SEARCH FOR MAGNETIC MONOPOLES IN THE ATLAS EXPERIMENT

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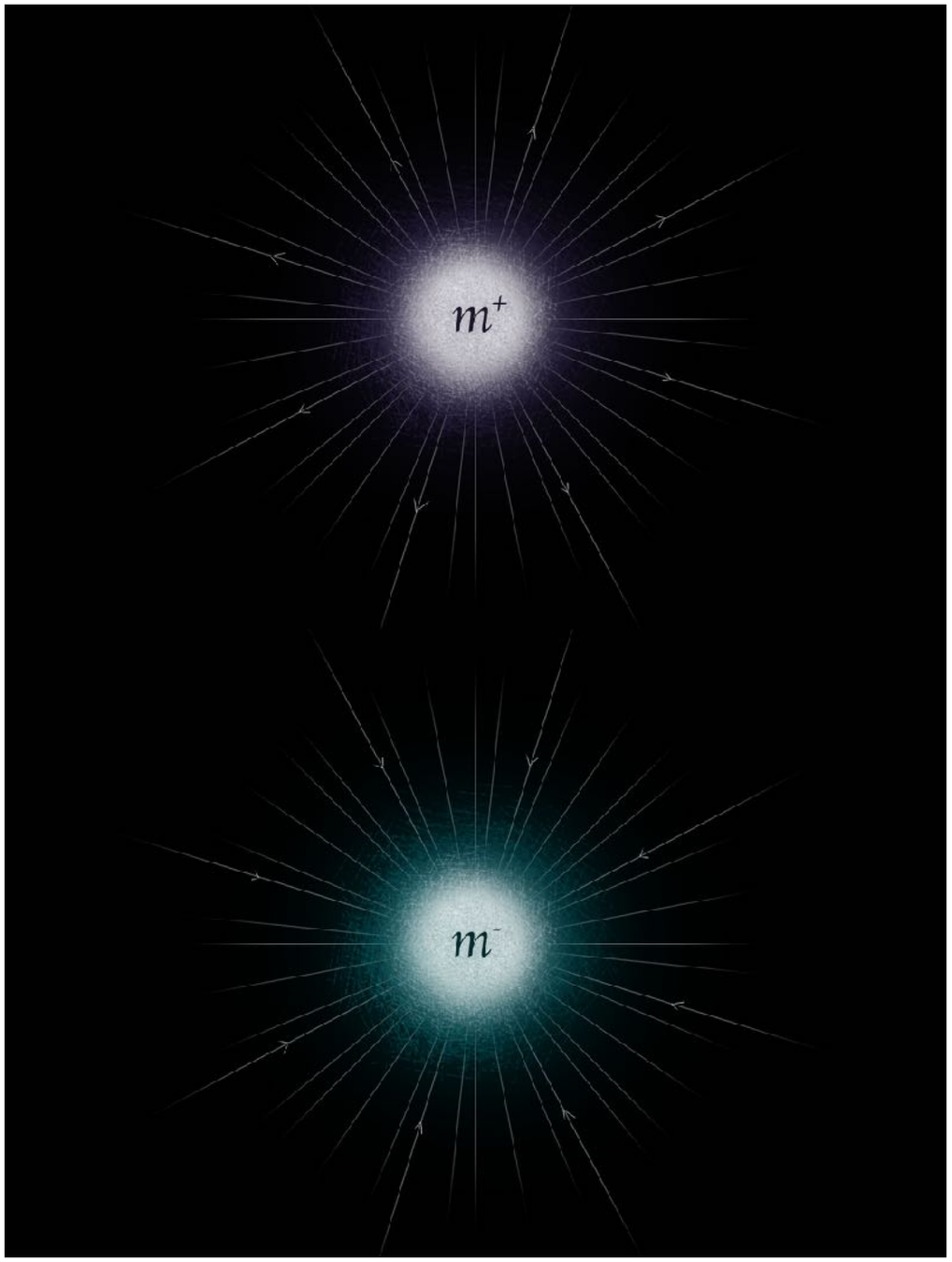
arXiv:1905.10130

ATLAS EXPERIMENT

YORK UNIVERSITÉ UNIVERSITY

WHAT ARE MAGNETIC MONOPOLES?

MAGNETIC MONOPOLE



- Electric monopole: particle with **electric charge "*e*"**
  - Static source of electric field
- Magnetic monopole: particle with **magnetic charge "*g*"**
  - Static source of magnetic field

WHY SEARCH FOR MAGNETIC MONOPOLES?

SYMMETRY IN MAXWELL'S EQUATIONS

In a sense, Maxwell's equations *beg* for magnetic charge to exist—it would fit in so nicely. And yet, in spite of a diligent search, no one has ever found any.

- Griffiths "Introduction to Electrodynamics" p.338

"Monopole-Free"

$$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \epsilon_0 \mu_0 \left(\mathbf{j_e} + \frac{\partial \mathbf{E}}{\partial t} \right)$$

$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{B}}{\partial t}$$

$$\rho_m = 0$$

$$j_m = 0$$

SYMMETRY IN MAXWELL'S EQUATIONS

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With Magnetic charge

$$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = \mu_0 \boxed{\rho_m}$$

$$\nabla \times \mathbf{B} = \epsilon_0 \mu_0 \left(\mathbf{j_e} + \frac{\partial \mathbf{E}}{\partial t} \right)$$

$$\nabla \times \mathbf{E} = -\mu_0 \left(\boxed{\mathbf{j_m}} + \frac{\partial \mathbf{B}}{\partial t} \right)$$

DIRAC MAGNETIC MONOPOLE

- Explanation for quantization of electric charge:

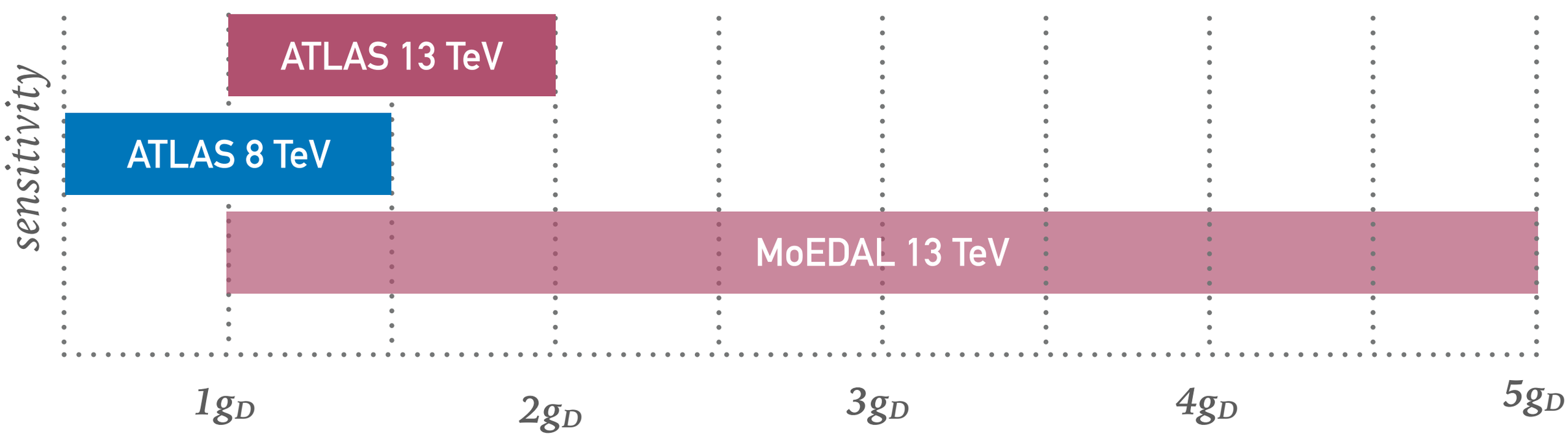
"The theory leads to a connection (…) between the quantum of magnetic pole and the electronic charge." -Dirac 1931

$$\frac{q_m q_e}{\hbar c} = \frac{n}{2} \qquad q_m = 68.5e = 1 g_D$$

- Fundamental, stable
- No constraint on mass or spin
- Interacts with matter as high electric charge object of the same mass

RELEVANCE OF THIS STUDY

- Magnetic Monopole has not been observed.
- LHC might be producing them.
- We have data: ATLAS experiment collects valuable "all purpose" data.
- Complements other Dirac Magnetic Monopole searches:



PRODUCTION MECHANISM AT THE LHC:

PAIR PRODUCTION MODEL

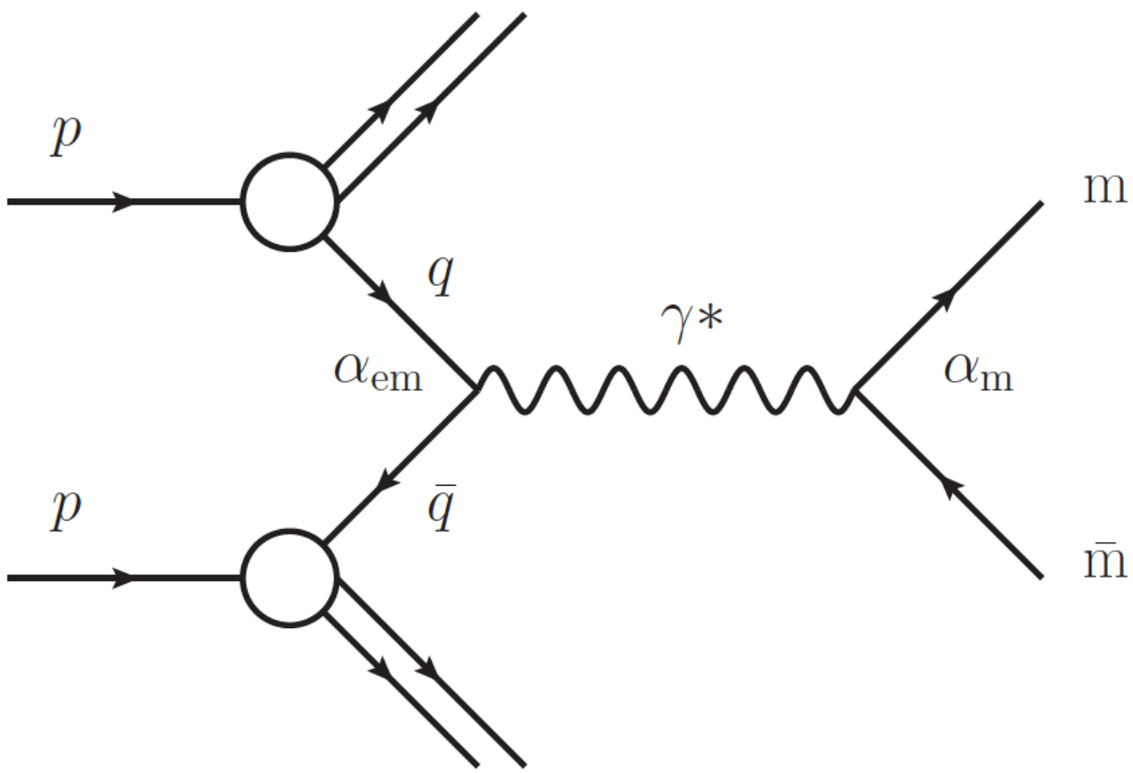


Diagram for Drell-Yan mechanism of magnetic monopole pair production: Two monopoles, of opposite magnetic charge, coupling to a photon.

- Monopoles interact through electromagnetic force - couple to photon
- **Drell-Yan (DY)** pair production
- We consider monopoles of:
  - Spin: 0 and 1/2
  - Charges $|g|=1\ g_D,\ 2\ g_D$
  - Masses: 200, 500, 1000, 1500, 2000, 2500, 3000 and 4000 GeV

WHAT SIGNAL ARE WE LOOKING FOR?

HIGHLY IONIZING PARTICLES: HIPs

~4700 x more ionizing than proton!

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 N_e}{m_e c^2 \beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2})\right]$$

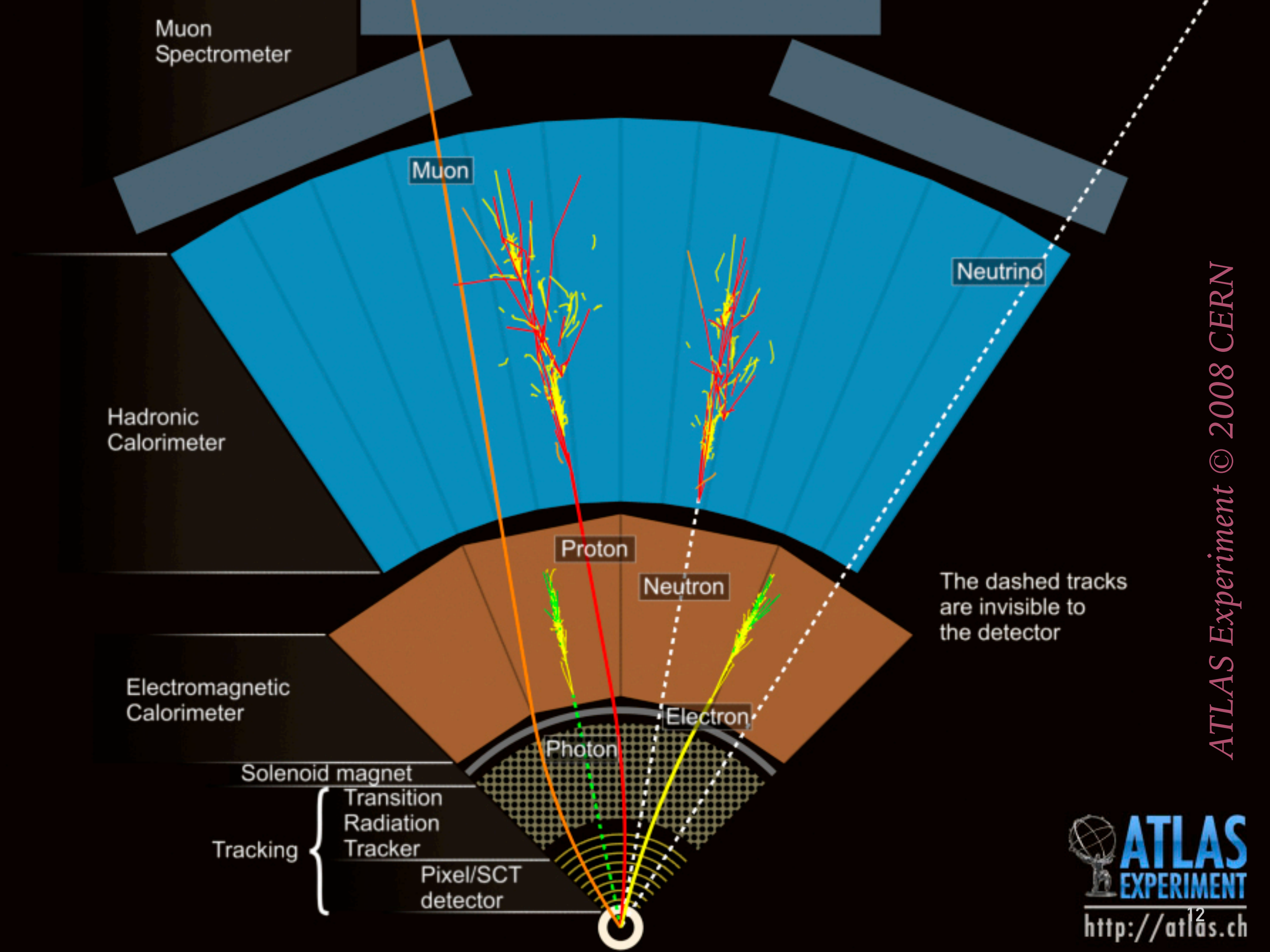
Bethe-Bloch

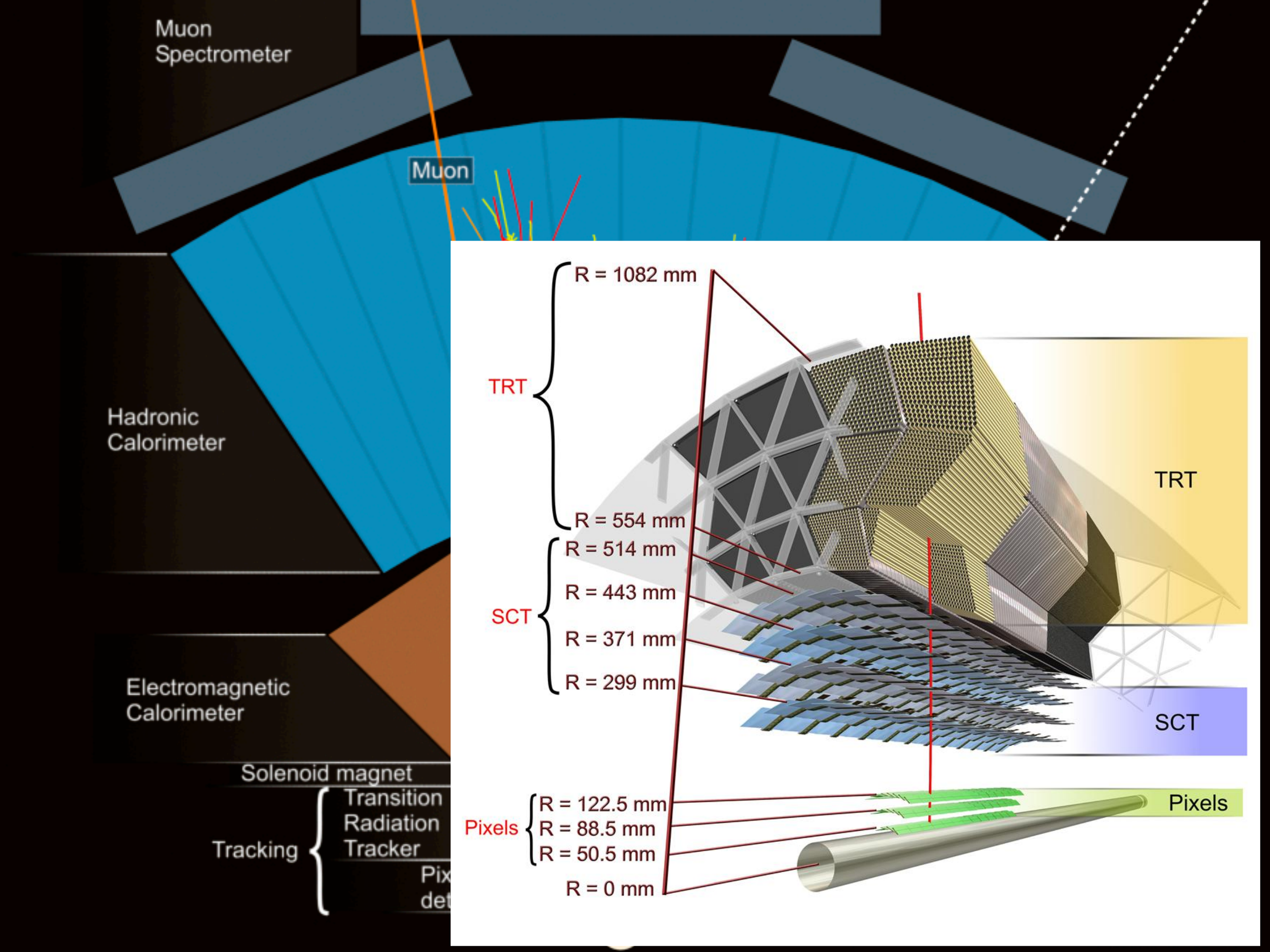
INTERACTION WITH MATTER

- HIPs don't shower in ATLAS (too massive)
- Ionization of the medium
  - Interaction with matter (Bethe-Bloch formula).
  - Energy loss ∝ charge^2

$$-\frac{dE}{dx} = \frac{4\pi e^2 g^2 N_e}{m_e c^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) + \frac{k(g)}{2} - \frac{1}{2} - \frac{\delta}{2} - B(g))\right]$$

Bethe-Ahlen Phys. Rev. D17(1978) 229


Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch
ATLAS Experiment © 2008 CERN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Transition
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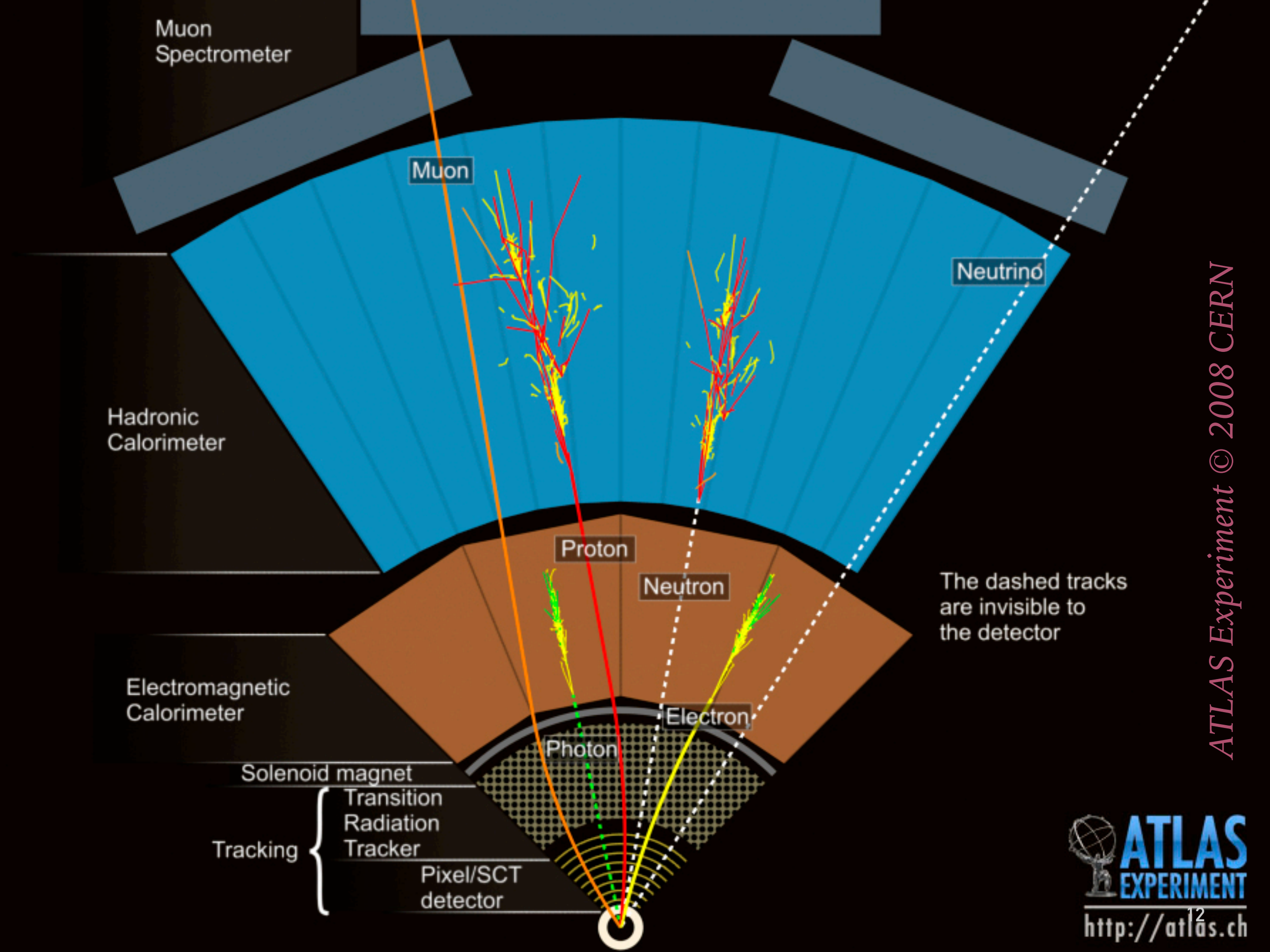
R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
TRT
SCT
Pixels
R = 122.5 mm
R = 88.5 mm
R = 50.5 mm
R = 0 mm
Pixels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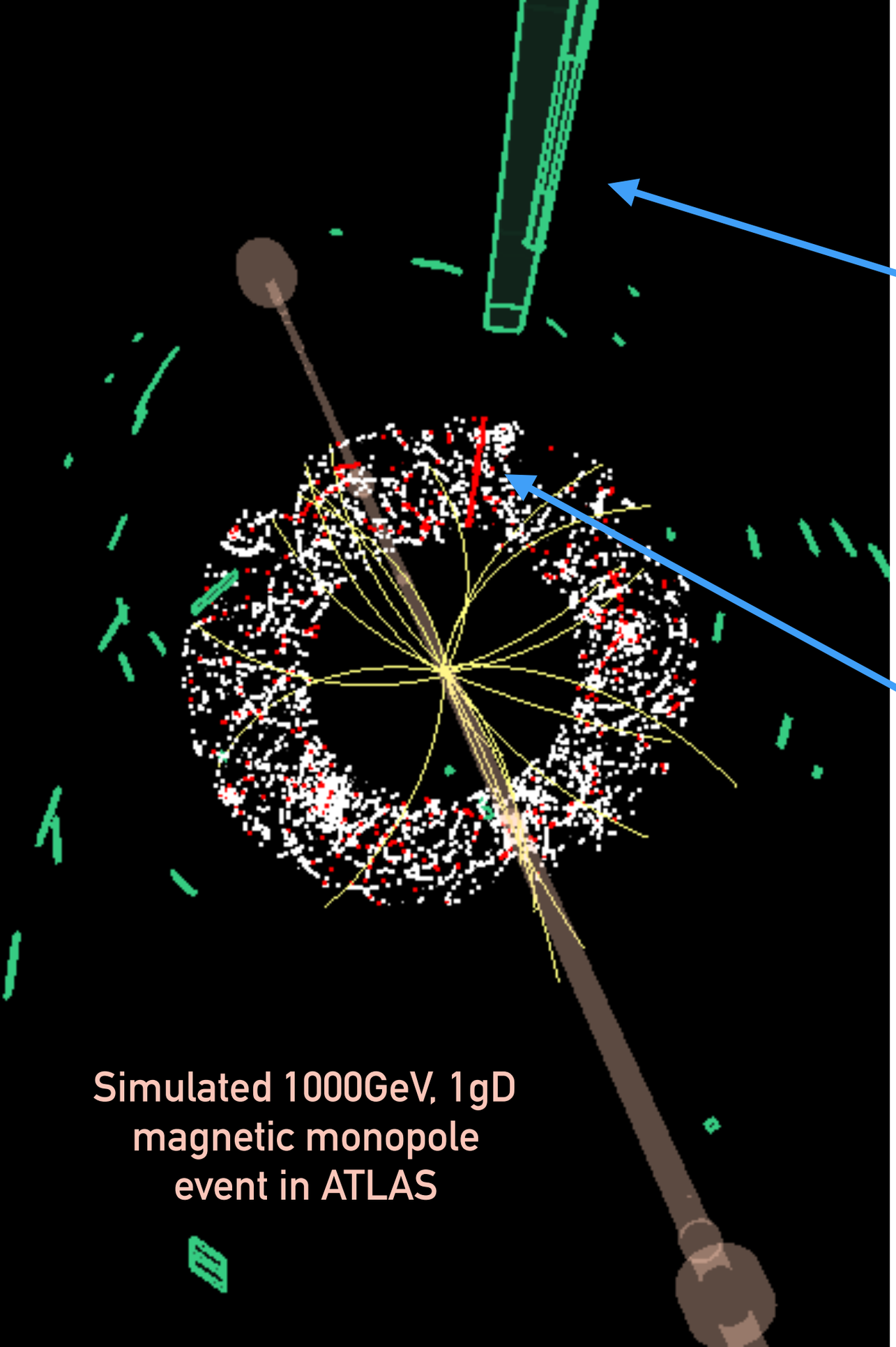
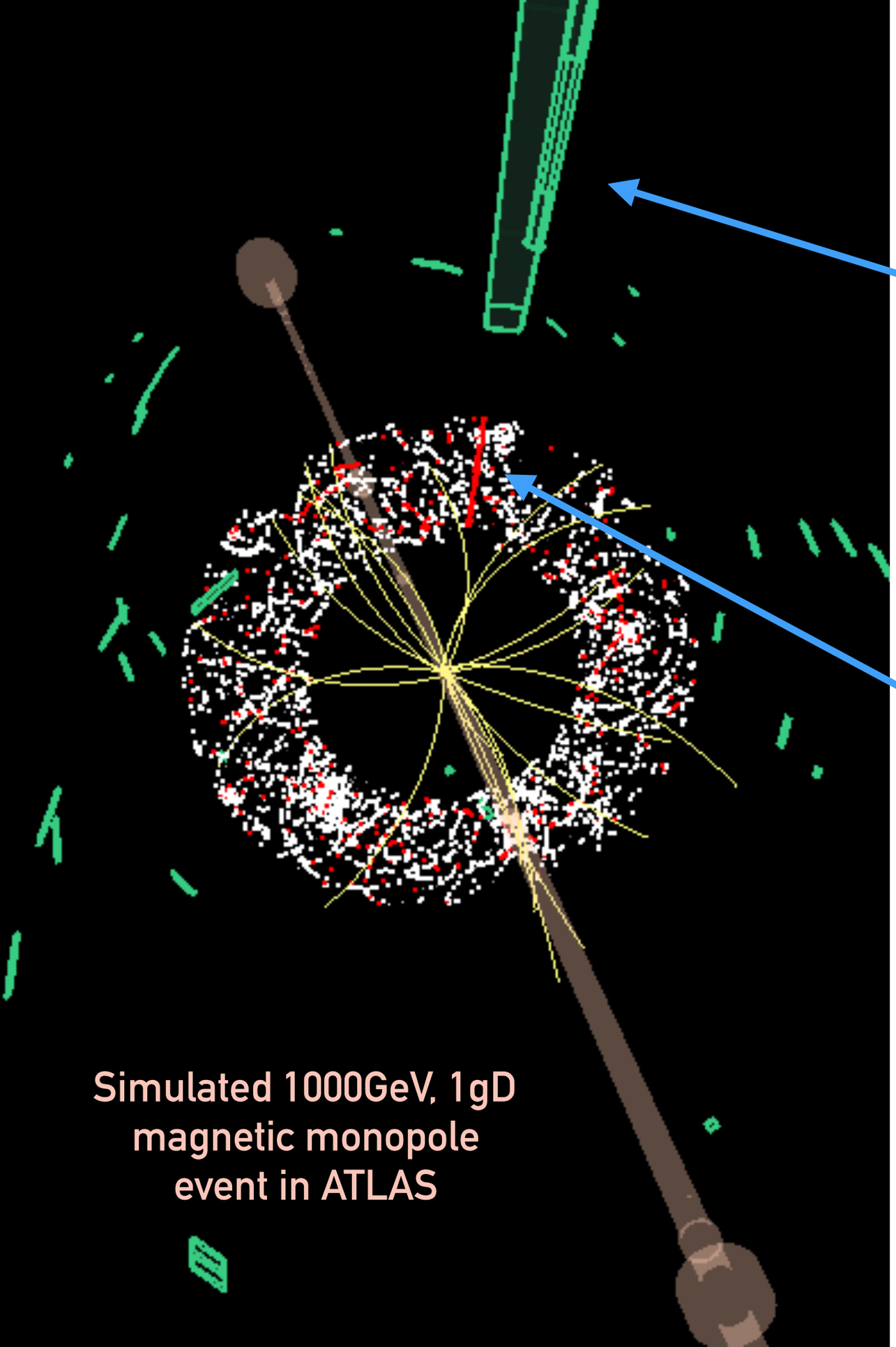


CHARACTERISTIC SIGNATURE OF HIPS:

- **Concentrated high energy deposition** in the LAr EM calorimeter.
- **TRT High Threshold hits**
  - High ionization trajectory



SIGNAL DISCRIMINATING VARIABLES:

- Average concentration of the cluster of energy deposited by the particle in the first three layers of the calorimeter:

$$w$$

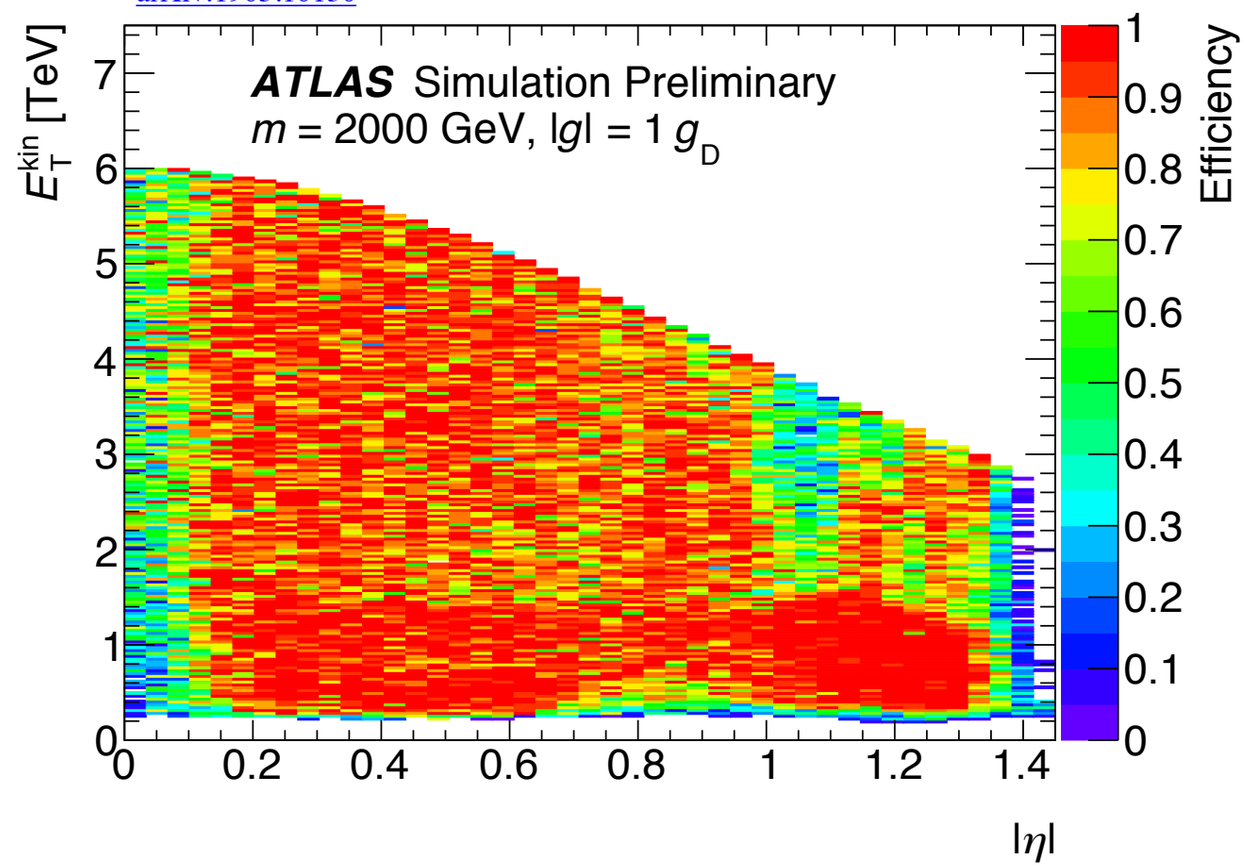
- Fraction of straws in the path of the particle that received an energy deposition which exceeded the high threshold:

$$f_{HT}$$

DATA AND MONTE CARLO

- **Data collected** during Run 2, 2015-2016, **13 TeV proton-proton collisions**
  - 34.4 fb^{-1} integrated luminosity
- MC:
  - **Full simulation (ATLAS Geant4):**
    - **Efficiency** of our signal
  - **MadGraph(complete):** 4-vectors (generator level) and cross sections

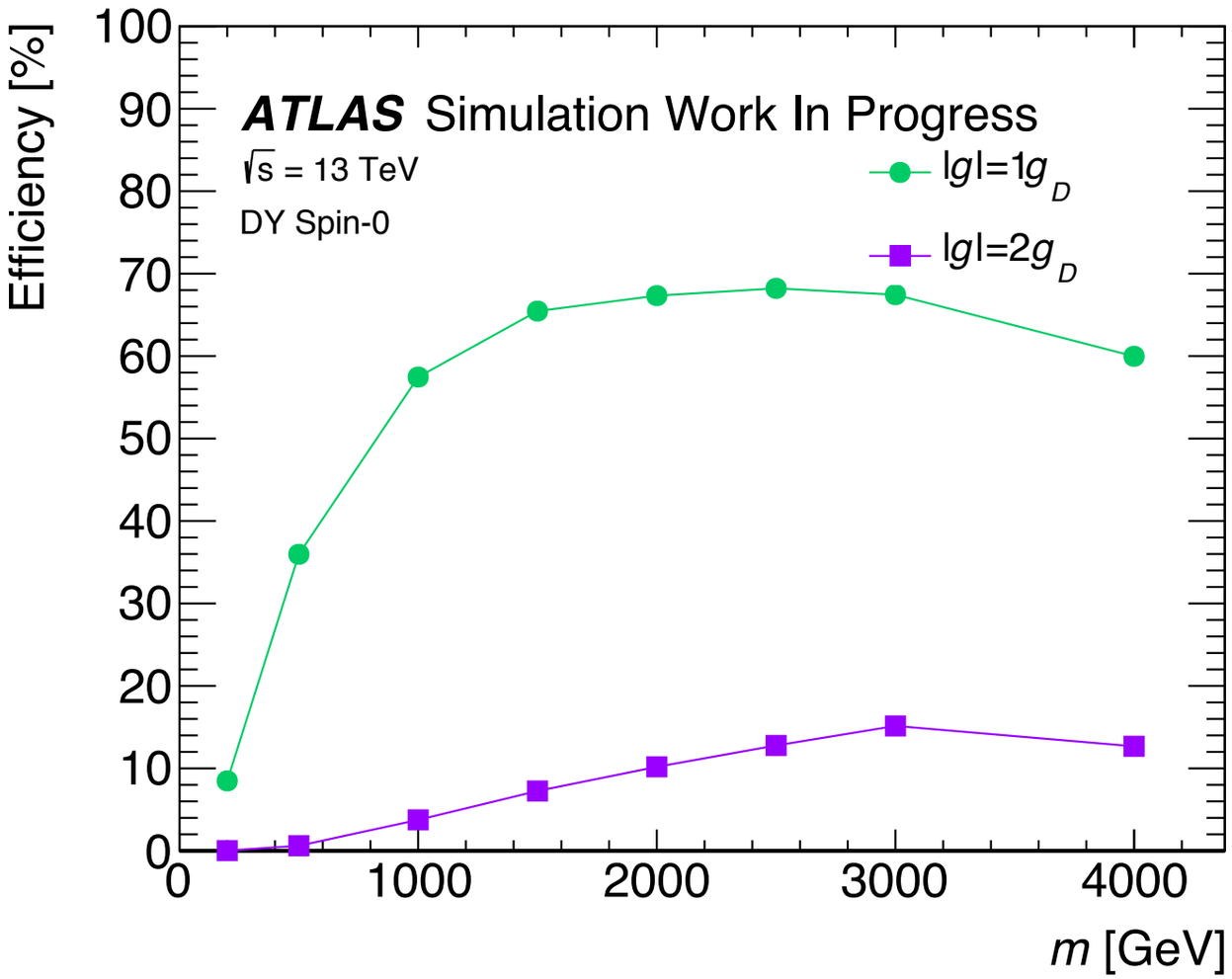
arXiv:1905.10130



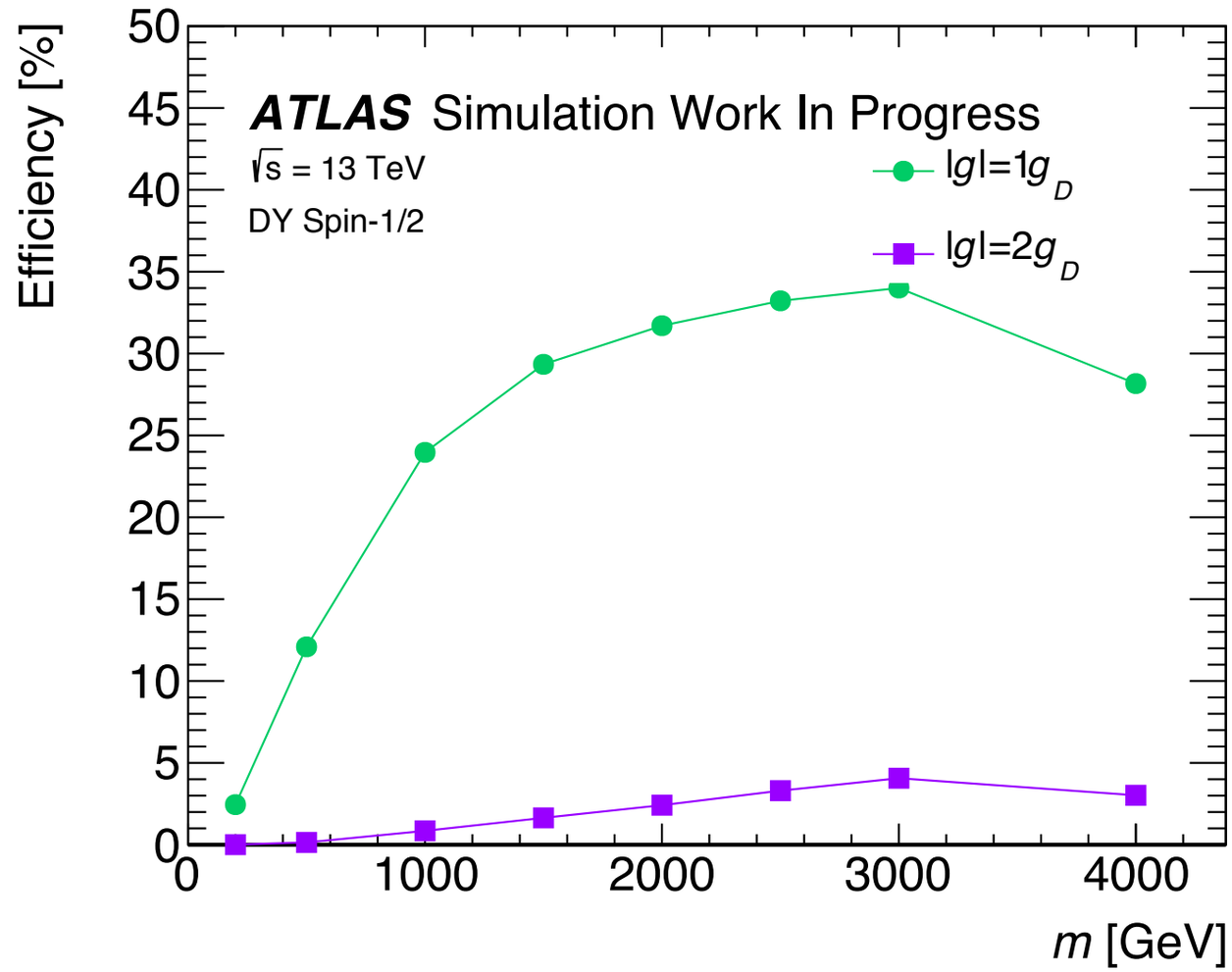
Final reconstruction efficiency vs transverse kinetic energy and |η| for single particle mass 2000GeV charge $1g_D$ monopole

OVERALL SIGNAL EFFICIENCY

SPIN 0



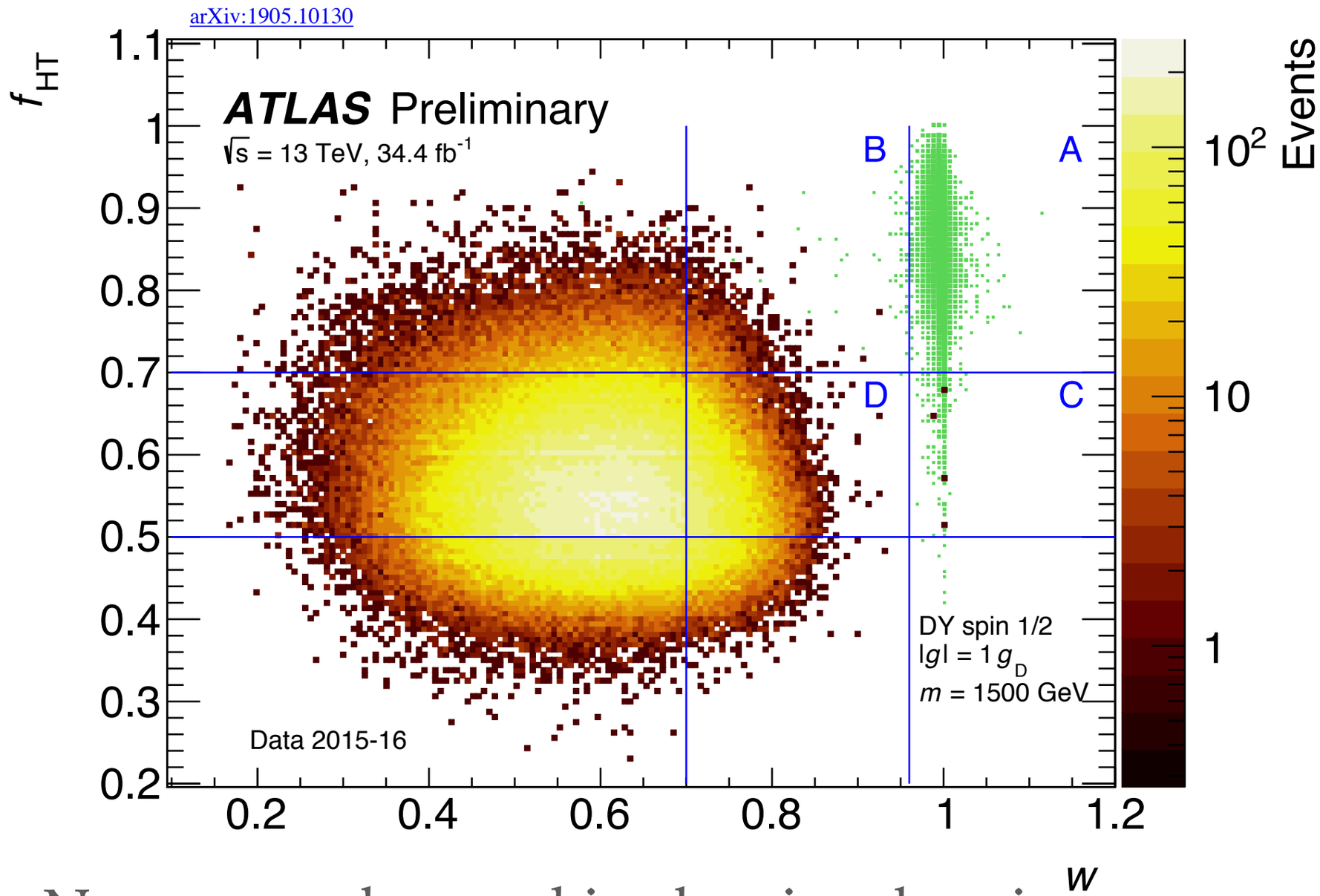
SPIN 1/2



Signal efficiencies for spin 0 (left) and 1/2 (right)
Drell-Yan Dirac Magnetic Monopoles.

WHAT DID WE FIND?

RESULTS



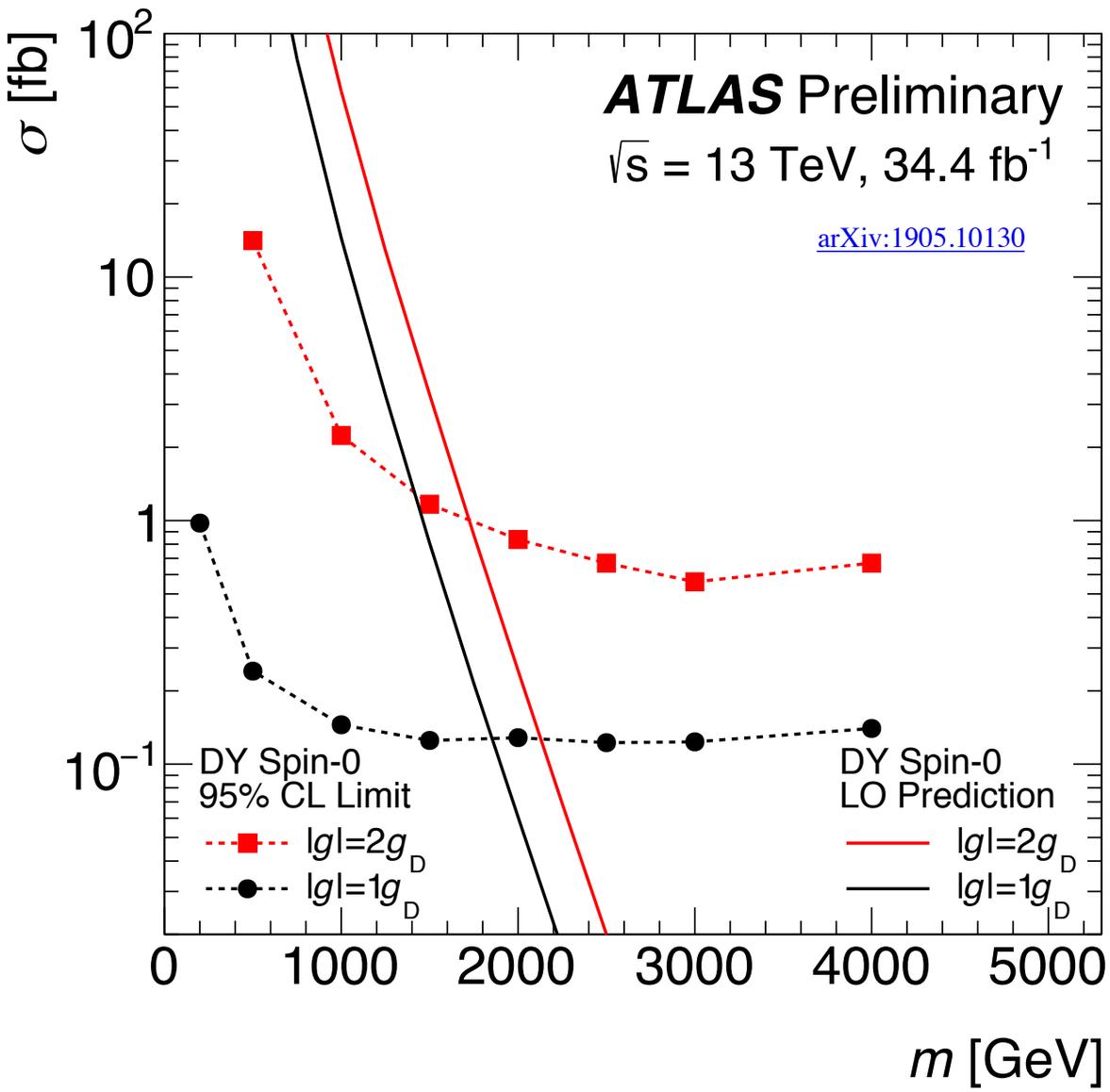
Distribution of discriminating variables: f_{HT} vs w for data (color scale) and a representative magnetic monopole (green).

- No events observed in the signal region.
- Background estimate:
  0.2 ± 0.11 (stat) ± 0.40 (sys) events.

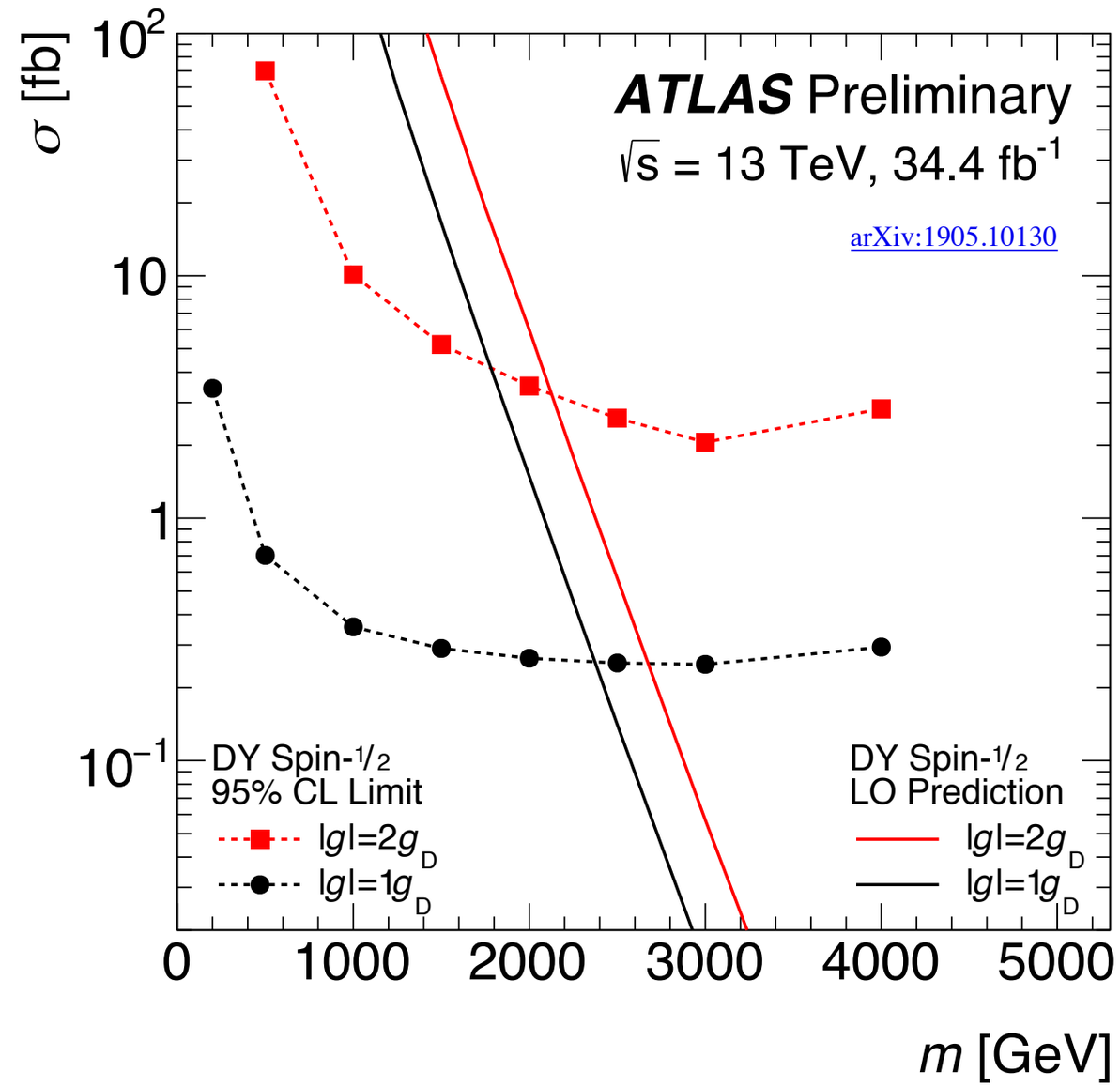
$$\frac{BC}{D} = A$$

CROSS SECTION UPPER LIMITS

SPIN 0



SPIN 1/2



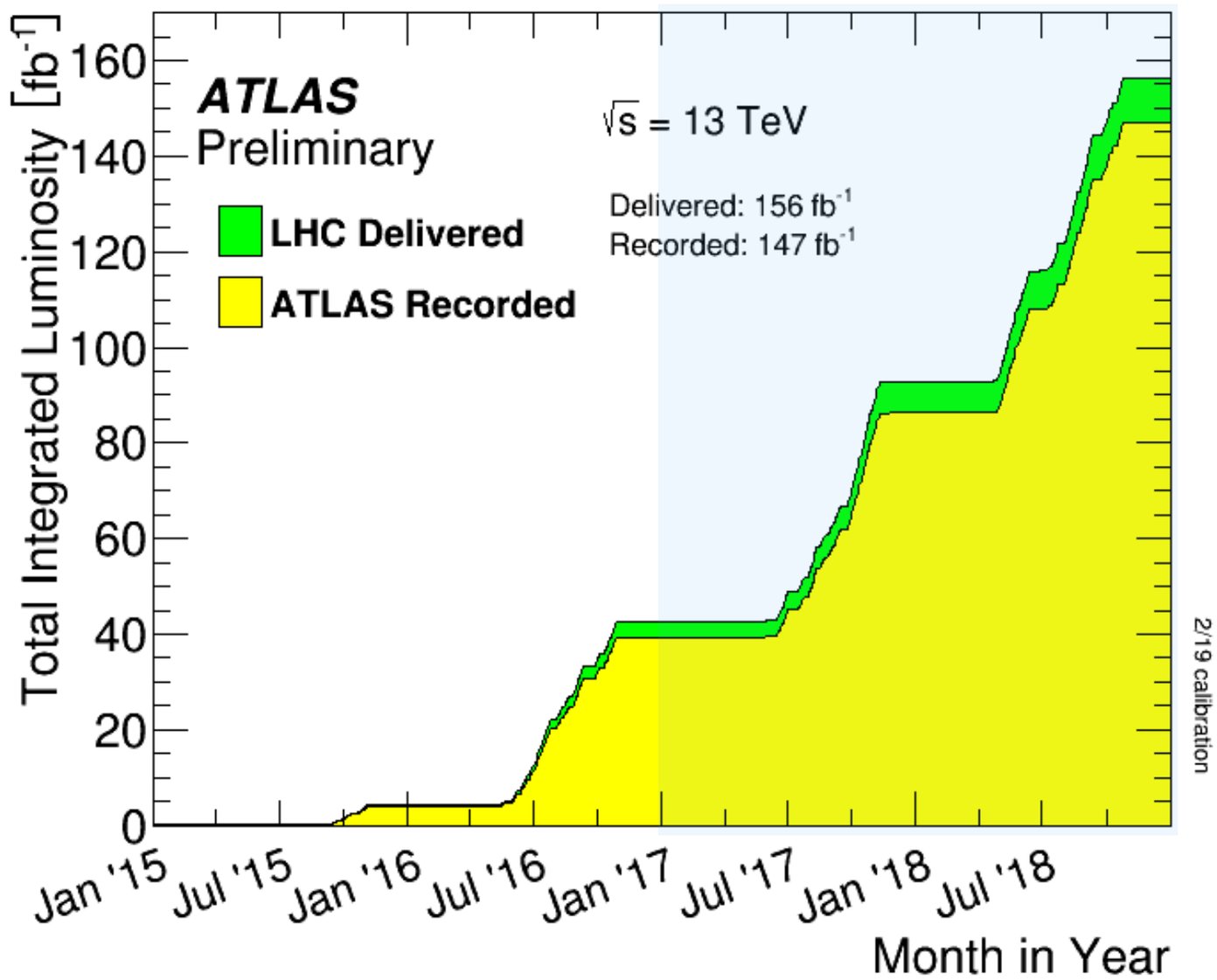
Observed 95% confidence-level upper cross-section limits for Drell-Yan spin 0 (left) and spin 1/2 (right) monopole production as a function of mass.

FUTURE PLAN:

- Keep looking for the Magnetic Monopole!
- More data:

$$\int L_{17+18} = 107.5\ fb^{-1}$$

- Aim to improve our signal to background



Cumulative luminosity versus time delivered to ATLAS (green) and recorded by ATLAS (yellow) during stable beams for pp collisions at 13 TeV centre-of-mass energy in LHC Run 2.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

THANK YOU!

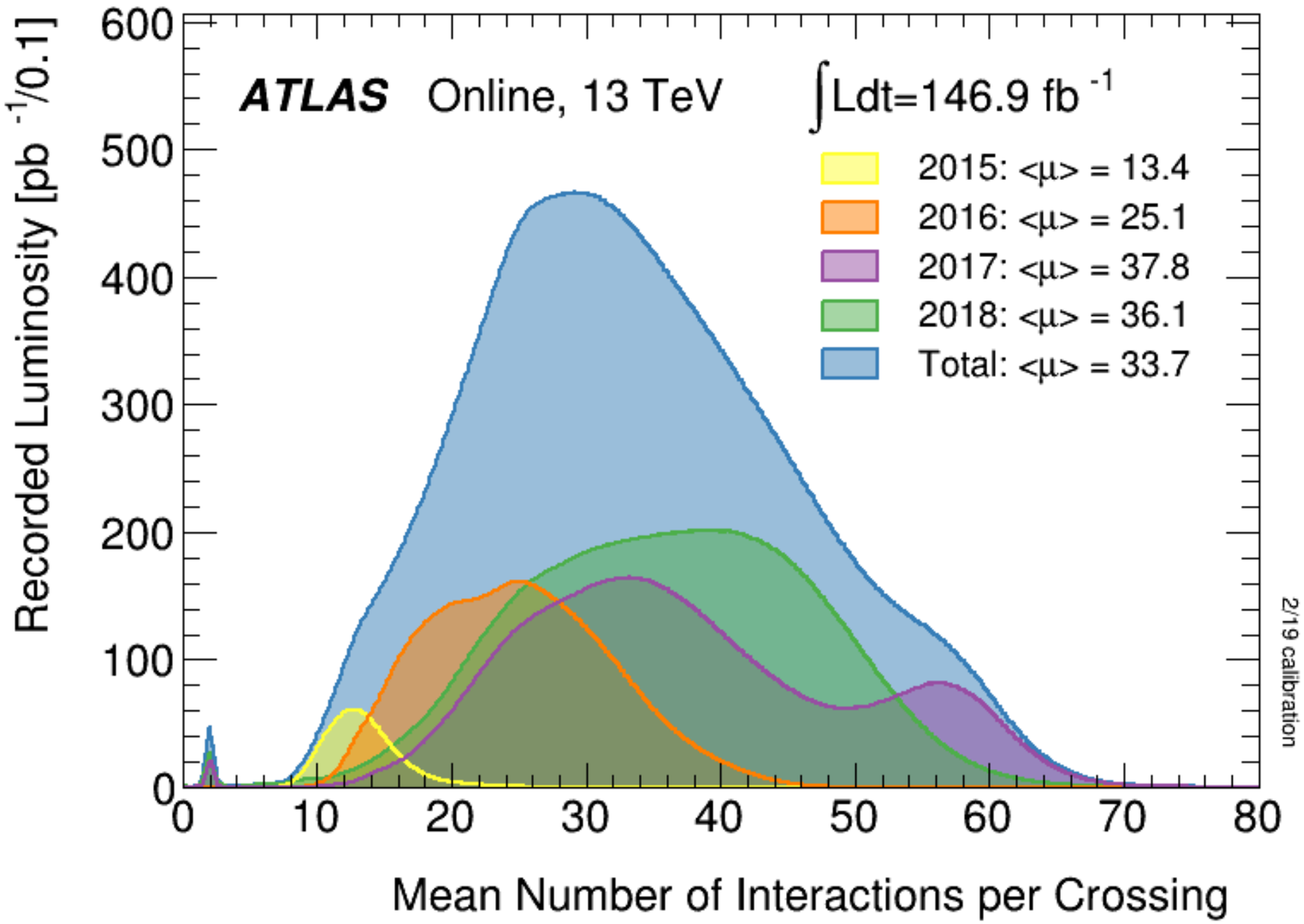
BACKUP SLIDES

FINAL SELECTION

- **Preselection**:
  - Level 1 EM calorimeter trigger to control rate $E_T > 22$ GeV
  - **Level 2** HIP trigger
  - Calorimeter cluster with $E_T > 18$ GeV
  - $|\eta| < 1.375$ to avoid transition regions and correlation between discriminating variables
- **Signal region** defined by:

$$w \geq 0.96 \text{ and } f_{HT} \geq 0.7$$

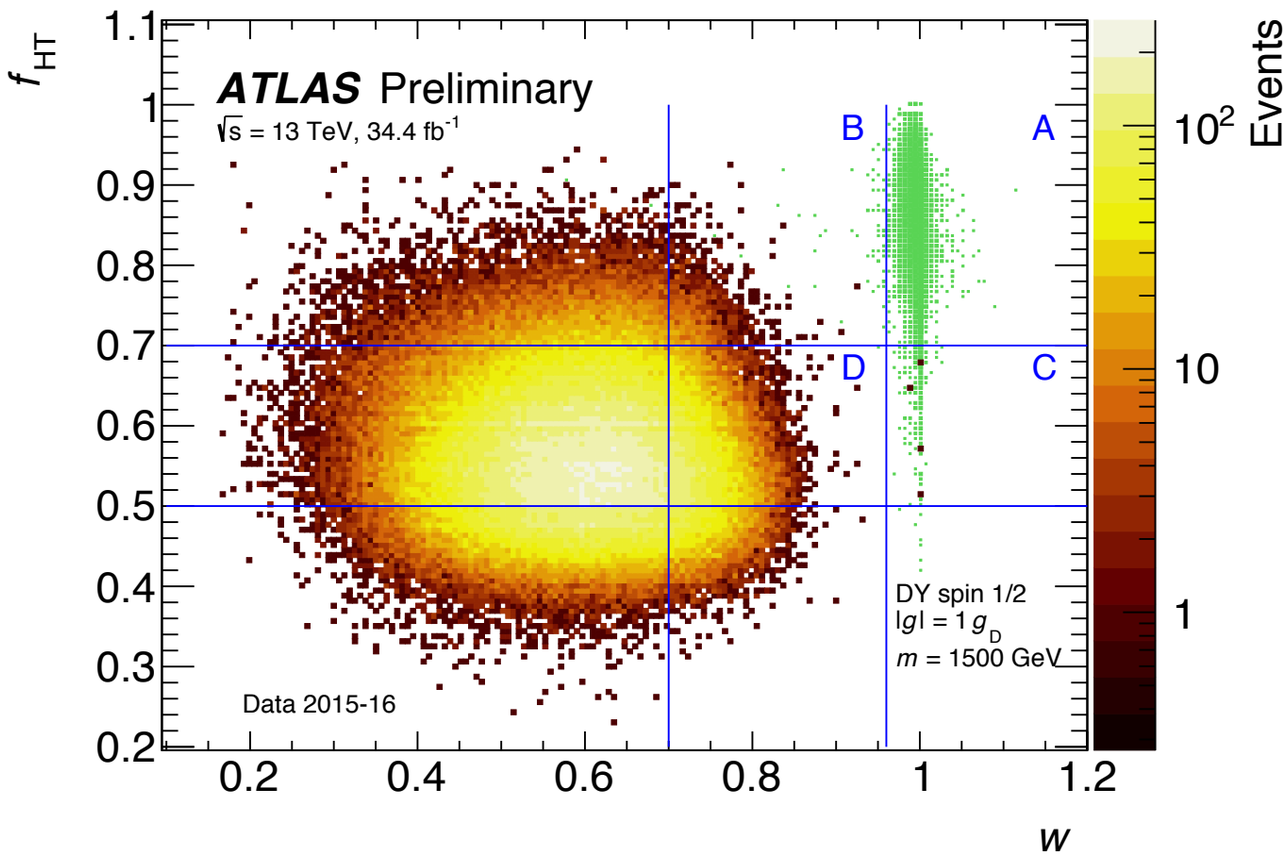
INTERACTIONS PER CROSSING



The luminosity-weighted distributions of mean interactions per bunch crossing for the different periods of data-taking in Run-2

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

arXiv:1905.10130



Two-dimensional distribution of variables fHT vs. w for data and DY spin 1/2 $|g| = 1g_D$ m = 1 TeV monopoles.

- Background estimate: **0.2 ± 0.11 (stat) ± 0.40 (sys)** events.

BACKGROUND ESTIMATE

- **Background** in signal region must be estimated
  - Absence of calibration source
  - data driven method
- **ABCD method**:
  - Three background regions (B,C,D), one signal region (A).
  - Two largely uncorrelated discriminating variables: **w** and **fHT**.
  - ***Transfer factor*** = B/D
  - C*B/D = A region background events estimate

ABCD METHOD CORRELATION STUDIES

The transfer factor evolves from 0.05 to 0.01 as we get closer to the signal region.

Choice for the larger transfer factor more conservative: (B*C/D=A).

Effects of averaging out the transfer factor (+/- 0.11).

The systematic uncertainty assigned (+/- 0.4) is quantifying correlation.

UNCERTAINTIES

- Reflect incomplete knowledge of simulation parameters
  - Detector material
  - Energy loss calculation yield
  - Range of δ-rays
  - Electron-ion recombination in EM calorimeter (Birks' law correction)
  - Energy cross-talk between adjacent EM Calorimeter cells
  - Calorimeter Arrival Time
  - Simulation of multiplicity of TRT low threshold hits as <μ>
  - Extrapolation
  - Pileup re-weighting
  - MC statistical uncertainty
  - Integrated luminosity (2.1%)

Δ-RAY PRODUCTION MODEL

- Monopole and δ-ray production **models in Geant4** have an **associated uncertainty of about 3%.**
- δ-ray production can **affect cluster width *w*** and **TRT HT hit fraction.**
- For monopoles, one can modify δ-ray production packages and randomly discard 3% of δ-rays.

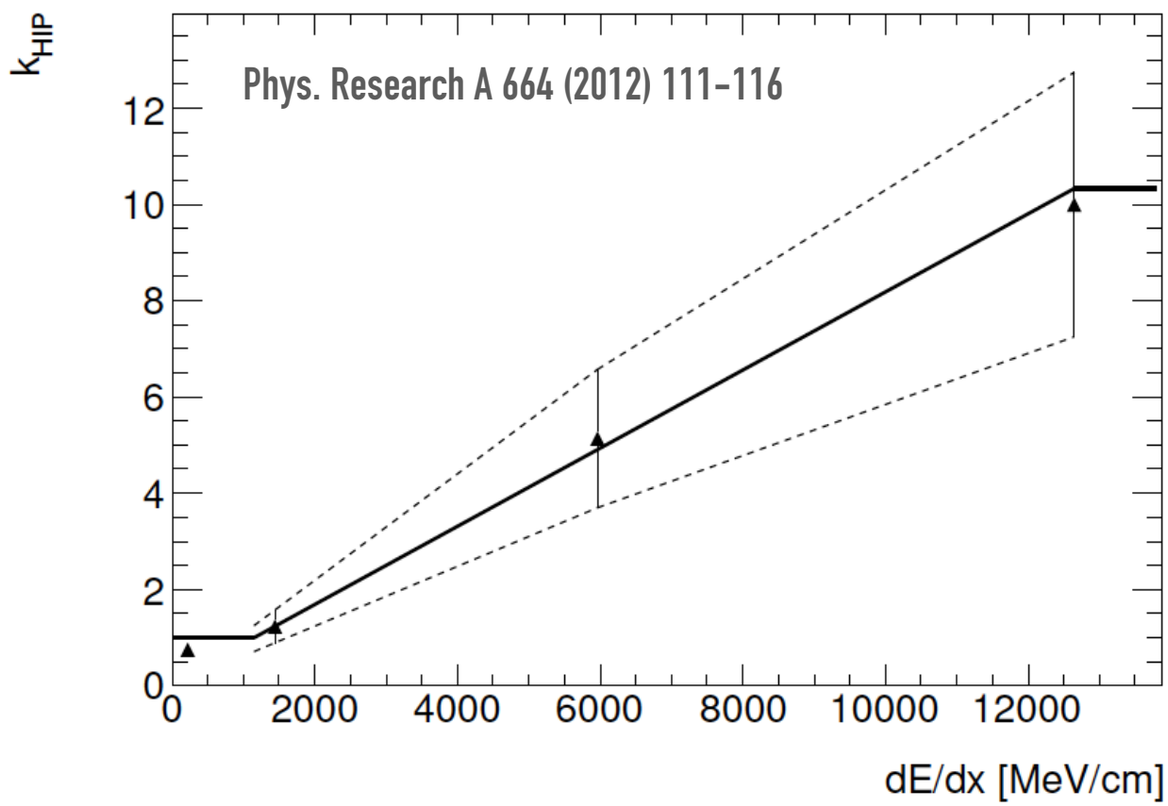
DETECTOR MATERIAL DENSITY

- Ionization is the dominant energy loss mechanism for HECO's and monopoles.
- Both Bethe-Bloch formula and its "equivalent" for magnetic monopoles depend on the material density.
- Innacuracy in the detector material results in uncertainty in the energy lost by the HIP.

GEANT4 RANGE CUT FOR Δ-RAYS

- **Geant4 does not** explicitly **simulate** low energy **δ-rays**.
- Energy corresponding to those δ-rays is added to the HIP trajectory in that "step".
  - This is crucial in the TRT, where this could **affect the HT fraction**.
- Shorter range cuts = more precise simulation.

BIRKS' LAW CORRECTION



Correction factor to Birks' Law for HIPs as a function of energy deposition in LAr. Dotted line represents upper and lower limits k uncertanty uncertainty.

- Energy deposited is quantified by charge collected in LAr cells.
- High ionization density (case with HIPs) can produce **recombination before** electron ionization is **recorded**. (Less charge recorded = Less energy recorded)
- **Birks' law finds factor** that "corrects" this **under estimation of energy**, depends on ICARUS data.
- There will be high and low estimates of these parameters.

FRACTION OF HIGH-THRESHOLD HITS: FHT

- Offline variable
  - Reconstructed object information
  - Uses **CaloCalTopoCluster**
- **fHT** calculated from 8mm rectangular road in TRT
  - Seeded from CaloCalTopoCluster
  - Iterative selection of high fHT regions with highest N_{HT}
  - Counting high and low threshold hits in a rectangular road (2 straws)

$$f_{HT,offline} = \frac{HT_{hits}}{HT_{hits} + LT_{hit}}$$

ENERGY DISPERSION: W

- HIPs **do not induce a shower** in the calorimeters
- **Narrow** energy deposition
- w_i is defined as the fraction of EMcluster energy contained in the most energetic 2 (4, 5) cells in the EM presampler (1, 2) for which :
  - $E_{0,1} > 10GeV$, $E_2 > 5GeV$
  - Either E_0 or E_1 condition has been satisfied.
- w = avg(w0,w1,w2)
- w of ~1 indicates narrow energy cluster.

BETHE-BLOCH

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 N_e}{m_e c^2 \beta^2}\left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2})\right]$$

z . . . charge of particle

βc . . . velocity of particle

I . . . mean ionization energy of material

δ . . . density effect correction

N_e . . . electron density of material or ze

$$-\frac{dE}{dx} = \frac{4\pi e^2 g^2 N_e}{m_e c^2}\left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right) + \frac{k(g)}{2} - \frac{1}{2} - \frac{\delta}{2} - B(g))\right]$$

$$B(g) = \begin{cases} 0.248 & |n| \leq 1, \\ 0.672 & |n| \geq 1.5, \end{cases}$$

$$k(g) = \begin{cases} 0.406 & |n| \leq 1, \\ 0.346 & |n| \geq 1.5 \end{cases}$$

$B(g)$ Bloch correction (low-energy collisions in which the monopole velocity approaches the orbital velocity of the electron).

$k(g)$ KYG correction (arises from the relativistic cross section)

BREMSSTRAHLUNG

Bremsstahlung

$$-\frac{dE_{rad}}{dx} = \frac{16NZ^2e^2g^4}{3\hbar mc^2}$$

Ionization

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 N_e}{m_e c^2 \beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \delta/2)\right]$$

$$-\frac{dE_{rad}}{dE_I} \approx \frac{4g^2Z}{3\pi\hbar c}\frac{m_e}{m} \approx 10^{-3}$$

$$\frac{4g^2Z}{3\pi\hbar c} \approx 10^4$$

$$\frac{m_e}{m} \approx 10^{-7}$$

High Level Trigger

- High-level trigger (**HLT_g0_hiptrt_L1EM22VHI**)
  - Deployed October 2015 after improvements from 2012 version.
  - $|\eta| < 1.7$ to avoid forward regions (high background rate)
  - Uses RoI **L1EM22VHI** as seed to define 0.2 rad wedge in φ in the TRT
  - Iteratively divides the wedge into bins and selects the bin with the **most High Threshold hits** $N_{HT,trig}$
  - Determines the fraction of high threshold hits applies a cuts to fHT and N_{HT}

$$f_{HT,trig} = \frac{HT_{hits}}{HT_{hits} + LT_{hit}}$$