Impact study of Arc UFO Events at 6.5 TeV

Thanks to

B. Auchmann, A. Lechner, W. Riegler, S. Rowan,

H. Schindler, R. Schmidt, F. Zimmermann

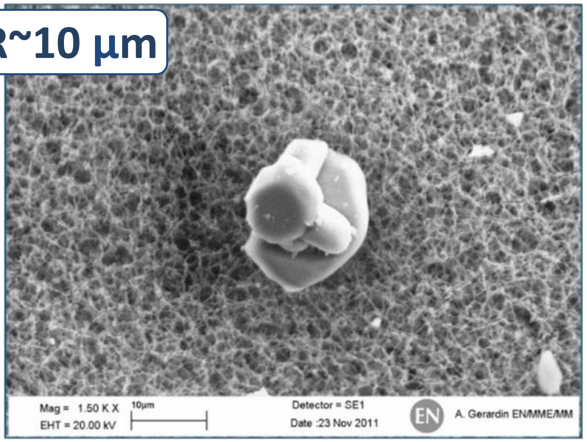
MPP Meeting - 16/11/2014

Technology Department

Outline

- **Introduction/Motivation**
- **Impact Study**
  - **Overview of Study**
  - **Explanation of Numerical Model**
  - **Monte Carlo Results**
- **Conclusions**

R~10 μm



A nice picture of some dust

T. Bar CERN-THESIS-2013-233

Introduction

- **Impact study of UFO Events at 6.5 TeV**
  - **Why do we care?**
    - Due to the increased energy and reduced quench margins, it is predicted that such an event is **more likely to cause a beam dump at 6.5 TeV**, ultimately affecting availability.
  - **What is our goal?**
    - **Attempt to numerically simulate such an event,** including the corresponding BLM signals, to estimate the **probability of UFOs resulting in a beam dump at 6.5 TeV**.

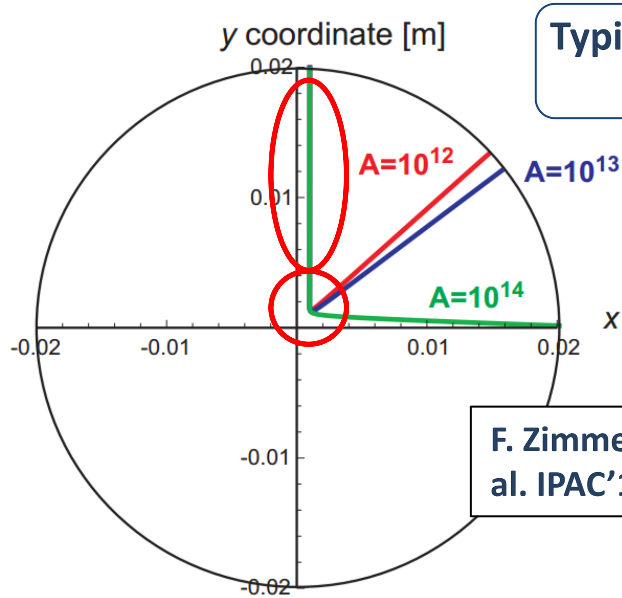
So what exactly is an "UFO event"?

- **An accepted interpretation of a UFO event:**

1. A **macroparticle (dust) falls** from the top of the beam screen with gravity.

2. The **macroparticle is subsequently ionized** due to elastic collisions with the beam and the release of the inherent 'knock-on' electrons.

Typical "flight-path" diagram



F. Zimmermann et al. IPAC'10

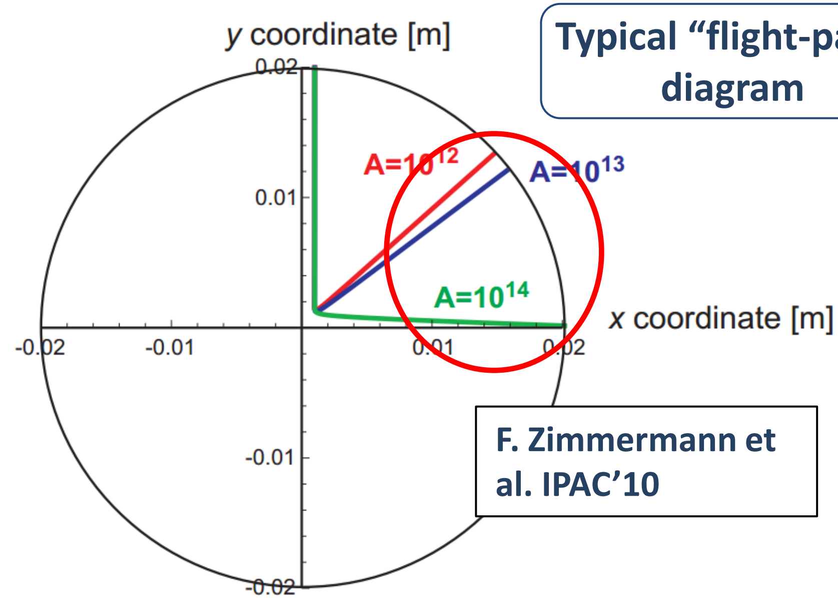
UFO simulation for a given mass, A.

So what exactly is an "UFO event"?

- **An accepted interpretation of a UFO event:**

3. The now positively charged **macroparticle is subsequently repelled away** from the beam due to its electric field

4. Note that for the duration of the UFO-to-beam interactions, there may be **significant losses due to inelastic collisions, resulting in a beam dump and or magnet quench!**



Typical "flight-path" diagram

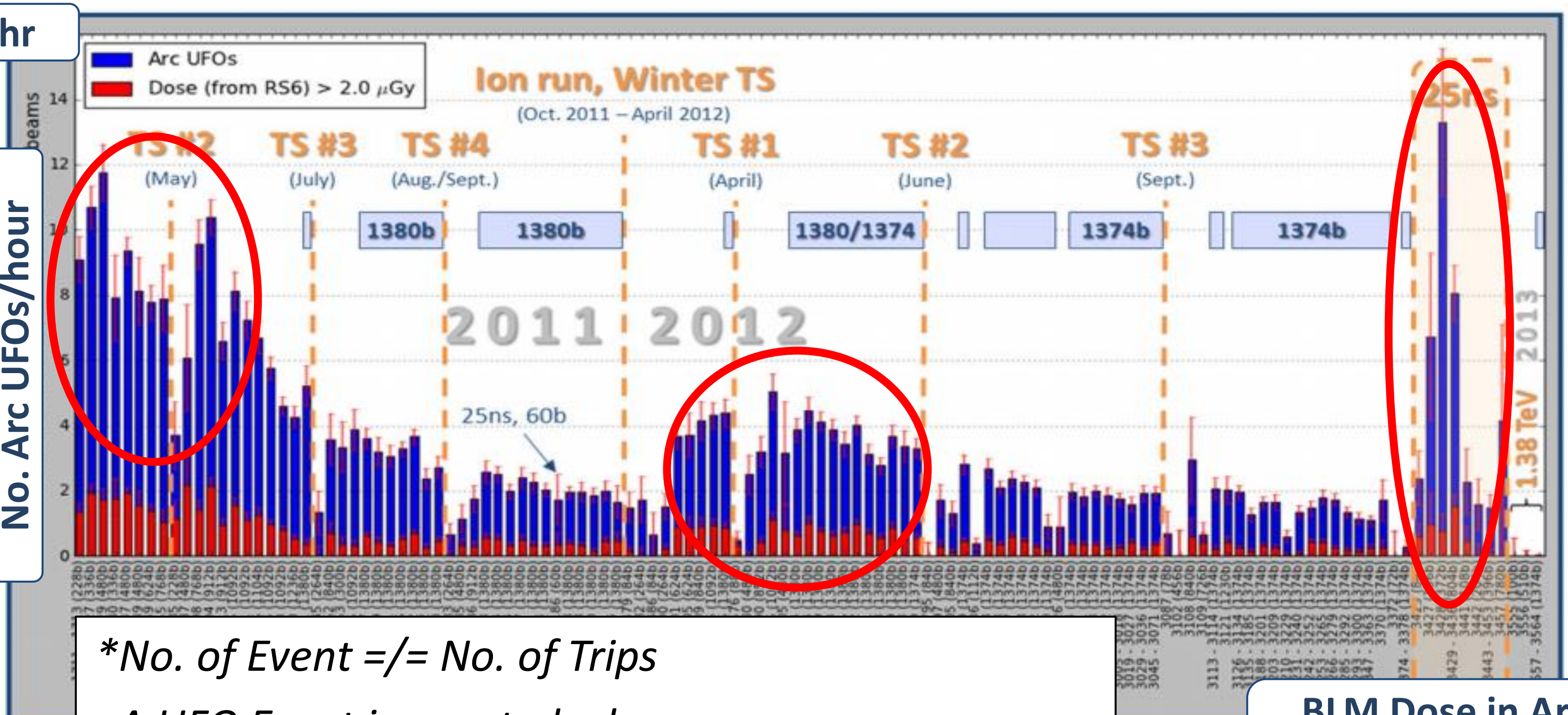
F. Zimmermann et al. IPAC'10

UFO simulation for a given mass, A.

Are such events common?

- **No. of UFO events** have been seen to **exceed 10+/hour** with notable increases after long shutdowns and or with an increase in beam frequency

16/hr



**No. of Event =/= No. of Trips*

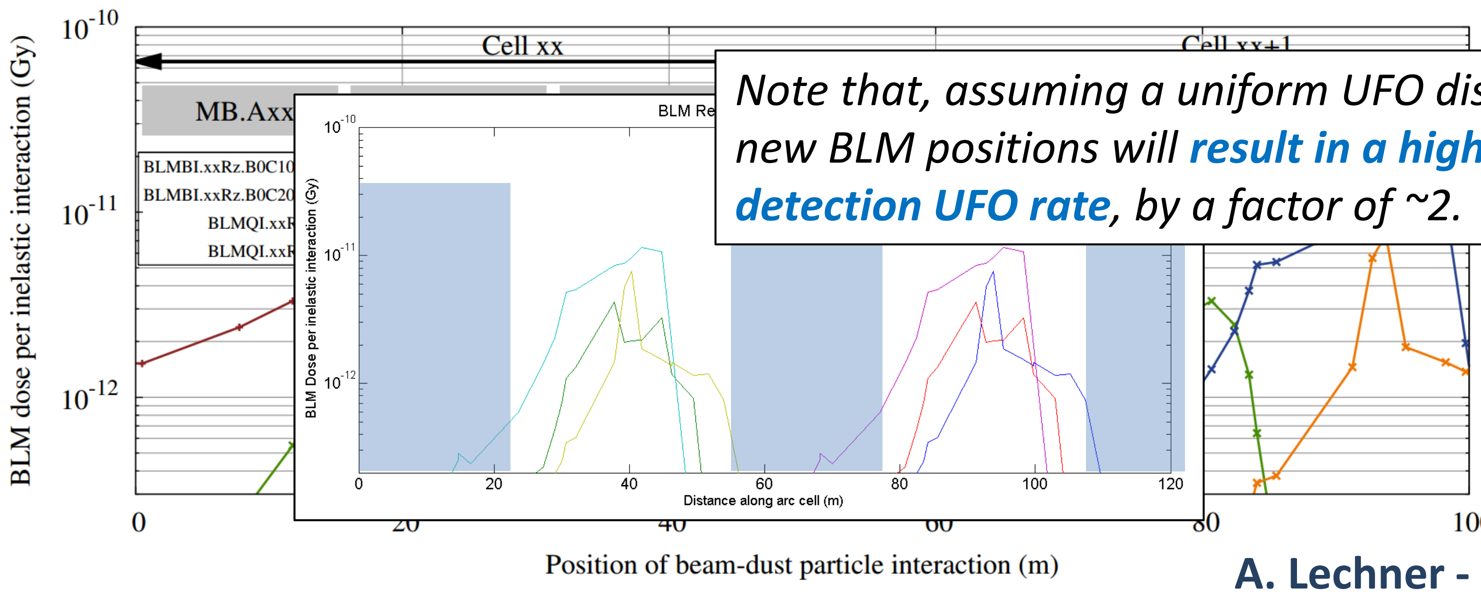
A UFO Event is counted when::
BLM Signal(RS@640us) > 5x Noise = 2x10-4 Gy/s

BLM Dose in Arc, Jan 2011-Dec 2012.

Impact Study Overview

Study Overview

- **New BLM Positions! Full Arc Coverage!**
- Shown is the **BLM 'response'** at 6.5 TeV for a given longitudinal location along a typical arc cell, **FLUKA**.
- The **BLM 'response'** is the signal produced from a **single proton to Carbon Nucleus collision** and such the **BLM 'signal' is the product of the response and the loss rate**



Note that, assuming a uniform UFO distribution, new BLM positions will ***result in a higher detection UFO rate****, by a factor of ~2.*

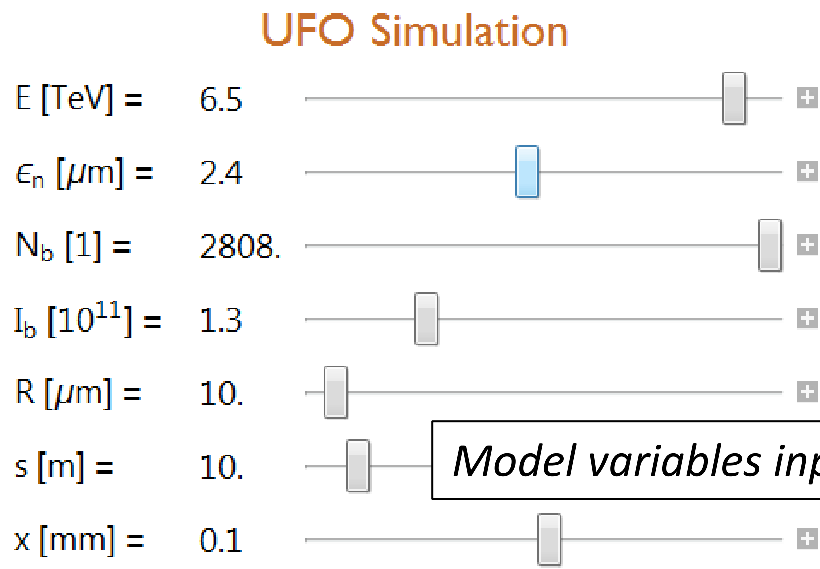
A. Lechner - Sept 2014

$$\mathrm{BLMSignal}(t,s) = -\dot{N}_{\mathrm{p}}(\vec{r}(t)) \cdot \mathrm{BLMResponse}(E_{\mathrm{p}},s),$$

Study Overview

- The following shows the concise **step-by-step processes** involved in the study:

STEP 1: Define Input Parameters



Beam Energy
Norm Emittance
No. bunches
Protons/bunch
UFO Radius
Longitudinal Location
Transverse Location

Model variables input console

Other inputs include: material properties and system constants (energy dispersion, LHC circumference for e.g.)

Study Overview

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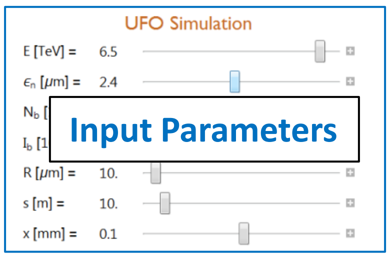
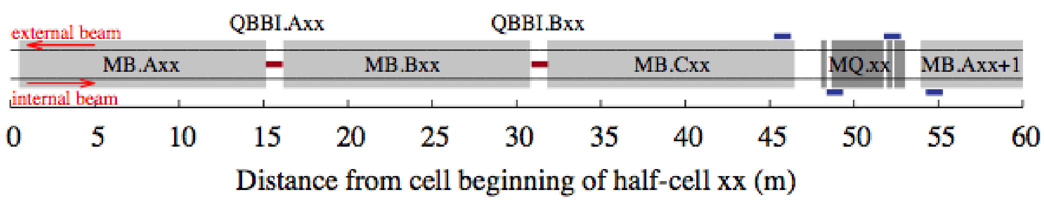


STEP 2: Define Input Distributions

- **Longitudinal Location**: Uniform
- **Transverse Location**: Uniform (within reasonable limits)
- **UFO Radius**: Unknown
  - (fitted to match 4 TeV results using an accepted parameter range of R=1-100um. Range taken from SM12 dust study, see T. Bar CERN-THESIS-2013-233)



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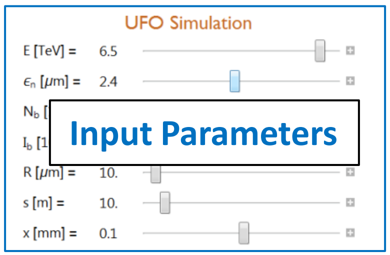
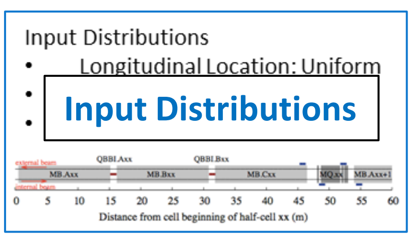
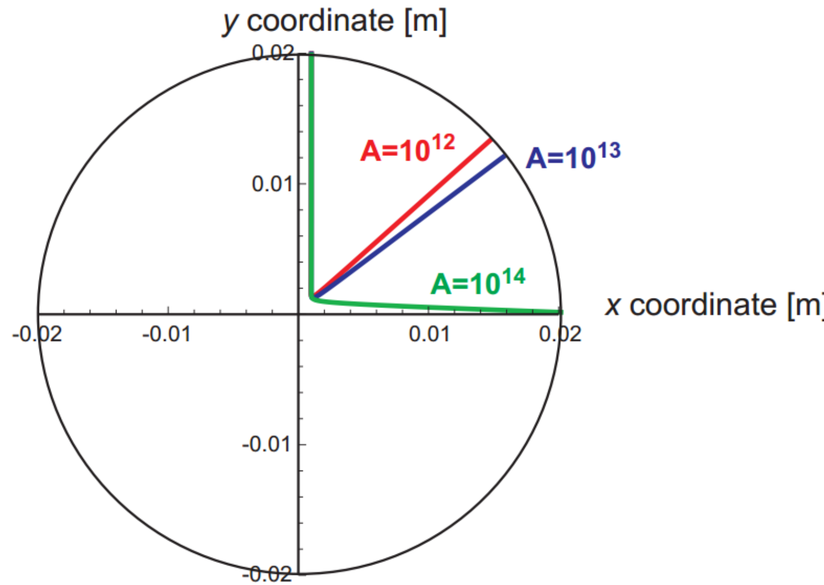


STEP 2:



STEP 3:
Run the model!



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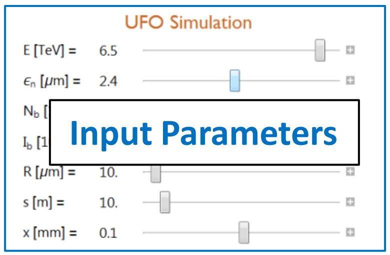

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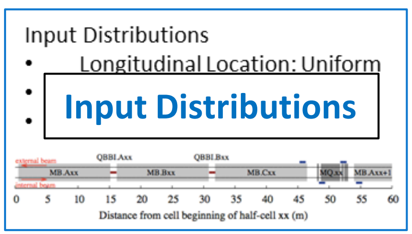

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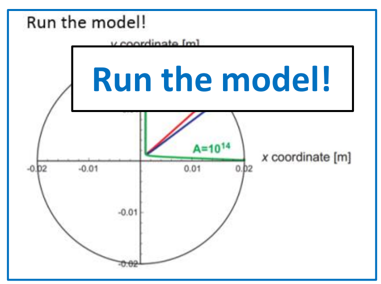
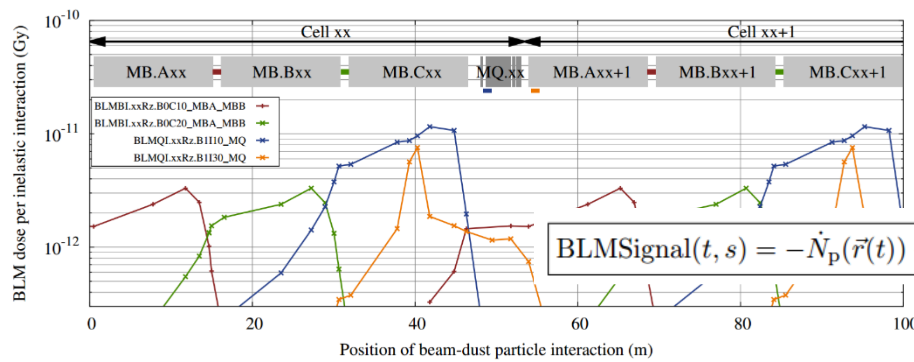


STEP 4: Calculate BLM Signals



$$\mathrm{BLMSignal}(t,s) = -\dot{N}_{\mathrm{p}}(\vec{r}(t)) \cdot \mathrm{BLMResponse}(E_{\mathrm{p}}, s),$$

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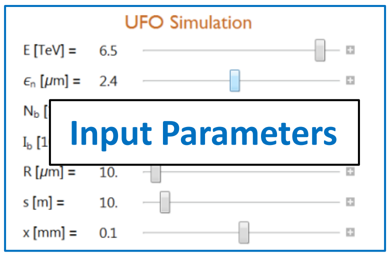

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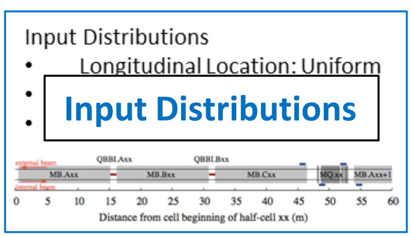

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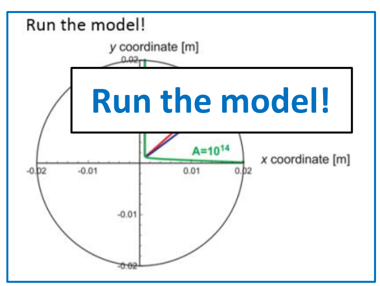
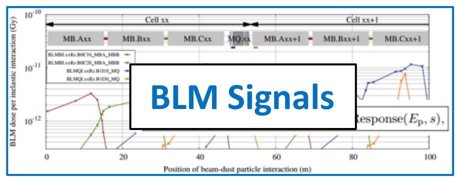
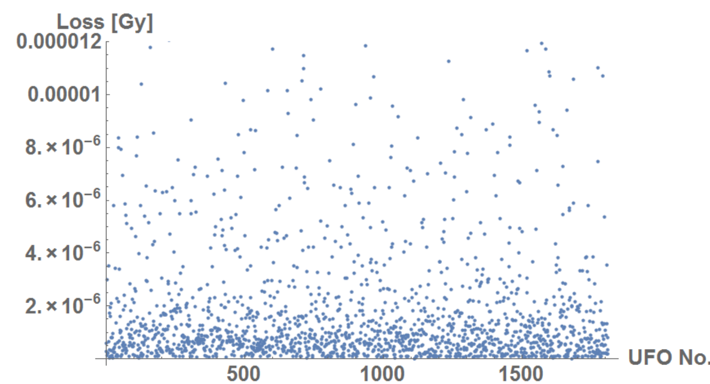


STEP 4:



STEP 5: Repeat Step 1:4 until study buffer is collected ~1800, after filtering criteria.

- **RS(640us) > 2x10^{-4} Gy/s**



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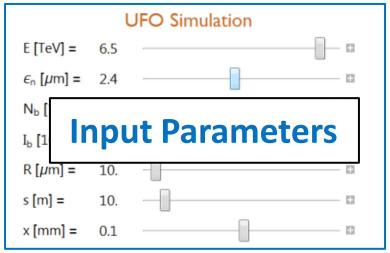

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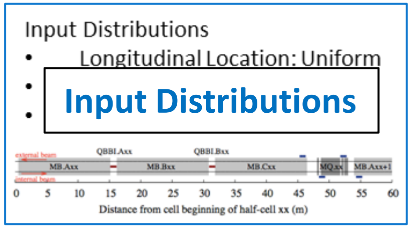

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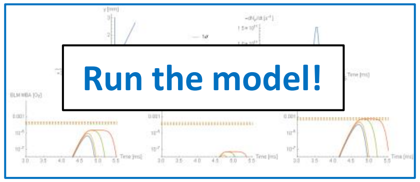

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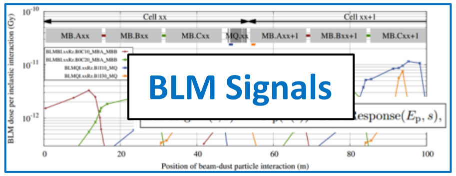
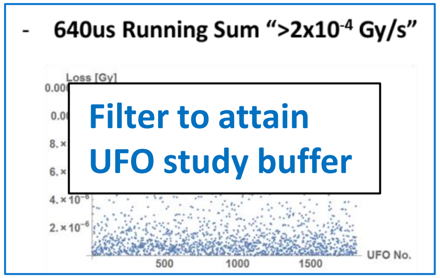


STEP 5:



STEP 6:

Compare numerical model with 2012 measured data

Finally:

If happy with 4 TeV results, run 6.5 TeV Monte Carlo

If not

Numerical Model

Main Considerations

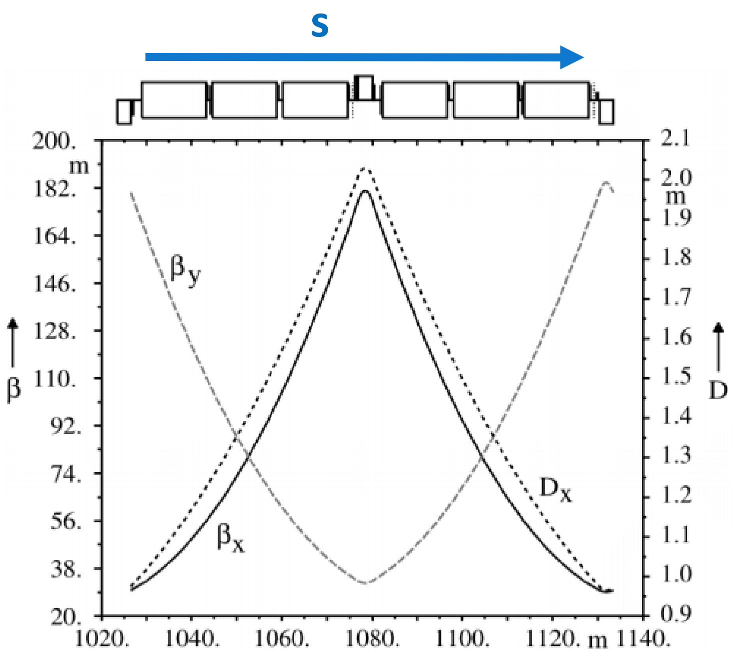
- **Main considerations** for the numerical model were as follows:
  - Input Parameters (covered)
  - Input Distributions (covered)
  - Beam Size
  - Electric Field Influence
  - Macroparticle Charge Rate
  - Beam Loss Rate

- It is of note that due to the amount of required simulations and model complexity, **memory efficiency and parallelization** were important aspects.
  - Model takes ~1hr to run a 10,000 iteration Monte Carlo simulation

(on a 16 core Xeon I might add)

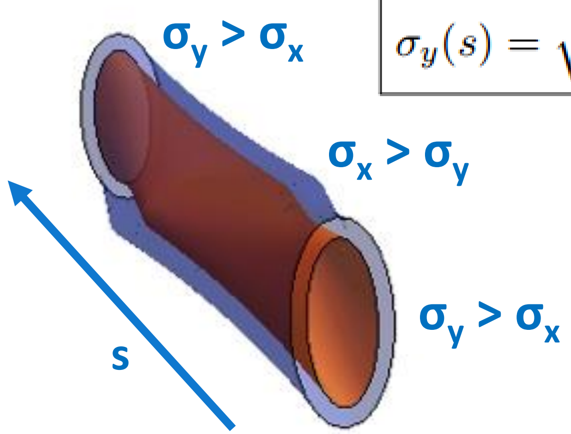
Beam size/shape

- The variation of **beam size/shape** along the arc was taken into account
- It is implement via a parabolic fit beta function, fit shown below:
- Beam size subsequently attained from the common relation. Depicted below



B variation along a full-cell

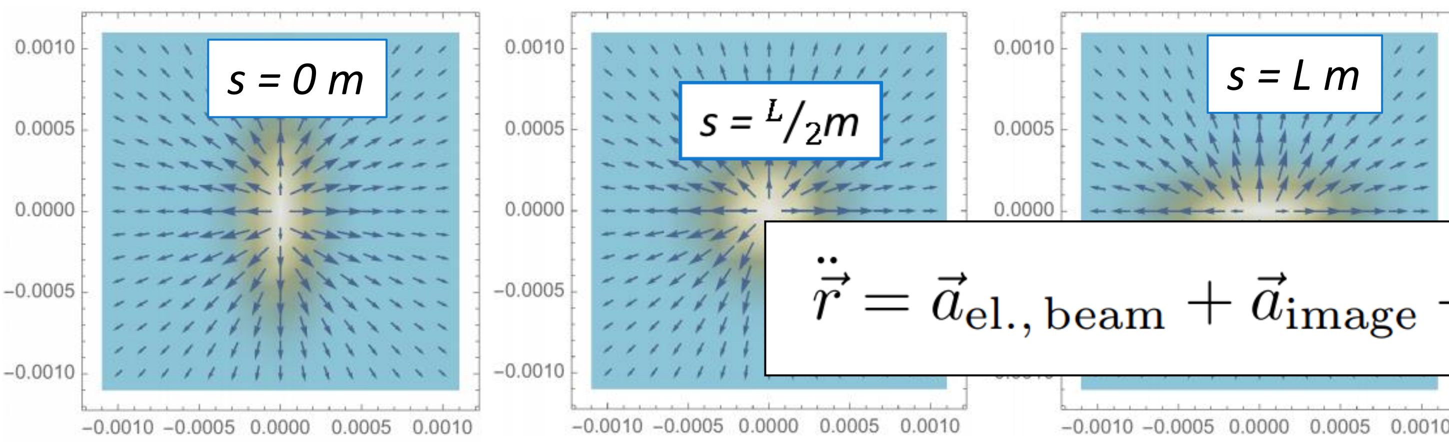
$$\sigma_x(s) = \sqrt{\beta_x(s)\epsilon},$$
$$\sigma_y(s) = \sqrt{\beta_y(s)\epsilon}.$$



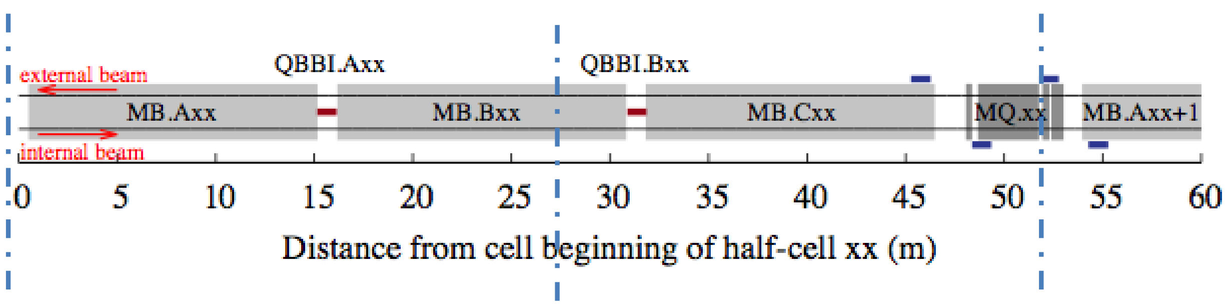
3D model of beam shape along an arc cell as implemented

Electric Field Influence

- The variation in beam size/shape along the Arc naturally influences the electric field. Shown is the **field variation across a typical half-cell**. Field is field modelled following the **Bassetti-Erskine formula** (2D Gaussian beam).



$$\ddot{\vec{r}} = \vec{a}_{\text{el., beam}} + \vec{a}_{\text{image}} + \vec{a}_{\text{grav}}$$



Macroparticle Charge Rate (1/4)

- Previous studies have also attempted to model UFO-to-beam interactions, Zimmermann circa 1993-2011
- All studies focused on a charge rate equation derived from a formula for the distribution of sufficiently high-energy 'knock-on' electrons within a solid.

$$\dot{Q} = \frac{2N_{\mathrm{p}} f R^3 \pi N_{\mathrm{A}} r_{\mathrm{e}}^2 m_{\mathrm{e}} c^2 \rho}{3\sigma_x \sigma_y T_{\min}(Q,R) M_{\mathrm{u}}} \, \mathrm{e}^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}} .$$

Derived from:

$$\frac{\partial^2 N}{\partial T \partial s} = 2\pi r_{\mathrm{e}}^2 m_{\mathrm{e}} c^2 z^2 n \frac{1}{\beta_{\mathrm{R}}^2} \frac{F(T)}{T^2}$$

Review of Particle Properties, 1992-1993
K. Hikasa et al. Phys. Rev. D 45 1992

- This study focuses on amendments to the **minimum energy factor, $T_{min}(Q,R)$,** and the implications on 6.5 TeV predictions.

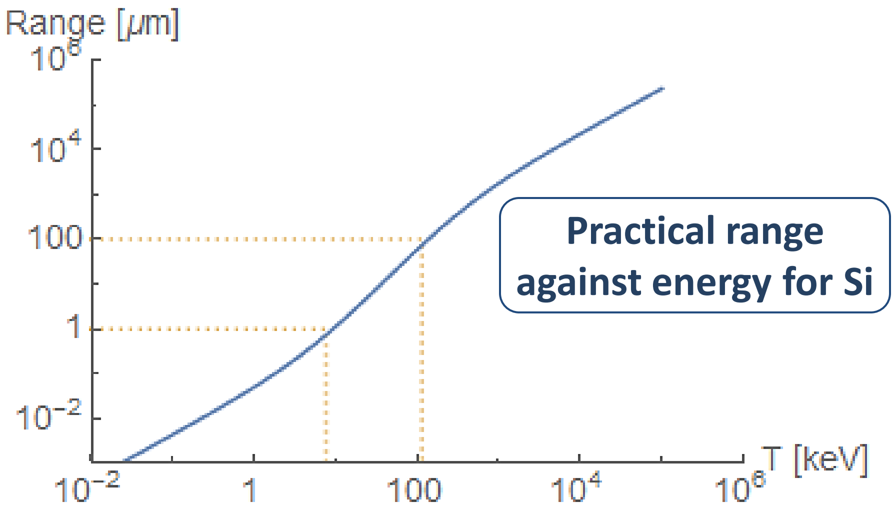
Macroparticle Charge Rate (2/4)

- **Ionization occurs when 'knock-on' electrons have sufficient energy** to travel at least the minimum distance to the edge of the macropartical
- **Tmin** can be described as the sum of the **Coulomb potential and the "escape energy"**, i.e., the energy required to travel the minimum distance
- The 'escape energy' is determine by two factors:
  - The **'practical range'** of an electron within a specific material for a given energy, defined as shown:

$$r(T) = \frac{AT}{\rho}\left(1 - \frac{B}{1+CT}\right)$$

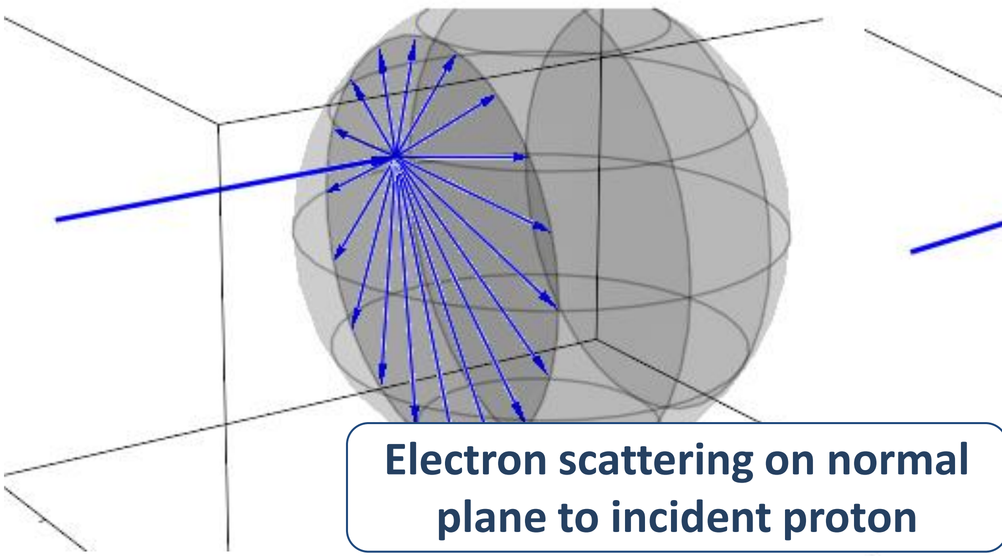
Particle Detection with Drift Chambers
W. Riegler et al, 2008

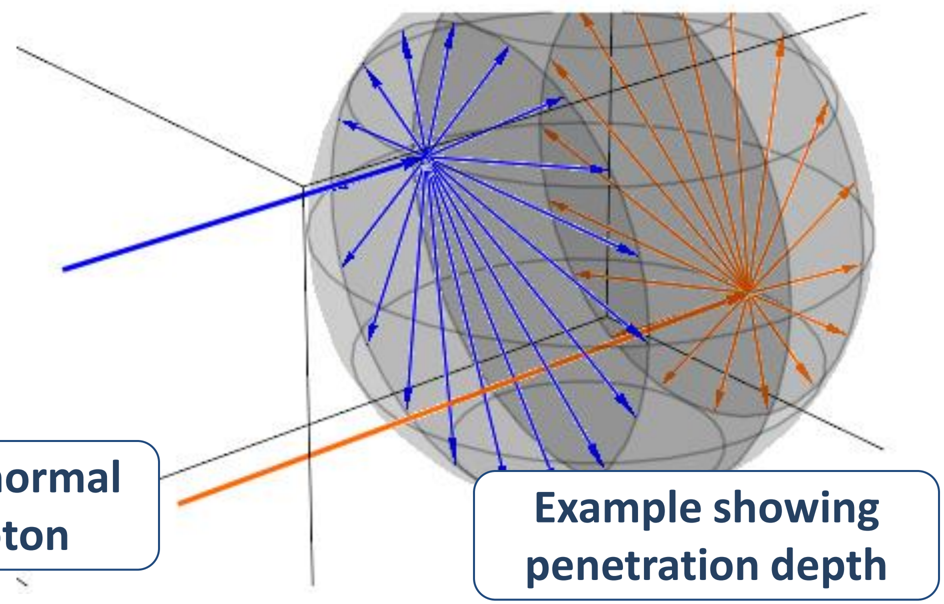
Where: A, B & C are empirical constants



Macroparticle Charge Rate (3/4)

- Shown is a depiction of the **possible perpendicular scattering paths for knock-on electrons** involved in calculating the average distance to the edge from any given location within a spherical macroparticle.





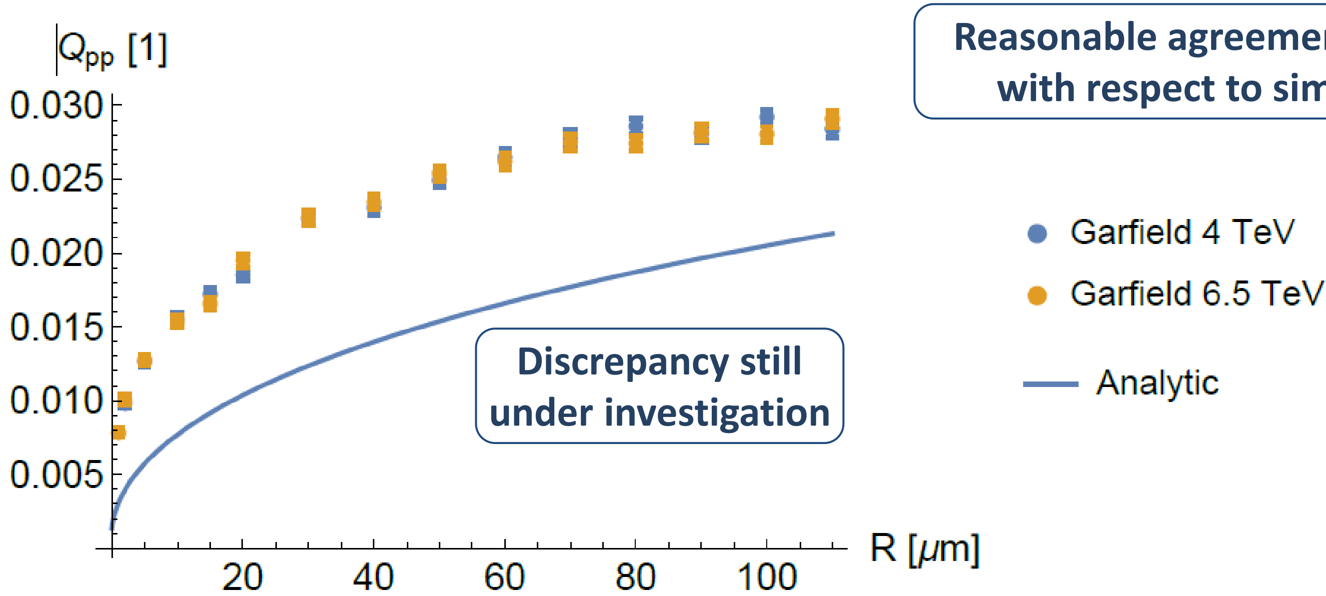
Volumetric Integral across: **Normal cross-section**
Penetration depth
Radial Integral across: **Azimuthal scattering angles**

Average Distance ~ R x 0.736

Macroparticle Charge Rate (4/4)

- Well? Does it work?
- Shown, is a direct comparison of the ionization charge produce by a single incident high-energy proton colliding with an initially neutral Si sphere.
- **Numerical results show a reasonable agreement** with simulations carried out in Garfield++ (assumed to be accurate – software used in detectors).

Reasonable agreement ~30-40% with respect to simulations



Beam Loss Rate

- **The proton loss rate** can be defined as the integrated number of interactions across the macroparticles **'flight path', shown below.**
  - Is a function of No. protons, beam shape, UFO size and material

$$\dot{N}_\mathrm{p} = -\int_{\mathscr{A}}\int_{\mathscr{S}} J(x,y)\Sigma_\mathrm{int}\,\mathrm{d}x\,\mathrm{d}a = -\frac{2N_\mathrm{p} f \sigma_\mathrm{iel} R^3 N_\mathrm{A}\rho}{3\sigma_x\sigma_y A M_\mathrm{u}} \mathrm{e}^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}}.$$

Same as Zimmermann model, but with σ_{iel} taken from FLUKA

Where:

$$\Sigma_\mathrm{iel} = \sigma_\mathrm{iel}\rho_A, \qquad \rho_A = \frac{N_\mathrm{A}\rho}{AM_\mathrm{u}},$$

'macroscoptic section' = nucleus interaction cross-section * atomic density

- As the macroparticle begins to interact with the beam, **losses are produced due to the inelastic collisions**.

And with that we have all the pieces of the puzzle!!!

Numerical Model Results

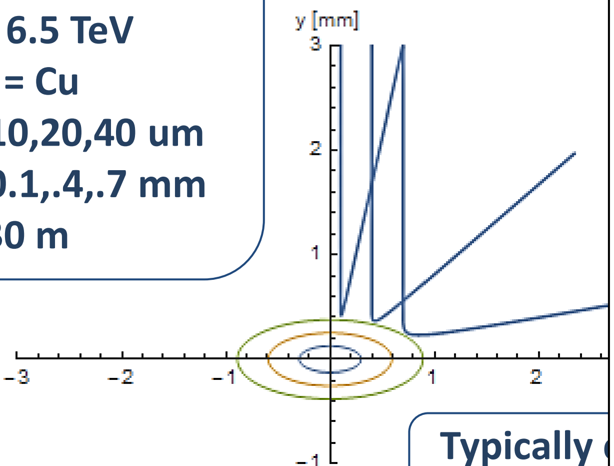
A Typical UFO Event Simulation

- Shown is the **flight path and loss rate of a typical UFO Event** simulate with the numerical mode.

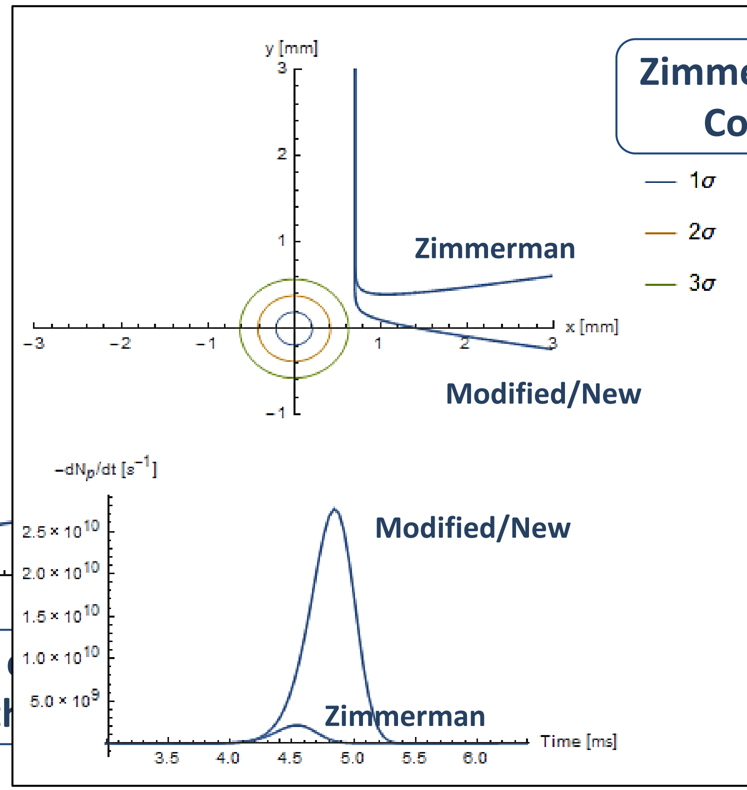
UFO flight-path diagram

Sim params:

Eb = 6.5 TeV
Mat = Cu
R = 10,20,40 um
X = 0.1,.4,.7 mm
S = 30 m

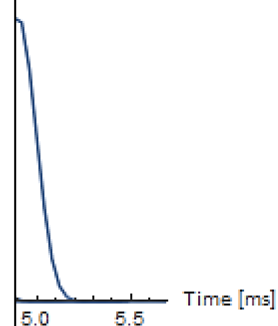


Typically ~3 σ of th



Zimmerman Model Comparison

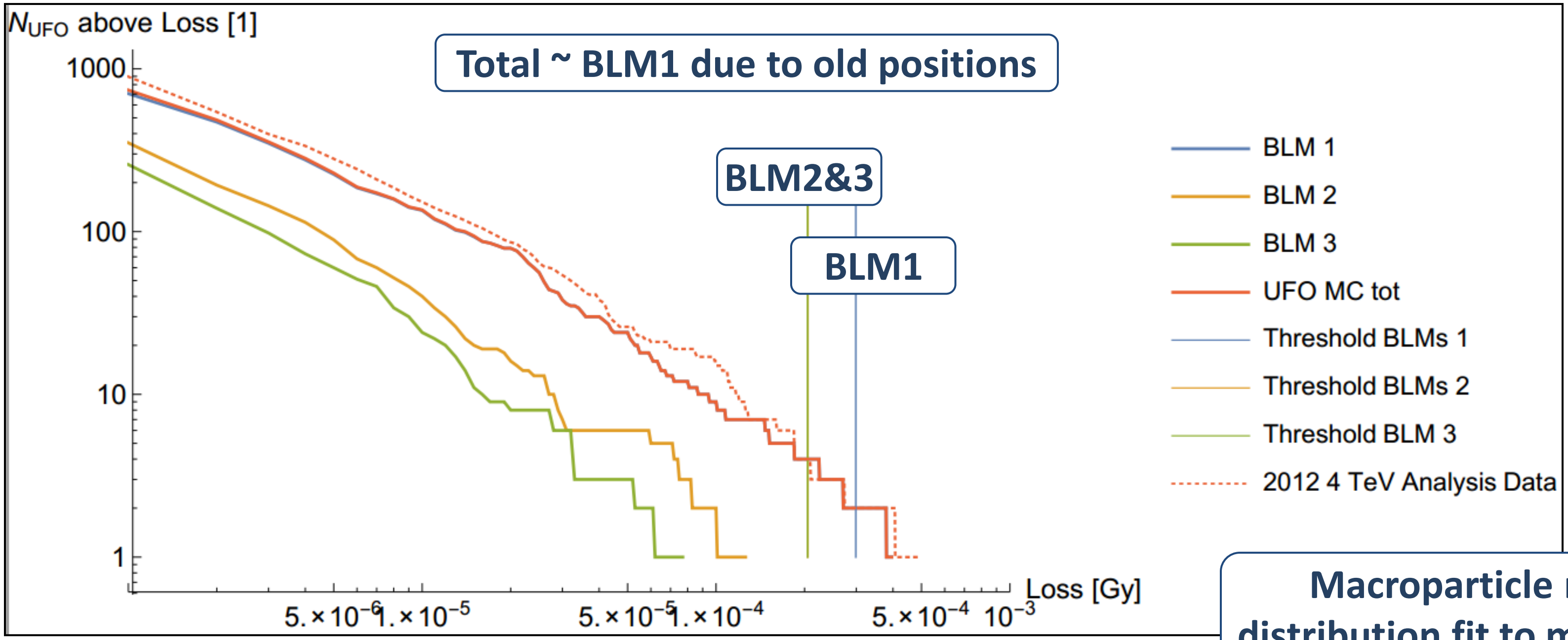
Asymmetric Gaussian



time 0.5-1 ms

2012 Buffer Data vs Numerical Monte Carlo

- Shown is the **comparison between 4 TeV data measured through 2012 and the results of the numerical model Monte Carlo**.
- Numerical Model results are fit to be within **very good agreement within 4 TeV measured data** using a **reasonable parameter ranges/distributions**.



Macroparticle radius distribution fit to match data

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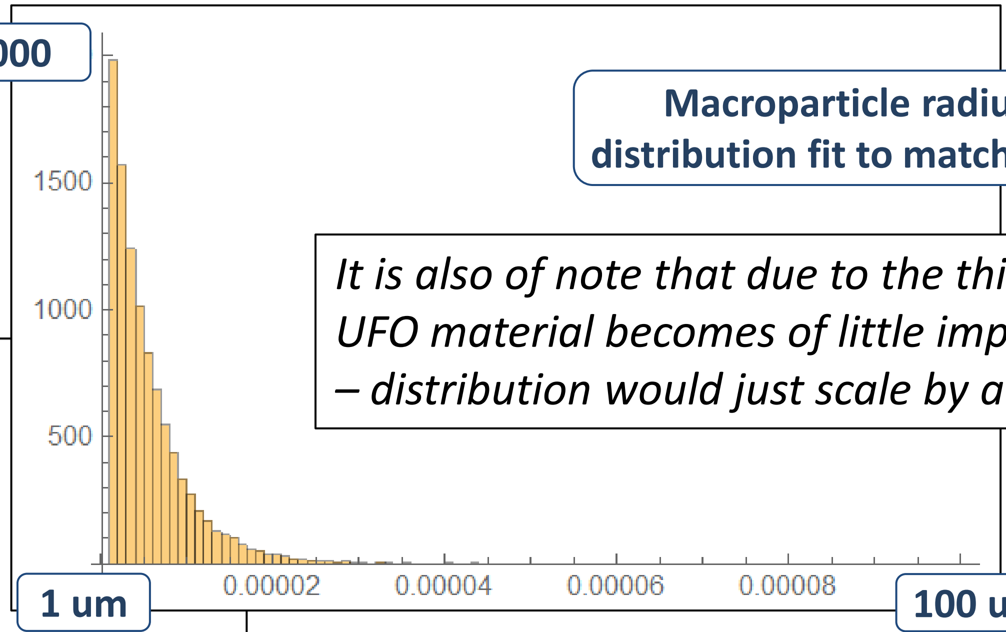
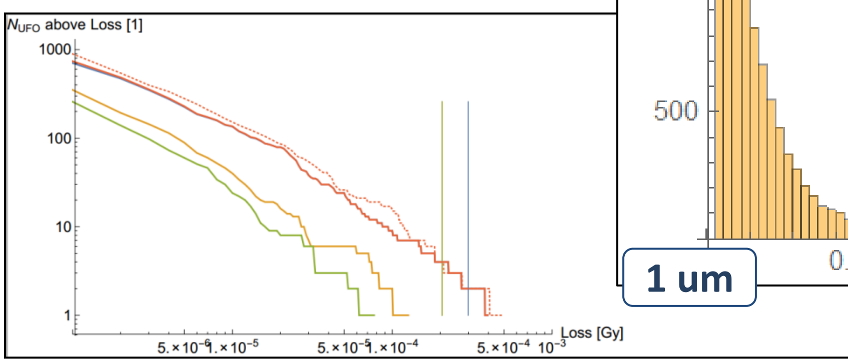


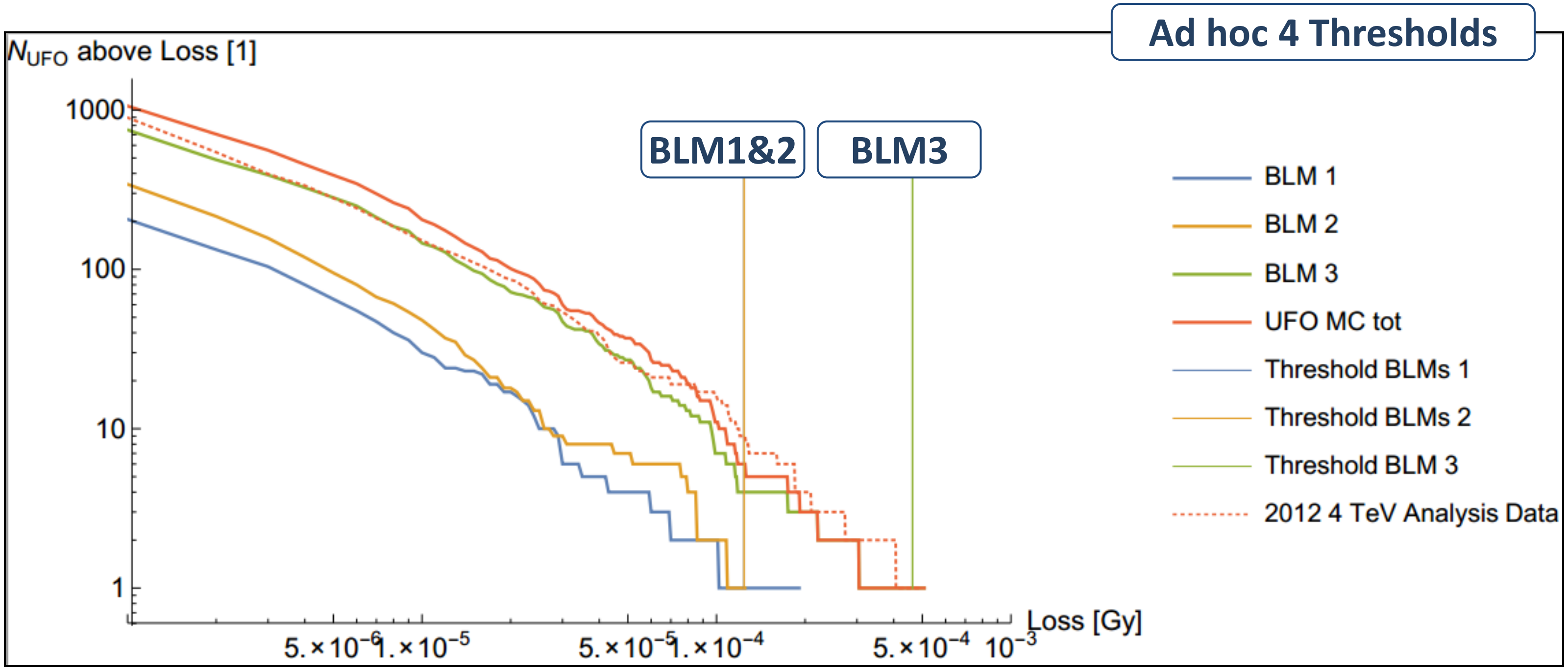
It is also of note that due to the this, the UFO material becomes of little importance – distribution would just scale by a factor.



6.5 TeV Monte Carlo Results

6.5 TeV Numerical Model Monte Carlo

- Shown is the **results of a 6.5 TeV Monte Carlo for a given fit radius distribution**
- Recall aforementioned '**Ad hoc factor**' for quench level uncertainty



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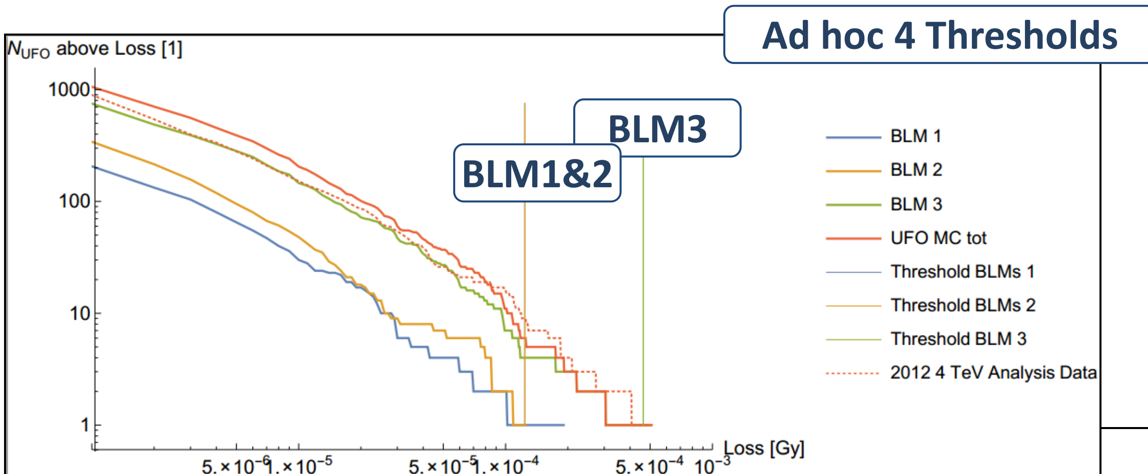
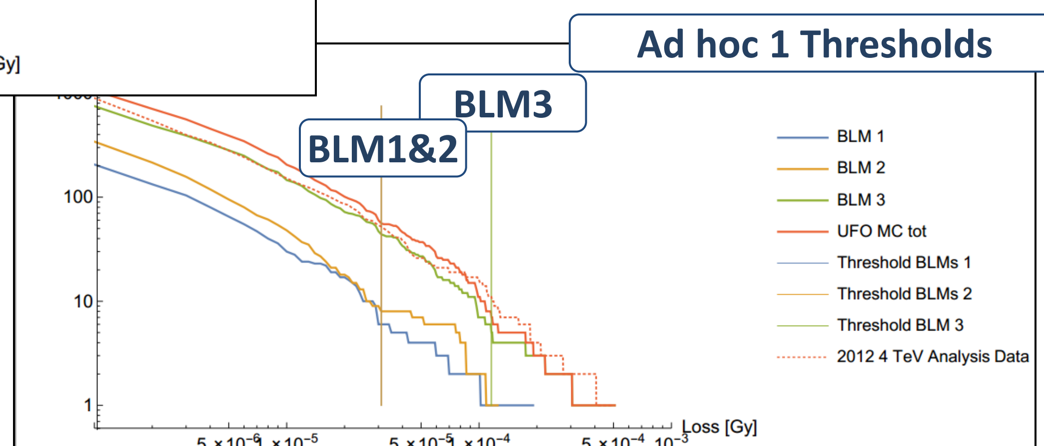


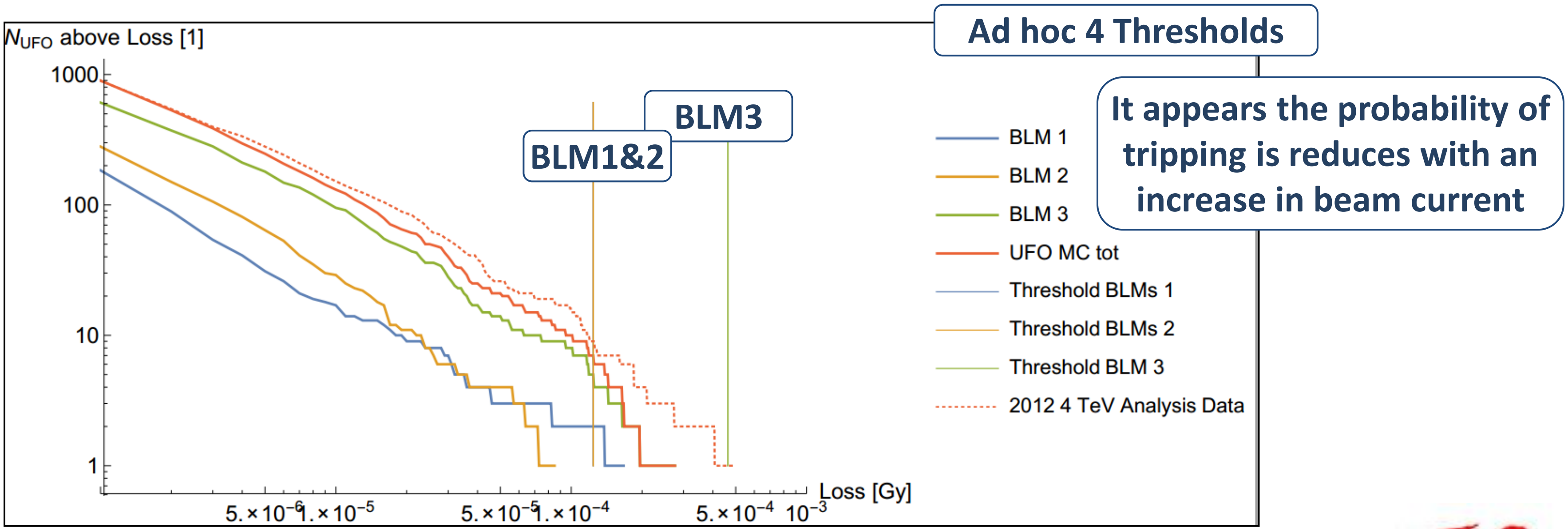
Results (1060/10000 buffer):
- Ad hoc 4 => ~1-3 trips
- Ad hoc 1 => ~10-30 trips



Note: BLM trips may or may not accumulate due to BLM coverage i.e. 1 UFO trips multiple BLMs

6.5 TeV Numerical Model Monte Carlo 25ns?

- Shown is the **results of a 6.5 TeV Monte Carlo for a given fit radius distribution**
- Recall aforementioned '**Ad hoc factor**' for quench level uncertainty



Results (898/10000 buffer):

- Ad hoc 4 => ~0-2 trips

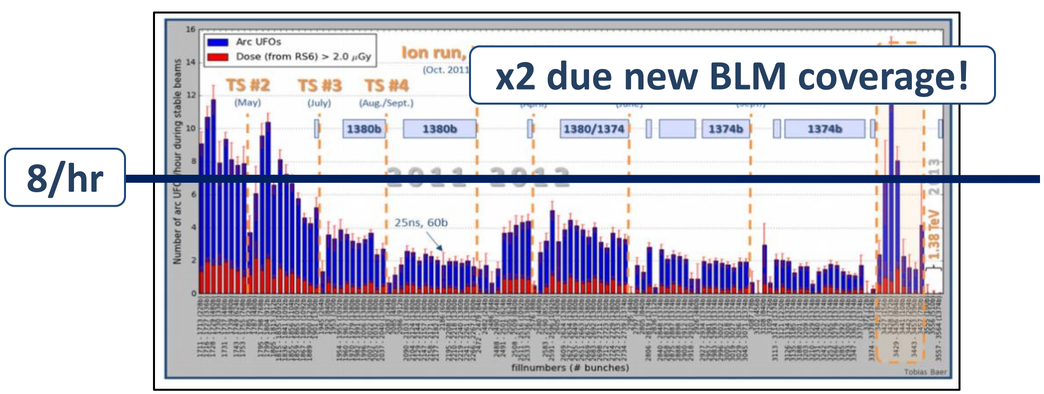
PRELIMINARY

Results Overview

- Table of results:

	BLM Positions	No. of Iter	No. of UFOs	No. of Trips
4 Tev - 50ns	Old	10000	740	1-2
6.5 TeV - 50ns - Adhoc 4	New	10000	1060	1-3
6.5 TeV - 50ns - Adhoc 1	New	10000	1060	10-30
6.5 TeV - 25ns - Adhoc 4	New	10000	898	0-2

- Putting that into little perspective (take with a pinch of salt):



Consider 16 ufo/hr and an 8 hr/day LHC uptime (~35% availability)…

50 ns Results predict:

- Ad hoc 4 => ~1-3 trips/7 days

- Ad hoc 1 => ~10-30 trips/7 days

Let's hope QP3 was indeed wrong!

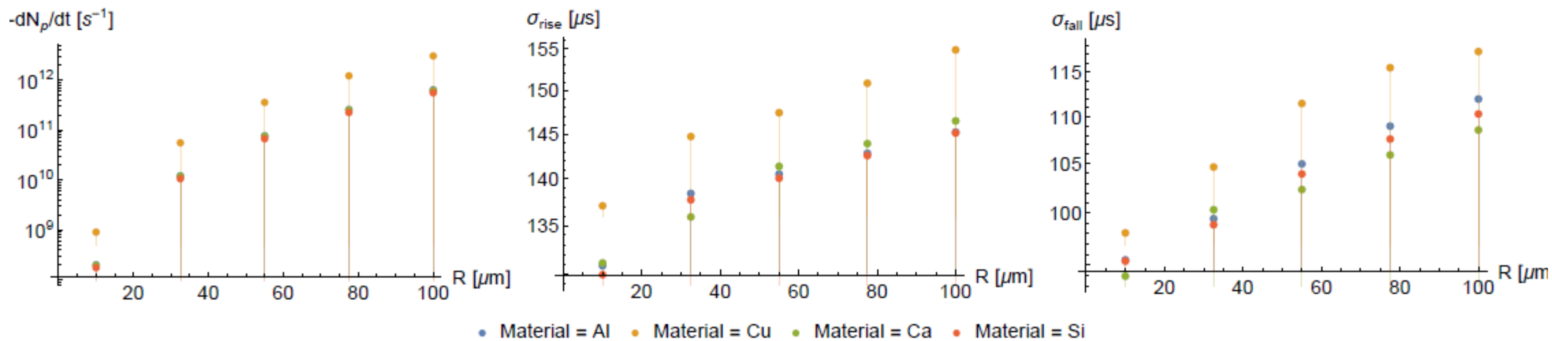
Conclusions/Further Work

- **Numerical model constructed and Monte Carlo simulations carried out**
- Model takes into account **longitudinal beam variation** and **re-absorbtion** of scattered ‘knock-on’ electrons during interaction
- Model allows for the first time an **impact study of the UFO threat to availability at 6.5 TeV**
- 4 TeV Monte Carlo results can be fit within very good agreement to measured data **using only acceptable parameter ranges**
- **6.5 TeV predictions show that the probability of a trip occurring is in the order of 0.1%/ufo**
  - Are these numbers troublesome? I’ll leave that conclusion up to you! ☺
- Studies into the **impact on availabilty, avoidable trips** and **mitigation strategies**, such as **defender bunches** and in planning or have already begun!

Thanks for listening!!

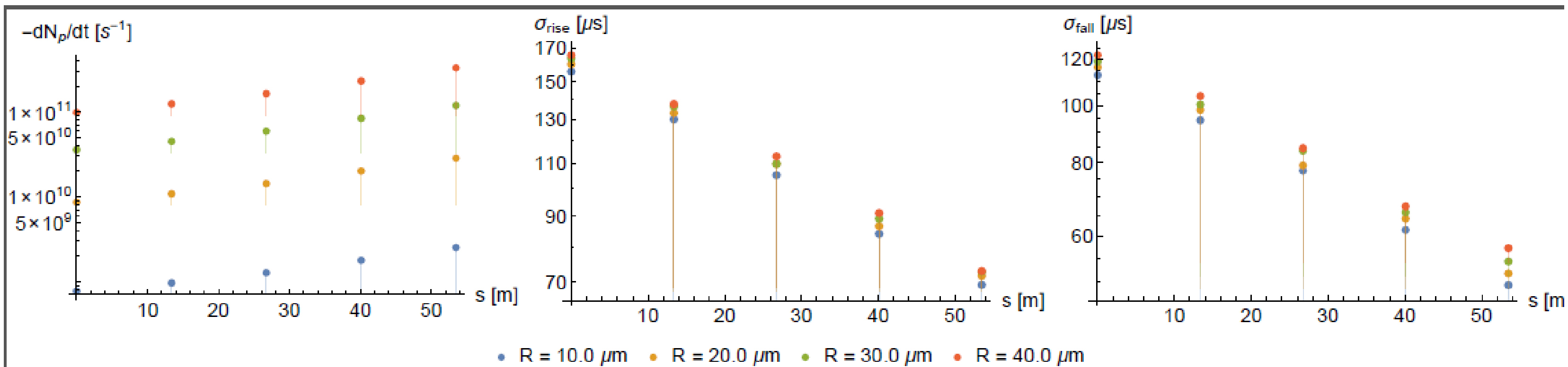
Appendix/Parametric Studies

Loss Rate vs Radius – Various Materials



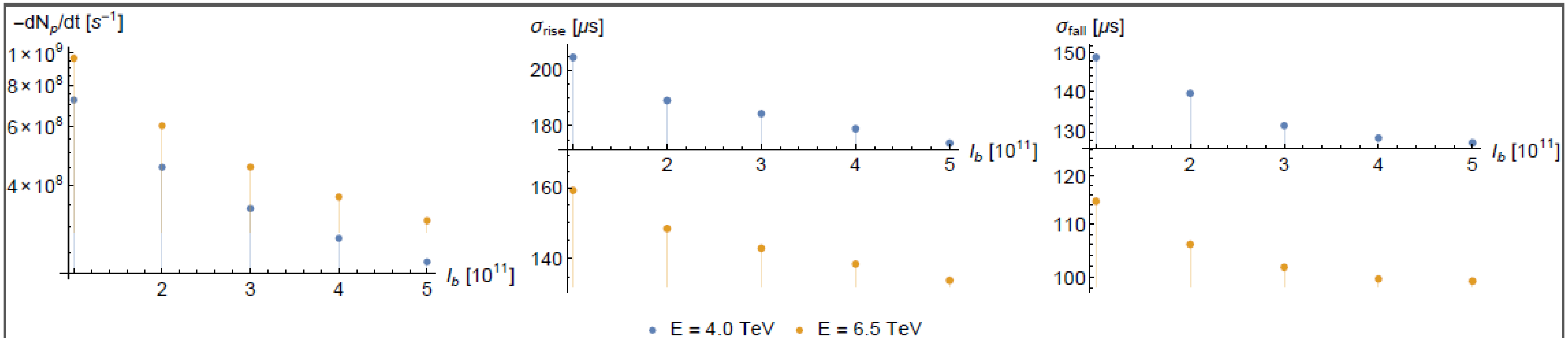
E [TeV] =	6.5	ϵ_n [μm] =	2.4	N_b [1] =	2808.	I_b [1] =	1.3×10^{11}	s [m] =	10.
x [mm] =	0.1	ϵ^*_n [μm] =	6.	N^*_b [1] =	100.	Defender =	0	AdHoc =	progressive

Loss Rate vs Long Location – Various Radii



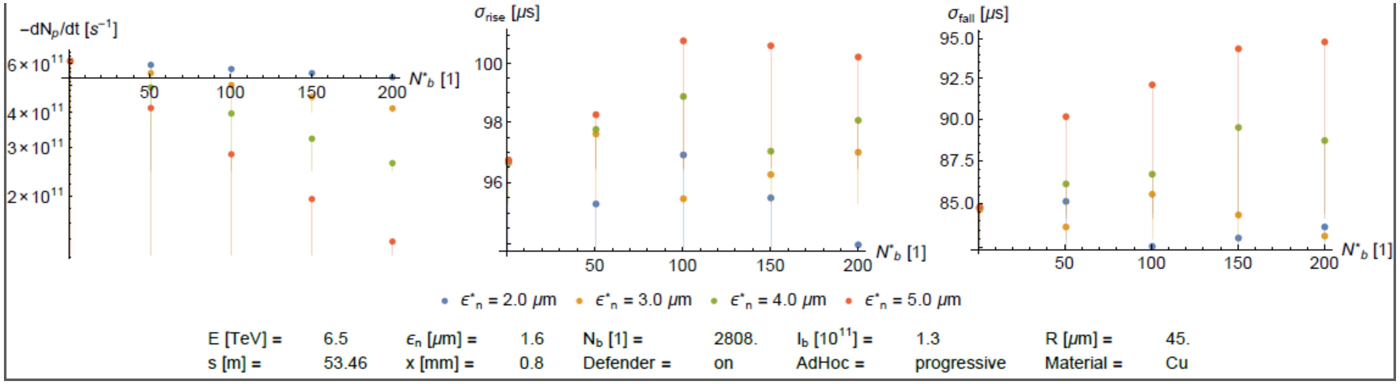
E [TeV] =	6.5	ϵ_n [μm] =	2.4	N_b [1] =	2808.	I_b [1] =	1.3	x [mm] =	0.1
ϵ^*_n [μm] =	6.	N^*_b [1] =	100.	Defender =	off	AdHoc =	progressive	Material =	Cu

Loss Rate vs Beam current – Diff Energies

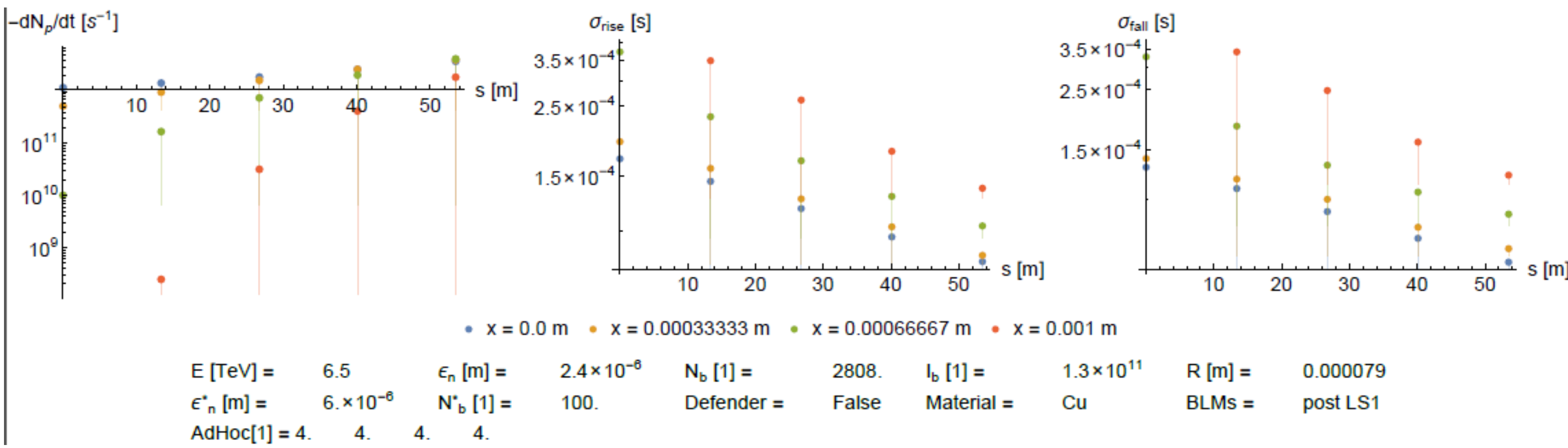


ϵ_n [μm] =	2.4	N_b [1] =	2808.	R [μm] =	10.	s [m] =	0.	x [mm] =	0.
ϵ^*_n [μm] =	6.	N^*_b [1] =	100.	Defender =	off	AdHoc =	progressive	Material =	Cu

Loss Rate vs No. of bunches – Varying Emittance



Loss Rate vs Radius – varying trans Loc



Defender Preliminary
- Various emittances/No. of Defenders