“UFOs” in the LHC

Overview of UFOs during LHC operation - what we know, what we do not know

Anton Lechner, Philippe Belanger, Bjorn Lindstrom, Rudiger Schmidt, Christoph Wiesner, Daniel Wollmann
(past contributions from Bernhard Auchmann, Tobias Baer, Laura Grob and many more)

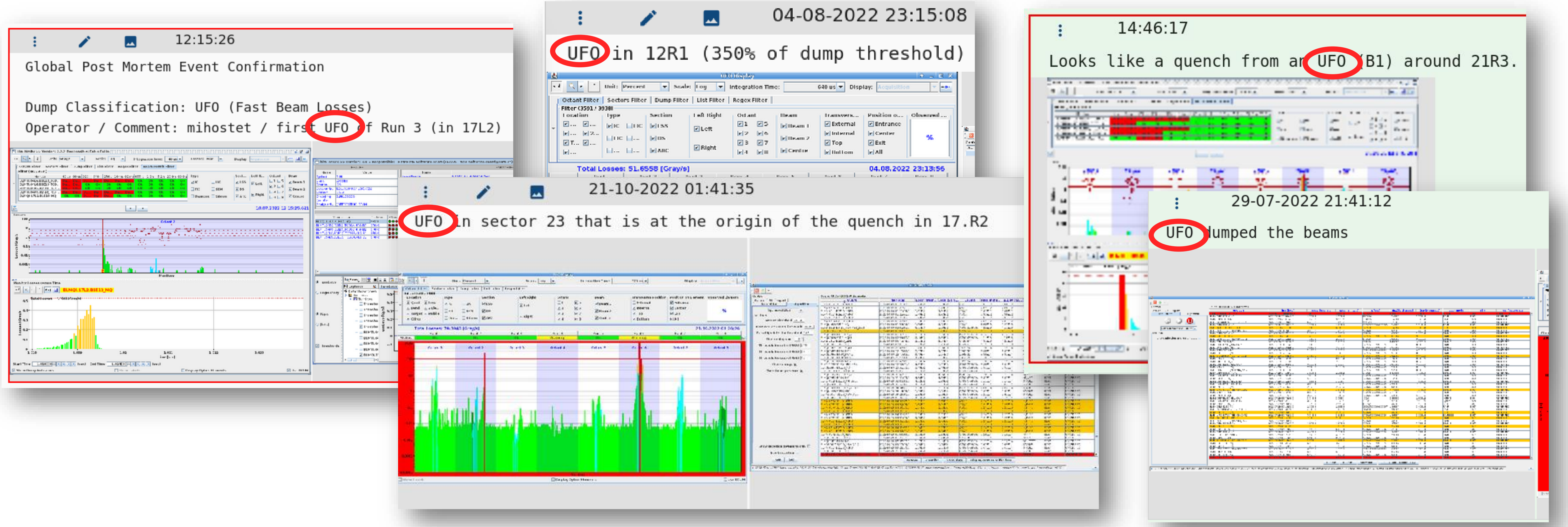
Workshop on Dust Charging and Beam-Dust Interaction in Particle Accelerators

14/06/2023

Snapshots from the LHC logbook

UFO = Unidentified Falling Object
Refers to a transient beam loss event caused by dust (*or another microscopic particulate*) in the LHC

Many UFO sightings …

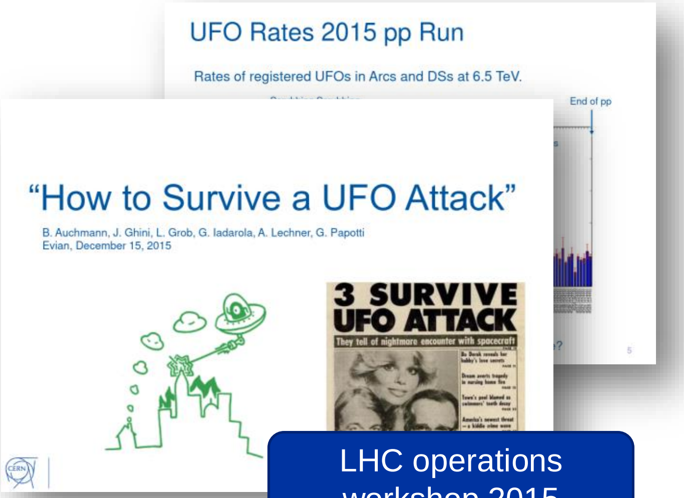


Dust-induced beam loss events

Disclaimer: in this presentation I will mainly focus on dust events in the cold sectors

- Occur all around the LHC – both in **room-temperature** and **cryogenic sections**
- Were present since the start of the LHC
- Came as a surprise – dust was not considered harmful for a proton collider (no dust-trapping in the beam like in electron storage rings)

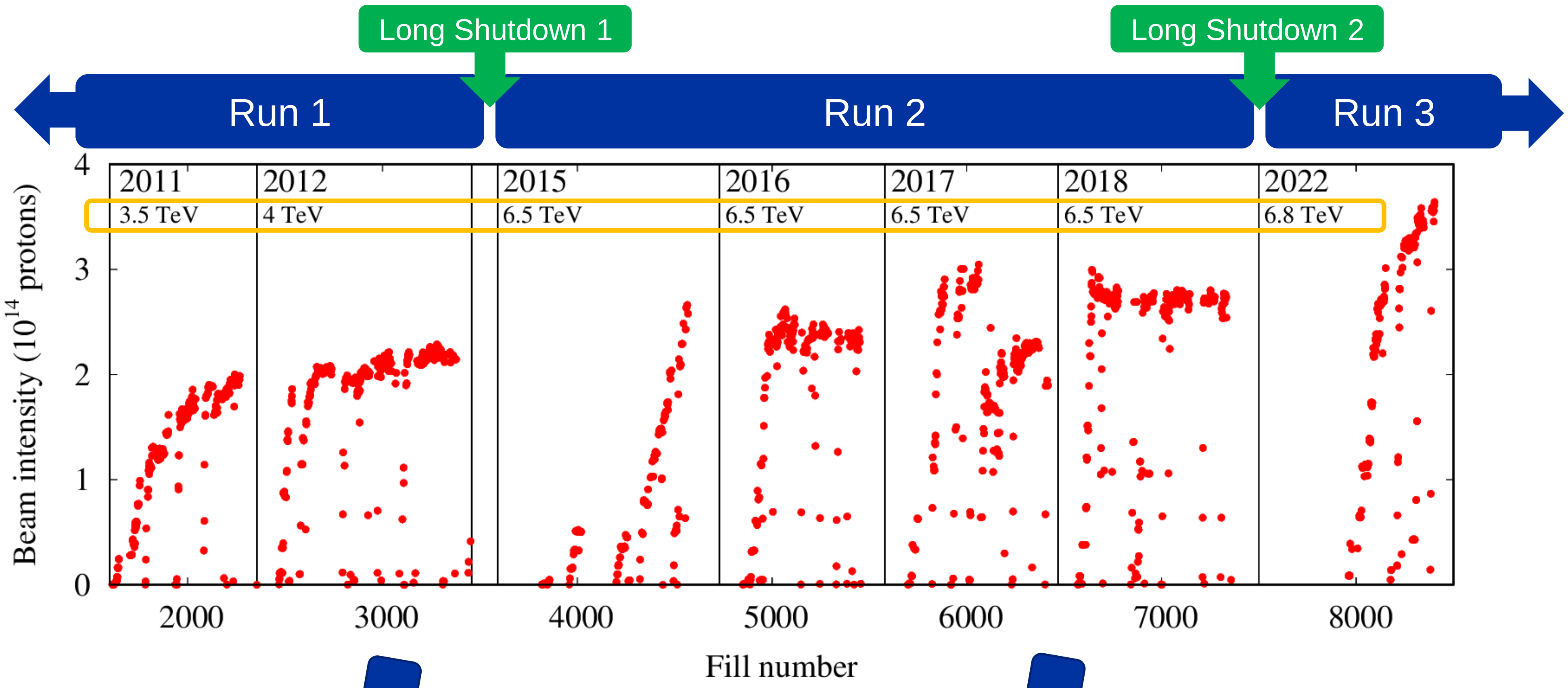
LHC performance workshop 2012



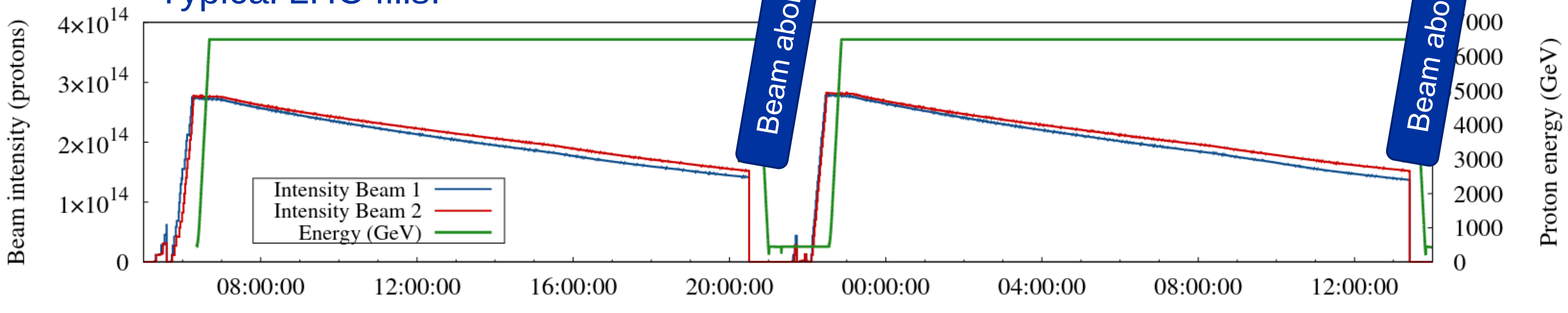
LHC operations workshop 2015

LHC performance workshop 2023

LHC runs



Typical LHC fills:



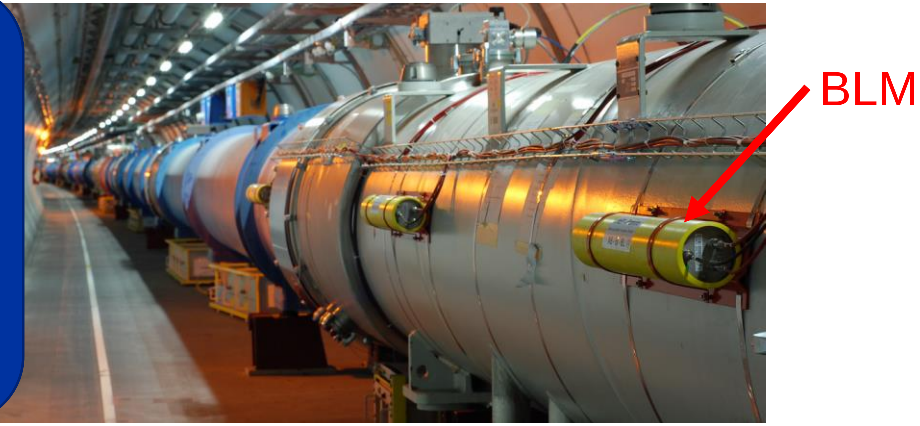
Why do we care about dust-induced beam losses?

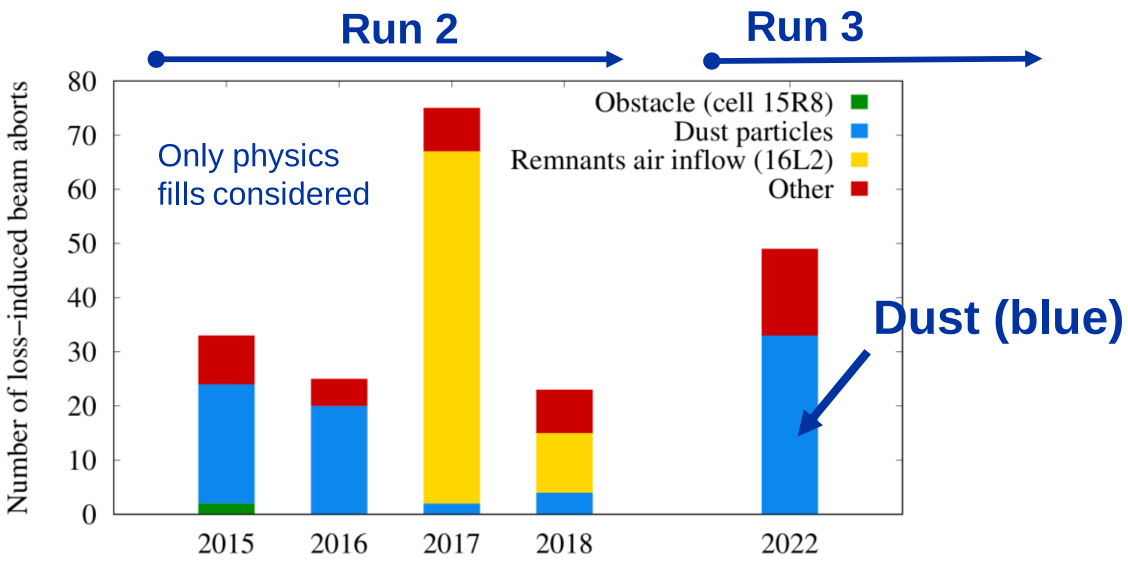
- **Premature beam aborts:**
  - Abort trigger by Beam Loss Monitors (BLMs)
  - Few hours lost (new accelerator cycle)
- **Quenches of superconducting magnets:**
  - Transition to normalconducting state
  - Half a day lost (quench recovery)

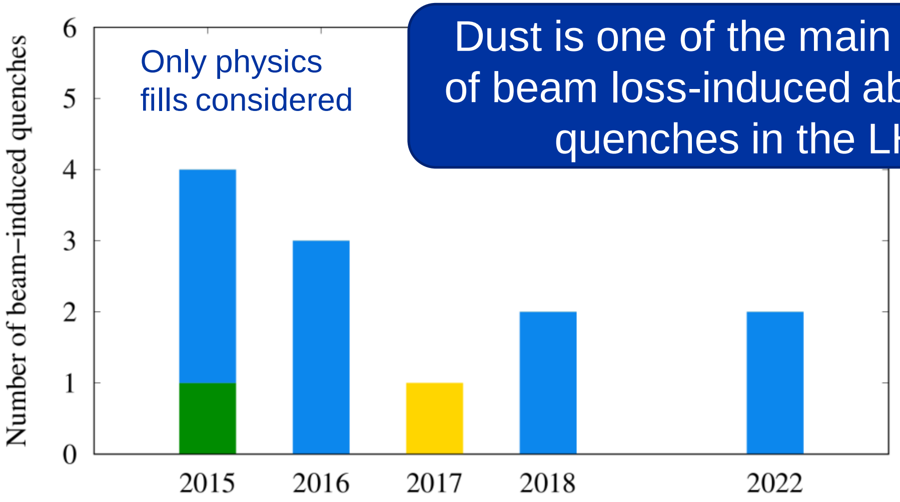
Stored beam intensity (2022): 3.5x10^{14} protons

⇕

Beam loss to quench a dipole: 6x10^{7} protons







Dust is one of the main sources of beam loss-induced aborts and quenches in the LHC

In addition, we record thousands of harmless dust events every year!

Understanding dust events in the LHC

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 124501 (2020)

Dynamics of the interaction of dust particles with the LHC beam

B. Lindstrom,[1,2] P. Bélanger,[1,3] A. Gorzawski,[1,4] J. Kral,[1,5] A. Lechner,[1] B. Salvachua,[1]
R. Schmidt,[1] A. Siemko,[1] M. Vaananen,[1] D. Valuch,[1] C. Wiesner,[1]
D. Wollmann,[1] and C. Zamantzas[1]
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PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 041001 (2022)
Editors' Suggestion

Dust-induced beam losses in the cryogenic arcs of the CERN Large Hadron Collider

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B. Lindstrom,[1,3] R. Schmidt,[1,4] and D. Wollmann[1]
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PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 101001 (2022)

Charging mechanisms and orbital dynamics of charged dust grains in the LHC

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R. Schmidt,[1] and D. Wollmann[1]
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Empirical studies (based on BLM measurements)
Frequency of events, distribution of events in machine, time profiles of events, …

Analysis of dust samples
Extraction of samples from magnets

Simulation studies (Dust dynamics and beam-matter interactions)
Reconstruction of dust trajectories, dust properties, nuclear collision rates, energy deposition, …

Assessment and mitigation of operational impact
Quantifying quench levels, shower simulations, adjustment of BLM abort thresholds, …

Some of the important questions we try to answer

There were some special hot spots (e.g. injection kickers in Run 1), but here I refer to the dust events we see all around the machine

Dust origin:

- Where does the dust come from? Is it old dust from the LHC construction (or the 2008 incident)? Or is it new dust introduced in shutdowns? Can dust migrate in the machine?

Dust properties:

- What are the properties of dust particles interacting with the beam, in particular what is their size distribution? What materials is the dust made of?

Release mechanism (→ frequency of dust events):

- What is the mechanism, which governs the release of dust into the beams? How is it influenced by the environmental conditions (e.g. heat load), shutdown activities (venting, warm-up), running conditions (time with and w/o beam) and beam parameters?

Beam-dust interactions (→ severity of dust events):

- How do dust particles interact with the LHC proton beams? What is the correlation between dust size and beam losses? Can the dust be subject to a phase transition?

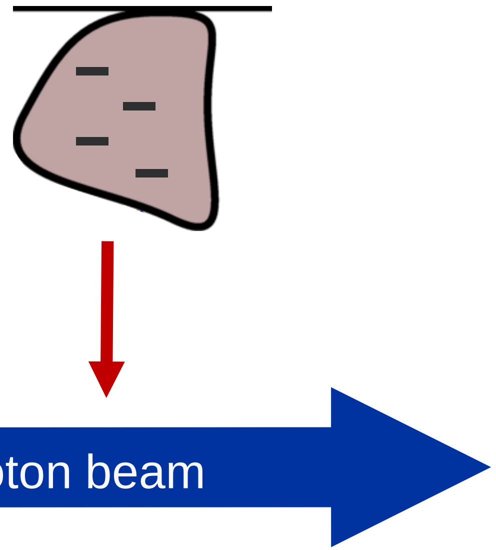
➡ **How can we suppress/mitigate detrimental dust events?**

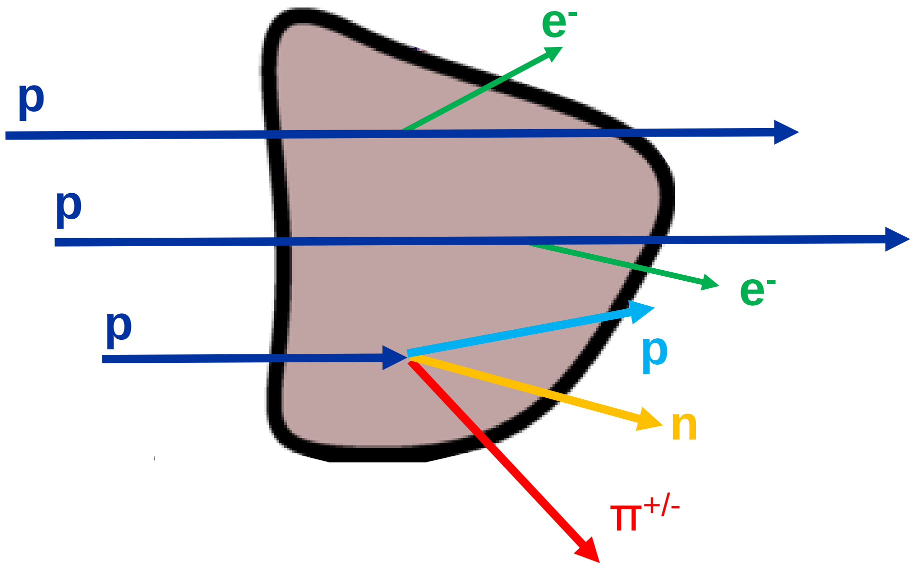
Learned a lot about dust events, **but some of these questions still remain**!

Beam-dust particle interactions in the LHC

1 Attraction by the beam:

Dust grains can acquire a *negative* charge and get attracted by the field of the circulating proton beam



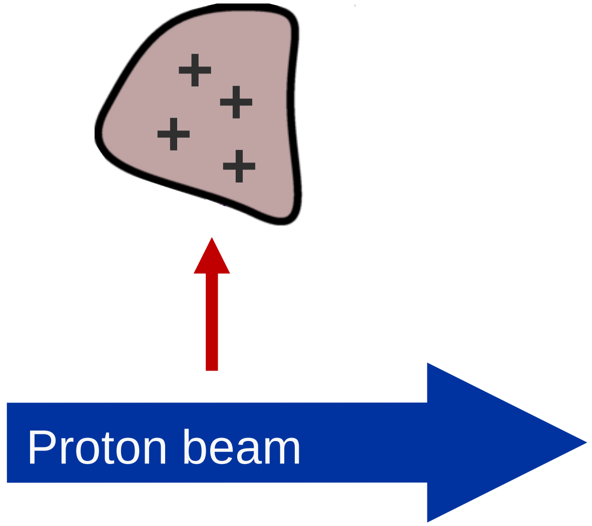


2 Proton-matter interactions:

- **When the dust grain enters the beam, it gets ionized by the traversing protons**
- **A small fraction of the protons has a nuclear collision → *beam losses***

3 Repulsion from the beam:

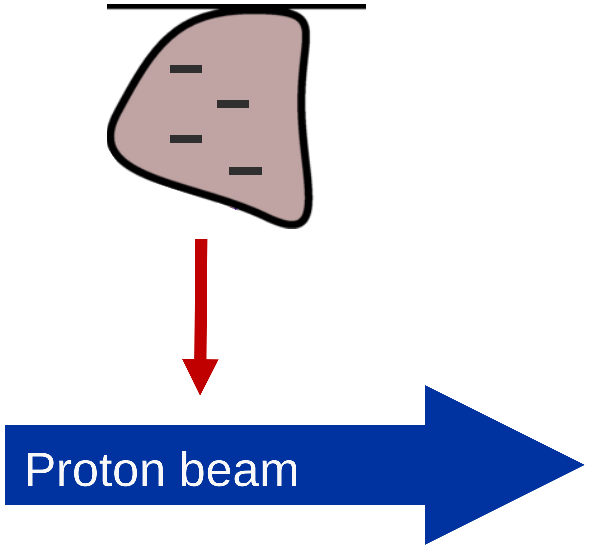
The now *positively* charged dust grain gets repelled from the circulating beam

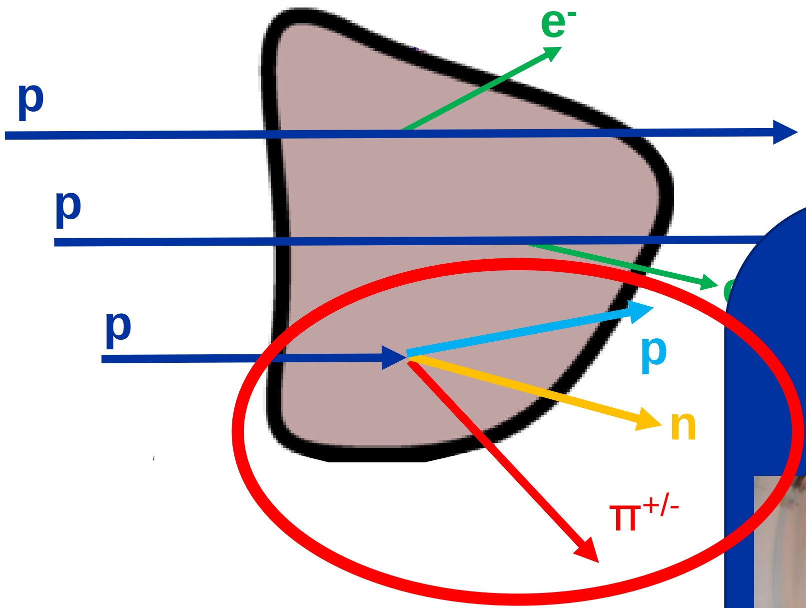


Beam-dust particle interactions in the LHC

1 **Attraction by the beam:**

Dust grains can acquire a *negative* charge and get attracted by the field of the circulating proton beam





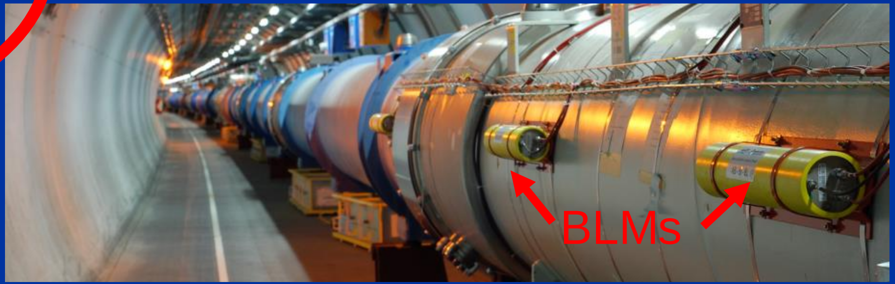
2 **Proton-matter interactions:**

- **When the dust grain enters th gets ionized by the traversing**
- **A small fraction of the proton nuclear collision → *beam loss***

3 **Repulsion from the beam:**

The now *positively* charged dust grain gets repelled from

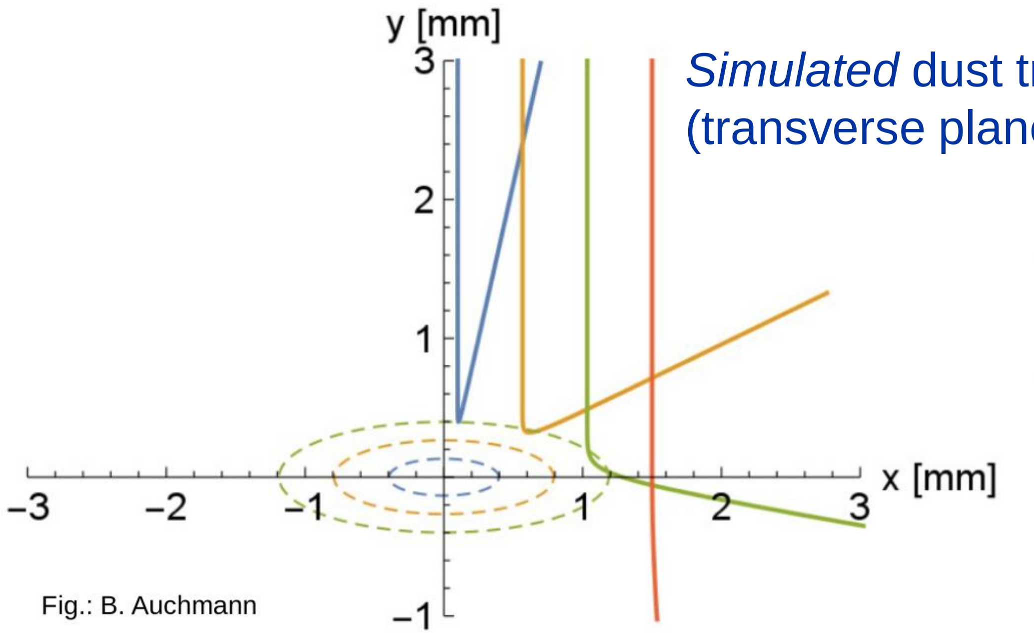
The particle showers induced by nuclear collision products are the only way to detect dust events in the LHC!



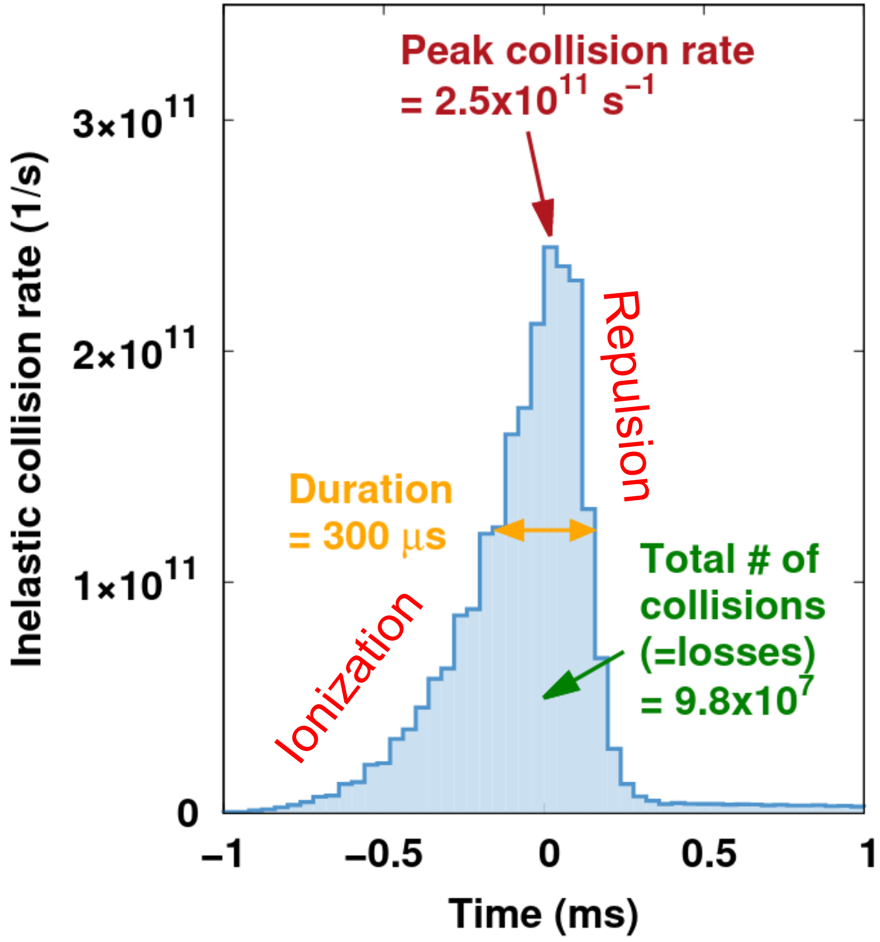
Beam intensity loss is so small that it cannot be measured directly!

Time scale of dust events in the LHC

More in the talk of B. Lindstrom

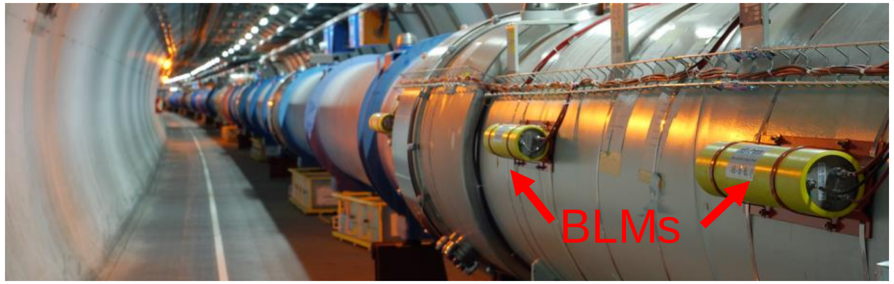


Measured time profile:



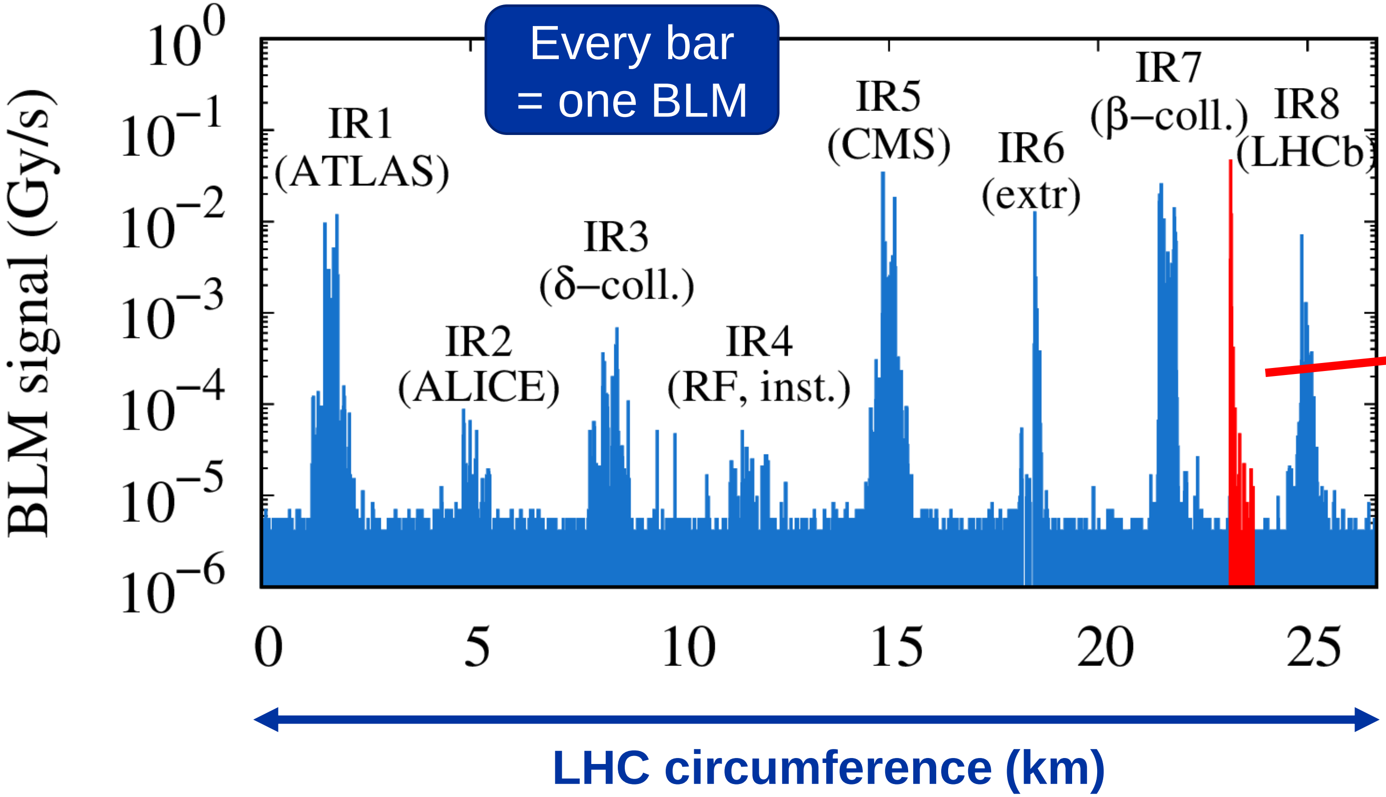
- **Dust particles don't reach the beam center**
- **The events have a typical duration of a few hundred μs (i.e. they are expelled in less than 10 turns of the beams)**

Example of a dust event in the LHC ring

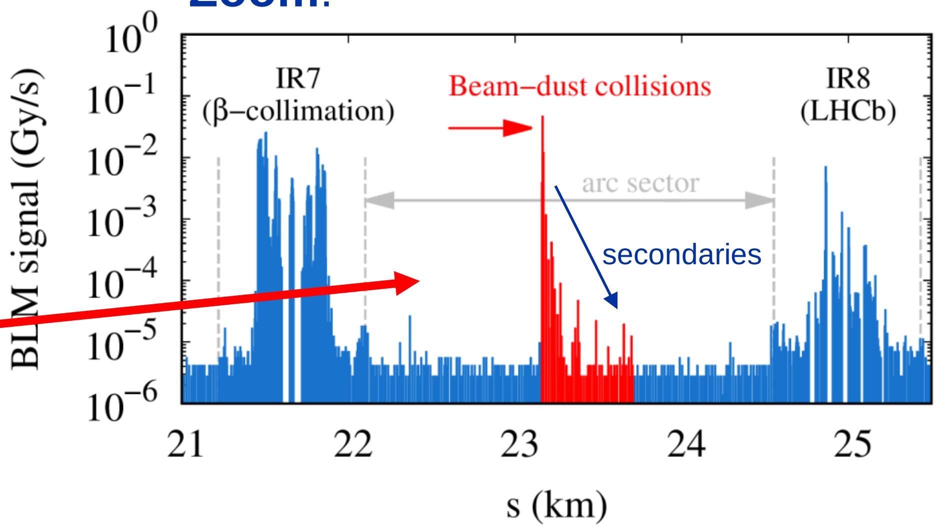


Blue signals = regular beam losses (proton-proton collisions, collimation, …)

Red signals = dust event

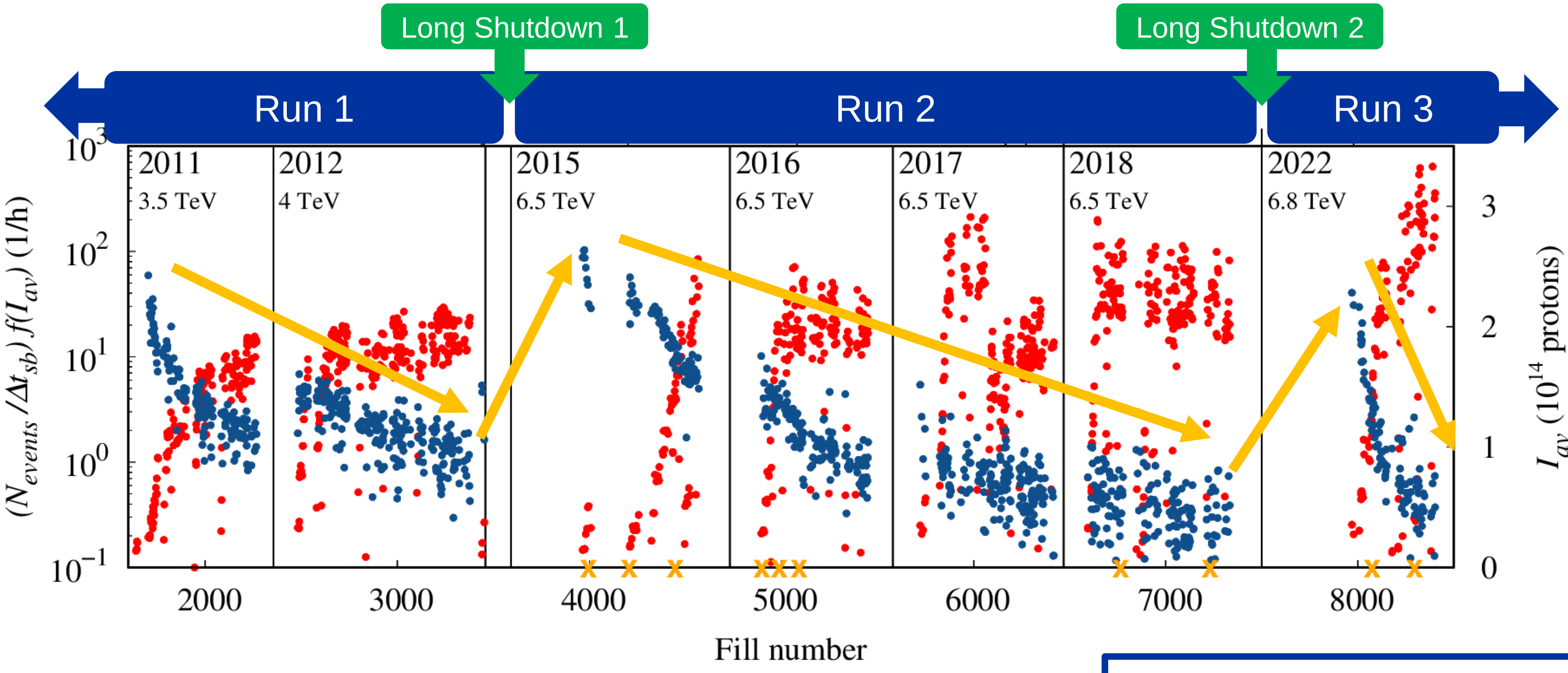


Zoom:



Only have reliable, long-term dust event statistics **for the cryogenic arc sectors** (other regions: dust events are often in the shadow of other losses)

Evolution of the dust event rate in the cold arcs



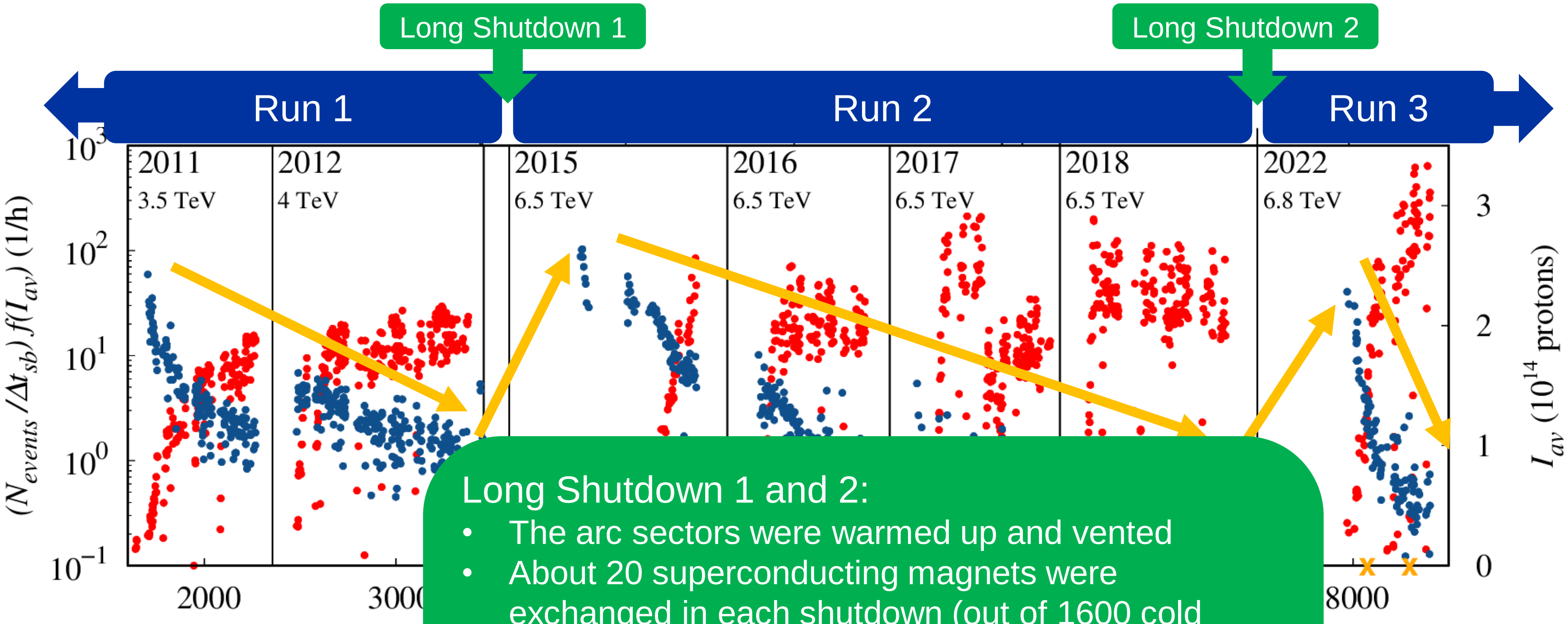
Blue dots = Average dust event rate per proton fill (stable beams)

Red dots = Average beam intensity in fills

Most of these events are harmless (no quench, no dump)
→ events statistics still a measure of dump/quench probability

The dust event rate is mainly driven by the long-term operational schedule:
- Deconditioning in long shutdowns
- Conditioning in multi-year runs

Evolution of the dust event rate in the cold arcs



Blue dots =
Dust event rate in proton operation (stable beams)

Red dots =
Average beam intensity in fills

Most of these events are l
→ events statistics still a r

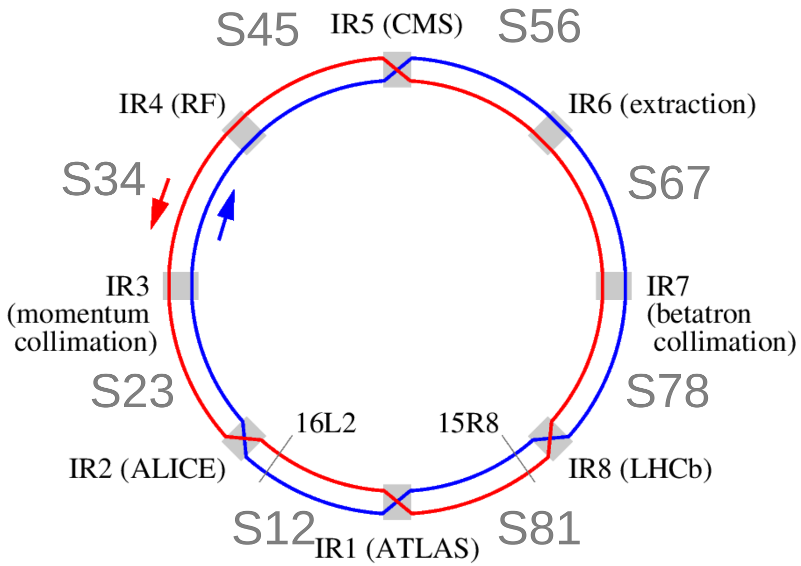
ent rate is mainly driven by the
perational schedule:
oning in long shutdowns
ing in multi-year runs

Long Shutdown 1 and 2:

- The arc sectors were warmed up and vented
- About 20 superconducting magnets were exchanged in each shutdown (out of 1600 cold dipoles and quadrupoles)
- RF ball pumped through the beam pipes to test for non-conform RF fingers

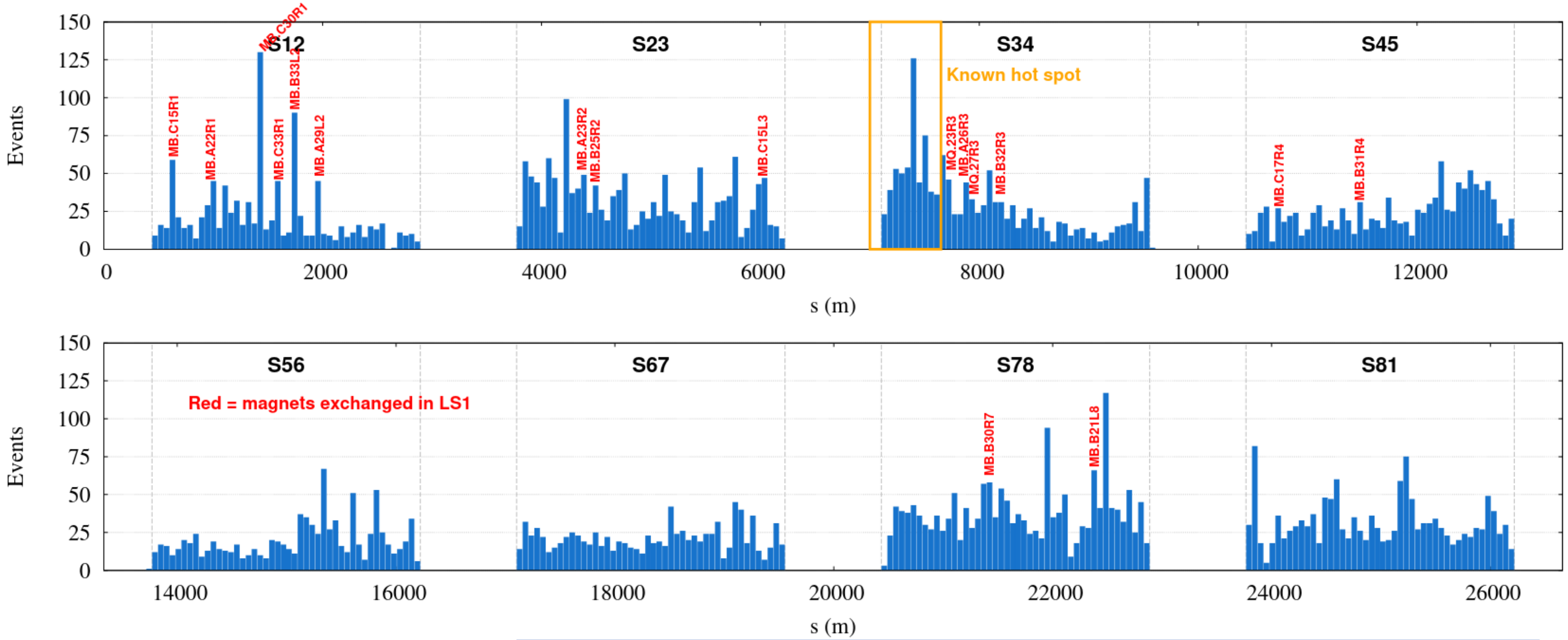
Did new dust contamination cause the increase of the event rate after long shutdowns?

"Old" vs "new" dust in the cold arc sectors (Run 2)



Each arc sector = 2.46 km

Spatial distribution of dust events in the cold arc sectors in the first 1.5 years of Run 2 (after Long Shutdown 1):

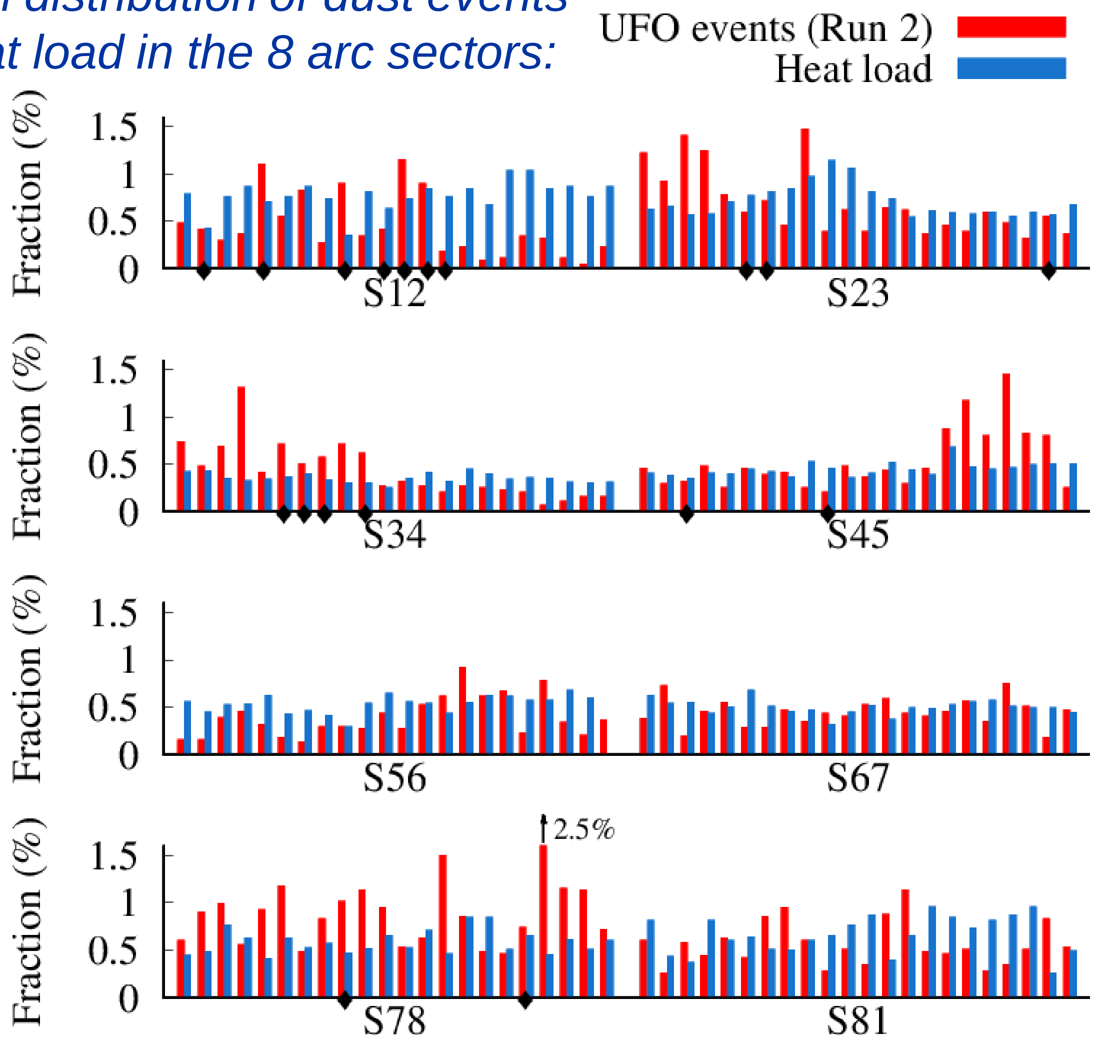


- Local hot spots in (some) cells, where magnets were exchanged
- However, these events represented only 10% of the total number of dust events in the arcs in Run 2

From a global perspective, "new" dust introduced in Long Shutdown 1 probably played a minor role and can likely not explain the increase of the rate at the beginning or Run 2

Event rate vs heat load (e-cloud)

Spatial distribution of dust events vs heat load in the 8 arc sectors:



Heat load due to e-cloud:

- The cryogenic LHC arc sectors suffer from non-negligible heat load to due e-cloud
- The heat load can strongly vary from arc-cell to arc-cell

Dust events vs heat load:

- No clear correlation between dust event multiplicity and heat load can be found
- Similar conclusions were found for the dust event rate (i.e. no dependence on filling scheme)

Heat load data courtesy of G. Iadarola (heat load distribution corresponds to a representative physics fill from Run 2)

Dust event rate vs release mechanism

Other dependencies of the dust event rate:

- Cannot find a strong dependency on the beam intensity (except maybe for low intensity beams)
- There was a visible increase of the event rate when warming up beam screens to 80 K (much higher temperature than caused by e-cloud), but the rate recovered quickly
- Sometimes we observed a sudden increase of the rate when new beam parameters were tested in special fills (tests with different bunch spacing in Run 1, tests with high bunch intensities in Run 3) → usually the rate recovers fast in these cases

The conditioning/deconditioning of the rate in runs/long shutdowns remains the main driving factor!

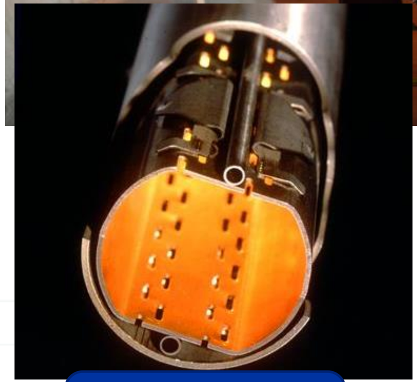
Release mechanism:

- We presently do not have a model, which can predict dust event rates
- A better understanding of the release mechanism *and its dependencies* remains key

What kind of dust is present in the vacuum chamber?

- The LHC was not assembled under clean-room conditions
- In 2017, dust samples were extracted from one of the arc dipoles, which was removed from the machine during the winter stop
- The samples confirmed the presence of dust, with particulate sizes ranging up to O(100 µm)

More in the talks of A. T. Perez Fontenla and C. Garion

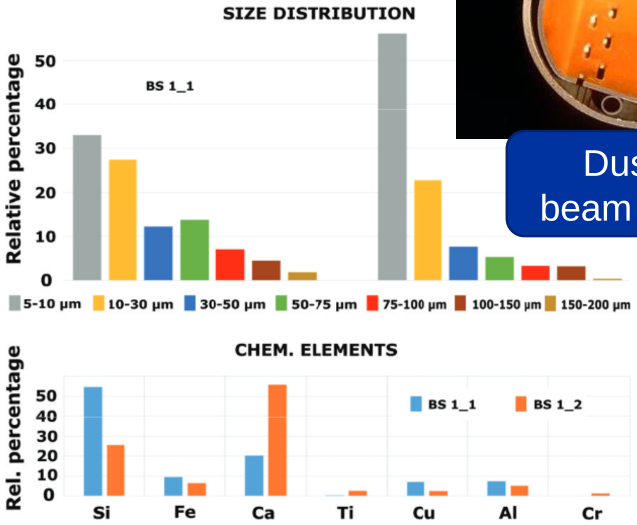


Dust on beam screen

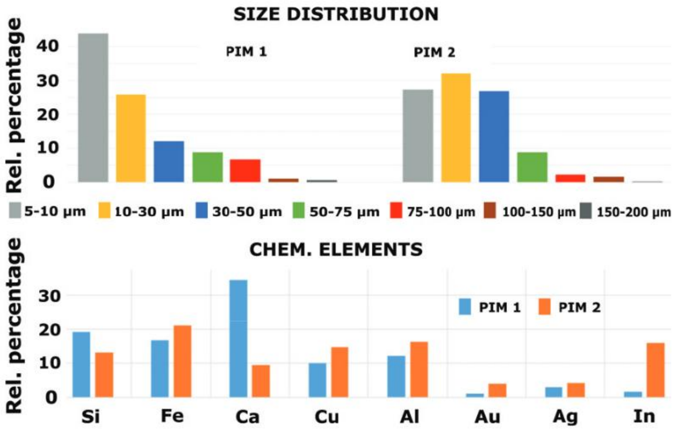
Dust in on plug-in module (magnet interconnects)

Materials from vacuum components (e.g. Fe, Cr, Cu, Ag, In), but likely also from external origin (e.g. Al, Si, Ca) were present

L. Grob et al., IPAC2019



Dust with <5µm not shown



Can we learn more about dust properties from the event characteristics?

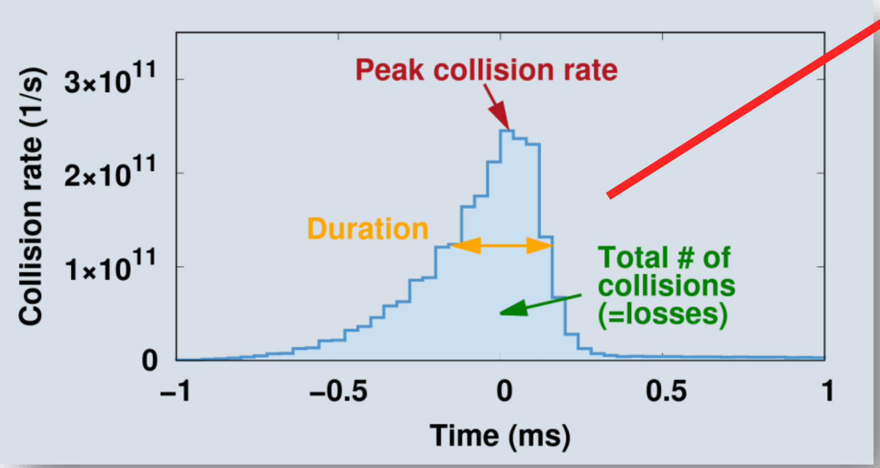


Figure: nuclear collision rate between proton beam and dust particle as a function of time (typical event)

Event characteristics depend on various parameters:

- Dust particle volume/size
- Dust particle material
- Dust particle pre-charge
- Initial dust particle position on the machine aperture

} unknown

- Beam parameters (intensity, emittance)
- Local beam optics

} known

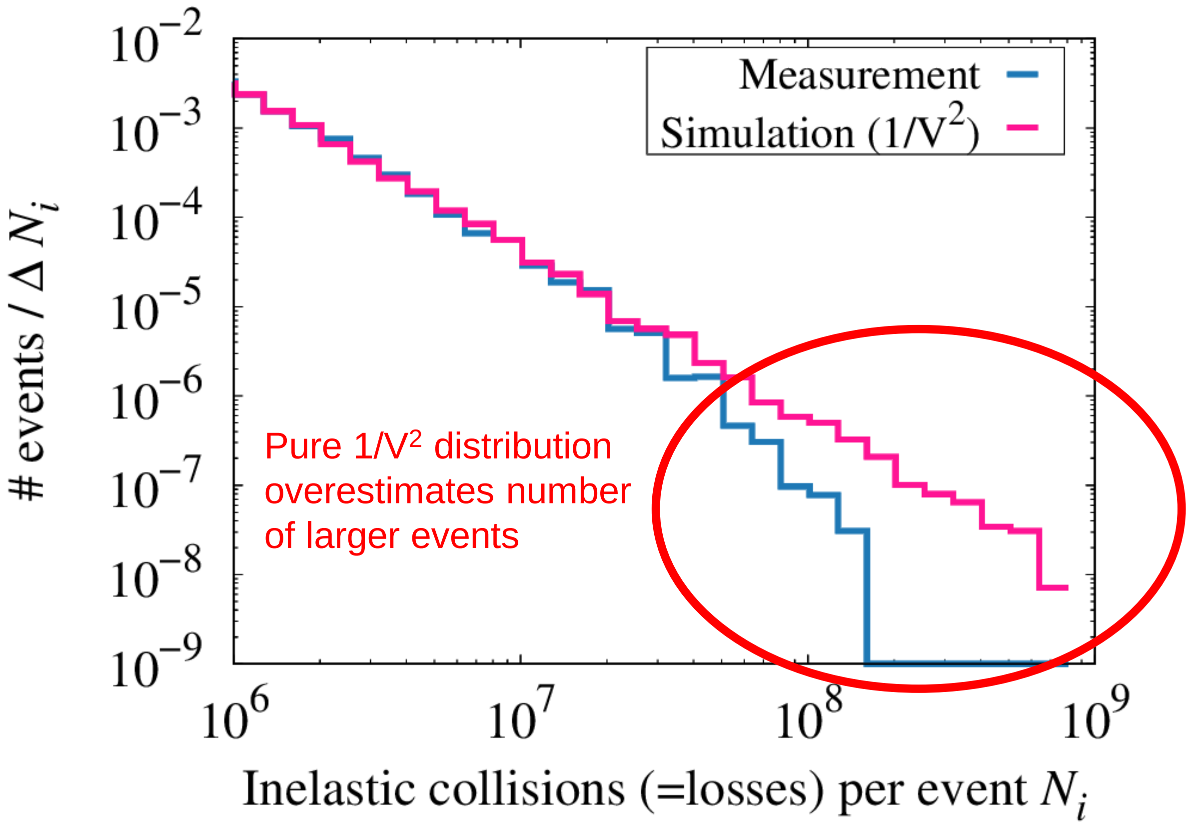
Approach: try to reproduce the event characteristics with dust dynamics simulations (Monte Carlo) for a large ensemble of measurement data

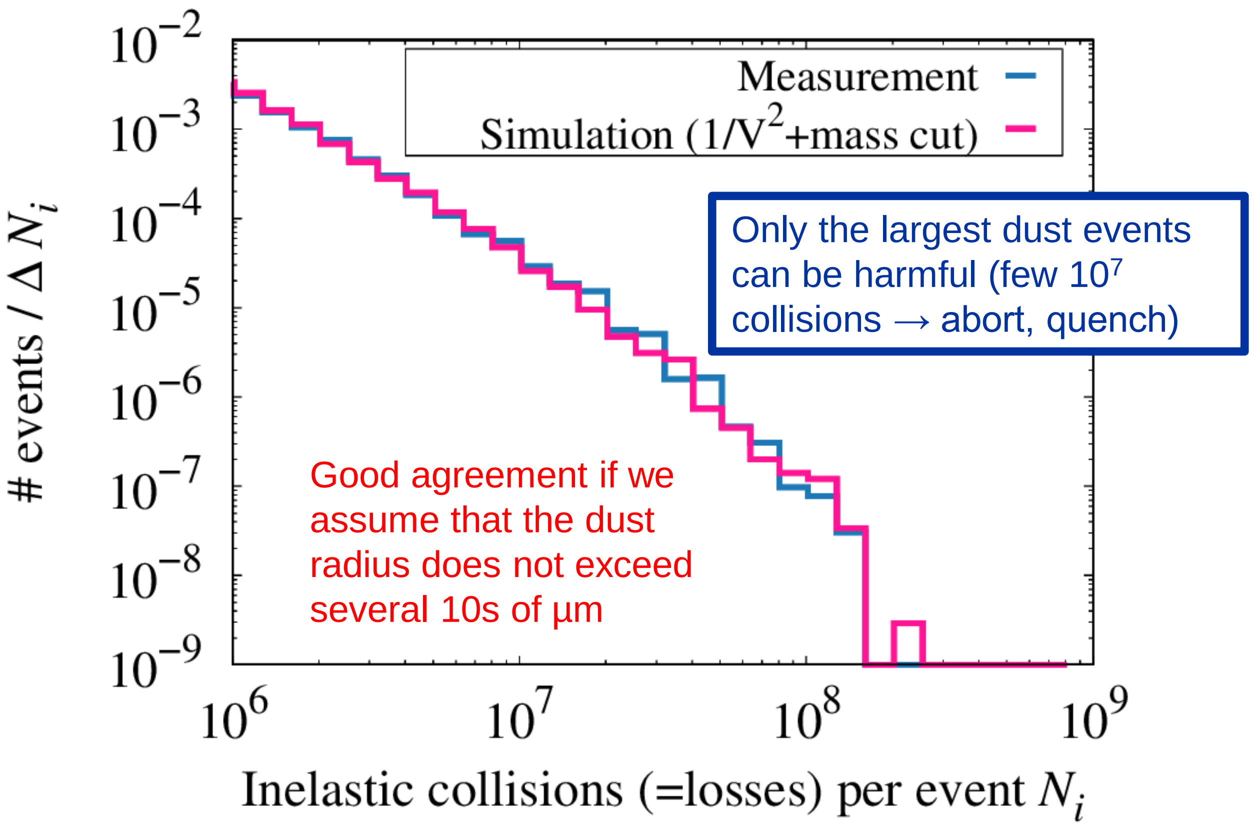
→provides information about dust size and pre-charge distribution

Beam losses per event → dust size

Simulation can produce well the measurements if we assume a **dust population proportional to 1/Volume^2**

Distribution of events as a function of the beam losses:

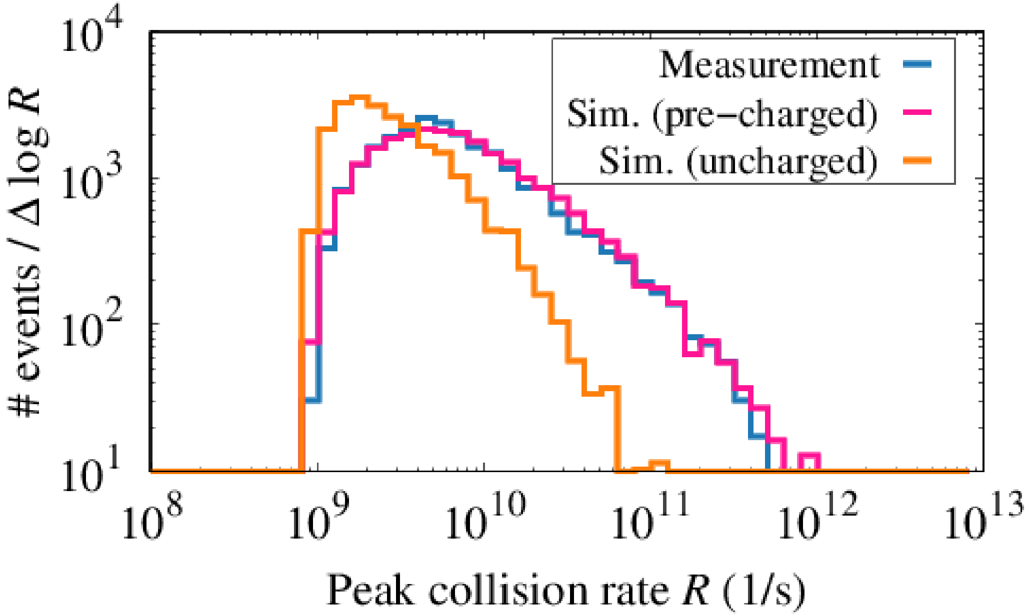




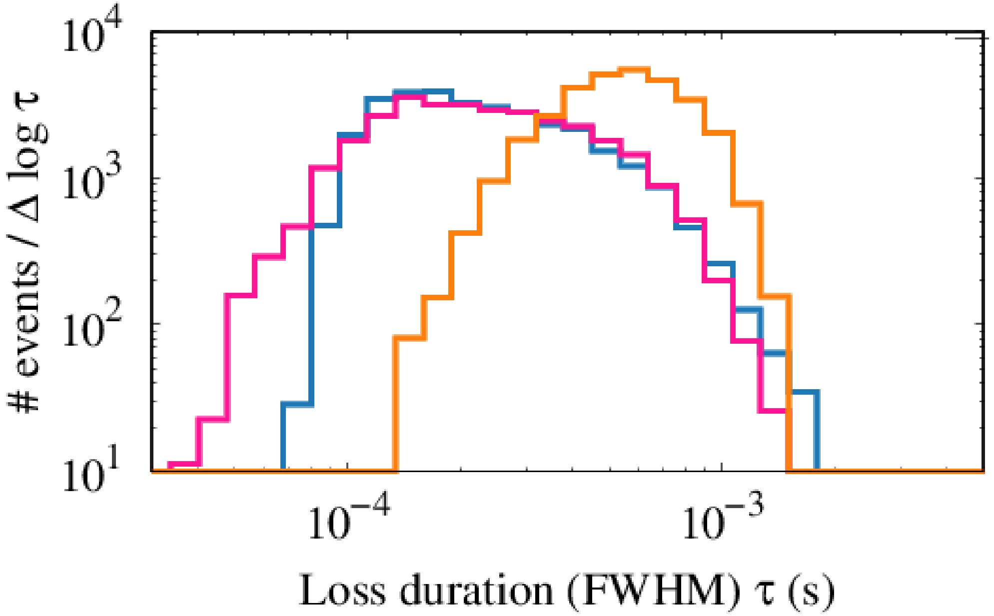
→ The 1/Volume^2 population is in agreement with the measured dust distribution in the magnet test halls!

Peak collision rate, event duration → dust pre-charge

Distribution of dust events as a function of the peak collision rate (collisions/s):



Distribution of dust events as a function of the loss duration (s):

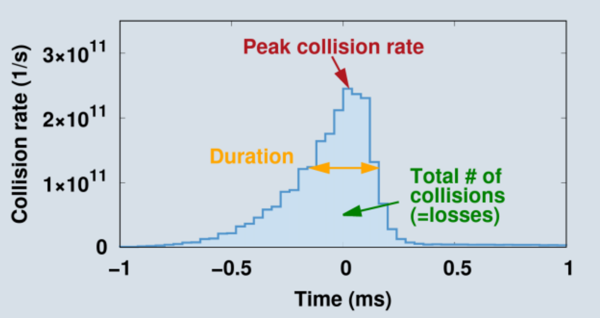


Figures consider only events with more than 5×10^5 collisions (i.e. only larger events), data from Run 2

The observed event characteristics can only be reproduced if the dust is assumed to be **negatively pre-charged ($|Q/m| > 10^{-3}$ C/kg) before entering the beam**

More in the talk of B. Lindstrom and P. Belanger

Event characteristics vs beam intensity

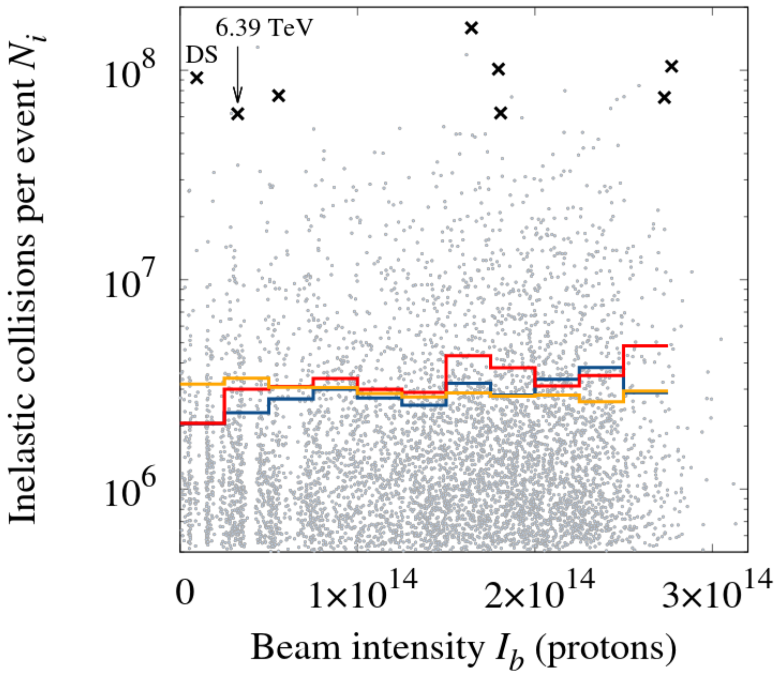


5000 largest dust events in the arcs in Run 2 (2015-2018)

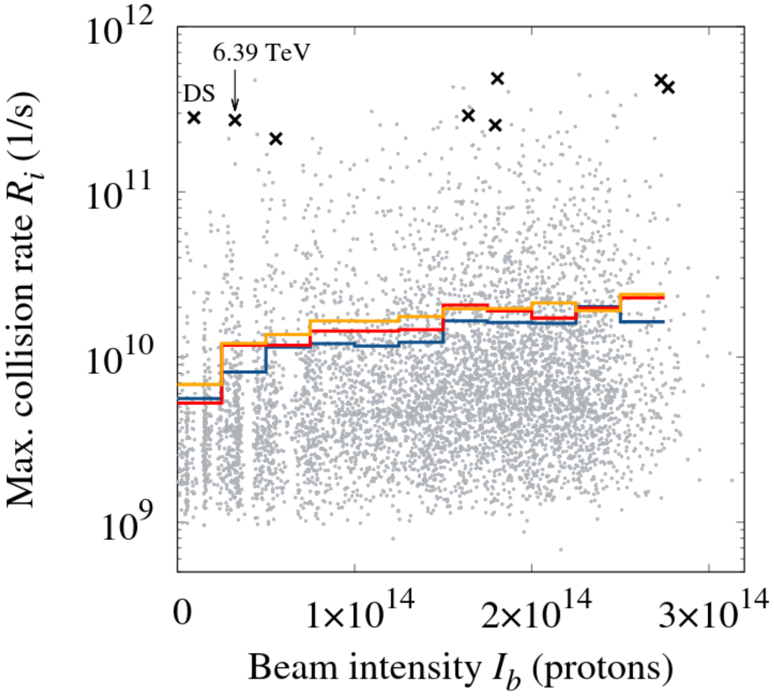
Blue line = average meas. Beam 1, Red line = average meas. Beam 2

Yellow line = dust dynamics simulations

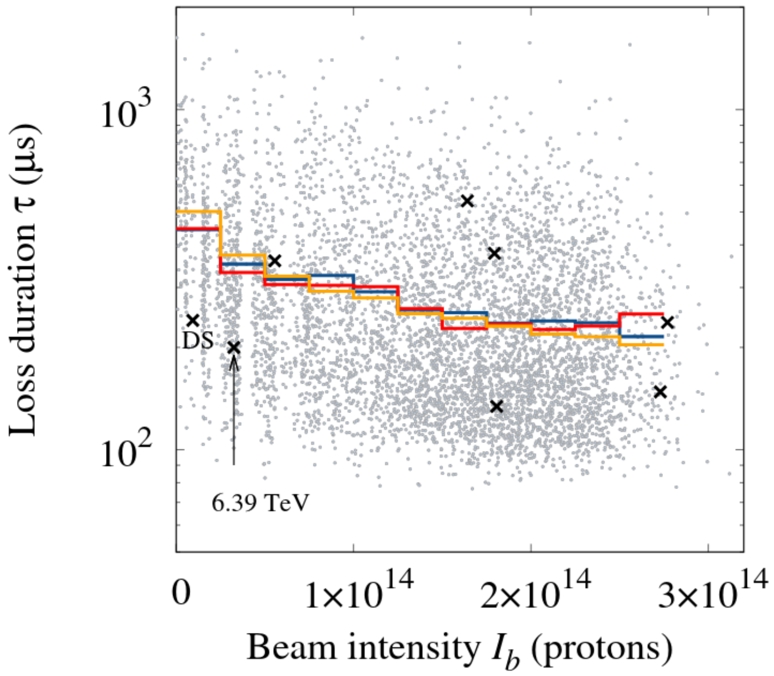
 # collisions (losses) per event vs beam intensity



Peak collision rate vs beam intensity



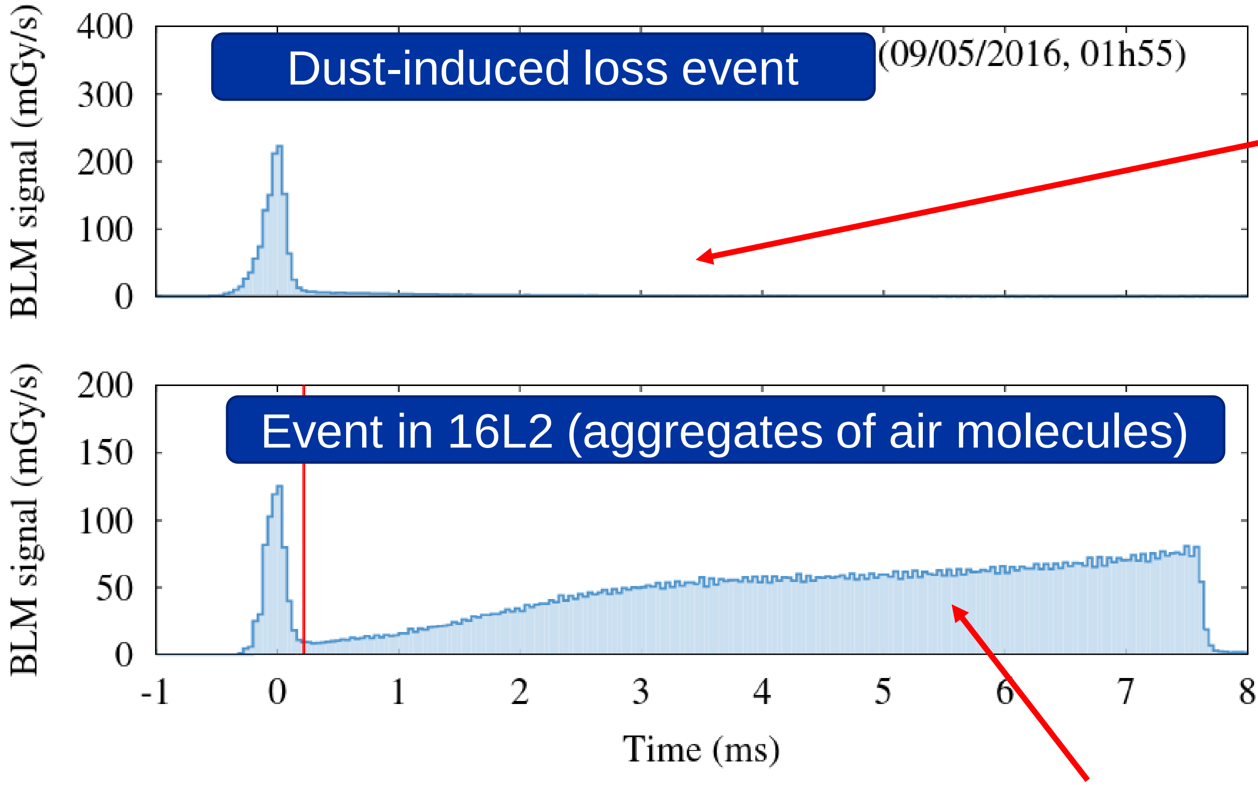
Loss duration vs beam intensity



Observed dependencies well reproduced if dust is assumed to be negatively pre-charged!

Heating of dust particles

Time profiles for a regular dust event vs an event in 16L2:



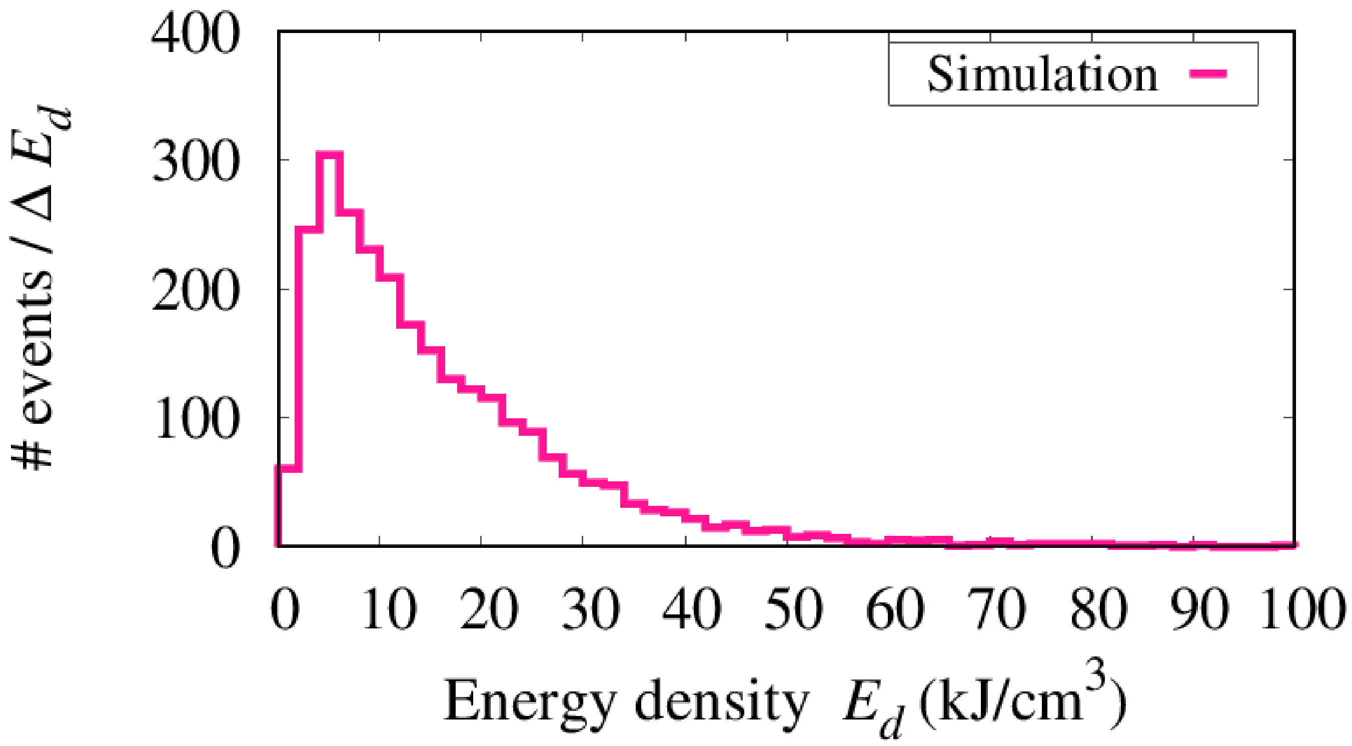
For regular dust events, loss tails were never observed, meaning that no matter/gas remains in the beam after the event

Different material

Was likely subject of a phase transition to gas phase due to heating (beam losses due to nuclear collisions between protons and gas)

Heating of dust particles

Simulated distribution of energy densities in dust particles made of Cu (assumed dust population $1/V^2$):



The results suggest that the energy densities in dust particles can reach very high values (tens of kJ/cm^3)

At least a fraction of dust particles is likely subject to a phase transition

Summary and conclusions

- Dust particles are the main source of **loss-induced beam aborts** and **quenches** in the LHC
- In addition, **thousands of harmless dust events** are detected every year
- An increase of the dust event rate is observed after long shutdowns (not obviously linked to new dust contamination), while the rate gradually decreases during runs
- The mechanism (and dependencies) governing the **release of dust particles** into the beams and **not yet well understood**, hence we do not have a model to predict event rates
- **No correlation** between the event rate and the **heat load** (due to e-cloud) was found
- The event characteristics suggest that dust particles are **likely negatively pre-charged** when entering the beam
- The beam-induced **energy density** in dust particles is expected to be **very high** – phase transitions cannot be excluded; yet no beam losses or other effects on the beam were observed beyond the millisecond scale

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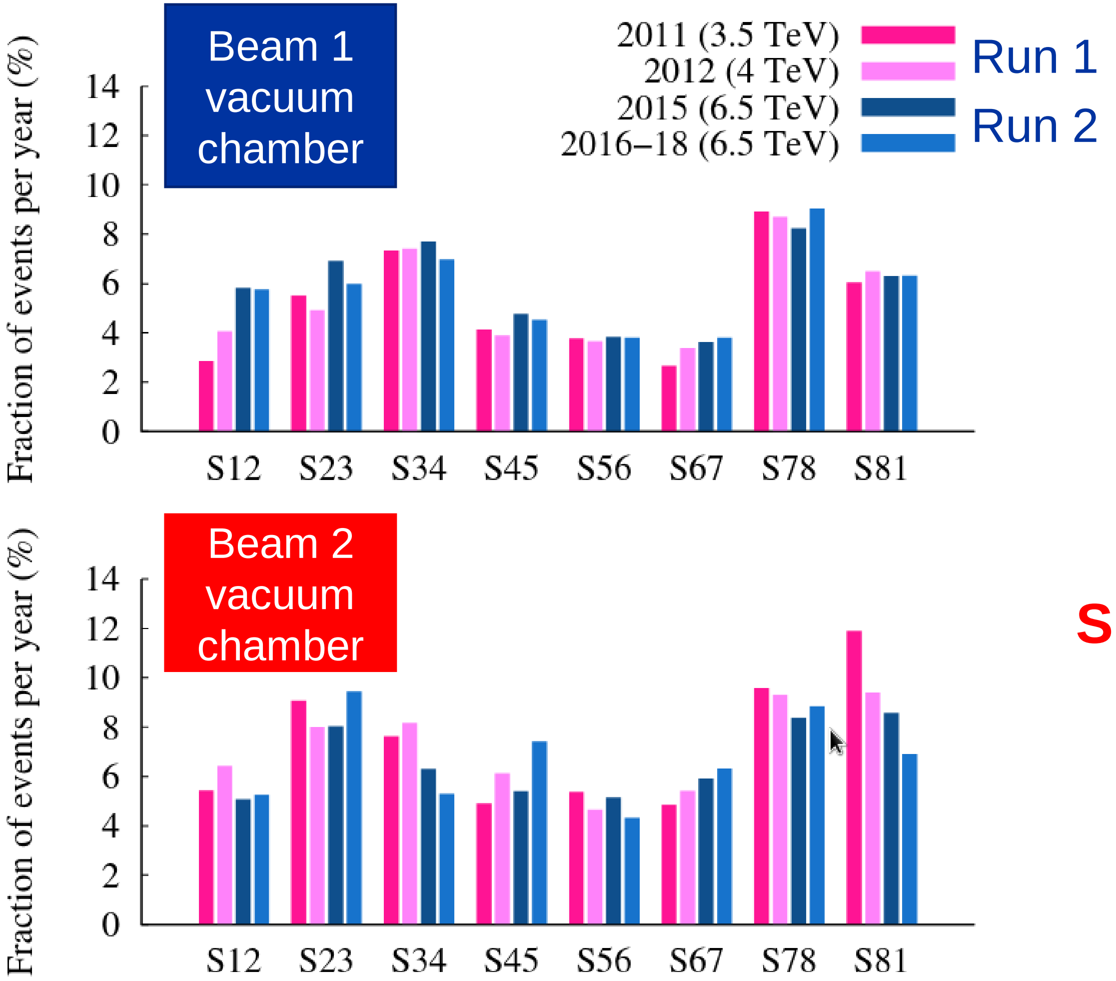
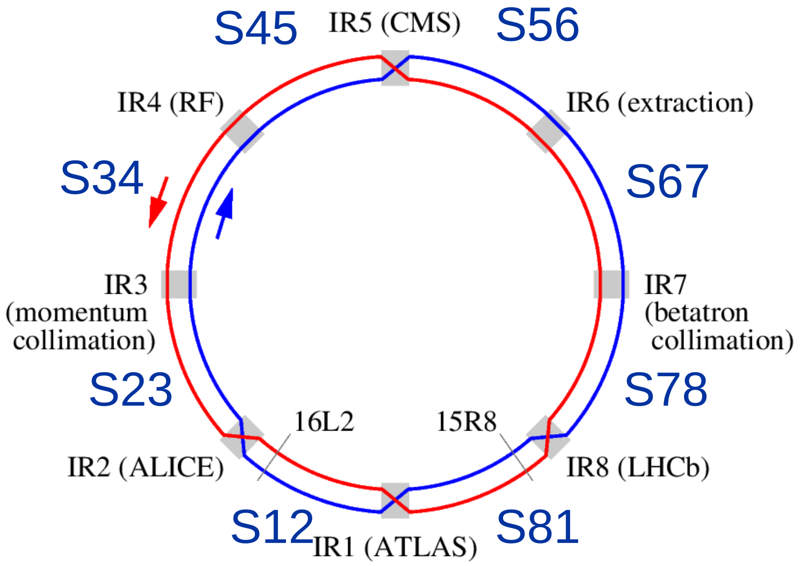
Relative dust event distribution per sector





Each arc sector = 2.46 km

Spatial event distribution:

- Global distribution between *sectors relatively similar in Run 1 and Run 2 – no significant excess of events in sectors with more new magnets*
- Reinforces the assumption that most events in Run 1 and 2 were due to “old” dust