 – 6500 GeV
emittance [μm rad]
0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
12
bunch number

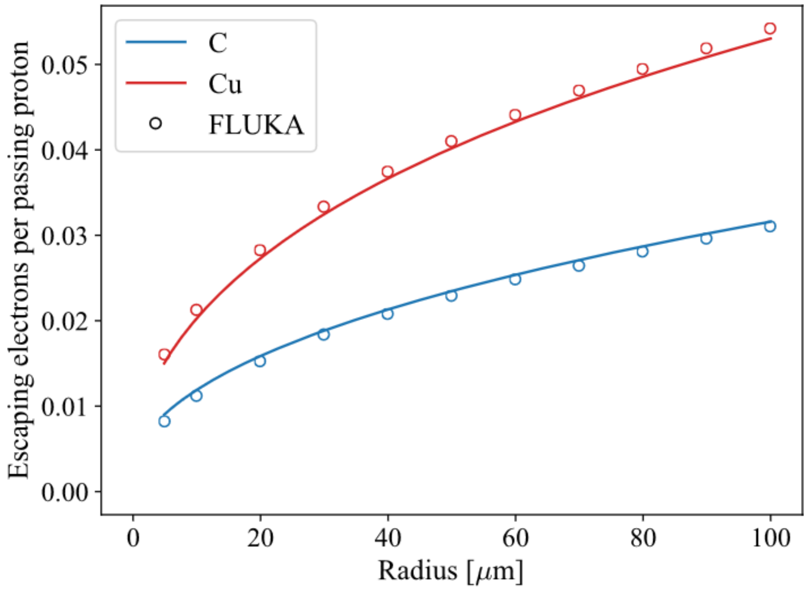


FIG. 4. Average number of escaping electrons per passing proton for a neutral UFO. The updated model (solid lines) is compared to FLUKA (circles).

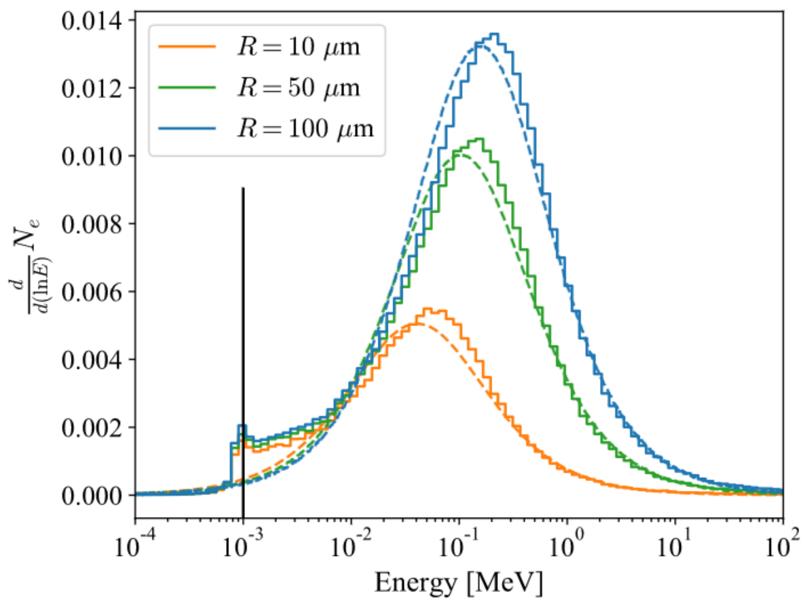


FIG. 5. Energy spectrum of knock-on electrons as they escape the UFO. The updated model (dashed lines) is compared to FLUKA (solid lines) for three dust particle radii. The energy cut for electron transport in FLUKA is shown by the black line, at 1 keV.

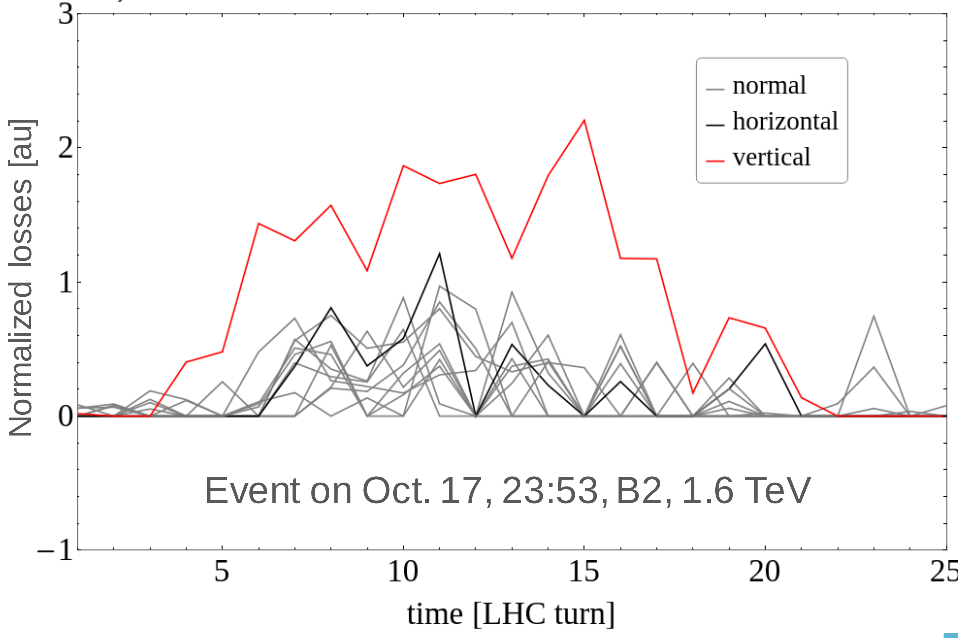
$$m_{ij} \equiv 2\ln\left[\frac{m_i}{m_j}\frac{\sigma_{xi}\sigma_{yi}}{\sigma_{xj}\sigma_{yj}}\right] = x^2(s_{xj}^2 - s_{xi}^2) + y^2(s_{yj}^2 - s_{yi}^2)$$

$$C_X = J C_M J^T$$

$$C_M = 4\hat{\sigma}^2 \begin{pmatrix} \frac{1}{N_1 m_1^2} + \frac{1}{N_2 m_2^2} & 0 & \frac{1}{N_2 m_2^2} \\ 0 & 0 & 0 \\ \frac{1}{N_2 m_2^2} & 0 & \frac{1}{N_2 m_2^2} + \frac{1}{N_3 m_3^2} \end{pmatrix}$$

Challenges of dBLM measurements

- Useful signal for **several turns** in only 4 events
  - 1 has **horizontal** preference / 2 have **vertical** preference
  - 1 was without blown-up bunches
- Useful signal during 2 turns in 3 events, and 1 turn in 5 events
  - Difficult to conclude about the dynamics in very fast events
- Even useful signal suffers from **fluctuations** (halo?)
- Multi-turn losses in IR7 distort the falling edge



- 10 out of 13 events **during ramp**
  - Is there a detection bias or an increased UFO rate?
- During validation period, before blown-up bunches, 8 out of 16 events were at 6.5 TeV and consequently signal to noise ratio much better

To draw conclusions, need to analyse dBLM data, UFO buster recordings and perform simulations